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Exploration of Options for Ultra-Fast Mass Spectroscopy for Pulsed Power Applications

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ABSTRACT

Mega-ampere class pulsed power machines drive intense currents into small volumes to study high energy and density environments. Power lost during these events is a difficult and paramount problem to solve. For example, facilities such as Sandia National Laboratories' Z machine experience meaningful power loss, which can be linked to non-linear ohmic heating at high currents (i.e., 26 MA on Z) leading to thermal desorption of contaminants and subsequent shunt plasma formation. Characterizing and understanding this type of thermal desorption is key to design optimizations necessary to minimize current loss, which will be even more important for next generation pulsed power. This type of characterization requires the ability to identify and determine concentration of analytes with nanosecond resolution given the pulse width of Z is on the order of 100 ns. This report summarizes progress on a small exploratory project focused on investigating options to meet this challenge using mass spectrometry. The main focus of these efforts utilized an Energy and Velocity Analyzer for Distributions of Electric Rockets intending to determine how quickly transient data could be resolved. This probe combines an electrostatic analyzer with a Wien velocity filter (ExB) to obtain ion energy and velocity distributions. Primary results from this exploratory project indicate significant additional work is needed to demonstrate a nanosecond time scale mass spectrometer for this application and also highlight that alternative detection methods such as laser-based diagnostics should be considered to meet the need for ultra-fast detection.

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ACRONYMS AND TERMS

Acronym/Term	Definition
AK	Anode Cathode
CEPPE	Center for Electric Propulsion and Plasma Engineering
CSU	Colorado State University
ESA	Electrostatic Analyzer
EVADER	Energy and Velocity Analyzer for Distributions of Electric Rockets
IEDF	Ion Energy Distribution Function
IMDF	Ion Mass Distribution Function
MCP	Micro-Channel Plate
MITL	Magnetically Insulated Transmission Line
TIA	Transimpedance Amplifier

1 PURPOSE AND OBJECTIVES

This project was initially proposed as a large effort to develop an ultra-fast (ns regime) mass spectrometer system capable of identifying and quantifying thermally desorbed analytes from rapidly heated electrode surfaces for pulsed power applications. Due to the high-risk nature and cost of this work, a small exploratory project was initiated to evaluate options with the goal of reducing risk prior to investing in a larger effort. Given limited funding, this project leveraged prior work between Sandia National Laboratories (Sandia) and Colorado State University (CSU) essentially modifying an off-the-shelf compact energy and charge state analyzer, the Energy and Velocity Analyzer for Distributions of Electric Rockets (EVADER). This device was originally designed to measure the temporal properties of ions flowing from plasma sources and served as an excellent, and affordable launch pad for this effort. Thus, the main objective of the project became to investigate limitations of the temporal measurement capability of the EVADER using both experimental measurements and numerical modeling. Following this, the intent was to make design modifications and investigate high-speed measurement schemes to overcome these limitations, and then, time permitting, attempt to quantify the new probe concept. If successful, this type of device would be useful for improving initial boundary conditions used for plasma simulations and predictive modeling of current loss in short-pulse, ultra-high-power devices.

Note: The majority of the work done on this project was well documented in the master's thesis by Susan Ossareh titled "A High-Speed Mass Spectrometer for Characterizing Flash Desorbed Species in Pulsed Power Applications" [1]. This thesis should be considered a companion to this report because the experimental designs, data, results, and analyses in this thesis are not duplicated here. A link for obtaining a copy of this thesis is included in the References.

2 INTRODUCTION

The Z-machine is the world's largest and most powerful pulsed power facility. It is located at Sandia National Laboratories where it is utilized for fusion and energy research for the Department of Energy. When the Z-machine fires, large capacitor banks quickly discharge and compress a load into a z-pinch. A single shot on the Z-machine can generate up to 26 mega-amperes through the load, allowing for particle physics experiments to be conducted in an extremely high energy environment. Next generation pulsed power machines aim to be more powerful, however there are some risks that need to be addressed to achieve that goal, such as ensuring acceptable levels of current loss that circumvents the load. This current loss can be due to the formation of a conductive plasma between the anode-cathode (AK) gap occurring at the inner magnetically insulated transmission lines (MITLs) due to the release of contaminants in flash desorption processes due to the rapid heating of the MITL surfaces. The Z-machine is a complex device, and use of any diagnostic like the one described herein is likely never to occur on Z, however, its use on smaller devices specifically designed to study flash desorption might be possible in the future. Data from these studies are hoped to elucidate methods to mitigate the flash-desorption-based current loss issue.

Mass spectrometry devices are being investigated in the Center for Electric Propulsion and Plasma Engineering (CEPPE) Laboratory at CSU for use in quantifying processes that occur in dynamic plasma devices. Sandia National Laboratories purchased a plasma diagnostic tool, the Energy and Velocity Analyzer for Distributions of Electric Rockets (EVADER), from Plasma Controls, LLC, which was developed in collaboration with the CEPPE Laboratory. This probe combines an electrostatic analyzer (ESA) with a Wien velocity filter (ExB) to obtain ion energy and velocity distributions. The EVADER is being evaluated to determine how quickly it can resolve transient data. The knowledge developed from learning about the limitations of this probe are hoped to lead to a diagnostic concept with the hope of resolving plasma dynamic processes occurring on the 100s of nano-second temporal scale.

