3D Particle-In-Cell study of the Electron Drift Instability in a E×B discharge

Willca Villafana ,CERFACS/PPPL
Bénédicte Cuenot, Olivier Vermorel, CERFACS

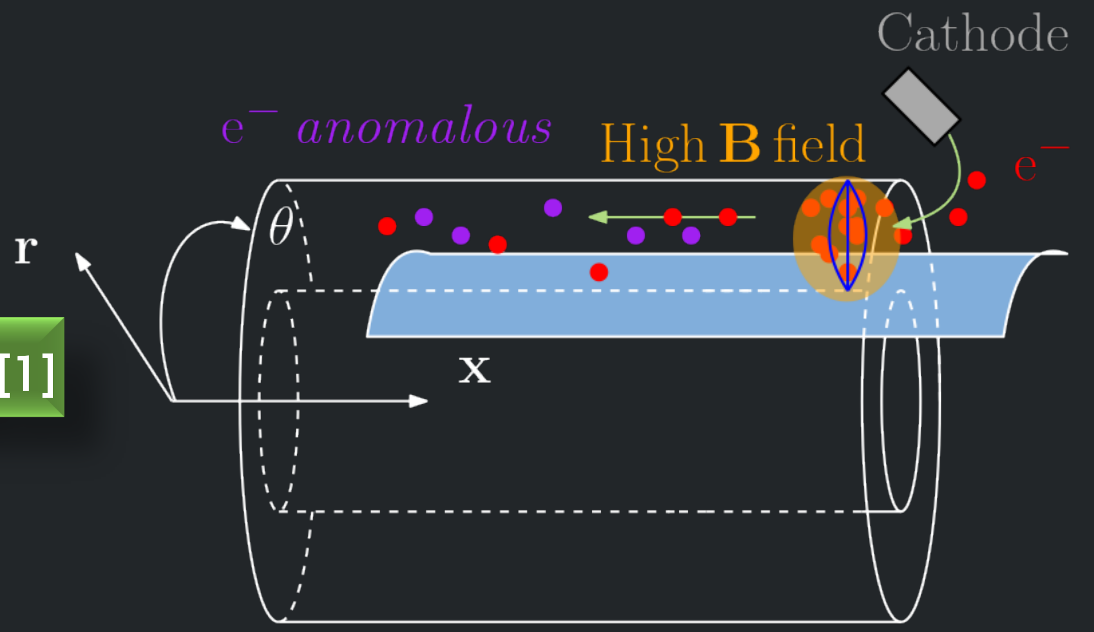
ExB Plasmas Workshop 2022
Madrid, online event

Motivation

Electron transport classically due to collisions

Actual measurements show a discrepancy with the theory [1]

Anomalous transport likely to be due to EDI [2,3,4]
via additional axial force $\mathbf{R}_{ei} = \langle\, \delta\, E_\theta\ \delta\, n_e\, \rangle_\theta \mathbf{x}$



- Numerous studies in
  - 1D θ: [2,5,6],
  - 2D $z - \theta$: [7,8]
  - and 2D $r - \theta$: [9,10]

[1]: Meezan et al.. (2001). Physical review. E. 63:026410
[2]: Lafleur et al. (2016a) Physics of Plasmas, 23(5):053502
[3]: Lafleur et al.(2016b). Physics of Plasmas, 23(5):053503.
[4]: Charoy, T. (2020). PhD thesis, Ecole Polytchnique.
[5]: Janhunen, S. (2018). Physics of Plasma, 25(1):011608
[6]: Smolyakov, A. et al. (2020). Plasma Physics Reports. 46:496-505
[7]: Adam et al. (2004). Physics of Plasma. 11(1):295-305
[8]: Coche et al. (2014). Physics of Plasma. 21(2):023503
[9]: Héron et al. (2014). Physics of Plasma. 20(8):082313
[10]: Croes et al. (2014). Plasma Sources Science and Technolgoy. 26(3):034001

Motivation

2D setups artificially prescribed the inherent 3D physics of HTs [1]

3D simulations are required for a more accurate physics.

What can we do ?

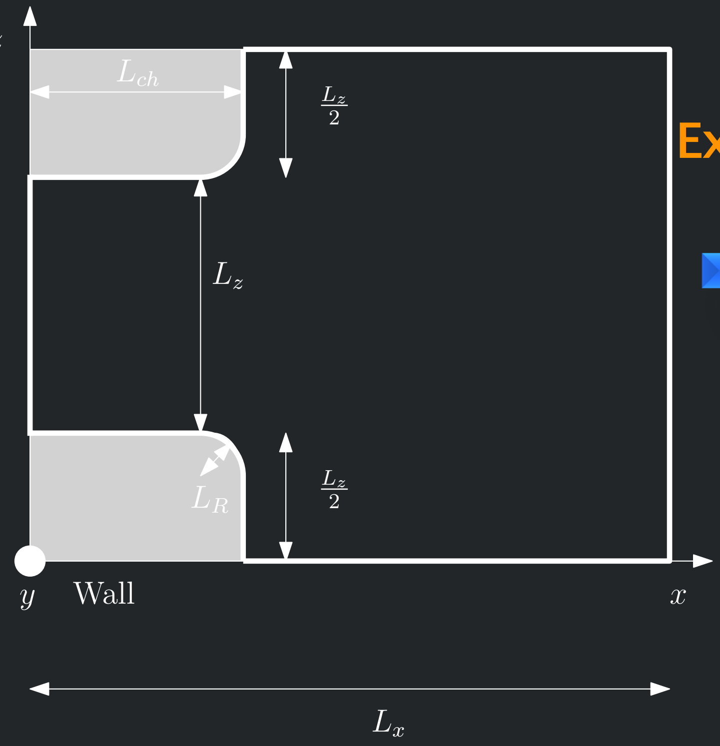
- Very scarce attempts of 3D configurations in literature because of computational cost
  - Reduced ion to electron mass ratio m_i/m_e, increase of vacuum permittivity ϵ_0 [2]
  - Miniaturized geometries [3,4]

