# Advanced 2D Fluid Modelling of Hall Effect Thruster Discharges

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# Motivation And Methodology

## The problem of the anomalous transport

Onset of plasma instabilities → Enhanced cross-field mobility of electrons
Reduced magnetic confinement

**No predictive models of Hall Effect Thrusters**

## Methodology:

- Development of 1D and 2D time dependent fluid models
- Characterisation of onset and saturation of instabilities

# Motivation And Methodology

Particle In Cell (PIC) codes are commonly used for ExB plasmas

## FLUID MODELS

**PROS**

- Deal with macroscopic quantities
- Easier to interpret
- Can be very flexible with the physics included
- Can describe many instabilities

**CONS**

- Maxwellian VDF
- Lack of kinetic effects
- Delicate numerical algorithms
- Numerical diffusion

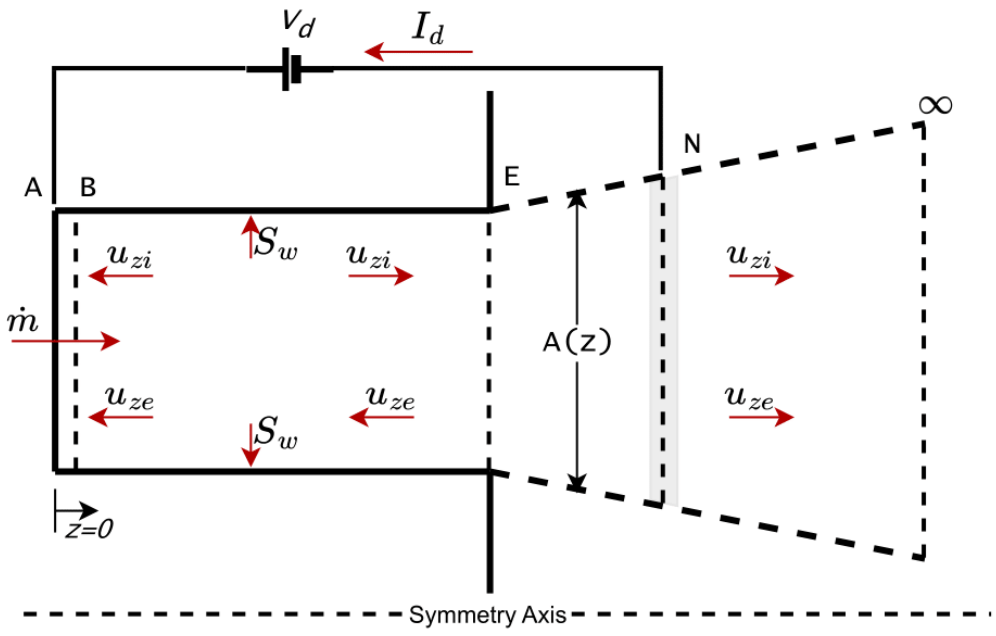
Combined use of PIC and fluid models can help characterizing the instabilities and their trigger mechanisms

