

Development and calibration of major components for the STEREO/PLASTIC (plasma and suprathermal ion composition) instrument

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Abstract

The plasma and suprathermal ion composition (PLASTIC) instrument will measure kinetic properties and charge states of solar wind ions and suprathermal ions as part of the solar terrestrial relations observatory (STEREO) mission. Two identical instruments located on separate spacecraft will provide in situ plasma measurements at ~ 1 AU to study physical processes low in the corona and in the inner heliosphere. In conjunction with the other in situ and remote sensing instruments of STEREO, as well as existing near-Earth observatories, the PLASTIC instrument measurements will contribute to the understanding of the three-dimensional structure of the heliosphere, with particular focus on Coronal Mass Ejections. As the primary solar wind instrument aboard STEREO, PLASTIC will measure bulk solar wind plasma parameters (density, velocity, temperature, temperature anisotropy, and alpha/proton ratio) and the distribution functions and charge state distributions of major heavy solar wind ions (e.g., C, O, Ne, Mg, Si, Fe). The measurement apparatus includes an electrostatic deflection analyzer for energy per charge measurement (E/q), a time-of-flight section utilizing carbon foils and microchannel plate detectors for time of flight measurement (TOF), and solid-state detectors for energy measurement (E). The instrument will provide a large instantaneous field of view (in-ecliptic and out-of-ecliptic angles distinguished) with measurements taken at high time resolution (1–5 min) spanning an ion energy range of 0.25–87 keV/e. To accommodate a large range of particle fluxes, the PLASTIC Entrance System employs collection apertures with different geometric factors for the bulk solar wind (H $\sim 96\%$, He $\sim 4\%$) and for the heavy, less-abundant ions ($<1\%$) and suprathermal ions. This paper focuses on the hardware development of major components for the PLASTIC instrument. The PLASTIC measurement principle is explained along with a presentation of the ion optic calibrations of the flight model Entrance Systems as well as calibrations of the microchannel plates and solid-state detectors.

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1. Introduction

1.1. PLASTIC instrument science objectives

The plasma and suprathermal ion composition (PLASTIC) instruments will measure properties of solar wind ions and suprathermal ions in the framework of the solar terrestrial relations observatory (STEREO) mission. Two identical instruments located on separate spacecraft will provide in situ plasma measurements from different vantage points at ~ 1 AU to study physical processes low in the corona and in the inner heliosphere. The STEREO mission will provide a unique opportunity to investigate the three-dimensional structure of the inner heliosphere. Of particular interest are the origin, evolution, and propagation of Coronal Mass Ejections (CMEs) through the inner heliosphere. The mission also seeks to determine the sites and mechanisms of energetic particle acceleration as well as a three-dimensional time-dependent understanding of the ambient solar wind properties. These goals will be achieved with simultaneous measurements at two different heliocentric longitudes, utilizing both remote sensing and in situ instruments aboard spacecraft moving away from the Earth at $22^\circ/\text{y}$.

PLASTIC will determine bulk solar wind plasma parameters (density, velocity, temperature, temperature anisotropy, and alpha/proton ratio) and the distribution functions and charge state distributions of the dominant heavy solar wind ions (e.g., C, O, Ne, Mg, Si, Fe). Elemental and charge state abundances will serve as tracers for the investigation of ambient coronal plasma, fractionated populations from coronal and heliospheric events, and local source populations of energetic particle acceleration. A full characterization of the solar wind and suprathermal ions will be achieved with a system that measures ion energy per charge (E/q), ion velocity ($\vec{v}$), and ion energy (E) for each registered ion.

1.2. PLASTIC instrument overview

The PLASTIC instrument (Fig. 1) consists of three main components: the Entrance System/Energy Analyzer (ESEA), the Time of Flight section (TOF), and the Electronic Box (E-box) (refer to Table 1 for a list of acronyms). The ESEA is an electrostatic deflection system, where solar wind and suprathermal ions enter the instrument. The ESEA selects ions by out-of-ecliptic angle and E/q . The Time of Flight (TOF) section accepts all ions passing through the ESEA and measures the ion time of flight (TOF). The ESEA selection for out-of-ecliptic angle and the ion TOF measurement, distinguished by in-ecliptic trajectory, give the three components of the ion velocity ($\vec{v}$). The TOF measurement used in conjunction with the ESEA E/q selection yields the ion mass per charge (m/q). Solid-state detector mea-

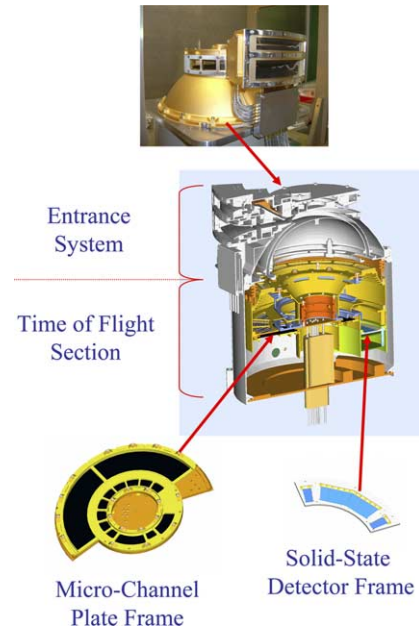


Fig. 1. The plasma and suprathermal ion composition instrument highlighting major sub-systems.

Table 1
List of acronyms

AUX	Auxiliary (SSD frame)
ESA	Electrostatic Analyzer
ESEA	Entrance System/Energy Analyzer
FM1, FM2	Flight Model 1, Flight Model 2
FOV	Field Of View
FS	Flight Spare
GF	Geometric Factor
MC	Main Channel
MCP	Microchannel Plate
PAC	Post-Acceleration
PHD	Pulse-Height Distribution
SC	S-Channel
SEE	Secondary-Electron Emission
SSD	Solid-State Detector
SWS	Solar Wind Sector
TOF	Time Of Flight
WAP	Wide-Angle Partition

surements provide the ion energy (E), thus yielding the ion mass (m). The Electronic Box or E-box provides electronics for the instrument operation and command.

1.3. Instrument development status

The PLASTIC instrument development project is entering the final phases. The PLASTIC engineering model has been tested. Both instrument flight models have been fully assembled and tested for measurement functionality at ion gun and ion beam facilities. Flight Model 1 (FM1) has passed all environmental tests and will now proceed to DPU testing prior to integration with the spacecraft (July 2005). Flight Model 2 (FM2)

functionality is being finalized and will proceed to environmental tests and spacecraft integration. Due to the constraints imposed by a rapid instrument development project to meet the goals of the STEREO mission, the development of instrument sub-systems has occurred in parallel. As such, detailed calibrations of major components or sub-systems have been undertaken prior to integration into the full PLASTIC instrument. This paper focuses on the sub-system details, in particular, the tests and calibrations of the Entrance System/Energy Analyzer (ESEA), the microchannel plates (MCP), and the solid-state detectors (SSD). The two flight models of the ESEA have been constructed and have undergone detailed tests and calibrations to verify functionality and determine operation parameters. Additionally, MCP and SSD detectors have been calibrated and delivered for integration in the TOF section.

This paper will present a description of the PLASTIC design and measurement principles, followed by a discussion of the ESEA ion optic calibrations as well as MCP detector response measurements and SSD energy measurements. A review of the full instrument performance as well as other instrument details will be undertaken once the full flight model calibrations have been finalized.

