Simulation of Hall thruster 3D plumes with EP2PLUS

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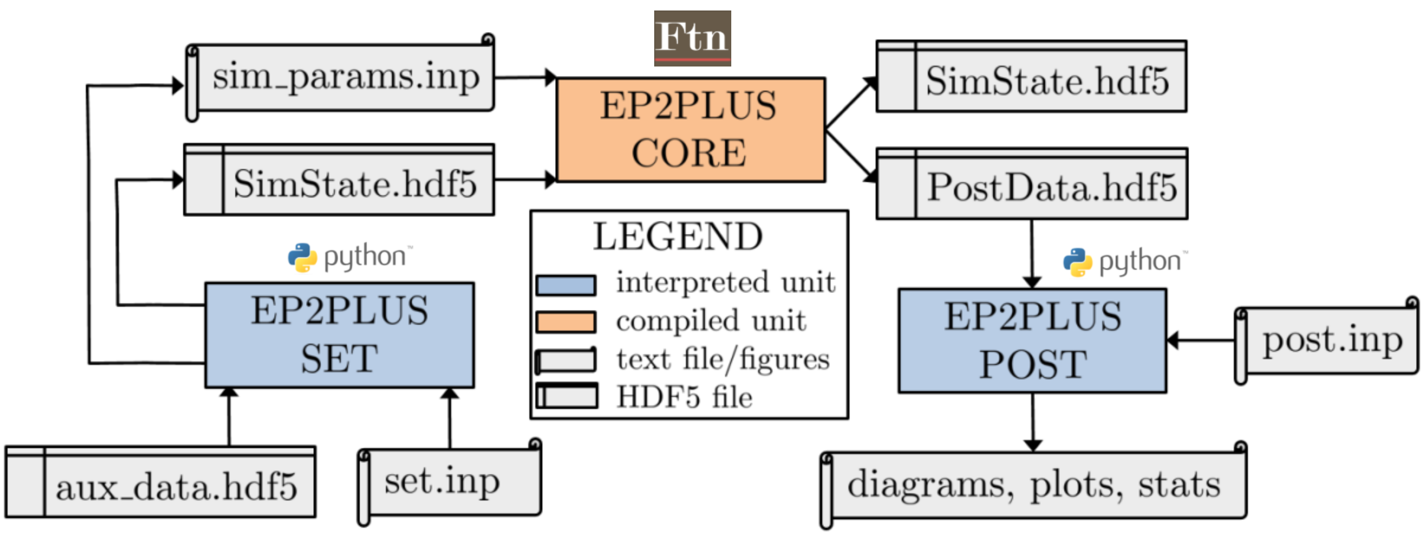
EP2PLUS and research goals

- EP2PLUS is a **3D code** for S/C-plasma plume interaction, featuring:
  - Industry-level standards
  - **Hybrid approach** → PIC ions/neutrals, and fluid electrons
  - Electron model solves for both **electric currents** and **magnetic field effects**
  - **Particle-material walls interaction** (reflection, recombination, sputtering, etc…)



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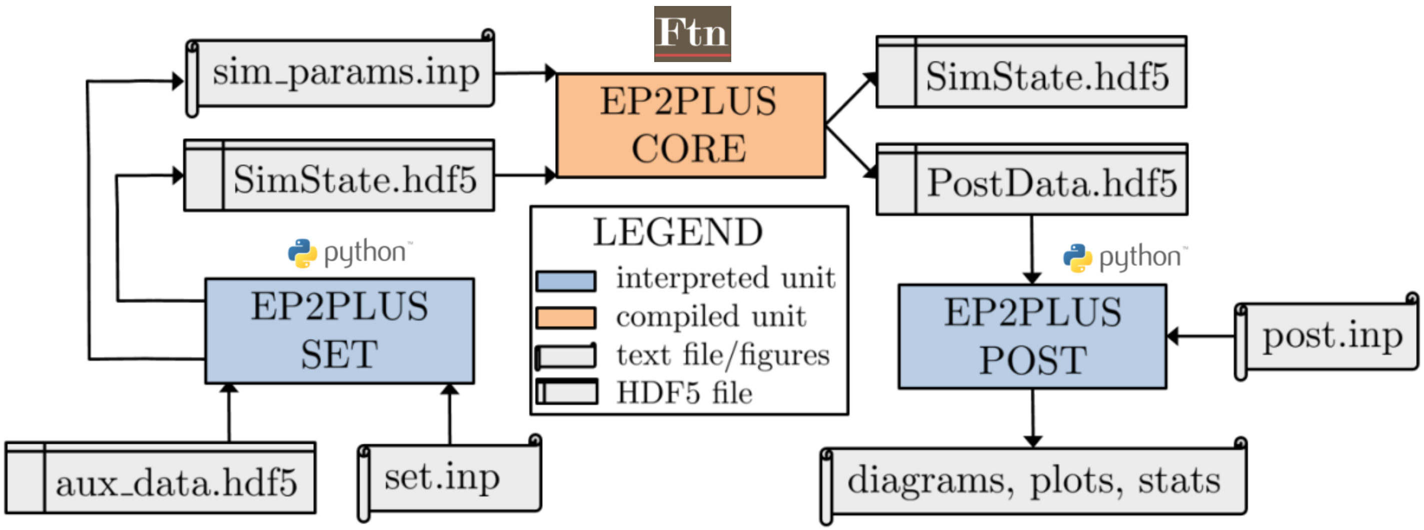
- EP2PLUS is here applied to a **magnetized HET plasma plume** simulation in order to:
  - Study the applicability of a **polytropic electron law** in a HET near-plume
  - Assess the **3D effects** of a **lateral neutralizer position**



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The magnetized electron fluid model

- Assumptions
  - Stationary plume properties: $\frac{\partial}{\partial t} = 0$
  - Inertialess electrons: $m_e \ll m_i$
  - Isotropic electrons: $\bar{\bar{P}}_e = p_e \bar{\bar{I}}$
  - Quasineutrality: $n_e = \sum_s Z_s n_s$
  - Polytropic electrons: $T_e = T_{e0}(n_e/n_{e0})^\gamma$ $\rightarrow \nabla h_e = \frac{\nabla p_e}{n_e} \rightarrow h_e = \frac{\gamma T_{e0}}{\gamma - 1}\left[\left(\frac{n_e}{n_{e0}}\right)^{\gamma-1} - 1\right]$

barotropy function h_e

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- Considered equations:
  - Electric current continuity : $\nabla \cdot (\boldsymbol{j}_e + \boldsymbol{j}_i) = 0$
  - Electron momentum balance : $0 = e n_e \nabla\phi - \nabla p_e + \boldsymbol{j}_e \times \boldsymbol{B} + \frac{m_e \nu_e}{e}(\boldsymbol{j}_e + \boldsymbol{j}_c)$

known values from PIC

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known values from PIC

- In terms of a thermalized potential $\Phi = \phi - \frac{h_e}{e}$, this system reduces to:

$$\bar{\bar{\mathrm{K}}} : \nabla\nabla\Phi + \nabla\Phi \cdot \left(\nabla \cdot \bar{\bar{\mathrm{K}}}\right) + \bar{\bar{\mathrm{K}}} \cdot \nabla\Phi \cdot \nabla \ln\sigma_e = \sigma_e^{-1} \nabla \cdot \left(\boldsymbol{j}_i - \bar{\bar{\mathrm{K}}} \cdot \boldsymbol{j}_c\right)$$

$\bar{\bar{\mathrm{K}}}$ = conductivity tensor

- Once Φ is known, electron current density and electric potential are obtained as:

$$\boldsymbol{j}_e = -\bar{\bar{\mathrm{K}}} \cdot (\nabla\Phi + \boldsymbol{j}_c) \quad ; \quad \phi = \Phi + \frac{h_e}{e}$$

