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RESEARCH ARTICLE

10.1002/2016JA022568

Special Section:

Measurement Techniques in
Solar and Space Physics:
Particles

Key Points:

- Instant hemispheric unobscured field of view electrostatic mirror (fish-eye) is developed
- The ion energy-mass analyzers with hemispheric mirror were developed for Phobos-Soil and BepiColombo missions
- Advantages and limitations of this element are discussed as well as the perspective of future applications

Correspondence to:

O. Vaisberg,
olegv@iki.rssi.ru

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The 2π charged particles analyzer: All-sky camera concept and development for space missions

O. Vaisberg¹, J.-J. Berthelier², T. Moore³, L. Avakov⁴, F. Leblanc², F. Leblanc⁵, P. Moiseev⁶, D. Moiseenko¹, J. Becker², M. Collier³, G. Laky⁷, J. Keller³, G. Koynash¹, H. Lichtenegger⁷, A. Leibov¹, R. Zhuravlev¹, A. Shestakov¹, J. Burch⁸, D. McComas⁹, S. Shuvalov¹, D. Chornay⁴, and K. Torkar⁷

¹Space Research Institute, Moscow, Russia, ²LATMOS/IPSL, CNRS-UPMC-UVSQ, Paris, France, ³Goddard Space Flight Center, NASA, College Park, Maryland, USA, ⁴University of Maryland at NASA/Goddard Space Flight, Greenbelt, Maryland, USA, ⁵LPP, CNRS-Ecole Polytechnique, Paris, France, ⁶Astron Electronics, Orel, Russia, ⁷Space Research Institute, Austrian Academy of Sciences, Graz, Austria, ⁸Southwest Research Institute, San Antonio, Texas, USA, ⁹Princeton University, Princeton, New Jersey, USA

Abstract Increasing the temporal resolution and instant coverage of velocity space of space plasma measurements is one of the key issues for experimentalists. Today, the top-hat plasma analyzer appears to be the favorite solution due to its relative simplicity and the possibility to extend its application by adding a mass-analysis section and an electrostatic angular scanner. Similarly, great success has been achieved in MMS mission using such multiple top-hat analyzers to achieve unprecedented temporal resolution. An instantaneous angular coverage of charged particles measurements is an alternative approach to pursuing the goal of high time resolution. This was done with 4-D Fast Omnidirectional Non-scanning Energy Mass Analyzer and, to a lesser extent, by DYMIO instruments for Mars-96 and with the Fast Imaging Plasma Spectrometer instrument for MErcury Surface, Space ENvironment, GEochemistry, and Ranging mission. In this paper we describe, along with precursors, a plasma analyzer with a 2π electrostatic mirror that was developed originally for the Phobos-Soil mission with a follow-up in the frame of the BepiColombo mission and is under development for future Russian missions. Different versions of instrument are discussed along with their advantages and drawbacks.

1. Introduction: Precursors

One of the major goals in designing plasma analyzers for space missions is to access the complete particle distribution in velocity space, i.e., to cover an angular field of view (FOV) of 4π for incoming particles, and, specifically for future magnetospheric missions, to reach the high time resolution needed to study fast plasma processes such as turbulence, particle acceleration by double layers, or magnetic field reconnection.

Such constraints can be met by using imaging instruments that provide the instantaneous coverage of the full range of one or, better, two parameters of the particle distribution function in velocity space. In addition, for ion instruments, one has also to implement a mass analysis function that allows identifying the ion species or, at least the m/q ratio.

Following the pioneering work of C.W. Carlson [Carlson *et al.*, 1985] who invented the first top-hat electrostatic analyzer, their high geometric factor and relative mechanical simplicity made such analyzers the heart of nearly all electron and ion instruments flown on board magnetospheric spacecraft or planetary probes in the last three decades. The addition of angular scanner to the top-hat significantly extended the capability of analyzer [e.g., Lin *et al.*, 1995]. Using four top-hat analyzer on the rotating MMS spacecraft enabled to reach temporal resolution of 30 ms for electron measurements and of 150 ms for ion measurements [Pollock *et al.*, 2016].

Section 2 is devoted to a brief review of top-hat analyzers and other instruments that need to scan energy and angle in order to cover the whole velocity space domain. The predecessor of the 2π analyzer, Fast Imaging Plasma Spectrometer (FIPS) [Andrews *et al.*, 2007; Zurbuchen *et al.*, 1998], is also described. We present in this paper the concept first proposed in Vaisberg *et al.* [2001] of panoramic instruments which use a rotationally symmetrical electrostatic mirror to obtain an instantaneous full half-space instantaneous FOV that is imaged on a microchannel plate (MCP) detector. Several variants of this concept were developed in the recent years to fly on planetary missions, and their principle and overall performances will be described.

1.1. Spectral Complex Analyzer-1 (SCA-1) Nearly 2π Toroidal Analyzer With Angular Scan on Interball-Tail Probe

Another approach of 3-D measurements was used on slowly rotating Interball (Prognoz type) satellite. The coverage of nearly 2π field of view was provided by electrostatic steering [Vaisberg *et al.*, 1995, 1997]. Figure 1 shows the schematics of SCA-1 ion spectrometer (abbreviation in Russian means: complex plasma spectrometer).

The toroidal electrostatic analyzer (ESA) selects ions by energy per charge coming from polar direction. MCP detector followed by eight collectors is used for counting the ions in eight azimuths of ESA. Angular scanner consists of hemisphere, external can, and front grid. The analyzer includes multiple sun shields needed to suppress solar UV induced photoelectrons from the negatively biased hemispheric electrode of the scanner. The analyzer mounted on the top of electronics box is shown on Figure 2.

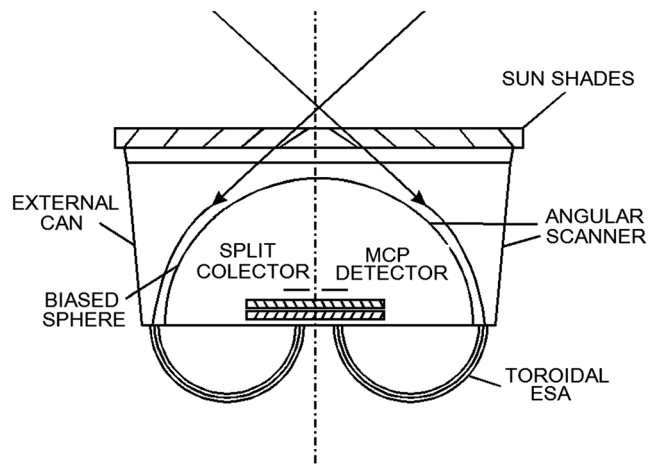


Figure 1. EU-1 sensor head of SCA-1 analyzer in Interball-Tail probe [Vaisberg *et al.*, 1995].



Figure 2. One of two heads of SCA-1. The analyzer is located on the top of electronics box.

