# EP2PLUS: Thruster-plume-facility coupled simulations

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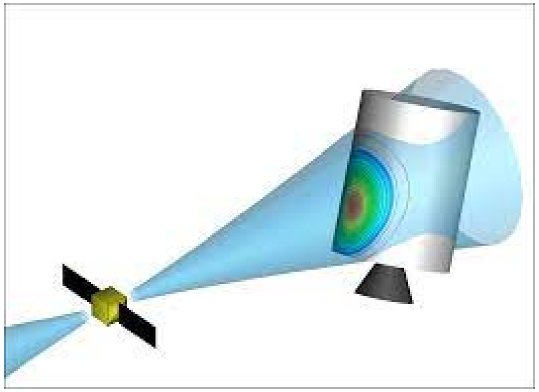
# EP2PLUS

- 3D hybrid simulator for plasma plumes & interaction with nearby objects
- Originally developed under FP7-LEOSWEEP for Active Debris Removal
- Upgrades: ion thruster plume neutralization, geomagnetic effects
- Ongoing upgrade: simulate Hall thruster plume inside vacuum chamber
  - To be applied in CHEOPS-LP, CHEOPS-MP, ASPIRE
- Parallel study (ECOMODIS): Characterization of electron kinetic effects



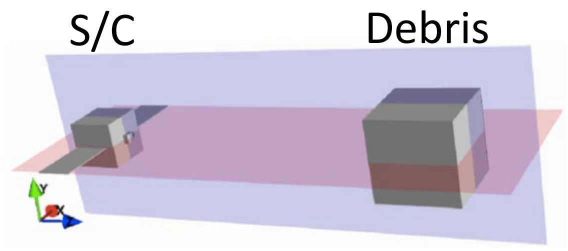
CHEOPS MEDIUM POWER ASPIRE ECOMODIS

# EP2PLUS - LEOSWEEP

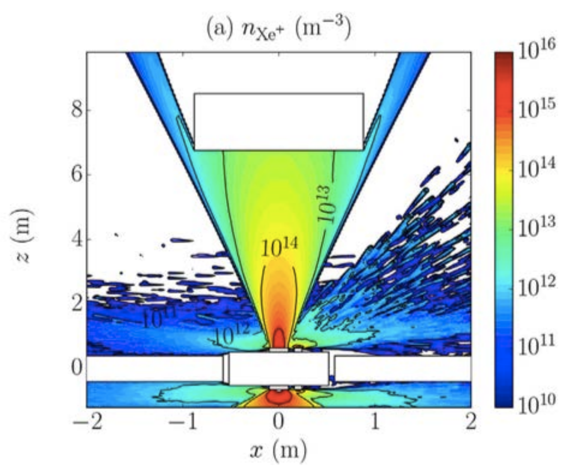
- Active debris removal with impingement of (unmagnetized) plasma beams
- Differences with HYPHEN
  - 3D single Cartesian-type mesh for 1-10m domains
    - Magnetic meshes unaffordable in such domains
    - Numerical diffusion at high Hall?
  - Electron fluid model with empirical polytropic closure

$$0 = -\nabla p_e + e n_e \nabla \phi + \boldsymbol{j}_e \times \boldsymbol{B} + \boldsymbol{F}_{res}, \quad p_e \propto n_e^{\gamma}$$

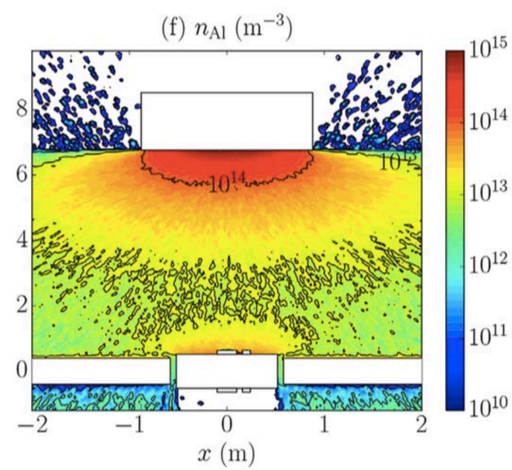
  - Poisson solver for non neutral regions
  - Fluid model solved with (non-conservative) finite differences



