Recommended Practice for Use of ExB Probes in Electric Propulsion Testing

IEPC-2025-483

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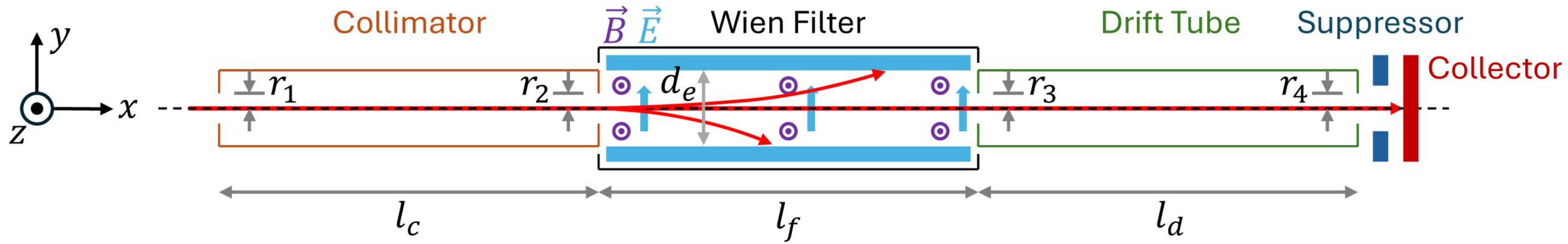
Theory – First Principles



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

$$\vec{E} = -\vec{v} \times \vec{B}$$

$$v = -\frac{E}{B} = v_{Wien}$$

$$E = \frac{V_{plates}}{d}$$

$$v = v_{Wien} = -\frac{V_{plates}}{Bd}$$

$$v = \sqrt{\frac{2qV_{accel}}{m}}$$

Mass-to-charge ratio filter

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

Charge state filter (const. m)

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

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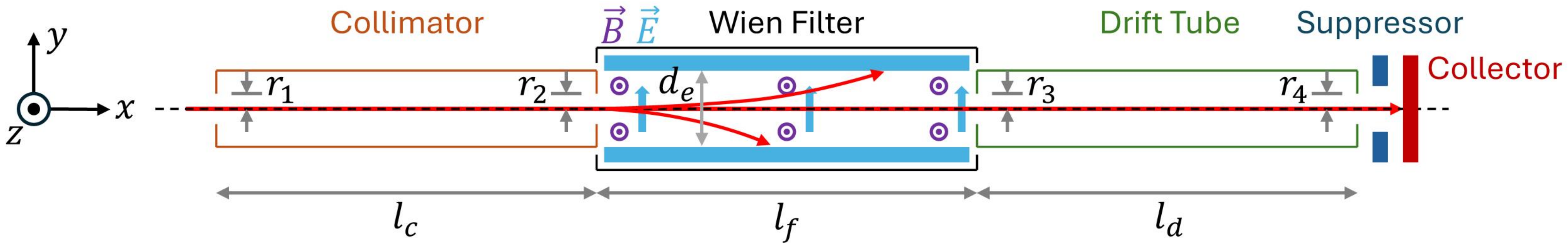

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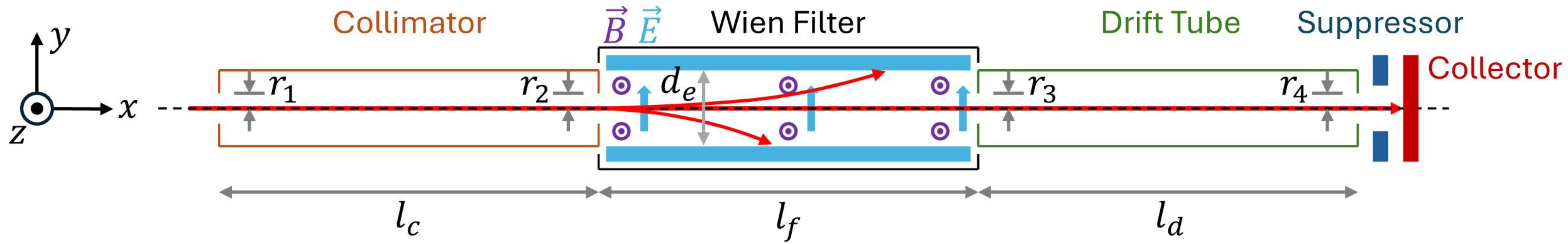

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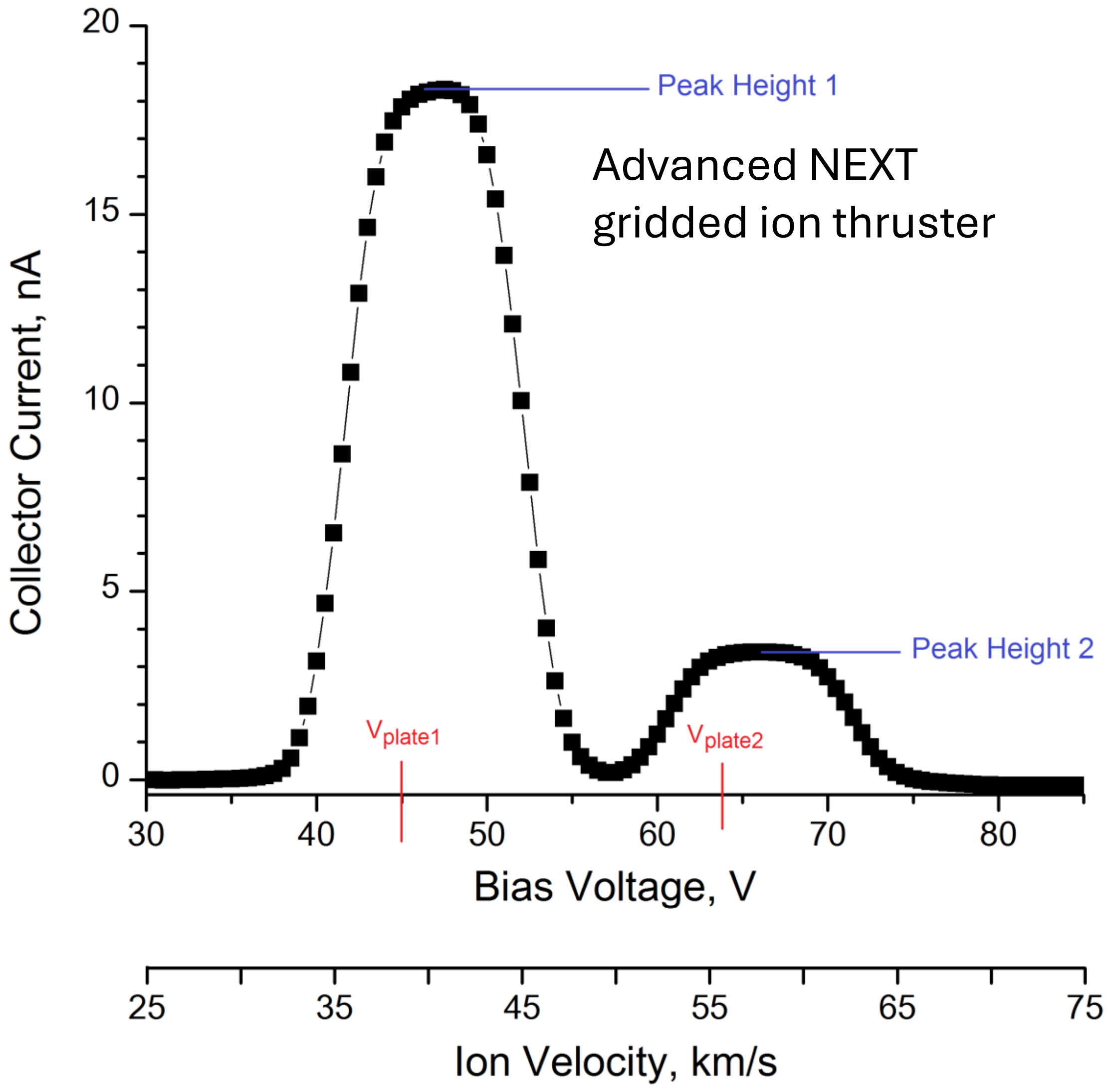