Table 1. Ion Analyzer SCA-1 (Interball-Tail)	
Energy Range	50 eV–5 keV
Energy resolution ($\Delta E/E$)	10%
Number of energy steps in logarithmic scale	15 (31 possible)
Azimuthal angles	8 directions \times 45°
Polar angles (from solar direction)	0°, 17°, 40°, 72°, 108°, 140°, 163°, 180°
Angular resolution (FWHM)	\sim 5°
Number of velocity space bins	960
Temporal resolution	\sim 10 s
Mass (kg)	26, 26 including another instrument
Power (W)	17

The basic measurement mode on Interball-Tail satellite was the following. The energy scans in eight azimuthal directions were performed successively along polar direction and three polar angle cones of 17°, 40°, and 72°. The voltage applied to the polar angle scanner changed to keep the same polar directions during the energy scan execution. Two analyzer heads, one Sun-oriented and the other anti-Sun oriented, provided \sim 10 s sampling of velocity space with E/Q analysis in 960 bins of velocity space. The relatively fast

3-D scan was necessary due to slow angular rotation of Prognoz-type satellite: 2 min revolution around Sun-oriented axis.

SCA-1 was initially proposed for VEGA (VEnera GALley) mission to Halley's comet but was not accepted. This ion analyzer quite successfully operated on Interball-Tail spacecraft for 5 years though its Sun-directed analyzer was steadily degrading due to overload by the solar wind (there was no provision to increase the voltage of MCP-detector supply). Degradation of MCP-detector was partly compensated by in-flight "calibration" of rotating analyzer with use of hot ions velocity distributions in the plasma sheet and in the magnetosheath. Parameters of SCA-1 analyzer are given in Table 1 (mass and power include two ion analyzers and another instrument which shared electronics with SCA-1). Examples of ion velocity distributions obtained from measurements of SCA-1 are shown in Figure 3 (Tables 2–5).

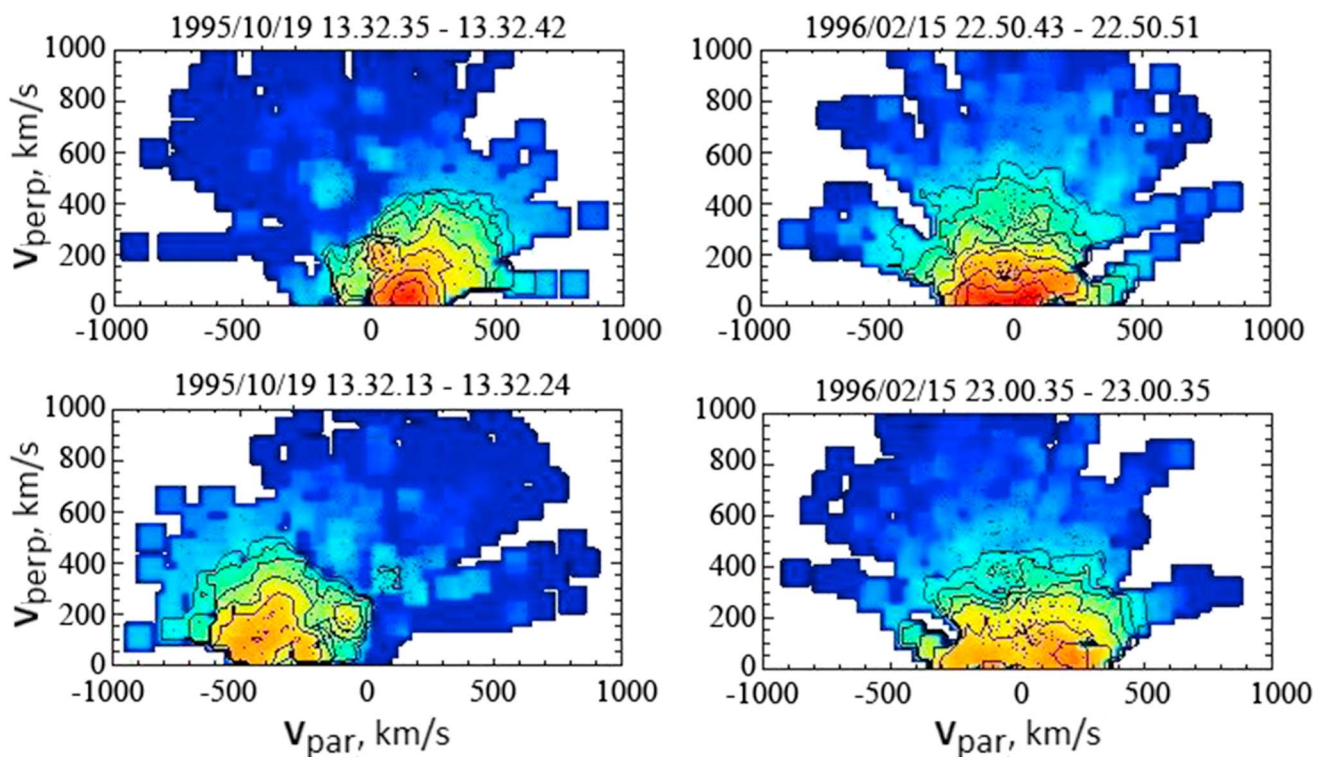


Figure 3. Ion velocity distributions obtained with SCA-1 (assuming all ions are protons) in local magnetic field coordinates plotted assuming ion gyrotropy. (left column) (top) magnetosheath and (bottom) tail distributions measured on two sides of magnetopause during northward. Interplanetary magnetic field. (right column) Low-latitude boundary layer velocity distributions indicating multiple active reconnection sites.

Table 2. Energy-Mass Analyzer FONEMA (Mars-96)

Sensor Unit Dimensions (mm)	260 × 320 × 381
Instant energy ranges (eV)	20–400, 54–1090, 150–2950, 400–8000
Mass ranges (amu)	0 to 1.5, 1.5 to 10, 10 to 20, over 20
Time resolution (max. in ms)	125
Angular coverage (sr)	4π
Angular resolution	Azimuth 60°, Elevation 30°
Data products	Full MCP images
Sensor unit weight (kg)	8.1
Sensor unit power (W)	6.65

Table 3. Fast Imaging Plasma Spectrometer (MESSENGER) From *Andrews et al.* [2007]

Energy Range (eV)	20–20,000
Mass Range (amu)	0 to 40
Time Resolution (max. in ms)	20
Angular Coverage (sr)	1.4π
Angular resolution	15°
Sensor Unit Dimensions (mm)	170 × 205 × 188
Sensor Unit Weight (kg)	1.41
Sensor Unit Power (watts)	2.1

Table 4. Some Characteristics of OLEG Camera GSFC Prototype

Energy Range (keV)	1–15 keV
Energy resolution	5–100% adjustable
Field of view (sr)	2π
Angular resolution	azimuth 30°, polar angle 16°
Geometric factor	$9.4 \times 10^{-5} \text{ cm}^2 \text{ sr}$
Mass (sensor and mounting plate) (kg)	0.583

Table 5. Energy-Mass Analyzer DI-Aries (Phobos-Soil)

Energy Range	3 eV–3 keV
Energy resolution ($\Delta E/E$)	8–10%
Number of energy steps in logarithmic scale	programmable
Angular coverage	2π
Azimuthal resolution	45°
Polar resolution	15°
Mass range	100
Mass resolution ($M/\Delta M$)	~25
Geometric factor ($\text{cm}^2 \text{ sr eV/eV}$)	5.3×10^{-5}
Mass (kg)	1.95
Power (W)	3

1.2. Four-Dimensional Energy-Mass Spectrometer Fast Omnidirectional Nonscanning Energy Mass Analyzer for Mars-96 Mission

The first nonscanning, “four-dimensional” (two angles, energy, and mass; title four dimension is more frequently used for time, but in this case separation of masses is achieved on MCP) plasma analyzer was developed for Mars-96 mission [Vaisberg *et al.*, 1990; Fedorov *et al.*, 1998; James *et al.*, 1998]. It can simultaneously measure velocity distributions of ions with mass resolution without angular, energy, or mass spectrum scanning. Work on conceptual design, computer modeling, and fabrication tasks was shared by Mullard Space Science Laboratory, University College London and Space Research Institute (IKI), Moscow, Russia. After consideration of different possibilities to achieve the desired measurement objectives, it was decided to include the following new elements: (1) an electrostatic mirror for 2π angular coverage to feed several energy-mass analyzers and (2) to use Thomson Parabola Analyzer [Thomson, 1911] that can provide instantaneous energy and mass spectrum.

