Modeling in 3D the effect of the channel walls in HTs

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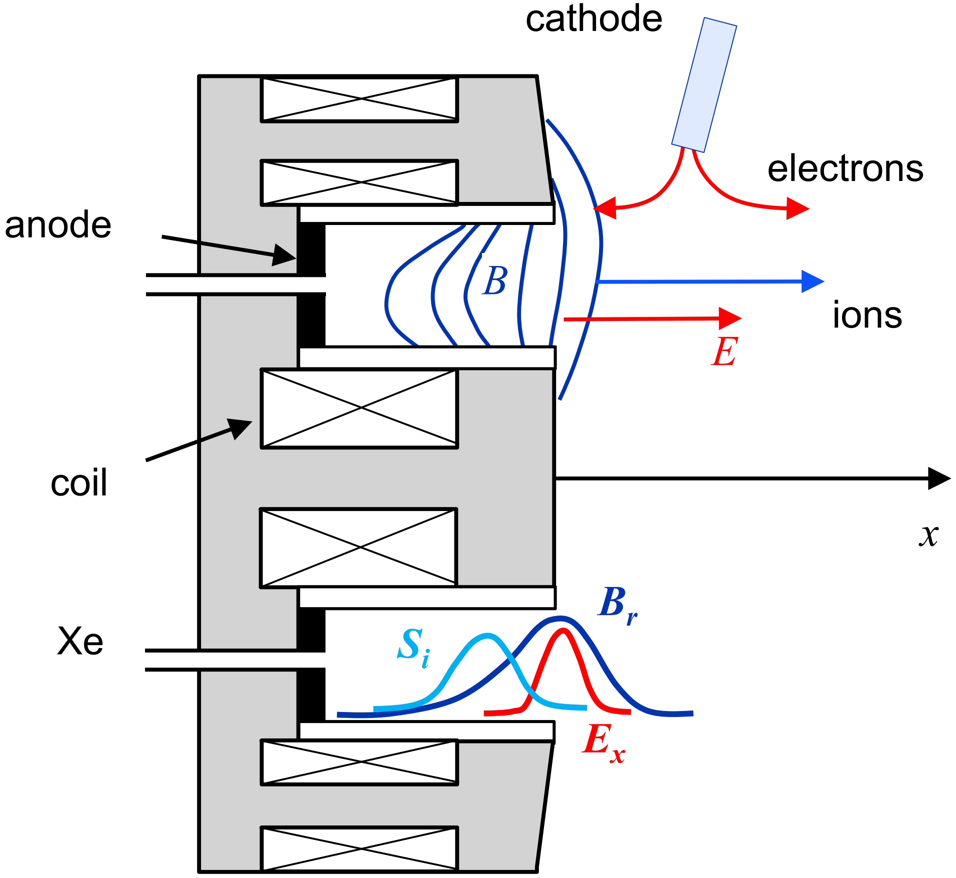
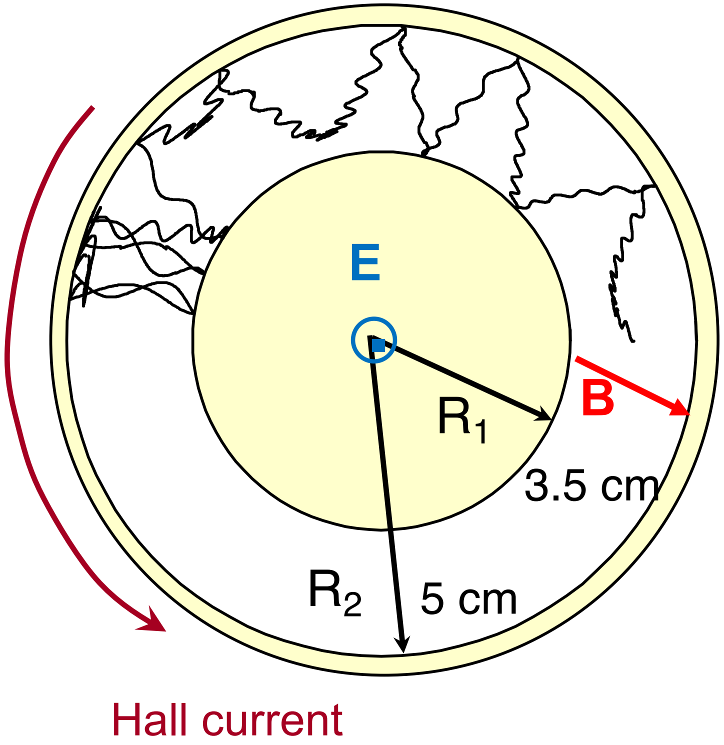
Schematic of a Hall Effect Thruster (HET)

