Modeling of Electron Cyclotron Drift Instability in ExB devices: issues and problems

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Motivation

- Electron Cyclotron Drift Instability– a robust kinetic instability driven by strong ExB drift (no density/magnetic field, etc gradients, nor collisions.. are required to trigger, but may be affected by all above)
- Has been well demonstrated in 1D (azimuthal) and 2D (azimuthal-axial, azimuthal-radial) simulations, 3D is not conclusive…
- Experimental evidences of small scale fluctuations
- Where we are now?
  - **Relatively easy to obtain in numerical codes, many groups…**
  - **Conversion of simulation results into practical predictions is difficult and lagging**
  - **Coordinated efforts are required: codes testing and benchmarking; suite of test cases, codes verification metrics, codes validation (agreement with experiment) metrics**
  - **Experimental diagnostics and data**

ECDI in ExB discharges, Hall thrusters and magnetron applications

- PIC simulations theory: Adam, Heron 2004, 2006,…, 2013; Ducroq 2006
- Tsikata- 2009, 2011, 2015…Collective light scattering measurements? Tsikata 2015 -Magnetron
- Cavalier 2013 (linear theory)
- Lafleur 2016 - PIC, Lafleur-theory of anomalous transport
- Katz, Mikellides 2015 –theory applied to HT
- Lafleur 2017, Croes 2017 – R-θ PIC simulations, theory
- Boeuf 2013, 2015, 2017 –review in J Appl Phys

Synopsis of ECDI status. I

Experiments:

Most of the measurements (Tsikata) are outside of the channel –ion sound dispersion

$$\omega = k_y c_S \quad c_S = \sqrt{T_e / m_i} \qquad \lambda = 2\pi / k = 0.3 - 1.5 \text{ mm}$$

Probe measurements: Brown, Z. and B.A. Jorns, *Spatial Evolution of Plasma Waves in the Near-field of a Magnetically Shielded Hall Thruster*, in *2018 Joint Propulsion Conference*. 2018,
Discreet set of cyclotron resonances , wavelength <2.5 cm

$$k_y V_E = m\omega_{ce}, \text{ m=1,2,3,...}$$

Downstream region >2.5 cm (to 12cm): linear ion-sound like dispersion, few cm wavelengths

Synopsis of ECDI status. II

Modeling:

Semi-empirical models of anomalous mobility based on the spatial-time dependent evolution of anomalous resistivity; quasilinear/non-magnetized plasma assumption

Mikellides, I.G., et al., *Hall2De Simulations with a First-principles Electron Transport Model Based on the Electron Cyclotron Drift Instability*, in *52nd AIAA/SAE/ASEE Joint Propulsion Conference*. 2016,

Lopez Ortega, A., I. Katz, and V.H. Chaplin, *Application of a first-principles anomalous transport model for electrons to multiple Hall thrusters and operating conditions*, in *2018 Joint Propulsion Conference*. 2018

…

…

Similar to the application to hollow cathode ion sound turbulence

Jorns, B.A., I.G. Mikellides, and D.M. Goebel, *Ion acoustic turbulence in a 100-A LaB6 hollow cathode.* Physical Review E, 2014. **90**(6).

Synopsis of ECDI status. III

Numerical simulations

Simplified models are used:

1D – azimuthal, periodic along the ExB drift direction

2D – azimuthal+ radial with the wall boundary conditions (sheath, SEE), a uniform electric field is imposed

2D –azimuthal + axial, plasma source (not self-consistent), external voltage applied across anode-cathode region

2D- azimuthal +radial, in the full cylinder annular region …

Instability is very robust (very strong) and can be easily observed in PIC simulations. It has been reported by several groups. Some groups insist that in the nonlinear regime the instability transits into the ion sound mode as in unmagnetized plasmas.
Other groups (U Sask) show that the instability remains in the form of the set of cyclotron resonance modes and accompanied by nonlinear development of large scale modes.

Synopsis of ECDI status,I+II+II

Experiments, Modeling and Numerical simulations are not conclusive if and how ECDI is present in Hall thruster conditions

- Some form of EDI is likely to be present
- How it is saturated, nonlinear stage and
- consequences are not clear
- Active work is being continued

Linear regime --**Electron Cyclotron Drift Instability (ECDI)** –is well understood

Nonlinear regime -- **Electron Drift Instability (EDI)**?

Cyclotron resonance and Bernstein modes

$$1 + K_i + K_e = 0 \qquad K_i = -\frac{\omega_{pi}^{\ 2}}{\omega^2}$$

$$K_e = \frac{1}{k^2 \lambda_D^{\ 2}} \left[1 + \frac{\omega - k_y v_0}{\sqrt{2} k_z v_{Te}} \sum_{m=-\infty}^{\infty} I_m\left(k_\perp^{\ 2} \rho_e^{\ 2}\right) \exp\left(k_\perp^{\ 2} \rho_e^{\ 2}\right) Z\left(\frac{\omega - k_y v_0 - m\omega_{ce}}{\sqrt{2} k_z v_{Te}} \right) \right]$$

Fluid resonances for

$$Z\left(\frac{\omega - k_y v_0 - m\omega_{ce}}{\sqrt{2} k_z v_{Te}} \right) \sim \frac{\sqrt{2} k_z v_{Te}}{\omega - k_y v_0 - m\omega_{ce}}$$

Cyclotron resonances/Bernstein modes $\qquad \omega - k_y v_0 - m\omega_{ce} \approx 0$

Fluid resonances overlap at finite k_z

Transition from the set of reactive instabilities to continuous dissipative (Landau type) instability: similar to Bernstein-Landau paradox (disappearance of Landau damping in magnetized plasma)

