EP2Plus: a hybrid plasma plume/spacecraft interaction code

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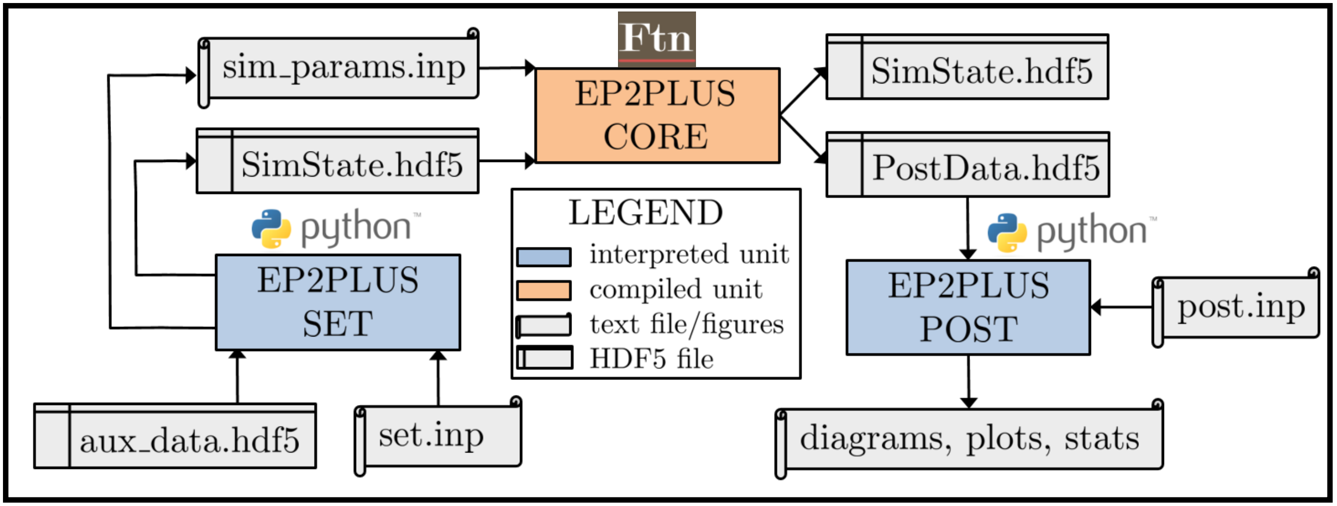
Contents

