# In LANDMARK : The 2D axial-azimuthal Particle-In-Cell benchmark on ExB discharges

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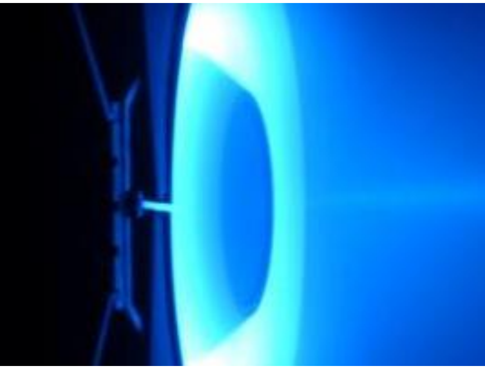
ExB workshop, Princeton University (USA)

Laboratoire de Physique des Plasmas



Thomas Charoy, J-P Bœuf, W. Villafana, A. Tavant, A. Bourdon, P. Chabert
thomas.charoy@lpp.polytechnique.fr

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# Outline

I. Why and how ?

II. Benchmark results

# I) Why and how ?

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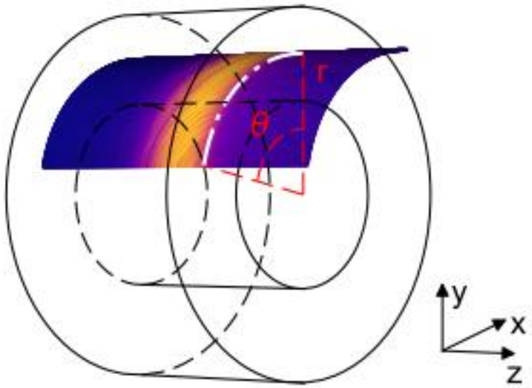
# Context : Hall effect thruster (HET)




Schematic view of the (z, θ) plane in a HET [1]

- Anomalous transport in the axial direction
- Instability propagation in the azimuthal direction
- 2D PIC simulations of axial-azimuthal directions (z,θ) are rare [1] [2]

[1] Trevor Lafleur, The role of instability-enhanced friction on ”anomalous” electron and ion transport in Hall-effect thrusters, Plasma Sources Sci. Technol. 27 (2018) 015003
[2] A. Héron, J. C. Adam, and G. Laval. Study of stationary plasma thrusters using two-dimensional fully kinetic simulations. Phys. Plasmas 11, 295, (2004).

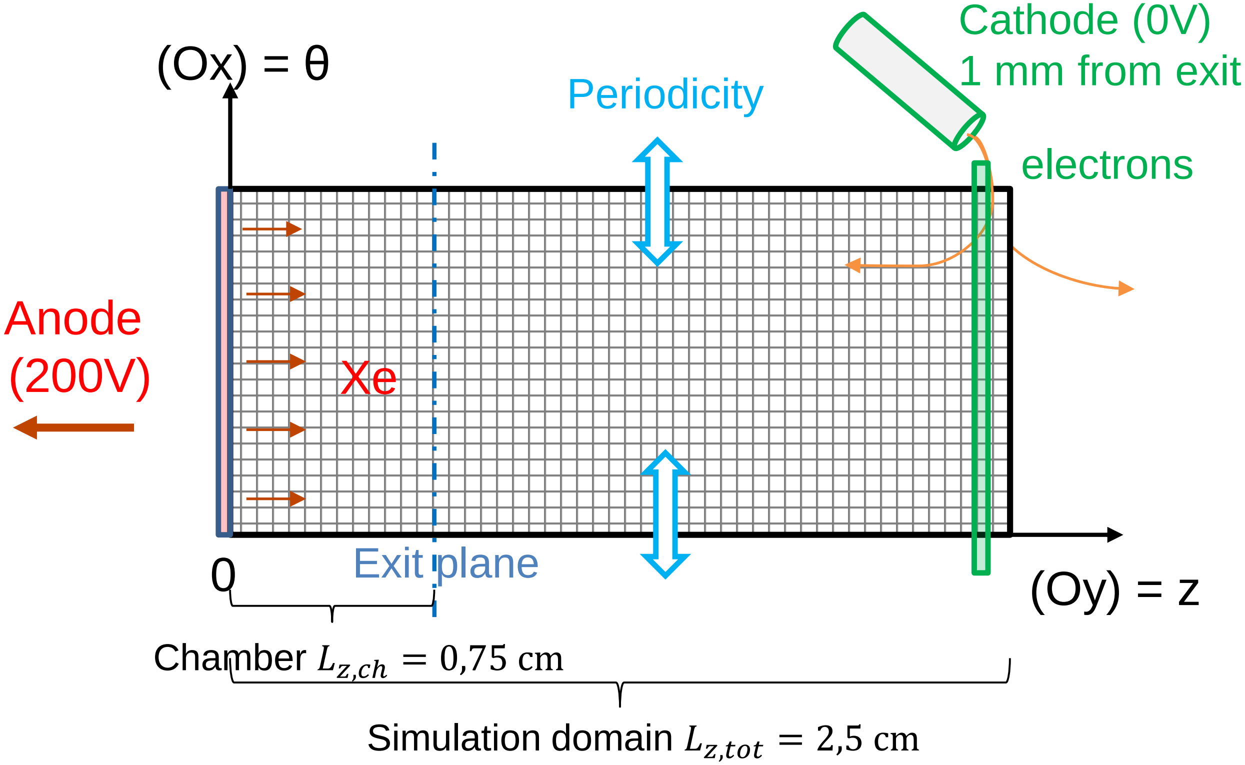
# Benchmarking with LPPic

- Recent study on this issue with a code developed by Bœuf and al. [1]
- Need to define a benchmark case to validate 2D PIC codes : see which effects give insights on the physics and which are only numerical ones

➔ Systematic comparison of our code results with the one of the quoted paper and those from W. Villafana (AVIP - CERFACS)

[1] J.P. Bœuf and L.Garrigues, *EXB Electron Drift Instability in Hall thrusters : Particle-In-Cell simulations vs. Theory,* Phys. Plasmas 25 061204 (2018)

# Benchmark description




- Mesh : 256 x 500
- $dt = 5.10^{-12}\ s$
- $N_a = 5000$
- $N_{part/cell} = 280$
- $T_e = 10\ eV$
- $T_i = 0{,}5\ eV$
- $N_{load\ balancing} = 30\ N_a$
- $N_{subcycling} = 11\ dt$
- Fixed magnetic field
- Fixed ionization profile
- No collision

NB : The number of particles per cell is normally 280 but we've seen that for 50, it gives similar results