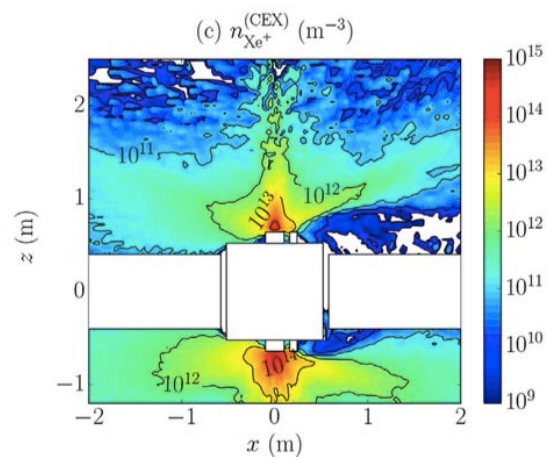

*Cichocki et al., Acta Astronautica v. 146, 216 (2018)*




Injected ions



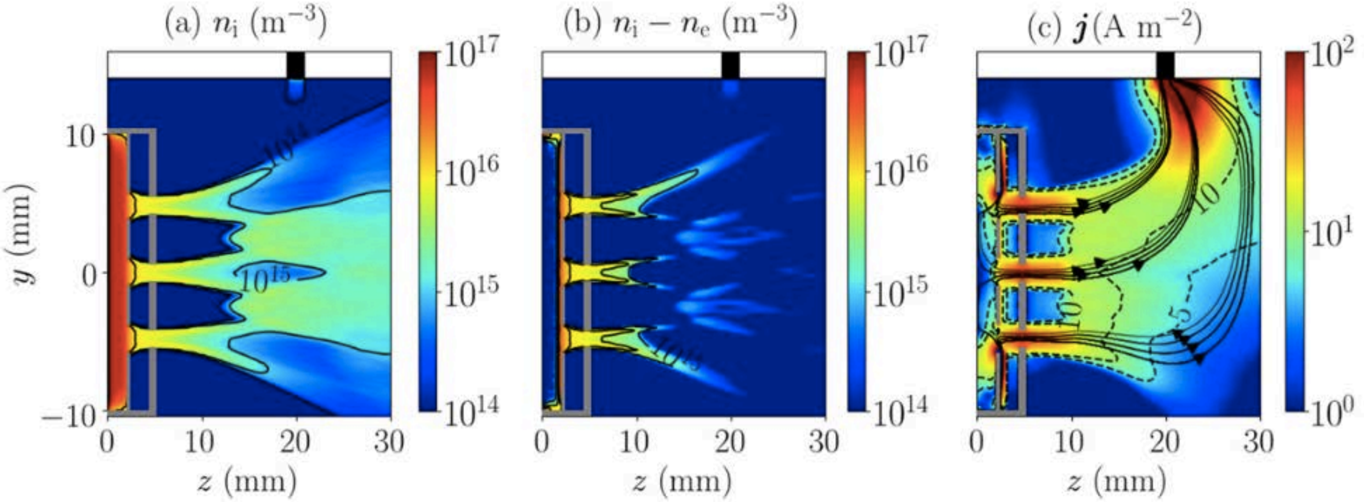

Sputtered Al



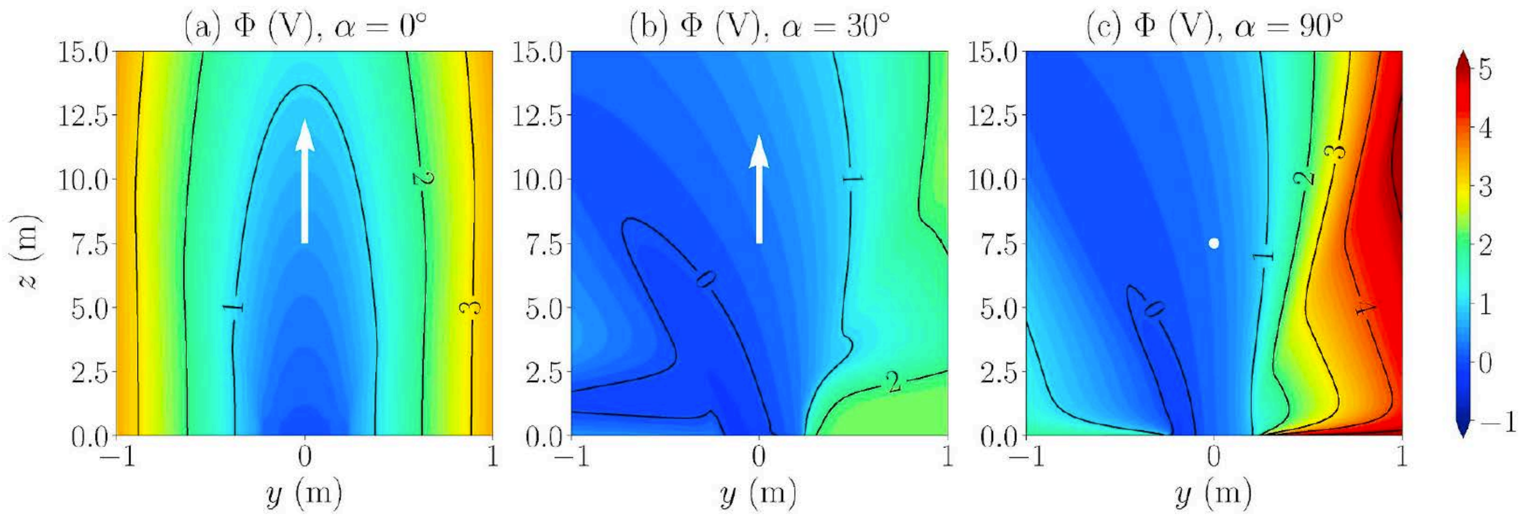

CEX ions

# EP2PLUS - APPLICATIONS

- GIT optics and beam neutralization, *Perales-Díaz et al. PSST 30, 105023 (2021)*



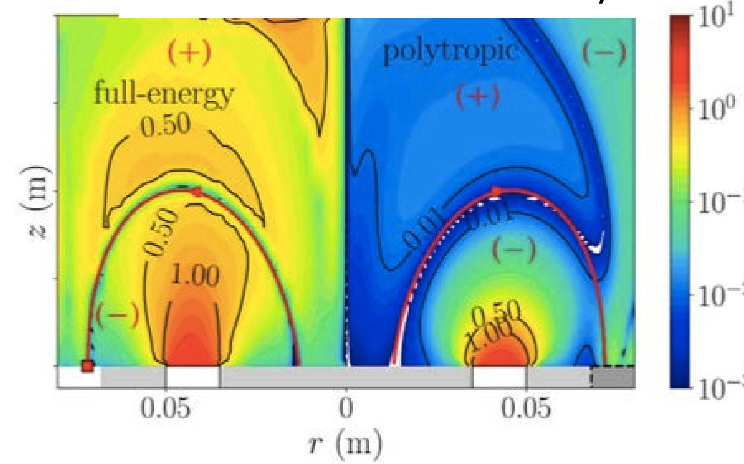

- Plume deflected by geomagnetic effects, *Cichocki et al. Acta Astron. 175, 190 (2020)*



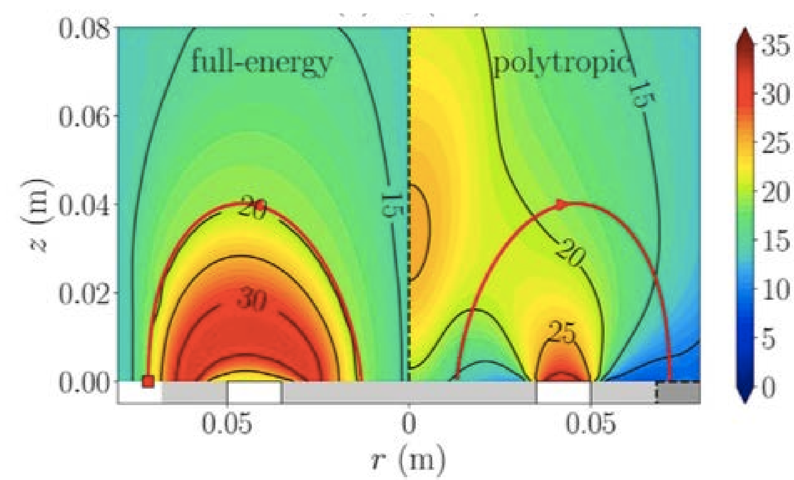
# EP2PLUS-HET PLUME

- HET near-plume
  - is highly magnetized
  - acceleration non completed
  - collisional processes are still relevant
- *Cichocki et al. Acta Astron. 187, 498 (2021)*
  - EP2PLUS reproduces well current $\theta$ −symmetrization from lateral cathode
  - Fails to solve well $T_e$ and $\phi$ maps
  - Requires very fine mesh for convergence
- EP2PLUS upgrading for HET plumes
  - To include electron energy equation
    - sources/sinks, heat flux
  - To deal with higher Hall
    1) use of (conservative) finite volume scheme
    2) further parallelization, better solvers
  - To implement rest of HYPHEN capabilities