The Thomson Parabola Analyzer (TPA) uses parallel electric and magnetic fields that provide images of the impact locations of ions along mass-dependent parabolas simultaneous with the energy distribution of each ion species along its own parabola. As it is not a focusing analyzer we used many (19) collimators directed to the same point at the detector plane. These collimators

increased the geometric factor of the TPA proportionally and provided a $\pm 5^\circ$ conic acceptance angle. This design allowed separating parabolas for ions H^+ , He^+ , O^+ , and O_2^+ on the detector plane (see Figures 4 and 5).

The goal of mirror (Figure 6) was to provide the desired viewing direction of analyzers and wide field of view for every analyzer. To simplify the fabrication of mirror and high transparency, its external grounded electrode was made of thin wires that formed hyperbolic paraboloid. The shape of internal electrode was optimized to provide further increase of acceptance angle of each analyzer, such that azimuthal width of each of analyzer covered approximately 60° azimuthal range, and three images on MCP detector covered polar sectors of 0°–30°, 30°–60°, and 60°–90°, respectively.

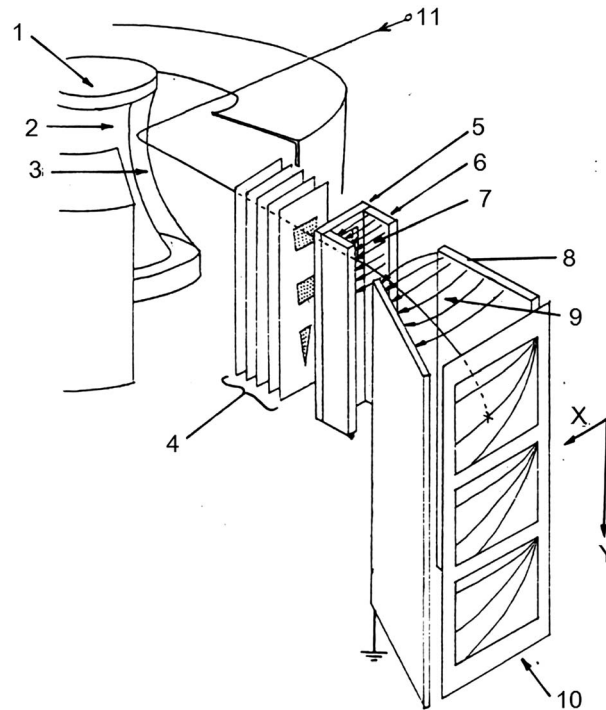


Figure 4. FONEMA sensor scheme. 1-electrostatic mirror, 2-inner core, 3-outer mesh, 4-focusing particle collimator, 5-magnetic shield, 6-permanent magnet, 7-magnetic field region, 8-high voltage, 9-electrostatic deflection region, 10-image plane, 11, 12, and 13-ion trajectories (m, V, Z) for three polar sectors: $0^\circ\text{--}30^\circ$, $30^\circ\text{--}60^\circ$, and $60^\circ\text{--}90^\circ$, respectively (modified from *James et al.* [1998]).

A single position-sensitive MCP-detector was used for three TPAs covering a sector of 60° in azimuth and three polar sectors of $0^\circ\text{--}30^\circ$, $30^\circ\text{--}60^\circ$, and $60^\circ\text{--}90^\circ$. A total of six assemblies of TPAs covered a hemisphere with help of electrostatic mirror that determined the viewing directions and solid angles of analyzers (Figure 4). Mass resolution was limited to four ranges determined by the mass resolution of TPA with multicollimator. Thus, He^+ and He^{++} cannot be separated. Four wide-energy range modes provided possibility to measure different populations in near-Mars space. Parameters of Fast Omnidirectional Nonscanning Energy Mass Analyzer are given in Table 2.

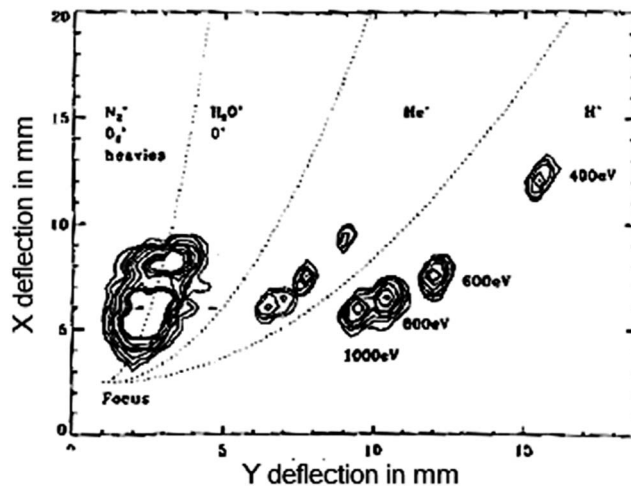


Figure 5. Laboratory test of mass and energy images on the MCP detector. Computed parabolas (dotted lines) and spots of ions with selected ion species and energies.



Figure 6. Mirror for Fonema/Mars-96 energy-mass analyzer providing wide-angle acceptance angles in hemisphere for 18 narrow-angle Thomson parabola analyzers. External transparent electrode is a parabolic hyperboloid made of thin wires. Design of external electrode was inspired by Shukhov’s tower by famous Russian engineer, architect, and scientist Vladimir Shukhov.

Fast Omnidirectional Nonscanning Energy Mass Analyzer (FONEMA) for Mars-96 consisted of two sensor heads. It provided velocity distribution of ions in 36 angular sectors instantly thus being 4-D ion energy-mass analyzer without time-aliasing common in stepping analyzers and providing a higher level confidence in the measured data. Such nonscanning instrument provided maximum temporal resolution 0.2 s based on calculated geometric factor. No other attempt to build similar instrument have been made after Mars-96 disaster in 1996.