3 THE EVADER PROBE

The EVADER probe combines an electrostatic analyzer in-line with a Wien velocity filter [1-4]. Figure 1 shows the primary components of an ESA and ExB, including the ESA spherical plates for energy per charge differentiation (see [1] or [5] for a drawing of these plates), ion collimators, the ion collectors, and the use of the ExB electric and magnetic field section for mass, velocity, and charge state differentiation. Note that one component serves as both the ExB collimator and the ESA ion collector, this enables the EVADER to act as a standalone ESA or as an energy filter feeding selected ions into the ExB stage.

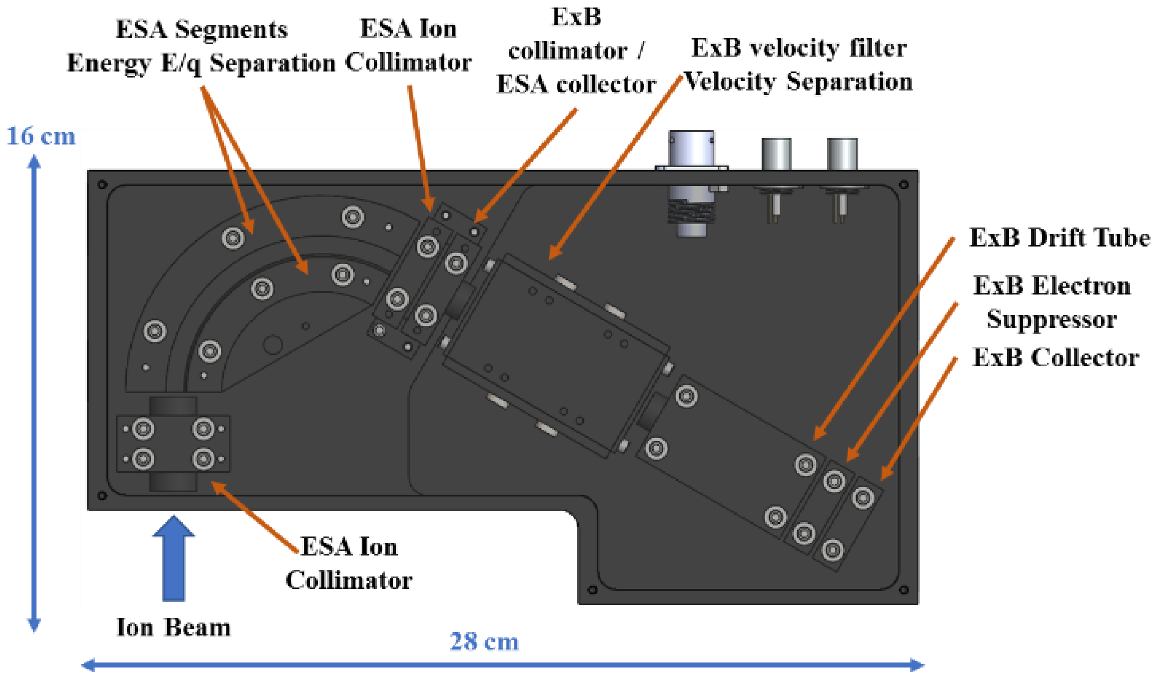

Figure 1. The schematic of the EVADER depicting both the ESA and ExB stages (reprinted with permission from [2])

An ESA is an analyzer that separates ions through deflection based on the energy-per charge ratio. Charged particles of a specific energy (transmission energy) follow a trajectory through parallel, curved plates of the ESA. If ions enter at an energy that is not the transmission energy, they are deflected off axis and are not able to pass to the next stage. A measurement of an ion energy distribution function can be constructed by sweeping the transmission energy and measuring the current to the ESA collector.

Differing charge states of an ion will experience the same potential energy but have different velocities at a given transmission energy, which sets a specific energy of ions that can pass through onto the ExB stage. The energy-selected ions enter the ExB region where the charged particles are separated by their velocity, which is determined by the mass and/or charge state of the ion using the Lorentz force equation. Charged particles that pass through the drift tube of the ExB stage are measured as current on the ExB ion collector. The ExB separates the ions by holding the magnetic field constant with permanent magnets and varying the electric field with a voltage difference, $\Delta\varphi$, between the parallel plates of the ExB drift tube. This creates a current-versus-voltage trace with peaks corresponding to the various ion masses or charge states passed to the probe.

4 PLASMA SOURCES

Testing the EVADER was conducted at CSU's CEPPE Laboratory. A plasma source is necessary to operate and characterize the EVADER. Two different sources have been used over the course of this project, which include a hidden anode plasma source referred to as the "Flamethrower" due to the dense, energetic plasma that expands from its ~1 mm exit orifice and an 8-cm diameter gridded ion source.

