Design, simulation and testing of low power Hall Effect Thrusters

PhD Doctoral meetings 2025 – PhD program in Aerospace Engineering UC3M

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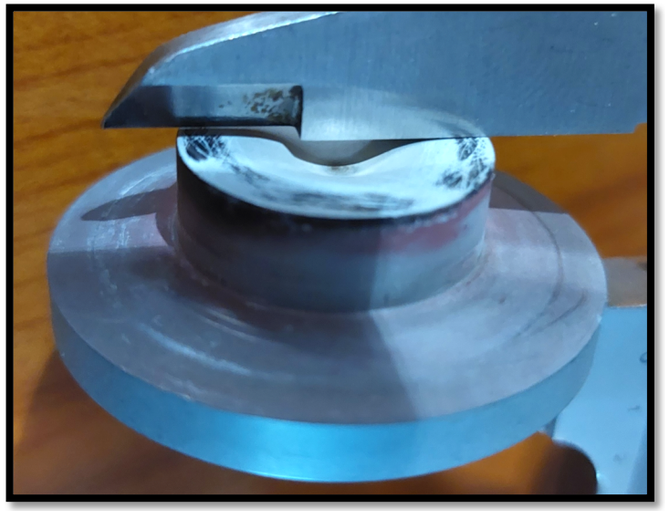
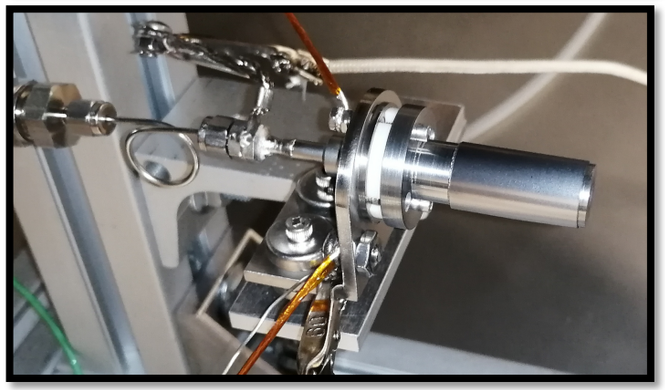
Thesis directors: Jaume Navarro-Cavallé, Pablo Fajardo

Motivation

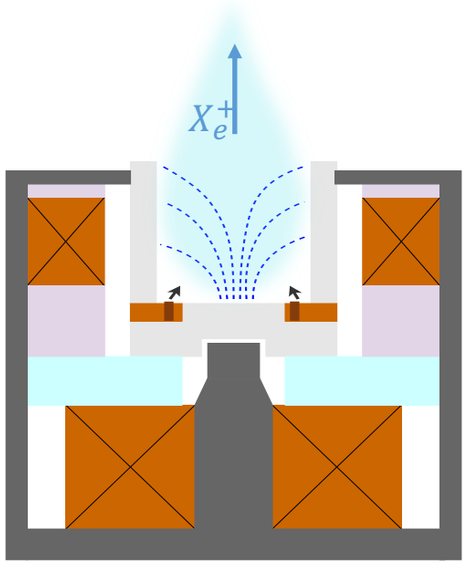
- Annular Hall thrusters: mature and high performance Electric Propulsion
- **Need for low-power**: downscaling is challenging (laws, heating, efficiency, manufacturing, cathode…)

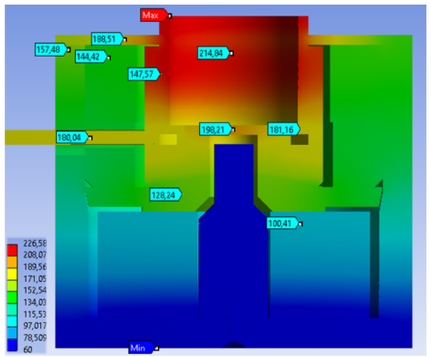
- Candidate: Cylindrical Hall Thruster (CHT)
  - Volume-to-surface ratio, wall losses
  - Central pole heating/erosion
  - Room for B
- Non-conventional design
- Few prototypes
- **Experimental data** necessary:
  - Optimization
  - Understanding physics (e.g. transport)
  - Validate models
  - Adapted neutralizer

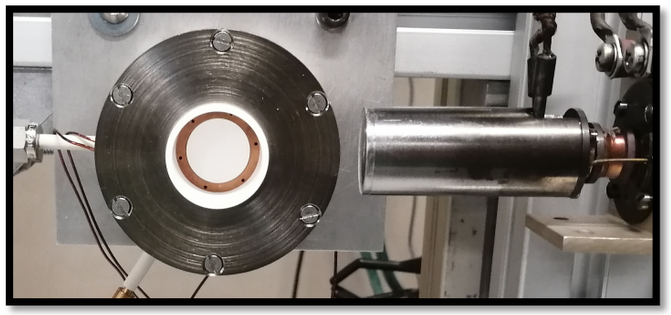




Objectives & approach







Optimize CHT performance

- **Design** 2 low-power CHTs
- Modularity (B, injector...)
- **Characterize performance & plasma**
- Develop diagnostics

Adapt neutralizer

- Test with various types of cathodes
- Design cathode (student)
- Cathodeless configuration

Couple numerical work

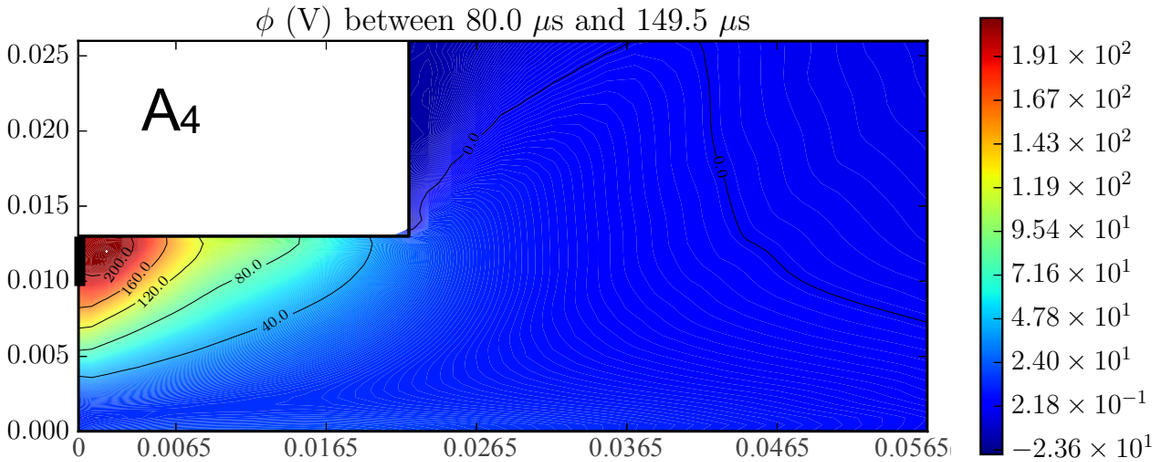
- **Experimental inputs** for models
- Parametric analysis for design

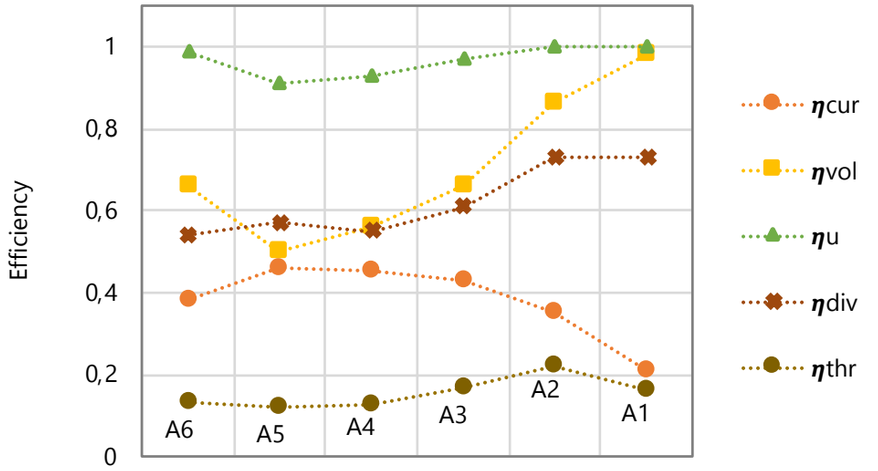
Results: overview

Simulations

- Parametric studies on CHT geometry

New **experimentally informed** simulations with HYPHEN (Iñaki)





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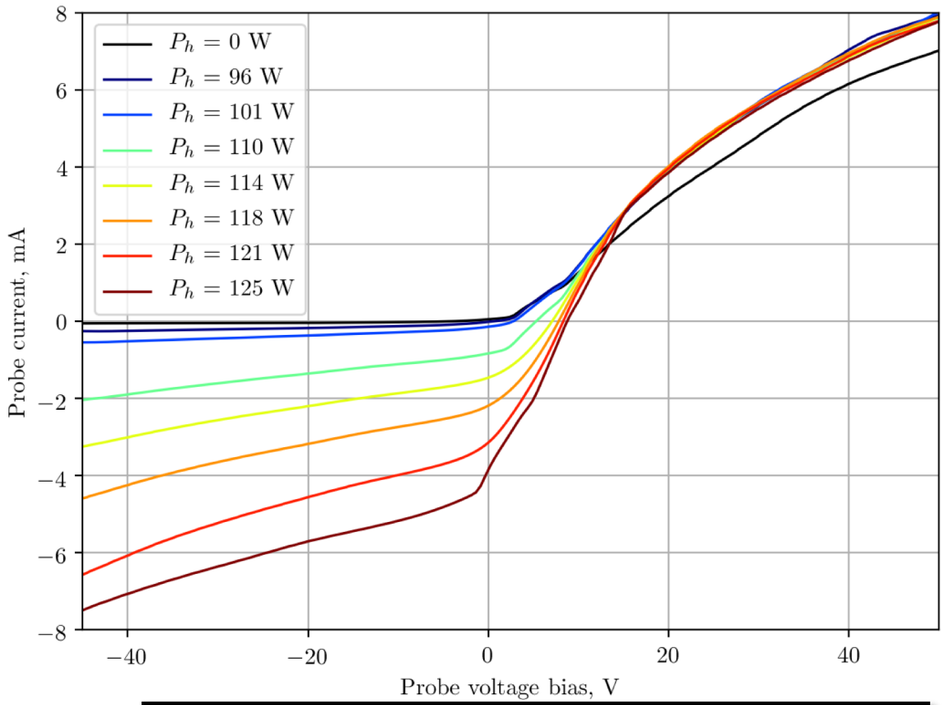
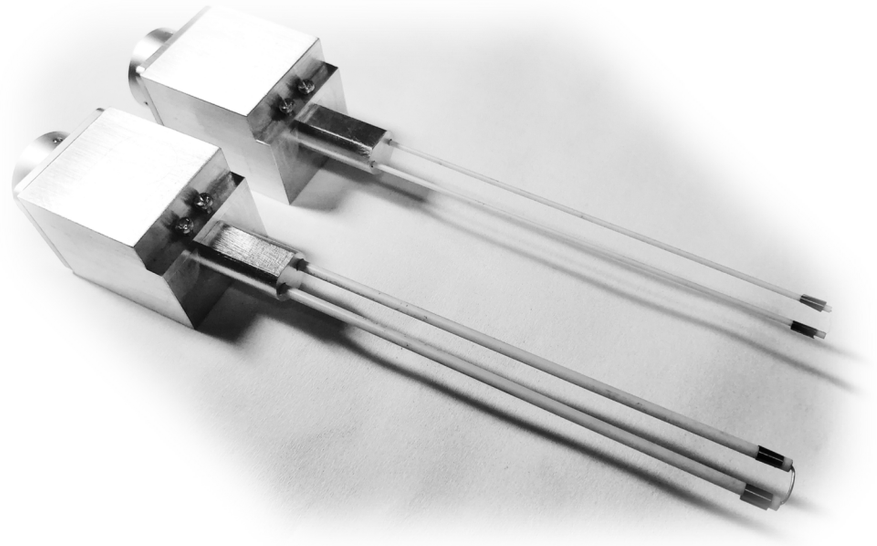
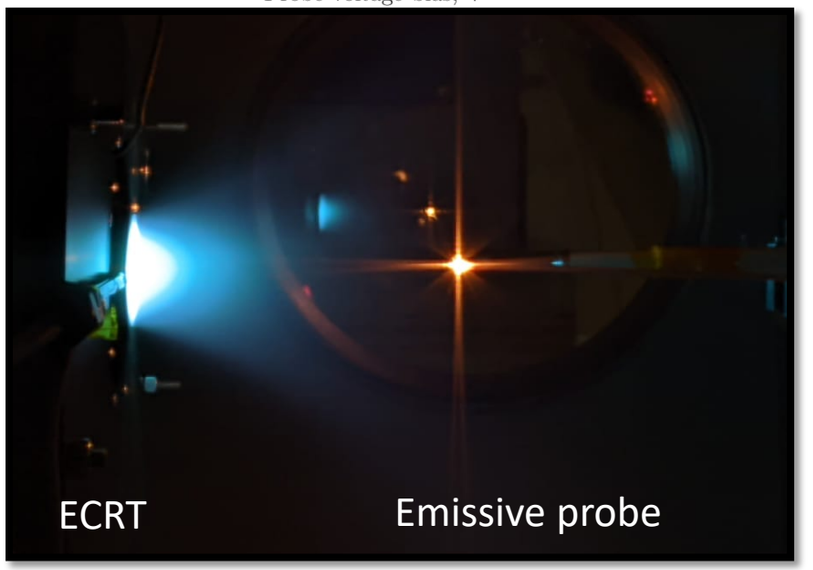
Diagnostics

- Two emissive probes built & used with ECRT







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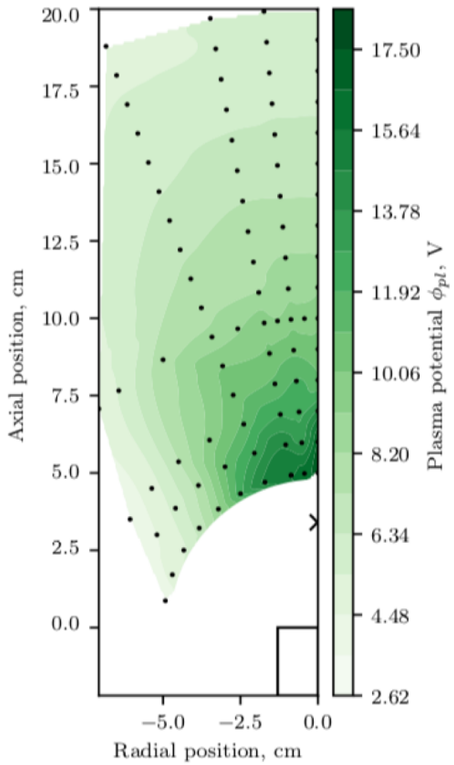
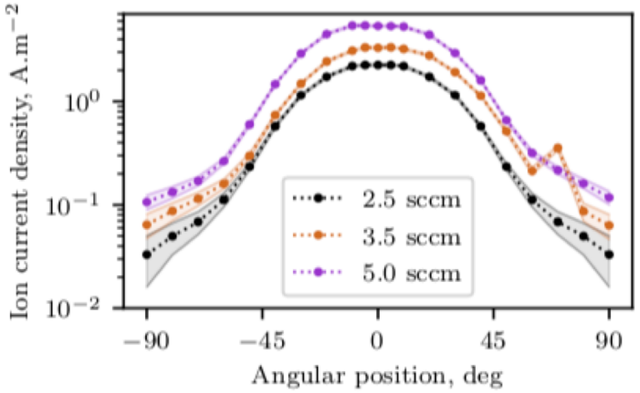
Hall thrusters

