Consiglio
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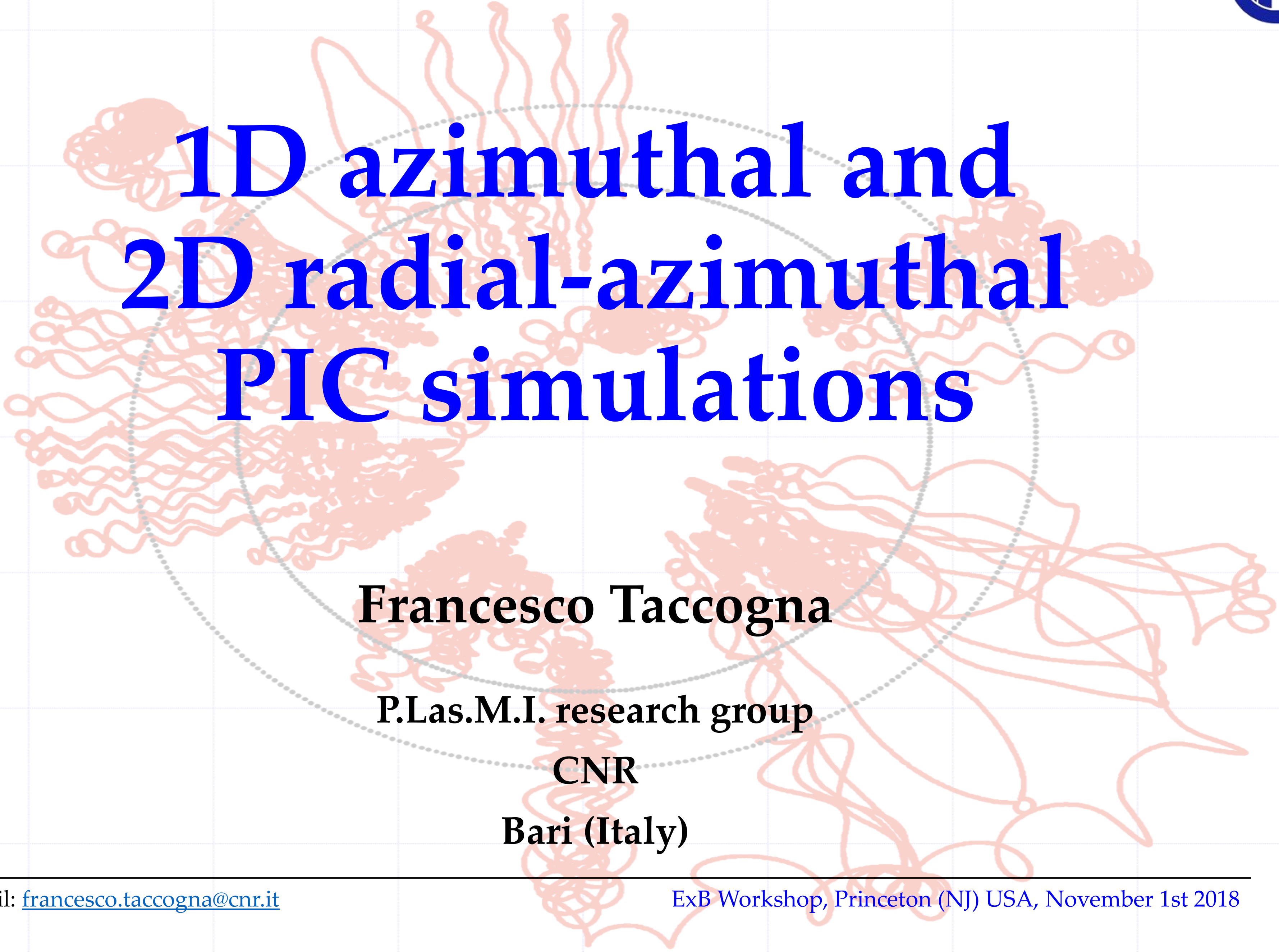

1D azimuthal and 2D radial-azimuthal PIC simulations

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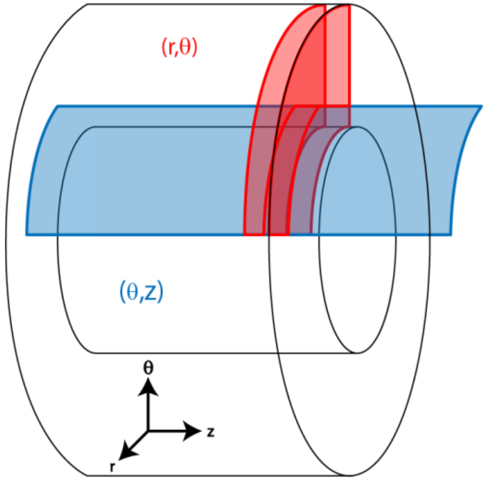
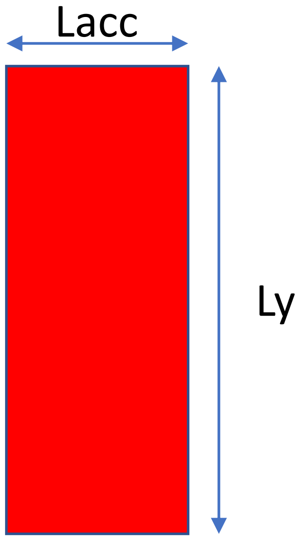
Outline

- Review of azimuthal PIC models: assumptions / differences / findings
- 1st problem: axial / radial replacement of particles (particle re-injection)
- 2nd problem: azimuthal length of the domain
- Results
- Extension to 2D: inclusion of radial direction
- Results
- Conclusions / Future works

The 1D-azimuthal model





- o Cartesian approximation / periodic condition
- o Fixed prescribed - Axial electric field Ez
  - Radial magnetic field Bx

  uniform along y
- o The axial dimension z is not solved / at the best particles are tracked along z
- o Initial particle loading: uniform Maxwellian plasma (n/Te/Ti)
  - drifting Maxwellian for ions: axial velocity v_{iz} is prescribed (ion axial velocity not updated)
- o No radial (direction of the magnetic field) x dynamics
- o Collisionless

