A Mission Enabling Compact Ion Mass Spectrometer for Ionospheric Outflow and Cold Magnetospheric Ion Observations

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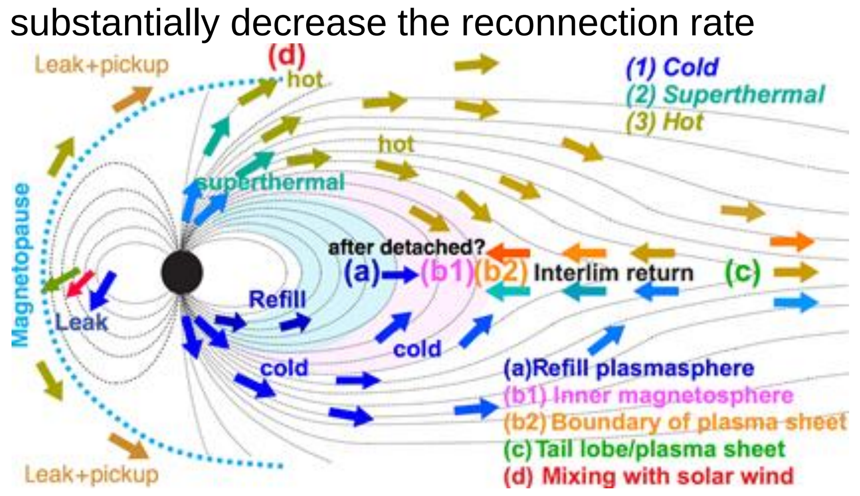
Abstract

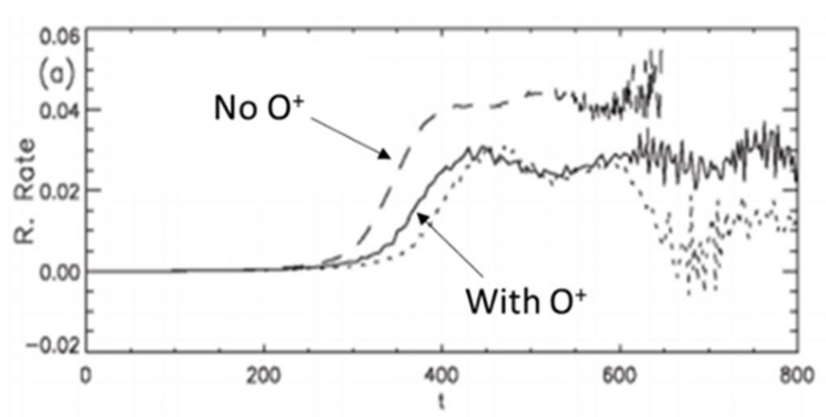
The Compact Ion Mass Spectrometer (CIMS) is a highly compact ion mass spectrometer capable of high-mass resolution for low-energy space plasma. CIMS is capable of measuring flux, energy, and mass of ions providing unique measurements of the ionospheric outflow and cold plasma in the magnetosphere. Measurements of the ionospheric outflow and cold-magnetospheric ion population will provide the necessary initial conditions of the ion populations that drive some magnetosphere-ionosphere (MI) coupling processes along with magnetospheric ion composition and dynamics. Simultaneous measurements of the cold and hot magnetospheric ion composition in the reconnection region at the magnetotail would provide clues for the outflowing ions as they journey through the plasmasphere and magnetosphere. These data are critical to advancing our current understanding of MI coupling and are required to answer the long-standing questions regarding ionospheric outflow, the source of magnetospheric mass loading, and the subsequent impact on magnetic reconnection.

Ionospheric Outflow, Cold Magnetospheric Plasma, and Magnetic Reconnection

There are two primary sources of plasma in the Earth's magnetosphere: the solar wind composed of predominantly hydrogen and high charge-state heavy ions and ionospheric outflow, such as the polar wind, composed of hydrogen and other heavy ions (O^+, He^+, N^+, N_2^+, and NO^+). The polar wind consists of ambipolar outflow of thermal ions from the high-latitude ionosphere along or near open magnetic field lines and into the low pressure magnetosphere [1, 2]. ***Ionospheric outflows, which can control the magnetospheric mass density, can have a direct role in controlling the dayside reconnection rate; therefore ionospheric outflows potentially have a significant role in controlling solar wind/magnetosphere coupling*** [3]. Computational investigations conducted by Shay and Swisdak [4] comparing two-species (H^+ and e^-) reconnection and three-species (H+, O+, and e-) reconnection indicate that the presence of the heavy O^+ ions of ionospheric origin substantially decrease the reconnection rate



