Advanced Plasma Analyzer for Measurements in the Magnetosphere of Jupiter

- Doctoral Thesis -

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“I cursed my luck again as I slid down the monkey’s throat. Have my dreams of guzzling grog and plundering galleons been reduced to this? ‘Three small trials and you’re a pirate like us.’ Fair enough. If only I could stomach the foul brew these scurvy seadogs swilled, the rest would be easy.”

Guybrush Threepwood
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Abstract

The Jupiter Icy Moons Explorer is a planetary exploration mission that aims to study the moons of Jupiter in the planet’s vast magnetosphere. Among the various instruments on board is the Particle Environment Package (PEP), that is led by the Swedish Institute of Space Physics (IRF) in Kiruna. The Jovian plasma Dynamics and Composition analyzer (JDC) is one of six sensors within PEP and focuses on the characterization of positive ions. To be able to measure their three-dimensional distribution and composition, in-situ and in high time resolution, JDC has to cover a large field of view of $2\pi$ sr, for the desired energy range, in just a couple of seconds. An electrostatic analyzer within the sensor determines the energy per charge of such particles and a time-of-flight mass spectrometer measures their mass per charge. Constraints on weight and the radiation environment of Jupiter drive the design of the sensor: small and lightweight to allow extra shielding, but still large enough to accomplish measurements in the harsh radiation environment of Jupiter.

This work focuses on a new type of compact, electrostatic analyzer using spherical wedges and the start signal generation for the time-of-flight measurement using new venetian blind-type surfaces. Simulations on the electrostatic analyzer showed that the most promising design is a hybrid variant, using an inner shell with spherical wedges and a spheroidal outer shell. A prototype sensor was built and tested with successful results.

A reflectron-type time-of-flight cell measures the time it takes for a particle to pass a linear electric field. The time measurement has to be very accurate and requires that all ions enter the reflectron from the same start position. Commonly this is achieved with thin carbon foils of some nanometer thickness to provide a very accurate start position. Upon impact and after leaving a foil, ions generate secondary electrons that act as start signals for the time measurement. Foils require a substantial pre-acceleration of several kilovolts for the ions to penetrate the foil, thus increasing the size and mass of the instrument.

When incident ions are reflected at grazing angles from a surface, secondary electrons are released in the same way as with foils. To increase position accuracy during this reflection process, venetian blind-type start surfaces are investigated, where many smaller surfaces replace a large flat surface. The most promising sample was found to be micro pore optics, that were initially designed to focus gamma rays. In several experiments it could be shown that micro pore optics show good reflection properties when used as start surfaces in the time-of-flight measurement.
Both improvements allow a more compact and lightweight sensor that can be better shielded against the harsh radiation environment in Jupiter’s system.

Jupiter hosts the strongest radiation environment in the solar system, that could kill an unprotected human thousand times over.
Chapter 1

Introduction

Exploration is the search for information and resources. It is conducted by any living being that is able to move. An evolutionary advantage can be gained by finding resources that are easier to access or gaining knowledge for later beneficial use. However, exploration is not without the risk of simply wasting time or even worse results. Humans have quite successfully explored Earth in their constant search for new resources and to satisfy their curiosity. With the development of rockets that are able to leave the planet in the 1950s, the 20th century was the birth of space exploration. From the Moon to the outer planets, the celestial bodies in the Solar System became reachable, with the available resources as the only limiting factor. One of the many interesting objects within reach is the planet Jupiter, or rather, because of its many moons, the system of Jupiter. Icy, rocky or volcanic, each of the moons shows features that are found on Earth but as a dedicated body. How much more could those moons have in common with Earth? Planetary exploration in the 21st century must be guided by specific questions regarding the objects of interest to justify the amount of resources devoted to missions that reach far into the solar system. Nevertheless, any mission of this kind will always encompass an act of going where no one has gone before.

It was probably very early in human history that Jupiter was noticed as being different from common stars, because of its brightness and path through the night sky. Using a technology that had been newly developed at the time, the telescope, Galileo Galilei discovered the four large moons of Jupiter in 1610. The names suggested by Galileo (“Medicean stars”) did not last. Instead, the moons were named by Simon Marius following a suggestion from Johannes Kepler: “I think, therefore, that I shall not have done amiss if the First is called by me Io, the Second Europa, the Third, on account of its majesty of light, Ganymede, the Fourth Callisto...” The names persisted, but the numbering became obsolete; as of 2015, 67 moons of Jupiter have been discovered, and Io has become number five in order of ascending distance. The four large moons are often referred to as the Galilean moons.
1.1 Scientific background

1.1.1 Environment of Jupiter

Jupiter is the largest planet in the Solar System, with a diameter eleven times that of Earth and orbiting the sun at approximately five times the distance of Earth. Unlike the rocky Earth, Jupiter is mainly composed of hydrogen and helium around a rocky core and is classified as a gas giant. Despite its composition, Jupiter has a density slightly higher than that of water. The strong gravitation of the planet allows hydrogen to exist in a conducting liquid state, as so-called metallic hydrogen. This conductive liquid, under the influence of the planet’s rapid rotation period of approximately 10 hours, is believed to form a dynamo that generates the strong magnetic field of Jupiter. This process in a conducting liquid material is comparable to that on Earth in which a molten metal (e.g., iron) forms such a magnetic dynamo. The magnetic field of Jupiter is approximately one order of magnitude stronger than that of Earth. The magnetosphere of Jupiter, which is formed by the interaction of its magnetic field with the solar wind, is the largest in the Solar System. If visible from Earth, the magnetosphere of Jupiter would be larger than the Moon.

The magnetosphere of Jupiter can be, somewhat arbitrarily, divided into three parts, the inner (<10 $R_J$), middle (10 - 40 $R_J$) and outer (>40 $R_J$) magnetospheres. Thus, the moons Io and Europa (at distances of 5.9 $R_J$ and 9.4 $R_J$) reside in the inner magnetosphere, whereas Ganymede and Callisto (at 15.1 $R_J$ and 26.6 $R_J$) lie in the middle part of the magnetosphere. The inner magnetosphere hosts the main plasma source and the radiation belts. In contrast to Earth, where most of the plasma is brought by the solar wind, the plasma populating the magnetosphere of Jupiter originates from the Jupiter system itself, particularly the moon Io and its volcanoes. The large amount of mostly neutral particles from Io form a neutral cloud at approximately 5 to 10 $R_J$ that consists predominantly of sulfur and oxygen. The neutral cloud follows Io in orbit until the particles are eventually ionized to form the Io ion torus, which surrounds Jupiter completely. The ions in the torus have multiple charge states, with thermal energies of approximately 1 to 100 eV. In fact, the moon Io produces nearly 90% of the plasma in the magnetosphere of Jupiter.

Also in the inner magnetosphere are the inner radiation belts of Jupiter, which form one of the most hazardous regions in the Solar System. Fig. 1.1 shows the energies of particles in orbit around Earth and Jupiter for comparison. They peak at distances between 3-5 $R_J$, with electron fluxes exceeding $10^8 \text{ cm}^{-2} \text{s}^{-1}$. Below 3 $R_J$, the electrons lose energy via synchrotron radiation, which can be detected from Earth. A complex system of currents flows along magnetic field lines into Jupiter’s upper atmosphere, where they generate the aurora of Jupiter.
Figure 1.1: Spectra of electrons and protons trapped in geostationary orbit around Earth ($R_E = 5.6$) and in the orbit of Europa ($R_J = 9.4$)

The corotation of the plasma slowly breaks down in the middle magnetosphere and forms a magnetodisc with plasma temperatures of up to 10 keV. The particles from this plasma or current sheet interact with the moons and thus are not only generated but also lost at the moons.

In the outer magnetosphere, the solar wind has greater influence. The magnetopause toward the sun can be between 45 and 100 $R_J$ because the magnetosphere and the currents within it are highly dynamic. On the night side, it stretches more than 7000 $R_J$ and frequently as far as Saturn’s orbit.

Figure 1.2 shows selected key plasma parameters as a function of the distance to Jupiter. The plasma azimuthal velocity and density give the estimates for the flux in the region. Whereas the plasma’s corotation speed only slightly increases with distance, the particle density decreases by over 4 orders of magnitude.
**Figure 1.2:** Density, corotation speed and resulting flux of the plasma in Jupiter’s magnetosphere. The energies of hydrogen and sulfur dioxide are determined from their relative speeds at their respective positions. The crosses mark the positions of the moons on the x axis. The data are from Kivelson et al. [9].

### 1.1.2 Moons of Jupiter

Jupiter has a collection of satellites that can be classified into three groups: the Galilean satellites and inner bodies, the irregular satellites and the Trojan satellites. The irregular and Trojan satellites are captured objects or comets (temporarily captured) from various sources in the Solar System. Whereas the irregular satellites orbit Jupiter in large, eccentric, highly inclined orbits, the Trojan satellites occupy Lagrangian points L4 and L5 between the Sun and Jupiter. These points lead and trail Jupiter’s orbit around the Sun by approximately $60^\circ$ [10]. However, the focus of interest is clearly the Galilean moons: Io, Europa, Ganymede and Callisto.

Io is a rocky world of 3660 km in diameter that is squeezed by Jupiter’s tidal forces. It shows the highest volcanic activity of any body in the Solar System. According to Bagenal et al. [11], Io’s entire body has been recycled several times over the age of the Solar System. The volcanoes spew out large amounts of material, with sulfur dioxide as the major compound ($\sim 1 \text{ t/s}$). Io is situated within the radiation belts of Jupiter, and any further exploration of it will face the harshest environment imaginable for spacecraft.

Europa is also mostly rocky, but it is expected to have a substantial shell of water, on the order of 100 km in thickness. The surface is frozen solid, with contaminations of minerals. Europa’s diameter is 3121 km. The moon shows tectonic formations
with distinct features such as cracks and slices. Europa is close enough to Jupiter that tidal forces (heating) act on this moon. It is thus assumed that the water layer is partially liquid. Large detected water plumes on Europa further support this theory [12]. The possible liquid water is a unique feature of this moon and offers the possibility of an extraterrestrial habitat, especially if the liquid layer extends down to the rocky bottom [13].

Ganymede is the largest moon in the Solar System, with a diameter of 5262 km. It is a mixture of approximately 40% ice and 60% rock, with an iron-rich core. The moon still shows signs of tectonic activity but, because of the greater distance from Jupiter, less so than Europa. Ganymede has an intrinsic magnetic field that is believed to be generated by a dynamo similar to that of Earth. Ganymede is a unique object for study: a magnetized body located within a magnetosphere (that of Jupiter).

Callisto, with a diameter of 4820 km, also consists of a mixture of rock and ice. Its surface does not show tectonic features like those of the other Galilean moons, but it is heavy cratered. Tidal heating depends on the distance to Jupiter, and thus, Callisto is rather inactive; however, it is nevertheless an interesting body with unique surface features [14].

1.2 Missions to Jupiter

Jupiter has been visited by a number of spacecraft during flyby missions [15]. The first encounter was that of Pioneer 10 in 1973, immediately followed by Pioneer 11 in 1974, at closest distances of 2.8 and 1.6 Jupiter radii ($R_J$). In 1979, the Voyager probes followed on their grand tour through the Solar System, with closest approaches of 4 $R_J$ and 9 $R_J$, and added further information valuable for understanding the Jupiter system. In 1992, Ulysses flew by Jupiter, and in 1995, Galileo became the first mission to orbit Jupiter for in-depth studies. Despite the major failure of the high-gain antenna, which did not deploy, Galileo was very successful and provided most of the current knowledge of Jupiter’s system. On its way to Saturn, the spacecraft Cassini conducted a flyby with a closest approach of 140 $R_J$ in the year 2000. The latest flyby was that of the spacecraft New Horizons in 2007, which reached 32 $R_J$ at its closest approach. Currently on its way to Jupiter is the Juno spacecraft, which is scheduled to arrive in July 2016. The next planned mission to Jupiter is the JUICE mission, which is anticipated for 2030.

Whereas JUICE will focus on the moons, and Ganymede in particular, Juno is focused on Jupiter itself. No close encounter with the moons is planned [17].

1.2.1 Jupiter Icy Moons Explorer

The Jupiter Icy Moons Explorer (JUICE) is the next scheduled mission to Jupiter, planned for launch in 2022. This European-led mission arose out of a former collaborative mission with the American National Aeronautics and Space Administration (NASA), the Europa Jupiter System Mission/Laplace (EJSM/Laplace). It was to
involve two spacecraft: the Jupiter Europa Orbiter (JEO, provided by NASA) and the Jupiter Ganymede Orbiter (JGO, provided by ESA). Unfortunately, NASA resigned from the project, and JEO was canceled. JGO was continued as JUICE, with additional planned flybys of the moon Europa. This decision maximized the scientific return without incurring the expenses of a full mission take-over of JEO by ESA. JEO’s originally planned >50 flybys of Europa would drastically increase its radiation requirements, thus drastically increasing costs. JUICE will study Jupiter, Callisto and Europa but will focus on Ganymede as its major goal. After the launch in 2022 and 8 years of traveling through space, JUICE will arrive at Jupiter in 2030. During the first phase, the Jupiter tour, JUICE will focus on Callisto, Europa and Jupiter itself. Through several gravity assists by Ganymede (Callisto transfer), Callisto and Europa will be encountered at closest approaches of 200 km and 400 km. After the flybys of Europa, the inclination of JUICE’s orbit will be increased to study the polar regions of Jupiter, with an additional 9 flybys of Callisto. With further gravity assists, the spacecraft will head to orbit Ganymede, its final destination. During the Ganymede tour, the altitude of the spacecraft will be decreased until a nearly circular orbit of 200 km altitude is achieved. The nominal end of the mission will be reached with the disposal of the spacecraft on the surface of Ganymede.

<table>
<thead>
<tr>
<th>Date</th>
<th>Phase</th>
<th>Duration</th>
</tr>
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<tr>
<td>2022</td>
<td>Launch and cruise phase</td>
<td>96 months</td>
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<tr>
<td>Jan. 2030</td>
<td>Jupiter orbit insertion - Jupiter tour</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transfer to Callisto</td>
<td>11 months</td>
</tr>
<tr>
<td></td>
<td>Europa phase: 2 Europa flybys and 3 Callisto flybys</td>
<td>1 month</td>
</tr>
<tr>
<td></td>
<td>Jupiter high-latitude phase: 9 Callisto flybys</td>
<td>9 month</td>
</tr>
<tr>
<td></td>
<td>Transfer to Ganymede</td>
<td>11 months</td>
</tr>
<tr>
<td>Sept. 2032</td>
<td>Ganymede orbit insertion - Ganymede tour</td>
<td></td>
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<tr>
<td></td>
<td>High-altitude phase</td>
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<td></td>
<td>Medium-altitude phase</td>
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<tr>
<td></td>
<td>Low-altitude phase</td>
<td>1 month</td>
</tr>
<tr>
<td>Jun. 2033</td>
<td>Nominal end of mission</td>
<td></td>
</tr>
</tbody>
</table>

Table 1.1: JUICE mission timeline as of 2014

The primary scientific objectives defined for JUICE are as follows: Ganymede as a planetary object and potential habitat, Europa’s recently active zones, Jupiter’s atmosphere and magnetosphere, Callisto as a remnant of the early Jupiter system, and the satellite and ring system of Jupiter in general.

These general objectives will be addressed by a number of specific experiments and instruments covering a wide range of physical properties.

\[^1\text{The author prefers the previous name: “Laplace”}\]
1.3 Plasma particle instrumentation at Jupiter

All missions\footnote{NSSDC Master Catalog: \url{http://nssdc.gsfc.nasa.gov/nmc/}} studying Jupiter, either orbital or flyby, carry plasma analyzers for a range of several eV to tens of keV. The designs are different, except for the sibling instruments on Pioneer 10/11 and on Voyager 1/2. Quadrispherical energy analyzers (see Fig. 1.3 as example) have been used on spinning platforms, such as on Pioneer\cite{19}, Ulysses\cite{20} and Galileo\cite{21}. The Voyager probes \cite{22} used Faraday cups with a retarding potential analyzer. The latest flyby missions, Cassini\cite{23} and New Horizons\cite{24}, used hemispherical analyzers.

1.3.1 Plasma analyzer experiment on Pioneer 10/11

The plasma analyzers on Pioneer 10 and 11 utilize a double quadrispherical electrostatic analyzer with two energy resolutions, Detectors A and B. Detector A has a high-energy-resolution electrostatic analyzer with an analyzer constant (see section 4.1.1) of 9 and 26 channel electron multipliers (see section 5.5) to simultaneously cover $\pm 51^\circ$ of angular space. Detector B is a medium-energy-resolution electrostatic analyzer with an analyzer constant of 6. Instead of channel electron multipliers, 5 “flat-surface current collectors” are used. Detector A was run in pulse-counting mode, and Detector B simply measured the incident current, much like a Faraday cup. Because of the spin stabilization of the spacecraft, the sensor covered a hemispheric field of view in 6.25 s for each energy step\cite{19}.

Pioneer 10 was the first spacecraft ever to reach Jupiter, and despite spending only a few days in Jupiter’s magnetosphere, it accumulated 450 krad (4.5 kGy) behind 3 mm of aluminum \cite{25}. Pioneer 11 followed a year later and received 120 krad (1.2 kGy), although it came closer to Jupiter \cite{15}.

Wolfe et al.\cite{19} further report on the background radiation issues during flyby: “Sporadic plasma ion fluxes were observed, but their analysis has been complicated by high background rates due to penetrating energetic electrons and protons. Other than these high background rates observed in Jupiter’s inner magnetosphere the plasma analyzer experiment successfully withstood Jupiter’s intense radiation zones.” These authors further report that all channel electron multipliers worked flawlessly and that no appreciable degradation was seen.

One can conclude that the simple design of the first plasma instruments used at Jupiter was sufficient. The instruments survived the harsh Jovian environment and provided useful measurements.

1.3.2 The plasma experiments on Voyager 1/2

The Voyager probes use Faraday-cup-based instruments for plasma measurements. The incoming flux is measured based on the amount of incoming charge deposited in an electrometer (ammeter). The energy is determined by applying a variable voltage to retarding grids in front of the Faraday cup, forming a retarding potential
analyzer. The potentials are adjusted such that only positive or negative particles of higher energies can pass. Directional information is obtained through the use of several Faraday cups or separate sensitive areas.

Podzolko et al.\cite{15} report a dose of approximately 500 krad (5 kGy) for Voyager. No dedicated publication on the matter is available; however, NASA states\footnote{http://voyager.jpl.nasa.gov/mission/didyouknow.html} that “[an] unprotected human passenger riding aboard Voyager 1 during its Jupiter encounter would have received a radiation dose equal to one thousand times the lethal level”.

Although the plasma instrument on Voyager 1 has stopped working, the one on Voyager 2 is still operational (2015).

### 1.3.3 Galileo plasma instrumentation

The Galileo plasma spectrometer (PLS) was designed based on the experience from Pioneer and Voyager. Together with advances in technology, considerably improved measurement capabilities were achieved for PLS. The energy selection is performed by means of 6 quadrupoles stacked on top of each other to form 2+2 electrostatic analyzers. A voltage can be applied to the 2nd and 5th plates to allow the simultaneous measurement of positively and negatively charged particles. The passing particles are then detected by seven pairs of channel electron multipliers, for either negative or positive particles. At three positions (1 at detector A and 2 at detector B) at the exit of the ion electrostatic analyzer, small electromagnets are placed. Together with 2 aperture slits, the electromagnets enable mass separation of the incident species with a mass resolution of approximately 2 - 4. An overview sketch is presented in Fig. 1.3.

The energy range extends up to 53 keV/q, which is approximately ten times the range of the previous Pioneer and Voyager instruments. The time resolution was improved from 200 s and 100 s, respectively, to 0.5 s. The detectors of PLS are shielded with a minimum of 1 mm aluminum in all directions\cite{21}. According to Fieseler et al.\cite{26}, no radiation-induced errors have been reported for PLS. However, two of seven electron detectors showed no counts after insertion into Jupiter’s orbit\cite{27}. The reason is not known.

The background radiation was a problem for PLS, as indicated by Paterson et al.\cite{28} and by Siler\cite{29}, who write that “..for the particular case of Galileo PLS data, most of the records have little to no counts above background...”. The problem can be partially attributed to pure statistics because of the failure of the high-gain antenna and the consequent reduction in data rate, but one can conclude that the background was too high for the chosen design.
Figure 1.3: Sketch, not to scale, of the operating principle of the Galileo PLS instrument. The top view shows the quadrupole design of the 2+2 electrostatic analyzers (B1, B2 and A1, A2) and the approximate positions of the three miniature mass spectrometers (Electromagnets). While on the top only positive trajectories are shown to indicate the focus point and the mass selection, the cross section shows negative and positive trajectories. Two voltages control the analyzer stack, marked as Voltages Detector A and B. Positive and negative particles passing through the entrance aperture and the electrostatic field of the analyzer at the same time and are detected by the corresponding CEMs. In total 14 of such CEMs are placed at different angular positions for positive (P) and negative particles (E), from where only 1 pair is shown. To separate species, three small electromagnets are placed in the instrument with two CEM detectors for each electromagnet. The CEM “MI” detects the integrated number of incident particles when the current source is switched off. When a current is applied, the CEM “MD” detects the corresponding masses that pass through the aperture slits immediately in front. With increasing current, heavier species are analyzed. For details, see Frank et al. [21]
1.3.4 Ion mass spectrometer on Cassini

The particle package on Cassini (CAPS - Cassini Plasma Spectrometer) contains an ion mass spectrometer (IMS), an analyzer based on the latest developments in the field and epoch. IMS was designed to measure the major species at Saturn, namely, hydrogen, oxygen and nitrogen, in different charge states and compounds. A very important requirement was to separate O\(^+\) (m/q = 16) from N\(^+\) (m/q = 14), which requires a mass resolution of at least 8. A time resolution of a few seconds was required to resolve the crossings of various plasma boundaries. IMS is a combination of a toroidal electrostatic analyzer (see chapter 4) and a time-of-flight reflectron cell (see chapter 2). This construction is a step forward compared with previous designs because of the instantaneous 360° view; however, only 160° of this view is used. The much-improved mass resolution of up to \(~\) 60 is owed to the time-of-flight reflectron. Because of the much lower penetrating radiation fluxes at Saturn, MCPs (see section 5.5) are used as start and stop detectors.

No information on the instrument’s sensitivity to penetrating radiation is available because the flyby at Jupiter was at 140 \(R_J\).

In summary, the evolution of plasma analyzers from simple energy and direction measurements to more complex, mass-resolving instruments is clearly reflected in the examples discussed above. The instrument selection was ultimately based on encounters with Jupiter and the experience gained therefrom, considering that many other instruments have been built for different missions and purposes.

1.4 The Particle Environment Package (PEP)

The Particle Environment Package (PEP) is a comprehensive package for particle measurements in the Jupiter magnetosphere and the environment of the Jovian moons. In 2013, the European Space Agency (ESA) chose to fly PEP onboard the JUICE mission. The scientific objectives of PEP are to understand processes, objects, domains, and their interactions in the Jovian plasma universe: mapping plasma flows around the icy moons in 3D to resolve the satellites’ electromagnetic interactions, combining remote imaging and in situ measurements to investigate the processes by which plasma is heated beyond coronal temperatures, performing the first-ever sampling of the moons’ exospheres and mapping of the surface weathering to determine how the icy moons release gas into space, and imaging the evolving moon tori to understand how gases released from icy moons affect the content and structure of a giant magnetosphere.

PEP will begin its compelling scientific investigation during the approach to Jupiter, by providing videos of the global structure and dynamics of the magnetosphere, the potential solar wind modulation and measurements of energetic electrons injected by this giant accelerator. This will be followed by a detailed investigation of the planet’s magnetosphere and satellites. During the flybys of Europa and Callisto, PEP will provide unprecedented plasma measurements and the first-ever neutral
exospheric gas measurements to understand the release of surface and, potentially, sub-surface materials. The global context and impact of those measurements will be understood by remotely imaging the plasma and neutral environments of Io and Europa. At Ganymede, PEP will provide a complete investigation of Ganymede’s complex magnetized plasma environment, its effects on the surface, and critical constraints for characterizing its differentiated interior.

PEP will address four overarching scientific questions:

1. How does the corotating magnetosphere of Jupiter interact with the complex and diverse environment of Ganymede?

2. How does the rapidly rotating magnetosphere of Jupiter interact with the seemingly inert Callisto?

3. What are the governing mechanisms and global impacts of the release of material into the Jovian magnetosphere from the seemingly inert Europa and active Io?

4. How do internal and solar wind drivers cause such energetic, time-varying and multi-scale phenomena in the steadily rotating giant magnetosphere of Jupiter?

PEP includes six sensors arranged in four mechanical units, which, in turn, are grouped into PEP-Hi (High) for measurements of energetic particles and PEP-Lo (Low) for measurements of particles with energies from the thermal level to a few tens of keV (Fig. 1.4). PEP covers nine orders of magnitude of particle energies and measures electrons, positive and negative ions, low- and high-energy neutral atoms, thermal plasma and neutral gas. Table 1.2 provides a summary of PEP and the key performance parameters of the sensors.
### Table 1.2: PEP sensors - overview

<table>
<thead>
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<th>Key performance parameters</th>
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<td><strong>PEP-Hi</strong></td>
<td></td>
</tr>
<tr>
<td><strong>JoEE - Jovian Energetic Electrons: Instantaneous pitch-angle distributions and spectra</strong></td>
<td>Energy range: 25 keV to 1 MeV, $\Delta E/E=20%$, $12^\circ \times 180^\circ$ FOV, $\Delta \Omega=12^\circ \times 22^\circ$</td>
</tr>
<tr>
<td><strong>JENI - Jovian Energetic Neutrals and Ions: Combined energetic-ion and ENA camera for global ENA imaging of the magnetosphere and neutral gas tori</strong></td>
<td>Energy range: (H, He, O, S) $\sim$ 0.5 keV to 300 keV (ENA), 5 MeV (ions), $90^\circ \times 120^\circ$ FOV, $\Delta \Omega=2^\circ \times 2^\circ$ (&gt; 10 keV H)</td>
</tr>
<tr>
<td><strong>PEP-Lo</strong></td>
<td></td>
</tr>
<tr>
<td><strong>JDC - Jovian plasma Dynamics and Composition: Instantaneous 3D distributions of positive and negative ions, capability to constrain charge states and measure electrons</strong></td>
<td>Energy range: $\sim$ 1 eV to 40 keV, $\Delta E/E=12%$, $m/\Delta m = 30$, $90^\circ \times 360^\circ$ FOV, $\Delta \Omega=5.5^\circ \times 19.5^\circ$</td>
</tr>
<tr>
<td><strong>JEI - Jovian Electrons and Ions: Instantaneous 3D distributions of plasma electrons, ion measurement capability</strong></td>
<td>Energy range: $\sim$ 1 eV to 50 keV, $\Delta E/E=5%$, $90^\circ \times 360^\circ$ FOV, $\Delta \Omega=20^\circ \times 10^\circ$</td>
</tr>
<tr>
<td><strong>NIM - Neutral gas and Ion Mass: Neutral gas and thermal plasma mass spectroscopy</strong></td>
<td>Energy range: &lt; 5 eV, Mass range: 1-1000, $m/\Delta m = 1100$, $10^\circ \times 360^\circ$ FOV</td>
</tr>
<tr>
<td><strong>JNA - Jovian Neutrals Analyzer: ENA camera imaging of the Io plasma torus, backscattered and sputtered surface products</strong></td>
<td>Energy range: ENA 10 eV to 3 keV, $15^\circ \times 150^\circ$ FOV, $\Delta \Omega=7^\circ \times 25^\circ$</td>
</tr>
</tbody>
</table>
Figure 1.4: Overview of the PEP sensor configuration. JDC is presented in the latest stage of development as of April 2016.
1.5 Jovian plasma dynamics and composition analyzer (JDC)

JDC measures the distribution functions of positive ions, electrons and negative ions. JDC has a hemispherical field of view (FOV) over an energy range from 10 eV/q to 25 keV/q and a reduced FOV of 360°x40° for up to 40 keV/q. The field of view is divided into 16 simultaneously measured azimuthal sectors, and the elevation direction is covered by electrostatic scanning. A full 3D distribution is obtained in 8 s for positive ions and for negative ions and electrons combined (electron mode). JDC covers an ion mass range of 1-70 u/q with a reflectron-type time-of-flight section. The reflectron provides a high mass resolution of \( \frac{m}{\Delta m} > 30 \) (composition channel) and a high sensitivity (dynamics channel) with a moderate mass resolution of \( \frac{m}{\Delta m} = 2-3 \). The geometric factor is controllable to accommodate high foreground rates.

After incoming particles pass through the elevation scanning system and the geometric-factor-controlling electrode, a spherical-wedge electrostatic analyzer provides selection based on energy per charge. The spherical wedges, which match the 16 azimuthal sectors, enable a very compact design while preserving the properties of a classical hemispherical analyzer. The time-of-flight start signals are obtained from secondary electrons generated in the start surface section, where particles reflect at grazing incidence from a surface. For details and illustrations, see chapter 5.2.

Secondary electrons are registered by compact radiation-tolerant custom-shaped ceramic channel electron multipliers. The use of surface interaction in the start surface section causes there to be no lower energy limit for heavy particles (unlike carbon foils), because particles do not penetrate but instead interact only with the start surface. A very moderate post-acceleration of a few hundreds of volts is sufficient over the full mass range. The highest voltage existing in the system is the reflectron voltage of +7 kV. When interacting with the start surface, the ions lose their initial charge state, and the particles assume a species-dependent charge-state distribution, similar to what occurs when interacting with foils. Particles entering the reflectron that are neutral or negatively charged propagate directly to the stop MCP and are registered in the dynamics channel. Particles leaving the start surface as positive ions are reflected by the linear electric field to the stop surface with a time-of-flight that is nearly independent of the particle energy. Secondary electrons generated on the stop surface are focused onto a small area on the stop MCP, where they are registered in the composition channel. The stop surface is part of an anti-coincidence solid state detector (SSD). The electronics are located in a common electronics rack and are shielded by the PEP mounting plate to a 50 krاد level. The electronics include front-end electronics (FEE), a multi-channel time-to-digital converter (TDC) system, high-voltage power supplies (HVPS), and sensor data processing. To reduce processing the load on PEP’s main processor, JDC includes its own central processing unit to control the HVPS and FEE and to process data from the TDC. Energy and deflection scanning is performed autonomously on the sensor from tables loaded into volatile memory upon sensor boot. JDC itself does not contain non-volatile memory. JDC performs all processing and binning of sensor data itself, except data compression, which is offloaded to the PEP’s main processor.
1.5.1 Measurements of negative ions, electrons, and charge states

JDC is optimized for measurements of positive ions, but it also has the ability to measure negative ions and electrons. Although the JUICE scientific requirements do not explicitly require charge-state measurements, JDC has the ability to constrain the charge states of the major ion species. Electrons and negative ions are measured by reversing the polarity of the ESA voltage. Low-energy electrons (< 300 eV) are steered directly to the start CCEMs by reducing the post-acceleration potential to 0 V. Electrons of higher energy (> 300 eV) create a forward-scattered electron at the start surface, enabling detection with a very short time-of-flight in the dynamics channel. Negative ions undergo charge exchange at the start surface to become positive ions or neutrals, because the final charge state does not depend on the initial charge state. They are then detected in both channels in the same way as positive ions. The time-of-flight in the dynamics channel (neutralized ions), \( t_d \), depends only on the primary particle mass \( m \) and energy \( E \) corrected for the calibrated energy loss. The time-of-flight in the composition channel (reflectron), \( t_c \), depends only on the primary particle mass, \( t_c \sim \sqrt{m/\bar{q}} = \sqrt{m} \), because independent of the initial charge state \( q \), the primary particles become singly charged after interaction with the start surface. The ESA voltage, \( V_{esa} \), is a function of the primary particle energy and charge, \( V_{esa} \sim E/q \). Therefore, by combining three measurable values, \( V_{esa} \), \( t_d \), and \( t_c \), one can statistically obtain the charge state \( q \) of the major ions.

1.5.2 Mitigation of penetrating radiation in JDC

Penetrating radiation is the major source of background because it both induces background counts inside the detectors and results in the production of secondary electrons inside the sensor, which, in turn, may reach the respective detectors. The associated effects are reduced by small cross sections of the detectors exposed to radiation, by shielding, and by a coincidence–anti-coincidence scheme for time-of-flight events.

All CCEMs are shielded with graded shielding equivalent to 20 mm of Al consisting of a tungsten copper alloy. The sensor has very small cross sections for penetrating radiation per azimuthal sector (< 1 cm²). The stop MCP is additionally buried in the PEP mounting structure. JDC uses two anti-coincidence mechanisms. A time-of-flight start signal is only accepted if the start detectors of two neighboring sectors do not produce start signals at the same time. Similarly, the SSD provides an anti-coincidence signal for the TOF stop signal for the composition channel and, with lower efficiency, for the dynamics channel. The SSD dead-layer thickness is chosen and the SSD’s lower energy threshold is set such that ions from the reflectron section do not trigger a detection. High-energy penetrating particles may also generate a secondary electron on the stop surface that will be collected in the composition channel, but for these, the SSD registers them and the composition stop signal is ignored. A valid TOF event requires three independent conditions to be met: a start and stop within a pre-set time-of-flight window, no anti-coincidence signal from the SSD for the start signal, and no anti-coincidence signal from the SSD for the stop signal. With the combination of these measures, the sensor is able to...
achieve a signal-to-noise ratio (SNR) of 100 for \( S^2^+ \) and an SNR of 18 for \( H^+ \) at Ganymede in both channels. At Europa, the sensor can achieve SNRs of 68 for \( S^2^+ \) and 12 for \( H^+ \) with additional background processing. There are no directly exposed high-voltage insulators in the sensor, and the insulators are designed with suitable margins to allow for total-dose-related degradation and for charging due to highly penetrating fluxes. The HVPS driving the exposed high-voltage electrodes, e.g., those of the elevation scanning system, are designed to drive additional currents of up to 1 \( \mu \)A from released secondary electrons, independent of voltage polarity. To monitor the instantaneous background rates, JDC will use a specially designed energy sweep consisting of sampling with zeroed deflector and analyzer voltages. This background will be subtracted from the recorded signal over the entire energy range.

### 1.5.3 JDC design approach

From an early design stage, JDC has been intended to be a very compact sensor to save mass. Size is, from experience, closely related to mass, and weight is a very crucial parameter for PEP. Size also affects the allocated shielding; for a given shielding thickness, a smaller shielded volume results in less total weight. Size also affects the total number of counts recorded by the sensor for a given environment and time. The Jupiter system presents a difficult environment for in situ particle detectors. The energetic particle background is added to the foreground signal and increases the total number of counts. Although the SNR does not scale with the dimensions of JDC, the total count rate does. If the sensor is too small, the counting statistics will be poor; if it is too large, the processing of counts will be inefficient. Therefore, the concept for JDC is to be as small as possible while still achieving good measurements.

To measure particle masses in the given energy range, there are two established concepts in space physics: the separation in a magnetic field and the time-of-flight technique. The use of magnets results in relatively low mass resolutions of only approximately 2 - 4, e.g., ASPERA-4 on Venus Express[30] or PLS on Galileo[21]. An increase in mass resolution to, e.g., \( \frac{\Delta m}{m} > 20 \) would require heavier permanent magnets or strong electromagnets. Furthermore, the magnetic separation of particle mass does not provide coincidence measurements to enhance the SNR.

