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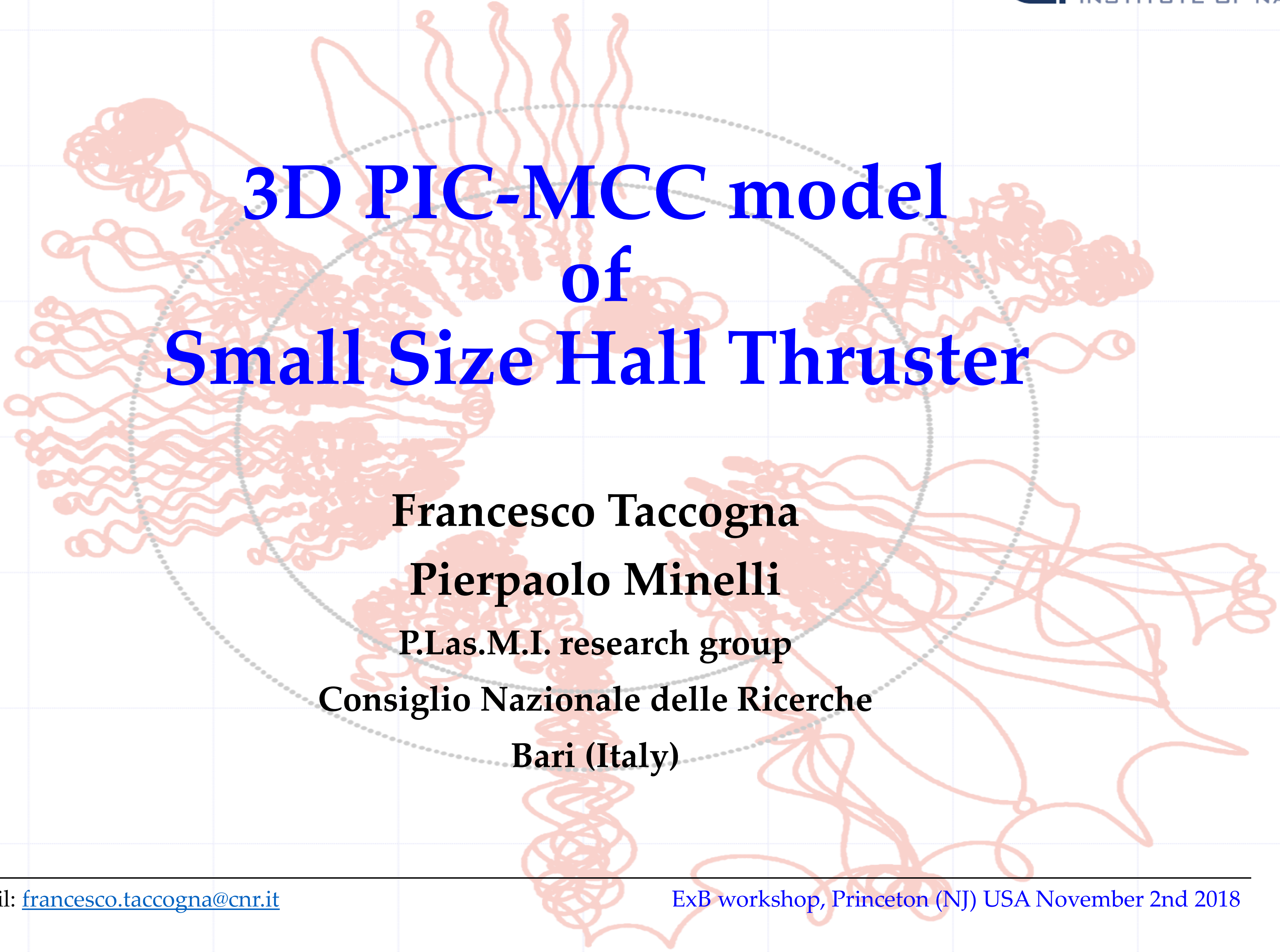

3D PIC-MCC model of Small Size Hall Thruster

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Outline

- Evidences for a 3D Model
- Inconsinstencies between Theory/Models and Experiments
- Geometrical Scaling
- Hall Thruster 3D PIC-MCC Model developed @ PLasMI lab
- Results
- Conclusions / Future works

Needs for a 3D representation

o Coupling and strong correlation among all the three directions:
radial clousure and axial convection

o Assesment of the different contributions to the anomalous transport:
- fluctuation-induced
- wall-induced

The two contributions does not simply add each other

o Don’t need any assumptions as for 2D: real self-consistent simulation

o Huge progress in HPC and Computer Technology in the last years: PIC scales well with the number of processors

Inconsistencies between Theory/Models and Experiments

o ExB electron drift instability seems explain the anomalous transport (no agreement on the instability amplitude and saturation mechanisms among the different models)…nevertheless discharge current strongly depends from material wall

o Experiments [2] observe a standing wave (probably result of two counterstreaming modes) while theory/models shows it moves with ion acoustic velocity.

o A moving wave is not compatible with the anomalous erosion.

o Counterlogical: with no-emissive wall material the electron current is larger [3].

o The way to distinguish different contributions to the mobility with different adjustable coefficients fail to match correctly the ion velocity profile measured by LIF technique [4].

