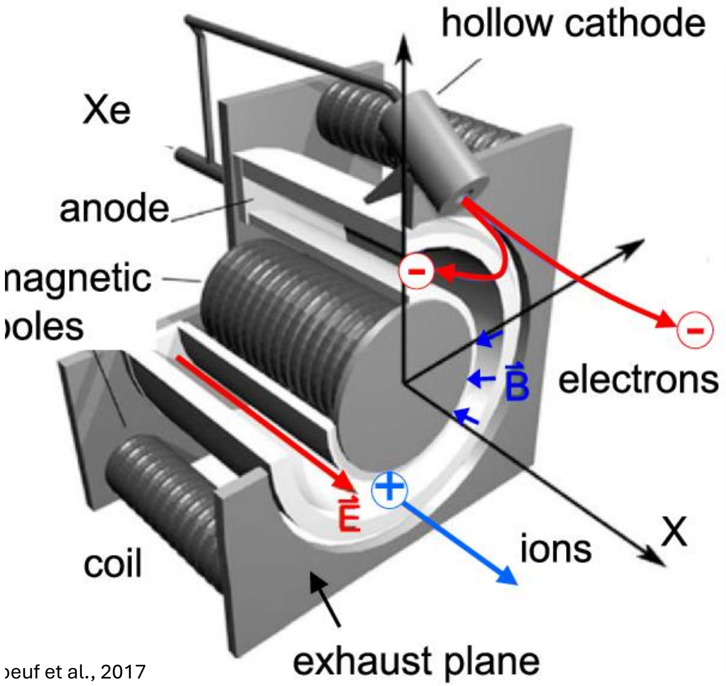
Design and characterization of a 200 W-class cylindrical Hall thruster

PhD Student: Tatiana Perrotin
Supervisor/s: Jaume Navarro-Cavallé, Pablo Fajardo

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

Motivation

- **Need for low-power** electric propulsion
  - **Hall thrusters**
    - Mature, high-performance, high thrust (for EP)



Annular chamber
Radial $\vec{B}$, axial $\vec{E}$ (anode-cathode)

Cathode electrons trapped in azimuthal ExB drift
Ionize neutral gas from anode
$\vec{E}$ accelerates ions
Cathode electrons neutralize beam

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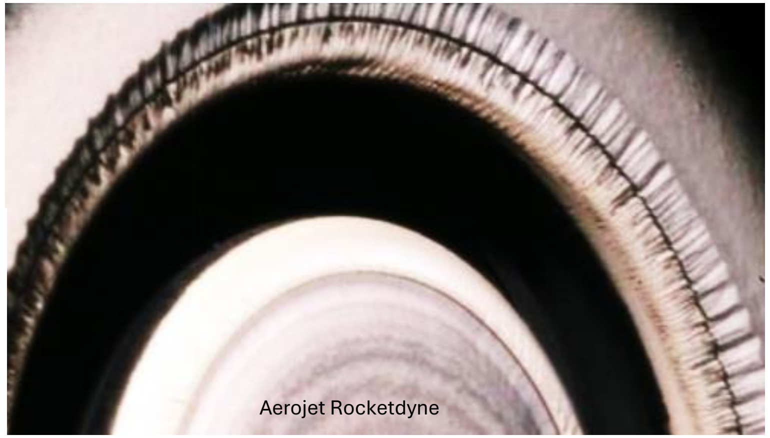
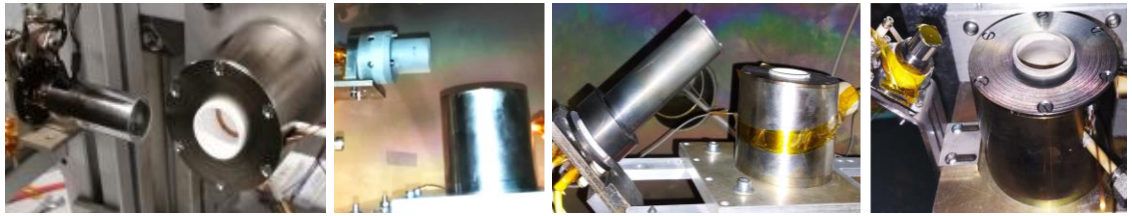
- **Challenges:**
  - No scaling laws
  - Miniaturization → thermal issues, B saturation, manufacturing…
  - Increased wall losses, erosion → efficiency & lifetime drop
  - Low-current neutralizer (small, unreliable, power & propellant consumption per current scale up)



Channel erosion



Low current cathodes

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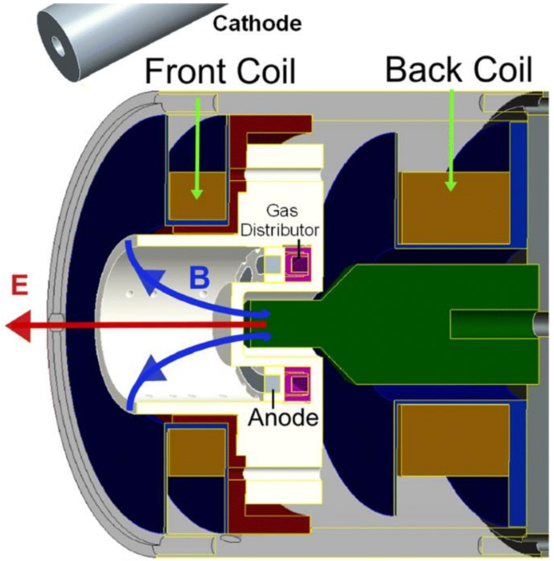
- **Cylindrical Hall Thruster** (CHT)
  - No inner wall to erode
  - Larger volume-to-surface ratio → reduce wall losses
  - Avoids small components
  - Room for $\vec{B}$ generation

  - Promising, non-conventional design, few prototypes
  - **Need for experimental data**
    - Understanding physics (e.g., transport, ion production, confinement, effects of $\vec{B}$)
    - Design optimization
    - Validate models

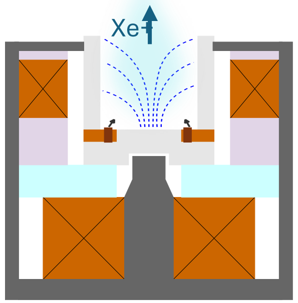


Ding et al., 2019

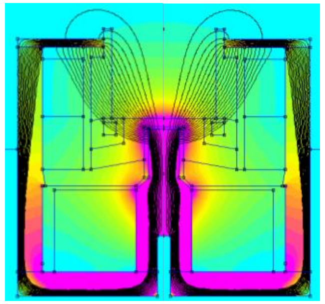
Approach

- Design and build

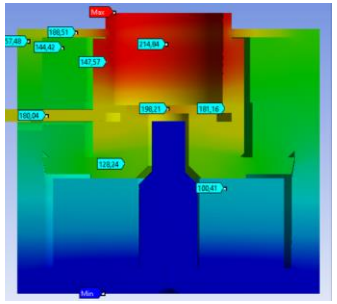
Concept



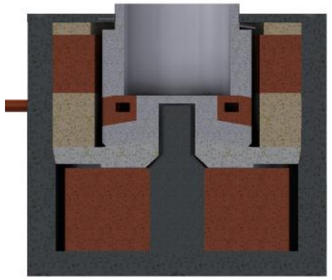
Magnetostatic



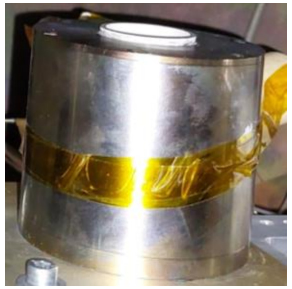
Thermal



Mechanical



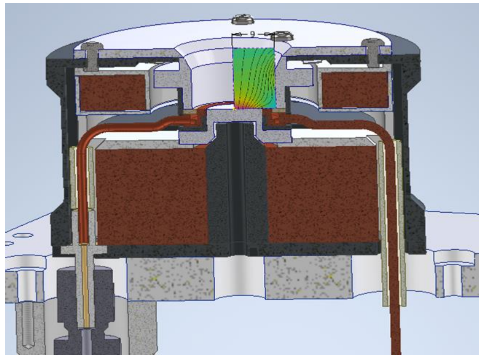
Assembly



- Model plasma discharge
- Characterize experimentally extensively
  - Response to inputs
  - Plasma properties
  - Performance