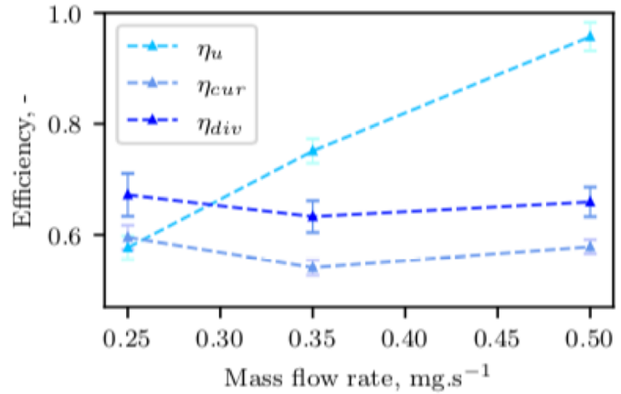
- 200 W prototype: 2 gases, 5 cathodes
- Characterization:
  - Far-field measurements
    - Langmuir Probe (T_e, ϕ, n), Retarding Potential Analyzer (IVDF), Faraday Cup (j_i)
    - Current oscillations

LP

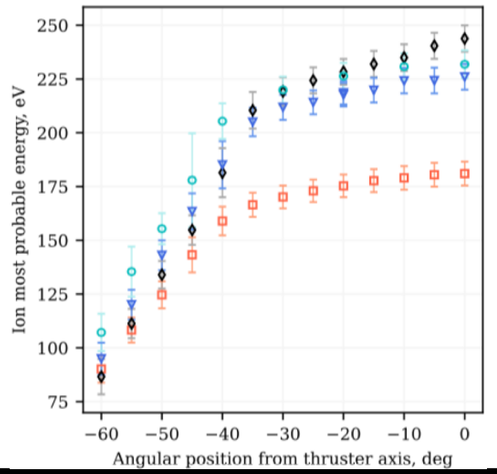


FC





RPA



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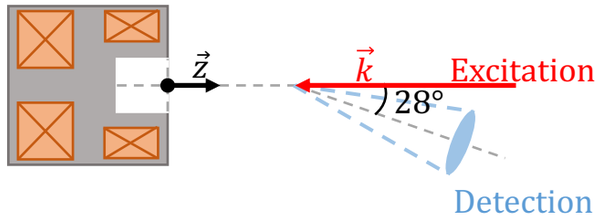
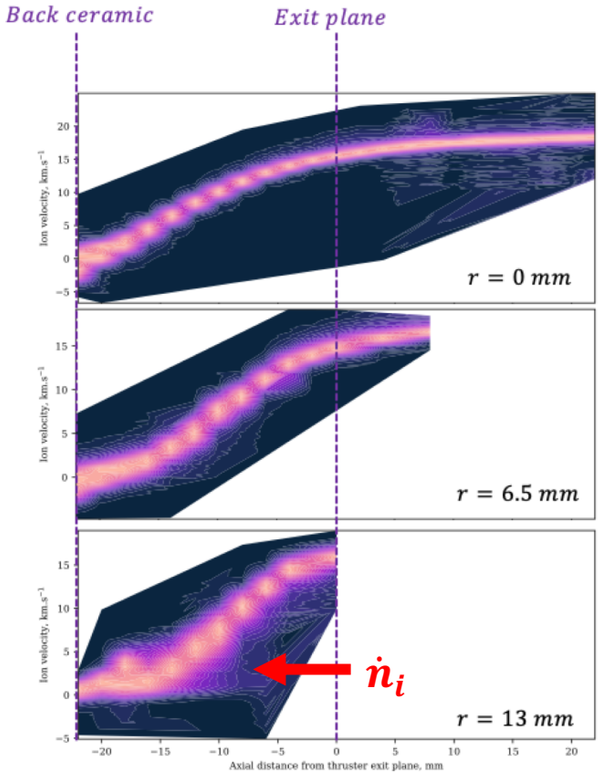
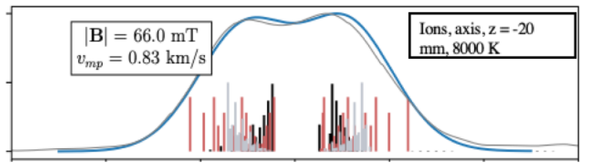
    - Current oscillations
  - Internal discharge and near-field measurements
    - Laser-Induced Fluorescence spectroscopy (in plane)
    - Xenon ion and atom axial VDF reconstruction



Set-up



Axial velocity r-z measurements



Spectra modeling

Results: overview

Simulations

- Parametric studies on CHT geometry

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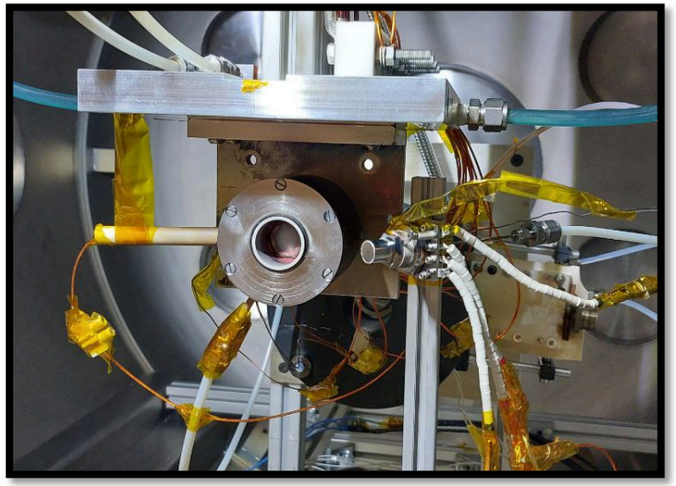
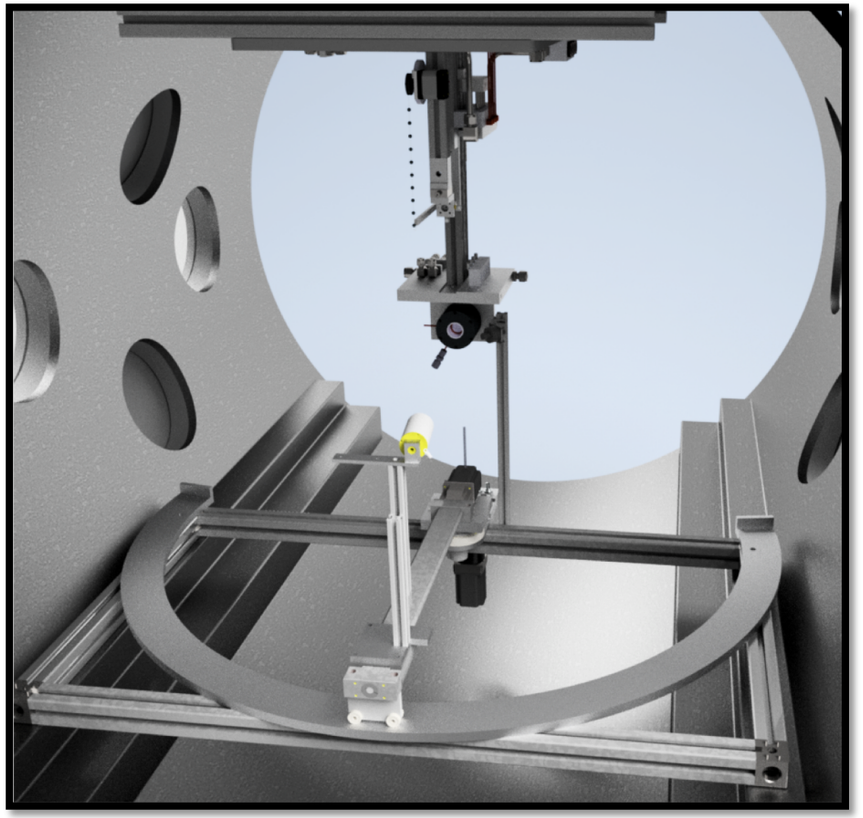
    - Current oscillations
  - Internal discharge and near-field measurements
    - Laser-Induced Fluorescence spectroscopy (2D plane)
    - Xenon ion and atom axial VDF reconstruction
  - Thrust and probe measurements
    - Mechanically amplified hanging pendulum thrust balance





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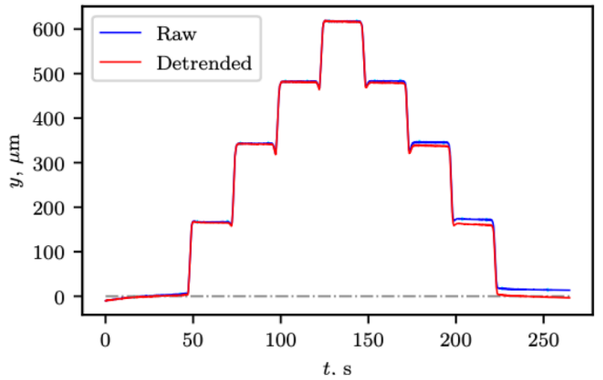
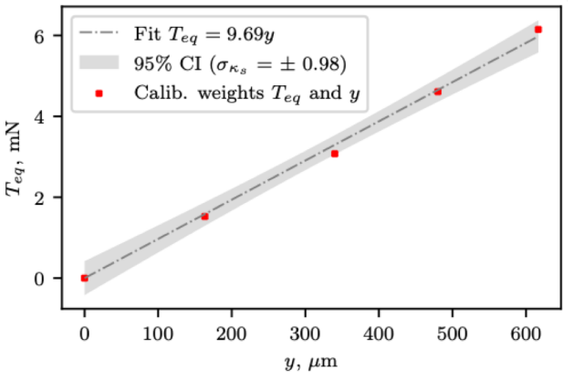
Calibration

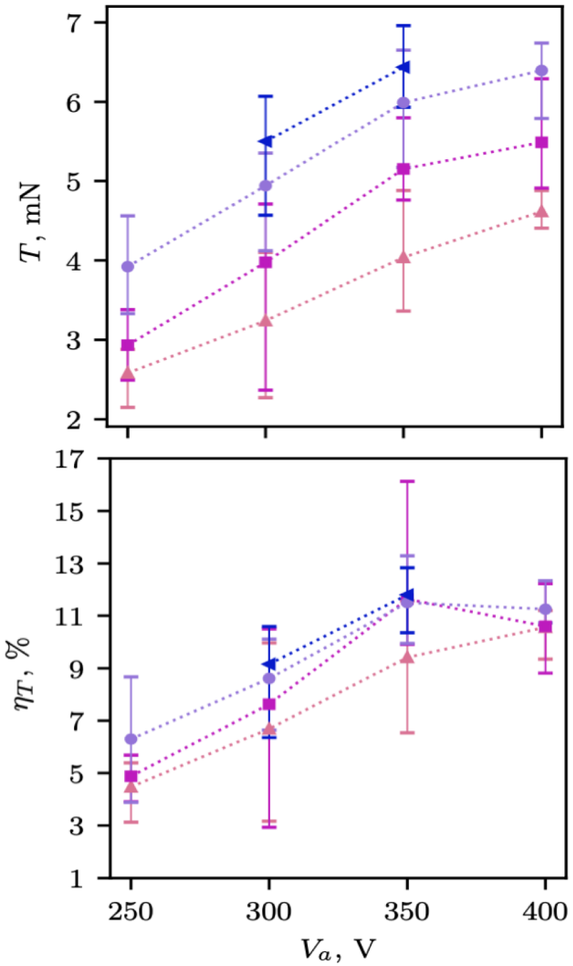




Performance characterization

Thrust balance

- Calibration procedure to **isolate real thrust** from external effects
- Thrust increases with $\dot{m}_a$ & V_d in covered range
- η_T depends on $\mathbf{V_d}$, maximum for 350 V, 0.4 mg s-1, ~325 W
  - Saturates with P_d for all $\dot{m}_a$



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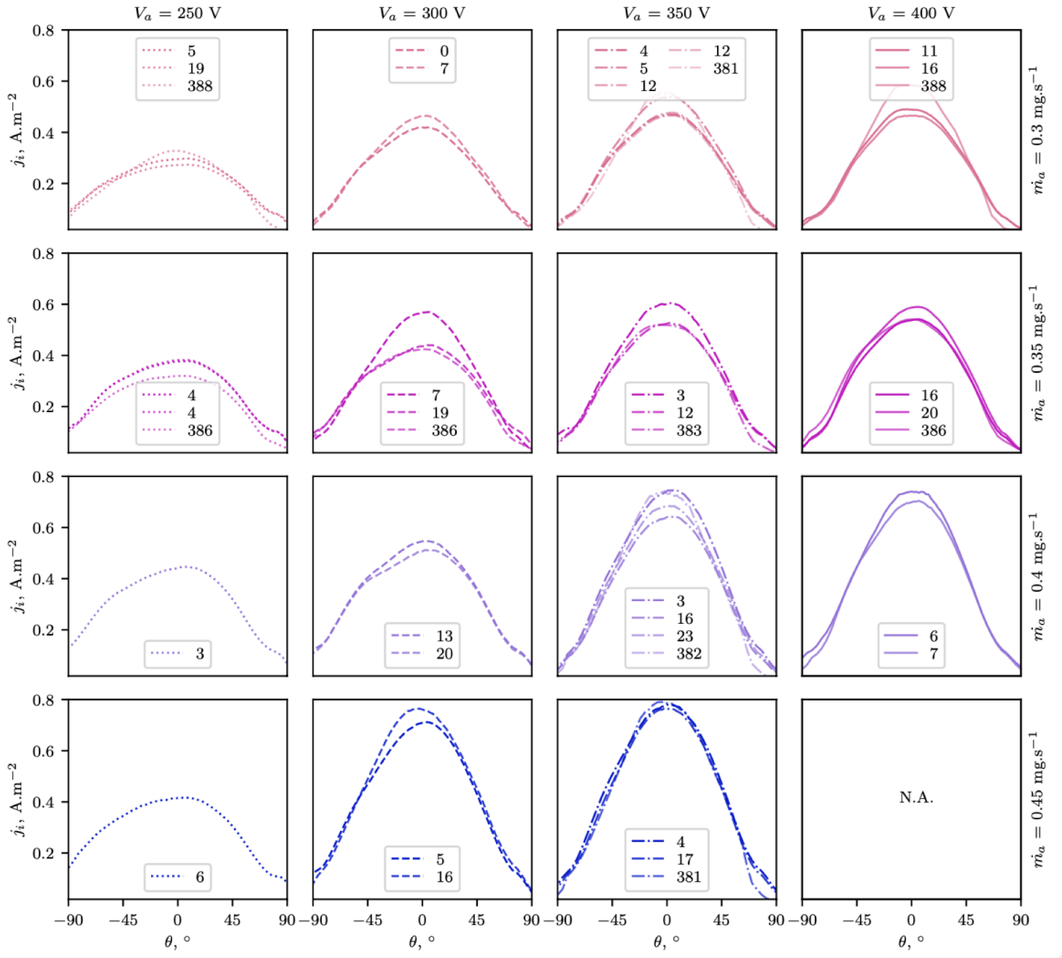
Faraday Cup

