Stability Analysis of magnetized plasma flows for space propulsion

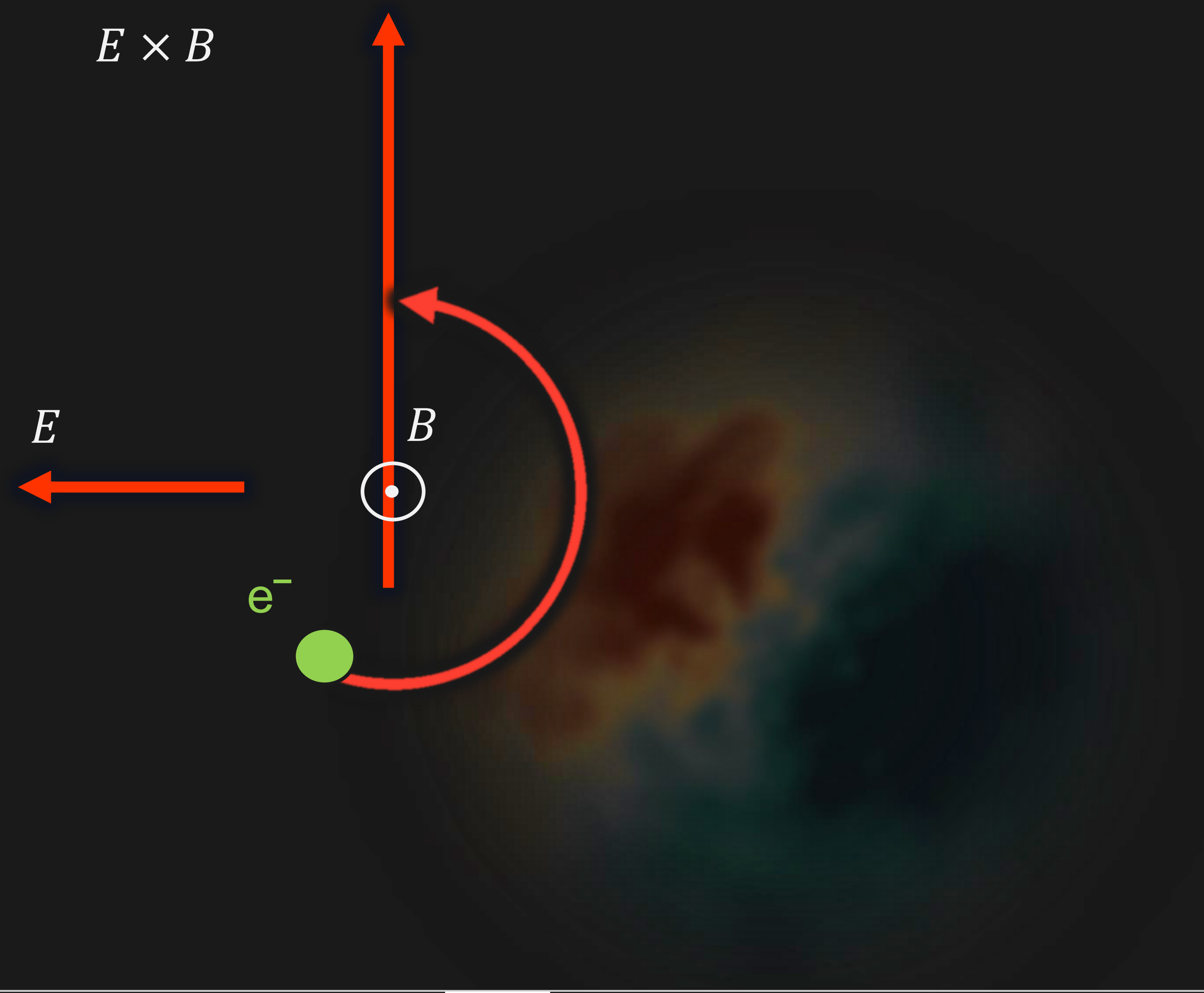
Matteo Ripoli
Supervisors: Mario Merino, Eduardo Ahedo

Doctoral Meetings 2026

Instabilities and turbulence in Plasmas

- Our thrusters behave as
  - Partially magnetized,
    - Magnetized e-
    - Inertial i+
  - ExB discharges