The problem of axial / radial replacement (particle re-injection) (I)

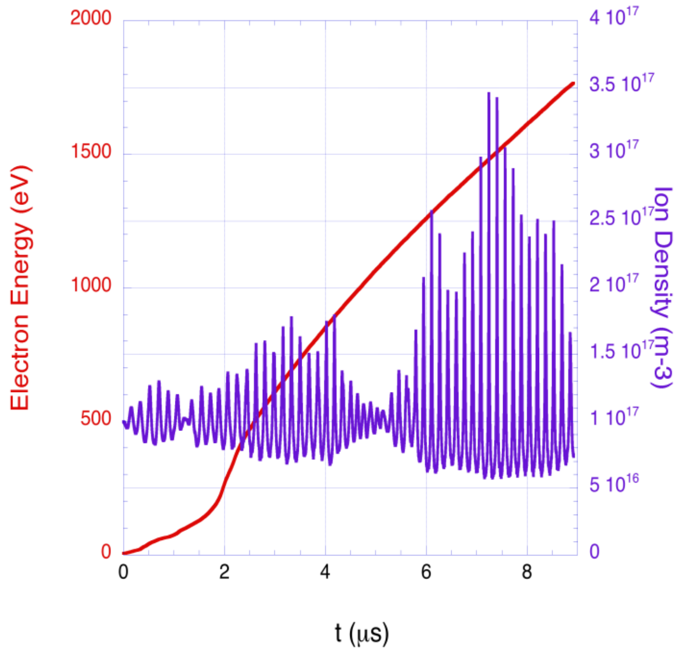
- We need to refresh particles in order to reproduce the effect of the axial current and the radial losses (removal of high-energetic tail).

- This mechanism:
  - has a thermostatic effect for electrons (otherwise the electron energy indefinitely increases leading to unphysical results);
  - replace the ion-energy distribution function (bump-on-tail due to electron-ion friction)

- It’s important for the non-linear development (occurring on temporal scale larger than 1 μs), but probably not relevant for the linear growth.

- It’s equivalent to a collisional effect (particles suddenly change their velocity with initial distribution) and then contaminate results.

Temporal evolution of electron mean energy and ion density at fixed location without particle re-injection



The problem of axial / radial replacement (particle re-injection) (II)

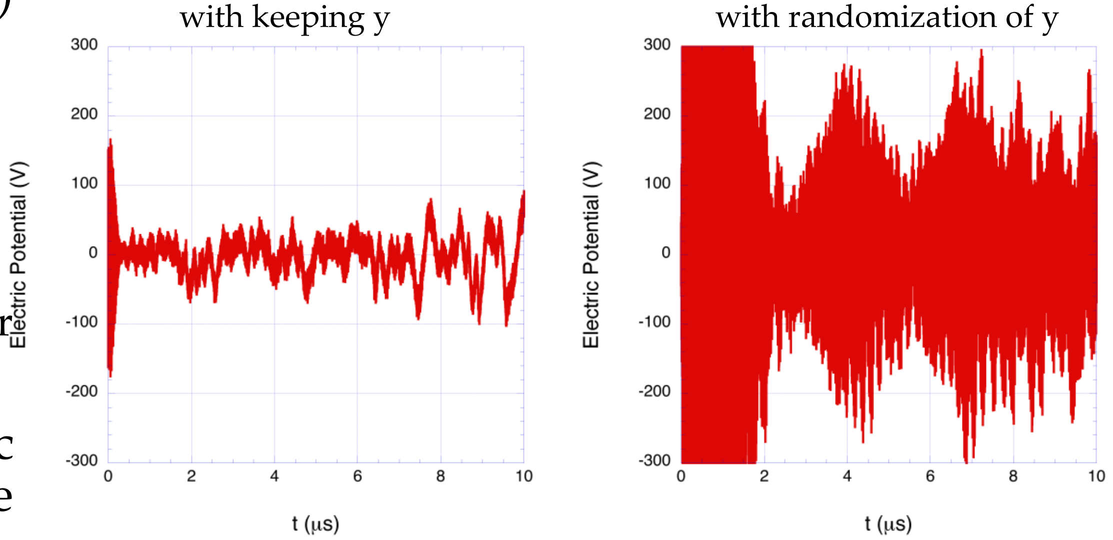
- Electrons/Ions are re-injected (initial temperature) when they travel an axial distance $z>L_{acc}$

- Depending on where particles are re-placed:
  - randomly along y
  - keeping their azimuthal position y before changing their velocity

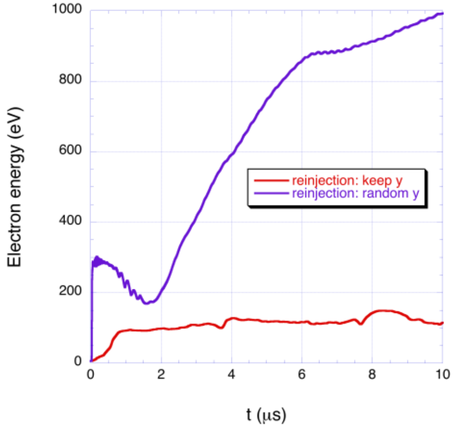
we have found important differences. Large electric fields and as a consequence electron energy are present when electrons are randomly reinjected.

- The problem is related to the large charge-imbalance artificially induced when one inject particles randomly and amplified by the fact that the model is 1D (every particles is a infinite plane). In fact, in the 2D(r,teta) version of the model, the random re-injection does not create large electric field.