- Plume **asymmetries** (cathode, injector, coils, alignment)
- **Divergence** & **current** utilization
  - Low, strongly affected by V_d, not by $\dot{m}_a$
- **Propellant** utilization **>1** → Xe^{2+}, Xe^{3+}



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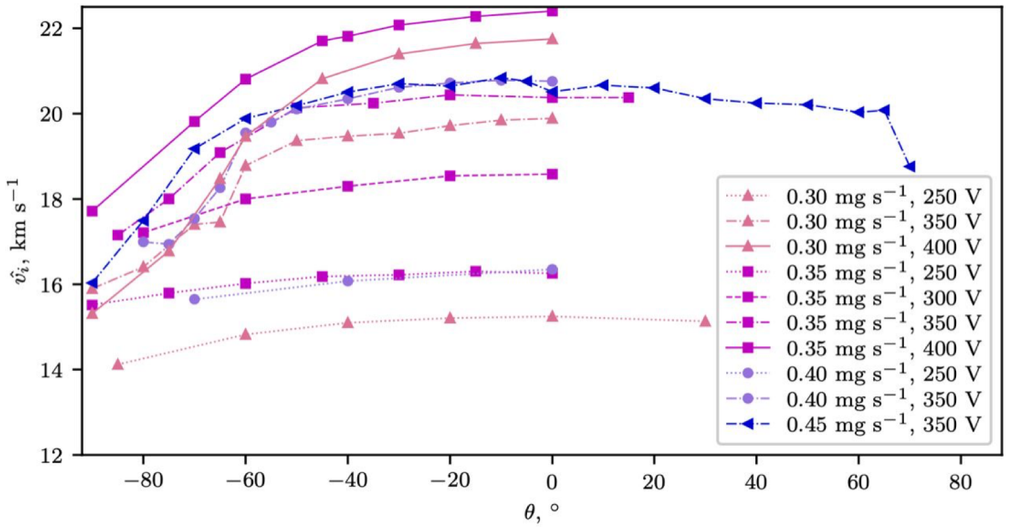
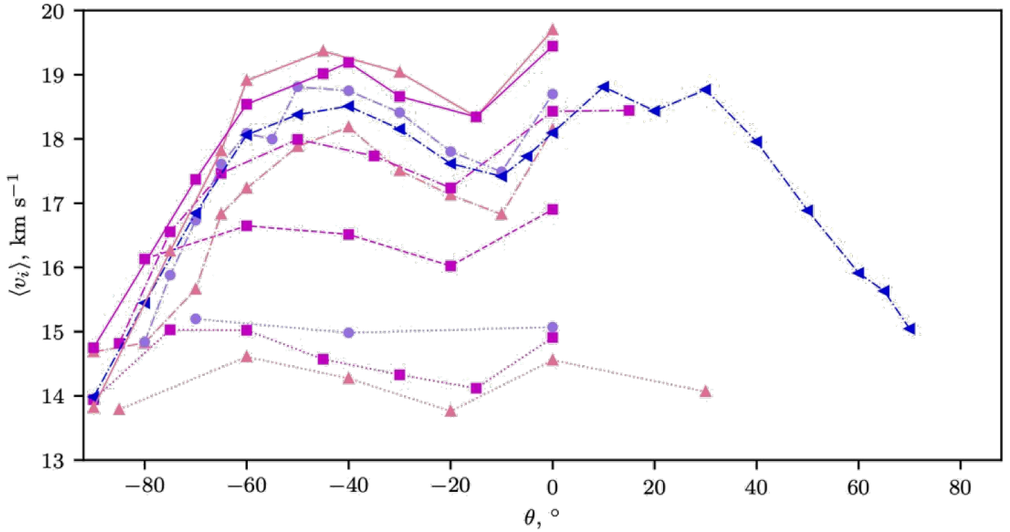
Retarding Potential Analyzer

- Ions within beam mostly come from **main ionization region**
- Significant **slow tail** lowers $\langle v_i \rangle$, specifically **on axis & at** $|\theta| \gtrsim 50°$

Most probable velocity



Average velocity



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Indirect performance

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

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

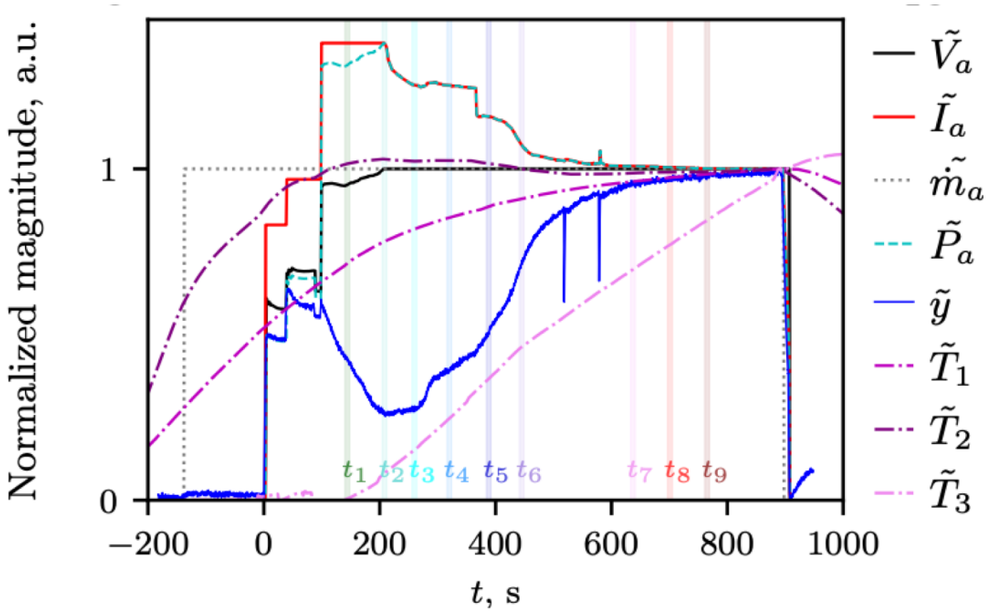
- Good **agreement direct/indirect**
- η_{cur} & η_{div} **shape the thrust efficiency**
  - main drivers of efficiency losses in this device
- **B** must be **optimized**
  - Maximize j_i, T, minimize divergence
  - Increase anode shielding

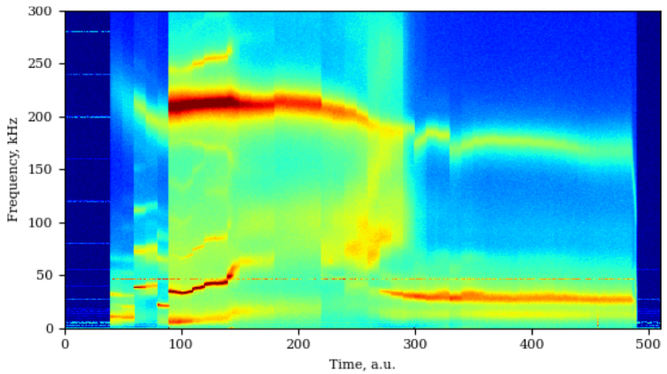
Transient & oscillations

- Time evolution of discharge **current frequency spectrum**
- Correlation with events in discharge behavior
  - transient
  - mode transitions

Suspected link: transient – high I_d – high f

Logs

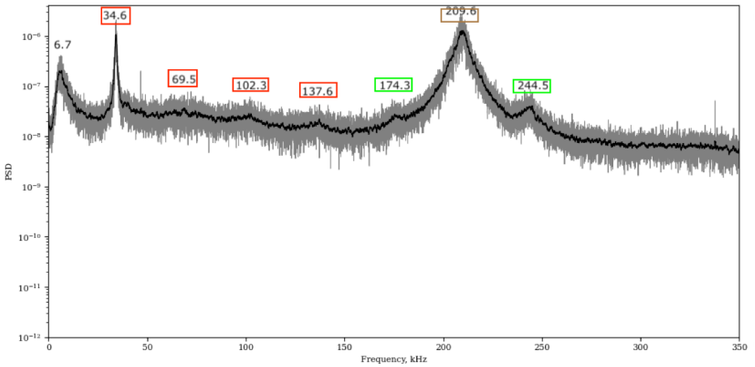


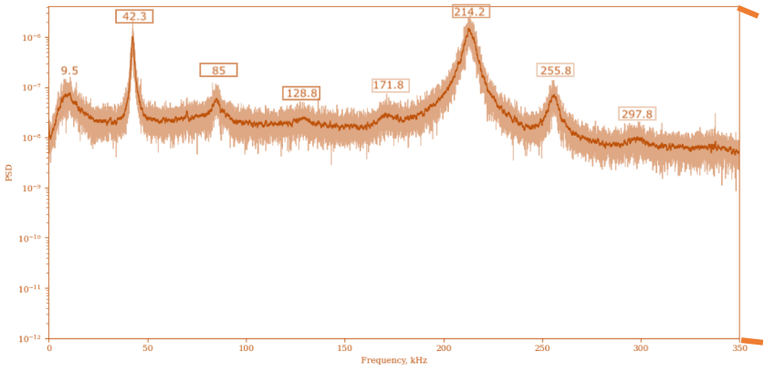


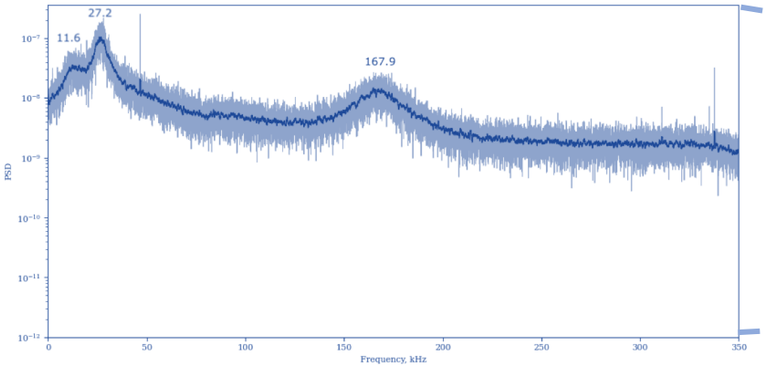
PSD time series

Transient & oscillations

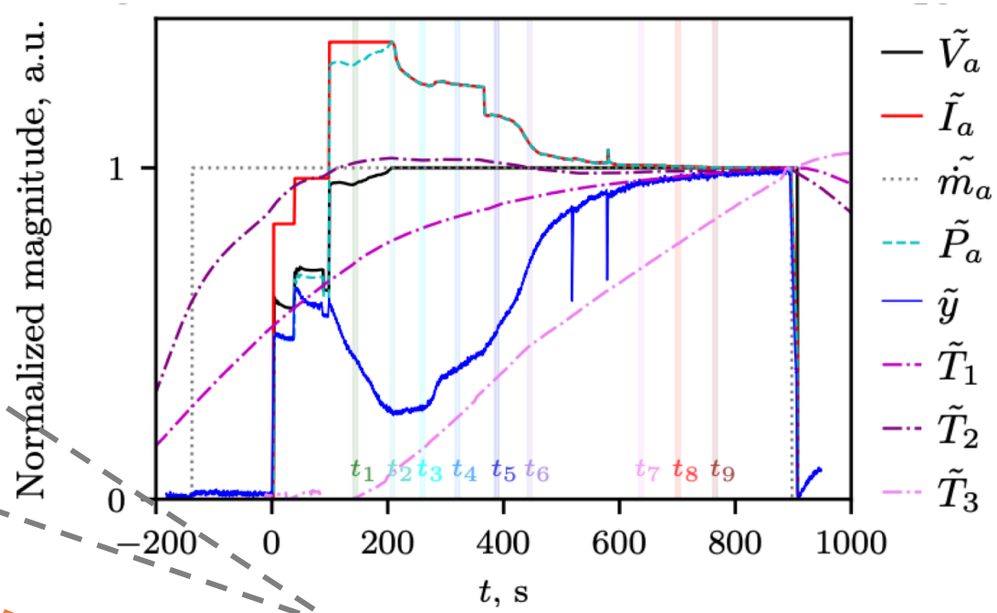
PSD snapshots

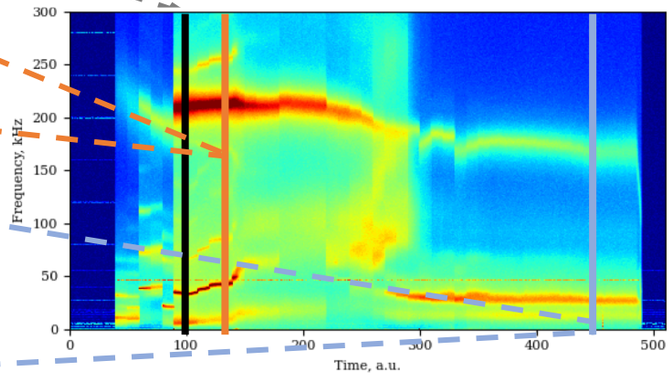






Logs





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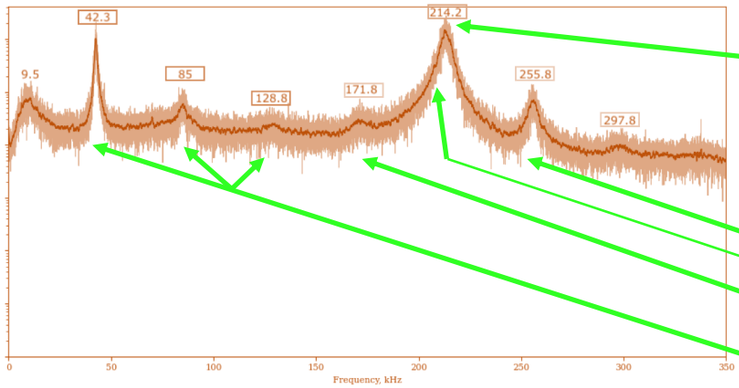
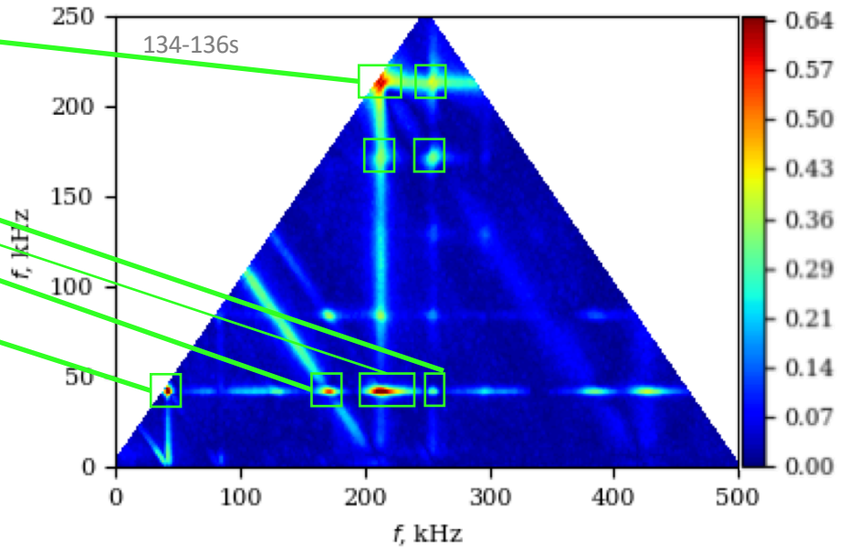
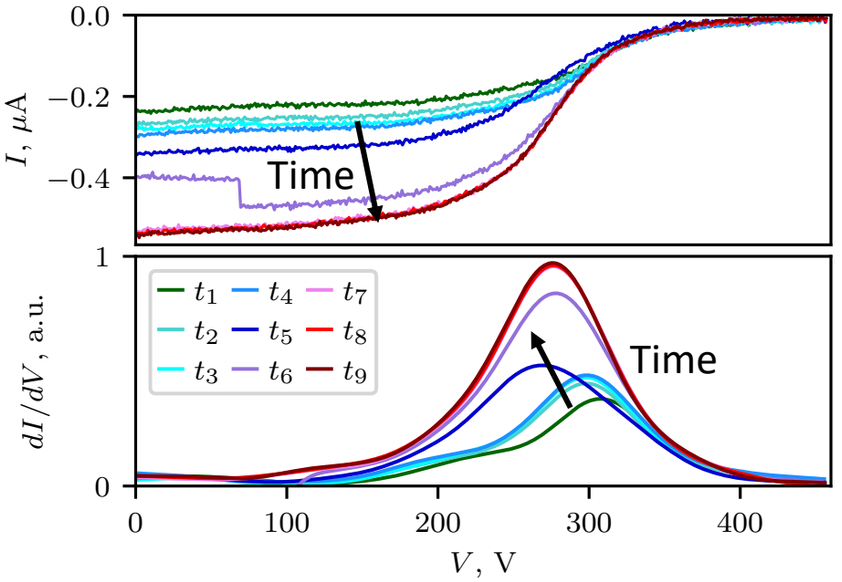