AVIP PIC: 3D configuration without these assumptions and with an unstructured grid

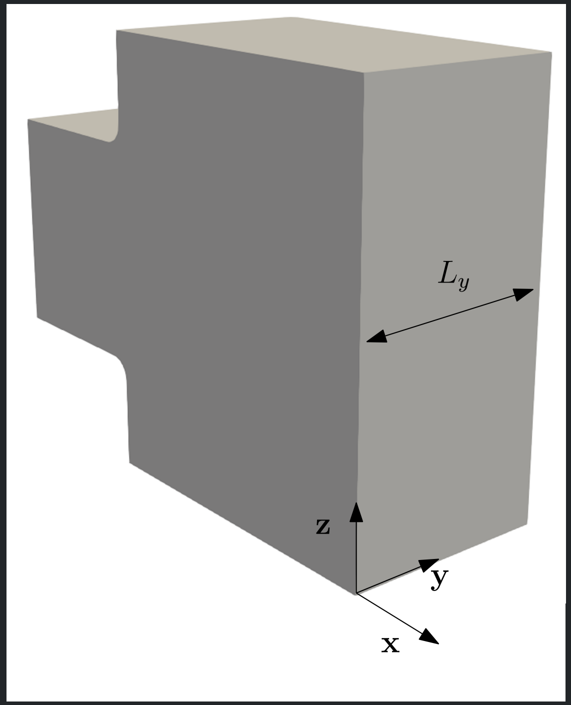
[1] Tsikata, S. (2010). Physics of Plasmas, 17(11):112110
[2] Hirakawa, et al. (1995). In Proceedings of the 24th International Electric Propulsion Conference
[3] Minelli, P. and Taccogna, F. (2017). IEEE Transactions on plasma science, 46(2):219-224
[4] Taccogna, F. and Minelli, P. (2018). Physics of Plasmas, 25(6):061208

Numerical setup

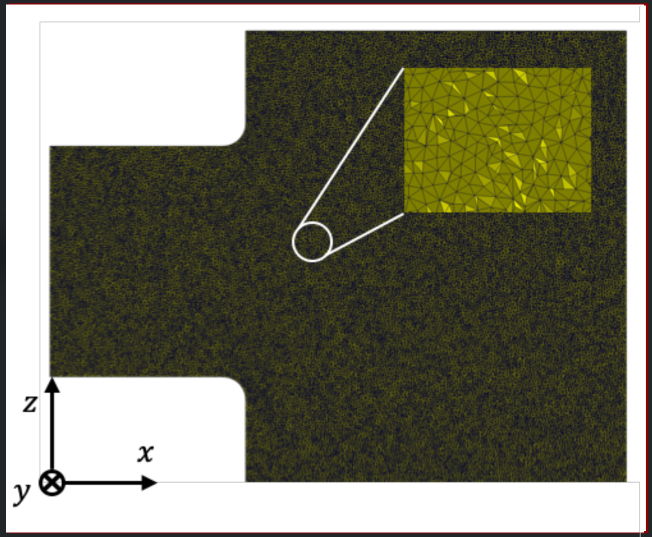
➢ Use CAD to define simulation domain



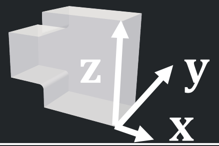
Extrusion in y direction



Meshing



Tetrahedral cells



Numerical setup

- Use same framework as in 2D benchmarks[1,2]
  - ➢ No curvature effects / Similar BCs
  - ➢ Collisionless case
  - ➢ Imposed ionization profile $S_i(x,z)$
  - ➢ Similar radial magnetic field $\mathbf{B}_z(x)$