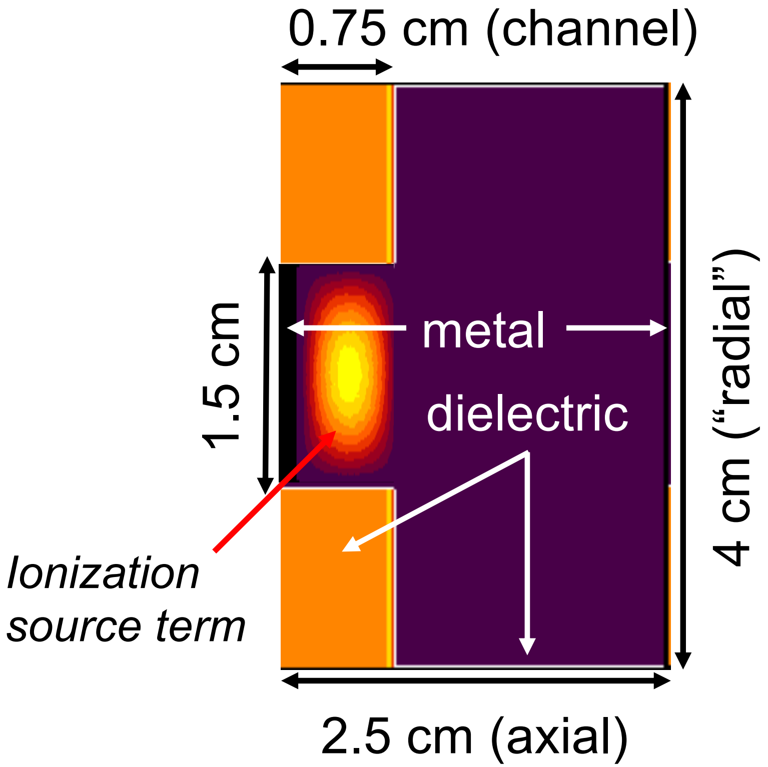


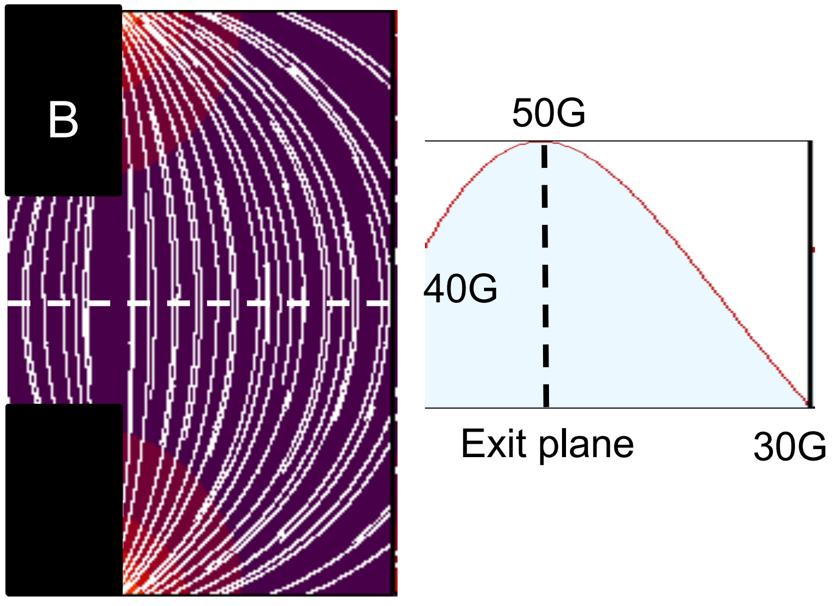


Scope of this project

- Study the effect of the channel walls on the electron transport & instability properties
- Model the behavior of the plume
- Keep the model as simple as possible and close to the 2D benchmark assumptions
- Workplan is to perform scans versus magnetic field strength and plasma density
- No secondary electron emission or neutral dynamics for now
- Ionization modeled via a source term inside the channel
- Magnetic field profile calculated analytically but fitted using FEM
- The simulation domain is Cartesian
- We assume an infinite curvature radius
- Part of the channel and the plume are modeled

