EP²

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Experimental investigation of the physics of Electrodeless Plasma Thrusters for in-space propulsion

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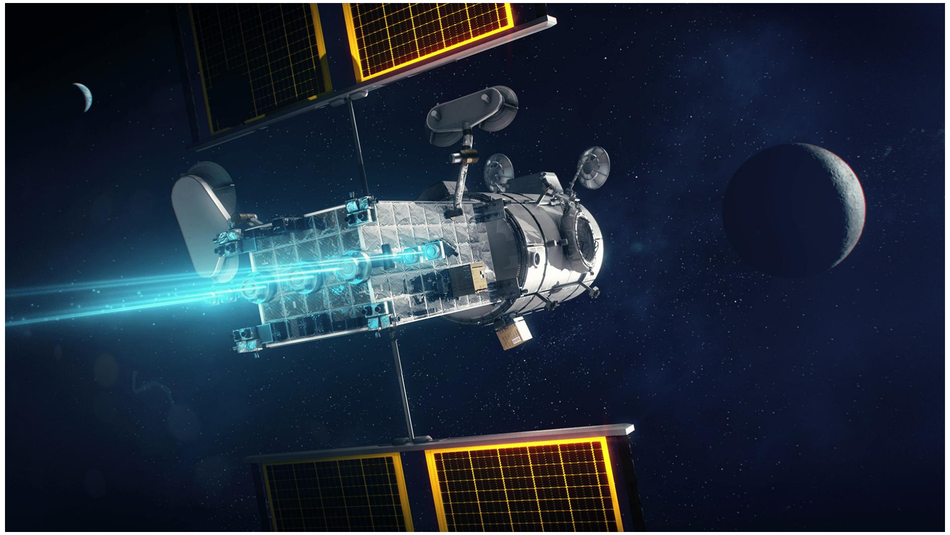
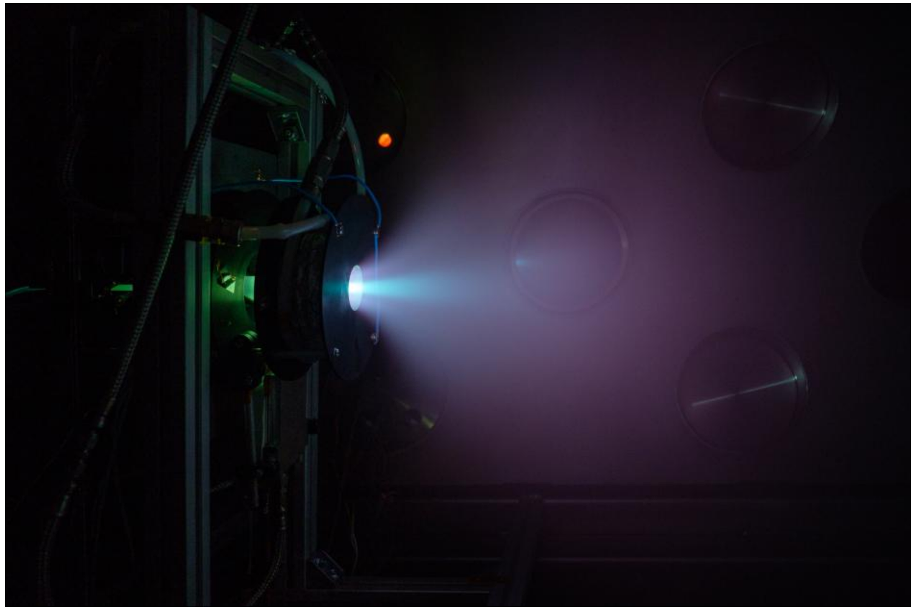
PhD Aerospace Engineering UC3M
Doctoral Meetings 2026
2nd and 3rd June 2026

Problem statement: EPTs and efficiency

- Electric Propulsion is an established technology for satellite station-keeping, orbit raising, satellite de-orbiting
  - +10.000 of EP thrusters in orbit
- However, mature thrusters (HET, GIT) are constrained by:
  - Limited propellant flexibility
  - Reliance on cathodes for plume neutralization/plasma production
- **Electrodeless Plasma Thrusters** (EPTs) offer an alternative with several advantages:
  - Cheaper, simpler PPU
  - Propellant agnostic
  - Operational flexibility
- However, they are limited by their **low efficiencies**





Problem statement: EPTs and efficiency

$$\eta_T = \frac{T^2}{2\dot{m}P}$$

Thruster output

Thruster input

$$\eta_T = \eta_u \eta_d \eta_\epsilon$$

Thruster efficiency can be decomposed into three partial efficiencies

- Propellant utilization efficiency
- Beam divergence efficiency
- Energy efficiency

Marco R. Inchingolo, Bayón-Buján, Borja and Jaume Navarro-Cavallé. " Experimental characterization of a waveguide ECRT with axial propellant injection." IEPC2025

Problem statement: EPTs and efficiency

$$\eta_T = \frac{T^2}{2\dot{m}P}$$

T^2 → Thruster output

$2\dot{m}P$ → Thruster input

$$\eta_T = 0.75 \cdot 0.5 \cdot 0.12 = \mathbf{4.5\%}$$

Thruster efficiency can be decomposed into three partial efficiencies

- Propellant utilization efficiency (30-75%)
- Beam divergence efficiency (35-55%)
- **Energy efficiency** remains the main bottleneck (4-12%)
  - Inelastic collisional loses
  - Particle/power lost to walls
  - EM power reflected/radiated away

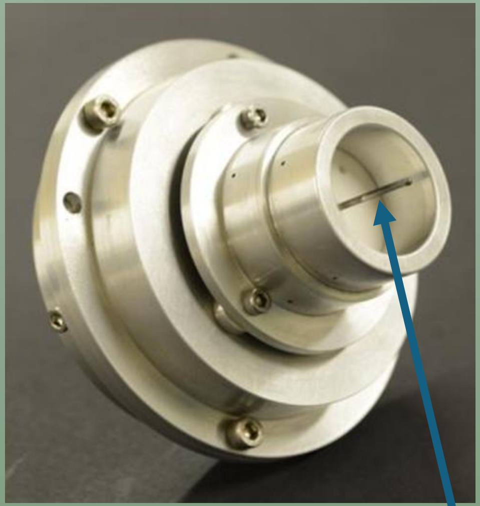
→ Poorly characterized experimentally

Marco R. Inchingolo, Bayón-Buján, Borja and Jaume Navarro-Cavallé. " Experimental characterization of a waveguide ECRT with axial propellant injection." IEPC2025

Problem statement: EPTs and efficiency. Success stories

RÉPUBLIQUE FRANÇAISE Liberté Égalité Fraternité — ONERA THE FRENCH AEROSPACE LAB

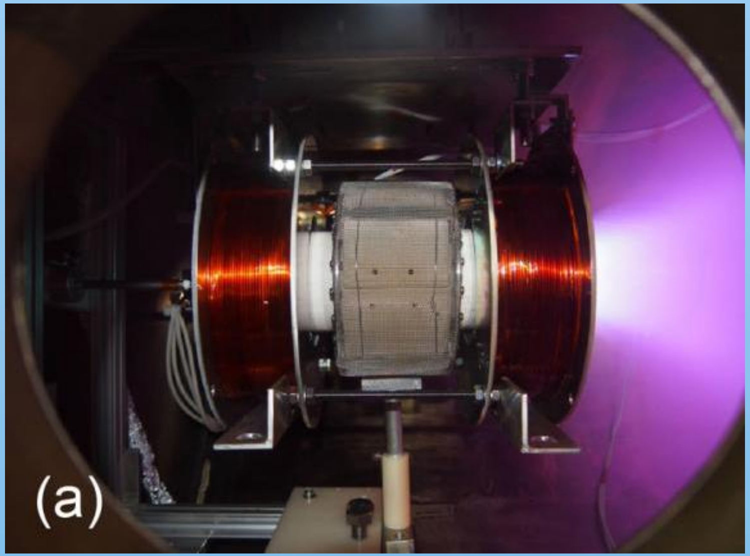
ONERA's ECRA



$\eta_T \leq 50\%$

(SoA)

Tohoku's University's HPT



$\eta_T \leq 35\%$

(this should be counted as an electrode btw…)

- Optimized through iterative design
- Poor attempts are made to explain what changed led to significant improvement
  - Not replicable by other groups
  - No lessons learnt

Objectives and methods

THESIS OBJECTIVES

Clarify main physical mechanisms governing plasma transport and wave coupling in EPTs and their MNs

METHODS:

- Design, implement and/or use cutting-edge diagnostics, validated with existing ones
  - **ExB probe** → $\boldsymbol{\eta_\epsilon}, \boldsymbol{\eta_u}$ (energy lost by generation of multiply charged ions)
  - Laser Induced Fluorescence → $\boldsymbol{\eta_\epsilon}$ (ion flux to the walls → wall loses)
- Develop digital twins of the diagnostics to relate measurements with plasma properties
- Characterize the EM wave energy loss pathways
- **By building physical models, propose ways to optimize existing EPTs**

