

Recommended Practice for Use of ExB Probes in Electric Propulsion Testing

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An ExB probe is an electric propulsion plume diagnostic that has at its core a Wien filter. Ions entering the instrument experience perpendicular electric and magnetic fields and are

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filtered based on their velocity. While the ExB probe can be used to estimate the ion velocity distribution function, in the electric propulsion community, it is commonly used to measure species fractions. There are numerous probe designs, implementation and operation procedures, and data analysis approaches described and in use across the community. This paper provides recommendations and descriptions of best practices for design, implementation, and data analysis for the ExB probe, with a particular emphasis on Hall and ion thrusters. This work contributes to the broader community goal to standardize the use of diagnostics in electric propulsion testing.

Nomenclature

$A_{beam,k}$	=	Ion beam cross-section area, m ²
A_i, A_v	=	Probe entrance aperture and venting areas, m ²
a, b, c, d, n, θ	=	Model and distribution function fitting parameters
$B, \vec{B}$	=	Applied magnetic field, T
B_{eff}	=	Effective magnetic field, T
B_o	=	Magnetic field at mid-point of the filter, T
B_{pra}	=	Practical magnetic field, T
C_{tot}	=	Probe total conductance, m ³ s ⁻¹
d, d_e	=	Electrode plate separation distance, m
$E, \vec{E}$	=	Applied electric field, V/m
E_{eff}	=	Effective electric field, V/m
E_o	=	Electric field at mid-point of the filter, V/m
e	=	Elementary charge of an electron,
$\vec{F}$	=	Force, N
f_k	=	Ion velocity distribution function, -
G	=	Probe geometric constant, m ⁻¹
g_k	=	Measured probe spectra, -
$\mathbf{I}$	=	Identity matrix
I_j, I_k	=	Measured probe current, A
l_c	=	Collimator length, m
l_d	=	Drift tube length, m
l_f	=	Wien filter length, m
J	=	Current density, A/m ²
j, k	=	Species, -
k_B	=	Boltzmann constant, 1.38x10 ⁻²³ J/K
m	=	Mass of a charged particle, kg

$\dot{N}$	=	Rate of neutral production, s ⁻¹
n_{inc}	=	Number density increase inside probe above background density, m ⁻³
n_k	=	Ion number density, m ⁻³
n_o	=	Background neutral number density, m ⁻³
n_p	=	Probe-internal neutral number density, m ⁻³
P	=	Neutral pressure, Pa
Q	=	Throughput, J/s
q, q_k	=	Charge, C
R	=	Voltage divider resistance, Ω
$r_{i=1,2,3,4}$	=	Aperture radius for different components along the beam line, m
T	=	Neutral gas temperature, K
T_k	=	Transmittance matrix, -
V_{accel}	=	Ion accelerating potential difference, V
V_p	=	Plasma potential, V
V_{plates}	=	Electric potential difference across probe electrodes, V
$V_{plates,range}$	=	Recommended range of V_{plates} values, V
$v, \vec{v}, v_{ion}$	=	Ion velocity, m/s
v_{Wien}, v_W	=	Wien velocity, m/s
$v_{w,eff}$	=	Effective Wien velocity, m/s
Z, Z_j	=	Charge state, -
z	=	Axial position downstream of thruster, m
α_{max}	=	Maximum collimator acceptance angle, radian
Γ	=	Particle flux, m ⁻² s ⁻¹
γ_k	=	Secondary electron emission yield, -
ϵ	=	Error or noise
ζ_j	=	Species fraction of the j-th species based on flux, -
λ	=	Regularization parameter, -
Π_n	=	Neutral buildup ratio, -
Π_τ	=	Optical depth ratio, -
σ_j	=	Charge-exchange cross-section, m ⁻³
Ω_j	=	Current fraction of the j-th species, -

I. Introduction

A major challenge across the space electric propulsion (EP) community is the standardization of practices, techniques, and approaches for the measurement and testing of EP devices. There is a need for accurate, consistent,

repeatable test results and the ability to compare results from different test facilities operated by different organizations, groups, and researchers. This can only be achieved through the development and application of common procedures and standards of measurement practice. If EP devices and technology are to continue to proliferate and transition from laboratory to flight, then there is a corresponding need for community standards.

With these challenges in mind, a previous effort by the American Institute of Aeronautics and Astronautics (AIAA) Electric Propulsion Technical Committee led to the publication of a series of papers on recommended practices for some of the important diagnostic and measurement approaches used in EP testing. Specifically, recommended practices were developed for pressure measurement and pumping speed calculations [1], flow control and measurement [2], thrust measurements [3], and use of the Faraday probe [4], Langmuir probe [5], emissive probe [6], inductive magnetic field probe [7], and electrostatic analyzer [8] in determining electromagnetic, plasma, and ion beam properties. While these have greatly aided the community, there are still additional diagnostics and techniques that lack recommendations and standardization of their application to EP testing. One of these additional diagnostics is the ExB (“E cross B”) probe, which is the subject and focus of this paper.

An ExB probe is a composite instrument that has a Wien filter at its core. It is a band-pass ion velocity filter that uses electric and magnetic fields that are orthogonal to each other and the ion velocity. This triad selectively filters ions based on their velocity. While the ExB probe can provide a measure of the ion velocity distribution function (IVDF), in the EP community, it is often configured as a mass spectrometer (or separator) and used to measure the ratios of the different charged species present in the emitted ion plume of a thruster. For example, when operating with a single noble gas propellant, e.g., xenon, as is common in EP testing, the ExB probe is used to measure the ratios of multiply charged ions in the plume. Multiply-charged ions reduce thruster efficiency [9], deposit more energy into thruster walls [10], and cause higher ion bombardment sputter erosion [11,12], so accurate characterization of multiply-charged species content is important for understanding and predicting thruster performance, lifetime, and spacecraft integration.

This paper describes recommended practices for ExB probe design, operation, and data analysis in electric propulsion testing. The following sections provide a brief history of the invention, development, and application of the probe to EP testing, and an overview of probe theory. Specific examples of ExB probes and their dimensions are provided in the design section, and recommendations on the implementation and operation of the probe are described. Probe data analysis for both estimating the IVDF and determining plume species current and charge-state fractions is described. Finally, a comparison is provided of the ExB probe with other common EP plume diagnostics for measuring similar properties. Recommended practices are contained throughout the manuscript.

II. A Brief History

A charged-particle velocity filter with orthogonal electric and magnetic fields was first documented by Wilhelm Wien in 1897 [13-16]. Wien used it to make one of the first measurements of the charge-to-mass ratio of electrons, and thereby showed that the cathode ray consists of particles with mass. Over the next fifty years, variants of the Wien filter (although it was rarely called that) were used extensively within the particle physics community. A typical implementation might include features such as electric and magnetic fields in tandem rather than superimposed and

curved or even circular geometries rather than the straight linear geometries used for EP diagnostics. In many cases the instrument was used to study the effect of electric and magnetic fields on beam focusing and dispersion [15,16]. The Wien filter has been and is still used in a variety of electron optics systems [17]. It has been used as an electron monochromator since the 1960s [18]. The use of two Wien filters as a double focus electron monochromator is still common today [19]. Further, the Wien filter is used to separate primary and secondary electrons [20], compensate for dispersion, second-order and higher-order aperture aberrations [21,22], and correct for chromatic and spherical aberrations in electron optics [22-24].

Perhaps one of the first descriptions of a Wien filter as a mass spectrometer (spectrograph) for heavy ions was by Bainbridge in 1933 [25]. Bainbridge describes an instrument with superimposed electric and magnetic fields and a set of beam collimating apertures for studying heavy ion isotopes. Seliger was perhaps the first to use the term ExB when referring to the instrument as an ExB mass separator in 1972 [26]. Seliger developed, linearized, and solved the governing equations for ion trajectories in an ExB mass separator and was focused primarily on beam astigmatism in isotope separation and ion implantation. Holmlid expanded upon this work in 1975 focusing on the mass dispersion and resolution of the Wien filter with homogeneous, purely orthogonal, electric and magnetic fields [27]. Since that time, the Wien filter has been used as an ExB mass spectrometer for a myriad of applications [28-32]. However, the EP community appears to be unique in its use of the Wien filter to measure and quantify multiply charged species in ion beams and plumes.

The Wien filter spectrometer was used in electric propulsion testing for the first time in 1973 by Vahrenkamp [33]. Vahrenkamp employed the probe to measure the singly, doubly, and triply charged mercury ion populations in the plume of a gridded ion thruster and incorporated these measurements into performance calculations. A subsequent parametric investigation developed correlations between the multiply-charged ion population and mass utilization efficiency [34]. Since that time the ExB probe has been used extensively to diagnose ion thruster performance and operation. Sovey used an ExB probe to show that, compared to a divergent magnetic field configuration, a ring-cusp magnetic field configuration in the discharge chamber has less centerline screen grid erosion due to lower concentration of doubly-charged ions for argon, krypton, and xenon propellants [35]. Williams et al. showed that the ratio of doubly-to-singly charged plume ions can be directly related to measured and calculated erosion rates of the grids of 30 and 40 cm xenon ion thrusters [36]. Pollard et al. used spatially-resolved charge-state distributions to derive thrust correction factors for a 36-cm NEXT ion thruster [37]. The ExB probe has become a common and important diagnostic in ion thruster wear tests [38], long-duration tests [39], life tests [40], and integration tests [41].

The Wien filter was first employed to study Hall thrusters by Kim and Gallimore, and they used it to investigate the plume of the SPT-100 [42,43]. Hofer and Gallimore used an ExB probe to interrogate the multiply-charged species content of the NASA-173Mv2 xenon ion plume [44], measuring doubly-charged fractions of 4-12% and triply-charged ion fractions of 1-2%, and then used these measurements in an efficiency analysis [45]. Ekholm and Hargus measured multiply-charged species in the plume of a 200 W xenon Hall thruster [46]. Reid et al. explored the angular dependence of multiply-charged species fractions [47]. Sullivan et al. used the ExB as a collimated velocity filter to map out the origins and trajectories of primary ions emanating from a Hall thruster [48]. Diamant et al. have used ExB probe measurements to characterize background pressure effects on Hall thrusters [49], as well as the performance and plume

properties of 2 kW [50] and 1.5 kW [51] Hall thrusters. More recently, Gurciullo et al. have used an ExB probe to investigate the ion plume of a Hall thruster operating with xenon-nitrogen and xenon-air mixtures [52], and Watanabe et al. explored the performance and plume of an 85 W class Hall thruster [53]. Hall et al. used an ExB probe to characterize the plume of a 100 kW nested channel Hall thruster [54]. Similar to ion thrusters, the ExB probe has become commonplace in Hall thruster wear testing and long duration testing [55,56].

III. Theory

An ExB probe is a composite instrument that consists of multiple sections along the beam line, including at least an entrance aperture, Wien filter, and collector to record ions. In addition, an entrance collimator, drift section, and suppressor aperture are also commonly included, as shown in Figure 1. Ions enter the probe from the outside plasma plume through the entrance aperture. Two apertures can be used to set a probe centerline axis and allow for a general ion acceptance angle into the probe. Some ions entering the probe traverse each section and reach the collector and register a current, while others are unable to reach the collector. For example, ions off centerline are physically stopped at the collimator or at the entrance to the Wien filter. Ions that enter the Wien filter experience electric and magnetic forces. If the electric and magnetic forces are balanced and there is no net force on the ion, then it passes through the filter (red arrow going through the filter in Figure 1). If there is a net force on the ion then it is pushed off axis, resulting in ions that strike the filter electrodes, drift tube surfaces, or suppressor aperture structure. Specifically, as shown in Figure 1, if the magnetic force dominates then the ion trajectory bends down (negative-y direction), and if the electric force dominates then it bends up (positive-y direction). Finally, ions that do reach the collector can cause secondary electron creation and emission from that surface. An electron suppressor structure can be used and electrically biased negative of the collector to return secondary electrons to the collector.

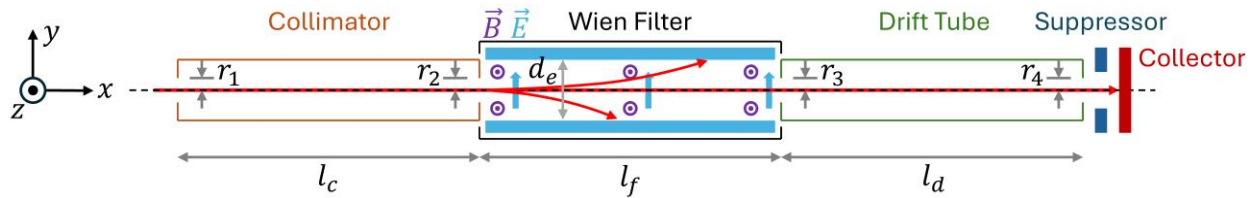


Figure 1: ExB probe schematic.

A. First Principles

Comprehensive modeling of charged particle motion through the instrument includes the entire composite ExB probe structure, but here the initial analysis focuses on only the Wien filter. In the Wien filter, ions experience superimposed electric and magnetic forces. Charged particle motion in electric and magnetic fields is governed by the Lorentz force equation, Eq. (1), where q is the particle charge, $\vec{E}$ is the electric field, $\vec{v}$ is the ion velocity, and $\vec{B}$ is the magnetic field. Particles that pass through the filter experience no net force. In this situation, Eq. (2) shows that the electric field can be written in terms of the charged particle velocity and magnetic field. As shown in Figure 1, the triad of particle velocity, electric field, and magnetic field are typically set up to be an orthogonal system. For the purposes of this paper, ion velocity, electric field, and magnetic field are assumed to be in the x, y, and z directions,

respectively. Equation (3) shows that the particle velocity passing through the filter (Wien velocity) can be selected by changing the magnitude of the electric and/or magnetic field. Ions with velocity slower than the Wien velocity experience a net force in the electric field direction, while ions with faster velocity experience a net force opposite to the electric field direction.

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) = 0 \quad (1)$$

$$\vec{E} = -\vec{v} \times \vec{B} \quad (2)$$

$$|\vec{v}| = \frac{E}{B} = v_{Wien} \quad (3)$$

Typically, a constant magnetic field is applied with permanent magnets and the electric field is created by applying a known electric potential difference between two parallel plates, V_{plates} , separated by a gap distance, d , as shown in Eq. (4). Combining Eqs. (3) and (4) into Eq. (5) shows that the ion velocity selected to pass through the filter can be adjusted by changing V_{plates} . In this way, the Wien filter acts as a charged particle velocity filter.

$$E = \frac{V_{plates}}{d} \quad (4)$$

$$|\vec{v}| = v_{Wien} = \frac{V_{plates}}{Bd} \quad (5)$$

The Wien filter is also used as a particle mass analyzer or mass spectrometer, or more specifically, as a particle charge-to-mass ratio analyzer. Conservation of energy requires that the change in kinetic energy of an ion with charge, q , and mass, m , is related to the change in electric potential energy, V_{accel} , as shown in Eq. (6) (assuming the ion starts from rest).

$$v = \sqrt{\frac{2qV_{accel}}{m}} \quad (6)$$

If all ions are accelerated by the same change in electric potential, V_{accel} , then the ion charge-to-mass ratio can be expressed as a function of the ExB probe plate potential difference, V_{plates} , by combining Eqs. (5) and (6) into Eq. (7). The Wien filter is a particle charge-to-mass ratio filter.

$$\frac{q}{m} = \frac{1}{2V_{accel}} \left(\frac{V_{plates}}{Bd} \right)^2 \quad (7)$$

Finally, in the case where all particles have the same mass, m , and the particle charge, q , is expressed as a multiple, Z , of the fundamental charge, e ($q = Ze$), then the Wien filter can be used as a particle charge-state filter, Eq. (8).

