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Key Points:
- Addresses several measurement challenges for in situ measurement of pickup ions
- Energy-per-charge filtering with minimal voltage stepping; 100 keV/e post acceleration
- Enables measurements of heavy pickup ion isotopes, solar deuterium abundance

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The Pickup Ion Composition Spectrometer

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Abstract Observations of newly ionized atoms that are picked up by the magnetic field in the expanding solar wind contain crucial information about the gas or dust compositions of their origins. The pickup ions (PUIs) are collected by plasma mass spectrometers and analyzed for their density, composition, and velocity distribution. In addition to measurements of PUIs from planetary sources, in situ measurements of interstellar gas have been made possible by spectrometers capable of differentiating between heavy ions of solar and interstellar origin. While important research has been done on these often singly charged ions, the instruments that have detected many of them were designed for the energy range and ionic charge states of the solar wind and energized particle populations, and not for pickup ions. An instrument optimized for the complete energy and time-of-flight characterization of pickup ions will unlock a wealth of data on these hitherto unobserved or unresolved PUI species. The Pickup Ion Composition Spectrometer (PICSpec) is one such instrument and can enable the next generation of pickup ion and isotopic mass composition measurements. By combining a large-gap time-of-flight–energy sensor with a −100 kV high-voltage power supply for ion acceleration, PUIs will not only be above the detection threshold of traditional solid-state energy detectors but also be resolved sufficiently in time of flight that isotopic composition can be determined. This technology will lead to a new generation of space composition instruments, optimized for measurements of both heliospheric and planetary pickup ions.

1. Introduction

Neutral gas from both interstellar and inner heliospheric sources can become ionized and picked up by the magnetic field carried in the solar wind. Due to their cyclical motion about the magnetic field, these pickup ions (PUIs) can have energies up to four times that of the local solar wind and can be separated from the more abundant, multiply charged solar wind ions based on their differences in charge and their velocity distribution. While some interstellar PUI measurements, such as the first in situ observation of the He focusing cone [*Möbius et al.*, 1995], have been made using sensors designed for magnetospheric environments, most low-charge-state ions discovered in the heliosphere have been measured by sensors that were optimized to observe the composition as well as the temporal, spatial, and energetic range of the high-charge-state solar wind. Such measurements include subsequent focusing cone observations [*Gloeckler et al.*, 2004a], the ^{3}He/^{4}He ratio in interstellar gas [*Gloeckler and Geiss*, 1996], the first in situ measurements of interstellar hydrogen [*Gloeckler et al.*, 1993], and other PUI components. Furthermore, such instruments have led to the discovery of cometary fragments and their composition [*Gloeckler et al.*, 2004b; *Gilbert et al.*, 2015] and also of ions originating at Mercury [*Zurbuchen et al.*, 2008], Venus [*Grünwaldt et al.*, 1997], Mars [*Lundin et al.*, 1989], and the Moon [*Hilchenbach et al.*, 1993].

Pickup ion observations from interstellar gas and other sources, such as inner heliospheric dust and particles interacting with asteroids and other planetary bodies, remain elusive because our measurements to date are at the very limit of what is possible. A more sophisticated instrument, dedicated to the observations of PUIs, will unlock high priority science results and give us new insights into the power of PUIs as a diagnostic for heliospheric plasma sources and the physical processes that shape them. To fully characterize PUIs, a new generation of plasma composition sensor is needed that overcomes the limitations of present-day mass spectrometers.

Innovative sensors that are optimized to measure low-density, low-charge state ions must overcome four main challenges: (1) the PUI energy range to be measured is very broad; (2) the hot distributions and low densities lead to the detection of a small fraction of incident ions in a typical ion mass spectrometer with stepped voltages; (3) instrument properties such as carbon foil effects and solid-state detector (SSD) energy thresholds reduce the probability of detection and degrade the resolution, preventing measurements of, e.g., heavy pickup ion isotopes; and (4) the level of background can be comparable to the signal of these tenuous species.