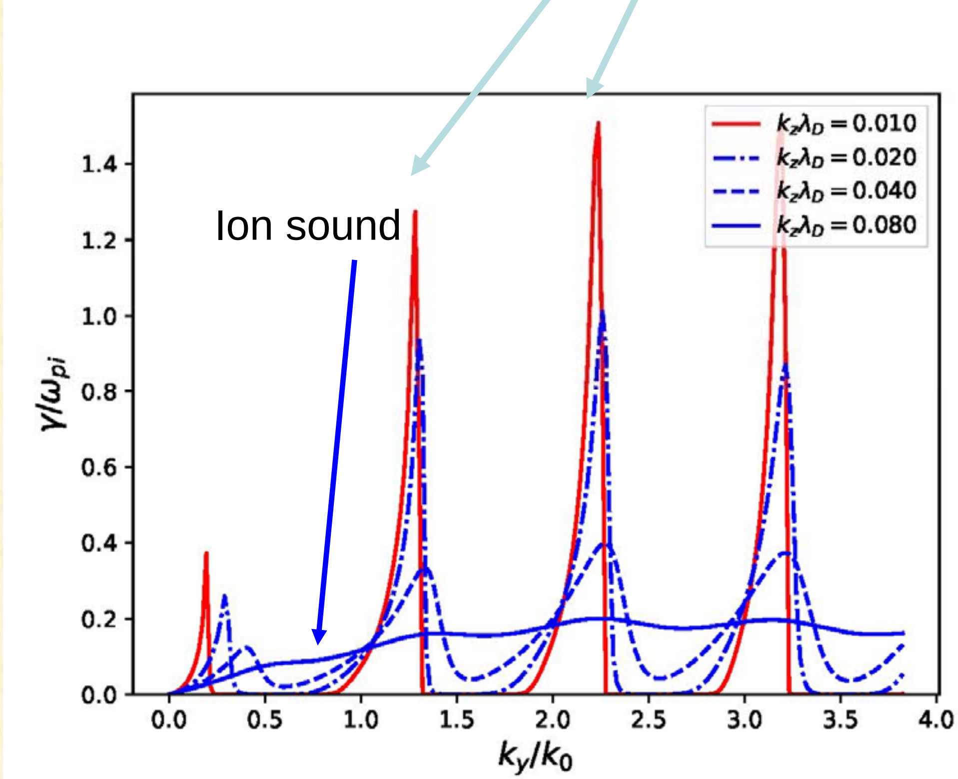
Electron cyclotron drift instability: Reactive (fluid) resonances regimes and transition to ion sound

$$\omega - k_y v_{ExB} = m\omega_{ce}$$

$$\omega \ll k_y v_{ExB} \sim m\omega_{ce}$$

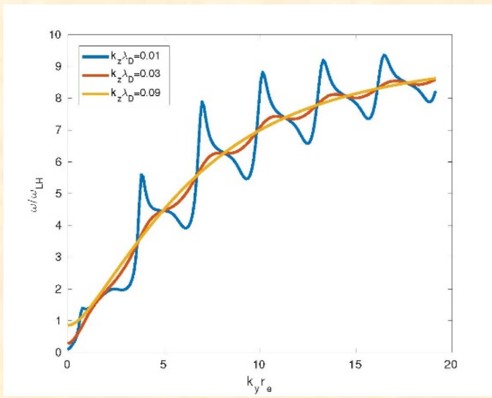
Thermal spreading
due to $k_z v_{te}$

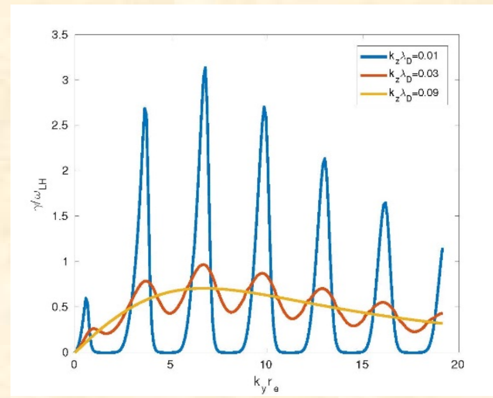
for relatively large k_z transition to unmagnetized ion sound instability driven by v_{ExB} beam (Gary, Sanderson, Lampe , Cavalier)



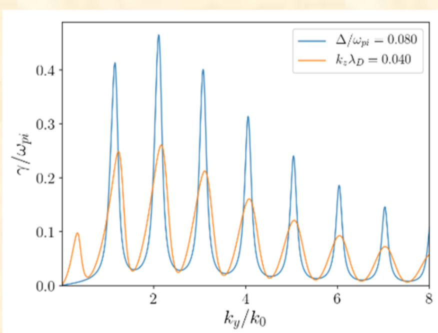
In the context of ExB discharges
Adam et 2004, Boeuf, Lafleur, Ducrocq,..