Temporal evolution of Electric Potential (V) at the center y(Ny/2)


with keeping y

with randomization of y



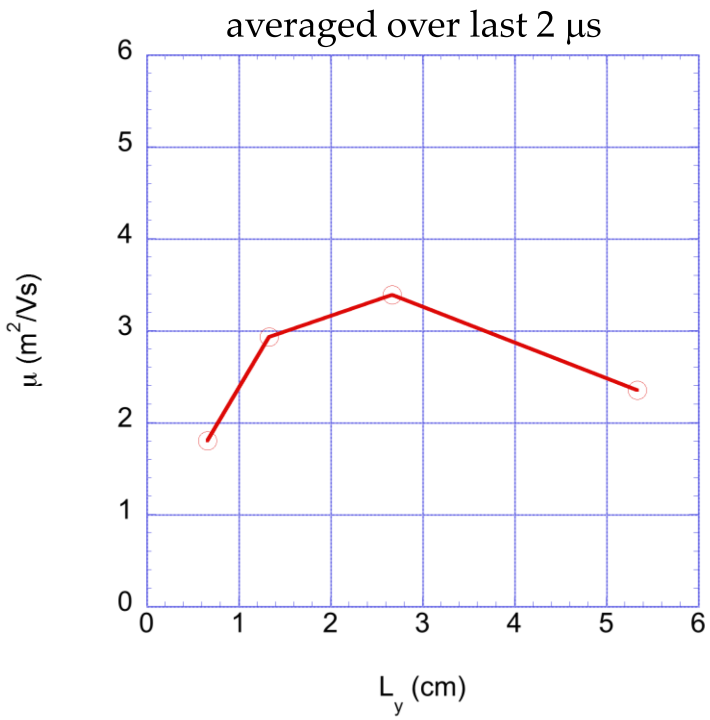
The problem azimuthal length Ly of the domain

- Results depend on the size of the azimuthal domain Ly; in fact, the nonlinear evolution towards low-wavenumbers can be influenced by the boundaries.

- The azimuthal length of the computational domain Ly determines the maximum wavelength supported by the simulation

$$\lambda_{max} = L_y \quad or \quad k_{min} = \frac{2\pi}{L_y}$$

artificially selecting in this way the instable modes to be present and eventually alterating the non-linear evolution (mode-mode interaction)



$$\mu = \frac{\sum_{p=1}^{N} v_{p,z}}{N E_z}$$

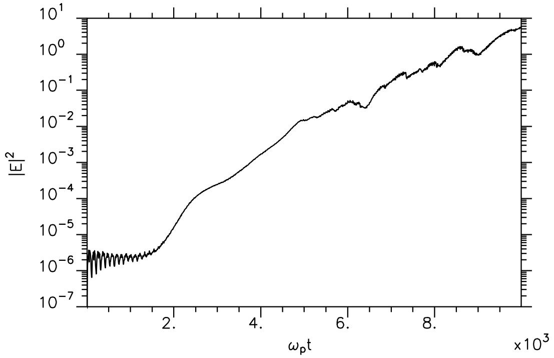
1D azimuthal y PIC models

Author / Year	Characteristics	Assumptions	Findings
Ducrocq 2006			
Lafleur 2016			
Janhunen 2018			
Boeuf 2018 - unpublished			
Taccogna 2018 - unpublished			
Hara 2018 - unpublished			

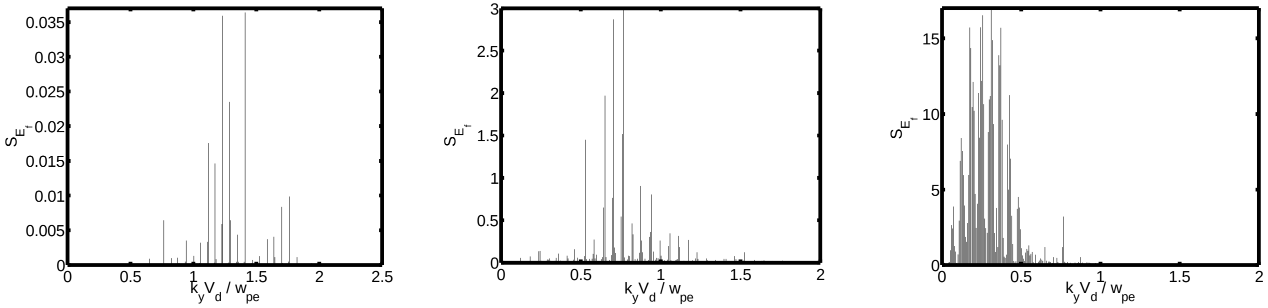
1D azimuthal y PIC models: Ducrocq2006

Author / Year	Characteristics	Assumptions	Findings
Ducrocq 2006	1D-2V(x,y) collisionless	- Ly=6.2 cm - No particle replacement	- Inverse cascade - EVDF flattening

Temporal evolution of the square amplitude of azimuthal field



Power density spectrum



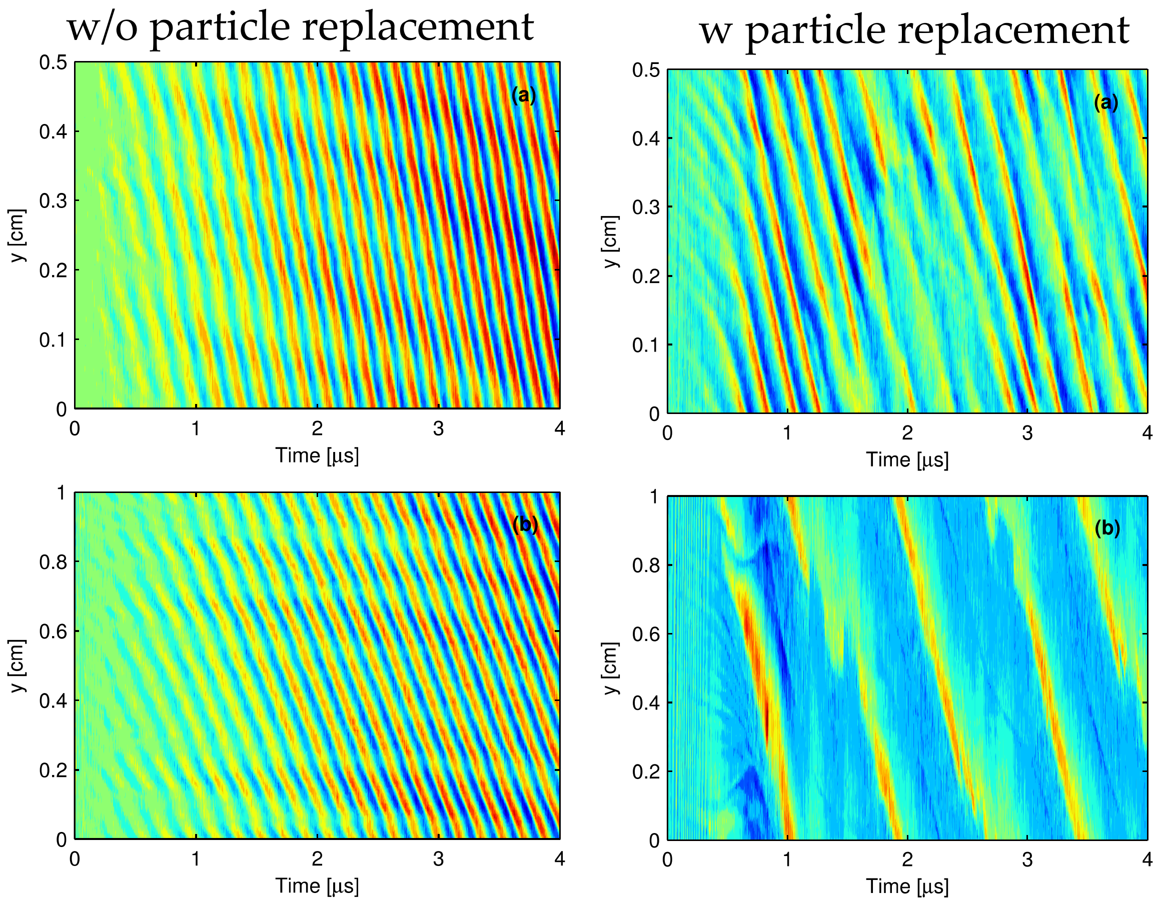
(c) $\omega_{pe}t = 2.4\ 10^3$ (d) $\omega_{pe}t = 5\ 10^3$ (e) $\omega_{pe}t = 7\ 10^3$