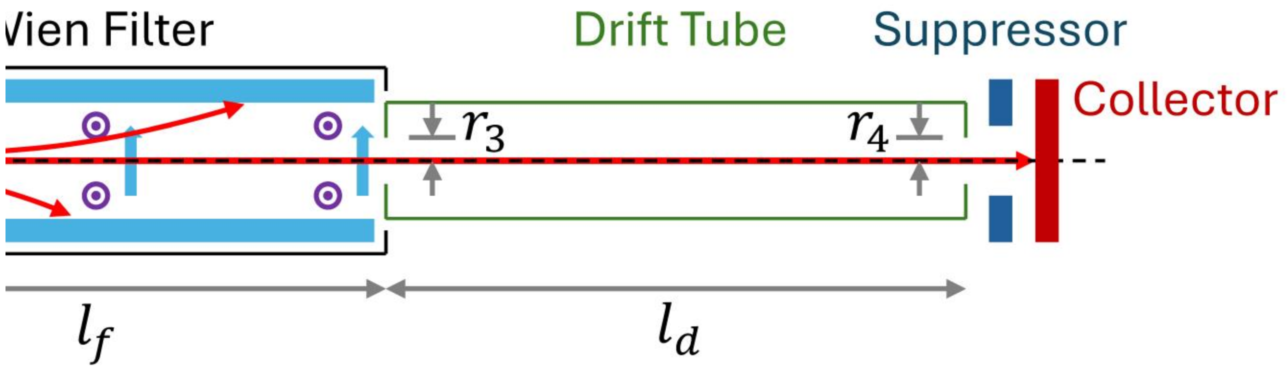

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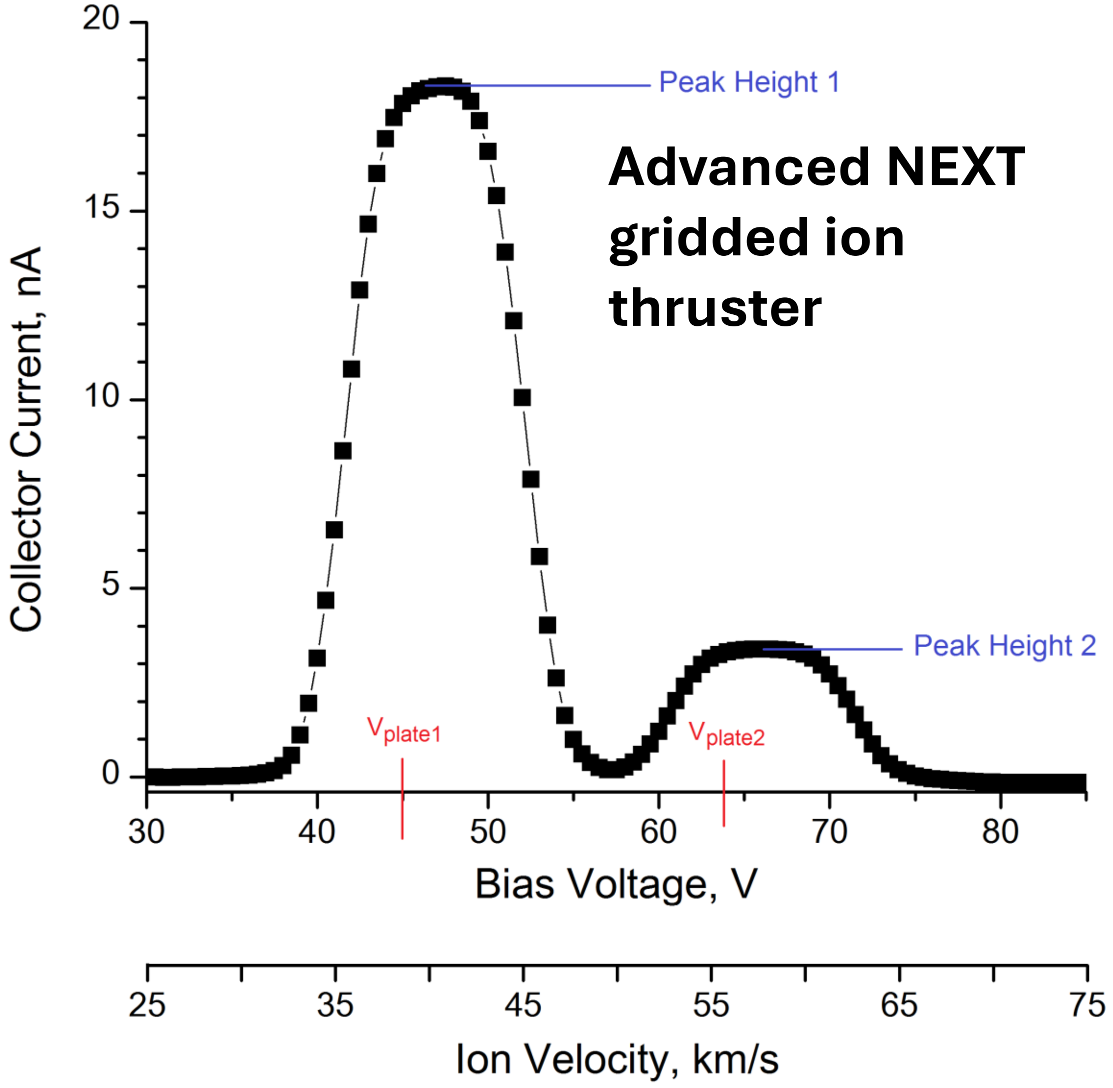

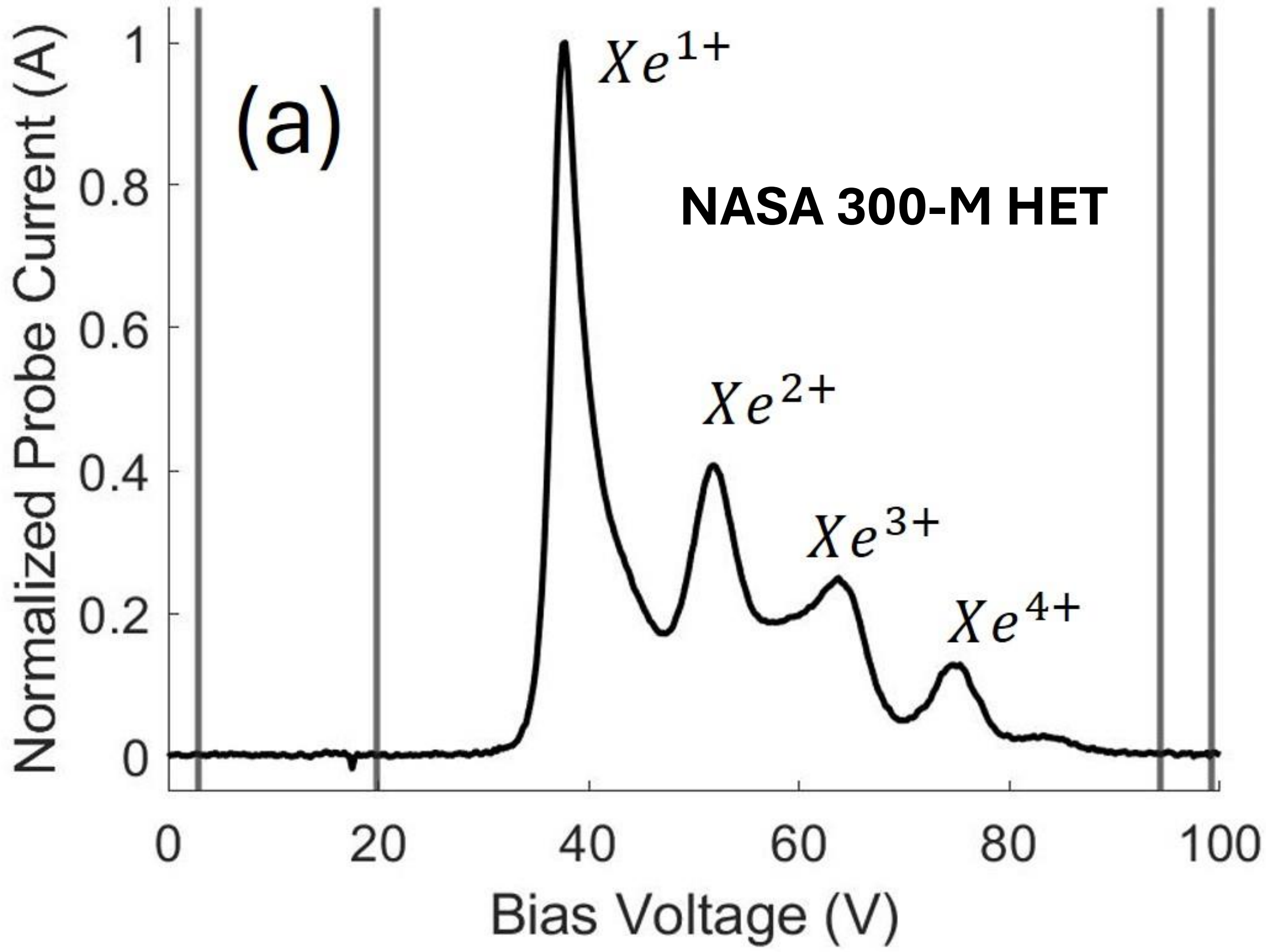

Velocity Resolution

$$\Delta v = \frac{m v_{Wien}^2}{ZeB} G$$

$$\frac{\Delta v}{v_{Wien}} = \frac{m v_{Wien}}{ZeB} G$$

Where G is dependent on probe dimensions

$$G = \left[\frac{a_2 + a_3 + (a_1 + a_2)(L_f + L_d)/L_c}{L_f^2 + 2L_d L_f} \right]$$