2. Pickup Ion Measurement Challenges

2.1. Large Energy Range

Composition measurements of the full distribution of heavy PUIs are beyond the range of most detectors (e.g., the pickup ion O^+ can have energies up to 64 keV in an average solar wind flow of 440 km/s), and PUIs span a large energy range (from <1 keV to 100 keV or above). Only mass spectrometers capable of accepting the full energy range of heavy pickup ions can map their full distribution. This first challenge has been addressed by innovative heavy ion sensors in the past, such as the Charge-Energy-Mass (CHEM) spectrometer (0.3–315 keV/e) [*Gloeckler et al.*, 1985], the Solar Wind Ion Composition Spectrometer (SWICS, energy range 0.6–100 keV/e) [*Gloeckler et al.*, 1992], and the Charge-Energy-Mass Spectrometer (CHEMS, 3–220 keV/e) [*Krimigis et al.*, 2004]. A pickup ion sensor *must be able to measure a large energy range*.

2.2. Low Densities

Key to making statistically significant measurements of PUIs in low-density interplanetary space is to have high collecting power. Successful pickup ion sensors must acquire sufficient counting statistics to achieve meaningful measurements, especially of sources with limited spatial extent. Low count rates in a sensor are due in part to the limited time it is able to spend analyzing each energy-per-charge (*E/q*) step, as well as the orientation of the instrument with respect to the PUI trajectories at any given time. These effects, as well as others, are described by the instrument geometric factor [*Sullivan*, 1971] and duty cycle [*von Steiger et al.*, 2000], which characterize the gathering power for incident ions and the fraction of time that they are able to enter the instrument for measurement. This includes limitations on the field of view and whether the sensor is mounted on a spinning spacecraft or an axis-stabilized one. Sweeping out a large angular field of view is important for PUI measurements, as inefficient pitch angle scattering may lead to anisotropic distributions [*Oka et al.*, 2002; *Gershman et al.*, 2014]. The low densities of these products of interstellar gas, cometary debris, and planetary exospheres lead to few measured events; often close to the noise floor of the instrument electronics. A pickup ion sensor must be able to measure ions during a large fraction of the time; i.e., it *must have high gathering power*.

2.3. Degraded Resolution

Upon passage through electrostatic deflection, the ions are often postaccelerated into the time-of-flight analyzer. The energy gained in postacceleration is directly proportional to the charge state of the ion, and for singly charged PUIs, this is often insufficient for the recording of an energy measurement on SSDs. The ions also suffer from substantial energy straggling and angular scattering as they pass through the thin carbon foils, which are used as secondary electron sources to trigger start signals in time-of-flight analyzers. Beyond the basic functionality of detection and identification, the next generation of mass spectrometers should be able to distinguish between isotopes of an ion species. Each of these difficulties can be addressed by increasing the energy of the ion in the postacceleration region. The postacceleration voltages used in solar wind spectrometers (10–30 kV) have been insufficient to capture energy measurements and resolve isotopes of heavy pickup ion species. In a straight-through time-of-flight–energy (TOF-E) analyzer, to overcome this third challenge, a pickup ion sensor *must have a sufficiently high postacceleration voltage* V_A.

2.4. Background and Noise

Pickup ion sensors will also face the challenge of providing excellent suppression of background and electronics noise to achieve the necessary signal-to-noise performance. Background can accumulate from processes within the instrument such as electron-stimulated desorption of ions from surfaces, ion-induced electron emission, UV photons, and penetrating radiation [*Gilbert et al.*, 2014]. Each of these processes can cause the detectors to be triggered, creating spurious signals in the data. In addition, without careful attention to electronics design and the choice of electrical components, the noise from instrument electronics can have a significant effect. A certain degree of degradation in the TOF signal due to the properties of the electrical components is unavoidable, but the effect can be mitigated by integrating the electronics where possible and by performing systems studies to reduce power consumption, increase resolution, and improve the likelihood of detection. One design consideration for excellent background suppression is the requirement of triple-coincidence detection for each measured ion. With start, stop, and energy signals occurring in coincidence, the standard for measurement is raised and the likelihood of false signals is reduced. Due to limitations such as imperfect detector efficiencies, the requirement of triple coincidence will necessarily result in fewer counts being recorded. However, low-charge ions can overlap the high-density solar wind ions when