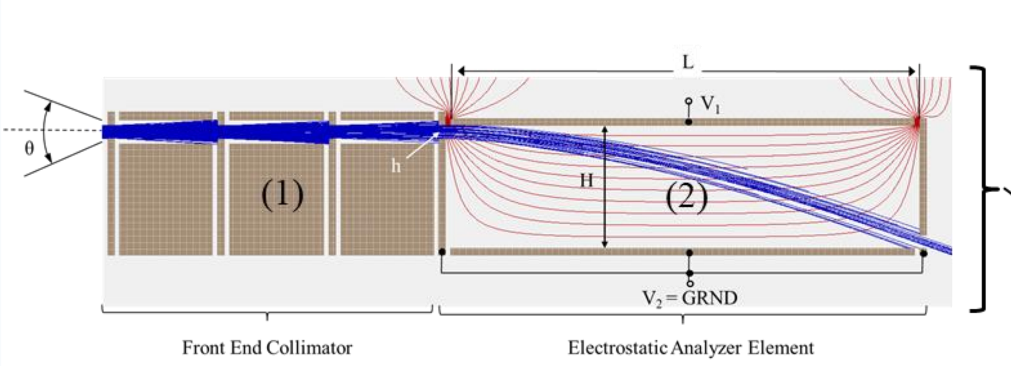
(Yamauchi, 2019)

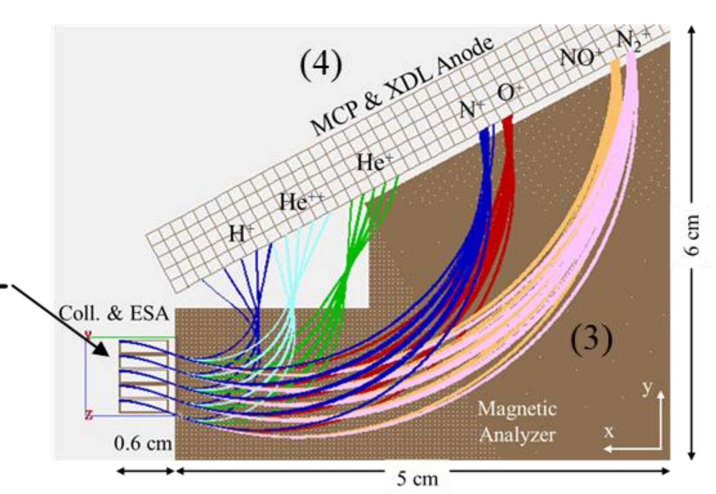


(Shay and Swisdak, 2004)

Compact Ion Mass Spectrometer

The instrument is cubesat compatible (1.5U) and comprised of: (1) a collimator to set the field-of-view; (2) a laminated electrostatic analyzer (ESA) to selectively filter ions by E/q; (3) a magnetic sector analyzer to separate ions by M/q; and (4) a micro-channel plate (MCP) followed by position sensitive cross delay anode (XDL) assembly to detect the location of the ions on the detector plane. The CIMS instrument concept was modeled using the SIMION software package using ion species relevant to ionospheric outflow and magnetic reconnection to demonstrate the feasibility of the design. The initial simulations demonstrate high-mass resolution at 30 eV between N^+ and O^+ with M/ΔM=8 while the clear distinction between NO^+ and N_2^+ demonstrates M/ΔM=30.