The time-of-flight technique is therefore the preferred conceptual choice for a low sensor mass and a high SNR. For CAPS/IMS (section 1.3.4), thin foils are used to generate secondary electrons for the start signal in a time-of-flight system. Passage through a foil requires particle energies of a few keV, and thus, for small energies, a substantial acceleration voltage of several kilovolts is needed. CAPS/IMS uses an acceleration potential of 15 kV, which requires larger gaps in the ion optics to avoid discharges within the instrument and larger power supplies. A different means of releasing secondary electrons is through surface scattering. Instead of passing through a foil, an ion reflects at a grazing angle from a surface. During this process, secondary electrons are released in the same way as they are during passage through a foil and are used as the start signal (see chapter 2). This concept has been proven in a number of sensors, including the Solar Wind Monitor (SWIM)[31].
the Chandrayaan Energetic Neutrals Analyzer (CENA)\textsuperscript{32} and the Neutral Particle Detector (NPD)\textsuperscript{33}.

These constraints converge to a design approach based on Young’s concept for CAPS/IMS\textsuperscript{23} on Cassini and the series of foil-free SWIM-type instruments that have been built at IRF\textsuperscript{31}.

In the following chapters, various parts of the instrument are explored in more detail, most notably the TOF cell, with a new foil-free design based on venetian-blind-like surfaces, and a new type of compact electrostatic analyzer. Furthermore, a comparison is presented between a JDC prototype that was constructed and used for initial performance tests and the ion optical simulations used in the design phase of the prototype.
Chapter 2

Time-Of-Flight Mass Spectrometer

2.1 Introduction

Mass spectrometers are used to determine the mass of single atoms or molecules. A mass spectrum shows the relative abundance of elements in a sample. The mass of an atom is described by its mass number $A$, which is the sum of nucleons (integer sum of neutrons and protons). This allows it to distinguish between the elements and their isotopes which for most applications in the field of plasma characterization is sufficiently accurate. Sometimes the atomic number $Z$ is found which identifies the sum of protons of an atom. The actual weight of atoms is defined as the unified atomic mass unit $u$. In addition, the unit Dalton $Da$ and the atomic mass unit $amu$ are used. While the Dalton is often found to describe heavier molecules and is equal to $u$, the atomic mass unit $amu$ had originally a different definition and is replaced by the unified atomic mass unit $u$. The $amu$, is however, still sometimes found but with the updated definition of $u$ or $Da$:

$$1 \text{ } u = 1 \text{ } Da = m_a^{(12}\text{C})/12 = 1.6605 \cdot 10^{-27} \text{ kg}$$ (2.1)

with $m_a^{(12}\text{C})$ as the atomic mass of a carbon-12 atom in its ground state, according to which $u$ is defined \[34\]. Values found in general mass tables are usually the relative atomic mass of larger samples, that includes their relative abundance of isotopes and as such an average mass of all atoms in a sample divided by $1 \text{ } u$. The mass number $A$ is therefore only an approximation of to the relative atomic mass \[34\]. Common weight scales using gravitational force would hardly provide sufficient accuracy or sensibility to do meaningful measurements, not to mention the difficulties in handling single particles. When atoms or molecules become ionized they follow electromagnetic fields and can thus be controlled in their motion. The mass of such charged particles can be retrieved by determining their velocity and energy. The underlying principle is formulated by the kinetic energy equation, omitting relativistic
velocities and energies:

\[ E = \frac{m}{2} \cdot v^2 \]  (2.2)

with \( E \) as energy, \( m \) as mass, and \( v \) as velocity. When using kg as mass and meter per second as velocity, the energy is measured in Joule. In particle physics it is more common to divide the energy by the elementary charge \( e \), to gain easier numbers in electronvolt [eV]. For a particle of a given energy, a mass measurement reduces to a velocity measurement. A mass spectrometer that measures the velocity of a particle through a time measurement \( v = s/t \), is called time-of-flight mass spectrometer. Each measurement records the time-of-flight for a single particle and requires vacuum conditions. The time is usually in the range of \( ns \) to \( ms \) and thus many measurements can be done in a relative short time interval. From the acquired time-of-flight values the mass is calculated and plotted in a histogram which gives a mass spectrum. A mass spectrum represents the composition of elements or molecules in a sample and allows further scientific conclusions, e.g. origin or history of a sample. Often the total energy of a particle is not known: instead the energy per charge is measured with an electrostatic analyzer (see section 4). The grade of ionization is determined by the charge state, \( q \). The charge state gives the difference in elementary charges from its uncharged state, e.g. a double positively charged helium ion is written: \( \text{He}^{2+} \), where \( q = 2 \). If no additional measurement of total energy is available Eq. 2.2 is modified to:

\[ \frac{m}{q} = \frac{2E}{qv^2} = \frac{2Et^2}{qs^2} \]  (2.3)

with \( q \) as charge state, \( t \) as time-of-flight and \( s \) as a known distance. The result is the mass per charge which does not always unambiguously identify a species, e.g. \( \text{N}^+ \) and \( \text{CO}^+ \) both have a mass per charge of 28. In characterizing natural plasma environments, such as solar wind or planetary magnetospheres, particles are usually already ionized and have a certain energy spectrum, which means they have different energies and charge states. In the field of material analysis or in the laboratory it is necessary to ionize and accelerate particles before the time-of-flight measurement. Mass spectrometers are mainly characterized by their ability to resolve mass (per charge), the mass resolution, \( m/\Delta m \), with \( \Delta m \) as the difference between two mass peaks that can still be distinguished from each other in a given mass spectrum. Additional parameters are the maximum mass per charge ratio that can be measured and its sensitivity.

To construct a particle stop-watch for a time-of-flight measurement it is required to have a start and a stop signal. In many laboratory systems, the start signal is generated by an extraction pulse or a gate where a group of ions is released at a time. The advantage is that the start signal is achieved without interfering with the ions, e.g. charge exchanges or disintegration of molecules and that several ions can be measured at the same time. This introduces a maximum duty cycle that puts a limit on the sensitivity of a sensor. Another way of obtaining a start signal is the generation of secondary electrons during a surface interaction at foils or solid
surfaces. Using foils, the ion has to penetrate a very thin foil. The foils are commonly made from carbon with a thickness of some tens of nanometers. To penetrate the foil the ion has to have a sufficiently high energy, usually $\sim 1\text{ keV/nucleon}$, depending on foil thickness. Secondary electrons are released at impact and when leaving the foil. These electrons can be detected by electron multipliers (see section 5.5) as a start event signal. In a similar fashion, the ion can also scatter from a solid surface which generates secondary electrons as well. As side effect for both variants, the initial charge state, direction and energy change.

However, after moving for a known distance the particle is detected again with a stop detector and subsequently the timing is stopped. From the time in between both signals, the time-of-flight is determined. This implies that the same ion was independently measured at two positions. The measurement is therefore referred to as a coincidence measurement. For a harsh radiation environment producing strong background signals, this improves the signal-to-noise ratio.

Where a coarse mass-per-charge resolution is not sufficient to separate, e.g., $\text{D}^+$ from $\text{He}^{2+}$ or $\text{CO}^+$ from $\text{N}_2^+$, there are two remedies: either the mass resolution is drastically increased or the total energy of the particle is measured. To separate deuterium $\text{D}^+$ from alpha particles $\text{He}^{2+}$ a mass resolution $\frac{m}{\Delta m}$ of $\sim 600$ is required and for carbon monoxide $\text{CO}^+$ and molecular nitrogen $\text{N}_2^+$ a resolution of $\sim 3300$ is needed depending on the relative abundance of their isotopes. To measure the total energy and therefore determine the charge state, solid state detectors are commonly used. At the stop position of the time-of-flight measurement, the particle is no longer needed after its detection and can thus be absorbed. A solid state detector as stop detector generates output pulses with a pulse height that depends on the total energy an incident particle. The subsequent pulse height analyses allows it to infer the total energy and thus the absolute mass and initial charge state of the particle.

### 2.2 Field free time-of-flight

A field free time-of-flight measurement consists of a start detector, an electromagnetic field free flight path (drift region) and a stop detector. Particles travel a known distance $s$ in a time $t$, the time-of-flight. The system determines the ion mass per charge ratio $m/q$ according to:

$$\frac{m}{q} = 2 \frac{E}{q} + \frac{|V_p| - E_s}{q} \left(\frac{2}{t^2}\right)^{\frac{1}{2}}$$  \hspace{1cm} (2.4)

where is $E$ the energy of the particle, $V_p$ the applied pre-acceleration potential and $E_s$ the energy loss at the start of the time-of-flight measurement. The mass resolution $m/\Delta m$ of this time-of-flight measurement, assuming $q = 1$, is determined by:

$$\frac{m}{\Delta m} = \left(\frac{\Delta E^2}{E^2 + \frac{4 \Delta t^2}{t^2} + \frac{4 \Delta s^2}{s^2}}\right)^{\frac{1}{2}}.$$  \hspace{1cm} (2.5)
with $\Delta s$ being the uncertainty of path length in the time-of-flight cell, $\Delta t$ the uncertainty of the time measurement and $\Delta E$ the uncertainty of the ion energy when entering the time-of-flight cell.

These uncertainties limit the mass resolution of field free time-of-flight mass spectrometers. Because of these effects field free time-of-flight mass spectrometers are difficult to design with mass resolutions better than 7 \cite{35}. A time-of-flight mass spectrometer with comparable dimensions and improved mass resolution is the linear field time-of-flight mass spectrometer (LEF or reflectron).

### 2.3 Linear electric field time-of-flight

A time-of-flight system using a linear increasing, axial electric field in the form of a cylinder is called a reflectron. The potential increases quadratically towards the end of the cylinder. For space applications, this was described by McComas et al. in 1990 \cite{35}. Accelerated positive ions enter the cylinder at negative acceleration potential. For a positive field, positive ions will turn around in the increasing electric field and are forced back onto the entrance plane. Negative particles will be focused to the end of the cylinder and neutral particles will just pass unhindered. The mass per charge in a reflectron is:

$$\frac{m}{q} = \frac{kt^2}{\pi^2},$$  \hspace{1cm} (2.6)

with $k$ being a device-specific factor depending on electro-mechanical construction. The device is therefore energy independent. For a perfect linear field the mass resolution depends only on uncertainties in time.

$$\frac{m}{\Delta m} = \frac{2\Delta t}{t}.$$  \hspace{1cm} (2.7)

Gilbert et al. \cite{36} showed an improved version where instead of detecting the positive ions at the entrance plane with large micro channel plates, the ions hit a stop surface at the same position. Secondary electrons are then focused by an electrode ring and the linear electric field towards the end of the cylinder. In this way the reflectron works with just one active stop detector. Such an instrument can reach good mass resolution at a small size. During the start event generation, not only positive ions are generated, but also negative ions and neutral atoms. Depending on incident energy and surface material usually the incident ion is neutralized and therefore neutral atoms dominate. Since the secondary electrons are focused quite well to the center of the stop detector, they can be separated from the negative ions and neutral atoms that arrive from the start surface or foil. This processes results in two detection channels, one for the positive ions and one for the negatives ions and neutral atoms. The positive detection channel provides high mass resolution with lower sensitivity, while the second detection channel has a high sensitivity but at a lower mass resolution.
2.3.1 Time-of-flight section of JDC

Jovian plasma dynamics and composition analyzer (JDC) will be operating in the harsh radiation environment of Jupiter. A reflectron time-of-flight system provides high mass resolution and a high signal-to-noise ratio at small form factor. The optimized version described by Gilbert was adopted by Wieser and Lue\[37\]. Since JDC uses surface scattering, ions at the exit of the electrostatic analyzer scatter into the time-of-flight cell with a selected E/q. Hereby the original charge state is lost and most of the scattered ions become neutralized or single charged\[38\].

The JDC time-of-flight cell is cylindrically symmetric with 9 ring electrodes to form the linear electric field. The cross-section is quadratic, such that height and diameter are both very compact at 60 mm. At the entrance of the cell (Fig. 2.1 to the right) is the entrance ring (START surface) at a radial distance of 15 to 18 mm from the symmetry axis. The stop surface is located in the center of that ring with a diameter of 26 mm. At the end of the cell (Fig. 2.1 to the left), is the stop detector. The stop detector (not to be confused with the stop surface) is a 25.4 mm diameter micro channel plate with two circular anodes. A very small center anode with a diameter of 3 mm (“STOP detector for high mass resolution” in Fig. 2.1), is used to collect the highly focused secondary electrons from the stop surface. The stop counts from this center anode are used for the high mass resolution of the composition channel. The larger anode (“STOP detector for low mass resolution” in Fig. 2.1) collects

\[\text{Figure 2.1: Initial time-of-flight design in SIMION from the internal IRF report by Lue}\[37\]. “The figure shows a cross-section of the cylindrical cell, created in SIMION 3D version 7. A positive ion enters the cell from the Electrostatic Analyzer (not shown) and hits the START surface, generating secondary electrons, detected by the START detector. After impact, the particle has a charge of +1, 0 or -1. Positive ions are reflected by the reflectron voltages and, at impact with the STOP surface, generate a secondary electron which travels to the high resolution STOP detector, guided by an electron focusing lens. Negative ions and neutrals travel on approximately straight trajectories, toward the low resolution STOP detectors.”\]
the neutral atoms and negative ions. The counts obtained from this anode are used for the dynamic channel. The dynamic channel has a higher sensitivity because the majority of particles entering the time-of-flight cell are neutralized at the start surface. Furthermore the losses in the straight trajectory to the stop detector are smaller compared to the positive ions, as they have to turn around and hit the stop surface. The small parts in Fig. 2.1 marked “Electron focusing electrode” form a ring electrode that is placed just in front of the stop surface. This ring shapes the reflectron field such that it focuses the secondary electrons from the stop surface onto the small center anode at the stop detector and therefore makes it possible to distinguish the electrons by position from the direct impacts of the neutral atoms and negative ions.

As an output of the simulations done by Wieser and Lue the key parameters regarding the start surface are shown in Fig. 2.2. These key parameters describe the optimal angle and position for positive ions entering the time-of-flight cell. The composition channel has a low detection efficiency because many positive particles are lost due the more complex trajectories necessary to produce secondary electrons at the stop surface. The detection efficiency is further reduced because of the expected low positive charge fraction for ions that leave the start surface. It is therefore crucial to design a start surface that generates as many positive ions as possible, within the obtained optimum parameters of Fig. 2.2.

**Figure 2.2:** Simulated surviving angular distribution over radial distance from the symmetry axis $x$ of the JDC time-of-flight cell. The single contour line on each panel marks approximately the area of 50% transmission. (person. communication with M.Wieser)

Figure 2.2 shows the distribution of successful trajectories, for injected positive ions versus their radial start position and versus their direction in $\theta$ and $\varphi$. The radial start position is the distance from the symmetry axis (“Ion start Y position [mm]” in Fig. 2.2) and corresponds to positions at the entrance ring mentioned above. On the left panel the optimum azimuth angle is given (“Ion start azimut [deg]” in Fig. 2.2) and on the right panel the optimum elevation angle is given (“Ion start elevation [deg]” in Fig. 2.2). To clarify the angles a sketch is given in Fig. 2.3.
Angles used in Fig. 2.2. Azimuth is symmetric around $\theta = 0^\circ$. Elevation is the angle between a trajectory and the symmetry axis $x$, denoted $\varphi$. A particle moving along the negative $x$-axis has $\varphi = 0$ and $\theta = 0^\circ$.

From Fig. 2.2 one can see that only radial positions between 15 and 18 mm distance generate stop counts in the composition channel as mentioned earlier. Preference should be given to the positions closer to the symmetry axis (15 mm to 16 mm). The optimal elevation angle $\varphi$ for trajectories into the time-of-flight cell is around $\varphi = 18^\circ$ at 15.5 mm distance from the symmetry axis. Within 50 % sensitivity, elevation angles from 12$^\circ$ to 20$^\circ$ are acceptable. For the azimuth only minor deviations can be accepted.

In section 5.3 these optimal positions and directions are used to design an ideal start surface geometry. The optimal parameters are also key parameters for the electrostatic analyzer design and optimizations in the ion-optical path between the electrostatic analyzer exit and start surface.

2.4 Detector efficiencies in time-of-flight systems

A generic time-of-flight system as, e.g. described above, generates start events, $n_s$, and stop events, $n_p$, within a measurement time $t_m$. Thus there is a start event rate $R_s = n_s/t_m$ and a stop event rate $R_p = n_p/t_m$. When the time between a start event and a stop event is smaller than the time-of-flight window $t_t$, it is assumed that one particle generated both events. This is called a coincidence event $n_c$. The maximum allowable $t_t$ can be estimated depending on species, energies and construction of the time-of-flight cell. To physically generate counts, usually electron multiplying detectors like channel electron multipliers (CEMs) or micro channel plates (MCPs) are used. These are described in more detail in section 5.5. Both use the principle of secondary electron multiplication in a strong electric field upon particle impact: at the end of such an avalanche process a small current pulse is generated. The pulses are often converted by charge-amplifiers and pulse shapers to conventional digital pulses that are processed by a time-to-digital converter (TDC). The time-to-digital converter not only determines the time between a start event and a stop event, it also handles multiple start or stop events. For example the device can be programmed to ignore multiple events or to record the shortest time between multiple events.

Electron multiplying detectors such as CEMs and MCPs have different quantum
detection efficiencies that depend on factors such as particle species and energy as shown, e.g., in section 5.5. The detection efficiency $\eta$ in a time-of-flight system combines such quantum efficiencies with the whole time-of-flight system efficiency. This includes scattering effects, ion-optical effects, effects of duty cycles, electronic effects and any other effect in between an incident particle hitting a detector and the registration of the event in the time-to-digital converter. The detection efficiency $\eta$ is thus not to be confused with the quantum efficiency of a specific detector.

A time-of-flight system with an unknown incident particle rate $R$ generates a start event rate $R_s$, a stop event rate $R_p$ and a coincidence event rate $R_c$. The detection efficiency for start events, $\eta_s$, and the detection efficiency for stop events, $\eta_p$, can be determined using the method described by Brehm et al. [39] and Funsten et al. [40]. The method uses the fact that the efficiency of detecting coincidence events, $\eta_c$, is the product of the start and stop efficiency $\eta_c = \eta_s \cdot \eta_p$. With the given measurements, $R_s$, $R_p$ and $R_c$, a system of three equations can be defined:

$$R_s = R \cdot \eta_s \quad (2.8)$$
$$R_p = R \cdot \eta_p \quad (2.9)$$
$$R_c = R \cdot \eta_s \cdot \eta_p \quad (2.10)$$

These can be solved for the unknown efficiencies $\eta_s$ and $\eta_p$ and the unknown incident rate $R$:

$$R = \frac{R_s \cdot R_p}{R_c} \quad (2.11)$$
$$\eta_s = \frac{R_c}{R_p} \quad (2.12)$$
$$\eta_p = \frac{R_c}{R_s} \quad (2.13)$$

The obtained efficiencies of such a time-of-flight system allows to convert the recorded events to a particle flux via the geometric factor (see section 4.2.4) of an instrument. The detector efficiencies are thus crucial parameters for instrument calibration but also for in-flight monitoring of detectors.

### 2.4.1 Detailed time-of-flight efficiencies

Under normal conditions, the given set of equations in the section above yields reliable and sufficiently accurate results. For high flux conditions as $R$ approaches $1/t_t$ or high background count rates a more detailed view is given in the next section. The probability of generating a coincidence event in a time-of-flight system with a start event rate and a stop event rate is not the only way to trigger the coincidence counter. For time-of-flight systems with detector efficiencies below 1, there exists a probability of generating a coincidence event by two separate foreground particles being detected within the time-of-flight window $t_t$, so called accidental coincidence
event. It is further possible that noise of all kinds generates counts in the detector system. A random start event and a random stop event can also be detected as coincidence event.

### 2.4.2 Accidental coincidence events

An accidental coincidence event in the time-of-flight system requires two particles within the time-of-flight window $t_t$. One particle triggers the start detector, but does not generate a stop event, while the other particle generates a stop event without a start event. Time-of-flight systems that have detector efficiencies below 1 must generate such events. Accidental events are part of the foreground signal but not of the previously defined coincidence efficiency and as such need to be subtracted from the efficiency calculation as shown later. A meaningful time-of-flight can only be acquired from a single particle, whereas from an accidental event the time-of-flight is a random value. Accidental coincidence events are therefore visible as uniform background in a time-of-flight spectrum, as shown in Fig. 2.4.

![Figure 2.4: Example time-of-flight for a H$^+$ beam of $\sim 2100$ eV. The tail towards longer times-of-flight is assumed to be caused by energy losses on the start surface of the instrument used by accidental coincidence events.](image)

The figure shows the measurement of a monoenergetic H$^+$ beam with a time-of-flight instrument that resolves energies with a resolution of about 6% and a mass resolution of about 2. The instrument uses start surfaces for the start event generation and is described in section 3.8. The main beam spot is at about 2100 eV with a time-of-flight of about 60 ns. A combination of an extended tail and a uniform background is visible that extends over the whole time-of-flight window, $t_t$, at the same energy bins as the ion beam. The data system of the instrument always records the shortest time in case of multiple events during a measurement frame of $t_m$. Thus the uniform background has an additional tendency to show the shape of a decreasing tail. Arbitrary noise can be excluded as a reason for such a background tail because
only the energy bins of beam energies are affected. Energy loss or sputter effects that would result in very slow times-of-flight at the start surface commonly cause a tail, but cannot explain an almost uniform distribution up to 10 times the time-of-flight of the main beam spot, especially when using hydrogen ions. The events causing this background tail are accidental coincidence events. Brehm et al. \cite{39} described this as “baseline in the time-of-flight-spectrum” and Wüest \cite{41} called it “chance counts”. The accidental coincidence event rate can be described using the same unknowns as for the coincidence event rate $R_c$ with the formula below \cite{41}:

$$R_a = R^2 t_t \eta_s \eta_p (1 - \eta_p) (1 - \eta_s) \quad (2.14)$$

One can see that the maximum of accidental counts for a given incident rate $R$ and a selected $t_t$ is obtained for $\eta_p = \eta_s = 0.5$.

### 2.4.3 Background events

Background events are signals generated by noise or instrument-penetrating particles. One can further divide them into internal and external sources. Internal sources could be heat, electronics or radioactive decay. External sources could be all sources of radiation and energetic particles. In this case the detectors or the electronics are triggered by particles entering the instrument either through the instrument aperture or by penetrating housing and shielding. However the result is a background event rate in each detector: the start background event rate $R_{BS}$ and the stop background event rate $R_{BP}$. Both background rates can, in a similar way to accidental events, generate coincidence events and are combined in the background coincidence rate $R_{BC}$. The background coincidence rate consists of three components: $R_{B1}$, $R_{B2}$ and $R_{B3}$. Coincidence events that are generated by noise at the start detector and a foreground particle at the stop detector are called $R_{B1}$. Coincidence events that are generated by noise at the stop detector and a foreground particle at the start detector are called $R_{B2}$. Coincidence events that are generated by noise at both detectors are called $R_{B3}$. These events are described by the following equations:

$$R_{B1} = R_{BS} R_t \eta_p (1 - \eta_s) \quad (2.15)$$

$$R_{B2} = R_{BP} R_t \eta_s (1 - \eta_p) \quad (2.16)$$

$$R_{B3} = R_{BP} R_{BS} t_t \quad (2.17)$$

The total background coincidence rate is given by the sum of the above events:

$$R_{BC} = R_{B1} + R_{B2} + R_{B3}$$

$$= t_t \left[ R R_{BS} \eta_p (1 - \eta_s) + R R_{BP} \eta_s (1 - \eta_p) + R_{BP} R_{BS} \right] \quad (2.18)$$
2.4.4 Total count rates

Combining the accidental and background rates from above one gets more refined equations for the detector rates. Accidental and background events generate times-of-flight that can in principle be negative, and are usually ignored by the time-to-digital converter. Hence any two particle events are divided by 2. For other instruments with different data processing, other factors may apply. The counts in the detectors as described in this work are therefore:

\[
R_s = R_S + R_t + R_{BS} \quad (2.19)
\]
\[
R_p = R_P + R_t + R_{BP} \quad (2.20)
\]
\[
R_c = R_t + \frac{R_a}{2} + \frac{R_{BC}}{2} \quad (2.21)
\]

with \( R_S \) being counts only registered by the start detector, \( R_P \) being counts only registered by the stop detector and \( R_t \) being counts that contribute to true time-of-flight events. Substituting \( R_S = R\eta_s(1 - \eta_p) \), \( R_P = R\eta_p(1 - \eta_s) \) and \( R_t = R\eta_s\eta_p \), one gets the following set of equations expressed in incident rate, background rate and detector efficiencies:

\[
R_s = R\eta_s(1 - \eta_p) + R\eta_s\eta_p + R_{BS} = R\eta_s + R_{BS} \quad (2.22)
\]
\[
R_p = R\eta_p(1 - \eta_s) + R\eta_s\eta_p + R_{BP} = R\eta_p + R_{BP} \quad (2.23)
\]
\[
R_c = R\eta_s\eta_p + \frac{R^2 t_t \eta_s\eta_p(1 - \eta_p)(1 - \eta_s)}{2} + \frac{t_t [R R_{BS} \eta_p(1 - \eta_s) + R R_{BP} \eta_s(1 - \eta_p) + R_{BP} R_{BS}]}{2} \quad (2.24)
\]

The system of equations is solved for the start efficiency \( \eta_s \) by putting Eq. 2.22 and Eq. 2.23 into Eq. 2.24 and using the substitutions of:

\[
R = \frac{R_s - R_{BS}}{\eta_s} \quad (2.25)
\]
\[
\eta_p = \frac{R_p - R_{BP}}{R_s - R_{BS}} \quad (2.26)
\]

The result is expressed as a quadratic equation in the form \( a\eta_s^2 + b\eta_s + c = 0 \) with the resulting coefficients \( a, b \) and \( c \):

\[
a = \frac{t_t R_p - R_{BP}}{2} \frac{R_a}{R_s - R_{BS}} [R_s R_{BP} - R_s R_{BS} - R_p R_{BS} + R_{BS} R_{BP}] \quad (2.27)
\]
\[
b = \frac{R_p - R_{BP} - \frac{t_t}{2} R_s R_P + \frac{t_t}{2} R_s R_{BP} + \frac{t_t}{2} R_s R_{BP}}{2} \frac{R_P R_{BS} - R_s R_p}{R_s - R_{BS}} \quad (2.28)
\]
\[
c = \frac{t_t}{2} R_s R_P - R_c \quad (2.29)
\]
The two solutions for the start efficiency \( \eta_s \) are given by:

\[
\eta_{s1,2} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}
\]  

(2.30)

With the requirement that \( 0 < \eta_s < 1 \) it is usually possible to rule out one solution, but there are possible combinations where both solutions are between 0 and 1. Thus it is necessary to compare the results to the original equation 2.12 and choose the closest value to \( R_c/R_p \). The original set of equations therefore represent good efficiency estimators for the more complex cases including accidental counts and noise. Evaluating the set of refined equations requires the knowledge, or an estimate of, the background rates in the start and stop detector.

Figure 2.5: Comparison between conventional efficiency calculation \([39, 40]\) and a more refined calculation, considering accidental events, as described in this section.

One can see in Fig. 2.5 that when the electrostatic analyzer of the instrument is fully tuned to the beam energy, the efficiency drops because of the intensive beam. The high count rate at the start CEM leads to smaller current pulses at the channel output. The channel can be compared to a capacitor and its time constant to charge to a constant voltage. For high count rates the channel does not fully recharge and thus the generated current pulses at the output become smaller. Subsequently the start efficiency \( \eta_{s} \) decreases\([42]\] with higher count rates. The count rate at the stop detector is usually lower and therefore this effect does not occur. Instead the detection efficiency \( \eta_p \) increases because more particles are detected, which is a result of Eq. 2.13. Further variations in efficiency are caused by the energy sweep of the instrument, when analyzing a monoenergetic beam. The beam illuminates different parts of the start surface inside the instrument. Without considering accidental events both efficiencies are overestimated by about 5 % in the particular case. While the more complex solutions give more accurate efficiencies under “extreme” conditions like high count rates and specific efficiencies, they also allow a time-of-flight
spectrum to be cleaned up, as shown in Fig. 2.6. With the calculations from the refined approach it is possible to subtract accidental events from the total coincidence events of a measurement. With a given number of total counts, \( N_T^* \), in a plot like Fig. 2.4 the total number of counts without the accidental events, \( N_T \), is given by:

\[
N_T = N_T^* \left(1 - \frac{R_a}{R_c}\right)
\]  

(2.31)

Since the total number of accidental events do not allow to identify a single count as an accidental event, the plot subtracts a uniform background of the same number.

The refined view on counts within a time-of-flight system shows that a high detector efficiency is not only needed for high instrument sensitivity, but also for a clean time-of-flight spectrum. Having start or stop efficiencies in the range of 0.5 should be avoided, because this will maximize accidental coincidence events and background coincidence events, as seen from Eq. 2.14 and Eq. 2.18. The time-of-flight window should be as small as possible for the same reasons.

Under conditions of high incident flux or high radiation background, the refined equations for the detector efficiencies allow more precise measurements if estimates for the background rates are available. For an instrument that is about to operate in a high radiation environment like in the system of Jupiter, a well understood counting mechanism is absolutely necessary.

Figure 2.6: Energy integrated counts from Fig. 2.4 for direct comparison of the removed accidental events.
Chapter 3

Mass analyzers based on surface scattering

3.1 Introduction

The time-of-flight technique allows one to build lightweight, small, spaceborne plasma spectrometers, as observed in chapter 2. Thin carbon foils are a common way of generating start signals but require larger power supplies and space between high-voltage parts. As an alternative, surface scattering can be used. When reflecting from a surface, a particle releases secondary electrons in the same manner as when passing through a foil. This concept has been proven in a number of sensors: the Solar Wind Monitor (SWIM)[31], the Chandrayaan Energetic Neutrals Analyzer (CENA)[32] and the Neutral Particle Detector (NPD) [33].

One drawback of a scattering surface compared to foil is the imprecise position of incident ions on the surface. An incident ion beam with a diameter \(d_B\) impinging in the normal direction on a foil generates secondary electrons at a very precise position along the beam direction because the beam penetrates the foil perpendicularly. An ion beam incident at a grazing angle \(\alpha\) on a surface causes an ellipsoidal spot on the surface from which it reflects. The width of the ellipsoidal beam spot is the incident beam diameter \(d_B\), and the length is the elongated beam diameter \(d_B^* = d_B / \sin(\alpha)\). For \(\alpha = 15^\circ\), the length \(d_B^*\) is approximately 4 times larger than the actual beam diameter and increases when approaching grazing angles of incidence. The distance \(d_B^*\) is therefore significantly larger than the surface, compared to a carbon foil, where \(d_B^*\) is negligible. Secondary electrons are released throughout the interaction area of the beam when impinging on a surface or foil. For the same beam, the interaction area is smaller with a foil at an incident angle of \(\alpha \sim 90^\circ\) compared to a surface with an incident angle \(\alpha < 15^\circ\). The electron flight time varies for both arrangements with approximately the same value when using a reflecting surface because the start detector can be placed more efficiently. While utilizing a foil arrangement, the start detector needs to be placed beside the beam path; when utilizing a surface arrangement, the the start detector can be directly pointed toward the center of the interaction area. This can compensate for the larger interaction area of a reflecting
surface.

The distance of flight $s$ will vary such that $\Delta s = d_B^*$. Although $d_B^* \sim 0$ for a foil system, $d_B^*$ for a reflecting surface increases with smaller incident angles and larger beam diameters.

The uncertainty caused by $\Delta s$ translates into lower mass resolution for both a field-free time-of-flight measurement and a linear field time-of-flight measurement. The effect is smaller for the latter because the mass resolution in a reflectron depends only on time inaccuracies; see Eq. 2.7 and Eq. 2.5.

One way to minimize the effect of $\Delta s$ is through the use of a position sensitive detector. This was implemented at CENA: the start electrons are detected with a micro channel plate with the length of $\Delta s = d_B^*$. The acquired position information is then used to correct the distance of flight at the cost of increased system complexity.

Another way to minimize inaccuracies in the flight distance $s$ is to decrease $\Delta s$ using multiple reflecting surface slats such as in a venetian blind. The principle is shown in Fig. 3.1, where it is shown that $\Delta s$ becomes smaller for a venetian-blind-type start surface compared to a simple and flat surface. Thus, the mass resolution improves without the need of a more complex start detection system.

![Figure 3.1: Improved position accuracy with venetian-blind-type slats: $\Delta s_2 < \Delta s_1$](image)

The technology needed for venetian-blind-type start surfaces can be classified into two parts: the material that such a start surface would be made of and the geometry it should have. The material can be of the same type as in previous instruments, e.g., tungsten, if it is available in a suitable shape. This is difficult to achieve because most suitable surfaces (ultra low surface roughness and high atomic mass) are treated, for example, by polishing from the top. The same surface treatments are unlikely available in the form of small slats inside a bulk material. An ideal surface geometry is described in section 5.3. As a proof of concept for different materials, several tests have been conducted to explore the feasibility of venetian-blind-type start surfaces, which are described in detail below.

### 3.1.1 Low-energy ion scattering

For atomic particles scattering from a surface with an incident velocity $\vec{v}$, an incident mass $m$ and an incident charge state $c$, only the mass remains unchanged if the particles leave the surface. The probability of leaving the surface is described by the reflection efficiency $r$. The change in direction is called angular scattering and, in spherical coordinates, consists of two directions $\Theta$ and $\Phi$ with corresponding
distribution functions, which each have both a maximum and a full-width-half-max (FWHM).

![Figure 3.2: Directions during a scattering event from a surface in spherical coordinates, described by the angles $\Theta$ (in-plane) and $\Phi$ (out-of-plane)](image)

The change in energy is described using energy loss and energy straggling. Particles lose a randomized amount of energy during the interaction with the surface, and straggling describes the width of this function at half the maximum (see chapter 3.6). For the given energy range, the energy loss can be described with binary elastic collisions of a scattered particle of initial energy $E_i$ and a scattered energy $E_s$, as done by Niehus et al. [43]. The mass ratio between the projectile and target is given by $R_m = m_t/m$, with $m_t$ being the particle mass of the target material and $m$ being the mass of the incident particle.

For $R_m > 1$:

$$\frac{E_s}{E_i} = \frac{(\cos \Theta + \sqrt{R_m^2 - \sin^2 \Theta})^2}{(1 + R_m)^2}$$  \hspace{1cm} (3.1)

For $1 > R_m > \sin \Theta$:

$$\frac{E_s}{E_i} = \frac{(\cos \Theta \pm \sqrt{R_m^2 - \sin^2 \Theta})^2}{(1 + R_m)^2}$$  \hspace{1cm} (3.2)

The charge state is quantified by the charge state fraction $\eta$:

$$\eta = \frac{N}{N^+ + N^- + N^0}$$  \hspace{1cm} (3.3)

with $N$ as the number of particles with the desired charge state, $N^+$ as the number of particles with a positive charge state, $N^-$ as the number of particles with a negative charge state, and $N^0$ as the number of neutral particles. During surface interaction, the incident ions loose their charge state, and the charge state of the scattered particle does not depend on the initial charge state. This was measured, for example, by Wieser et al. [38] for energies up to 3000 eV and primary beams of positive ions and neutral atoms.
In addition to the properties describing the effects on an incident particle, other effects occur: Secondary electrons are released during the interaction. The secondary electron yield is defined as the amount of secondary electrons per incident particle. These electrons have peak energies of approximately 2 eV, with a tail to higher energies of \( \sim 20 \) eV \[44\]. Heavier particles of the same energy have a higher secondary electron yield\[44\]. In addition to secondary electrons, secondary atomic particles can also be ejected from the surface during the interaction. Again, heavier incident ions of the same energy generate more secondary particles \[46\]. Most surfaces acquire an atomic water layer during preparation, and thus, most secondary particles are hydrogen. Depending on the incident energy, heavier secondary particles usually have substantially lower energies than the scattered incident particles or the sputtered hydrogen and are subsequently not detected in the experiment. Nevertheless, heavy surface material is sputtered as well.