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[1] Raitses, Y., Smirnov, A., Staack, D., and Fisch, N. J., Phys. Plasmas 13, 014502 (2006).
[2] S. Tsikata, N. Lemoine, V. Pisarev, and D. M. Gresillon, Phys. Plasmas 16, 033506 (2009)
[3] S. Tsikata, A. Héron, and C. Honoré, Phys. Plasmas 24, 053519 (2017)
[4] Boniface, C., Garrigues, L., Hagelaar, G. J. M., Boeuf, J. P., Gawron, D., Mazouffre, S., Appl. Phys. Lett. 89, 161503 (2006)

Geometrical Scaling

o Impossible to afford a 3D problem with real dimensions: 1000^3 mesh nodes.

o Better than other scaling (ion mass and/or vacuum permittivity) since it is based on HT scaling down rules.

o Every dimension is reduced by f increasing by the same f magnetic field and neutral density.

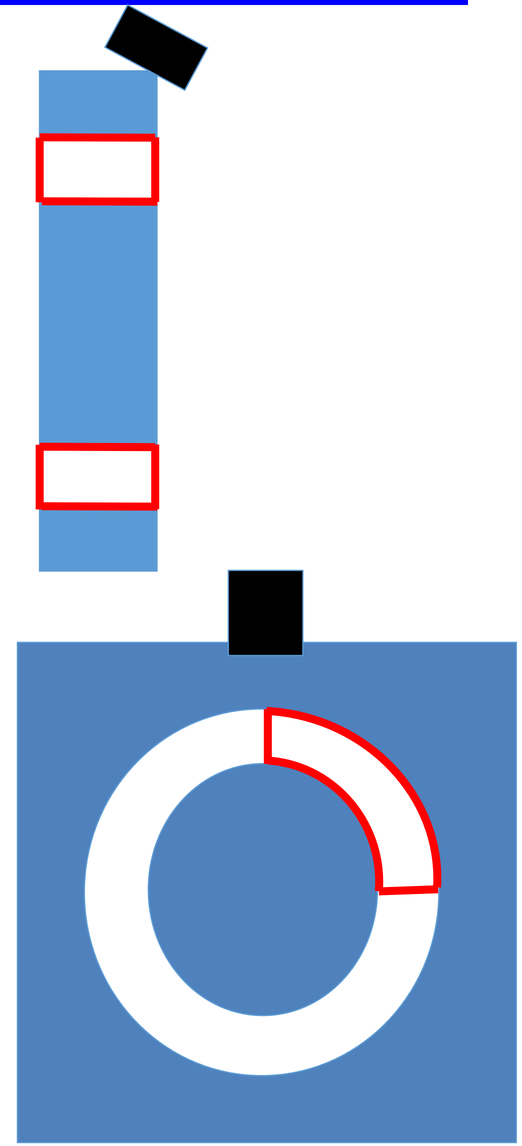
o Knudsen (the ratio of the electron mean free path length to the characteristic size of the thruster) and Hall (the ratio between the electron gyro-frequency, and the electron-heavy particle collision frequency) parameters keep constants.

o Current is reduced by f^2 (current density remains the same).

o We have used f=10 → SPT10

Quantity	Scaling law
Debye length	f^0
Electron Larmor radius	f^{-1}
Gradient length	f^{-1}
Electron, ion frequencies	f^0
Electron-neutral collision frequency	f^1
Electron-wall collision frequency	f^1
Electron cyclotron frequency	f^1
Electron ExB drift velocity	f^0
Diamagnetic, gradient-B drift velocities	f^0
Ion beam velocity	f^0
Convection time	f^{-1}

3D(r,θ,z) Model



o 3D(r,θ,z) / discharge channel

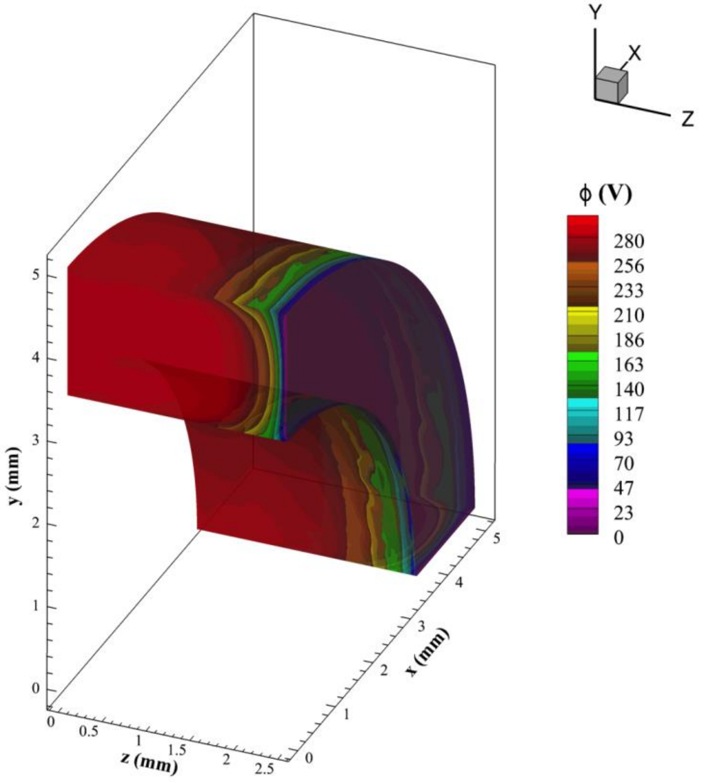
- Domain: - radial from inner to outer wall;
  - azimuthal: π/2
  - axial from anode to exit plane (plume not included)
- Initial condition: start from scratch
- Injection condition: steady-state electron current control method