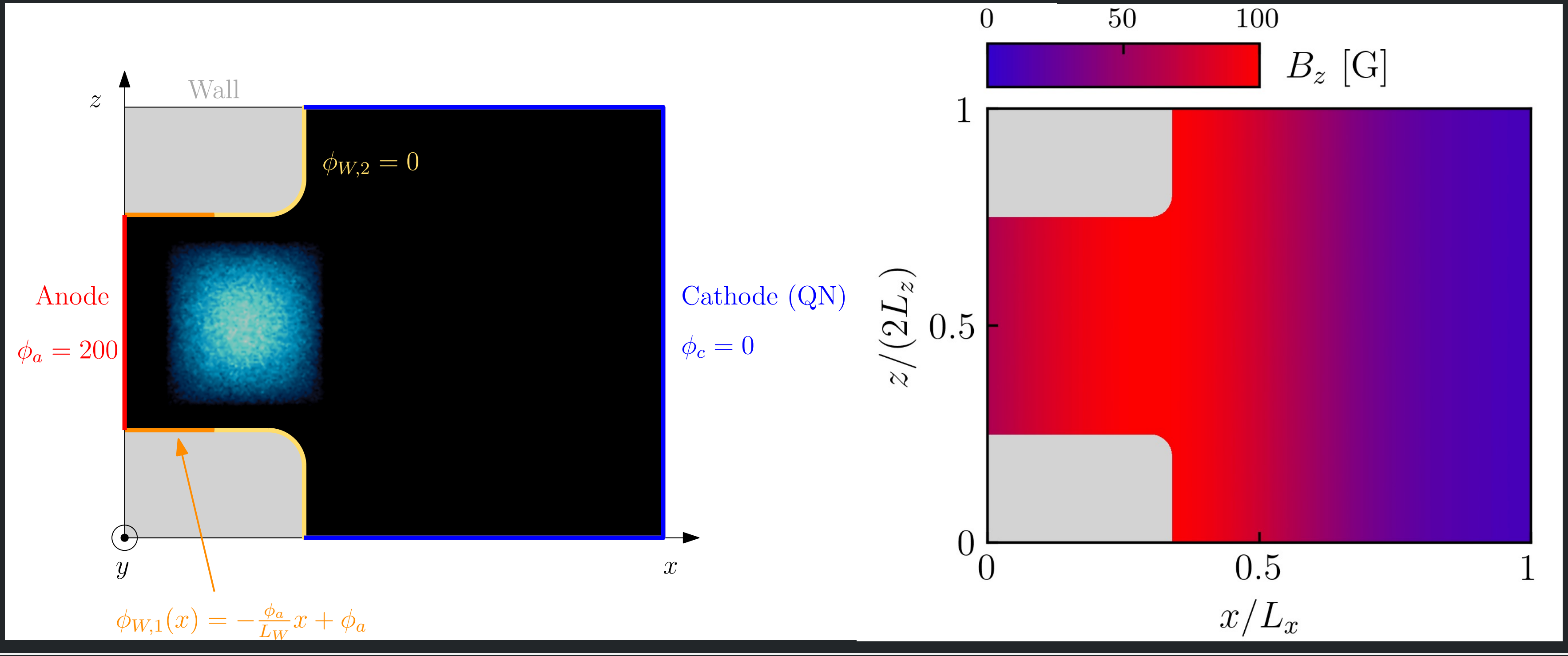
Run parameters

13.6×10^6 cells $\quad L_x\times L_y\times L_z = 2.5\times1.28\times1\mathrm{cm}^3$

$\overline{\Delta l} = \overline{V_{cell}^{1/3}} = 67\mu\mathrm{m} \quad n_{X_e^+,0} = n_{e,0} = 10^{17}\ \mathrm{m}^{-3}$

$\Delta t = 5\mathrm{ps} \quad t_{total} = 10\mu s$

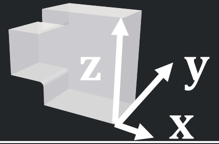
[1] Charoy, T. et al (2019). PSST, 28(10), 105010
[2] Villafana, W. et al (2021). PSST, 30(7), 075002