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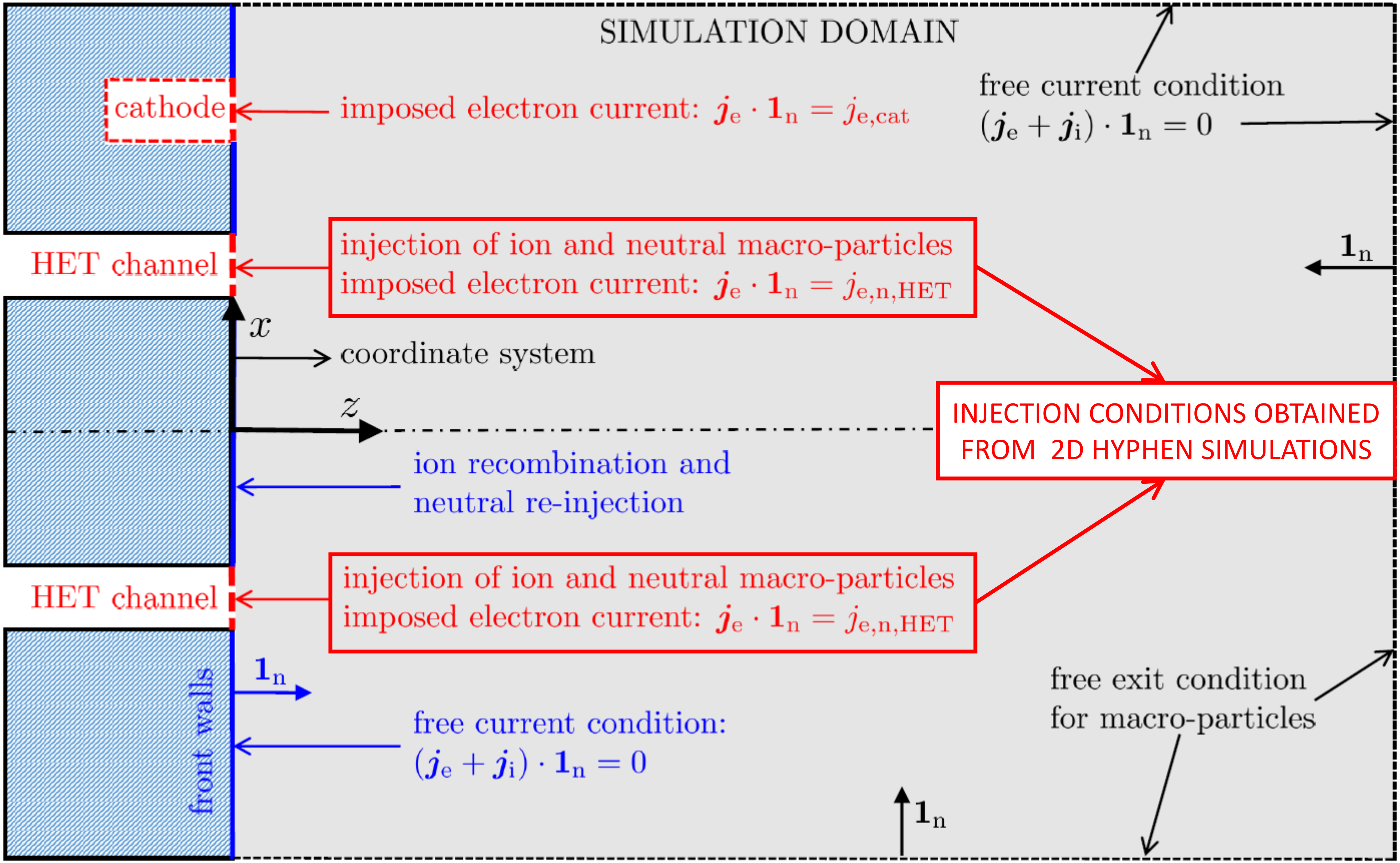
Simulation setup

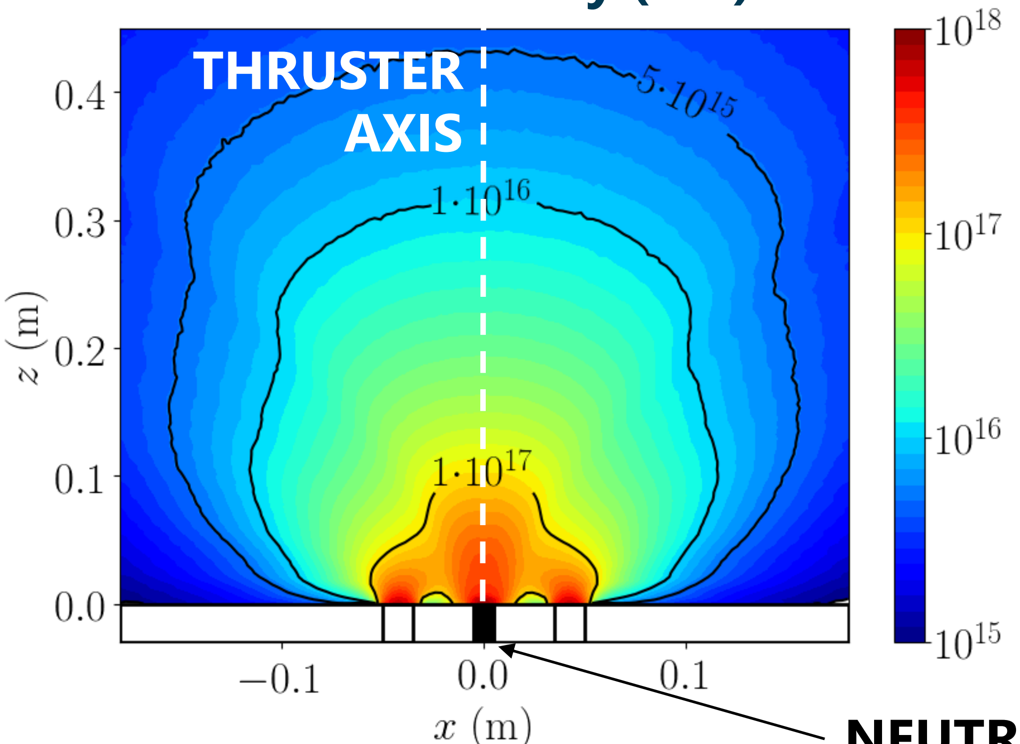


Contents

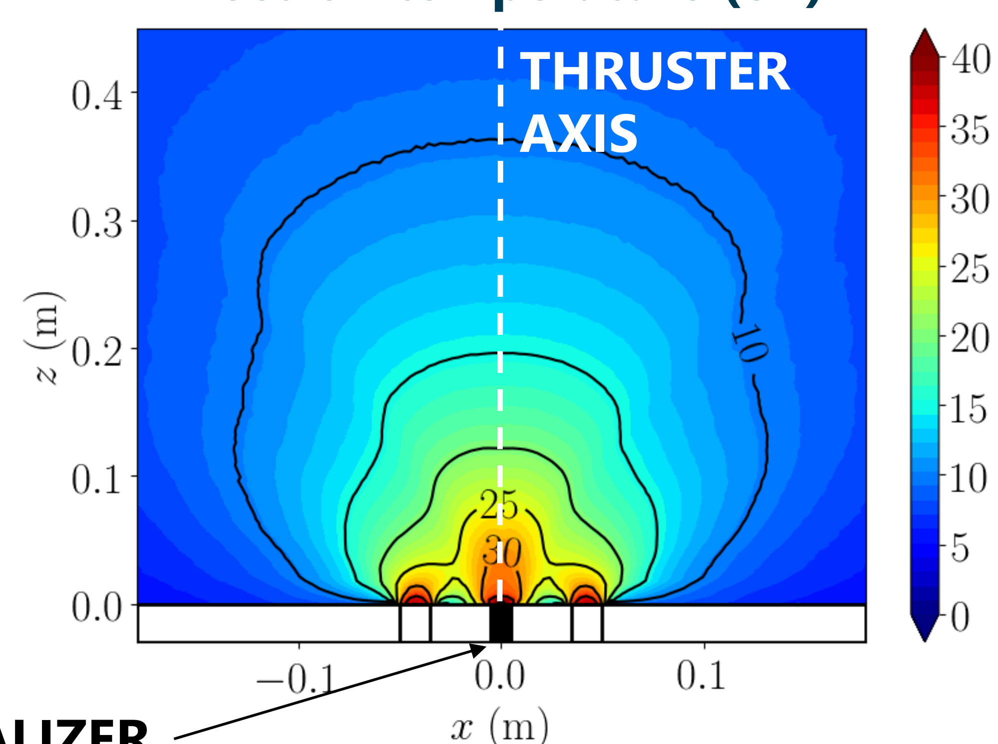
Nominal simulation results (1)