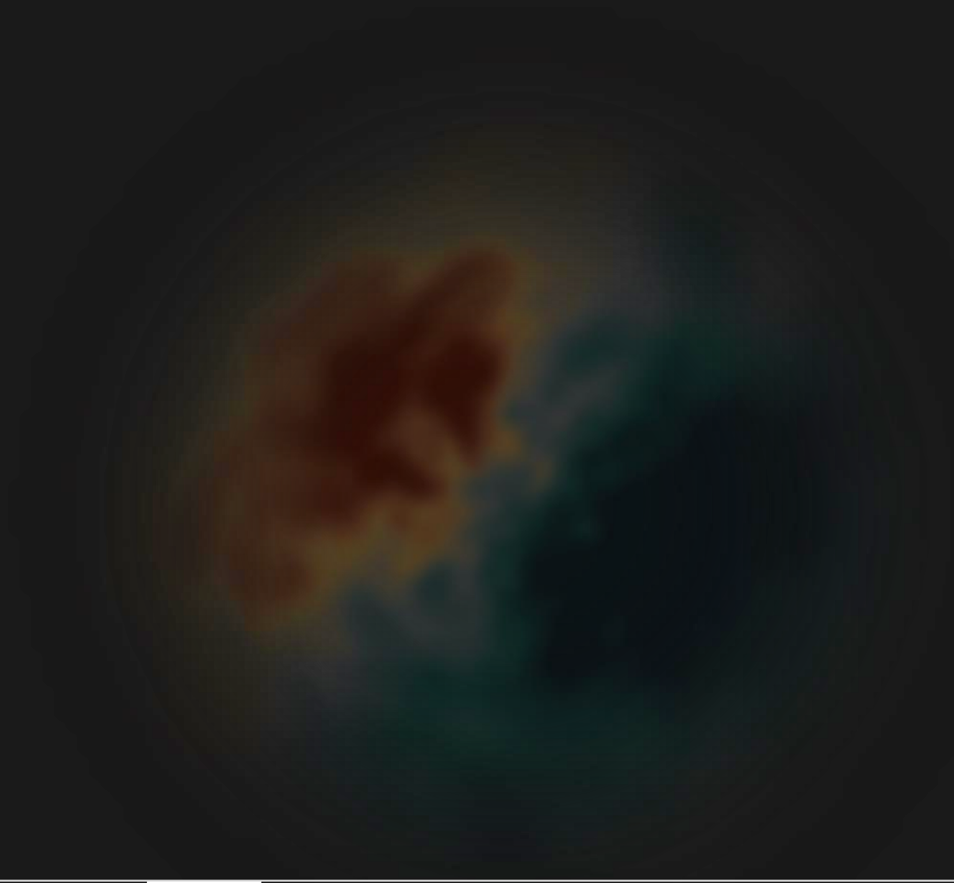
- Oscillations
  - Instabilities
    - Turbulence and cross-field transport



Instabilities and turbulence in Plasmas

- Linear and quasi-linear models
  - Instability triggering
  - “Weak” turbulence
    - Needs saturation criterion

- Non-linear models
  - Numerical in general
    - Many approaches
    - Particle-in-Cell (PIC)

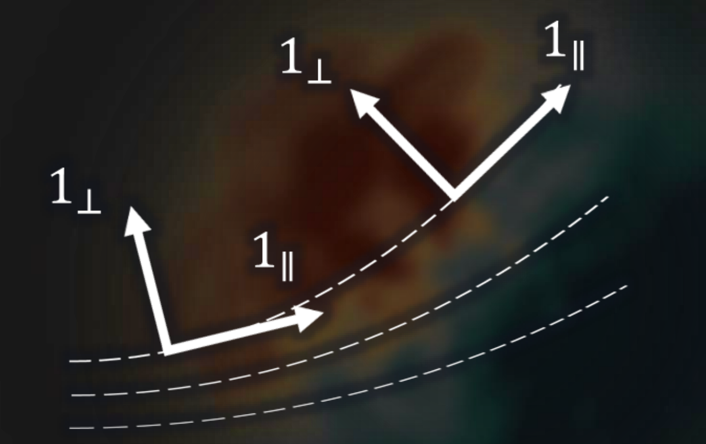


Fluid local linear analysis

- Small perturbations → linear approach
- Instabilities caused by interspecies drift
- Gradients cause drifts

M. Ripoli, E. Ahedo and M. Merino; **Drift-gradient instabilities in a plasma with 2D gradient effects: Application to a magnetic nozzle**. *Phys. Plasmas.* 2025

- We applied it to a magnetic nozzle
  - Added the effects due to 2D topology
  - New dispersion relation
  - Generalized classical instability criteria to more complex geometries