# II) Benchmark results

# A) Case J = 400 A/m²

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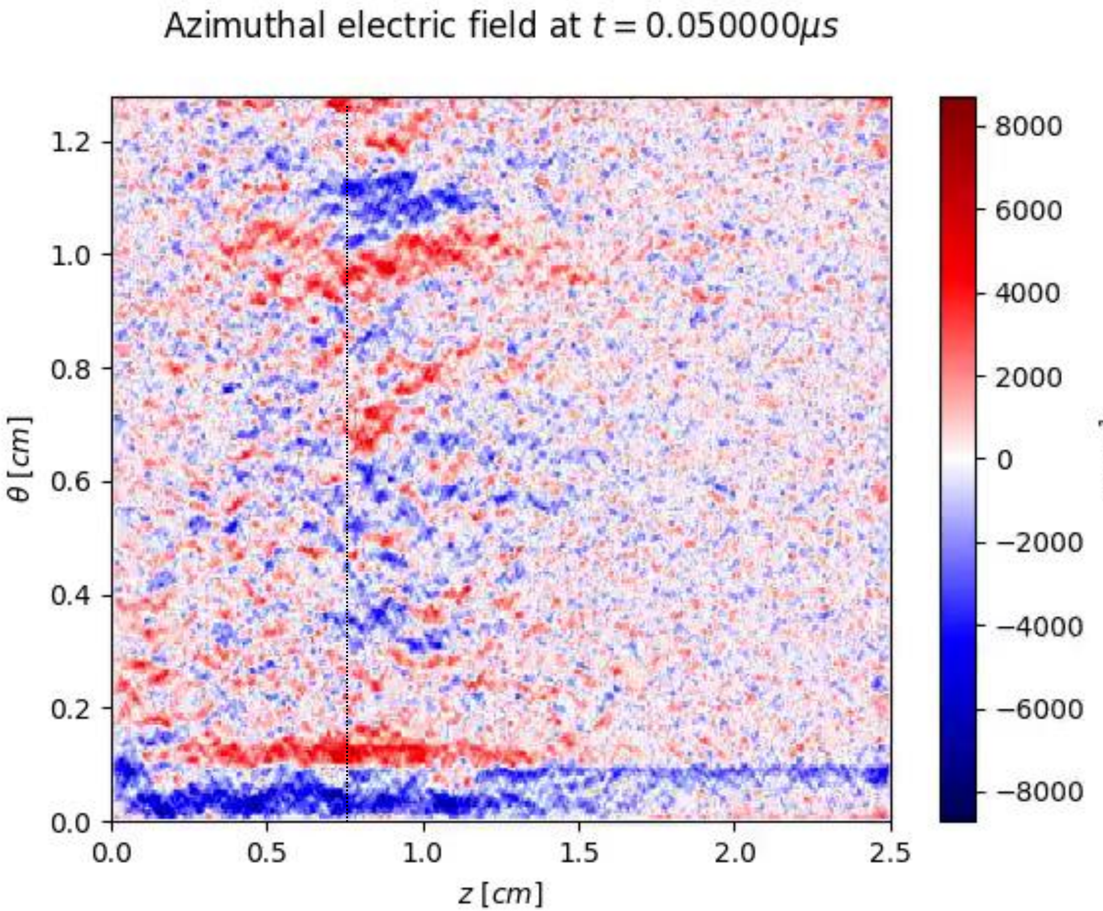
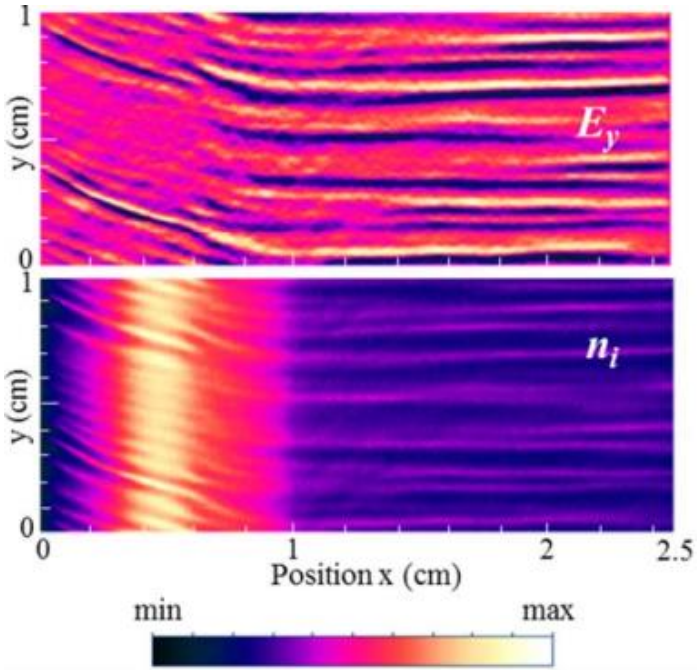
# First insight on azimuthal instabilities

Time evolution of $E_\theta$ ($B_{max}$ at 0.75 cm)

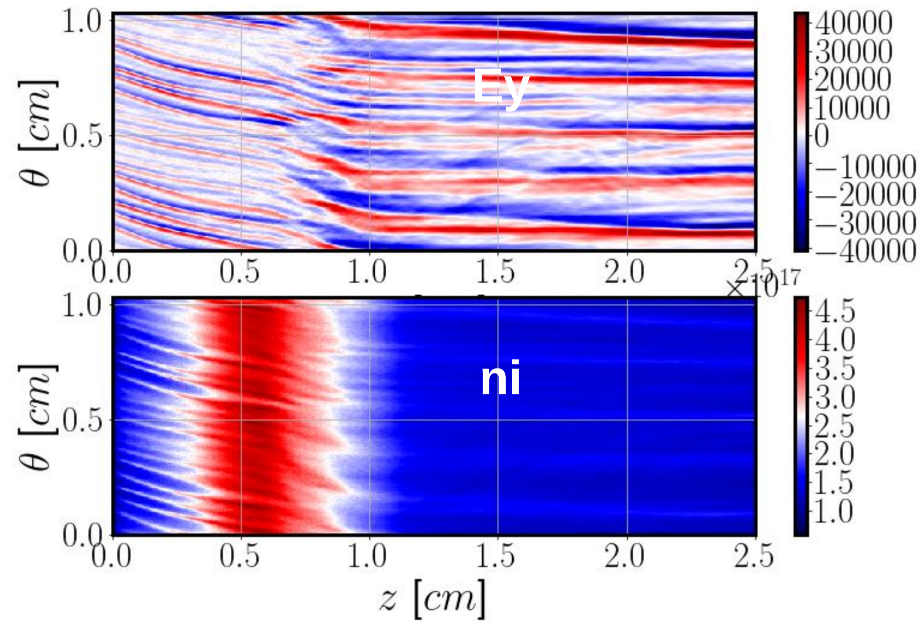


# 2D maps - Azimuthal electric field and ion density

J.P. Bœuf [1]