Simulation domain

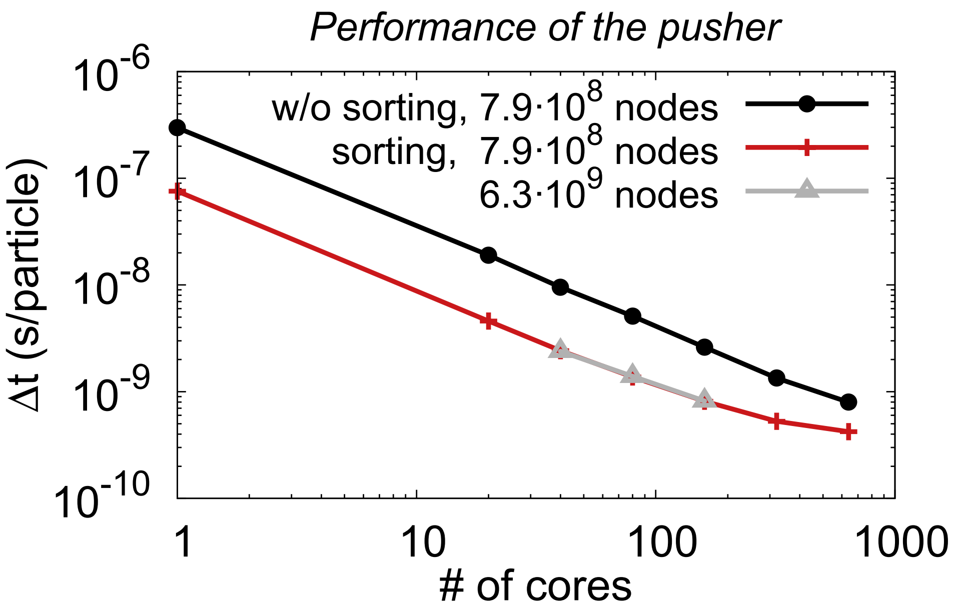


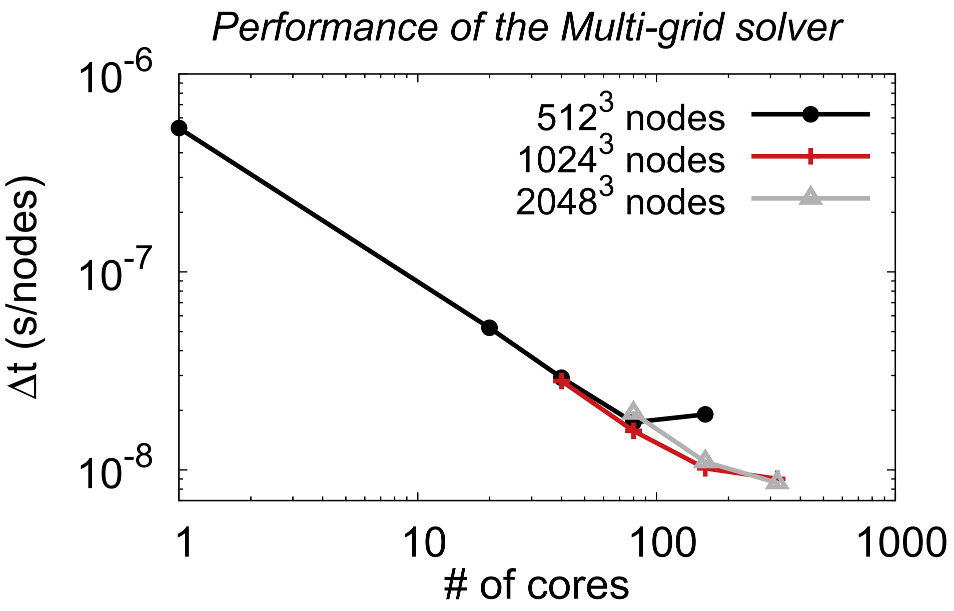


- 1.25 cm along the ”azimuthal” direction
- Cathode polarized at 0V & 300V for the anode
- 256×384×128 grid nodes.
- $\langle n_p \rangle = 1.2\times10^{17}$ m^{-3} , C= 0.3 μF/m^2 ($\Delta V=\Delta Q/C$ in the model)
- Electrons injected at the cathode side, 1 mm inside volume: $I_{inj} = I_{ea} - I_{ia}$
- Start with B_m= 50G to keep a realistic $\omega_p/\Omega_c \gg 1$ (~20 with ρ_c ~2 mm in our case)

Numerical model

- 3D Particle-in-Cell (PIC) with Monte-Carlo-Collisions (MCC)
- Parallelized using MPI and OpenMP
- Domain decomposition for Poisson (homemade Multi-Grid solver)
- Particle decomposition for the pusher