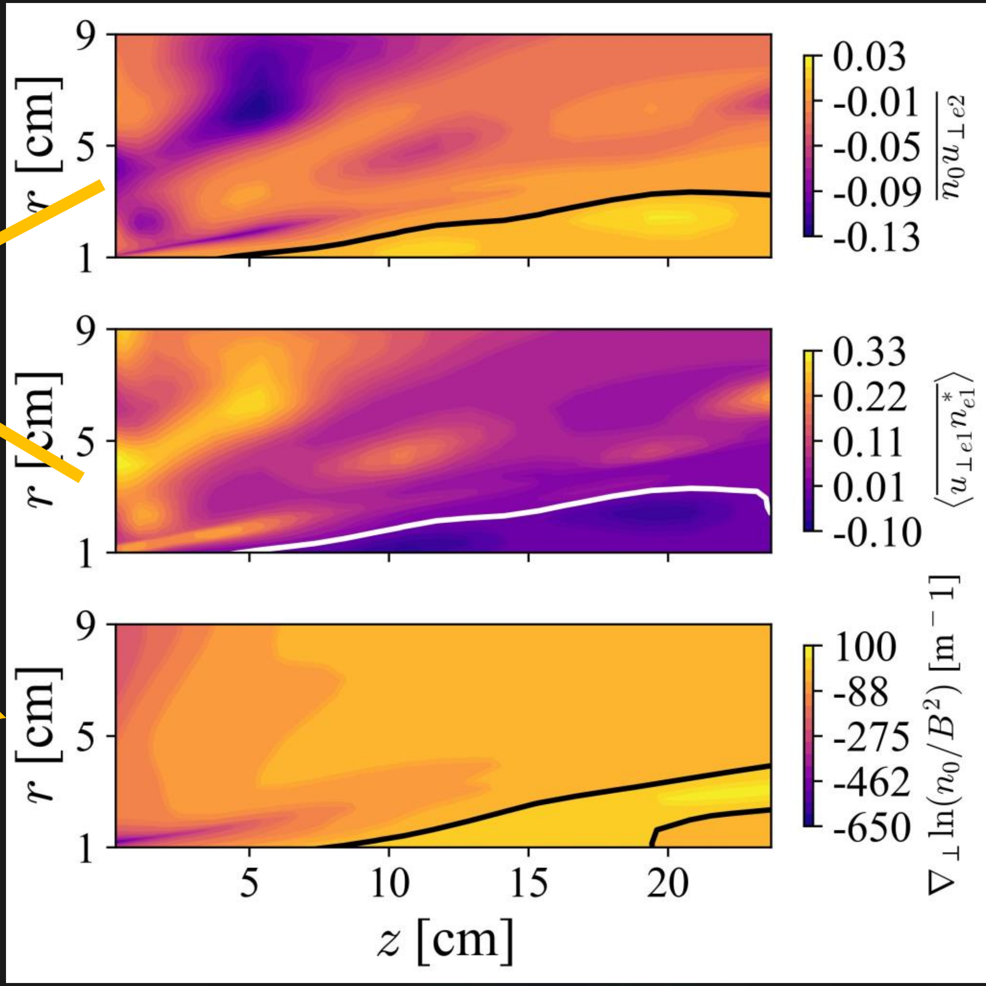


Fluid local quasi-linear analysis

- Small perturbations → weak turbulence
- Quasi-linear effect on equilibrium

- In a magnetic nozzle:
  - Outward electron flux
  - Goes against $\nabla \frac{n_0}{B^2}$

+

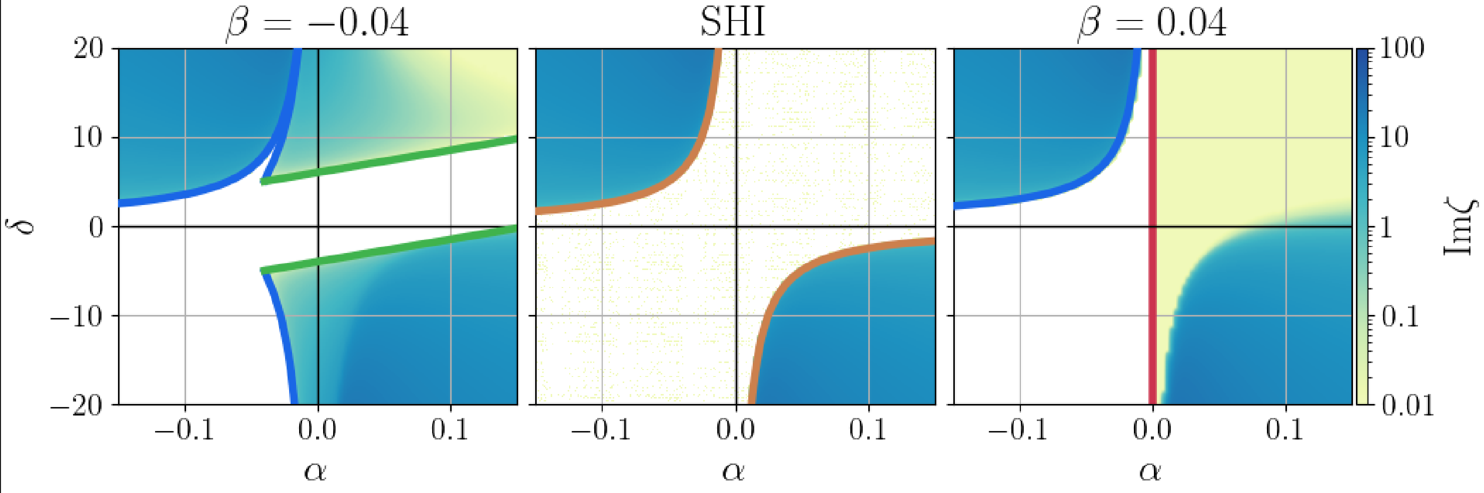


KINETIC LOCAL LINEAR ANALYSIS

- Kinetic approach → particle-wave interaction
- Resonances between waves and particle drifts