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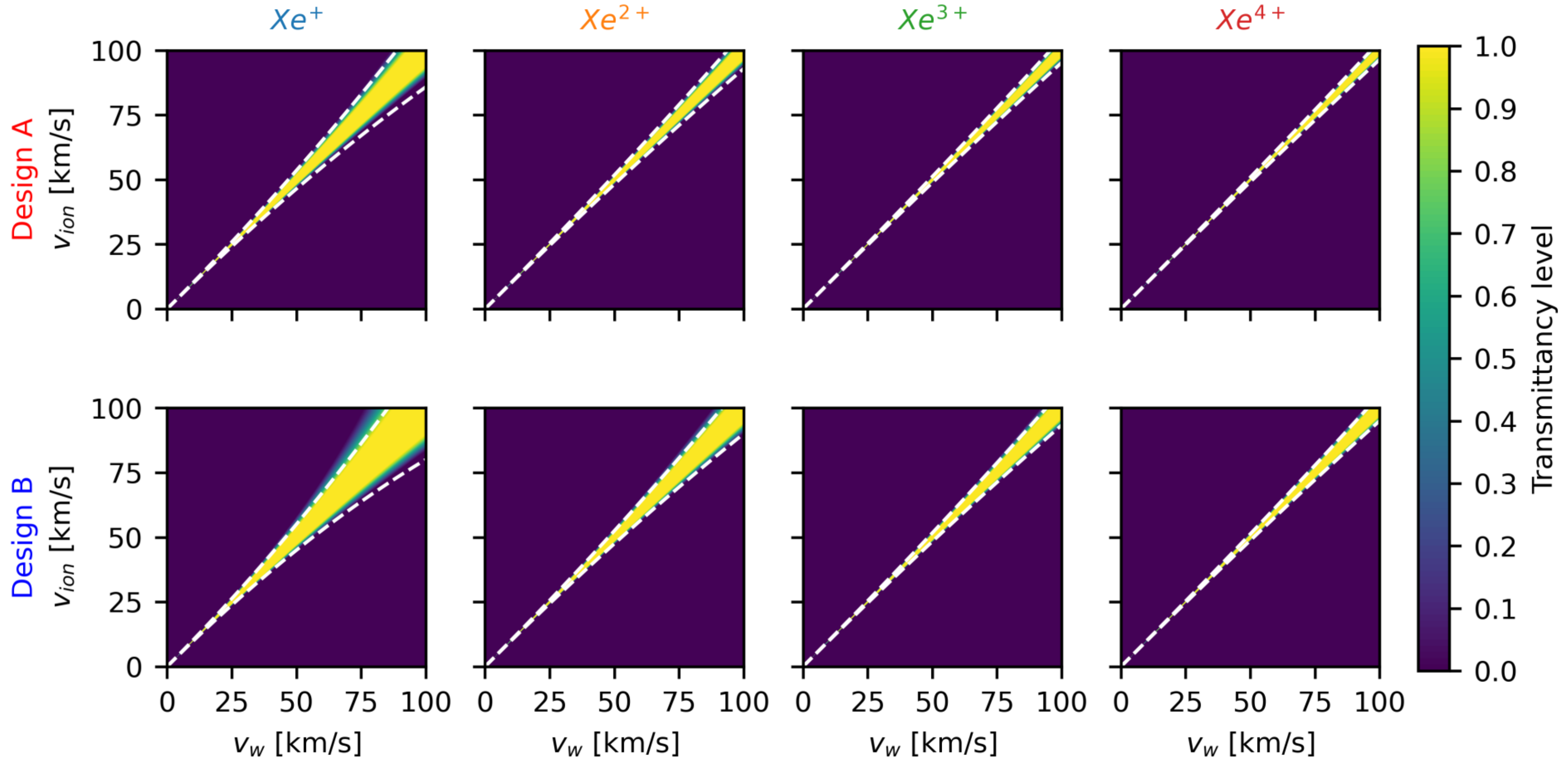
	Aperture Radius (mm)				Length (mm)			Plate Sep. (mm)	Magnetic Field (T)	(1/m)
Probe	r1	r2	r3	r4	lc	lf	ld	de	B	G
A	1	2	3	4	100	200	50	10	0.2	0.208
B	1	2	3	4	100	125	50	10	0.2	0.364



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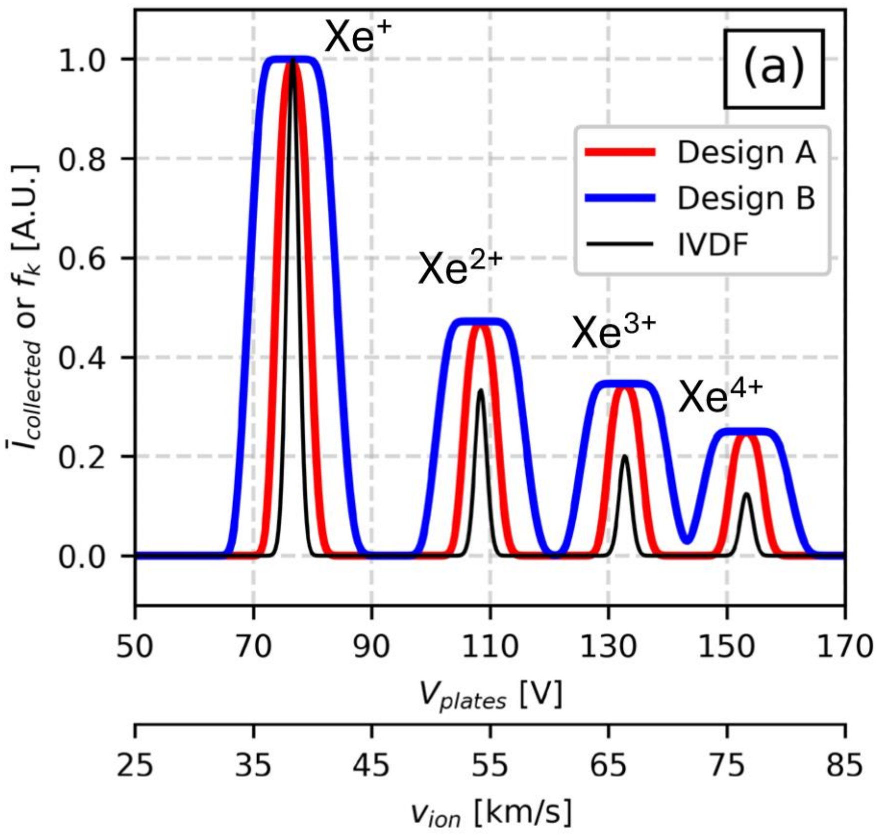
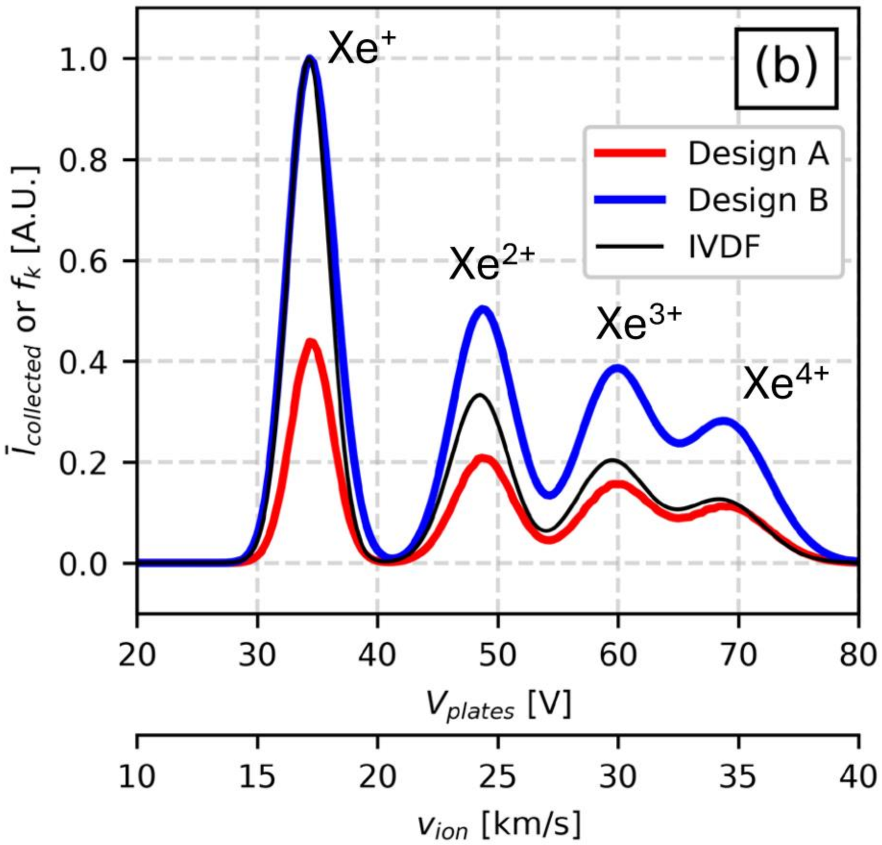
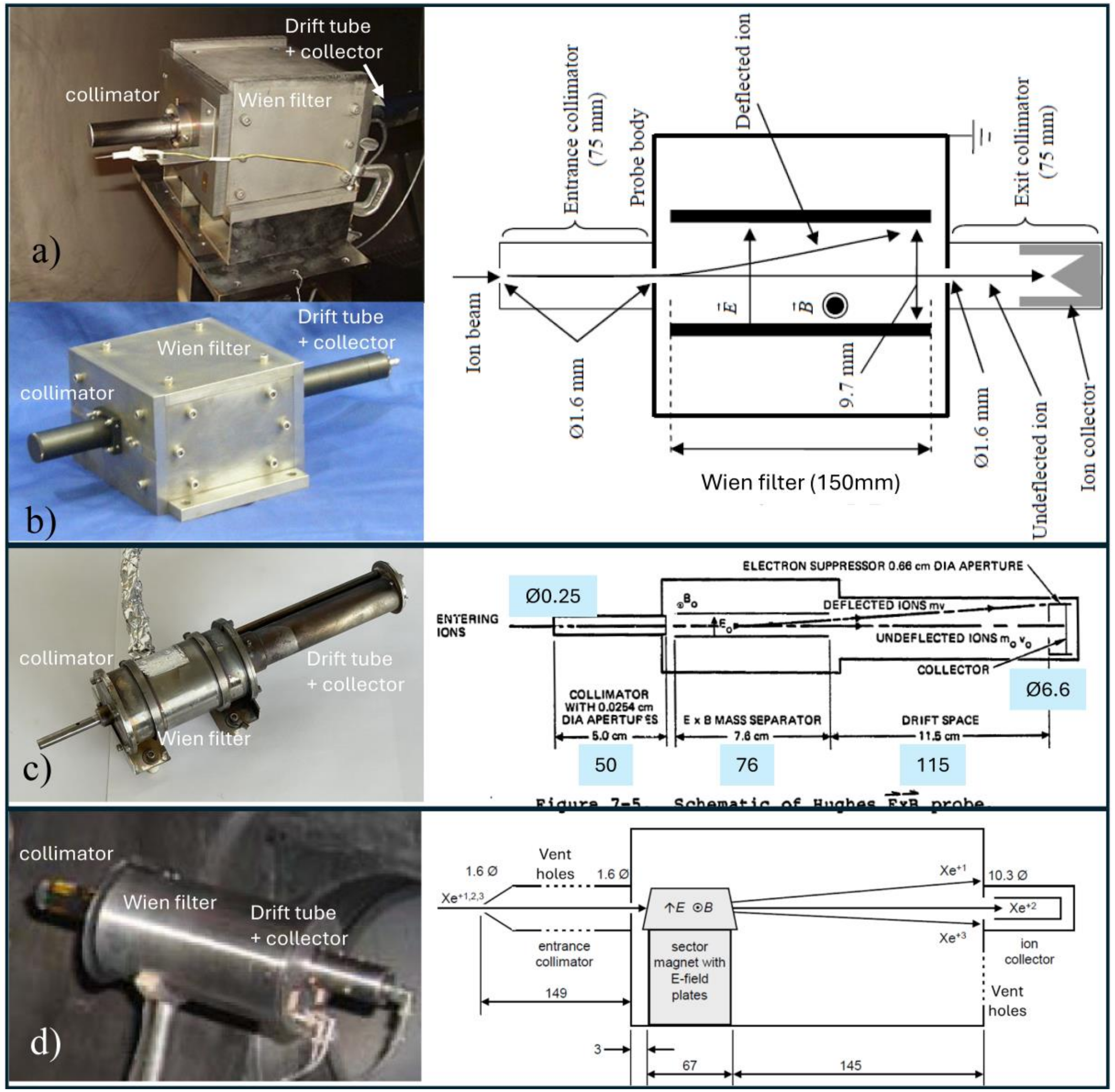
GIT Example