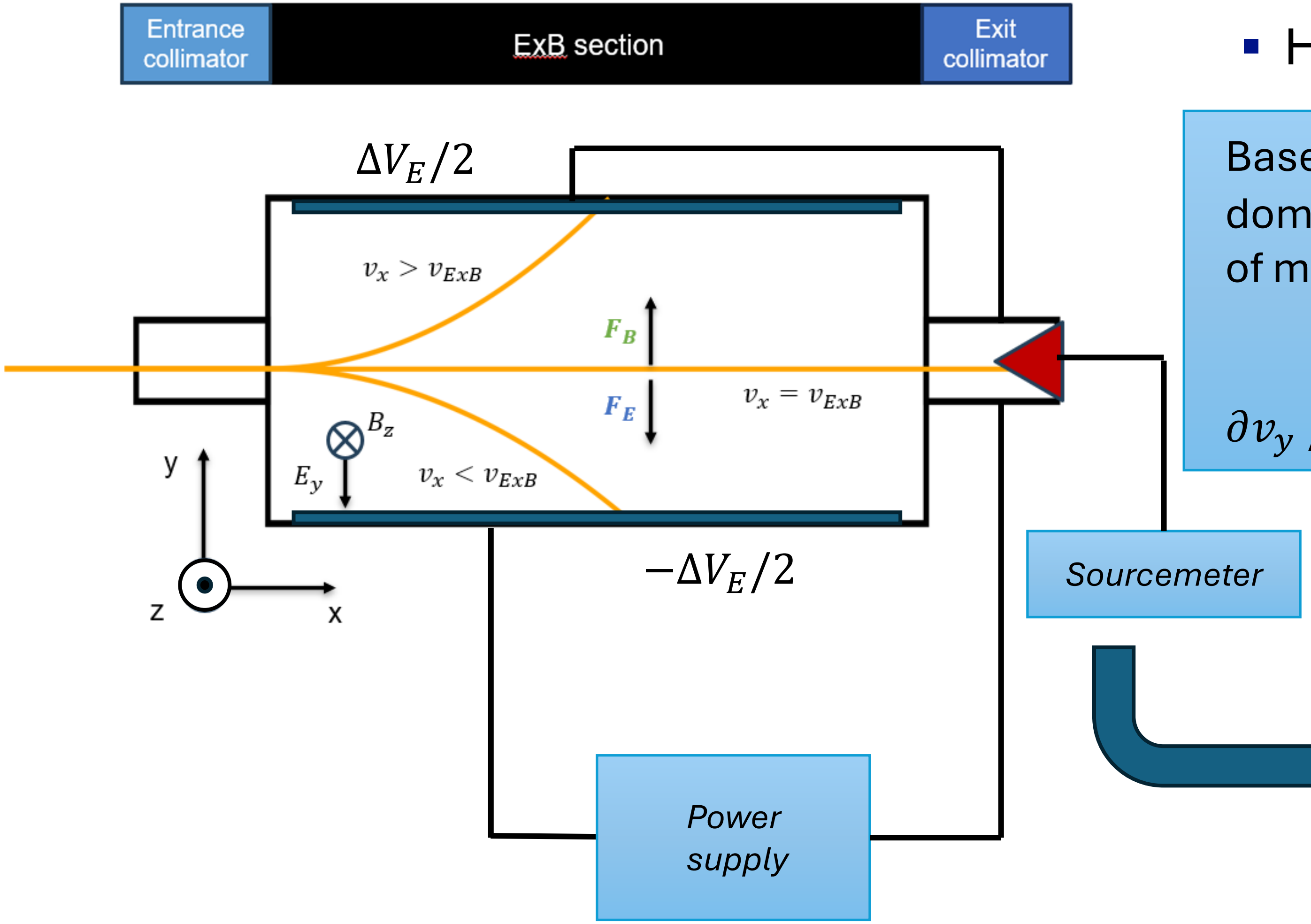
Development of the EP2 ExB probe

EP2 ExB probe development

$$v_{x,0} = \sqrt{\frac{Z}{m} e\Delta\phi_a} \propto \sqrt{\frac{Z}{m}}$$

- Why?
  - IVDF measurements needed for most of EP2 thrusters: ECRT, HPT (+air), CHT
    - Characterize multiply charged ions, plume composition
    - Correct thruster efficiency, also validate simulations
  - Gain experience in design, development and testing

EP2 ExB probe development

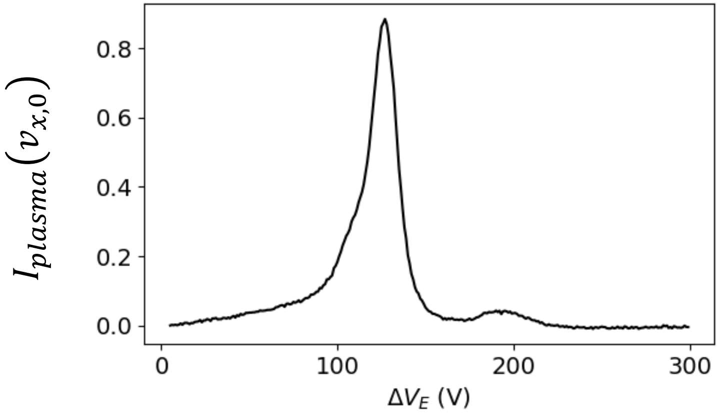


- How?

Based on crossed $\vec{E} = E_y\hat{y}$ and $\vec{B} = B_z\hat{z}$, the dominant term/component of a charged particle eq. of motion is

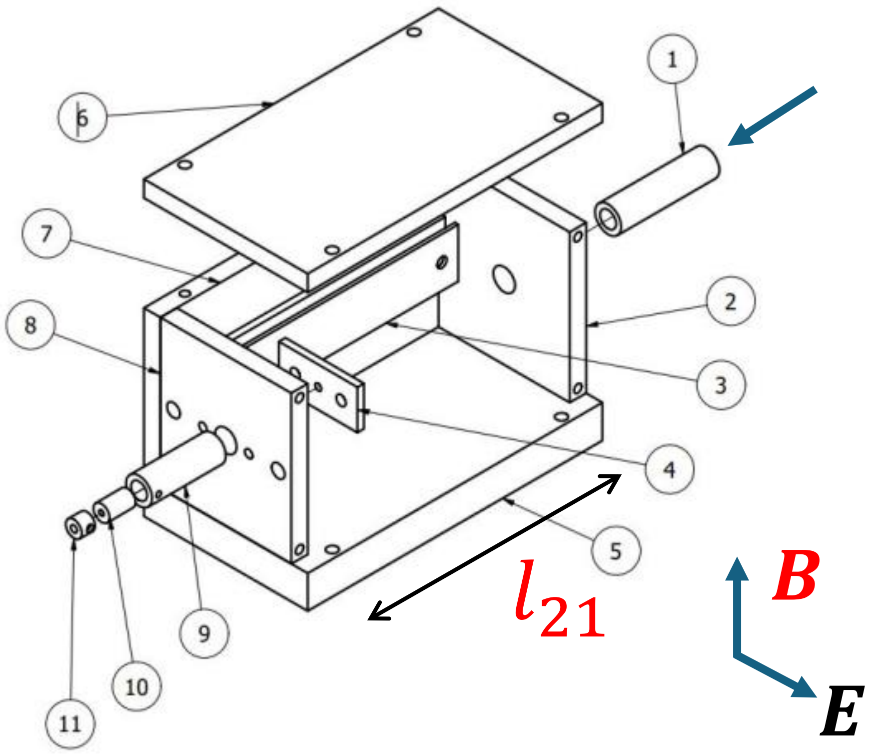
$$\frac{\partial v_y}{\partial t} = \frac{q}{m}(v_x B_z - E_y)$$

$\partial v_y/\partial t = 0$ if $\boldsymbol{v_x} \equiv v_{ExB} = \boldsymbol{E_y/B_z}$, **the "ExB velocity"**



$$I_{plasma}(v_{x,0}) = \sum_i Z_i e A_{coll} v_{x,0} f_i(v_{x,0}) \Delta v_{x,0}$$

EP2 ExB probe development

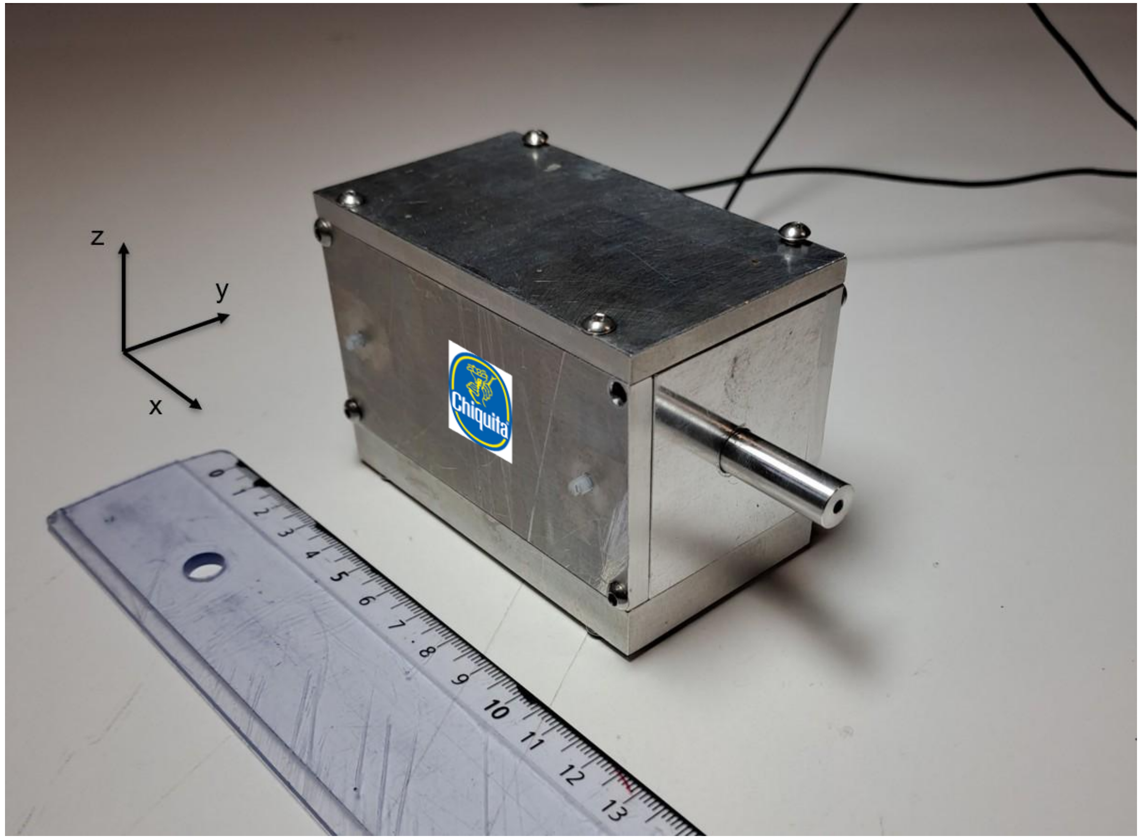


EP2 ExB probe

$\delta v_x^g \sim 1km/s, l_{21} = 80mm,$
$B_z = 0.3T$

- Design is mainly driven by the probe's "geometric" velocity resolution
$$\delta v_x^g = \frac{(d_1 + d_2)}{\boldsymbol{l_{21}^2 B_z}} 2\Delta\phi_a$$
- For a given resolution, there is a balance between the probe's length and magnetic field strength
  - However, in the literature most probes share:
    - $l_{21} > 100mm$
    - $l_{11} + l_{21} + l_{31} \sim 300mm$
    - $B_z = 0.1 - 0.15T$
  - Can they be made **smaller**?
    - In principle, no scaling forbade this