➢ Ion energy & current change along transient



➢ **Self bicoherence $I_d - I_d$: non-linear wave coupling**

- ❑ **Harmonics** of 28 kHz & 213 kHz
- ❑ Non-linear coupling 28 & 213 kHz – **Three Wave Coupling**
  - ❖ $f_2 - f_1$, $f_2 + f_1$, $f_2 - 2f_1$, $f_2 + 2f_1$
- ❑ No interaction $f_0 \approx 7.4$ kHz & rest of spectrum
- ❑ Interaction f_2 with all smaller frequencies: broadband

➢ Possible identification:

- ❑ Ionization instability: **breathing mode** $\sim \frac{\sqrt{v_i v_n}}{2\pi L}$
- ❑ Ion Acoustic Turbulence
- ❑ **Ion Transit Time Instability** $\sim \frac{v_i}{L}$
- ❑ Ion-Ion Two Stream Instability?

$P_d \searrow$
$T \nearrow$
$\} \; \boldsymbol{\eta_T} \nearrow$

$I_d \searrow$
$j_i^{\theta=0} \nearrow$
$\} \; \boldsymbol{\frac{I_{ib}^{\theta=0}}{I_d}} \nearrow$

$\widehat{E_i} \searrow$

Associated to mode change:

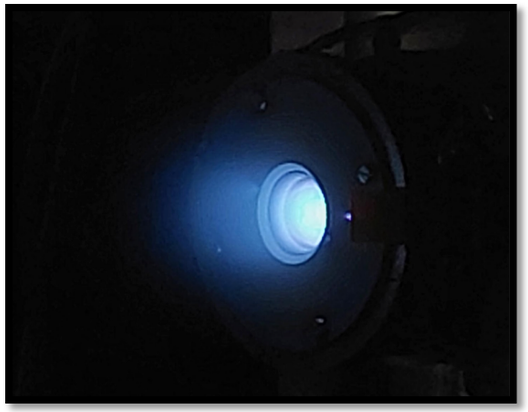
- ❑ Current level
- ❑ Frequency spectrum
- ❑ Ion beam properties
- ❑ Electron **transport**
- ❑ CRP $\longrightarrow$ 0

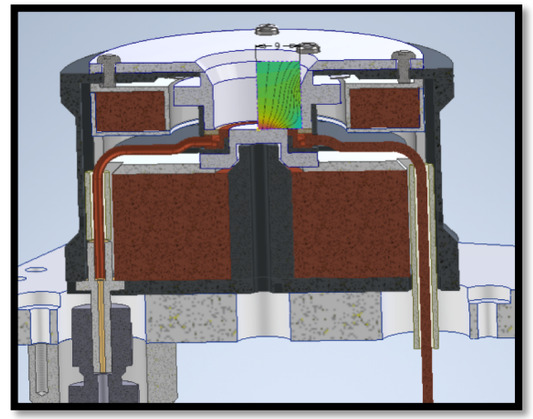
Remaining PhD work

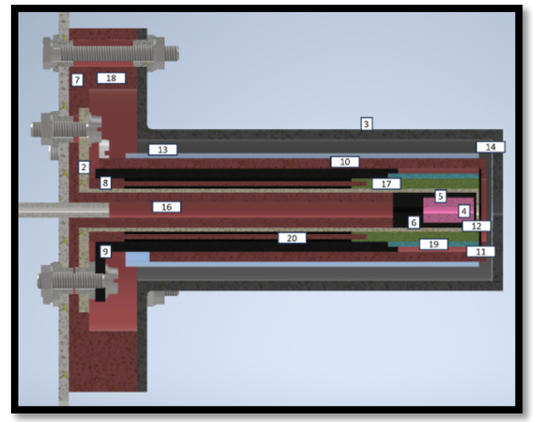
- Finalization and submission of journal paper on direct & indirect thrust measurements
- **Thesis writing**

Continuation of Hall research

- **200 W** CHT design iteration (efficiency, thermal, erosion, symmetry…) & ExB characterization
- **100 W** CHT: ignited with MUSIC (MS/no MS, 2 injectors, 2 coils configurations)
- 1 A hollow **cathode**
- HET test bench automation
- Investigation of instabilities in these devices with new diagnostics







Achievements

Conferences

- **Presentation** & **paper** for the international Space Propulsion Conference (SPC) 2021
  - *Design and preliminary study of a 200W Cylindrical Hall Thruster*
- **Presentation** for the online MicroPropulsion and CubeSats Workshop (MPCS) 2021
  - *Development of a low-power Cylindrical Hall Thruster*
- **Presentation** for the online IEPC Student Summer Competition 2021
  - *200 W Cylindrical Hall Thruster design and preliminary testing*
- **Presentation** & **paper** for the International Electric Propulsion Conference (IEPC) 2022
  - *Characterization of a low-power Cylindrical Hall Thruster*
- **Presentation** & **paper** for the European Conference for Aerospace Sciences (EUCASS) 2023
  - *Measurements of xenon ions and atoms velocity in Cylindrical Hall Thruster with Laser-Induced Fluorescence spectroscopy*
- **Presentation** & **paper** for the International Electric Propulsion Conference (IEPC) 2024
  - *Direct thrust measurements of a 200 W Cylindrical Hall Thruster*
  - *Design, assembly and validation test of a sub-1Amp LaB6 hollow cathode (co-author, presentation and paper writing by TFM student)*

Stays

- **Research stay 2022**: ICARE laboratory, Centre National de la Recherche Scientifique (CNRS)
  - Test campaign for the characterization of the CHT plume with electrostatic plasma diagnostics
- **Research stay 2023**: ICARE laboratory, Centre National de la Recherche Scientifique (CNRS)
  - Test campaign for the characterization of the CHT plume with optical diagnostics (LIF)

Publications

- **Journal paper** published in Journal of Applied Physics
  - *Plume characterization of a low-power Cylindrical Hall Thruster*
- Journal paper to be submitted to journal (in writing)
  - *Performance analysis of a 200 W Cylindrical Hall Thruster using direct thrust measurements and plasma diagnostics*

Projects

- PROMETEO, ESPEOS, COMIT, E.T.PACK, SUPERLEO, MARTINLARA PLUS

Other

- **TFM co-supervision:** Simulation and design of hollow cathode
- **TFM co-supervision:** Assembly and testing of hollow cathode

Thank you! Questions?

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web: ep2.uc3m.es
Twitter: @ep2lab

Back-up

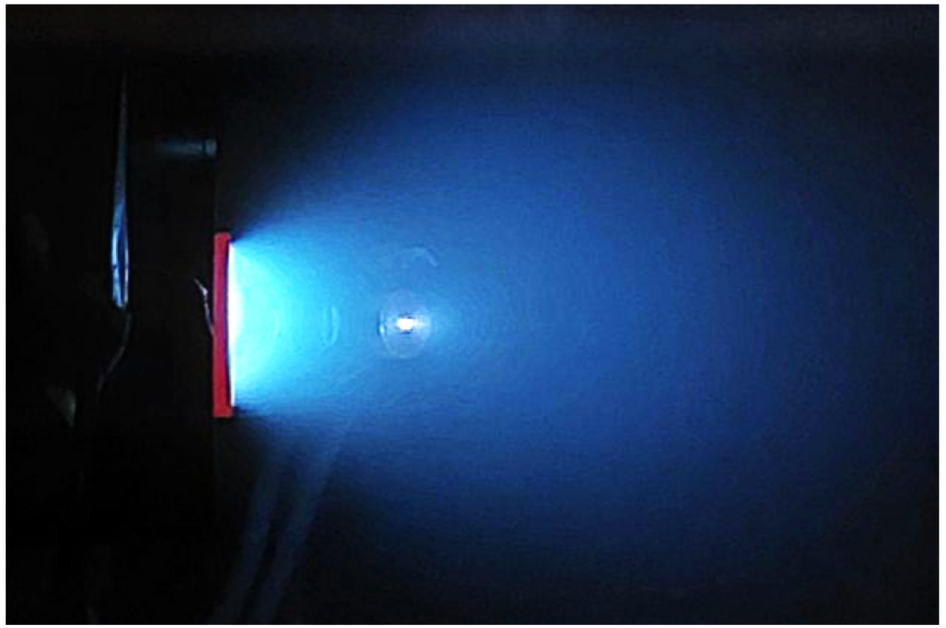
Why further iterate on CHT200 design?

Optimize thruster to enable investigation:

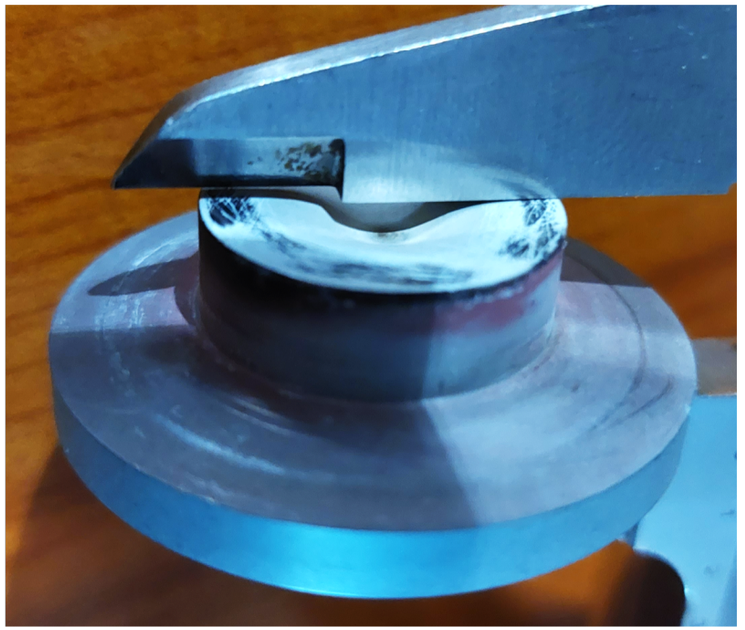
- ❑ reduce **wall losses** - slower **heating** - more **time for diagnostics & safer operation**
- ❑ less frequent need for **components replacement** (coils, ceramics, anode) - **time & cost** savings
- ❑ discharge **stabilization** - **repeatability & adapted diagnostics**