- Neutralizer is located at the thruster axis
- Anomalous transport modeled by adding (to the electron collision frequency) an anomalous collision frequency $\nu_{an} = \alpha_{an}\omega_{ce} = \alpha_{an}eB/m_e$
  - $\alpha_{an} = 0.025$ in nominal simulations

Electron density (m^{-3})



Electron temperature (eV)

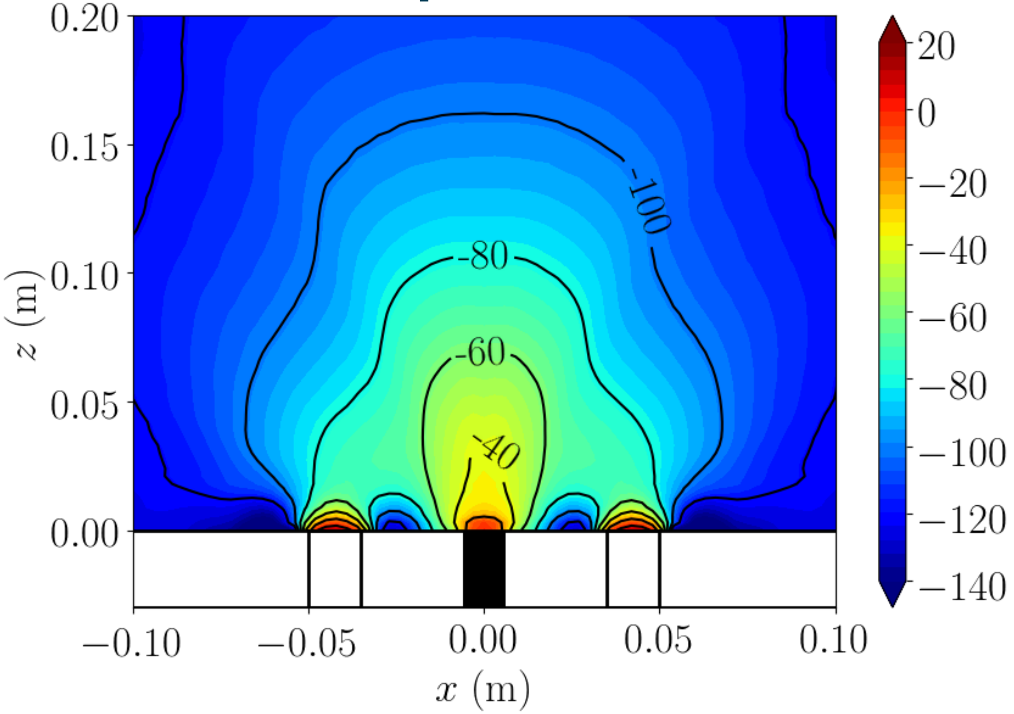


NEUTRALIZER

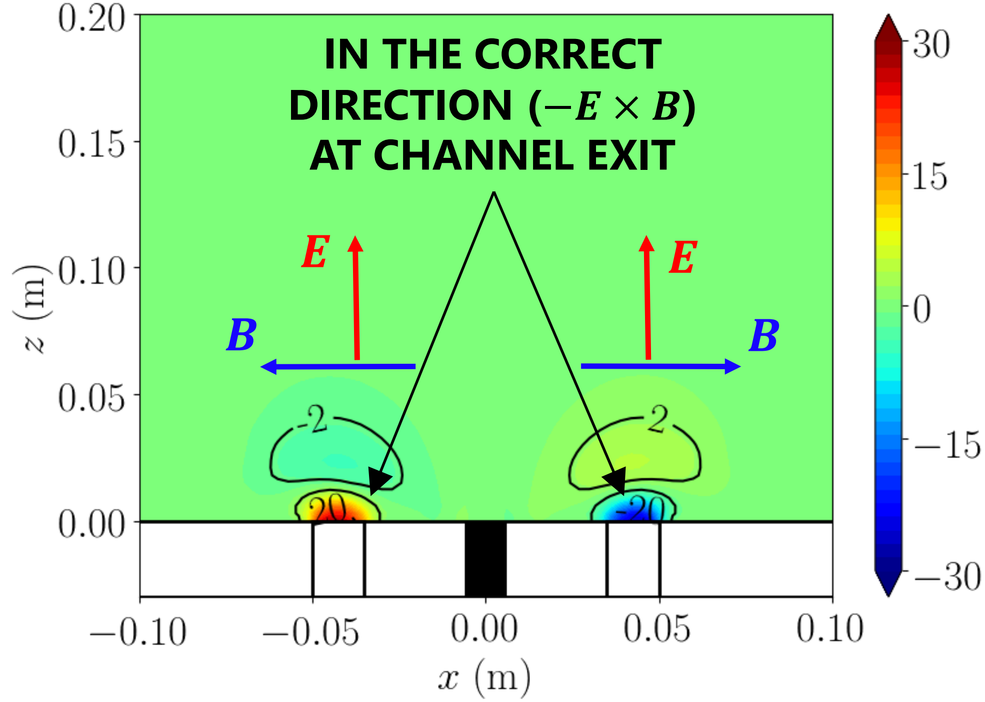
Nominal simulation results (2)

- Solution symmetric also in electric potential and electron current
  - Steep potential drop at channel exit, due to axial magnetic force on electrons
- The model reproduces correctly the **azimuthal Hall current** density:
  - Correct direction ($-\boldsymbol{E} \times \boldsymbol{B}$)
  - Correct magnitude ($\approx$ 30 kA/m^2)

Electric potential (V)

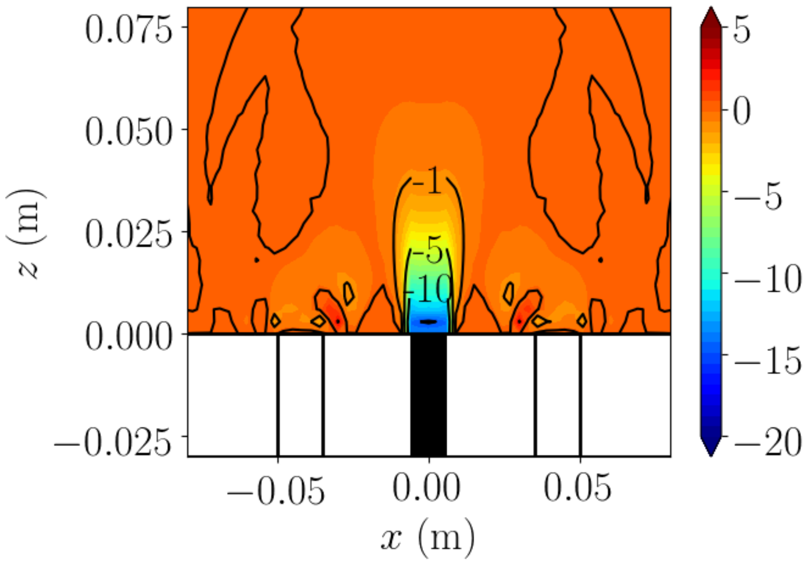


Out-of-plane electron current density (kA/m^2)

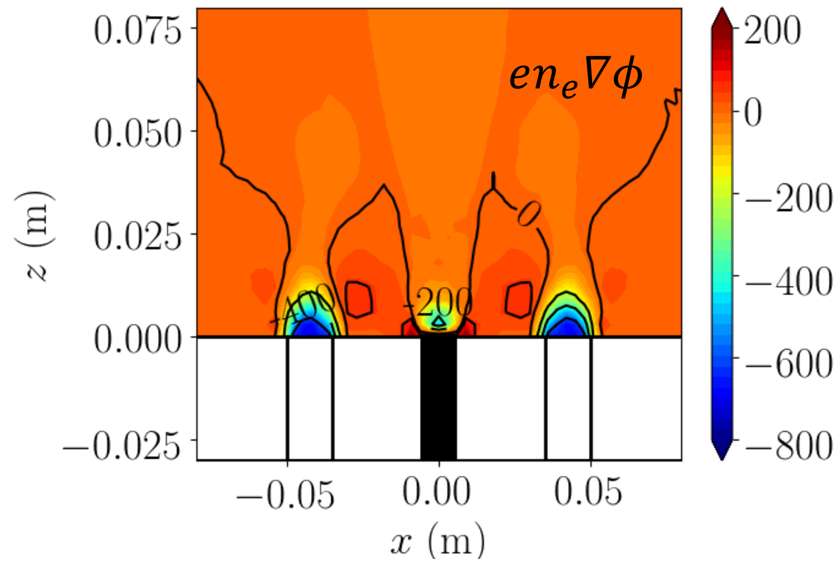


Nominal simulation results (3)