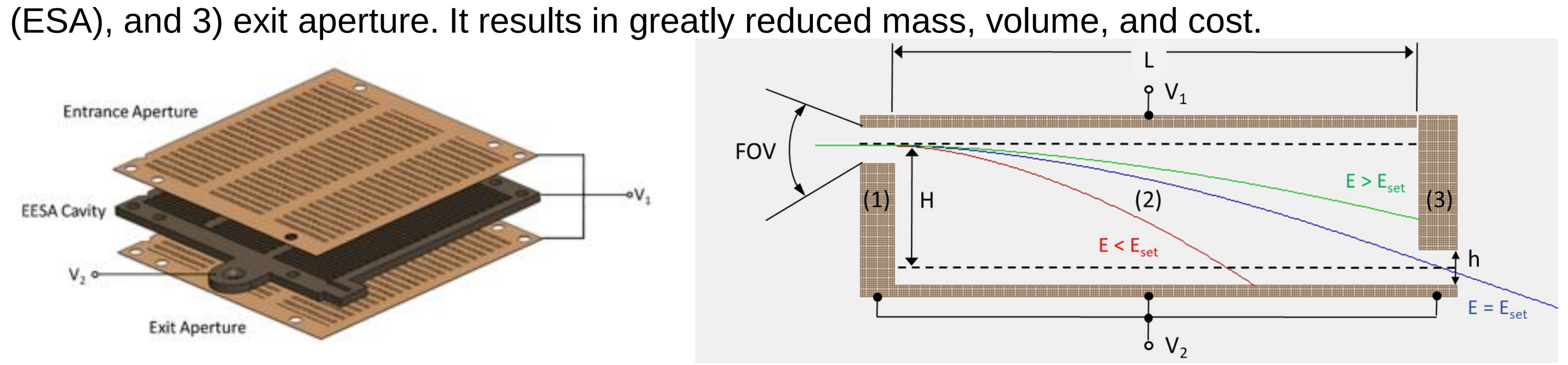




Laminated Electrostatic Analyzer

Design Overview

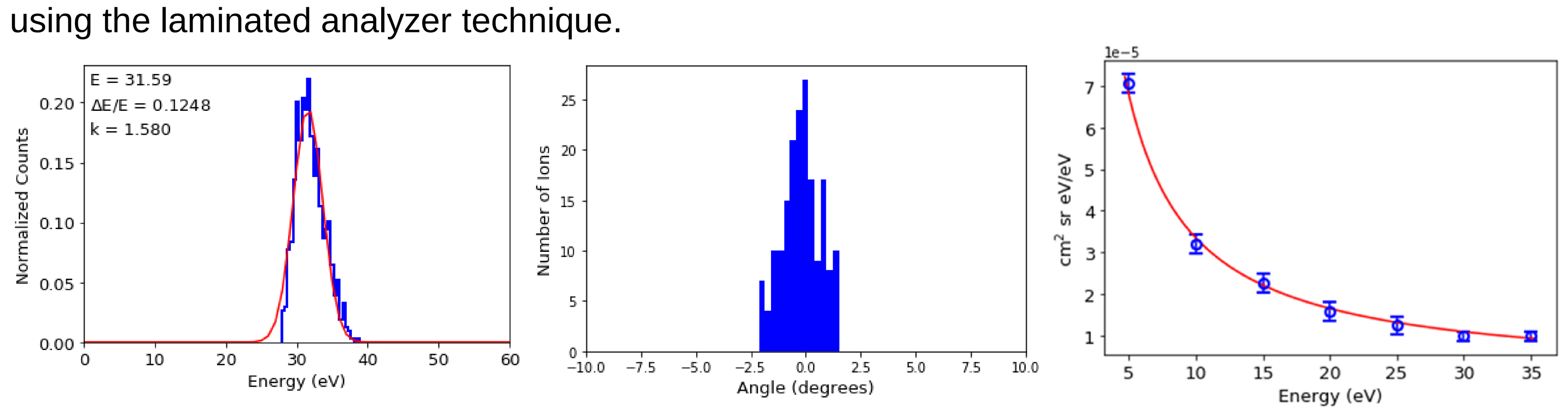
The front energy analyzer for the CIMS is based on a laminated analyzer design and uses geometry coupled with a transverse electric field to act as a bandpass filter. The sensor is composed of stacked conducting electrode layers with precise patterns of holes and slots machined in each layer to create a number of analyzer elements that consist of 1) an entrance aperture, 2) electrostatic analyzer (ESA), and 3) exit aperture. It results in greatly reduced mass, volume, and cost.



An electric field is created by applying a bias to the discriminator plate, V_1, while holding the opposite plate, V_2, at the spacecraft frame potential. The combination of the applied electric field and analyzer geometry allow ions within a narrow range of a specified bandpass energy ($E/q = E_{set}$) to successfully travel through the entrance aperture, become deflected by the transverse electric field in the ESA cavity, and exit the cavity to impinge on a current collector plate (not shown).The analyzer geometry alone determines the range of E/q accepted. The polarity of the biased plate V_1 is selected to repel the species of the charged particle under analysis, i.e. positive for ions and negative for electrons.