# Methodology – Axial Instability

## 1D Quasineutral /Non-neutral Time Dependent Model

1D axial time dependent models of the Hall thruster discharge

- Resolving axial instabilities
- Performance analysis
- Parametric studies



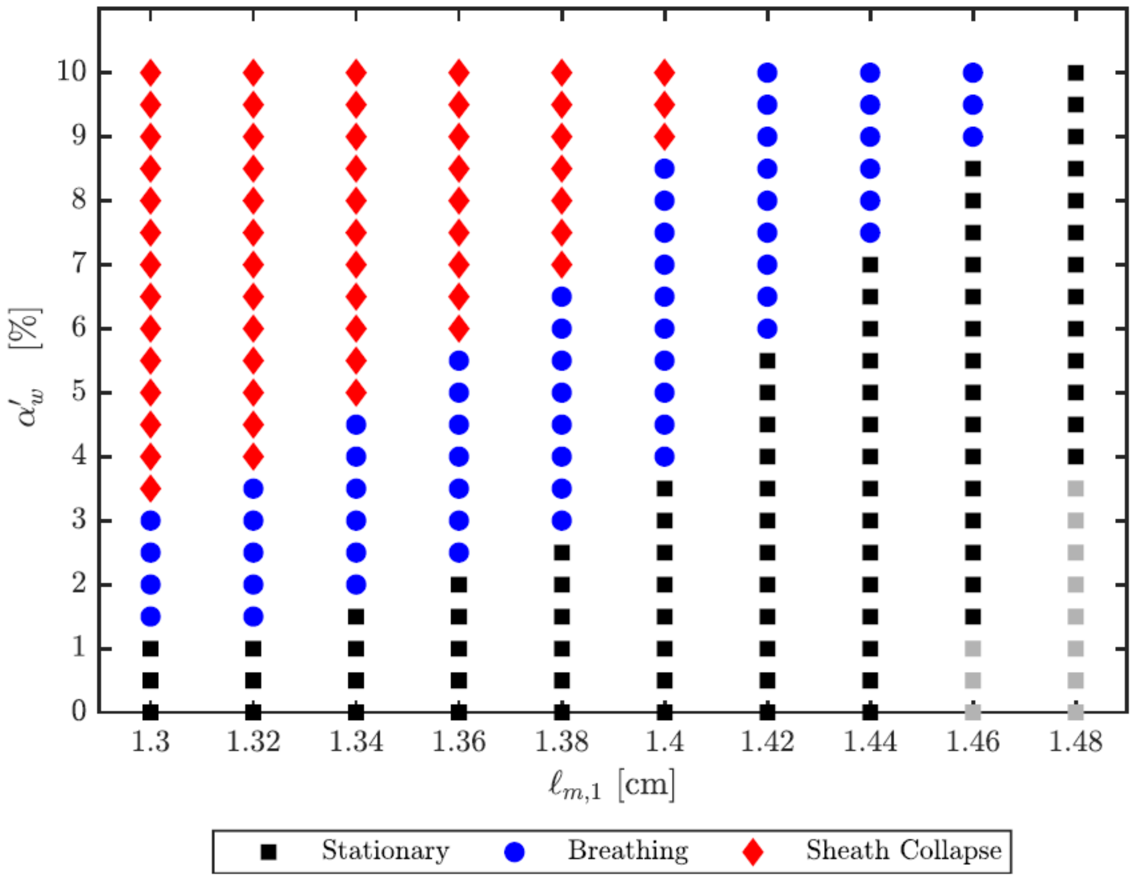

*D. Poli, E. Bello-Benítez, P. Fajardo, and E. Ahedo, Time-dependent axial fluid model of the Hall thruster discharge and its plume.* 10.1088/1361-6463/ace2d0

*D. Poli P. Fajardo, and E. Ahedo, A Non-neutral 1D Fluid Model of Hall Thruster Discharges: full electron inertia and anode sheath reversal 10.1088/1361-6595/ad6500*