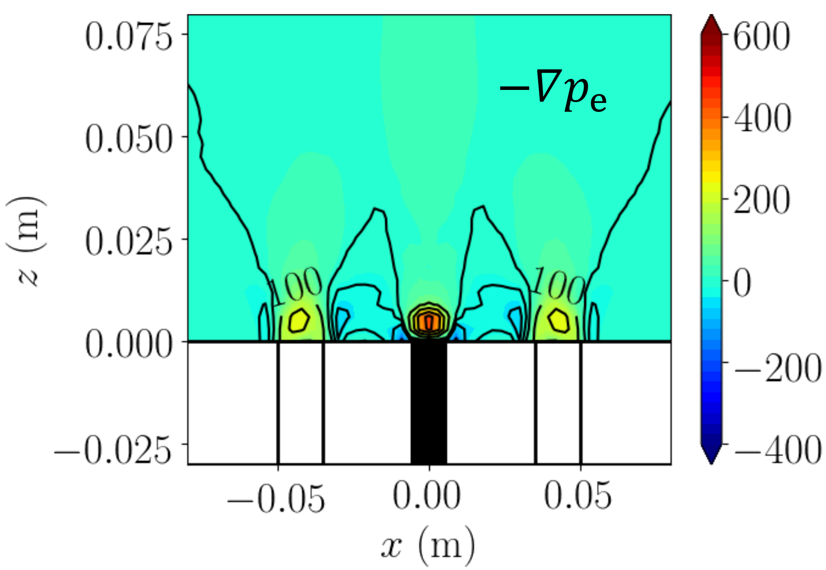
COLLISIONAL FORCE (N/m³)



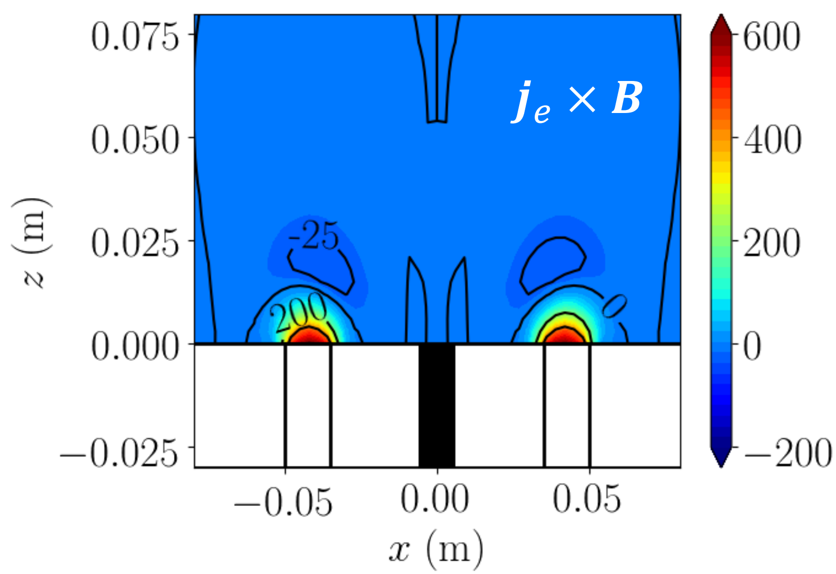
ELECTRIC FIELD FORCE (N/m³)



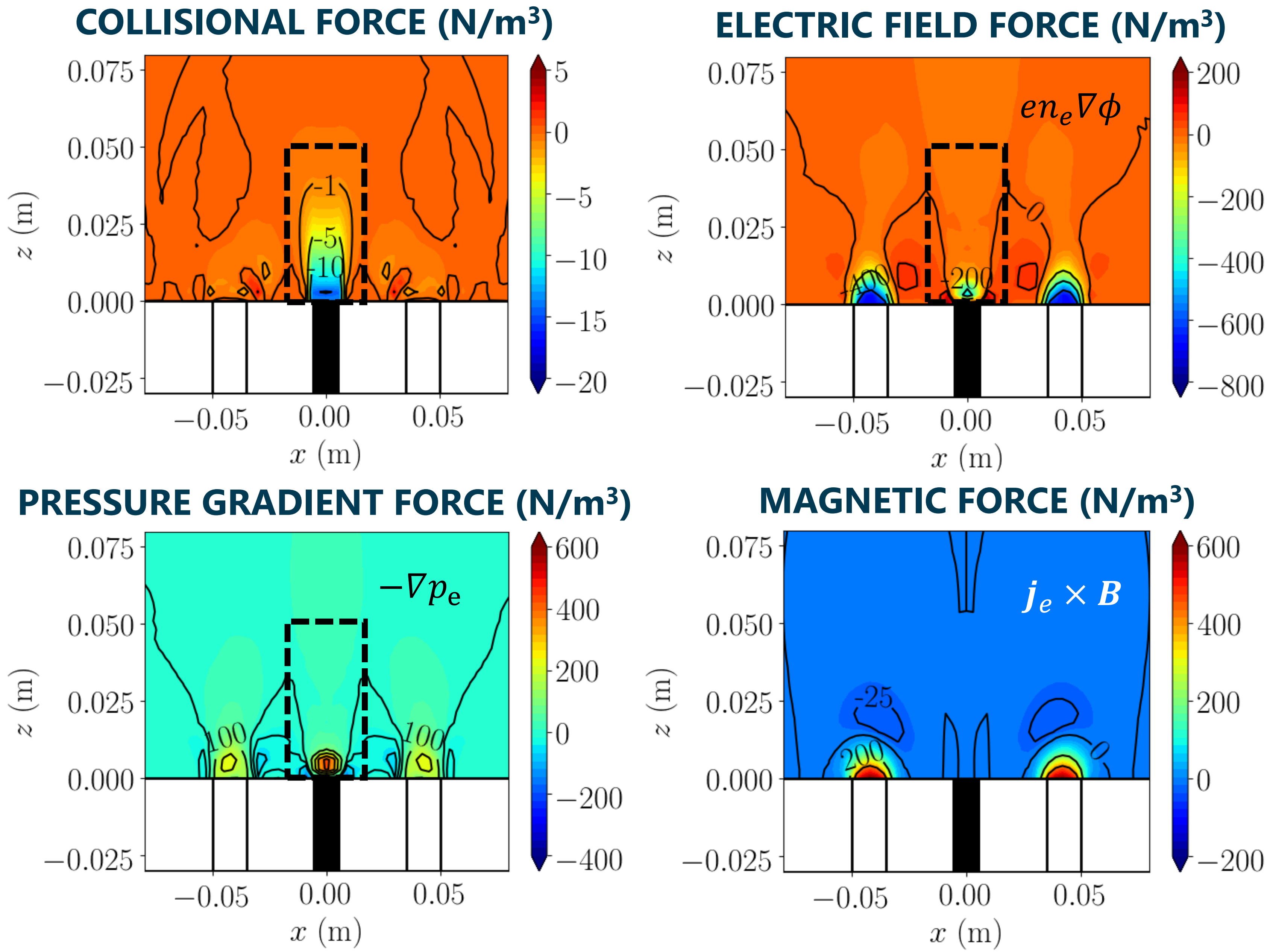
PRESSURE GRADIENT FORCE (N/m³)



MAGNETIC FORCE (N/m³)