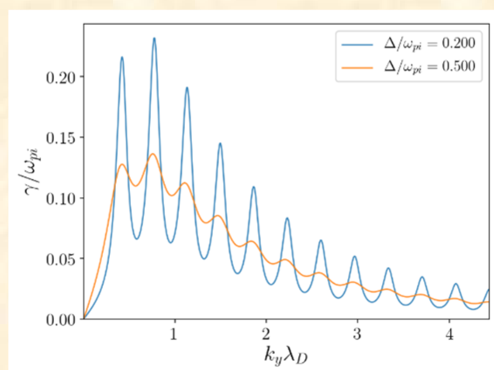
Finite k_z (along the magnetic field) effects

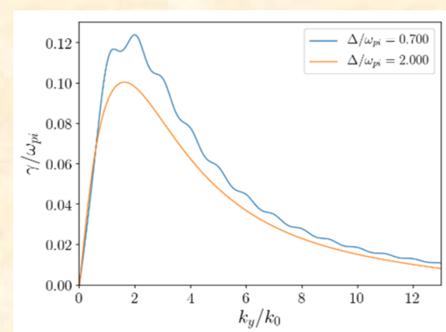




Nonlinear broadening is similar to kz effect



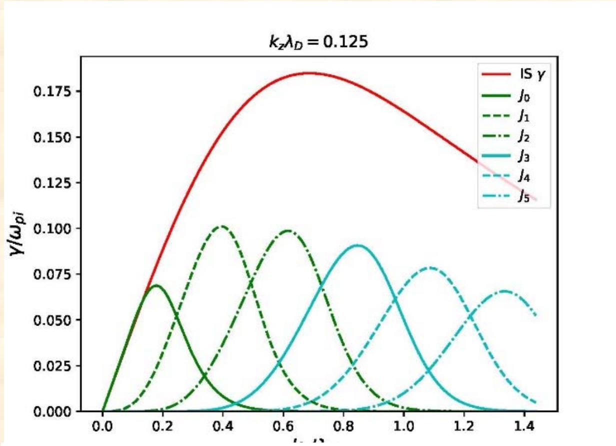




Structure of cyclotron resonances and transition to ion sound modes due to finite temperature and finite wave-vector along B

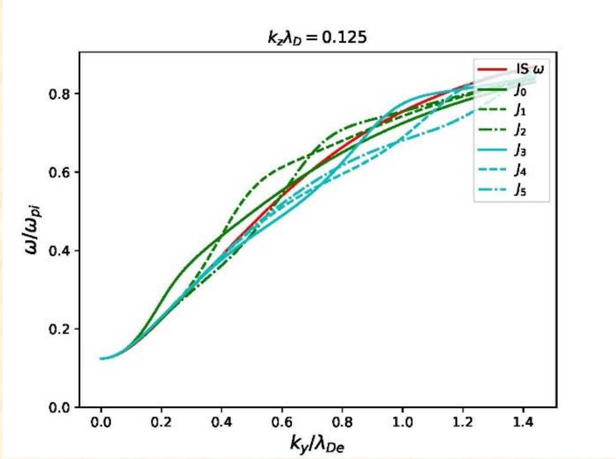
Thermal spreading due to $k_z \mathrm{v}_{\mathrm{te}}$

Growth rate



for relatively large k_z transition to unmagnetized ion sound instability driven by v_{ExB} beam (Gary, Sanderson, Lampe , Cavalier)

Real frequency



Linear mechanism

Each harmonic looks like a sound wave
Unmagnetized sound wave is a sum of many

Nonlinear broadening in numerical simulations?

- Inconclusive: may be some signatures, but generally cyclotron resonances survive
- **Typically well coherent (single mode?) is observed; broad spectrum would normally be expected for strong drive**
- May be different in 1D and various versions of 2D simulations

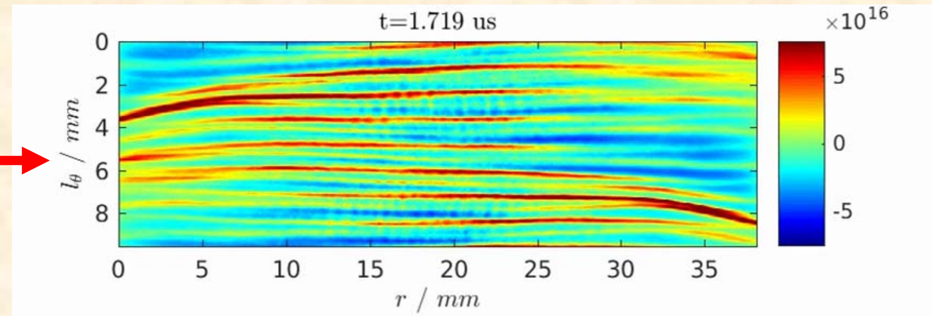
Inverse cascade to longer wavelength

- Observed in 1D and 2D system
- Simulation box dependent
- Anomalous transport is dominated by long wavelengths
- Magnitude of the anomalous current depends on the size of the simulation box
- The dissipation at large scale (not included in current models) will affect the transport