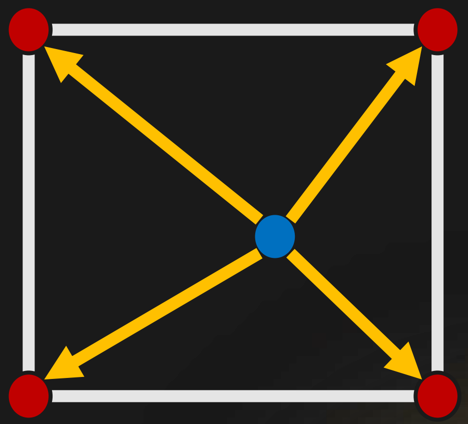
- Kinetic effects in long-wavelength regime
  - Magnetic drift resonance
  - Kinetic Electron Temperature Gradient (ETG) mode
  - Alternative to other short-wavelength models

J.J. Ramos, M. Ripoli, **Kinetic theory of drift-gradient modes in a partially magnetised $E \times B$ plasma**. *Journal of Plasma Physics*. 2026



PIC structure (2D example)

- Finite difference (FD) PIC
  - Particles weighted on a grid
  - Fields interpolated from grid
    - Introduces aliasing, finite-grid instabilities

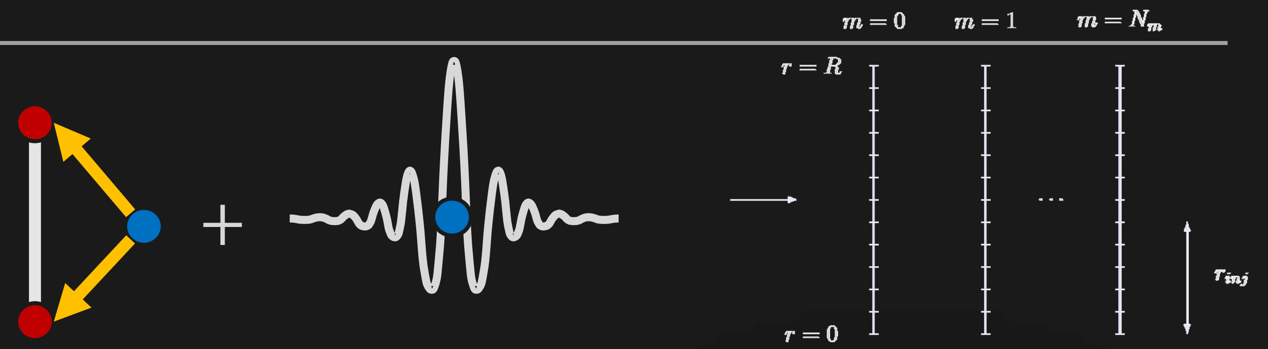


- Cylindrical geometry of discharges
  - Fields are periodic in θ
  - Particles can be weighted spectrally
  - Spectral fidelity (no aliasing)
  - **Particle-in-Fourier (PIF)**