4.1 Flamethrower

The Flamethrower, shown operating in Figure 2, produces an expanding plasma plume composed of multi-charged ions with wide ranges of ion energy from a gas fed to the device, often krypton or argon. A hidden anode behind a small orifice is fed gas and collects energetic electrons from a remotely located hollow cathode. The electrons flowing through the small orifice on their way to the anode bombard the neutral krypton atoms, ionizing the gas and possibly further ionizing the ionized gas, thus forming multi-charged ions. This dense plasma energetically expands into the regions downstream of the device where diagnostics are placed.

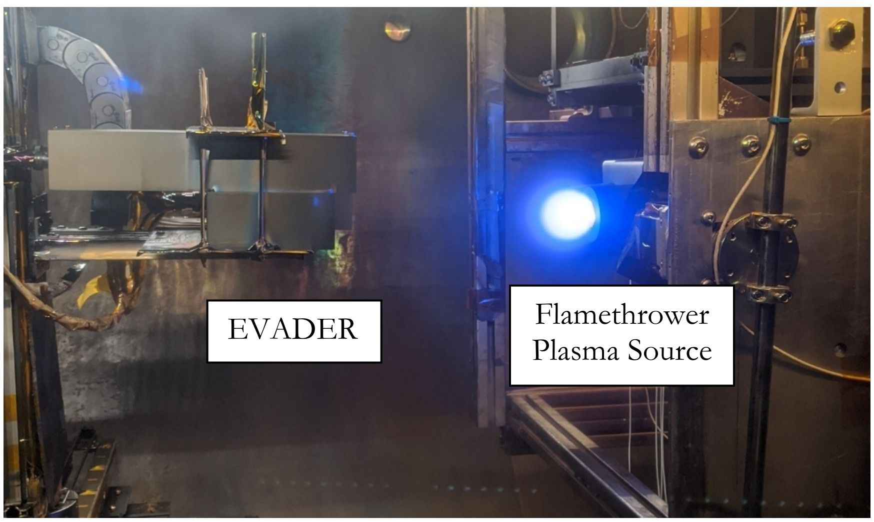

Figure 2. The EVADER probe is aligned with the Flamethrower 25cm away, collecting steady-state data on a krypton plasma.

4.2 Gridded Ion Source

While the Flamethrower is a unique plasma source, and data was collected with it, a gridded ion source was also used to study the EVADER probe. A gridded ion source produces a more-controlled beam of ions by accelerating them from a plasma using a charged grid assembly often referred to ion optics, as shown in Figure 3. The beam voltage and current, along with other parameters, can be easily controlled, which allows for improved characterization of the EVADER.