- Iterate design, testing, and modelling

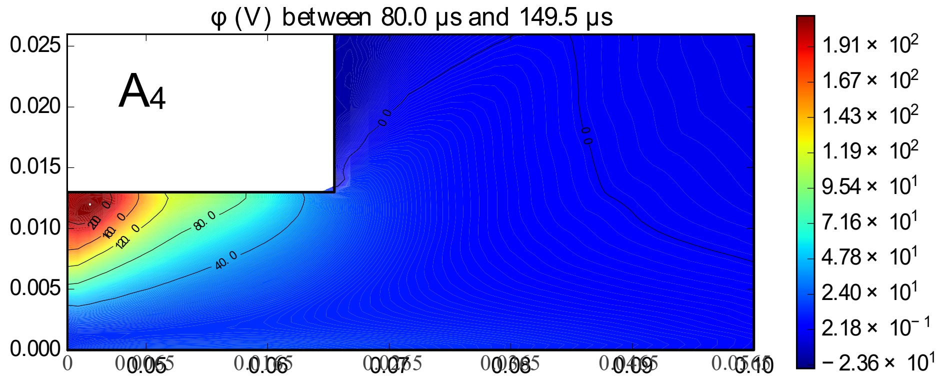
Second prototype

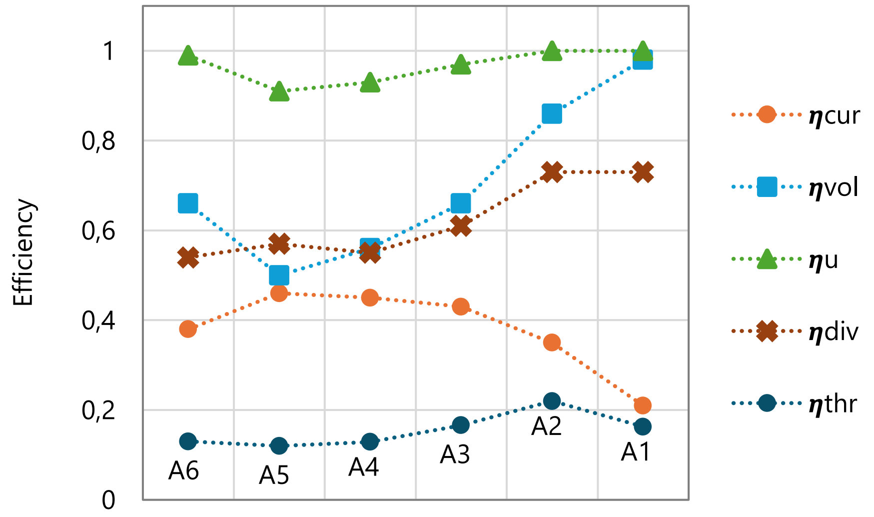


Results: overview

Simulations

- Parametric studies on CHT geometry (anode, injector, dimensions, wall, cathode)





Optimal anode/injector radius balancing losses

- Useful current vs divergence & acceleration

Shorter channel reduces recombination

Cathode location affects ionization

Results: overview

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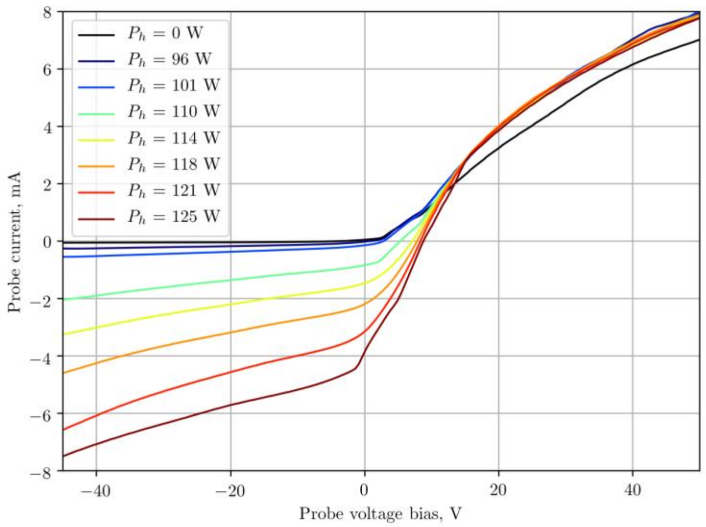
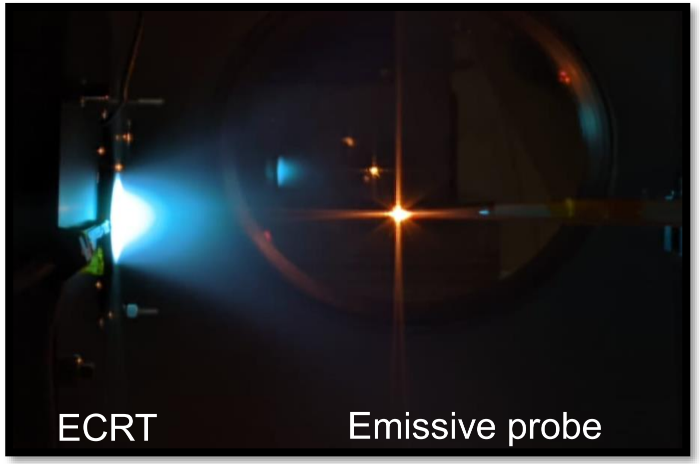
Diagnostic development

- Two emissive probes built & used with ECRT
- Comparison with theoretical model for tethers





Need for better theory and modeling for EP plasma

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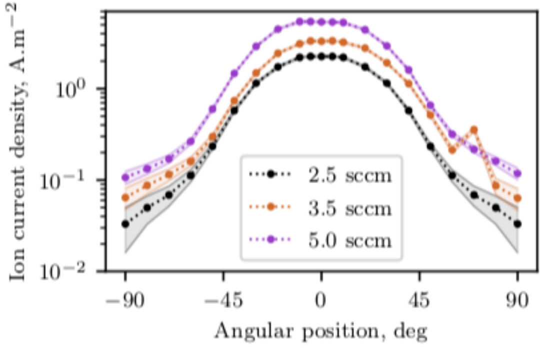
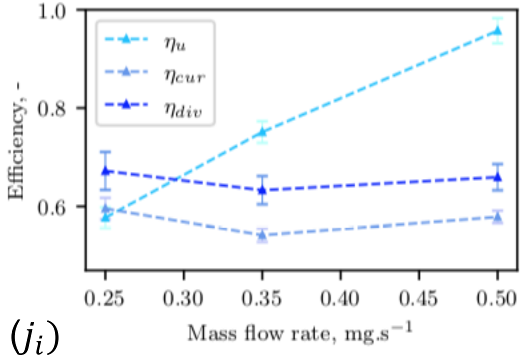
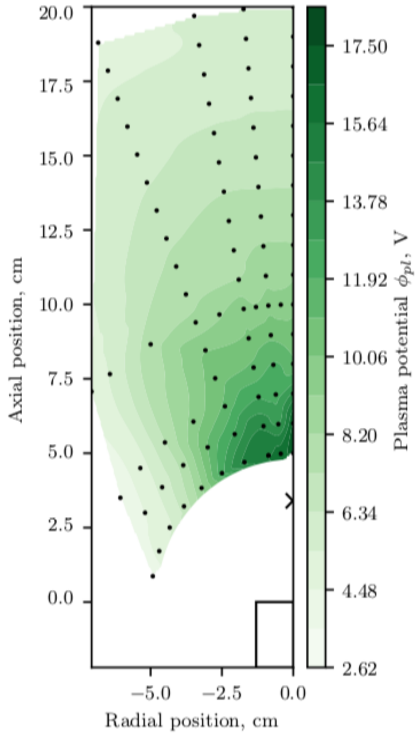
Prototype characterization
- 200 W prototype built & tested
- 2 gases, 5 cathodes
- **Far-field measurements**
  - Langmuir Probe (T_e, ϕ, n), Retarding Potential Analyzer (IVDF), Faraday Cup (j_i)
  - Current oscillations







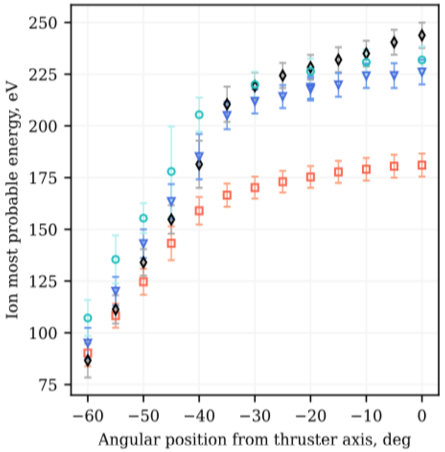
$\vec{B}$ - nearly no effect

$\dot{m}_a$ - better ionization but lower energy

V_d - enhances energy, current, focusing

Clear energy drop outside beam angle

Measurement of polytropic index $\left(\frac{n_e}{n_{e0}}\right)^{\gamma-1} = \frac{T_e}{T_{e0}}$