$$n_s(r,\theta,t) = \Re\left[\sum_{m=0}^{N_m} n_s^m(r,t)\exp(im\theta)\right]$$

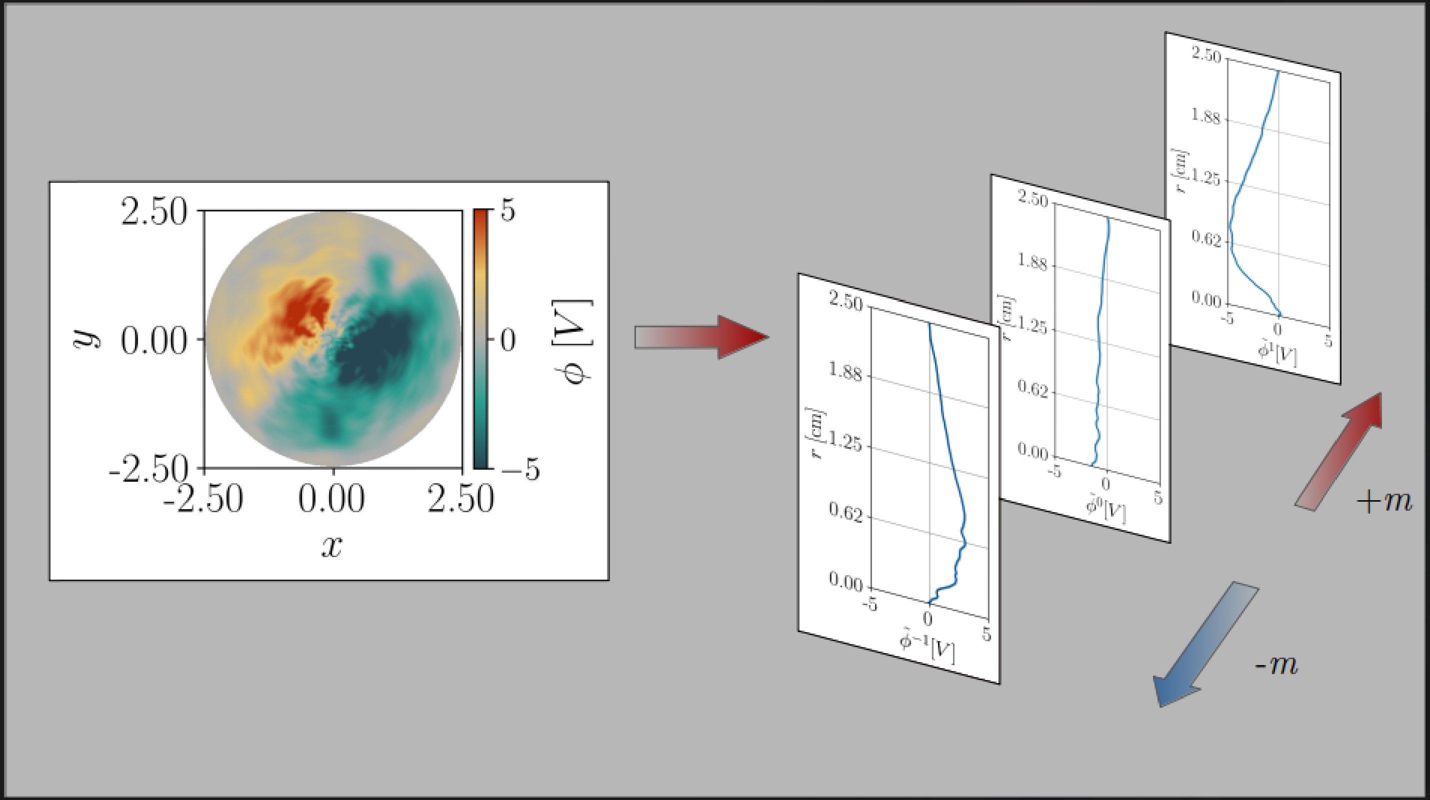
PIC+PIF

- FD in r + Fourier in θ
  - Physical grid only in 1D
  - Gridless azimuthally



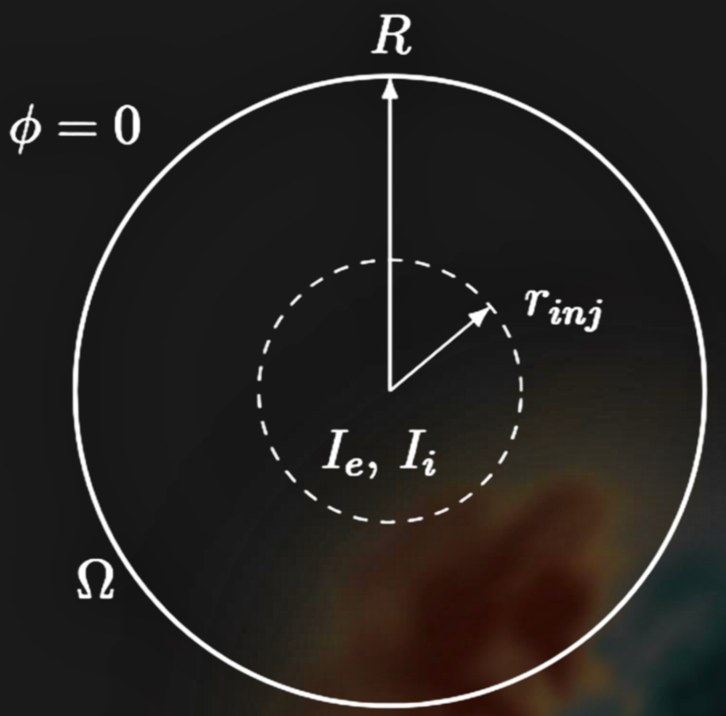
- 2D problem can be solved as multiple 1D problems
  - $\nabla^2\phi^m = \dfrac{\rho^m}{\varepsilon_0}$