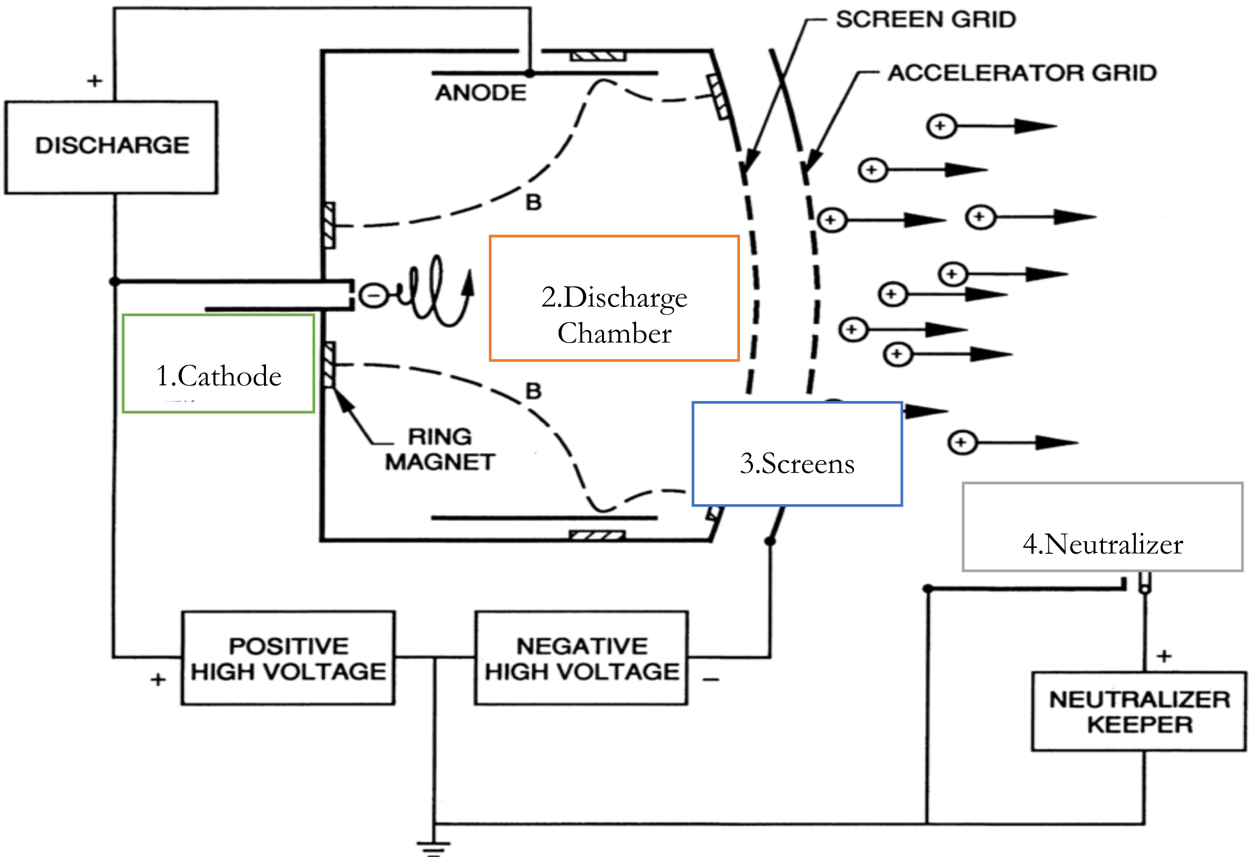

Figure 3. Schematic of a gridded ion source

An inert gas, such as argon or krypton, flows into the discharge chamber of the gridded ion source. The cathode filament is heated to thermionically emit electrons. These electrons are accelerated into the discharge chamber and bombard the gas atoms creating positive ions and additional electrons that become part of the discharge chamber plasma. An applied, axially diverging magnetic field within the discharge chamber is used to contain the electrons and enhance plasma production. The ion optics of this plasma source utilizes two grids, a positively biased screen grid and a negatively biased accelerator grid, to create a potential difference that accelerates ions from the discharge chamber plasma into beamlets emerging from each aperture set at the discharge chamber exit. A neutralizer is placed downstream of the ion optics assembly to emit electrons into the ion beam to create a neutral plasma beam. The ions in the plasma beam are allowed to enter the EVADER, which is typically placed ~20-50 cm downstream of the ion source on its centerline such that the EVADER entrance collimator is aimed at the ion source.

5 DATA COLLECTION WITH THE EVADER PROBE

The EVADER probe can be used to take two types of measurements that yield information about the plasma beam, the ion energy distribution function (IEDF) and ion mass distribution function (IMDF). The IEDF is obtained when the EVADER is operated as an ESA, and the IMDF is obtained when it is operated as an ExB probe. Figure 4 depicts a solid model of the EVADER probe along with a wiring diagram showing how the analyzer and ExB segments are connected and operated. This diagram will be used to explain measurement of energy and mass distributions as well as the iterative steps that are being taken to modify the probe to enable measurement of temporally changing distributions.

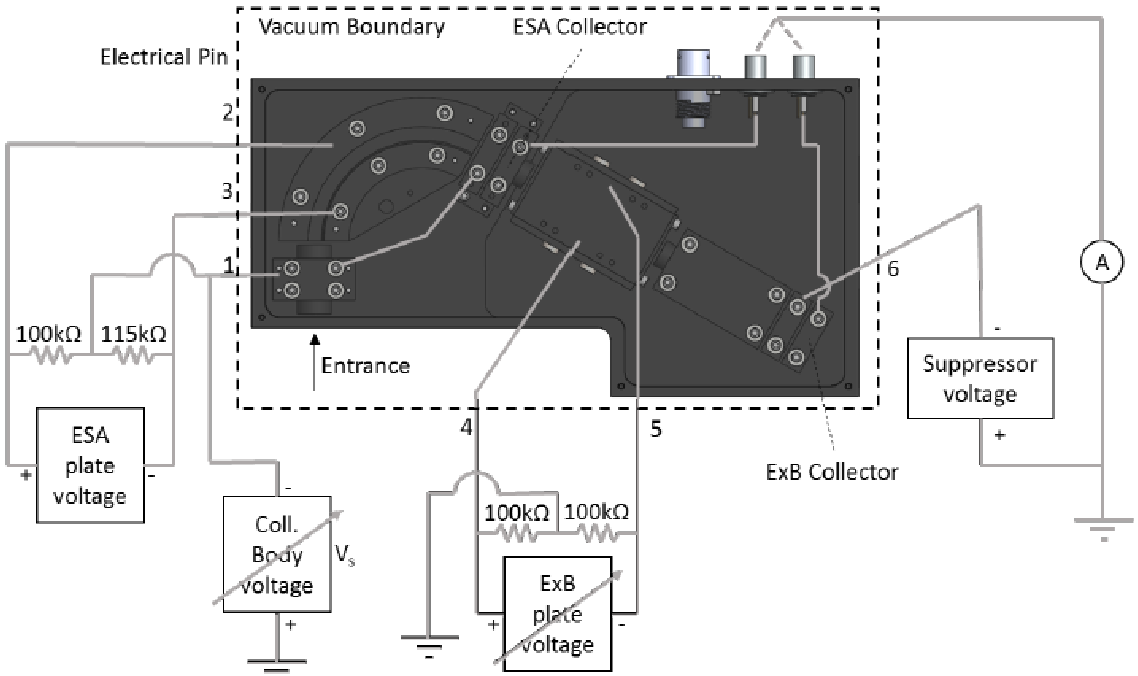

Figure 4. EVADER solid model and electrical schematic in its traditional configuration (reprinted with permission from [1])