2000 CPUs

40 days of continuous run

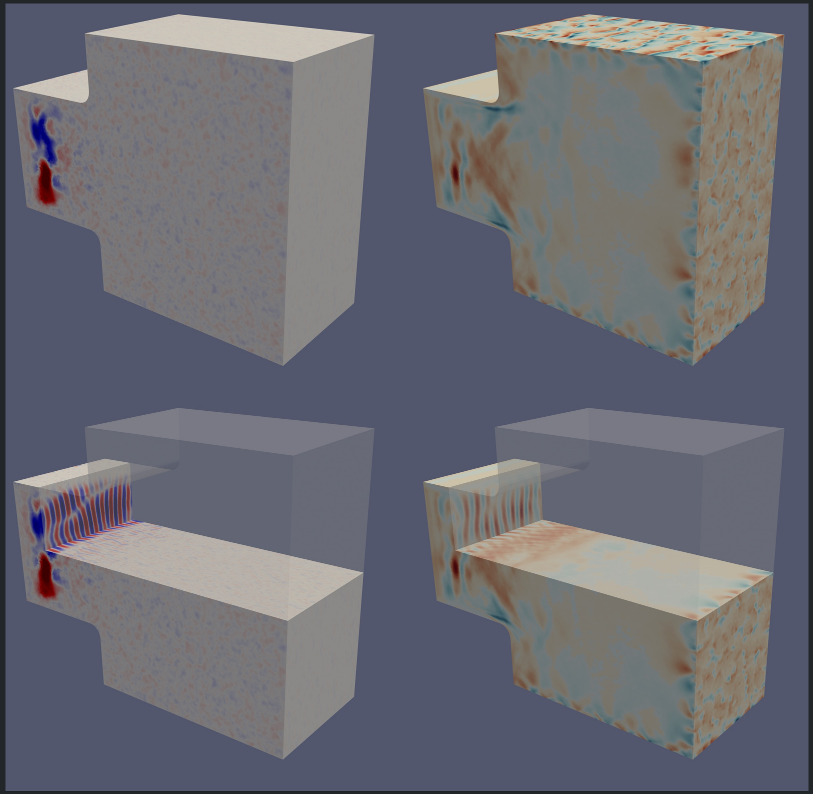
3.5 billion particles



Results: timeline

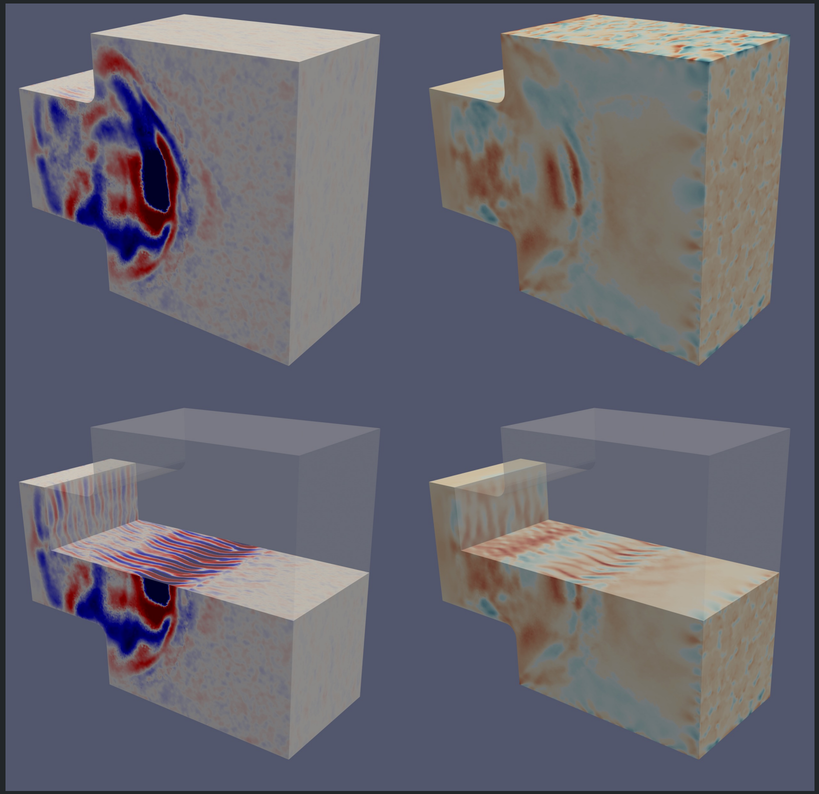
- EDI grows near anode

$t = 0.20\mu s$



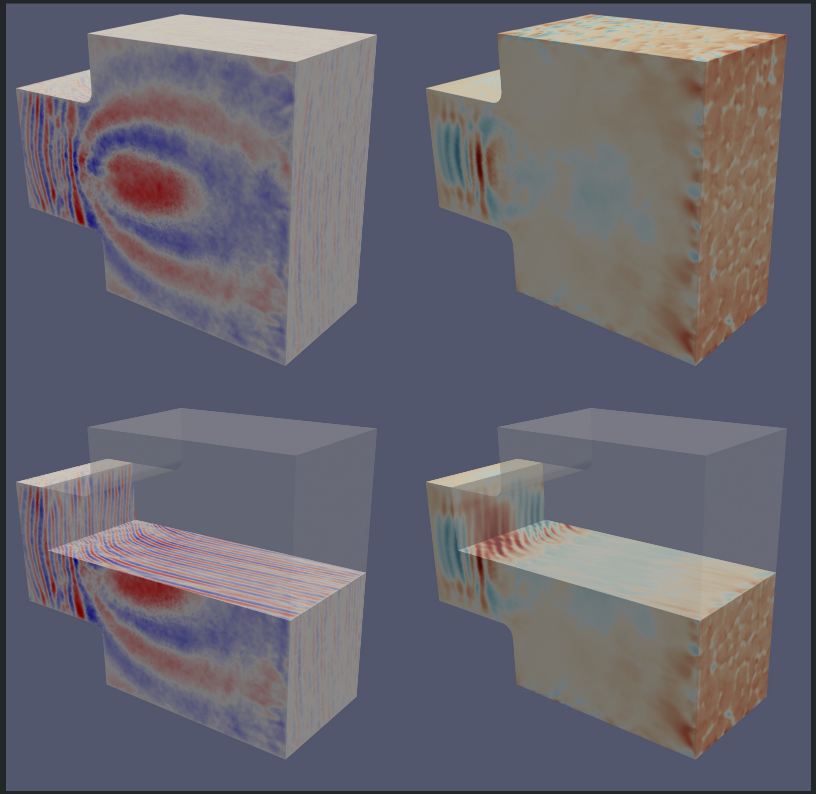
- EDI propagates downstream

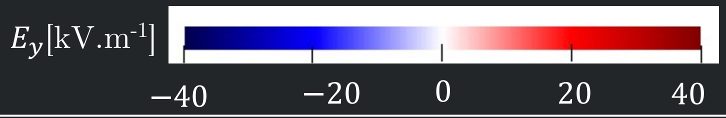
$t = 0.90\mu s$

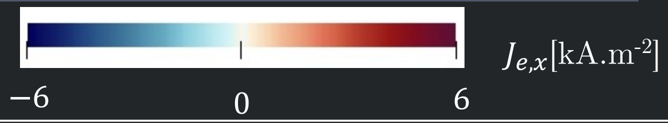


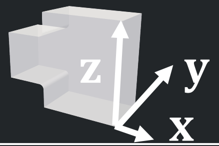
- EDI in 3D and signature of MTSI?