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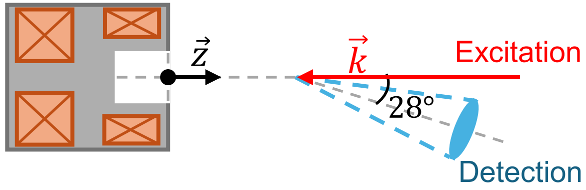

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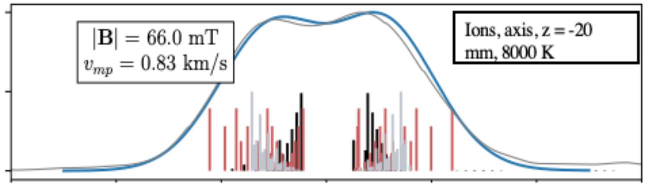
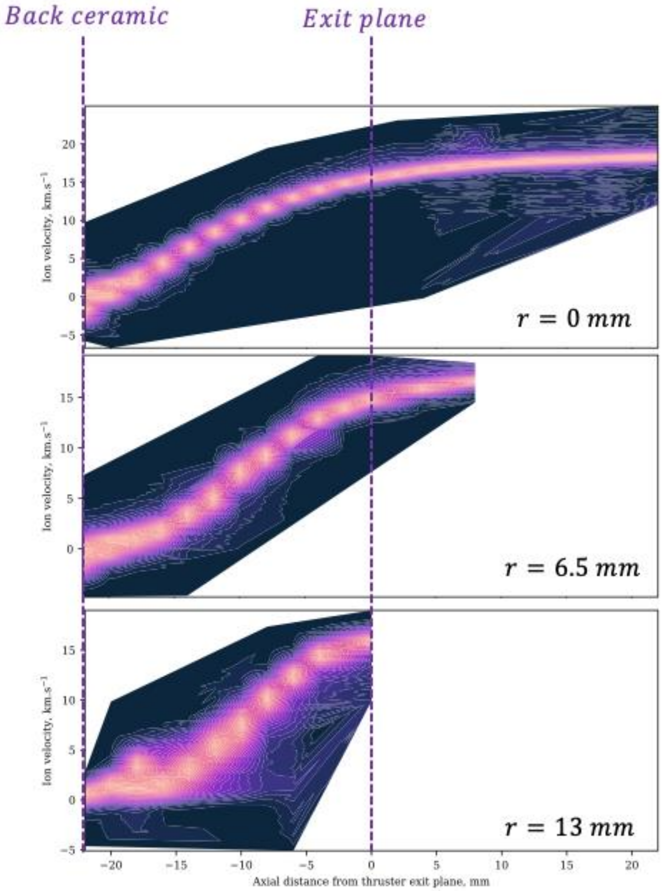
- **Internal discharge and near-field measurements**
  - Laser-Induced Fluorescence spectroscopy (2D plane)
  - Xenon ion and atom axial VDF reconstruction

Doppler velocimetry $v = c\left(1 - \frac{\lambda}{\lambda_0}\right)$

- Lineshape modeling enables VDF reconstruction with Zeeman, isotopes, …
- Acceleration within channel
- Acceleration more upstream on axis but compensated by $\vec{E}$
- Wall recombination
- Neutral T_n, v_n



Axial velocity r-z measurements



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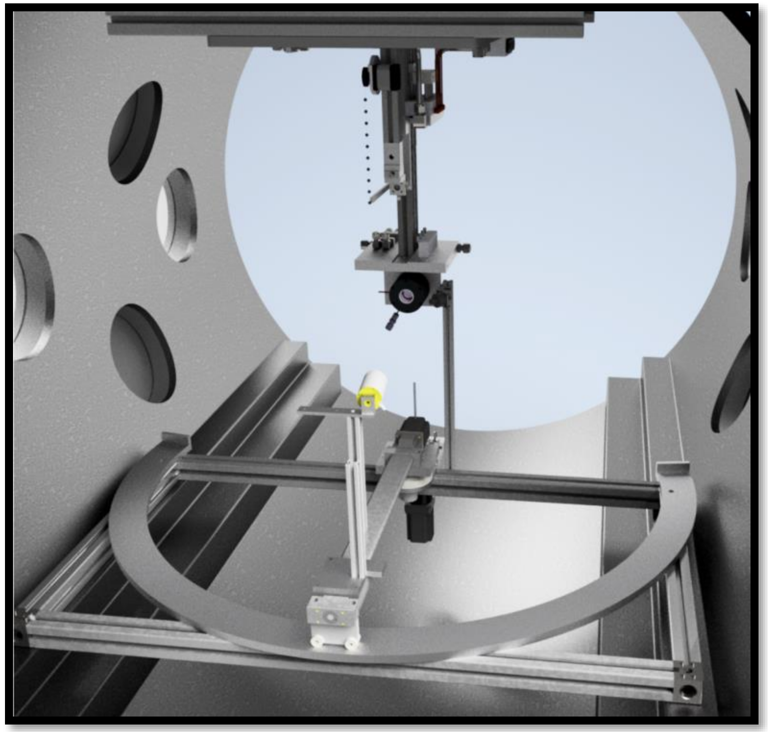
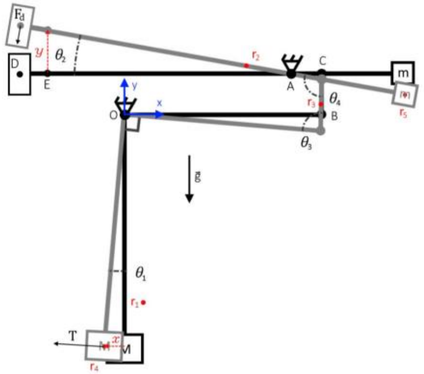
- **Performance measurements**
  - Direct thrust
  - Probe far-field plasma for decomposition



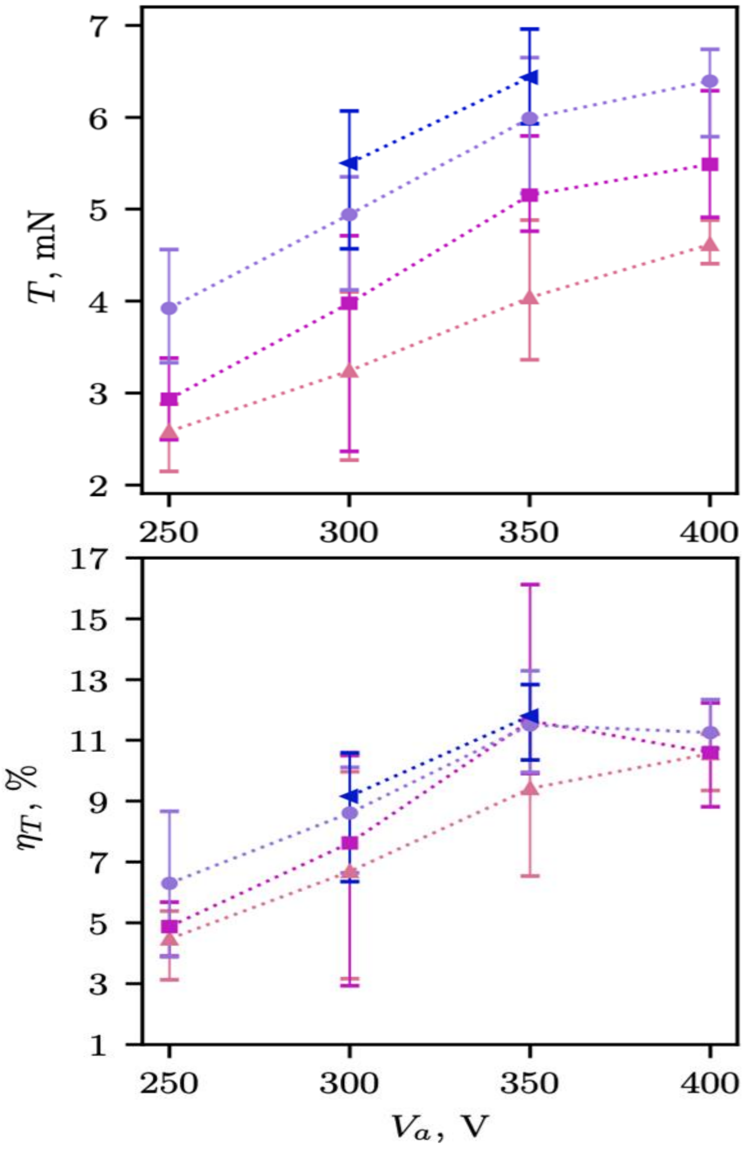


Hanging pendulum thrust balance

Performance characterization

Thrust balance

- Thrust and efficiency trends with $\dot{m}_a$ & V_d
- $\boldsymbol{\eta_T}$ mainly depends on $\mathbf{V_d}$ and saturated with $\boldsymbol{P_d}$ for all $\dot{m}_a$