Note, Eq. (8) shows that, in ExB data (spectra), the peaks associated with different charge states, Z , are separated by the square-root of the plate potential difference, V_{plates} . This is the common application in Hall-effect thruster and gridded ion thruster tests to measure the multiply-charge ion composition of the plume, e.g., the fraction of plume ion species that are singly-, doubly-, triply-charged.

$$Z = \frac{m}{2eV_{accel}} \left(\frac{V_{plates}}{Bd} \right)^2 \quad (8)$$

B. Non-uniform fields

In a real Wien filter, one must account for the fact that the electric and magnet fields are not perfectly uniform. For the B-field, the best practice is to measure the actual field along the probe centerline. Instead of measuring only the peak B-field strength and assuming the peak value is constant and uniform along the axis, it is recommended to measure the entire B-field axial distribution, ideally by using a motion stage to translate a magnetic field probe attached to a Gaussmeter. If comprehensive direct measurements are not feasible, the next best approach is to simulate the field profile using the probe geometry and a 3D finite-element EM field simulator, such as Ansys Maxwell or COMSOL AC/DC Module. While simulated field shapes are generally reliable, the absolute field strength often deviates from actual values, so at least one direct measurement datapoint is needed to anchor and scale the simulation. Due to the challenges in measuring the E-field, a 3D EM field simulation is typically the best option. Although a 2D finite-element EM simulator, such as FEMM, offers faster simulations and is often available for free, it should be used only for early-stage design, as it lacks the full accuracy needed for final analysis. Effective electric (E_{eff}) and magnetic (B_{eff}) field strengths can be calculated from the measured or simulated field profiles ($E(x)$ and $B(x)$) using Eqs. (9) and (10), respectively. The effective Wien velocity that accounts for the field non-uniformity is given by Eq. (11) [57]. In this equation, B_{pra} is the practical B-field strength, and E_0 is the E-field strength at the center of the filter section, which typically matches well with V_{plates}/d_e . The ratio of the effective to the center E-field strength (E_{eff}/E_0) is generally close to, but less than, one, and independent of the applied potential difference (V_{plates}).

$$E_{eff} = \frac{1}{l_f} \int_0^{l_f} E(x) dx \quad (9)$$

$$B_{eff} = \frac{1}{l_f} \int_0^{l_f} B(x) dx \quad (10)$$

$$v_{w,eff} = \frac{E_{eff}}{B_{eff}} = \frac{V_{plates}}{d_e} \frac{1}{B_{pra}} = \frac{V_{plates}}{d_e} \frac{E_{eff}/E_0}{B_{eff}} \quad (11)$$

Figure 2 shows example simulated E- and B-fields for the typical ExB probe geometries. The x-axis corresponds to the axial distance from the center of the filter section normalized to the filter section length l_f . The E- and B-fields

are normalized to their values at $z = 0$ ($E_{y,0}$ and $B_{z,0}$). The net effect of spatial non-uniformity of the fields can often cause B_{pra} to be 85-95% of the B-field strength at the center of the filter section. This difference can cause systematic error in the calculated ion velocity.

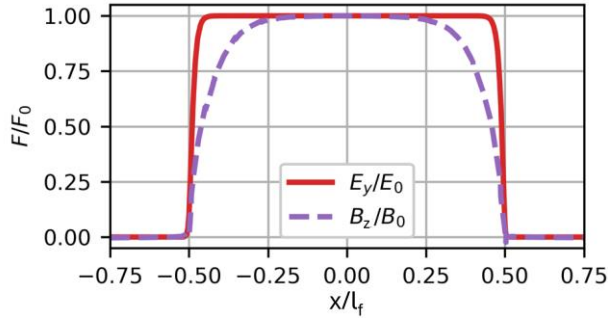


Figure 2: Example typical non-uniform electric and magnetic field profiles along the ExB probe axis (x-axis in Figure 1).

C. Instrument Transmittance and Velocity Resolution

The Wien filter analyzed in the previous section is only one part of the composite ExB instrument (as shown in Figure 1), and more complex models account for the transmission of ions through all parts of the probe. In other words, real-world effects such as the finite geometry and size of the instrument, non-uniformity of the applied fields, particle collisions, and non-axial velocity component enable ions that are not at the ExB Wien velocity to pass through the probe and be collected. In the most general sense, the filtering properties of the composite ExB probe can be modeled and analyzed by considering it as a blur filter with an associated transmittance. Figure 3 shows the concept of transmittance. A single-species, monoenergetic ion beam enters the filter region from the left. In this case, the ion beam is deflected downward by a distance Δy_f because the ion velocity is slightly less than the Wien velocity. Even though the ion velocity is different than the Wien velocity, the measured current is not zero because a fraction of the beam still reaches the collector. The measured current is proportional to the fraction of the ion beam current that is transmitted and reaches the collector. The transmittance and the convolution matrix of a specific probe geometry can be obtained analytically [57] or computationally by Monte Carlo simulation of the trajectory of ions through the instrument [59].

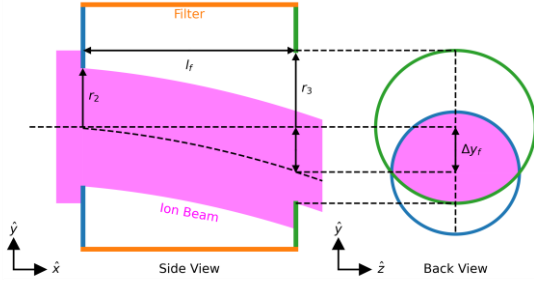


Figure 3: Illustration of transmittance that is the fraction of the ion beam transmitted from probe entrance orifice to collector.

The ExB probe analyzes a population of charged particles whose velocity is described by a velocity distribution function, f , and for a particle species, k , the true IVDF of those particles is f_k . Ions with velocity that is different than the Wien velocity may still reach the collector (transmittance is not zero) and the ExB probe counts these ions as ions at the Wien velocity. Therefore, the ExB probe acts as a blur filter of the true IVDF. The current collected at a given plate potential, and corresponding Wien velocity, for ion species k is given by:

$$I_k|_{V=V_{plates}} = A_{beam,k} q_k n_k \int_0^\infty [T_k(v, v_{Wien}) \cdot v f_k(v)] dv \quad (12)$$

where $A_{beam,k}$ is the unfiltered beam diameter and n_k is the number density of species k . T_k is the transmittance and is a geometric parameter of the probe. The transmittance has a value from 0 to 1 and acts as a weighting factor in the convolution matrix. The output data from the ExB probe, i.e., the ExB probe spectrum, can be interpreted as a convoluted image of the true IVDF. The measured probe current can be represented as Eq. (15), where $g_k|_{v=v_{Wien}}$ is the measured distribution function of the velocity v_{Wien} . Equations (12) and (13) together then form the convolution relation for the ExB probe, which reduces to Eq. (14). The measured probe spectrum (g_k) is modified from the true IVDF (f_k) dependent on the probe transmittance (T_k). With numerical regularization techniques it is possible to recover the true IVDF from the measured probe spectrum when the probe transmittance is known. These data analysis techniques are described in Section VI.

$$I_k|_{V=V_{plates}} = A_{beam,k} q_k n_k v_{Wien} g_k|_{v=v_{Wien}} \quad (13)$$

$$g_k = \frac{v_{ion}}{v_{wien}} T_k f_k \quad (14)$$

Figure 4 shows the transmittance matrix computed for xenon ions and two different conceptual ExB probe designs (A and B). The assumed probe dimensions are given in Table 1 and correspond to Figure 1. Generally, probe A is a longer Wien filter length and/or smaller orifices. Figure 4 shows plots of the velocity of ions entering the probe that

are collected (y-axis) as a function of the imposed Wien velocity (x-axis). In the ideal case, the only ion velocity passing through the probe would be exactly the Wien velocity (Eq. (5)). In reality, a range of ion velocity is collected.

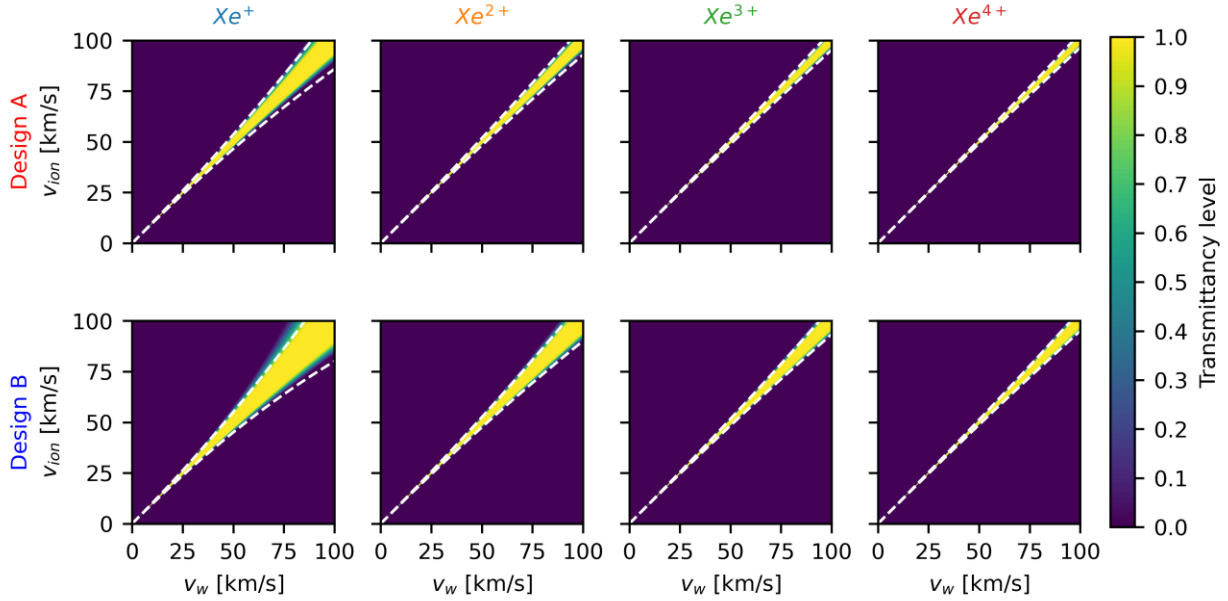


Figure 4: Resolution and transmittance of two different ExB probe designs of Table 1.

Table 1: Example ExB probe design dimensions.

	Aperture Radius (mm)				Length (mm)			Plate Sep. (mm)	Magnetic Field (T)	(1/m)
Probe	r1	r2	r3	r4	lc	lf	ld	de	B	G
A	1	2	3	4	100	200	50	10	0.2	0.208
B	1	2	3	4	100	125	50	10	0.2	0.364

Probe velocity resolution is related to the transmittance and is the maximum range of ion velocity that can transmit through the probe at a given set point Wien velocity. The velocity resolution can be seen in Figure 4 as the vertical span of the colored region for a given Wien velocity. From Figure 4, it is clear that the velocity resolution is broader (worse) for larger Wien velocity, larger ion mass, and smaller ion charge state. A direct estimate of the probe velocity resolution can be determined by considering the single particle equation of motion of an ion passing through the probe, as was done by Huang and Shastry [58]. The resulting probe velocity resolution, Δv , is given in Eq. (15), where G is similar to the transmittance and is a constant based on the probe geometry and size, i.e., collimator length, aperture radii, filter length, etc., and is given in Eq. (16). The G value is given in Table 1 for the two notional probes whose transmittance is shown in Figure 4. Each plot in Figure 4 shows two white dashed curves that are the maximum and minimum ion velocity collected by the probe at a given Wien velocity due to the finite velocity resolution (Eq. (15)).

$$\Delta v = \frac{mv_{Wien}^2}{ZeB} G \quad (15)$$

$$G = \frac{2r_2 + 2r_4 + 2(r_1 + r_2) \frac{(l_f + l_d)}{l_c}}{l_f^2 + 2l_d l_f} \quad (16)$$

Figure 5 shows the effect of probe transmittance and velocity resolution on the resulting measured ExB probe spectra for xenon ion beams. Figure 5A shows a notional narrow beam energy distribution representative of a gridded ion thruster (GIT), while Figure 5B shows a broader energy beam representative of a Hall-effect thruster (HET). Both are shown with up to quadruply-charged ions. The measured ExB probe spectra are different depending on the probe geometry and corresponding probe velocity resolution. For a narrow beam energy source like a GIT, even the wide velocity resolution probe B measures a spectrum with clear separation between the different ion charge-state species. The velocity resolution is so wide that it collects the entirety of each different charged species and the spectrum is a series of approximately flat constant current measurements for each species. While the shape of the measured ExB spectrum is different than the true IVDF, it is relatively straightforward to compare the magnitude of each plateau and thereby estimate the relative species fractions. For a broader beam source like the HET, the IVDFs of the different charge-state species overlap. In this case, the wide velocity resolution of probe B is unacceptable. Even the narrower resolution probe A measures a spectrum with overlap and convolution of the IVDFs of the different species. In general, a recommended rule of thumb is that the probe velocity resolution should be an order of magnitude smaller than the width of the IVDF so that the IVDF can be resolved. However, this is not always possible because a confounding tradeoff is that narrower velocity resolution generally results in lower signal-to-noise ratio. This effect can also be observed in Figure 5B where the narrower velocity resolution probe A has a lower current. Further, even with a finer velocity resolution probe, more sophisticated data analysis techniques are generally required to analyze broad-beam ion source data, like the HET, because the IVDFs of different species overlap. These data analysis techniques are described in detail in Section VI.

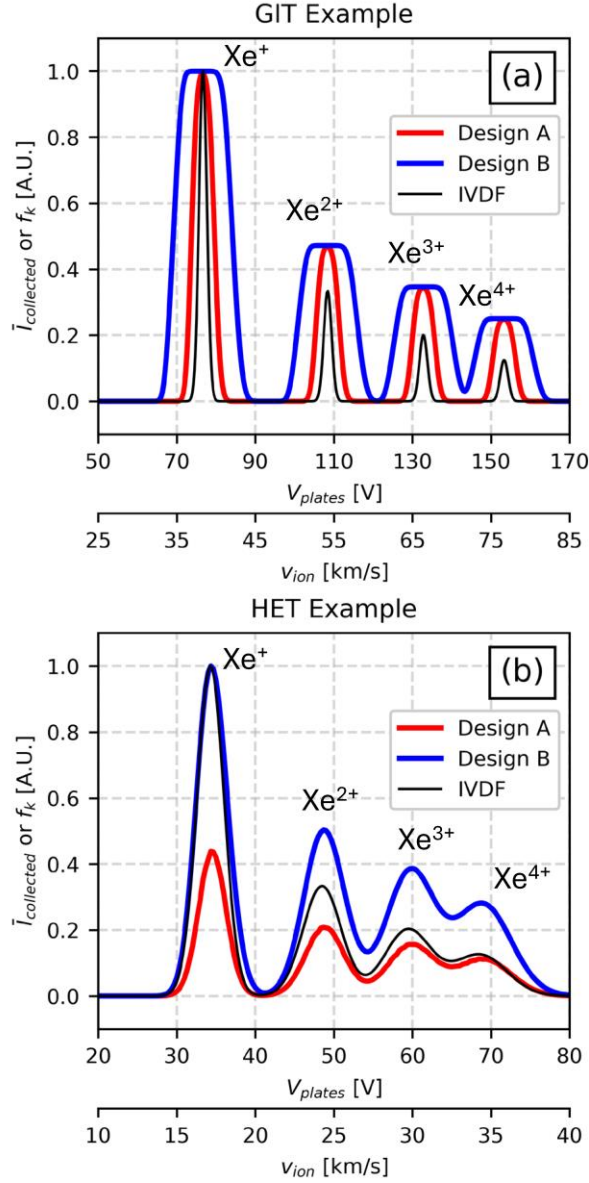


Figure 5: Effect of velocity resolution on the measured ExB probe spectra.