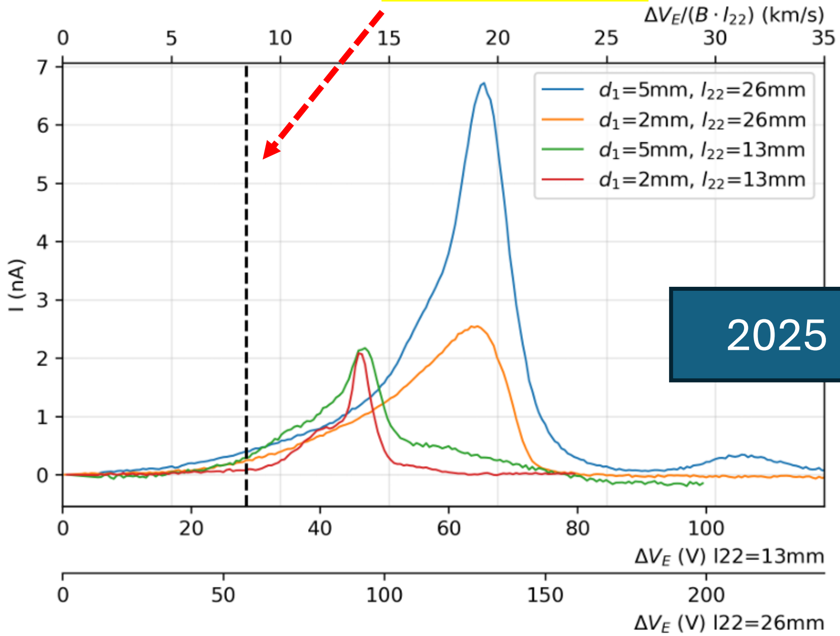
EP2 ExB probe development



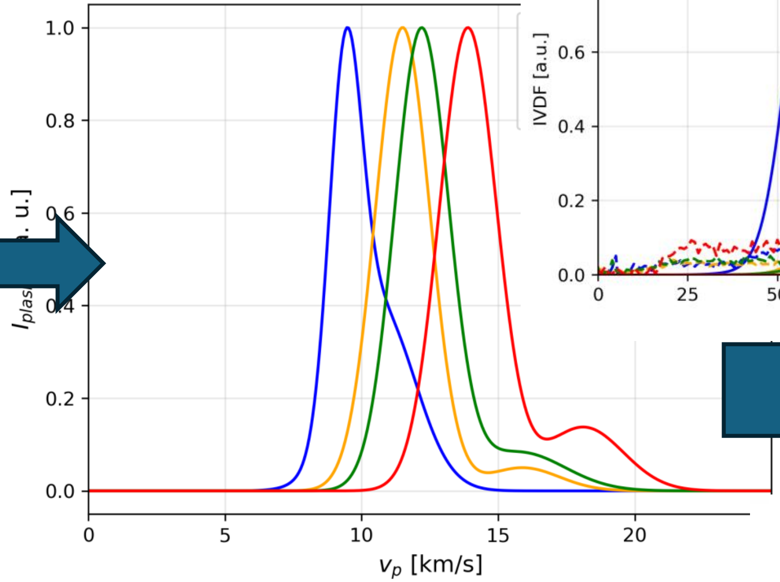
(Might be missing a better reference object, for scale)

1.5 years later

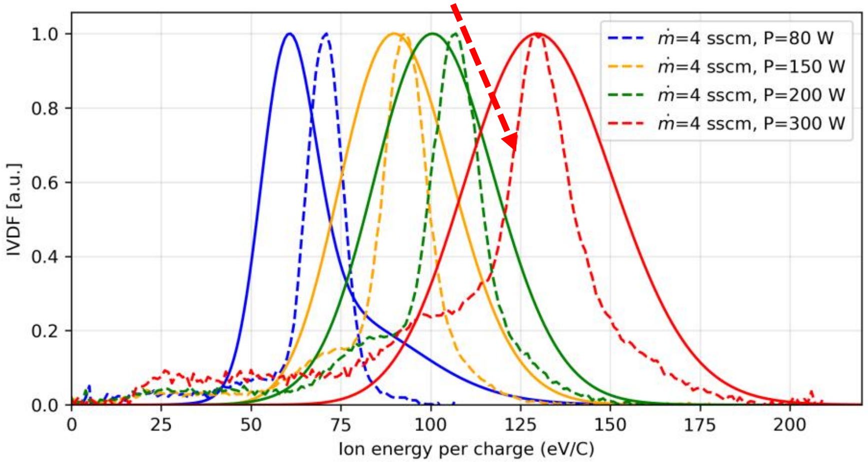
expectations



2025



expectations



2026

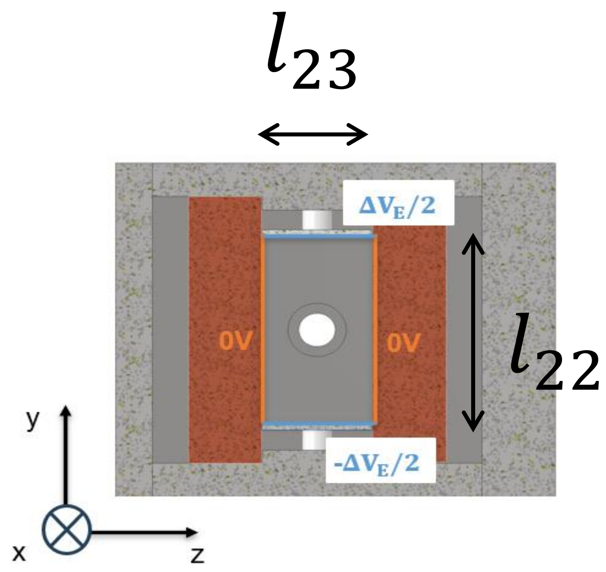
- Three main problems encountered when validating with other diagnostics
  - Velocity overestimated
  - Unexpected shape
  - Excessive broadening
- Seen across different probe configurations: understanding needed.

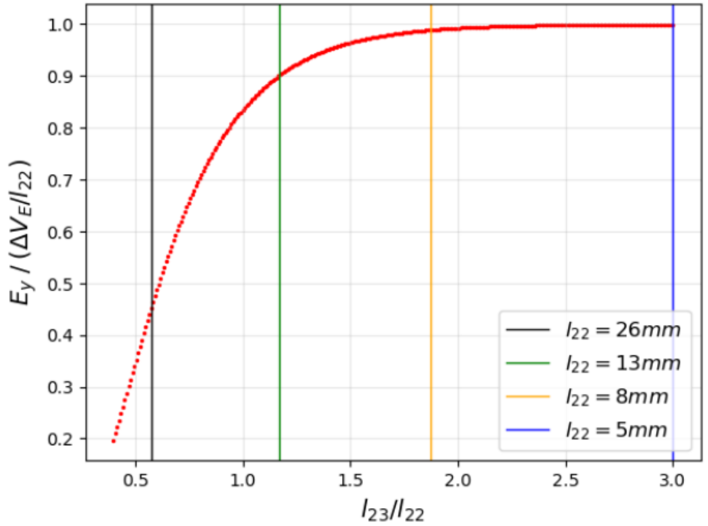
Towards a working probe

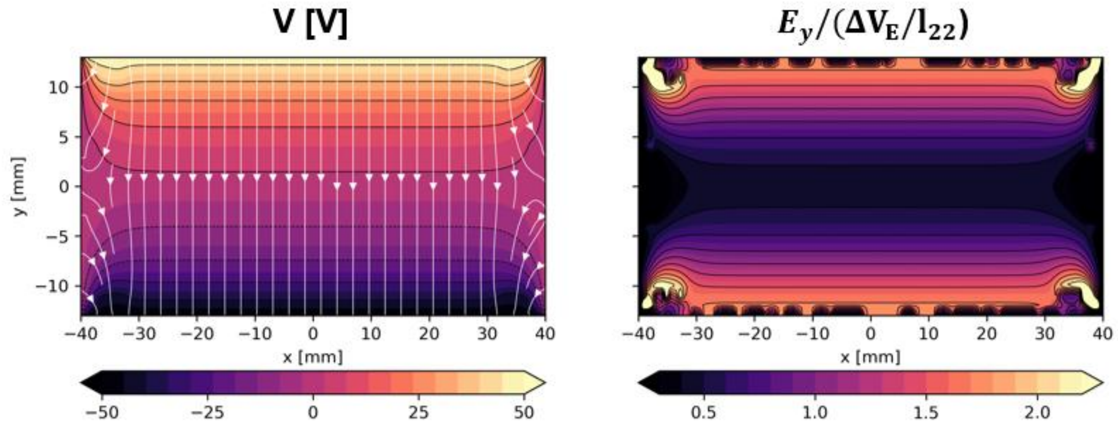
3 main problems

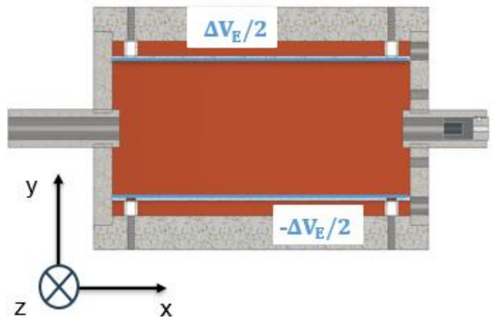
1st problem: overestimation of the particle velocity

- The small ExB dimensions makes electric field not uniform
  - Not just two parallel plates in a vacuum
  - Grounded magnets impose strong boundary conditions
  - If $E_y \neq \frac{\Delta V_E}{l_{22}} \rightarrow v_{ExB}$ **incorrectly estimated**
- Lessons learnt:
  - Probe must have $l_{23}/l_{22} > 1.6$
  - (Should always simulate in 3D)