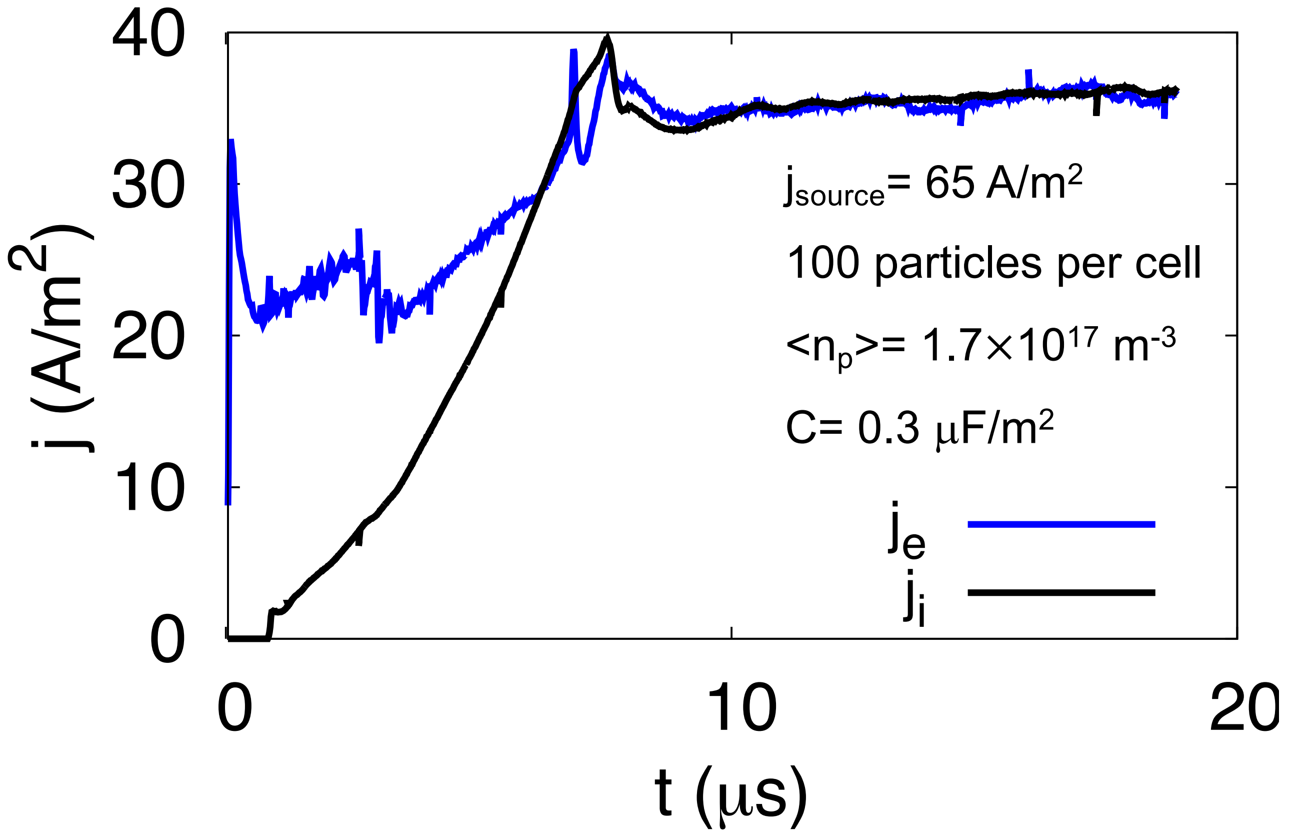




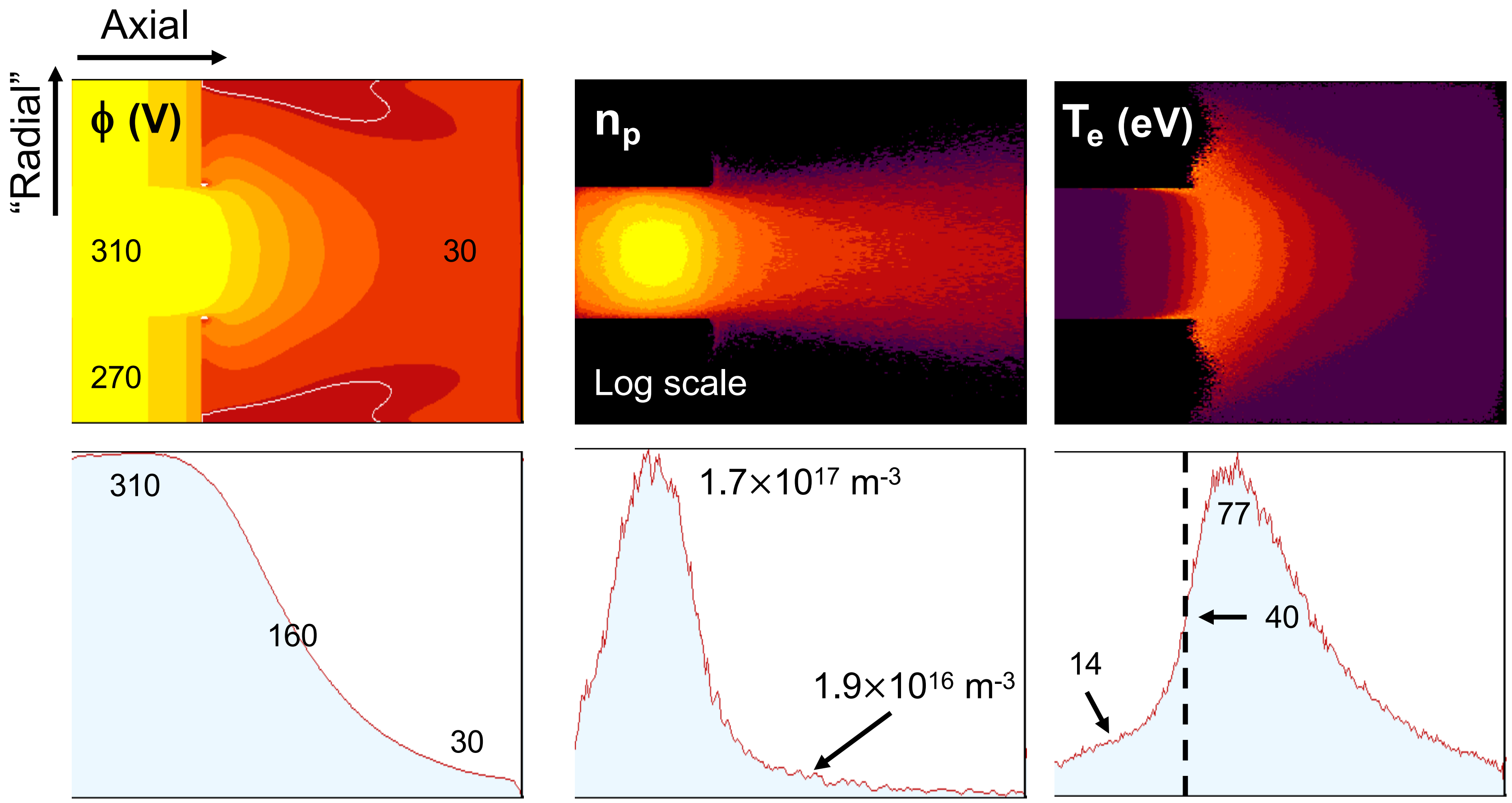
The calculation was performed on a 10 cores Intel Xeon processor E5-2680 v2 (25M cache, 2.80 GHz). We set the number of OpenMP threads to 10.