Injector sputtering, Asymmetric injection

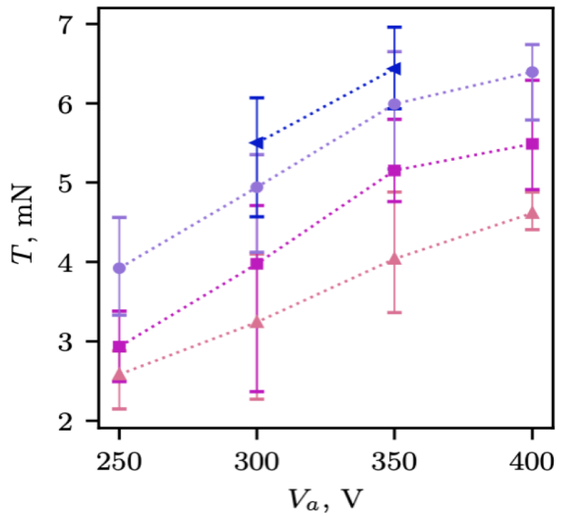
Overheating

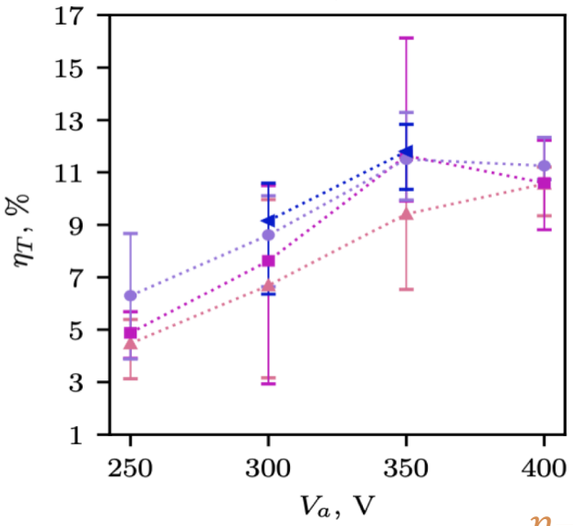


Erosion



Thrust balance





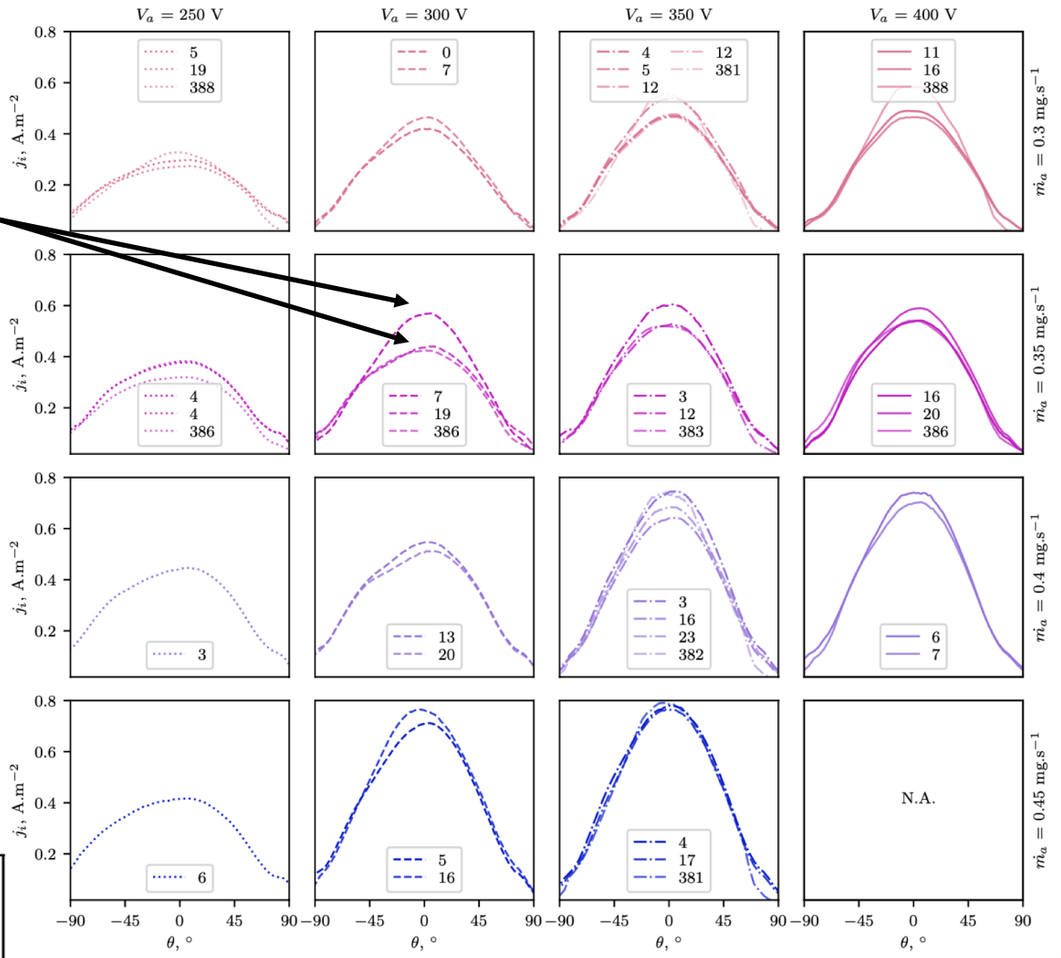
- Calibration procedure to **isolate real thrust** from external effects
- Thrust increases with $\dot{m}_a$ & V_d in covered range
- η_T depends on $\mathbf{V_d}$, maximum for 350 V, 0.4 mg s-1, ~325 W
  - Saturates with P_d for all $\dot{m}_a$
- $\eta_T \ll$ best low-power CHTs
- No trend $\eta_T - P_d$ in other low-power CHT: thruster-specific
- **B** must be **optimized**
  - Maximize j_i, T, minimize divergence
  - Increase anode shielding from electron current & increase η_{cur} (one of the main CHT weak points)cc

$$\eta_T = \frac{T^2}{2P_d(\dot{m}_a + \dot{m}_c)}$$

Probe measurements

- Plume **asymmetries**
  - cathode, injector, coils, alignment

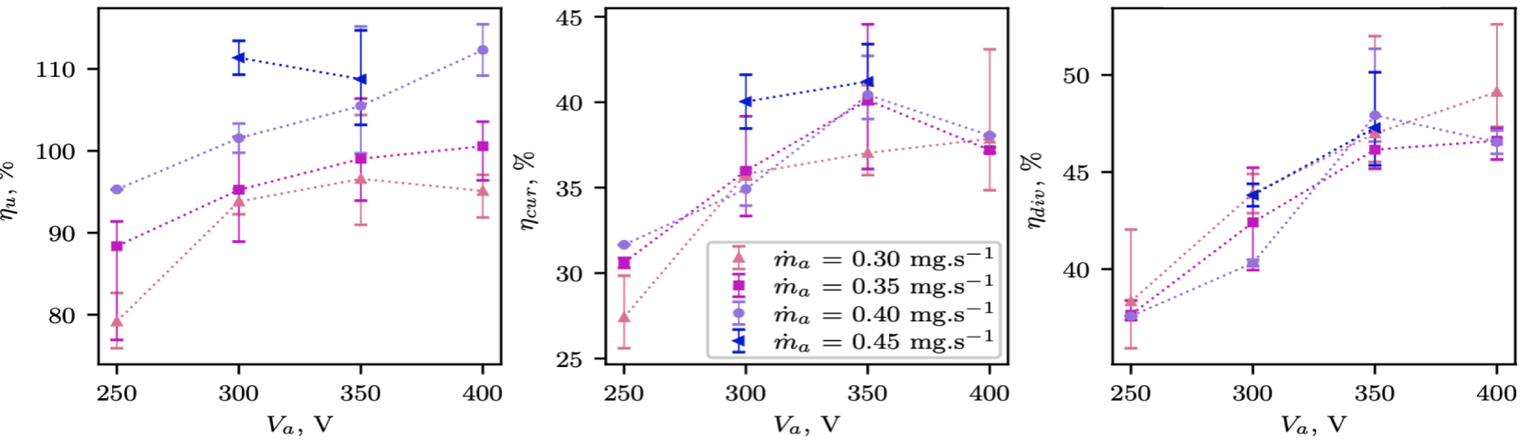
Dispersion of I_d
(>1 year scattered meas.)



- Partial efficiencies obtained by integrating beam current density

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

$$\eta_u = \frac{I_{ib} m_i}{q(\dot{m}_a + \dot{m}_c)} \qquad \eta_{cur} = I_{ib}/I_d \qquad \eta_{div} = (I_{i,z}/I_{ib})^2$$

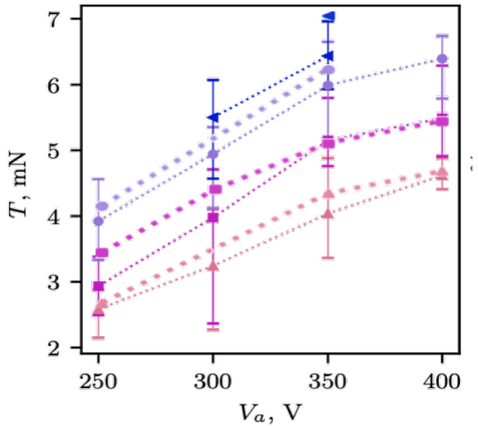


- **Divergence** & **current** utilization
  - Strongly affected by $\boldsymbol{V_d}$, not by $\dot{m}_a$
- **Propellant** utilization
  - Sensitive to $\boldsymbol{V_d}$ & $\boldsymbol{\dot{m}_a}$
  - **>1** → Xe^{2+}, Xe^{3+}

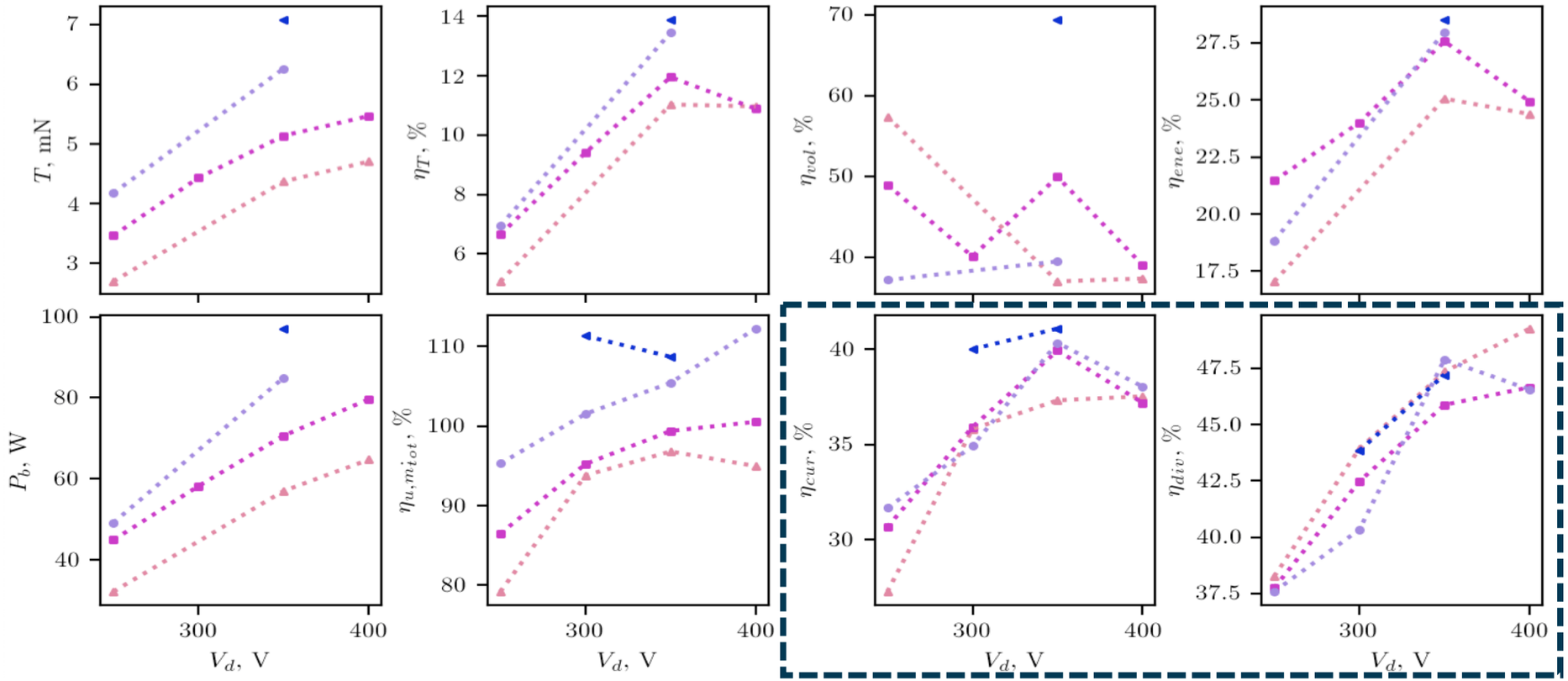
Indirect thrust & partial efficiencies

- η_{cur} & η_{div} **shape the thrust efficiency** (and energy)
  - main drivers of efficiency losses in this device

- η_{vol} not very conclusive, but possible effect of CRP
- η_{ene} very low



Rather **good agreement** with **direct** thrust measurements



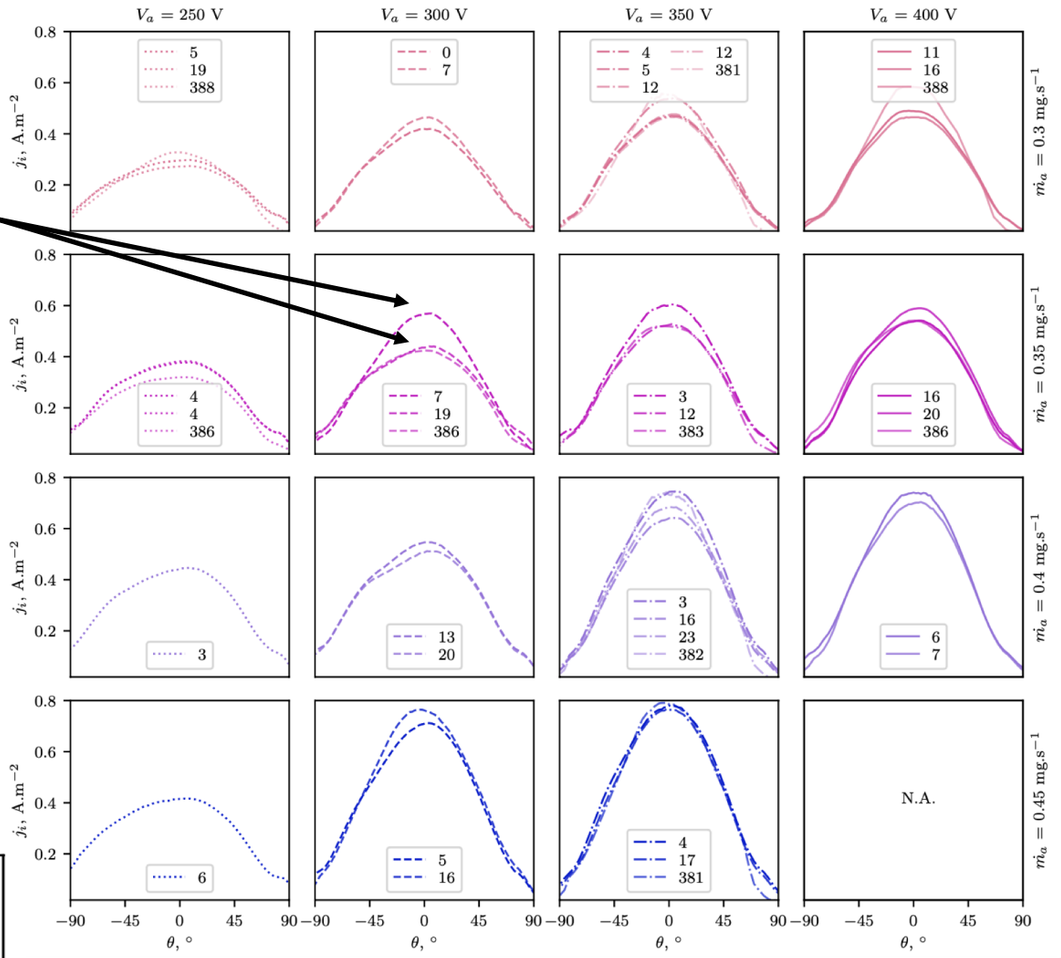
"Patchwork" of data:

- 2 campaigns
- 2 cathodes
- dispersion in I_d
- Measurements in different ignitions
- partial angular RPA scan
- Assumes singly-charged ions

Faraday cup

- Plume **asymmetries**
  - cathode, injector, coils, alignment

Dispersion of I_d
(>1 year scattered meas.)