To operate the EVADER in the IMDF mode, only the ESA portion is used. Two of four power supplies are active: the ESA plate power supply and the variable-output voltage collimator body power supply. The power supplies are used in conjunction with a low-current ammeter to measure the signal from the ESA collector. The varying bias on the collimator body is used to accelerate ions into the probe. The ESA plate power supply biases the curved ESA plates relative to each other to set the trajectory of the incoming ions. Only ions within a narrow band of energy per charge will transit through the curved plates of the ESA to the ion collector. Ions entering the probe with an energy per charge less than or greater than the "pass" energy per charge will fall into the inner or outer curved plate and be neutralized. The voltage difference between the plates specifies the energy per charge of ions that pass through this region, but their velocities, charge state, and mass can differ. Once the pass energy per charge is set (typically selected to be 375 eV/z with z being the charge state of the ion), the collimator body power supply is swept through a voltage range, for example from -375 V to -10 V, and the ion current to the ESA collector is measured to create a current vs. voltage trace of the IEDF. The whole process is best understood if one considers an ion with a given energy that is headed toward the EVADER entrance aperture, for example an ion produced with a potential of 100 V above ground near the plasma source. If two electrons are stripped from an atom to form a doubly charged ion, its charge state is +2. If this ion is created in such a manner that its initial kinetic energy is very close to zero and the EVADER entrance is then held at ground potential, this doubly charged ion would enter the EVADER probe at 200 eV or 100 eV per charge (i.e., 200 eV/2). This ion will only travel through the curved parallel plates of the ESA if its energy per charge is equal to the ESA transmission energy, which is typically set to 375 eV per charge. The necessary collimator body voltage to accelerate this 100 eV per charge ion to 375 eV per charge is -275 V. Hence, in this manner of sweeping the collimator body voltage and measuring the ESA collector current, a trace is built to map an IEDF by assigning the collimator body voltage, V_{cb}, for each measured ion energy per charge, which would be "375 - V_{cb}" in this example where the transmission energy is set to 375 eV per charge.

Some ions are allowed to pass through an orifice in the ESA collector electrode so that they can continue to the ExB segment. In this way, at a selected collimator body voltage, one can then study the velocity, charge state, and mass of the ions with known energy per charge within the ExB segment of the probe. In this mode of operation, the ExB plate power supply is swept through a range of voltages to vary the electric field in the ExB stage and differentiate the incoming ions relative to their velocity, which can be used to infer their mass or charge state. The measurement of the ExB ion collector current and ExB plate voltage can be used to create a mass distribution function (or a charge state distribution function if all the ions entering the probe have the same atomic mass). The suppressor power supply is also active in the acquisition of the ExB trace and reflects any secondary electrons that are emitted from the ExB ion collector so that ions are not measured twice.

As noted in Section 1, a detailed summary of much of the work is contained in the thesis written by Susan Ossareh (see: Ossareh, S.J. (2022), "A high-speed mass spectrometer for characterizing flash desorbed species in pulsed power applications"). The remainder of this report contains information pertaining to work done after Susan's thesis was completed.

6 WORK TO MEASURE TEMPORALLY VARYING IONS

The following project activity was intended to advance the EVADER concept so it could be operated in a manner where temporally varying IEDFs and IMDFs could be measured. An in-house model at CSU that uses the Euler method to solve for forces acting on a charged particle was developed for the EVADER to evaluate possible modifications. This model is flexible and can accommodate a range of energies and mass species as well as charge state. Figure 5 shows a plot of the ESA sector model solved with ions at the transmission energy of 375eV.