2. The PLASTIC instrument measurement principles

2.1. Entrance System/Energy Analyzer

The PLASTIC Entrance System/Energy Analyzer is designed to select solar wind ions for out-of-ecliptic angle of incidence and solar wind and suprathermal ions for energy per charge (E/q). Ions are accepted through three apertures with different geometric factors (GF), each designed to distinguish different components of the solar wind and suprathermal ion populations. The two apertures located in the solar wind sector (SWS) are the proton-alpha channel (S-Channel) and the heavy ion channel (Main Channel), positioned one above the other. The SWS is centered on the Sun and spans a 45° in-ecliptic field of view (FOV) for up to $\pm 20^\circ$ out-of-ecliptic angle. The SWS thus accepts the main distribution of the solar wind. The remainder of the 360° in-ecliptic field of view (with the exclusion of spacecraft and instrument blockage) is spanned by the Wide-Angle Partition (WAP) with an out-of-ecliptic FOV $\sim 6^\circ$. The WAP accepts ions with suprathermal energies off the thermal distributions, which are of particular interest for shock-accelerated particle and heliospheric pick-up ion studies. The combined instrument thus covers a large instantaneous field of view.

The Entrance System/Energy Analyzer employs a complex system of electrodes to steer and filter ions for measurements. The SWS sector employs entrance

aperture deflector plates, referred to as “duck bills”, to select ions by out-of-ecliptic angle trajectory with a resolution of 0.4° and 2° for S- and Main Channels, respectively. Ions thus selected for out-of-ecliptic incident angle pass through a deflection gate. Ions are then filtered by E/q with an electrode pair of toroidal deflection analyzer domes, known as the electrostatic analyzer (ESA), before passing to the TOF section (Ewald and Liebl, 1955; Young et al., 1988).

Only one channel of the solar wind sector (SWS) is enabled at a time. In scanning from high to low E/q , different species of the solar wind are collected. Since the various solar wind species travel at roughly the same flow speed, the high-mass species will be observed with higher energies. For the higher E/q settings of the ESA electrodes, the less-abundant ion species of the solar wind are collected through the Main Channel with a large active area ($A_{\text{act}} \sim 0.8 \text{ cm}^2$). In stepping down to lower E/q , the instrument begins to collect ions from the bulk of the solar wind distribution, corresponding to an increase in ion flux. A high ion flux will degrade the SSD with collected fluence (Simons et al., 1997) and, at a high enough level, saturate the data acquisition system. To limit the collected flux, the instrument switches from the Main Channel collection (large GF) to the S-Channel (small GF) when a given flux level is exceeded. The channel switching allows for the determination of the heavy ions of low abundance (Main Channel), while accommodating the higher fluxes of the solar wind hydrogen and helium (S-Channel, $A_{\text{act}} \sim 1.5 \times 10^{-3} \text{ cm}^2$). An electrostatic gate disables the Main Channel and simultaneously enables the S-Channel steering electrodes. Ions entering the S-Channel are thus deflected into the ESA. Since the ESA is cylindrically symmetric about the instrument azimuth, suprathermal ions entering the Wide-Angle Partition (WAP) are measured for E/q in the same manner as the SWS. The out-of-ecliptic angle of the incidence is not determined for the ions collected by the WAP (large GF). However, the WAP is continuously enabled, operating in parallel with the S- and Main Channels.

To handle a wide range of particle fluxes, the S-Channel and Main Channel accept solar wind with geometric factors that differ by over three orders of magnitude. The S-channel incorporates a small geometric factor ($\text{GF} \sim 2\text{--}3 \times 10^{-7} \text{ cm}^2 \text{ sr keV/keV per } 22.5^\circ \text{ sector}$),¹ ideal for measurements of the highest ion fluxes in the bulk solar wind, predominantly hydrogen ($\sim 96\%$) with a significant component of helium ($\sim 4\%$). The Main Channel is optimized for the collection of the heavier, less-abundant ions ($< 1\%$) by utilizing a large geometric factor ($\sim 1\text{--}2 \times 10^{-3} \text{ cm}^2 \text{ sr keV/keV}$). Since low fluxes are expected for the suprathermal ion species, the

¹ Geometric factor henceforth quoted per 22.5° sector.

Wide-Angle Partition (WAP) utilizes a slightly larger geometry factor ($\sim 3\text{--}4 \times 10^{-3} \text{ cm}^2 \text{ sr keV/keV}$) compared to the Main Channel. Ions passing through all entrance apertures enter an electrostatic analyzer, which selects ions with a $\sim 6\%$ E/q bandwidth in a range from 0.25–87 keV/e before passing to the TOF section.

In addition to the instrument ion measurement properties, the ESEA must also suppress solar UV radiation, solar wind electrons, and any ions reflected within the system. This is achieved with material and design properties of the instrument to maximize spurious particle absorption. All electrode surfaces are blackened with copper-sulfide (Cu_2S) and many surfaces are constructed with sawteeth grooves. The instrument is designed to minimize direct exposure of internal components to solar photospheric UV radiation.

2.2. Time of flight section

The Time of Flight (TOF) section accepts ion filtered by E/q in the Entrance System/Energy Analyzer. Ions entering the TOF section from the ESEA are subject to a post-acceleration field before passing through a carbon foil. The ion time of flight (TOF) is measured after passing from thin carbon foils ($3.5 \mu\text{g/cm}^2$) to microchannel plates (MCP) or solid-state detectors (SSD). Microchannel plate (MCP) detectors amplify secondary electrons (SEE) released from the carbon foils, thus generating a start pulse associated with the arrival of the ion. Past the carbon foil the ion strikes a collection detector (either an MCP or SSD), generating a stop signal from which a time of flight (TOF), and thus a velocity (v), can be determined.

The TOF measurements are distinguished by azimuth using MCPs in conjunction with position-sensing anodes. The carbon foil SEE amplified by the MCP passes a start grid generating a start signal. The charge pulse is then collected on a position-sensing anode, giving the azimuthal position of ion interaction with the carbon foil. The in-ecliptic angle of the ion trajectory can thus be determined. Pixelated anodes are used in the WAP, while a resistive anode is used in SWS for higher angular resolution. The in-ecliptic resolution is anticipated to range from 2° to 5° in the SWS and 22.5° in the WAP.

To determine the ion TOF , a stop signal is needed. The stop pulse is generated either when an ion terminates on an MCP directly or when SEE from an SSD are passed to the MCP. In two quadrants of the WAP, an MCP collects the ion to yield a stop charge pulse, which is subsequently collected by a stop signal plate. The remaining two quadrants of the TOF, including the SWS, each utilize a small MCP pair in conjunction with a frame of SSD pixels. The ion passes from the carbon foil to the SSD, secondary electrons are released from the SSD and subsequently collected by the small MCP detector for the stop signal. A TOF is then deter-

mined from the collected start signal and stop signals and the velocity is therefore determined from the effective ion flight path length. Additionally, the measurement rates can be used to derive ion densities. Of particular interest are the rates in the SWS where the resistive anode can accommodate rates up to 840 kHz (at least 625 kHz required).