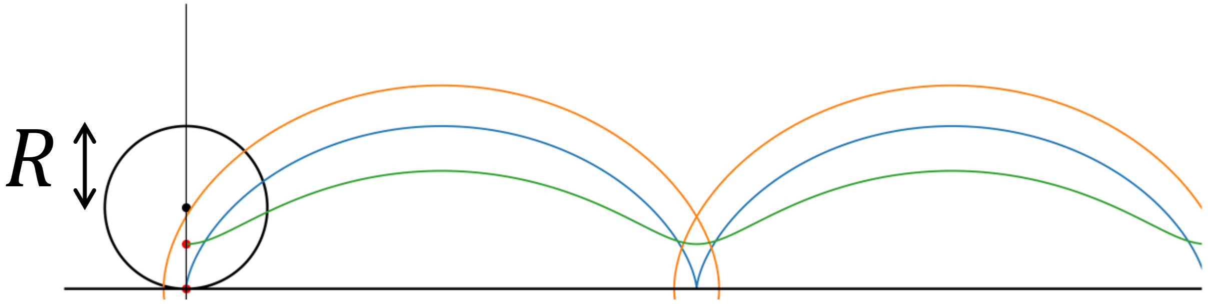




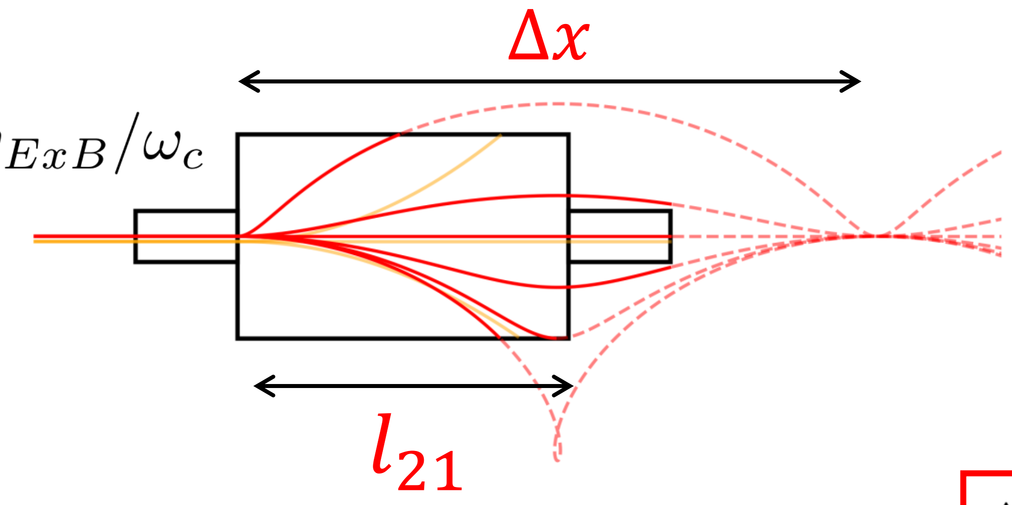




2^{nd} problem: erratic measurements for low particle velocities



$$R = v_{ExB}/\omega_c$$



- If EoM are solved analytically, **trajectories are trochoid-like** (not ballistic)
  - Does not significantly affect results if $\Delta x < l_{21}$
  - However, below ΔV_E for which $\Delta x = l_{21}$, particle collection becomes erratic
    - Strong dependence on probe geometry
    - Under real fields, unpredictable. Reconstruction is not a possibility
- ExB probes **cannot* measure slow ions**
  - Ion speeds in EPTs are significantly lower than in GIT, HET

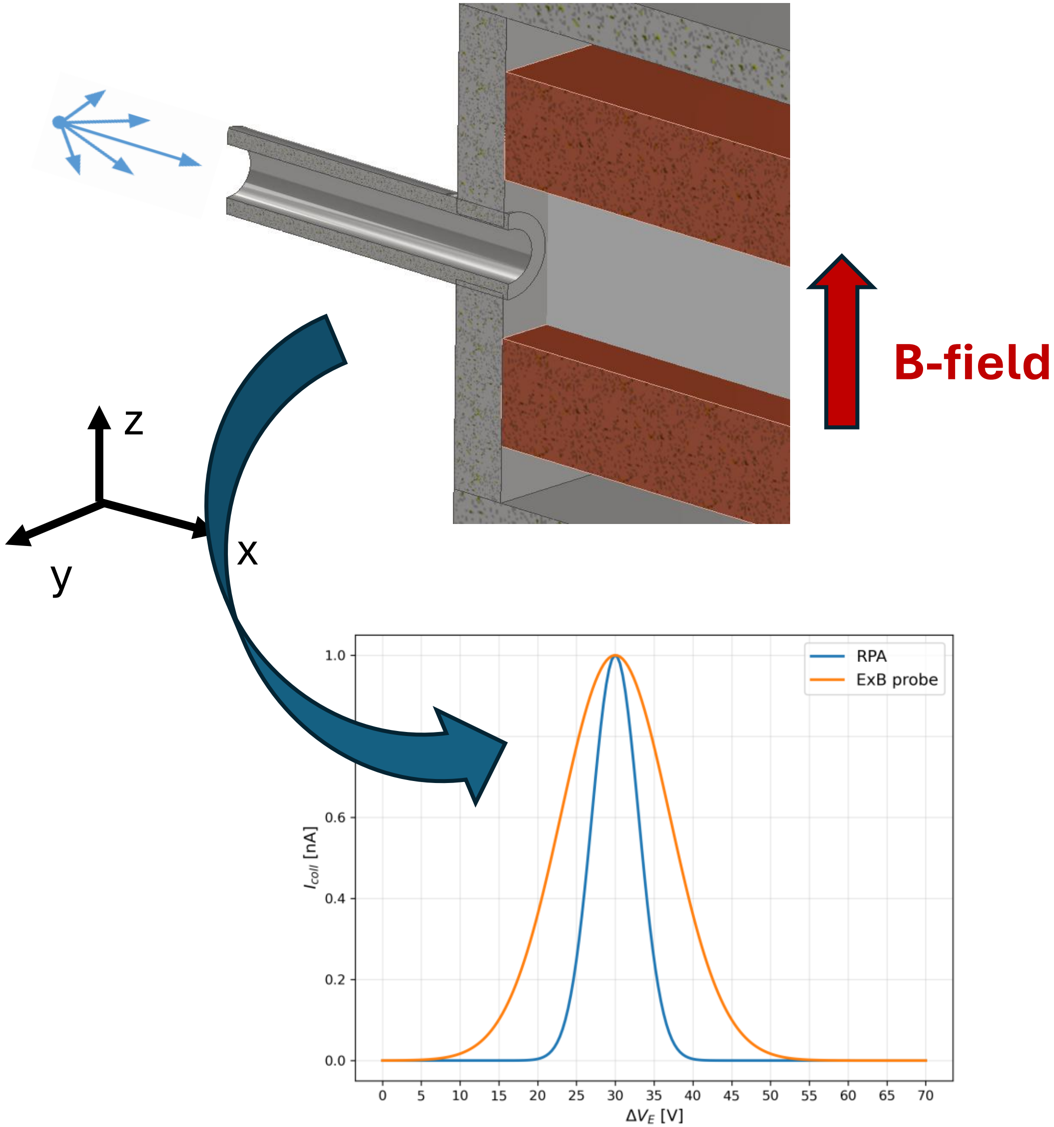
$$\Delta x = 2\pi R < 2l_{21}$$

$$\Delta V_E^{min} = ZeB_z^2 l_{21} l_{22}/m_i\pi$$

$$m_i\ddot{\mathbf{r}} = q(\mathbf{E} + \dot{\mathbf{r}} \times \mathbf{B}) = \begin{cases} m_i\ddot{x} = qB_z v_y \\ m_i\ddot{y} = qE_y - qB_z v_x \\ m_i\ddot{z} = 0 \end{cases} \Rightarrow \begin{aligned} x &= \frac{v_{ExB} - v_{x,0}}{\omega_c} sin(\omega_c t) + v_{ExB} t \\ y &= \frac{v_{ExB} - v_{x,0}}{\omega_c} cos(\omega_c t) - \frac{v_{ExB} - v_{x,0}}{\omega_c} \end{aligned} \Rightarrow v_{ExB}^{min} = ZeB_z l_{21}/m_i\pi$$

- For our probe $v_{ExB}^{min} \approx 4.6 km/s$ (Xe, Z=1)

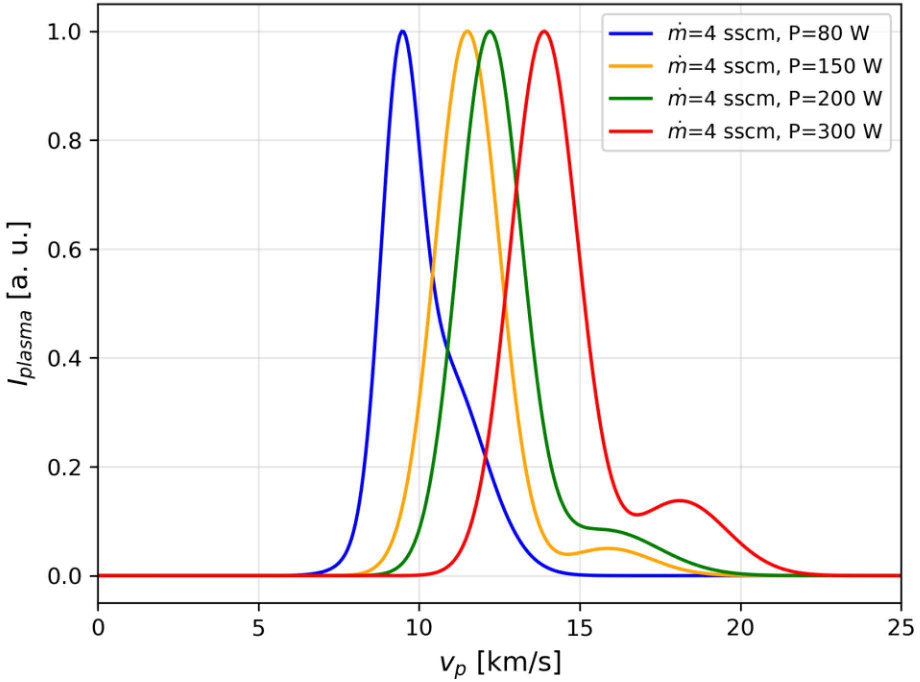
3rd problem: artificial broadening of the IVDF



- What if something were making particles enter the probe at an angle?
  - Even when testing different collimator apertures, broadening remained
  - Plasma sheaths inside the collimator *may be* causing the observed broadening
    - $\lambda_{De} \approx 1 - 5mm \approx d_{coll}$