1.3. Fast Omnidirectional Nonscanning Energy Mass Analyzer (FIPS)

The nearly 2π field-of-view energy and mass-analyzer FIPS (Fast Imaging Plasma Spectrometer) successfully performed measurements of ions on MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) Mercury orbiter [Andrews et al., 2007; Zurbuchen et al., 1998]. It consists of wide-angle two-chamber electrostatic analyzer that produces an image of ion angular distribution on multihole collimator

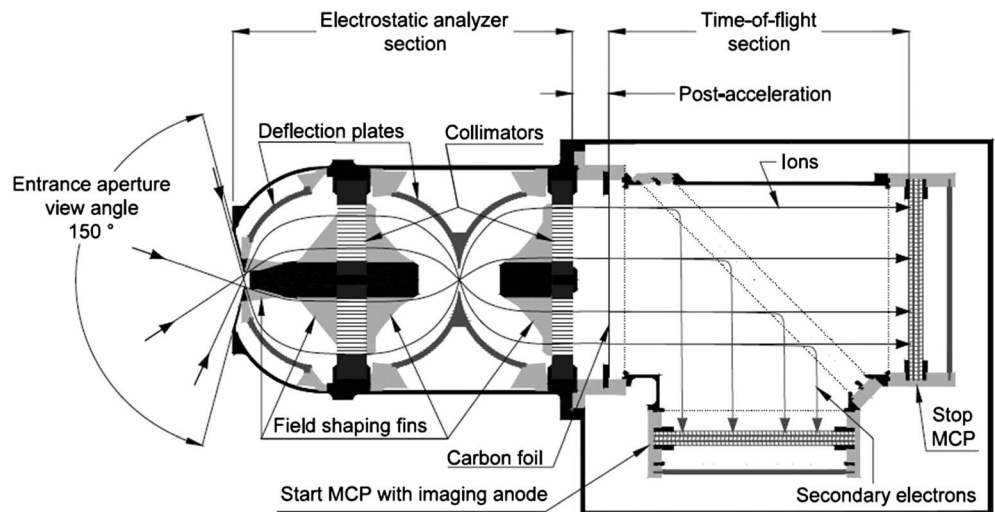


Figure 7. Nearly 2π energy mass-analyzer FIPS (Fast Imaging Plasma Spectrometer) successfully flown on Messenger spacecraft to Mercury [Andrews et al., 2007; Zurbuchen et al., 1998; Zurbuchen and Gershman, 2016].

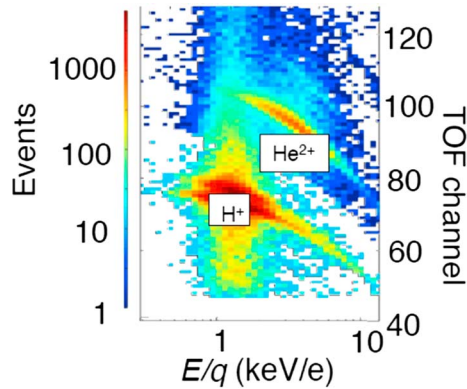


Figure 8. Solar wind measurements in the heliosphere by the Fast Imaging Plasma Spectrometer (FIPS). The data are resolved in both E/q and time of flight, allowing an easy separation of the He_2^+ and H^+ components [Zurbuchen and Gershman, 2016].

located in front of time of flight (TOF) chamber. Electrons ejected by ion from the carbon foil are reflected by diagonal electrostatic mirror producing start pulse on imaging MCP detector. Each ion proceeds to stop MCP-detector producing a stop pulse (Figure 7). Parameters of Fast Omnidirectional Nonscanning Energy Mass Analyzer are given in Table 3.

An example of solar wind measurements by FIPS is shown in Figure 8.

2. The 2π Electrostatic Mirror

During the preparation of a proposal for Solar Probe at Goddard Space Flight Center in 2000 a novel concept of 2π electrostatic mirror was designed, analogous of a fish-eye lens in optics (Figure 9) with unobscured instantaneous view of hemisphere [Vaisberg et al., 2001; Vaisberg, 2003] (old intention to find a scheme with instantaneous 2π field of view was finally stimulated by a success of solution found by Zurbuchen et al. [1998]). The shape of the mirror is chosen to ensure that particles within 2π are passing through the pinhole. The planar ESA is used behind the pinhole as an option for making complete E/Q charged particle analyzer with 2π FOV. MCP detector is used for instantaneous recording of hemispheric particle flux distribution.

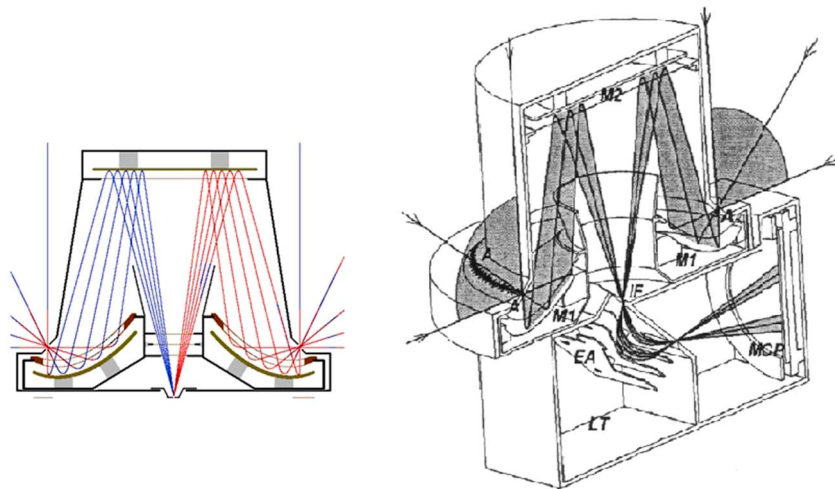


Figure 9. (left) Original scheme of 2π mirror concept. (right) SIMION ray tracing of 2π mirror followed by electrostatic analyzer that make complete electro-optics of wide-angle E/Q analyzer. M1 = primary mirror, M2 = secondary mirror, IF = pinhole, EA = planar electrostatic analyzer, and MCP = imaging detector. Shaded area is planar section of particles entering spectrometer and passing through analyzer to the detector.

The scanning energy selection voltage applied to ESA electrodes provides the measurements in three dimensions. A triple bounce requirement ensures sufficient suppression of UV background.

The voltage on the secondary mirror determines the upper energy limit of instrument. One needs to put retarding grid between the internal diaphragm and MCP in order to determine lower limit of the energy window. The ratio of the upper boundary of selected energy band to the voltage applied to the mirrors is ~ 1 . Thus, the energy range is limited to a lower value compared to conventional electrostatic analyzers because of the lower analyzer constant in the retarding part of the analyzer.

2.1. GSFC Laboratory Model of Omnidirectional Low-Energy Geoplasma Camera (a.k.a. UFPA)

A first prototype of 2π mirror design, an analyzer (referred to as Omnidirectional Low Energy Geoplasma (OLEG), is based on the 2π mirror was included in Goddard Space Flight Center (GSFC) proposal in response to NASA Solar Probe AO. In preparation of the proposal the team performed detailed ray tracing analysis. For simplicity the cylindrical mirror was replaced with a sectored one (Figure 10) even though it was leading to sectored viewing angle (Figure 11).

A laboratory prototype with sectored mirror was also fabricated and tested (Figure 10). The result of polar angle coverage simulation is shown in Figure 11. Laboratory tests are shown in Figure 12. These tests confirmed that mirror provides coverage of polar angle from 0° to 90° . Some characteristics of OLEG Camera GSFC prototype are given in Table 4.

The following are the advantages of the instrument: complete 2π steradian field of view with no gaps; integral and differential energy bandwidths are possible; best angular resolution in the central part of FOV; high temporal resolution; high degree of UV rejection; can be used as feeding optics for additional particle analyzers;

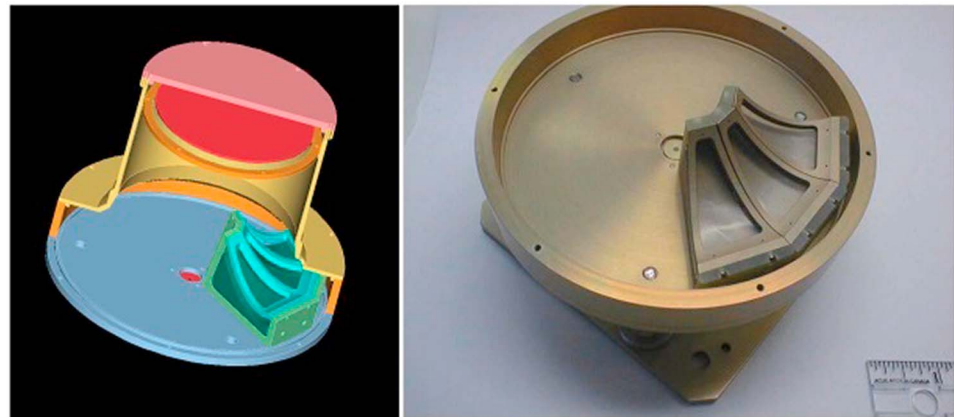


Figure 10. Design of (left) laboratory model and (right) fabricated mirror.