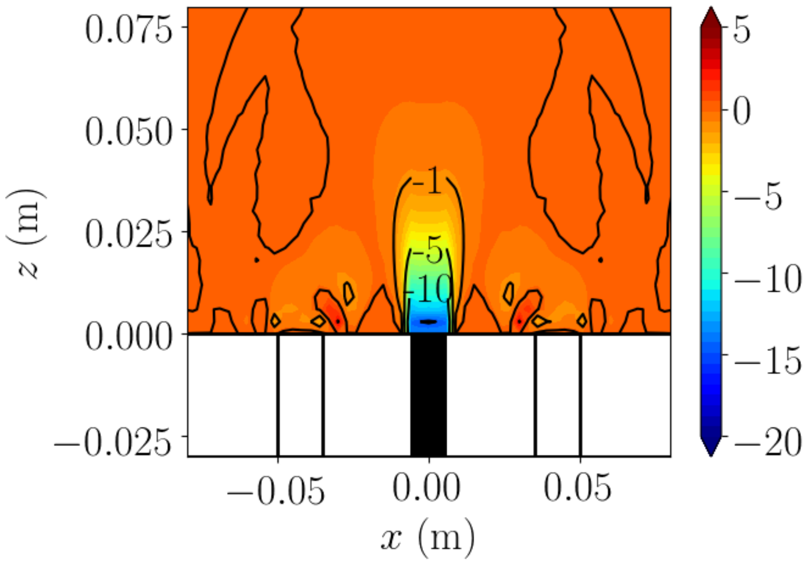


Nominal simulation results (4)

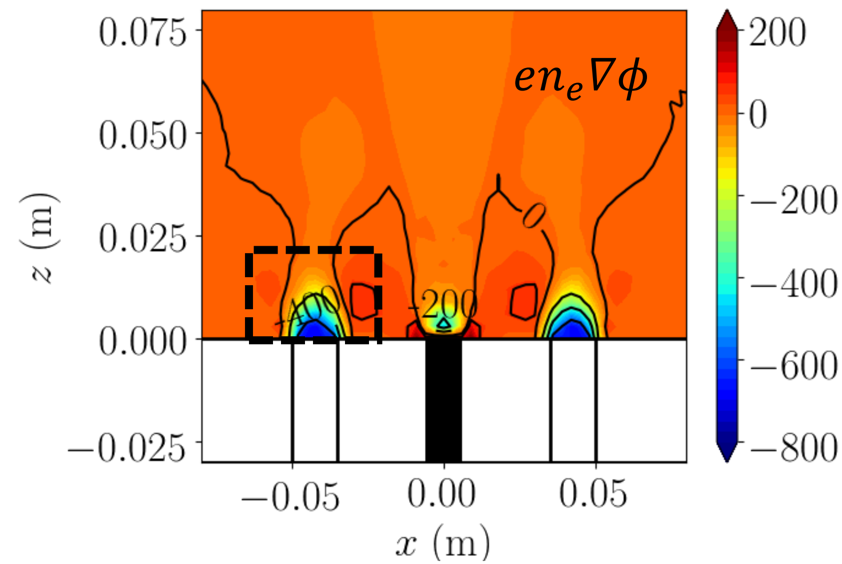


Nominal simulation results (5)

COLLISIONAL FORCE (N/m³)



ELECTRIC FIELD FORCE (N/m³)



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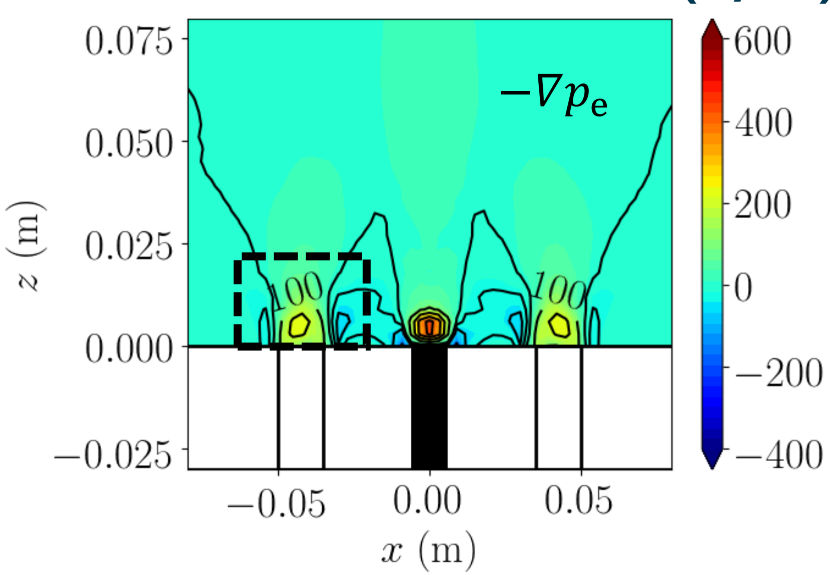
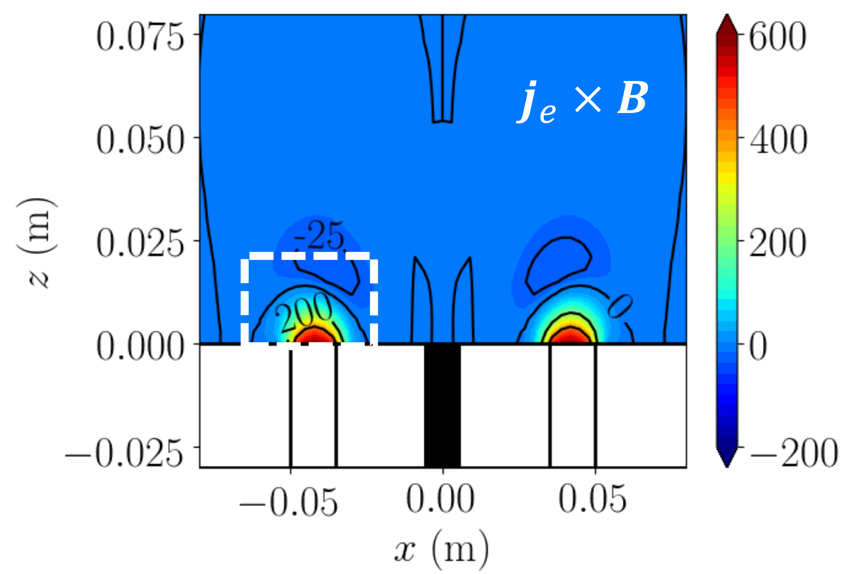


MAGNETIC FORCE (N/m³)