- Model developed for probe "angular response" supports this hypothesis

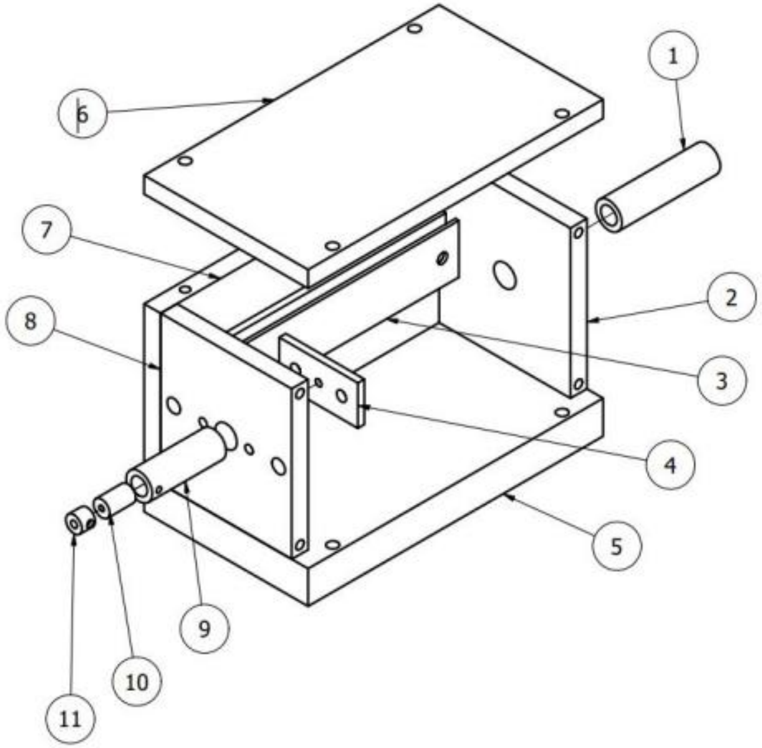
Latest results



- Doubly-charged (Z=2) ions identified for the first time in the plume of a waveguide ECRT
  - As power increases, relative amount of Z=2 current becomes significant
  - Indicative of increasing density and/or T_e inside the source
- More certainty on the reconstructed spectra is needed to make further conclusions

Re-cap and next steps

- In the last year:
  - **Improved understanding** of ExB probe design and operation
  - **Expanded existing scaling laws** for the design ExB probes
  - Demonstrated the **existence of multiply charged ions** in waveguide ECRT



- Coming next:
  - Get measurements with a new entrance collimator to “fix” spectral broadening
  - Publish journal article with new design criteria, measurements in ECRT
  - Re-design EP2 ExB probe, **characterize plume of air-breathing HPT, CHT**
  - Survive (together with supervisors) rest of the thesis

Achievements

- Presentation in Giessen Workshop on Plasma Diagnostics for EP
- **Bayón-Buján, B.,** Inchingolo, M. R., & Navarro-Cavallé, J. (2025). Challenges in the design of an ExB probe for Electrodeless Plasma Thrusters presented at the 39th International Electric Propulsion Conference (London, UK)
- **Bayón-Buján, B.,** Inchingolo, M. R., & Navarro-Cavallé, J. (2026). On the broadening of the Ion Velocity Distribution Function measured with ExB probes in Electrodeless Plasma Thrusters. Presented at the 10th Space Propulsion Conference (Bari, Italy)
- Published two articles from previous work
  - Maddaloni, D., **Bayón-Buján, B**., Navarro-Cavallé, J., Merino, M., & Terragni, F. (2025). Low-frequency oscillations in the magnetic nozzle of a Helicon Plasma Thruster. *Plasma Sources Science and Technology*, *34*(4), 045008.
  - **Bayón-Buján, B.,** Bello-Benítez, E., Zhou, J., & Merino, M. (2025). Data-driven analysis of anomalous transport and three-wave-coupling effects in an E× B plasma. *Journal of Electric Propulsion*, *4*(1), 58.
- Lecturer in
  - Classical Mechanics for Aerospace Engineering (2nd year Bachelor, 1st semester)
  - The Conquest of Space (1st year Bachelor, 2nd semester)

Thank you! Questions?

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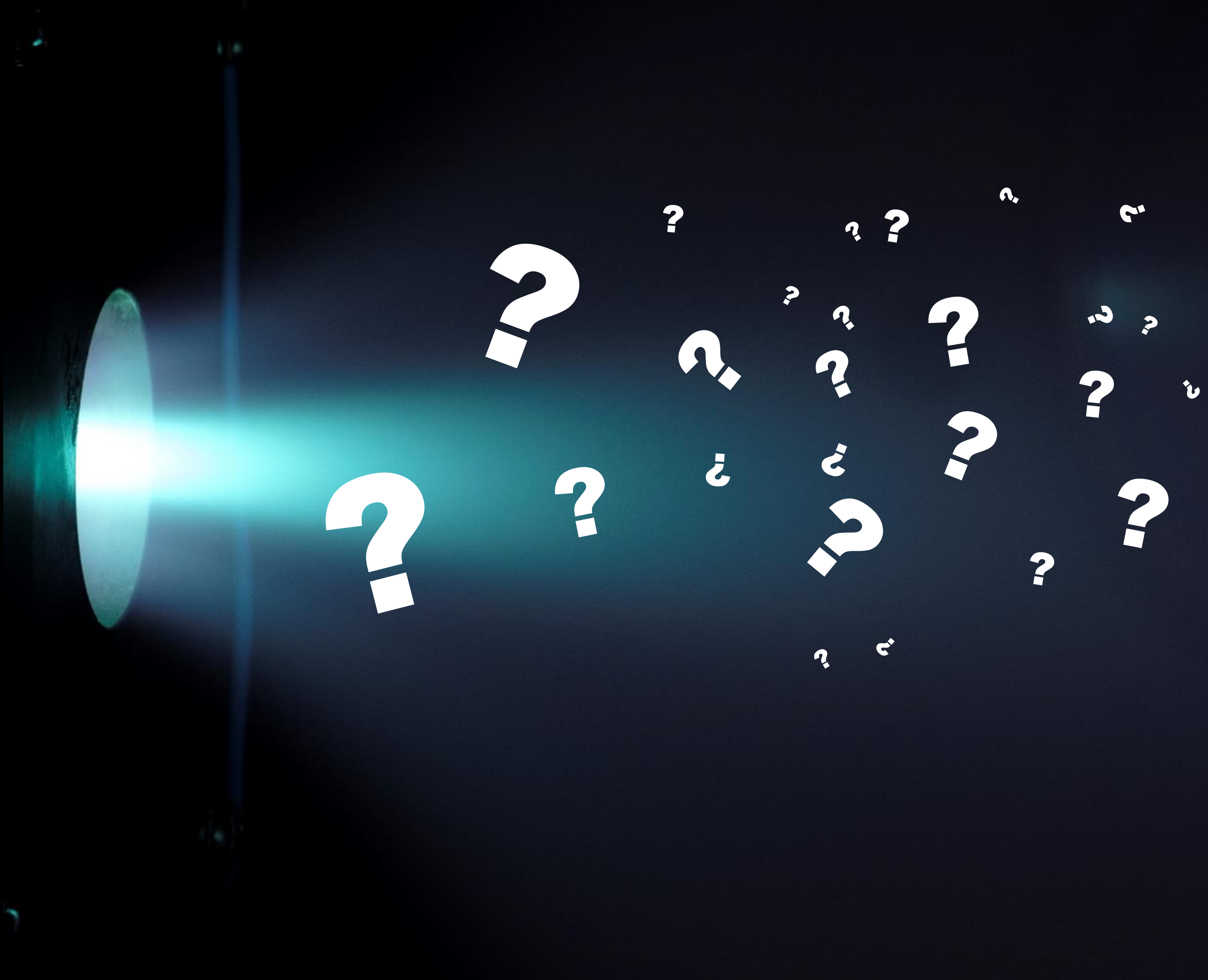

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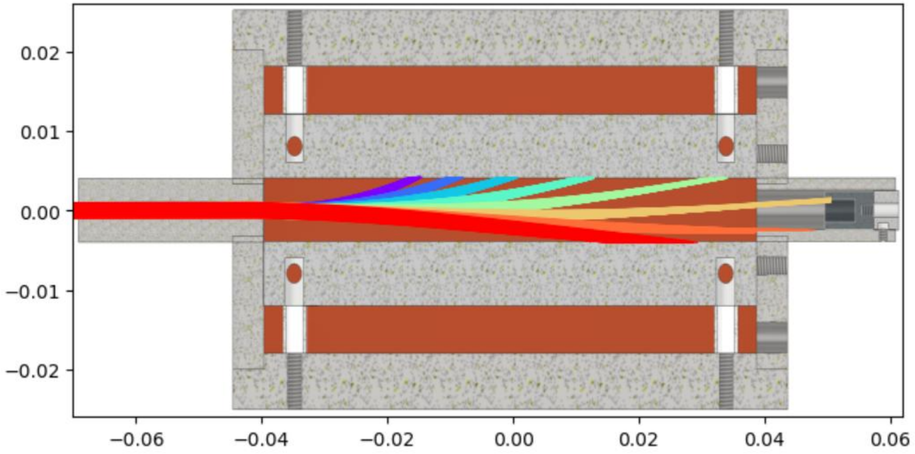
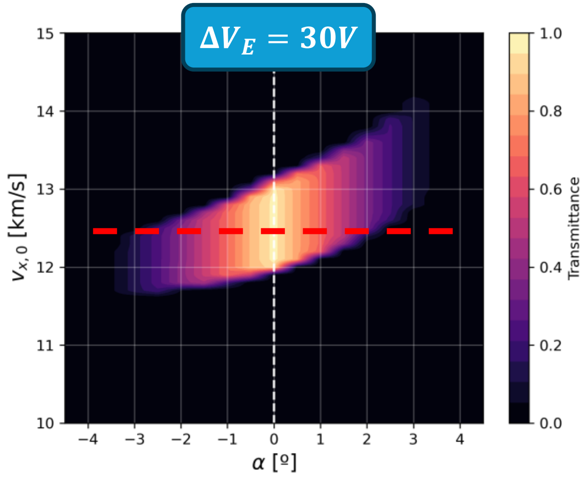
General framework: probe transmittance and IVDF reconstruction