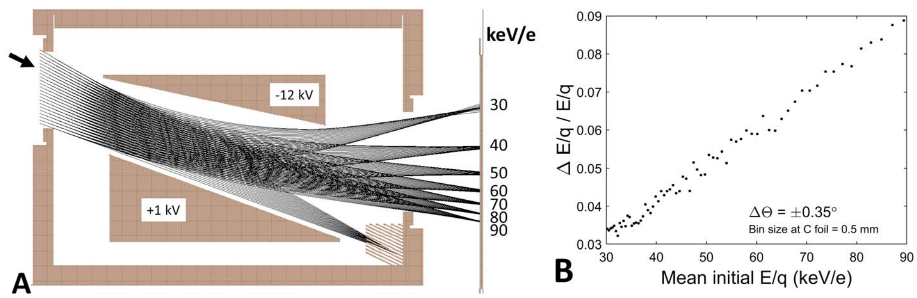

Figure 1. Ion optics simulations of the PICSpec ESA, which simultaneously sorts ions within $(E/q)_{max} = 3(E/q)_{min}$. The measured *E/q* value is determined by the impact position at the carbon foil. The *E/q* resolution varies between 3% and 9%, with the best resolution found where the lowest *E/q* focuses in each voltage step.

only TOF is measured [*Gilbert et al.*, 2015]. The ability to separate solar wind species such as the lower charge states of Fe from the pickup ion signal, or to reduce spurious signals from accidental coincidences and high-energy particles, is greatly enhanced when triple-coincidence detections are established. A sensor designed for PUI measurements *must have excellent background suppression*, *including triple coincidence*.

In the next section, we will describe the Pickup Ion Composition Spectrometer (PICSpec), which is designed to address each of these issues. We will also show that the technologies developed for PICSpec can also be used to measure the ratio of deuterium to hydrogen in the solar wind, an important cosmological parameter.

3. Instrument Description

Once the design requirements are understood, a sensor optimized to make the necessary measurements can be developed. PICSpec is such a sensor and consists of three primary systems: an electrostatic analyzer (ESA) that sorts ions by *E/q* using electrostatic deflection, a postdeflection acceleration region, and a TOF-E analyzer that measures the speed and energy of detected ions. The fundamental principles that govern each of these sections, as well as the methods employed to derive the ion mass and charge state, are described in *Gloeckler et al.* [1998]. While this sensor follows traditional principles, there are several innovations in the PICSpec design that allow it to overcome the limitations faced by legacy plasma sensors when measuring low-charge state plasma such as pickup ions.

Novel design elements in the PICSpec ESA address the first two challenges for a pickup ion sensor. The PICSpec ESA is designed to allow passage of ions *within a large E/q range of* $<$*1 keV/e up to* $>$*100 keV/e*, which will cover most heavy ion species carried along with solar wind traveling at nominal speeds. The instantaneous *E/q* passband increases the amount of time that the sensor can spend at each voltage step, allowing it to bring the low-density pickup ion signal above the floor of background signals that may obscure the measurement. Traditionally, the electrostatic deflection plates found in typical ESAs are stepped across a range of voltages to scan the measurement space of *E/q*. Such a scan results in ions of a specific *E/q* value only being measured during a fraction of the instrument's observing time. The PICSpec ESA (Figure 1) is designed to mitigate this limitation by reducing the need to step the deflection voltages during an *E/q* scan. The fundamental concept is an ESA designed to simultaneously pass ions with a wide range of *E/q* values through a large-gap exit aperture, and differentiate them by their impact positions [*Gilbert*, 2008]. Suppression of photons in the PICSpec ESA is accomplished using a collimator (not shown) that focuses ions and photons toward a baffled light trap, as well as scalloping and black coating of the deflection plates, as discussed in *Gilbert et al.* [2014]. PICSpec can pass ions within an *E/q* range of $(E/q)_{max} = 3(E/q)_{min}$ (e.g., 1–3 keV/e, 30–90 keV/e, etc.) with each voltage setting, covering in five voltage steps the same *E/q* range that similar heritage sensors cover in 60 (e.g., SWICS, *Gloeckler et al.* [1992]). The entrance aperture spans 6° in elevation and 70° in azimuth (rotated ±35° about an axis of symmetry), which is also similar to the design of SWICS. Mounted properly on a spinning spacecraft, this sensor will have a large window of acceptance, sweeping out a FOV of 70° × 360° and can use a sit-and-stare approach of pickup ion measurement while it spans the necessary energy range with minimal voltage stepping, leading to a sensor with *very high gathering power*. In the simulation shown in Figure 1a, an *E/q* range of 30–90 keV/e was used to illustrate the focusing capabilities over a typical range for heavy pickup ions; the focus is similar for any *E/q* range in which the maximum *E/q* is a factor of 3 greater than the minimum, with electrode voltages