- $\boldsymbol{E}$ intepolated in r and evaluated in θ



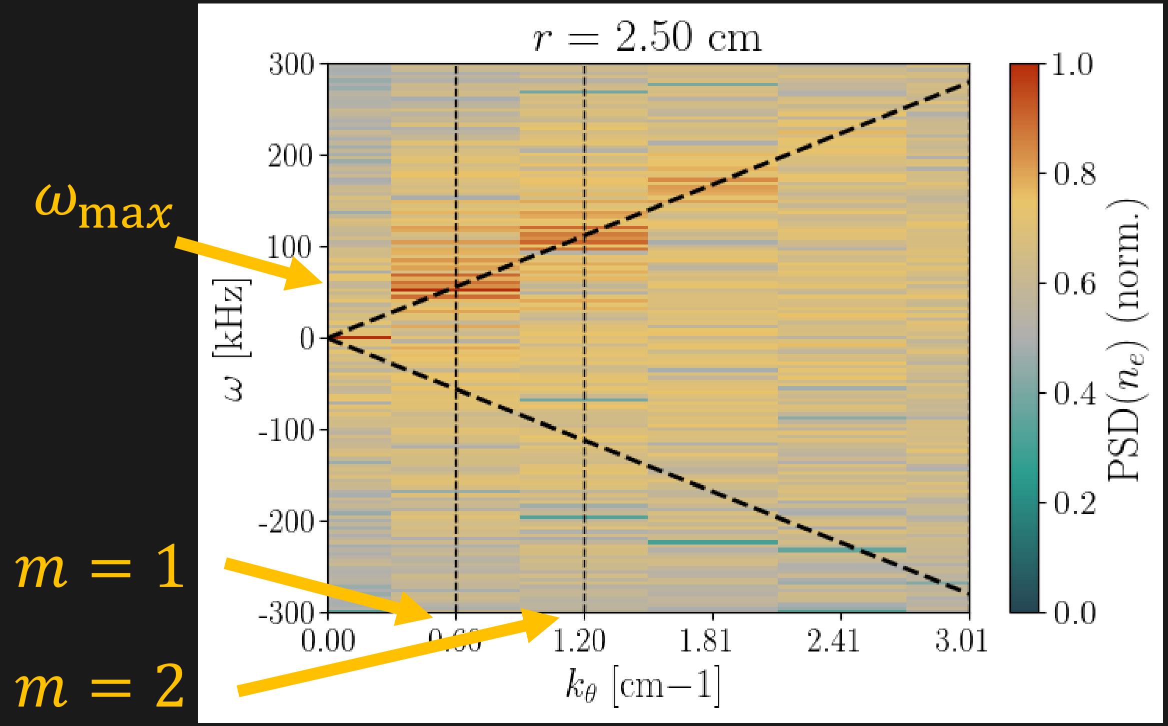
Application case: Penning discharge

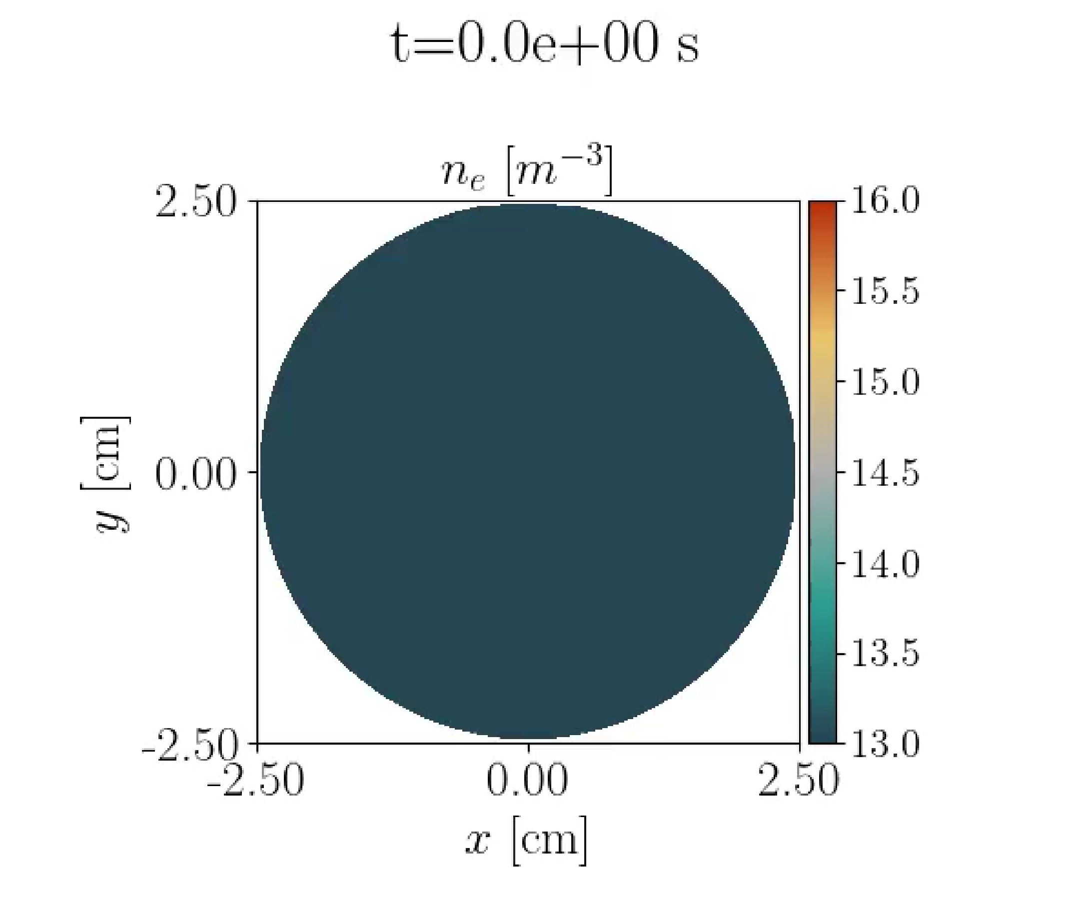
- Cylindrical Penning discharge
  - Non-neutral injection
    - $I_e > I_i$
  - Different BCs at each mode
    - $\left.\frac{\partial \phi^0}{\partial r}\right|_{r=0} = 0$ and $\phi^0|_{r=R} = 0$
    - $\phi^m|_{r=0,R} = 0$