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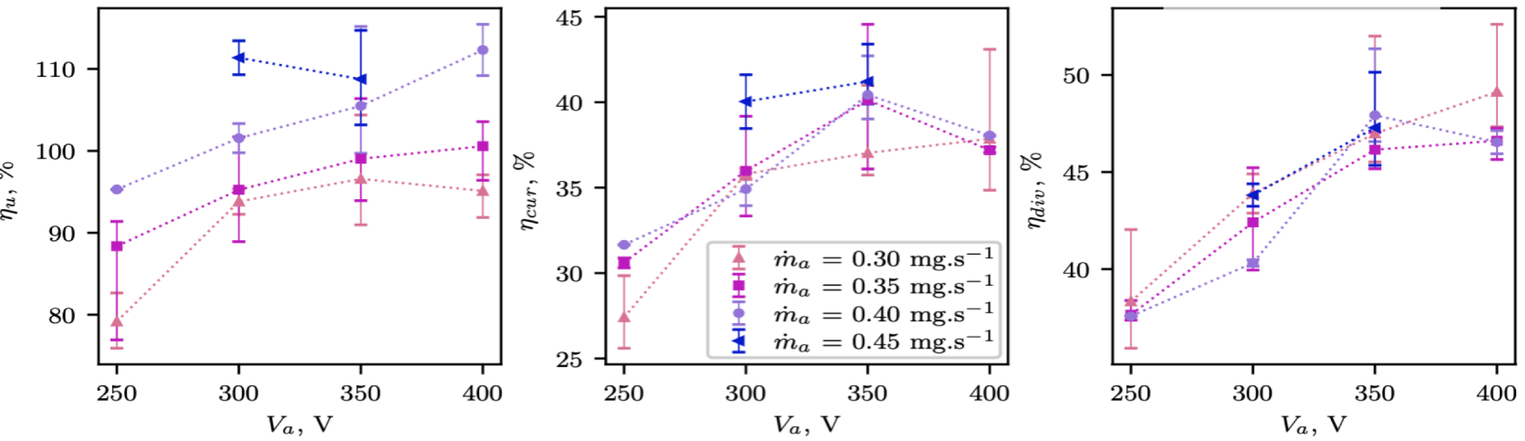

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  - Strongly affected by V_d, not by $\dot{m}_a$
- **Propellant** utilization
  - Sensitive to V_d & $\dot{m}_a$
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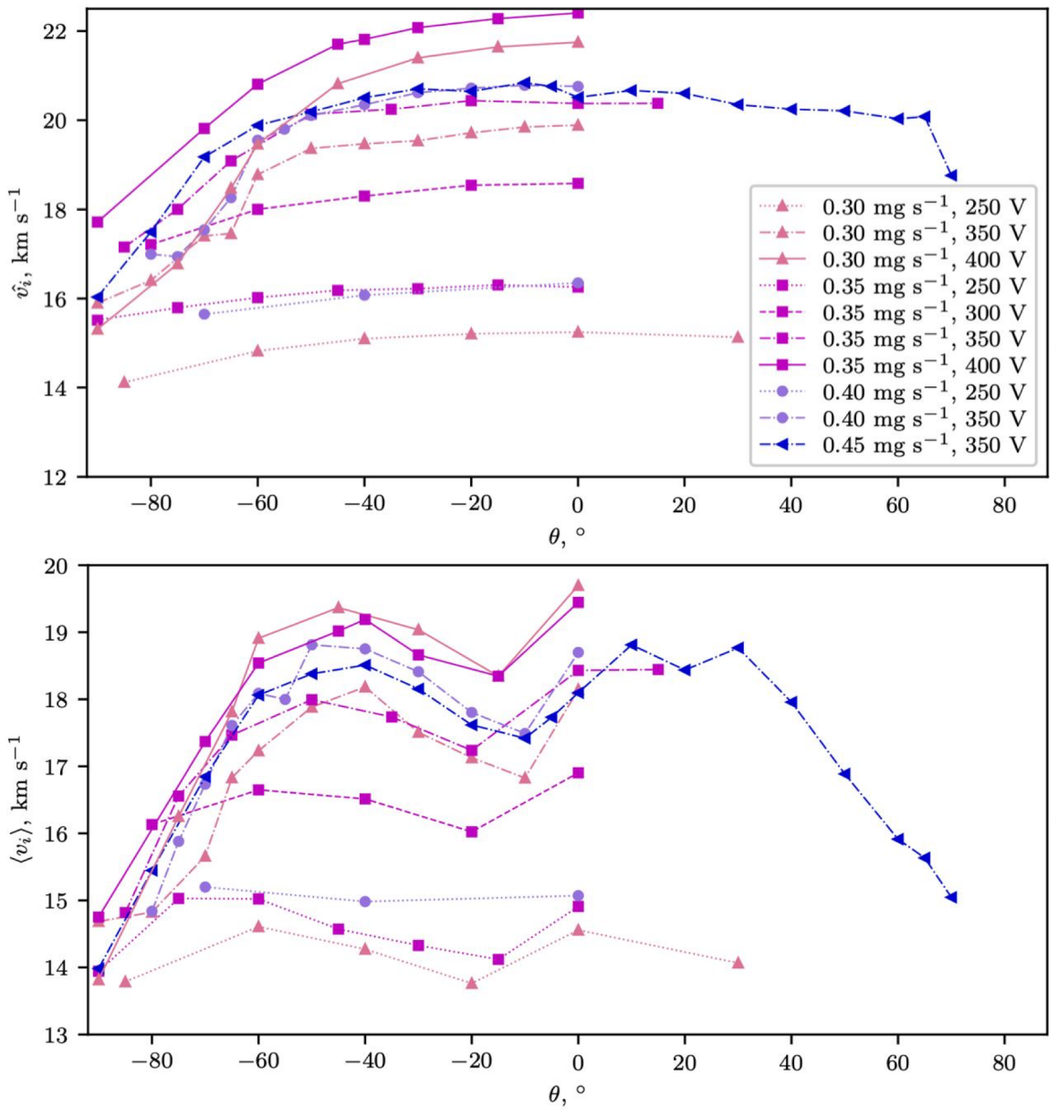
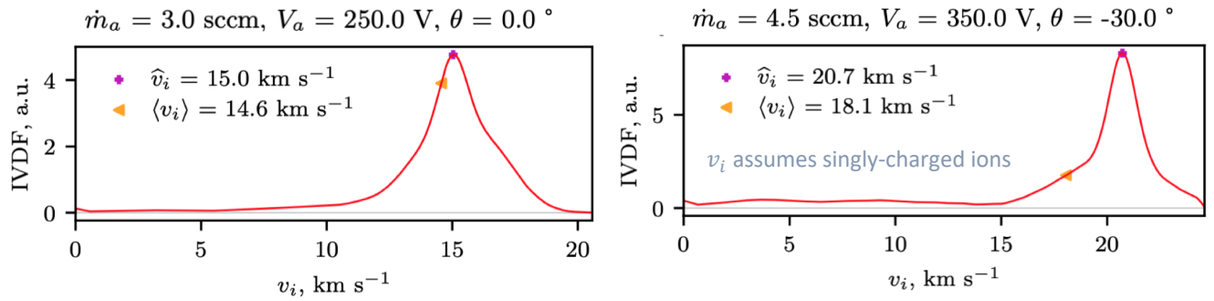
Retarding Potential Analyzer

➢ IVDF measured for a set of $(\dot{m}_a, V_a, \theta)$



Some IVDF examples



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

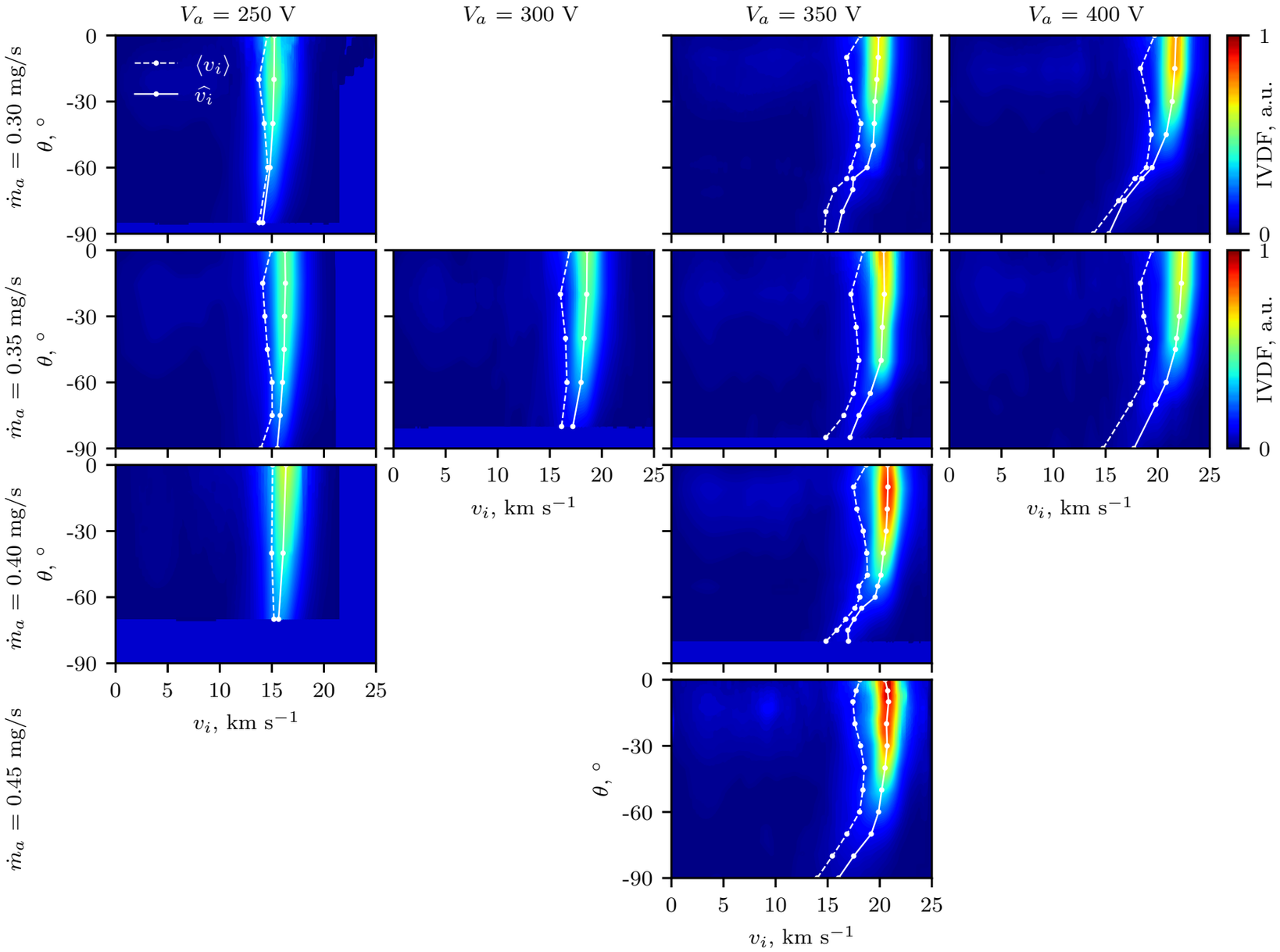
➢ Ions within beam mostly come from **main ionization region**

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 $|\theta| \gtrsim 50°$**

IVDF overview



Combined j_i & E_i information

Indirect beam power & thrust estimation

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

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

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

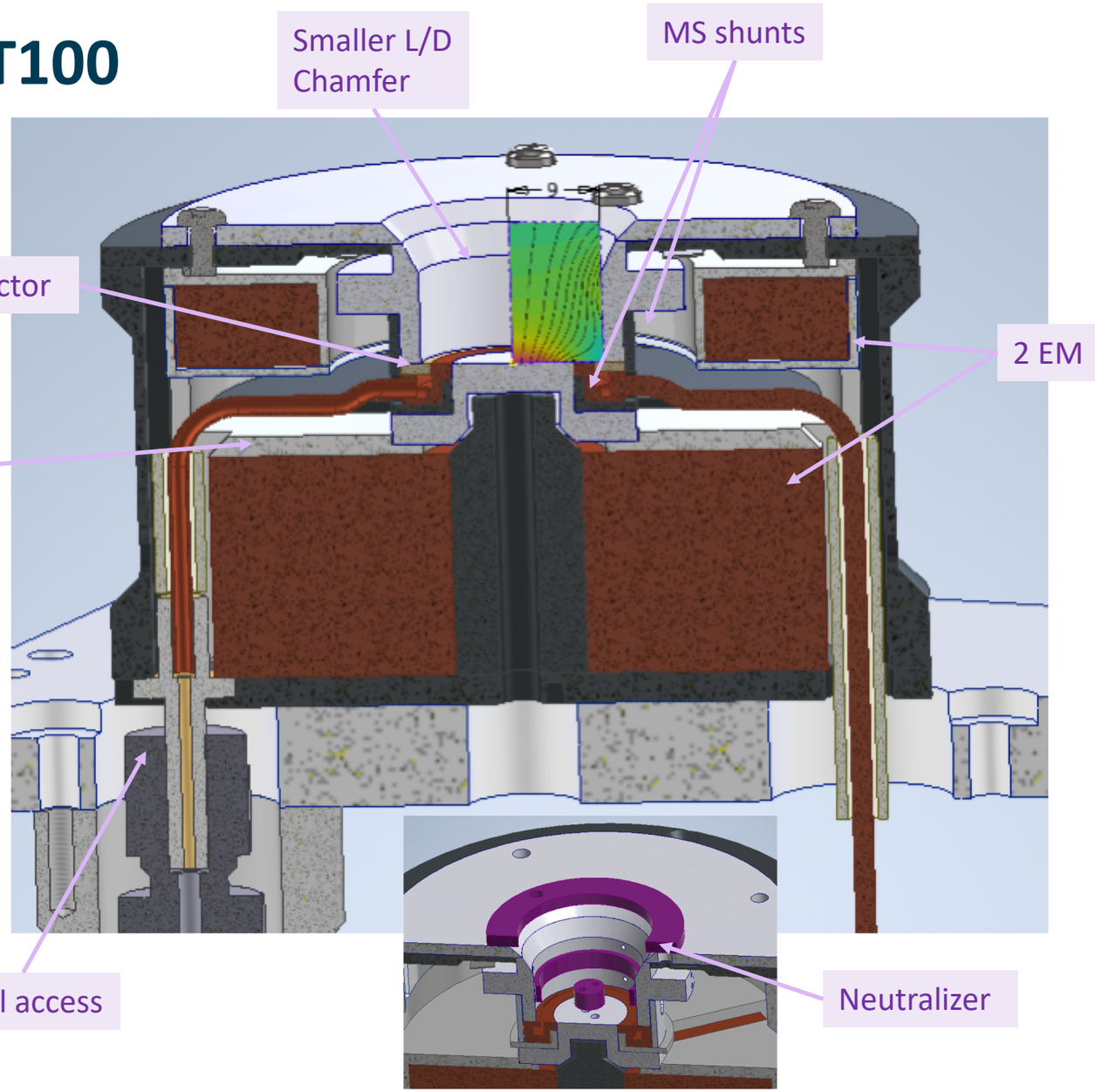
CHT100

➢ Objectives:

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

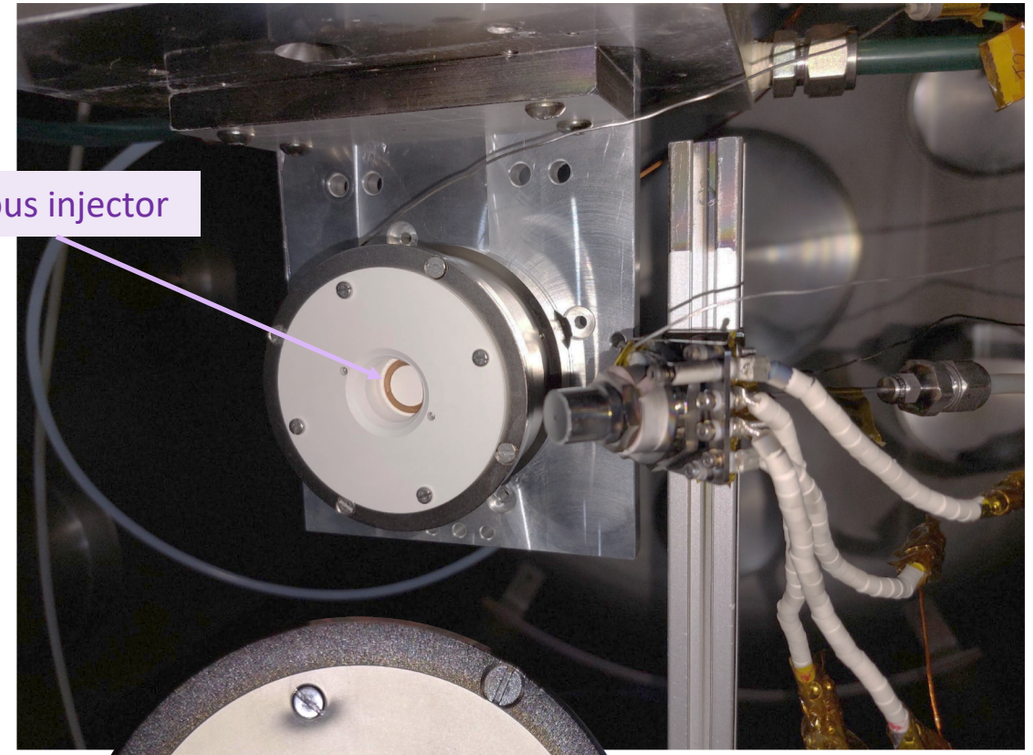
➢ Design features:

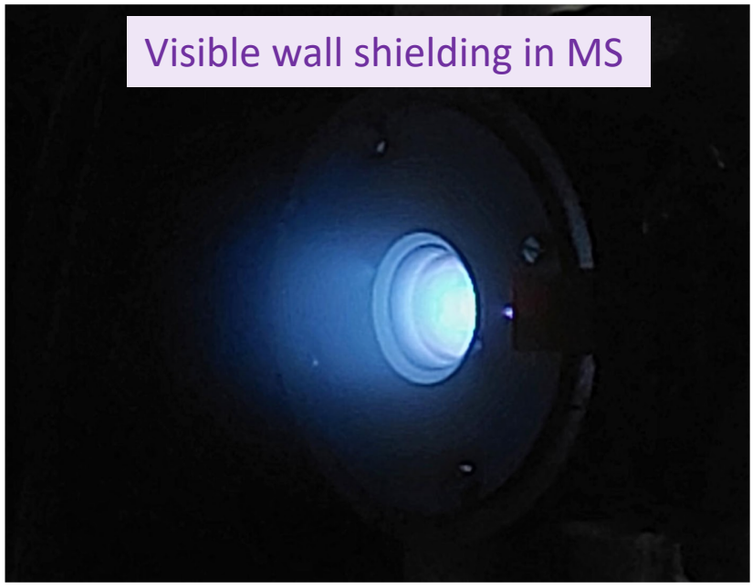
- Smaller channel **length/diameter, chamfer**
- Porous ceramic / slit injector: homogeneity, sputtering
- Thick wack wall for **erosion**
- 2 electromagnets & optional shunts: MS/non-MS
- Thermal management (coils)
- Probes accessibility
- No radial connection, exposed biased component
- Adaptable to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



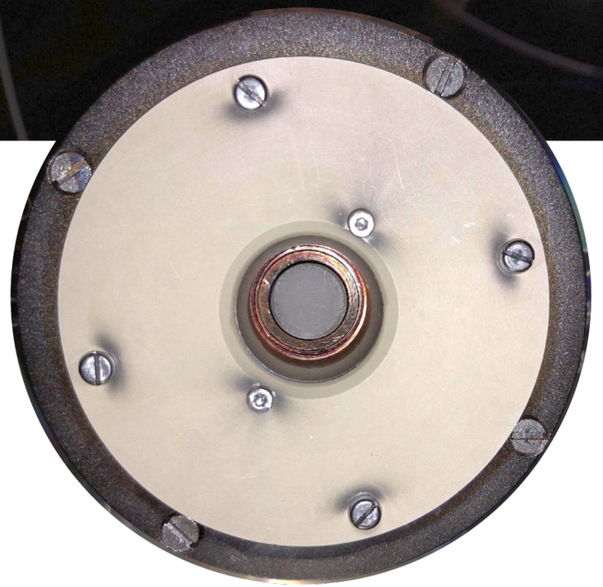
Ignition with MUSIC cathode

- 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)



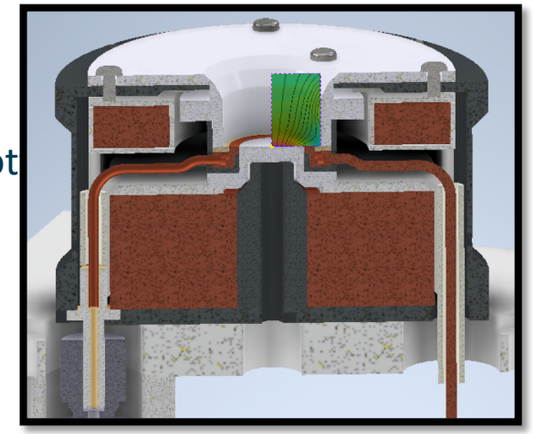


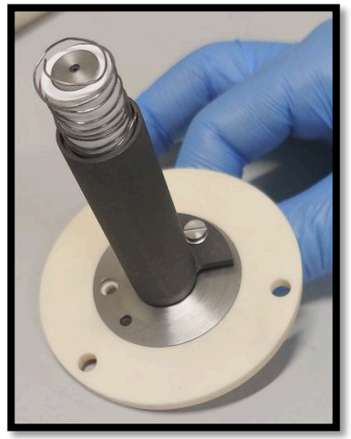
PEEK gas injector overheating → ceramic
Partially obstructed gas line limiting I_d

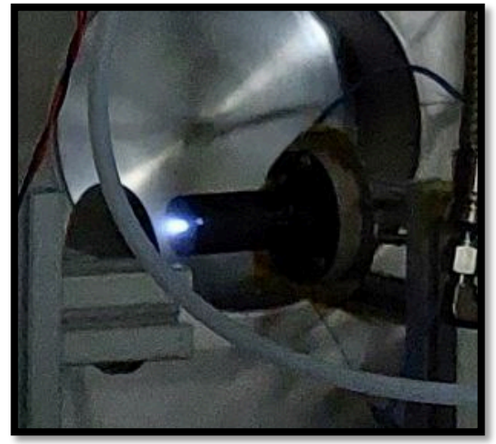


Detailed objectives of future experimental HET-related work for EP2

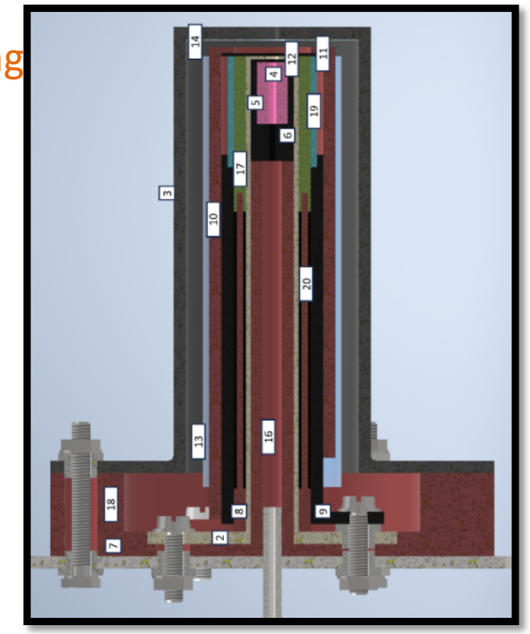
- Design of 100 W CHT prototype
  - Downscaling of 200 W CHT
  - Improvements from simulations and tests of first protot
    - Channel geometry
    - Gas injection
    - Mechanical and thermal aspects
  - Magnetic shielding
  - Towards dry and/or power-free cathode

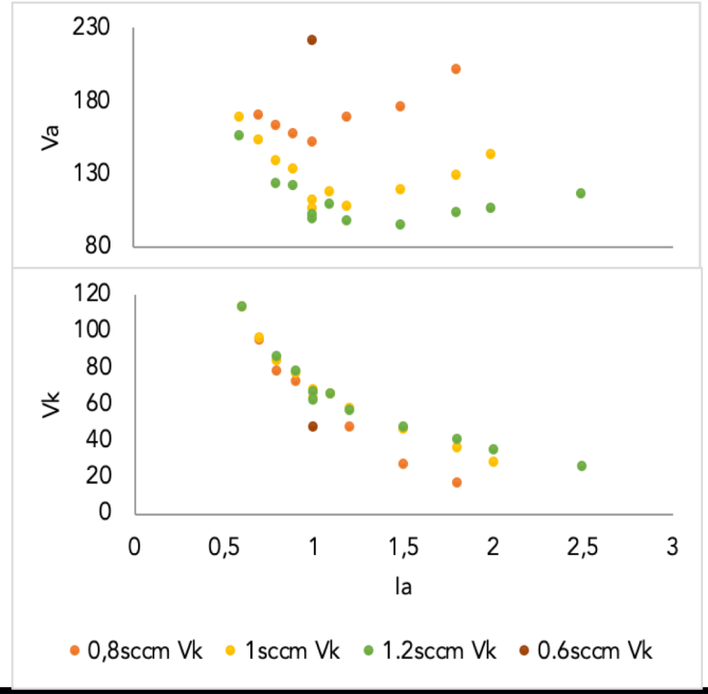






- TFM co-supervision: 1A hollow cathode design, assembly, testing
  - Thermal simulations, materials selection, components sizing
  - Procurement and assembly
  - Preliminary tests with xenon:
    - Ignition characterization (300W, 500V, 12 sccm)
    - Triode and diode test: matrix of mass flow rates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



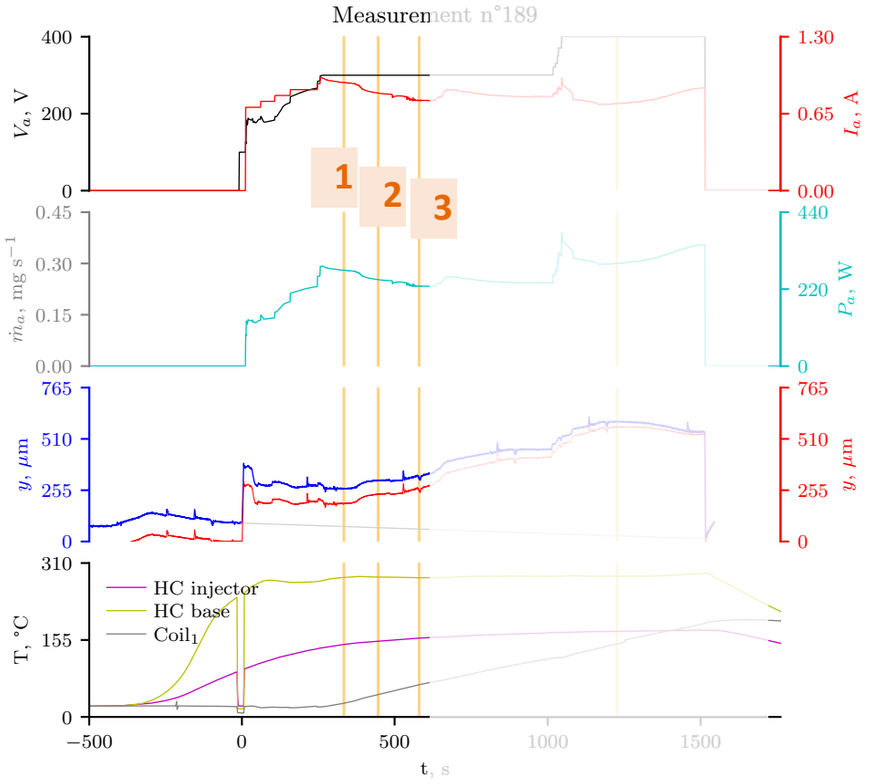


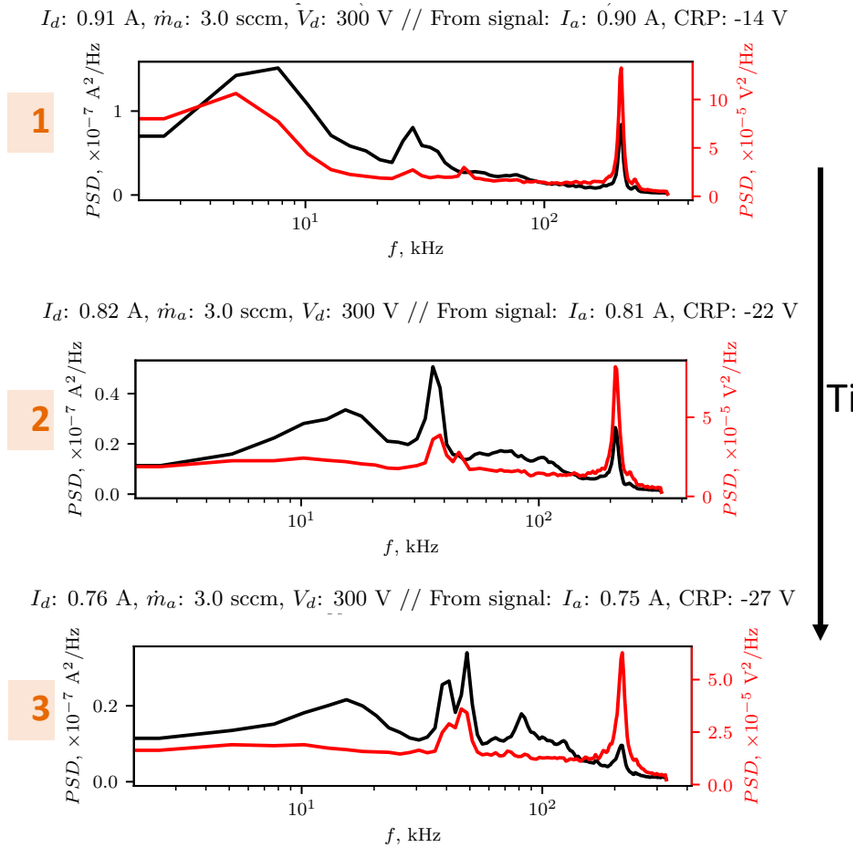
Cathode spectra

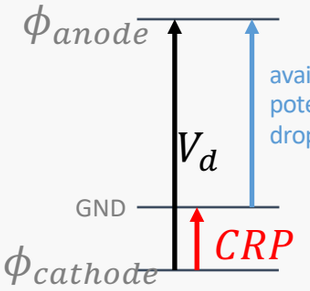
Simultaneous spectras of I_d and CRP, evolution through 2 changes of mode

- Low f components dominant in I_d
- High f component dominant in CRP: related to cathode?