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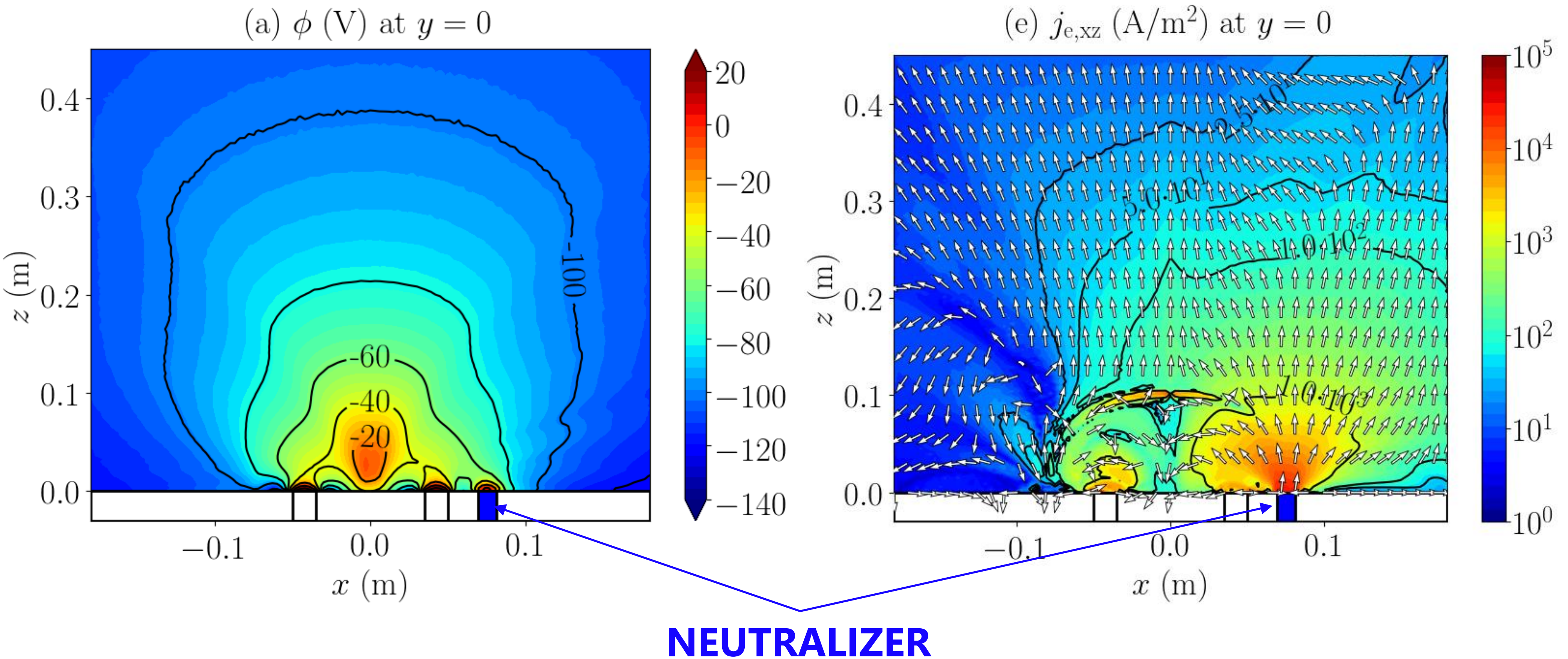
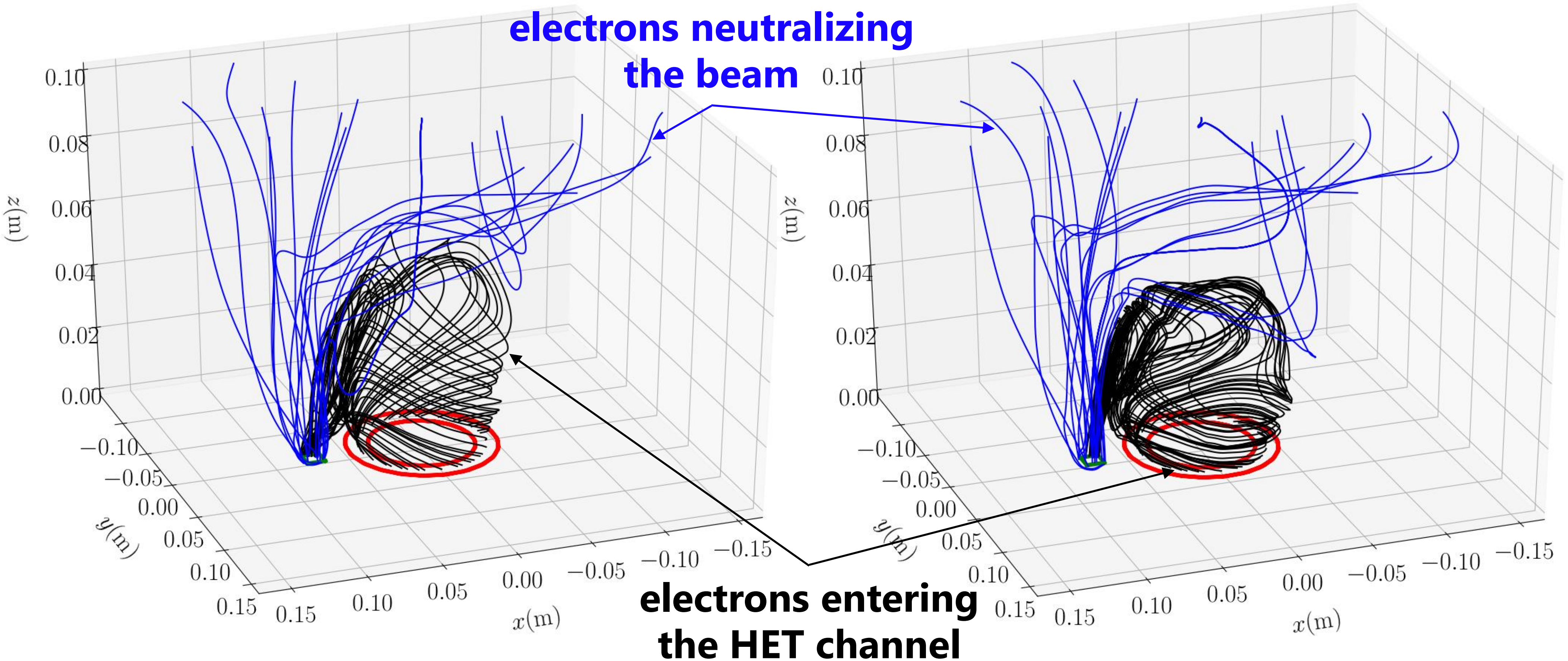
Off-axis cathode simulation results (1)

- Asymmetries in electric potential quickly disappear downstream
- Electron current density is strongly asymmetric downstream, except at the entrance of the HET channel



Off-axis cathode simulation results (2)

$\alpha_{an} = 0.2 \quad , \omega_{ce}/\nu_e = 5$ $\alpha_{an} = 0.1 \quad , \omega_{ce}/\nu_e = 10$



- Increasing the Hall parameter, a stronger azimuthal drift is observed
- At the red HET exit channel, electron current is mainly azimuthal and axisymmetric

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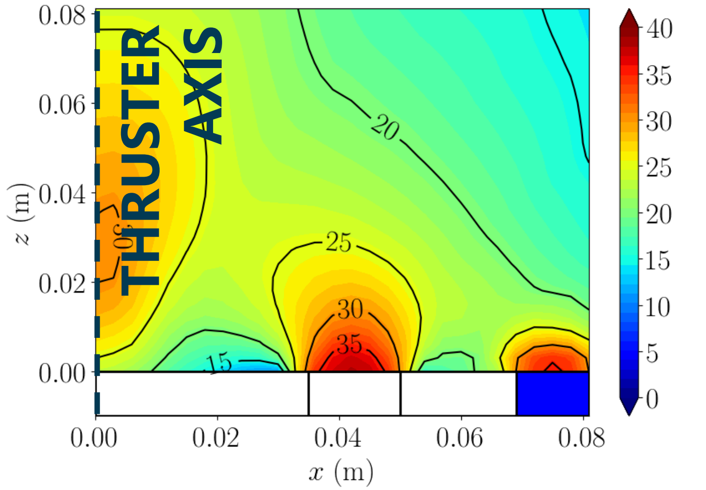
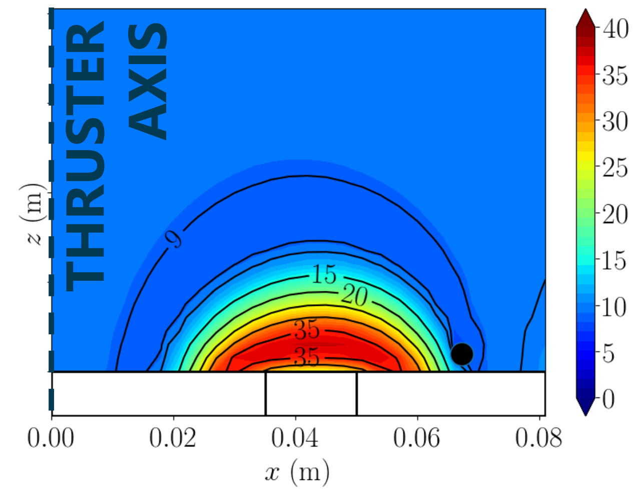
Comparison with HYPHEN 2D code

EP2PLUS (3D+polytropic electrons) | HYPHEN: 2D+electron energy eq.