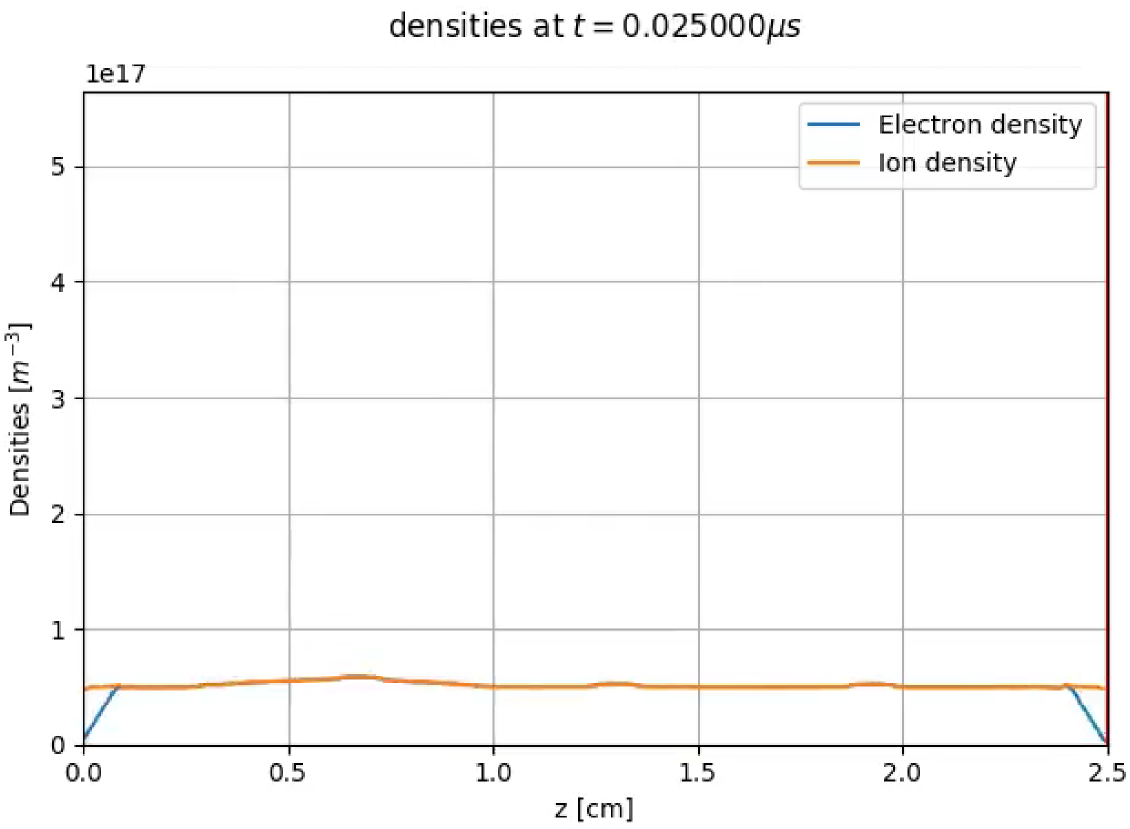



LPPic




[1] J.P. Bœuf and L.Garrigues, *EXB Electron Drift Instability in Hall thrusters : Particle-In-Cell simulations vs. Theory*, Phys. Plasmas 25 061204 (2018)

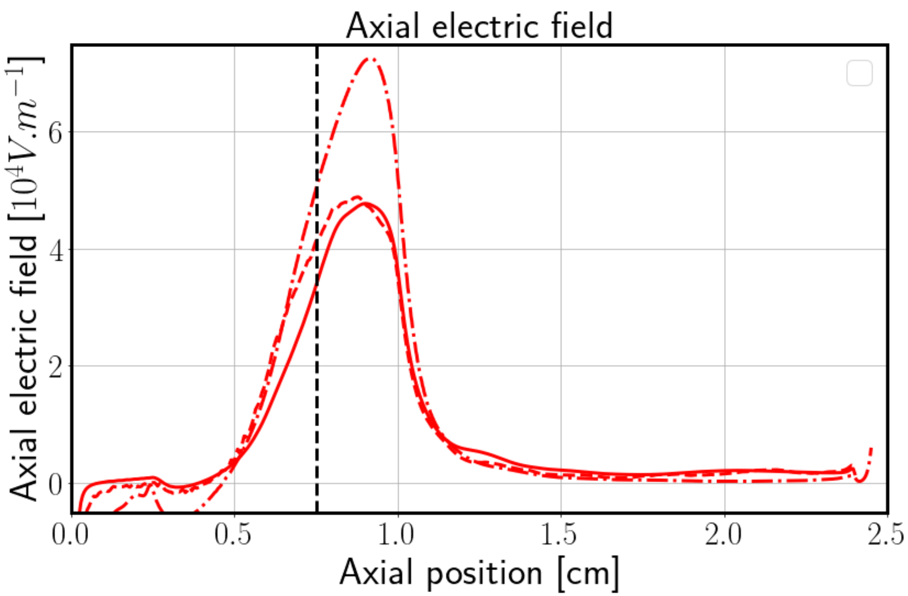
# Temporal evolution of densities

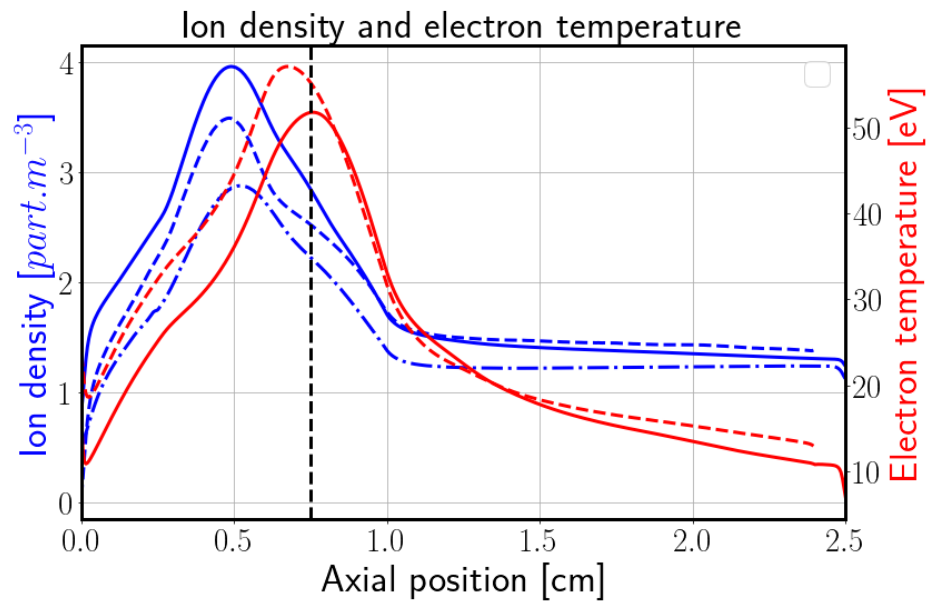



➔ **Stationary state reached around t ~ 10 µs**

# Axial electric field, Ion density & Electron temperature

—— : LPPic - - - - : Bœuf - — - : AVIP CERFACS ($T_e$ not shown)