Azimuthal current density




Electron temperature




HYPHEN EP2PLUS

# EP2PLUS upgrading

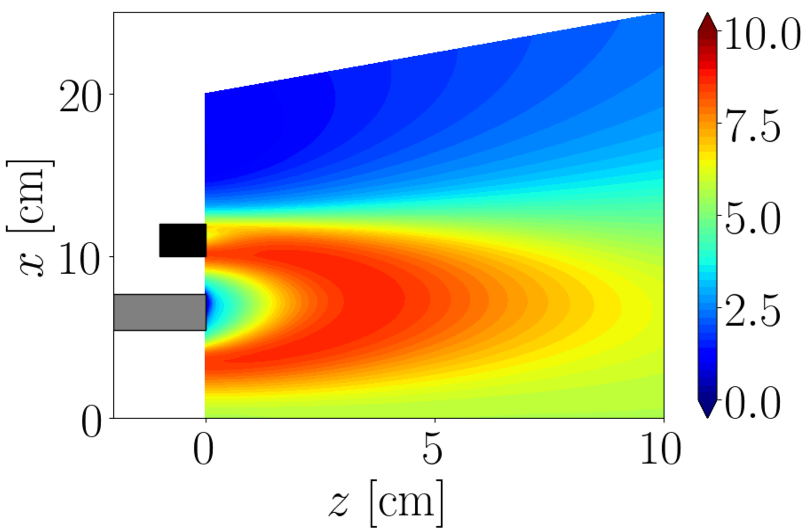
- Implementation of conservative finite volume methods
  - Better global conservation of plasma properties.
  - Better convergence for magnetized scenarios
    - maximum Hall parameter still limited
  - Coarser meshes can be used
    - reduction of computational time

| $I_z^+$ (A) in FD scheme | | | |
|---|---|---|---|
| | **41x41x101** | **81x81x201** | **121x121x301** |
| $\chi_{max} = 35$ | 0.453 | 0.544 | 0.583 |

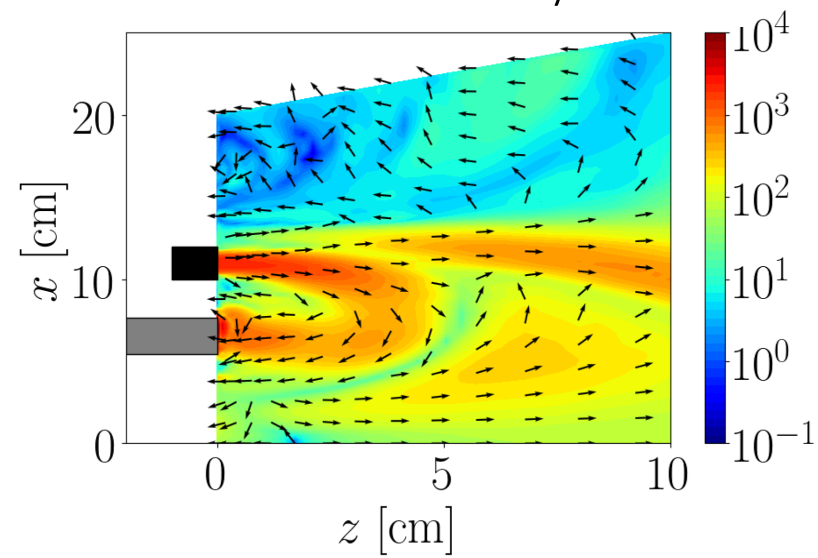
| $I_z^+$ (A) in FV scheme | | | |
|---|---|---|---|
| | **41x41x101** | **81x81x201** | **121x121x301** |
| $\chi_{max} = 35$ | 0.664 | 0.671 | 0.676 |

- Better compilers and solvers.
  - g fortran/PARDISO → intel fortran/MKL PARDISO→ 5-8 improvement in computation
- Implementation of the energy balance