IV. Design

Designing an ExB probe requires balancing resolution, signal strength, mechanical complexity, and environmental robustness. Finer velocity resolution is generally achieved through smaller entrance and exit apertures, longer Wien filter and drift sections, and tighter geometrical tolerances. These changes reduce the geometric transmission constant G , improving resolution as shown in Eq. (15), but they also decrease ion transmission and collected current, which in turn decreases signal-to-noise ratio and may strain detection electronics and limits. The resolving power of the probe is highly sensitive to its geometry, including collimator dimensions, filter length, and suppressor aperture size, all of which determine the range of ion trajectories that reach the collector. Crucially, the ExB filtering relies on strict

orthogonality between the ion velocity, electric field, and magnetic field vectors; thus, precise alignment between the entrance collimator and the Wien filter is essential. Misalignment can introduce deviations from the ideal force balance and degrade velocity filtering. In practice, optimizing resolution must be weighed against practical constraints on probe size, manufacturability, and signal detectability. This section outlines recommended design practices for each major component of the probe, including guidance on materials, geometry, and practical tradeoffs related to signal quality and measurement fidelity.

A. Examples of Specific ExB Probe Designs

Figure 6 shows photographs of specific ExB probes found in the literature and in use by the authors. In all the photographs, the collimator tube can be seen on the left, the Wien filter is in the middle, and the drift tube and detector are the tube on the right. Some designs are “bare” ExB probes (Figure 6a through f) where the collimator, filter, and drift tube are the exterior plasma-facing surfaces of the probe. Other designs enclose these components within a box such that the box is the exterior plasma-facing surface (Figure 6g and h). Further, some probes (Figure 6g and h) include an ion-induced electron emission (IIEE) suppression electrode between the drift tube and collector.

B. Design Considerations for Specific Probe Components

1. Collimator

The collimator acts as a mechanical filter, limiting ion acceptance to those entering at small angles relative to the probe centerline. This ensures accurate velocity filtering and minimizes the impact of off-axis ions. The maximum acceptable incident angle is given by Eq. (17). To prevent contamination from thermal electrons, the entrance aperture radius should be smaller than the local Debye length ($r_1/\lambda_d \ll 1$). Additionally, longer collimators improve angular filtering, but reduce signal due to geometric constraints. Finally, the collimator should be conductive and electrically connected to the grounded ExB probe body. Additionally the collimator will experience ion bombardment sputter erosion so selection of low-sputtering material and a design that allows easy replacement of the collimator and/or orifice are recommended.

$$\alpha_{max} = \tan^{-1} \left(\frac{r_1 + r_2}{l_c} \right) \quad (17)$$

2. Wien Filter

The Wien filter is the core velocity selection mechanism of the ExB probe. It consists of two parallel electrodes that generate an electric field and two permanent magnets that produce a transverse magnetic field. These fields are oriented orthogonally to one another and to the ion velocity vector. The electrodes must be electrically isolated from the rest of the probe. Symmetric plate biasing is recommended to minimize field distortion, and electrode geometries should be optimized to reduce edge effects. The magnetic field is typically generated using permanent magnets, with the body of the filter designed to help guide and shape the field. High-uniformity fields can be achieved using a k=2 Halbach array configuration.

For the filter electrodes, stainless steel or molybdenum are commonly used, with gold plating optionally applied to maintain electrical conductivity and prevent oxidation in humid environments. The housing that supports the electrodes and magnets may either contribute to magnetic field shaping or serve as a passive structural element. If field shaping is desired, soft magnetic materials such as low-carbon steel or magnetic stainless (e.g., 430SS) can be used to guide the magnetic flux. In designs where the magnetic field is self-contained, such as with a Halbach array, non-magnetic materials like graphite or aluminum are suitable alternatives, offering lower sputter yields and simplified machining. For electrical isolation, high-temperature ceramic insulators such as alumina, steatite, macor, or boron nitride are recommended due to their dielectric strength and thermal resilience. Polymeric insulators like PEEK may be used in low-temperature environments.

Permanent magnets must maintain their magnetic field strength under elevated temperature conditions typical of EP testing. Common choices include samarium-cobalt (SmCo), neodymium-iron-boron (NdFeB), and ceramic magnets. SmCo is often preferred for its superior thermal stability. Field strength is typically in the range of 0.15 to 0.4 Tesla.

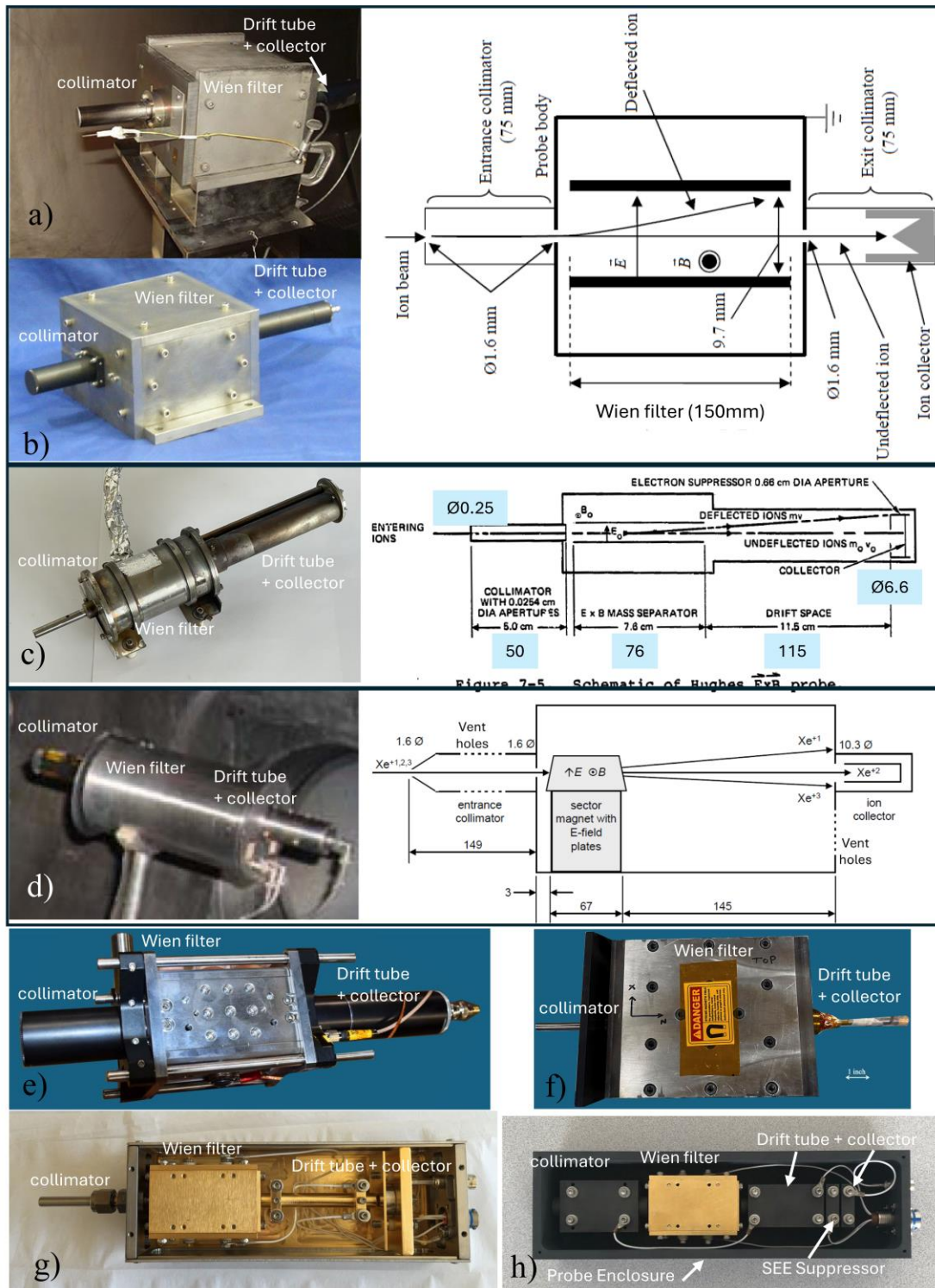


Figure 6: Photographs and schematics of ExB probes reported in the literature; a) and b) from Reid, et. al. [47] in use at University of Michigan and Georgia Tech, respectively, c) Vahrenkamp [33] and Beattie [60], d) Pollard [37], e) Naval Research Lab, f) University of Illinois dual-collector probe [61], and g) and h) Plasma Controls LLC. Units in mm.

3. Drift Tube and Collector

The drift tube connects the Wien filter to the collector and provides space for velocity-based deflection to occur. A longer drift length increases the ion trajectory separation, thereby improving resolution. However, longer tubes also reduce transmitted current and increase probe size. The drift tube should be conductive and electrically connected to the grounded ExB probe body. Additionally the drift tube may experience ion bombardment sputter erosion so selection of low-sputtering material is recommended.

The collector serves as the detection element of the ExB probe, measuring the ion current that passes through the filter and drift sections. Ion induced electron emission (IIEE) can artificially inflate measured current. The IIEE yield, sometimes referred to as ion-induced secondary electron yield (IISEY), depends on several factors, including ion species, charge state, and kinetic energy, as well as properties of the target material such as work function and surface condition [62-64]. IIEE is often divided into potential and kinetic components. The potential electron emission is independent of projectile energy and attributed to Auger or resonance neutralization. In contrast, the kinetic emission is energy-dependent and occurs via direct momentum transfer from the projectile. It dominates at keV energies but can sometimes contribute below 1 keV. To reduce IIEE, the collector is typically made from materials with low secondary electron yields, such as molybdenum or tungsten, where molybdenum is easier to machine. The IIEE yield of molybdenum and tungsten under xenon bombardment is given in Table 2 [65-67]. The ion current measured for each species can be expressed including IIEE as Eq. (18), where γ_k is the IIEE yield for species k at the ion energy of interest.

$$I_k = q_k n_k v_k A_c (1 + \gamma_k) \quad (18)$$

Table 2: IIEE yield for xenon ion bombardment of common collector materials in electrons per ion [65-67].

Xenon Charge State	Molybdenum	Tungsten
1	0.022	0.016
2	0.20	0.20
3	0.70* est. from W	0.71

To mitigate IIEE from the collector, a combination of geometric and electrical suppression techniques is typically employed. One common approach is to shape the collector using a cone-in-cylinder geometry that helps recapture emitted electrons. This geometry for the collector is shown in the schematic of the probe of Figure 6a and b. Additionally, a suppressor electrode may be implemented just upstream of the collector and biased slightly negative, typically in the range of -20 to -30 V, relative to the (usually grounded) collector. This negative bias repels secondary electrons and prevents them from escaping the collector region. This approach is shown in the probes of Figure 6g and h.

The ion current signal can be in the low pA range downstream of typical thrusters, particularly off axis. Earlier ExB probe designs often employed electron multipliers (e.g., a channeltron) to boost the signal-to-noise ratio when high-sensitivity detection electronics were not readily available. Many recent measurements have instead relied on

shielded signal transmission using coaxial or triaxial cables and a low-noise amplifier, for instance a picoammeter or electrometer.

4. Probe-Internal Neutral Density and Venting Effects

In low-conductance probes, especially those with narrow apertures and long collimators, neutral gas can accumulate. This may affect measurement fidelity due to charge exchange (CEX) reactions within the probe volume. Vent holes may be utilized and necessary to prevent pressure buildup and can be protected with fine metal mesh to avoid plasma ingress. While probe data analysis must include CEX corrections along the beam path from the source to the probe, this section describes design recommendations for probe venting to reduce the effect CEX collision inside the probe.

Ions entering the probe volume through the entrance aperture are assumed to be neutralized and subsequently thermalized when striking the collector or other surfaces, producing a source of neutral atoms inside the probe. The total neutral density within the probe, n_p , may exceed the chamber background density, $n_0 = P/(k_B T)$, leading to additional CEX beam attenuation inside the probe prior to ion collection. The probe-internal neutral density is written as:

$$n_p = n_0 + n_{inc} \quad (19)$$

where n_{inc} represents the increase in neutral density due to ion beam interactions within the probe. Here, we make an estimate of n_{inc} using a simple gas balance model to gauge the size of n_p relative to n_0 .

CEX attenuation of ions occurs in two regions: (1) between the thruster and the probe entrance, with chamber density n_0 over distance z , and (2) inside the probe between the entrance and the collector, with density n_p over distance z_p , and attenuation in these two regions can be written as Eq. (20).

$$(I/I_0)_Z = \exp(-n_0 \sigma_Z z - n_p \sigma_Z z_p) \quad (20)$$

The rate of neutral production is $\dot{N} = \Gamma A_i$ (in particles/s) due to the ion flux, Γ , and entrance aperture area A_i , assuming each ion becomes one neutral. In terms of current fractions, the flux is $\Gamma = \frac{j}{e} \sum_i \frac{\Omega_i}{Z_i} = \frac{j}{e \bar{Z}}$, where $\bar{Z} = \frac{1}{\sum_i \frac{\Omega_i}{Z_i}}$ is the mean charge state at the entrance of the probe (for example $\bar{Z} \sim 1.5$ from the data of Table 3). This neutral source corresponds to a gas throughput, or gas load, $Q = \dot{N} k_B T$. The neutral flow out of the probe is through the entrance aperture area, A_i , and any additional non-front-facing vent area, A_v . Assuming free molecular flow and thin-orifices, the total conductance (in volume/s) of these openings is $C_{tot} = \frac{1}{4} (A_i + A_v) \bar{v}$, where $\bar{v} = \sqrt{\frac{8 k_B T}{\pi m}}$ is the mean thermal speed of neutrals at the probe temperature.

At steady-state, the internal pressure rise, $P_{inc} = n_{inc} k_B T$, is such that the gas throughput $Q = \dot{N} k_B T$ equals the outflow through the conductance, $Q = C_{tot} P_{inc}$. Combining the above relations yields:

$$n_{inc} = \frac{\dot{N}}{C_{tot}} = \frac{\frac{j}{e\bar{Z}}A_i}{\frac{1}{4}(A_i + A_v)\bar{v}} \quad (21)$$

This expression highlights that probes at high incident current density (j) and with small exit conductance ($A_i + A_v$) are more susceptible to internal neutral accumulation. Note that when there is no additional probe venting, $A_v = 0$, the neutral density increase does not depend on the area of the entrance aperture. If the “exits” in the conductance term are not thin orifices, i.e., are instead finite length holes or tubes, the effective areas will go down according to transmission (Clausing) factors and the density will increase.