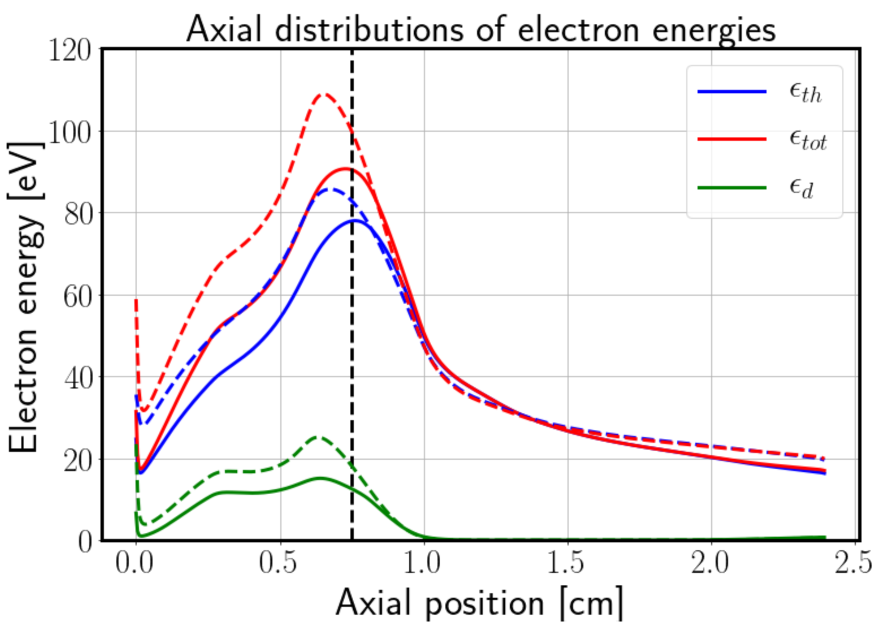


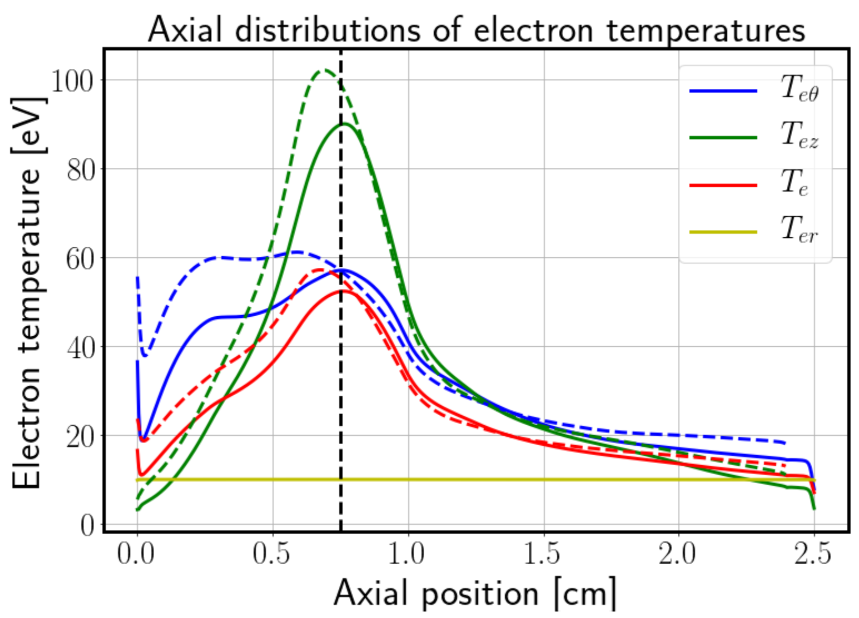




*Black dashed line = magnetic field maximum position*

# Electron energies & temperatures

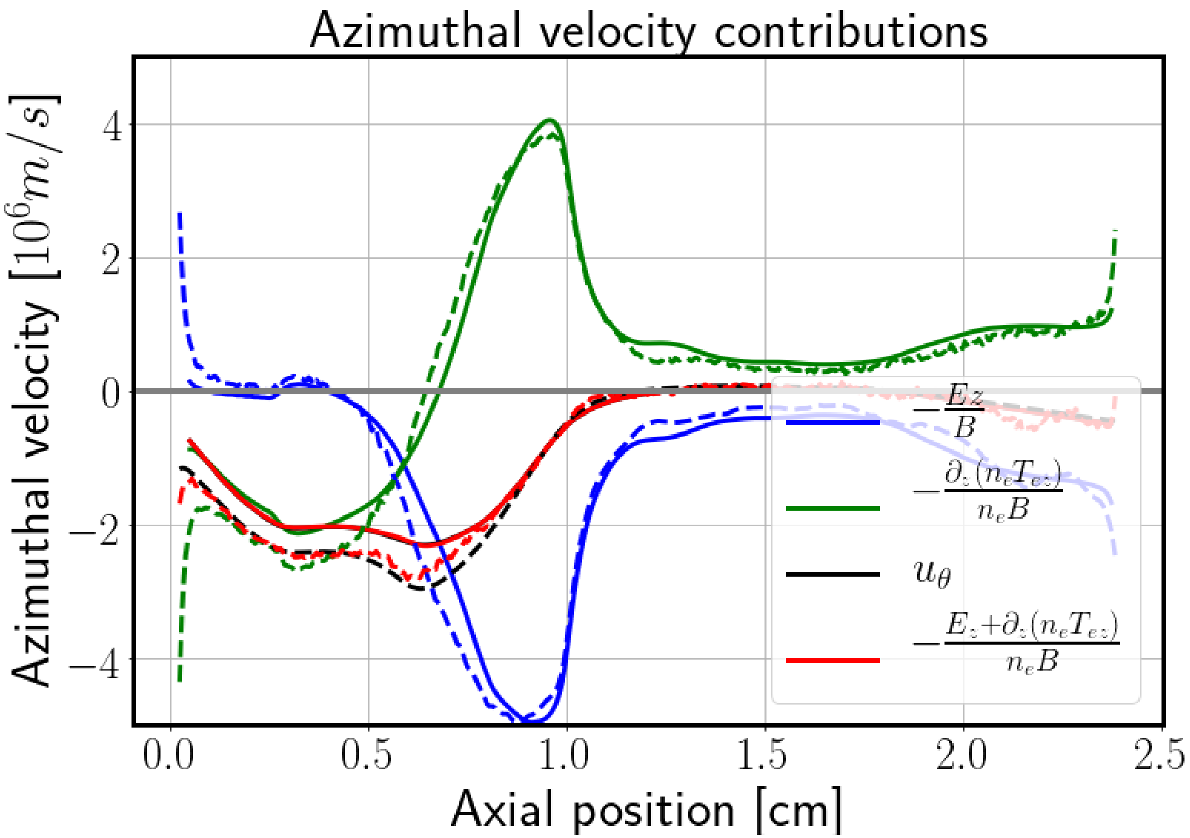
—— : LPPic  - - - - : Bœuf



# Azimuthal velocity contributions

——— : LPPic ---- : Bœuf



# A) Where these differences can come from ?

- Temporal averages differents (here, last 160 samples of the simulation i.e. ~ 4 μs)
- Azimuthal length longer (1,28 cm > 1 cm)
- Ionization model (different randomization : global or local)
- Ionization scattering included or not ?
- Random number generator : necessary to validate on He benchmark [1]