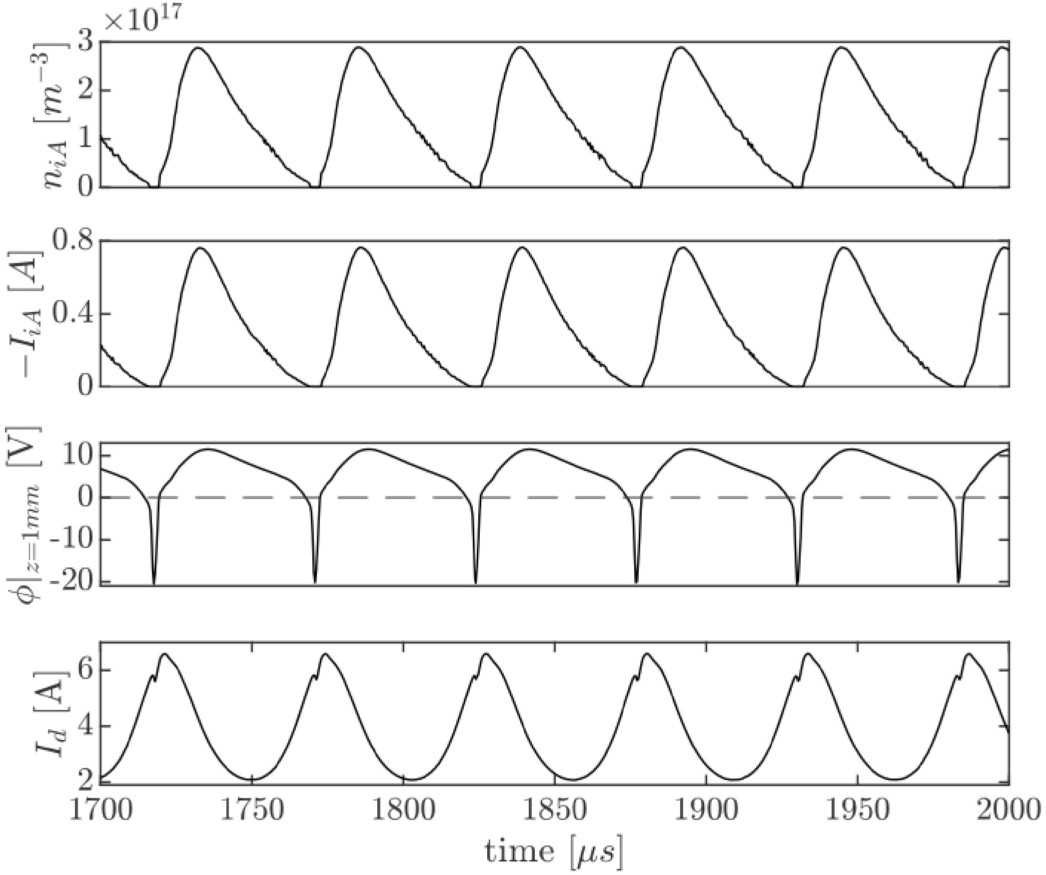
# Methodology – Axial Instability

## Breathing mode

### Quasi neutral model




### Non neutral model



# Methodology – Azimuthal Instability

## Axial-azimuthal model

Time dependent 2D model of the discharge

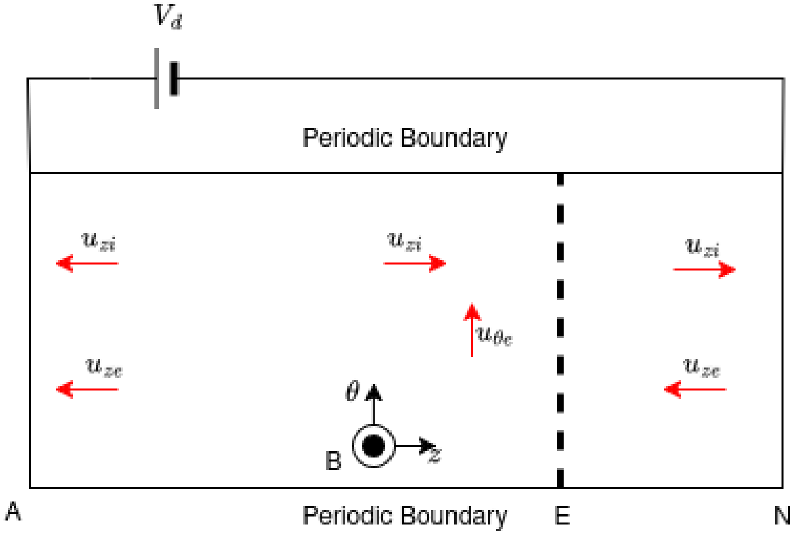
**Model**

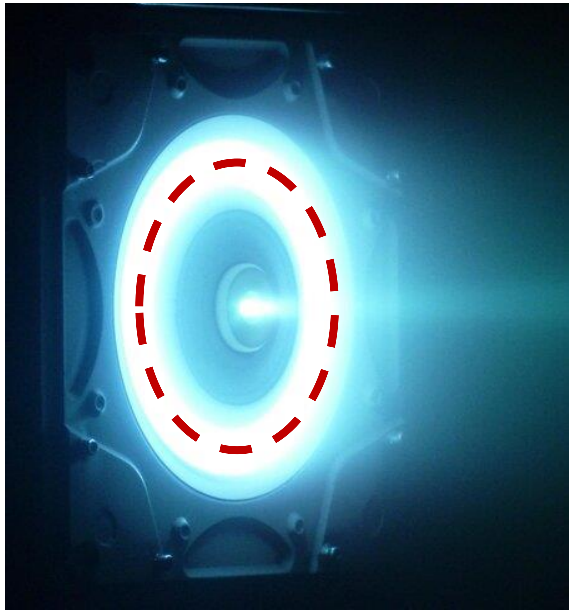
- Z-θ plane
- 3-fluid model
- Full electron inertia
- Non-neutral effects
- Neutral dynamics

**Code**

- Finite Volume based
- MPI parallelisation

Difficult simulation !



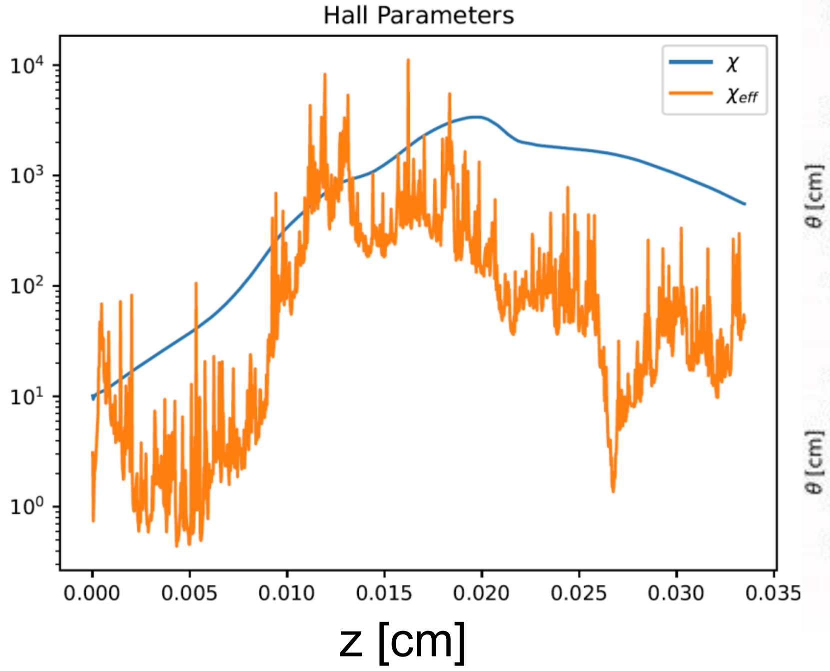



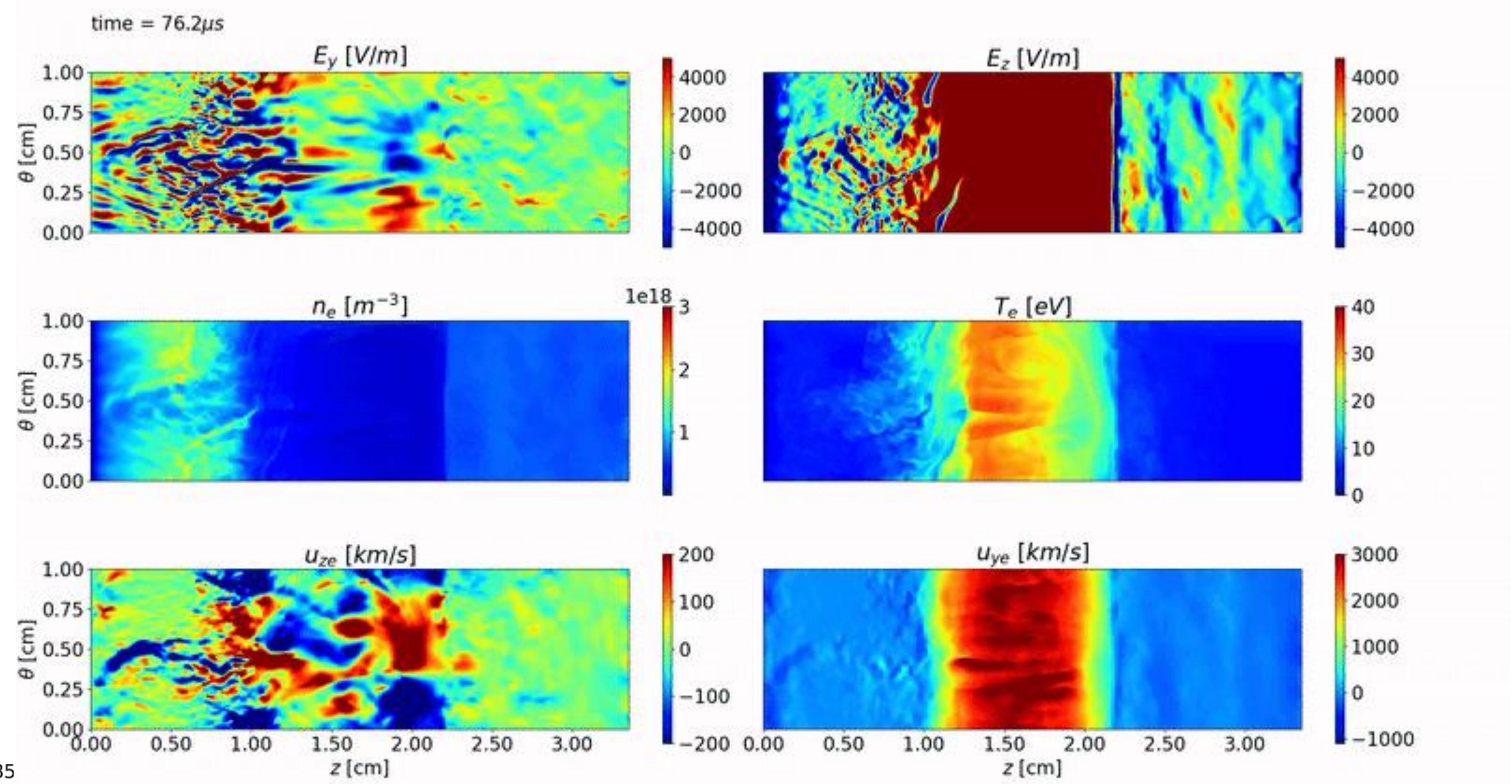
Busek BHT-1500
https://www.busek.com/hall-thrusters