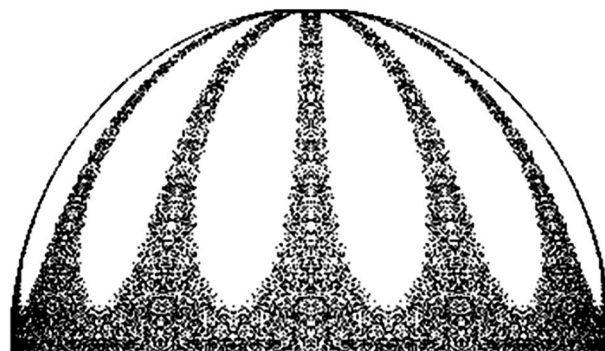


Figure 11. Computed Azimuth—Elevation viewing map (shaded areas represent viewed angles). White sectors are blind due to sectored mirror properties.

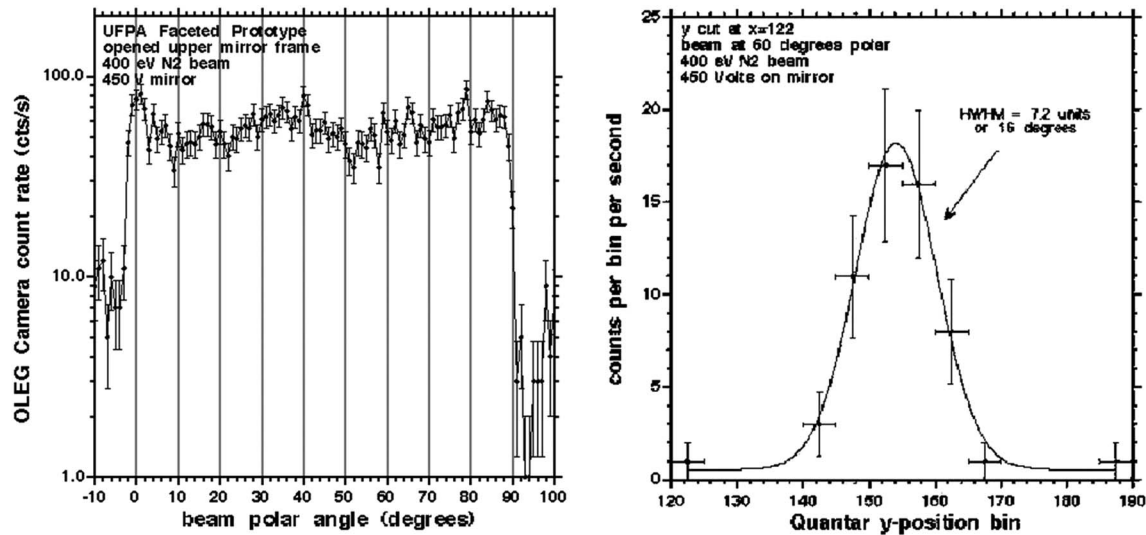


Figure 12. (left) The distribution of counts on the imaging detector for a series of four different polar angles: 0, 30, 60, and 90°. Ion beam of 400 eV. The prototype has full polar angle coverage with some variation of throughput (right) The shape of the spot on detector from parallel ion beam; the half width at half maximum of the polar angle is about 16°.

adaptation to specific requirements of the experiment is easy (FOV, mass analysis); flexibility of choosing energy bandwidth and angular resolution; and can be also used for electron measurements.

The disadvantage of instrument is limited in high-energy range by the voltage applied to mirrors.

All material of this section is from unpublished repost of *Collier et al.*, [2002].

2.2. IKI Model of 2π Mirror

Another prototype of 2π mirror with continuous coverage in azimuth was designed and tested in Space Research Institute (IKI) in Moscow in 2002 (Figure 13).

The geometric factor was calculated at the point of the hole's location (IF in Figure 9). With a hole of 0.35 mm diameter and a solid angle ~0.1 sr the geometric factor for a monoenergetic ion beam was calculated as $\sim 1 \times 10^{-4} \text{ cm}^2 \text{ sr}$. Allowing a transmission of ~0.3 for the primary mirror with slits, the factor of 0.8 for the secondary mirror, and a 0.7 MCP efficiency, one receives an effective geometric factor of $\sim 2 \times 10^{-5} \text{ cm}^2 \text{ sr}$ [unpublished IKI internal report].

The results of this model's tests in the vacuum chamber are shown in Figure 14. They show satisfactory angular coverage and image quality of this model.

There is significant difference between narrow-angle analyzers and this design with virtual aperture in the ratio of accepted particles from narrow-angle distribution and from wide-angle distribution. Due to



Figure 13. (left) Electrostatic mirror electrodes and (right) external electrode representing made of single appropriate shaped detail with radial slits.

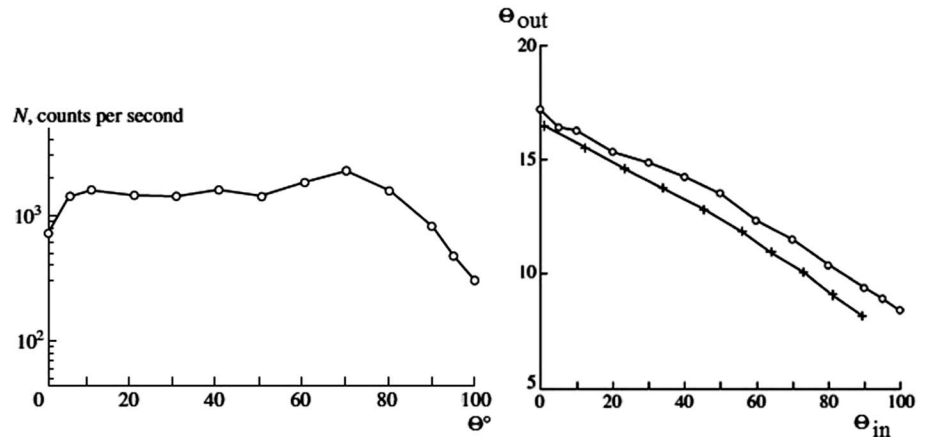


Figure 14. (left) The angular diagram of acceptance for a laboratory model derived from measurements made in a vacuum chamber. Θ is the polar angle measured from the axis of the instrument, and N is the number of pulses at the output. (right) The dependence of the output angle Θ_{out} of the ion beam on the angle of incidence Θ_{in} . Circles and crosses represent the experiment and simulation data, respectively [Vaisberg *et al.*, 2005, unpublished IKI internal report].

different entrance areas of the entrance apertures of this design, the ratio of accepted fluxes from narrow-angle flux and from wide-angle flux is significantly smaller for this design compared to one of narrow-angle analyzer.