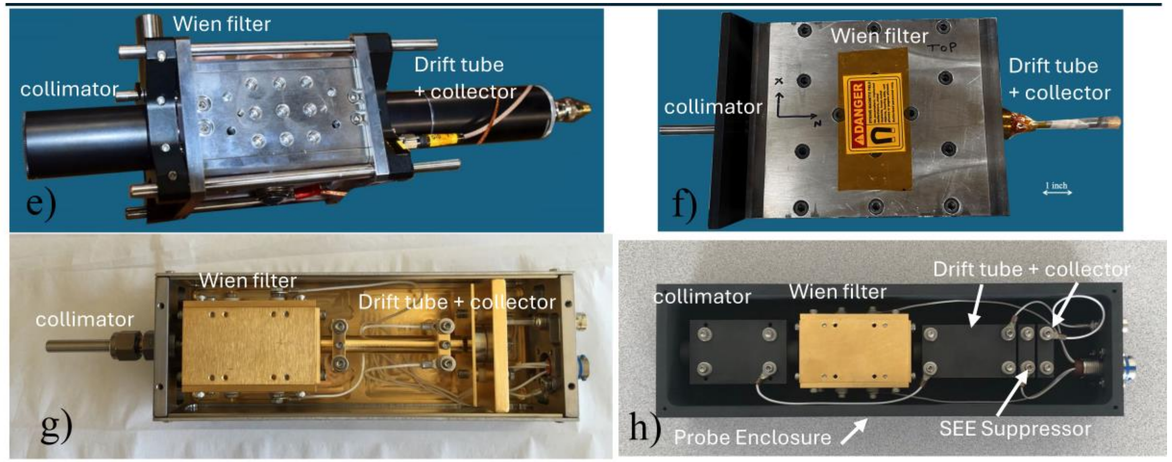
HET Example



Design

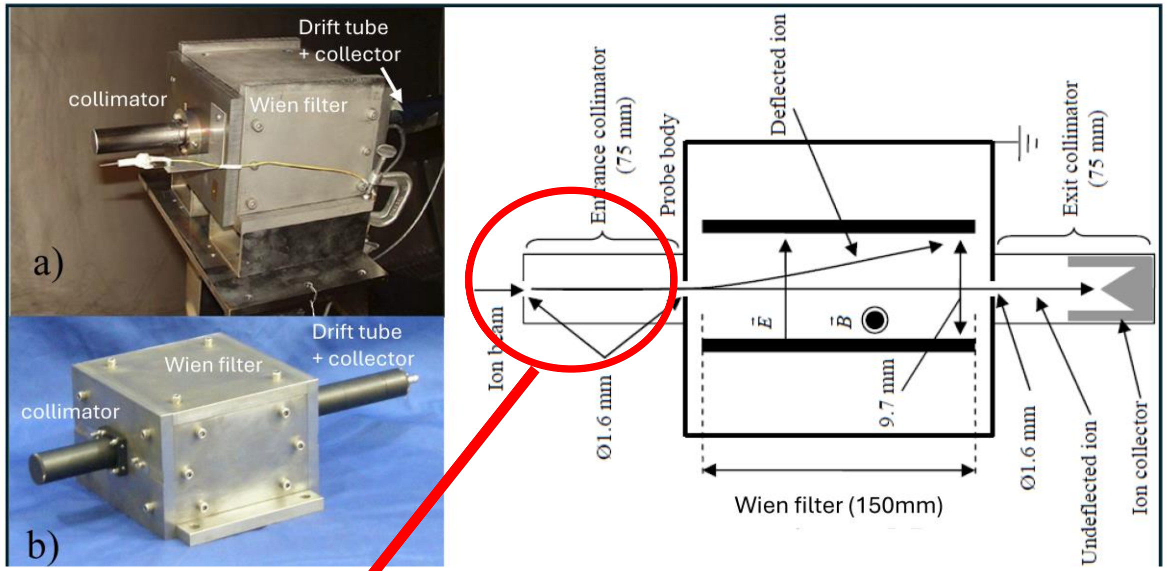


Drift tube
+ collector
collimator
Wien filter
a)
Drift tube
+ collector
Wien filter
collimator
b)
Entrance collimator
(75 mm)
Probe body
Deflected ion
Exit collimator
(75 mm)
Ion beam
Ø1.6 mm
9.7 mm
Ø1.6 mm
Undeflected ion
Ion collector
Wien filter (150mm)
collimator
Drift tube
+ collector
Wien filter
c)
ELECTRON SUPPRESSOR 0.66 cm DIA APERTURE
Ø0.25
ENTERING IONS
DEFLECTED IONS mv
UNDEFLECTED IONS m_o v_o
COLLECTOR
Ø6.6
COLLIMATOR WITH 0.0254 cm DIA APERTURES
E x B MASS SEPARATOR
DRIFT SPACE
5.0 cm
7.6 cm
11.5 cm
50
76
115
Figure 7-5 Schematic of Hughes ExB probe
collimator
Wien filter
Drift tube
+ collector
d)
1.6 Ø
Vent holes
1.6 Ø
$Xe^{+1,2,3}$
Xe^{+1}
10.3 Ø
Xe^{+2}
Xe^{+3}
entrance collimator
sector magnet with E-field plates
ion collector
Vent holes
149
3
67
145



Wien filter
collimator
Drift tube
+ collector
e)
Wien filter
collimator
Drift tube
+ collector
f)
Wien filter
collimator
Drift tube + collector
g)
Drift tube + collector
collimator
Wien filter
h)
Probe Enclosure
SEE Suppressor

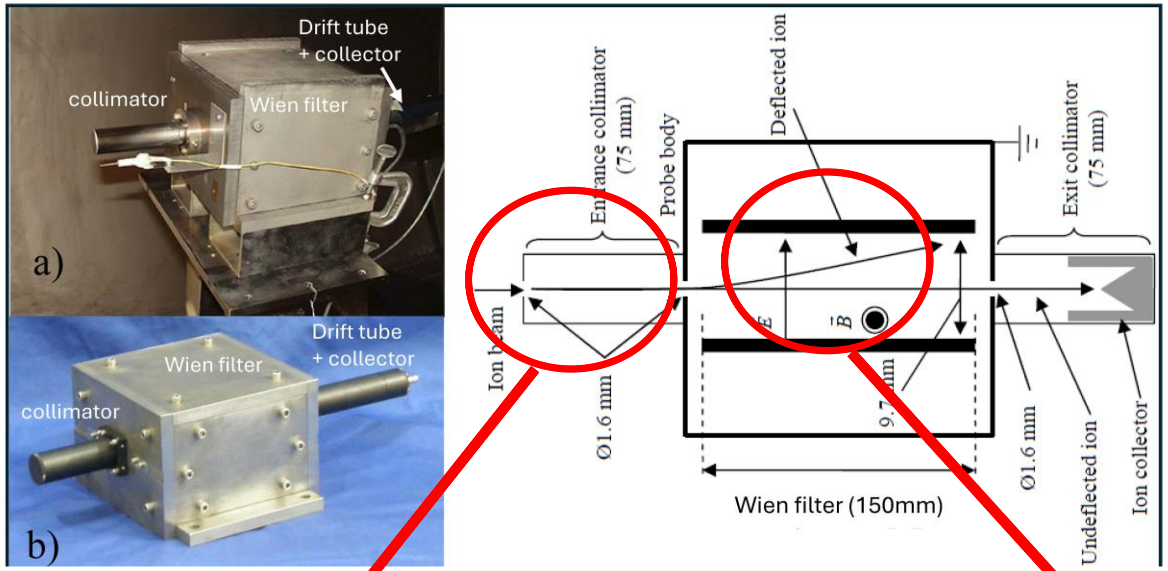
Design



Collimator:

- Entrance orifice size to Debye length ratio: r_1/λ_d << 1
- Collimator OD to orifice ratio for flat sheath: $r_1/r_{collimator}$ << 1
- Longer improved angular filtering but reduces signal: $\alpha_{max} = \tan^{-1}\left(\frac{r_1 + r_2}{l_c}\right)$