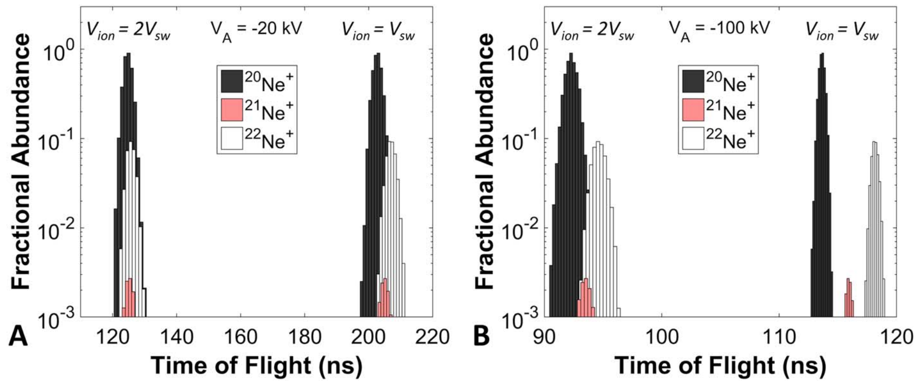

Figure 2. Ion optic time-of-flight simulations of the isotopic resolution of neon for two different postacceleration voltages. The simulations assume an *E/q* resolution of 6% and energy straggling through a carbon foil of thickness 1.5 μg cm^{-2}. (a) With a postacceleration voltage of $V_A = -20$ kV, there is a degree of overlap among the isotopes to the extent that they cannot readily be resolved from one another by their time of flight. (b) All three PUI isotopes are sufficiently separated at $V_A = -100$ kV when measured at nominal solar wind speeds ($V_{sw} = 440$ km/s), and the two major isotopes can be distinguished for that part of the PUI distribution traveling at $2V_{sw}$.

set accordingly. The results of a Monte Carlo simulation of the ion optics are shown in Figure 1b, with the initial elevation angle varying by $\Delta\Theta = \pm 0.35°$ to account for the spread within a collimator channel, and a postacceleration voltage of 0 V. The full-width half-maximum *E/q* resolution, $\eta = (\Delta(E/q))/(E/q)$, of this design varies with impact position, with values between 3% and 9%. The best resolution is found where the lowest *E/q* values focus during each voltage step. This focusing is heavily dependent on the angular spread allowed through each collimator channel, however. If the ions are allowed to enter the ESA with a spread of $\Delta\Theta = \pm 0.5°$ in elevation through each collimator channel, for example, then η will range between 4% and 13%. The accuracy of the collimator, therefore, is critical to this design. When a postacceleration voltage is applied, it serves to straighten out the trajectories as they leave the ESA, guiding them straight toward the carbon foil with acceleration proportional to the ion's *E/q*. As the intent here was to illustrate the separation and focus of ions over the range of *E/q* values, the postacceleration was not used in these simulations.