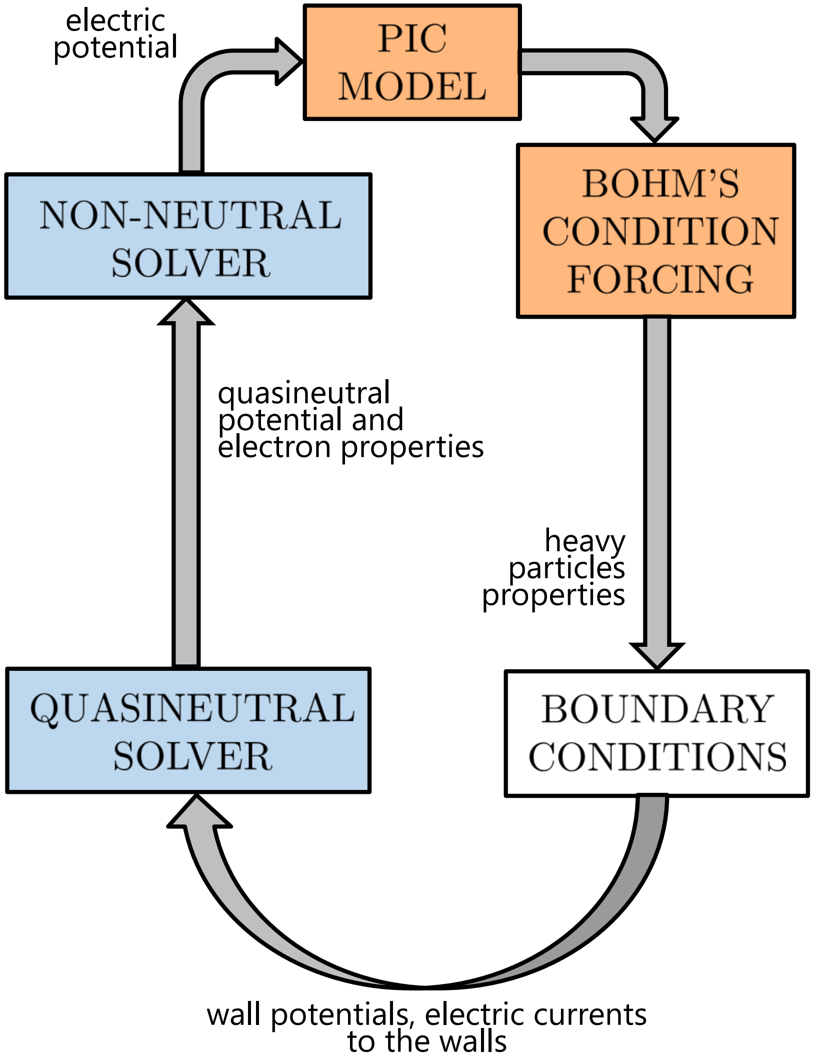
Introduction to EP2PLUS

- EP2PLUS: *Extensible Parallel Plasma PLUme Simulator*
  - 3 independent modules: SET, CORE, POST
- Industry-level standards
  - HDF5 format I/O files
- Strict development and validation standards
  - Test Driven Design (TDD) → A tests-suite with up to 20 tests
- Parallelization with OpenMP
- Most distinguishing simulation capabilities:
  - **New electron model** → electric currents in the plasma
  - **Non-neutral code** → very low density plasma
  - **Sputtering** effects modeling



Hybrid simulation loop

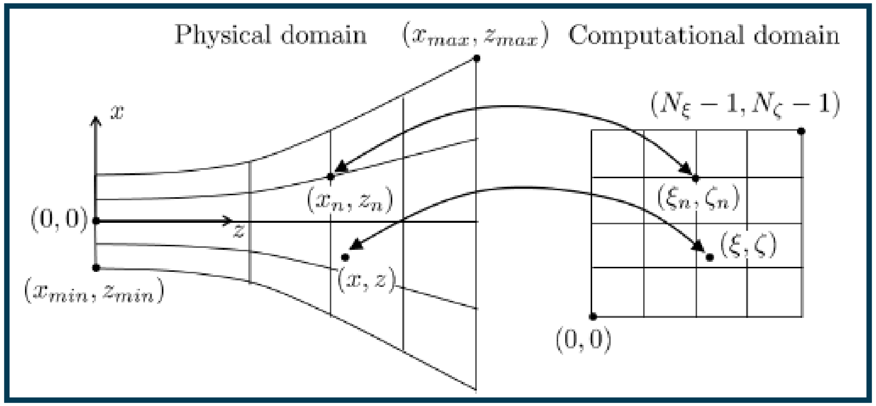
THE HYBRID CODE LOOP



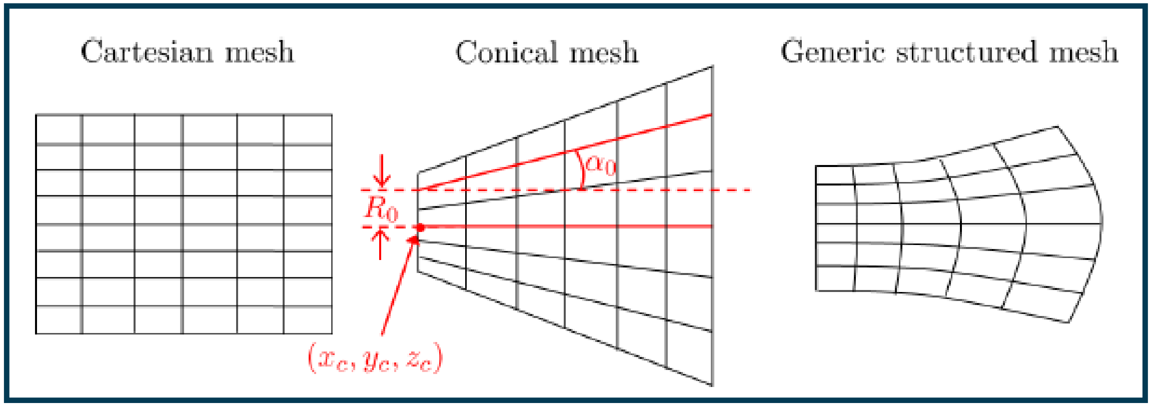
- PIC model + Bohm's condition forcing
  - ❑ Macro-particles injection
  - ❑ Macro-particles collisions (DSMC, MCC)
  - ❑ Moving macro-particles
  - ❑ Surface crossing detection
  - ❑ Sorting and volume weighting
  - ❑ Surface effects on macro-particles
  - ❑ Surface weighting and Bohm's condition forcing
- Boundary conditions
  - ❑ Plasma sheaths solving
  - ❑ Equivalent circuit solving
- Electron fluid model
  - ❑ Solving for electric potential and electron properties with quasineutrality
  - ❑ Correct quasineutral solution in non-neutral regions