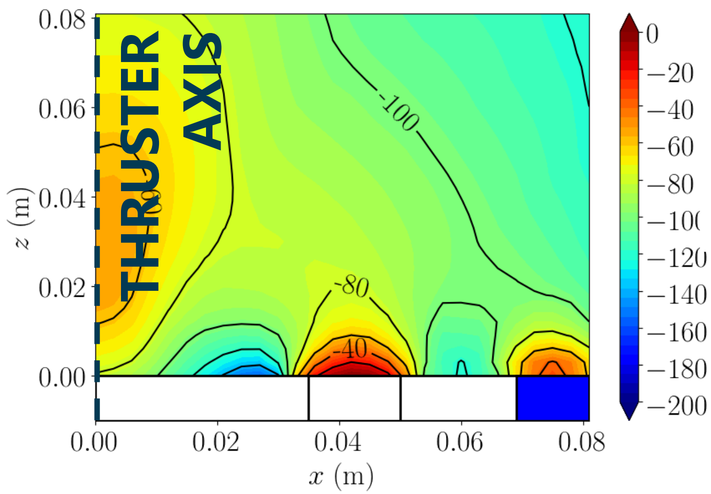
Electron temperature

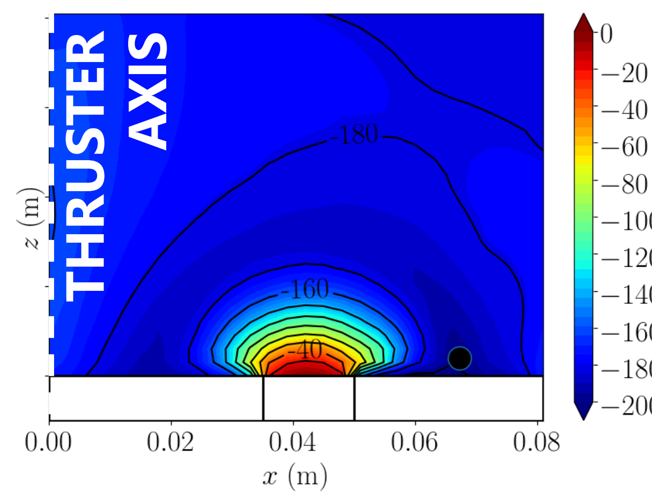




Polytropic model cannot reproduce correct temperature evolution

Electric potential





Large differences, except at the HET channel exit, where gradients are equal

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Conclusions and future work

- **EP2PLUS** and **HYPHEN** magnetized electrons models have been benchmarked against each other:
  - Predicted electric fields are very similar in an initial expansion region, close to the HET channel
  - Large errors in prediction of the electron temperature downstream → **near-plume physics of HETs requires solving** for an **electron energy balance**
- 3D EP2PLUS simulations have shown that a lateral neutralizer position produces:
  - **Important asymmetries** in the **electron current downstream**
  - **Negligible effects** on the **electric potential** and **thruster performance figures computation**
- Future work: implementation of a **3D energy balance equation** in EP2PLUS

Thank you! Questions?

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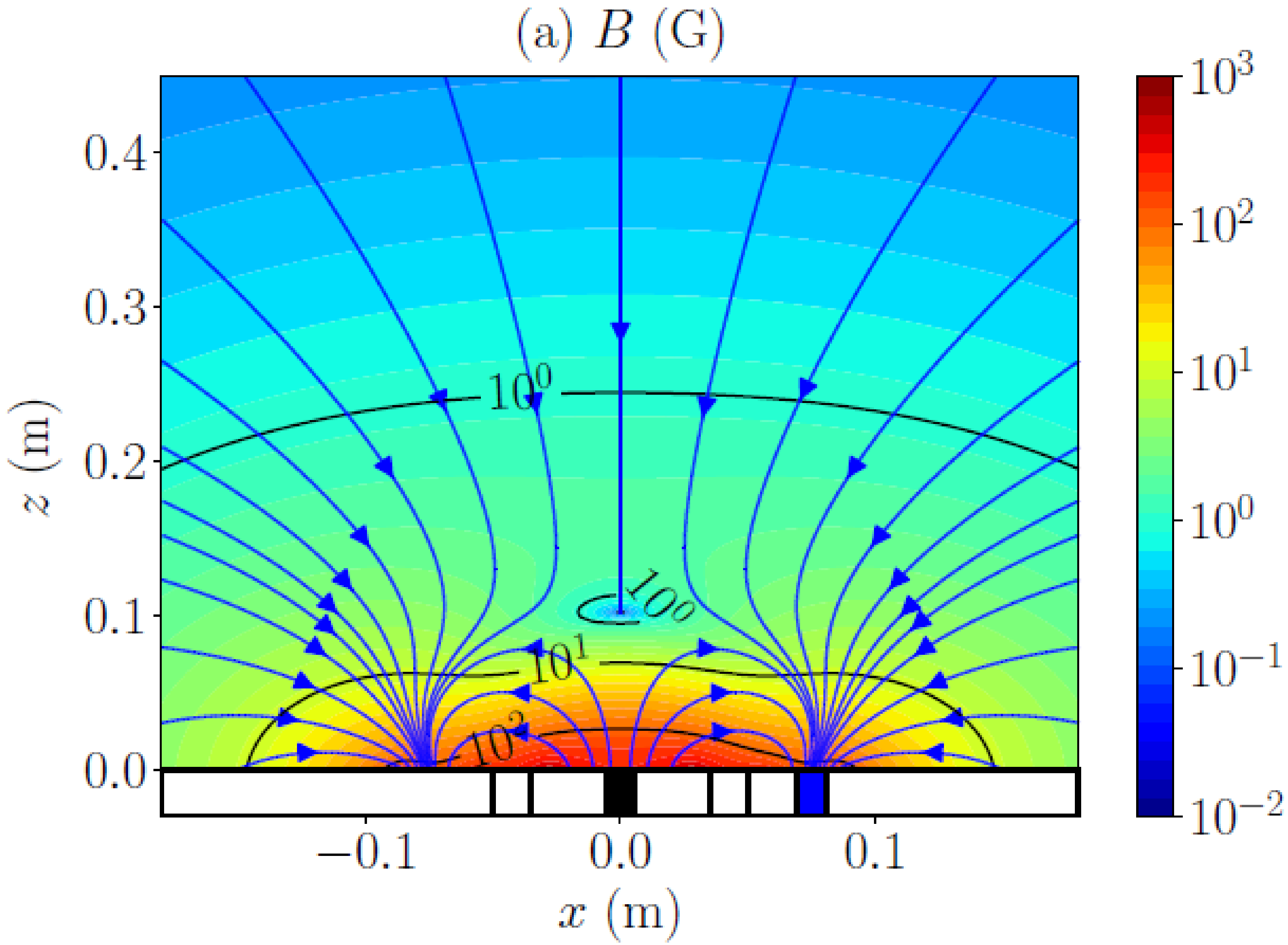
Magnetic field topology