Electron temperature

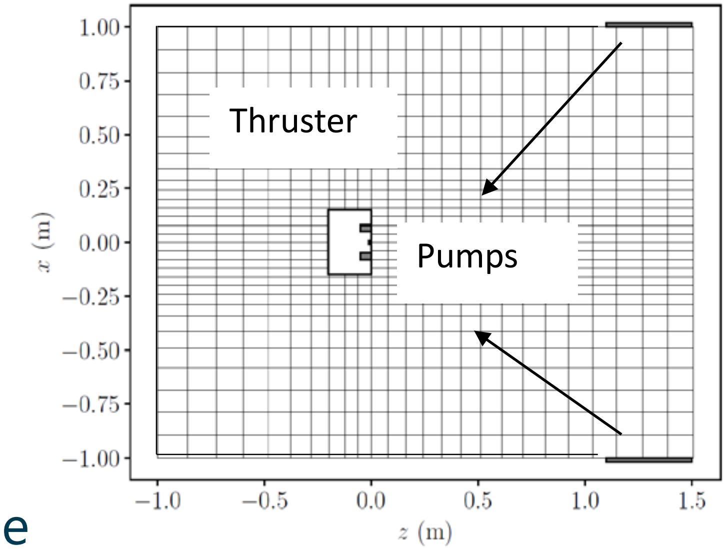



Electron current density

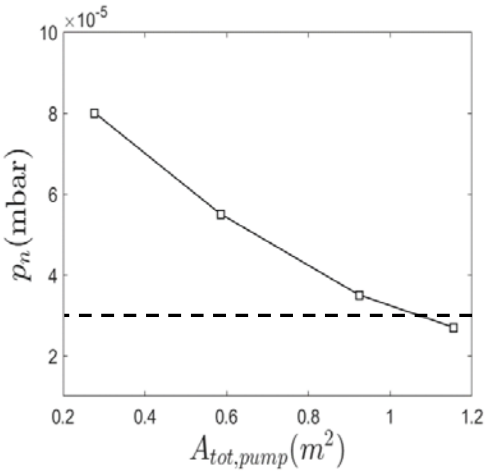


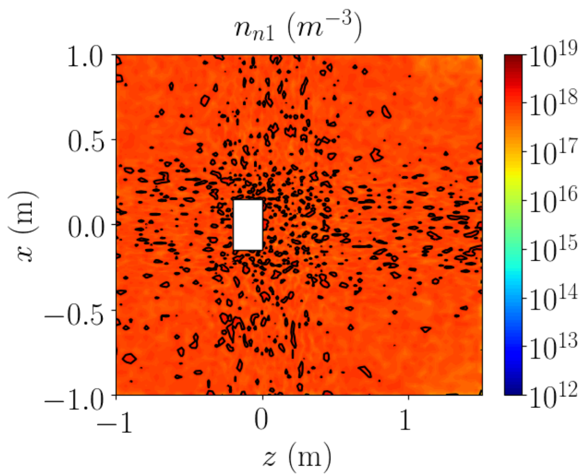
# Thruster-Vacuum Chamber simulations

- Goals:
  - Interpret results from testing campaigns of ASPIRE, CHEOPS-LP, CHEOPS-MP
  - Analysis of background pressure effects
  - Analysis of electrical connections among different surfaces and plasma
  - Prediction of thruster operation in free-space



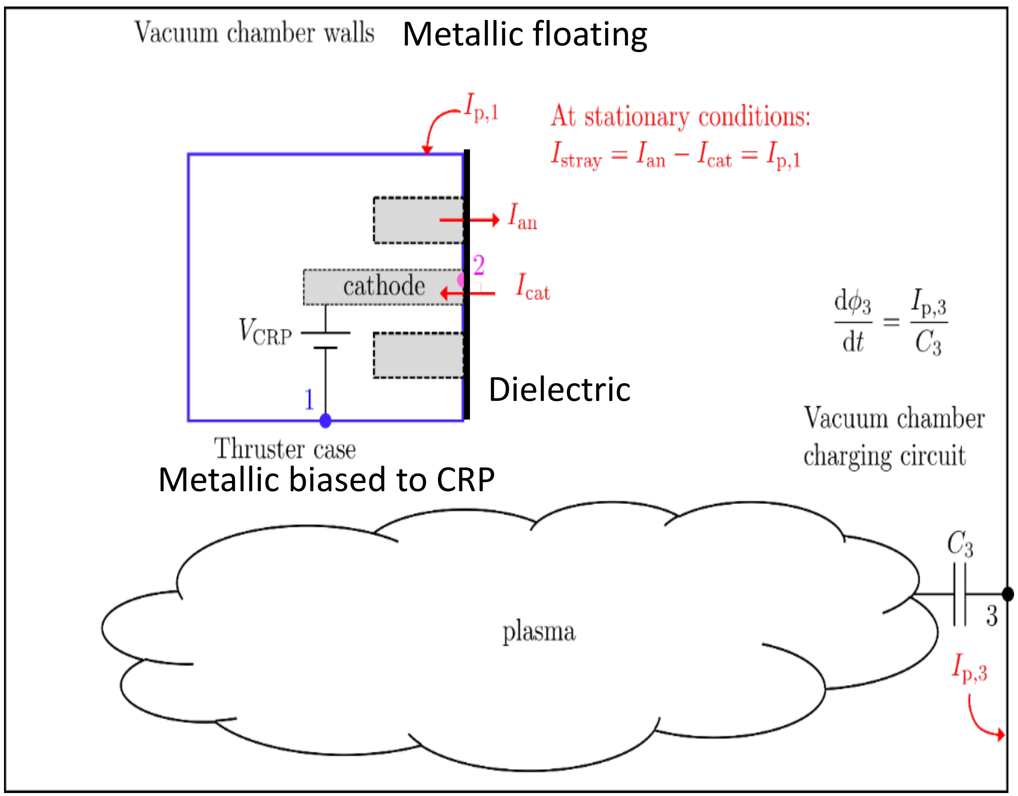

- Simulations. 1st step
  - Thruster emits just neutrals
  - Pumps are free loss surfaces.
  - Background pressure is proportional to pump area
- Second step.
  - Thruster firing: Plasma emission