Results: reference case

- Reference: $N_m = 10$
- Quasi-neutral discharge
- Dominance of $m = 1$



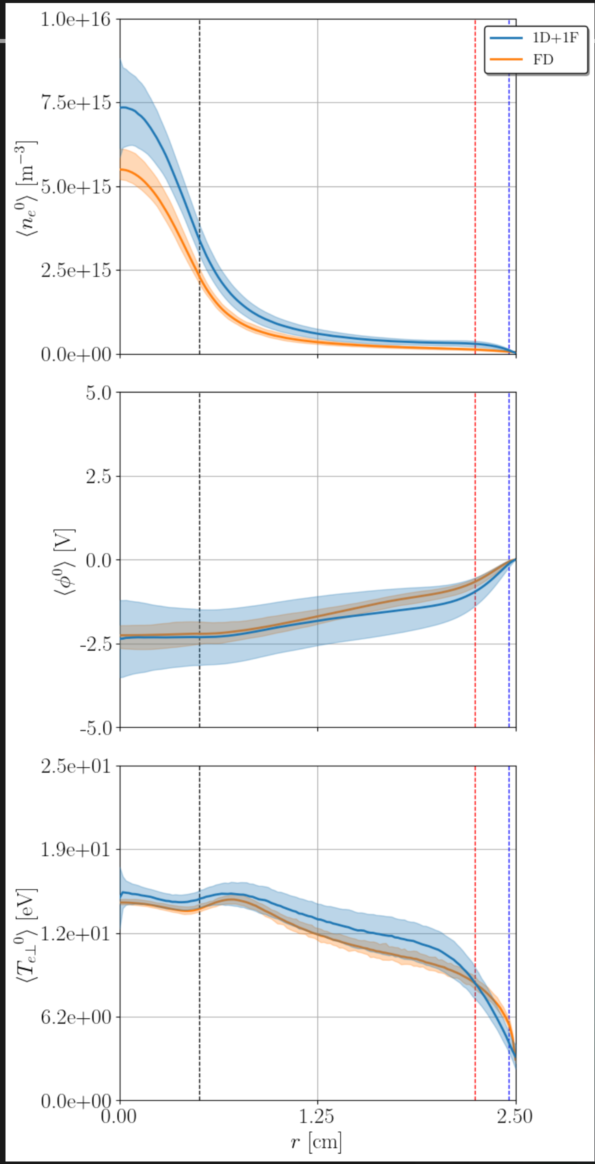


Results: comparison with Benchmark

- Reference: $N_m = 10$

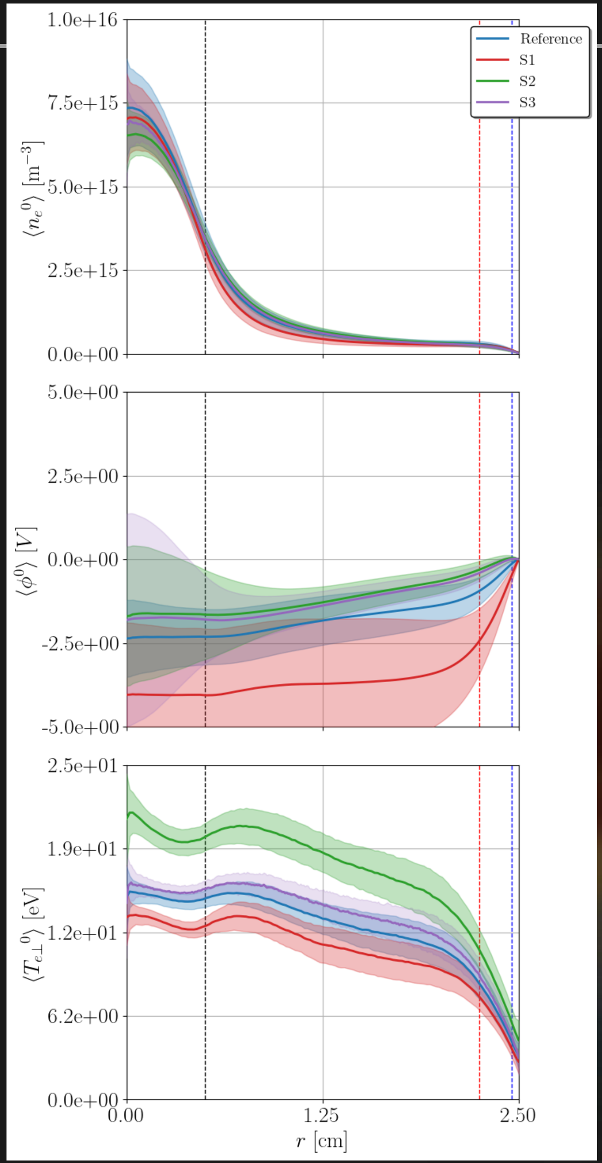
- Comparison with benchmark results (for $m = 0$)
  A.T. Powis et al.; **Benchmark for two-dimensional large scale coherent structures in partially magnetized E × B plasmas—community collaboration & lessons learned**.
  Plasma Sources Science and Technology. 2026