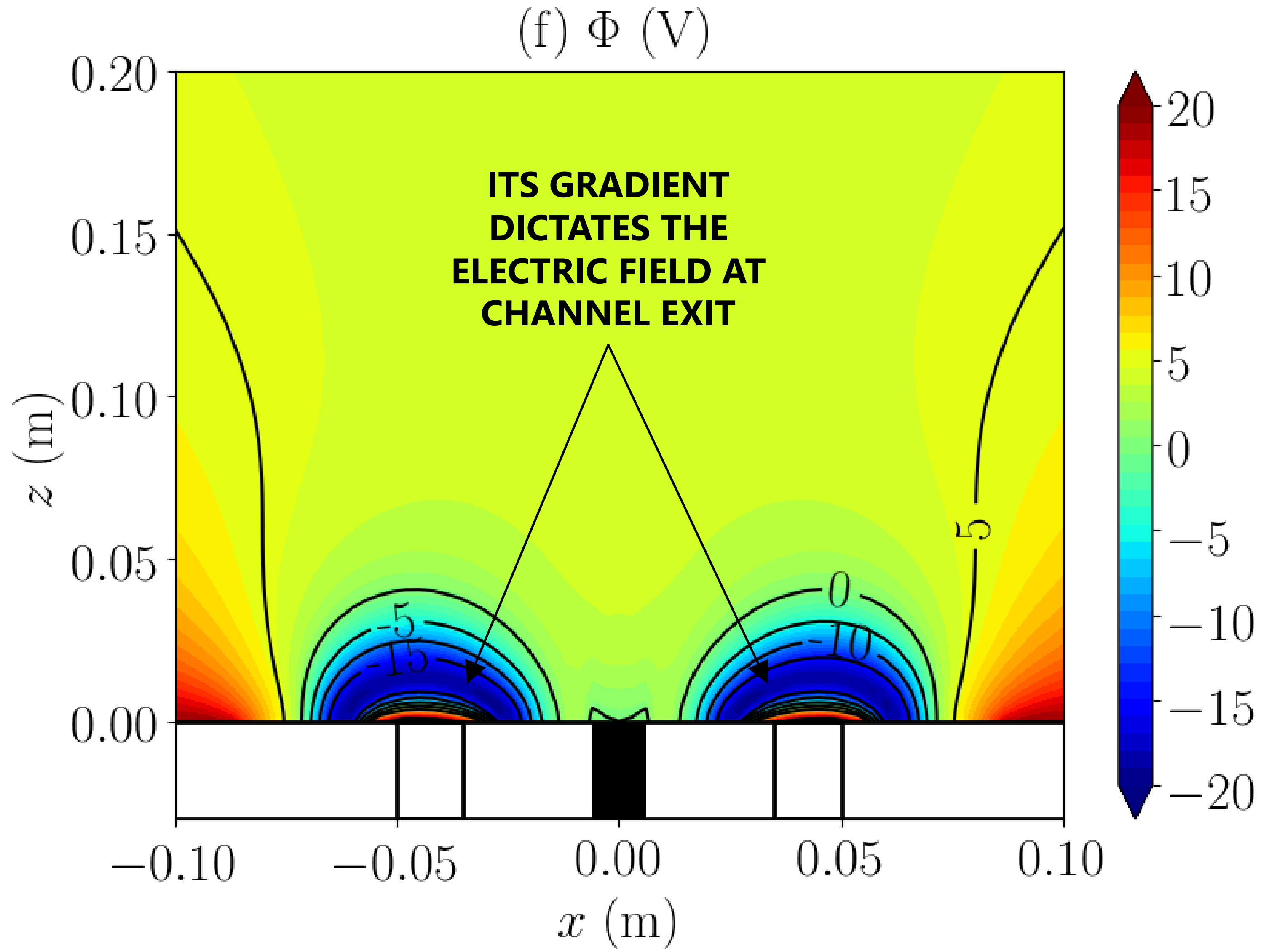


Tensor electron conductivity

$$\bar{\bar{\mathrm{K}}} = \begin{bmatrix} 1 & \chi b_z & -\chi b_y \\ -\chi b_z & 1 & \chi b_x \\ \chi b_y & -\chi b_x & 1 \end{bmatrix}^{-1}$$

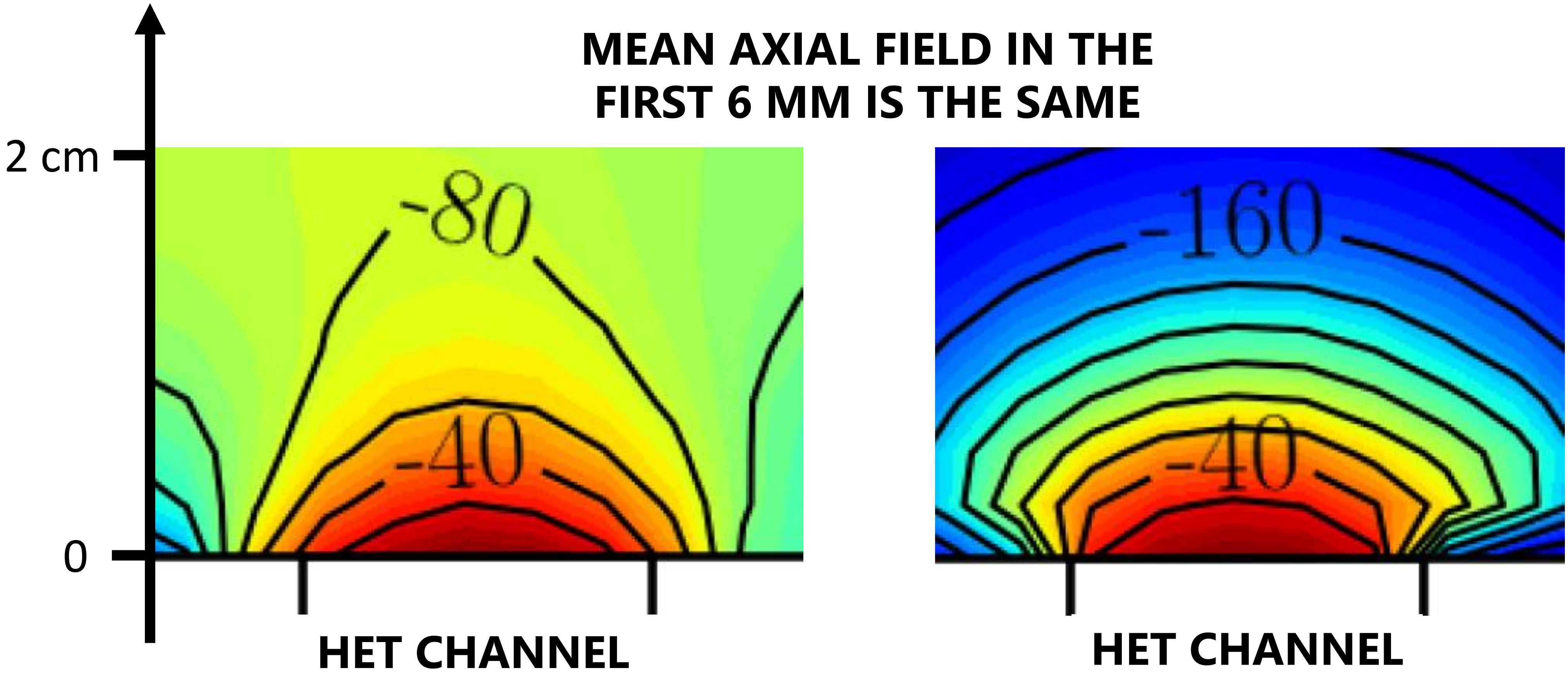
$$\chi = \frac{eB}{m_e \nu_e}, \qquad (b_x, b_y, b_z) = \boldsymbol{B}/B$$

Thermalized potential (V)



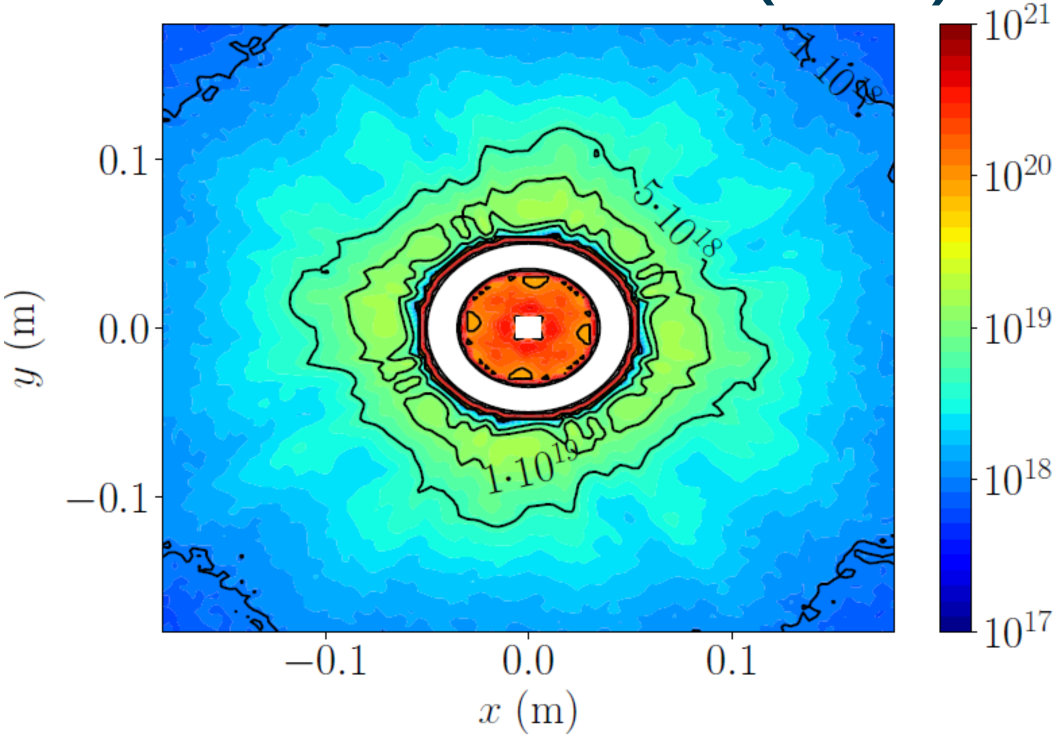
Comparison (zoom) of electric potentials

MEAN AXIAL FIELD IN THE FIRST 6 MM IS THE SAME



Fluxes to the HET front walls

IONS BACKWARDS FLUX ($m^{-2}s^{-1}$)



IONS IMPACT ENERGY (eV)