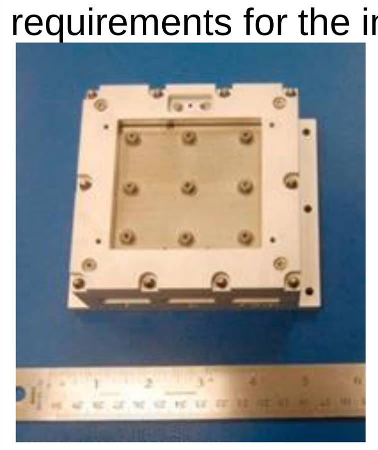
Electro-Optic Modeling

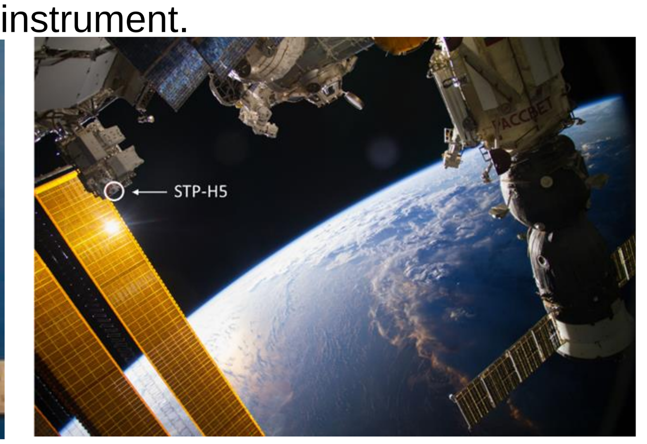
The electro-optics response of the laminated analyzer was conducted using the SIMION software package. The performance characteristics of interest are the energy resolution, angle resolution, analyzer constant, and geometric factor. Note, the geometric factor is the aggregate response of 2025 individual analyzer elements that were created in approximately 38 cm^2 of the detector surface using the laminated analyzer technique.

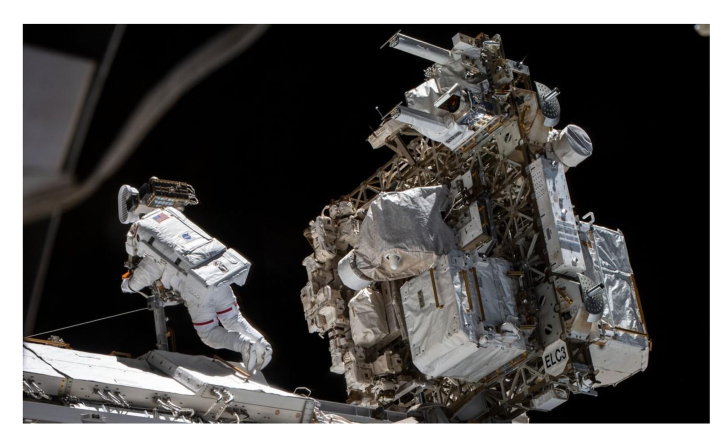


Flight Heritage

The laminated plasma spectrometer design has been developed as miniaturized, rugged, and low-cost instruments capable of providing in-situ measurements of ion or electron energy along with subsequent derived density, temperature, and spacecraft potentials. The iMESA-R family of instruments has flown as science payloads on a number of missions including Space Test Program Satellite-3 (STPSat-3), STPSat-4, STPSat-5, Green Propellant Infusion Mission, Orbital Test Bed, along with the STP-H5 and STP-H6 missions to the ISS [6, 7]. It should be noted that a new generation of higher energy electrostatic analyzer has been developed based on the iMESA heritage and will fly as a payload on STP-H10 [8, 9]. The laminated front end analyzer of the CIMS provides a high technology readiness level (TRL) and enables the low ultra-low mass and volume resource requirements for the instrument.