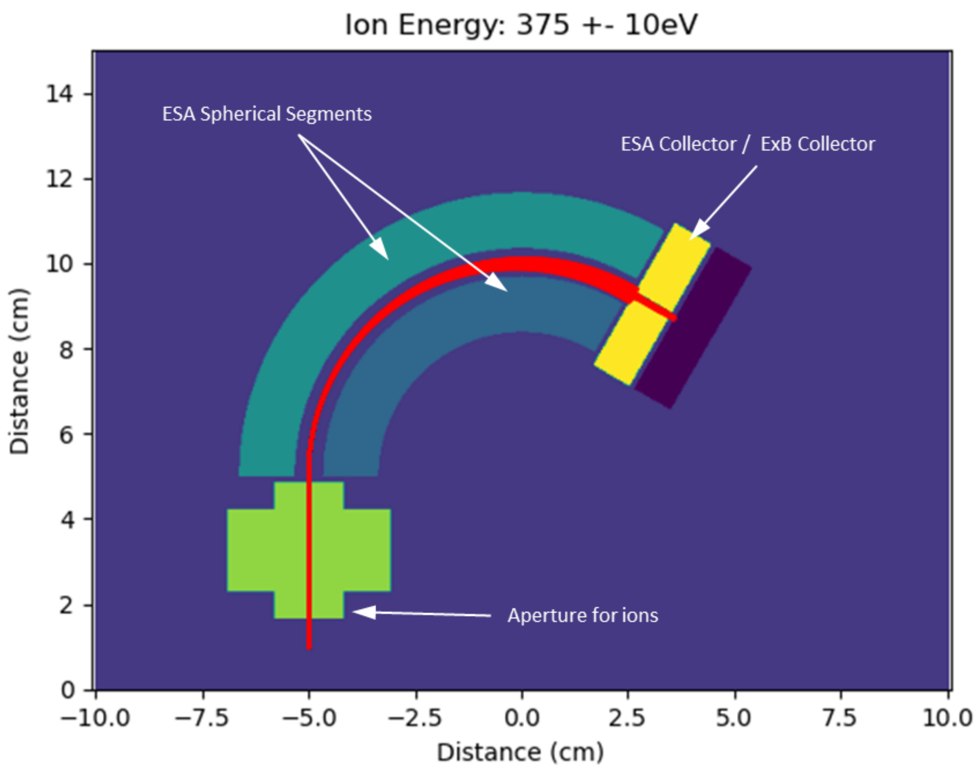

Figure 5. Simplified model of the ESA section of the probe with 375 eV ions travelling between the curved parallel plates to the collector

Further development to enable high-speed operation of the EVADER probe will require the elimination of a voltage sweep requirement to distinguish ion species using velocity in the ExB section of the probe. To do this, the ExB section could be replaced by a magnetic sector (mag sector) that can separate different ion velocities (and therefore mass) into separate streams. The inhouse model described briefly above can be used to show how ions of similar energies (coming from the ESA sector) would separate out in the uniform magnetic field created within the mag sector. The model was applied to some common species of interest and ion trajectories were solved using two magnetic field strengths, 0.1T and 0.3T. The results of these simulations are shown in Figures 6-8, with the dark areas of the plot representing the sector of uniform magnetic field strength. It is worth noting that the lighter species are easily separated at the lower 0.1T magnetic field, but higher mass and molecular ion species only show significant separation at 90 degrees from the entry plane under higher 0.3T magnetic fields.

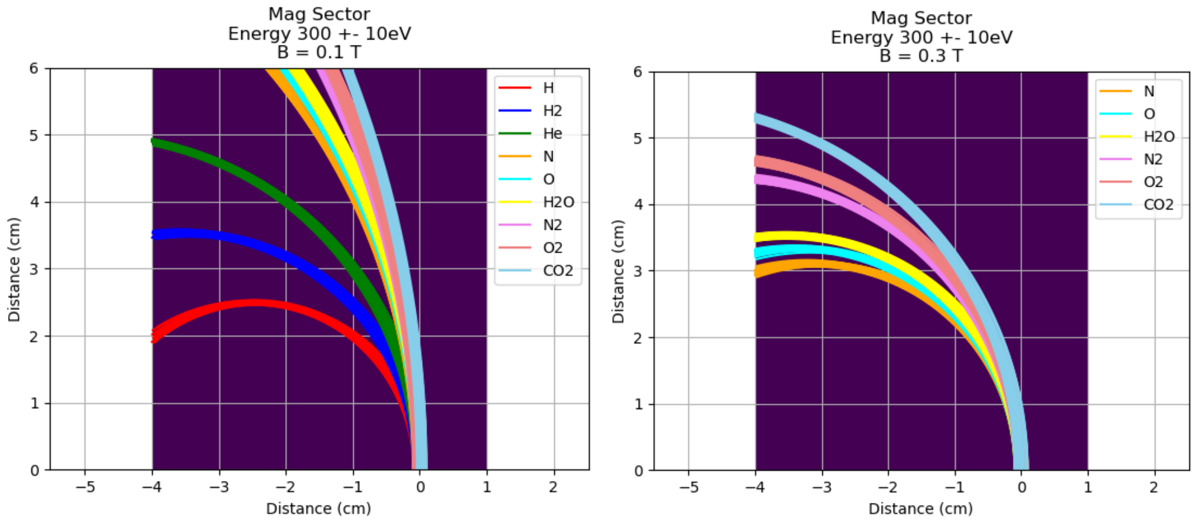

Figure 6. Trajectories of fixed energy singly charged ion species with varying mass that enter a mag sector of uniform 0.1T (left) and 0.3T (right) magnetic field

The magnetic sector was then added to the model of the ESA sector to show an example of how a new probe concept would distinguish particles of different masses but similar energy. The results of this proposed feature are shown in Figure 6.