EP2PLUS: mesh and PIC sub-model

PHYSICAL AND COMPUTATIONAL DOMAINS



AVAILABLE MESH TYPES



- ➢ Structured mesh:
  - ❑ Cartesian: simple generation, uniform resolution
  - ❑ Conical: reduced downstream noise in plume-only simulation
  - ❑ Generic: dedicated mesh deformation algorithm
- ➢ Efficient indexing of PIC mesh cell-faces with 3 indices:
  - ❑ Objects represented by a list of material cell-faces
- ➢ Main PIC model features:
  - ❑ Macro-particles in dedicated lists in terms of charge, mass and origin
  - ❑ Population control with generation weights
  - ❑ Bohm's condition forcing at quasineutral material boundaries

The electron model (1)

- Major assumptions:
  - ☐ Kinetic fitting for the electron pressure and inertialess electrons
  - ☐ Unmagnetized plume
  - ☐ Elastic collisions with heavy species
  - ☐ Non-neutral plasma

CURRENT CONTINUITY

$$\frac{\partial \rho_c}{\partial t} + \nabla \cdot \boldsymbol{j} = 0$$

MOMENTUM BALANCE

$$0 = -\nabla p_e - e n_e (-\nabla \phi) - \sum_{s=1}^{L} \nu_{es} m_e n_e \left(\boldsymbol{u}_e - \boldsymbol{u}_s \right)$$

$$\nabla^2 H_e + \nabla \ln \sigma_e \cdot \nabla H_e = -\frac{e}{\sigma_e} \left(\nabla \cdot \boldsymbol{j}_d + \frac{\partial \rho_c}{\partial t} \right)$$

UNKNOWN BERNOULLI'S FUNCTION

ELECTRON CONDUCTIVITY

$$\boxed{\sigma_e = \frac{e^2 n_e}{m_e \nu_e}}$$

DRIVING CURRENT (PIC)

$$\boxed{\boldsymbol{j}_d = \boldsymbol{j}_i - \frac{e n_e}{\nu_e} \sum_{s=1}^{L} \nu_{es} \boldsymbol{u}_s}$$

ELECTRIC CURRENT DENSITY

$$\boxed{\boldsymbol{j} = \frac{\sigma_e}{e} \nabla H_e + \boldsymbol{j}_d}$$

- Boundary conditions on electric currents

The electron model (2)

- In general the equation for H_e is coupled to Poisson's equation:

POISSON'S EQUATION

$$\nabla^2\phi = -\frac{\rho_c}{\epsilon_0} = -\frac{e}{\epsilon_0}\left(n_e^* - n_e\right)$$

QUASINEUTRAL PLASMA DENSITY

- The quasineutral solver assumes quasineutrality

QUASINEUTRALITY

$$\rho_{c,e} = \rho_{c,i} \rightarrow n_e = n_e^*$$

PIC MODEL → QUASINEUTRAL ELECTRON PROPERTIES → QUASINEUTRAL SOLVER → BERNOULLI'S FUNCTION

- Then, the electric potential is retrieved as:

$$\phi^* = \frac{h_e^*(n_e^*) - H_e^*}{e}$$

NEGLECTED IN MOST HYBRID CODES

KNOWN BAROTROPIC FUNCTION

Ongoing kinetic studies (e.g. Merino 2017) aim at evaluating γ and other applicable closures