$t = 5\mu s$



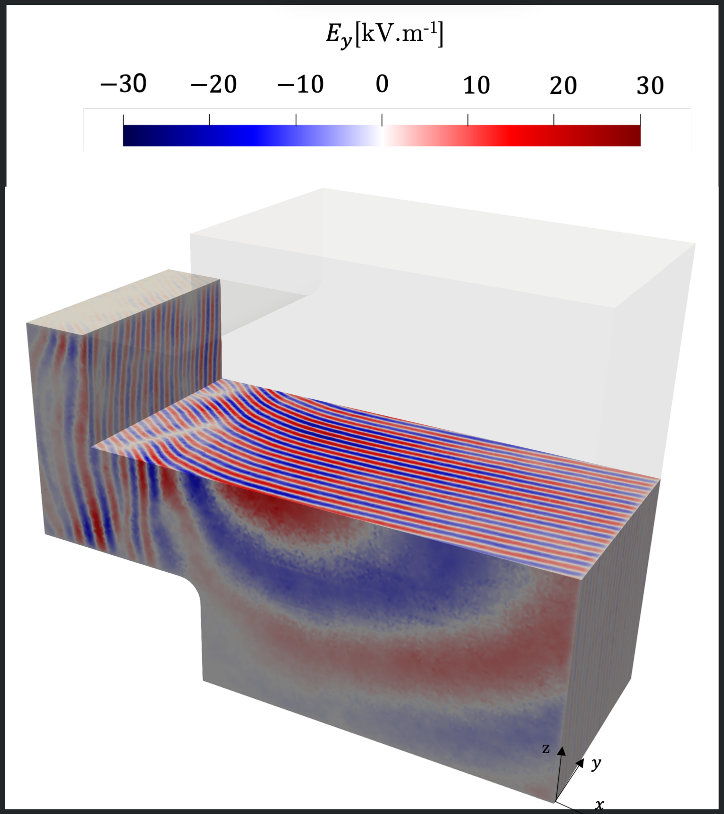






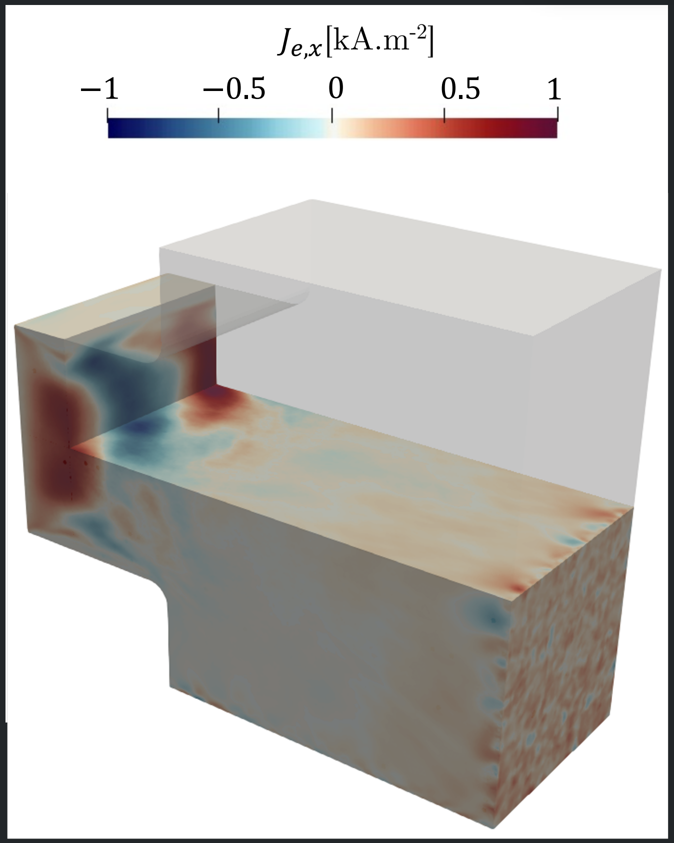
Results: mode reconstruction via DMD

ECDI

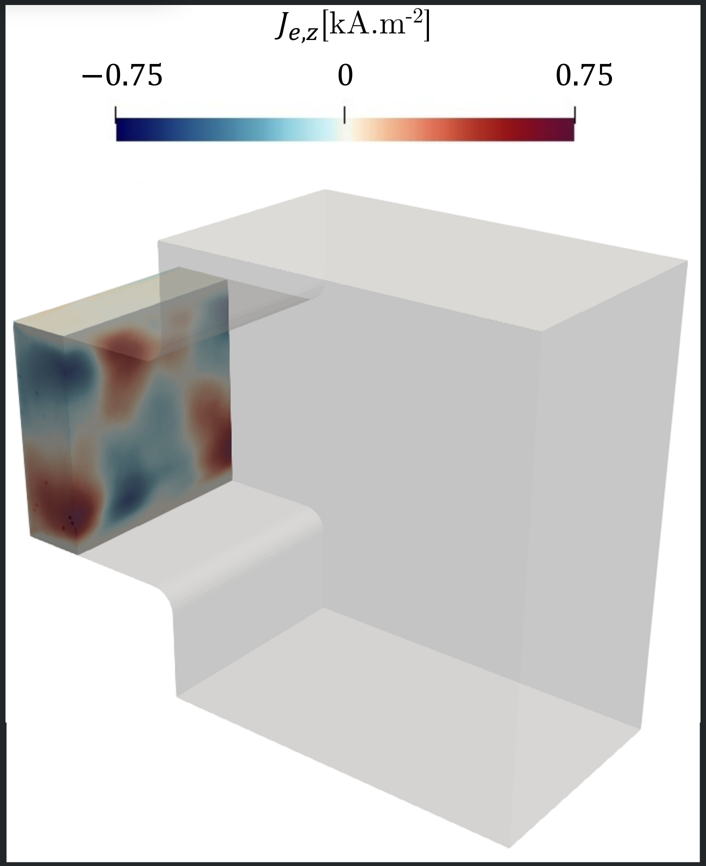


- Mainly driven by k_x, k_y in channel
- Mainly driven by k_x, k_z in the plume

Signature of MTSI?