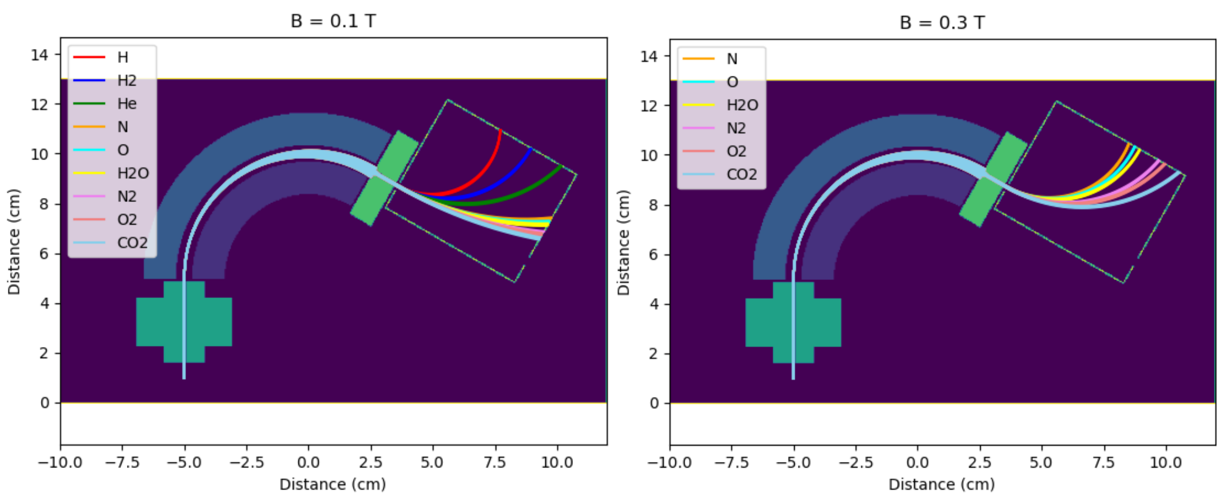

Figure 6. Example of how either of the previously modeled magnetic sectors would be integrated into the EVADER to separate out the ion species that pass through the ESA segment

Both Figure 6 and Figure 7 show the separation of the ion species of different masses but similar energies moving through the new probe concept. However, to enable high-speed measurement of these species, collectors will need to be added to the mag sector walls to measure the relative ion current of each species. This can be accomplished with a segmented collector that only measures ions of a specific velocity, shown in Figure 8. Each segment could correspond to a given velocity range for ions, effectively binning the different velocity ranges. It is worth noting that depending on the size limits for the next generation probe, collectors could be placed on the wall 180 degrees from the entrance into the magnetic sector where the separation would be highest.

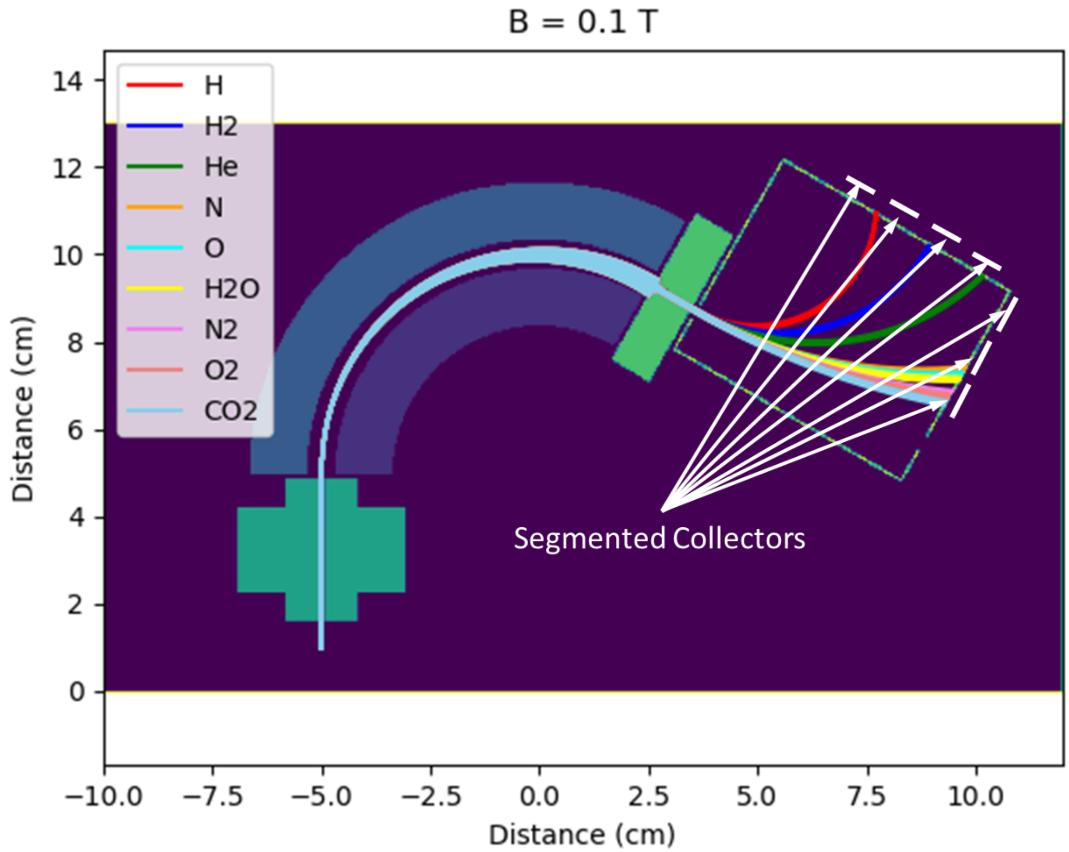

Figure 7. Example model of a new design concept utilizing segmented ion collectors

To help separate out the ions, drift tubes can be employed with collectors at the end in the area of the predicted location for specific species.