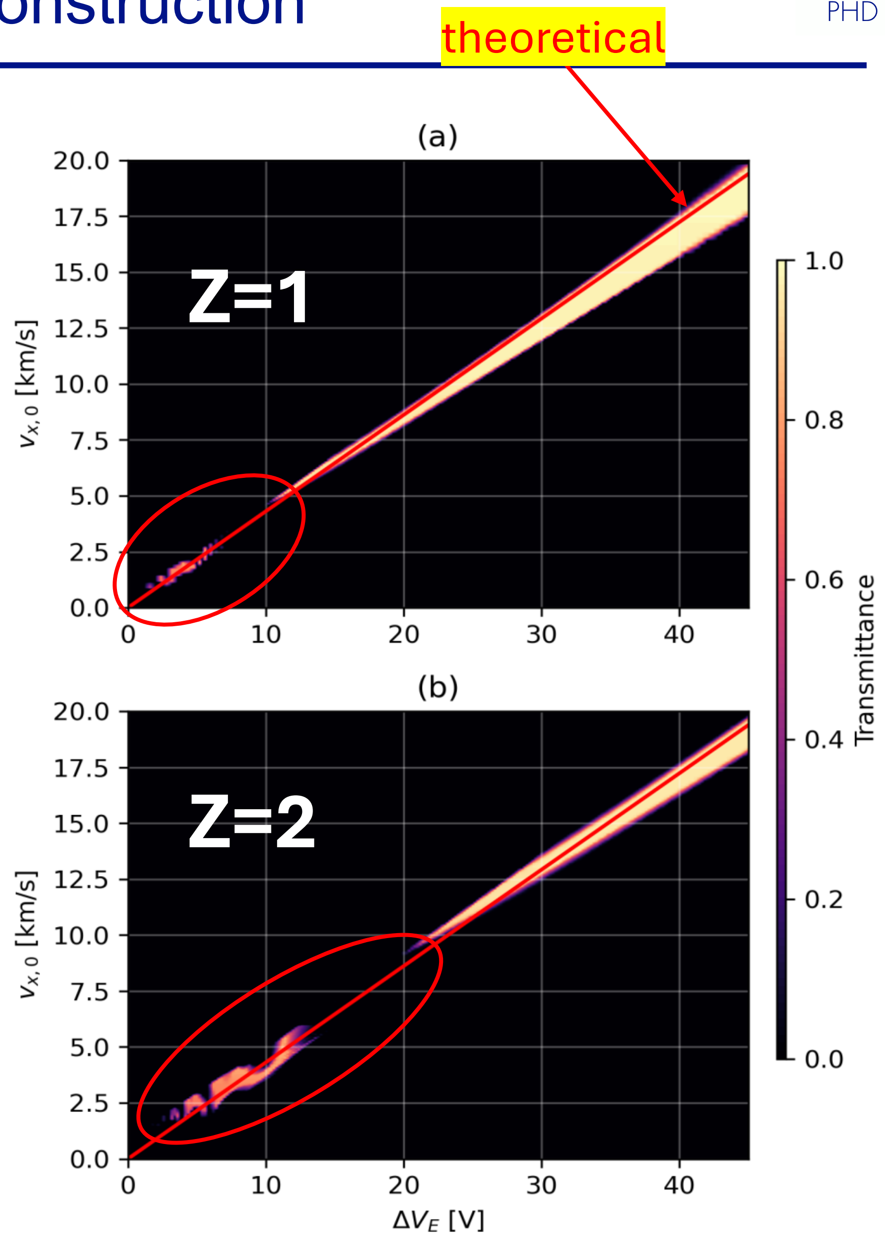
- The measured $I_{coll}(\Delta V_E)$ is the result of convoluting the IVDF with the probe's transfer function: the **transmittance**

$$I_{coll}(\Delta V_E) = I_{plasma}(v_{x,0}) \otimes \boldsymbol{T}(\boldsymbol{\Delta V_E}, \boldsymbol{v_{x,0}})$$

  - Ideally, $\boldsymbol{T} \sim \mathbf{1}$. As was seen, in general, not the case.
  - $\boldsymbol{T}$ depends on probe geometry and fields.
- From the simulated transmittance, compared against the theoretical v_{ExB}
- Transmittance can be used to reconstruct $I_{plasma}(v_{x,0})$