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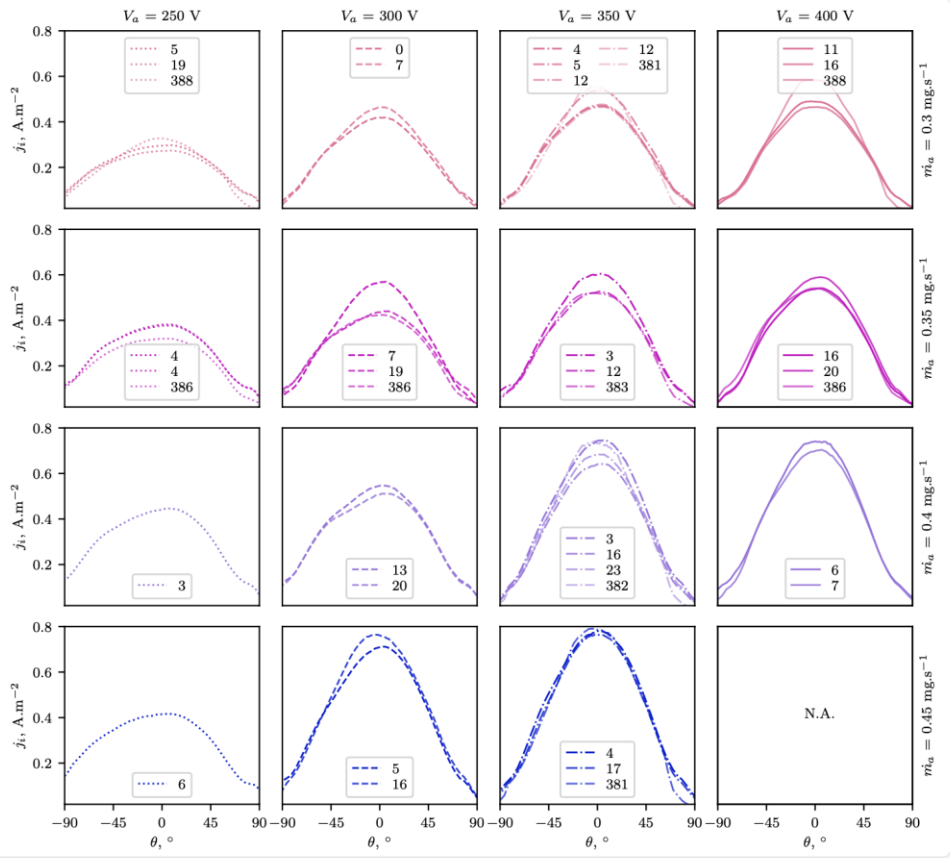
Faraday Cup

- Plume asymmetries
- Divergence & needs large $\mathrm{I_d}$ to produce beam current
- Propellant utilization >1 → $\mathrm{Xe}^{2+}, \mathrm{Xe}^{3+}$



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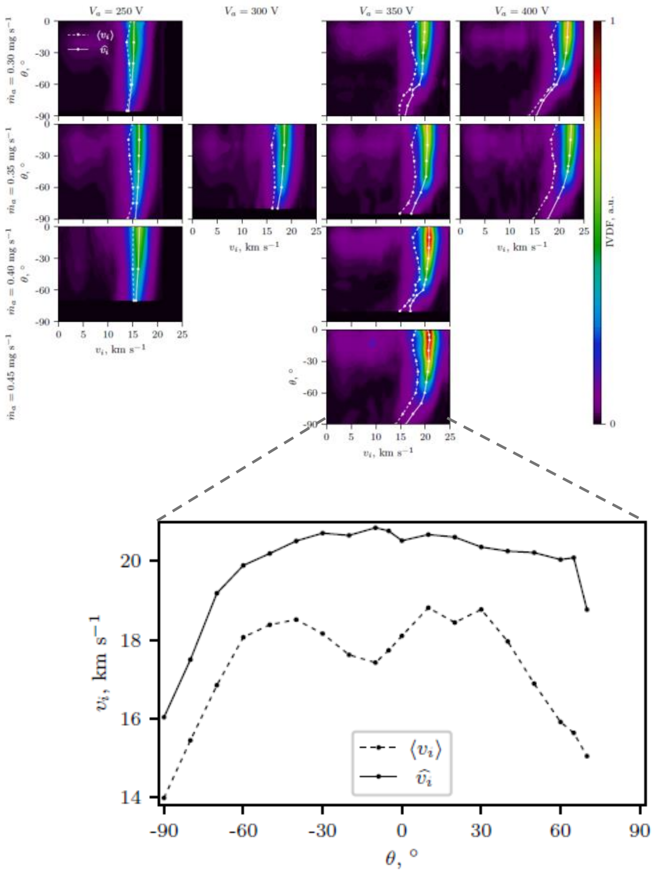
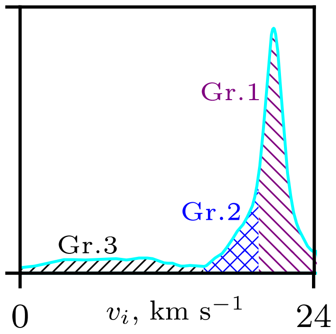
Retarding Potential Analyzer

- 3 ion groups:
  - anode region
  - extended/secondary region
  - CEX/recombined
- Slow ions lower average velocity on axis & at $|\theta| \gtrsim 50°$





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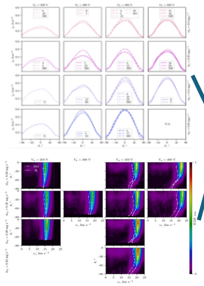
Indirect performance estimation



$$P_b \approx \pi r^2 \int_{\theta=-\frac{\pi}{2}}^{\theta=\frac{\pi}{2}} \langle E_i \rangle(\theta) j_i(\theta) |\sin\theta| \, d\theta$$

$$F \approx \pi r^2 \frac{m_i}{q} \int_{\theta=-\frac{\pi}{2}}^{\theta=\frac{\pi}{2}} \langle v_i \rangle(\theta) j_i(\theta) \cos\theta |\sin\theta| \, d\theta$$

η_{div}
η_{ene}
η_{vol}
η_{cur}
η_F

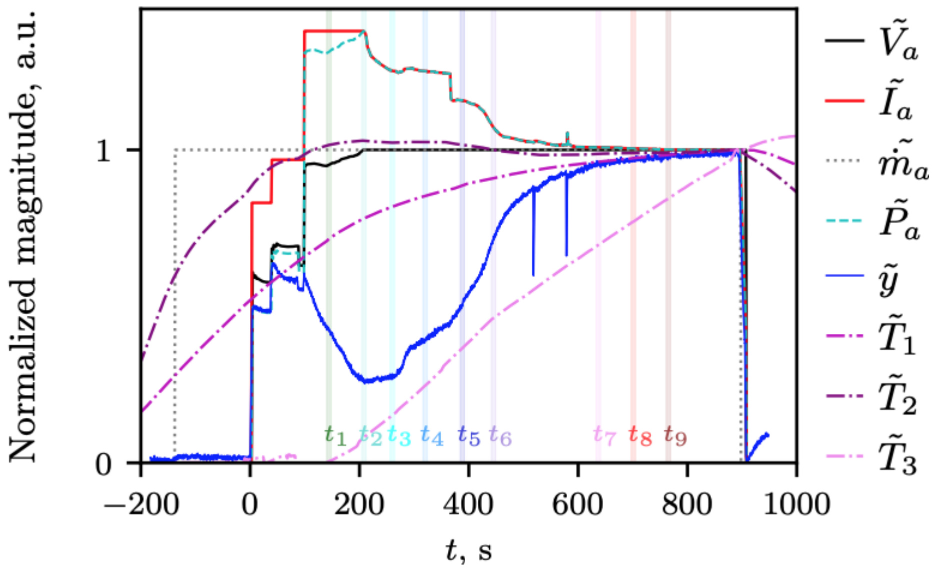
- Good agreement direct/indirect
- Confirms **divergence** and **current conversion** = **main drivers of efficiency losses**
- **B** must be **optimized**