### 3.1.2 Positive ionization yield

For a start surface that is required to produce positive particles leaving the surface, the positive charge fraction \( \eta^+ \) and the reflection efficiency \( r \) can be combined to obtain the positive ionization yield \( Y^+ \). This yield can also be defined using the incident flux \( F_i \) and the scattered positive flux \( F_s^+ \) because

\[
\eta^+ = \frac{N^+}{N_s} = \frac{F^+_s}{F_s} \tag{3.4}
\]

with \( F_s \) as the scattered particle flux of all charge states, \( N_s \) as the number of all scattered particles, and \( N_i \) as the number of all incident particles. In addition,

\[
r = \frac{N_s}{N_i} = \frac{F_s}{F_i} \tag{3.5}
\]

One thus obtains the following result:

\[
Y^+ = r \cdot \eta^+ = \frac{F_s^+}{F_i} \tag{3.6}
\]

To measure \( Y^+ \), a setup that determines either the relevant fluxes as stated in Eq. 3.6 or using the quantities of Eq. 3.4 and 3.5 is needed. Ideally, \( Y^+ \) equals unity; specifically, all incident particles are positively scattered. \( Y^+ \) is defined to a single species such that secondary products are excluded.

Simulations with SRIM, i.e., the Transport of Ions in Matter \[47\] software package, allow one to simulate angular and energy distributions. However, charge fractions and surface roughness are not considered in SRIM. Experiments are needed to measure the positive ionization yield. A SRIM simulation was performed to verify the relevant parts of the experiments wherever possible.

Two different experimental setups were used to analyze the positive ionization yield: an established setup at the University of Bern, Switzerland and a new setup at the
Swedish Institute of Space Physics in Kiruna, Sweden. The Imager for Low Energetic Neutral Atoms (ILENA) experiment [48] at the Physics Institute of the University of Bern is specifically designed for surface scattering experiments and determines $r$ and $\eta^-$. The setup in Kiruna uses the Laboratory Ion Scattering Analyzer (LISA) to measure positive ion fluxes.

### 3.2 ILENA experiment

#### 3.2.1 Setup

The Imager for Low Energetic Neutral Atoms (ILENA) enables scattering experiments for positive ions in a quick-to-setup small vacuum chamber. Samples are placed between the ion source and the detector such that the ion beam is fully blocked when using a flat, solid sample. This is ensured by a small aperture just in front of the sample and protects the detector from the strong signal of the incident beam. ILENA supports different species up to approximately 2 keV, mainly limited by the temperature of the electromagnet inside the ion source, which separates the ion species with its magnetic field. Different species are supplied by standard gas bottles that are added to the ion source. The sample and the detector can both be rotated in the same plane of the scattering angle $\Theta$, as shown in Fig. 3.3.

![Figure 3.3: Top view of the ILENA experiment, with the indicated detector images over the polar scattering angle $\Theta$. The incident angle $\alpha = 15^\circ$ is measured between the incident beam and the scattering surface.](image)

The sample is electrically insulated from the chamber ground and connected to a pico-ammeter to measure the incident beam current. A Retarding Potential Analyzer (RPA) is placed in front of the detector to deflect charged ions. The position sensitive detector is produced by Quantar Technology (3395A) and can be at a floating potential. In conjunction with the RPA, this allows one to deflect charged particles such that only neutral particles are detected. The detector has a field of view of $\sim 25^\circ$ in the polar and azimuth directions, given by its diameter of 40 mm and distance of 90 mm to the sample. A complete description of the experiment was published by Wahlström et al. [48]. The experiment is commonly used to record...
angular scattering profiles for incident ions under grazing angles ($< 10^\circ$) on very smooth surfaces [49]. For smooth surfaces and small incident angles, this field of view is sufficient to cover most of the scattering distribution. For the present experiment with an incident angle $\alpha = 15^\circ$, the detector had to be rotated manually over four positions (see the color-coded density plots in Fig. 3.3) around the probe to cover the full angular distribution over $\Theta$. The out-of-plane angle $\Phi$ can be covered for $\pm 10^\circ$ with this arrangement.

### 3.2.2 Detector efficiency

To obtain measurements of the charge fractions, the relative efficiency of the detector system must be known. The micro channel plate in the ILENA detector has different efficiencies for different charge states of the same species at the same energy. This was shown by Peko & Stephen [50, 51] with a comparable detector from Quantar Technology for hydrogen and oxygen of energies below 1 keV. In particular, negative ions show a higher detection efficiency than do positive ions or neutral atoms. The exact detection efficiency of a specific detector for a specific event depends on, for example, energy, mass, charge number, incident angle, MCP geometry and applied voltages [52]. Furthermore, the aging of a detector can change the efficiency as well. Without a dedicated efficiency measurement, it is difficult to apply the absolute efficiencies to the measurements, in particular for energies below 1 keV. One can bypass the direct use of absolute efficiencies for positive ions ($\epsilon^+$), negative ions ($\epsilon^-$) and neutral atoms ($\epsilon^0$) by using efficiency ratios, as shown in Eq. 3.7, to ensure minimal eventual deviations. This assumes that changes in the efficiency are likely affecting the efficiencies for all charge states in a similar manner. The negative charge fraction is thus expressed as

$$\eta^- = \frac{N^-}{N^- + N^+ + N^0} = \frac{1}{1 + \frac{N^+}{N^-} + \frac{N^0}{N^-}}$$

(3.7)

and the positive charge fraction is consequently

$$\eta^+ = \frac{1}{1 + \frac{N^-}{N^+} + \frac{N^0}{N^+}}$$

(3.8)

In this way, it is possible to apply the absolute efficiencies reported by Peko & Stephen [50, 51] to the present experiment. The absolute efficiencies determined by Peko & Stephen [50, 51] along with suitable empirical fit functions used for interpolation are given in Fig. 3.4 and Fig. 3.5.
The empirical fit equations are given for each species and charge state:

\[
\epsilon_{\text{H}}^{-} \approx 0.819 \left[ 1 - e^{-\left(\frac{E}{51.408} + 0.337\right)} \right]
\]  
(3.9)

\[
\epsilon_{\text{H}}^{0} \approx 0.871 \left[ 1 - e^{-\left(\frac{E}{56.836} - 0.079\right)} \right]
\]  
(3.10)

\[
\epsilon_{\text{H}}^{+} \approx 0.850 \left[ 1 - e^{-\left(\frac{E}{60.642} - 0.087\right)} \right]
\]  
(3.11)

Figure 3.4: Absolute detector efficiencies for hydrogen. Peko and Stephen\textsuperscript{[50]}

Figure 3.5: Absolute detector efficiencies for oxygen. The fit for positive oxygen could not be achieved with a single equation. Stephen and Peko\textsuperscript{[51]}
\[ \epsilon_0 \approx 0.844 \left[ 1 - e^{-\left( \frac{E}{1.65 \times 10^7} + 0.127 \right)} \right] \] (3.12)

\[ \epsilon_0^0 \approx 0.918 \left[ 1 - e^{-\left( \frac{E}{1.35 \times 10^7} - 0.019 \right)} \right] \] (3.13)

The fit to the positive charge state of oxygen is split into two parts, one for values below 200 eV and one for values above 200 eV:

\[ \epsilon_0^+(E < 200 \text{ eV}) \approx 7253 \left[ 1 - e^{-\left( \frac{E}{2.69 \times 10^7} \right)} \right] \] (3.14)

\[ \epsilon_0^+(E > 200 \text{ eV}) \approx 0.917 \left[ 1 - e^{-\left( \frac{E}{1.27 \times 10^7} - 0.084 \right)} \right] \] (3.15)

### 3.2.3 Retarding potential analyzer and lens effect

The system consisting of the retarding potential analyzer (RPA) and the detector is sketched in Fig. 3.6. The RPA consists of three grids. A voltage can be applied to the center grid to deflect particles of the same charge state as the applied voltage polarity. The two outer grids are constantly connected to ground. The voltage at the center grid is chosen to be sufficiently high such that it exceeds the incident beam energy. The detector itself has another grid slightly in front of its MCP to improve its detection efficiency by reflecting secondary electrons from its surface back to the detector. This grid has a constant potential of -20 V to the MCP. The grid and MCP can be on a floating potential called “HV1”. The voltage is chosen likewise to the RPA center grid but with opposite polarity and thus deflects negative particles.
Figure 3.6: Each panel shows a cut through the RPA/Detector system at ILENA. The three grids at the entrance form the RPA, with the center grid as the controlling element and the outer grids permanently at ground potential. The grid and the detector can be at a floating potential. Panel a) shows the RPA and the floating potential HV1 switched off. Particles of all charge states reach the detector. Panel b) shows the RPA center grid at a positive high voltage (+HV) and the subsequent deflection of a positively charged particle. In panel c), the RPA is at a positive high voltage (+HV), and the detector floats at a negative high voltage (-HV). In this configuration, positively and negatively charged particles are deflected, and only neutral particles reach the detector.

From panel b) in Fig. 3.6, it is clear that the trajectory of the negatively charged particle is deformed but only under the conditions of panel b). When blocking the positive fraction of scattered particles, the RPA forms an einzel lens, which focuses
negative particles onto the MCP. This effect is small; however, when measuring charge fractions of a few percent, the effect increases the number of detected negative counts \( N^- \) by a significant amount. The true number of negative counts is obtained by introducing a correction factor \( \beta \) such that \( N^- = \beta N^*_\Leftrightarrow \). The factor \( \beta \) depends on the angle of a trajectory through the RPA, the voltage of the center grid and the energy of the particle and is described as the ratio of negative ions to neutrals. \( \beta \) can be analytically described by relating the areas covered on the MCP for neutrals, namely, \( A^0 = \pi R_0^2 \), and negative particles, namely, \( A^- = \pi (R_0 - \Delta R)^2 \).

\[
\beta = \frac{A^-}{A^0} = \frac{(R_0 - \Delta R)^2}{R_0^2} \tag{3.16}
\]

With \( l = 97.5 \text{ mm} \) as the distance from the sample to the detector and \( \gamma \) as the angle between the trajectory and the grid surface normal, the radius \( R_0 \) becomes

\[
R_0 = l \tan \gamma \tag{3.17}
\]

The focusing effect of the einzel lens results in a virtual decrease in \( R_0 \) expressed as \( \Delta R \). This decrease depends on the distance \( d = 6.75 \text{ mm} \) between the grids of the RPA, their voltage and the energy of the particle. The particle velocity changes during the RPA passage in the direction of the grid surface normal; hence,

\[
\Delta R = 2d \left( \tan \gamma - \frac{\sqrt{E \sin \gamma}}{\sqrt{E \cos \gamma} + \sqrt{e V_{RPA}}} \right) \tag{3.18}
\]

with \( V_{RPA} \) as the center grid voltage, \( e \) as the elementary charge, and \( E \) as the initial energy of the particle. The dependence on the angle \( \gamma \) is rather weak and can therefore be set to a fixed angle of a few degree, e.g., \( 6^\circ \), as half the angle of the maximum field of view of the detector \( (\pm 12^\circ) \).

Figure [3.7] shows the behavior of the correction factor \( \beta \) for some energies and different voltages applied to the RPA center electrode.

![Figure 3.7: Correction factor $\beta$ for negative particles passing the retarding potential analyzer (RPA). Different lines refer to different voltages applied to the RPA center electrode.](image-url)
3.2.4 Other effects

Other effects are shown in Fig. 3.8. In the panel on the right, a blind spot of the MCP is shown slightly above the red area, where the efficiency of the MCP is reduced. Here, the skew angle of the individual MCP channels aligns with the trajectory of the incident particles and causes fewer interactions of the incident particle with the sensitive surface of an MCP. This effect is ignored because of the relative nature of the measurements in which counts are compared at identical positions of the detector. In the panel on the left in Fig. 3.8, one can see a full image of the detector at $\Theta = 0^\circ$ for RPA and HV1 off such that all charge states reach the detector. The incident beam is shown on the very left in dark red as it passes the slit structures of a sample. The sample itself is visible as a shadow. A large green half circle indicates the usual detector position. In the large shadowed area of the sample, one can see some counts due to scattering processes at the sample. Around this shadow, counts that must originate from in front of the sample are visible because they form a shadow. It is assumed that this shadow is composed of scattered particles from the entrance aperture or some structure close to that position of the ILENA experiment. This form of positive particle contamination has a larger impact at lower energies. It leads to overestimated positive fractions. As a remedy, the detector is divided into three parallel areas, from which only measurements are considered in which all three areas show roughly the same number of counts.

![Figure 3.8](image)

**Figure 3.8:** Left: Blind spot of MCP at the top for a solid sample. The grids in front of the detector are visible as a quadratic pattern. Right: Shadow of the venetian-blind-type sample in the beam; the green circle indicates the usual detector position.

3.2.5 Method

Only neutral particles are used to measure the angular distribution over $\Theta$. The detector covers approximately $20^\circ$ of $\Theta$ at one position. For wider scattering distributions, as they occur for larger incident angles and rough surfaces, the detector is manually moved to four detector positions to cover the whole distribution. The positioning is performed via manual gears and a relative position decoder with a positioning accuracy of approximately 2 degrees. The accuracy is usually higher;
however, during the experiment, it was found that the gears had too much play, and it was not possible to redo the experiments.

The charge fractions are measured using the RPA and the floating potential, as shown in Fig. 3.6. The voltage applied to the RPA, \( V_{RPA} \), and as a floating potential to the detector, \( V_{HV1} \), is selected according to the energy and measurement case. The panels in the figure correspond to cases a), b) and c). Case a) is a measurement of all charge states, case b) measures only negative and neutral particles, and case c) measures only neutral particles.

As mentioned in section 3.1.1, secondary particles are released during scattering such that each charge state consists of primary (P) and secondary (S) particles, where primary particles have a higher energy compared to secondary particles. The charge fraction in Eq. 3.3 is therefore expanded for primary (index P) and secondary (index S) counts:

\[
\eta = \frac{N_S + N_P}{N_S^0 + N_P^0 + N_P^- + N_S^- + N_S^+ + N_P^+}
\]  

The interesting quantity for which this experiment is conducted is the charge fraction from the primary scattered particles \( \eta_P \); thus,

\[
\eta_P = \frac{N_P}{N_P^+ + N_P^- + N_P^0}
\]  

To separate secondaries and primaries, it is necessary to determine the secondary population \((N_S^+, N_S^-, N_S^0)\) or the so-called “sputter background”.

At ILENA, this is commonly done for the negative charge fraction through the use of noble gas ions under the same scattering experiment setup. Noble ions do not (or typically do not) form negative ions during scattering. Thus, during measurement case b), only neutral particles and negative secondary particles reach the detector. If this measurement is subtracted from a measurement of the same type but for ions with a comparable mass, one obtains the “negative sputter background”. This is then subtracted from the original measurement to obtain the primary population.

However, for measurements that include the positive charge fraction, this would not be possible because all noble gas ions form positive ions. Alkali metals are also not an option because they form positive ions during surface interactions.

Another way around the problem of secondary particles is to prevent them from reaching the detector. For this to work, primary ions and secondary ions must have a significantly different energy. This was tested with a measurement of 1000 eV Ne\(^+\) ions and for case b). The RPA has a voltage of +1200 V and thus prevents any positive particles from reaching the detector. Because Neon does not produce negative ions, the total number of counts consists only of \( N_S^- \), \( N_S^0 \), \( N_S^+ \). Now, if the floating potential HV1 is decreased, starting from zero, the amount of negative secondary ions should decrease as well, which can be observed in Fig. 3.9.
Figure 3.9: Reduction of secondary particles by decreasing Voltage HV1 (see Fig. 3.6). The counts are normalized to the counts at HV1 = 0 V. The circle indicates the chosen “sputter repelling potential” $V_{SRP}$ at 30% of the initial beam energy. The measurement used Ne$^+$ at 1000 eV with the RPA at 1200 V.

Furthermore, one can deduce a suitable voltage from Fig. 3.9 that sufficiently repels most of the secondary ions. A compromise was found to be 300 V for an incident beam of $E_i = 1000$ eV. The voltage is called the sputter repelling potential (SRP) and is defined as

$$V_{SRP} = 0.3 \frac{E_i}{q}$$  (3.21)

$V_{SRP}$ is applied to the floating potential HV1 during the measurements of case a) and b) and to the RPA center grid during case a). To block any ion of incident energy $E_i$, the voltage $V_{HV}$ is applied to the RPA and HV1 such that

$$V_{HV} = 1.2 \frac{E_i}{q}$$  (3.22)

Therefore, in case a), $V_{RPA} = +V_{SRP}$ and $V_{HV1} = -V_{SRP}$ to let only primary ions pass. In case b), $V_{RPA} = +V_{HV}$ and $V_{HV1} = -V_{SRP}$ to block all positive incident ions. Case c) blocks all ions from entering the detector using $V_{RPA} = +V_{HV}$ and $V_{HV1} = -V_{HV}$.

The resulting charge fraction $\eta_P$ is given by

$$\eta_P = \frac{N_P}{N_P^+ + N_P^- + N_P^0 + N_S^0}$$  (3.23)

Thus, the charge fraction can be determined without secondary ions because the error in the measurement of $\eta_P$ remains as the secondary neutral population. From Fig. 3.9, one can conclude that most secondary particles have energies below 50 eV, which is significantly lower than the incident energy. For hydrogen and oxygen, the detection efficiency for particles with energies <100 eV is approximately 10 times smaller than that for energies >500 eV, as observed in Fig. 3.4 and Fig. 3.5.
Therefore, it is assumed that the error in the achieved results is at an acceptable level.

A drawback of using $V_{SRP}$ is the more complex situation for the lens correction factor $\beta$. Without $V_{SRP}$, one $\beta$ is required to compensate for the lens effect in measurement case b). When applying $V_{SRP}$, $\beta$ changes because negative particles are passing the $-V_{SRP}$ that is applied to the detector. Thus, a $\beta_{Nb}$ that combines the lens effect of the RPA and $V_{SRP}$ at the detector assembly is introduced. Following the same logic, two more correction factors are needed to compensate for the effects in measurement case a), where all charge states above the $V_{SRP}$ potential reach the detector: $\beta_{Na}$ to correct the negative particles for case a) and $\beta_{Pa}$ to correct the positive particles.

Although a single grid can be described analytically (see 3.2.3), the combination of voltages at RPA and HV1 become too complex. The RPA and the detector were therefore simulated in SIMION to determine numerically the required $\beta$ for each measurement case. In the simulation, a number of neutral particles is sent toward the detector such that the micro channel plate is fully covered. The same amount of particles is then sent, with a different charge state, in the same direction. The ratios of charged particles to neutral particles at the detector area are the lens correction factors $\beta_{Nb}$, $\beta_{Na}$ and $\beta_{Pa}$. The results of the simulation are numerically fitted to a power law and represent energies between 390 eV and 1500 eV. For an energy $E_s$, a reasonable average value of the scattering process has to be estimated using Eq. 3.1 or Eq. 3.2.

\begin{align*}
\beta_{Nb} &= 0.810 \cdot E_s^{0.0221} \quad (3.24) \\
\beta_{Na} &= 0.763 \cdot E_s^{0.0248} \quad (3.25) \\
\beta_{Pa} &= 7.4 \cdot 10^{-6} \cdot E_s + 0.997 \approx \text{const.} \quad (3.26)
\end{align*}

With the correction factors $\beta_{Nb}$, $\beta_{Na}$ and $\beta_{Pa}$, the true numbers of neutral, negative and positive particles $N^0$, $N^-$, and $N^+$, respectively, can be retrieved from the subtraction of the measured quantities for each case:

\begin{align*}
N^0 &= N_c \quad (3.27) \\
N^- &= (N_b - N_c)\beta_1 \quad (3.28) \\
N^+ &= \left[ N_a - N_b \frac{\beta_{Nb}}{\beta_{Na}} + N_c \left( \frac{\beta_{Nb}}{\beta_{Na}} - 1 \right) \right] \beta_{Pa} \quad (3.29)
\end{align*}

with $N_c$ as the neutral counts in measurement case c).

\begin{align*}
N^0 &= N_c \quad (3.27) \\
N^- &= (N_b - N_c)\beta_1 \quad (3.28) \\
N^+ &= \left[ N_a - N_b \frac{\beta_{Nb}}{\beta_{Na}} + N_c \left( \frac{\beta_{Nb}}{\beta_{Na}} - 1 \right) \right] \beta_{Pa} \quad (3.29)
\end{align*}
with \( N_a \) as the counts of all charge states from case a) and \( \beta_{N_a} \) and \( \beta_{Pa} \) as lens correction factors. With the obtained and corrected counts \( N^0, N^- \) and \( N^+ \) from above and the detector efficiencies of Eq. 3.9 to Eq. 3.15, it is possible to calculate the charge fractions according to Eq. 3.7 and Eq. 3.8.

To determine the positive ionization yield according to Eq. 3.6, a measurement of the reflection efficiency \( r \) is required. The reflection efficiency of a conductive sample was measured by electrically insulating the sample from the chamber and connecting the sample to an ammeter. In the present case, the pico-ammeter, a Keithley 6517A, was used with a measurement range down to 0.1 fA (10^{-15} A). The effective achievable resolution of the setup was approximately 5 fA. At ILENA, such small currents are usually measured with a dedicated system using a Lock-in amplifier; however, the system was not operable during the experiment. Therefore, the DC-current measurement using the pico-ammeter was used instead.

The reflection efficiency is given by

\[
 r = \frac{N_{out}}{N_{in}} = \frac{N_{out}}{I_{in}} = \frac{(N^0 + N^+ + N^-)}{t} \frac{1}{k(I_s + I^{2e} + I^- - I^+)} \tag{3.30}
\]

with \( N_{out} \) as the total number of particles scattering from the sample; \( N_{in} \) as the number of ions incident on the sample, which can be described as a current \( I_{in} \) as well; \( t \) as the integration time used to acquire the counts; \( k \) as a correction factor, which includes the detector field of view, the sample geometry and the transmission of the grids; and \( I_s \) as the measured current from the sample. \( I^{2e} \) is the current of secondary electrons leaving the sample, \( I^- \) is the current of negative particles leaving the sample, and \( I^+ \) is the current of positive particles leaving the sample.

The current incident on the sample is given by \( I_{in} = I_s + I^{2e} + I^- - I^+ \). The measured current \( I_s \) is therefore only an approximation of the incident current \( I_{in} \). A coil that generates a small magnetic field on the order of mT is placed directly at the sample holder to reflect the secondary electrons back onto the sample; therefore, \( I^{2e} = 0 \). \( I^- \) and \( I^+ \) can be estimated using the measured charge fractions \( \eta^- \) and \( \eta^+ \) (Eq. 3.7, Eq. 3.8): \( I^- = \eta^- I_s \) and \( I^+ = \eta^+ I_s \). These fractions are usually small compared to the neutral fraction, and the error introduced by approximating the currents \( I^- \) and \( I^+ \) via the sample current \( I_s \) is small.

The correction factor \( k = k_1 \cdot k_2 \cdot k_3 \) can be described as follows: The factor \( k_1 \) relates the area of the sample that is able to scatter particles in the direction of the detector to the area upon which the beam is incident. For example, for the Cu-sample, a value of \( k_1 = 0.488 \) was used due to its venetian-blind structure, for the flat DLC-sample, \( k_1 \) is equal to 1.

\[
k_2 = \frac{\Omega_{detector}}{\Omega_{scattering}} \approx \frac{(25^\circ)^2}{(\frac{1}{2} \Theta_{FWHM})^2} \tag{3.31}
\]

The factor \( k_2 \) accounts for the smaller field of view of the detector compared to the total scattering distribution over \( \Theta \) and \( \Phi \). The approximation of the solid angle \( \Omega_{scattering} \) is taken from Wahlström et al. [49], and the parametrization of their
The parameterization is tailored to the knowledge of the incident angle $\alpha < 20^\circ$ and for very smooth surfaces of $R_{RMS} < 10$ nm. When the angular distribution in $\Theta$ is already measured, as in Fig. 3.16 and a $\Theta_{FWHM}$ can be determined, the data of Wahlström et al. [49] allow one to approximate the corresponding $\Phi_{FWHM} = \frac{3}{2} \Theta_{FWHM}$. In this way, the surface properties, e.g., surface roughness, are better represented as by using only the knowledge of the incident angle.

The factor $k_3$ represents the transmission of all the grids in front of the detector. The transmission of each of the four grids in front of the detector is estimated as 85% and thus gives $k_3 = 0.85^4 = 0.52$.

### 3.3 LISA experiment

#### 3.3.1 Setup

The scattering experiment at IRF/Kiruna measures positive ion fluxes to determine the positive ion yield according to Eq. 3.6. The ion fluxes were measured in a first attempt using the qualification model of the Miniature Ion Precipitation Analyzer (MIPA) [53]. The experiment and results are described in section 3.8. Soon after conducting the experiment, MIPA became unavailable because it was refurbished into a flight spare model. Because of the good results obtained with MIPA, a dedicated instrument was built: the Laboratory Ion Scattering Analyzer (LISA).

Both instruments use the same principle of combining an electrostatic analyzer with a field-free time-of-flight measurement in a very compact form factor. Because the instrument was designed to monitor the solar wind, the mass resolution is $\frac{m}{\Delta m} \approx 2$ for positive ions of energies per charge between $\sim 20$ eV/q and approximately 15 keV/q. More details on MIPA can be found in [53]. LISA is a descendant of the solar wind ion monitor (SWIM) family [31] of sensors. It used spare parts of predecessor instruments such as MIPA [53], PRIMA [54] (PRISMA) and YPP (Yinghuo-1 [55]). LISA features a spherical electrostatic analyzer from YPP, whereas MIPA has a cylindrical electrostatic analyzer. The electronics for LISA are spares from PRIMA. The highly polished tungsten start surface, as used by MIPA, was unfortunately not available for LISA. This results in higher losses at the start surface and thus a lower stop efficiency. The FWHM field of view of LISA is approximately $4.2^\circ \times 10.0^\circ$, giving a solid angle of $\Omega \approx 0.013$ sr and a FWHM energy resolution of $\frac{\Delta E}{E} = 4.5\%$. 
The LISA experiment setup is shown in Fig. 3.10. The setup is similar to the MIPA setup used in section 3.8. The experiment is placed in the vacuum chamber of the Kiruna calibration laboratory under pressures of typically $10^{-6}$ mbar. The LISA detector is placed on an aluminum disc, which is referred to as the table. Two control pins are placed on the table such that it is possible, via rotation of the table around $\Theta$, to place the sample into and out of the incident ion beam. Thus, it is possible to characterize the incident ion beam and the scattered ions for angles $\Theta$ between $\sim -15^\circ$ and $\sim +90^\circ$. The corresponding out-of-plane angle is $\Phi$ (see Fig. 3.2). The sample holder is fixed to the vertical arm of the manipulator such that it follows the rotation in $\Phi$ but not in $\Theta$. This means that the incident angle of the sample is fixed as well. Out-of-plane scattering in the direction of $\Phi$ could only be measured by rearranging the setup, including making a new holder and subsequently turning the sample by $90^\circ$.

### 3.3.2 Method

The setup relates the scattered positive flux $F^+_s$ to the incident flux of the ion beam $F_i$ on the sample (Eq. 3.6). The incident flux is determined by pointing the detector straight into the beam. If the sample is transparent, it can be used as a reduction in beam intensity to maximize the scattered flux. The scattered flux is measured over different angular positions $\Theta$, as was the case with MIPA. However, for individual positions of $\Theta$, during the MIPA experiment, integration times of 3 h where required to obtain significant numbers of positive scattered ions into the detector. For a full angular scan with sufficiently small angular steps, the measurement would likely take too long depending on the sensor sensitivity and scattering flux. To overcome the problem, a new measurement scheme was developed: the angular positions are measured with a more intense beam to record the shape of the angular distribution over $\Theta$. This enables a smaller integration time of approximately 15 min per angular
position. After, the beam intensity is reduced so that the beam itself and the scattering can be measured at specular reflection. The previously measured angular distribution is then normalized to the single measurement at specular reflection. The conversion of the measured counts to the flux follows the same method as described in section 3.8.

3.4 Samples

During 3 measurement campaigns (ILENA, MIPA & LISA), a total of 4 different materials were tested in several versions. Unfortunately, no inter-calibration between ILENA and the other measurements is available. In the following subsections, the different samples of start surfaces are described. An overview is given in Tab. 3.1. The aspect ratio is a term used to describe a structure, e.g., a hole, and is the ratio of the depth over the structure’s width such that a large aspect ratio represents a deep, thin hole.

3.4.1 Summary of samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Aspect Ratio</th>
<th>Surface Roughness</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>2</td>
<td>( R_a \sim 200 \text{ nm} )</td>
<td>ILENA</td>
</tr>
<tr>
<td>DLC</td>
<td>-</td>
<td>( R_{RMS} \sim 1 \text{ nm} )</td>
<td>ILENA</td>
</tr>
<tr>
<td>MPO</td>
<td>1.5 &amp; 10</td>
<td>( R_{RMS} &lt; 1.5 \text{ nm} )</td>
<td>LISA</td>
</tr>
<tr>
<td>Si</td>
<td>4</td>
<td>( R_{RMS} &lt; 5 \text{ nm} )</td>
<td>LISA</td>
</tr>
</tbody>
</table>

Table 3.1: Summary of samples used in the scattering experiments. The surface roughness is often given in \( R_a \), which is the arithmetic mean of a measurement, or in \( R_{RMS} \) as the “Root Mean Square”. Both values are comparable to each other.
3.4.2 Laser-ablated copper “Cu”

![Laser-ablated copper sample: top view (left) and bottom view (right). Outer dimensions: 7.8 mm x 9.2 mm](image)

The first venetian-blind-type start surfaces were designed by M. Wieser as two pieces stacked together. One example is shown in Fig. 3.11 from the top and from the bottom. Due to the applied machining process, the slits open up to the bottom. Copper was chosen as the material to minimize energy losses during scattering because it is easy to machine and has a high atomic mass. The samples were machined using laser ablation (Coherent, Super Rapid 2nd batch). With a pulse width of \(\sim 10\) ps, each sample took \(\sim 110\) minutes to machine. Materials with comparable treatment are reported to have a surface roughness of approximately \(R_a \sim 200\) nm \(^{56}\). \(R_a\) describes the surface roughness as the arithmetic mean height measured over a certain distance.

3.4.3 Hard disc platter “DLC”

Diamond-Like Carbon (DLC) is reported to have an excellent surface roughness at the atomic level and a high negative ion fraction \(^{49}\). DLC is an interesting material for start surfaces and conversion surfaces if the scattered particles present a high positive charge fraction. Although this sample does not provide as suitable a geometry as the venetian-blind-type copper, it was tested together with the copper sample. DLC samples with very low surface roughness are costly. Hard disc platters for personal computers use DLC to achieve a very smooth and durable surface. If such hard disc platter surfaces would provide acceptable results, conversion surfaces could be simply bought at any electronics store.

XSAN (eXtra Small Analyzer of Neutrals) is a project to study the moon soil in 2018 and is another descendant of the SWIM \(^{31}\) series of instruments. For analyzing neutral particles, the neutrals entering the instrument need to be ionized for further characterization in the electrostatic analyzer and time-of-flight cell. The ionization process is performed using a conversion surface. Incident neutral particles on a conversion surface are converted into charged particles via surface interaction. Such
a surface is required to have a high positive ionization yield similar to the start surfaces mentioned in this thesis. To minimize the instrument budget, it was planned to test hard disc platters coated with DLC during the campaign at ILENA. Hard disc platters are surfaces that are tailored to industrial performance requirements [57], e.g., corrosion protection, wear resistance, thermal insulation, electrical conductivity, diffusion barrier and adhesion to the substrate. For the test, a Toshiba MK4018GAS hard disk was cut into suitable slices, as shown in Fig. 3.12.

![Cut, 63.5 mm diameter, hard disc platter, MK4018GAS](image)

Because the exact composition of such a platter was unknown, X-ray photo electron spectroscopy (XPS) was performed on the surface (Umeå University, A. Shchukarev). XPS is specifically suited to unveil the structure of surface compositions for atomic masses above helium. The result was a composition of roughly 42% C bonded $sp^2$, 13% C bonded $sp^3$, 15% other C, 13% other O, 5% other N and 12% $CF_2$, with traces of Cp, Pt and Cr. The sheet resistance was measured to be approximately 3 $k\Omega/sq$.

Even though this DLC sample has no direct application as a start surface for JDC, the test was useful for comparing the copper sample to a much smoother sample.

### 3.4.4 Micro pore optics “MPO”

Micro pore optics are described in detail in section 3.8. In addition to the sample described in section 3.8, three more MPO samples were retrieved later.
Table 3.2: Tested MPO samples, sample code: MPO-[pore]SQ[size], with [pore] as the size of the pore in µm. SQ notes a quadratic pore, and [size] is in mm x mm. The endings are internal company codes.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Aspect Ratio</th>
<th>note</th>
<th>short name</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPO-686SQ31X31-1/H</td>
<td>1.5</td>
<td>H reduced</td>
<td>Q30</td>
</tr>
<tr>
<td>MPO-100SQ10X10/E</td>
<td>10</td>
<td>H reduced</td>
<td>Q10</td>
</tr>
<tr>
<td>MPO-100SQ15X15/E</td>
<td>10</td>
<td>H reduced,polished</td>
<td>Q15-093</td>
</tr>
<tr>
<td>MPO-100SQ15X15/E</td>
<td>10</td>
<td>H reduced</td>
<td>Q15-098</td>
</tr>
</tbody>
</table>

Tests using Q15-093 did not produce reliable data because of problems with the test setup, and Q15-098 was not tested. Thus, the results are restricted to the samples Q30 and Q10. All samples provide the same grade of surface roughness. The large sample, Q30, was tested with MIPA and LISA. The other sample, Q10, was only tested with the LISA experiment.

3.4.5 Etched silicon “Si”

In collaboration with the University of Chalmers of Gothenburg (S. Rahiminejad), slits of different sizes were etched in silicon. Micro machining of silicon is a well-established technology that can provide high flexibility in the design of venetian-blind-type start surfaces. In combination with coating technologies, e.g., coating with gold, promising designs that are otherwise very difficult to achieve are possible. In this first attempt, different sizes of slit structures were etched in pure silicon wafers with a thickness of 525 µm.

Figure 3.13: Silicon samples from Chalmers University, wall thicknesses: 1=90 µm, 2=110 µm, 3=120 µm, 4=110 µm, and 5=120 µm. All samples were designed with 125 µm slits (+ over etching)

The walls were found to be over etched by approximately 10%, e.g., the 90 µm walls
were found to be 82 µm in width; thus, the slits are 133 µm wide. All samples are gold plated. The inner wall surface roughness was measured to be $R_{RMS}$ of $\sim$ 5 nm. $R_{RMS}$ is a measure of surface roughness for a height profile but is defined as a root mean square value. The value is comparable to $R_a$.

![Figure 3.14](image.png)

**Figure 3.14:** Cross-section of 2.5-mm-long slit structure. The measured wall thickness is 82 µm, which gives an undercut of approximately 4 µm on each side.