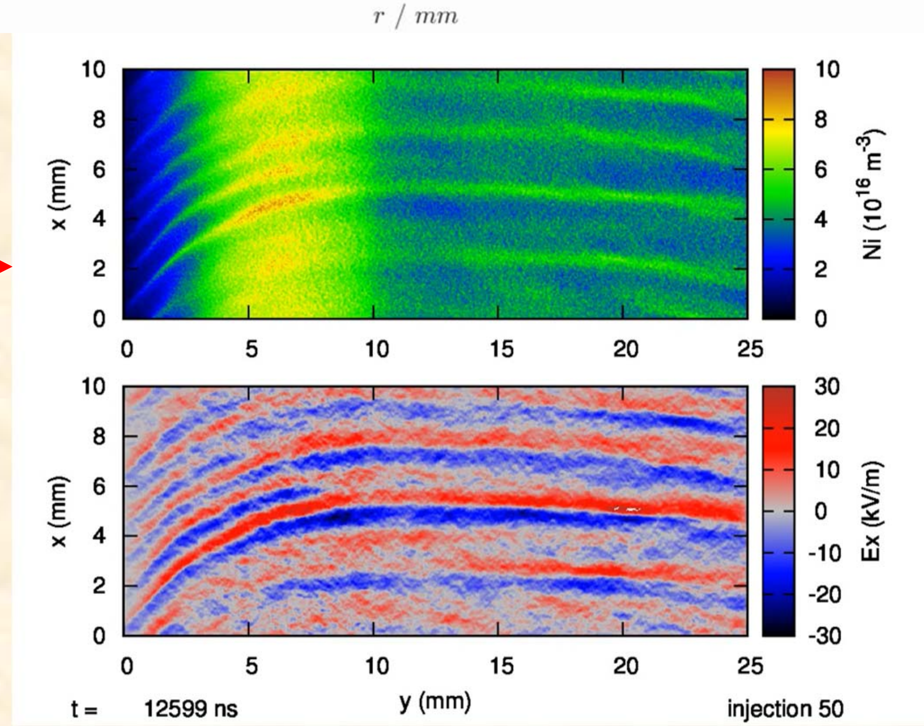
Coherent modes in 1D and 2D simulations

Lafleur 2016, Boeuf .. 2017, Janhunen et al, Phys Plasmas 2018a,b;
Sydorenko 2018, Zintel 2019, Charoy et 2019, Taccogna 2019

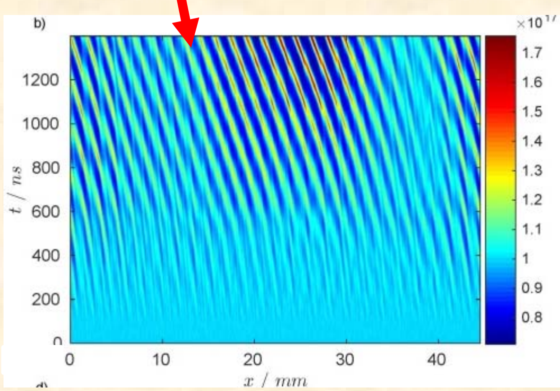
2D: azimuthal -radial



2D: azimuthal -axial



1D azimuthnal



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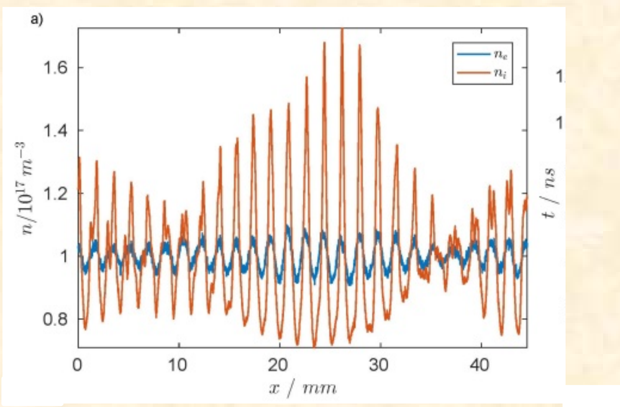
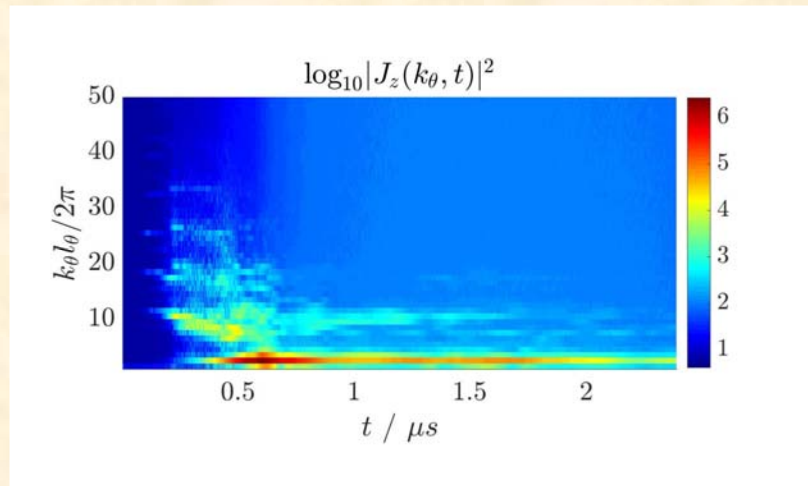
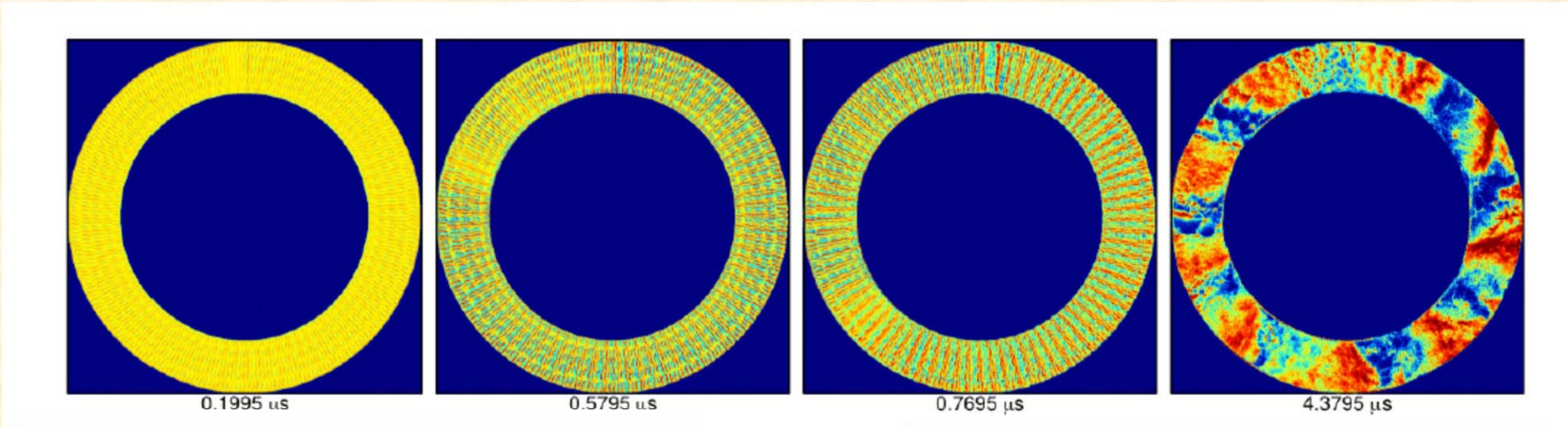
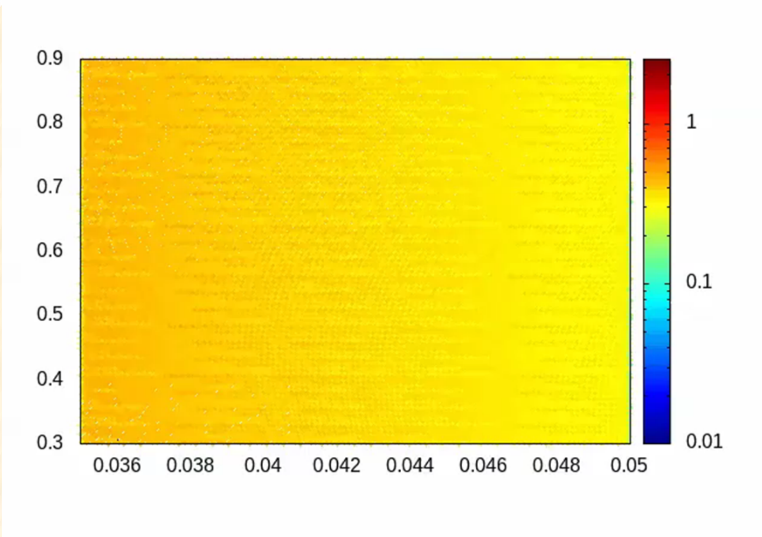