3. Phobos-Soil Energy-Mass Analyzer

The 2π energy-mass analyzer DI-Aries (DI is for Sensor of Ions in Russian and Aries is for Zodiac constellation) was included in the scientific payload of the Russian mission Phobos-Grunt (Phobos-Soil). In this very complex mission with a wide range of scientific objectives the goal of this instrument was to study the Martian plasma at the orbit of Phobos as well as the plasma environment specific to Phobos, including secondary ions emitted from the surface that help characterizing the surface materials.

The electro-optics of DI-Aries is shown in Figure 15. In order to overcome the difficulties with multiple mirrors, it was decided to use toroidal electrostatic analyzer to redirect ions to the detector. That enabled the use of the ESA as a part of time-of-flight subsystem. Design of DI-Aries is shown in Figure 16 and the fabricated instrument Figure 17. Electro-optics, MCP-detector, and all electronics were in one block with mass of 1.95 kg.

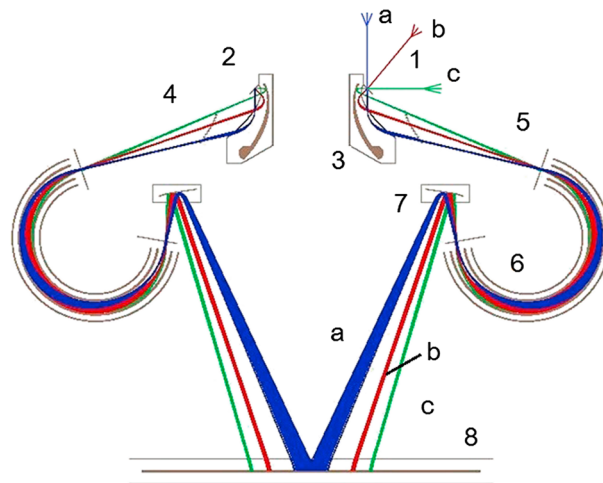


Figure 15. Electro-optics of DI-Aries. 1 = ions entering circular window 2 (a is for ions entering at the pole, b is for ions at polar angle 45° , and c is for ions entering at 90° polar angle), 3 = 2π mirror, 4 = comb gate, 5 = ESA entrance window, 6 = toroidal electrostatic analyzer, 7 = secondary mirror, and 8 = imaging MCP detector [Vaisberg *et al.*, 2010].

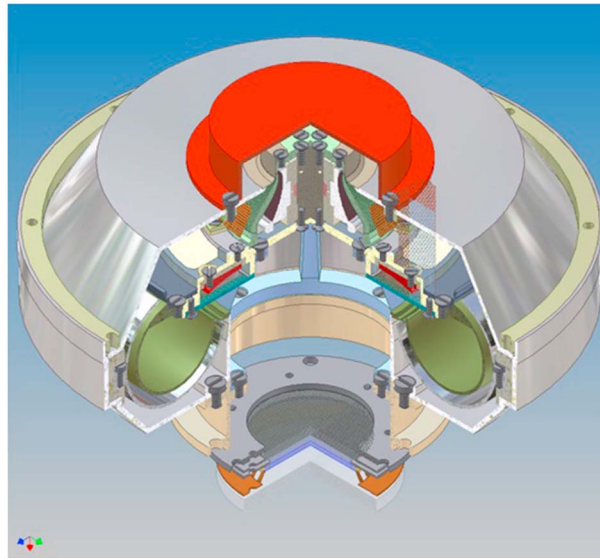


Figure 16. Cutout of electro-optics design of DI-Aries for Phobos-Soil.

The energy analysis mode is executed by the scanning voltage applied to the external electrode of ESA and to the mirror 2, thus producing successive images of ion flux distributions at hemispheric cross sections of velocity space. The voltage at the comb gate is at zero in this mode. The range of energies scanned, the number of energy steps, and the duration of counts accumulation at each energy step can be selected by telecommand. Coordinates of the first 256 particles counted by MCP detector are recorded as well as total number of counts at each energy step.

Energy-mass analysis is performed in time-of-flight mode. Gate 3 blocks ions from entering the ESA entrance by applying alternate positive and negative voltages to the wires of gate. The gate opens for a short duration by bringing voltages to 0, injecting short beam of ions to the entrance of toroidal electrostatic analyzer. On the way from gate to MCP this beam passes through three field-free regions (from gate to ESA, from ESA to M2, and from M2 to MCP) and two regions with electric field (toroidal ESA and M2). In the field-free regions the ion beam stretches due to different ion velocities in the beam. In the regions with electric field the faster ions have longer trajectories and slower ions catch the faster ones. The sizes of electro-optics elements and the lengths of the field-free regions were adjusted to synchronize the time-of-flight of faster and slower ions between the gate and MCP. The disadvantage of the gated mass-spectrometer is the short duty cycle



Figure 17. DI-Aries for Phobos-Soil mission in vacuum chamber. Preparing to test of the response to UV.

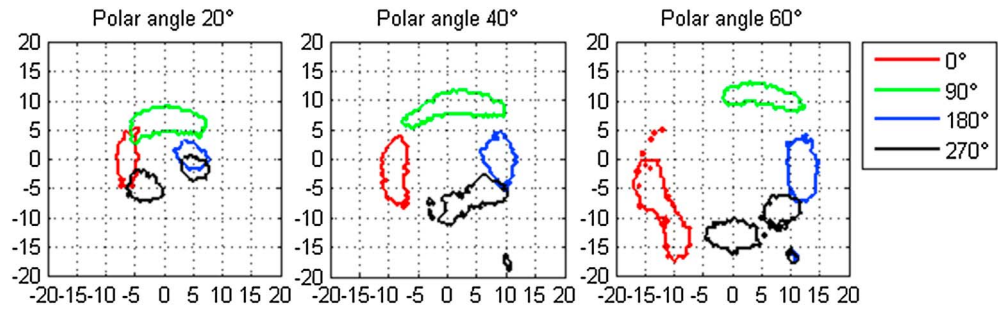


Figure 18. Images of monidirectional monoenergetic beam on position-sentitive detector of DI-Aries instrument. The shape of the images is the level of 1/2 of the maximum counting rate. Polar and azimuthal angles are indicated [Vaisberg et al., 2014].

imposed by the desired mass resolution and ion propagation time. However, the proposed 3-D scheme of DI-Aries did not allow us to use another mass-analyzing method.

Prototypes and flight model were developed and tested. Primary mirror 3 was made of thin blades fixed in a metallic frame. Cut layout of instrument is shown in Figure 16. Flight model is shown in Figure 17. Image of the beams launched at a grid of polar and azimuthal angles are shown in Figure 16.

The flight model was tested in the vacuum chamber of the IKI group. Figure 18 shows three images of the ion beams on the MCP detector for polar angles of 20°, 40°, and 60° and for azimuthal angles 0°, 90°, 180°, and 270° [Vaisberg et al., 2014]. It is seen that as fabricated, the electron optics significantly distorts the image. However, knowing the response of instrument one can restore the angular distribution within limits dictated by the resolving power of the electron optics. The reason for the image distortion will be discussed in section 5 below.