The received samples make a very good impression. The walls, according to Fig. 3.14, are straight and do not present a significant deviation from a rectangular shape. The surface roughness is promisingly low and in the range of the MPO samples. The active area of each sample is approximately 3.3 mm x 2.5 mm, with an overall size of 10 mm x 10 mm.

In the experiment, sample “4” with 110 µm walls was used.

### 3.5 Angular scattering

Angular scattering is the change in direction after an ion is reflected from a surface. It is the result of the interaction with the atomic structure of the target material. Angular scattering is described using spherical coordinates, with both the in-plane angle $\Theta$ and the out-of-plane angle $\Phi$ and the FWHM of their distributions. The distribution around $\Phi$ is usually symmetric about specular reflection, whereas the scattering over $\Theta$ has a Gaussian onset and an exponential tail toward higher scattering angles. Angular scattering at start surfaces is generally unwanted because it reduces the efficiency of the detector and thus has to be minimized. Angular scattering depends on energy, material, incident angle and surface conditions.

Among the parameters that influence angular scattering, surface roughness is an important parameter and describes the small-scale structure of the surface. Through a literature study, a correlation could be found between surface roughness and angular scattering, as shown in Fig. 3.15. For the plot, the incident angle was normalized by the $\Theta_{FWHM}$ of the angular distribution, and the resulting ratio was plotted along
the y-axis. On the x-axis, the surface roughness is plotted in $R_a$ or $R_{RMS}$, depending on the publication.

![Graph](graph.png)

**Figure 3.15**: Literature survey for angular scattering from smooth surfaces. The y-axis shows the incident angle, normalized to the $\Theta_{FWHM}$ of the corresponding distribution. “Arezki 1998”, “Riedo 2012”, “Wahlström 2008”, “Wieser 2002”, “Wieser 2005”, other data points are from within this work. Note that the given data points are retrieved from different experiments with different species and energies. The trend line $t_i$ is given by $t_i = 0.66 \cdot R^{-0.17}$.

An ideal scattering surface would be atomically flat, meaning that not even a single atom step would be found over the whole surface. Such an ideal value would result in a measurement of $R_{RMS} < 0.1$ nm. Measurements are often performed using an atomic force microscope (AFM), in which the height profile is recorded for a given distance. The root mean square (RMS) of the height values is then given as a surface roughness $R_{RMS}$. $R_a$ would be the average of the height values and is thus a comparable value. The surface roughness inside the slit for a venetian-blind-type start surface is commonly described as side wall roughness.

With the ratio of the incident angle over $\Theta_{FWHM}$ of the scattering distribution and the surface roughness Fig. 3.15, different experiments become comparable at a basic level. Despite showing a clear trend, the experiments vary in terms of ion species, target materials, energies and setups. The ratio value on the y-axis should be as large as possible for a surface that minimizes scattering. The near-atomically flat samples of Wahlström et al. give a ratio of approximately 1 for incident angles over $\Theta_{FWHM}$ of the angular distribution, which is therefore considered as a very good target value. To obtain this value, surface roughness values on the order of $R_{RMS} < 1$ nm are needed.

Despite the large variations in the plotted data, a significant outlier from the general trend is observed in the points of Wieser. The reported surface roughness...
of $R_{RMS} = 30$ nm corresponds to a sample at room temperature as received. In contrast to the other points in the same publication, the outlier point was measured with a different apparatus and by heating the sample to more than $1000^\circ C$ (annealing). Heating is a very efficient way of lowering the surface roughness \[61\]. The $R_{RMS}$ value of that data point is therefore unknown but can be estimated to be better than $R_{RMS} < 1$ nm.

Surface flatness is a parameter that is usually not considered. Flatness describes the eventual curvature of a sample. Although this is usually not of concern for flat surfaces, for example, single crystal materials, it can turn out to be a problem for venetian-blind-type structures with small slats. Such slats might bend when subjected to heat or other forms of mechanical stress.

To measure the angular distribution over $\Phi$, the experimental setups of ILENA and LISA would require different mechanical sample holders. For the experiments presented in this work, time did not allow for such measurements. Fortunately, as described earlier, the scattering over $\Phi$ forms a symmetrical shape around $0^\circ$. Wahlström et al. showed measurements of varying incident angles \[49\]. The achieved values from their publication allow one to parametrize their measurements to deduce the angular distribution over $\Phi$ from the angular distribution over $\Theta$. The method is described in more detail in 3.8.

### 3.5.1 Angular scattering results

#### 3.5.1.1 Cu and DLC

The results for the “Cu” sample and for the “DLC” sample are plotted for different energies in Fig. 3.16.
The error bars represent the accuracy of the manual positioning and are between 1 and 2 degrees. The position of the maximum of each scatter function is given in the upper panel of Fig. 3.16. For the “Cu” sample, the position of the maximum is rather constant, except for lower energies, where the maximum tends toward larger \( \Theta \). The measurement using sample “DLC” suffered from an inaccuracy for the incident angle, which translates into a larger error in the scattering angle \( \Theta \). From the results, it is rather certain that the incident angle \( \alpha = 13^\circ \) and not \( 15^\circ \), as for the “Cu” sample.

### 3.5.1.2 Micro pore optics and silicon

The angular distribution over \( \Theta \) of hydrogen and nitrogen ions incident upon the measured MPO and silicon samples are shown in Fig. 3.17. The counts are normalized to 1 and, for each sample, are fitted to an exponentially modified Gaussian of the measured data.
The relation with the surface roughness is plotted in Fig. 3.18 with the same normalization of the y-axis as for Fig. 3.15. The trend from the literature study of Fig. 3.15 is shown as well.

Figure 3.17: Scattering distributions for measured samples with LISA for 2000 eV $H^+$ and $N^+$

Figure 3.18: Angular scattering from MPO, Si, Cu and DLC samples. The y-axis shows the incident angle, normalized to the FWHM of the corresponding angular distribution. The trend line is taken from Fig. 3.15
3.5.2 Discussion

In general, the samples show the maximum of the angular distribution at $\Theta \leq 2\alpha$, and thus, the venetian-blind-type structures are comparable to flat surfaces. An exception is sample Q30 under incident nitrogen ions, where the maximum is found at $\Theta = 45^\circ$ and the distribution over $\Theta$ shows a more Gaussian shape with no exponential tail. An explanation for this is to be found in the charging up of the sample during the measurement of nitrogen (see section 3.6 and Fig. 3.28). The beam current was set quite high to achieve a high scattering flux. The movement of the grounded instrument around the charged up sample causes a distortion of the angular distribution along $\Theta$. The position of the sample was identical to other experiments and can be ruled out as a potential problem. The curve for nitrogen is therefore erroneous and gives too small of a FWHM value at an incorrect maximum position. Scattering hydrogen from sample Q30 shows a typical behavior: the maximum appears at slightly smaller $\Theta$ than $2\alpha$, and at larger $\Theta$, a typical exponential tail can be seen. For the silicon sample, a typical shape as for incident hydrogen at Q30 is visible; in addition, the tail is weaker. Nitrogen from the Si sample shows a small difference in both position and $\Theta_{FWHM}$ but with a similar tail. The larger $\Theta_{FWHM}$ results in a smaller ratio $\alpha/\Theta_{FWHM}$ in Fig. 3.18. As shown in the next section, heavier particles experience larger energy losses and larger energy straggling, which could be the reason for the larger spread over the scattering angle $\Theta$ for heavier incident particles.

For the sample Q10, basically no difference is observed between hydrogen and nitrogen for the angular distribution over $\Theta$. The shapes of the functions follow a substantially more Gaussian type than for the Si sample or the larger sample Q30.

This is assumed to be an effect of the higher aspect ratio of 10 compared to 1.5 or 4 as explored in Fig. 3.19. The depth distribution of the slit for a parallel incident beam is shown for different aspect ratios and incident angles. The depth for each combination is calculated with simple geometries and straight trajectories of a virtual incident ion beam. For a large incident angle, e.g., $\alpha = 20^\circ$, and a large aspect ratio, e.g., 10, a parallel incident beam only covers the first 20% of the slit.
The sample Q10 was tested under an incident angle $\alpha = 7^\circ$, and thus, only the first 60% of the slit was illuminated by the incident beam. This results in a loss of the exponential tail of the original scattering distribution, as visible for the silicon sample or for the hydrogen curve at Q30. The measured distribution thus has a smaller $\Theta_{FWHM}$, i.e., a higher ratio in Fig.3.15. This could also be the explanation for the silicon samples because they have a higher ratio as well. With an aspect ratio of 4 and an incident angle of $\alpha = 15^\circ$, the beam reaches 80% into the slit; however, some parts of the tail can very well be lost in the structure, similar to the Q10 sample, and artificially increase the ratio $\alpha/\Theta_{FWHM}$.

In conclusion, most samples show expected distributions of $\Theta$ or a deviation that can be explained. For a comparison to flat surfaces, the experiments need to consider the aspect ratio and the charging of the sample in the strong incident beam. Samples with low aspect ratio are needed to achieve the same distributions as for flat samples. Higher aspect ratios cause a loss of the tail of the angular distribution inside the slit structures. Considering the direct use of the present samples, the results provide valuable information on the scattering processes for high-aspect-ratio samples of high resistivity and enable a more refined design of a venetian-blind-type start surface as an entry point for a reflectron-type time-of-flight cell. In particular, the comparison to other materials, e.g., the silicon samples, proved to be of great value.

### 3.6 Energy loss and energy straggling

During surface interaction, the incident ion loses energy to the surface via collisions. Considering the incident angle here, the target surface and the ion species are the most important parameters. For the given energy range, binary collisions are assumed, and thus, the heavier the surface material is or the lighter the incident particle is, the smaller the energy loss becomes, as described by Eq. 3.1.
The energy loss $L_E$ is defined as

$$L_E = 1 - \frac{\hat{E}}{E_i} \quad (3.32)$$

with $\hat{E}$ being the main peak position and $E_i$ being the incident energy. Energy straggling $S_E$ describes the width of the distribution:

$$S_E = \frac{E_{FWHM}}{E} \quad (3.33)$$

with $E_{FWHM}$ being the Full-Width-Half-Max of the energy peak.

The copper sample should have the smallest energy loss because of its high atomic number; however, ILENA does not directly offer energy discrimination, and no data are available for this sample. For the DLC sample, the energy loss should be the highest because of its low atomic number; however, again, no data are measured. The MPO (silicon dioxide substrate) and the silicon sample were measured with MIPA and LISA.

In the conducted experiments, it is assumed that a layer of water can be found on the tested surfaces because no special treatments, such as heating, were applied during preparation of the experiments and samples.

### 3.6.1 Energy loss and energy straggling results

First, the energy spectra for the sample Q30 are replotted from section 3.8 in Fig. 3.20 because the absolute differential flux is given instead of the relative flux, as in 3.8. Hydrogen spectra for different positions of $\Theta$ are plotted in the upper panel. Note that, for nitrogen in the lower panel, only a single measurement exists and that all measurements in Fig. 3.20 were acquired with MIPA instead of LISA.

All energy spectra have been fitted with an exponentially modified Gaussian [62] of the form

$$f_s = h \cdot e^{-\frac{(E-\mu)^2}{2\sigma^2}} \cdot \frac{\sigma}{\tau} \cdot \sqrt{\pi/2} \cdot \text{erfcx} \left[ \frac{1}{\sqrt{2}} \left( \frac{E - \mu}{\sigma} + \frac{\sigma}{\tau} \right) \right] \quad (3.34)$$

with $h$ as the amplitude of the Gaussian, $E$ as the energy, $\mu$ as the center of the Gaussian, $\sigma$ as the width of the Gaussian, and $\tau$ as the exponential modification of the Gaussian.
Figure 3.20: Energy distribution of scattered ions for sample Q30, measured with MIPA. The dashed lines are fits to the primary scattering peak.

The energy spectra for sample Q30 using the LISA instrument and the slightly different method as described in 3.3.2 are given in Fig. 3.21. In contrast to the first measurements with MIPA, the nitrogen panel contains energy spectra at different positions of $\Theta$. 
**Figure 3.21:** Energy distribution of scattered ions for sample Q30, measured with LISA. The dashed lines are fits to the primary scattering peak.

<table>
<thead>
<tr>
<th>Ion species</th>
<th>Θ</th>
<th>Main peak energy</th>
<th>$L_E$</th>
<th>$S_E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$^+$</td>
<td>45°</td>
<td>1497 eV</td>
<td>25%</td>
<td>44%</td>
</tr>
<tr>
<td>H$^+$</td>
<td>30°</td>
<td>1601 eV</td>
<td>20%</td>
<td>31%</td>
</tr>
<tr>
<td>H$^+$</td>
<td>20°</td>
<td>1714 eV</td>
<td>14%</td>
<td>26%</td>
</tr>
<tr>
<td>N$^+$</td>
<td>30°</td>
<td>1088 eV</td>
<td>38%</td>
<td>46%</td>
</tr>
<tr>
<td>H$^+$</td>
<td>45°</td>
<td>1380 eV</td>
<td>31%</td>
<td>53%</td>
</tr>
<tr>
<td>H$^+$</td>
<td>30°</td>
<td>1463 eV</td>
<td>27%</td>
<td>40%</td>
</tr>
<tr>
<td>H$^+$</td>
<td>20°</td>
<td>1633 eV</td>
<td>18%</td>
<td>28%</td>
</tr>
<tr>
<td>N$^+$</td>
<td>40°</td>
<td>1250 eV</td>
<td>28%</td>
<td>53%</td>
</tr>
<tr>
<td>N$^+$</td>
<td>30°</td>
<td>1305 eV</td>
<td>35%</td>
<td>45%</td>
</tr>
<tr>
<td>N$^+$</td>
<td>20°</td>
<td>1432 eV</td>
<td>38%</td>
<td>33%</td>
</tr>
</tbody>
</table>

**Table 3.3:** Maxima and FWHM of energy spectra for sample Q30

Hydrogen does not generate notable amounts of secondary ions, as observed in Fig. 3.21. In the previous measurements with MIPA, the lower energies were been measured.

Notable differences between MIPA and LISA are visible in the nitrogen panels for the
secondary ion population. For larger scattering angles $\Theta$, the population increases and moves toward higher energies, which is assumed to be a charging effect. The energy positions of the primary peaks differ slightly between the measurements using MIPA and LISA.

Fig. 3.22 shows the energy spectra for sample Q10.

![Energy spectra for sample Q10](image)

**Figure 3.22:** Energy distribution of scattered ions for sample Q10, measured with LISA. The dashed lines are fits to the primary scattering peak

<table>
<thead>
<tr>
<th>Ion species</th>
<th>$\Theta$</th>
<th>Main peak energy $L_E$</th>
<th>$S_E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{H}^+$</td>
<td>20°</td>
<td>1648 eV 18%</td>
<td>26%</td>
</tr>
<tr>
<td>$\text{H}^+$</td>
<td>14°</td>
<td>1748 eV 13%</td>
<td>16%</td>
</tr>
<tr>
<td>$\text{H}^+$</td>
<td>8°</td>
<td>1804 eV 10%</td>
<td>11%</td>
</tr>
<tr>
<td>$\text{N}^+$</td>
<td>20°</td>
<td>1266 eV 37%</td>
<td>42%</td>
</tr>
<tr>
<td>$\text{N}^+$</td>
<td>14°</td>
<td>1438 eV 28%</td>
<td>33%</td>
</tr>
<tr>
<td>$\text{N}^+$</td>
<td>8°</td>
<td>1539 eV 23%</td>
<td>22%</td>
</tr>
</tbody>
</table>

**Table 3.4:** Maxima and FWHM of energy spectra for sample Q10

Sample Q10 was measured at different angular positions because the incident angle during the measurement had to be changed. Sample Q10 has an aspect ratio of 10, for which an incident angle of 15° would not allow the scattered particles to leave the micro pores. Therefore, the incident angle was changed to $\alpha = 7^\circ$; hence, specular reflection occurs at $\Theta \approx 14^\circ$. In comparison to sample Q30, the secondary
peaks are much less intense and with lower energies and are without as clear a $\Theta$ dependence as sample Q30 (nitrogen panel Fig. 3.21). This is either because of the different angular situation or the aspect ratio.

The energy spectrum of the silicon sample is shown in Fig. 3.23.

![Energy spectrum of scattered ions from the Si sample](image)

**Figure 3.23**: Energy spectrum of scattered ions from the Si sample. The main peaks are fitted with an exponentially modified Gaussian.

<table>
<thead>
<tr>
<th>Ion species</th>
<th>$\Theta$</th>
<th>Main peak energy</th>
<th>$L_E$</th>
<th>$S_E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$^+$</td>
<td>50°</td>
<td>1414 eV</td>
<td>29%</td>
<td>59%</td>
</tr>
<tr>
<td>H$^+$</td>
<td>30°</td>
<td>1561 eV</td>
<td>22%</td>
<td>35%</td>
</tr>
<tr>
<td>H$^+$</td>
<td>20°</td>
<td>1746 eV</td>
<td>13%</td>
<td>18%</td>
</tr>
<tr>
<td>N$^+$</td>
<td>45°</td>
<td>701 eV</td>
<td>65%</td>
<td>78%</td>
</tr>
<tr>
<td>N$^+$</td>
<td>30°</td>
<td>1074 eV</td>
<td>46%</td>
<td>56%</td>
</tr>
<tr>
<td>N$^+$</td>
<td>20°</td>
<td>1302 eV</td>
<td>35%</td>
<td>42%</td>
</tr>
</tbody>
</table>

**Table 3.5**: Maxima and FWHM of energy spectra for the silicon sample.

The top panel of Fig. 3.23 for the silicon sample shows the typical behavior of scattered hydrogen: very low secondary ion counts at low energies and higher energy loss and increasing energy straggling with increasing $\Theta$. In the nitrogen panel, three distinctive peaks can be seen: the main peak at approximately 1000 eV and two
secondary peaks at approximately 250 eV and 80 eV. A charging of the sample is impossible because of the gold plating and the semi-conductor properties of silicon. Although the energy loss for hydrogen is approximately equal to that for other samples, the energy loss for nitrogen is the highest among the tested samples.

3.6.2 SRIM simulations

The experiments were simulated with the SRIM code [47]. The simulations do not consider charge fraction effects or surface parameters. The simulation assumed a field of view of $10^\circ \times 20^\circ$. As the target material, lead glass with a 1 nm water layer on top was used because it well compares to the material used in micro pore optics.

![Figure 3.24: Simulated energy distribution for 2 keV H\(^+\) incident on lead glass with a 1-nm-thick water layer under an incident angle of 15\(^\circ\).](image)

As shown in Fig. 3.24, hydrogen was scattered from lead glass. The incident angle was $\alpha = 15^\circ$, and the incident energy was 2000 eV. With hydrogen as the projectile, almost no secondary ions can be seen, and the main peak is at energies of approximately 1500 eV. The simulated spectrum does compare well to the measured energy spectrum. The main peak consists solely of hydrogen; however, a few oxygen particles are visible at lower energies.
In Fig. 3.25, the same surface was simulated; however, nitrogen was used as the incident particle. The spectrum shows three regions: a main peak at approximately 1200 eV consisting of nitrogen, secondary ion peaks at lower energies of approximately 40 eV, and third region at energies of approximately 300 eV. The main peak shows a larger energy loss compared to hydrogen, similar to the measurements. The secondary ions are mostly the water constituents, i.e., hydrogen and oxygen. Above 200 eV, some silicon and nitrogen are visible but not at a significant level. The simulation qualitatively represents the scattering process as well with nitrogen as with hydrogen. The three regions for incident nitrogen can be observed in Fig. 3.22.

Because the SRIM code was able to reproduce the scattering experiments for hydrogen and nitrogen at 2 keV on a basic level, the SRIM code was used to simulate different energies and species. One important species for JDC is sulfur, an abundant species around Jupiter and therefore expected to be detected with the instrument. Sulfur is more difficult to handle in the laboratory and is therefore rarely available for tests, especially at higher energies. The results of this simulation are summarized in Fig. 3.26.
The simulation used hydrogen, nitrogen and sulfur at energies of 0.2 keV, 2 keV and 20 keV. This was chosen such so the measured energy regime of JDC would be included in the simulation. Sulfur (32 u) and sulfur dioxide (64 u) are expected to be the heaviest particles measured with JDC and, together with hydrogen (1 u), represent the covered mass range of the instrument. Nitrogen is expected to behave similar to oxygen in the simulation and thus represents the mid-range masses. The energy loss $L_E$ is plotted on the x-axis, and the simulated reflection efficiency is plotted on the y-axis. The plot provides an estimate of the behavior of particles scattered into the time-of-flight cell and their impact on instrument sensitivity. For example, if 200 eV hydrogen is scattered from pure tungsten, the energy loss is very small; however, most of the particles become stuck in the target surface. Glass shows little difference between the clean state and that with a water layer, which might result in long-term stability, whereas tungsten exhibits large differences. Sulfur, for example, is estimated to lose 90 % of its energy for a tungsten surface with a water layer but only 20 % when scattering off a clean tungsten surface. In conclusion the energy loss seems to be a more variable parameter, whereas the reflection efficiency remains comparatively stable.

### 3.6.3 Discussion of energy loss and energy straggling

It could be confirmed from measurements and simulation that hydrogen does not produce any significant amount of secondary particles when scattered off a surface.
at 2 keV despite the water layer on the surface and the light target material. This is important for the interpretation of charge fractions at the ILENA experiment because it shows that no “sputter background” is present for measurements using hydrogen. The experiments measuring the energy spectrum of scattered ions agreed well with the simulations.

To obtain a better overview of all measurements, energy loss and energy straggling are plotted against the scattering angle $\Theta$ in Fig. 3.27.

**Figure 3.27:** Comparison of energy loss and energy straggling for measured samples. ‘Q30*’ was measured with MIPA

For better visibility, triplets of the angular distribution over $\Theta$ for each sample are plotted. Each triplet consists of one measurement at specular reflection and two adjacent positions, except for the nitrogen measurement of MIPA, where only one
measurement is available. Sample Q30 is denoted as Q30* if measured with MIPA. The comparison of the different samples in Fig. 3.27 shows that the energy loss and energy straggling values are quite variable. Sample Q10, with its smaller incident angle of 7°, presents the smallest energy loss and straggling, as expected. The energy loss and the energy straggling increase with increasing Θ. Nitrogen presents a generally larger energy loss and larger energy straggling.

One would expect similar values for Q30 and Q30*; however, the identical sample shows different results. Q30* presents a smaller energy loss for \( H^+ \) but a larger energy loss for \( N^+ \). As reported earlier, sample Q30 exhibited a charging effect that disturbed the angular distribution and the position of the maximum. It is thus possible that the charging disturbs the energy spectrum as well.

The energy distributions for the silicon sample and Q10 match the simulations from SRIM in Fig. 3.25 quite well. One should however keep in mind that the simulation does not take charge fractions into account. The measurements show only positive scattered ions. It could be that the secondary, low-energy population has a much lower probability to become positively charged and thus is under represented in the measurement.

When scattering nitrogen from the Q30 sample, a high secondary ion population is observed for both measurements. For the LISA measurements in Fig. 3.21, the difference between \( Θ = 30° \) and \( Θ = 50° \) causes a 200 eV increase in the secondary ion population. For the same positions for the silicon sample or the smaller Q10, no significant shift is visible. Furthermore, there are no counts at energies below 200 eV for the Q30 sample, in contrast to the Q10 and Si samples. It is thus assumed that the secondary peak has moved to approximately 200 eV - 500 eV because the MPO sample charges up positively in the incident beam. The silicon sample is assumed to show the actual position of the secondary scattering ion peak in the energy spectrum correctly because the sample has a higher conductivity than glass and is gold plated to provide a low-resistance aperture surface. To examine this effect more thoroughly, different measurements on different days and with different setups have been collected and plotted over the corresponding beam current in Fig. 3.28.
The position of the highest secondary ion peak is plotted on the y-axis, and the current density $J$ of the incident beam is plotted on the x-axis. An empirical trend line is given with $E_{sp} = 6.8 \cdot 10^{10} J + 109$, where $E_{sp}$ is the energy peak position of the secondary ions.

It can be observed in Fig. 3.28 that the position of the secondary ion peak depends linearly on the current density of the incident ion beam. The current density of the incident beam is measured for each setup with a Faraday cup at the beam entrance to the vacuum chamber. Because of the correlation between current density and peak position, it is concluded that sample Q30 is charging up. The measurements of the angular distribution and the energy spectrum of the scattered ions become distorted.

### 3.7 Positive ionization yield

#### 3.7.1 ILENA

The positive ionization yield $Y^+$ is calculated for the ILENA measurements by determining the reflection efficiency and the charge fraction according to Eq. 3.35

$$Y^+ = r \cdot \eta^+$$

with $r$ as the reflection efficiency as defined in Eq. 3.30 and the positive charge fractions as defined in Eq. 3.8

The results are given in Tab. 3.6
<table>
<thead>
<tr>
<th>Sample</th>
<th>$\eta^+$</th>
<th>$r$</th>
<th>$I_s$ [fA]</th>
<th>k</th>
<th>$N^0$</th>
<th>$Y^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$^+$, Cu, 1.5 keV</td>
<td>0.05</td>
<td>0.173</td>
<td>17</td>
<td>0.034</td>
<td>535</td>
<td>8.7 $\cdot 10^{-3}$</td>
</tr>
<tr>
<td>O$^+$, Cu, 1.0 keV</td>
<td>0.005</td>
<td>0.158</td>
<td>23</td>
<td>0.051</td>
<td>490</td>
<td>0.8 $\cdot 10^{-3}$</td>
</tr>
<tr>
<td>H$^+$, DLC, 1.5 keV</td>
<td>0.25</td>
<td>0.135</td>
<td>10</td>
<td>0.182</td>
<td>1314</td>
<td>33.8 $\cdot 10^{-3}$</td>
</tr>
<tr>
<td>O$^+$, DLC, 1.0 keV$^1$</td>
<td>0.08</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>8.0 $\cdot 10^{-3}$</td>
</tr>
</tbody>
</table>

Table 3.6: Obtained charge fractions, sample currents, k-factors, neutrals (1 sec.) and resulting positive ionization yield $Y^+$, $^1$ no sample current was measured, assuming $r$ as 0.1

3.7.2 LISA

The yield obtained from the LISA experiments is defined by Eq. 3.6 as

$$Y^+ = \frac{F^+_s}{F_i}$$ (3.36)

The detector is sensitive to positive ions and thus can directly determine the directional positive flux for the field of view of the detector. The complete scattered flux has to be extrapolated because of limits on the experimental setup with the method given in section 3.8. The measured angular distributions and the corresponding extrapolations are shown in Fig. 3.29 for selected examples.
Figure 3.29: The panels to the left show the measured flux relative to the incident flux over the scattering angle $\Theta$. In the right panel, the extrapolated complete angular distribution over $\Theta$ and $\Phi$ for incident $H^+$ is shown. The extrapolation is based on the scattering results of Wahlström et al. [49] and shows the same relative flux as the left panels.

The measured incident fluxes and extrapolated scattered fluxes are given in Tab. 3.7

<table>
<thead>
<tr>
<th>Sample</th>
<th>Species</th>
<th>$F_i \cdot 10^6$</th>
<th>$F_s \cdot 10^3$</th>
<th>$Y^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>$H^+$</td>
<td>1.4 (±0.4)</td>
<td>1.7 (±0.1)</td>
<td>1.2·10^{-3} (±0.06)</td>
</tr>
<tr>
<td></td>
<td>$N^+$</td>
<td>1.8 (±0.1)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Q10</td>
<td>$H^+$</td>
<td>1.6 (±0.3)</td>
<td>5.3 (±0.6)</td>
<td>3.3·10^{-3} (±0.07)</td>
</tr>
<tr>
<td></td>
<td>$N^+$</td>
<td>1.3 (±0.3)</td>
<td>0.3 (±0.2)</td>
<td>0.2·10^{-3} (±0.01)</td>
</tr>
<tr>
<td>Q30</td>
<td>$H^+$</td>
<td>1.3 (±0.2)</td>
<td>25.1 (±5.2)</td>
<td>19·10^{-3} (±0.46)</td>
</tr>
<tr>
<td></td>
<td>$N^+$</td>
<td>3.5 (±0.5)</td>
<td>17.3 (±2.5)</td>
<td>5.0·10^{-3} (±0.1)</td>
</tr>
</tbody>
</table>

Table 3.7: Obtained fluxes, ionization yields and 1σ errors
3.7.3 Discussion

The positive ionization yield is a material property. Only in combination with angular information is it possible to compare start surfaces and concepts for a specific use. The positive ionization yield density $y$ is a new property that relates the ionization yield $Y$ to the solid angle. For a well-collimated incident ion beam on a scattering surface, the solid angle is very small. After scattering from a surface, the beam scatters with a certain FWHM in the spherical parameters of $\Theta$ and $\Phi$ and thus in a scattered solid angle $\Omega_{\text{scattered}}$. The ionization yield per solid angle can be used to judge more easily if a surface is a suitable candidate for scattering applications. Therefore:

$$y^+ = \frac{Y^+}{\Omega_{\text{scattered}}}$$

(3.37)

In Tab. 3.8, the parameter $y^+$ is given for all tested samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Ion species</th>
<th>$Y^+$</th>
<th>$\Omega_{\text{scattered}}$ [sr]</th>
<th>$y^+$ [10$^{-3}$ sr$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>H$^+$</td>
<td>8.7 $\cdot$ 10$^{-3}$</td>
<td>0.70</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>O$^+$</td>
<td>0.8 $\cdot$ 10$^{-3}$</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>DLC</td>
<td>H$^+$</td>
<td>33.8 $\cdot$ 10$^{-3}$</td>
<td>0.35</td>
<td>109</td>
</tr>
<tr>
<td></td>
<td>O$^+$</td>
<td>8.0 $\cdot$ 10$^{-3}$</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Si</td>
<td>H$^+$</td>
<td>1.2 $\cdot$ 10$^{-3}$</td>
<td>0.20</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>N$^+$</td>
<td>−</td>
<td>0.25</td>
<td>−</td>
</tr>
<tr>
<td>Q10</td>
<td>H$^+$</td>
<td>3.3 $\cdot$ 10$^{-3}$</td>
<td>0.05</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>N$^+$</td>
<td>0.2 $\cdot$ 10$^{-3}$</td>
<td>0.04</td>
<td>5</td>
</tr>
<tr>
<td>Q30</td>
<td>H$^+$</td>
<td>19 $\cdot$ 10$^{-3}$</td>
<td>0.35</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>N$^+$</td>
<td>5.0 $\cdot$ 10$^{-3}$</td>
<td>0.25</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 3.8: Positive ionization yield density $y^+$ for all tested samples

One can see from Tab. 3.8 that DLC presents a high yield density because the sample combines a high $Y^+$ and very good angular scattering properties. Although the reason for the angular properties is the very smooth surface, the reason for a high positive ionization yield is beyond the scope of this thesis and is simply described as a material property.

DLC coatings are standard industrial applications and are possible to combine with, for example, silicon. The silicon sample itself provided good results in terms of angular scattering; however, the positive ionization yield was low. Because silicon technology can offer countless coatings and surface treatments, the results are promising, and further investigations could lead to competitive results. However, this would not be an “off-the-shelf” solution, but rather an extensive research project, e.g., a
DLC-coated silicon start surface. Micro pore optics, on the other hand, are readily available in a desired geometric structure that can be ordered immediately. Both tested samples present an ionization yield density $y^+$ that compares to that of DLC.

For JDC and relectron-type time-of-flight measurements, micro pore optics would work well as start surfaces. For field-free time-of-flight instruments, the involved energy loss might be unacceptable, depending on the instrument requirements.

The copper sample, due to its manufacture using laser ablation, suffers from a high surface roughness. The angular scattering is therefore wide and, together with the low ionization yields, especially for heavier particles, does not perform very well. Although, the concept could be investigated further, other technologies, such as DLC, Silicon and MPO, are far more promising.

An open question for all tested samples is the behavior for higher energies. In Fig. 3.26, this issue was addressed through simulations with the SRIM code. The code is unable to reproduce charge fractions, and thus, it is not possible to estimate the behavior of the tested samples for higher energies. For a dedicated instrument for higher energies, it will be eventually required to have a start surface made from a heavier material to minimize energy losses. A metal such as copper could therefore be interesting as a start surface if the charge fractions increase for higher incident energies.

Measurements of the yield density are difficult to perform, and published data are sparse due to the high grade of specialization required for such parameters. It could be shown, with the conducted experiments, that the principle of a venetian-blind-type start surface is working and that micro pore optics are strong candidates for further development of instruments such as JDC.
3.8 Publication I

Stude et al. [2016]

“Scattering of hydrogen, nitrogen and water ions from micro pore optic plates for application in spaceborne plasma instrumentation”

Preprint submitted to Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, Received April 20, 2016

The publication investigates the scattering properties of the micro pore optics sample Q30 using the MIPA detector. The setup is similar to the LISA setup, as given in Fig. 3.10. We measure the angular distribution in the direction of \( \Theta \) and determine the positive ionization yield from scattering ions of \( H^+ \), \( N^+ \) and \( O^+ \) with energies of 2 keV. The micro pore optics sample Q30 presents a comparably high positive ionization yield of up to 2\% and is used in further development of the instrument.

I, Joan Stude, performed the experiment and the data analysis. I was the lead author of the text and generated all plots and figures. Dr. M. Wieser and Prof. S. Barabash suggested the experiment and the mechanical design. Throughout the experiment, assistance was provided by Dr. M. Wieser. Both, Dr. M. Wieser and Prof. S. Barabash contributed to the writing process.
Scattering of hydrogen, nitrogen and water ions from micro pore optic plates for application in spaceborne plasma instrumentation

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Abstract

Time-Of-Flight mass spectrometers for upcoming space missions into enhanced radiation environments need to be small, light weight and energy efficient. Time-Of-Flight systems using surface interactions as start-event generation can be smaller than foil-type instruments. Start surfaces for such applications need to provide narrow angular scattering, high ionization yields and high secondary electron emissions to be effective. We measured the angular scattering, energy distribution and positive ionization yield of micro pore optics for incident hydrogen, nitrogen and water ions at 2 keV. Positive ionization yields of 2% for H+, 0.5% for N+ and 0.2% for O+ were detected.

Keywords:
ion scattering, surface interaction, micro pore optics, Time-Of-Flight, spectrometer, ionization yield, angular scattering, charge fraction

1. Introduction

In situ measurements of plasma populations in space require mass-, energy- and size-efficient instrument designs. In the energy range from several eV to several hundreds of keV, time-of-flight systems allow for compact and capable designs [1, 2, 3, 4, 5]. An ion mass spectrometer can, for example, be built by combining an electrostatic analyser with a time-of-flight cell. For the time measurement, the generation of a signal is required to start a clock when a particle passes a known start position and a second signal to stop the clock when the particle reaches a known stop position. At the start position, the particle should be as minimally affected as possible, whereas at the stop position, the particle can be absorbed. A common method of start-event generation is to detect secondary electrons generated when a particle penetrates a thin carbon foil [4]. To penetrate such a foil, ions require typically ~1 keV per nucleon of kinetic energy. For the efficient detection of low energy, heavy ions, such as O+ and S+, pre-acceleration by potentials exceeding 10 kV is needed [6]. High voltages drive the instrument size (and mass) to ensure electrically insulating gaps. Surface interactions provide an alternative to carbon foils. Instead of penetrating a foil, the particles reflect on a surface at a grazing angle of incidence. In the process, a secondary electron is emitted and registered as the start-event. Surface interactions have no lower energy limit [7], and a pre-acceleration voltage of a few 100 V is sufficient to ensure a high secondary electron yield. A number of surface interaction-based time-of-flight instruments have been successfully flown in space. Examples include the Solar Wind Monitor (SWIM) and the Chandrayaan Energetic Neutrals Analyzer (CENA) [5] or the the Neutral Particle Detector (NPD) [8] part of the ASPERA-3 and ASPERA-4 instrument packages flown on the Mars Express and Venus Express missions.