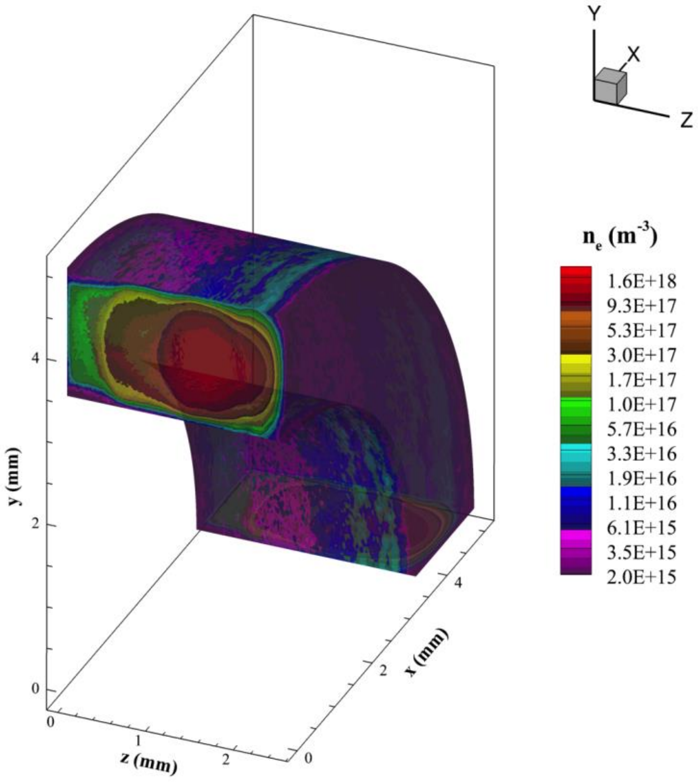
$$\Delta n_{e,inj} = \Delta n_e^{anode} - \Delta n_i^{anode} - (\Delta n_i^{exitplane} - \Delta n_e^{exitplane})$$

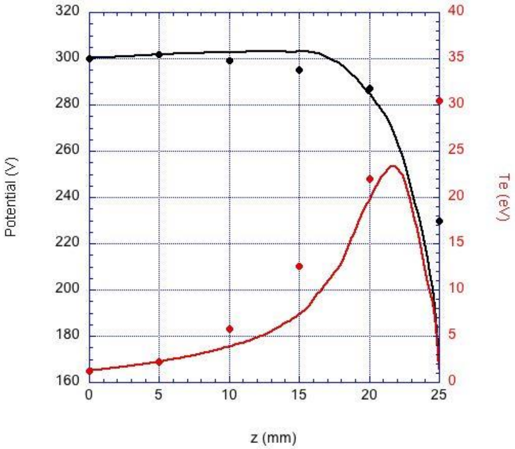
$$\frac{\partial \phi}{\partial r} = \frac{\sigma}{\varepsilon_0}$$

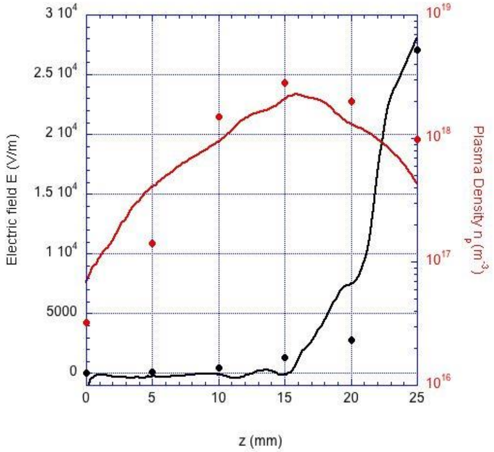
- Field solve: E negligible in the material
- electron-atom MCC module
- electron-wall SEE module
- Realistic ion mass, vacuum permittivity
- Assumption: - fixed potential (cathode) at the exit plane
  - geometrical scaling
- Numerical parameters: - $N_g = N_r x N_\theta x N_z = 100x128x160$ (grid points)
  - $N_p/N_g = 50$ (particles per cell)