[1] M. Turner, A. Derzsi, Z. Donko, and T. Lafleur, "Simulation benchmarks for low pressure plasmas: capacitive discharges," Phys. Plasmas, vol. 20, no. 1, (2013)

# B) Electron Cyclotron Drift Instabilities (ECDI)

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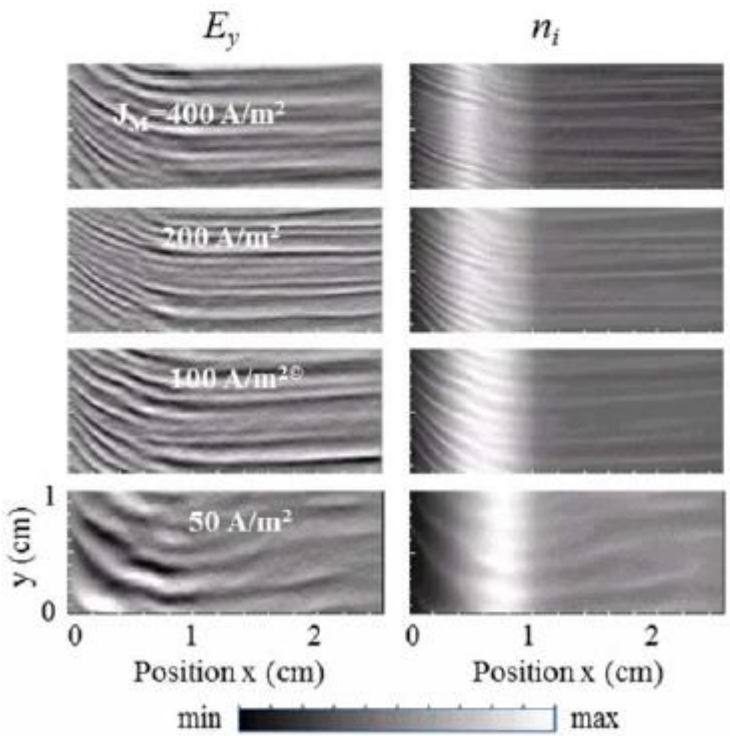
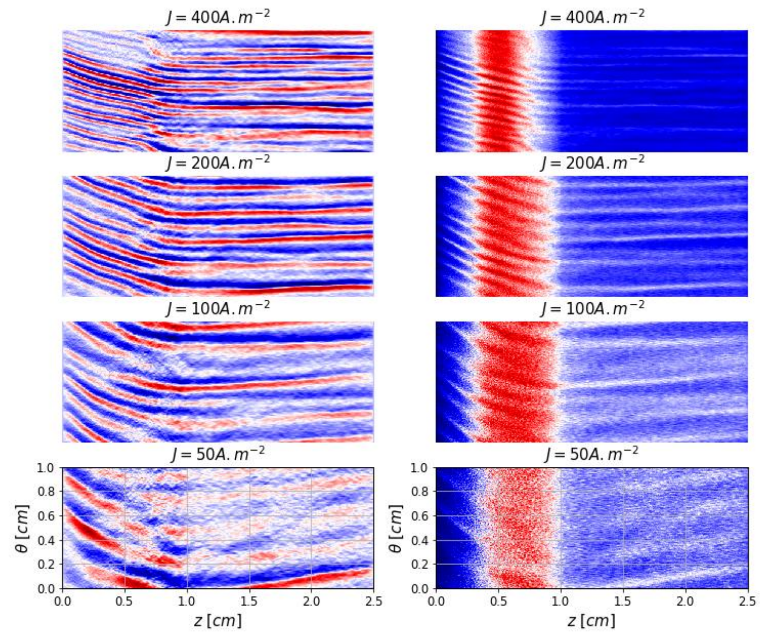
# Variation of current density J

J.P. Bœuf [1]




LPPic ($N_{part/cell}$ = 50)



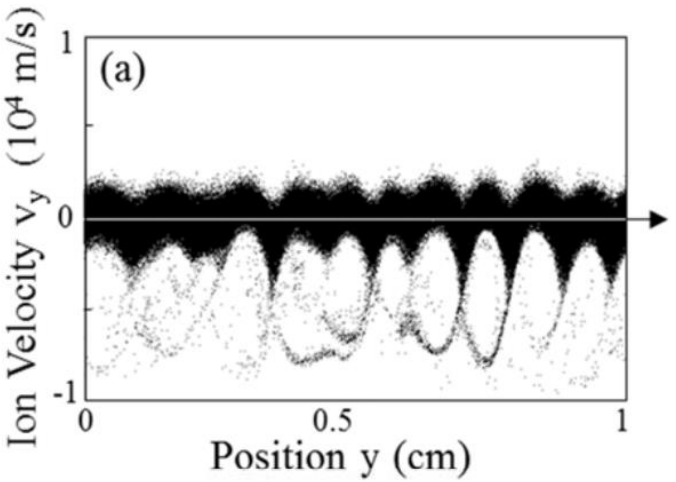

$$\lambda = 2\pi\sqrt{2}\,\lambda_{De} \quad \text{with} \quad \lambda_{De} = \sqrt{\frac{\varepsilon_0 T_e}{|q| n_e}}$$


[1] J.P. Bœuf and L.Garrigues, *EXB Electron Drift Instability in Hall thrusters : Particle-In-Cell simulations vs. Theory*, Phys. Plasmas 25 061204 (2018)