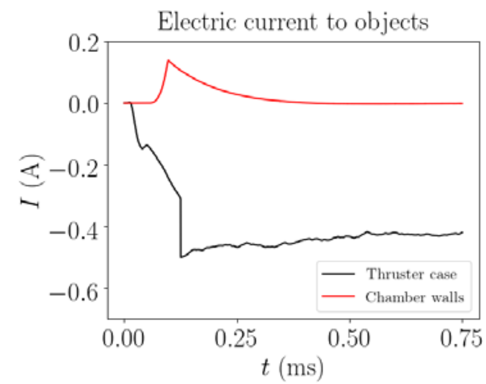


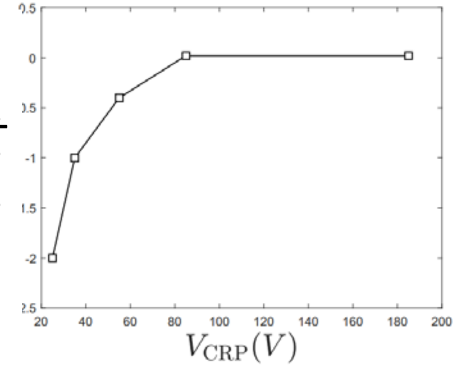
# Thruster-VC simulations

- Walls constitute additional electric paths for plasma
- Electric coupling (thruster + cathode + plume + chamber +…) can have large impact in
  - plume properties.
  - electric currents to different elements
- Very relevant for analyses of experimental results
- Effect in performances is probably limited, but it can have some impact