E.G. FROM POLYTROPIC CLOSURE

$$h_e(n_e) = \begin{cases} T_{e0}\ln\left(\frac{n_e}{n_{e0}}\right) & \text{for } \gamma = 1 \\ -\frac{\gamma T_{e0}}{(\gamma-1)}\left[1-\left(\frac{n_e}{n_{e0}}\right)^{\gamma-1}\right] & \text{for } \gamma > 1 \end{cases}$$

The electron model (3)

- Quasineutral solution used to split the domain into quasineutral and non-neutral regions
- Bernoulli's function recomputed with previous time step values of the non-neutral electron conductivity and driving current

$$\sigma_e \rightarrow \sigma_e^{(k-1)} \quad , \quad \boldsymbol{j}_d \rightarrow \boldsymbol{j}_d^{(k-1)} \qquad \rightarrow \qquad H_e$$

- Electric potential is obtained from a non-linear Poisson's equation with appropriate boundary conditions

ION CHARGE DENSITY

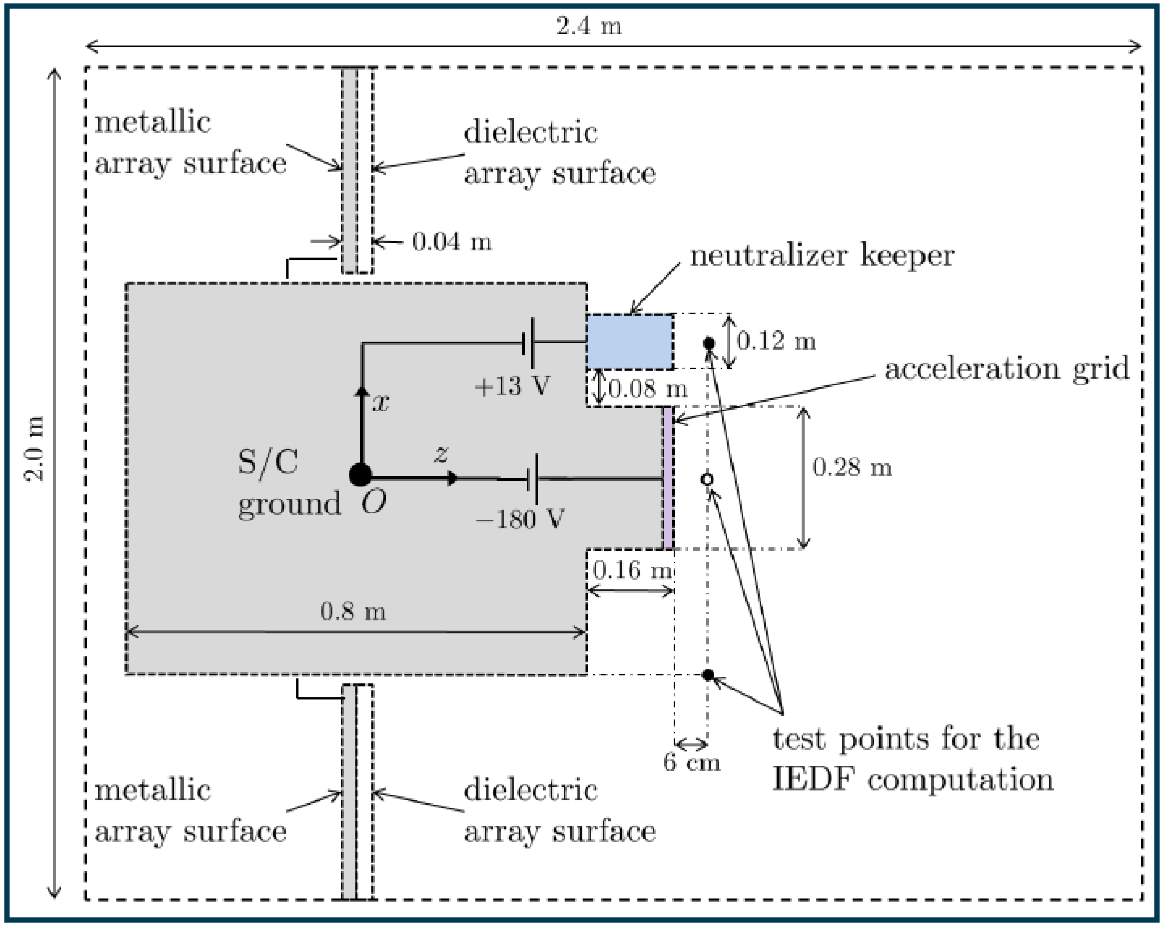
NON-LINEAR FUNCTION OF BOTH ϕ and H_e

$$\nabla^2 \phi = -\frac{e}{\epsilon_0}\left(n_e^* - n_e(\phi, H_e)\right)$$

- Boundary conditions:
  - ❑ Wall potential at non-neutral boundaries