# Methodology – Azimuthal Instability

## Simulation results

- 500,000 cells
- 52 M steps
- 150 us



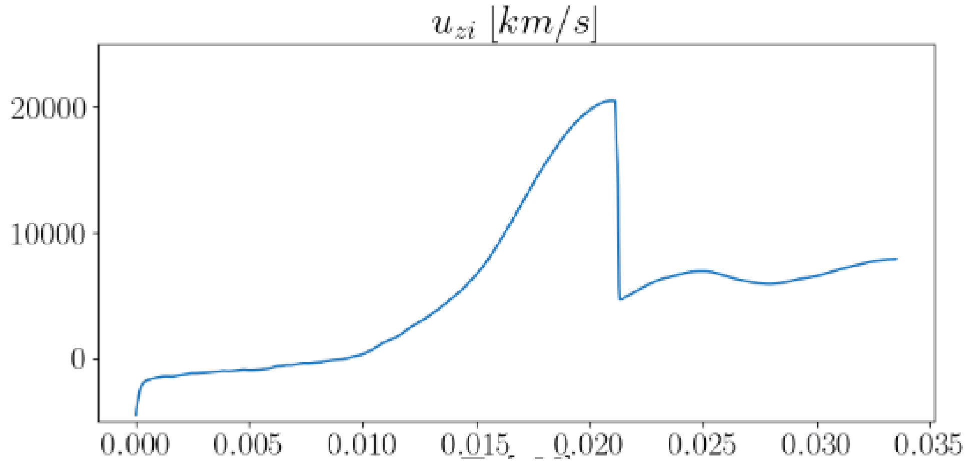
# Methodology – Azimuthal Instability

## Onset of ITTI in 2D simulations

Onset of Transient Time Instability (axial instability).

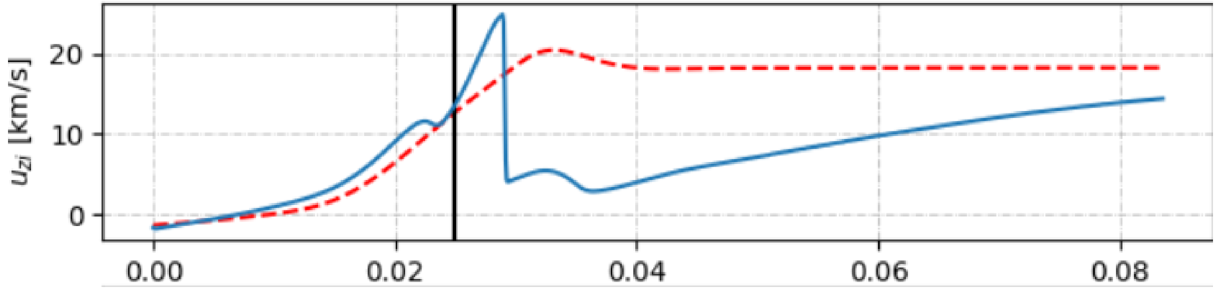
- Triggered by low electron mobility
- Appears as a strong shock in the ion axial velocity
- Recovered in quasi neutral code decreasing the anomalous transport

2D code




z [m]

1D Quasi neutral code

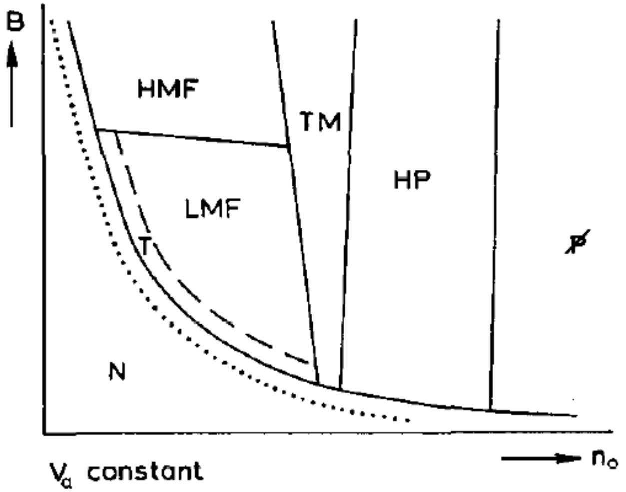



z [m]