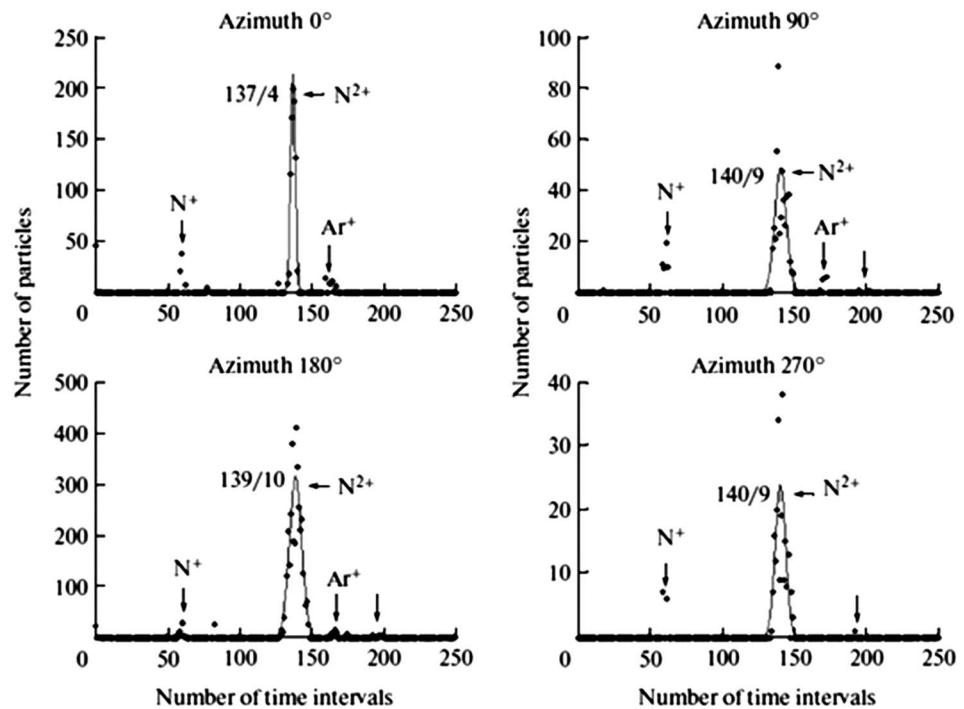


Figure 19. Mass spectra obtained by illuminating the instrument with an ion beam at the polar angle 40° for azimuthal angles of 0°, 90°, 180°, and 270°. Ion peaks of N^+ , N_2^+ , Ar^+ , and the trace of other unidentified ions are marked. N_2^+ peaks are approximated by Gaussian distribution, and a ratio of the peaks positions to a full width at half maximum are indicated in each graph.

The mass spectrum of the residual gas in vacuum chamber measured in the gated time-of-flight mode is shown in Figure 19 [Vaisberg *et al.*, 2014]. The detected Ar^+ ions originate from residual Ar gas in the ion source of the chamber. The tests of mass resolution were limited due by the tight schedule of instrument preparation. However, it was possible to evaluate mass resolution of analyzer. Gaussian fits give $M/\Delta M \sim 34$ for azimuth 0° and $M/\Delta M \sim 15$ at other angles. One can notice that peak count values are higher by factor of 1.5–2. Using the ratio of the half width at the azimuth 0° and allowing for significantly higher measured peaks of the N_2^+ line at other azimuths compared to Gaussian peaks, we found the mass resolution of instrument $M/\Delta M \sim 25$. Characteristics of DI-Aries are given in Table 5.

The DI-Aries ion spectrometer was launched on board the Phobos-Soil on 3 November 2011 and burned in the Earth's atmosphere on 15 January 2012.

4. Planetary Ion CAMera on BEPI-COLOMBO/MPO

Following the work at GFSC and IKI the group from ESA and Russia proposed an experiment for ESA's BepiColombo Planetary Orbiter. The initial design of this proposed instrument is represented in Figure 20 with simulated ion trajectories. This configuration used 2π mirror as front optics providing the necessary acceptance angle, time-of-flight section with deflecting gate and TOF velocity synchronization, and position-sensitive MCP detector with central hole. The instrument was selected and became the part of SERENA consortium with three other instruments [Orsini *et al.*, 2010].

A rotationally symmetrical electrostatic mirror as front optics provides the necessary acceptance angle of 2π steradians for ions entering through the circular entrance slit. Two successive planar mirrors are used to redirect the ions toward the imaging detector, the second one, located at the top of instrument, is used as an energy analyzer with the voltage on its reflecting electrode defining the upper limit of the energy step and the retarding grid located above the detector defining the lower limit of the energy step. TOF measurements are achieved using the gate located approximately halfway between the two planar mirrors, fine tuning and aberration corrections of TOF for various ion trajectories being made possible by a convenient adjustment of the position of the gate and of the geometry and voltages applied to the two planar mirrors.

Severe mass and thermal constraints were imposed on the PICAM (Planetary Ion CAMera) low-energy ion analyzer selected as part of the SERENA package on board the MPO planetary orbiter of the ESA BEPI

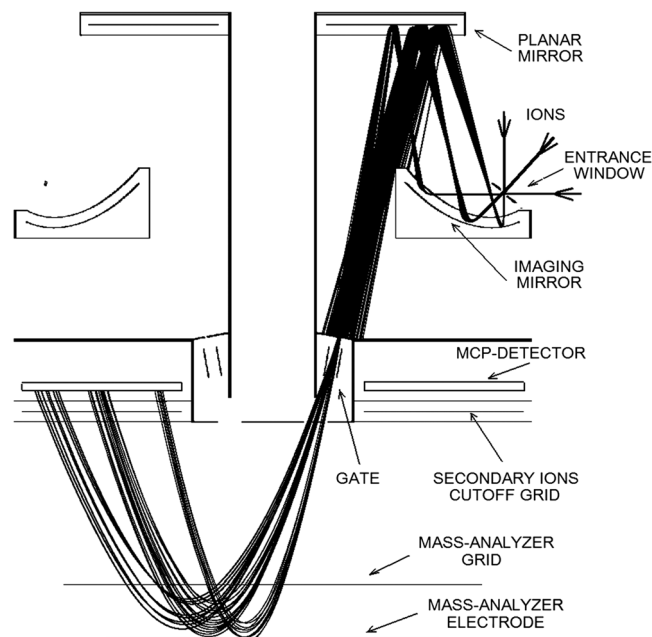


Figure 20. The Planetary Ion Camera selected as part of the SERENA consortium: shown are the entrance 2π mirror, the reflecting planar mirror, the intermediate TOF section with electrostatic gates and a TOF synchronization secondary mirror, and the exit section with an RPA grid and the imaging MCP-based detector (PICAM proposal and Vaisberg *et al.* [2006]).

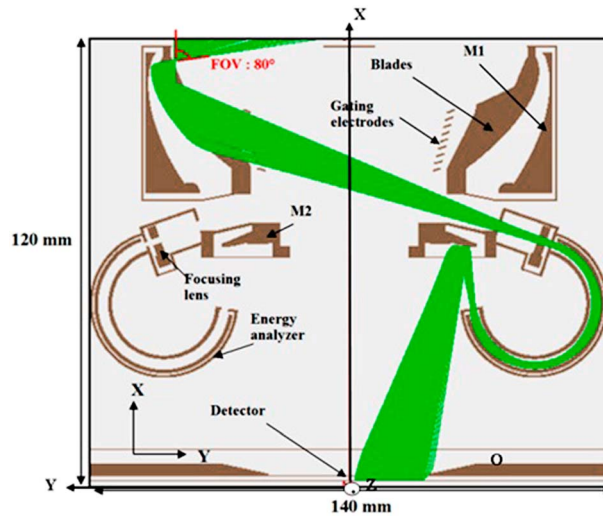


Figure 21. Schematic diagram of the PICAM ion optics [from Becker, 2013].