  - ❑ Zero normal electric field at non-neutral external boundaries
  - ❑ Quasineutral electric potential solution at other boundaries

S/C-plume interaction (1)

- Benchmark case:
  - ❑ Cubic satellite geometry
  - ❑ NSTAR thruster and a neutralizer



EQUIVALENT CIRCUIT

- ❑ S/C cubic body (**0V**)
- ❑ Back face of solar arrays and thruster cases (**0V**)
- ❑ Neutralizer (**+13V**)
- ❑ Last grid of the NSTAR (**-180V**)
- ❑ Front face of solar array is dielectric

S/C-plume interaction (2)

- Non-neutrality criterion for plasma nodes:

RELATIVE CHARGE DENSITY ESTIMATION

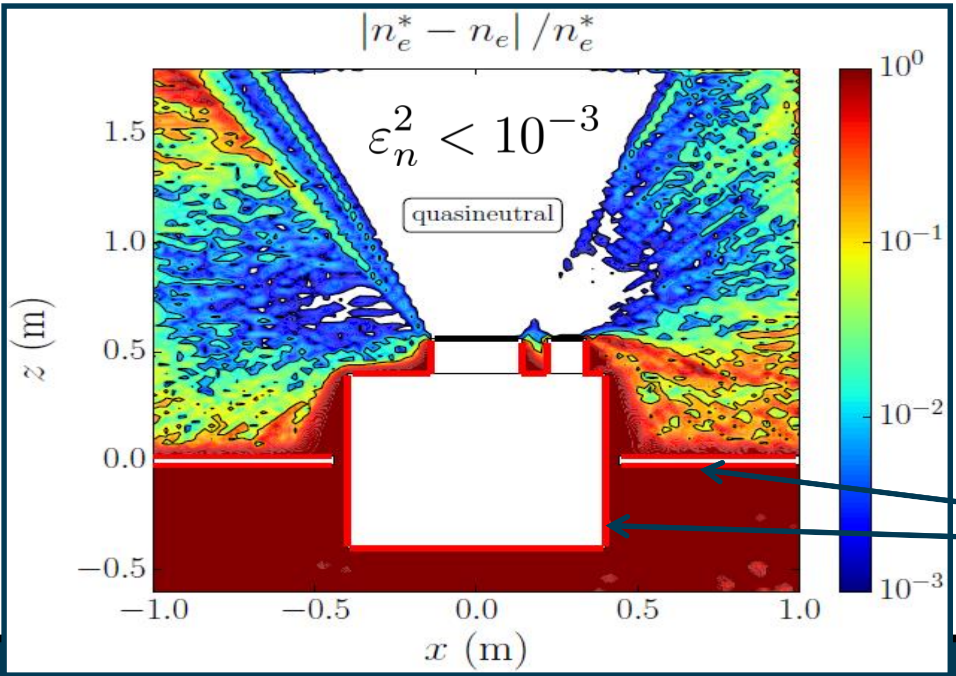
$$\varepsilon_n = \left|\frac{n_e^* - n_e}{n_e^*}\right|^{1/2} = \left|\frac{\epsilon_0 \nabla^2 \phi^*}{e n_e^*}\right|^{1/2} < \varepsilon_{max}$$

- Non-neutrality criterion for material cell-faces:

DEBYE LENGTH TO CELL SIZE RATIO

$$\varepsilon_f = \frac{1}{\Delta l}\sqrt{\frac{\epsilon_0 T_e^*}{e^2 n_e^*}} < \varepsilon_{max}$$