Physical time required for simulation to converge

Extracted ion/electron currents versus time

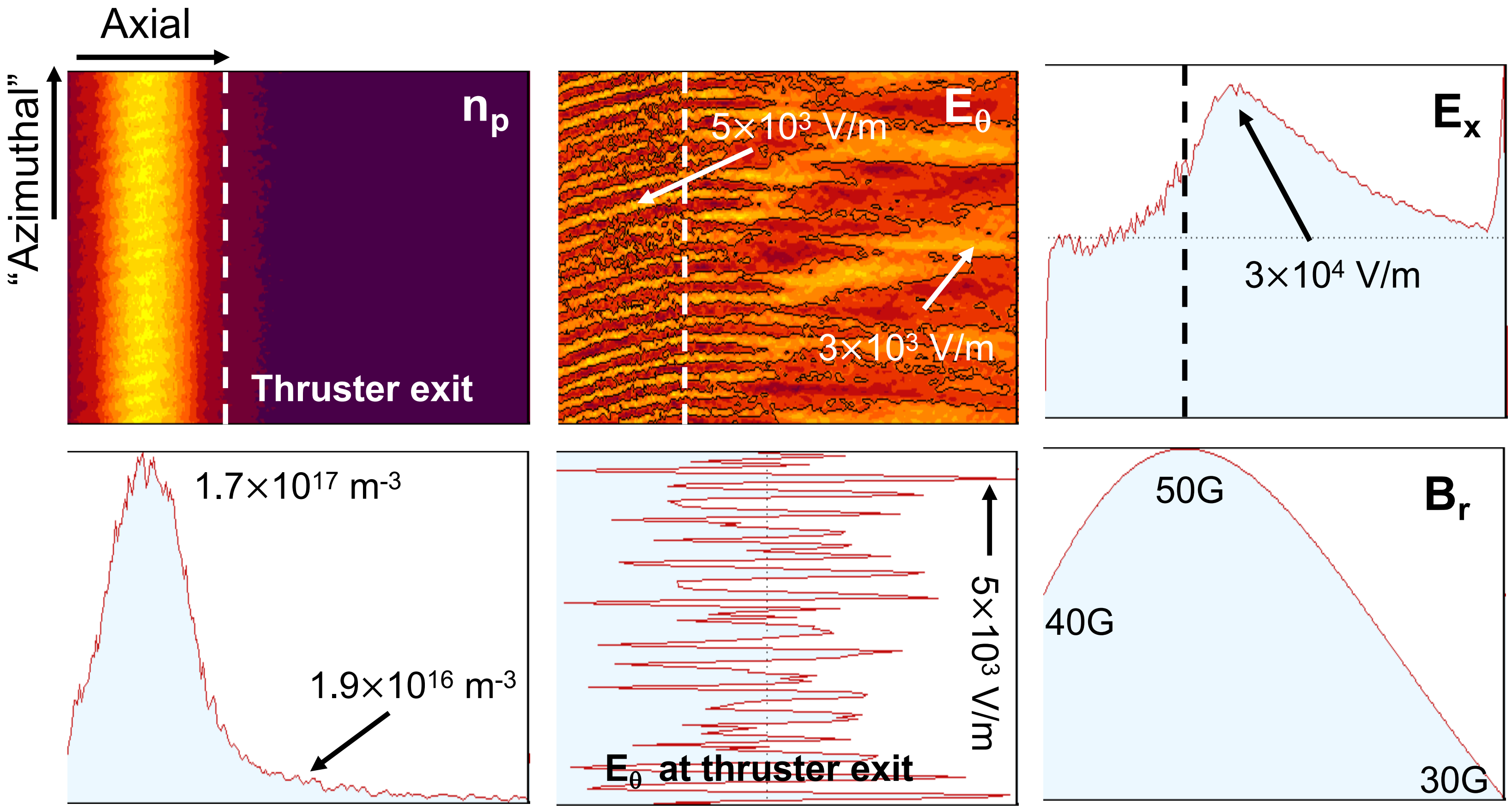


Plasma & plume properties: axial-radial plane