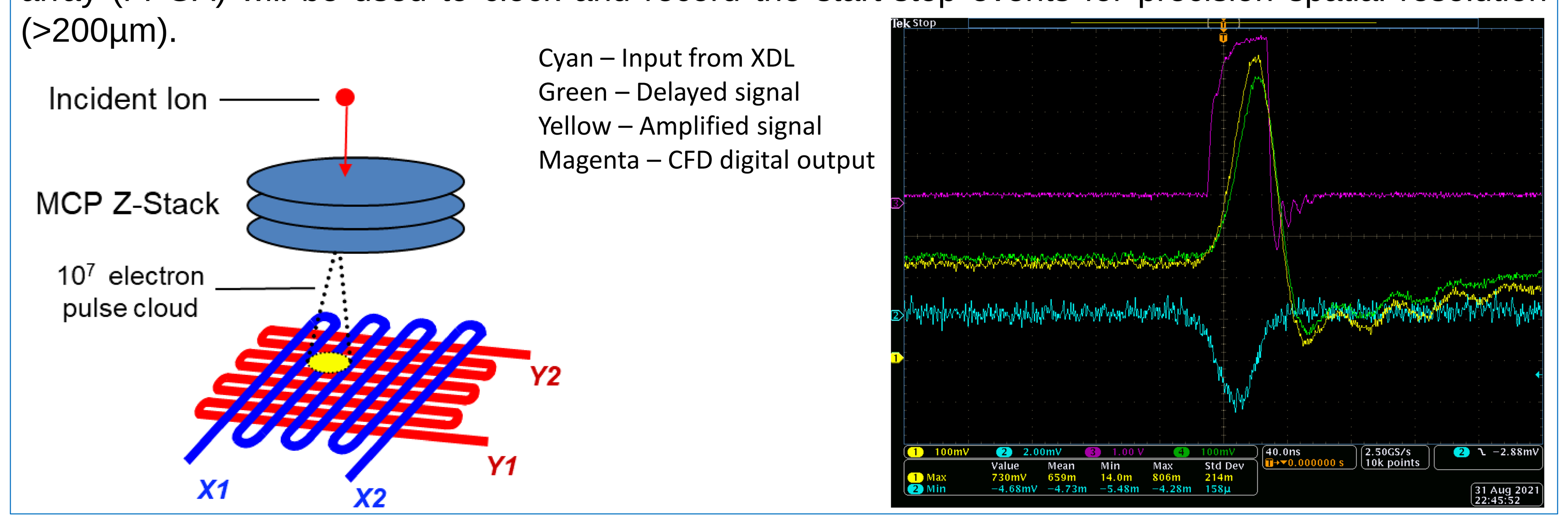






2D Imaging Cross-Delay Anode and MCP

The location of the ions incident on the detector plane will be observed using an MCP stack followed by an XDL anode. The XDL assembly consists of a standard MCP detector in a z-stack (3 plate) configuration followed by a cross delay-line anode. An incident ion strikes the front of the MCP detector and generates a secondary electron avalanche, resulting in a gain of ~10^7, which exits the MCP depositing the resulting charge on the anode. The XDL anode is formed by two orthogonal serpentine conductors and the position of the charge pulse is then determined by the difference in arrival time of the pulse at the ends resistive-capacitance delay lines. The XDL electronics will consist of fast amplifiers driving comparators at the end of each delay line followed by time-to-digital converters. The resolution of the assembly will be determined by the event timing error which is dominated by dispersion and noise in the analog constant fraction discriminator stage. An initial XDL sensor with diameter of 94 mm has been selected for the CIMS prototype A field-programmable-gate array (FPGA) will be used to clock and record the start-stop events for precision spatial resolution (>200µm).



Conclusions

- Developing a low SWAP-C CIMS capable of serving as a secondary/tertiary payload for small to large satellites or as primary payload for cubesats is critical to maintaining a robust and diverse set of planetary and heliospheric science missions
- Ion mass spectrometers provide critical data for planetary ionospheric and magnetospheric studies regarding plasma dynamics and processes
- Low SWAP-C allows for implementation in large constellations and/or planetary missions and therefore increased probability of payload selection, i.e. HelioSwarm and Europa Clipper type missions
- A constellation of low energy IMS measurements in LEO and GEO providing ionospheric outflow and cold magnetospheric plasma data would help answer long standing questions regarding the source of magnetospheric plasma, magnetosphere-ionophere coupling, mass loading of the magnetosphere, and magnetic reconnection
- The number of instruments required to obtain the necessary multi-point measurements precludes current state-of-the-art IMS designs due to their significantly higher cost making the CIMS a mission enabling design

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