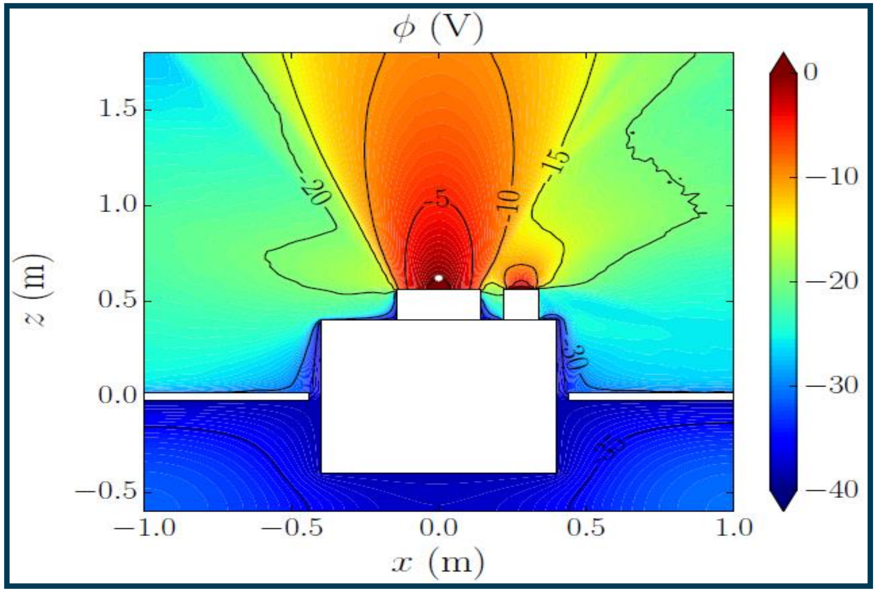
RELATIVE CHARGE DENSITY



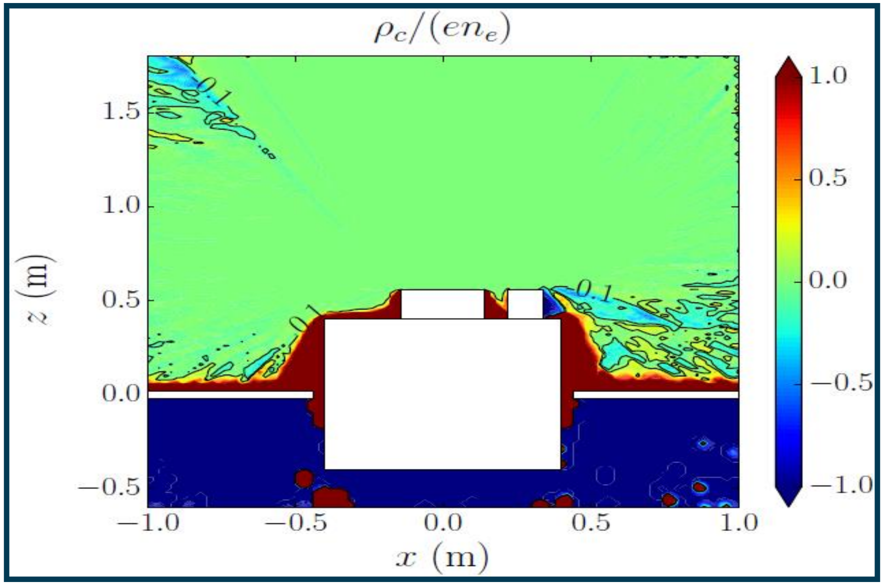
NON NEUTRAL BOUNDARIES

S/C-plume interaction (3)