Design



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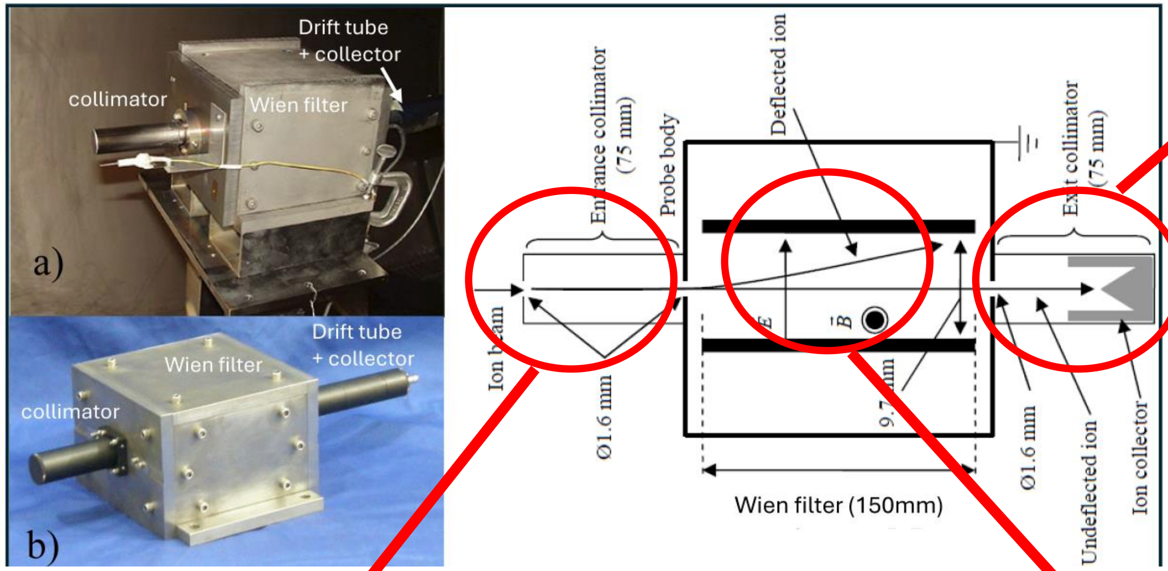
Wien Filter Region:

- Bfield – high temp. SmCo permanent magnets – 0.15 – 0.4 T
- SS or Mo electrodes – some gold plating
- Housing – shapes field (low-carbon steel, 430SS) or passive (alum, graphite)
- Electrical isolation – high temp ceramic insulators (alumina, macor, BN)

Design



Collector:

- Secondary electron emission mitigation with cone-in-cylinder design, low SEE material, (e.g., Mo, W), SEE suppression electrode
- SEE correction with known SEE yield

$$I_k = q_k n_k v_k A_c \left(1 + \gamma_k\right)$$

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

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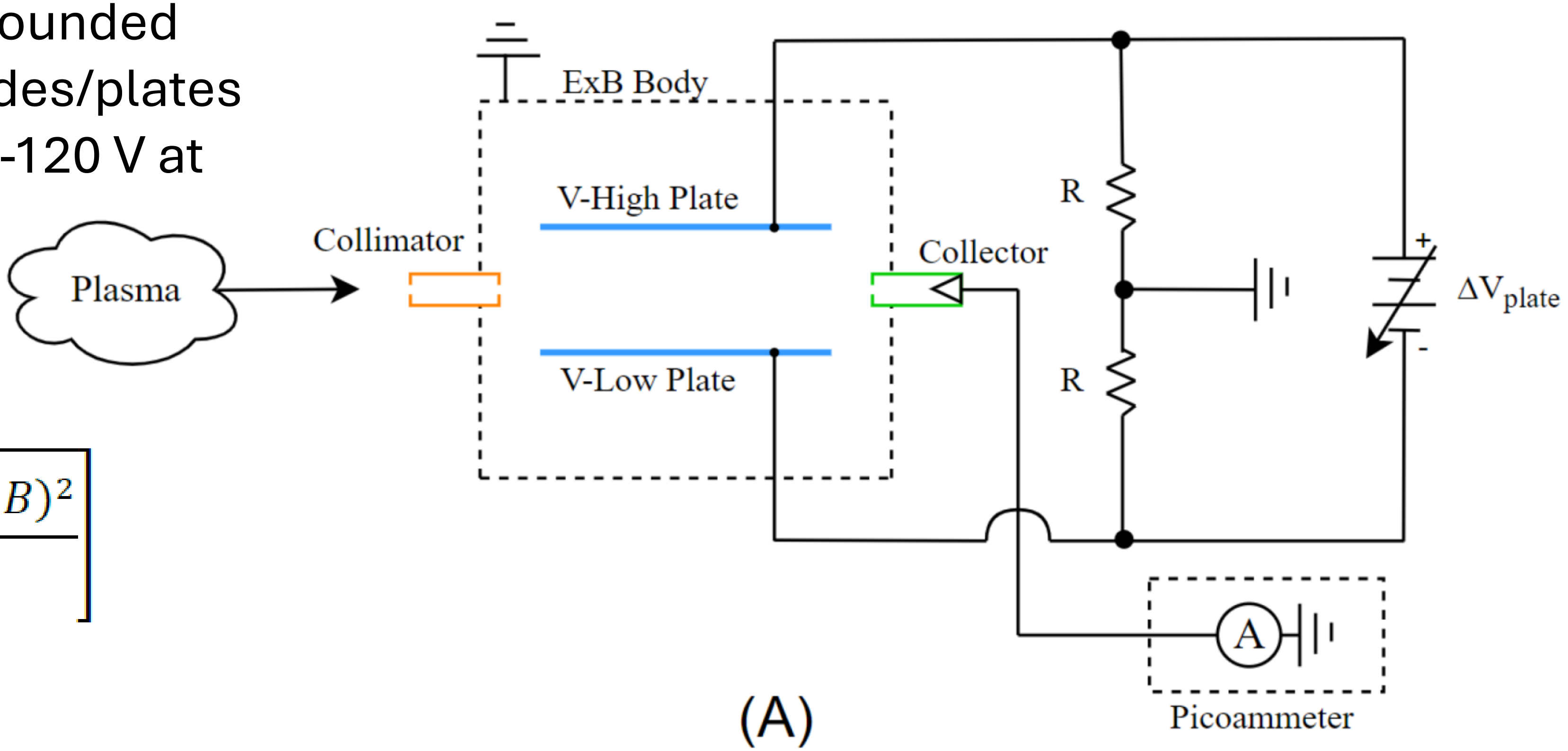
Implementation and Operation

Electrical:

- Grounded probe body – exterior surfaces in contact with plasma are grounded
- Symmetric biasing of electrodes/plates
- Plates biasing range typical 0-120 V at typical 1 V increments

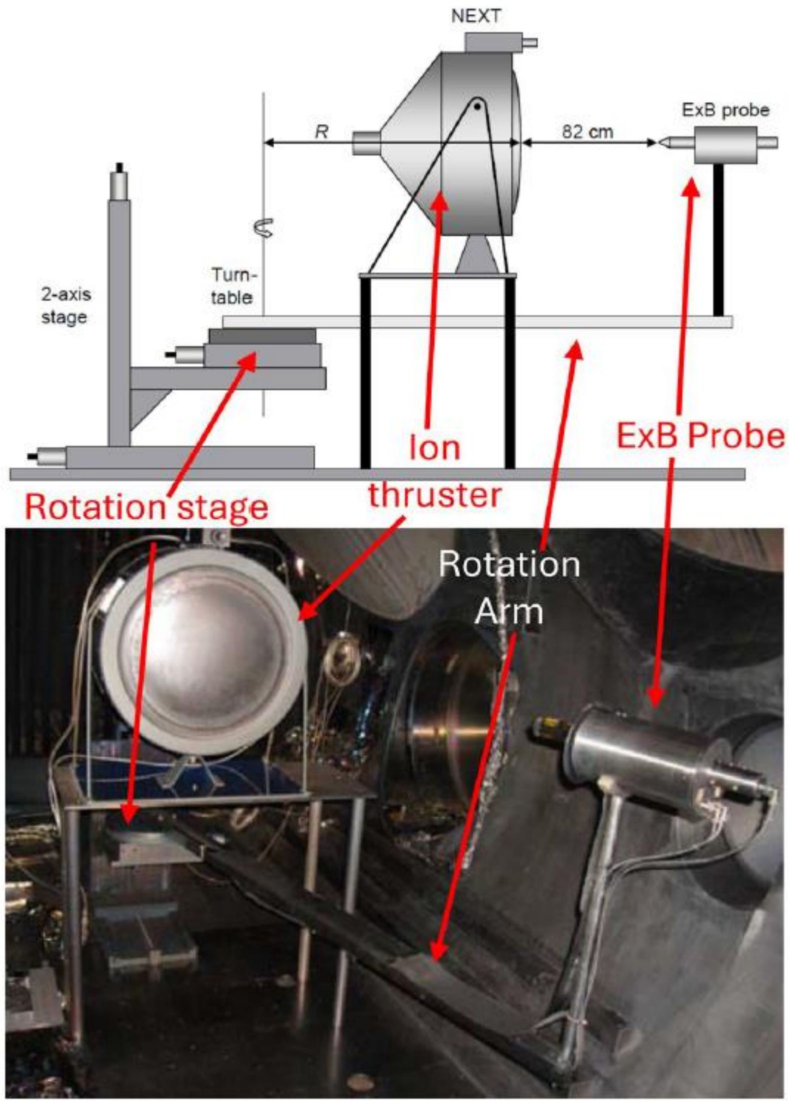
$$V_{plates,range} = \left[0, 1.5\sqrt{\frac{2eZV_{accel}(d_e B)^2}{m}}\right]$$