The energy loss of a particle during the interaction with the start foil or surface is only statistically known. This energy loss is one of the limiting factors for the mass resolution that can be obtained from such a system. The factor can be eliminated by introducing a reflectron section into the time-of-flight cell containing a linear electric field (LEF) [4]. The linear electric field in the reflectron can be seen as one half of a harmonic potential. For a charged particle of mass $m$ and a potential polarity such that the particles are reflected in the reflectron, the flight time $t_{\text{LEF}}$ in the reflectron is independent of the particle energy $E$ and is given by

$$t_{\text{LEF}} = \frac{\sqrt{m}}{|q| e k}$$

with $q$ being the charge of the particle, $e$ being the elementary charge and $k$ being a constant representing the reflectron geometry and potential magnitudes. If the start section is field free and has a length $s$ along the particle trajectory, the total observed time of flight is expressed by

$$t = t_{\text{LEF}} + t_s$$

$$t = \frac{m}{|q| e k} + \Delta s \sqrt{\frac{m}{2E}}$$

For carbon foils, $\Delta s$ corresponds to the thickness of the foil and is negligible; however, when using surface interactions for start-event generation, $\Delta s$ is an important source of uncertainty.
because it is normally not known where exactly along the length \( \Delta s \) the start electron is generated. Particles interact with the surface at grazing incidence, resulting in a large interaction length. An ideal start surface combines low angular scattering, high reflection efficiency of the preferred charge states and high secondary electron yield. The angular scattering is optimized by very smooth scattering surfaces [9, 10, 11]. The charge state fraction can be altered using different surface materials ranging from polished W(110) single crystals [12], Al\(_2\)O\(_3\) films [11], LiF crystals [13], MgO coatings [10], to diamond-like carbon (DLC) surfaces [14]. The secondary electron yield depends on the particle type, energy and surface material [15]. The influence of \( \Delta s \) on the measured time of flight can be minimized by measuring the location on the start surface with a positionsensitive detector. Such a scheme is used in the Chandrayaan Energetic Neutrals Analyzer (CENA) [5]; however, the scheme increases instrument complexity.

An alternative solution is a geometric form of small, repeating, reflective surface elements shaped like a window blind. Despite the good availability of polished single crystals as start surfaces, it is challenging to achieve low surface roughness with a window-blind geometry. The active surfaces inside the structures are difficult to access for processing (e.g., polishing). For use as a window-blind type of start surface in a time-of-flight spectrometer, micro pore optics designed for X-ray imaging applications [16] were investigated. Angular scattering, energy loss, and incident and scattered fluxes were characterized for H\(^+\), H\(_2\)O\(^+\) and N\(^+\) ions.

2. Material and methods

2.1. The Sample

A common method of focusing X-rays is by reflection under grazing angles of incidence. Micro pore optics are developed as a key element of lightweight X-ray optics. To efficiently reflect X-rays with wavelengths of less than \(< 10\) nm, surfaces with “near perfect flatness and very low roughness” [16] are required. Micro pore optics are stacks of small quadratic channels arranged as in a micro channel plate. The channel surface properties and geometrical structure make micro pore optics an interesting candidate for reflecting particles instead of X-ray photons. Micro pore optics are available with channels of different sizes and with different skew angles. We evaluated an off-the-shelf micro pore optics sample (MPO-686-SQ31x31-1H PT001-1) that was obtained from PHOTONIS [17]. The sample (Fig. 1) has straight quadratic channels with a width of 686 \(\mu\)m and a wall thickness of approximately 200 \(\mu\)m. The sample is 1 mm thick and has an area of 31 mm x 31 mm [16].

The substrate material of the micro pore optics is hydrogen-reduced glass that includes high-Z elements such as lead [18]. The surface roughness, \(r_{RMS}\), is better than 1.5 nm [18]. The sample was not specially treated, for example, by heating or cleaning prior to the scattering experiment.

2.2. Experimental Setup

The experiment was performed at the instrument calibration facility at the Swedish Institute of Space Physics in Kiruna.
charge and mass per charge of the positive ions entering the analyser. The detector energy range is 10 eV/q to 15 keV/q, and the energy resolution $\Delta E/E \approx 6.4\%$. The mass resolution $m/\Delta m \approx 2$. The input aperture was modified with respect to MIPA using a collimator to obtain a field of view of $3.7^\circ \times 6.3^\circ$. The geometric factor of the instrument without efficiency is $2.69 \cdot 10^{-5} \text{ cm}^2 \text{ sr eV/eV}$. The detector efficiencies are determined for each species during the experiment using the method described by Brehm et al. [20] and Funsten et al. [21]. Accidental counts due to finite efficiencies have been considered as well (Wüst et al. [22]).

2.4. Measurement

The ion scattering flux was measured in counts per second at different angular positions $\Theta$. Using the geometric factor of the instrument, the count rate is converted into the differential number flux $f$. The energy of the ions is resolved at all measurements.

The positive ionization yield ($Y^+$) is the ratio of the scattered positive ion flux $F_s$ to the incident positive ion flux $F_i$.

$$Y^+ = \frac{F_s}{F_i} \quad (4)$$

The theoretical maximum of $Y^+$ is 100%, which would mean that all impinging positive ions on the surface are reflected towards the detector without changing their charge state. Apart from scattering, other processes, such as secondary electron release and sputtering, occur. Positively charged particles, such as secondary ions, are also recorded by the detector. In particular, for incident particles heavier than hydrogen, the total number of sputtered particles can exceed the number of scattered primary ions. We constrain our positive ionization yield by requiring that the scattered species be identical to the incident species.

The scattered positive flux $F_s$ is measured by integrating the differential flux $f_s = f_s(E, \Omega)$ over energy and solid angle:

$$F_s = \int_{E_{\text{min}}}^{E} \int_{\Omega_{\text{sc}}} f_s(E, \Omega) \, dE \, d\Omega \quad (5)$$

where $f_s$ is the differential number flux of the scattered positive ions, $E$ is the energy, and $\Omega$ is the mean solid angle. To exclude sputtered ions, we integrate fluxes above an energy threshold $E_{\text{min}} \approx E_i/4$, with $E_i$ being the incident ion energy. Due to the fixed incident angle, the geometry of the micro pore sample (thickness over pore size), a fraction of the beam is back-scattered, a fraction passes the sample unhindered, and a fraction is forward scattered (Fig. 2). The incident flux $F_i$ is the fraction of the beam that hits the scattering surface, as shown in Fig. 2. $F_i$ is determined indirectly by measuring the transmitted part $F_t$ of the incoming beam with the detector at $\Theta = 0^\circ$. By simple geometry, a factor $k$ relates the transmitted flux $F_t$ to the incident flux $F_i$:

$$F_t = F_i \cdot k \quad (6)$$

With the given setup and $\alpha = 15^\circ$, the factor $k$ becomes 0.64.

3. Results

3.1. Impinging Beam

Ions beams of $H^+$, $N^+$ and $H_2O^+$ with an energy $E_i$ equal to 2000 eV were used. At this energy, most of the impinging $H_2O^+$ dissociates at the scattering surface into hydrogen and oxygen [10, 23, 24]. The impinging water beam thus scatters as an oxygen beam and is subsequently referred to as $O^+$. Residual $H^+$ with energies $< 200 \text{ eV}$ is below the energy cut-off $E_{\text{min}}$ and thus not considered. The obtained incident fluxes are given in Table 1.

3.2. Scattered Beam

For impinging $H^+$, the detector measured the scattering ions from 1000 eV to 2500 eV, whereas for impinging $N^+$ and $H_2O^+$, the detector measured the scattering ions from 20 eV to 2500 eV. For $N^+$ and $H_2O^+$, the scattering was measured at the single angle of $\Theta = 30^\circ$.

Figure 3 shows the energy spectrum of the scattered positive ions for the incident $N^+$ and $O^+$ at $\Theta = 30^\circ$ and 2000 eV (vertical line). The main peaks are marked A·C (see text for details). The error bars are shown for the incident $N^+$ only but are representative for incident $O^+$ as well. The thin lines at the bottom denote the noise levels.

The energy spectrum of $N^+$ and $H_2O^+$ in Fig. 3 shows three different peaks, marked as (A), (B) and (C). The peak (A) corresponds to scattered ions, whereas peaks (B) and (C) are secondary products. The scattered $N^+$ and $O^+$ show primary peaks at approximately 1100 eV, which corresponds to an energy loss of $\sim 45\%$. The energy straggling is defined as the energy peak to its centre energy with $\sim 35\%$. Time-of-flight data of scattered $N^+$ and $O^+$ for energies below $E_{\text{min}} = 500\text{eV}$ indicate masses of $m = 1$ and thus consist mainly of sputtered $H^+$. An energy threshold at $E_{\text{min}}$ thus represents an effective way to separating secondary ions from primary ions. The secondary peaks (B) and (C) are assumed to be sputter products and $H^+$ recoils, respectively. Due to the high electrical resistance ($R_{el} \approx 50\text{MO}\Omega$) of the micro pore optics sample and a rather high incident beam current of $\sim 0.45 \cdot 10^{-10} \text{ A/cm}^2$, the sample is charging up to approximately 200 V. Therefore, the sputtered products, normally released with energies of a few eV, are accelerated to 200 eV.
The primary charged particles are not affected. For operation in space, this is not a problem because such high currents are not reached inside an instrument.

The energy spectrum for scattered \( \text{H}^+ \) is shown in Fig. 4 for different scattering angles. The primary peak for the specular reflection is at approximately 1600 eV and moves slightly towards lower energies for increasing angles \( \Theta \). The distribution flattens out at higher \( \Theta \). At the specular reflection \( \Theta = 30^\circ \), the energy loss is \( \approx 20\% \), with an energy straggling of \( \approx 30\% \). For \( \Theta = 60^\circ \), the energy loss is \( \approx 30\% \) with an energy straggling of \( \approx 55\% \).

Fig. 5 shows the energy-integrated differential flux of the scattered positive ions, normalized to the incident flux.

For \( \text{H}^+ \), measurements were taken between \( \Theta = 15^\circ \) and \( \Theta = 55^\circ \) and fitted with an exponential modified Gaussian.

### 4. Discussion

The binary collision model described by Niehus et al. [26] predicts an energy loss of less than 5 \( \% \) for \( \text{H}^+ \) impinging on glass (SiO\(_2\)) due to the large mass difference between H and Si or O. The measured energy loss in our experiments is 20\% to 40\%, most likely due to the “as received” samples. Indeed, when the micro pore optics sample is on air, a water layer builds up quickly at its surface. Instead of a simple binary collision, a collision cascade of the incident \( \text{H}^+ \) with the water layer and the actual surface material occurs. The SRIM code [27] is able to reproduce the characteristics of the energy distribution with a multilayer of water on lead-glass substrate.

With the obtained energy-integrated differential fluxes, it is possible to approximate the angular distribution in \( \Theta \) and \( \Phi \) to obtain the scattered positively charged flux \( F_s \) for each species. The change in flux over angle \( \Theta \) is well approximated by an exponentially modified Gaussian [25], as shown in Fig. 5. To estimate the change over \( \Phi \), a conventional Gaussian is used. Wahlström et al. [9] presented measurements of the angular distribution in \( \Theta \) and \( \Phi \) for \( \text{O}^+ \) (500 eV) scattering from very smooth surfaces of diamond-like carbon. They used incident angles \( \alpha \) of 2\(^\circ\), 8\(^\circ\) and 12\(^\circ\) to the surface and achieved a similar scattering behavior in the direction of \( \Theta \), as we observed in our \( \text{H}^+ \) experiment. From their plots, the angular out-of-plane distribution in \( \Phi \) can be approximated with a Gaussian function:

\[
\Phi = h \cdot e^{-\frac{\alpha^2}{2\sigma^2}}.
\]

The amplitude \( h \) of the Gaussian function is obtained during scanning of \( \Theta \) and equals the maximum of the \( \Theta \) distribution (Fig. 5). The position \( \mu \) of the Gaussian is in the plane of \( \Theta \) \( (\Phi = 0) \). The width, \( \sigma \), is parametrized and approximated from Fig. 3 in Wahlström et al. [9] for the range of incident angles \( \alpha \): 2\(^\circ\) \( < \alpha \) \( < \) 20\(^\circ\):

\[
\sigma = 0.051\alpha^2 - 0.206\alpha + 4.113
\]

For \( \text{N}^+ \) and \( \text{O}^+ \), the same distribution of \( \Theta \) as for \( \text{H}^+ \) is used and scaled to correspond to single-point measurements. Figure 6 shows the contours of the estimated distributions of \( \Theta \) and \( \Phi \) for \( \text{H}^+ \) for the incident angle \( \alpha = 15^\circ \).

The positive ionization yield is now calculated by integrating over the incoming solid angle expression (Eq. 5). The fluxes and resulting yields (Eq. 4) for each species are given in Table 1. The errors for the yields result from beam variations, counting statistics and uncertainties in detector efficiency.

We define the ionization yield as a ratio of the scattered positively charged ion flux to the incoming positively charged ion flux (Eq.4). Moreover, it is more common to measure the charge fraction \( \epsilon^+ \) [28, 29, 30, 31, 32]. The positive ionization yield \( \epsilon^+ \) can be expressed as the product of the reflection efficiency \( r \) and \( \epsilon^+ \).
In-plane angle $\Theta$ [°] 
Out-of-plane angle $\Phi$ [°] 

<table>
<thead>
<tr>
<th>$F_i$ $\text{[cm}^{-2}\text{s}^{-1}]$</th>
<th>$Y^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H^+$</td>
<td>$(2.4 \pm 0.9) \cdot 10^6$</td>
</tr>
<tr>
<td>$N^+$</td>
<td>$(4.5 \pm 0.2) \cdot 10^6$</td>
</tr>
<tr>
<td>$O^+$</td>
<td>$(18.4 \pm 3.0) \cdot 10^6$</td>
</tr>
</tbody>
</table>

Wieser et al. [10] measured the positive charge fractions and the reflection efficiency over a comparable energy for impinging $H^+$ and $O^+$ on MgO coatings of smooth surfaces with $r_{RMS} < 5$ nm[10]. Wieser et al. estimated a reflection efficiency of approximately $r = 0.2$ from magnesium oxide into his detector. The measured positive charge fractions of $H^+$ and $O^+$ were 0.1 and 0.01, respectively. This gives a $Y_{H^+} \approx 2 \cdot 10^{-2}$ and $Y_{O^+} \approx 0.2 \cdot 10^{-2}$. Thus, the tested micro pore optics performs comparably to MgO-coated surfaces.

5. Conclusions

Micro pore optics are considered for use as start surfaces in ion and energetic neutral atom (ENA) instruments for space applications. We investigated micro pore optics properties for scattering beams of $H^+$, $N^+$ and $H_2O^+$ at an energy of 2000 eV and an impinging angle of 15°. We determined the energy distribution, the scattering functions and the positive ionization yield of the scattered particles. The angular scattering from the inner surfaces of micro pore optics is similar to other surfaces considered for similar applications. The measured positive ionization yield of up to 2% is comparable to that of other surfaces for similar applications, e.g., magnesium oxide. The very low surface roughness minimizes the angular scattering. Additional experiments on the secondary electron extraction, out-of-plane scattering, a wider energy range and improved accuracy are planned.

References

Chapter 4

A new type of electrostatic analyzer

4.1 Introduction

An electrostatic analyzer is a device that selects incident charged particles based on energy per charge. The underlying physical principle is the Lorentz force $F_L$ acting on a particle of charge $q$ with velocity $\vec{v}$:

$$\vec{F}_L = q \left( \vec{E} + \vec{v} \times \vec{B} \right) \quad (4.1)$$

where $\vec{E}$ is the electric field and $\vec{B}$ is the magnetic field.

For $B = 0$, Eq. (4.1) simplifies, and the force $\vec{F}_L$ acting on a charged particle depends only on the charge state and electric field:

$$\vec{F}_L = q \cdot \vec{E} \quad (4.2)$$

A particle traveling against a force $F_L$ with an initial energy $E_0 = \frac{mv^2}{2}$ can only travel a distance $s = \frac{V^2}{2a} = \frac{E_0}{F_L}$, resulting in

$$a = \frac{q \cdot \vec{E}}{m} = \frac{E_0}{m \cdot s}; \quad (4.3)$$

thus, the distance traveled $s$ depends only on the charge state and initial energy:

$$s = \frac{E}{e \cdot \vec{E}} \quad (4.4)$$

It is therefore possible to design a geometric construction that only allows particles of a certain energy per charge to pass. Such an energy filter is called an electrostatic analyzer (ESA), and the basic principle is shown in Fig. 4.1. Electrostatic analyzers
are standard ion optical components and are widely used in laboratories and in space, where plasma resides naturally.

![Figure 4.1: Parallel-plate electrostatic analyzer](image)

Fig. 4.1 shows the basic principle for ions entering a parallel-plate electrostatic analyzer at an incident angle $\varphi$, where one plate is set to an electric potential $V$. Note further that no force acts on the particle in the $x$-direction, i.e., $d^2x/dt^2 = 0$, and the only force acting in the $y$-direction is the Lorentz force, i.e., $d^2y/dt^2 = \vec{F}_L/m$. The ion trajectory in Fig. 4.1 is thus expressed as

$$y = x \tan \varphi - \frac{qVx^2}{4dE \cos^2 \varphi} \quad (4.5)$$

With $x = L$ as the distance to the center of the gap in front of the detector, the energy of the particle going through the center of the gap is $E_c$:

$$E_c = \frac{qVL}{2d \sin(2\varphi)} \quad (4.6)$$

This simplified view implies that $d$ is sufficiently large to let the respective trajectory exist and that field distortions at the entrance and exit are omitted. The basic principle of a parallel-plate analyzer can be expanded to a cylindrical construction and further to spherical shells, where $d$ becomes a gap between two hemispherical shells. Such a hemispherical analyzer is a standard tool for many applications in beam diagnostics and space plasma physics. As an ion optical element, it does not only filter energies but also provides angular focusing behavior.

The first concept was reported by Hughes and Rojansky in 1929 as a “Spherical Condenser” [63] and described by Purcell [64] in 1938 as an energy analyzer or electrostatic spectrograph.

For early scientific space missions, the spherical analyzer became popular as a quadrisphere (a quarter of a sphere) or spherical plate deflector (a section of a sphere). In 1982, Carlson et al. [65] introduced an improved variant, the top-hat analyzer, featuring full 360 deg coverage, i.e., a hemisphere. The analyzer was first used on the AMPTE mission [66] and became a standard design for spaceborne applications used today.
To improve certain aspects in instrument design, different variants of the spherical analyzer have been built, especially when combined with other ion optical parts such as deflector electrodes for looking into different directions or time-of-flight cells for measuring the mass per charge of the passing particles [67]. Increasing demands on size and weight lead to the conceptual idea of a spherical-wedge electrostatic analyzer. The spherical-wedge analyzer is an attempt to shrink a spherical analyzer with a given radius while locally maintaining the spherical properties.

4.1.1 Spherical analyzer

A spherical electrostatic analyzer consists of two hemispheres (or sections of hemispheres) that are stacked on top of each other with a well-defined gap between them. This construction was analyzed in depth by F. R. Paolini and G. C. Theodoridis [68, 69] as well as Gosling et al. [70] and Mukai et al. [71].

Figure 4.2: Top-hat electrostatic analyzer and the basic focusing properties of parallel and energy constant trajectories. $R_i$ denotes the inner radius of the ESA electrode and $R_o$ the outer radius of the ESA electrode. Drawing from Carlson [65] and Paolini [68]. The azimuthal direction of the particles is described with $\theta_{ESA}$. The opening angle $\varphi_{ESA}$ describes the effective angular size of the analyzer. In the case of a top-hat analyzer, $\varphi_{ESA} \approx 90^\circ$.

The top-hat electrostatic analyzer is described in Carlson et al. [72] and sketched in Fig. 4.2. To allow particles to enter from all directions $\theta_{ESA}$, the top-hat analyzer has a circular opening in the outer electrode $R_o$. This opening is covered by a lid to allow an electrical field to guide charged particles into the spherical part of the
electrostatic analyzer. The lid forms the top-hat of the electrostatic analyzer, hence the name. The figure further shows some basic trajectories to indicate the focusing behavior of the device. In the top view, three parallel, charged particles with the same energy are focused in one point at the exit of the analyzer. In the cut-away view below, the same trajectories are shown but now parallel in height. A more detailed discussion of energy and angular focusing is given by Paolini et al. [68].

An important parameter of any electrostatic analyzer is the analyzer constant $k$. The analyzer constant gives the ratio of the center energy $\hat{E}/q$ of an analyzer passing ion population to the voltage at the analyzer electrodes.

$$k = \frac{\hat{E}/q}{\Delta V} \quad (4.7)$$

For a spherical analyzer of $\varphi_{ESA} = 180^\circ$, as mentioned by Farnell et al. [73], the analyzer constant $k_F$, sometimes called the calibration factor, is given by

$$k_F = \left( \frac{R_o}{R_i} - 1 \right) = \left( \frac{(R_o - R_i)(R_o + R_i)}{R_o R_i} \right)^{-1} \quad (4.8)$$

with $R_o$ and $R_i$ defined as in Fig. 4.2. Assuming a very small gap, $R_o \approx R_i$ and $k_F$ can be reformulated to obtain the geometric analyzer constant $k_g$:

$$k_F \approx \left( \frac{(R_o - R_i)(2r)}{r^2} \right)^{-1} = \frac{r}{2d} \quad (4.9)$$

with $r = \frac{R_i + R_o}{2}$ as the center radius and $d = R_o - R_i$ as the gap size.

If the electrostatic analyzer is used with a single voltage such that the outer electrode is at ground potential and only the inner electrode is at a voltage (unipolar ESA), incoming ions will experience an average acceleration of half the ESA voltage, and the analyzer constant becomes

$$k_U = \frac{\hat{E}/q - V/2}{V} = \frac{\hat{E}/q}{V} - \frac{1}{2} \quad (4.10)$$

Thus, to correctly estimate the analyzer constant $k$ for an unipolar voltage, using the geometric analyzer constant $k_g$, it is necessary to subtract $1/2$ as above:

$$k_\varphi U = \frac{r}{2d} - 0.5 \quad (4.11)$$

The energy resolution of a spherical electrostatic analyzer describes the energy selection of an analyzer, or the ratio of energy bandwidths $\Delta E$ at full width half maximum, over the center energy of the same distribution of particles that are able to pass the analyzer. In a spherical analyzer with $\varphi_{ESA} = 180^\circ$, the energy resolution is geometrically approximated in Paolini et al. [68] by

$$\frac{\Delta E}{\hat{E}} \approx \frac{d}{r} \quad (4.12)$$
For a top-hat design wherein the particle experiences $\varphi_{ESA} = 90^\circ$, the energy resolution becomes

$$\frac{\Delta E}{E} \approx \frac{2d}{r} = k_g^{-1}$$

(4.13)

Therefore, we obtain, for the unipolar spherical analyzer,

$$E_{res} = \frac{\Delta E}{E} \approx \frac{2d}{r} - 0.5 = k_gU^{-1}$$

(4.14)

Previous ESA designs almost fully rely on a rather complete analytical understanding to assure a well-understood and optimized geometry. The increased complexity due to other highly integrated components at the entrance or exit of the analyzer makes it very difficult to apply an analytic expression. For an even more complex analyzer consisting of non-constant curvatures, an analytic solution does not exist. Analytic solutions thus are replaced by computer simulations. The following description of a spherical-wedge electrostatic analyzer depends fully on simulations.

### 4.1.2 Spherical-wedge analyzer

The spherical-wedge electrostatic analyzer is constructed out of 16 spherical wedges, similar to slices of an orange. Each wedge is part of an azimuthal sector that covers $22.5^\circ$ of the hemispherical field of view. The curvature of each wedge is given by the radius of the original sphere that formed the wedge and is constant over the whole wedge surface. The 16 wedges are then individually moved toward the center of the original sphere, as shown in Fig. 4.3.

![Spherical-wedge electrostatic analyzer](image)

**Figure 4.3:** Spherical-wedge electrostatic analyzer. To provide a better visualization, only 8 wedges are used to describe the principle of shrinking. The symmetry axis is along $x$, and the arrows depict the movement of the wedges to obtain the desired shape.

In this way, the spherical-wedge analyzer essentially forms a spherical corridor for each azimuthal sector if the same principle is applied to the outer and inner analyzer electrodes.
The idea was initially developed by M. Wieser (personal communication) and R. M. Ruano from 2003 - 2010 [74]. Due to limitations in computing, Ruano simulated a simplified shape of a lemon as a surface of revolution [75].

The desired benefits of a spherical-wedge analyzer are its reduced size and weight. This means that compromises have to be accepted in terms focusing properties compared to a construction as a spherical analyzer with the same spherical curvature.

4.2 Simulations

Ion optical simulations have been conducted using SIMION®8.1 [76]. The simulations in this section are combinations of simple geometric shapes, which are programmatically generated. The intention is to find a promising prototype geometry that can be built and subsequently tested. This includes the whole instrument together with the electrostatic analyzer. In the following sections, the simulations and how the results are obtained are described; in the end, the results of the simulations are given.

4.2.1 Coordinate system of SIMION and JDC

The instrument JDC is described in detail in section 1.5.3 and Ch. 5; thus, here, only a short overview is given to be able to explain the simulations and coordinates.

JDC includes hemispherical angular coverage in 16 azimuthal sectors. In a spherical coordinate system, the azimuth is described with $\theta$, and the elevation is described with $\phi$. The instrument therefore has two extreme viewing directions, the zenith view, which is looking toward the pole with $\phi = 90^\circ$, and the horizontal view, which is given by $\phi = 0^\circ$, as shown in Fig. 4.4.
JDC’s central axis is the x-axis pointing from the bottom in Fig. 4.4, where the ESA exit is placed at the top, where particles enter from the hemispherical view into the ESA entrance. The x-axis uses only positive values. The values of y and z can be positive or negative. The direction of a particle is the direction from which it came; thus, negative elevations would describe particles that move in the direction of +x, and positive elevations describe a particle moving in the direction of -x.

For JDC, the azimuth $\theta$ is in the zy-plane, and the elevation $\varphi$ is the angle between the x-axis and the components of a direction vector $\vec{v}$. The equations used to transform between a Cartesian and spherical coordinate system for JDC are thus as follows:

\[
\begin{align*}
\theta &= \text{atan2} \left( \frac{-z}{-y} \right) \\
\varphi &= \text{atan} \left( \frac{x}{\sqrt{y^2 + z^2}} \right)
\end{align*}
\] (4.15)

SIMION uses a rotated spherical coordinate system with the azimuth $\theta_S$ in the zx-plane and elevation $\varphi_S$ as the angle between the y-axis and the components of a direction vector $\vec{v}$. (Index S for SIMION)

\[
\begin{align*}
\theta_S &= \text{atan2} \left( \frac{-z}{x} \right) \\
\varphi_S &= \text{atan} \left( \frac{y}{\sqrt{x^2 + z^2}} \right)
\end{align*}
\] (4.16)
4.2.2 Geometry definition

In SIMION, electric fields are defined by conductive electrodes that are set to individual electric potentials. Any electrode inside SIMION is made from volume elements, similar to how pixels are the basis of a digital image. The higher the resolution, the greater the number of volume elements in a simulation.

Three-dimensional geometries can be defined in SIMION using two methods: stl-files and gem-files. stl-files are a widely supported format for describing 3D models. Almost any CAD software for mechanical engineering supports this format, and thus, it is possible to load any 3D structure into SIMION. Complete instruments can be loaded, converted and simulated (see chapter 6). This however makes it difficult to implement incremental changes or geometric optimization processes. For such demands or at early development stages, it is necessary to generate objects using a programming language. For example, OpenSCAD (http://www.openscad.org/) allows the construction of 3D stl-files objects using its proprietary language code. SIMION itself offers its own geometric description language, the so-called “constructive solid geometry (CSG) primitives” or simply “gem-files”. Geometries using gem-files are restricted to simple shapes and forms such as rectangles, rotations, circles and similar shapes.

As an example, an inner spherical-wedge electrode can be constructed out of displaced spheres, as shown in the code example below:

```plaintext
electrode(1) { fill { within { sphere(0, dr, 0, r) sphere(0, -sin(22.5)*dr, -sin(22.5*3)*dr, r) sphere(0, -sin(22.5*2)*dr, -sin(22.5*2)*dr, r) sphere(0, -sin(22.5*3)*dr, -sin(22.5)*dr, r) sphere(0, 0, dr, r) } } }
```

with \( dr \) as the displacement of the spheres and \( r \) as the radius of the spheres. The displacement \( dr \) describes the inward motion of the spherical wedges, as shown in Fig. 4.3. The code allows one to logically “AND” the spheres such that only the parts that overlap remain as a solid.

![Figure 4.5: Inner electrode of a spherical-wedge electrostatic analyzer. Note the spherical wedges as faint color differences.](image)

The result is a spheroid body with 16 spherical wedges. The complete model of JDC consists of six major parts: the deflector electrodes, the ESA entrance, the inner and...
outer ESA electrodes, an exit aperture, the start surface ring and the start detectors (Fig. 4.6). The deflector electrodes are not used for the evaluation of the ESA and kept at ground potential. Between the deflector electrodes and the electrostatic analyzer is the ESA entrance, a field-free space that connects the ESA electrodes to the deflector electrodes. Particles that eventually make it through the electrostatic analyzer have to pass another aperture: the ESA exit aperture. These are slightly in front of the start surface section. The apertures form due to the necessary spokes that hold the inner ESA electrode. The exit apertures have a width of 19° azimuth for each of the 16 azimuthal sectors.

![Diagram of ESA setup](image)

**Figure 4.6:** Model that is used to evaluate the properties of a spherical-wedge ESA. The housing and grids are omitted for greater visibility

After passing the ESA exit apertures, a particle enters the start surface section. The start surfaces in this simulation are modeled by a simple solid ring. The ring is biased to -400 Volts and provides a moderate post acceleration for particles prior to their interaction with the solid ring. To guide secondary electrons from the start surface to the start detectors, a voltage of +100 V is applied to the entrance of the start detectors. The start detectors are modeled by 16 basic blocks, where each block mimics the front of a channel electron multiplier (CEM). Post acceleration and the CEM front form a radial electrical field that guides secondary electrons from the start surface position radially outward into the CEMs.

The overall construction is initially based on only three constraints, as shown in Fig. 4.7: the position of the start surfaces $r_s$ and the ESA opening angles $\varphi_{in}$ and $\varphi_{out}$. The total ESA opening angle is given in Fig. 4.2 as $\varphi_{ESA} = \varphi_{in} + \varphi_{out}$. To obtain an optimal focus of particles at the exit of a spherical analyzer, $\varphi_{ESA}$ should be 90°.

The start surfaces require incident particles to have a certain incident angle to maximize the efficiency of the time-of-flight cell (see chapter 3). Depending on the actual choice of start surfaces, their geometry or requirements from the time-of-flight cell, the ions departing the analyzer need to have a certain direction. This coarse direction is given by $\varphi_{out}$, and for JDC, it is restricted to 30°.
On the other end of the analyzer, an optimal $\varphi_{in}$ would be $45^\circ$ because it would ensure a normal viewing direction of $45^\circ$. Furthermore, the deflector electrodes could be kept symmetric in shape. This conflicts with best focusing properties at $\varphi_{ESA} = 90^\circ$, and thus, a compromise for the spherical-wedge ESA was set to $\varphi_{ESA} = 80^\circ$, which results in $\varphi_{in} = 50^\circ$.

![Figure 4.7: Initial constraints for the construction of the initial simulation model of JDC. The radius of the start surface ring $r_s = 16.5$ mm. $x_c$ marks the center of the analyzer.](image)

All electrodes have to be electrically insulated by gaps to ensure a maximum voltage of 5000 V. Because the maximum allowed electrical field is approximately 2000 V/mm, to avoid discharges in high vacuum, the gaps between electrodes have to be a minimum of 3 mm.

### 4.2.3 Simulation parameters

Because SIMION is a geometric simulation, the resolution of the model must have a minimum value. If important parts or curvatures are coarsely modeled, the results will be different under different resolutions. To obtain an idea of the required resolution, a crucial geometric detail is examined. For the spherical-wedge electrostatic analyzer, the smallest structural distance is the radial difference between the face of a spherical wedge and the edge between two spherical wedges. Fig. 4.8 shows a cut view through a simplified spherical-wedge ESA with only eight wedges in the $yz$-plane at $x_c$ (see Fig. 4.7).
Although the radius of each wedge is the same, the distance from the center of the spherical-wedge analyzer to the surface of a wedge varies by a small amount. The distance from the center of the coordinates in Fig. 4.8 to the edge between two spherical wedges is denoted \( r_{\text{max}} \). The distance \( r_{\text{min}} \) stretches from the center of a wedge or its face to the center of the coordinates. It is thus possible to calculate \( \Delta r_{\text{wedge}} = r_{\text{max}} - r_{\text{min}} \) to obtain a minimum resolution required for the simulation. If the resolution of the simulation cannot resolve \( \Delta r_{\text{wedge}} \), then the simulation cannot “see” the spherical wedges.

\[
\Delta r_{\text{wedge}} = r \sqrt{1 - \left( \frac{d_r \sin \frac{\alpha}{2}}{r} \right)^2} - d_r \cos \frac{\alpha}{2} - (r - d_r) \approx 0.15 \text{ mm} \quad (4.17)
\]

with \( d_r \) as the displacement of the spheres (10.9 mm), \( \alpha \) as the angle of an azimuthal sector (22.5°), and \( r \) as the wedge radius (37 mm).

SIMION reserves \( \sim 10 \) bytes of computer RAM-memory for each volume cell in each electrode in the simulation. Despite the increasing availability of RAM-memory in computers, RAM-memory often limits the resolution of a SIMION simulation for a certain simulation space. The instrument model (without the time-of-flight cell) is approximately 127 mm in the \( x \) direction and 98 mm in the \( y \) and \( z \) directions. The minimum resolution of the simulation was chosen as 0.125 mm for \( \Delta x \), \( \Delta y \) and \( \Delta z \). To fit the instrument in the simulation space, including some margin, a simulation space of 150 x 100 x 100 mm was used. Each length was divided by the resolution to obtain the total number of SIMION volume elements and total amount of RAM-memory:

\[
\frac{x}{\Delta x} \cdot \frac{y}{\Delta y} \cdot \frac{z}{\Delta z} \cdot 10 \text{ byte} \approx \frac{150 \cdot 100 \cdot 100}{0.125^3} \cdot 10 \text{ byte} = 7.68 \cdot 10^9 \text{ byte} \quad (4.18)
\]

With six different electrodes, a total of \( 6 \times 7.68 \text{ GB} \approx 46 \) GB of RAM-memory is needed in the computer that is used to simulate the instrument. SIMION provides...
two means of reducing the RAM-memory requirements: the usage of symmetries in the model and the combination of high-resolution electrodes with low-resolution electrodes. The latter was not used in the initial simulations but was later explored for the simulation of a prototype (see section 6.3). The instrument fortunately has symmetries that can be used to minimize computer RAM-memory usage. The 16-spherical-wedge electrostatic analyzer can be cut along the x-axis and mirrored in the y and z directions. This preserves the wedge structure and reduces the necessary RAM-memory for the dimensions given above to \( \sim 12 \text{ GB} \) for the whole instrument. Because \( \sim 12 \text{ GB} \) at the time did not allow for a simulation on an office machine, SIMION was run in parallel sessions on a remote computer (server). Increasing the resolution by a factor of two increases the amount of memory needed in the simulation 8 fold. In total, approximately \( 1 \cdot 10^7 \) particles were launched for each simulation. Although RAM-memory is the limiting factor for the simulation resolution, it is the computing power, or speed, that limits the number of particles that can be launched in a given time.