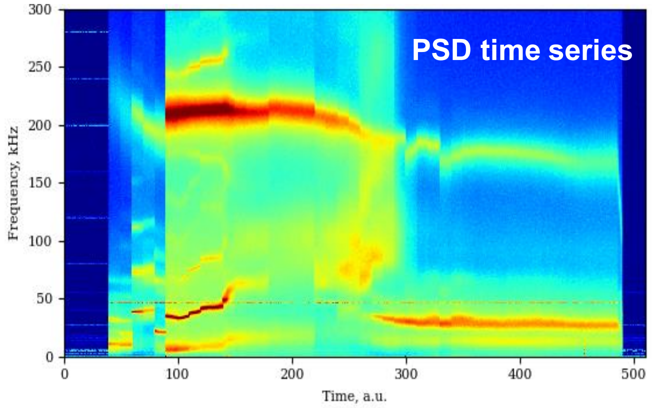
Transient & oscillations

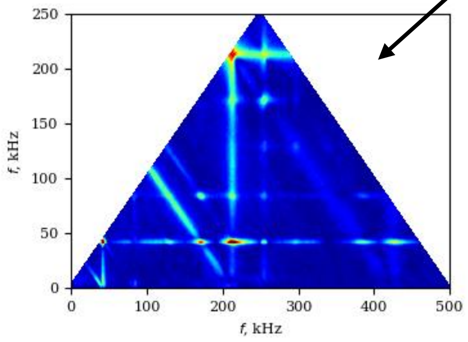
- Time evolution of discharge current frequency spectrum through
  - Transient
  - Mode transitions

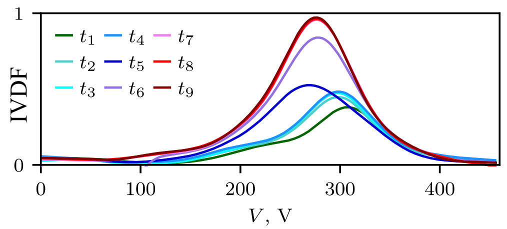
- Correlation: transient – high $\mathrm{I_d}$ regime – high f
- Affects:
  - j_i, IVDF
  - Performance
  - Transport?

- Self bicoherence $\mathrm{I_d}$-$\mathrm{I_d}$:
  - **Harmonics**
  - **Possible non-linear wave coupling**









Remaining work

- Thesis writing

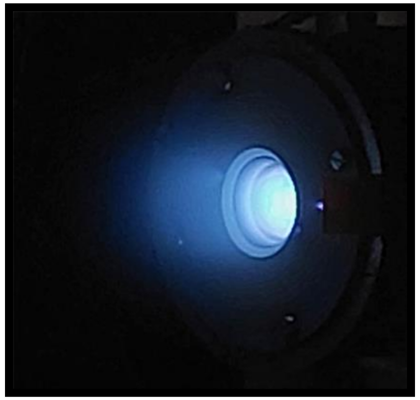
Future research

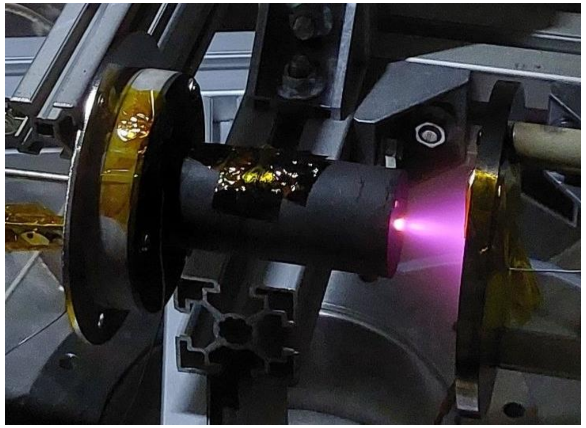
- 200 W CHT design iteration (efficiency, thermal, erosion, symmetry…)
- 200 W CHT ExB characterization
- 200 W CHT investigation of instabilities with new diagnostics

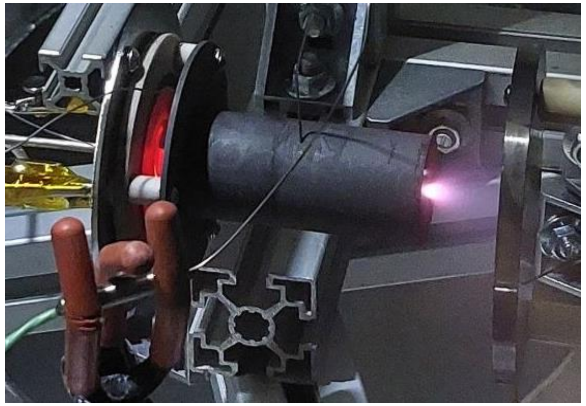
- 100 W CHT testing and study with new EP2 diagnostics

- 1A hollow cathode design iteration & coupling
- CHT-ECR cathode coupling

- HET test bench automation







Achievements

- **Conferences**
  - **SPC 2021**, *Design and preliminary study of a 200W Cylindrical Hall Thruster* - Presentation & paper
  - **MPCS 2021**, *Development of a low-power Cylindrical Hall Thruster* - Presentation
  - **IEPC 2021***, 200 W Cylindrical Hall Thruster design and preliminary testing* - Presentation
  - **IEPC 2022**, *Characterization of a low-power Cylindrical Hall Thruster* - Presentation & paper
  - **EUCASS 2023**, *Measurements of xenon ions and atoms velocity in Cylindrical Hall Thruster with Laser-Induced Fluorescence spectroscopy* - Presentation & paper
  - **IEPC 2024**, *Direct thrust measurements of a 200 W Cylindrical Hall Thruster* - Presentation & paper
  - **IEPC 2024**, *Design, assembly, and validation test of a sub-1Amp LaB6 hollow cathode* - Presentation & paper *(co-author, presentation and paper writing by TFM student)*
  - **IEPC 2025**, *Performance analysis of a low-power Cylindrical Hall Thruster coupled with a sub-Ampere hollow cathode using direct thrust measurements and plasma diagnostics* - Presentation & paper
  - **IEPC 2025**, *Experimentally-informed 2D hybrid simulations of a low-power cylindrical Hall thruster* - Presentation & paper *(co-author, presentation and paper writing by I. Fernandez)*
- **Publications**
  - **Journal paper** published in Journal of Applied Physics, 2024*, Plume characterization of a low-power Cylindrical Hall Thruster*
  - **Journal paper** to be published soon in Plasma Sources Science and Technology, 2026*, Analysis of a low-power cylindrical Hall thruster with 2D hybrid plasma simulations* (second author, *paper writing by I. Fernandez*)
  - **Journal paper** under review by Journal of Propulsion and Power, *Experimental characterization of low-power cylindrical Hall thruster performance and efficiency loss mechanisms*
- **Research stays**
  - **ICARE** laboratory, Centre National de la Recherche Scientifique (CNRS, France), 2022, *Test campaign for the characterization of the CHT plume with electrostatic plasma diagnostics*
  - **ICARE** laboratory, Centre National de la Recherche Scientifique (CNRS, France), 2023,*Test campaign for the characterization of the internal discharge with optical diagnostics (LIF)*
- **Other**
  - **TFM co-supervision**, 2023, *Simulation and design of hollow cathode*
  - **TFM co-supervision**, 2024, *Assembly and testing of hollow cathode,*
  - **TFM co-supervision**, 2026, *Experimental and numerical investigation of hollow cathode design variations*

Thank you!
Questions?

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Ackowledgments

PROMETEO, Comunidad de Madrid, grant Y2018/NMT4750,
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SUPERLEO, Agencia Estatal de Investigación, European Union NextGeneration, grant TED2021-132484B-I00,
MLPLUS-CM, Comunidad de Madrid, grant TEC-2024/TEC-263.

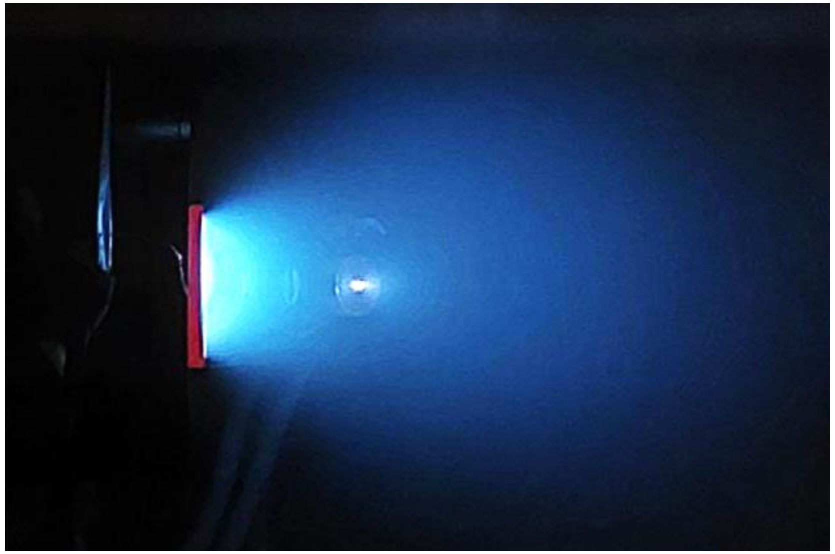
Why further iterate on CHT200 design?