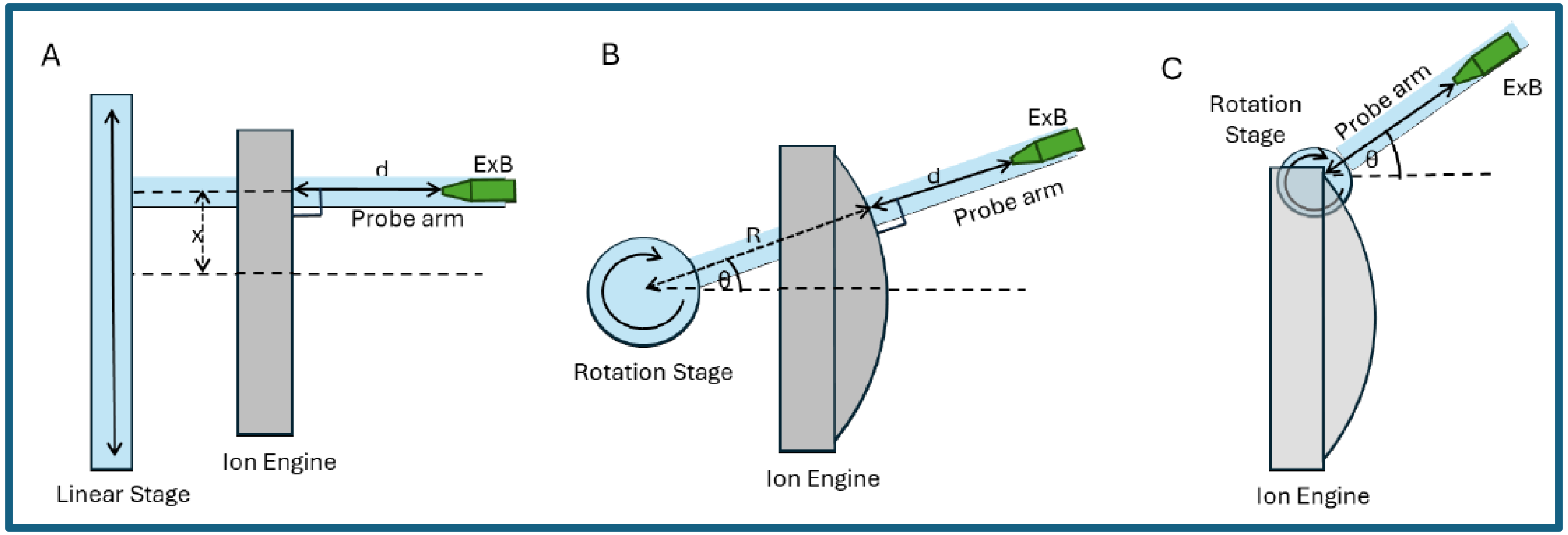


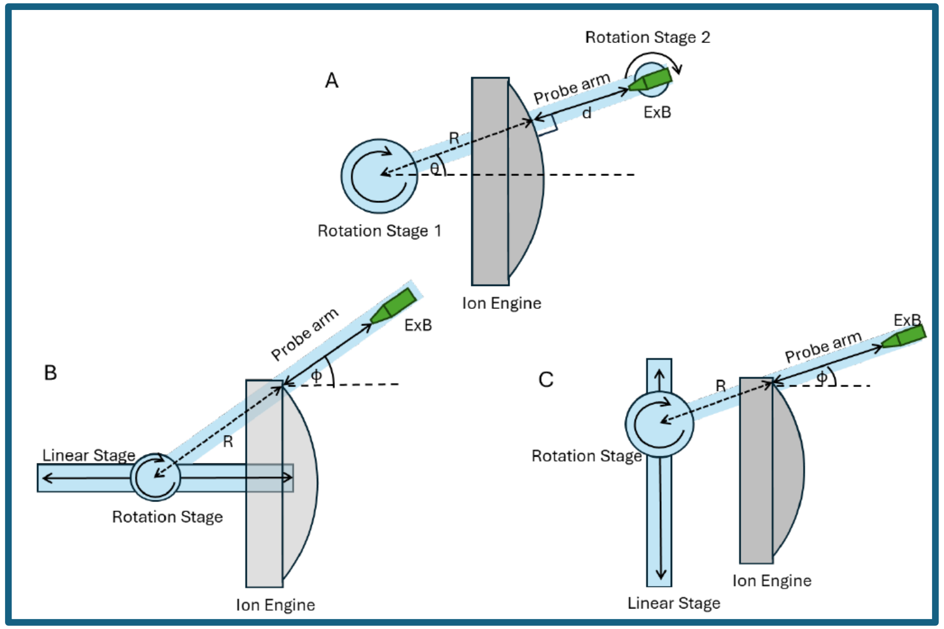
(A)

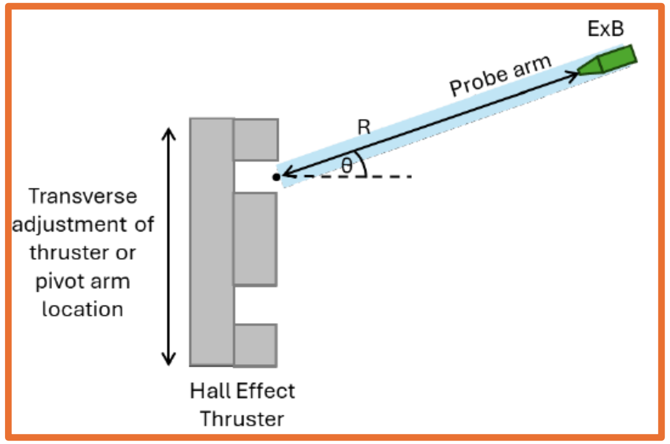
Implementation and Operation

Physical Setup:









Data Analysis

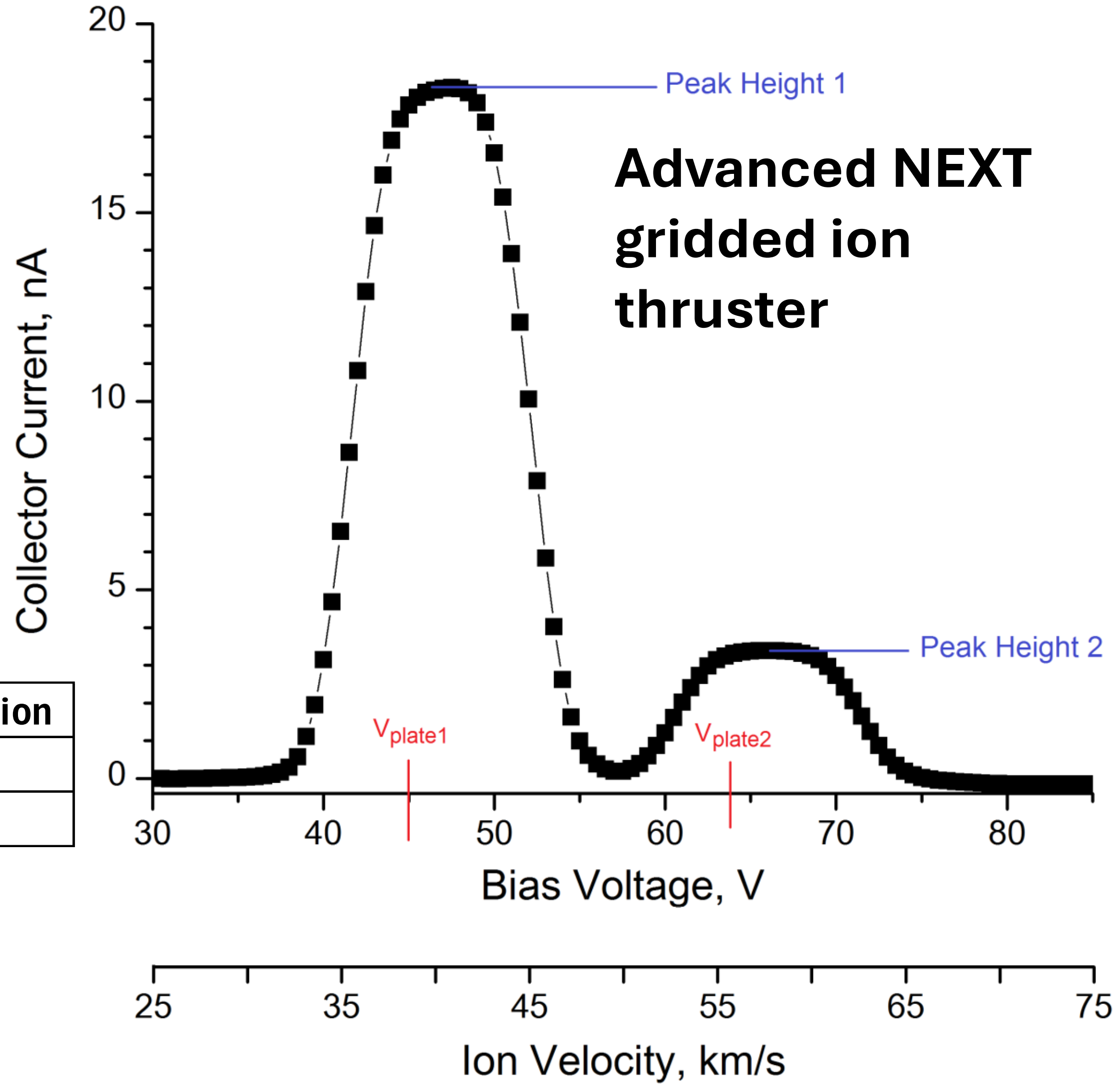
Peak Height Analysis:

- Recommended for:
  - Narrow monoenergetic ion beams (all ions same V_{accel})
  - Relatively wide velocity resolution probe
  - Clearly separated species mass spectrum
- Typical in GIT current ratio and species ratio analysis

Species fraction $$\zeta_j \approx \frac{\Omega_j / {Z_j}^{3/2}}{\sum_j \Omega_j / {Z_j}^{3/2}}$$

j species	Z charge-state	I (nA)	Ω (-) Current Fraction	ζ (-) Species Fraction
1	1	18.5	0.841	0.937
2	2	3.5	0.159	0.063