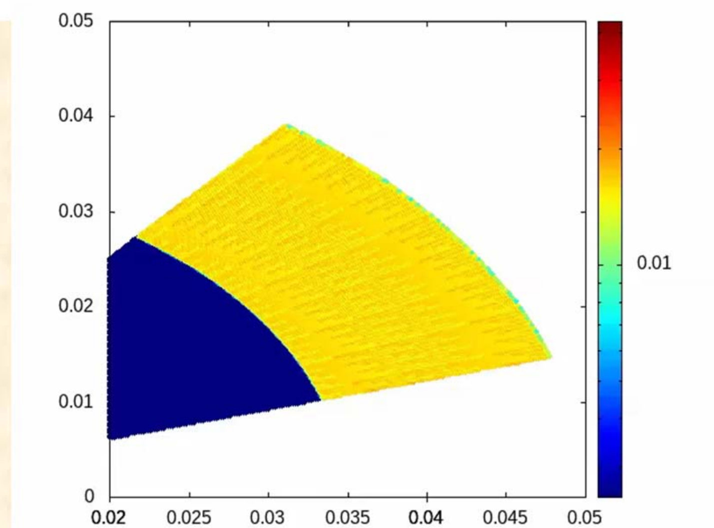


Current condensation toward long wavelength

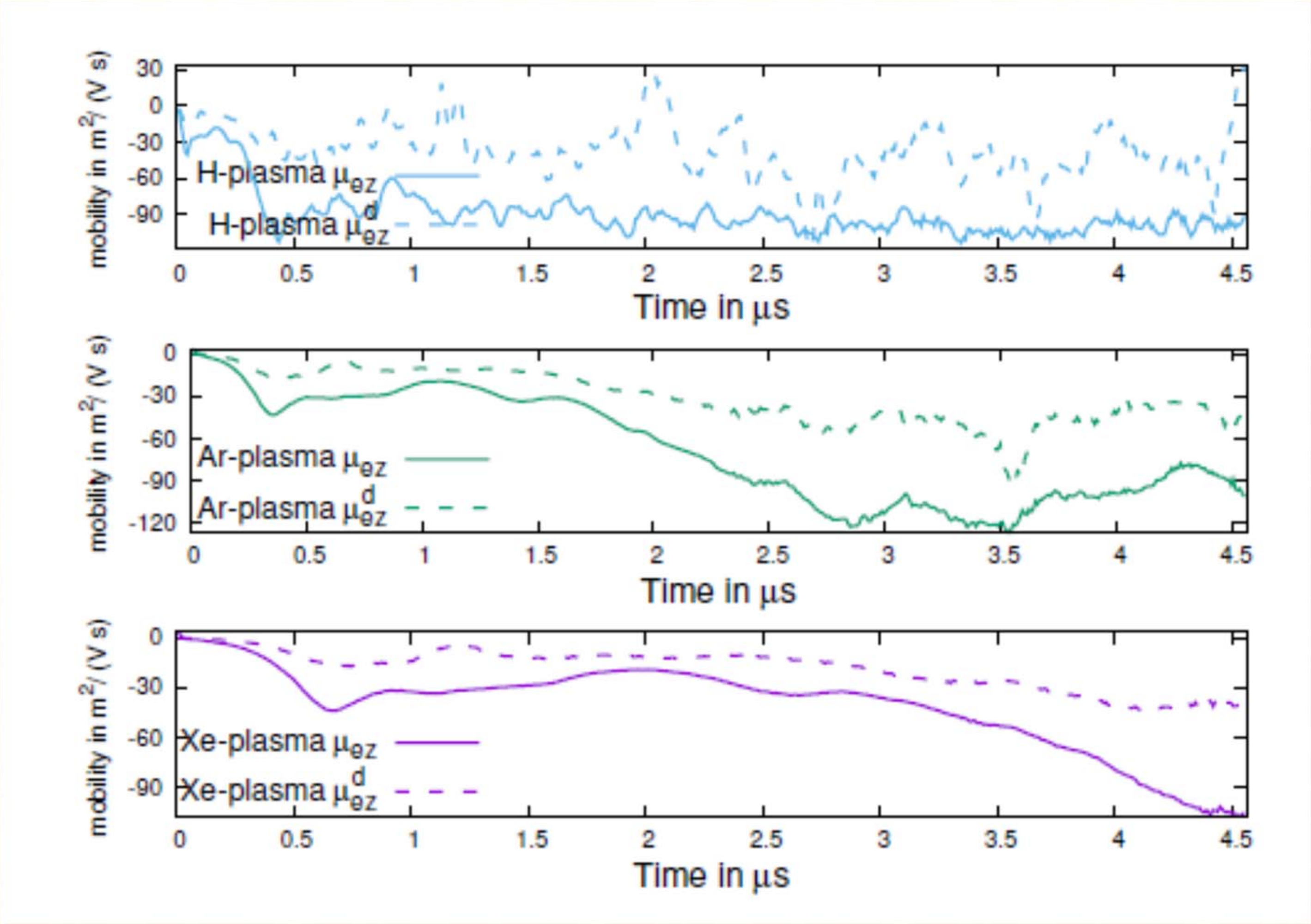
Mode transitions towards longer wavelengths
2D azimuthal-radial