Optimize thruster to enable investigation:

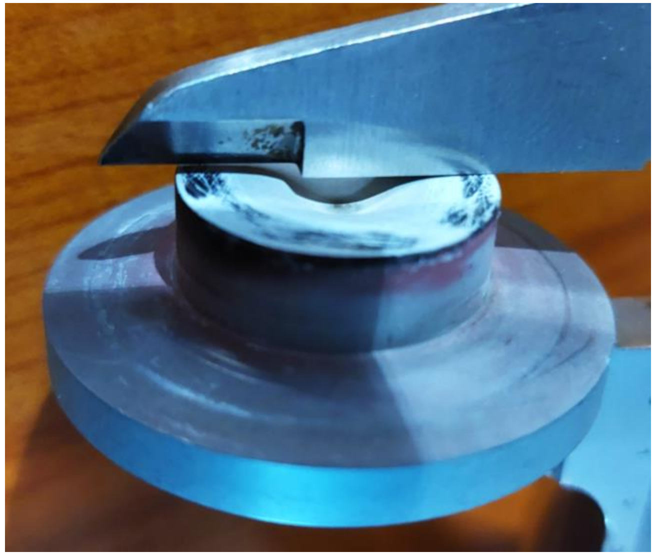
- reduce **wall losses** - slower **heating** - more **time for diagnostics & safer operation**
- less frequent need for **components replacement** (coils, ceramics, anode) - **time & cost** savings
- discharge **stabilization** - **repeatability & adapted diagnostics**

- Injector sputtering, Asymmetric injection

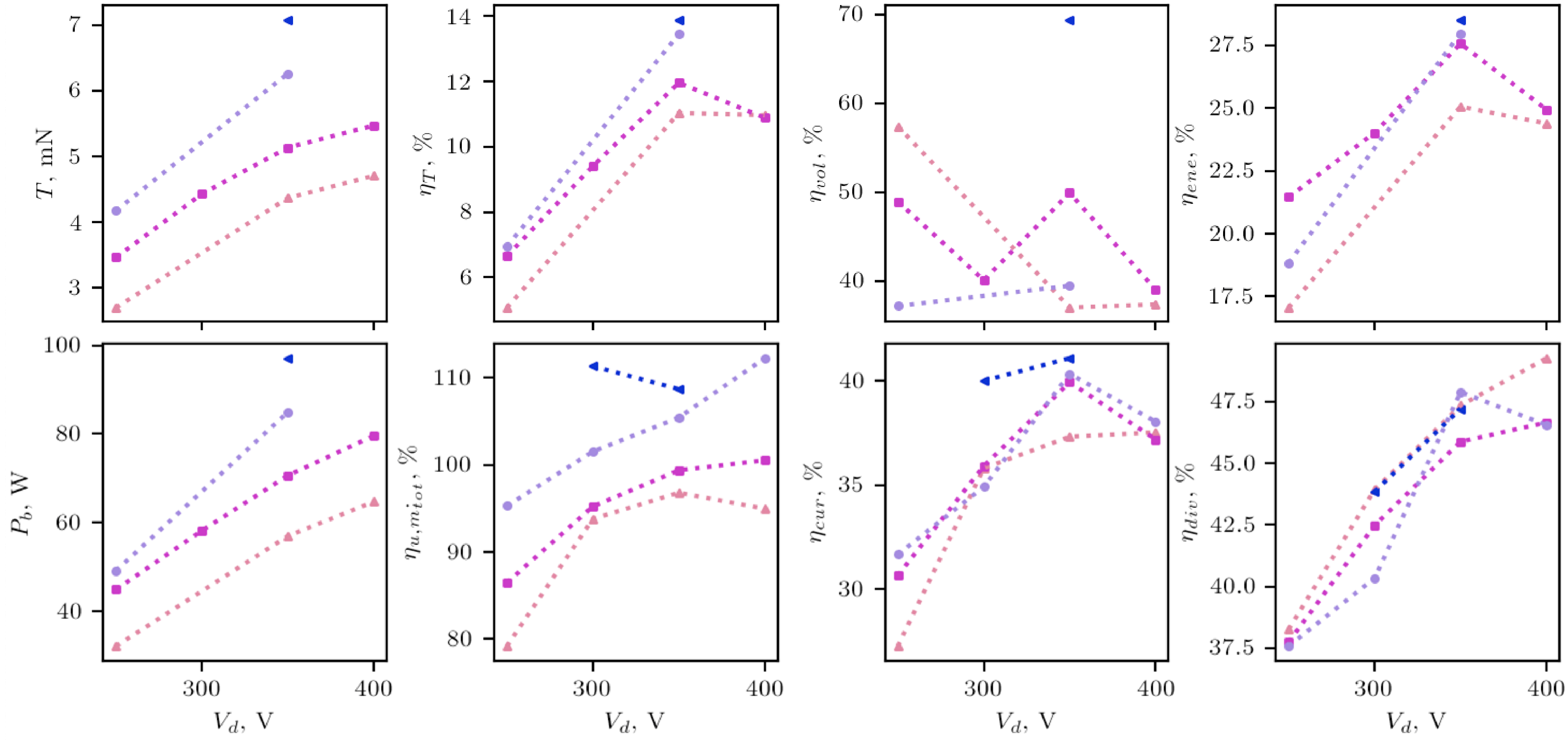
Overheating



Erosion



Indirect thrust & partial efficiencies



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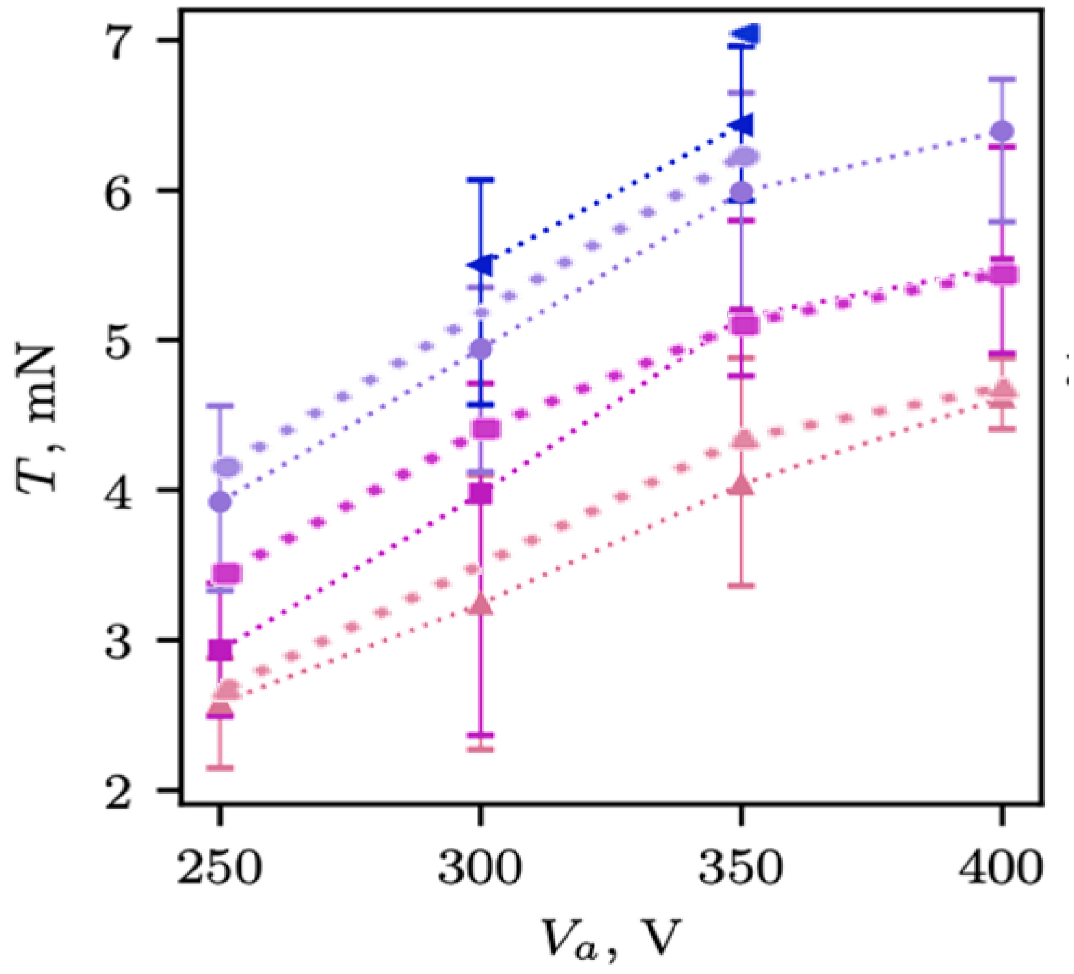
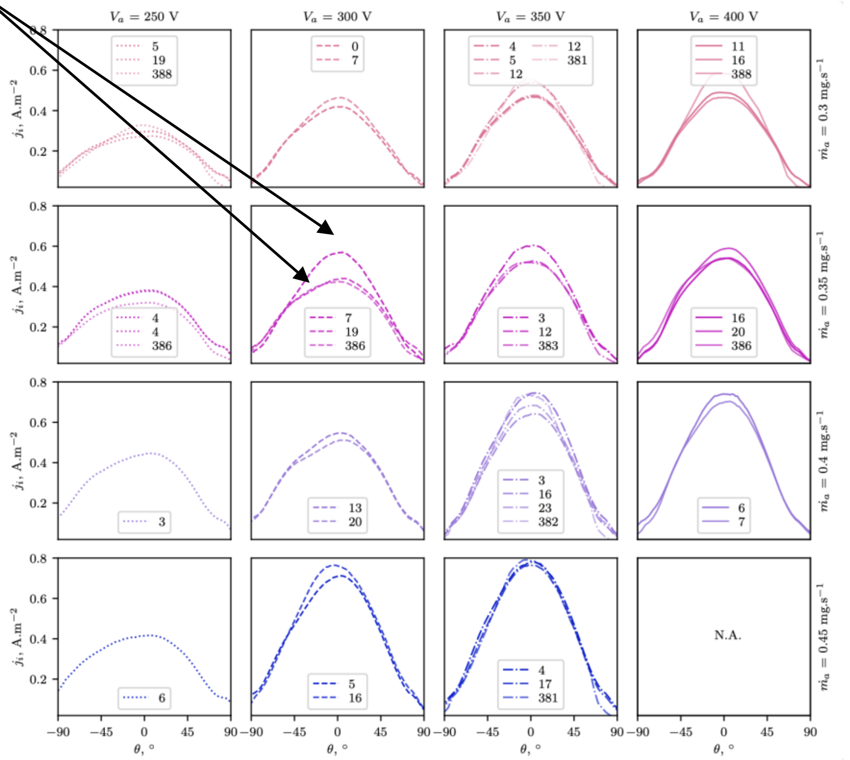