- A. Ducrocq, Role des instabilités electroniques de derive dans le transport ́electronique du propulseur a effet Hall, Ecole Polytachnique Paris (2006).
- A. Ducrocq, J. C. Adam, A. Héron, and G. Laval, High-frequency electron drift instability in the cross-field configuration of Hall thrusters, Phys. Plasmas 13, 102111 (2006).

1D azimuthal y PIC models: Lafleur2016

Author / Year	Characteristics	Assumptions	Findings
Lafleur 2016	1D-3V	- Ly=0.5 cm - Particle replacem. (random y; L_{acc}=1 cm) - N_{ppc}=100-1000	- $\mu_{\perp} = 6\, m^2/Vs$ - Monomode

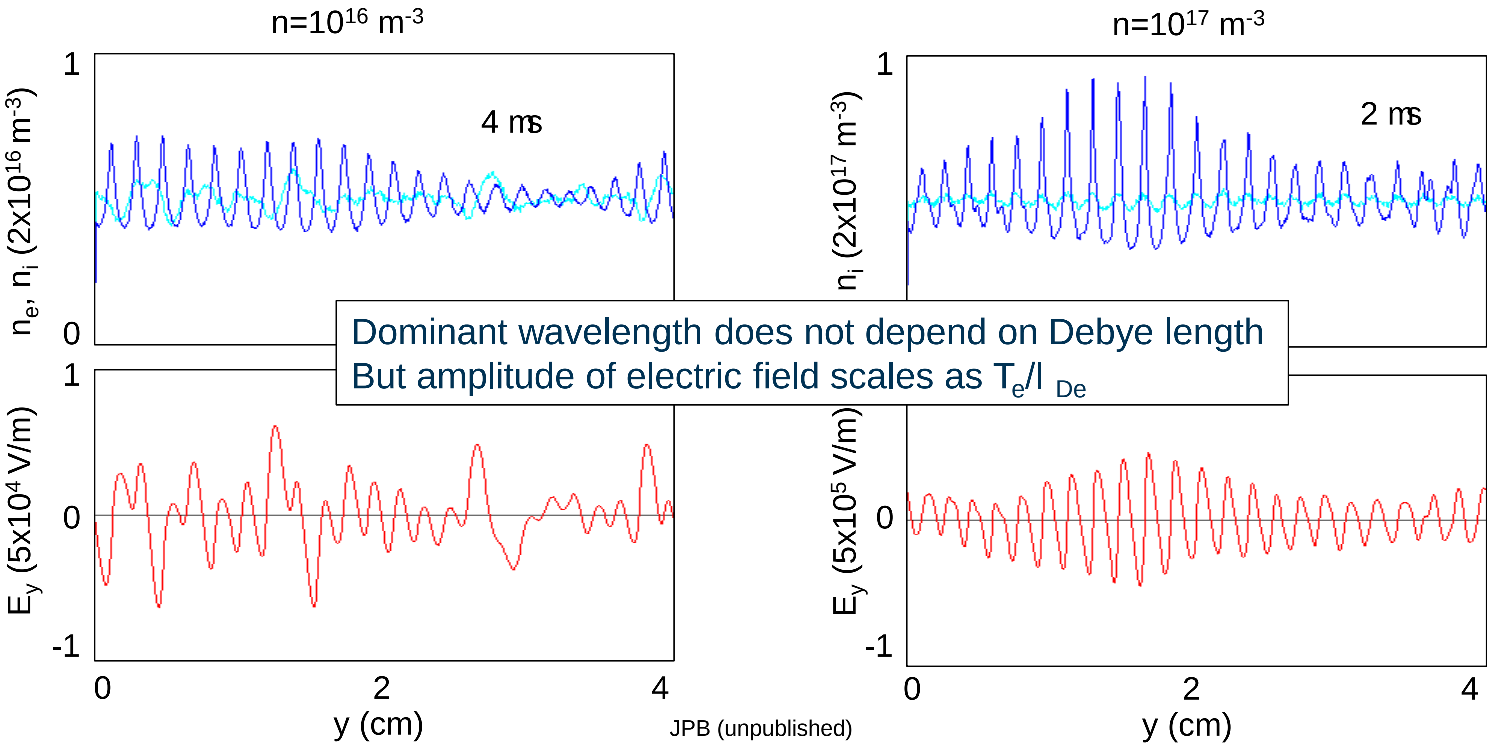
Effect of the azimuthal length Ly



T. Lafleur, S. D. Baalrud, and P. Chabert, Theory for the anomalous electron transport in Hall effect thrusters. I. Insights from particle-in-cell simulations, Phys. Plasmas 23, 053502 (2016)