Classification of PUIs is improved when a triple-coincidence measurement is made—start and stop time-of-flight signals and an energy measurement. The energy that ions gain during postacceleration serves not only to increase the likelihood of triggering an energy measurement in the TOF-E analyzer but also to reduce the energy straggling and angular scattering inherent in passage through the thin carbon foil that marks the entrance. Because the energy gained is proportional to the ion charge state, singly charged pickup ions benefit the least from this boost. PICSpec mitigates this issue with a -100 kV power supply for postacceleration. Such a magnitude is desired for several reasons. Accelerated pickup ions will be readily detectable by traditional SSDs, and the isotopic resolution of heavy ions is possible in a straight-through time-of-flight design. Figure 2 shows ion optics simulations of the separation possible for the stable isotopes of neon, $^{20}Ne^+$, $^{21}Ne^+$, and $^{22}Ne^+$, picked up by the solar wind and measured by an instrument having an *E/q* resolution of $\eta = 6$ %. Ions traveling at average solar wind speeds ($V_{sw} = 440$ km/s) have ~1 keV/nucleon; Figure 2 shows pickup ions traveling at both the nominal solar wind speed V_{sw} and at the characteristic $2V_{sw}$ cutoff. Energy straggling is modeled through a carbon foil of thickness 1.5 μg cm^{-2}; secondary electron trajectories and angular scattering through the foil were not included for these simulations. For illustrative purposes, the isotopic fractional abundances measured on Earth were used here [*de Laeter et al.*, 2003], which are slightly different than the heliospheric neon isotopic abundances measured in samples of trapped solar wind gases [*Eberhardt et al.*, 1970; *Grimberg et al.*, 2006]. With a postacceleration voltage of $V_A = -20$ kV (Figure 2a), there is substantial overlap in time of flight among the isotopes, rendering them nearly indistinguishable from one another. When $V_A = -100$ kV (Figure 2b), all three isotopes are separated and the $^{21}Ne^+$ can be clearly resolved in the slower pickup ions, and the two major isotopes are moderately separated even at the faster speeds. For reference, the full-width at half-maximum mass resolution of the $^{20}Ne^+$ peaks at $V_{ion} = V_{sw}$ for Figures 2a and 2b are $m/\Delta m \approx 30$ and $m/\Delta m \approx 90$, respectively.

Observations of the isotopic composition of plasma, such as abundance ratios of neon or oxygen isotopes, provide vital clues to the evolution of the Sun, planets, and other bodies; and, unlike elemental composition, isotopic composition is not affected by factors such as different ionization rates. For example, the ratio of

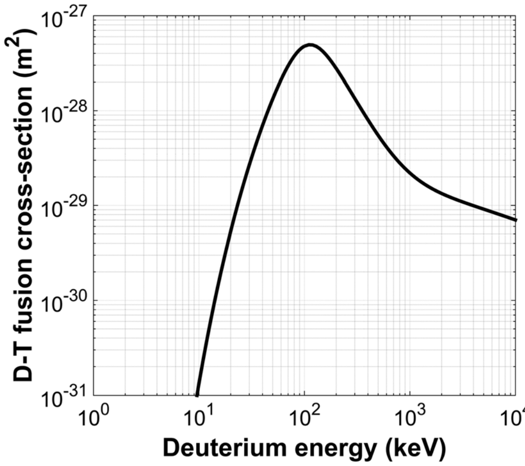

Figure 3. Fusion cross section for deuterium-tritium reactions as a function of deuterium energy. The peak cross section occurs at 100 keV and rapidly falls off with lower energy [*Kikuchi*, 2011].

deuterium (^{2}H or D) to hydrogen is an important parameter in cosmology because it can be used to measure the amount of cosmic baryons produced during Big Bang nucleosynthesis. While D can be produced in stellar flares, the overall value of D/H is believed to be monotonically decreasing over time [*Prodanović and Fields*, 2003]. While D can readily be separated from H using isochronous TOF techniques, the *M/q* and *E/q* of D in the solar wind is the same as that of He^{2+} and that highly abundant peak will overlap and conceal the D peak in a straight-through TOF measurement. However, the solar D/H ratio can be measured by accelerating deuterium into a tritium target and measuring the energies of the resulting alpha particles, as described in *Scherb* [2009]. The peak cross section for such an interaction occurs at 100 keV (Figure 3) and falls off rapidly at lower energies, reducing to 80% of the peak value at 80 keV and 30% of the peak cross section at 50 keV [*Kikuchi*, 2011]. A power supply capable of accelerating these 1–2 keV singly charged ions to this peak energy is required for such a measurement.

Measurements enabled by power supplies capable of such high voltages include PUIs and the composition of isotopes such as D/H. Power supplies with the capacity for 100 keV acceleration were developed [*Sutton and Stern,* 1975] and flown on high-altitude sounding rocket experiments [*Lynch et al.*, 1976], but the program was terminated after the rocket flights due to lack of financial support for further development (F. Scherb, private communication, 2011). High mass resolution can be obtained using other techniques, such as the isochronous time-of-flight systems of the high-resolution MASS spectrometer (MASS) on *Wind* [*Gloeckler et al.*, 1995], the Mass Time-of-Flight (MTOF) sensor on the Solar and Heliospheric Observatory (*SOHO*) [*Hovestadt et al.*, 1995], or the Ion Mass Spectrometer (IMS) on *Cassini* [*Young et al.*, 2004]; however, such designs lack the ability to measure absolute energy, and make high-resolution isochronous measurements only on ions that exit the time-of-flight carbon foil with a positive charge. The majority (~70%) of ions exit as neutrals and are measured at low resolution in a straight-through TOF measurement. Even with these limitations, isotopes of heavy ions can be resolved [e.g., the cometary pickup ions measured by the *Rosetta*/Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA), *Balsiger et al.*, 2007]. The next generation of PUI spectrometers must be able to perform energy measurements with isotopic resolution, which can be achieved in PICSpec due to its *−100 kV postacceleration voltage*.