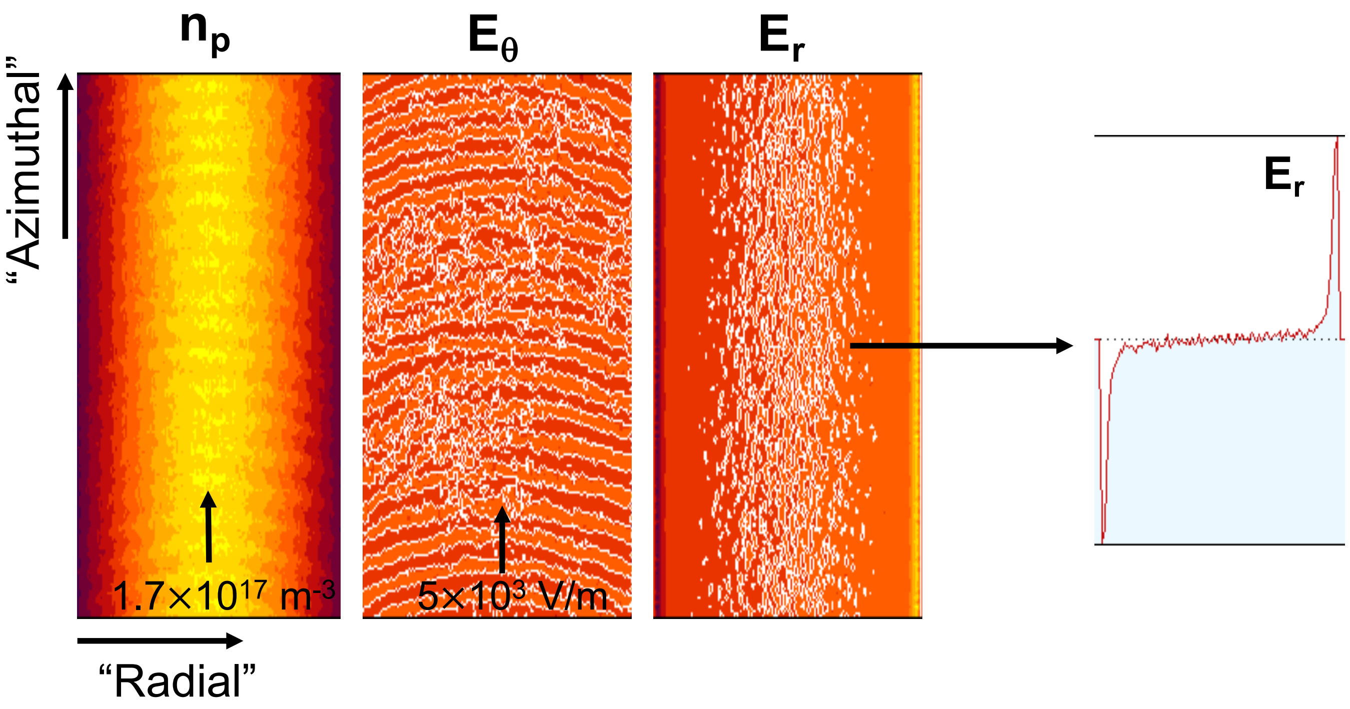
- Ratio of cathode current flowing back toward channel/extracted ion current ~30%
- Imprint of the magnetic field lines visible on the electron temperature and potentiel