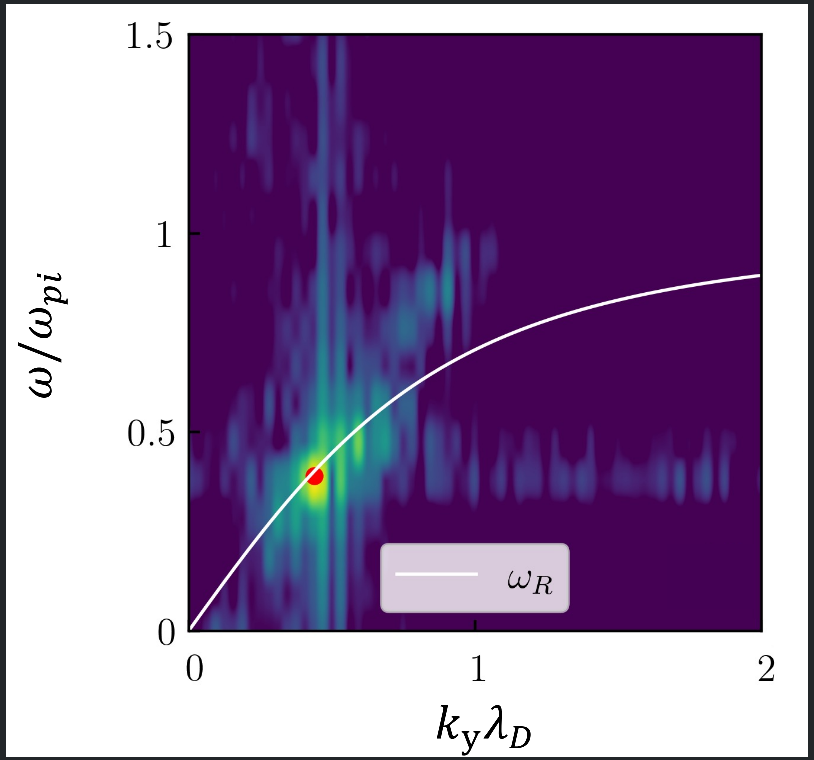
- Long azimuthal wavelength

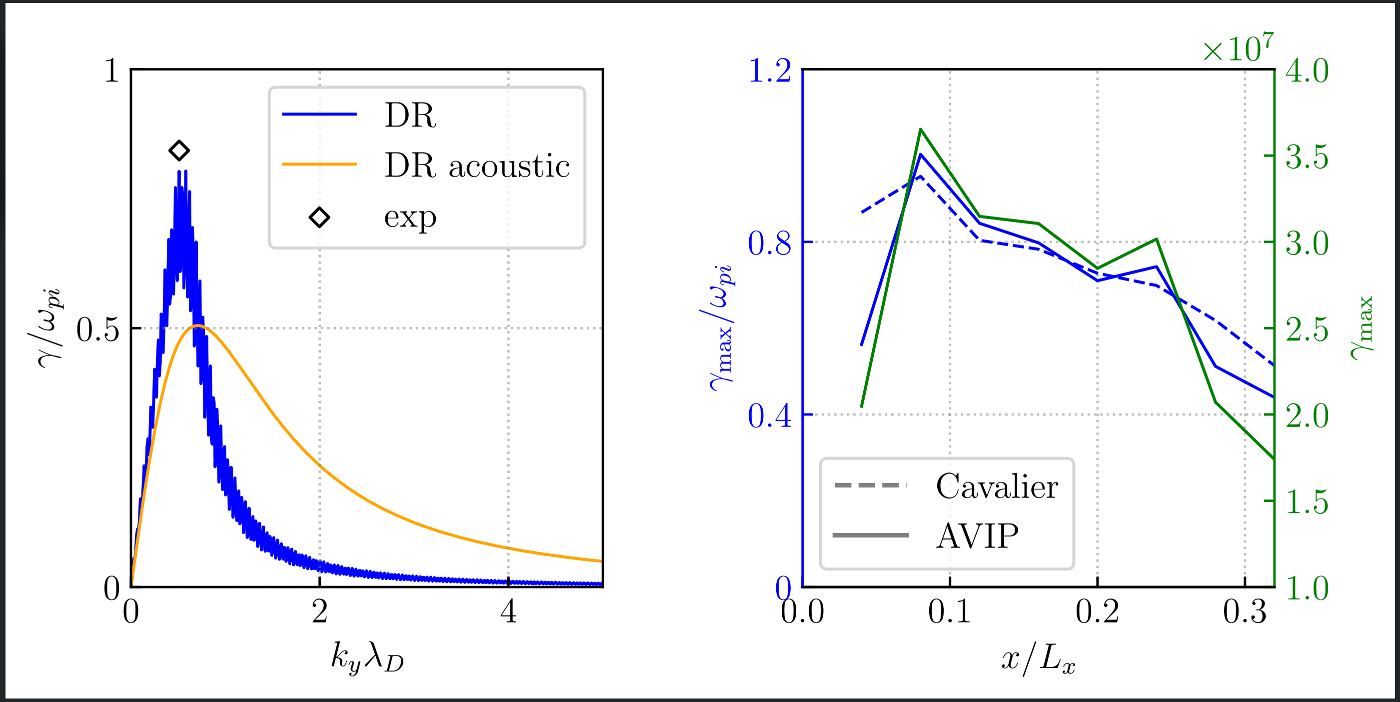


- Also a radial pattern

EDI theoretical analysis

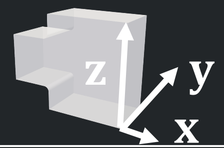
✅ **During transient, main E_y mode corresponds to ECDI expected growth rate γ [1]**