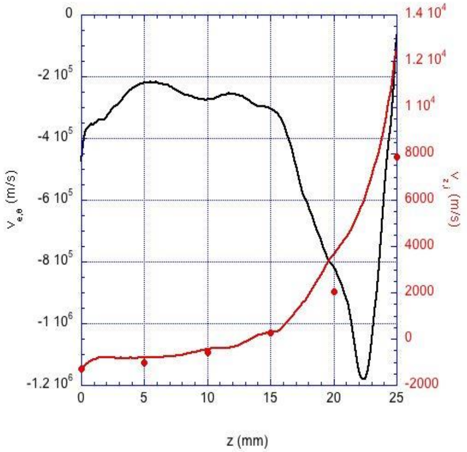
Results – 3D Map





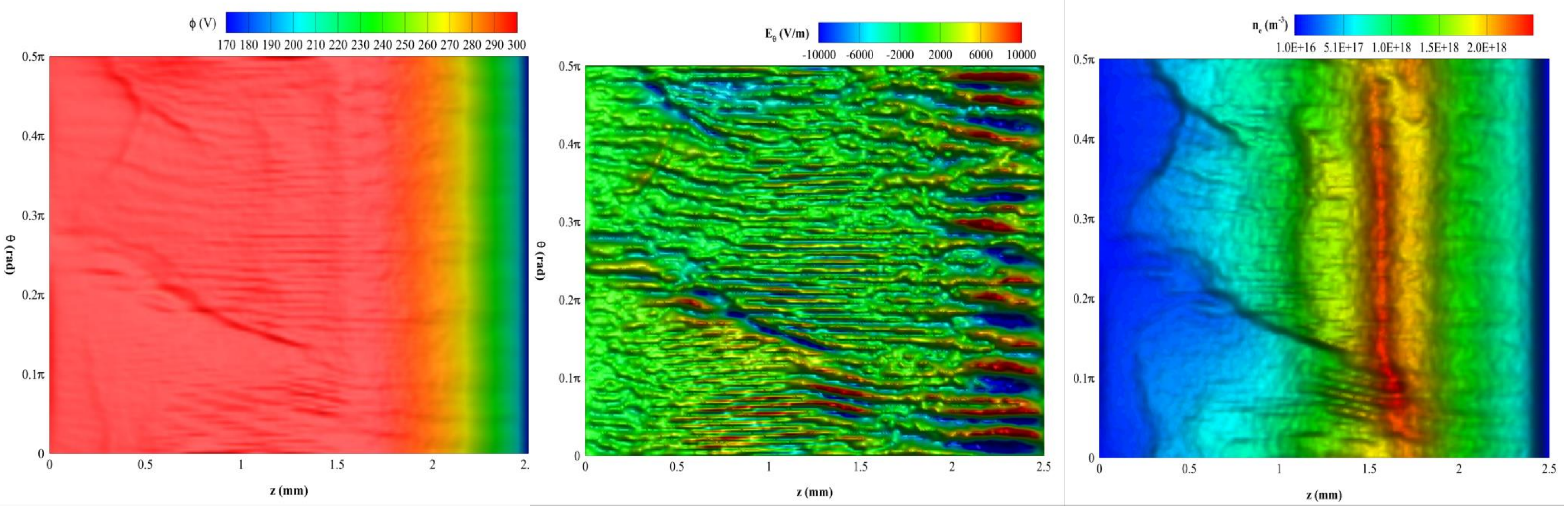






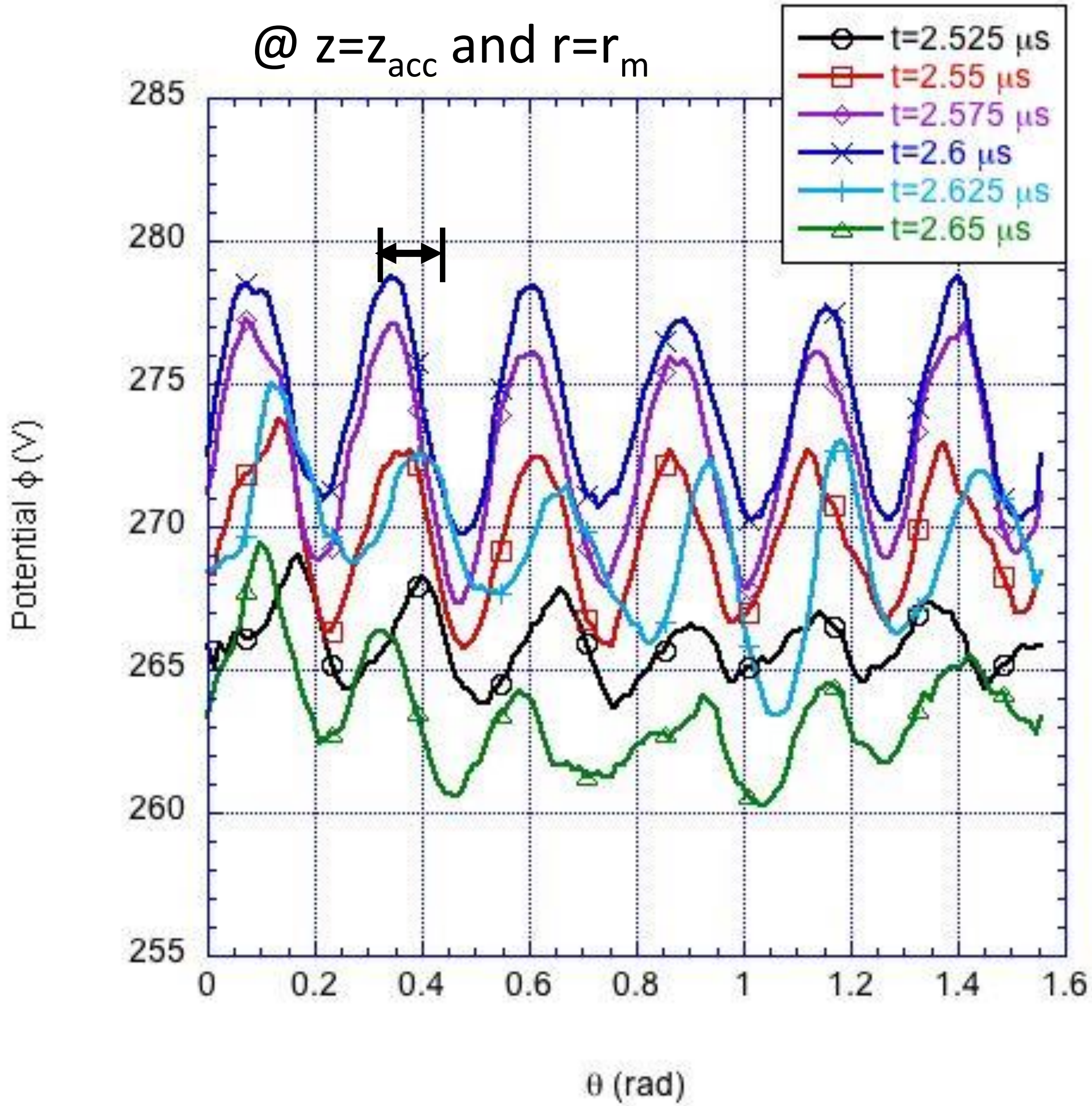