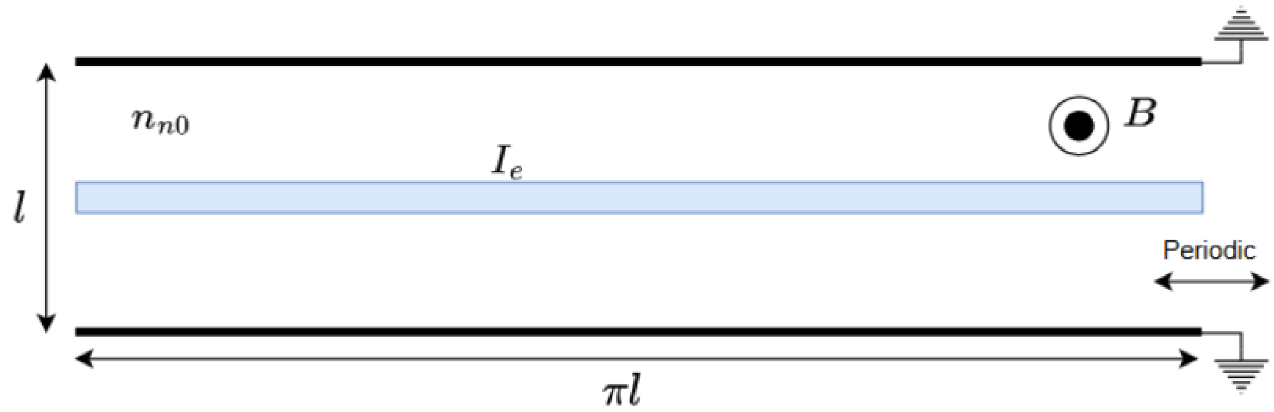
# Methodology – Azimuthal Instability

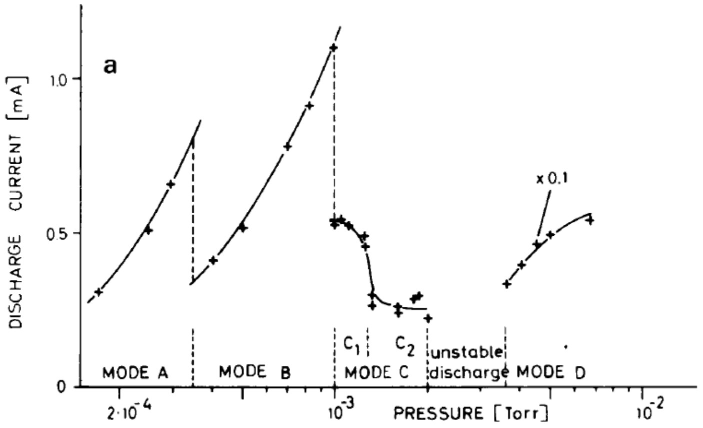
## Mode transitions (Penning-like configuration)

- Conceptually simpler than Hall thruster
- Difficult numerical modelling (near vacuum)
- Simulation of modes transition in plasma instabilities
- No similar fluid simulations in the literature