The internal pressure rise $P_{inc} = n_{inc}k_B T$ is calculated for xenon at an average charge state $\bar{Z} = 1$ and $T = 298$ K in Figure 7 for a probe having no venting ($A_v = 0$) and one having a vent area that reduces the pressure rise by 10x ($A_v = 9A_i$).

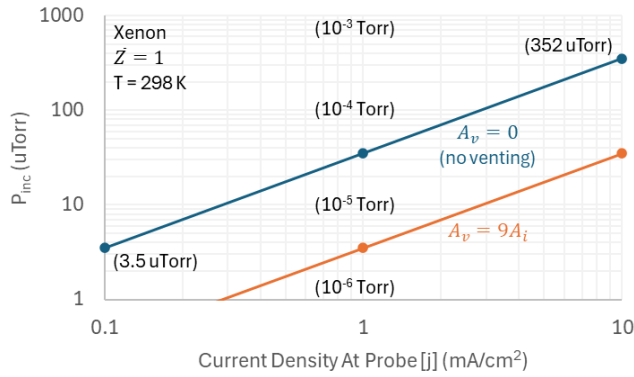


Figure 7: The increase in internal probe pressure as a function of incident current density with and without probe venting.

Two metrics can be computed to help determine the impact of probe venting and thereby impact the probe design. These are the neutral buildup ratio, Π_n , and the optical depth ratio, Π_τ .

$$\Pi_n = \frac{n_{inc}}{n_0} = \frac{P_{inc}}{P_0} \quad (22)$$

$$\Pi_\tau = \frac{n_p z_p}{n_0 z} = \frac{(P_0 + P_{inc})z_p}{P_0 z} \quad (23)$$

Π_n is a simple comparison of the neutral pressure rise relative to the chamber pressure, which could be on the order of 10⁻⁵ Torr in many chambers. If $\Pi_n \ll 1$, the internal neutral density is close to the chamber background density and probe venting is unlikely to be a first order concern. If $\Pi_n \gtrsim 1$, the probe interior density could be at multiples of

background and accounting for pressure rise may be advisable for low-conductance/unvented probes or moderate or greater current density measurements.

The parameter Π_τ is the ratio of internal-to-external optical depth, which compares the strengths of the internal ($n_p z_p$) and external ($n_0 z$) exponential arguments of the correction $(J/J_0)_Z$. $\Pi_\tau < 0.1$ suggests that internal buildup of neutrals would be unlikely to affect corrected charge-state fractions and venting may not be of concern. This would be the case for a short probe placed far away from a thruster at very low current density. If $0.1 \leq \Pi_\tau \leq 1$, internal beam attenuation effects are comparable to facility-path effects. For the probes described herein (Figure 6), the internal path length is approximately 30 cm on average [$z_p = 22$ to 36 cm]. Factoring signal strength and chamber size, many experimental setups could position the entrance of the probe at ~ 100 cm [50 to 200 cm] downstream of the thruster, yielding z_p/z values in the 0.1 to 0.7 range. Thus, regardless of pressure rise or venting, the value of Π_τ suggests that because the internal path length is commonly a significant fraction of the thruster-to-probe distance, CEX correction should at least include the distance z_p . Adding vent area may independently be valuable. If $\Pi_\tau > 1$, internal effects may dominate, and explicit internal-density correction and/or adding venting is recommended.

Finally, it is interesting to consider the temporal dynamics of the build-up and decay of neutral density inside the probe as it is exposed to and removed from the ion beam. The total number of neutral particles within the probe volume V is $N(t) = n(t)V$. The transient balance is $V \frac{dn}{dt} = \dot{N} - C_{tot}(n - n_0)$, and the solution has an exponential form with a characteristic time constant $\tau = \frac{V}{C_{tot}}$ (in seconds). When the probe is placed in the beam (assuming $n(0) = n_0$), ion flux causes the density to rise above the chamber density: $n(t) = n_0 + n_{inc}(1 - e^{-t/\tau})$, where $n_{inc} = \frac{\dot{N}}{C_{tot}}$ as before. When the probe is taken out of the beam at time t_1 , $\dot{N} = 0$ and the density decays back to n_0 as: $n(t) = n_0 + (n(t_1) - n_0)e^{-(t-t_1)/\tau}$. Both the rise and the fall have the same time constant τ , where $\sim 95\%$ of the pressure change occurs in $\sim 3\tau$. Also note the time constant does not depend on the current density. A typical probe could have an internal volume between 100 and 450 cm³, and an orifice diameter between 1.6 and 3.8 mm for the probes mentioned herein. Using xenon at 298 K, $\bar{v} = 219$ m/s, and for an unvented probe ($A_v = 0$), time constants could span a wide range from 0.2 to 4 seconds, or longer for reduced conductance of non-thin orifices. A vented probe should have much greater conductance and equilibrate faster. Even for a large probe, a 10 mm vent diameter should have a time constant below ~ 0.2 s. If a large vent area is created using metal mesh, care should be taken to ensure that plasma is not entering the probe, even when a fine mesh is used.

5. Other Considerations

The housing (plasma-facing surfaces) should be made of materials with low sputter yield and high thermal tolerance. Graphite is often used due to its durability and low sputter rate. To protect sensitive components from thermal loads, a grounded graphite or similarly heat-tolerant thermal shield may be installed in front of the probe.

Alignment of all probe components is key. A common mechanical approach to aid alignment is the use of gauge pins or dowel pins inserted through precision-machined alignment holes to maintain coaxiality between components like the collimator and Wien filter. Typically, the pins are inserted during assembly to hold parts in place while fasteners are tightened, and then removed prior to operation to avoid mechanical over-constraint, interference with

thermal expansion, or electrical issues. In setups where sub-millimeter alignment is required, optical alignment methods—such as using laser beams projected through apertures—can help verify probe orientation relative to the thruster centerline or specific plume features.

C. Design Material Considerations for Alternative Propellants

There is increasing interest in using alternative propellants for electric propulsion [68-71]. These non-noble gases can present some material compatibility considerations for diagnostic probes swept through the plume of a thruster. In addition to minimizing sputtering, surfaces facing into the plume need to consider corrosion and oxidation. Cesium and oxygen-based propellants are uniquely challenging as they are both reactive and effective at sputtering. For species that are a liquid or gas at room temperature, a good first reference is the standard material compatibility chart provided by laboratory gas handling vendors like Matheson, Linde, AirGas, etc. This suggests metals like Monel and stainless steel are more compatible probe construction materials and aluminum and copper-containing alloys are less compatible. For plastics, a good additional reference is chemical storage and personal protective gear compatibility charts.

Reactive molecular species like iodine, ammonia, and ionized oxygen species from water or air are corrosive to many metals and plastics. Refractory metals like tungsten, molybdenum, and nickel tend to be more resistant but there are exceptions for each propellant species. Further guidance can be found in Ref. [72] for oxygen-containing species, Ref. [73] for iodine, and Ref. [71] for ammonia and hydrazine-like species. Reactive species can also transform conductive surfaces into insulators, such as the case of aluminum and silver exposed to atomic oxygen [72]. This can result in undesired surface charging within the probe, altering ion paths. Hence, one must also endeavor to use materials less susceptible to oxidation in ion optics assembly. Finally, redeposited condensed metal propellants may gradually coat insulators, resulting in parasitic currents between electrodes within the ion optics. This can be mitigated by shadow shielding.

V. Implementation and Operation

This section describes the recommended electrical and mechanical setup and operation of the probe in an EP test facility. Additionally, recommendations on the probe motion or sweep through the thruster plume and the pointing and orientation of the probe with respect to the thruster are also described. Recommendations regarding probe field-of-view, alignment, and check-out procedures are also provided.

A. Electrical Setup

An ExB probe has at its core a velocity filter containing orthogonal electric and magnetic fields. Typically, the magnetic field is held constant with permanent magnets while the plate voltage is adjusted to impose an electric field of varying strength and thereby adjust the filter band-pass velocity. The ions that pass through the filter collide with a collector electrode and are recorded as current. Thus, the base electrical configuration of the ExB probe should allow for (1) adjusting the electric potential difference between two plates (V_{plates}) to establish the electric field and (2) precise collection and measurement of ion current at the collector. Considerations regarding power supply biasing,

probe body biasing, and current collection are essential to ensure precise and accurate probe measurement and operation.

Data analysis generally requires curve-fitting to the recorded data. The resolution and range of V_{plates} potential difference values investigated must be sufficient to enable the data analysis. Generally, it is recommended to set the range of V_{plates} values by first estimating the V_{plates} value required to detect the highest charge-state specie and then add an extra 50%. Thus, the recommended minimum plate voltage range ($V_{plates,range}$) is given by Eq. (24) [74]. A general estimate of V_{accel} is 75-97% of the discharge voltage for Hall-effect thrusters [45,75]. $V_{plates,range}$ should be calculated for each expected species charge-state, and the most conservative (largest) value should be used. For example, for the probe in Figure 6A, the $V_{plates,range}$ used during HET testing is typically 0 to 120 V. The resolution of the V_{plates} setpoints is typically on the order of 1 V.

$$V_{plates,range} = \left[0, 1.5 \sqrt{\frac{2eZV_{accel}(d_eB)^2}{m}} \right] \quad (24)$$

Increased signal-to-noise ratio is possible by performing multiple sweeps and then averaging, i.e., collecting multiple current-voltage characteristics and then averaging them, and/or by acquiring multiple current measurements at a given V_{plates} set point and averaging. It is recommended to acquire at least two current measurements at each plate potential set point. The probe and harnessing can typically respond to kilohertz changes in applied plate potential without loss or distortion, so the current measurement is typically the time-limiting or measurement rate limiting step in the data acquisition process. Finally, it is recommended that preliminary data be acquired by sweeping the V_{plates} potential in both low-to-high and high-to-low directions, and the resulting current-voltage characteristics should be compared to ensure the results are the same, i.e., there is no hysteresis.

The recommended electrical configuration for the bare and enclosed E×B probes are shown in Figure 8A and B, respectively. An important consideration that drives this electrical configuration is the fact that the probe is immersed in plasma and therefore there exists a plasma sheath at all surfaces exposed to plasma. For the bare probe, the collimator, filter, and drift tube external surfaces are exposed to plasma, while the enclosed probe has a box surrounding those components and they are not in direct contact with the plasma. In either case, an incoming ion must pass through the sheath to enter the probe and this can result in an additional accelerating force if the electric potential of the external plasma is different than the internal probe potential [52]. With this in mind, it is recommended to ground the probe body or enclosure box that is in contact with the plasma. While floating the chassis should result in even less mismatch with the plasma potential, grounding arguably provides superior electrical shielding against noise.

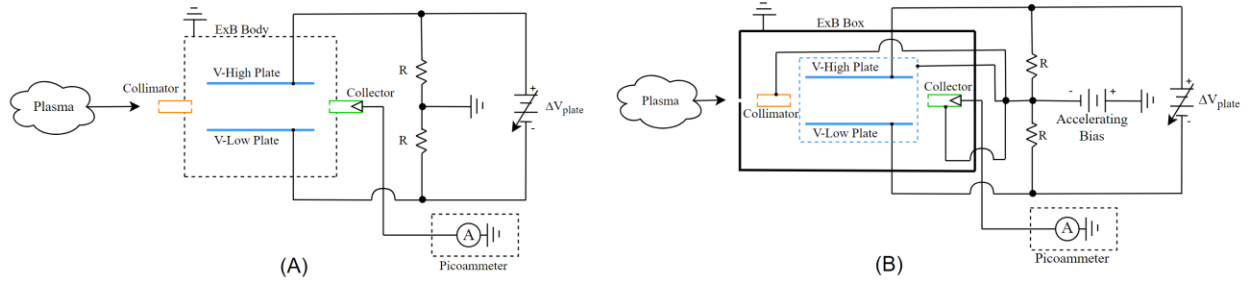


Figure 8: Recommended ExB probe electrical configuration: (A) bare and (B) enclosed probe, respectively.

Any biasing (including grounding) of the probe body or enclosure affects the plasma sheath. For example, as probe body or enclosure potential decreases, the sheath expands and disturbs the local plasma environment and can thereby affect ion trajectories entering the probe and the band-pass velocity [43]. Hence, it is important to measure the local plasma potential at the entrance of the probe, which can be accomplished using a Langmuir [5] or emissive probe [6]. But, generally, the plasma potential in the plume at the probe location is only a few volts above facility ground (e.g., 3-15 V) and this is small compared to the typical beam energy (100-1000 V), so any ion energy/velocity gain between plasma potential and ground is small and typically neglected.

In the case of the bare probe of Figure 8A, it is recommended to also set the probe interior centerline potential to ground potential. To achieve this, it is recommended that the two plate electrodes be symmetrically biased such that the centerline potential is zero. That is, the electrodes should have the same electric potential magnitude, but one electrode should be positive potential with respect to ground and the other negative. This is achieved using a grounded voltage divider circuit on the supply voltage (as shown in Figure 8). The voltage divider resistances, R , should be equal and are recommended to be in the hundreds of $k\Omega$ to $M\Omega$ resistance range to minimize leakage current.

This same grounded-centerline-potential approach can be taken for the enclosed probe of Figure 8B. However, in this case, since the probe body is not in direct contact with the external plasma, it can be biased negatively relative to the enclosure. This allows ions to accelerate in the gap between the enclosure and the collimator entrance orifice, thus increasing the ion velocity (Eq. (6)) and correspondingly the Wien velocity at which the ion transmits through the probe. This is shown by Eq. (25), where V_p is the plasma potential and V_{accel} is the magnitude of the negative accelerating bias potential. Essentially, the accelerating potential increases the separation between the plate voltages for each m/q species in the measured ExB spectra.

$$v_{w,k} = \sqrt{v_w^2 - \frac{2q_k}{m_k}(V_p - V_{accel})} \quad (25)$$

The capability to accelerate ions immediately before they enter the probe has important benefits for studies on low energy ion populations, such as charge exchange ions and ion beams with multiple species with similar mass-to-charge ratio (e.g., air) [76]. An example of this is shown in Figure 9 for a notional low-energy air ion beam. There are four possible ion species: O_2^+ , N_2^+ , O^+ , and N^+ , which have mass-to-charge ratios of 32, 28, 16, and 14 amu/ q , respectively.

All species are assumed to have beam most probable energy of 20 eV. Because of the relatively low energy and small separation in mass-to-charge ratio of these species, the probe is unable to resolve all four species, and the measured probe spectrum has only two distributions: diatomic and monatomic species. When an accelerating bias potential of 280 V is applied, the distributions shift to higher Wien velocity (v_w or plate voltage $V_{electrodes}$) in the measured probe spectrum. Further, the two distributions bifurcate and now show the presence of two diatomic and two monatomic species.