Postacceleration on PICSpec is determined by a high-voltage power supply capable of providing up to −100 kV at 10 W. This highly compact design is scaled from past flight designs set in cascading, field-controlled stages. This cascaded voltage stage approach also allows for straightforward AC drive with voltage isolation in controlled 25 kV steps, capable of delivering low-voltage power to any electronics contained within the HV section of the instrument. Engineering models of both the −100 kV high-voltage power supply and the 10 W isolated low-voltage drive system have been built and tested in a laboratory setting up to full capacity. These will be fully integrated into the lab prototype that will also include all of the usual noise control features necessary for proper operation.

Original design elements combined with well-known techniques were used in the development of the high-voltage power supply. Like the −100 kV power supply flown on the sounding rocket experiments described in *Sutton and Stern* [1975], this design uses a Cockcroft-Walton style of voltage multiplication. Unlike that design, which managed voltages using a pressurized vessel and no encapsulation, this power supply utilizes proven encapsulation methods, special bobbins, careful winding, and shaped conductors for field control.

Schematic descriptions of the high-voltage system are given in Figure 4. A single 40 kHz current-fed, self-resonant oscillator with a preregulator will drive a Cockcroft-Walton series high-voltage multiplier consisting of four cascaded 12-stage modules. Each of the cascaded stages generates −25 kV, adding to a total of

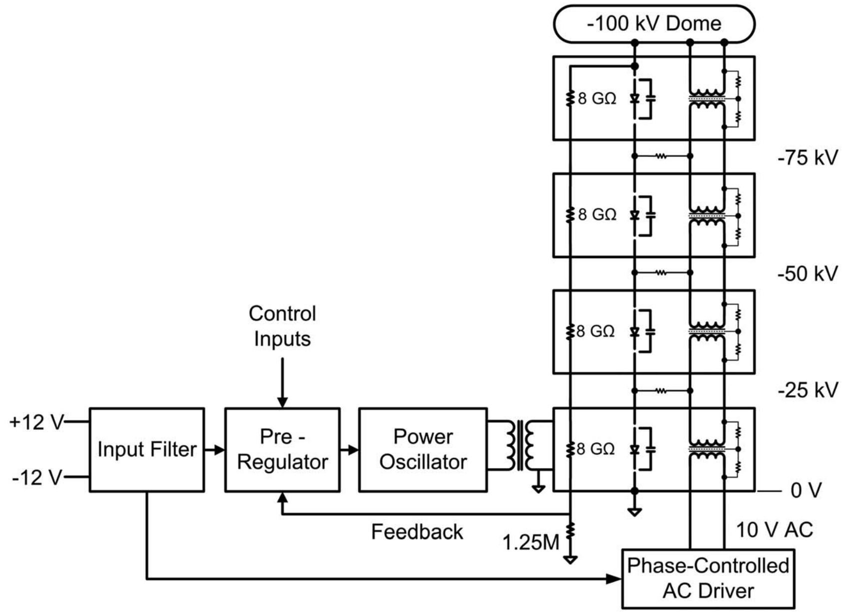

Figure 4. High-voltage system block diagram. Voltage is multiplied across four subsequent stages of −25 kV each, with 10 W of total power delivered. Not shown is the external Faraday enclosure around the unit or the associated local noise filtering for the floating dome instrumentation.

−100 kV. DC feedback is provided by 16 2000-MΩ 10-kV resistors connected in series on each stage for a total feedback resistor of 8 GΩ per 25 kV stage and therefore 32 GΩ for the four stages combined in series. This limits the total power dissipation in the feedback network to 0.31 W.