The three components of the ion velocity can be determined using the TOF distinguished by in-ecliptic angle along with the ESEA selection for out-of-ecliptic angle. Knowing the ion E/q and velocity, the ion m/q can be determined. In two of the four quadrants of the TOF section, SSDs additionally measure the ion energy (E), thus providing the ion mass (m). In the SSD quadrants, the ion energy (E) is measured by one of the SSD pixels spanning $\sim 5.6^\circ$ of the azimuth. Thus the properties of the ion species are fully distinguished by mass (m), charge state (q), and velocity distribution ($\vec{v}$) in the TOF quadrants with SSDs. In the TOF quadrants with MCPs only, ions are diagnosed for mass per charge (m/q) and velocity distribution ($\vec{v}$). A post-acceleration (PAC) field (up to 25 kV) in the TOF section allows the SSDs to diagnose solar wind in the low energy range. Additionally, the PAC enhances the TOF resolution and therefore the m and m/q resolution.

The remainder of the details of the TOF section, namely the electrode system and electronics, are beyond the scope of this paper and therefore will not be described further. Additionally, the complex operation of the E-box will only be summarized in Section 2.3. Suffice to say that the ultimate result of the measurements is an $m - m/q$ matrix from which the fluxes of different species and charge states can be discerned. Fig. 2 shows a simulation of the PLASTIC measurement for typical solar wind utilizing various inputs from the design and preliminary calibrations.

2.3. Electronics box

The Electronics Box or E-box contains the operation and command electronics of the instrument. The power supplies provide voltage to the instrument components, specifically the ESEA deflection electrode bias, the post-acceleration (PAC) bias, and the voltage for all detection sub-systems electronics. The E-box also contains all of the electronics for commanding sub-system operations and for transferring data to and from processing units. A logic board performs the analog-to-digital conversion of measured signals and communicates all data between sub-systems and the classifier board. The classifier board processes the data further including the generation of the $m - m/q$ matrices from the collected count rates. Data is communicated to and from the instrument DPU, which is external to PLASTIC and shared with the STEREO/Impact instrument suite. The DPU tasks for PLASTIC include instrument control, collection

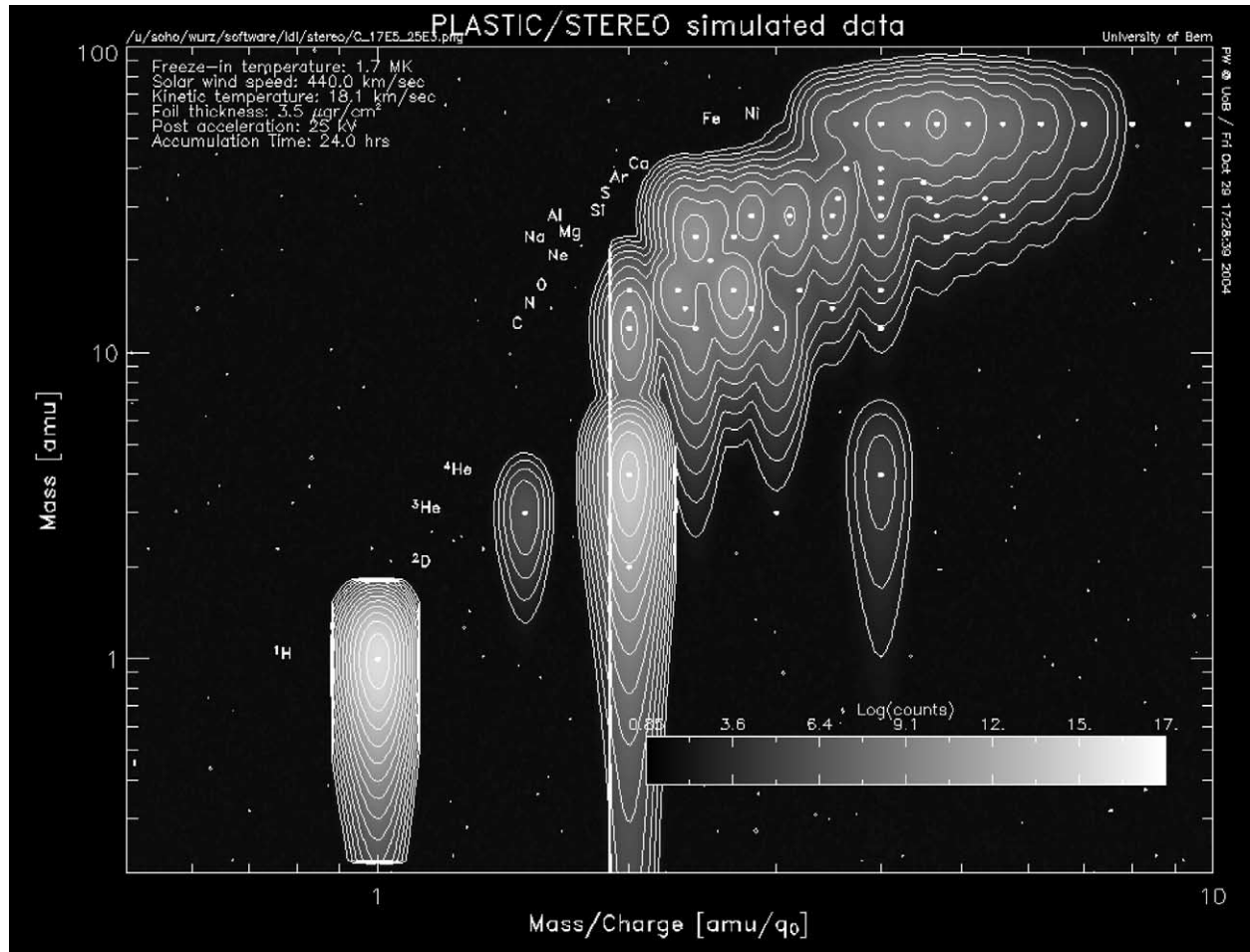


Fig. 2. Simulations of the PLASTIC instrument response $m - m/q$ matrix for typical solar wind parameters.

and formatting of housekeeping, rate and raw event data, and on-board computation of the moments of the plasma distribution function. The resulting data will be telemetered to Earth with time resolutions of 1–5 min.

3. Entrance System/Energy Analyzer ion optic calibration

3.1. Entrance System/Energy Analyzer design and testing

Because of the intricate electrode design, the Entrance System/Energy Analyzer has undergone extensive prototyping, design, and testing prior to finalizing the flight models. A prototype of the ESEA was designed and constructed at the University of Bern. Following detailed simulations and ion optic testing of the functionality (Allegrini, 2002) a full engineering design of the ESEA was undertaken. An Engineering Qualification Model (EQM) was constructed and has been fully tested and calibrated (Blush et al., 2003) driving only minor design changes for the flight models. Two Flight Models (FM1, FM2) and a Flight Spare (FS) of the PLASTIC

Entrance System/Energy Analyzer have been constructed and undergone detailed tests and calibrations to verify functionality in preparation for integration with the PLASTIC TOF section and E-box.