### 4.2.4 Geometric factor

The geometric factor (without efficiency) of an instrument is defined as:

\[
GF^*=\int_{\Omega} \int_{E} \int_{A} T(\Omega, E, A) \, dA \, dE \, d\Omega
\]  

(4.19)

where \( A \) is the aperture area, \( E \) is the energy, \( T \) is a transfer function \([0,1]\), and \( \Omega \) is the solid angle or field of view.

The geometric factor for a single azimuthal sector can be simulated using virtual ions of uniform density from all directions (solid angle \( \Omega \)) and at all energies \( (E) \). The uniform density enables this by counting the surviving ions, and the area \( A \) is retrieved. If computing power would not be an issue, one would thus simulate particle trajectories from a full hemisphere of positions and vary all angles and energies. That would result in huge numbers of trajectories to be calculated and thus a very long simulation time. This might be possible in the near future because of the increasing computing power available. For now, this is not an option, and the numbers of outer positions, directions and energies have to be narrowed down such that the number of simulated particle trajectories can be minimized. To identify relevant trajectories for a specific azimuthal sector and viewing direction, the simulation is started with a run in reverse. The model inside SIMION is set to a specific energy and viewing direction by assigning appropriate voltages to the electrodes in the simulation and are kept constant for each run. The first run (inside-outside) calculates the trajectories of particles randomly distributed over the start surface of one sector for all energies, directions and positions on that start surface sector. Ions that make their way through the instrument model are binned outside in angular \( (\Delta \Omega) \) and energy space \( \Delta E \). For each outside bin of solid angle and energy, a single representative trajectory is chosen. Each representative trajectory builds the seed particle of a uniform density beam by copying and shifting the trajectory to parallel, equidistant positions just wide enough to cover the instrument aperture. In Fig.,
two examples of resulting beams (simplified) are shown in green and red. Each beam has an identical direction and energy such that a beam exists for each bin of solid angle and energy.

The second part of the simulation calculates the trajectories of the generated beams from the first simulation run but with the opposite direction such that the particles move back into the instrument. This is possible because the trajectories of charged particles in electrostatic fields (conservative field) are reversible.

By counting the surviving particles back at the start surface inside the instrument, a differential area $\Delta A$ for each beam is obtained. The differential solid angle $\Delta \Omega$ is the size of the outside angular bin, and the differential energy $\Delta E$ is the size of the energy bin in the outside energy space. Each beam thus has a differential geometric factor, and by summing all the differential geometric factors, the total simulated geometric factor of the instrument model $GF_s^*$ [cm$^2$/sr] for one sector is calculated as follows:

$$GF_s^* = \sum_i^{n_E} \left( \sum_k^{n_B} \cos(\phi_k) \varphi_0 \theta_0 c_k \delta_A \frac{\Delta E}{E_k} \right)$$

(4.20)

with symbols as shown in table 4.1.
4.2.5 Energy resolution

The energy resolution of the electrostatic analyzer is the full energy width at half maximum (FWHM) of all ions that survived the outside-inside simulation divided by the mean energy of the surviving ions.

\[ E_{\text{res}} = \frac{E_{\text{FWHM}}}{\bar{E}} \]  

(4.21)

In collapsing the elevation axis of panel a) in Fig. 4.10, the energy distribution of a model is obtained for a fixed voltage at the inner analyzer electrode. Because the energy distribution is usually Gaussian, a Gaussian fit is applied to obtain \( \bar{E} \) and \( E_{\text{FWHM}} \). During the simulation of the geometric factor, the data allow one to determine the energy resolution.

4.2.6 Angular resolution

The angular resolution describes the field of view for one azimuthal sector and one viewing direction. It is defined as the FWHM of either the elevation or azimuth direction for all energies of surviving ions in the outside-inside simulation. For a hemispherical field of view, the azimuth covers ±180°, and the elevation angle is 90°. The azimuth is divided into 16 sectors of 22.5°.

As with the energy resolution, the angular resolution is retrieved from the data of the geometric factor simulation. In contrast to the energy resolution, which is divided by the center energy, the angular resolution is given in degrees.

4.2.7 Cross-talk

Cross-talk, \( CT \), is the ratio of the number of particles that arrive at the correct sector of the start surface but that originated from outside the desired azimuthal...
22.5° field of view of the same sector to the number of particles that arrived from the correct azimuthal field of view. This ratio describes direct cross-talk and should be minimized during the design of the instrument. Indirect cross-talk is caused by reflections, secondary electrons and other sources and is not considered at this stage. For a sector with its center at \( \theta = 0° \), the direct cross-talk are particles that originate from the directions \( \theta > 11.25° \) and \( \theta < -11.25° \).

\[
CT = \frac{\sum_{\theta < -11.25°} n}{\sum_{\theta > 11.25°} n}
\]  

with \( n \) as particles in the simulation. Acceptable values for \( CT \) should be well below 10%.

### 4.3 Results

#### 4.3.1 Original design

The original design (model 1) includes spherical wedges on the outside of the inner analyzer electrode and on the inside of the outer analyzer electrode. The center of a spherical wedge is aligned with the center of the corresponding sector at the start surface.

The angular properties for model 1 are plotted in Fig. 4.10. The geometric factor, cross-talk and a summary of Fig. 4.10 are given together with other analyzer variants in Fig. 4.13.

The color density plot in panel a) of Fig. 4.10 shows the counts of one sector at the start surface versus elevation and energy. The inner analyzer electrode is at a potential of -375 V. The distribution is typical for spherical analyzers except for the small wing at an elevation of approximately 38° for energies below 2400 eV. These ions originate from larger azimuth directions but with a low fraction compared to all ions. Panel b) shows the elevation distribution with the energy axis collapsed. The elevation resolution at full-width-half-max (FWHM) and full-width-quarter-max (FWQM) are given in the center of the plot. The origin of the small double peak is unknown. It could simply be a result of the design or possibly a simulation artifact due to the limited resolution. The distribution shows a elevation resolution of approximately 7°. The energy distribution is shown in panel c), with the elevation axis collapsed. The energy resolution is 14.0%, and the analyzer constant \( k = |2774 \text{ eV} / -375 \text{ V}| = 7.4 \text{ eV/V} \). Panel d) shows the distribution of azimuthal directions, where the plot is collapsed over the energy axis similarly as in panel b). The distribution covers a wide range up to ±20° at the bottom of the triangle-like distribution. At FWHM, a value of approximately 14° is achieved.
Figure 4.10: Angular and energy resolution of model 1. Panel a) shows the distribution of counts versus elevation angle $\varphi$ for the normal viewing direction with the deflector electrodes at ground potential. Panel b) shows the elevation distribution from summing over all energies. Panel c) shows the energy distribution from summing over all angles. Panel d) shows the azimuthal distribution summed over all energies. Within panels b), c) and d) the full-width-half-max (FWHM) and full-width-quarter-max (FWQM) values are given. In panel c), the term “Gauss” denotes the FWHM of the fitted Gaussian.

4.3.1.1 Discussion

The simulation results are only partly acceptable, as explained below. A resolution in elevation of $7^\circ$ is satisfactory for the design, e.g., the CAPS/IMS instrument had a resolution of $8.3^\circ$ [23]. The resolution in the azimuthal direction exhibits a triangular shape with too small of a width and too wide of a bottom, therein covering neighboring azimuthal sectors. The resulting cross-talk $CT$ of $\sim 13\%$ is not an acceptable value. The design of model 1 causes a locally spherical behavior for each of the 16 azimuthal sectors, and a parallel beam from $0^\circ$ outside the azimuth is well focused on the start surface, as shown in red in Fig. 4.11.
A NEW TYPE OF ELECTROSTATIC ANALYZER

Figure 4.11: Focusing properties of model 1 for three parallel beams of $0^\circ$ (red) and $\pm10^\circ$ (blue, green). The figure shows 3D particle trajectories from the top view and a 2D cut of the model to indicate the positions of the trajectories for illustration purposes only. The circles mark the approximate position of the focal point of the corresponding beam.

Two beams of $\pm10^\circ$ in the azimuthal direction are also plotted. The focal points of the $\pm10^\circ$ beams are located well before the central beam and thus become defocused. This explains the wide distribution at the foot of the azimuthal distribution. The small FWHM has a second cause: trajectories from larger azimuthal directions (blue & green in Fig. 4.11) run toward adjacent spherical wedges inside the analyzer. The analyzer electrodes and thus the electrostatic field configuration vary between two adjacent wedges. Trajectories from larger azimuthal directions eventually become lost at the edge between two spherical wedges or become slightly deflected. At the analyzer exit aperture, such a deflection results in a loss at the spokes or in hitting a neighboring sector.

The simulated analyzer constant of $7.4 \text{ eV/V}$ is quite close to the estimation of Eq. 4.11:

$$k_y U = \frac{r}{2d} - 0.5 = \frac{37}{2 \cdot 2.4} = 7.21$$

(4.23)

Thus, the estimate for the energy resolution becomes

$$E_{res} = \frac{1}{k_y U} = 13.8\%$$

(4.24)

One can therefore conclude that the simulated spherical-wedge analyzer of model 1 shows spherical properties for particles at the center of the azimuthal distribution. Larger azimuthal directions result in high cross-talk and a non-optimal azimuthal distribution.

4.3.2 Spheroidal variants and hybrids

Because of the unsatisfactory results of the angular resolution and cross-talk of model 1, other variants of the same general idea have been simulated. One variant
is an analyzer without spherical wedges, which simplifies to a lemon-shaped analyzer electrode. Another variant is a rotated version of the previous spherical-wedge analyzer. Because of the lost trajectories for larger azimuthal directions in model 1 and the unsatisfactory azimuthal distribution, it was assumed that, by rotating the spherical-wedge analyzer around the symmetry x-axis by $11.25^\circ$, the focusing properties would improve for larger azimuthal directions. In the original design of model 1, the faces of the wedges are aligned with the azimuthal sector, as shown in the left panel of Fig. 4.12. With the applied rotation of $11.25^\circ$, the face-aligned sectors become edge aligned such that trajectories in one sector use two different wedges.

Figure 4.12: Rotation of the spherical-wedge electrode over $11.25^\circ$ such that the edge between two wedges is aligned with an azimuthal sector. To provide better visualization, only eight wedges are shown.

With the above-mentioned two variants, it may be further possible that combinations of spherical wedges and lemon-shaped electrodes, so-called hybrids, will present better properties than model 1. Thanks to computer simulations, the results of applying such ideas are quickly explored with minor modifications to the simulation code. The spherical wedges are normally applied to the inner and outer analyzer electrode; however, the possible rotation of the inner and outer analyzer electrodes and the use of lemon-shaped inner or outer electrodes result in seven hybrid variants, as shown in Tab. 4.2. All models are listed with an arbitrary number. The original idea as mentioned above became model 1, and the last version, the lemon-shaped analyzer without spherical wedges, became model 9. The rotation of the inner or outer analyzer electrodes is a rotation around the x-axis for $11.25^\circ$, as shown in Fig. 4.12. If for example both analyzer electrodes of model 1 are rotated by $11.25^\circ$ around the x-axis, model 5 results.
Table 4.2: Model Descriptions, model 1 is the original design. “wedge” refers to an electrode with spherical wedges, and “lemon” refers to a shape without wedges.

<table>
<thead>
<tr>
<th>Model</th>
<th>inner shape</th>
<th>outer shape</th>
<th>inner rotation</th>
<th>outer rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>wedge</td>
<td>wedge</td>
<td>0°</td>
<td>0°</td>
</tr>
<tr>
<td>2</td>
<td>wedge</td>
<td>wedge</td>
<td>11.25°</td>
<td>0°</td>
</tr>
<tr>
<td>3</td>
<td>lemon</td>
<td>wedge</td>
<td>-</td>
<td>0°</td>
</tr>
<tr>
<td>4</td>
<td>wedge</td>
<td>wedge</td>
<td>0°</td>
<td>11.25°</td>
</tr>
<tr>
<td>5</td>
<td>wedge</td>
<td>wedge</td>
<td>11.25°</td>
<td>11.25°</td>
</tr>
<tr>
<td>6</td>
<td>lemon</td>
<td>wedge</td>
<td>-</td>
<td>11.25°</td>
</tr>
<tr>
<td>7</td>
<td>wedge</td>
<td>lemon</td>
<td>0°</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>wedge</td>
<td>lemon</td>
<td>11.25°</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>lemon</td>
<td>lemon</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The detailed angular results for each model can be found in the appendix pages 176-180.

Fig. 4.13 shows a summary of all simulation results: the geometric factor of one sector in panel a), the cross-talk ratio in panel b), the energy resolution in panel c) and the angular distributions in panels d) and e). The figure further presents a figure of merit, panel f), which consists of the scaled individual results, e.g., a model with a figure of merit of 5 would have the best result in terms of every characteristic.

In panel a) of the geometric factor figure, one can see two groups. Most models have a geometric factor of approximately $3.9 \cdot 10^{-4}$ cm$^2$ sr eV/eV, except model 5 and model 6. The crosstalk in b) exhibits larger variations. One can see that model 1 has the highest value of 13%, whereas model 5 performs best, at approximately 3%. The energy resolution in panel c) shows that the achieved resolutions are mostly above the estimated value of Eq. 4.24. Model 4 has the lowest energy resolution, at 17.8%.

The angular resolutions vary the most for the azimuthal direction and exhibit little variation in elevation. Model 1 obtains the smallest azimuthal resolution, with a FWHM of $\sim 14^\circ$, and model 8 obtains a maximum of 20.5°.

4.3.3 Discussion

The general variation between all variants is small and can be explained by the small mechanical differences between the analyzer designs. For a total diameter of approximately 50 mm, a maximum difference in curvature of 0.3 mm cannot cause extreme changes. This can be interpreted such that, for the given constraints and variants, the design has little freedom to work on, and an optimization is likely a compromise between a preferred property and a less important one. For example, model 1 performs the worst in azimuthal resolution and cross-talk but obtains a good geometric factor. On the other hand, model 5 performs well in azimuthal resolution and cross-talk but obtains the smallest geometric factor. The elevation resolution is
a bit on the low end for all models. This is due to the rather long ESA entrance, which acts as a collimator.

The variations in Fig. 4.13 allow one to choose the most promising design for the desired instrument. From panel f) with the figure of merit, one can see that model 1 shows the weakest performance, whereas model 5 and model 8 produce the best results. Model 5 and model 8 both have a rotated inner analyzer electrode (edge aligned). The difference between the two models is that model 8 is a hybrid, whereby the outer ESA electrode has no spherical wedges.

The results of model 1, in comparison to the other models, show that face-aligned azimuthal wedges do not represent an optimum solution. Model 5 shows that the angular response for edge-aligned wedges clearly improves because the spherical wedges now allow particles from higher azimuthal directions to reach the start surface. An in-depth analysis of the trajectories showed that trajectories from larger azimuthal directions move, on average, closer to the inner analyzer electrode. Thus, the hybrid model 8 offers a spherical shape for high azimuthal trajectories, with less defocusing behavior for trajectories of smaller azimuthal directions.

Because model 8 obtains the best azimuthal resolution, a good geometric factor and minimal cross-talk, it was chosen as the basis of a prototype design. Another advantage of model 8 is that the inner analyzer electrode does not need to be aligned with the outer analyzer electrode, which presumably avoids issues for integration and mechanical construction. Furthermore, it is assumed that the manufacture of the
inner electrode with its convex curvature is more precise than that with the concave curvature of the outer electrode.

### 4.3.4 Hybrid model No.8

A comparison of the location of the focal points between model 1 (Fig. 4.11) and model 8 (Fig. 4.14) shows a clear change. The focal point from the center beam of model 8 moves closer to the analyzer. The central beam (red) is defocused at the start surface, in contrast to model 1, where the start surface is almost at the focal point. The focal points of the beams from larger azimuthal directions (blue, green) move slightly toward the start surface and thus closer to the central beam. The losses of the azimuthal beams are minimized, and the azimuthal resolution increases.

![Figure 4.14](image_url)

**Figure 4.14:** Focusing properties of model 8 for three parallel beams of $0^\circ$ (red) and $\pm 10^\circ$ (blue, green). The figure shows 3D particle trajectories as a top view and a 2D cut of the model to indicate the positions of the trajectories for illustration purposes only. The circles denote the approximate position of the focal point of the corresponding beam.

The angular and energy distributions are shown in Fig. 4.15. The elevation plot in the upper right shows that a double peak is no longer present and that the same resolution as model 1 of approximately $\sim 7^\circ$ is obtained.

The energy resolution increases to approximately 16%. The analyzer constant becomes

$$k = \left| \frac{2833 \text{ eV}}{-375 \text{ V}} \right| = 7.6 \ \frac{\text{eV}}{\text{V}} \quad (4.25)$$

The azimuthal resolution has a sharp separation between the azimuthal sectors. This is likely caused by the ESA exit aperture of Fig. 4.16.

The cross-talk remains present but at 3.5%, well below the limit of 10%.
Figure 4.15: Angular and energy parameters for model No. 8, which was chosen to become a prototype.
Chapter 5

JDC Design

5.1 Introduction

As mentioned in section 1.5.3, the design is mostly driven by mass constraints and Jupiter’s radiation environment. The accommodation of the sensor on the spacecraft will be optimized to maximize the use of the spacecraft’s structure for mutual shielding. Inside the instrument, only passive electronic components are placed, e.g., resistors and capacitors. Front-end electronics, counters, data processing and power supplies reside in a separated box in close vicinity below the spacecraft hull.

A key element in the design of JDC is the time-of-flight cell described in the internal technical report of C. Lue [37]. The time-of-flight cell is optimized for particles entering the time-of-flight cell with specific positions and directions, as shown in Fig. 2.1. These positions for the basis of the placement of the start surfaces and thus represent a fix point in the design of JDC.

JDC can be divided into four, ion-optically relatively independent parts: the deflector section where particles enter, the electrostatic analyzer section, the start section and the time-of-flight section (Fig. 5.1). A detailed description is given in the following sections of this chapter.
5.2 Ion Optics

5.2.1 Introduction

This thesis is being written during the ongoing development of JDC, and the description in this chapter represents the design as of Fall 2014. The instrument is described from the top in Fig. 5.1 where particles enter the deflection system, to the bottom in Fig. 5.1 where the time-of-flight cell is placed.

Figure 5.1: The Jovian plasma Dynamics and Composition analyzer (JDC) and its functional sections. A typical ion trajectory is given in red, with the resulting secondary electrons shown in green.
The instrument is required to cover a hemispherical field of view. The view is described using spherical coordinates of azimuth and elevation, as shown in more detail in the previous chapter (section 4.2.1). The instrument simultaneously covers the azimuthal plane in 16 azimuthal directions, giving $360^\circ$ of azimuthal coverage. To allow the instrument to cover a full hemisphere, it is necessary to scan the field of view over $90^\circ$ of elevation angle. This is accomplished through two deflector electrodes, as shown in Fig. 5.2. These electrodes generate an electric field that guides ions with the desired energy per charge and the desired elevation viewing direction into the electrostatic analyzer. The two rotational symmetric deflector electrodes are named the top-deflector electrode and the side-deflector electrode (Fig. 5.2). A field-free drift region separates the electrostatic analyzer and the deflector electrodes. The voltages applied to the deflector electrodes and to the electrostatic analyzer electrode are selected such that full energy and angular coverage is obtained.

To electrostatically shield the deflector electrodes to space, a grid covers the entrance to the instrument over both deflectors. The grid is held by 16 spokes, which form the first entrance aperture to the instrument. The positions of the spokes match the positions of the spokes that form the ESA aperture between the ESA section and the start section. The transmission rate of the grid for normal incidence is 86%. One of the spokes is used to hold a small tube, which guides the electrical connection to the top-deflector electrode. The grid and the housing, including spokes, is held at ground potential. Between the side-deflector electrode and the housing, one can note five baffle structures in Fig. 5.2. These structures prevent unwanted stray light from entering the detector.

The ability to guide ions into the electrostatic analyzer is called the deflection power.
$p$ and is defined analogously to the analyzer constant of an electrostatic analyzer:

$$p = f \left( \frac{\Delta V}{E/q} \right)$$  \hspace{1cm} (5.1)$$

where $E$ is the energy, $q$ is the charge, and $\Delta V$ is the voltage.

![Graph showing the relationship between deflecting power $p$ and elevation angle](image)

**Figure 5.3:** For a given geometry, the deflecting power $p$ indicates the achievable elevation for any given energy and voltage at the deflectors. The open symbols result from a simulation that varies the azimuth, elevation and energy for certain viewing directions. The variation in the open symbols thus indicates the variation for a complete sector at the given viewing direction in elevation. All other points are single-particle simulations. The numerical fit is an inverse sinusoid of the form: $\arcsin(1.36p)40.26 + 61.03$

To first order, the shape of the function $p$ depends on the size of the deflector electrodes. For a given maximum voltage of the deflector electrodes, the size of the deflector electrodes has to increase until sufficient deflection for a particle with a desired energy per charge is achieved. The function $p$ exhibits a steeper slope in this case. The deflectors can be operated in uni- or bipolar mode. In unipolar mode, one deflector electrode is always at ground potential, whereas the other electrode is at an energy- and elevation-dependent voltage. In bipolar mode, both deflector electrodes are at energy- and elevation-dependent voltages. The bipolar mode allows one to obtain a larger $\Delta V$ for a maximum allowable absolute voltage that a power supply can provide. The technical complexity increases for a bipolar mode because two power supplies are required.

Different designs of the deflection system were considered, as shown in Fig. 5.4.
At the beginning of the development process, the use of the unipolar approach was attempted for the deflector electrodes by introducing a grounded center grid between the top- and side-deflector electrodes (panel a) in Fig. 5.4). This would allow the use of a single high-voltage power supply. A center grid between the deflector electrodes increases the deflection power under unipolar mode by increasing the electric field strength between the grid and the active deflector. The idea produces acceptable results in simulations but generates a blind spot in the field of view because of the finite thickness of the grid. Furthermore, the electric field becomes disturbed at the center grid, as observed in panel a) of Fig. 5.4. A unipolar mode without a center grid does not provide sufficient deflection power for higher particle energies. This is indicated by the equipotential lines in panel b). A bipolar power supply is needed to achieve full angular coverage up to $\sim 25 \text{ keV}/q$, as indicated in panel c). Another argument against a center grid is the increased complexity of the resulting
grid construction.

The angular arrangement of the deflector electrodes follows the design of the electrostatic analyzer, and in particular, the angle $\varphi_{in} = 50^\circ$, as shown in Fig. [4.7]. Because of the unipolar operation of the electrostatic analyzer and the resulting fringe field, an additional $2^\circ$ are assigned to a potential center particle trajectory, as shown in Fig. [5.5]. Therefore, the normal viewing direction has a maximum at an elevation of $38^\circ$, which corresponds to an angle $\varepsilon = 52^\circ$. This is an asymmetric configuration for the deflector electrodes.

![Diagram of deflector electrode design](image)

**Figure 5.5:** Illustration of the deflector design regarding the arc angles. With a central particle trajectory at an angle $\varepsilon = 52^\circ$, the resulting arc angle $\sigma$ for the side deflector electrode becomes $38^\circ$. The top-deflector electrode has an arc angle $\delta$ of $45^\circ$. The radius $r$ is equal at both deflector electrodes, with $r = 50$ mm.

The side deflector electrode accounts for an angle $\varepsilon$, with an arc angle of $\sigma = 38^\circ$. For a radius $r = 50$ mm, the length of the deflecting arc becomes 33.2 mm. Following the same logic, the top-deflector electrode should have an arc angle $\delta$ of $52^\circ$. This would result in a rather long and protruding top-deflector electrode. To keep the top-deflector electrode at a reasonable size, the arc angle was reduced to $\delta = 45^\circ$. The deflecting arc length of the top-deflector electrode becomes 39.3 mm because the same radius as for the side deflector electrode is used. The simulations showed that the resulting deflecting power is sufficient for energies up to 25 keV/q.
5.2.3 Electrostatic Analyzer Section

This section includes the electrostatic analyzer (see chapter 4) and the electrostatic analyzer entrance and exit apertures. The electrostatic analyzer is constructed out of three components: the inner analyzer electrode, which is a single piece (red part in Fig. 5.6), and the outer analyzer electrode, which is split into two pieces (green part in Fig. 5.6). The outer electrostatic analyzer consists of two pieces to enable the integration of the inner electrode during assembly. The compartment between the electrostatic analyzer and the housing is used for passive electronics from the start detectors, as described in the next section. The inner electrode is held by an insulating construction that is fixed to the exit apertures. The analyzer exit apertures are at a post-acceleration potential of -400 V. The post-acceleration field accelerates particles toward the start surface to keep the start efficiency high for particles of lower energies. The outer electrostatic analyzer electrode is at ground potential at any time. The inner electrostatic analyzer electrode is used to apply a voltage for the energy per charge selection.

5.2.4 Start Section

This section includes the electrostatic analyzer entrance and exit apertures. The electrostatic analyzer is constructed out of three components: the inner analyzer electrode, which is a single piece (red part in Fig. 5.6), and the outer analyzer electrode, which is split into two pieces (green part in Fig. 5.6). The outer electrostatic analyzer consists of two pieces to enable the integration of the inner electrode during assembly. The compartment between the electrostatic analyzer and the housing is used for passive electronics from the start detectors, as described in the next section. The inner electrode is held by an insulating construction that is fixed to the exit apertures. The analyzer exit apertures are at a post-acceleration potential of -400 V. The post-acceleration field accelerates particles toward the start surface to keep the start efficiency high for particles of lower energies. The outer electrostatic analyzer electrode is at ground potential at any time. The inner electrostatic analyzer electrode is used to apply a voltage for the energy per charge selection.
The start section interfaces the electrostatic analyzer to the time-of-flight cell. Particles leaving the ESA scatter on-through the start surfaces and enter the time-of-flight cell. The start surfaces are arranged along a radial ring in 16 sectors. During the scattering process, secondary electrons are released inside the start surface slits. These electrons are guided by a radial electric field to the channel electron multipliers (CEMs) placed just on top of the start surfaces. The radial field ensures that electrons from a certain azimuthal sector cannot enter a neighboring sector. The start surfaces are at a post-acceleration potential of -400 V. Above the CEMs is a ring-shaped circuit board that hosts the passive electronic components for the CEMs. The start signals generated by the CEMs are routed out of the instrument to the pre-amplifiers inside a separate electronics box.

5.2.5 Time-Of-Flight Section

![Diagram of time-of-flight cell](image)

**Figure 5.8:** Time-of-flight cell for JDC. A detailed description is given in section 2.3. Typical trajectories in the time-of-flight cell are shown for a positive ion \((X^+\)) and a negative ion \((X^-)\) and a neutral atom \((X^0)\). The positive ion is reflected by the linear electric field to the stop surface. A secondary electron from the interaction with an incident positive ion is focused to the stop MCPs. A complete positive ion trajectory is given in Fig. 5.1

The time-of-flight section is a linear electric field reflectron type, as described in more detail in chapter 2. Ions scatter into the TOF cell from the start surfaces and become neutral or negatively or positively charged due to surface interactions. Negative and neutral particles form the dynamic channel “D” \((X^-\) and \(X^0\) in Fig. 5.8) with moderate mass resolution and high sensitivity, and positive ions form the composition channel “C” \((X^+\) in Fig. 5.8) with high mass resolution and lower sensitivity. A micro channel plate is used as the stop detector, with an anode composed of two concentric areas. The innermost anode collects the secondary electrons from the stop surface for the composition channel, while the outer ring collects the particles from the dynamic channel. The ring-shaped electrode in front of the stop surface
is used to focus the secondary electrons onto the stop detector. The stop detector consists of two standard, circular micro channel plates. Both plates have a diameter of 25.4 mm and are arranged in a chevron configuration, which means that the skews of their channels oppose each other, as sketched in Fig. 5.20.

### 5.3 Ideal geometry of a start surface

With some tested samples and identified materials from chapter 3, the question remains as to how an ideal start surface would look and on what parameters would it depend for the presented application. This section formulates requirements for defining an optimum geometry of the start surface. A venetian-blind-type start surface (Fig. 3.1) scatters the incident ions into the time-of-flight cell. This requires the scattering surfaces, i.e., the slats, to be at an optimal angle, i.e., the slat angle. The optimal slat angle for a scattering surface is determined by the incident angle distribution, the acceptance angle of the TOF cell (see section 2.3.1) and the scattering function of the particle/surface pair. The angular distribution of particles on the start surface $f(\phi_1)$ as well as the preferred angular input distribution $f(\phi_3)$ for the time-of-flight cell (Fig. 5.9) are obtained from ion-optical simulations of the electrostatic analyzer.

![Figure 5.9](image)

**Figure 5.9:** Angle clarifications for an incident particle (red, $\phi_1$) on a surface (slat, black, $\phi_2$) and the outgoing particle (acceptance angle of TOF) angle (blue, $\phi_3$). Instrument axes are given as x and y.

The mean angles $\bar{\phi}_1$ and $\bar{\phi}_3$ of both distributions vary with the radial distance from the symmetry axis-x inside the instrument, as shown in Fig. 5.10. The mean elevation angle $\bar{\phi}_1$ increases for smaller radial distances on the start surface, whereas the TOF acceptance angle $\bar{\phi}_3$ for the time-of-flight cell decreases for smaller radial distances. Thus, the optimum slat angle produces the continuous black line “Ideal $\phi_2$”. Fortunately, the ideal line is rather constant because the distributions of $\bar{\phi}_1$ and $\bar{\phi}_3$ match each other. The start surface can therefore have slats with a constant angle of $\phi_2 = 24.5^\circ$, which results in the dashed, light blue line ($\phi_3^*$) of Fig. 5.10.
However, the ideal slat angle in Fig. 5.10 depends on the approximation for specular reflection. Specular reflection is merely a rough approximation of ions scattering on a surface (section 3.5). An efficient geometry maximizes the number of particles that scatter into the acceptance cone of the time-of-flight cell, considering the angular spread around specular reflection for different aspect ratios and mirror angles. A Monte Carlo simulation for a single slit was conducted. Particles are injected into the slit to generate an angular distribution according to Wahlström et al. [49] of scattered secondary particles that are counted at the exit. Multiple reflections of the secondary particles are not considered, e.g., secondary particles that hit the slat structure again are lost.

In addition to reflecting most particles of the input distribution at an optimum angle, another important constraint in the slat design is that the start surfaces shall not be transparent for incident particles from the electrostatic analyzer. A transparent condition is obtained when the slat angle becomes too large or the aspect ratio (Fig. 5.11) becomes too small, and no surface interaction occurs. In this case, incident ions would flood the time-of-flight cell without generating start events and thus increase background counts. For the geometry of the start surface, three different designs are considered, as shown in Fig. 5.11.

The results of the Monte Carlo simulation are shown for different slat angles and
different aspect ratios in Fig. 5.12. The color code represents the reflection ratio: the number of all secondary ions passing out of the slit over the total number of generated secondary ions. The black line indicates the transparency limit. Note that the simulation depends on the output distribution of a specific electrostatic analyzer.

**Figure 5.12:** Slat design matrices from left to right: skewed slats, straight slats, and wedged slats. The reflection ratio is a figure of merit indicating the number of ions leaving the slit over the total number of generated secondary ions.

When choosing a large slat angle, the incident angle on the slat decreases. This minimizes angular scattering, energy loss and the sputter ratio. The aspect ratio should be small to ensure that the slits are as wide as possible. This makes the electron extraction more efficient, which leads to increased start efficiency. The simulation shows that wedged slats do not have a good reflection ratio because they become transparent for most of the simulated design space. The skewed slats have a slight advantage over the straight slats because the same reflection ratio is achieved with smaller aspect ratios. The optimum under this approach is thus a start surface that uses skewed slats with an aspect ratio of 6 or 7 and a slat angle of $\phi_2 = 24^\circ$. The resulting incident angle $\alpha$ for the surface interaction of incident particles at $\phi_1 = 32^\circ$ would thus be $\alpha = \phi_1 - \phi_2 = 8^\circ$.

### 5.3.1 Electron Extraction

With an ideal slat geometry with aspect ratios of larger than 2, it is necessary to investigate secondary electron extraction. Guiding the secondary electrons that are inside a slit following the scattering process out of the slit is a crucial aspect of venetian-blind-type start surfaces. Secondary electrons are released during the interaction of an incident particle with the slat surface. Inside the slits, the angular distribution of those electrons is assumed to be hemispheric. However, Burns [78] showed that, for electrons incident at an angle of less than 45° and at an energy of 800 eV, the secondary electron distribution for energies < 10 eV deviates from
hemispheric. The distribution shows intensity peaks in the direction of the incident electrons and in the direction of specular reflection. If the same is true for incident ions, the assumption of a hemispheric secondary electron distribution does not apply. A secondary electron distribution with a preferred direction toward the incident direction would be fortunate for the present situation, where the secondary electrons are required to leave the slit along the backward direction of the incident ion to the start detector.

The energy distribution of ion-induced secondary electrons has a peak at approximately 2 eV, with a monotonously decreasing tail to approximately 10 eV \[44\]. Small amounts of secondary electrons (Auger electrons) can reach higher energies on the order of 50 to 100 eV \[79\].

An outside electric field would effectively extract electrons for aspect ratios up to \(\sim 2\) because the field reaches sufficiently deep inside the slit. For higher aspect ratios, an electric field is needed throughout the slit to guide the electrons out. A voltage applied to a highly resistive material or a stacked construction of electrically insulated conducting surfaces can provide such an electric field.

For straight slats out of a resistive bulk material, the field inside the slits is constant, with horizontal equipotential lines as shown in Fig. 5.13 to the left. With skewed slats, the equipotential lines tilt slightly to the right toward the scattering surface, as in the right panel of Fig. 5.13.

![Figure 5.13: Electric field simulation](image)

For straight slats, a vertical field would guide secondary electrons out, and by increasing the applied voltage, the number of extracted secondary electrons would increase as well. For skewed slats, an increasing voltage would force the secondary electrons to collide with the slat because of the geometry and the tilted field. An increase in voltage would therefore decrease the number of extracted electrons.

This was simulated using SIMION for a slat angle of \(\phi^* = 24^\circ\) with an aspect ratio of approximately 7.5 under three different configurations (Fig. 5.14): skewed slats with a rightward tilted electrical field, as shown in panel a); straight slats with a strict vertical electrical field, as shown in panel b); and a combination of skewed...
slats at 12° and an angled start surface at 12°, as shown in panel c). Together, a slat angle $\phi_2$ of 24° is obtained and thus combines the effects from panel a) and b). The rightward tilt occurs in a skewed slat design of a resistive material with a conductive top and bottom and an applied voltage according to Fig. 5.13.

**Figure 5.14:** Cut through different slit structures ($\phi_2^* = 24°$). Panel a) shows skewed slats, panel b) shows straight slats, and panel c) shows a combination of a) and b). The equipotential lines range from 10 V at the bottom to $\sim 100$ V at the top. The colored electron trajectories represent three different source positions inside the slit. Red originates from deeper in the slit, green is roughly in the middle, and blue is from the upper part of the slit. The electron energy is 2 eV at each start position and follows a uniform hemispheric angular distribution. $E$ indicates the field inside the slit.