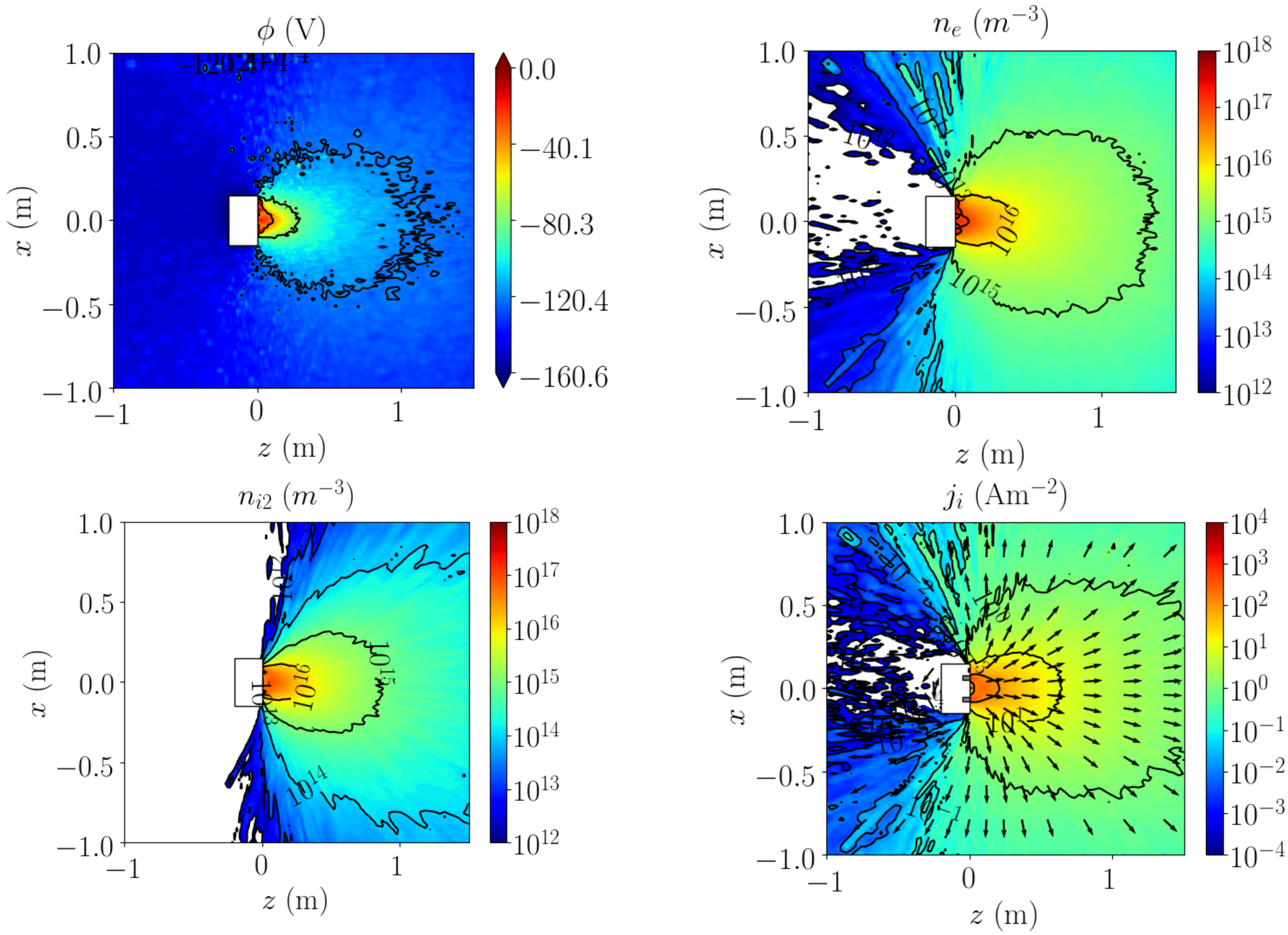



Stray currents vs Vcrp



# Thruster-VC simulations

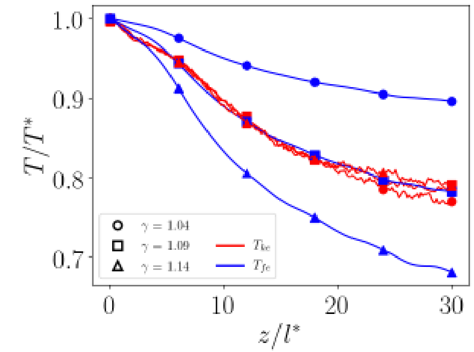


# Kinetically-optimized EP2PLUS

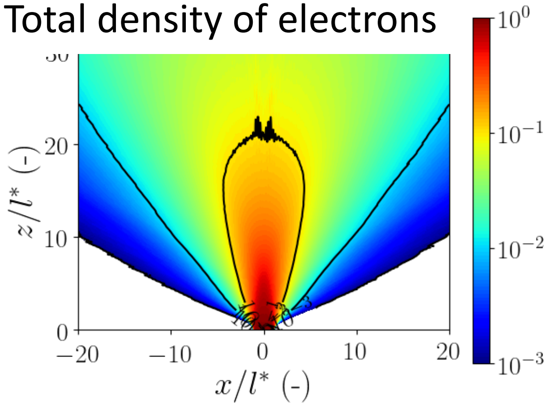
- Developed under ECOMODIS for ESA (UC3M, JLU-Giessen, AirbusDS, ArianeG)
- Goals:
  - Consistent macroscopic description of electrons in 2D-3D rarified plumes
  - Experimental verification from testing GIT and ECR plumes
  - Theoretical verification with 1D kinetic codes (AKILES,…)
- Our (first) approach:
  - Use EP2PLUS-1 (PIC ions, fluid electrons, polytropic closure, quasineutrality)
  - We add a partial population of PIC electrons
  - PIC electrons 'inform' of macroscopic properties (e.g. $\gamma$) to electron fluid
  - These properties can be adapted in fluid model
- Advantages
  - Large saving in length ($\gg \lambda_D$) and time scales ($\gg \omega_{pe}^{-1}$)
    - Much less expensive than full PIC codes $\rightarrow$ 1-2 orders saving in computation
  - Direct verification of macroscopic properties

# Kinetically-optimized EP2PLUS

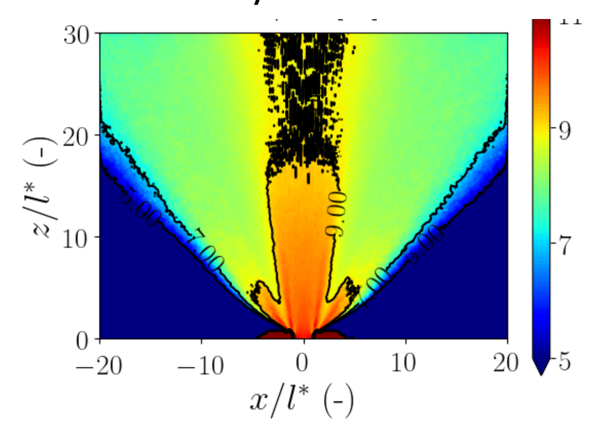
- Example: unmagnetized, collisionless, 2D plume
- There is an optimal polytropic coef. $\gamma$ fitting $T_{kin}(z,0)$
- Still, fluid physics are complex:
  - lateral cooling is higher than axial one
  - the cooling is locally anisotropic: $\nabla \cdot \bar{\bar{p}}_e \neq \nabla p_e$
  - (collisions isotropize partially)