Prior to ion optic calibrations, each model of the ESEA was subject to a rigorous program of environmental tests including thermal cycling, high voltage partial discharge, and vibration tests. All tests were passed successfully. Additionally, the ESEA was tested for ultraviolet light suppression capability to confirm that any light incident on the entrance apertures will not pass to the TOF section. The UV suppression tests were carried out in the MEFISTO chamber at the University of Bern (Marti et al., 2001), which is equipped with a collimated UV light source. The suppression factors (defined as ratio of the photon flux at the entrance to the flux at the exit) exceed 10^8 in all three models FM1, FM2, and FS. This suppression factor is deemed sufficient to ensure negligible signal contamination by spurious counts generated by solar UV interaction with the carbon foils or MCPs. Following these operational tests, the ESEA were calibrated for ion measurement functionality.

3.2. Ion optic calibrations goals

As one of the major components of the PLASTIC instrument, the detailed testing of the Entrance System/Energy Analyzer ion optical functionality provides invaluable information for setting the flight operations parameters and for interpreting the response of the full instrument. Following the environmental and UV suppression tests, each ESEA was fully characterized for ion optical behavior in both the CASYMS and MEFISTO ion beam facilities at the University of Bern (Ghielmetti et al., 1983; Steinacher et al., 1995). The aim of the ion optic testing was to verify and assess measurement capability of the PLASTIC instrument from the solar wind (and suprathermal ion) inlet apertures to the entry of the TOF section. Considering the complex ion optic system of the PLASTIC instrument, calibration of the separate sub-systems aids the development and understanding of the instrument behavior according to the isolated functions. Since full instrument testing time is limited, not all possible measurement scenarios can be assessed prior to instrument integration with the spacecraft. As such, component testing and calibration, carried out in conjunction with ion-optical simulation, elucidates the full instrument response and assists the interpretation of the resulting solar wind data.

Entrance System/Energy Analyzer calibrations provide an assessment of the out-of-ecliptic angle and E/q selection capability, as well as the measurement resolution of these values. Calibrations determine the specific relation between electrode tuning and measured ion characteristics, namely the deflection and analyzer constants. Knowledge of these values is imperative in setting flight operation voltages, since the relative tuning of various electrodes (particularly the S-Channel electrode series) is locked prior to launch. Ultimately, a geometric factor or instrument response function is required for all possible measurement scenarios. The collected ion flux will be deconvolved from instrument geometric factors and the measured count rates. These values are needed prior to flight as a certain amount data reduction will be undertaken on the spacecraft (e.g., plasma distribution moment calculations) and full raw data sets are excluded from telemetry data.

3.3. Experimental apparatus

For calibrations, the ESEA was mounted in the CASYMS ion beam vacuum chamber on an elevation translation table (z) and a 2-axis rotation table (α , β) with an additional rotation table (θ_{CASYMS}). The entrance apertures were irradiated with a broad ion beam of uniform flux (~ 10 cm diameter). Additional measurements were taken in the MEFISTO facility with a pencil beam (~ 1 cm diameter) and 2-axis rotation table. Ions collected through the instrument were recorded with a

particle-counting detector (measuring system utilizing MCP detectors, position-sensing anode, and image processing computer) mounted near the exit of the ESEA. The ESEA ion response is thus registered as count rates in a pixilated image of particle deposition near the exit slit. Since the particle-counting detector is absolutely calibrated against a beam flux monitor (channeltron detector), the throughput or transmission can be determined by comparison of the flux at the ESEA inlet and that measured at the exit slit for the various instrument settings.

3.4. Ion optic calibrations results

For a given beam energy, scans of out-of-ecliptic angle and of electrode voltages give a characterization of the Entrance System/Energy Analyzer response and selection capabilities. All the ion optical tests were performed for the Main Channel, S-Channel, and WAP. Of key importance in calibration is the determination of the proportionality between applied electrode voltage and the ESEA response, known as the analyzer and deflection constants,

$$k_{\text{electrode}} = E/qV_{\text{electrode}}^{-1}, \quad (1)$$

$$k_{\text{DB}} = \theta E/qV_{\text{DB}}^{-1}, \quad (2)$$

in units of (keV/e) kV^{-1} and $^\circ$ (keV/e) kV^{-1} , respectively. The analyzer constant specifies the relation between an electrode voltage ($V_{\text{electrode}}$) and the measured ion E/q . The deflection constant specifies the relation between the deflector electrode voltage (V_{DB}) and the measured out-of-ecliptic incident angle (θ). The ion count rate ($N(\theta, \phi, E/q)$ where ϕ is the azimuthal or in-ecliptic angle) measured at the ESEA exit slit gives the instrument response or transmission. For a given ion beam E/q and angle of incidence, an electrode voltage is scanned (or vice versa) to determine the optimal voltage setting (essentially maximum transmission) and the bandwidth of the response or resolution ($dE/q, d\theta$). The mean voltage tuning of the scanned transmission distribution defines the analyzer constants and deflection constants, from which the flight operation voltage levels are determined. In turn, the constants are used in the data reduction to assess solar wind properties for the applied in-flight voltage steps.

The electrode tuning is not only needed to determine ion acceptance characteristic, but also to determine the relation between the different electrodes, as they do not operate independently. Particularly noteworthy is the S-Channel consisting of two separate steering electrodes diverting the ion path into the ESA electrodes. Calibration will set the exact relation between this series of three electrode sets prior to mission launch.

The ESEA calibrations yield similar results for the two flight models (FM1, FM2) and the flight spare

Table 2

Analyzer electrode constants (units of (keV/e) kV^{-1}) and E/q resolution for the different ion acceptance apertures

Channel	Electrode	FM1		FM2		FS	
		$k_{\text{electrode}}$	FWHM (%)	$k_{\text{electrode}}$	FWHM (%)	$k_{\text{electrode}}$	FWHM (%)
S-Channel	SCO-L	3.23 ± 0.01	10.4	3.25 ± 0.01	10.6	3.19 ± 0.01	10.4
	SCI-U	3.68 ± 0.01	13.2	3.64 ± 0.01	10.8	3.59 ± 0.02	13.8
	ESA	8.46 ± 0.01	6.34	8.46 ± 0.01	6.26	8.38 ± 0.03	6.12
Main Channel	ESA	8.26 ± 0.01	6.12	8.26 ± 0.02	6.48	8.25 ± 0.02	6.30
WAP	ESA	8.25 ± 0.05	6.77	8.26 ± 0.01	7.30	8.28 ± 0.01	6.67

Measurements were taken with Ar^+ ion beams of various E/q . The E/q resolution (FWHM) was taken for 3 keV/e Ar^+ beam. Comparable values of the relative E/q resolution (FWHM/(E/q)) were found at other energies.

Table 3

Angular deflection electrode constants (units of $^\circ$ (keV/e) kV^{-1}) and angular resolution

Channel	FM1		FM2		FS	
	k_{DB}	FWHM ($^\circ$)	k_{DB}	FWHM ($^\circ$)	k_{DB}	FWHM ($^\circ$)
S-Channel	0.117 ± 0.001	0.37	0.114 ± 0.001	0.27	0.112 ± 0.001	0.32
Main Channel	0.128 ± 0.003	1.9	0.127 ± 0.003	1.8	0.126 ± 0.007	1.9
WAP	n/a	3.2	n/a	3.1	n/a	3.2

Measurements were taken with 3 keV/e Ar^+ ion beams.