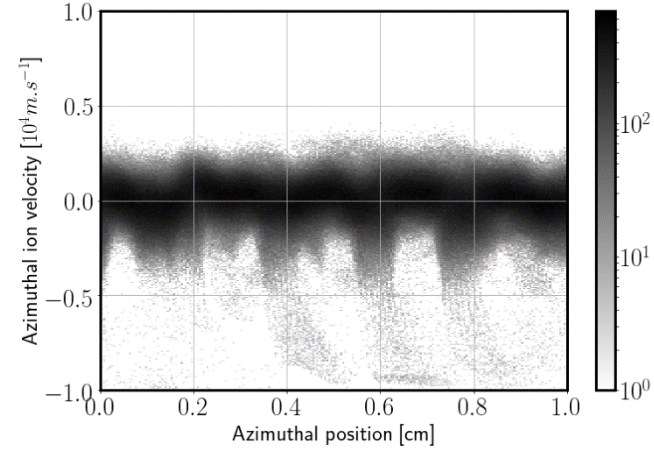
# Ion trapping (J=400 A/m²)

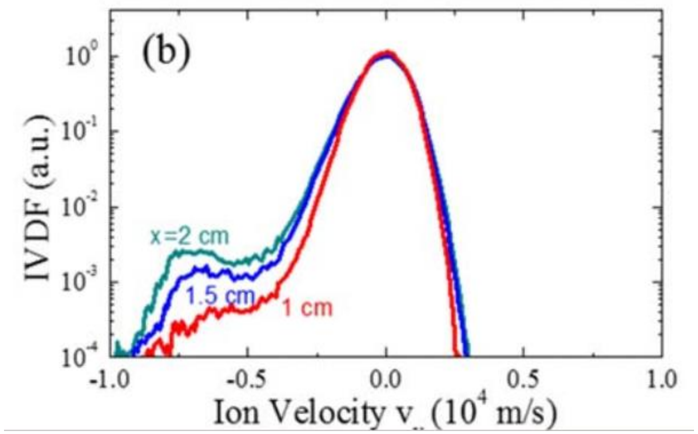
J.P. Bœuf [1]

LPPic

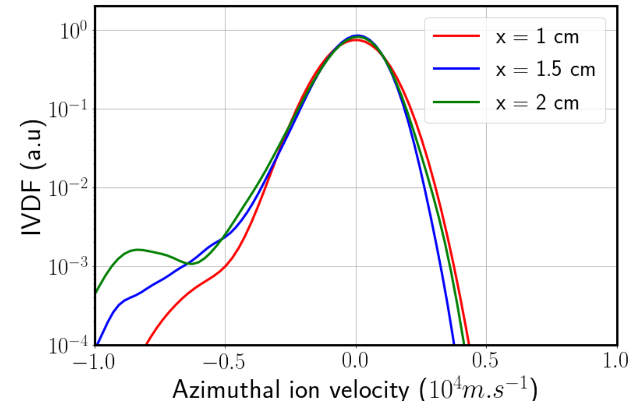



Azimuthal ion phase space between z=1,75 and 2 cm



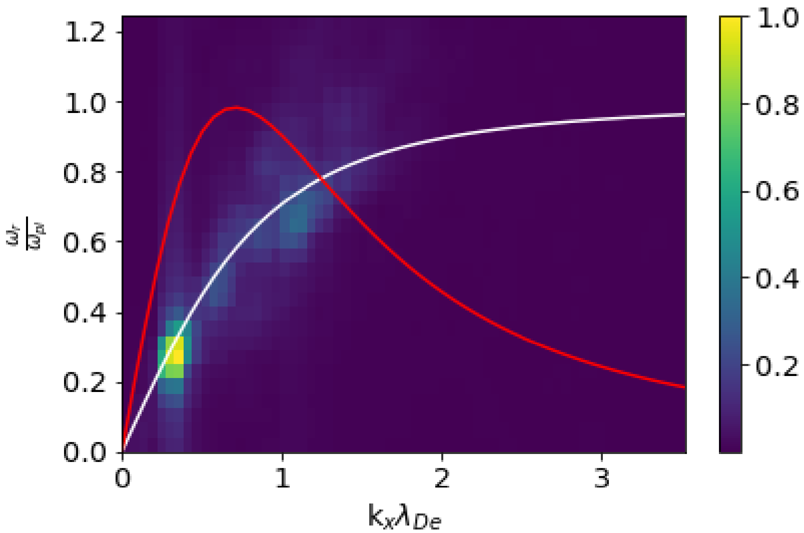




IVDF for azimuthal direction, at 3 different axial positions



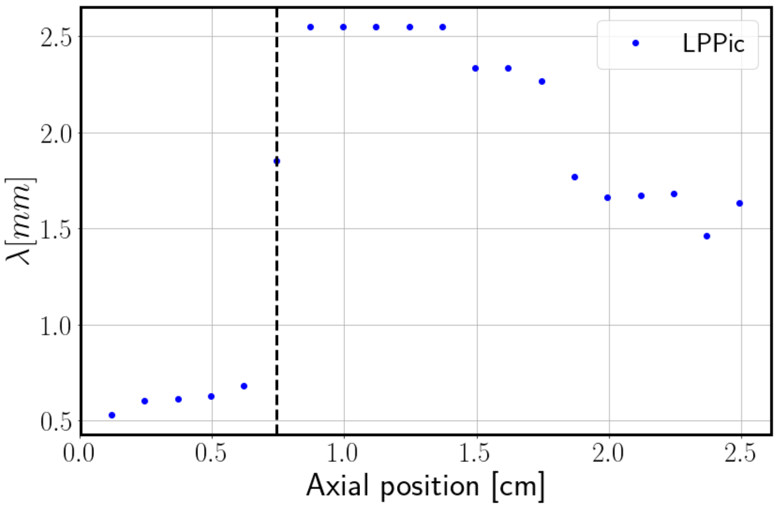

[1] J.P. Bœuf and L.Garrigues, *EXB Electron Drift Instability in Hall thrusters : Particle-In-Cell simulations vs. Theory*, Phys. Plasmas 25 061204 (2018)

# ECDI analysis (J=400 A/m²)




**2D FFT of $E_\theta$ at z = 1 cm**

*White : dispersion relation for modified ion acoustic approximation [1]*
*Red : growth rate (rescaled) with [1]*




**Instability wavelength = f(axial position)**

- It seems that we get a different wavelength than Bœuf and al. at z = 1cm ($\lambda_{Boeuf} \sim 1\ mm$) BUT $\lambda_{Boeuf}$ was estimated roughly

➔ Need to investigate more


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

# Conclusion

✓ The preliminary results show a good correspondance for most of the plasma characteristics.

▲ However, it is not enough for a proper benchmarking ! The differences needs to be at least < 5%.