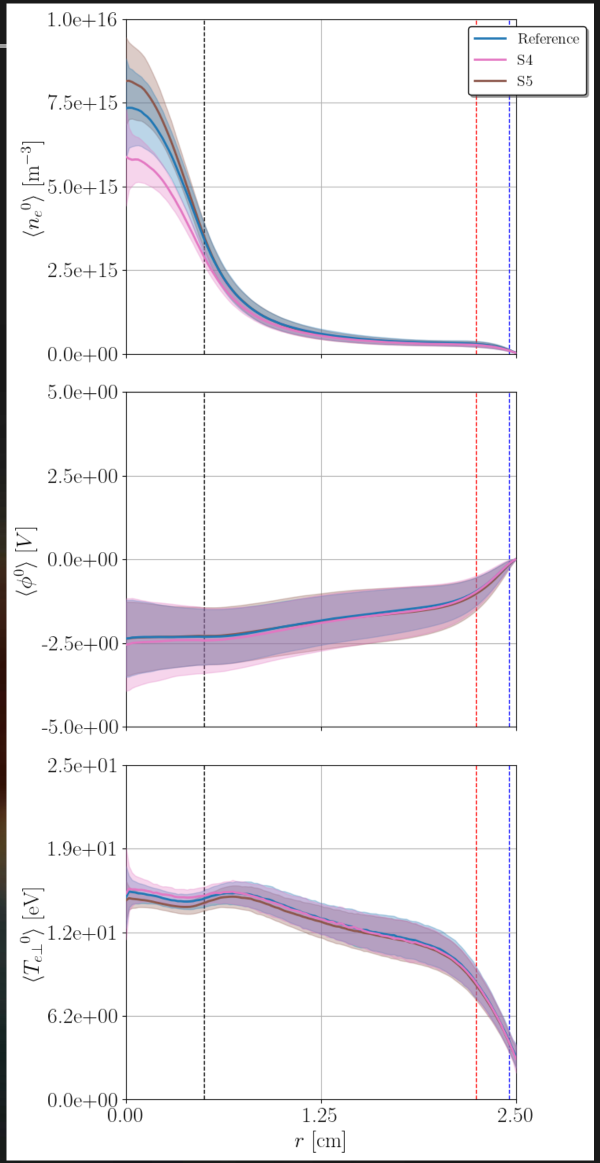
- Good match in ϕ and T_e
- Larger density peak
  - Differences in geometry, noise etc…



Results: varying N_m and weight

- Convergence analysis
  - Vary N_m to see how it affects axisymmetric profiles
    - Complex behaviour with N_m and coupled to other num. params.
  - Vary w_p to see how much the transport is affected by noise





Summary and What next

- PIC+PIF seems promising
  - Competitive runtimes (if N_m not excessive)
  - Easy to retrieve turbulence-sensitive data

Case	t^*_{wall}	Total macroparticles
Reference	4d 7h	$3.34 \cdot 10^5$
S1	5d 17h	$2.84 \cdot 10^5$
S2	7d 15h	$3.40 \cdot 10^5$
S4	1d 19h	$1.45 \cdot 10^5$
S5	8d 23h	$6.74 \cdot 10^5$
2D PICASO	16d 18h	$\simeq 10^7$

Runtimes on 15 Intel Xeon GOLD6542Y CPUs

- Unoptimized code
  - Spectral weighting may be performed more efficiently
  - Weighting over modes should be cheaper on GPU
  - Full characterization of the code convergence still pending work

- Next: application to 3D
  - Magnetic Nozzles → focus on macroturbulence
  - Huge memory saving (no need for 3D grid)

Publications, Conferences...

- Publications
  - M. Ripoli, E. Ahedo and M. Merino; **Drift-gradient instabilities in a plasma with 2D gradient effects: Application to a magnetic nozzle**. *Phys. Plasmas.* 2025
  - J.J. Ramos, M. Ripoli, **Kinetic theory of drift-gradient modes in a partially magnetised $E \times B$ plasma**. *Journal of Plasma Physics.* 2026

- Conferences
  - *Analysis of Drift Instabilities in Magnetic Nozzles*, 38° IEPC, Tolouse, France
  - *Analysis of drift-gradient instabilities and associated transport ina magnetic nozzle plasma*, 39° IEPC, London, UK
  - *Particle in Cell algorithm with azimuthal Fourier mode decomposition for the study of instabilities in cylindrical plasma sources*, SPC 2026, Bari, Italy (presented by Guillermo Cuerva-Lazaro)

- Dissemination
  - *Pintura Acustica: Convertir Imagenes en Musica*, Semana de la Ciencia 2024
  - *Cubo mini, misión grande : ¡monta tu satélite!*, Noche Europea de los Investigadores 2025

Acknowledgments

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 950466)

Additional support came fromthe R&D project PID2023-150052OB-I00 (ADAPT) funded by MICIU/AEI/ 10.13039/501100011033 and by ERDF, EU.

Thank you!

mripoli@ing.uc3m.es

Extra Slides