(FS), as seen in Tables 2 and 3 giving the analyzer and deflection constants. The analyzer and deflection constants are determined from a linear regression of data sets of electrode voltage vs. E/q and deflection angle vs. electrode voltage, respectively. The constants are quoted with a measurement resolution given by the FWHM of a Gaussian convoluted with a trapezoid as well as absolute error bars on the analyzer and deflection constants given by the uncertainty of the linear fit.² In each model, the energy analyzer constants (k_{ESA}) for the S-Channel, Main Channel and WAP are similar since the different acceptance channels access the same cylindrically symmetric energy per charge analyzer (ESA). The S-Channel k_{ESA} differs slightly from the others, due to the different angle from which S-Channel ions enter the ESA hemispheres. All energy analyzer constant values are approximately 8 (keV/e) kV^{-1} according to the ESA design parameters.³ Ions are collected through the ESEA with an E/q resolution of 6–7% for various ion energies (Fig. 3). In flight, the measured ion E/q will be diagnosed from 0.25 to 87 keV/e in a logarithmic stepping sequence of 128 steps in 4.7% increments.

² The uncertainty of linear fit is given by relative error defined as the square root of the sum of all relative errors. Error sources included are the Poisson statistics counting uncertainty, the temporal fluctuation of the ion beam intensity, and the uncertainty on the average of the spatial ion beam intensity variation.

³ These design values result from an engineering compromise between maximum acceptable electric field (and voltage) required to deflect ions of a given E/q through the system and limiting the size of the ESA hemispheres. An additional design concern is the gap between ESA electrodes, which has implications of the field uniformity and E/q bandwidth according to achievable mechanical tolerances.

The angular resolution differs for the three entrance apertures: 0.37 $^\circ$ and 1.9 $^\circ$ for S- and Main Channels, respectively, and 3.2 $^\circ$ for the WAP in FM1, with comparable parameters for FM2 and FS (see Table 3). The mapping of the out-of-ecliptic component of the solar wind angular distribution will be achieved with measurements taken for a total of 32 angular steps from $\pm 20^\circ$ (SWS only). This scan is achieved by applying voltage to curved “duck bill” electrodes, the deflection constants for which are found in Table 3 and Fig. 4.

Ultimately we need the geometric factor (GF) of the instrument to extract the solar wind ion fluxes from the measurement count rates (Fig. 5). The geometric factor gives the angular acceptance of the instrument within an energy bandwidth,

$$\text{GF} = \int \int \int T \cos \theta \cdot dA_{\text{eff}} dE/E d\Omega, \quad (3)$$

where T is the transmission, dA_{eff} is an element of effective area with θ specifying the angle to normal, $d\Omega$ is an element of solid angle. The ESEA geometric factors have been measured for the S-Channel, Main Channel, and WAP (at various azimuthal locations) and are found to be 3.0×10^{-7} , 1.58×10^{-3} , and $\sim 2\text{--}4 \times 10^{-3} \text{ cm}^2 \text{ sr keV/keV}$, respectively, for FM1. Table 4 again shows similar results for FM1, FM2, and FS.⁴ The results confirm the ability of the instrument to measure a wide range of ion fluxes by utilizing both large-GF and small-GF apertures, differing by four orders of magnitude. During the FM1 geometric factor measurements for the WAP, a smaller GF was observed at

⁴ Slightly different S-Channel entrance slit widths (24–40 μm) result in slightly different geometric factors.

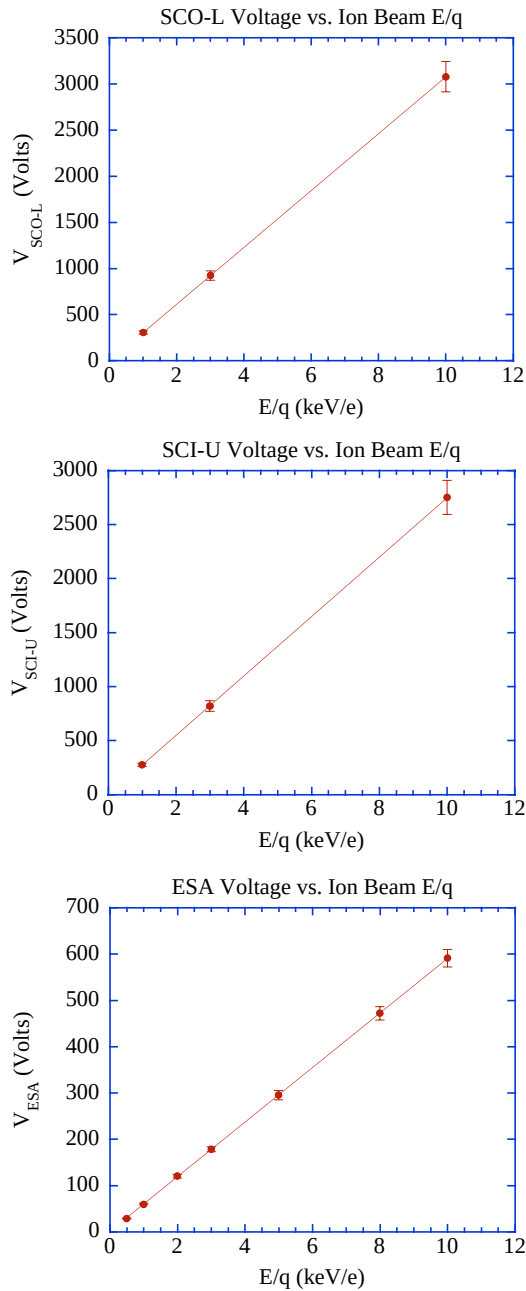


Fig. 3. FM2 ESEA electrode voltage tuning for various ion beam E/q , which provides the S-Channel steering electrode constants (SCO-L and SCI-U) and E/q analyzer constant (ESA). The error bars indicate the E/q resolution or bandwidth, given as the FWHM of transmission response of a voltage scan for constant ion beam energy.

an azimuthal angle of 321.5° from SWS center. The factor of two difference results from structural blockage near this position. Since the ESEA measurements were taken in the absence of the TOF post-acceleration structure and electric field, the ion deposition image at the exit slit exhibited broadening relative to that expected in the full PLASTIC instrument. Azimuthal GF uniformity will improve with the PAC field as it will accelerate and focus ions onto a small section of the carbon foil.

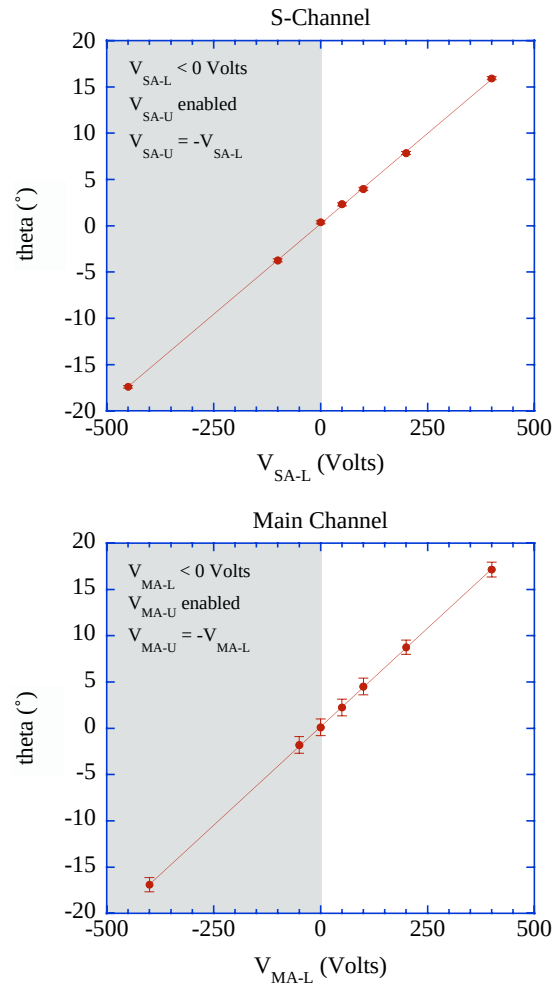


Fig. 4. FM1 out-of-ecliptic angular acceptance and resolution showing the “duckbill” electrode ability to deflect ions for collection through S-Channel and Main Channel. The error bars indicate the angular resolution or bandwidth, given as the FWHM of transmission response of an angular beam scan. Note that only one “duckbill” electrode is biased to a positive voltage at a time, while the other is biased to zero Volts (the plotted negative values for MA-L and SA-L electrode voltages correspond to the bias of the MA-L and SA-L electrode to the associated positive voltage values).