W. Schuurman **(1966)**.
Investigation of a Low-Pressure Penning Discharge



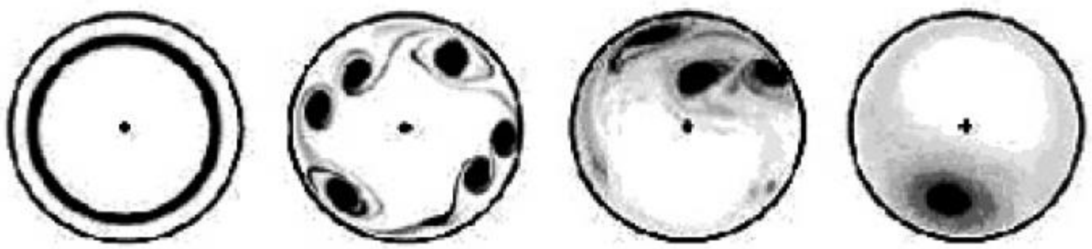




Rohwer, P. et al.
Nucl. Instrum. Methods Phys. Res., 211(2/3), 543–546

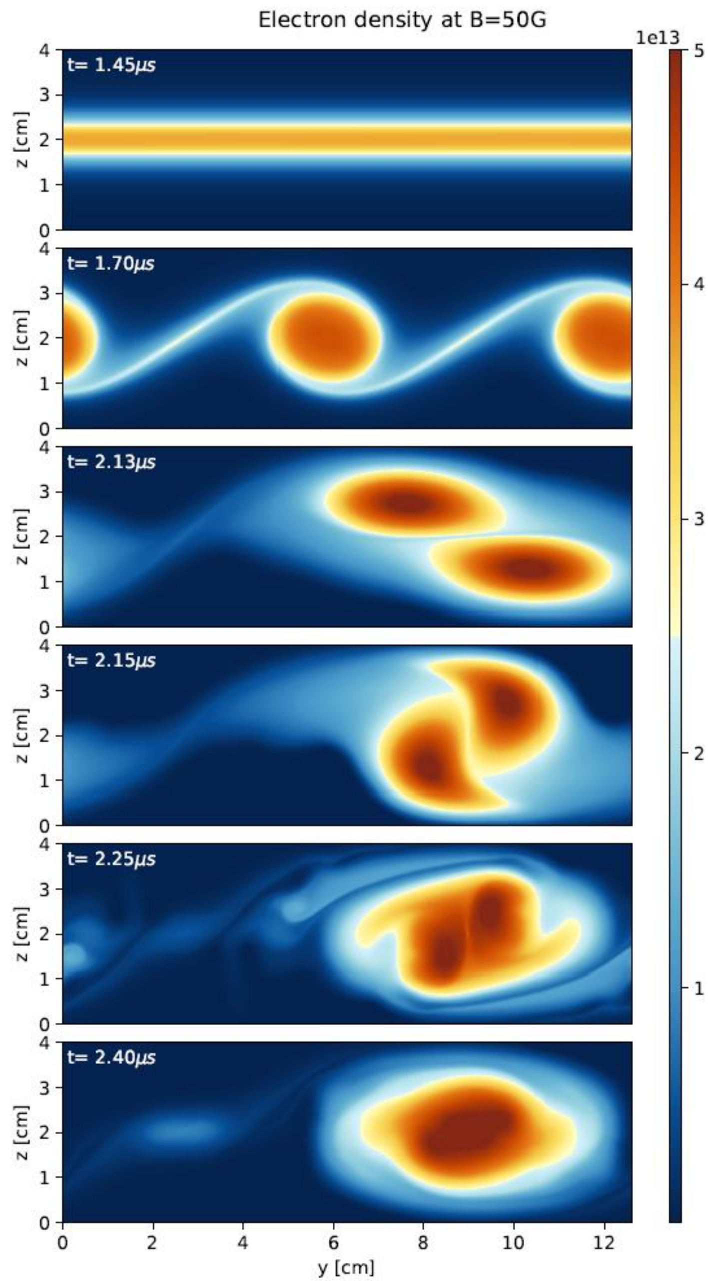
# Methodology – Azimuthal Instability

## Mode transitions (low pressure regime)

- Limit of low-pressure regime P=0
- Pure electron plasma
- Onset of Diocotron instability
- Electron vortexes interaction



Hollow electron beam evolution (experiment),
Phys. Rev. Lett 93, 215002 (2004).

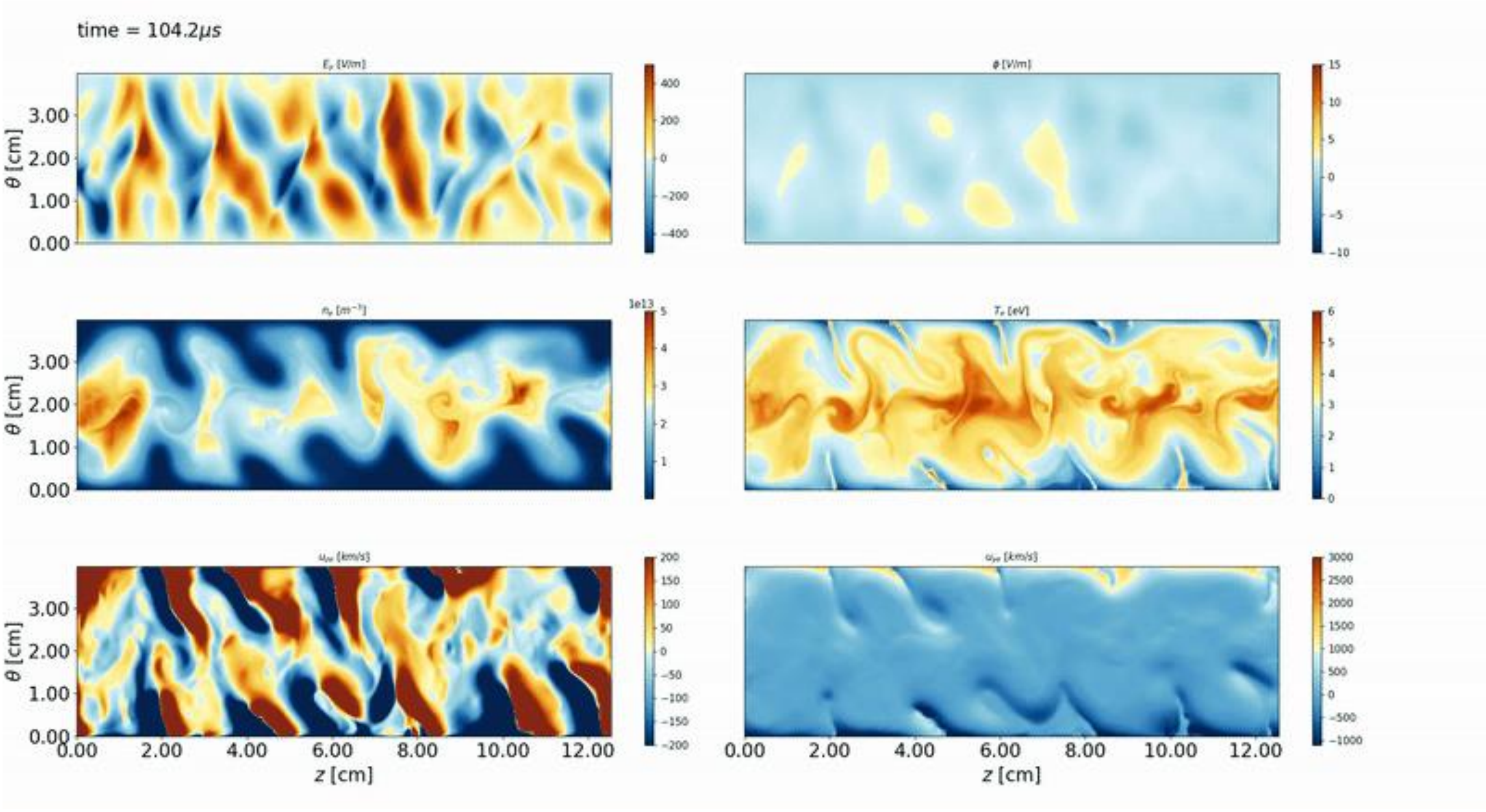


# Methodology – Azimuthal Instability

## Mode transitions (high pressure regime)

Spokes formation

- MSHI ?
- CIV theory?
- Drift Dissipative?