✅ **At steady state, the ECDI has transitioned to an ion acoustic wave[2]**

[1] Cavalier, et al., Physics of Plasmas, 20(8):082107. (2013)
[2]: Lafleur et al.(2016b). Physics of Plasmas, 23(5):053503

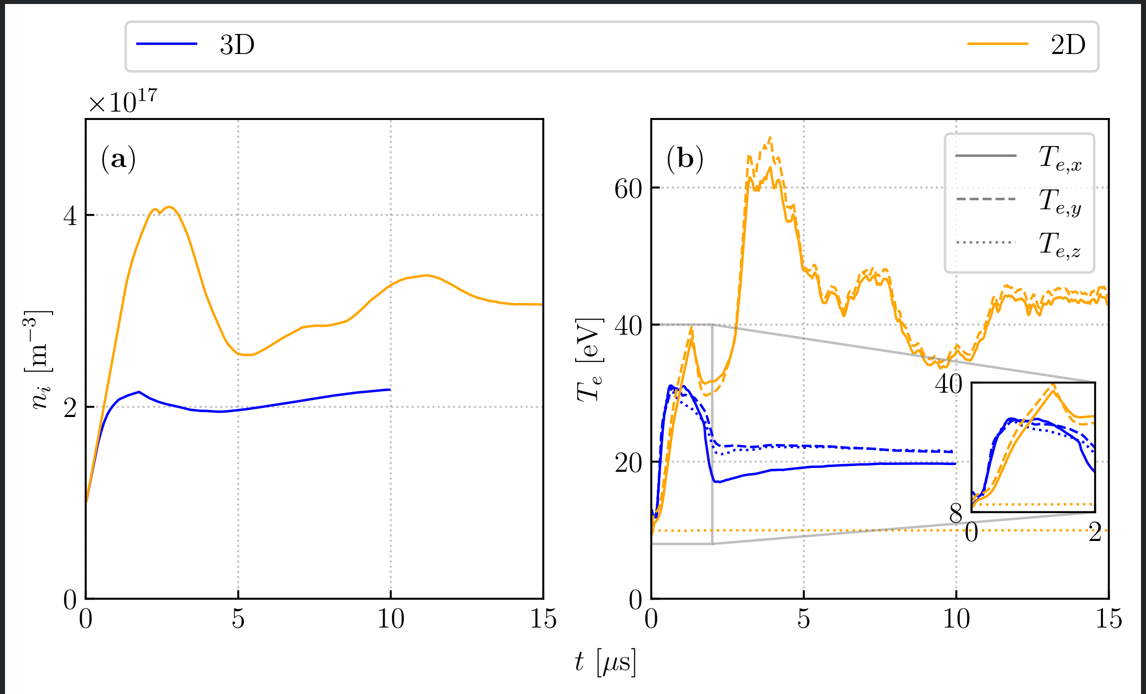


EDI theoretical analysis

- Comparison with pure 2D case axial–azimuthal

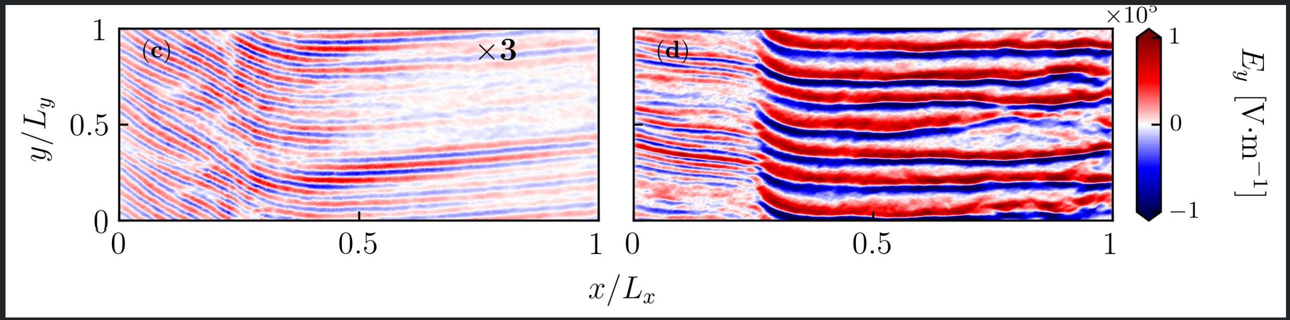
ECDI saturates at a higher energy level in 2D