In a parallel leg to each stage, four series-connected AC drive transformers are incorporated with the cores biased at the midpoint of the local voltage stage. Thus, each transformer will have the requirement of dealing with a local winding-to-core maximum DC breakdown voltage of 12.5 kV and a stage-to-stage voltage of 25 kV. The transformers are driven as a group using a resonant zero-voltage switching approach at approximately 90 kHz, with an efficiency of approximately 70% for 10 W of delivered power. This approach is unique in the ability to transfer as much as 10 W of power at high efficiency across a 100 kV boundary through multiple transformers using segmented field control. Similar techniques have been employed using single and dual transformers but only with 20 kV to 30 kV of voltage isolation at powers in the range of 5 W.

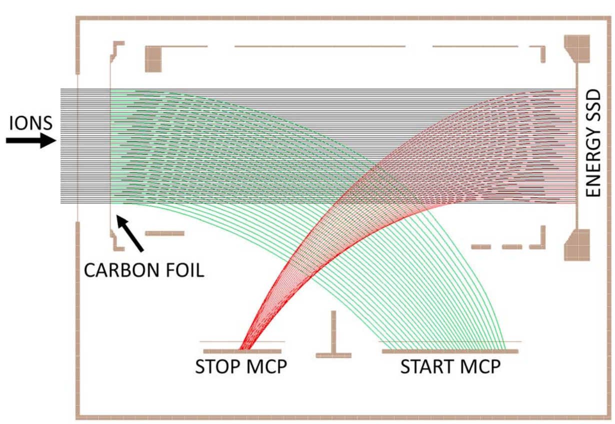

Figure 5. Ion optics simulations of the PICSpec TOF-E analyzer. Ions (black) travel straight through from left to right and trigger an energy measurement. Secondary electrons are released from the carbon foil to trigger a position-measured start signal (green) and from the SSD to trigger a stop signal (red).

The acceleration created by this high-voltage power supply addresses the third challenge of measuring pickup ions, the reduced resolution due to carbon foil effects, and energy threshold limitations on low-charge species in TOF-E sensors.

Ion optics simulations of the PICSpec TOF-E analyzer (Figure 5) show an adaptation of that used on SWICS [*Gloeckler et al.*, 1992], with modifications that allow it to accommodate the aperture of the large-gap ESA. The ESA and TOF designs *follow established background suppression principles* [*Gilbert et al.*, 2014] such as a light trap, black coatings, and scalloped plates for UV suppression; avoidance of ion or electron paths that would lead to false coincident measurements; and improved timing electronics [*Gilbert et al.*, 2010] to address the fourth challenge of pickup ion measurement. Such design elements on SWICS have resulted in a reduction of background by incident UV photons to better than 1:10^{12} [*Gershman and Zurbuchen*, 2010].

Once secondary electrons are released from the carbon foil by traversing ions, they impact the start MCP assembly, where their impact position is recorded by a position-sensitive anode. This start anode acts as a mapping of impact positions on the carbon foil and, as illustrated in Figure 1, contains information regarding the *E/q* value of the incident ion. Secondary electrons released from the SSD upon ion impact are guided to the stop MCP assembly, where their impacts are recorded to reconstruct the ion time of flight. The final energy of the ion is recorded upon impact with the SSD and is used in concert with the other measured parameters to determine the ion mass and charge.

4. Summary

Next-generation plasma spectrometers will require significant technological advancements as they are tasked to measure ion species that are at the limits of present-day instrumentation. We have made a case for the importance of a dedicated pickup ion instrument, PICSpec, which can measure the composition and variability of PUI sources with isotopic resolution. We have shown that there are two enabling technologies for such a dedicated pickup ion instrument. First is a large-gap ESA to reduce voltage stepping and still span the necessary energy range required for the full distribution of PUI species. Second, an internal ion acceleration provided by a −100 kV power supply to separate heavy ion isotopes, to reduce energy straggling and angular scattering from thin carbon foil transit, and to trigger a PUI energy measurement on even high-threshold SSDs. These, together with design requirements focused on background reduction, allow the tenuous signal of PUIs to be seen in the high background of the solar wind and other sources. The technologies developed for this sensor will lead to a new generation of space plasma composition instruments that are optimized for measurements of both planetary and heliospheric PUIs, the measurement of which has been identified as one of the top opportunities for innovation in plasma sensors during the next decade [*Zurbuchen and Gershman*, 2016].

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