Mode transition in anomalous mobility



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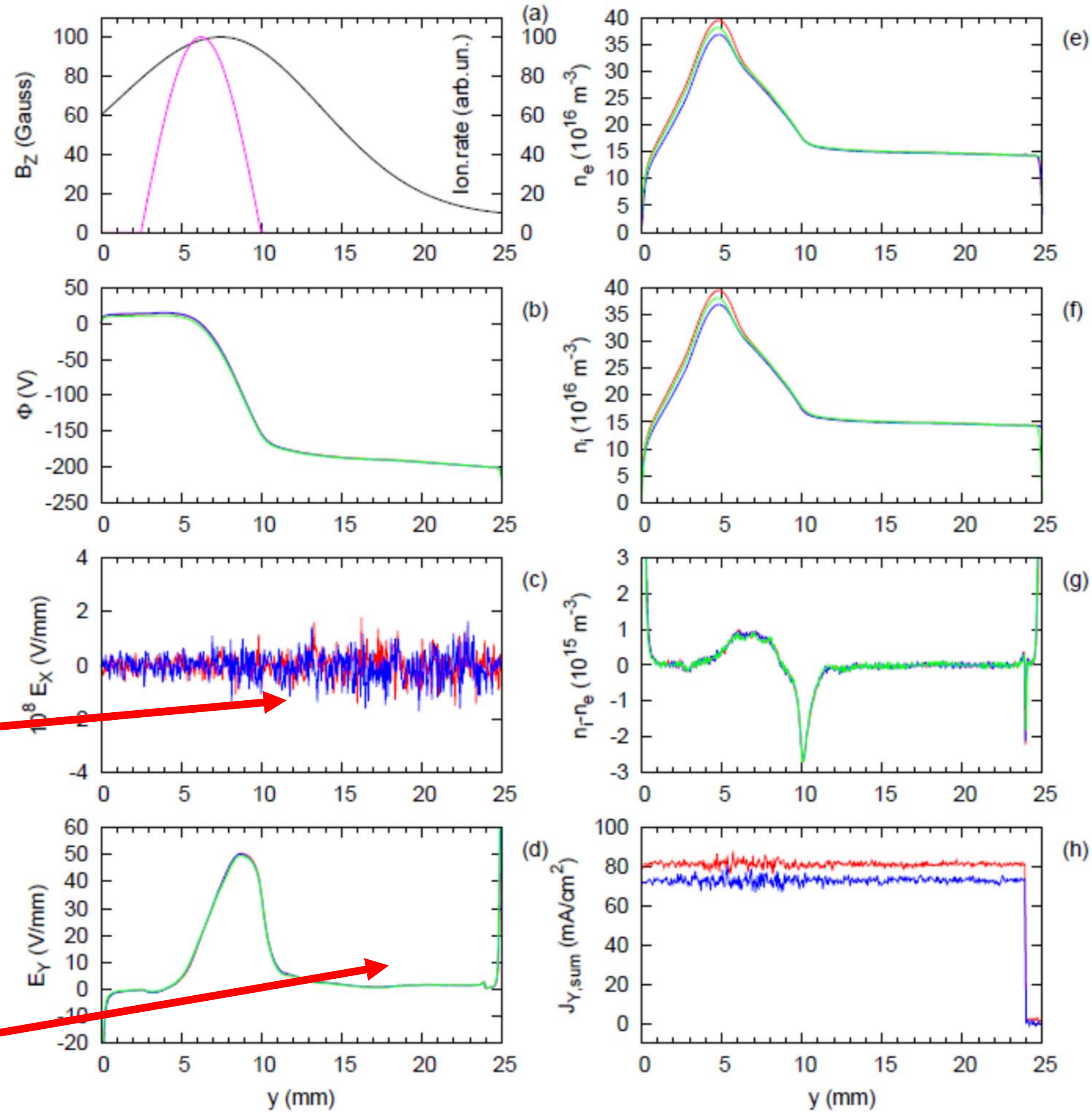
Benchmarking
PSST2019

LLP, Ecole Polytechn
CERFACS, France
Rurh University
Usask
LAPLACE, Tolouse
PPPL
UTAM

Increase of oscillations amplitude ?