1D azimuthal y PIC models: Boeuf2014

Author / Year	Characteristics	Assumptions	Findings
Boeuf 2018	1D-3V collisional	- Ly=6 cm - No Particle replacement - Nppc=4000	- Inverse cascade - No IAI transition - $\mu_{\perp} = 0.3\ m^2/Vs$ - Plasma density scaling



Dominant wavelength does not depend on Debye length
But amplitude of electric field scales as T_e/l_{De}

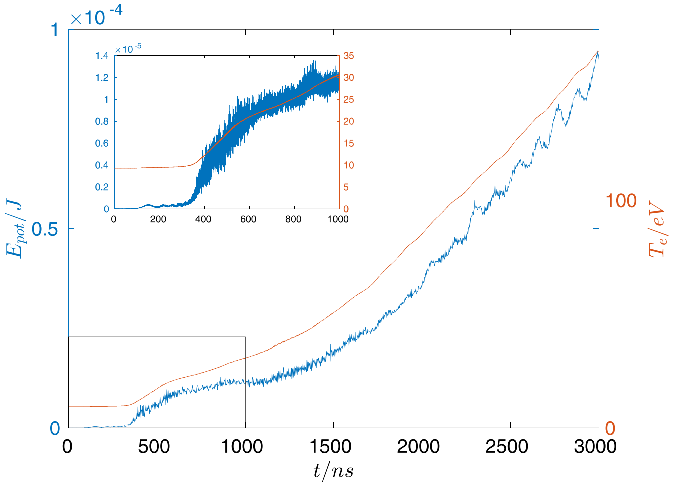
JPB (unpublished)

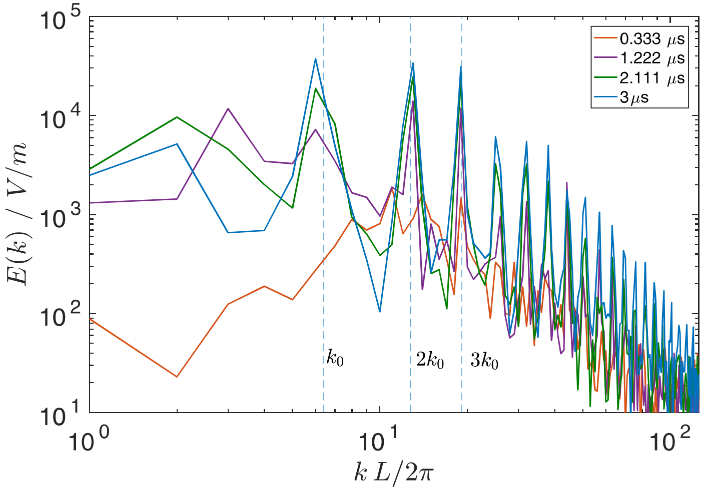
$$k_{ECDI} = \frac{\Omega_{ce}}{v_{ExB}}$$

$$k_{IAI} = \frac{1}{\sqrt{2}\lambda_{De}}$$

1D azimuthal y PIC models: Janhunen2018

Author / Year	Characteristics	Assumptions	Findings
Janhunen 2018	1D-3V	- Ly=4.456 cm - No particle replacement - Nppc=40000	- Inverse cascade - No IAI transition - EVDF flattening - $\mu_\perp = 0.3\ m^2/Vs$



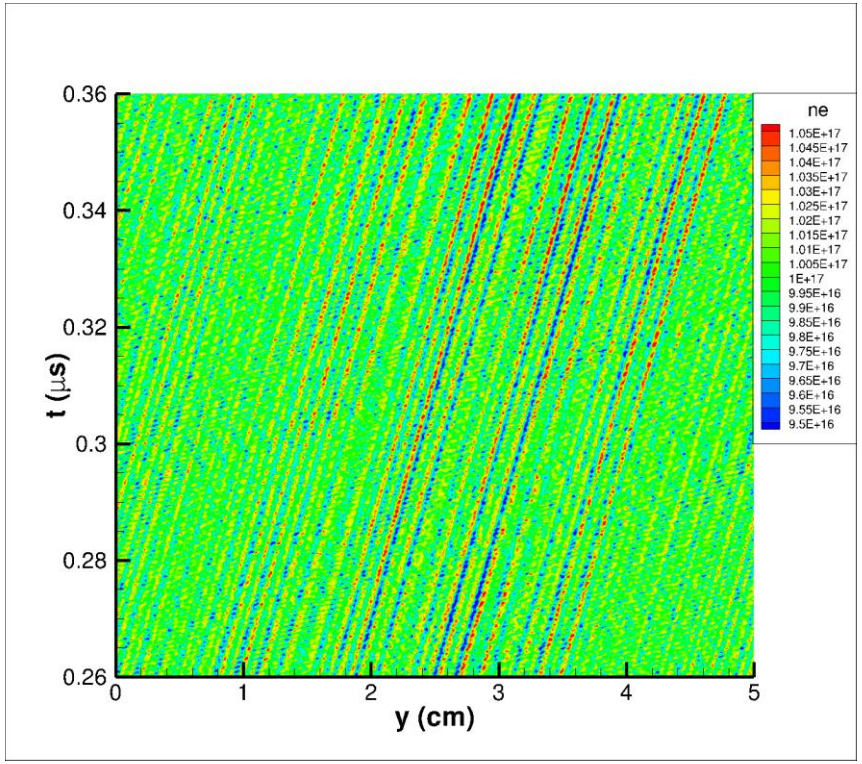


Numerical noise better damped for high-k -> high-k modes better represented,
-> low-k modes need more Nppc

S. Janhunen, A. Smolyakov, O. Chapurin, D. Sydorenko, I. Kaganovich, Y. Raitses, Nonlinear structures and anomalous transport in partially magnetized ExB plasmas, Phys. Plasmas 25, 011608 (2018).