- High f remains in cathode in all modes
- 30-50 Hz nearly absent from cathode initially



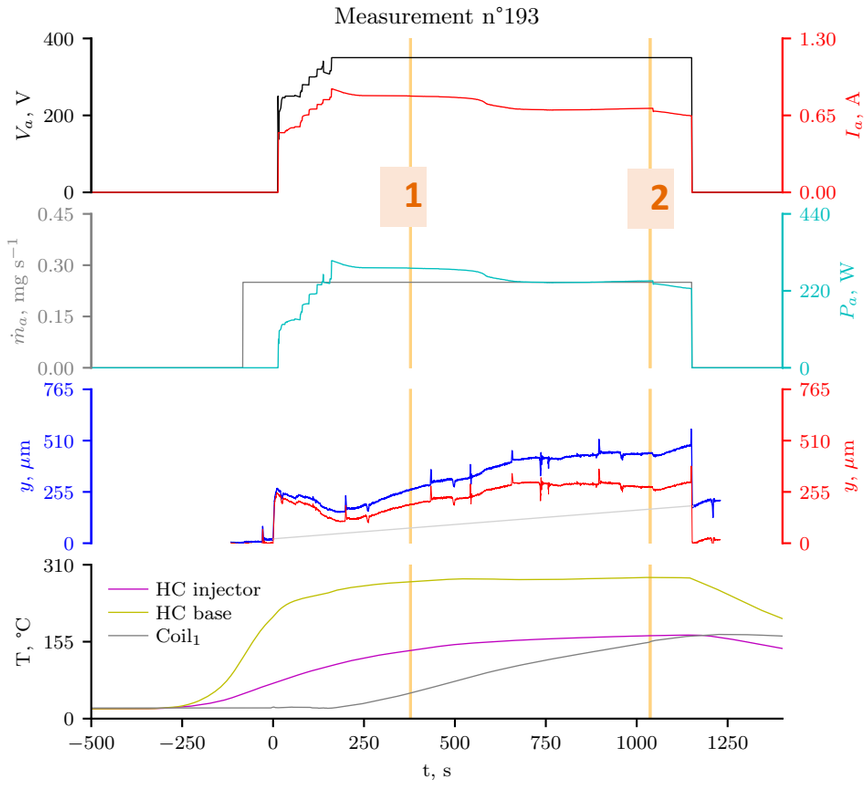


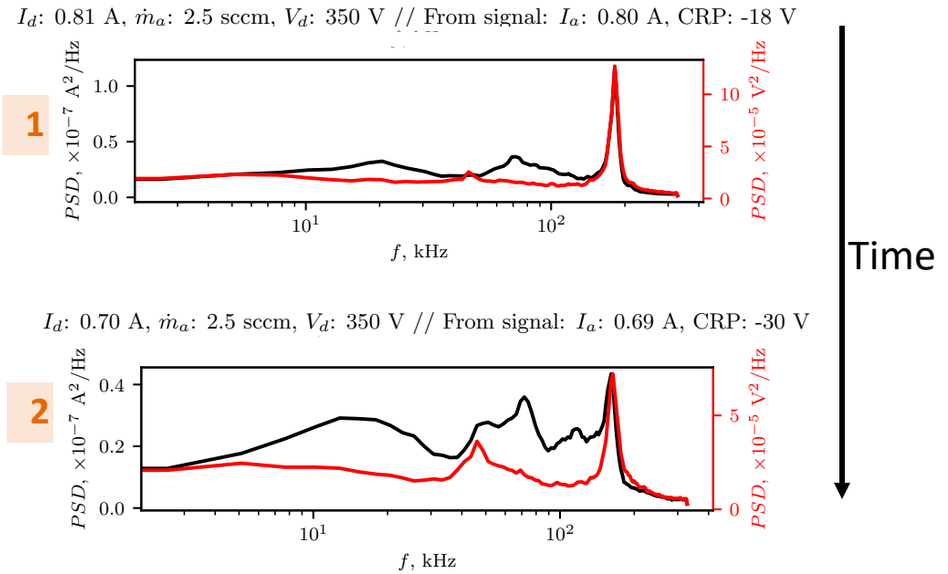


Cathode Reference Potential:
floating potential of the cathode *wrt* ground
Indicator of cathode health / ability to provide electrons

Simultaneous spectras of I_d and CRP, evolution through 1 change of mode

- Similar behavior
- High f present in both modes
- Low f components growing in I_d & CRP

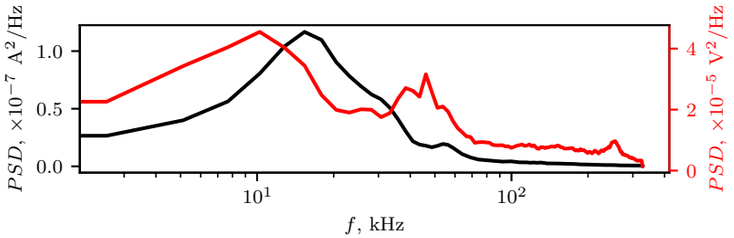




Example of case with:

- High f totally **absent** from I_d
- High f in CRP with very low amplitude compared to low f

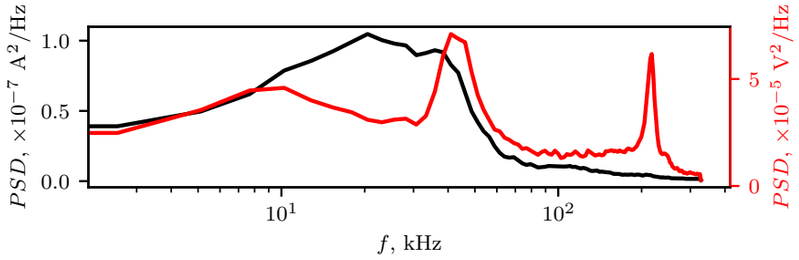
I_d: 0.72 A, $\dot{m}_a$: 3.5 sccm, V_d: 350 V, CRP: -30 V // From signal: I_a: 0.66 A, CRP: -36 V

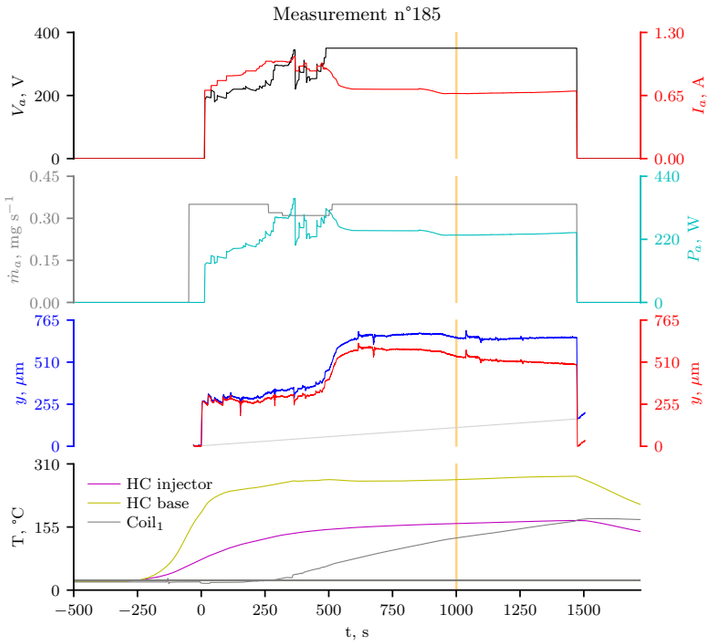


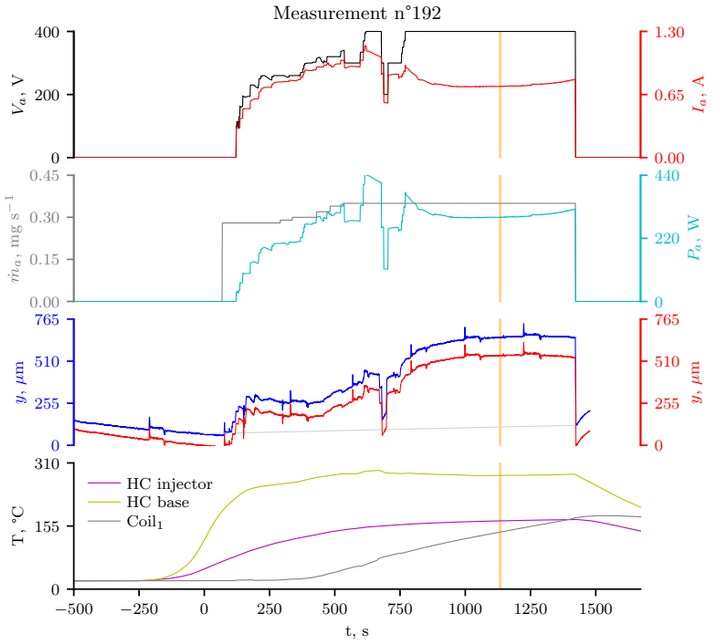
Example of case with:

- High f totally **absent** from I_d
- High f in CRP with significant amplitude

I_d: 0.73 A, $\dot{m}_a$: 3.5 sccm, V_d: 400 V, CRP: -34 V // From signal: I_a: 0.72 A, CRP: -34 V







Indicates that

- instability originates from cathode?
- instability dies out with delay in plume/cathode?

Summarizing observations on high frequency oscillations:

- appearing/disappearing **spontaneously**

- appear to be associated to **large discharge current & low thrust** (inferred from TB displacement, assuming small & slow drifts)
- altering **IVDF**
- seems associated to **CRP closer to 0**
  - likely due to larger cathode heating because of large I_d
  - observed for at least two test points

- affected by ignition **procedure** (triggers?)
- related to ignition **transient**? over seconds to tens of minutes…

- cathode related?
- thruster or cathode thermal inertia affecting emission & triggering ionization/acoustic instabilities?
- relation with cathode/thruster surface state?

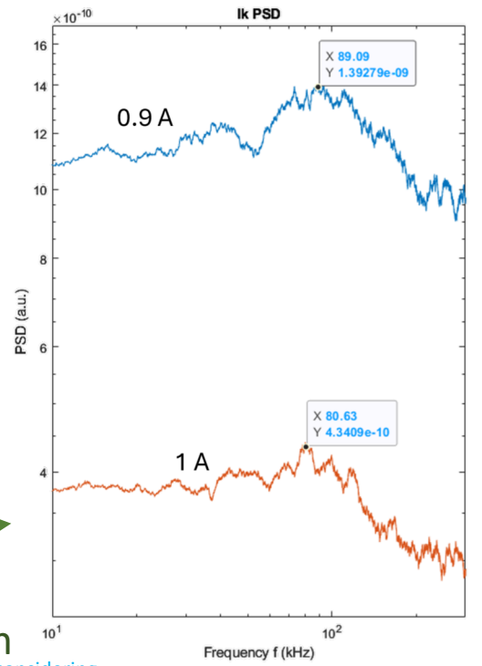
Identification: inputs from literature and Aliena

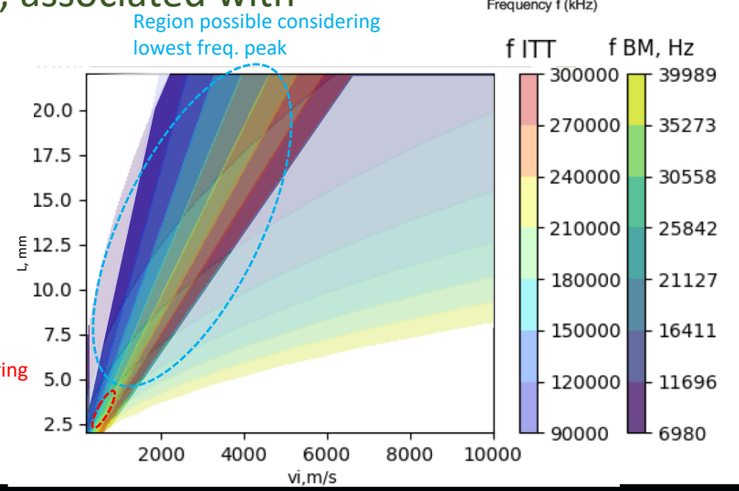
- Insufficient spatial information to determine dispersion relation
- ~210 kHz falls in range of:
  - Ion Transit Time (Hall, little confirmed experimental evidence, seen with models, stability with $\nabla \mathbf{B}$?)
  - Ion Acoustic (cathode in plume mode triggered by $\frac{I_d}{\dot{m}_c}$/self-heating, uncertain, very broadband, often closer to MHz)
    - I_d range 0.73 – 1.2 A with $\dot{m}_c$ = 0.8 sccm, while indicated 0.9 – 1.65 sccm Xe (diode) → "starved" cathode

❑ Originating fom cathode?

- MUSIC HC in diode: No peaks except broad ~85 kHz for 0.9-1A
- MUSIC HC coupled with MUSIC-HT: BM & 600 kHz-1.3 MHz broadband with peak, associated with IAT or ExB drifts

Potrivitu and Xu *Journal of Electric Propulsion* (2022) 1:6
https://doi.org/10.1007/s44205-022-00005-y





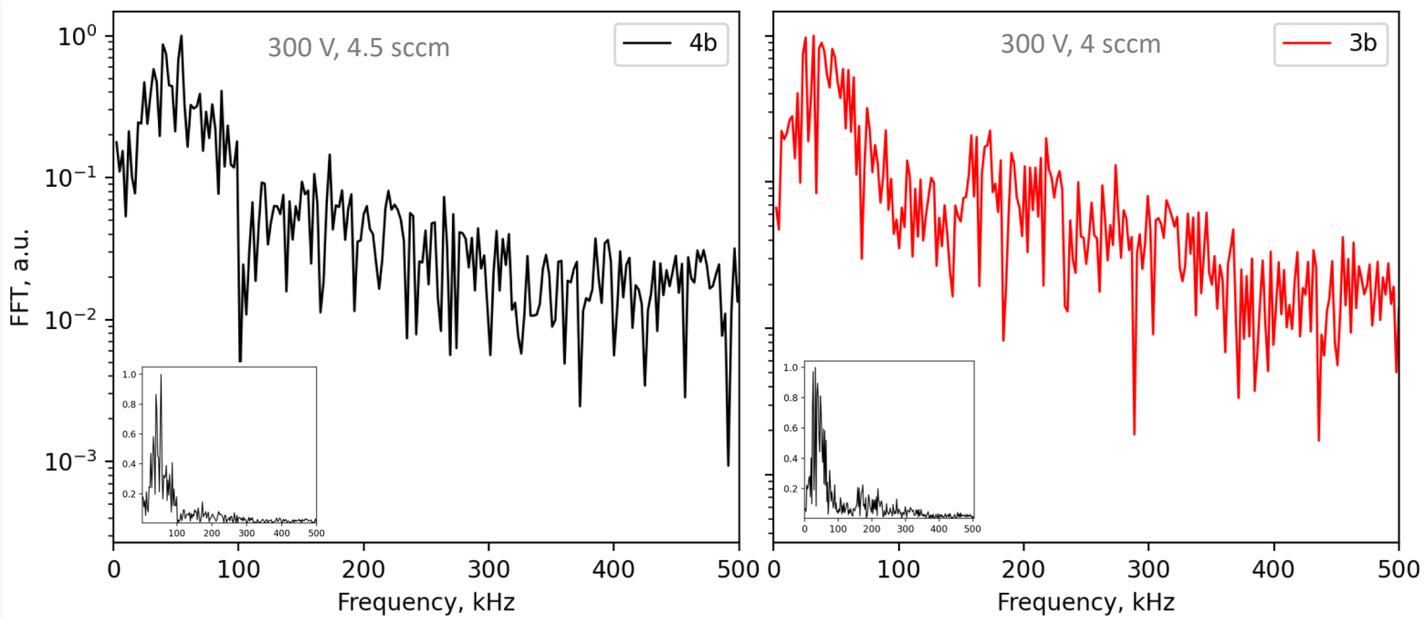
➢ Possible match with expected BM ~$\frac{\sqrt{v_i v_n}}{2\pi L}$ and ITT ~$\frac{v_i}{L}$ frequencies,

➢ although difficult to predict given geometry of ionization & acceleration regions

E. Y. Choueiri, Phys. Plasmas 8, 1411 (2001); doi: 10.1063/1.1354644
Y. Esipchuck, A. Morozov, G. Tilinin, and A. Trofimov, Sov. Phys. Tech. Phys. **18**, 928 (1974).

What do models show?

- HYPHEN:
  - Similar observation by Maddaloni with HET
    - BM, ITT & their interaction
  - Iñaki with CHT: BM and ~200 kHz



1D code Poli SPT100, similar spectral shape:

- BM + harmonic(s) BM^n
- ITT (?)
- Coupling: ITT ± BM^0, and ITT ± BM^n
- ITT associated to transport
- Accompanied by strong perturbation in $\vec{E}$ propagating downstream
  - Could explain seeing it in CRP