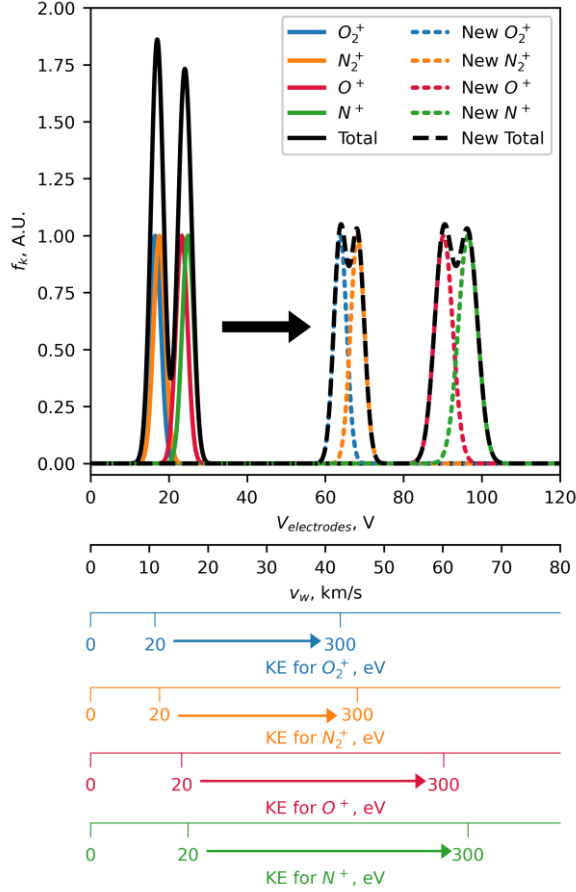


Figure 9: Applying an accelerating potential to ions entering the ExB probe shifts the spectrum to larger Wien velocity and separates the distributions of species with similar mass-to-charge ratio.

It is important to mitigate plasma interactions and ambient noise within the probe to ensure accurate current measurements and a high signal-to-noise ratio. Internal to the E×B device, the plates and collector surface should possess strong isolation, both from each other and from probe body. Typically, these components are mounted on ceramic structures, or other structures of high dielectric properties, and the electrical connections are routed to avoid contact to a conductive surface. To minimize spurious particle scattering in the probe, only low-outgassing materials should be used. If the probe body is properly grounded, the electrical connections internal to the E×B probe can either route via wire or coaxial cable with a low risk of signal interference. The maximum current that reaches the collector

is a function of the $E \times B$ geometry, operational plume current density, and plume species composition, but is typically on the order of tens of picoamperes to nanoamperes [43,46,47,52,58,74]. To maintain a clean and accurate signal with these low currents, special attention must be placed on the collector wires and current measurement device. It is recommended to use grounded shielded wire to transport the collector current and a picoammeter to measure the current as its current measurement range aligns with the operational range of most $E \times B$ configurations. Figure 10 is a photograph of the electrical connections to the ExB probe shown in Figure 6A.

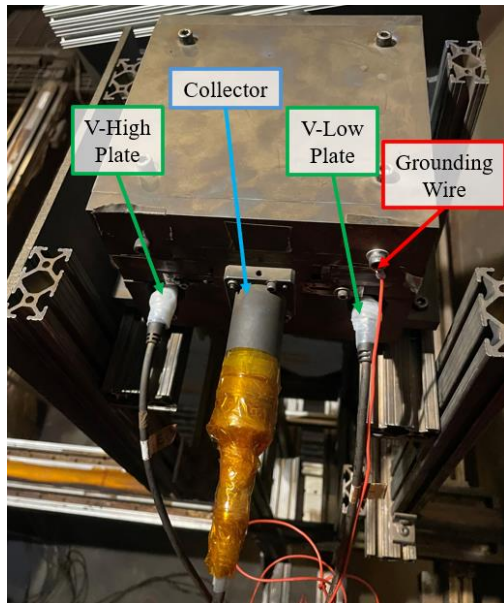


Figure 10: Electrical connections of probe shown in Figure 6A.

B. Physical Setup

The basic setup is an ExB probe placed downstream of and in the plume of the thruster test article, inside a high vacuum test facility. The probe may either be stationary or attached to a motion stage, co-located with additional plasma diagnostics or isolated. When developing the test geometry and sweep routine for the probe, one must consider thermal issues and signal strength, probe alignment, type of thruster, and type of data one hopes to gather.

1. Thermal and Sputter Erosion Issues

For applications involving high-power thrusters or when the ExB probe may be exposed to high level of thermal energy, it is recommended that the probe be installed with a protective shield. This shield should also be designed to minimize sputter erosion by energetic ions, which can produce contamination that backstreams onto the thruster. One approach is to place a low sputter-yield graphite plate or sheet metal with graphoil between the probe and the thruster. This shield should have minimal area to reduce the absorption of thermal power and be mounted with thermal conductive materials (e.g. not stainless steel) to an ambient or cooler surface to ensure it does not overheat. The use of a shutter to protect the entrance of the probe may also be warranted depending on application. If a protective shield

is used, ensure that the protective shield is conductive and electrically tied to the same electrical plane as the entrance collimator of the ExB probe (e.g., electrically tie both components to facility ground). If the shield is at different electric potential than the entrance collimator (10+ eV), the resulting electric potential gradient can lead to abnormal behavior in the signal measured by the probe, leading to erroneous results. A conical shield or entrance aperture can also redirect sputter products away from the thruster.

For high-power application, the temperature of the ExB probe should be monitored to ensure any permanent magnets in the probe do not exceed their operating temperature limit. Note that operating temperature limit of permanent magnet is when the magnet strength begins to degrade, which is lower than the temperature when the magnet experiences permanent demagnetization (a.k.a. the Curie temperature). For reference, an ExB probe, protected by a thermal shield, that was swept at 1.5 m from a 12-kW thruster over ~1 hour experienced approximately 20-25 °C increase in temperature. After a full day of testing (~8 hours of sweeping), the ExB probe temperature reached around 50-60 °C. The key to keeping the probe cool is to make sure the heat on the thermal shield is effectively carried away from the vicinity of the probe.

2. Probe Alignment

The ExB probe requires precise line of sight alignment to the thruster to ensure sufficient signal to noise ratio and proper collection of the desired ion species. One alignment method to ensure proper probe alignment is to use an alignment laser to adjust the ExB position. With this method, the collector is removed from the rear of the ExB probe and an alignment laser is replaced in the collector position. The ExB apertures are then adjusted to maximize the laser transmission through the probe and the probe is positioned to project the alignment laser on the thruster area of interest. Figure 11 illustrates the alignment laser projection process while aligning the ExB probe to the centerline of the P5 thruster.

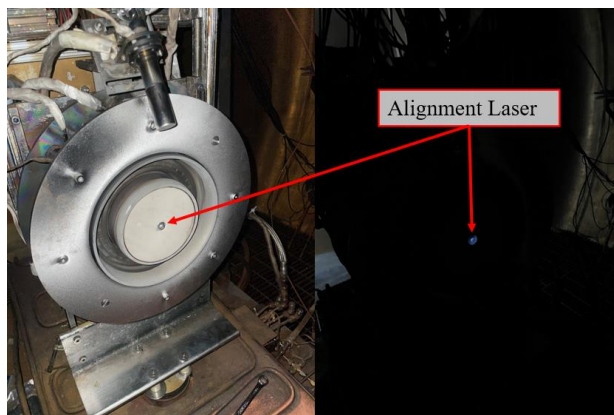


Figure 11: ExB laser alignment to centerline of the P5 Hall effect thruster.

If the thruster is attached to a motion stage, one must ensure the probe remains aligned to the desired target position or positions throughout the range of motion. Misalignment can occur if the axes of the motion stages do not line up properly with the appropriate axes of the thruster (e.g. centerline, plane of the thruster face, etc) or the probe is not

pointing completely orthogonal to the appropriate axis of motion (e.g. an axis of rotation). The vertical alignment can be verified by placing a horizontal laser level at the height of the target and ensuring laser passes through the centerline of the front and the back of the probe over the range of motion. For a polar angle probe sweep with a fixed target on the face of the thruster, the horizontal alignment can be verified by placing a vertical laser level across the face of the thruster and ensuring the laser passes through the centerline of the probe when it is at $+90^\circ$ and -90° .

3. Field of View Considerations and Recommendations

The ExB probe is highly sensitive to orientation angle because of its collimating inlet. Consider the ExB described in Ref. [37]. It has an acceptance angle of 0.6° , resulting in an 8 mm viewing spot on the propulsion device face at distance of 82 cm. If this probe is on the thruster axis, this spot drifts 14 mm across the face of the thruster for each degree of misalignment. Hence a small shift in alignment could change where, or if, ions are being sampled from the thruster. This is in stark contrast with many other plasma probes used for characterizing EP devices. For example, a Faraday probe may be angled up to 8° from optimum orientation, such that it is not even pointing at the thruster and only lose 1% of its current collection area.

It is possible to increase the ExB field of view either by reducing the ExB collimation or by increasing the distance of the probe. The former decreases the ExB velocity resolution, eventually interfering with charge state analysis. The latter is limited by test chamber geometry and can result in increased systematic effects, e.g., charge-exchange between the thruster and the probe. Accepting that the field of view may be smaller than the thruster face, it is natural to ask where on the thruster should the field of view be positioned and located. This depends greatly on the geometry of the thruster being interrogated. Careful alignment of the probe to a pointing angle that provides the strongest and most representative signal is critical.

Sensible test geometries for gridded ion engines are well documented (e.g. [37,77]). The key is that the probe should always point normal to the grids while in the central region of the ion beam and maintain a fixed distance, d , from the grids. This ensures it will capture the maximum current of each beamlet within its field of view. Often the ExB probe is translated through the plume to obtain spatial distributions of charge-state information. For example, previous studies found that the empirical origin of high angle ions was predominantly from the near edge of the grids for a convex dished ion engine [37,77]. Maintaining probe alignment normal to the grids requires special consideration depending on the geometry of the grids. While a simple linear translation is relevant for flat grids, a rotational motion of the probe is required for dished grids where the axis of rotation is placed at the radius of curvature of the grids.

The test geometry used for Hall thrusters in previous literature is typically such that the probe is aligned with the center of the thruster or the discharge channel. The former seems to be dictated more by convenience as one typically mounts an ExB alongside a variety of other probes with broad view factors and comparatively insensitive orientation requirements. For an annular Hall thruster, the true origin of the accelerated ions is not the thruster centerline but the annular channel surrounding it (technically the acceleration region may extend somewhat beyond the channel). This was demonstrated by Sullivan et. al. [48], where they scanned an ExB probe across the thruster face at different polar angles relative to the thrust axis and found two distinct signal peaks associated with the near and far channels. They also found evidence of a “central jet” with apparent origin at the center of the thruster, but only for very low angles

(e.g. $<10^\circ$). Finally, it is important to consider the possible curvature of ion trajectories within the near-field of the thruster. The line-of-sight field-of-view of the ExB is then slightly different from the true field-of-view, accounting for ion curvature. Empirically, this may result in the optimally aligned ExB probe having a line-of-sight to slightly different locations on the thruster face for each polar angle.

C. Considerations on Multiple Ion Populations with Different Energy Distribution and Location of Origin

It is common for the EP thruster plume in a test facility to consist of multiple ion populations with different energy distributions and locations of origin. For example, plume ion interaction with the facility background gas gives rise to CEX collisions and correspondingly a population of lower energy CEX ions that originate outside the thruster. An ExB probe may preferentially measure more or less of a particular distribution depending on its location and angle relative to the thruster. For example, any given Hall thruster will exhibit at least two ion populations with very different characteristics. They are typically called the beam ion population, which has energy near the discharge potential, and the CEX ion population, which has energy around tens of eV. Note that while most CEX ions are created from interaction of beam ions with facility background neutrals, some CEX ions are created from interactions of beam ions with thruster neutrals and will be present even in space. In many Hall thrusters, particularly magnetically-shielded Hall thrusters, one or more ion populations of medium energies (typically 100 to 200 eV) have also been observed [78,79]. Each of the aforementioned ion populations have different points of origin and trajectories, and will exhibit higher or lower signal strength depending on where the ExB probe is placed relative to the thruster and what direction the probe is pointed.

Typically, the region within ± 45 degrees of the firing axis of a Hall thruster is called the main plume or main beam as the plasma in this region is dominated by the beam ion population. The region outside of the main plume is sometimes referred to as the side plume, and non-beam populations including CEX and medium energy ions dominate. The angles that define the transition from main plume to side plume varies with thruster and tends to be larger for operating conditions with lower discharge voltage (60-80 degrees from the firing axis for 300 V discharge) and smaller for operating conditions with higher discharge voltage (40-60 degrees from the firing axis for 600 V discharge). Within the transition region, the overlap between competing ion populations can render accurate analysis of the data difficult to impossible. Figure 12 shows ExB probe data taken at four different angles relative to the firing axes of a thruster operating at 600 V, 12.5 kW [80]. This probe was pointed at radial center of the thruster exit plane. Notably, beam ions dominate the data at 0 and 30 degrees from the firing axis with a medium energy population starting to appear at 30 degrees. In the same figure, CEX and medium energy ions dominate the data at 60 and 90 degrees from the firing axes.

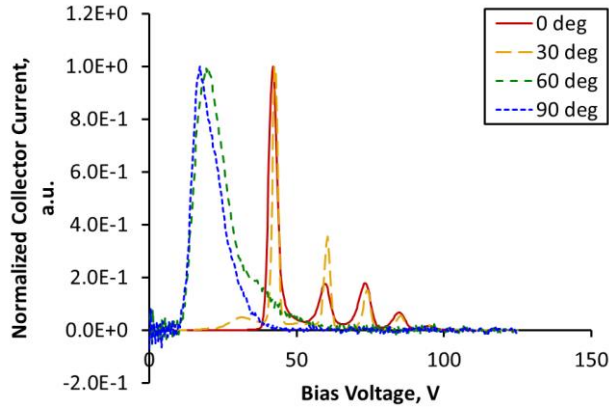


Figure 12: ExB probe data taken at four different angles relative to the firing axes of a thruster operating at 600 V, 12.5 kW [80].

When using ExB probe to characterize the contributions of multiply-charged species to thruster inefficiencies, the measurements should focus on the main plume, as they are responsible for >90% of the thrust generated. Empirical experience suggests that if measurements are made from beyond approximately 4 times the mean diameter of the discharge channel, the probe can usually be aimed at the center of the channel at the exit plane and achieve sufficient signal-to-noise ratio (SNR). Note that questions remain as to whether data collected in this manner will always be representative of the majority of ions originating from the discharge channel, particularly outside the central jet region [48]. If possible, the superior approach is to find the pointing angle at each polar angle where signal is maximized. This is expected to occur when the discharge channel falls within the acceptance angle of the probe. If measuring from closer than 4 times the mean diameter, the probe may need to be aimed at the center of the discharge channel to achieve sufficient SNR.

When using the ExB probe to characterize the contributions of multiply-charged species to erosion of the thruster and/or spacecraft, the measurements should focus on the side plume, as ions velocities that are mostly tangential to the firing axis are responsible for most of the plume-induced erosion. The distance at which these measurements are made depends on the focus of the characterization (e.g., measurements supporting spacecraft wear analysis should be beyond 4 times the mean diameter of the discharge channel). When measuring the side plume, it may be necessary to aim the ExB at a location downstream of the exit plane as many CEX and medium energy ions appear to be born downstream of the exit plane.