1D azimuthal y PIC models: Taccogna2018

Author / Year	Characteristics	Assumptions	Findings
Taccogna 2018	1D-3V collisionless	- Ly=5 cm - Particle replacement (fixed y) - Nppc=25000	- Inverse cascade - EVDF flattening - No demagnetization - $\mu_\perp = 1\, m^2/Vs$



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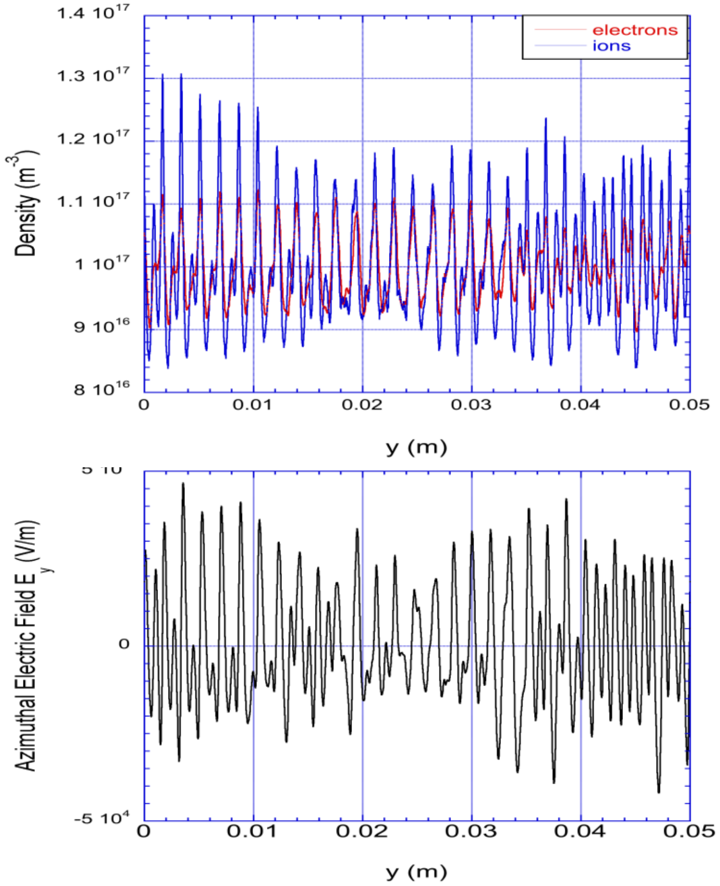
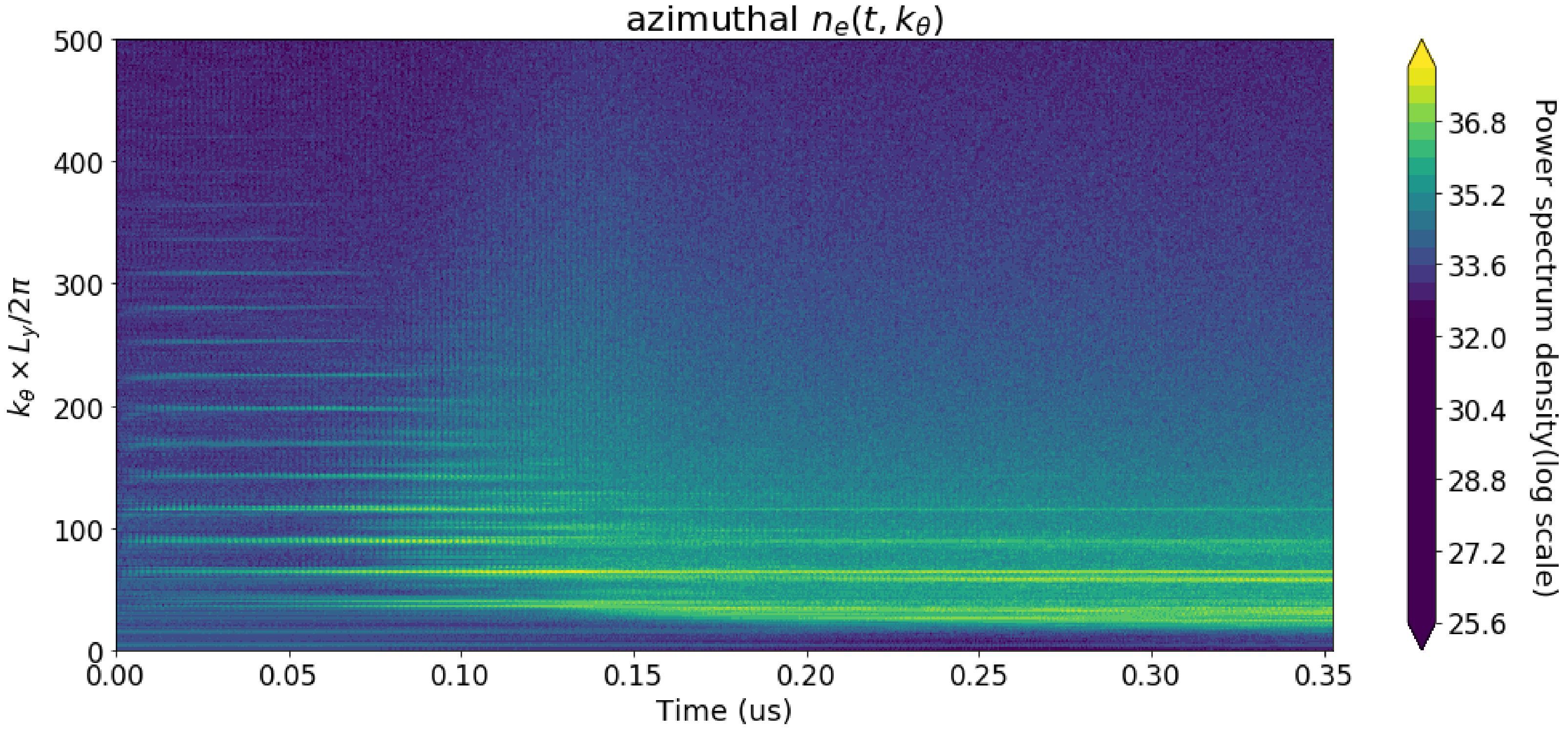
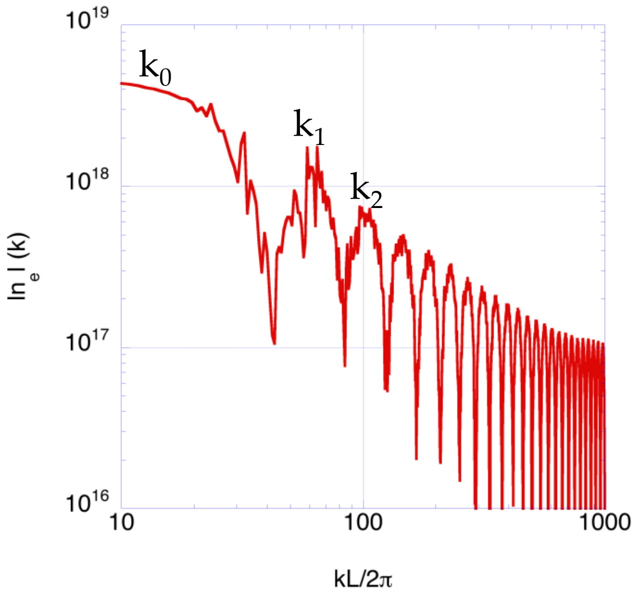