Axial-azimuthal plane



- Inside the channel: ~18 periods over 12.5 mm (λ= 690 μm). λ_{th} ~ 9 λ_{De} ~ 600 μm
- λ_{th} corresponds to the theoretical wavelength for modified ion-acoustic at saturation
- Near the cathode: λ ~ 3.1 mm and λ_{th}~ 2.3 mm
  - Note that λ_{De} varies axially (factor of ~4 from left to right)

Azimuthal electric field profile is bended in the "radial"-"azimuthal" plane



- Radial potential profile is ambipolar
- The instability does not have any short wavelength radial component ($k_r L \ll 1$)
- Electron temperature at injection: 10 eV
  - Temperature at HT' exit: axial= 22 eV, radial= 16 eV, azimuthal= 40 eV
  - Electrons are hence heated radially in the model

Computer power required to model 150 A/m^2 of extracted ion current from the HT

- We modeled up to ~40 A/m^2 (B_m=50G) using a grid of 256×384×128 nodes.
- The CPU time per step was 1s for 100 particles per cell using 96 cores
- This translated into 1.3 μs of physical time per day
- Simulations need about 30 μs to fully converge (3 weeks) using C= 1 μF/m^2
- To model an HT ion current of ~150 A/m^2 would require doubling the mesh size
- Assuming the parallelization scales perfectly, then one would need ~1500 cores
  - 16 times larger (8 times more grid nodes & half the time step)
- In our case, domain decomposition for the particles must be implemented
- Keep in mind that we only modeled a fraction of the total azimuthal length (1.25 cm)
- Including neutrals and secondary particle production will increase convergence time

Conclusion and perspectives

- The 3D calculations were performed in a lower than real density regime
  - The working assumption was to keep a realistic ratio ω_p/Ω_c (~20)
- We could not go beyond a density of 1.2×10^{17} m^{-3} for now, hence we decreased B_m
- We found an instability well defined inside the channel and plume area
- The wavelength fits the one derived from a modified ion acoustic instability (channel)
    - Although one cannot conclude yet as a density scan is necessary
- The instability does not have any short wavelength radial component
- We observe a bending of the azimuthal electric field profile near the sheath
- The electron temperature radially is 1.6 times larger than the initial one
  - There is hence some particle heating which is occurring in the model
- Simulating a HT with B_m= 150G and ω_p/Ω_c ~12 would typically require:
  - 3 weeks using ~1500 cores (100 particles per cell)
- The model neglected secondary particle production and collisions with neutrals
- We kept it as simple as possible and this could be used as a base for benchmarking