D. Pre-test Checkouts

Certain specific probe checkouts are recommended to limit measurement uncertainty in the data collection process and reduce the resultant systematic uncertainty. Probe checkouts can be categorized into electrical and operational checkouts, and are recommended prior to operating the ExB probe. For the electrical checkouts, it is imperative that the following surfaces are isolated from each other and from ground: (1) Collector, (2) V-High Plate, (3) V-Low Plate, (4) Electron Suppression Grid (if installed). If the probe design includes a grounded enclosure (shield) with biased internal probe body, the elements of that body, including collimators, test section, and drift section should be

electrically continuous with each other while isolated from ground. The signal shields and enclosure should be in physical contact with each other and electrically connected to a common ground. If the probe design requires a fully grounded body, the probe body components and shielding should be continuous and in physical contact with each other and connected to a common ground.

The operational checkouts consist of measuring the magnetic field along centerline and centerline gap distance to ensure there are minimal degradations to the probe, and if any deviations from standard measurements exist, the updated values should be used for probe data processing. The permanent magnets in the ExB probe may degrade over time, either due to excessive probe heating close to the Curie temperature, chemical or physical events causing a change in the magnetic microstructure, or time-based magnetic creep [81,82]. Thus, it is recommended to measure the magnetic field strength on probe centerline with a Gauss meter prior to each use to quantify any degradations. Similarly, having an accurate measurement for the gap spacing between the electric field plates in the ExB probe is important since this spacing directly affects the strength of the produced electric field. Periodically measuring and recording this gap distance will ensure there are no shifts over time in the plate positioning and produced electric field strength.

VI. Data Analysis

Over the decades, electric propulsion researchers have developed a variety of approaches to analyzing Wien filter data, some of which are device specific. For ion thrusters, peak height analysis is common because it is a narrow beam source and so a wide resolution ExB probe can be used. The resulting probe data tend to have well-separated non-overlapping peaks corresponding to each charge state. An example ion thruster ExB probe data set is shown in Figure 5A. For the Hall thruster, which is a broader beam source, the most common approach is to perform some form of integration of the data while assuming a particular form for the velocity distribution function. This is often done with a variety of corrections depending on the level of fidelity that the user is trying to achieve. There is a tradeoff between minimal effort and fidelity for the different data analysis methods and the user is advised to weigh the trade-offs. For example, a user developing a new Wien filter for a laboratory that is likely to be used for ten years may opt to spend the upfront effort to develop an automatic data analysis script that achieves a high level of accuracy. Whereas a user working with data in a one-off application without detailed knowledge of the probe may forego some correction factors that are effort intensive to implement. In all cases, the user should try to estimate the uncertainty in the final results associated with the fidelity of analysis performed. Note that if multiple sweeps were taken within a given test setting to increase signal to noise ratio, these sweeps should be averaged prior to any further analysis.

For new ExB probe users, it is recommended that the user follow the flow chart in Figure 13 below for ExB probe data analysis. Oval boxes show decision nodes while rectangular boxes show action nodes. Names of the analysis techniques shown in the action nodes correspond to titles of sub-sections within this section. Note that for the first decision node, if the ion distributions are known to be broad and overlapping but you still get peaks with flat tops, your ExB probe may be damaged. Once a user has some experience with this diagnostic, the user is advised to weigh the trade-offs of different methods for their application. See each sub-section for details about usage and limitations of each analysis approach.

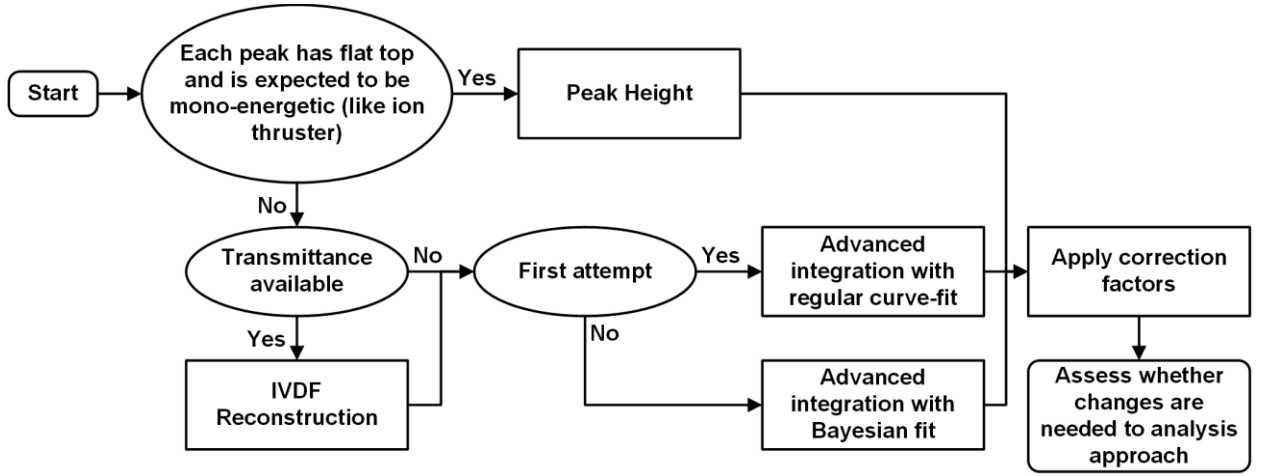


Figure 13: Step-by-step approach to ExB probe data analysis for new users.

A. IVDF Reconstruction

The recorded ExB probe spectrum is a convolution of the true IVDF, as described by Eq. (14). An estimate of the true IVDF can be reconstructed from the measured ExB probe spectrum and the inverse of the convolution matrix, as described by Eq. (26) (bold text indicates matrices).

$$\mathbf{f}_k = \mathbf{T}_k^{-1} \mathbf{g}_k \quad (26)$$

The convolution matrix of the ExB probe may not have an inverse or may be ill-conditioned. In this case the problem can be viewed as a linear inverse problem as shown in Eq. (27), where ϵ represents noise or errors in the measured data. Simply trying to solve Eq. (27) using a least squares technique can lead to unstable solutions. Regularization helps by imposing additional constraints that lead to more stable and realistic solutions. The most common form of regularization is Tikhonov regularization [59,83-85], which adds a penalty on the size of the solution. The modified minimizing function is given by Eq. (28), where λ is the regularization parameter. The solution can be obtained analytically as Eq. (29).

$$\mathbf{g}_k = \mathbf{T}_k \mathbf{f}_k + \epsilon \quad (27)$$

$$\min_{\mathbf{f}_k} (\|\mathbf{T}_k \mathbf{f}_k - \mathbf{g}_k\|^2 + \lambda \|\mathbf{f}_k\|^2) \quad (28)$$

$$\mathbf{f}_{k,est} = (\mathbf{T}_k^T \mathbf{T}_k + \lambda \mathbf{I})^{-1} \mathbf{T}_k^T \mathbf{g}_k \quad (29)$$

The regularization parameter must be chosen to balance the fit and the smoothness of the data. Larger value of λ smooth the solution more, but may underfit the data. There are a number of mathematical discussions on the regularization techniques [86]. The iterative Tikhonov regularization method has been used in a prior application of ExB probe in Hall thruster [59]. Figure 14 shows an example of the IVDF reconstruction technique. The synthetic

probe spectrum from ExB probe B of Figure 5B is used here. The cyan dashed line represents the IVDF reconstructed from synthetic ExB probe spectrum via the iterative Tikhonov regularization technique. By applying the regularization technique, the IVDF was reconstructed from the measured spectra. After the IVDF has been reconstructed, the current and species fractions can be determined using the techniques described next.

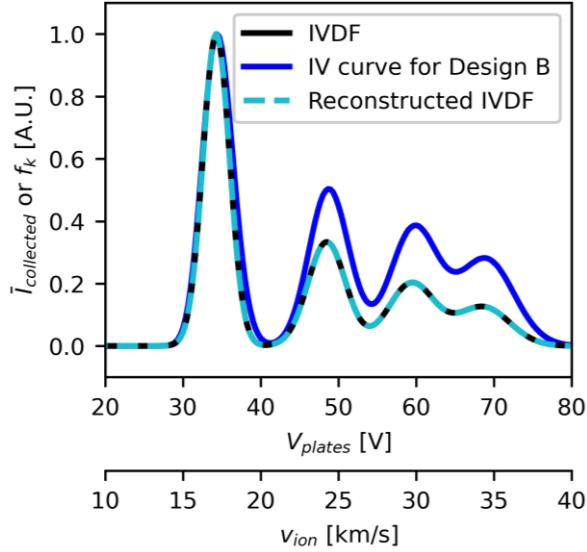


Figure 14: Example of the reconstruction of the IVDF from the ExB probe spectrum of Figure 4B.

B. Calculating Current and Species Fractions

The most basic information obtained from an ExB probe is the current and species fraction. Various analysis methods for deriving these quantities in a Hall thruster setting are described here, roughly in order of increasing effort. Note that the species fraction is based on flux, i.e., ζ_j is the fraction of the incoming flux of particles that are of the j -th species.

1. Peak height

The simplest method for analyzing Wien filter data is to assume that the height of each peak is equal to the relative amount of current associated with each species. Assuming a single propellant and all charged species undergo roughly the same potential drop, the peak associated with the lowest probe bias should be the singly-charged species, the peak with the next higher bias should be the doubly-charged species, and so on. Further, the peaks should be separated by a ratio of the square root of the charge state (i.e., higher charge states are at higher plate potential difference, as described by Eq. (8)). After the relative current fraction of each species is calculated, the species fraction can be approximated using Eq. (25) [87], where ζ_j is the species fraction of the j -th species, Ω_j is the current fraction of the j -th species, and Z_j is the charge of the j -th species.

$$\zeta_j \approx \frac{\Omega_j / Z_j^{3/2}}{\sum_j \Omega_j / Z_j^{3/2}} \quad (30)$$

If multiple propellants are present and the potential drop experienced by each propellant are roughly the same, all singly-charged species of each propellant should be separated by a ratio of the inverse of the square root of atomic mass (i.e., the lighter ions of a given charge show up at higher plate potential difference, as described by Eq. (7)). The remaining description assumes a single propellant unless otherwise specified.

The peak height method is very simple to code and avoids the complexities associated with areas of the data where the distributions of different species overlap. While it may be an acceptable analysis approach for ion thrusters under specific conditions, it has been shown to be highly inaccurate for Hall thrusters [58,87]. Specifically for ion thruster application, the energy spread of the incoming ion beam of each charged species must be narrow enough relative to the resolution of the ExB probe such that the probe is capturing all ions of a given charge-state species. When this condition is met, the resulting current-voltage characteristic exhibits flat tops at the height of each peak (as shown in synthetic data of Figure 5A and empirical data of Figure 15). A sample ExB probe trace illustrating the peak height analysis method is shown in Figure 15. The data were collected using the Advanced NEXT gridded ion engine; details of the thruster design, test facility, and operating conditions are provided in Ref. [88]. The probe design shown in Figure 6H was used, with the probe swept radially at a fixed axial distance of 82 cm downstream of the accelerator grid. Charge-exchange effects were addressed using the method described in Section VI.C., resulting in corrections of approximately 5% depending on the operating condition and background pressure. The doubles-to-singles current ratio was calculated to be 0.18 for the shown trace. The spatially resolved signals were analyzed using the peak height method and numerically integrated to determine the multiply charged ion thrust correction factor, which has previously been shown to closely align with independent thrust stand measurements [89].

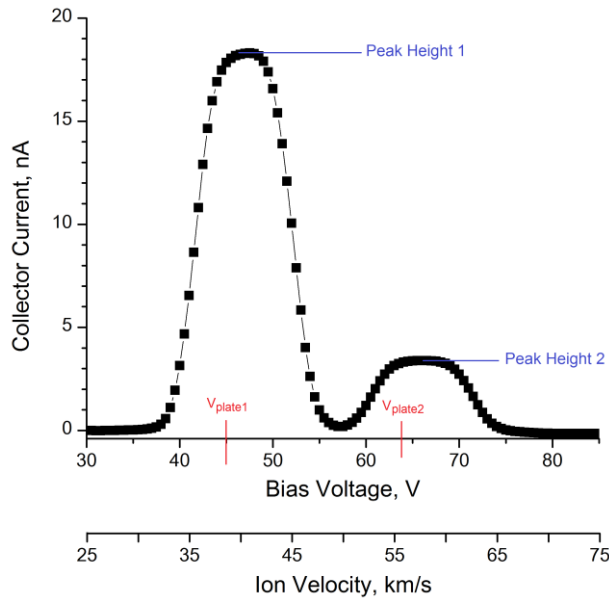


Figure 15: ExB probe trace acquired on centerline of the Advanced NEXT engine at a beam voltage of 1068 V and beam current of 6.0 A. The measured peak locations show good agreement with the predicted values (V_{plate1} , V_{plate2}) from Eqn. (8).

2. Simplified integration

Another method for analyzing ExB probe data is to assume that the area under the curve associated with each peak is the total current of the corresponding charged species. This method will be referred to as “simplified integration”. If the peaks are clearly separated and there is no DC offset in the data, the simplified integration method can yield approximate results. Note that when measuring small current signals with a trans-impedance amplifier, it is common for a portion of the measurement circuit to be floating, which can introduce a DC offset in the measurement. If such an offset is present, it must be subtracted and removed prior to applying any integration method. Further note that Hall thruster plume ions are often not clearly separated. To use this method, one must assume a form for the IVDF and perform the appropriate curve-fit prior to integration. A variety of IVDFs have been used in past literature [42,90-92] and the common forms are shown in Eqs. (31)-(35). They are, in order, triangle, Gaussian, variable exponent, twin/bi Gaussian, and skew-normal distributions. In these equations, f_j is the distribution function of the j -th species, and a , b , c , d , n , a_1 , b_1 , c_1 , a_2 , b_2 , and c_2 , are fitting constants. The $\text{erf}[]$ term refers to the error function. The form of the IVDF commonly employed by the authors in their research is skew-normal or twin/bi Gaussian.

$$\text{Triangle:} \quad f_j(v) = \begin{cases} (-a/b)|v - c| + a, & c - b < v < c + b \\ 0, & \text{else} \end{cases} \quad (31)$$

$$\text{Gaussian:} \quad f_j(v) = a \exp[-b(v - c)^2] \quad (32)$$

$$\text{Variable Exponent:} \quad f_j(v) = a \exp[-b|v - c|^n] \quad (33)$$

$$\text{Twin/Bi Gaussian:} \quad f_j(v) = a_1 \exp[-b_1(v - c_1)^2] + a_2 \exp[-b_2(v - c_2)^2] \quad (34)$$

$$\text{Skew-Normal:} \quad f_j(v) = a \exp\left[-\frac{(v - c)^2}{2b^2}\right] \left\{1 + \text{erf}\left[-\frac{d * (v - c)}{\sqrt{2}b^2}\right]\right\} \quad (35)$$

Note that because particle velocity scales with plate potential per Eq. (5), plate bias voltage can be substituted into velocity without any special conversion for the simplified integration method. However, this introduces errors associated with various non-idealized factors, which are addressed in more advanced analysis methods and correction factors described in subsequent sections of this article.