1D azimuthal y PIC models: Taccogna2018

Author / Year	Characteristics	Assumptions	Findings
Taccogna 2018	1D-3V collisionless	Ly=5 cm Particle replacement (fixed y) Nppc=25000	- Inverse cascade - EVDF flattening - No demagnetization - $\mu_\perp = 0.2\ m^2/Vs$





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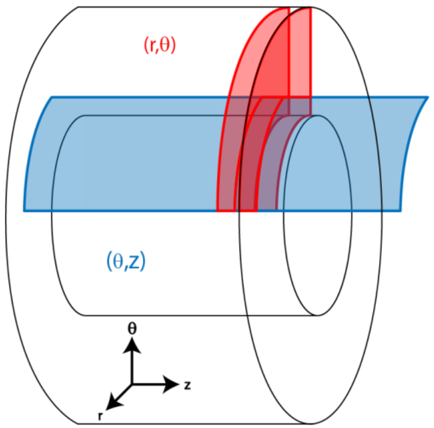
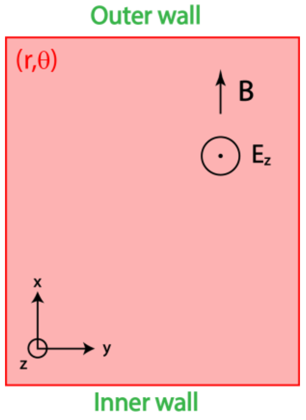
2D radial-azimuthal Models