- ➢ Necessary to explicit all the parameters properly (input and post processing tools)
- ➢ Maybe more relevant to simplify the cathodic injection and do other parametric verifications (Ionization profiles, …)
- ➢ Instability characteristics need to be investigated more deeply

# Thanks for your attention !

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# Annexes

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# Case description

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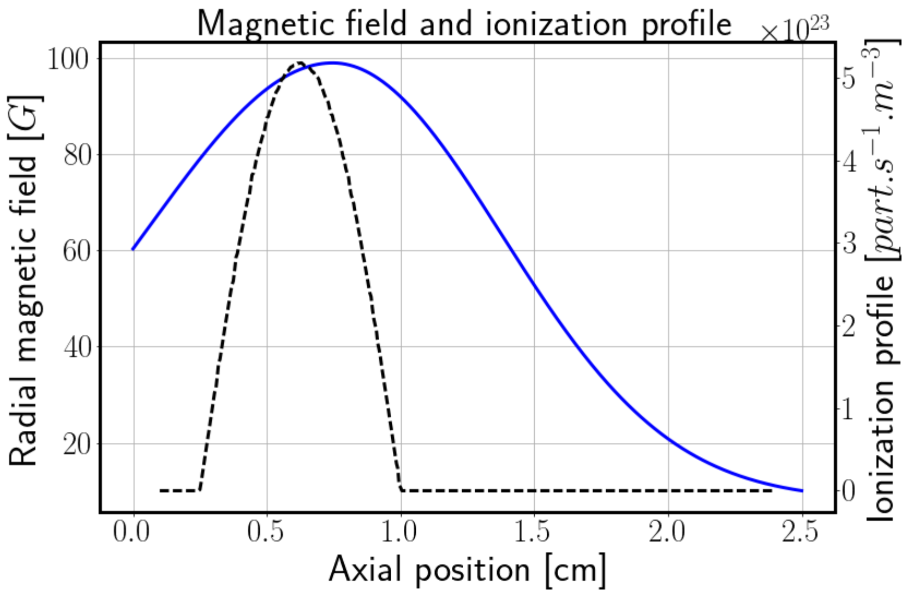
# A) Ionization & B field profiles




- **Fixed ionization profile S :**

$$S(x) = S_{max}\cos(\pi\frac{x - x_m}{x_2 - x_1}) \text{ for } x_1 \leq x \leq x_2$$

Maximum determined by the value of J :

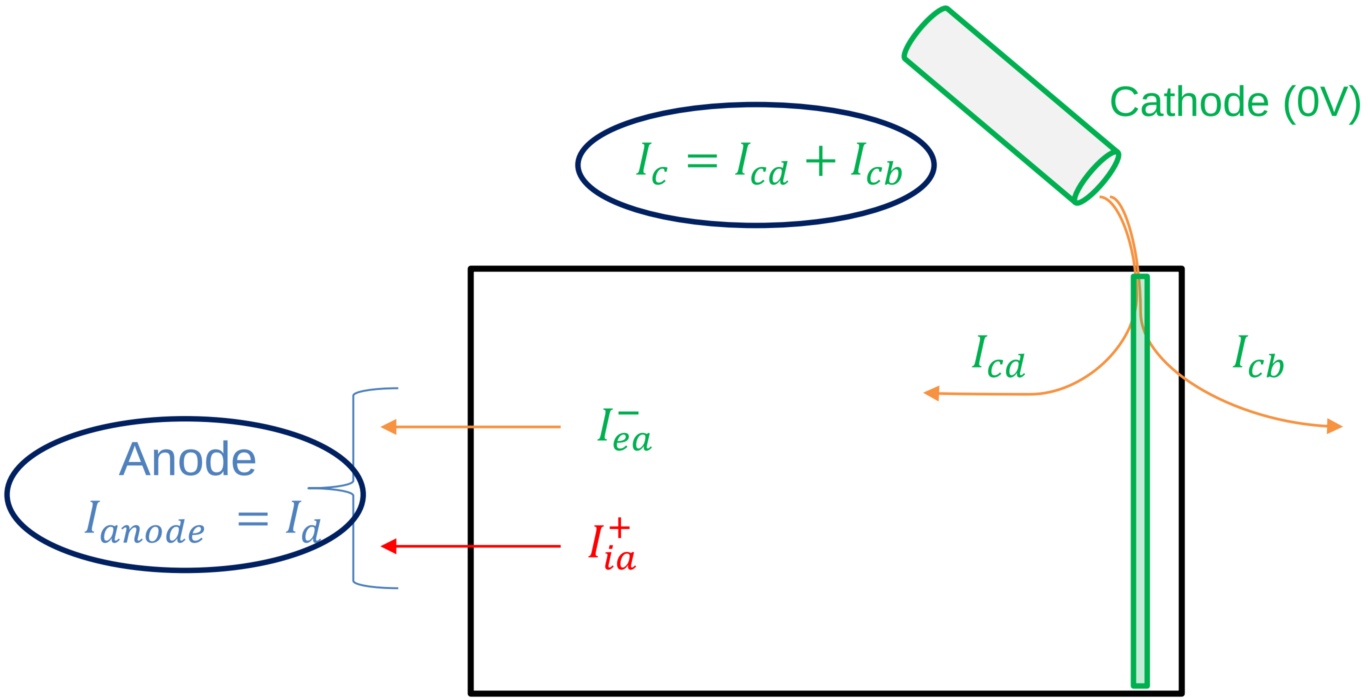
$$J = e\int_0^{L_z} S(x)dx = \frac{2}{\pi}(x_2 - x_1)eS_{max}$$

- **Fixed magnetic profile B :**

$$B(x) = a_k \exp\left(-\frac{(x - x_{Bmax})^2}{2\sigma^2}\right) + b_k$$

- **No collision module**

# A) Charge injection & currents




- $\boldsymbol{I_c = I_a}$ **=>** $\boldsymbol{N_{e,emi} = \Delta t \times I_c}$
- Uniform injection along θ
- Full-Maxwellian distributions in every direction

# A) Boundary condition for potential

$$\varphi'(x,y) = \varphi(x,y) - \frac{y}{y_{inj}}\overline{\varphi_{inj}}$$

Where :

- $\varphi$ solution of Poisson : $\Delta\varphi = -\frac{e}{\varepsilon_0}\rho$

  (with $\varphi(x,0) = V_a \; and \; \varphi(x,L_z) = 0$ )

- $\overline{\varphi_{inj}}$ azimutally averaged potential at injection plane :

$$\overline{\varphi_{inj}} = \frac{1}{L_\theta}\int_0^{L_\theta}\varphi(0,y_{inj})$$

Then, $\varphi'(x,y)$ used to compute E.