After a form of the IVDF is selected and fitted to the ExB probe data, Eq. (36) can be used to calculate the current fractions by performing the integrals shown, where I_j is the probe current for species j , and V_{plates} is the potential difference across the probe plates. Assuming all charged species undergo roughly the same voltage drop, Eq. (30) can then be used to calculate the species fraction. The integration approach presented in this section assumes the velocity resolution is a constant function of probe plates bias voltage, which is physically incorrect as shown in Section III.C. However, the results are a good approximation so long as the peaks are narrow and all charged species undergo roughly the same potential drop.

$$\Omega_j = \frac{\int_0^\infty I_j(V_{\text{plates}}) dV_{\text{plates}}}{\sum_j \int_0^\infty I_j(V_{\text{plates}}) dV_{\text{plates}}} \quad (36)$$

As an example, Figure 16 shows a typical data fitting procedure for the simplified integration method. The ExB spectrum was acquired on the NASA 300-M thruster operating at 500 V, 20 kW on xenon propellant using the probe shown in Figure 6D. Figure 16A is the raw measured probe spectrum and shows the measured current as a function of the plate electrodes bias voltage. This spectrum has four distinct peaks corresponding to each xenon charge state. To start the analysis, in Figure 16A, the DC offset is subtracted. The DC offset is calculated most commonly by one of three methods. In each method, an average of the current is taken when no (or very little) ions are impacting the collector. The methods are (a) averaging current from the beginning and end of trace, (b) averaging current at the end of the trace only, or (c) averaging over a null trace (thruster off). In the example shown in Figure 16, option (a) is utilized. An average of the collected current over the range $V_{\text{plates}} < 20$ V and $V_{\text{plates}} > 90$ V is calculated and subtracted from the spectrum. The two averaging windows are shown in Figure 18A between each set of grey vertical lines. This offset is an artifact of the instrument used and is removed during data analysis.

Next, each of the four distributions are sequentially fit with a Bi-Gaussian. In each case, the bounds are user-selected. This fitting process typically starts with the lowest charge-state, Xe^+ , and subsequent fits to higher charge-states are done after removing (subtracting) the fit(s) from the prior lower charge-state(s). The fitting bounds for each charge state are shown as vertical lines in the figure, and the curve fits for singly-, doubly-, triply-, and quadruply-charged xenon are shown in Figure 16B, C, D, E, respectively. The residual indicates the difference between the raw current measurement and the curve fit. Again, note that when fitting to a given charge-state, the residual for it and lower charge-states is near zero because the curve fit(s) for it and the lower charge-state(s) has been subtracted from the raw current measurement. A summation of the four Bi-Gaussian distributions is shown in Figure 16F and compared with the raw measured current. In this case, the fit and the raw current are in close agreement, highlighted by a R^2 value close to unity. The R^2 value, at least in principle, is a good metric to check whether the assumed IVDF shape (Bi-Gaussian) and fitting windows were properly selected for the data. Current and species fractions are calculated using the four Bi-Gaussian distributions fit to the data and Eqs. (30) and (36), respectively. These values are given in Table 3. Note that CEX corrections have not been made for these data (to be discussed in Sec. C).

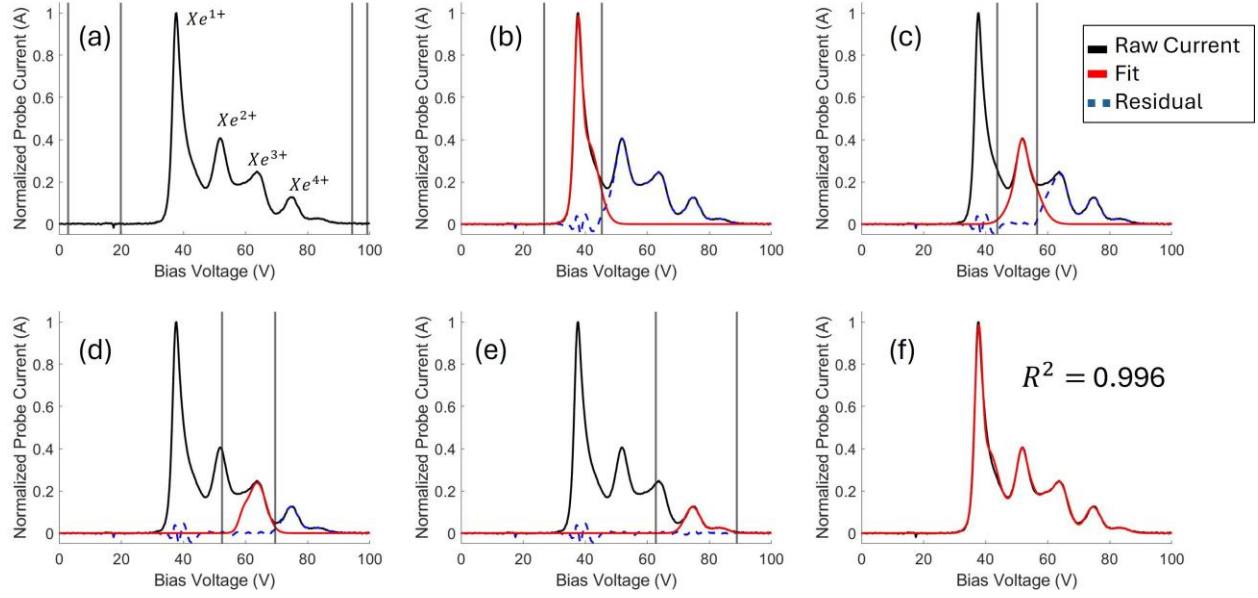


Figure 16: Example fitting procedure for ExB probe spectra.

Table 3: Current and species fractions calculated from the data of Figure 18.

Species	Current fraction (Ω)	Species fraction (ζ)
Xe^+	0.48	0.78
Xe^{2+}	0.24	0.14
Xe^{3+}	0.19	0.06
Xe^{4+}	0.09	0.02

3. Advanced integration

In an idealized ExB probe, the maximum deviation in velocity that a particle can have from the Wien velocity (v_{Wien}) and still make it through to the detector scales as square of the Wien velocity (Eq. (15)) [58]. The Wien filter velocity scales with applied probe plates bias for a given strength of magnetic field, accounting for the probe resolution means that an additional V_{plates}^2 term is needed in the integration. This integration approach will be referred to as “Advanced integration”. Specifically, after a curve-fit form is chosen, Eq. (37) is the actual form to be fitted to the data, where K_1 and K_2 are probe-specific geometric constants and n_j is the absolute density of the j-th species. Since K_1 and K_2 are probe-specific geometric constants, they will cancel out when calculating relative current and species fractions. In theory, it is possible to calculate the absolute density if K_1 is known, but this is difficult for most practical devices and is not necessary for deriving relative current and species fractions.

$$I_j(V_{plates}) = K_1 n_j V_{plates}^3 f_j(K_2 V_{plates}) \quad (37)$$

When the curve-fit constants are found, Eqs. (38) and (39) can be used to calculate the current and species fractions, respectively [58]. Assuming all charged species undergo roughly the same voltage drop, Eq. (30) could also be used to calculate the species fraction from the current fraction. In practice, using Eq. (30) instead of computing the integral (Eq. (39)) introduces error that is negligible relative to other sources for data from Hall thrusters operating at 300 V or more. If uncertain, it is recommended to compute the integral for a few representative cases as a check. Assuming the IVDFs are narrow and all charged species undergo the same potential drop, it is possible to show that Eqs. (38) and (39) reduce to the same result [58]. In practice, for Hall thruster plasmas, the simple integration of area under the curve and integration with idealized probe resolution differs by at most a few percent. The difference tends to be larger for ion beams with wider IVDFs.

$$\Omega_j \equiv \frac{I_j}{\sum_j I_j} = \frac{Z_j \int_0^\infty \frac{I_j(V_{plates})}{V_{plates}^2} dV_{plates}}{\sum_j Z_j \int_0^\infty \frac{I_j(V_{plates})}{V_{plates}^2} dV_{plates}} \quad (38)$$

$$\zeta_j \equiv \frac{n_j}{\sum_j n_j} = \frac{\int_0^\infty \frac{I_j(V_{plates})}{V_{plates}^3} dV_{plates}}{\sum_j \int_0^\infty \frac{I_j(V_{plates})}{V_{plates}^3} dV_{plates}} \quad (39)$$

Figure 17 is a set of bar graphs that compare the current fraction results using the simplified versus the advanced integration method with the skew-normal IVDF form [58]. Figure 18 is a set of bar graphs that compare the current fraction results using the advanced integration method with different IVDF forms for three representative throttle points of the NASA-300M. Also shown are the results the peak height method [58]. Note that all results shown in Figure 17 and Figure 18 are after correction for charge exchange effects. In general, the results show that the advanced integration method is more accurate while requiring a bit more effort to code. Since the integration is not a simple area under the curve, verification using simple shapes or against prior data should be performed to ensure the code is performing the integration properly.

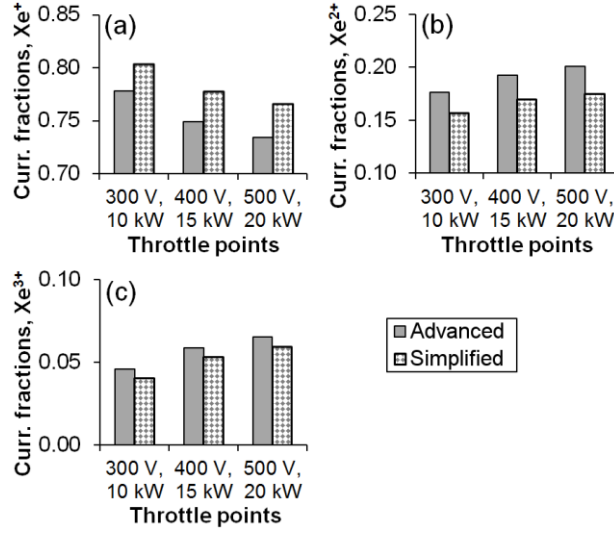


Figure 17: Comparison of current fraction results between the simplified and advanced integration methods. Reproduced from [58] with permission.

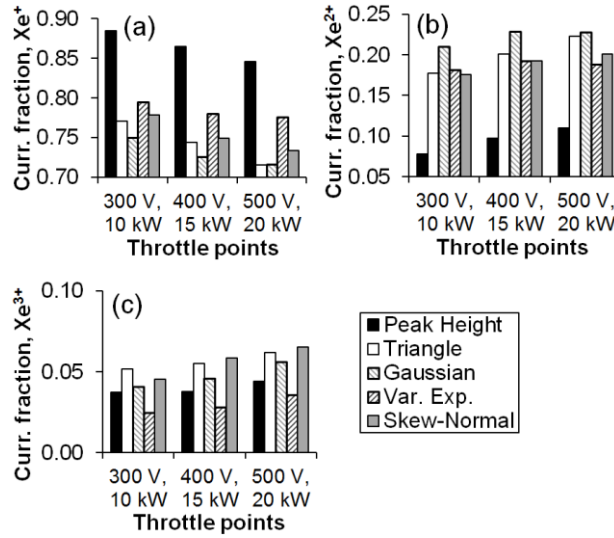


Figure 18: Comparison of current fraction results using the advanced integration method with different IVDF forms of Eqs. (31) to (35). Reproduced from [58] with permission.

4. Bayesian fit

Instead of using curve-fits, users can implement Bayesian inference techniques to fit the ion population. When appropriately implemented, this method avoids ambiguities associated with user selected bounds for each fitting window and provides a more systematic and robust approach to fitting the data. To perform Bayesian fit, the Wien filter spectra, f_{ExB} , can be defined as the sum of the IVDFs for each individual ion species f_k as shown in Eq. (40).

$$f_{ExB} = \sum_k f_k(\theta) \quad (40)$$

In this formulation, θ represents the model fitting parameters. For example, a single population spectrum that is assumed normally distributed would have three fit parameters: $\theta = \mu, A, \sigma$, where μ is the average, A is the intensity, and σ is the variance of the normal distribution. In Bayesian inference, the model parameters are distributions that are updated after introducing data, d , through Baye rule as shown in Eq. (41).

$$P(\theta|d) \propto P(d|\theta)P(\theta) \quad (41)$$

Here, $P(\theta|d)$ is the posterior distribution of model parameters, $P(d|\theta)$ is the likelihood function, and $P(\theta)$ is the prior distributions. The likelihood function, or model, is the summation of the assumed IVDFs for each species. The prior distribution for each parameter represents the state of knowledge before introducing the data. Selection of the prior is the most subjective part of Bayesian inference but can be a useful tool to avoid unphysical parameter values. Continuing with the example of a single normally distributed population, negative values for the intensity, A , or the variance, σ , can be avoided by specifying a uniform prior $U(0-x)$.

For ExB probe spectra, most assumed IVDFs will be non-linear, requiring the use of techniques like Markov-chain Monte Carlo to sample from the un-normalized posterior distribution $P(\theta|d)$ [93]. For each posterior sample, the area under the curve method, Eq. (36), or advanced integration techniques, Eqs. (37) and (38), should be used to evaluate the current fractions. After evaluating the current fractions for each sample, statistics like the mean, maximum a-posteriori, and variance can be inferred from the result. These statistics provide estimates for both the species current fractions and fit uncertainty. Automatic uncertainty analysis is one primary advantage of Bayesian inference over the sequential fitting methods. This can be particularly helpful when there is significant distribution overlap, and the location of peaks is ambiguous [94]. ExB probe uncertainty analysis is discussed further in Section VI.D.

C. Correction for Beam Attenuation due to Charge Exchange Effects

Regardless of the exact method for deriving the current and species fractions, ExB probe data obtained in most ground test environment must be corrected for CEX effects. The effect of charge exchange with background neutrals is typically corrected by modifying the integrated current and integrated density. The correction scheme using Xenon CEX cross-sections, shown in Eqs. (42)-(44), was first presented by Shastry, et al. [87]. In these equations, J is the current density a distance z away from the thruster exit plane, J_o is the current density at the thruster exit plane, and n_o is the average background neutral density. The ion energy per charge, V_1 , V_2 , and V_3 for Xe^+ , Xe^{2+} , and Xe^{3+} , respectively, are either measured by another probe (e.g., a retarding potential analyzer) or assumed to be equal to the discharge voltage. Using the discharge voltage instead of measurements for V_1 , V_2 , and V_3 typically introduces <1% systematic error for ExB probe data that are taken on or near the thruster firing axis [87]. In other situations, an uncertainty analysis should be performed to characterize the error. The value of n_o is typically calculated from facility pressure readings from ion gauges [1]. Finally, note that these relationships, Eqs. (42)-(44), are written for the path length, z , from the source to the probe entrance. It may be important to also include CEX attenuation inside the probe,

as described in Section IV.B.4., depending on the probe venting and internal pressure. In this case, the attenuation due to CEX can be described by two parts, one outside the probe and one inside the probe, as shown in Eq. (20).

$$(I/I_0)_1 = \exp(-n_0\sigma_1 z), \quad \sigma_1 = [87.3 - 13.6 \log(V_1)] \times 10^{-20} m^2 \quad (42)$$

$$(I/I_0)_2 = \exp(-n_0\sigma_2 z), \quad \sigma_2 = [45.7 - 8.9 \log(2V_2)] \times 10^{-20} m^2 \quad (43)$$

$$(I/I_0)_3 = \exp(-n_0\sigma_3 z), \quad \sigma_3 = [16.9 - 3.0 \log(3V_3)] \times 10^{-20} m^2 \quad (44)$$

$$\Omega_j^c = \frac{\Omega_j [(I/I_0)_j]^{-1}}{\sum_{j=1,2,3} \Omega_j [(I/I_0)_j]^{-1}} \quad (45)$$

Equation (45) is used together with the correction factors in Eqs. (42)-(44). The term Ω_j^c denotes the corrected current fraction of the j -th species and Ω_j is the uncorrected current fraction determined from Eq. (36) or (38). Species fraction can be corrected in the same manner. Prior works have shown that asymmetric charge exchange (e.g., $\text{Xe}^{2+} + \text{Xe} \rightarrow 2\text{Xe}^+$) can be neglected for Hall thruster application [87]. For most electric propulsion applications, analysis and CEX correction of Xe^{4+} can be neglected. For example, in the study of a 12.5-kW Hall thruster with operating conditions spanning 300 to 800 V and 4.7 to 12.5 kW, Xe^{4+} current fractions ranged from 0.005 to 0.072, corresponding to species fractions of 0.0007 to 0.015. The influence of Xe^{4+} on the final results was less than the measurement uncertainty of the diagnostic [80]. In this same study the CEX corrections for Xe^+ , Xe^{2+} , and Xe^{3+} varied from 4 to 20% depending on background pressure, which means the CEX correction for each of the first three charged species typically exceeded the magnitude of the fourth charged species, and the correction for the fourth charged species would have been another order of magnitude lower in its effect on the final results. While accounting for Xe^{4+} is generally unnecessary, the user should collect data covering quadruply and higher charged species, if possible, and check whether the amount of quadruply and higher charged species present is ignorable in their analysis.