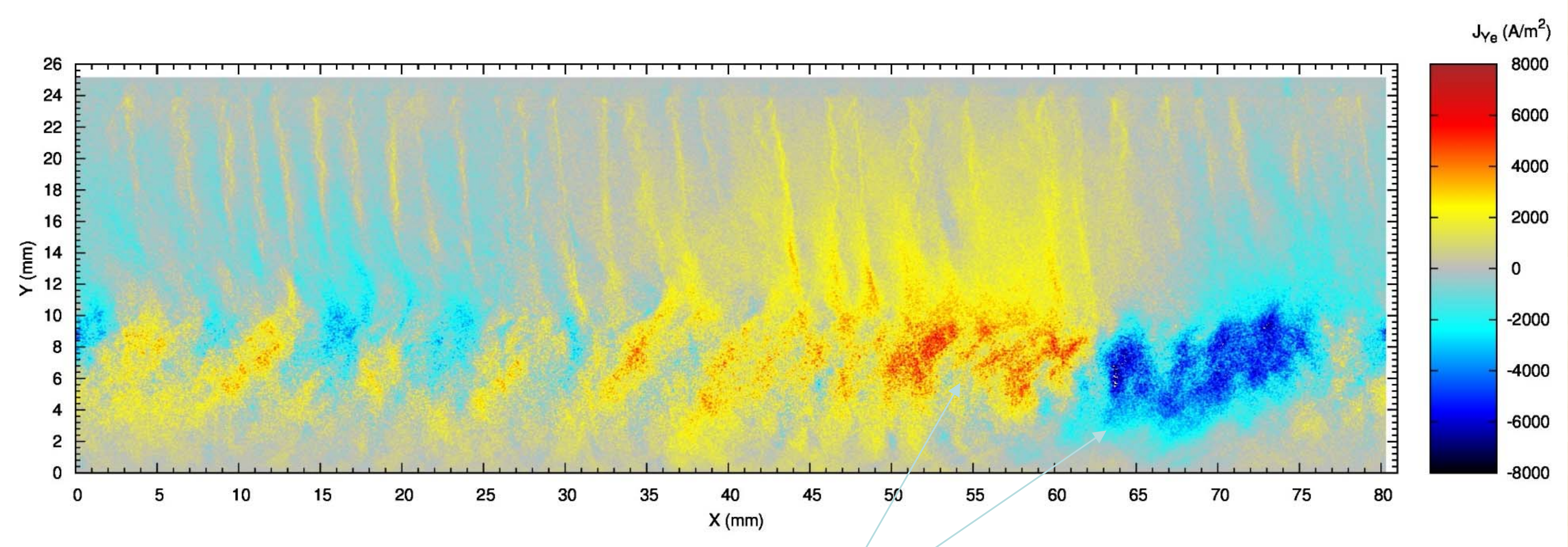
Large current in the region of the low electric field?
Will mobility suffice?