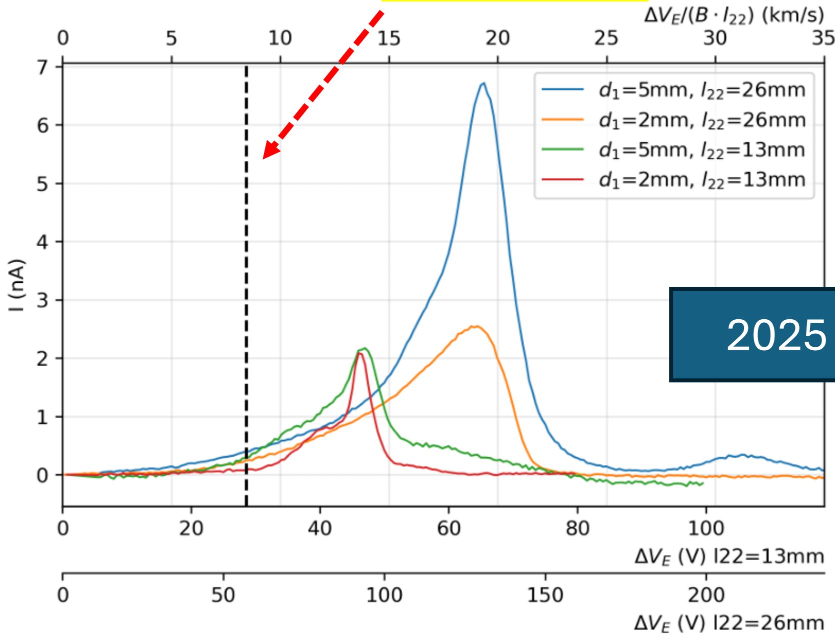




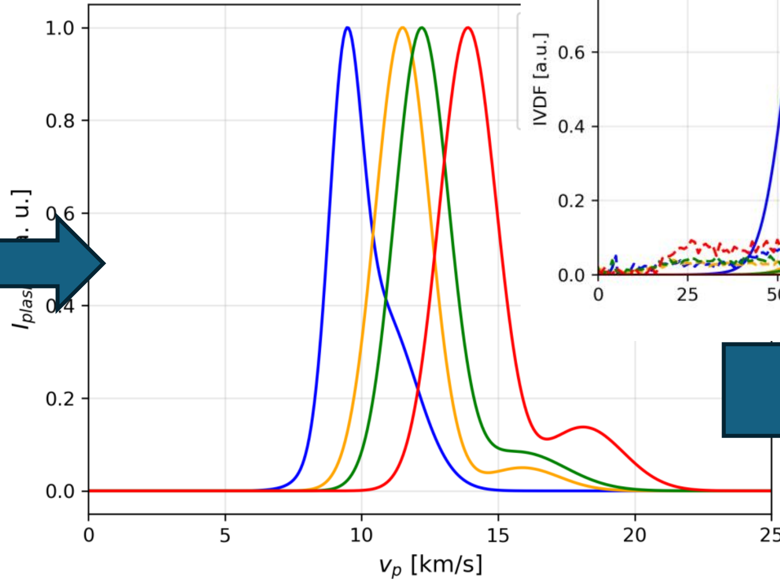


1.5 years later

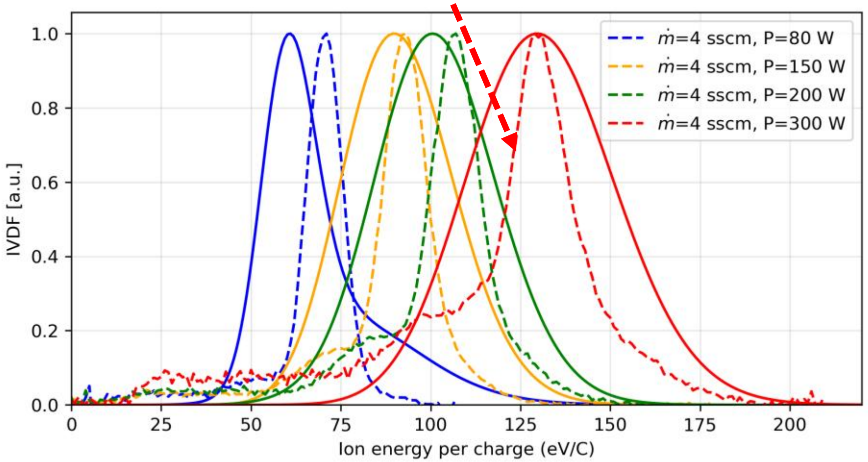
expectations



2025

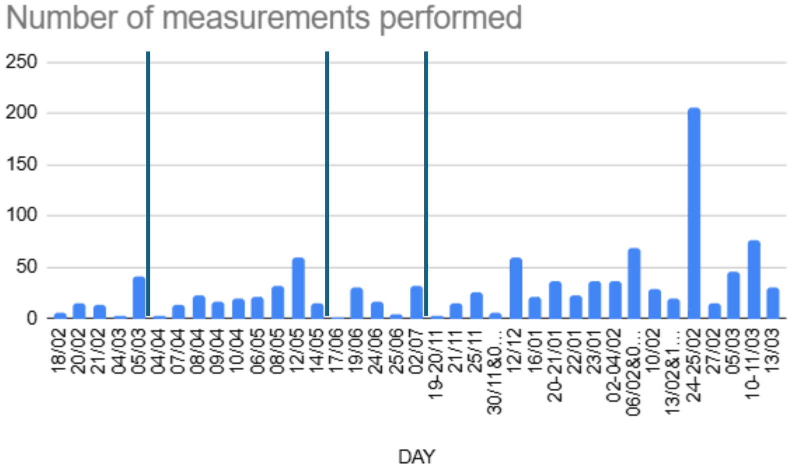


expectations



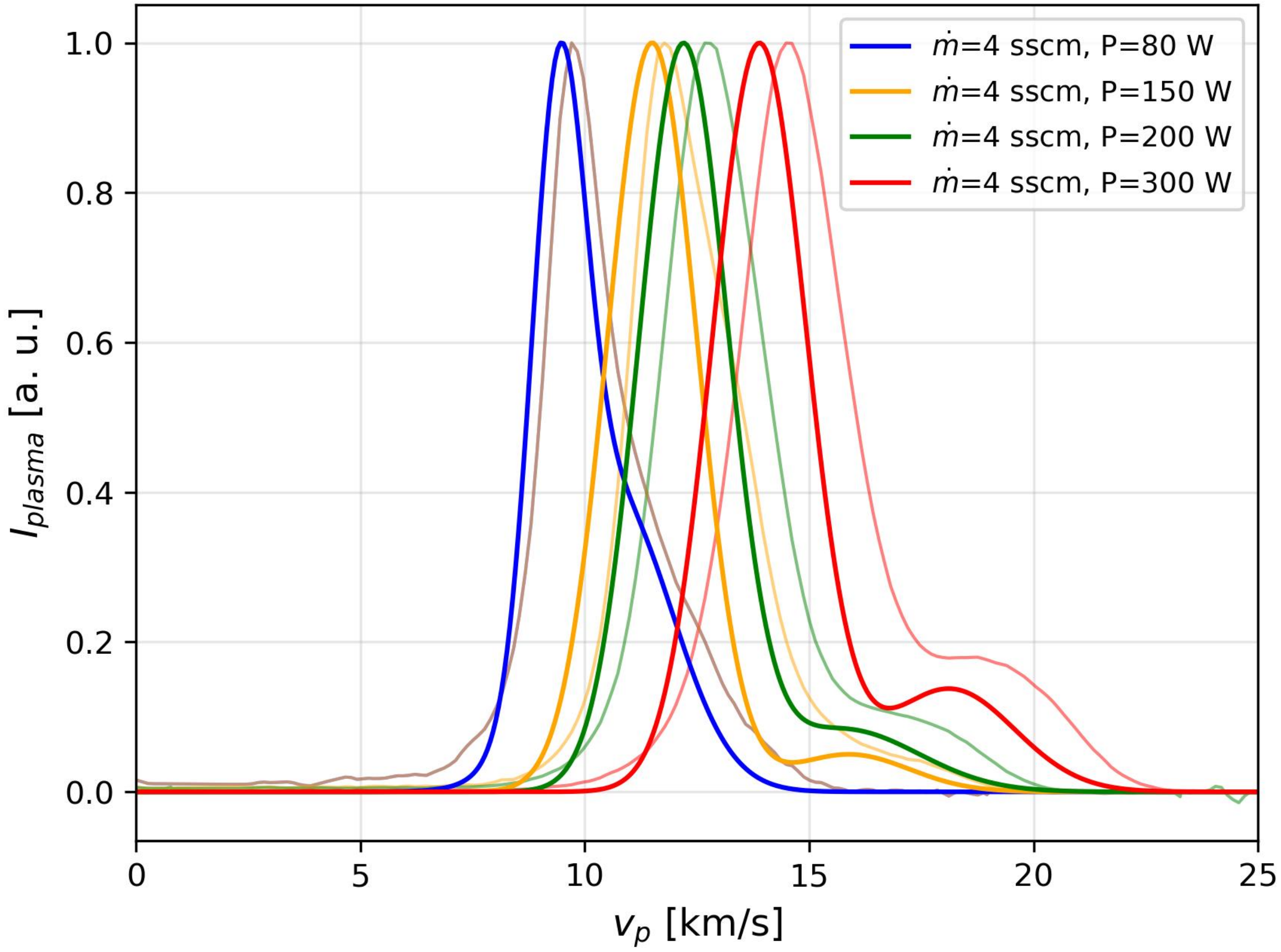
2026

- Carried out 4 separate experimental campaigns, **548 data points**
  - Spectra did not match expectations
  - Changed thruster type, propellant, operation point, probe configuration, position and orientation…
  - Carried out validation with other EP diagnostics (RPA, FC)
  - Learnt A LOT along the way
  - Simultaneously developing ExB probe simulations



Spectra reconstruction

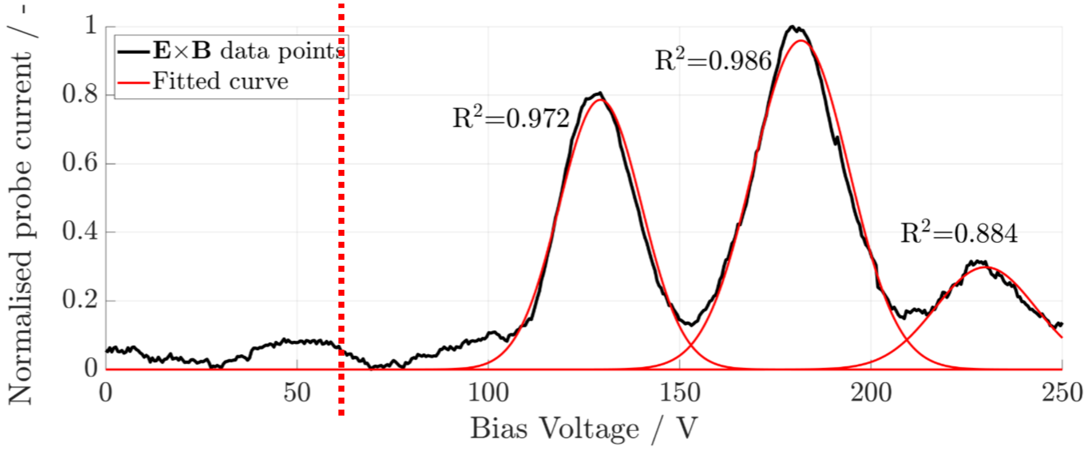
- Use of vExB can lead to severe (1km/s) velocity overestimation
- Doubly charged peak is also overrepresented

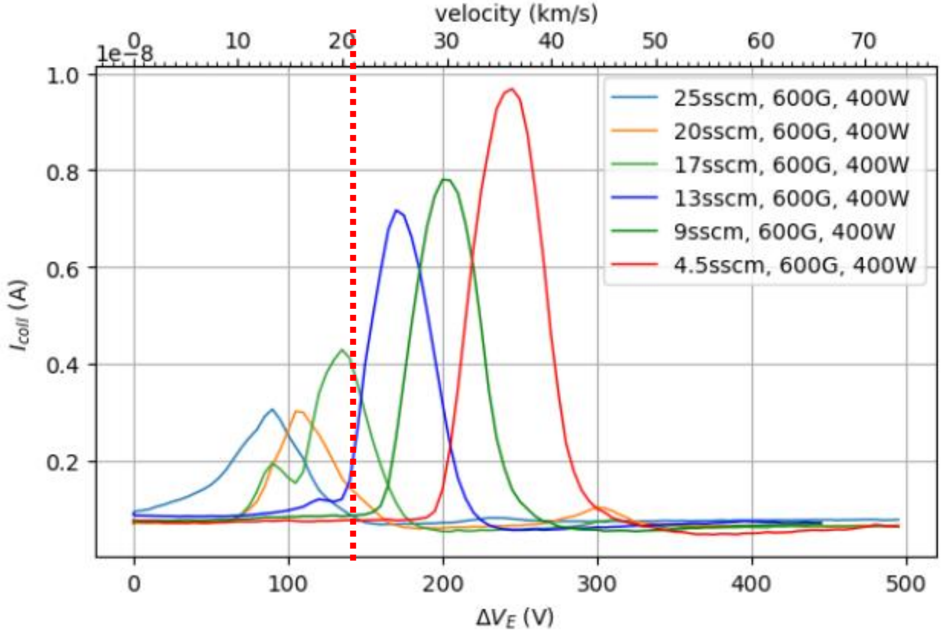


Trochoidal trajectories?

- Some examples on “trochoidal effects”

**Silvia Masillo and Andrea Lucca Fabris.
"Characterisation of the Halo Thruster: Plasma diagnostics and ground-test facility effects” IEPC25





Thruster efficiency

$$\eta_F \approx \frac{F_{i\infty}^2}{2\dot{m}_p P_T} = \eta_u \eta_d \eta_e \eta_s,$$