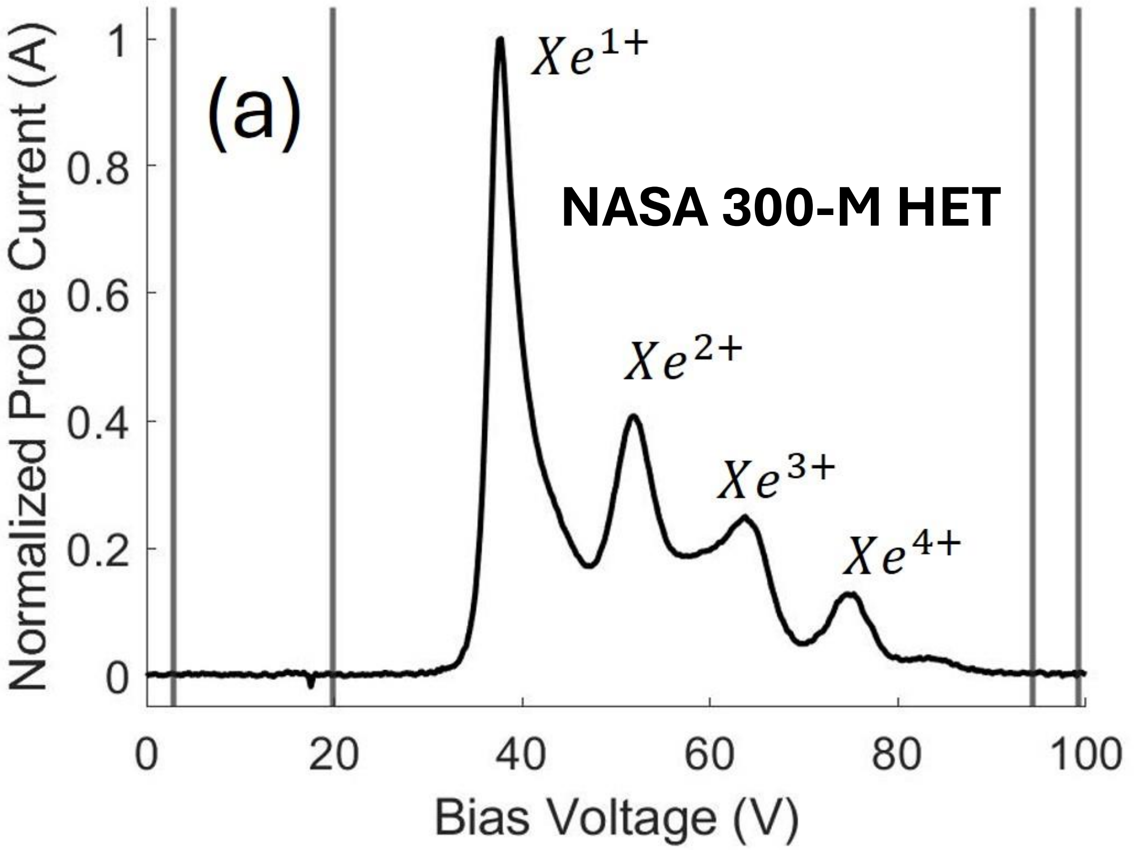
Doubles-to-Singles Current Ratio 19%



Data Analysis

Simplified Integration:

- Recommended for:
  - Broader energy ion beams
  - Identifiable, but overlapping species mass spectrum
- Directly fit an assumed IVDF shape to the measured IV curve from the probe
- Ignores velocity resolution scaling with Wien velocity, $\mathrm{I_j(V_{plates}) = K_1 n_j} V_{plates}^3 \mathrm{f_j(K_2 V_{plates})}$
- HET current ratio and species ratio analysis



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

Gaussian: $$f_j(v) = a\,exp[-b(v-c)^2]$$

Variable Exponent: $$f_j(v) = a\,exp[-b|v-c|^n]$$

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

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

Current Ratio

"Area under the curve"

$$\Omega_j = \frac{\int_0^\infty \mathrm{I_j(V_{plates})\,dV_{plates}}}{\sum_j \int_0^\infty \mathrm{I_j(V_{plates})\,dV_{plates}}}$$

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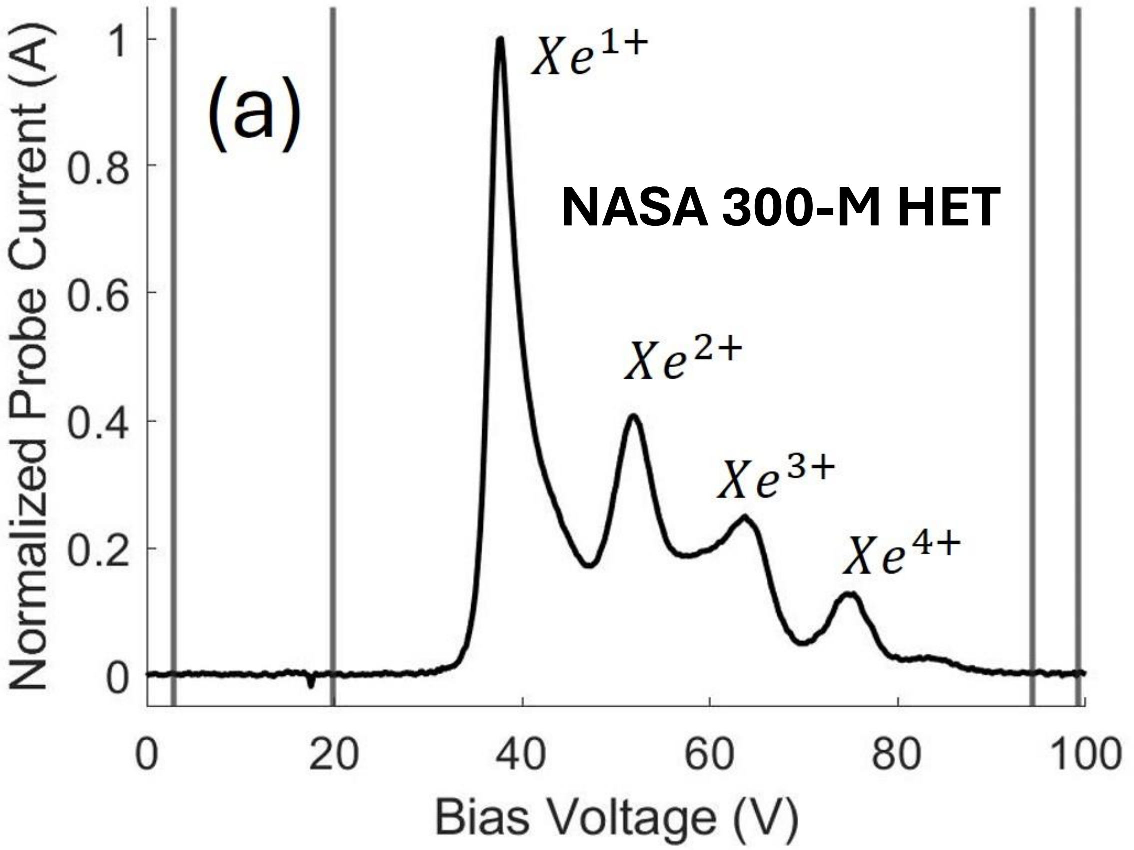

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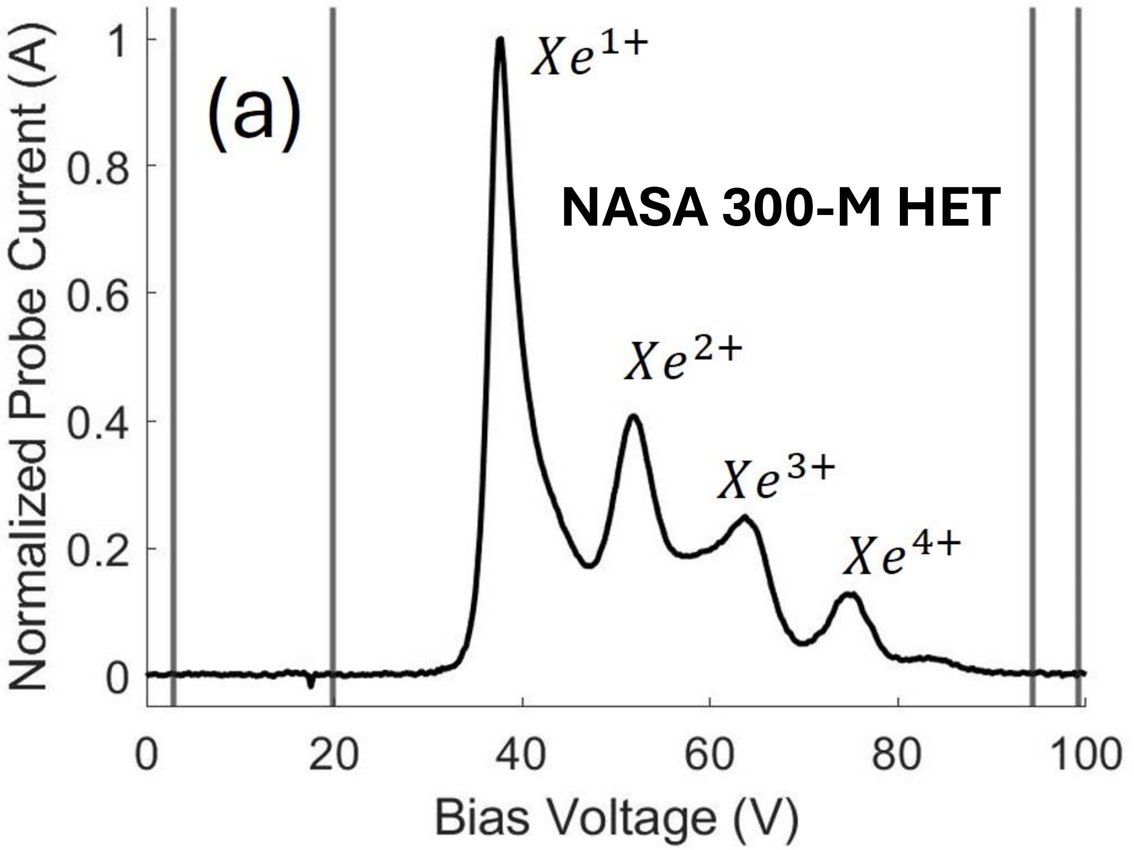