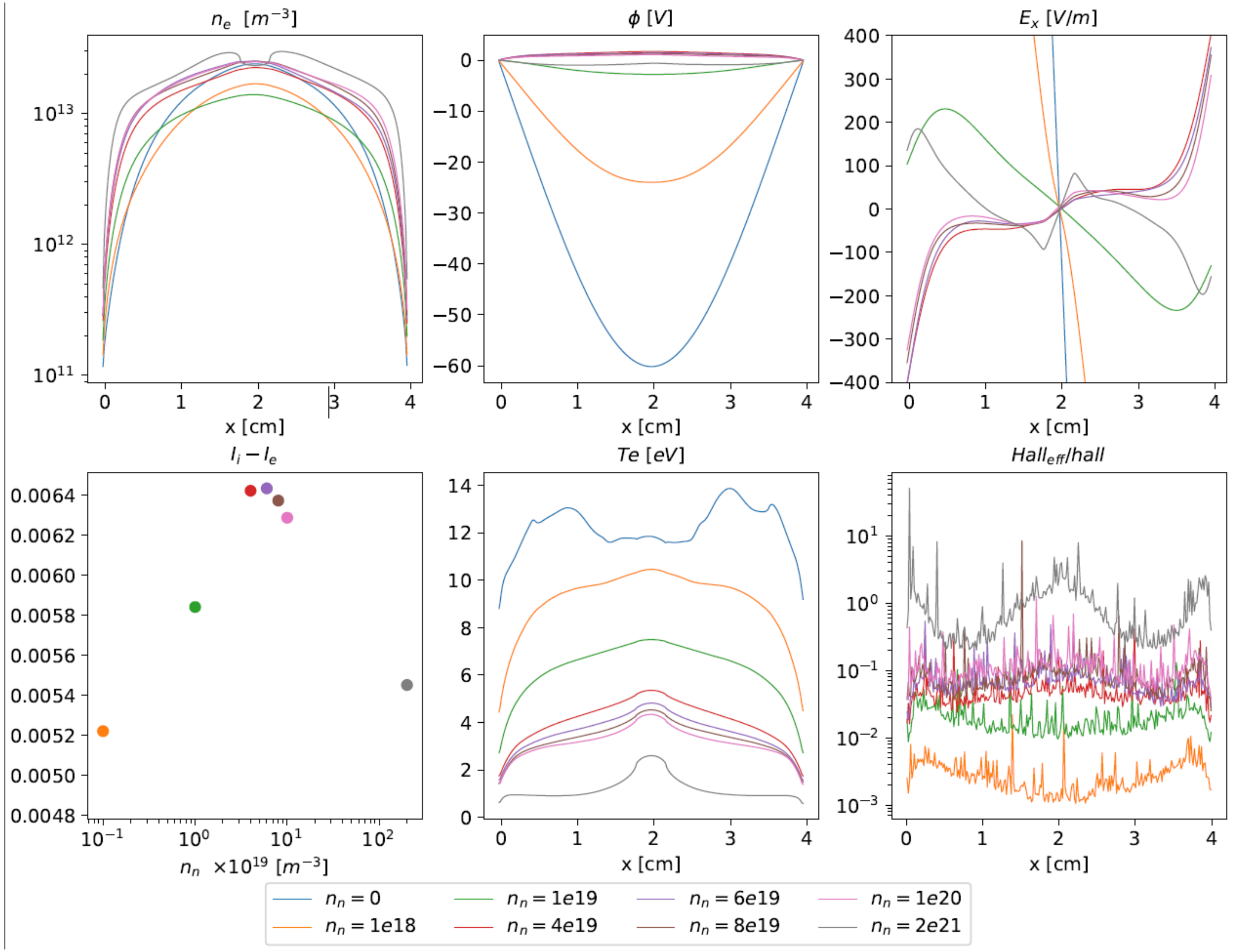
# Methodology – Azimuthal Instability

## Mode transitions

- Maximum in the wall current
- Change of plasma potential
- At high pressure collisional transport dominates
- Quasi neutrality at larger pressures

What happens at larger B?

What triggers the spoke transition?



# Extra Activities

## Completed research stay at Laplace laboratory, Toulouse

- Comparison of in-house 2D code with the one developed at Laplace
- Results presented at IEPC2024

## Upgrade of computational resources of EP2 with Matteo Guaita

- Definition of the cluster architecture, purchase and SLURM configuration
- Internal seminar on how to use the cluster and good practices

# Next Steps

- SFMC 2025 conference
- IEPC 2025 conference
- 2D code journal
- Conclusion of the PhD

# Conferences

- Space Propulsion Conference 2022, Estoril, Portugal - *D. Poli, E. Bello-Benítez, P. Fajardo, and E. Ahedo, Non stationary fluid modelling of plasma discharge in Hall thrusters* + best PhD paper award

- International Conference on Phenomena in Ionized Gases (ICPIG), 9-14 July 2023, Egomond Aan Zee, The Netherlands - *D. Poli, E. Bello-Benítez,L. Garrigues,  P. Fajardo, and E. Ahedo ,  Fluid vs kinetic simulation of the Penning discharge* .

- Internetional Electric Propulsion Conference (IEPC), 23-28 June 2024, Toulouse, France - *D. Poli,G. Hagelaar,  P. Fajardo, and E. Ahedo , Two-dimensional full fluid simulations of ExB plasmas*.