6.1 Transimpedance Amplifier

This task involved making further improvements to the design of a low-current measurement circuit based on a transimpedance amplifier (TIA) to replace existing commercially available, pico-/femto-ammeters from Keithley or Keysight. Previously, the EVADER probe employed a low-current ammeter to detect signals from both the electrostatic analyzer portion and the full EVADER scan. These instruments are expensive and have a limited sample rate that severely limits the measurement speed. A TIA circuit enables higher-speed measurements, and two TIA circuits were investigated. One is based on an evaluation board from Texas Instruments, the LMP7721. More information on this TIA is included in [1, p. 28-31]. A second custom circuit, designed by Dr. Parris Neal at the US Air Force Academy, was selected for evaluation, which utilizes an OPA656 operational amplifier. This custom-designed circuit also includes a 0-100 V sweeping power supply, which would simplify implementation of a new concept probe design. Dr. Neal has provided detailed schematics and instructions along with a bill of materials and printed circuit manufacturing instructions. This detailed information would enable the modification of the circuit so it could be tested with different operational amplifiers and to quantify their maximum measurement speeds. Under the scope of this project, neither TIA concept was demonstrated or characterized.

6.2 Micro-Channel Plate Amplifier

The EVADER and other concept probes collect extremely small currents, which can be below the limits of the TIA circuit. To address this, a micro-channel-plate (MCP) can be used to amplify the ion current at the ion collector within the probe. Testing of an MCP was not completed under the current project due to unexpected challenges including long delays caused by extended lead times for US-based MCP manufacturers. Additionally, the expense of machining parts to modify existing EVADER probes was limited by funding for this project. An MCP was identified and ordered from Photonis (part number 36604PS). A preliminary mount was designed, but no hardware has been fabricated to enable integration of the MCP into the EVADER probe.

6.3 Implementation of a High-Voltage, Fast-Sweeping Power Supply

To acquire data at high rates, a fast-sweeping power supply is required to sweep voltages in the EVADER probe. The CEPPE Lab has a KEPCO bipolar operational power supply/amplifier capable of sweeping voltages from 0-200 V at a 20 kHz rate. Sweeping voltages in the original set-up required multiple seconds to complete a trace, whether with a Sorenson power supply or a Keithley 6517b electrometer and power supply. Voltages can be swept at a much faster rate using the KEPCO, enabling higher measurement speed. This fast-sweeping concept was not tested during the current project due to insufficient time.

6.4 Electrical Shutter

Stopping the flow of ions to the collector on some known, very short time interval using an electrical shutter that repels or deflects ions at the entrance to the EVADER probe could aid in determining the highest speed at which the TIA can resolve rapidly changing ion arrival conditions. With the existing EVADER probe, this would entail selecting fixed ESA and ExB plate voltages and measuring the current flowing to the ion collectors as the shutter is activated. The currents detected with a TIA circuit could be measured using an oscilloscope.

An electrical shutter would prevent ions from entering the ESA segment by driving the potential voltages of an aperture set positioned at the entrance to the probe. At least one of the voltage signals applied to the aperture set would be rapidly pulsed over a range of frequencies to determine the bandwidth of the combined probe and TIA circuit. Both insulted-gate bipolar transistor (IGBT) and high voltage metal-oxide-semiconductor field-effect transistor (MOSFET) driver circuits were considered, but the initial testing was to use a pulsed DC power supply for magnetron sputtering due to its technological maturity and availability at the CEPPE Lab. The available power supply was an Advanced Energy Pinnacle Plus+ pulsed DC supply with adjustable frequencies up to 350 kHz and a variable duty cycle up to 45%, requiring 3-phase 480V AC power to operate. This power circuit was unavailable in the CEPPE Lab, and the required facility integration and approval prevented the testing of an electrical shutter during this project.

7 CONCLUSIONS

This exploratory project was initiated to determine options for further development of an ultra-fast (nanosecond regime) mass spectrometer to identify and quantify analytes thermally desorbed from rapidly heated pulsed power surfaces. During this project, personnel changes and technical challenges severely impacted the progress on this challenging task. The collaborative work with CSU on the EVADER system did make significant progress in evaluating the potential of this concept, but limited funding and technical challenges resulted in many of the initial objectives not being completed. Nevertheless, our limited results indicate this device and methodology has the potential to demonstrate a system with 10s of microsecond resolution, significantly slower than our goal of the nanosecond regime. Further, even if this device/methodology was able to capture a nanosecond regime event, there are still many challenges with proof of concept in a controlled laboratory environment. One main limitation identified is an inability to rapidly ionize neutral analytes in representative vacuum environments at some physical distance (inches to feet) while collecting sufficient signal to overcome signal-to-noise limitations. To conclude, additional exploratory work would be needed prior to investing in a development effort for an ultra-fast mass spectrometer and that alternative methods including laser-based diagnostics should also be considered for meeting this need.

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*This thesis includes information on the experimental modifications to test the EVADER probe to enable ultra-fast detection along with data, results, and analyses that are not duplicated in this report. It also includes a bibliography with 36 references relevant to this report. This thesis is available at: https://www.proquest.com/docview/2672311202?pq-origsite=gscholar&fromopenview=true

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