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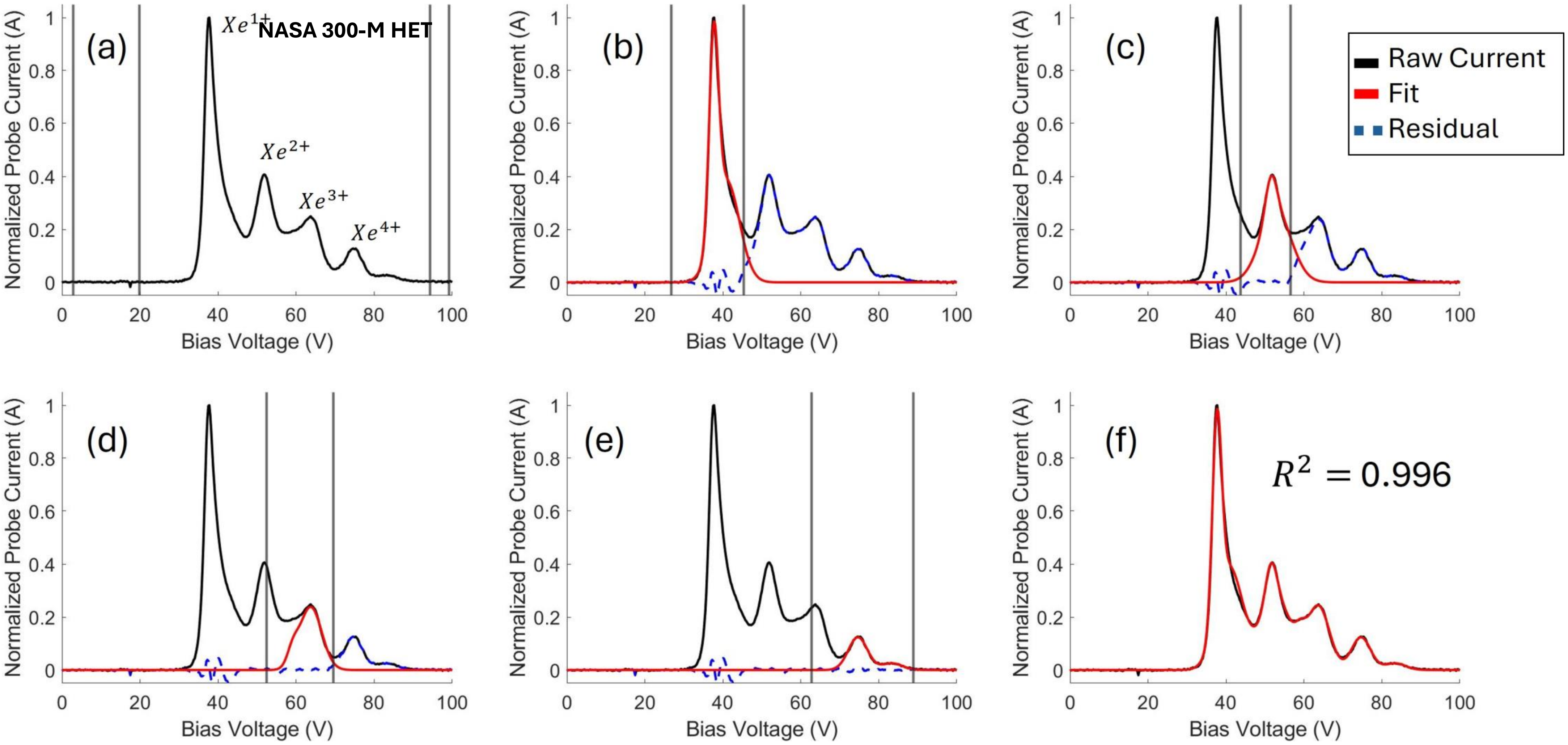

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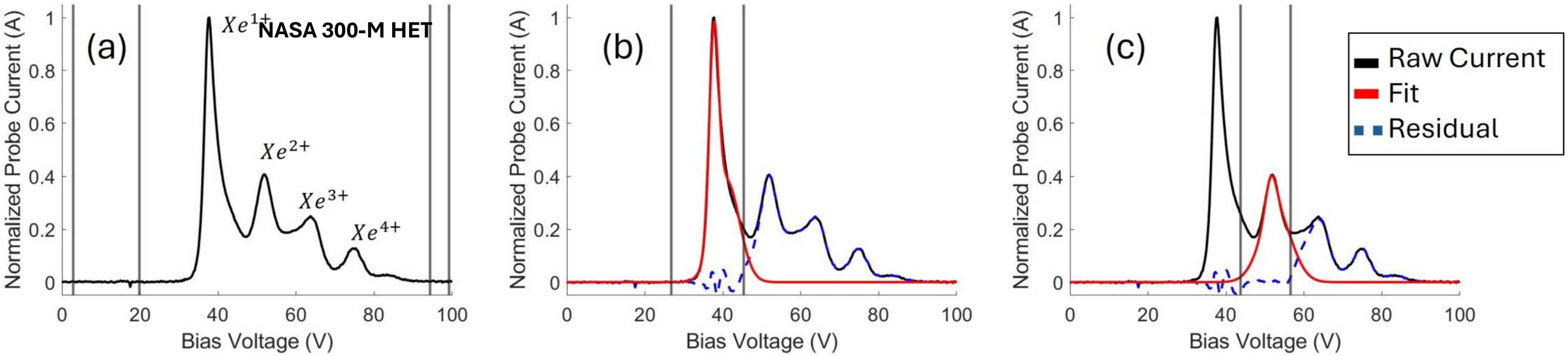

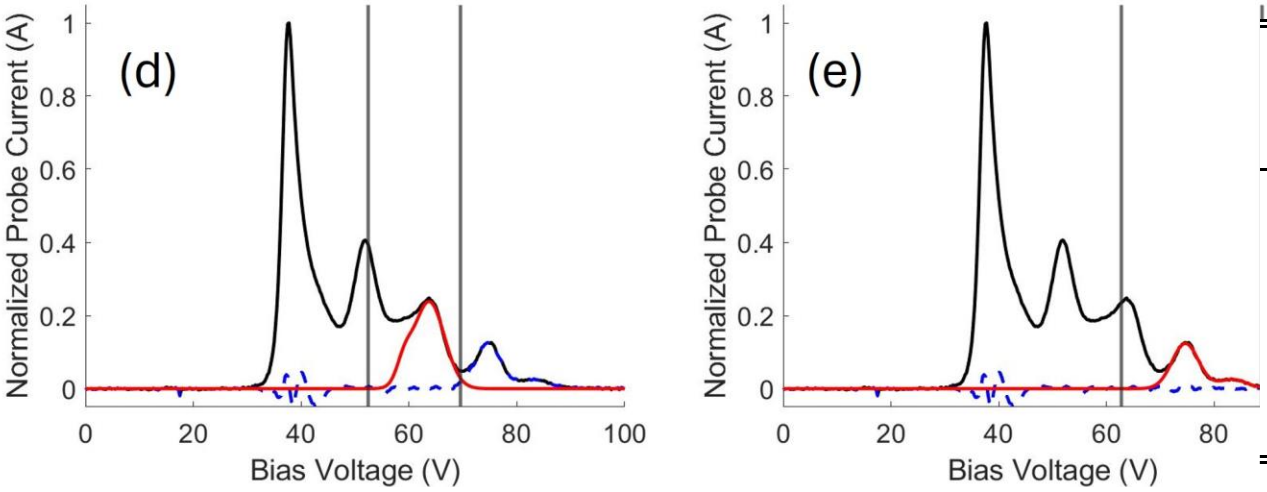

Species	Current fraction (Ω)	Species fraction (ζ)
Xe^{+}	0.48	0.78
Xe^{2+}	0.24	0.14
Xe^{3+}	0.19	0.06
Xe^{4+}	0.09	0.02

Data Analysis

Charge Exchange Correction:

- Recommended that ExB data always be corrected for CEX
- Current density at the probe is lower/attenuated due to CEX collisions with background gas
- Attenuation is different for different species

$$(J/J_0)_1 = exp(-n_0\sigma_1 z), \quad \sigma_1 = [87.3 - 13.6\, log(V_1)] \times 10^{-20} m^2$$
$$(J/J_0)_2 = exp(-n_0\sigma_2 z), \quad \sigma_2 = [45.7 - 8.9\, log(2V_2)] \times 10^{-20} m^2$$
$$(J/J_0)_3 = exp(-n_0\sigma_3 z), \quad \sigma_3 = [16.9 - 3.0\, log(3V_3)] \times 10^{-20} m^2$$

CEX Corrected Current Fraction

$$\Omega_j^C = \frac{\Omega_j\left[(J/J_0)_j\right]^{-1}}{\sum_{j=1,2,3}\Omega_j\left[(J/J_0)_j\right]^{-1}}$$

Current Fraction from Peak Height or Simplified Integration

Conclusion

Recommendations Include:

- Sizing the probe velocity resolution for the application with resolution 10x smaller than IVDF width
- Probe component scaling and material considerations are recommended:
  - Collimator OD and orifice size
  - Collector SEE effects mitigation and correction
- ExB measurements should be accompanied by Langmuir probe or emissive probe measurements to correct for sheath ion acceleration by plasma potential
- An ExB plate bias voltage range and resolution is recommended.
- Data analysis:
  - Peak Height data analysis is recommended for ion sources with narrow IVDF (e.g., GIT)
  - Simplified Integration analysis is recommended for broader energy ion sources (e.g., HET)
    - When used in this way, other sources of uncertainty dominate over the analysis
  - Data must be corrected for charge-exchange attenuation
- Additional recommendations regarding probe Transmittancy and IVDF reconstruction are provided in the paper