Probe measurements

- Plume **asymmetries**
  - cathode, injector, coils, alignment
- Partial efficiencies obtained by integrating beam current density

Dispersion of I_d
(>1 year scattered meas.)



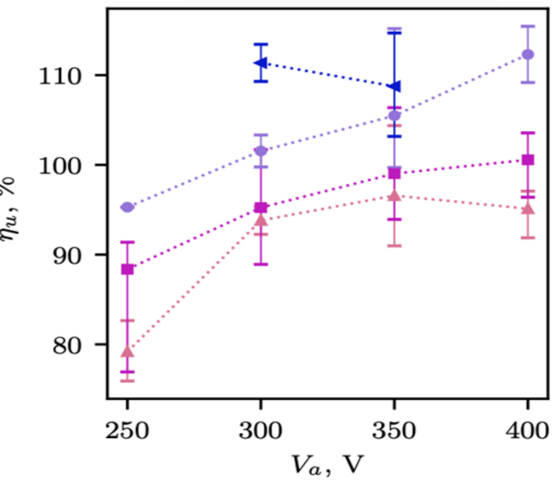
$$I_{ib} = \pi r^2 \int_{-\pi/2}^{\pi/2} j_i(\theta) |\sin(\theta)| \, d\theta,$$

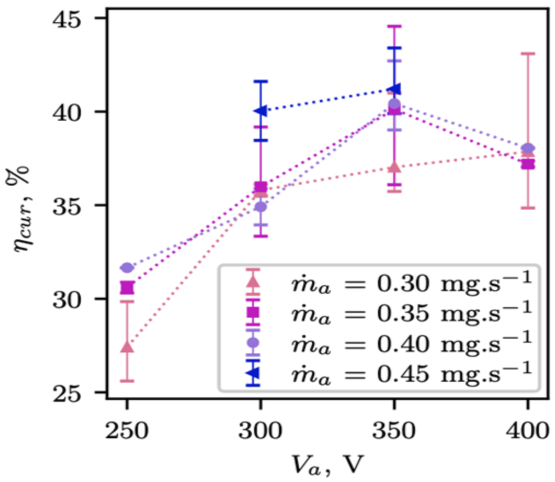
$$I_{i,z} = \pi r^2 \int_{-\pi/2}^{\pi/2} j_i(\theta) \cos(\theta) |\sin(\theta)| \, d\theta$$

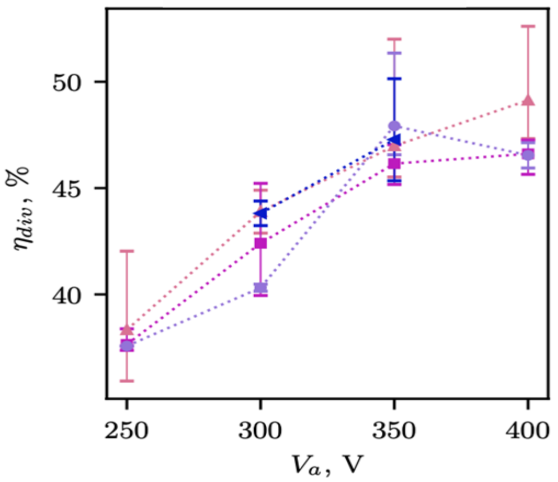
$$\eta_u = \frac{I_{ib} m_i}{q(\dot{m}_a + \dot{m}_c)}$$

$$\eta_{cur} = I_{ib}/I_d$$

$$\eta_{div} = (I_{i,z}/I_{ib})^2$$







RPA

Most probable ion velocity $\hat{v}_i$ (peak)

- ❑ Wide beam
- ❑ Clear **drop** outside beam for high voltages (like previous measurements)
- ❑ **Nearly flat** at low voltage

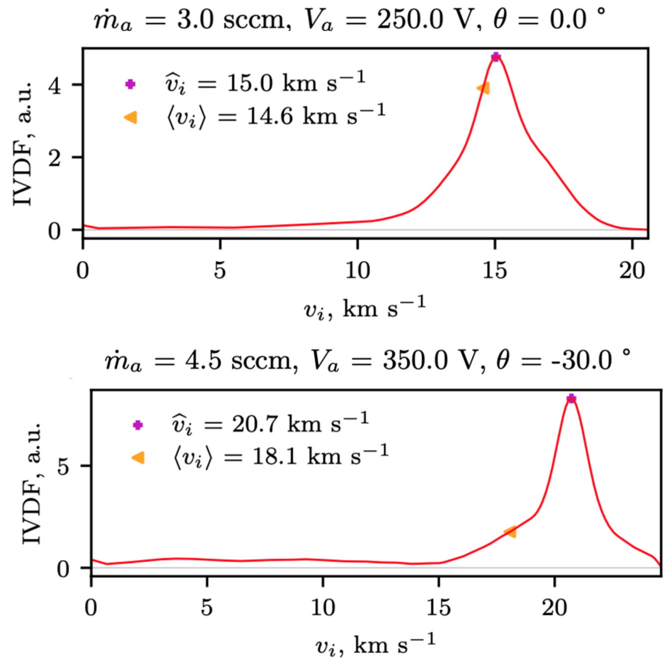
- Ions within beam mostly come from **main ionization region**

Average ion velocity $\langle v_i \rangle$ ($\langle v_i \rangle = \frac{\int v f(v) dv}{\int f(v) dv}$)

- Little gain in $\langle v_i \rangle$ past 350 V
- **Off-centered, asymmetric, hollow beam**
  - marked at **high voltage,** not visible in $j_i(\theta)$

- Significant **slow tail** lowers $\langle v_i \rangle$, specifically **on axis & at $|\theta| \gtrsim 50°$**