# Stationary state

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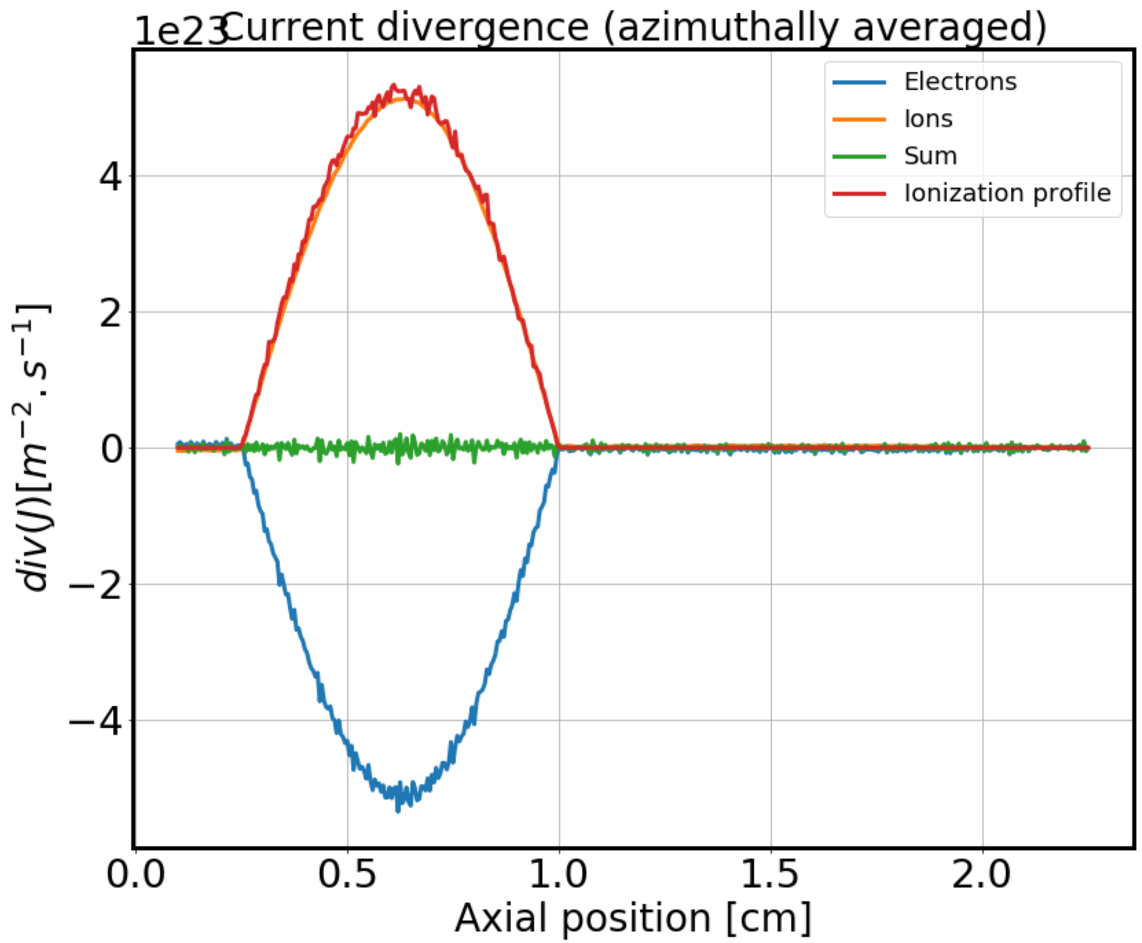
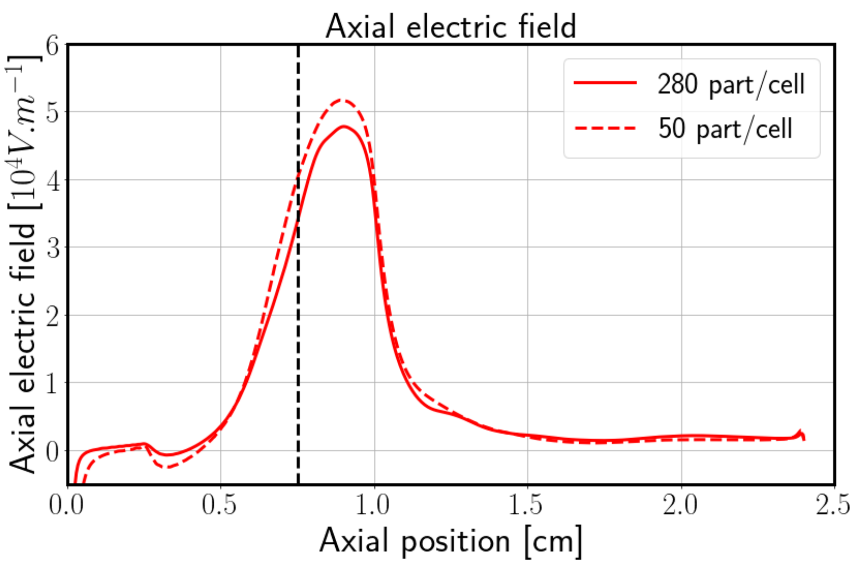
# Current equality

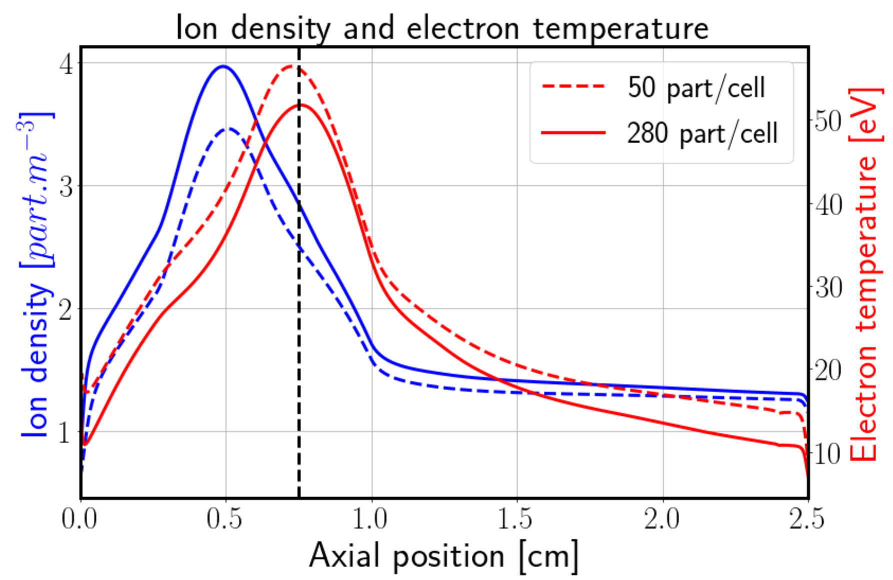


# Influence of some parameters

# Influence of N_part/cell

**If only 50 particles/cell instead of 280**




➔ Very small changes !

# Influence of azimuthal length