Results – V, E_θ, n_e in (θ,z) plane

@ $r=r_m$



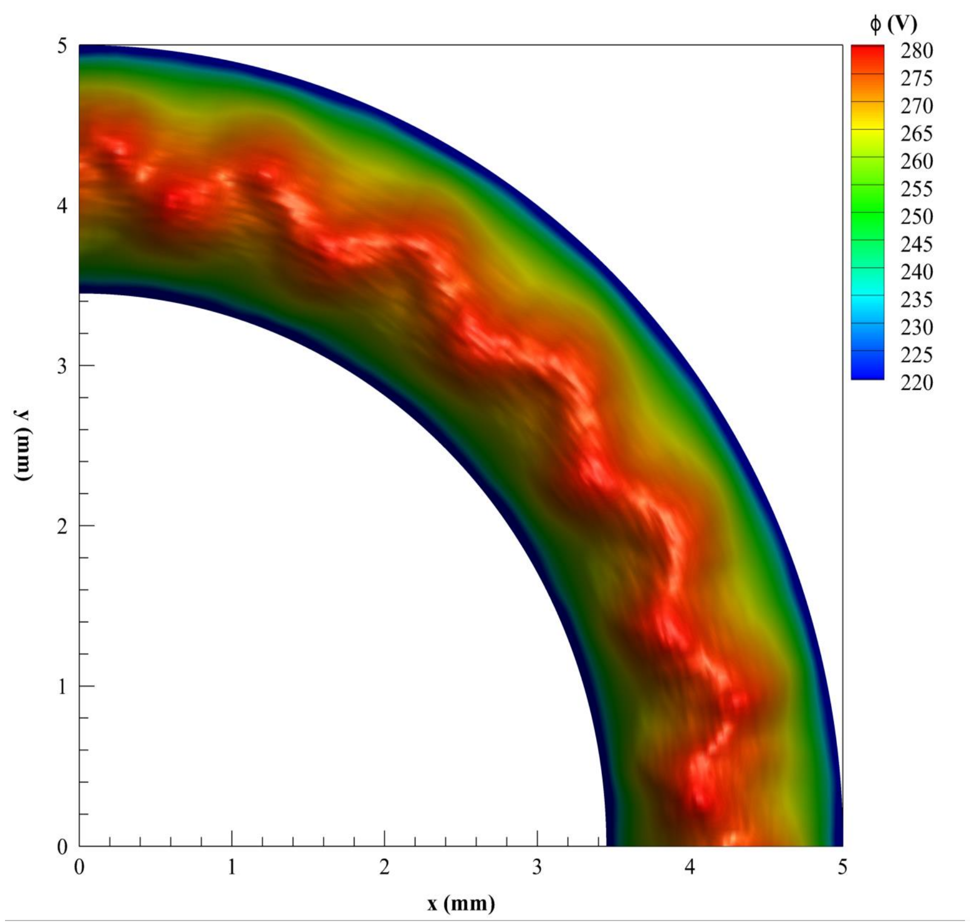
Results – V along θ direction

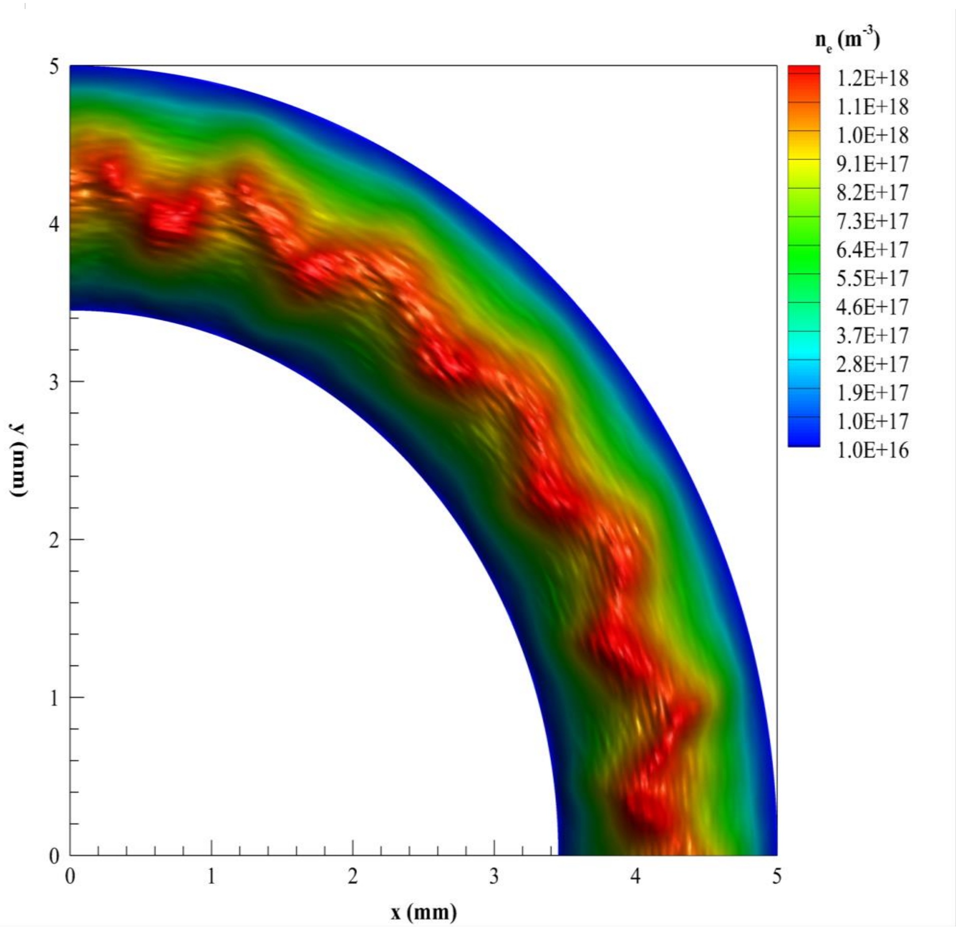
@ $z=z_{acc}$ and $r=r_m$