Future testing will utilize a floatable particle-counting detector in conjunction with the upper TOF post-acceleration structure to refine the measurements in the presence of the electric fields expected in the TOF section near the ESEA exit slit.

Additional tests have been undertaken with the flight models and flight spare of the ESEA, although these will not be presented in detail as they are beyond the scope of this paper. The azimuthal response uniformity of other instrument parameters has been assessed. Other tests have focused on the verification of Main Channel electrostatic gate function, which closes the Main Channel when the S-Channel is enabled. The signal through the gated Main Channel is suppressed by at least 2×10^{-5} over the un-gated value, however the current

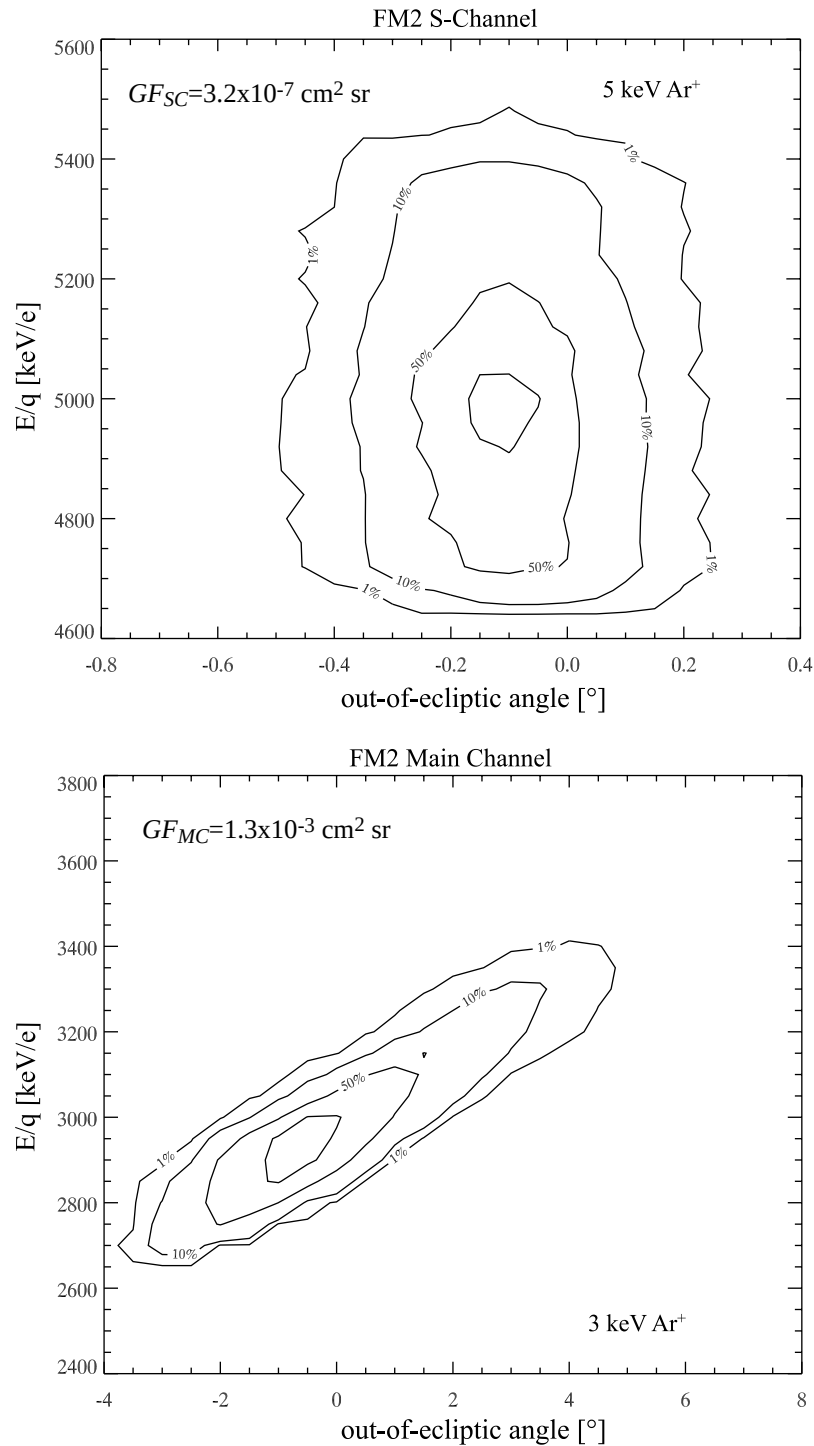


Fig. 5. FM2 geometric factor measurements of the proton-alpha S-Channel and heavy ion Main Channel (GF quoted per 22.5° sector).

results are limited by the fact that any gated signal is indistinguishable from background noise. Higher suppression factors are expected. Future measurements will endeavor to refine the suppression factor measurements to more precise values.

Another concern for future consideration is the collection of reflected particles. Although the system is designed to impede reflected particles for passing to the

TOF section, the mechanism should be studied to ascertain whether any such particles cause a discernable effect. Currently, the FM1 and FM2 Entrance System/Energy Analyzer have been delivered for full instrument integration and all further detailed tests will be undertaken with the Flight Spare (FS) unit.