- Future participation in Spanish Fluid Mechanic Conference (SFMC), 24-27 June 2024, Málaga, Spain - *D. Poli, P. Fajardo, and E. Ahedo , Fluid Modelling of a Hall-effect Plasma Thruster*.

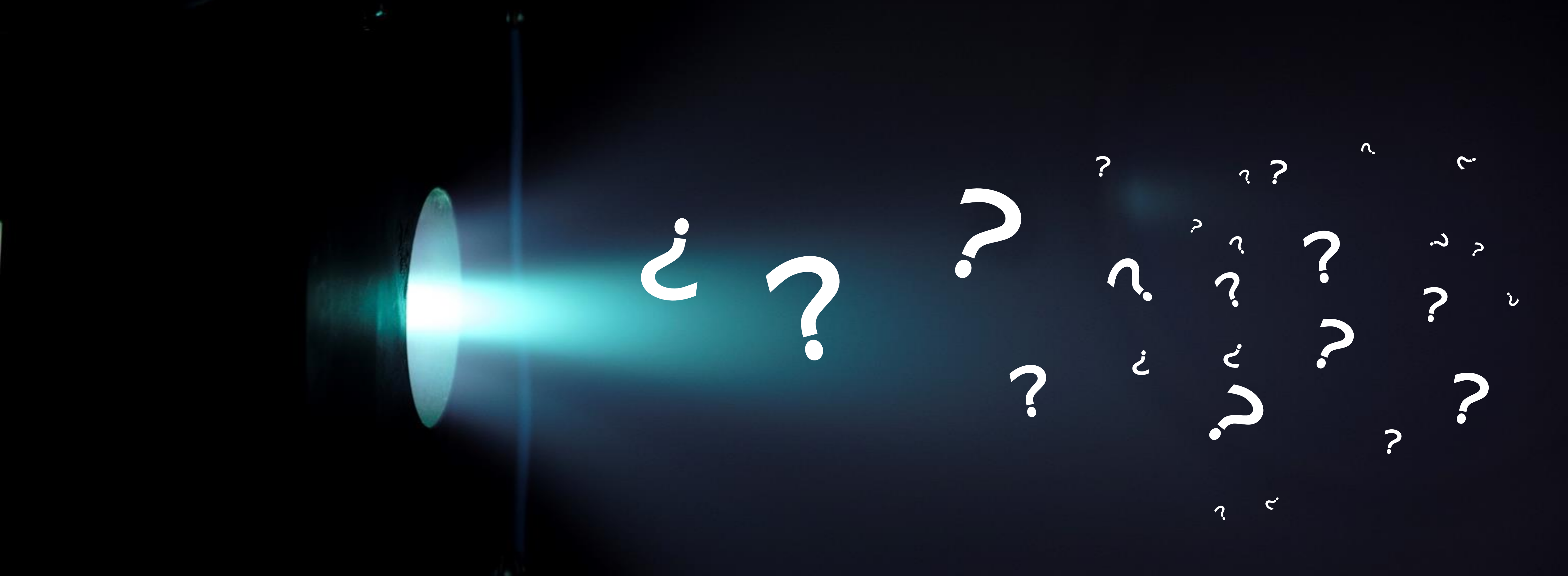
- Future participation Internetional Electric Propulsion Conference (IEPC), 14-19 September 2025, London, Uk - *D. Poli, and E. Ahedo , Towards Full-fluid Modelling of the Axial-azimuthal Hall Thruster Discharge*.

# Publications

- Published article to Journal of Physics D - *D. Poli, E. Bello-Benítez, P. Fajardo, and E. Ahedo,  Time-dependent axial fluid model of the Hall thruster discharge and its plume. 10.1088/1361-6463/ace2d0*

- Published article to PSST - *D. PoliP. Fajardo, and E. Ahedo, A Non-neutral 1D Fluid Model of Hall Thruster Discharges: full electron inertia and anode sheath reversal  10.1088/1361-6595/ad6500*

# Thank you! Questions?



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# Research Stay at Laplace, Toulouse

## NNC

### Physics

- Eqs. in conservative form
- Electron inertia
- Non-neutral effects

$$\nabla^2 \phi = \frac{e}{\epsilon_0}(n_e - n_i)$$

### Numerical

- FVM
- HLLC + 2° order MUSCL
- Strang splitting + SSP-RK3
- Structured mesh + MPI

## MAGNIS

### Physics

- Non conservative formulation
- Quasi drift-diffusion electrons
- Quasi-neutrality

$$\frac{\partial \mathbf{u}_i}{\partial t} + \mathbf{u}_i \cdot \nabla \mathbf{u}_i = \frac{e}{m_i}(\nabla\phi - \mathbf{u}_i \times \mathbf{B}) - \frac{\nabla p_i}{m_i n_i} - \frac{S_{pi}}{n_i}\mathbf{u}_i$$

$$0 = -\frac{e}{m_e}(\nabla\phi - \mathbf{u}_e \times \mathbf{B}) - \frac{\nabla p_e}{m_e n_e} - \left(\nu_e + \frac{S_{pe}}{n_e}\right)\mathbf{u}_e - \beta\frac{\partial \mathbf{u}_e}{\partial t}$$

$$\nabla \cdot (n_i \mathbf{u}_i - n_e \mathbf{u}_e) = 0$$

### Numerical

- FVM 2° order MUSCL
- Semi-implicit
- Predictor-corrector segregated
- Structured mesh

# Research Stay – Semi-periodic Plasma Layer

- Numerical diffusion changes dramatically the instability
- MAGNIS and NNC differences are not due to numerical diffusion
- Lack of electron inertia in MAGNIS could be crucial

IEPC 2024- *D. Poli, G. Hagelaar, P. Fajardo, and E. Ahedo, Two-dimensional full fluid simulations of ExB plasmas*.

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