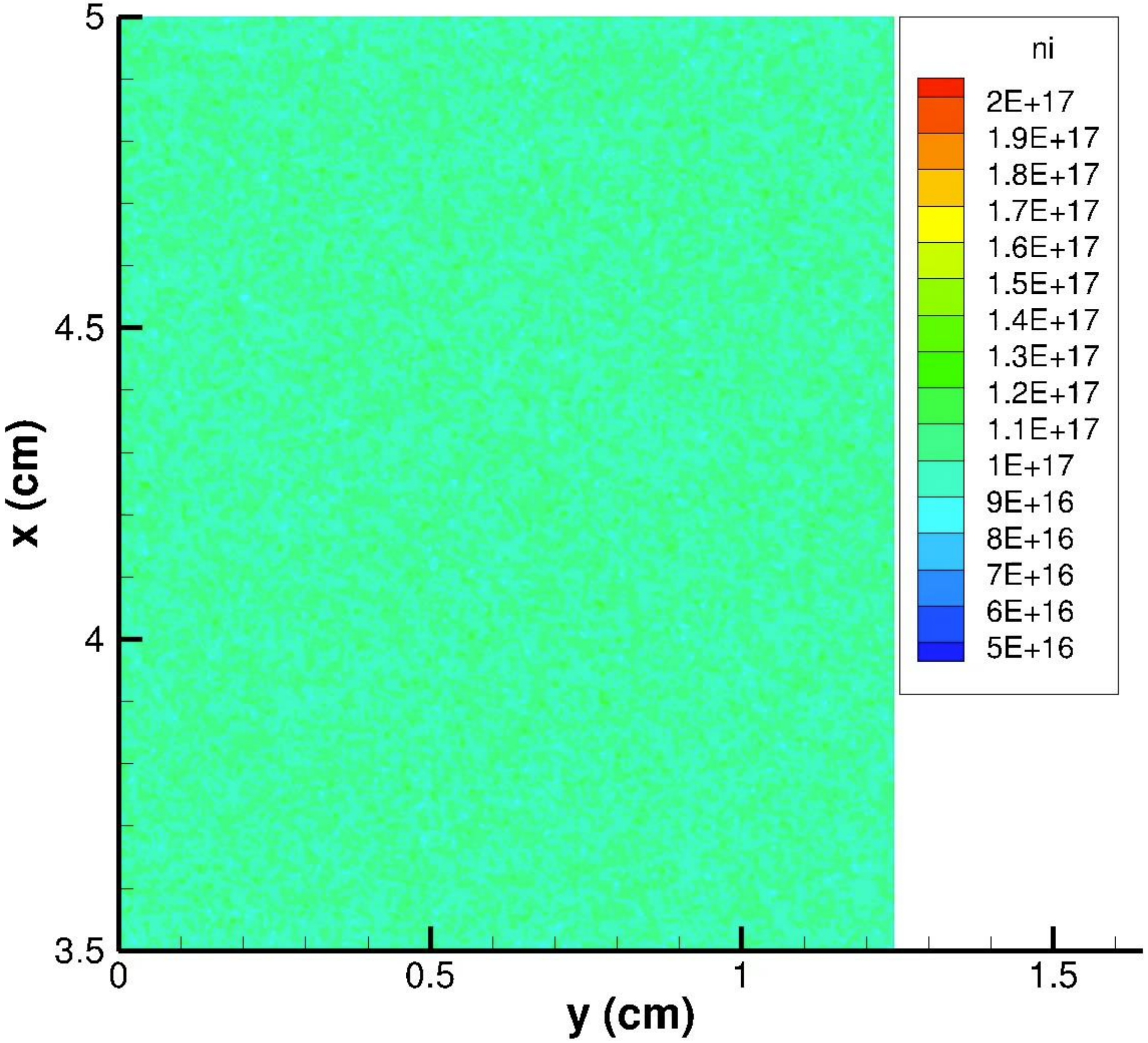
2D radial-azimuthal models

1. Taccogna-Minelli 2007
2. Héron-Adam 2013
3. Croes et al. 2017
4. Hara-Cho 2017
5. Janhunen et al. 2018

- Domain: - radial from inner to outer wall (Lx=1.5 cm);
- - azimuthal: Ly=1.25 cm (cartesian approximation)
- Initial condition: uniform Maxwellian for electrons and drifting Maxwellian (v_{iz}) for ions
- Injection condition: fixed ion number
- Particle replacement (random along y – proportional to n along r)
- Field solve: E negligible inside the material $\left.\frac{\partial\phi(y)}{\partial x}\right|_{x=w} = \pm\frac{\sigma(y)}{\epsilon_0}$
- electron-atom MCC module (only for energy loss)
- electron-wall SEE module (see Presentation NWC session)
- Numerical parameters: - $N_g=N_r x N_\theta=300x250$
  - $N_p/N_g=500$

- F Taccogna, R Schneider, S Longo, M Capitelli, Plasma Sources Sci. Technol. 17 (2), 024003 (2008)
- A. Héron, J. C. Adam, Physics of Plasmas 20, 082313 (2013)
- V. Croes et al., Plasma Sources Sci. Technol. 26 034001 (2017)
- K. Hara, S. Cho, IEPC-2017-495 (2017)
- S. Janhunen et al. Physics of Plasmas 25, 082308 (2018)

2D(x,y) – Ion Density Evolution



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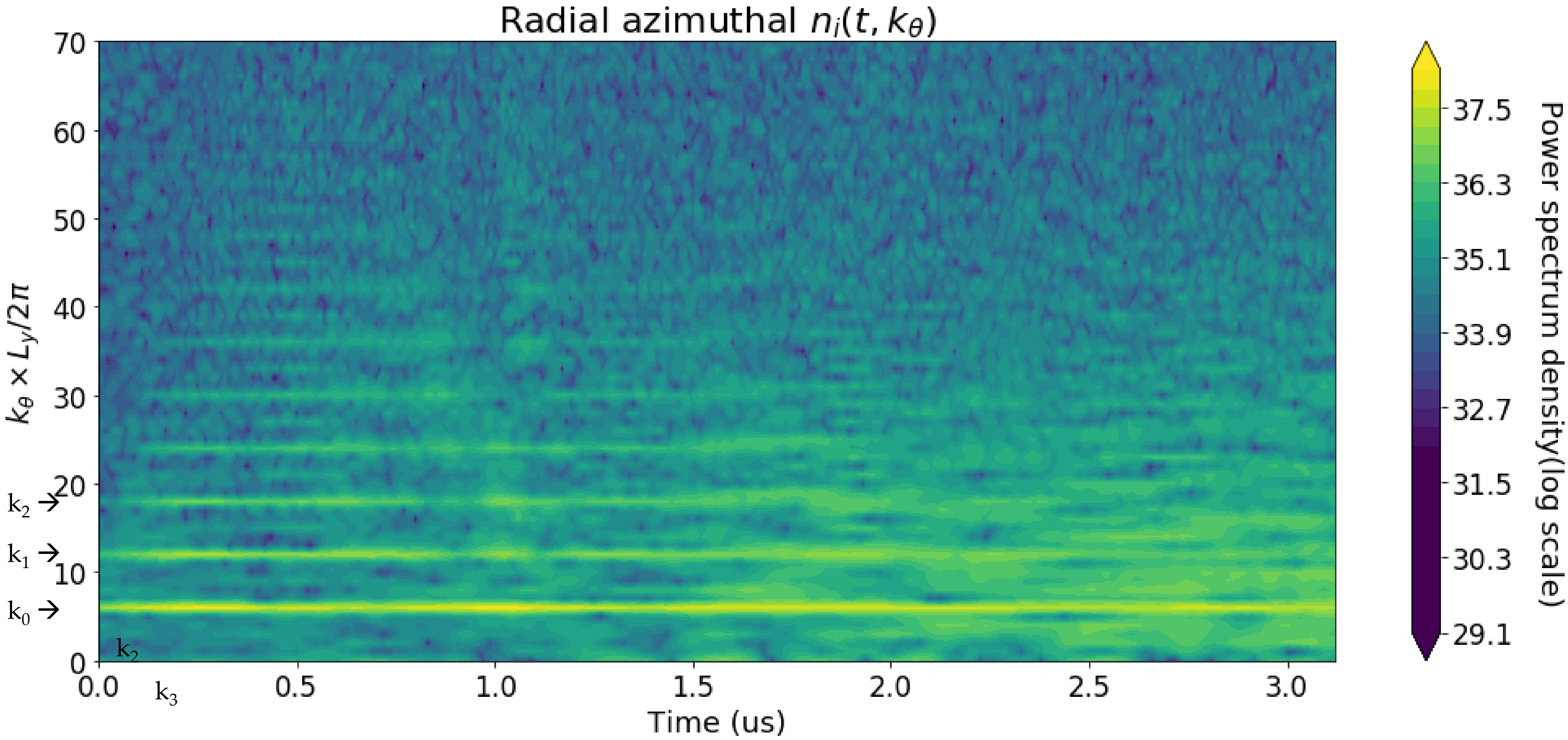
2D(x,y) – Power Spectral Density



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Conclusions

o 1D azimuthal: first preliminary benchmark (Taccogna-Boeuf-Janhunen) shows:

- agreement with no-particle re-injection (no axial boundary);
- with particle re-injection, only the fixed-y replacement works;
- transition to low-k modes but electrons keeps magnetization feature: no ion acoustic transition;
- this is also confirmed by the fact that wavenumber does not scale with Debye length
- mobility is about 0.3-1 m^2/Vs

o Necessity to study the convergence under Ly and Nppc

o 2D radial extension: Necessity to define a test case

o 2D also shows a transition to low-k modes with the presence of a radial modulation (modified two stream instability)