Fig. 5.14 indicates that, for the skewed slats in panel a) and a rightward tilted field, $E$, the extraction efficiency, is the lowest, as expected. Panel b) indicates a good extraction efficiency for straight slats and a straight field that aligns with the slats. The design in panel c) indicates that a slightly improved extraction efficiency is obtained by combining the effects from panel a) and b).

It is theoretically possible to control the field inside a slit by applying a resistive coating to the top of a slit construction such that each slit experiences a reduced total voltage. Such a field configuration and the corresponding SIMION results are shown in Fig. 5.15. The voltage gradient on the top forces the electric field vector from a leftward tilt at the top toward a slit-aligned field at the bottom. When forcing the field leftwards, an improvement in extraction efficiency is obtained.
Figure 5.15: Cut view of the skewed slats of panel a) in Fig. 5.14 with a different electric field configuration. The left panel shows the equipotential lines for an additional voltage gradient on the top of the design. The utilized voltage is larger, as in the SIMION simulation, to better visualize the idea. The electric field is now tilted to the left at the top and gradually changes direction toward the bottom. The right panel shows the resulting SIMION trajectories similarly as in Fig. 5.14 with $\phi_s^* = 24^\circ$.

The four configurations from above are summarized in Fig. 5.16. The extraction efficiency is the ratio of electrons exiting the slits over the total number of generated electrons. This ratio is plotted versus the voltage applied across the slit. The top voltage gradient of Fig. 5.15 scales with the applied voltage.

Figure 5.16: Extraction efficiency versus voltage over the slit construction for different start surface designs. The electron energy is 2 eV for three start positions at different depths of the slit with a hemispheric angular distribution.

The ratio of extracted electrons is plotted in Fig. 5.16 for a hemispheric angular distribution of the secondary electrons with an initial energy of 2 eV and three different positions in the slit.

With skewed slits and a resulting rightward tilted field, as would exist for a resistive bulk material, e.g., silicon, electron extraction is limited to approximately 45% at a voltage of 35 V. A straight configuration reaches an electron extraction of up to
85% but at the expense of a voltage of 400 V across the slit. A combination of designs with skewed slats and a tilted surface achieves an extraction rate of 60% at a moderate voltage of 50 V. The more complex approach of a gradually leftward tilting electric field achieves 68% electron extraction at a voltage of 90 V.

The analysis of the simulation shows that the maximum extraction efficiency varies with a factor of approximately 2 between the different slat and field geometries at their respective optima. For JDC and the desired venetian-blind-type start surfaces, the design using straight slats and a tilted start surface (panel b) in Fig. 5.14 would most likely consume the increase in position accuracy, which was the basic idea of introducing a venetian-blind-type geometry. The optimal solution is the combination of skewed slats with an angled start surface because this solution offers the highest extraction efficiency for low voltages across the slits. The control of the field vector, as shown in Fig. 5.15, is rather infeasible for production and does not provide a significant improvement over the combination variant.

The combination of skewed slats with an angled start surface (panel c) in Fig. 5.14 would enable the coating of the top of the start surface with a conductive layer to prevent surface charging.

Note that an electrical field in the form shown above can only be applied using a resistive material.

5.4 Variable Geometric Factor

JDC will perform measurements in the system of Jupiter and at locations with different environments. The expected flux of the foreground ions changes over almost 4 orders of magnitude, as observed in Fig. 1.2. Count rates could exceed the maximum allowable rates of the detectors and electronics. The geometric factor is the relation between the count rates and the outside flux. The geometric factor is a function of the instruments aperture, solid angle and energy resolution. A reduction in the geometric factor will reduce the count rates. Along with the higher fluxes at smaller distances to Jupiter, the background of penetrating particles increases, and additional counts are generated. The background count rates cannot be changed with a variable geometric factor.

Because of losses in the start surface and in the time-of-flight cell, the stop efficiency is lower than the start efficiency. JDC therefore includes a dedicated start detector for each of the 16 azimuthal sectors but only one stop detector. To reduce the count rates in this system, a true reduction in particle flux is needed. A virtual reduction in count rates, e.g., by increasing the threshold of the pre-amplifiers, is not sufficient because the detectors will saturate despite such measures. Furthermore, a reduction in, for example, the start efficiency will not change the number of accidental counts. Depending on the exact values, an increase in accidental counts is possible (Eq. 2.14).

Ideally, a reduction in the geometric factor would result in a decrease in aperture size, which would allow the operation of the instrument in the exact same manner as without a geometric factor reduction. Thus, no change in energy resolution or
field of view occurs. This requires a mechanical type of shutter or blind that reduces the incoming flux over the whole aperture area. By shadowing only certain parts of the aperture area, the resulting reduction can effect parts of the energy response or of the field of view.

For example, one could introduce a mechanical shutter between the deflector electrodes and the electrostatic analyzer. A grid of the desired reduction factor is moved in and out of this field-free region in the instrument. This however requires mechanical movements of mechanical parts. The jamming of movable parts represents a large risk to instrument reliability on a space craft that is scheduled to operate for several years in space.

Electric solutions for deceasing the geometric factor without moving parts are preferred and were investigated by Collinson et al. [81] for three methods of obtaining geometric factor reduction: the defocusing of particles at the exit of an electrostatic analyzer, the split of the inner electrostatic analyzer electrode and a top-cap electrode. The defocusing of particles at the exit of an electrostatic analyzer removes the particles before they reach the detector without any change to other parts of the instrument. In the case of JDC, the “detector” would be the start detectors. A split inner analyzer electrode effectively turns the electrostatic analyzer into two electrostatic analyzers that can be tuned to slightly different energies to provide high attenuation. The top-cap applies an additional field at the entrance of the electrostatic analyzer to steer away incident particles. Such a design was successfully tested by Rohner et al. [82]. For JDC, the Split-ESA and the top-cap configuration were further investigated.

![Figure 5.17: Electrodes for adjustable geometric factor for JDC](image)

The split electrostatic analyzer is achieved by electrically insulating the already separated bottom and top parts of the outer analyzer electrode. The bottom part is then used as an additional electrode. For the design involving a top-cap, the tip between the deflector electrodes and the ESA is used as an electrode marked as Top-Electrode, as shown in Fig. 5.17. The achieved reduction in the geometric factor and the changes in angular resolution and viewing direction are shown for both variants in Fig. 5.18.
Figure 5.18: The impact on the geometric factor, angular resolution and mean elevation (viewing direction) for different voltage ratios for the investigated cases Split-ESA and Top-Electrode. The voltage ratio is the applied voltage to the respective extra electrode over the analyzer voltage. The deflector electrodes are at ground potential.

The term voltage ratio is used for the comparison of the voltage at the inner analyzer electrode to the respective electrode used to provide the geometric factor reduction. The Split-ESA configuration presents a higher attenuation for a voltage ratio $< 1$. The Top-Electrode configuration requires larger voltage ratios of $> 1$ to achieve comparable attenuations. The changes in angular resolution and viewing direction are comparable for both configurations, with the split configuration showing less distortion in the azimuthal resolution for similar attenuation factors.

When using the deflector electrodes, e.g., to scan the field of view, the applied voltage used to reduce the geometric factor will distort the viewing direction. Fig. 5.19 compares this behavior for five different viewing directions given by fixed deflector electrode voltages. For the simulation of the field of view, the Split-ESA is set to a voltage ratio of 0.4, and the Top-Electrode is set to 1. This represents the maximum attenuation for each configuration without the need for an additional power supply. The JDC design without geometric factor control shows an elevation range of $\sim 10^\circ$ to $70^\circ$. The Split-ESA configuration increases this range slightly for lower elevations from $\sim 5^\circ$ to $70^\circ$. The Top-Electrode design decreases the range from $\sim 10^\circ$ to $55^\circ$ (Fig. 5.19). The decrease in the field of view in the Top-Electrode design can be compensated with higher voltages at the deflector electrodes; however, for a given maximum voltage at the electrodes, the maximum energy for which a full hemisphere can be covered must also decrease. With the chosen settings, an average reduction
in the geometric factor of 0.18 for the Split-ESA configuration and of 0.26 for the Top-Electrode configuration can be achieved. Higher attenuation will result in either severe distortions of the field of view or require additional power supplies.

![Figure 5.19](image)

**Figure 5.19:** Change in angular coverage and geometric factor. The top line shows the behavior of the instrument without geometric factor (GF) control.

As expected, both configurations will distort the angular response of the instrument and thus require an additional calibration set for each reduction setting. The simulated results are comparable with the results given by Collinson et al. [81]. He reports an improvement when a reduction is applied but also mentions the drawbacks in construction, especially for the Split-ESA configuration. The bottom part of the outer ESA electrode has to be electrically insulated from the top part of the outer ESA electrode, and a careful design of the gap between the bottom and top outer ESA is needed to prevent discharges and fringe fields.

As a conclusion, the Split-ESA enables an easier implementation in terms of control and electrical power but increases complexity in terms of ion optics. A voltage ratio <1 allows the split configuration to use a fixed fraction of the inner analyzer electrode voltage and thus does not require an extra power supply.

The Top-Electrode configuration suffers from increased complexity in terms of control and electrical power but allows for a simpler implementation into the existing ion optical design. The Top-Electrode is already present, and a single additional wire is needed to connect the electrode to a power supply. Because the Top-Electrode configuration does not need any change in ion optical parts, it may represent the preferred choice for JDC.
5.5 Detectors

5.5.1 Introduction

The choice of detector for single particles depends largely on the particles’ energies. For particle detectors in high-energy applications, such as in accelerator science (CERN) and cosmic ray studies, a number of different technologies are available, including gas detectors, semi-conductor detectors, scintillation counters and Čerenkov counters. However, in space-related, low-energy (< 100 keV) applications, the most common technologies are electron multipliers and silicon solid-state detectors [77]. Solid-state detectors measure not only the presence of a particle but also its deposited energy. The number of charge pairs generated by the energy deposition of an incident particle translates into an electrical current pulse that is proportional to the deposited energy in the detector volume. The energy threshold for a detection is usually above 10 keV because particles have to first penetrate a dead layer of a few 100 nm. Advances in semi-conductor technology may eventually reduce this energy barrier (STJ detector [83]).

For JDC, two types of electron multipliers are considered: channel electron multipliers (CEMs) and micro channel plates (MCPs). Both multipliers use the same principle of generating an electron avalanche via an electrical field. An incident particle (ion, atom, molecule, electron, or photon) generates one or more secondary electrons at the inner surface of a channel. Because of the present electric field, these electrons are accelerated such that they can generate more secondary electrons upon impact with the surface but at a slightly deeper depth into the channel. This process repeats until an electron cloud can be registered at an anode at the end of the detector as an electrical current pulse.

5.5.2 Start detector

In the present design, the start detector has to detect single electrons with energies of approximately 100 eV from the start surfaces. Because it is part of a time-of-flight system, the detector must have a high detection efficiency of approximately 1 (see section 2.4.2). The radiation environment of Jupiter and the rather exposed position of the instrument, on the other hand, requires a low detection efficiency for penetrating radiation (MeV electrons and gamma photons). Background counts induced by such an environment reduce the signal-to-noise ratio. Funsten et al. [84] reported a significant difference in detection efficiency between CCEM and MCP for gamma photons of 662 keV. CEMs are approximately 10 - 15 times less sensitive to 662 keV gamma photons than are MCPs. The sensitivity to gamma photons is an important criteria because any energetic penetrating particle produces additional gamma photons through Bremsstrahlung. For example, a 1 MeV gamma photon has a stopping range of 60 mm in aluminum, whereas an electron only penetrates 2 mm [85]. The high stopping range in matter makes it very difficult to shield against gamma photons. Although the quantum detection efficiency for gamma photons is generally low for both detector types, the large amount of gamma photons makes their contribution to the recorded background counts dominating. The lower
detection efficiency of CEMs to penetrating radiation can be explained by the fact that penetrating energetic particles are crossing the active surface of an MCP many times compared to a CEM, as shown in Fig. 5.20. An MCP has such a large number of channels that the probability of releasing a secondary electron into one of its channels is much higher than in the single channel of a CEM. Other advantages of a ceramic CEM are their rugged construction using ceramic materials and their large gain, which simplify the front-end electronics. Therefore, CEMs as start detectors represent an optimal choice. An actual picture of such a detector can be found in Fig. 6.34.

Values of the CEM efficiency of electrons and gamma photons were searched following a literature study. Below particle energies of 1 MeV, many publications on efficiencies can be found; however, such information is sparse above 1 MeV. The found efficiencies for CEMs are shown in Fig. 5.21 for electrons and photons.

Figure 5.20: Cross section of an MCP and a CEM. Although a penetrating particle would cross the surface of a single channel of a CEM at exactly two positions, the same particle would cross many such positions at an MCP. Both detectors are sensitive to penetrators at approximately the first 50% of a channel length. At the output anode, the generated electron clouds are collected, and particles for normal detection enter at the corresponding opposite side.
5.5.3 Stop detector

The stop detector is required to detect the ions and neutral atoms in the direct channel as well as secondary electrons collected from the stop surface. A coarse spatial resolution is needed in the form of two ring-shaped anodes. Although a design using CEMs would be preferred, an MCP is the natural solution because of their usual shape as a disc. Instead of a single channel, an MCP consists of many micrometer-sized channels, commonly arranged in a disc. The channels are slightly tilted to ensure incident particles generating secondary electrons at the inner walls of a channel. The gain of an MCP is lower, which results in smaller pulses being detected. To improve the gain, several MCPs are stacked on top of each other. When using two MCPs, the arrangement is called a chevron stack (see Fig. 5.20). A triple stack is also common and is called a Z-stack. A review can be found, for example, in the work of J. L. Wiza [95].

Values for the MCP efficiency of electrons and gamma rays were investigated in a similar literature study as on CEMs. Efficiency information for MCPs above 1 MeV is as sparse as for CEMs. The MCP efficiencies that were found are shown in Fig. 5.22 for electrons and photons.

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**Figure 5.21:** Channel electron multiplier detection efficiencies for electrons and photons. Sources for electrons: Sjuts.com [42], Bordoni (1971) [86], Paschmann (1970) [87], Archuleta (1971) [88], Sharber [89], Egidi [90], Vaziri [91], Andresen [92]. Sources for photons: Sjuts.com [42], Bordoni (1974) [93], Burle.com, Suzuki (1985) [94], and Funsten (2015) [84].
5.6 Additional measurement capabilities

JDC is designed for the characterization of positive charged particles up to 41 keV/q. By switching the polarity of the electrostatic analyzer, particles with a negative charge (electrons and negative ions) can be analyzed as well.

Because this additional capability is a secondary goal, the only additional technical change is the power supplies, which need to be bi-polar; this is usually achieved at almost no extra cost in terms of weight and size. The deflector system is already designed as bi-polar and thus fully supports a negative particle mode.

5.6.1 Electron mode

For electrons, the instrument differentiates between energies below 300 eV and above. Below 300 eV, the electrons leaving the ESA are detected directly by the CEM. This mode is a non-coincidence measurement. For energies above 300 eV, the electrons are scattered from the start surface and release secondary electrons that are detected as in positive ion mode. After scattering from the start surface, the electrons follow the direct channel path and can thus be counted in a coincidence mode with the stop detector.

5.6.2 Negative ion mode

Negative ions are detected like positive ions, except for energies below 300 eV, where they cannot be distinguished from electrons. Above 300 eV, the incident ions interact with the start surface in the same manner as positive ions. Because the initial charge state is lost during surface interaction, the resulting ions can be positive, negative or neutral particles when scattering into the time-of-flight cell. Therefore, they
can follow the same time-of-flight path as described for incident positive ions. The reflectron time-of-flight cell works in the same manner as for positive ions and allows for mass per charge analysis.

With the additional measurement, the instrument becomes a comprehensive ion and electron analyzer with minor energy limitations for negatively charged particles.

5.7 Radiation mitigation strategies

The instrument’s design is strongly driven by the expected energetic electron and gamma photon fluxes in the system of Jupiter. Sensitive areas at the detectors are minimized, and the time-of-flight technique provides a good signal-to-noise ratio. However, the environment is so severe that this is not sufficient to operate in this environment, and JDC contains an additional anti-coincidence system. Coincidence is when two events are necessary for a valid detection. Anti-coincidence is a third requirement for a valid detection. It is realized in the form of a solid-state detector (see section 5.5.1) for penetrating particles. Only when the solid-state detector does not register an event are the time-of-flight signals considered valid. To be efficient, the solid-state detector has to be placed as close as possible to the position where the anti-coincidence is needed. In the case of JDC, this is slightly above the stop surface of the composition channel.

Shielding is the ultimate radiation mitigation method but also the most expensive method because it requires mass. Sensitive volumes or whole instruments are enclosed in a suitable shielding material such as aluminum or tungsten. Although it is possible to shield electrons quite effectively, the stopped electrons generate additional Bremsstrahlung in the form of gamma photons. Not enclosing the whole instrument but using spot shielding of sensitive volumes to keep the shielding mass low represents an optimization problem. For JDC, at its present design stage and for the prototype that is derived from it, only a preliminary design of the shielding exists because a final ion-optical design of the instrument is necessary to optimize shielding.
Chapter 6

JDC Prototype

6.1 Introduction

A prototype of an instrument is required to verify the general functionality and performance of the chosen measurement concept, the utilized mechanical and electronic design solutions and the simulation models. Due to the novelty and complexity of the JDC instrument, it was decided to divide the prototype into two subsystems: the time-of-flight section, including a simplified start section and the deflector section, the analyzer section and the start section (see Fig. 5.2). The start surface section is the interface between the time-of-flight section and the analyzer section and therefore belongs to both prototypes.

In this work, the term prototype refers to the deflector section, the analyzer section and the start section. The time-of-flight section prototype is not included in this work.

Two main experiments were conducted, an ion optics test, “first light”, without start surfaces and a CEM test, which included operational CEMs, where the start surfaces are replaced by a simple aluminum ring. A detailed setup description is given for each experiment in the corresponding sections.
6.2 General prototype description

The JDC prototype’s mechanical design is based on an early version of the hybrid model No.8 (see section 4.3.4) and is described in chapter 5. As mentioned before, the prototype does not include a time-of-flight cell (reflectron). It further does not contain start surfaces, as with those tested in chapter 3. The prototype is therefore fully representative in terms of field of view and energy selection.

The main materials used in the prototype are aluminum 7075 (alloy of aluminum and zinc) and PEEK. PEEK is a thermoplastic widely used in space applications for electrical insulating parts because of its high electrical resistance of approximately $\sim 10^{16} \Omega \text{cm}$. Parts of the prototype were chromate conversion coated (Iridite) to prevent the built up an insulating oxide layer, hence the yellowish color.

![Figure 6.1: JDC Prototype, LEFT: The fully integrated prototype mounted on a holder plate. RIGHT: Prototype with removed housing and deflector section.](image)

The major difference between the prototype and the simulated hybrid model No. 8 (section 4.3.4) concerns the backside of the ESA exit apertures. The apertures are formed by spokes holding the inner analyzer. The modeled version of hybrid model No.8 accounted for the spokes with an angular size of $3.5^\circ$; however, in the mechanical model, the spokes were designed with an angular size of $7.5^\circ$. This was necessary to feed a single high-voltage wire into the inner ESA electrode, as shown in Fig. 6.2.
One azimuthal sector of the instrument has an angular size of 22.5°. With a spoke width of 7.5°, the resulting ESA exit apertures become 15° wide instead of the desired 19°. These spokes, immediately in front of the start surfaces, limit the azimuthal resolution of a sector by blocking the corresponding trajectories, which can be observed in the results when comparing to the initial simulations of section 4.3.4.

The ion optical elements of the prototype are sketched in Fig. 6.3. The prototype uses six electrodes: post-acceleration (PAC), CEM front (CF), electrostatic analyzer (ESA), Ground (GND), side deflector electrode (DS) and top deflector electrode (DT). All electrodes are powered by external power supplies.
6.2.1 Experiment 1

In a first experiment, the prototype consisted of the ion optical elements, as described above, and served as a “first light” experiment.

The start surface assembly for experiment 1 is shown in Fig. 6.4. Instead of real CEMs, dummy CEMs are installed on 13 azimuthal sectors. These dummy CEMs consist of simply the ceramic body and the front metalization. Because the CEM’s front is at a potential of approximately 100 V, the dummies are needed to provide correct electrical field configurations. The 3 unpopulated CEM spots are left open. The prototype is mounted on the manipulation system such that the ion beam does not reach these positions. To be able to detect the incident ion beam during the test, a position-sensitive detector (micro channel plate - Quantar 2401B) with a sensitive area of $\varnothing = 40$ mm is placed at a position of 23 mm behind the start surface ring (Fig. 6.3). Thus, particles that normally would hit the start surfaces will be registered with the temporally installed, position-sensitive detector. The mechanical alignment was tested by setting the inner ESA electrode at a fixed voltage and allowing the elevation and azimuth to vary at two azimuthal positions $90^\circ$ apart.

The energy and angular resolutions are tested at three different viewing directions (see Fig. 6.5). Each viewing direction has a mean elevation, given by constant deflector electrode potentials. In the normal viewing direction ($\varphi \approx 38^\circ$), the deflector electrodes are at ground potential. The horizontal viewing direction ($\varphi \approx 12^\circ$) describes low elevation angles; consequently, the deflector electrode DS is at a negative potential, and the deflector electrode DT is at a positive potential (positive ions). In the zenith viewing direction ($\varphi \approx 65^\circ$), the instrument observes at higher elevation
angles, and the potentials on the electrodes are reversed.

To determine the energy resolution of the prototype, the voltage at the inner ESA electrode is varied for a constant energy of incident ions. This gives a similar result as varying the ion energy and is much easier to achieve; it also ensures a constant ion beam profile.

Figure 6.5: Viewing directions of the prototype using 3 different deflector settings. The horizontal describes a direction with a low elevation angle. For a positive ion to pass into the analyzer, the top deflector electrode (DT) would need to be at a positive potential and the side deflector electrode (DS) at a negative potential.

All measurement in Experiment 1 used 3 keV hydrogen ions (H$^+$). The pressure is held at approximately $1 \cdot 10^{-6}$ mbar.

6.2.2 Experiment 2, CEM Test

In the second experiment, the remaining three azimuthal sectors were equipped with three custom-made CEMs. A simple aluminum ring was used as the start surface (see Fig. 6.6). Incident ions will produce secondary electrons on the aluminum ring that are detected by the CEMs. Because dedicated instrument electronics were not available, spare parts from other instruments were used to read the CEM pulses. Detector electronics were available from the LISA instrument ([31], see section 3.3). Those electronics are designed to read out two CEMs, one as start and one as stop, for a time-of-flight system.
For experiment 2, the prototype start assembly was equipped with three functional CEMs and an aluminum ring as start surface replacement. In the picture, the CEM’s entrances are protected by tape.

All measurements with the CEMs used 3 keV $N^+$ instead of $H^+$ as in the first-light experiment. The average pressure in the vacuum system was maintained at the same level as for the previous experiment of approximately $1 \cdot 10^{-6}$ mbar. The turn table of the IRF calibration facility allows one to automate the rotation in the azimuth and elevation; however, the voltages of the ESA and the deflector electrodes have to be set manually for a prototype without dedicated ground support equipment. For measurements covering many positions in angular and energy space, it is necessary to make compromises to fit an ordinary working day. Furthermore, the ion beam has a time constant of approximately 15 min and thus will change over time or even be interrupted during a day. The time for a measurement of one property should thus not exceed a couple of hours. Therefore, the measurements are divided into a set with a focus on the angular space and a set with a focus on energy resolution. Both variants have been measured for three different deflector settings.

Because the CEMs were new, it was necessary to define their operating point by exposing them to an ion beam and successively increasing their bias voltage. Their gain increases with increasing voltage until a plateau is reached, were a higher voltage does not increase the number of counts. An excessive voltage however is avoided because this decreases their lifetime. This test was conducted two times on one day (6h apart) to observe eventual changes in the operating point. As shown in Fig. 6.7 a shift in the operating point occurs in particular for CEM H, which was used most during that day. The operating voltage of the setup was determined to be 2500 V (CEM_HV in schematics) as a compromise between gain and risk of aging.
6.3 Prototype simulation

Because the final mechanical design of the prototype is different from the initial conceptual design, a new simulation round was initiated. To simulate the behavior of the prototype, the CAD files that are used to machine the prototype are also used as an input to the geometry definition in SIMION.

Functional groups are exported from the CAD design system as high-resolution stl-files. These files are commonly used to export or import between 3D mechanical design tools. Each part that is on the same electrical potential is then combined into new stl-files. SIMION converts these files into its own proprietary format of potential arrays, or pa-files. This process can lead to very large files that produce size conflicts with the available computer memory. A minimum resolution was estimated to be 0.15 mm in SIMION to observe the spherical wedges at the electrostatic analyzer (Eq. 4.17); however, a higher resolution is desired. SIMION allows for the nesting of potential arrays with different sizes and resolutions. First, a full 3D model is converted into the corresponding pa-files at the minimum resolution. In a second step, using the same input files, a volume of high resolution is defined and saved as an additional pa-file. If defined reasonably, the resulting additional pa-file has a substantially smaller volume. The smaller volume can now have an increased resolution. It was thus possible to simulate the spherical-wedge electrostatic analyzer over three azimuthal sectors with a resolution of 0.0625 mm. The used RAM-memory was approximately 20 GB, which would otherwise in a full 3D model be approximately 500 GB of RAM-memory. This concept is shown on page 130 for all three previously mentioned geometry definitions for SIMION as cut models.

In Fig. 6.8 the initial simulations using geometry definition files (gem-files) are visualized. The figure below (Fig. 6.9) shows the result of importing a stl-file into
SIMION with a minimum resolution of 0.125 mm. Fig. 6.10 shows the nested pa-
files with resolutions 0.0625 mm (ESA) and 0.125 mm (deflector electrodes). For
greater visibility, the underlying full model with minimum resolution was removed
in Fig. 6.10.

Figure 6.8: Initial gem file definition with a resolution of 0.125 mm

Figure 6.9: Converted stl-file definition with a resolution of 0.125 mm
6.4 Mechanical symmetry

The alignment of the assembly was tested by comparing different azimuthal sectors based on their symmetry. The normalized plots in Fig. 6.11 show two different sectors and their field of view for a fixed analyzer voltage. Although the distribution in the azimuthal direction is identical, a small difference of approximately 0.5° in the elevation distribution is visible. The manipulator system inside the vacuum chamber has an accuracy of approximately 1°, and therefore, the differences in the fine structure cannot be distinguished from uncertainties of the setup.
Figure 6.11: The angular distribution was scanned for sector 1 at $0^\circ$ and sector 5 at $-90^\circ$ for an analyzer voltage of -410 V using an ion beam of 3 keV, H$^+$. The responses are similar and indicate no misalignment of the assembly.

In a different test, the instrument was rotated over a larger azimuthal range. The analyzer was held at -410 V with the deflector electrodes at ground potential as before. In contrast to the scans in Fig. 6.11, the elevation was set to a fixed position of $\varphi = 40^\circ$. The azimuthal response shows good agreement between the sectors, except at the very top and bottom of the peaks. These differences originate in the fixed elevation setting and the constant analyzer voltage. Identical peaks would only be visible for an ideal alignment of the prototype around its symmetry axis, which is not possible to achieve with the given setup.

Figure 6.12: Azimuthal scan for a fixed elevation and ESA voltage.
6.4.1 Conclusion

When building an electrostatic analyzer, mechanical alignments and precision are important. The initial test in Fig. 6.11 shows that sector 1 and 5 give comparable but not identical results. The small differences that are observed can be explained by the limitations of the manipulator table and the mounting of the prototype.

Machining and integration achieved the basic accuracy needed to proceed with the experiments.

6.5 Field of view

The field of view of one azimuthal sector is ideally obtained by scanning over all ion energies and all directions at a specific ESA voltage. For JDC and the prototype, one azimuthal sector has a size of 22.5° in azimuth and 90° in elevation. For the measurement of the angular resolution with a constant ion energy, the ESA voltages are varied in the same way as in section 6.2.1. An angular scan with a resolution of 1°, 10 ESA voltages and a time of 2 s per angular step would take approximately 11 hours for a fully automatic scanning system. For a semi-automatic system, as was used during the experiment (see 6.2.2), the total measurement time would further increase, and thus, it is necessary to take compromises for the scanning resolutions. The field of view over the elevation range of 0° to 90° is sampled at the three positions according to Fig. 6.5. The elevation at the respective positions is varied with 1° steps, and the azimuth is varied with 2° steps. The ESA voltage is varied at 20 V increments for an incident beam energy of 3 keV.

6.5.1 Normal viewing direction

For a selected azimuthal sector from the instrument, the recorded angular distribution over different voltages at the ESA is shown in Fig. 6.13. One can see how the ESA voltage moves the response over the elevation positions, which is an effect of the energy resolution, as described in the next section. For the panel with the maximum number of counts (E/V = -7), the ratio of E/V is comparable to the analyzer constant $k$. The sum of all counts for the different ESA voltage steps from Fig. 6.13 is plotted in Fig. 6.14. From the sum of all counts over all voltages, the angular resolution is deduced by collapsing the energy axis.
Figure 6.13: Sequence of all voltage steps used to scan one instrument viewing direction over elevation and azimuth with a beam energy of 3000 eV. All counts are normalized to 1.

Figure 6.14: Summation of counts over all ESA voltages and collapsed angular axes for normal viewing direction (deflectors at ground potential).

The system was simulated under conditions identical to those in the experiment (Fig. 6.15). The simulations and measurements agree almost perfectly.
Figure 6.15: Comparison of measured and simulated angular resolution for normal elevation (deflectors off). The measurement plot is shifted -2 degrees in the azimuthal panel and +1 degree in elevation to provide better visibility. The shifts are due to the inaccuracy of the manipulation system.

6.5.2 Horizontal and zenith viewing direction

In the same way as described above, the other two elevation cases are compared in Fig. 6.16.
Figure 6.16: Comparison of measured and simulated angular resolutions for horizontal a) and b) and zenith c) and d) directions. Measurement plots are slightly shifted to overlap and account for the inaccuracy in the manipulator system.
6.5.3 Summary plot field-of-view

Figure 6.17: Angular resolution for measured (left) and simulated (right) views in elevation. The separation in azimuth is for visualization only. Measurements are interpolated to the same grid as used in the simulations.

Figure 6.18: The same data as in Fig. 6.17 but in Cartesian coordinates.
6.5.4 Discussion

The angular resolution in Fig. 6.15 and Fig. 6.16 shows good agreement to the simulation. This means that the mechanical prototype and the ion-optical design files match and that the system is fully represented with the simulation. The exception is the zenith viewing direction, where notable differences can be seen: the measured azimuth and elevation distributions are slightly larger, as shown in the simulation. Additionally, Fig. 6.16 shows that the simulation includes some discontinuities at the high elevation side of the curve that are not seen in measurement. Although the measurement did not cover the low elevation side of the curve, it seems that the problem is restricted to high side. The effect is likely a simulation artifact that originates in the finite size of the simulated grid in front of the deflector electrodes. Due to the asymmetric arrangement of the detectors, ion trajectories in the zenith case, pass the grid under a smaller angle, than for the horizontal case. With the coarse grid in the simulation, certain particle positions are absorbed and result in the discontinuities at the high elevation side. The grid was simulated with coarser resolution than the grid used in the prototype.

The simulated angular resolution for normal viewing direction of the initial model hybrid model No.8 (see Fig. 4.14) was $20.6^\circ$ in the azimuth and $7.1^\circ$ in elevation, both being full-width-half-max values (FWHM). The measured values of $15.7^\circ$ in the azimuth and $6.4^\circ$ in elevation meant that the requirements for elevation could be met; however, for the azimuth, a reduced value was achieved with the prototype. The reduced azimuthal resolution can entirely be explained by the reduced size of the ESA exit apertures in the prototype (Fig. 4.6). It is very likely that the required larger azimuthal resolution can be achieved with larger ESA exit apertures.

Fig. 6.19 shows possible azimuthal responses for JDC. The ideal response is rectangular, with a width of $22.5^\circ$, a sharp cut-off between each sector and ideally no cross-talk. For comparison, three possible Gaussian-shaped responses are plotted in the same figure. The dashed variant to the left is minimized for cross-talk and thus has a small FWHM. The continuous line in the middle panel shows the same distribution but as a sum of two Gaussians placed a few degrees apart, which approximates the ideal rectangular response. The last curve in the panel on the right (dash-dot) shows a Gaussian distribution wherein the FWHM has a width of one sector ($22.5^\circ$). Cross-talk is visualized as the gray area in the panel in the middle and on the right.
6.6 Energy resolution

In the same way as for the angular resolution, the data are retrieved from measurements, as shown in Fig. 6.13. However, instead of summing over all voltages to plot the elevation and azimuth, the data are summed over azimuth and plotted as elevation versus energy-voltage ratio (top panel Fig. 6.20). The bottom panel of Fig. 6.20 is generated by collapsing the elevation axis. The energy resolution is retrieved from the FWHM of the resulting curve.
An energy resolution of approximately 13.3 % was measured for the normal viewing direction and is comparable to the value obtained from simulations: 15.0 % (Fig. 6.21). The energy response plot allows one to directly determine the analyzer constant $k_m$:

$$k_m = \frac{E_m}{V_m} = \frac{3000 \text{ eV}}{-431 \text{ V}} = 6.96 \left[ \frac{\text{eV}}{\text{V}} \right]$$

(6.1)

with $E_m$ as the incident ion beam energy and $V_m$ as the ESA voltage at maximum transmission for measured values.

The simulation is processed in the same way as above and yields an energy resolution of 15.0 %, with a simulated analyzer constant $k_s$ of

$$k_s = \frac{E_s}{V_s} = \frac{3000 \text{ eV}}{-409 \text{ V}} = 7.33 \left[ \frac{\text{eV}}{\text{V}} \right]$$

(6.2)

where $E_s$ is the center of the ion beam energy and $V_s$ is the ESA voltage at maximum transmission for the simulated values.

The measured and simulated energy responses of the prototype are shown in the comparison of Fig. 6.21. Because of the clear difference between measurement and simulation, additionally, the simulated data are shown scaled on the x-axis by a factor of 0.945 to accommodate the difference between the simulated and measured analyzer constants.
Figure 6.21: Comparison between measured and simulated energy resolutions for the normal viewing direction (deflectors off). The arrows indicate the FWHM values. The thin dashed line “Sim/0.945” corresponds to the simulated data shifted in energy by a factor of 0.945.

6.6.1 Energy resolution for horizontal and zenith direction

In the same way as described above, the other two elevation viewing directions are compared in Fig. 6.22.

Figure 6.22: Comparison of measured and simulated angular resolution for horizontal (upper panel) and zenith (lower panel) directions. The arrows mark the FWHM values.

Figure 6.23 summarizes the energy-voltage ratio versus elevation response for all three investigated viewing directions. Measurements are shown in the panel on the, and simulations in are shown in the panel on the right. The rather constant shift by
the factor $\sim 0.95$ on the x-axis between the measured and simulated cases is clearly visible for all viewing directions. As a result, the prototype instrument needed a higher voltage to measure the same energy as in the simulation predictions.