Results – V, n_e in (r,θ) plane

@ $z=z_{acc}$

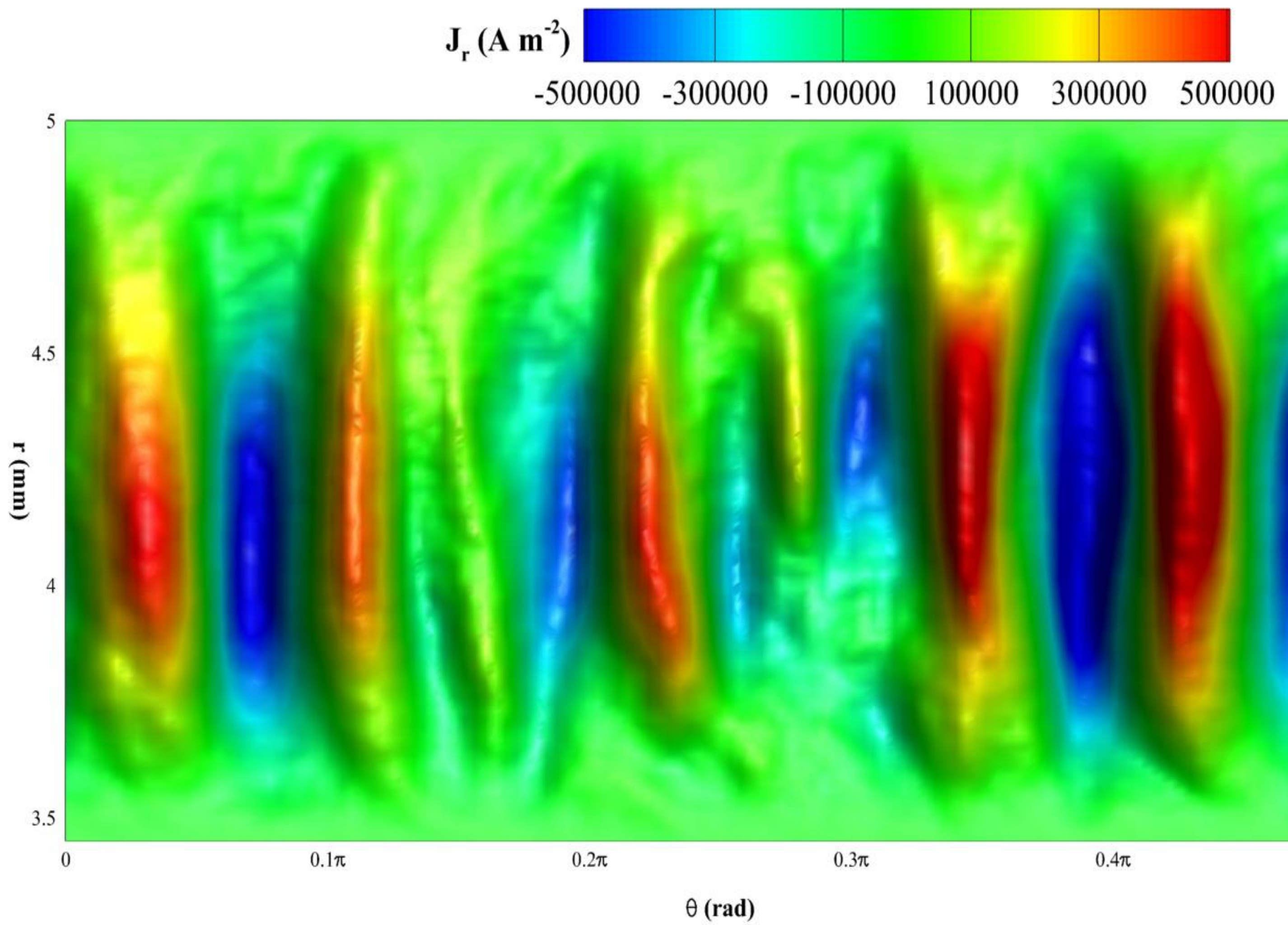




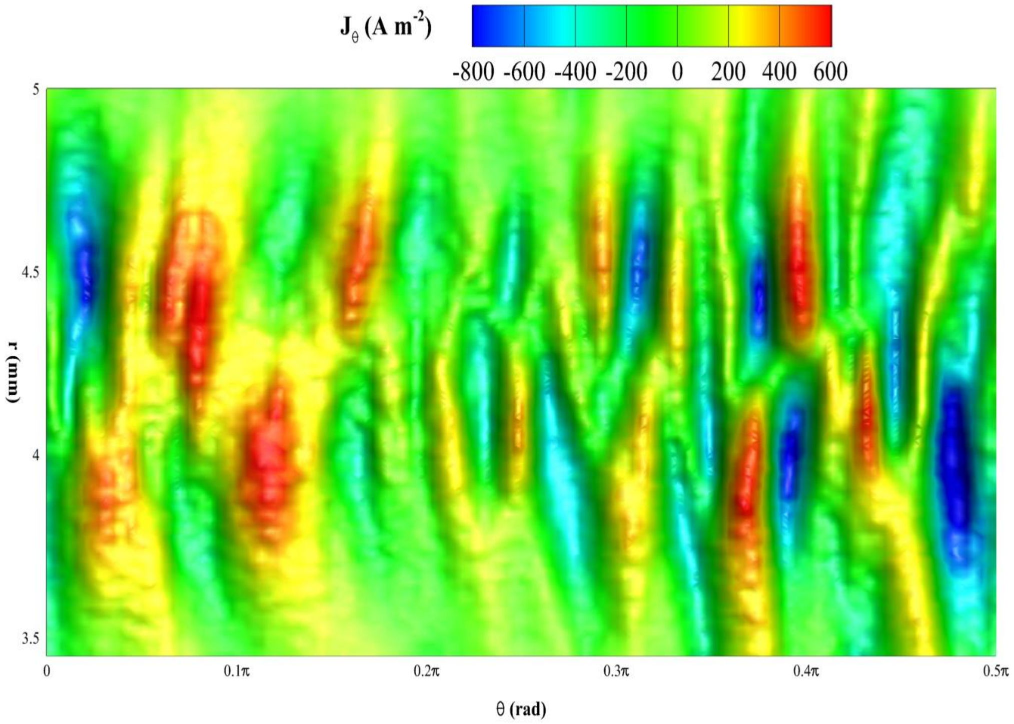
Important radial component due to wall current closure / geometrical scaling:
Feeding back the ExB drift instability
Sheath is azimuthally modulated -> creates preferential location for ion erosion