D. Uncertainty Analysis

1. Uncertainties in the measurement system

In an appropriately designed ExB probe system, probe and electronics uncertainties are typically not the driver of the overall uncertainty. However, these uncertainty factors should be characterized and minimized to ensure they do not drive the overall measurement uncertainty of the system. The energy resolution of the probe, described in in section III.C., represents the lowest achievable measurement uncertainty contributed by the ExB probe itself. Probe misalignment, whether due to poor construction or setup, can increase uncertainty by preferentially collecting ions on angled trajectories. While this uncertainty source can largely be mitigated with modern machining techniques and in-situ laser alignment, it can cause elusive errors if care is not taken. Furthermore, as discussed in section III.B., non-uniform electric and magnetic fields can distort the ion distributions. Detailed modeling, combined with post-fabrication field mapping can help reduce this source of uncertainty.

All electronics have measurement uncertainties described in their respective manufacturing specifications. ExB probe system typically rely on accurate nanoampere or even picoampere meters. These low-current meters are susceptible to thermal drift. If their thermal drift characteristics have not been characterized by the manufacturer, then

they should be characterized to ensure their contribution to total uncertainty is low. If custom components are used (such as external shunts, trans-impedance amplifiers, etc.), the entire measurement electronic system should be characterized together to determine the overall system uncertainty. For example, one can attach a precise current reference (such as a calibrated sourcemeter) to the input of the measurement electronic system and check how the measured value changes over time and as ambient temperature changes. The rate of change combined with time between calibration and typical range of ambient temperature can then be used to determine whether the electronics uncertainty is a driver of the overall uncertainty.

2. Uncertainties in data analysis

Two of the most prevalent sources of uncertainty in data analysis for ExB spectra are a) overlapping velocity distribution functions, and b) charge exchange correction factors. Overlapping IVDFs can lead to a large uncertainty in the relative current/species fractions. The degree to which the species overlap is a function of both thruster type and operating condition. For example, in ion thrusters and non-magnetically shielded Hall thrusters, the distributions are typically distinct. In contrast, magnetically shielded Hall thrusters, especially at high discharge current densities, typically exhibit significant distribution overlap.

An example of distribution overlap is illustrated in Figure 19, which is an example ExB probe spectra from a magnetically shielded Hall thruster at two different operating conditions. The degree of overlap can vary, ranging from easily discernable peaks at low current (Figure 19a) to strongly convoluted at high current (Figure 19b). When the saddle point between distributions is clear, as in Figure 19a, Huang et. al. [58] devised a method to estimate the maximum uncertainty through geometric arguments. While this conservative approach is sufficient in most cases, when the location of saddle points is ambiguous (c.f. Figure 19b), other methods must be used. The preferred method to estimate uncertainty in cases of significant IVDF overlap is to implement a Bayesian fitting approach. As outlined in section VI.B.4., using Bayesian inference techniques to learn the distributions avoids ambiguity of user selected bounds, and statistics like the variance provide automatic uncertainty quantification [94].

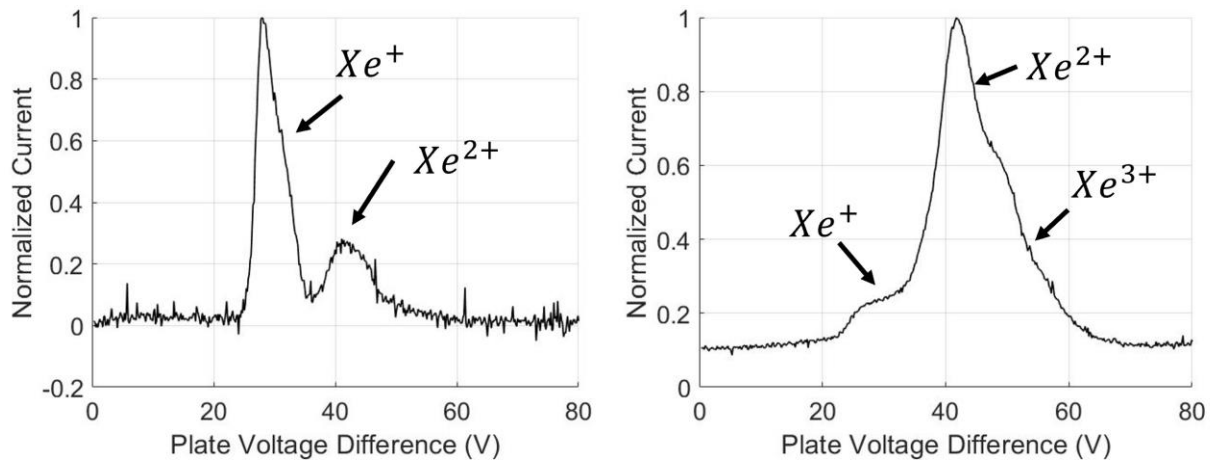


Figure 19: ExB spectra from the H9 magnetically shielded Hall thruster operating on xenon at a) 300 V, 15 A and b) 300 V, 100 A [94]. These data were acquired with the ExB probe of Figure 6A.

In addition to the overlapping IVDFs, there can be significant uncertainty associated with the CEX correction of raw integrated current fractions. As discussed in section VI.C., different CEX collision cross sections for each ion species with the background neutral gas changes the beam composition at the entrance of the ExB probe compared to immediately downstream of the thruster exit plane. The key inputs to the correction model (Eqs. (42)-(44)), are the CEX collision cross section, σ , the distance of the ExB probe, z , and the background neutral density, n_0 . Of these three inputs, the dominant uncertainty source is the estimate of background neutral density, n_0 . Background neutral density is typically calculated from pressure measurements made with ionization gauges with a typical uncertainty of 10-20%. Further, the calculation may be an underestimate because ion gauge measurements are typically made at a lower pressure region at or near the vacuum test facility wall [1], which is outside the high density plume region where ions are having CEX collisions. The CEX correction model assumes a constant background neutral density along the flight path from the thruster to the ExB probe. In reality, the neutral density is non-uniform and likely decreases an order of magnitude within 1 m downstream on thruster centerline. Analysis by Shastry et. al. [87] demonstrated that under most situations where the probe is located far from the thruster (many thruster diameters), CEX attenuation of the beam ions is dominated by collisions with neutrals from the facility background rather than neutrals from the thruster. However, if the probe is placed close to the exit plane (a few thruster diameters) then it is likely that the thruster neutral pressure cannot be neglected and may dominate. Compared to background neutral density, the uncertainty of the other two inputs is negligible. Collision cross section only depends on the ion energy in a logarithmic fashion, and the distance to the ExB probe can be measured precisely, rendering these uncertainties negligible.

Focusing on the uncertainty in background neutral density, the uncertainty in current fractions can be determined from Eq. (46). Following the analysis of Huang et al. [58], the partial derivative of Eqs. (42)-(45) are taken with respect to neutral density and the CEX correction uncertainty is propagated to the current fraction estimate. The result is Eq. (46) and, in this formulation, δn_0 is the uncertainty in the neutral pressure.

$$\left(\frac{\delta \Omega_j^c}{\Omega_j^c}\right) = (n_0 z)^2 \left[\sum_{k \neq j} (\sigma_j - \sigma_k) \Omega_k^c \right]^2 \left(\frac{\delta n_0}{n_0}\right)^2 \quad (46)$$

VII. Comparison with Other Diagnostic Approaches

There are numerous other diagnostics commonly employed to characterize and interrogate the velocity and energy properties of particles in EP thruster plasmas and plumes. A summary of these diagnostics and relevant characteristics is given in Table 4. Retarding Potential Analyzer (RPA) and Electrostatic Analyzer (ESA) [8] are widely used plasma diagnostic probes for analyzing the ion energy distribution function (IEDF). The RPA operates as a high-pass ion energy filter by sweeping a voltage across a set of grids. It provides a cumulative IEDF, requiring users to numerically differentiate the measured data to obtain the energy distribution. In contrast, the ESA functions as a band-pass ion energy filter by sweeping a voltage between two electrodes, allowing ions with specific energies to reach the detector

directly. This enables users to obtain the IEDF without additional data processing. While the ExB probe can separate particles based on their mass-to-charge ratio, both the RPA and ESA analyze energy per unit charge, meaning they cannot distinguish ions with different mass-to-charge ratios. This limitation can sometimes be advantageous, such as in double-layer plasmas. The RPA and the ESA offer advantages in their compact sizes and relatively simple constructions.

Table 4: Summary of characteristics for each velocity (energy) determination technique. Y as yes, N as no.

	ExB	RPA	ESA	TOF	QMS	LIF	EVADER
Typical Size/Mass	Large	Small	Medium	Medium	Large	Outside	Large
Can discriminate species?	Y	N	N	Y	Y	N	Y
Pass-band filter?	Y	N	Y	N	Y	Y	Y
Invasive?	Y	Y	Y	Y	Y	N	Y
Needs V_p correction?	Y	Y	Y	Y	Y	N	Y

The Time-of-Flight (TOF) technique measures the ion velocity by determining the difference in arrival times of ions. It functions as a high-pass velocity filter, with the filter velocity varying as a function of time. To obtain the IVDF, users must differentiate the measured data. However, the species discrimination capability of the TOF techniques is generally inferior to that of the ExB probe, particularly when the density of minor species is significantly lower than that of major species. Another limitation of the TOF technique is its reduced effectiveness in time-varying plasmas when the plasma timescale is faster than the TOF device's operational timescale. While the TOF system can be constructed to be lighter than an ExB probe, its overall size is often comparable, as it requires a certain length to achieve optimal performance.

The Quadrupole Mass-Spectrometer (QMS) is a highly sensitive (can be <0.1 amu) mass filter for ions, which is often integrated into Residual Gas Analyzers (RGAs). In a QMS, four conductive rods are arranged parallel to the ion traveling direction. Two of the rods, maintained at positive DC and alternating RF potentials, function as a high-pass filter, while the other two, held at negative potentials, act as a velocity filter. A very narrow band-pass can be achieved by precisely tuning the amplitudes of the DC and RF potentials, as well as the RF time constant. This level of mass resolution is challenging for most ExB probes to replicate. However, the QMS's complex design and the high cost of commercial systems make it a less accessible option.

Laser-Induced Fluorescence (LIF) is an optical diagnostic technique used to determine the IVDF for a specific species. LIF involves directing a laser at a specific wavelength to excite particles (ions or neutrals) and detecting the light emitted as the particles spontaneously radiatively decay to their original energy state. By analyzing the emitted light, the VDF of the targeted species can be determined. A key advantage of LIF is that it is non-invasive, and the measurements can be done without significantly disturbing the plasma properties. Additionally, LIF can be focused on challenging regions, such as the inside of a Hall Effect Thruster (HET) channel. However, LIF has limitations, including a minimum detectable particle density determined by the sensitivity of the detector system. Furthermore,

the technique requires lasers tuned to the specific wavelength(s) of the particular species being studied. As a result, LIF is typically applied to measure the IVDF of the dominant species in a plasma.

Another recently developed diagnostic for interrogating ion beams is called the EVADER [95]. The EVADER diagnostic combines a spherical electrostatic analyzer (ESA) with a Wien-filter (ExB) stage in a single line-of-sight package. The instrument first filters ions based on their energy-per-charge (E/q) using the ESA sector. The narrow E/q beam exiting the ESA then enters the ExB probe where it is filtered based on particle mass-per-charge (m/q) ratio. For an ion beam where all the ions have the same mass, e.g., xenon ion beam, the EVADER provides a measure of the energy distribution of each charge-state species within the beam. Specifically, each ExB spectrum is recorded at a known, user-selected E/q band, so a sequence of spectra taken across the global ion energy distribution function (IEDF) can be stitched together to reconstruct species-specific IEDFs and current fractions. This type of probe was initially demonstrated by Thompson et. al., who used the probe to characterize a 1.5 kW krypton Hall thruster [95].

The motivation for this combined probe resulted from the observation that Hall-thruster plumes—and especially magnetically-shielded or high-current density operation—produce broad energy and species distributions that force the singly- and multiply-charged peaks in a conventional ExB probe spectra to overlap as shown in Figure 21b. Analyses that rely on peak heights or fitted IVDFs are then more susceptible to the assumed IVDF shape and fitting window. By pre-selecting a user-defined E/q band, the EVADER can remove much of the overlap before the ExB stage, so each spectrum contains better-resolved, less-convoluted peaks.

In the context of other diagnostic approaches, discussed above, for measuring energy, species, and velocity distributions, the EVADER retains the functionality of both an ESA and ExB probe, but with the added benefit of the reduced overlapping of velocity distributions collected in the ExB stage. The primary drawback of the probe is the added experimental complexity of the combined probe operation, relative to a standalone ExB or ESA. This includes an additional set of power supplies necessary for sweeping the effective E/q transmission band and the ExB probe plates, while measuring low nano- and picoamp currents at both the ESA and ExB collectors, respectively. Although the improved minor species sensitivity may surpass that of some TOF systems, the mass sensitivity is significantly coarser than that of a QMS. The EVADER bridges the gap between energy-filtering and velocity-filtering (mass-to-charge-filtering) diagnostics. By reducing peak overlap it provides reliable species fractions obtained in wide-energy EP plumes, while offering actionable, species-resolved IEDFs to inform performance, lifetime, and modeling efforts.

VIII. Conclusions

This paper presented recommended practices for the design, operation, and data analysis of ExB probes used in electric propulsion testing. The ExB probe is primarily configured to measure ion charge-state ratios within the plasma plume, offering valuable insights into thrust loss mechanisms, energy deposition, and sputter erosion of thruster and spacecraft surfaces. Several probe designs were described, along with guidance on proper implementation and operation. Methods for analyzing probe data to estimate the ion velocity distribution function (IVDF) and charge-state fractions were described. The paper also addressed corrections for ground test facility effects and included an uncertainty analysis. Finally, a comparative assessment of the ExB probe with other commonly used plume diagnostics was provided, highlighting their relative capabilities in characterizing ion velocity and energy distributions. The

recommended practices outlined in this work aim to support experimentalists in the effective design and interpretation of ExB probe measurements, promoting consistency and accuracy across the field.

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