As a major sub-system of the PLASTIC instrument, the Entrance System/Energy Analyzer must meet spe-

Table 4

Geometric factors showing response within angular resolution and E/q bandwidth (units of $\text{cm}^2 \text{ sr keV/keV}$ per 22.5° sector)

Channel	Azimuth ($^\circ$)	Geometric factor			
		FM1	FM2	FS	Simulations
S-Channel	0	$3.0 \pm 0.3 \times 10^{-7b}$	$3.2 \pm 0.2 \times 10^{-7a}$	$1.6 \pm 0.2 \times 10^{-7a}$	3.6×10^{-7d}
Main Channel	0	$1.58 \pm 0.02 \times 10^{-3a}$	$1.26 \pm 0.02 \times 10^{-3c}$	$1.21 \pm 0.02 \times 10^{-3a}$	2.4×10^{-3}
WAP	270	$4.18 \pm 0.03 \times 10^{-3a}$			3.5×10^{-3}
	180	$3.41 \pm 0.04 \times 10^{-3a}$	$3.22 \pm 0.03 \times 10^{-3c}$	$3.20 \pm 0.03 \times 10^{-3a}$	3.5×10^{-3}
	321.5	$1.60 \pm 0.02 \times 10^{-3b}$			

^a Ar⁺ ion beam with central voltage tuning for 5 keV/e.^b He⁺ ion beam with central voltage tuning for 5 keV/e.^c Ar⁺ ion beam with central voltage tuning for 3 keV/e.^d S-Channel simulation for 25 μm slits.

cific design requirements, which have been achieved in this design. The required $\sim 8\%$ E/q resolution will be achieved with the 6–7% E/q resolution measured for the ESEA and the instrument 4.9% E/q stepping sequence. Knowledge of solar wind direction with an accuracy of at least 5° will be achieved with the 0.4° resolution S-Channel (2° Main Channel) and out-of-ecliptic stepping sequence in increments of $\sim 1.5^\circ$. Additionally, the out-of-ecliptic field of view is required to be $\pm 15^\circ$, while measurements demonstrate over $\pm 20^\circ$ FOV. Although actual measurement rates, from which fluxes and densities will be calculated, cannot be determined until full instrument efficiencies are assessed, the required active areas of the ESEA are given for solar wind measurement with reasonable statistics down to 1 min times scales (5 min for the most abundant heavy ions). Active areas of $1 \times 10^{-3} \text{ cm}^2$ are required for the highest solar wind fluxes. The ESEA incorporates an S-Channel aperture of $A_{\text{act}} \sim 1.5 \times 10^{-3} \text{ cm}^2$ for the bulk solar wind distribution. As large an active area possible is desired for the heavy elements and suprathermals requiring at least $A_{\text{act}} \sim 0.25 \text{ cm}^2$. The Main Channel and WAP apertures achieve active areas of $\sim 0.8 \text{ cm}^2$ and up to 1 cm^2 , respectively. The ESEA has thus satisfied the design specifications.

4. Microchannel plate calibrations

In the PLASTIC instrument, MCPs are mounted in a circular configuration with chevron-paired plates in each quadrant. Since two of the four quadrants accommodate two SSD frames, mounted concentrically with the MCPs, two sizes of MCPs are required. The geometry of each plate is a 90° circular arc. Each PLASTIC flight model utilizes two pairs of small MCPs and two pairs of large MCPs. The MCPs were custom made (Photonis S.A.S.) to fit into the geometric and operational specifications of PLASTIC. All MCPs have channels of $12.5 \mu\text{m}$ diameter with $15 \mu\text{m}$ center-to-center spacing. The plates are rimless and 1 mm thick. The plates can be operated at a bias voltage of up to 1600 V per plate.

The small MCPs have an azimuthal channel bias angle of 13° , whereas the large MCPs have a radial bias angle of 19° .

The main aim of the MCP calibrations was to grade the detector for flight selection as well as understand the response of these particular MCPs. Tests were carried out on individual detector pairs. The characterizations focused on the MCP gain response and background noise level response for various MCP bias voltages. MCPs chosen for flight should exhibit high gain at moderate bias voltages. This allows for a low initial bias voltage while attaining maximum detection efficiency of single charge pulses. Additionally, the background response level of the MCP in the absence of a direct particle source should be at a minimum.

To characterize the MCPs, a detector pair and anode plate were mounted in the Kafka vacuum chamber (University of Bern) facing a Ni-63 beta decay source. Under vacuum the source could be shielded to allow for background measurements in conjunction with beta irradiation measurements. The MCP bias voltage was varied and for each voltage step a pulse-height distribution (PHD) was measured yielding the gain response. The peak of the signal distribution gives the detector gain, while a comparison of signal to background gives a measure of pulse detection efficiency. These tests were repeated for all available detectors. All MCPs have now been graded and integrated in the TOF section of the PLASTIC flight instruments.

Fig. 6 shows a plot of MCP gain (in number of electrons per incident particle) vs. MCP bias voltage for various pairs of the small MCPs. Small MCP gains are typically in the range of 2×10^7 – 1×10^8 for measurements with bias voltages of 2400–3000 V (~ 1200 – 1500 V per plate). The plots indicate high gain for moderate bias voltages. Similar results were attained for the large MCP, although they exhibited slightly lower gains of 6×10^6 – 5×10^7 for test range of 2500–3100 V (~ 1250 – 1550 V per plate).

In the engineering model of the PLASTIC instrument, start–stop efficiency tests have been carried out. The MCPs should be operated with a high start–stop pulse

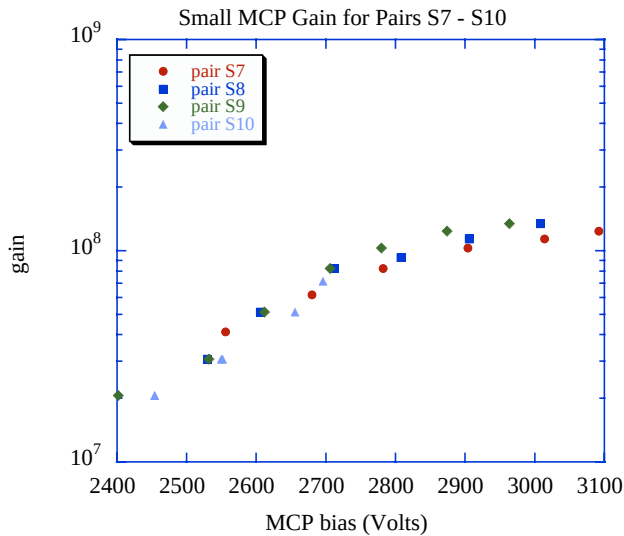


Fig. 6. Small MCP calibrations giving detector pair gain (in electrons per incident particle) under Ni source beta irradiation for various bias voltages.

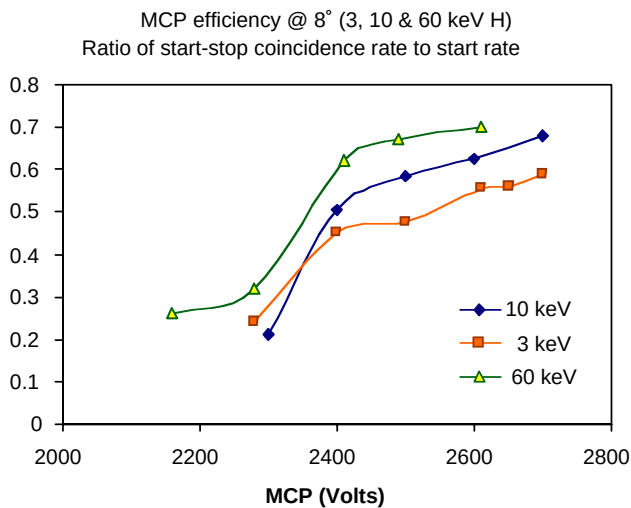


Fig. 7. Integrated PLASTIC EQM small MCP start-stop pulse efficiency for various bias voltage.

coincidence rate to maximize the measurement efficiency, which tends to increase with bias voltage. However, the MCP should be operated with a low bias voltage to minimize extracted charge since the gain degrades with total extracted charge from the MCP. Fig. 7 shows the MCP start-stop efficiency under H⁺ irradiation as a function of bias voltage. Above ~2400 V bias, the start-stop efficiency changes only a minor amount, making this the optimum MCP bias value.