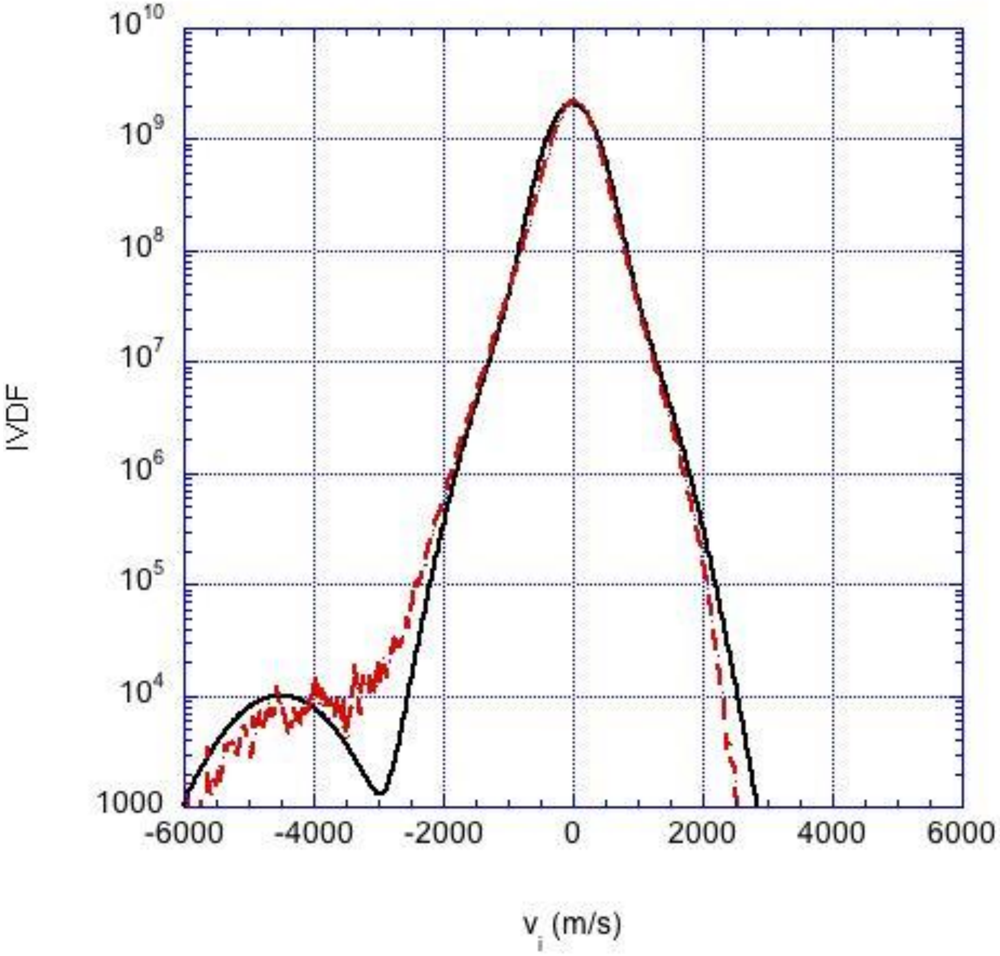
Results – Electron channeling in (r,θ) plane

@ $z=z_{acc}$



Results – Saturation mechanism: ion phase space





Results – Contributions to anomalous transport

Quantity (scaled values)	CASE 1: 3D(r,θ,z) w SEE	CASE 2: 3D(r,θ,z) w/o SEE	CASE 3: 2D(r,z) w SEE
Electron current injected at exit plane $I_{e,inj}$ (x10^{-2} A)	1.4	1.9	1.4
Ion beam current $I_{i,beam}$ (x10^{-2} A)	3.1	2.6	3.1
Electron current at r_{in} $I_{e,in}$ (x10^{-2} A)	0.43	0.15	0.24
SEY at r_{in} γ_{in}	0.64	/	0.66
Electron current at r_{out} $I_{e,out}$ (x10^{-2} A)	0.65	0.2	0.41
SEY at r_{out} γ_{out}	0.67	/	0.71
Max electron temperature $T_{e,max}$ (eV)	20	21	20
Max Potential fluctuation amplitude $\delta\phi_{max}$ (V)	10	15	/
Max density fluctuation amplitude $(\delta n/n)_{max}$	0.23	0.33	/

Conclusions

o **Importance of having a detailed up to kinetic level model: deviation from Maxwellian has important macroscopic effects (instability, wall losses and sheath, ionization rate, etc.)**

o **Low-dimensionality models help to understand limitations of using fixed external parameters (that otherwise play a relevant role due to strong correlation among the different dimensions)**

o **The ExB EDI wave becames a standing wave probably die to the scaling**
o **Strong radial component due to current-closure condition on lateral walls**
o **Azimuthal fluctuating field has double structure along r**

o **Saturation mechanism: ion heating and rotation before to be convected.**

o **Secondary electron emission helps to reduce the amplitude instability (thermostatic effect)**