COLOMBO mission. From preliminary design studies, an ion optics layout similar to that of DI-Aries was felt as the only one able to cope with these constraints. The major constraint was the heavy thermal load set by the low-altitude orbit of MPO above the hot surface of Mercury which leads to temperatures of the outer part of the ion optics close to entrance ranging between -100°C on the night side of the orbit to even more than $+200^{\circ}\text{C}$ on the dayside. In this respect, the advantage of the DI-Aries configuration is the large enough distance between the MCP detector and this outer part of the ion optics, as well as the above mentioned compactness and light weight of the ion optics.

However, in DI-Aries the primary mirror has a concave (in a radial plane)/convex (in azimuth) geometry which is known to defocus ion beams with possible consequences on both the instrument sensitivity and imaging performances. It was thus decided to change the primary mirror to a concave/concave geometry as shown in Figure 21. The larger radius of the circular entrance slit also increases the effective entrance area thus the geometrical factor, at the price of a $\sim 10^{\circ}$ reduction of the angular FOV in the symmetry plane for entering ions of $\sim 80^{\circ}$ compared to 90° of a fully hemispherical FOV. A second modification was brought by adding a new electrostatic converging lens before the ESA entrance. This lens improves the focusing of ion trajectories in the symmetry plane toward ESA and simultaneously increases the angular width of the beam at ESA entrance from $\sim 7\text{--}8^{\circ}$ to $\sim 12^{\circ}$. The angular width of the ion trajectories at ESA exit is similarly increased which leads to an enlarged image on the detector plane after ions are reflected by the secondary mirror M2. The

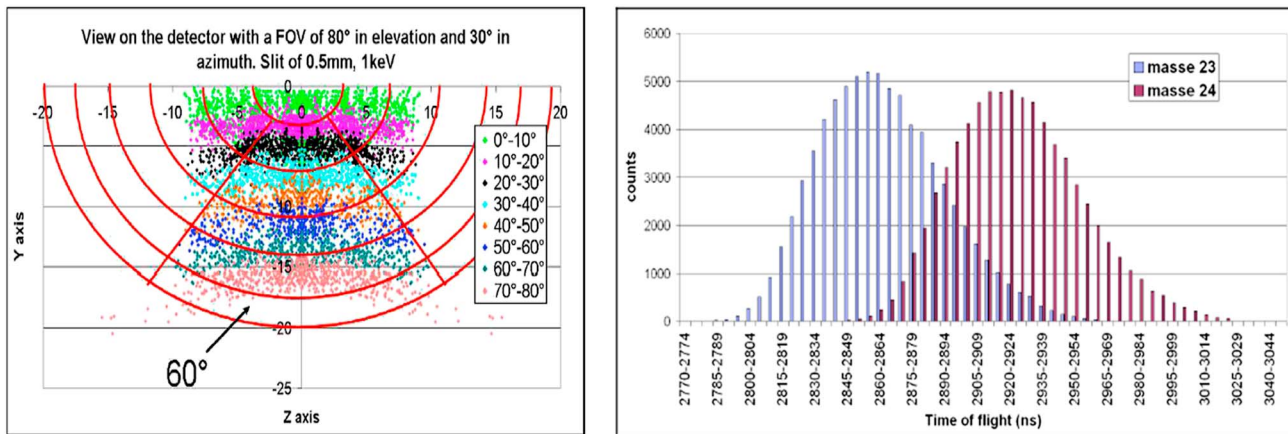


Figure 22. Overview of the modeled imaging and mass resolution capabilities of PICAM. (left) Distribution of ion impacts on the MCP for ions sent through the entrance slit over the 60° azimuthal extent of the central sector and at polar angles between 0° and 80° . (right) Simulated mass spectrum showing that Mg^+ and Na^+ ions can be distinguished.

grounded electrode in mirror M1 is made of thin azimuthal blades that are designed to maintain the azimuth angles of ion trajectories within proper limits before ESA entrance and keep the azimuthal resolution of the instrument according to specifications in spite of the wide (in azimuth) length of the entrance slit.

A complete description of the PICAM modeling and optimization is beyond the scope of this paper and will be published later. Displayed in Figure 22 are two diagrams obtained from the complete numerical model of the instrument [Becker, 2013] illustrating its imaging and mass-resolving capabilities. The detector is organized in six sectors 60° in azimuthal extent with a total of 31 pixels, one central common to all sectors and five in each sector covering the radial extent of the MCP, thus providing a polar angle resolution of about 15° per pixel. The azimuthal resolution is satisfactory for polar angles larger than 15° but unimportant for smaller polar angles since all ion impacts are counted in the central pixel common to all sectors. The mass resolution allows to distinguish Mg^+ and Na^+ , two expected and important species on Mercury. Improved setting of the operating voltages and further optimization of the shape of the second mirror which determines the radial extent of the image on the detector were performed at Institute für Weltraum Forschung (IWF) during calibration leading to imaging properties in accordance with design goals and significantly better mass resolution $m/\Delta m$ close to ~ 50 .

5. Conclusion: Perspectives and On-Going Studies of Energy-Mass Ion Analyzers

There has been consistent development of large field-of-view plasma analyzers during the past 20 years. Simplified system, such as the Fast Imaging Plasma Spectrometer (FIPS) on MESSENGER, have performed well in flight and have shown that these new systems not only present a valid lower resource alternative to use of multiple top-hats but can enable unique measurements in diverse plasma environments. More sophisticated 2π or 4π systems have been developed in parallel and will likely fly.

Specifically, the DI-Aries ion analyzer has been selected on several future missions that are planned to be launched by the Russian Space Agency: three lunar missions where the instrument will perform a study of the lunar regolith using secondary ions mass-spectrometry and the magnetospheric mission "Strannik-Resonance." Due to their tight initial schedules, there was no possibility to introduce substantial changes to the design of the instrument and only some modifications are currently being worked out such as increasing the diameter of the MCP and adding a motor to close the entrance window and avoid dust contamination of the ion optics during the landing and surface excavation phases of the lunar mission.

As indicated in section 3, we have to correct the distortion of the image on the MCP detector which is thought to arise from inaccuracies in the overall mechanical mounting due to the large number of successive mechanical parts between the entrance slit and the detector. Owing to the complex ion trajectories within the ion optics, all small deviations in the dimensions and/or positioning of the electrodes add to modify the location of ion impacts and deteriorate the quality of the image on the MCP. The most sensitive of the instrument appears to be the interface between ESA and the secondary small mirror 2 which controls for a main part the extent and shape of image on the detector. Extremely careful and detailed calibration over the full range of azimuth and polar angles and ion energies are under way to obtain a sufficiently accurate instrument transfer function and correct the measured image during data processing.

The successful development and testing of DI-Aries and PICAM has validated the new concept based on rotationally symmetrical electrostatic mirrors to build ion analyzers with instantaneous half-space FOV. At each energy step, the ion optics and its associated electronics determine the mass resolved ion velocity distributions by providing a 2-D image on the MCP detector of the ion velocity angles with high temporal and reasonable angular resolution. These instruments operate at energies $< \sim 5\text{--}7$ keV and offer an innovative solution to studies of thermal and low-energy ion populations in terrestrial and planetary environments. Current and future studies will be mainly focused at increasing the instrument geometrical factor and achieving simpler and more accurate mechanical design.

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