5. Solid-state detector calibration

The PLASTIC SSDs are mounted in Macor frames each comprising a quadrant of the instrument. The

quadrant in the solar wind sector holds the SWS frame with a total of ten SSD pixels. One of the WAP quadrants holds the auxiliary (AUX) frame with a total of eight pixels. The custom-made SSDs (Canberra Industries) are fully depleted silicon PIPS detectors. Each SSD is cut from a silicon wafer at a 7° angle to the (1,1,1) crystal axis. This was chosen to minimize the effect of crystal-axis channeling for ions with normal incidence (Gemmell, 1974; Wiesmann, 2003). The detectors have a thin entrance window of 25 nm Si, ideal for low ion energy detection (with a post-acceleration of ~20 kV in the instrument, solar wind ion energy will be resolved into the low energy range). The detectors have a 500 µm depletion depth.

The goal of the SSD calibrations was to verify electrical functionality of the SSDs within the frame configuration and to characterize the SSD functional response to ion irradiation. The initial acceptance tests were performed at the University of New Hampshire with the flight electronics to verify SSD resistance, total leakage current, and signal measurements using radioactive gamma sources. Functional performance calibrations were performed in the MEFISTO ion beam facility (University of Bern) utilizing test electronic apparatus to measure the SSD energy response for various incident ion species with various energies.

Prior to characterizing the full set of PLASTIC flight SSDs, detailed functional tests were undertaken for one detector frame to understand the general response of the detectors under ion and gamma irradiation. Radioactive gamma sources of Ba-133, Co-57, and Am-241 were used to calibrate the energy response of the data acquisition system. From these calibrations the multi-channel analyzer measurements could then be related to the SSD ion energy response. Detailed measurements with argon, hydrogen, oxygen, carbon, and nitrogen ions have been made for various energies ranging from 9 to 630 keV. The pulse-height distribution measurements provide key information regarding the measured pulse-height defect for these particular detectors. The defect refers to the energy lost in dead layer or entrance window and energy lost to nuclear collisions and recombination within the solid. Or more concisely, the incident ion energy not deposited into measurable electron ionization within the active region of the detector. In addition to the peak energy response, the PHD yields information about the energy resolution (PHD broadening) and the noise threshold above which an energy pulse can be discerned. Channeling also affects the pulse-height distribution (Gemmell, 1974). Since ions measured by the SSDs in the PLASTIC instrument will enter from a range of incident angles (greater than 0.1–0.2°), the channeling effect in this application would result in a broadening of the PHD and thus a decrease in energy resolution (Wiesmann, 2003).

SSD ion measurements are compared with an analytic model of energy defect accounting for dead layer and nuclear collisions, shown in Figs. 8 and 9 for hydrogen and heavier ions, respectively. Of particular scientific interest are the measurements at very low energies, as shown for hydrogen with incident energies as low as 10 keV. Minimal energy loss in a thin entrance dead layer allows for ion energy measurements to such a low range. Larger energy defect is observed for larger

mass ions, as expected for the energy range under consideration. For a given ion energy, more of the primary ion energy is collected in the SSD for the low mass elements, since the cross-section for ion interaction with electrons of the solid is larger. The interaction cross-section essentially scales with ion velocity. Subsequent work will consider more detailed simulation of the ion–material interaction as well as experimental measurements of more ion species.

Following the initial detailed tests, calibrations of the available set of detectors were undertaken. From the resulting data sets, SSD detector frames were graded for ion beam response according to assessment parameters of minimum energy defect, minimum pulse width, and minimum noise. The tested Flight SSD have been delivered for integration in the TOF section along with some additional flight spare detectors. The remainder of the flight spare frames will be tested during subsequent measurement campaigns.

6. Future work

The next step in the PLASTIC diagnostic development project has been the full instrument functional tests and ion beam calibrations undertaken in 2005. Finalization of FM2 functionality and detailed analysis of both flight model data is underway. Additionally, sub-system experiments will continue. Entrance System/Energy Analyzer response will be measured under a post-acceleration field, focusing on the azimuthal variation of the measurement parameters. The gate functionality will be further considered. SSD measurements will be continued to diagnose energy response for more ion species, e.g., iron, magnesium. Previously reported carbon foil studies can be extended (Allegrini et al., 2003; Luethi, 2003). The driving force for the envisioned experiments is the refinement of instrument simulations in order to explore how each of the components will affect the ultimate measurement of various solar wind and suprathermal conditions. Understanding of the influence of the PLASTIC sub-systems will aid the interpretation of the PLASTIC instrument measurement following STEREO launch in 2006.

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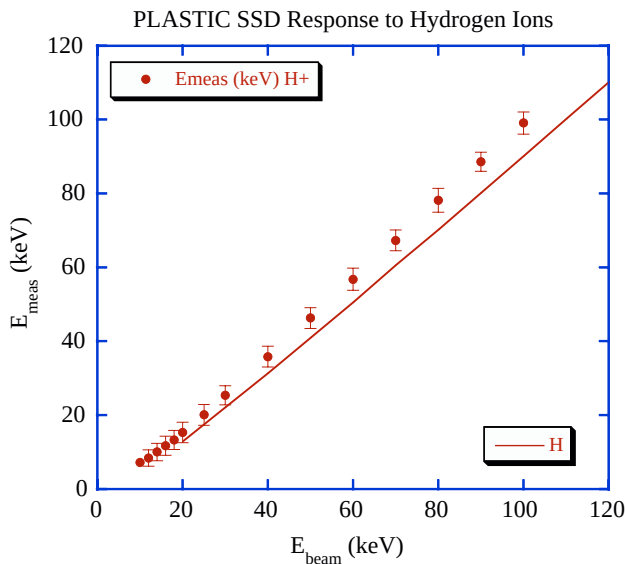


Fig. 8. SSD measured energy vs. hydrogen ion beam energy indicating the pulse-height defect of the PLASTIC flight SSDs. Measurements (data points) are compared with an analytic model (lines) of dead layer and nuclear interaction losses.

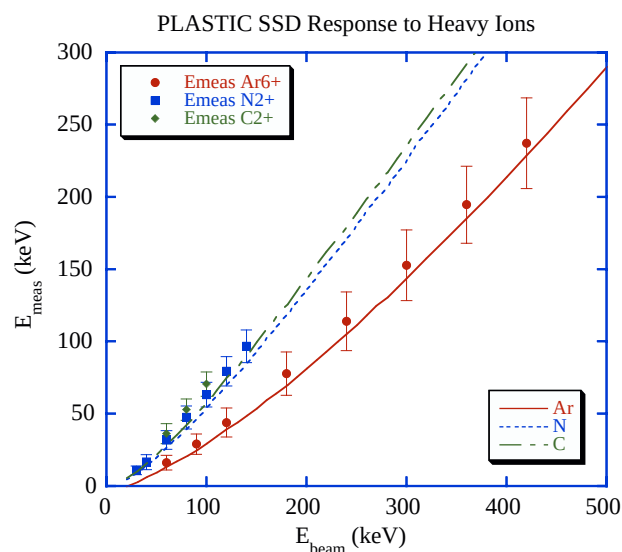


Fig. 9. SSD ion energy measurements indicating the pulse-height defect for argon, carbon, and nitrogen (comparable to plots presented in Fig. 7 extended to higher mass elements).

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