$$\eta_u = \frac{I_i m_i}{\dot{m}_p e},$$

$$\eta_e = \frac{P_{i\infty}}{P_T},$$

$$\eta_d = \left(\frac{I_{zi}}{I_i}\right)^2,$$

$$\eta_s = \kappa_2^2/\kappa_3,$$

ECRT thruster efficiencies

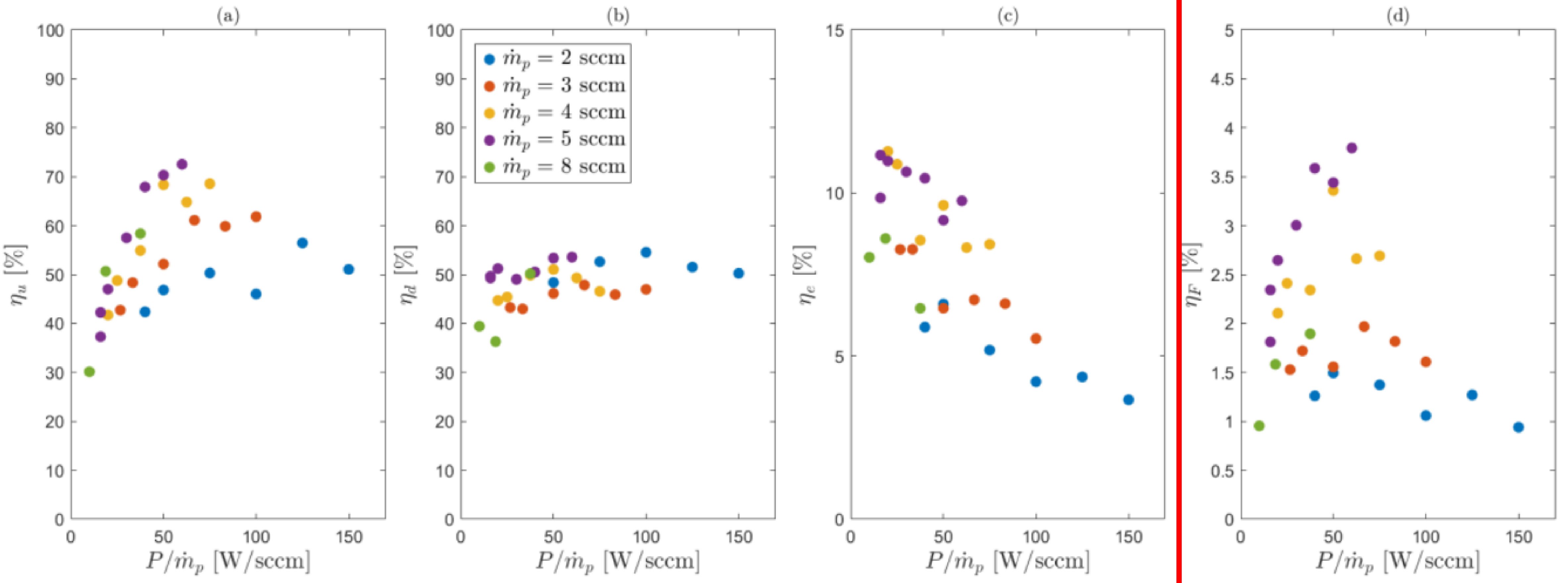
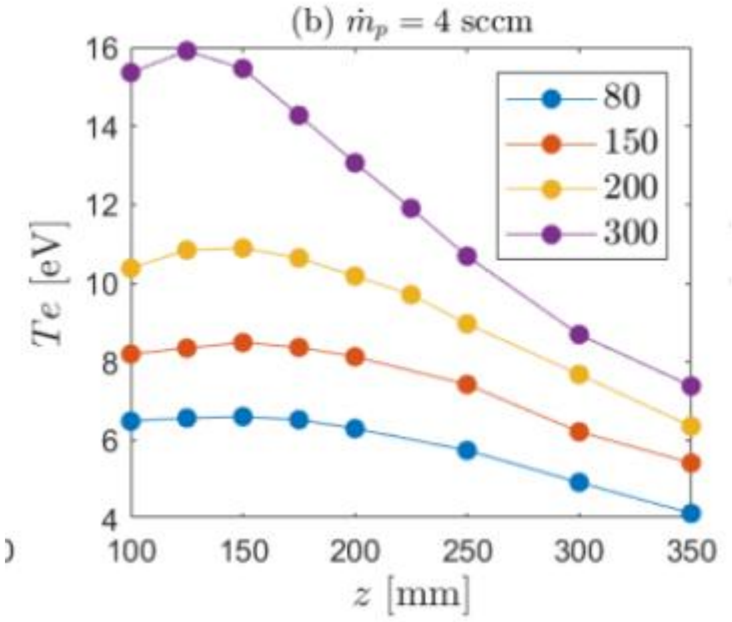
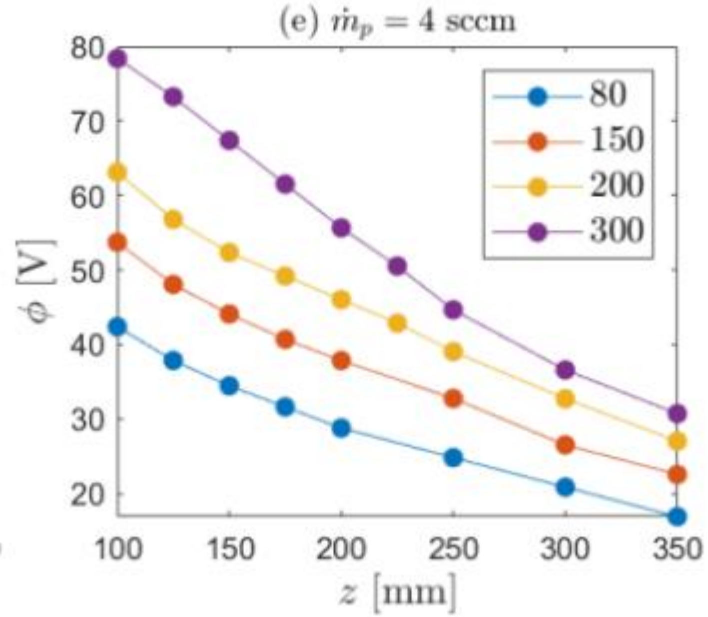


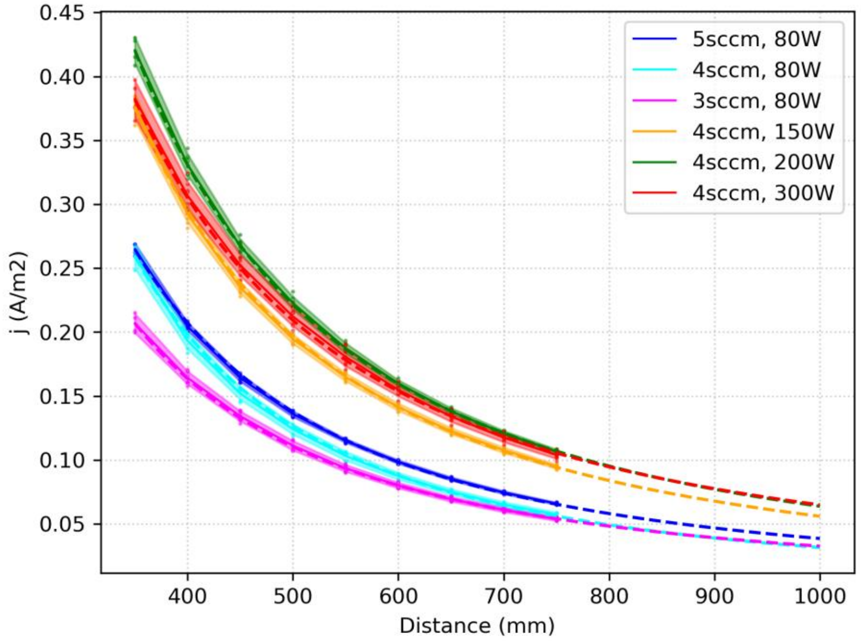
Figure 15. Partial efficiencies obtained with the Faraday cup and RPA measurements plotted against the power to mass flow rate ratio $P/\dot{m}_p$. (a), (b), (c), (d) are respectively the utilization η_u, divergence η_d, energy efficiency η_e and the thrust efficiency η_F.

Marco R. Inchingolo, Bayón-Buján, Borja and Jaume Navarro-Cavallé. " Experimental characterization of a waveguide ECRT with axial propellant injection." IEPC2025.

ECRT far-plume

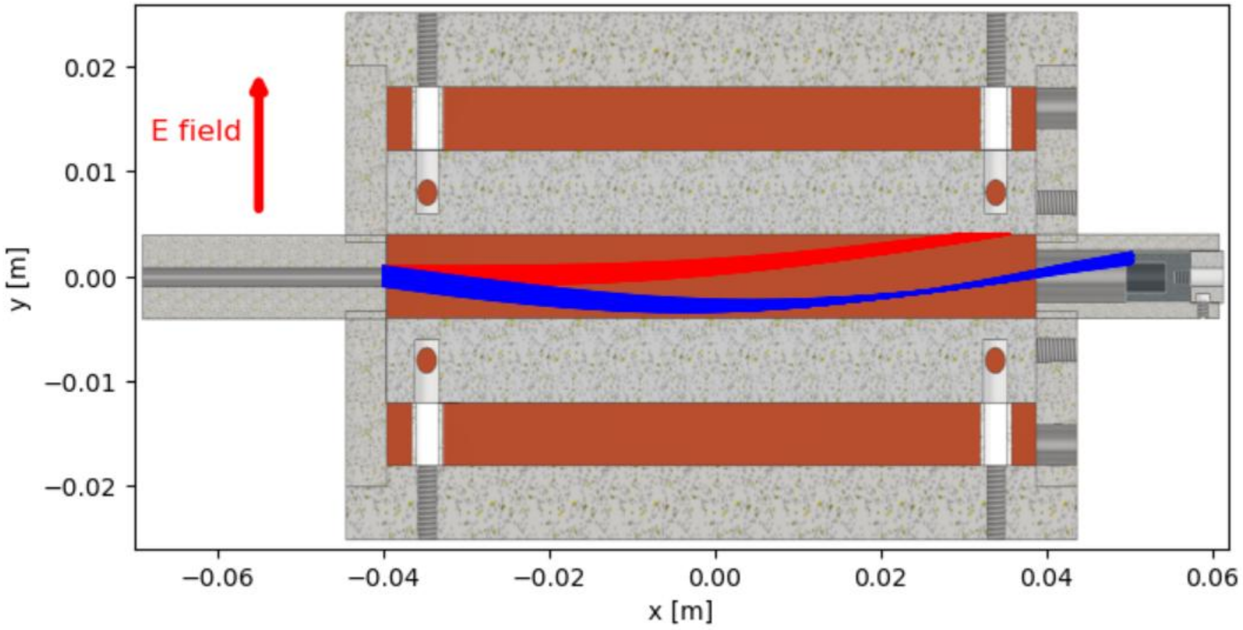






Broadening

- If particle inertia opposes the dominant force direction, particles with $v_x \neq v_{ExB}$ can be collected



$$\Delta v_{ExB} = v_{x,0} - v_{ExB} = \frac{\Delta y - l_{21} tan\alpha}{\frac{Z}{2}\frac{eB_z}{m_i}(\frac{l_{21}}{v_{x,0}})^2}$$

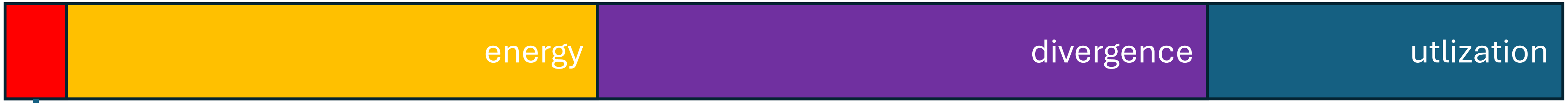
Problem statement: EPTs and efficiency

$$\eta_T = \frac{T^2}{2\dot{m}P}$$

T^2 → Thruster output

$2\dot{m}P$ → Operation point

$$\eta_T = \eta_u \eta_d \eta_\epsilon$$



“Remaining” thrust(er) efficiency (**useful power**)

$$\eta_T = 0.75 \cdot 0.5 \cdot 0.12 = \mathbf{4.5\%}$$

Thruster efficiency can be decomposed into three partial efficiencies

- Propellant utilization efficiency (30-75%)
- Beam divergence efficiency (35-55%)
- **Energy efficiency** remains the main bottleneck (4-12%)
  - Inelastic collisional loses
  - Particle/power lost to walls
  - MW power reflected/radiated away

→ Poorly characterized experimentally

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