Anomalous mobility in 1D simulations

Role of structures on transport

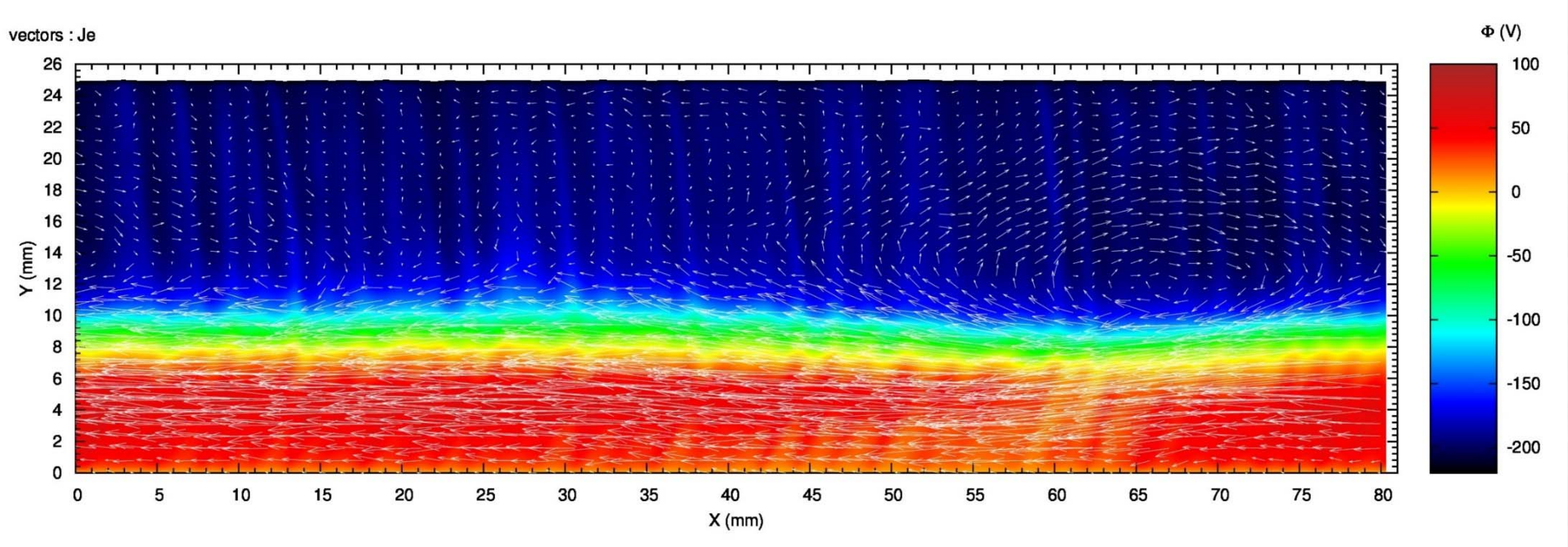
Axial electron current

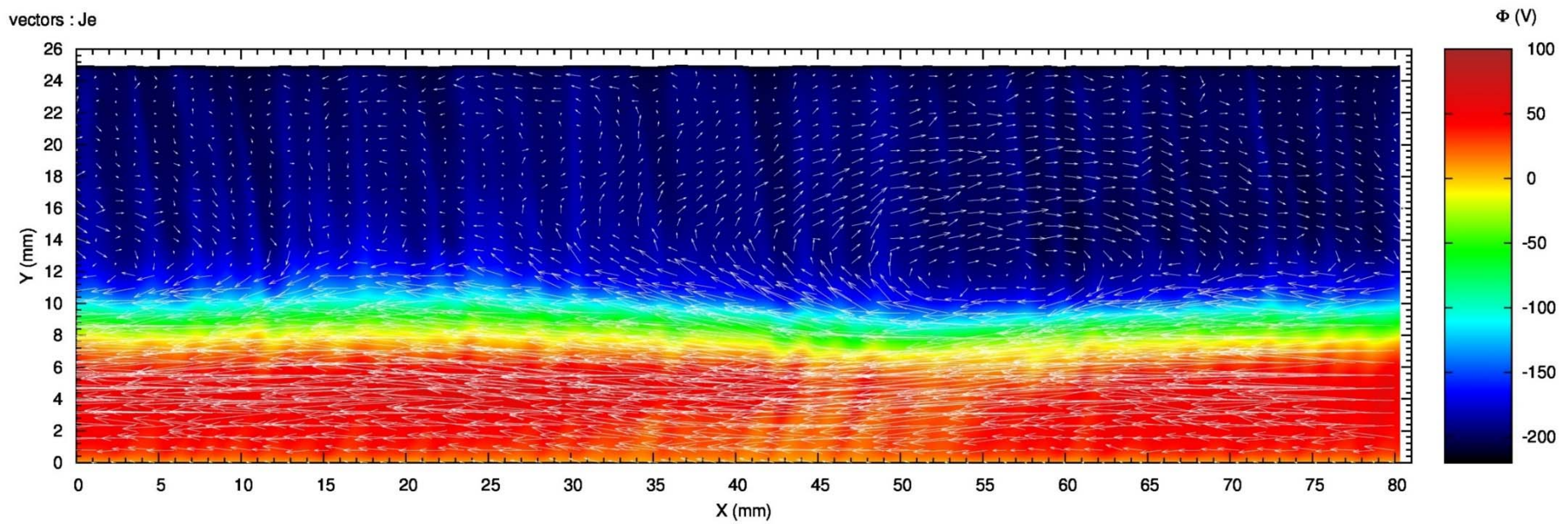


t = 10.6 mks

Elecron current vortex

In fact, the electron current forms a vortex (or two) in the transport region (minimal axial potential gradient)




vectors : Je
Φ (V)
100
50
0
-50
-100
-150
-200
Y (mm)
26
24
22
20
18
16
14
12
10
8
6
4
2
0
X (mm)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80

Questions and problems:

- Inverse cascade to long wavelength is box size (and large scale dissipation) dependent
- Large scale structures contribute to transport. How to characterize? Does the concept of averaged mobility apply?
- Ion trapping, ion rotation and nonlinear saturation

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Low temperAture magNetizeD plasMA benchmaRKs

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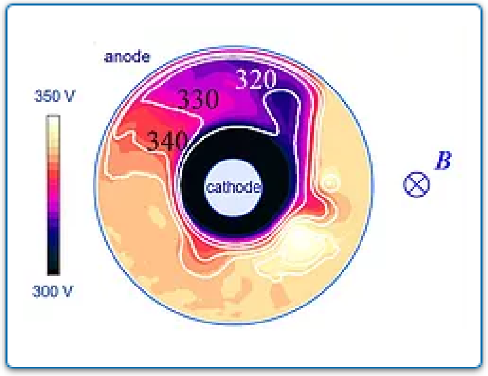
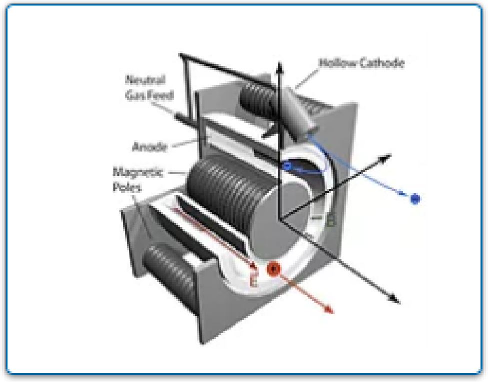
Aim and scope

The physics of low temperature magnetized plasmas or ExB plasma devices is very specific and different from that of fusion plasmas. This distinct area of basic plasma physics has been poorly explored and is not well understood but is within the reach of current analytical and numerical capabilities as well as powerful modern diagnostics tools.
The physics of magnetized plasmas and EXB devices is however complex and very non-linear and the scientific community must organize itself to better understand and quantify the properties of these plasmas.



The **LANDMARK** project aims at

- providing an open forum for evaluating methods of description of plasma transport in non-fusion magnetized plasmas (eg ion sources, HALL thrusters, magnetrons, cusped-field thrusters ...)
- defining benchmark test cases for PIC, fluid and hybrid methods
- addressing physics issues related to the questions of anomalous transport across magnetic field, instabilities, plasma wall interactions and their influence on particle and energy transport
- facilitating international collaboration and enhance mutual understanding among researchers
- publishing benchmark results



https://www.landmark-plasma.com/

Thank you!