Some IVDF examples



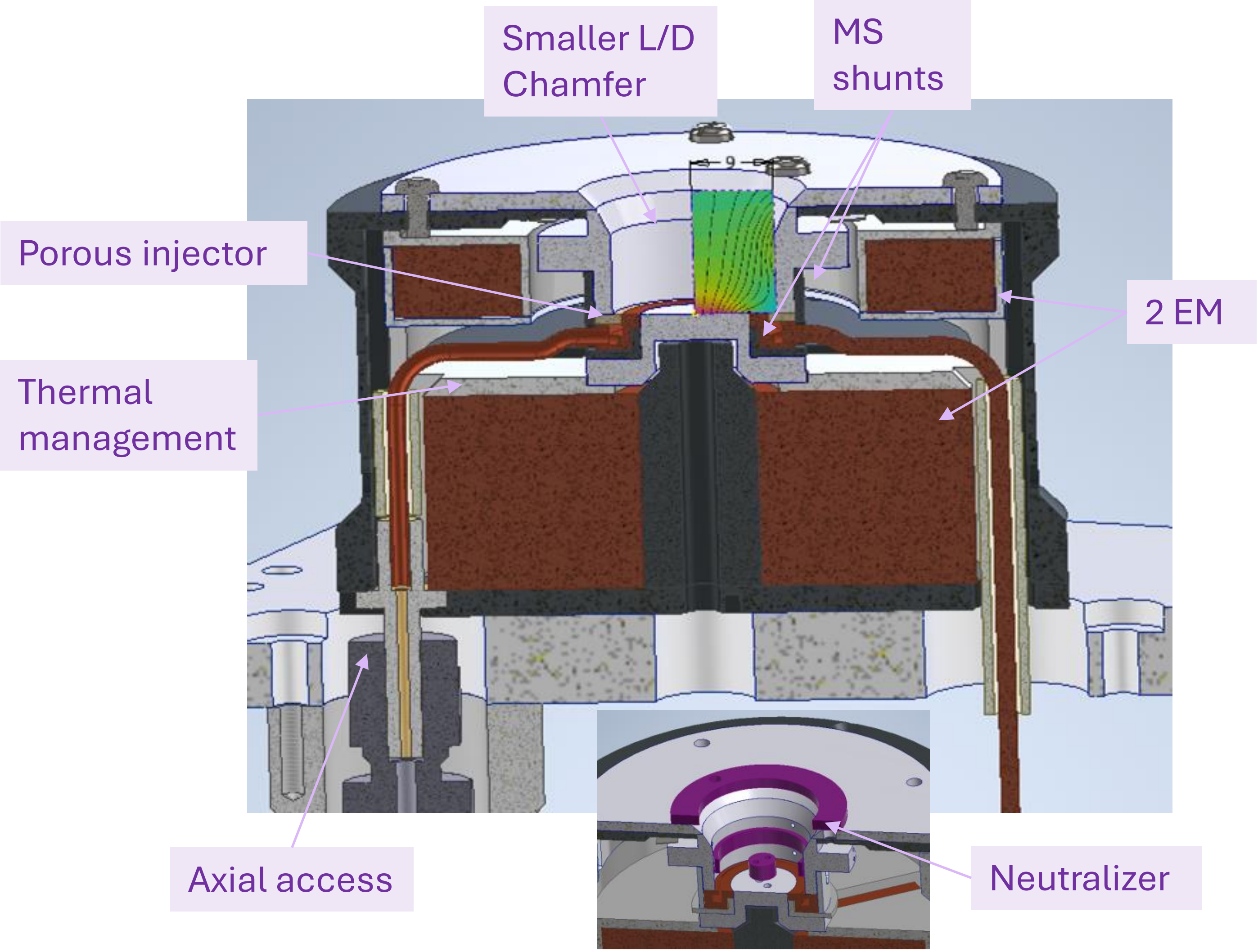
Limits/assumptions:

- **Multiply-charged** ions ($\eta_T > 1$)
- **Axisymmetry** & **off-centered** beam
- Zero **potential energy**
- Set-up limits due to offset (**alignment**, missing wide angles)
- **Probes bias** optimization
- **Ion momentum** only

CHT100

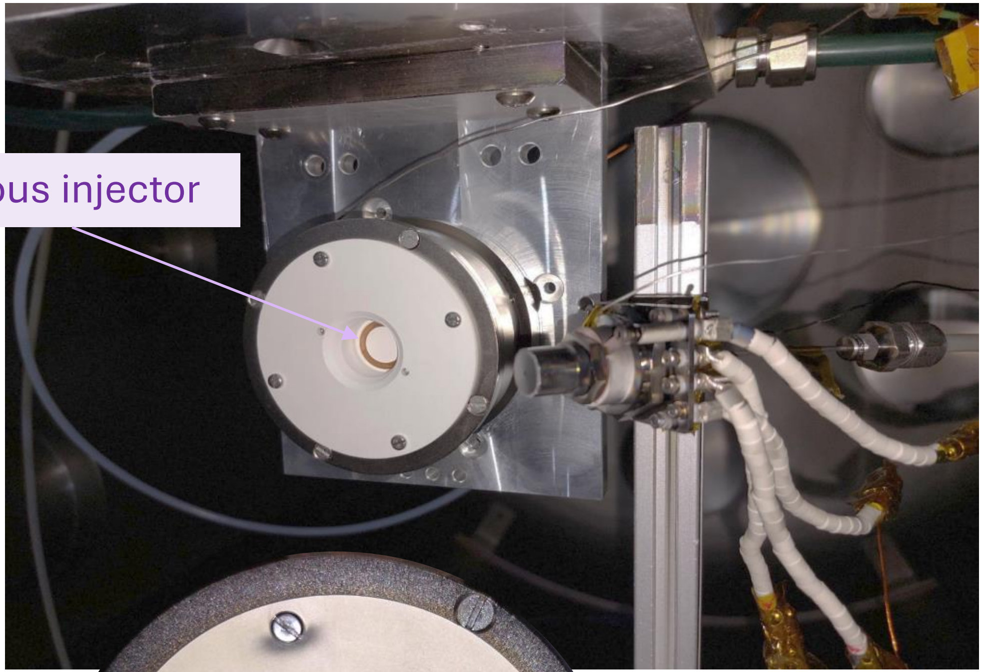
- Objectives:
  - Extend capabilities to very low power (**50 – 100 W**)
  - Apply knowledge from CHT200
  - Explore **magnetic shielding** in CHT
  - Explore **alternative neutralizers**

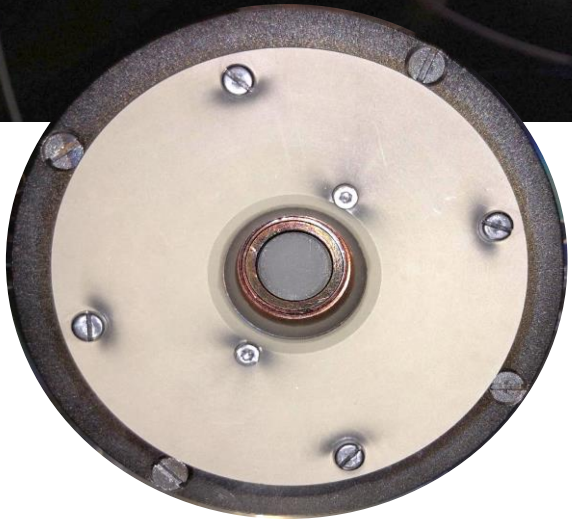
- Design features:
  - Smaller channel **length/diameter, chamfer**
  - Porous ceramic / slit injector: homogeneity, sputtering
  - Thick wack wall for **erosion**
  - 2 electromagnets & optional shunts: MS/non-MS
  - Thermal management (coils)
  - Probes accessibility
  - No radial connection, exposed biased component
  - Adaptable to alternative neutralizers
  - Ceramic front plate for arcs
  - Vented inner volume



Ignition with MUSIC cathode

- Tested over a few days before end of Aliena cathode lease
  - Succesful ignition with **porous ceramic injector & slit**
  - **Direct/cusped** coils configuration & various currents
  - **MS/non-MS** (no shunts)
  - Preliminary result show promising performance (T)

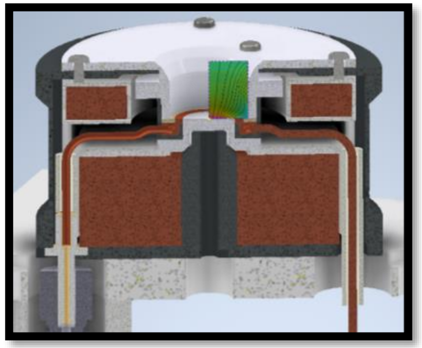


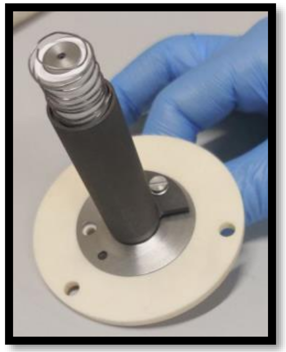


PEEK gas injector overheating → ceramic
Partially obstructed gas line limiting I_d

Detailed objectives of future experimental HET-related work for EP2

- Design of 100 W CHT prototype
  - Downscaling of 200 W CHT
  - Improvements from simulations and tests of first prototype
    - Channel geometry
    - Gas injection
    - Mechanical and thermal aspects
  - Magnetic shielding
  - Towards dry and/or power-free cathode





- TFM co-supervision: 1A hollow cathode design, assembly, testing
  - Thermal simulations, materials selection, components sizing
  - Procurement and assembly
  - Preliminary tests with xenon:
    - Ignition characterization (300W, 500V, 12 sccm)
    - Triode and diode test: matrix of mass flow rates and currents
- Test bench automation for Hall thrusters and cathode
- Optimization CHT200
- Instabilities with dedicated diagnostics