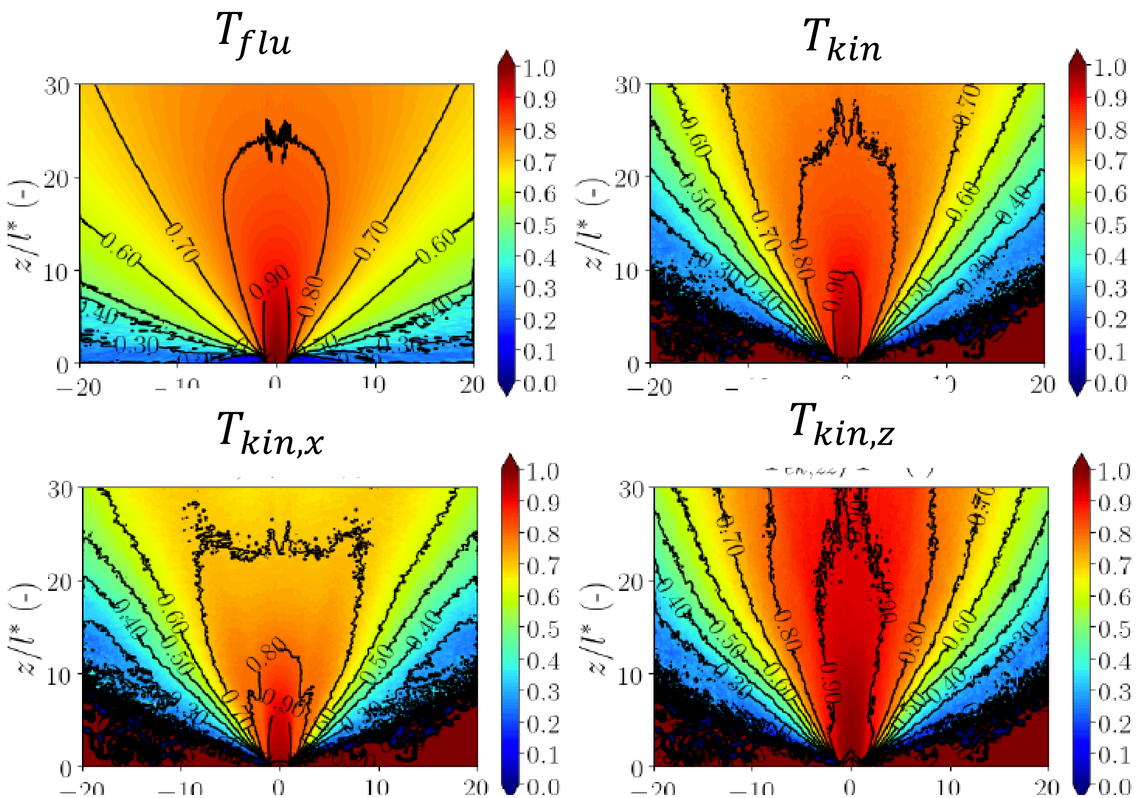



Total density of electrons

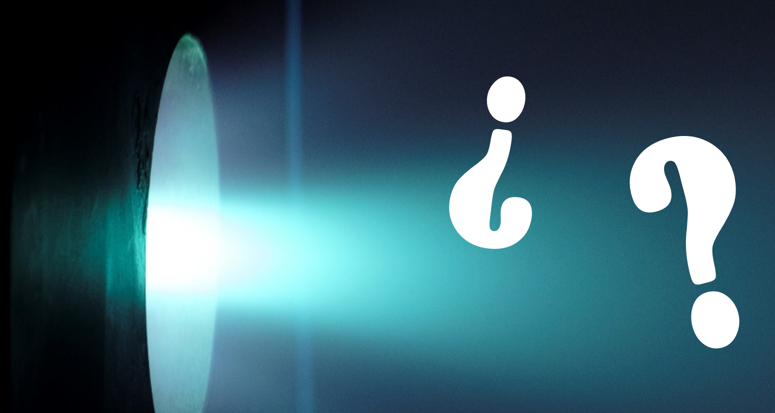



Relative density of kinetic electrons



# Thank you! Questions?



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