![Figure 6.23: Comparison of measurement (left) and simulation (right) of elevation versus energy-voltage ratio. Measurements were performed using a 3 keV N$^+$ ion beam. The obtained counts are normalized to a maximum value of 1 in each data set. Deflector voltages DT/DS: low elevation: +500 V/-500 V, center: 0 V/0 V, high elevation: +400 V/+400 V.](image)

**6.6.2 Discussion**

Fig. 6.21 and Fig. 6.22 show that the measured energy resolutions do fit the simulations but are displaced by a factor of 0.94 to 0.95. This shift corresponds to a smaller analyzer constant in the prototype and results in higher voltages needed for the same energy pass band of incident particles. Missing measurements at low elevations, as observed in the upper panel of Fig. 6.20, may represent a partial explanation. The missing values will decrease the calculated energy resolution of the measurement. It is however more likely that the electrostatic analyzer gap, the distance between the outer and inner analyzer electrodes, differs between simulation and prototype. The difference in the analyzer constant at a 5% level is at an acceptable level but is quite large compared to other measurements with the prototype. Therefore, a closer look at the errors is needed to eventually explain the disagreement between measurement and simulation.

First, a purely geometric approach is used to approximate the analyzer constant
using Eq. 4.11

\[ k_g = \frac{\bar{r}}{2 \bar{d}} - 0.5 \]  

(6.3)

where \( \bar{r} \) is the mean center radius of the ESA and \( \bar{d} \) is the mean gap width between inner and outer analyzer electrodes. Due to the spherical-wedge structure at the inner ESA and the spheroidal outer ESA, the gap distance varies with azimuth, as shown in Fig. 6.24.

![Figure 6.24: ESA gap distance over one azimuthal sector](image)

With \( \bar{r} = 36.98 \) mm and a gap of \( \bar{d} = 2.35 \) mm, the geometric estimate of the analyzer constant \( k_g \) becomes 7.37 eV/V ±0.13 and fits the simulation well. The machining precision is estimated to be 0.02 mm. The misalignment and assembly errors could result in larger errors, which may vary over different sectors.

To estimate the error of the measurement, the voltage of the power supplies and the beam energy is considered as follows:

\[ \sigma(k_m) = \sqrt{\left( \frac{1}{V_m} \right)^2 \sigma_{E_m}^2 + \left( \frac{E_m}{V_m^2} \right)^2 \sigma_{V_m}^2} \]  

(6.4)

with \( \sigma_{E_m} \approx 20 \) eV as the energy uncertainty of the ion beam at 3 keV and \( \sigma_{V_m} \approx 5 \) V as the setting accuracy of the utilized power supplies (Stanford Research Systems, PS350). The resulting error of \( k_m \) is approximately \( \sim 0.1 \), which is similar to the machining errors.

The simulation errors are mostly due to the finite spatial resolution of the simulation software SIMION. When loading a standard 3D model (stl-files) into SIMION, the model is approximated by SIMION with small volume elements that are defined in size by the grid unit of a simulation. SIMION approximates the position of each volume element according to the stl-file. The error of such a simulation can thus be estimated as 1 grid unit of the inner and outer ESA electrode radii (\( r_i \) and \( r_o \)). Thus, the error scales with the simulation resolution set by the size of 1 grid unit. For the modeled ESA, the grid unit is 0.0625 mm, and thus, \( \sigma(r_i) = \sigma(r_o) = 0.0625 \) mm. Using Eq. 6.3 as a basis for the error estimate, one obtains 0.42 eV/V as the resulting error for the analyzer constant. This makes the error of the simulation
approximately four times larger than with machining or by measurement. With the simulated analyzer constant of $\sim 7.3$, the result is acceptable based on its errors. Zouros et al. [102] studied the accuracy of SIMION simulations in detail for gem-file simulations (see section 4.2.2), which is the native way for SIMION to construct simulation geometries. An important result was the general reduction in the outer radius of curved structures, as with electrostatic analyzers, by 1 grid unit. When using stl-files, such a reduction can be applied by reducing the actual size of the outer ESA electrode in the simulation. Such an adjustment is possible when using stl-files by scaling the electrostatic analyzer to approximately 1 grid unit, which in the present case corresponds to a reduction factor of 0.996. A simulation applying this 1 grid unit correction results in a perfect match to the measurement, as shown in Fig. 6.25. It is however not fully clear if this correction is required when using stl-files and was therefore not considered in the main simulations shown in this chapter.

Newer versions of SIMION provide a feature called “surface enhancement”, whereby surfaces of curved structures are calculated using fractal methods. With the surface enhancement feature, the 1 grid unit correction becomes obsolete. This feature is unfortunately not yet available for stl-file-based simulations (April, 2016).

![Diagram](image)

**Figure 6.25:** Analyzer constant for the outer ESA electrode of 0.996 times the size of the original.

In conclusion, pure machining or voltage uncertainties are unlikely the cause of the full analyzer constant shift. Eventual misalignments during integration could not be quantified and are therefore not considered. An analytical approach to the problem is impossible for the given geometry, and the calculation using the mean radius is clearly an approximation. The scaled outer ESA electrode might be the solution to the difference in analyzer constants because it applies an exactly 1 grid unit correction to achieve a perfect match to the measurement.

A smaller analyzer constant results in a lower maximum energy that the instrument can cover. For the given maximum voltage at an ESA of 5000 V, the maximum particle energy per charge is approximately $\sim 39$ keV according to simulations and approximately $\sim 37$ keV according to measurement. The maximum energy of the ESA is shown in Fig. 6.26 as a vertical line. The small change does not affect the instrument capabilities to address the scientific objectives.
6.7 Deflector performance under maximum voltages

To show the energy acceptance under maximum voltages at the deflectors and ESA, a simulation was run with reduced accuracy and a minimum number of test particles. The deflector electrodes were set to their maximum voltage of 5000 V in the corresponding polarity for the zenith and horizontal viewing directions. The ESA voltage was then set to the same maximum of 5000 V and then gradually decreased. Figure 6.26 shows that even at the highest energies of almost 40 keV/q, a useful field of view remains. The full hemispheric field of view can be reached for the maximum energy of 23 keV/q for the zenith view and of 25 keV/q for the horizontal view.

![Figure 6.26: Maximum elevation angles for the maximum deflector voltage of 5000 V. The full hemispheric field of view can be maintained to approximately 23 keV/q for zenith viewing directions and 25 keV/q for horizontal viewing directions. Larger energies result in a smaller field of view, which is ultimately limited by the maximum electrostatic analyzer voltage.](image)

6.8 Geometric factor from measurement

The geometric factor including detector efficiencies, GF, is defined as

\[
GF = \int_{\Omega} \int_{E} \int_{A} \epsilon(\Omega, E, A) \, dA \, dE \, d\Omega
\]  

(6.5)

where \( \epsilon \) is the transmission function, \( A \) is the aperture area (\( \sim \) aperture), \( E \) is the energy, and \( \Omega \) is the solid angle. The transmission \( \epsilon \) also includes efficiencies (\( \eta \)), for example, the quantum detection efficiency for an incident electron, ion-optical effects and limitations on the electronics.
The integral (Eq. 6.5) can be approximated by the finite sum

\[ GF_m = \Delta A \Delta E \Delta \Omega \sum_{\Omega, E, A} \epsilon(\Omega, E, A) \]  \hspace{1cm} (6.6)

If an instrument is exposed to an almost parallel beam (divergence \(<< \Delta \Omega \)), which is monitored by a Faraday cup of area \(A_{Fc}\), the transmittance at a fixed direction is related to the instrument count rate \(c/\Delta t\) as

\[ \epsilon(\Omega, E, A) = \frac{c}{\Delta t} \cdot \frac{q \cdot A_{Fc}}{I_{Fc} \cdot \delta} \]  \hspace{1cm} (6.7)

where \(c\) is the instrument counts, \(q\) is the elementary charge, \(\Delta t\) is the count time, \(I_{Fc}\) is the Faraday cup current measured to ground, and \(\delta\) is a factor considering the remaining beam divergence of the setup.

![Figure 6.27: Calibration facility at IRF, Kiruna. The Faraday cup has an aperture radius of 2.0 cm.](image)

From Fig. 6.27 we can calculate the factor \(\delta\) as the ratio of the corresponding distances:

\[ \delta = \left( \frac{d_F}{d_P} \right)^2 = 0.296 \]  \hspace{1cm} (6.8)

The measured geometric factor \(GF_m\) differs from the simulation by the efficiency of the detector. Fortunately, for the prototype tests, a time-of-flight system was used. The system measures the time of flight between two CEM detectors (Fig. 6.30) and thus generates coincidence counts that can be used to calculate the efficiency of the measurement setup using the formulas of section 2.4. An example of the relevant time-of-flight spectrum is shown in Fig. 6.31. The efficiency is calculated as

\[ \eta = \frac{N_C}{N_P} \]  \hspace{1cm} (6.9)

where \(N_C\) are coincidence counts and \(N_P\) are stop counts.
It was not possible to determine the efficiencies for every measurement, and thus, it is necessary to define a single value for all measurements. Measurements where the efficiency was available are plotted in Fig. 6.28. With the lowest and highest efficiencies removed, the mean of the remaining values defines the prototype efficiency to 3 keV incident nitrogen ions $\eta(N^+, 3\text{ keV})$. With the retrieved value of $\eta(N^+, 3\text{ keV}) = 0.19$, it is possible to compare measurements and simulations.

![Efficiency vs. ESA voltage](image)

**Figure 6.28:** The detector efficiencies retrieved from the time-of-flight data between the CEMs. A simple machine-grade aluminum ring was used as the start grid, resulting in a rather low mean efficiency of $\eta = 0.19$.

However, where measurements of efficiency were available, a trend that the efficiencies are not a constant value is visible, as shown in Fig. 6.28. A dependence on the ESA voltage and viewing direction can be seen. The ESA voltage steers particles of constant energy over the start surface and thus causes different start positions, which can explain the changing efficiencies. The dependence on the viewing direction might be explained by the non-optimal deflector voltages. For optimal sensitivity, the voltage at the deflector electrodes has to follow the ESA voltage; however, in the experiment, the deflector electrodes were set to a constant value. It is thus possible that a more optimal voltage at the deflector electrodes could lead to an increased efficiency for different viewing directions.

### 6.8.1 Results

The measured and simulated geometric factors are given in Table 6.1. Note that, for the measured geometric factors, some part of the elevation distribution was missing (Fig. 6.15 and Fig. 6.16d). The calculated values are therefore assumed to be biased toward lower values, especially for the zenith case.

The measured geometric factors do differ from the simulations, with a tendency for lower values, but in general match the simulations given the error bars. The zenith viewing direction is the exception due to missing positions during measurements in elevation space and a poorer representation of the field of view in the simulation.
<table>
<thead>
<tr>
<th>Source</th>
<th>$GF \ [10^{-4} \text{cm}^2 \text{sr} \text{eV/eV}]$</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. “normal” view</td>
<td>$2.01 \pm 0.74$</td>
<td>0.19</td>
</tr>
<tr>
<td>Sim. stl-file</td>
<td>$2.72 \cdot 10^{-4} \pm 0.30$</td>
<td>1.0</td>
</tr>
<tr>
<td>Exp. “horizontal” view</td>
<td>$1.91 \pm 0.70$</td>
<td>0.19</td>
</tr>
<tr>
<td>Sim. stl-file</td>
<td>$2.29 \cdot 10^{-4} \pm 0.25$</td>
<td>1.0</td>
</tr>
<tr>
<td>Exp. “zenith” view</td>
<td>$0.87 \pm 0.64$</td>
<td>0.19</td>
</tr>
<tr>
<td>Sim. stl-file</td>
<td>$2.83 \cdot 10^{-4} \pm 0.32$</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 6.1: Measured and simulated geometric factors for one azimuthal sector.

6.8.2 Conclusion

Beside the analyzer constant shift and the differences in the zenith case, the prototype performs as expected. The new type of compact electrostatic analyzer is functional and performs with the expected field of view, energy resolution and geometric factor in most cases.

6.9 Cross-talk

Cross-talk is the detection of particles from one azimuthal direction in an azimuthal sector that is not assigned to that direction. The effect is illustrated in Fig. 6.19 as a gray area; in the figure, cross-talk only affects neighboring sectors. The experiment showed a significant amount of cross-talk between azimuthal sectors at even further sectors than simply neighboring sectors.

For a fixed ESA voltage and a fixed ion beam, an angular scan by rotating the instrument in the elevation and azimuthal directions is shown in Fig. 6.29. The plot spans an azimuthal rotation of the prototype over 90° (4 sectors).
Counts received by CEM “H” for a constant ion beam arriving from a direction of $-20^\circ$ azimuth with the sensor rotated. A constant voltage was applied to the ESA over a large angular range; see also Fig. 6.30.

In the angular scan of Fig. 6.29, the nominal signal is centered at approximately $-20^\circ$ azimuth and $40^\circ$ elevation. Ghost images are visible up to $+40^\circ$ azimuth 3 sectors away. The signal drops by approximately one order of magnitude per sector. The total amount of cross-talk in the measurement sums to approximately 3.5% of the total number of counts, which is considerably higher than the expected 0.5% from initial simulations of model hybrid model No.8 (4.3.4) or of the simulations in this chapter of approximately 0.3%. The explanation is found when analyzing the mechanical design of the start section with the aluminum ring replacing the start surface, as shown in Fig. 6.30.

An incident beam of ions generates secondary electrons in one azimuthal sector.
These are detected at the corresponding channel electron multiplier. The incident particle is now scattered into another sector and detected directly or indirectly by the adjacent detector. Due to the large incident angle of approximately $60^\circ - 70^\circ$ to the surface normal, the scattering distribution is quite hemispheric, with a lobe radially inward. This effect can be observed in the time-of-flight data between two CEMs (Fig. 6.31). The distance of flight between two CEM detectors varies with radial position from 5 mm to 8 mm of the initial hit location on the start surface.

![Figure 6.31: Time-of-flight spectra between two detectors “H” and “F” (crosses) and between detectors “H” and “E” (circles)](image)

A peak at approximately 40 ns in Fig. 6.31 corresponds well to an average distance of flight for incident nitrogen ions at 3.4 keV (beam energy + post acceleration). A nitrogen ion will scatter from the aluminum with approximately half the incident energy or less. After reflection, it is scattered to a location up to three sectors away. With $e$ as the elementary charge, $E_N = 1.7$ keV, $m_N$ as 14 times the proton mass and with an average distance of $d_N = 6.5$ mm, the time of flight is estimated as

$$t = \sqrt{\frac{m_N d_N}{2eE_N}} \approx 43 \text{ ns}$$  \hspace{1cm} (6.10)

This is further backed by measurement, where the start and stop detectors are two sectors apart, and consequently, the most likely time of flight is roughly doubled.

The cross-talk in Fig. 6.29 is therefore mostly a result of incident ions that scatter randomly from the installed aluminum ring. Because the effect can be well explained, the remaining part of cross-talk due to ion-optical effects or focusing issues of the ESA is small.
6.10 Secondary electrons in the simulation

Secondary electrons generated in the area between the start surface and the ESA exit apertures are subjected to the electric fields in the region. The electrical fields present in this region are always radially oriented, as shown in Fig 6.32.

![Radial field in front of the channel electron multipliers with shown equipotential lines.](image)

Because of the radial field and the potential of at least +100 V at the CEM entrance, secondary electrons (<20 eV) can hardly jump between sectors. Secondary electrons are generated wherever ions out of the electrostatic analyzer hit a surface. If they are generated between the CEM entrance and ESA exit apertures, they can be accelerated toward the CEM front and generate tertiary electrons. As a result, additional start counts can be generated. For example, ions that hit the structure of the ESA exit aperture and are actually absorbed might cause secondary electrons that remain detected. Electrons generated between the ESA exit aperture and the electrostatic analyzer are mostly guided to the outer ESA electrode and are thus not detected.
Figure 6.33: Secondary electrons in the JDC prototype. Position 1 indicates the field-shaping electrode in front of the CEM at +100 V (CF), position 2 indicates a field shaping electrode as well but one that is at -400 V (post-acceleration voltage), and position 3 indicates the ESA exit aperture.

Because any secondary electron is likely to be observed by detectors even from trajectories that do not enter the time-of-flight cell, a high start rate is expected. This can be an issue under extreme conditions where, for example, penetrating particles cause the start detectors to saturate.

Secondary electrons from scattering events within one sector can increase the start rate of the same sector but are unlikely to generate cross talk between neighboring channels.

To further understand the scattering and subsequent secondary electron effects in front of the CEM detectors, another experiment with the prototype was conducted: the solid aluminum start surface ring was modified with small openings, as shown in Fig. 6.34. At this position, real start surfaces will have a certain open area ratio. Ions incident on the start surface or supporting structure will create start counts even if they do not proceed into the time-of-flight cell. Only when incident ions enter the structure of a real start surface can a time-of-flight measurement occur. Thus, the open area ratio at this point relates possible time-of-flight start counts to all start counts.
In the experiment, the ESA voltage was varied together with the viewing direction. The result is compared to a previous measurement with the solid aluminum ring in place. Varying the ESA voltage steers the incident ions of constant energies over the start surface area. When comparing a measurement with openings to a measurement without openings, it is possible to obtain the effective open area ratio of the structure in front of the channel electron multipliers.

At first order, one would expect a clear drop in signal when the ion beam is scanned over the start surface for a well-focusing ESA because the beam is passing through the openings of the aluminum ring. For the given design of the spherical-wedge analyzer, however, an incident beam at the center of the azimuthal sector is defocusing on the start surface, as shown in Fig. 4.14. The signal should therefore not drop completely. This effect can be observed in measurements and simulations with com-
parable amplitude in Fig. 6.35. In the simulation, the drop in signal is approximately 32% of the counts, whereas in the measurement, it is only 42%. Thus, the structure around the openings generates a quite large extra contribution to the start signal. The position of the opening differs between simulation and measurement: the ESA voltage required to guide most of the particles through the openings is obtained by taking the difference between the measurements of a closed ring and of a ring with openings (arrow in Fig. 6.35). In the simulation, the largest drop in signal occurs at lower ESA voltages of approximately -370 V. At this voltage, the simulated beam passes almost completely through the opening and thus generates minimal start counts. At ESA voltages of lower absolute value, the incident beam hits radially outward closer to the channel electron multiplier. The beam moves radially inward toward the center of the instrument with increasing absolute voltage.

6.11 Electronics

A part of the instrument design was the development of front-end electronics that could potentially be used in flight. To read out channel electron multipliers as described in section 5.5, the current pulse from the anode of the CEM is fed to an amplifier that converts the pulse to a digital signal, which is further processed. This analogue electronics part is referred to as the front-end electronics or FEE. The requirement for JDC was to include a threshold control and to have a fast rising edge at the digital output because of the needed high-resolution time-of-flight measurement. To fulfill the requirements concerning radiation dose and power consumption within the JUICE mission, Amptek preamplifiers were used.

The Amptek A101 preamplifier has a long standing heritage and was often used in previous systems at the institute. The digital output of this amplifier has a rising edge of approximately ∼6 ns, and the threshold is set by a resistor. Although it is technically possible to develop electronics around the A101 that improve the timing accuracy and allow the threshold to be controlled by a voltage, the Amptek A121 was considered as an alternative because it offers a faster rising edge of ∼2 ns and provides voltage-controlled threshold adjustment without additional electronics.

Using a complete design of a front-end system, a comparison of both amplifiers (A101 and A121) was conducted. The front-end system was needed for the prototype to interface with the data acquisition system.

6.11.1 Preamplifier test setup

The A121 preamplifier is designed to measure pulses as low as ∼0.01 pC. CEM pulses are specified from the manufacturer to be 40 - 140 mV at 50 Ω with a typical pulse width of 8 ns[42]. This gives typical pulse charges in the range of 5 - 25 pC, with a mean value of 15 pC. As a threshold setting for the preamplifier, a value of approximately 1 pC is recommended by the same manufacturer [42]. This coincides with the measurements given in Vaziri et al.[91], where typical values of 6 pC to 10 pC were measured for comparable CEMs, as intended to be used in JDC.
For the A121 preamplifier, this would mean that its threshold would be set to the maximum value in the datasheet. It is necessary to reduce the input pulse amplitude with a fixed resistor divider to be able to adjust the threshold over a certain range and to protect the sensitive input of the A121. To compare both amplifiers A101 and A121, a test pulse generator was built to generate pulses of varying size to measure the propagation delay in relation to pulse height and to determine a proper threshold setting for the front electronics.

![Test Pulse Generator Diagram](image)

**Figure 6.36:** Principle of test pulse generation by discharging a small capacitor of 1 pF to 15 pF (see Appendix for complete circuit drawings).

The circuit uses capacitors of 15 pF and 1 pF for two different charge pulses. A fast transistor that allows at least 15 V to be switched \( (V_{CEO} > 15\, V) \) discharges the capacitors to ground and thus generates negative current pulses with pulse widths of approximately 8 and 2 ns, respectively. It is possible to vary the generated charge by adjusting \( V_{CEO} \). Care has to be taken in terms of the layout when using such small capacitors to minimize parasitic capacitance and stray capacitance.

The injected charge can be measured in two ways:

\[
Q = t_{FWHM} \cdot \hat{I}
\]  

(6.11)

where \( t_{FWHM} \) is the pulse width and \( \hat{I} \) is the maximum amplitude of the current.

Another way is to measure the voltage amplitude versus the known capacitance:

\[
Q = C \cdot V \cdot r
\]

(6.12)

where \( C \) is the capacitor value, \( V \) is the voltage at the capacitor, and \( r \) is a factor that mimics the resistor network between capacitor and amplifier input.

The resulting function of the supply voltage \( V \) and resulting charge \( Q \) of a pulse is shown in Fig. 6.37. The figure shows that both measurements agree and that the charge of the pulse into the preamp can be determined by measuring the voltage over the capacitor.
Figure 6.37: Charge of a single pulse of the test pulse generator using a 15 pF capacitor. $Q(V,r)$ is calculated from Eq. 6.12 using $r=55/2700$, and $Q(I,t)$ is calculated from Eq. 6.11.

To compare the A101 and A121 preamplifiers, both threshold functions were measured by decreasing the pulse charge from the generator until the amplifier did not detect the pulse train anymore, which means that the threshold setting was reached.

Figure 6.38: Threshold measurement for Amptek A101 and A121 preamplifiers using a 1 pF capacitor in the test pulse generator and a resistive divider on the input of the preamplifier. The given charge in the plot is what the corresponding amplifier input receives.

Figure 6.38 shows that, for the A101, the measured thresholds follow the datasheet quite well but with a constant offset factor. The factor in the charge can be well explained by parasitic capacitance in the setup and to a lesser extent by other inaccuracies such as the resistor and capacitor values and datasheet accuracy. The result is different for the A121: the measured curves do not follow the datasheet. Several units were tested, and all presented rather non-constant changes in the threshold-to-threshold setting, with a large unit-to-unit variation.

The propagation delay is an important parameter in time-of-flight measurements
between pulses of varying height. The propagation delay is the time between the input pulse edge and the output pulse edge. Ideally, this is independent of the input pulse height because the propagation delay is directly converted to a time-of-flight inaccuracy and therefore a reduced mass resolution. For JDC, the stop detector is a micro channel plate that generates shorter pulses (< 2 ns) with a smaller amplitude than the channel electron multiplier pulses mentioned above. The change in propagation delay for varying pulse heights is therefore smaller for micro channel plates than for channel electron multipliers.

For the test of the propagation delay, both amplifiers were subjected to a CEM pulse with charges of 5 pC - 25 pC. The pulse width was 5 ns to 8 ns. For the A121, a suitable input divider was found to be 51 Ω in parallel with 1800 Ω in series with the input. This allowed one to adjust the center threshold to a level of approximately 1 pC.

The results presented in Fig. 6.40 show that the amplifiers behave fundamentally different. Although the A101 preamplifier’s propagation delay seems to be constant for different thresholds but changes for different pulse heights, the A121’s propagation delay varies for different thresholds but remains more constant for pulse height variations. The change over the range of tested CEM pulse sizes is approximately 6 ns for the A101 and just 3 ns for the A121.
The different behavior of the pulse height variations can also explain the comparable large variations in the threshold settings of Fig. 6.38. Another but unexplored source of error is the response of the preamplifiers to different rise times at the input. Such a test would need a rise time adjustment of the input pulse and was beyond the scope of this measurement.

In conclusion, the A121 is a well-suited preamplifier for time-of-flight measurements because of the more constant behavior of the propagation delay. The drawback is the need to calibrate each channel for the change in propagation delay for different threshold settings. Although there are solutions providing higher timing accuracy, for example, constant fraction discriminators, the overall performance including reliability, heritage and power consumption makes the Amptek A121 a competitive preamplifier. See Tab. 6.2 for a detailed comparison of both amplifiers.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A101</th>
<th>A121</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power at 100 kHz</td>
<td>20 mW</td>
<td>25 mW</td>
</tr>
<tr>
<td>Volume</td>
<td>0.91 cm³</td>
<td>0.96 cm³</td>
</tr>
<tr>
<td>Weight</td>
<td>2.7 g*</td>
<td>3.5 g</td>
</tr>
<tr>
<td>Radiation</td>
<td>&gt; 100 krad</td>
<td>300 krad</td>
</tr>
<tr>
<td>Output rise time</td>
<td>6 ns</td>
<td>2 ns</td>
</tr>
<tr>
<td>Propagation delay $t_p^*$</td>
<td>20 ± 10 ns</td>
<td>25 ± 10 ns</td>
</tr>
<tr>
<td>$\Delta t_p^*$</td>
<td>6 ns</td>
<td>3 ns</td>
</tr>
<tr>
<td>max count rate</td>
<td>4 Mhz</td>
<td>12 Mhz</td>
</tr>
</tbody>
</table>

Table 6.2: Comparison of Amptek A101 and A121 preamplifiers for selected parameters. Data taken from Amptek datasheets and our measurements(*)

**Figure 6.40:** Propagation delay of Amptek A101 and A121 preamplifiers for 3 different charge pulse sizes above the threshold of the device.
6.11.2 CEM power supply and signal feed through

The prototype is designed to house the required passive electronics for connecting the channel electron multipliers to the power supply and decouple their output signals from the high-voltage anode. After decoupling, the signals are routed by a coaxial cable out of the vacuum chamber to the preamplifiers. Because of the compact construction of JDC, it was necessary to design a PCB for all needed components and to attach the cables. The circuit board was made in-house using surface-mounted devices such as resistors because of their small size. Power capacitors and coupling capacitors are through-hole components because of their high voltage rating of up to 6 kV. To satisfy the power constraints on the surface-mounted resistors, the required value was spread over three to four single components in series. A capacitor for each channel electron multiplier buffers the high-voltage power source and prevents high-voltage transients that could potentially damage the surface-mounted resistors.

![Figure 6.41: High voltage and signal connections of the CEMs at the JDC prototype. A full schematic can be found in the Appendix.](image)

The board and signal transmission worked flawlessly throughout the experiments.
Chapter 7

Conclusions and outlook

The ESA mission, Jupiter Icy Moons Explorer, is a large scale planetary exploration mission to Jupiter and in particular to the planet’s moons. This work contributed to the development of a new plasma analyzer that is part of the selected Particle Environment Package (PEP). The Jovian plasma dynamics and composition analyzer, JDC, measures three-dimensional distributions of charged particles up to 41 keV/q with a high time resolution of a few seconds for a hemispheric field-of-view. JDC can be divided into four sections, the deflector section, the electrostatic analyzer section, the start section and the time-of-flight section. The first part of the contribution to the development of JDC focuses on the ion optical design of the deflector section and the electrostatic analyzer. With the help of the software package SIMION all ion optical relevant structures, from the deflector section down to the start section, were designed and their performance numerically evaluated. Most notably the electrostatic analyzer was modeled and optimized to the best performance for the given design constraints. An electrostatic analyzer commonly consists of a vertical stack of two hemispherical shells. The spherical shape of these shells shows ideal focusing behavior for charged particles from all radial directions.

To incorporate such a shape into a more compact design and to efficiently couple it to the start section and the time-of-flight section, the rotationally symmetric spherical shells were divided into 16 radial sectors. Each sector has the shape of a spherical wedge, like a piece of an orange. The spherical wedges are then moved towards the center of the instrument to gain a more compact design, but preserve the local spherical curvature. It was found that, for the given design constraints a combination of an inner spherical-wedge shell and an outer spheroidal shell gave best angular properties. The design is a result of extensive simulations regarding different shapes and combinations and was implemented into a prototype of the instrument. The prototype was tested in the facilities of the Swedish Institute of Space Physics (IRF) in Kiruna, that is leading the development of the whole instrument package. The results show that the design works as predicted, with only minor deviations from the simulations. The main deviation concerns the analyzer constant and results in a slightly higher voltage required to select an energy band. The cause of the deviation is unknown and thus remains as open item to study in the future. Other parameters showed performances as predicted and can be included in the ongoing development.
of JDC.

The second contribution to the development of JDC regards the start signal generation of the time-of-flight measurement. The time-of-flight section consists of a linear field mass spectrometer commonly called a reflectron. The mass resolution of such a time-of-flight spectrometer depends on the accuracy of the time measurement.

To detect the presence of a particle one uses secondary electrons that the particle generates when it interacts with a surface. The electrons are detected and act as start signal for the time measurement. Small differences in start position result in a time inaccuracy and thus lower the mass resolution. Carbon foils of some nanometer thickness are commonly used to provide an accurate start position. Foils however, require a substantial pre-acceleration of several kilovolts for the ions to penetrate a foil thus increasing the size and mass of the instrument. When incident particles are reflected at grazing angles from a surface, secondary electrons are released in the same way as with foils. A single flat surface would introduce an inaccuracy in position and would therefore lower the mass resolution. To increase position accuracy during this reflection process, venetian blind-type start surfaces were investigated. These designs use many but smaller start surfaces to replace a single, flat surface.

In this work, three variants of venetian blind-type start surfaces were tested in two different experiment setups. Both experiments showed that the mechanical design of such surfaces results in comparable angular scattering as with single surfaces. The width of the scattering function mostly depends on the surface roughness of the sample. For the reflectron to work efficiently, the reflected particles should be mostly positively charged which is described with the positive ionization yield. It could be shown that micro pore optics have a high positive ionization yield compared to silicon samples or copper samples. While the silicon samples can be manufactured with a similar low surface roughness as micro pore optics, the positive ionization yield is considerably lower. The large availability of processes in silicon technology would likely allow the design of a competitive start surface but would out of scope for this thesis. The performance of micro pore optics is available today and suitable shapes can be ordered. The ongoing development of the instrument will therefore incorporate such surfaces.

The experiments conducted with micro pore samples were limited to hydrogen ions and nitrogen ions of 3 keV energy. The energy of 3 keV was selected because it is easy to handle in the laboratory. With the knowledge gained on conducting such experiments it would be interesting to see results for other energies, e.g. at 300 eV and 10 keV to stay within the limits of the laboratory equipment used. An attempt to predict the behavior for higher energies and heavier species, was made by the use of SRIM code. The result is a strong increase in energy loss of the reflected particles, for higher incident energies and heavier species. The code does not allow to distinguish between charge states and thus additional experiments are recommended.

With a final decision on the start surface and a final design of the reflectron, an optimization of the start surface section is needed. However, this thesis was just the start of the development and personally I cannot wait to see the first data from Jupiter.
Acknowledgments

I would like to thank Stas Barabash for the opportunity of contributing to planetary exploration. Many thanks go to the whole staff at IRF for supporting this quest on every corner in the building (especially the workshop and the true chef of IRF). Thanks to Jonas Olsen for helping with the cover of this work. Thanks to Sheila Kirkwood and Rick McGregor for the last-minute help on language. Thanks to my (former) fellow students, most notably Charles Lue, Hans Huybrighs, Jesper Lindkvist, Katarina Axelsson, Richard Larsson, Rikard Slapak, Robin Ramstad, Shahab Fatemi and Bishops Arms. Thanks to Joël Arnault for his advises on vertical sidewall roughness. Thanks to Anders Tjulin, Birgit Ritter, Gabriella Stenberg-Wieser, Georgios Nicolaou, Jana Mendrok, Uwe Raffalski and Xiao-Dong Wang for the professional talks and also for the unprofessional talks.

The special thanks go to “the superwieser” and “Doktorvater”, Martin Wieser, for his constant advise, time and extra time he spend on guiding me through those small trials.

Kiruna might be place of sparse culture but has an overwhelming nature, which is the exact opposite to my hometown, Berlin. Both are extremes in their sense and both have shadows and light, but with a different concept.

They say you cry two times when coming to Kiruna, first when you arrive and second when you leave.

Thanks to every musician, that has ever performed in Kiruna because without music, everything is nothing. Thanks to Mattias for canyoning on skies and the many discussions about life, the universe and everything. Thanks to my “homies” at the “Kings” house, Miriam and Etienne for their good hospitality!

I apologize for all the impatience when passing the spark for skiing!
I apologize for everything i did not mentioned but should have, because i forgot the ...
Bibliography


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Appendix
.1 Angular results ESA variants

Figure 1: Angular and energy resolution of model 1 (see Tab. 4.2): Spherical wedges at inner and outer ESA electrode, both face aligned. Numbers within the plots give the full-width-half-max (FWHM) and full-width-quarter-max (FWQM). “Gauss” in the lower left panel is the FWHM of the fitted Gaussian.

Figure 2: Angular and energy resolution of model 2 (see Tab. 4.2): Spherical wedges at inner and outer ESA electrode, inner edge aligned, outer face aligned. Numbers within the plots give the full-width-half-max (FWHM) and full-width-quarter-max (FWQM). “Gauss” in the lower left panel is the FWHM of the fitted Gaussian.
1. ANGULAR RESULTS ESA VARIANTS

Figure 3: Angular and energy resolution of model 3 (see Tab. 4.2): no wedges at inner ESA electrode, spherical wedges at outer electrode, outer face aligned. Numbers within the plots give the full-width-half-max (FWHM) and full-width-quarter-max (FWQM). “Gauss” in the lower left panel is the FWHM of the fitted Gaussian.

Figure 4: Angular and energy resolution of model 4 (see Tab. 4.2): Spherical wedges at inner and outer ESA electrode, inner face aligned, outer edge aligned. Numbers within the plots give the full-width-half-max (FWHM) and full-width-quarter-max (FWQM). “Gauss” in the lower left panel is the FWHM of the fitted Gaussian.
Figure 5: Angular and energy resolution of model 5 (see Tab. 4.2): spherical wedges at inner and outer ESA electrode, both edge aligned. Numbers within the plots give the full-width-half-max (FWHM) and full-width-quarter-max (FWQM). “Gauss” in the lower left panel is the FWHM of the fitted Gaussian.

Figure 6: Angular and energy resolution of model 6 (see Tab. 4.2): no wedges at inner electrode and spherical wedges at outer ESA electrode, outer edge aligned. Numbers within the plots give the full-width-half-max (FWHM) and full-width-quarter-max (FWQM). “Gauss” in the lower left panel is the FWHM of the fitted Gaussian.
Figure 7: Angular and energy resolution of model 7 (see Tab. 4.2): spherical wedges at inner electrode and no wedges at outer ESA electrode, inner face aligned. Numbers within the plots give the full-width-half-max (FWHM) and full-width-quarter-max (FWQM). “Gauss” in the lower left panel is the FWHM of the fitted Gaussian.

Figure 8: Angular and energy resolution of model 8 (see Tab. 4.2): spherical wedges at inner electrode and no wedges at outer ESA electrode, inner edge aligned. Numbers within the plots give the full-width-half-max (FWHM) and full-width-quarter-max (FWQM). “Gauss” in the lower left panel is the FWHM of the fitted Gaussian.
Figure 9: Angular and energy resolution of model 9 (see Tab. 4.2), no wedges at both ESA electrodes. Numbers within the plots give the full-width-half-max (FWHM) and full-width-quarter-max (FWQM). “Gauss” in the lower left panel is the FWHM of the fitted Gaussian.

2 Schematics