1. Pure 2D has a hotter and denser plasma



3D

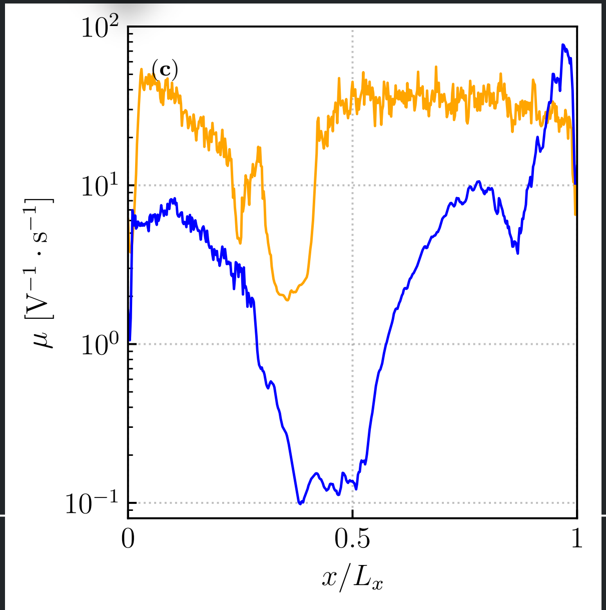
2D



Lower losses

Higher azimuthal amplitudes

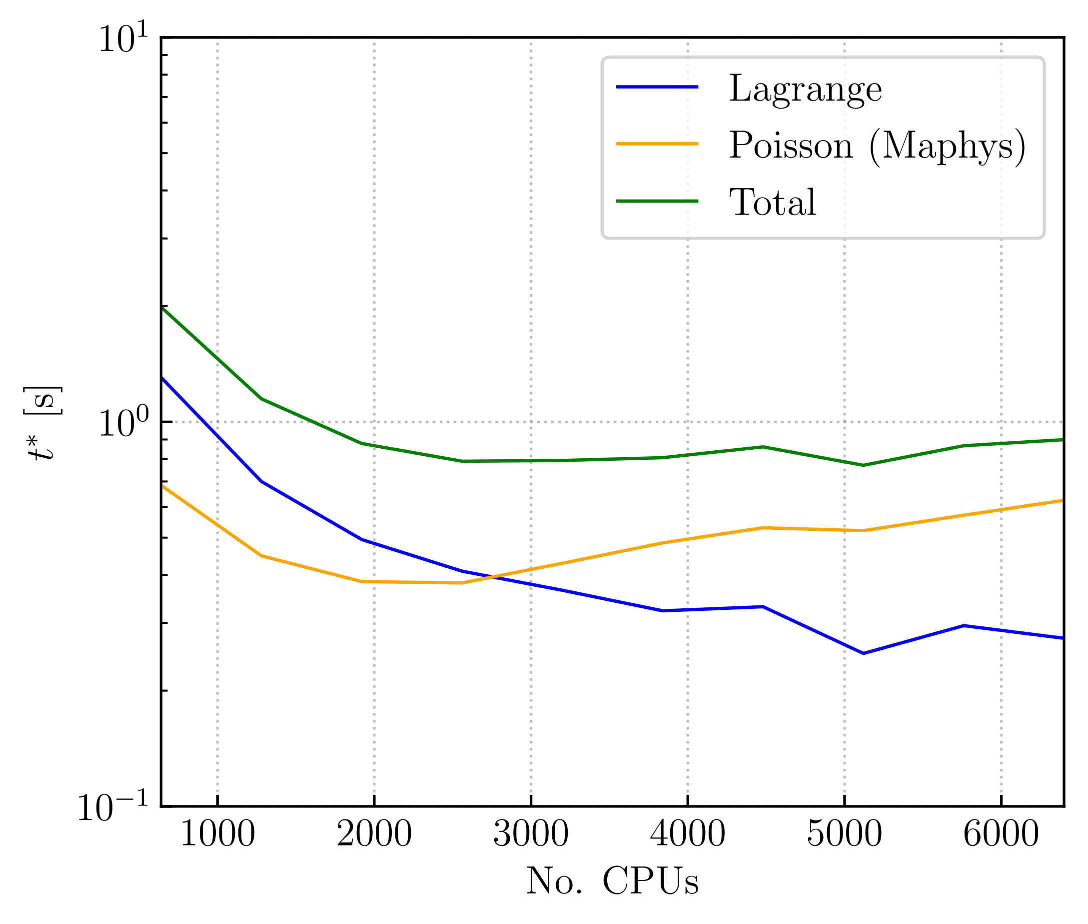
$\langle \delta E_\theta \, \delta n_e \rangle_\theta$



Lower axial mobility in 3D

What's the cost?

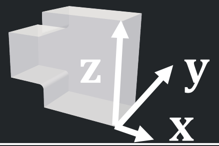
- MPI Domain decomposition over ~2.26 million nodes for 3.5 billion particles



Good strong scalability for Lagrangian kernel

Poisson solver remains limiting factor

1–1.5 months of simulation for 1.4M CPUh



Conclusion

- Summary

  ✓ The 3D structure of the EDI was successfully identified using an unstructured framework based on domain decomposition

  ➔ Poisson solver remains the limiting factor for 3D PIC calculations

  ✓ The anomalous mobility is lower in 3D than in 2D and is affected by the possible signature of the MTSI

- Ongoing work

  ⚙️ Ongoing advanced study with LAPLACE laboratory on similar 3D setup

Acknowledgments

- This work used the HPC resources of IDRIS/TGCC/CINES under the allocation A0102A06074 made by GENCI
- We acknowledge financial support from a Safran Aircraft Engines within the project POSEIDON (ANR-16-CHIN-003- 01)