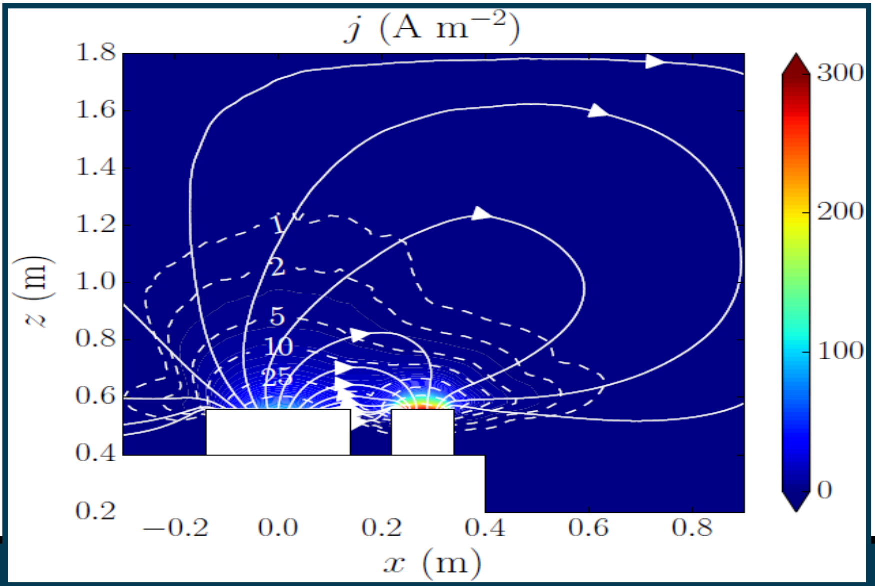
ELECTRIC POTENTIAL



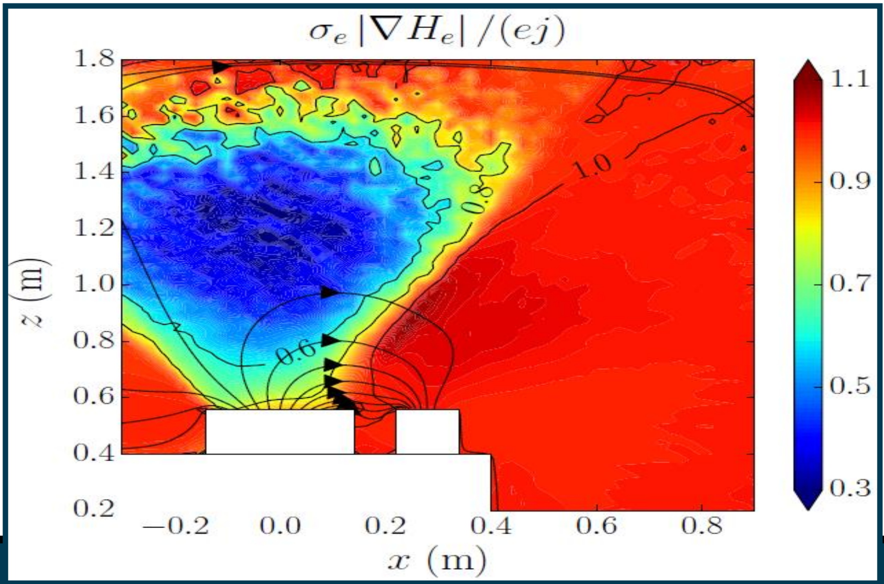
CHARGE DENSITY



ELECTRIC CURRENT DENSITY

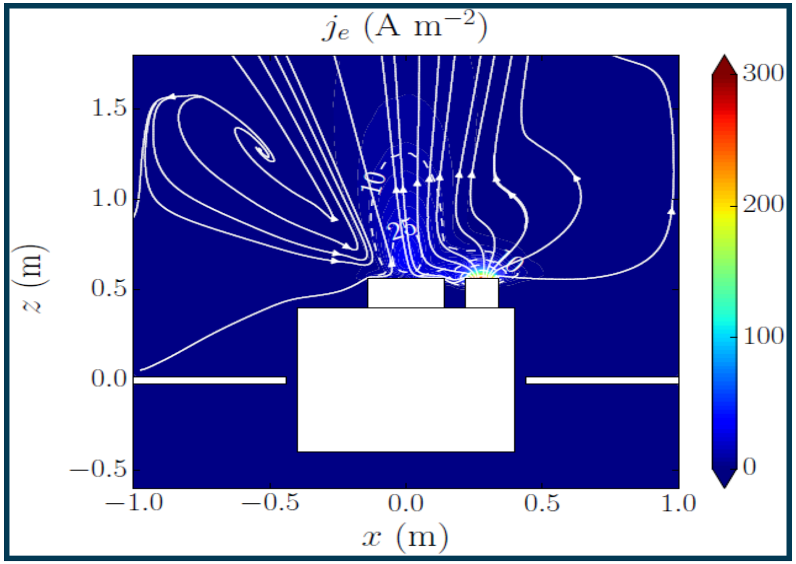


RELATIVE CURRENT CONTRIBUTIONS

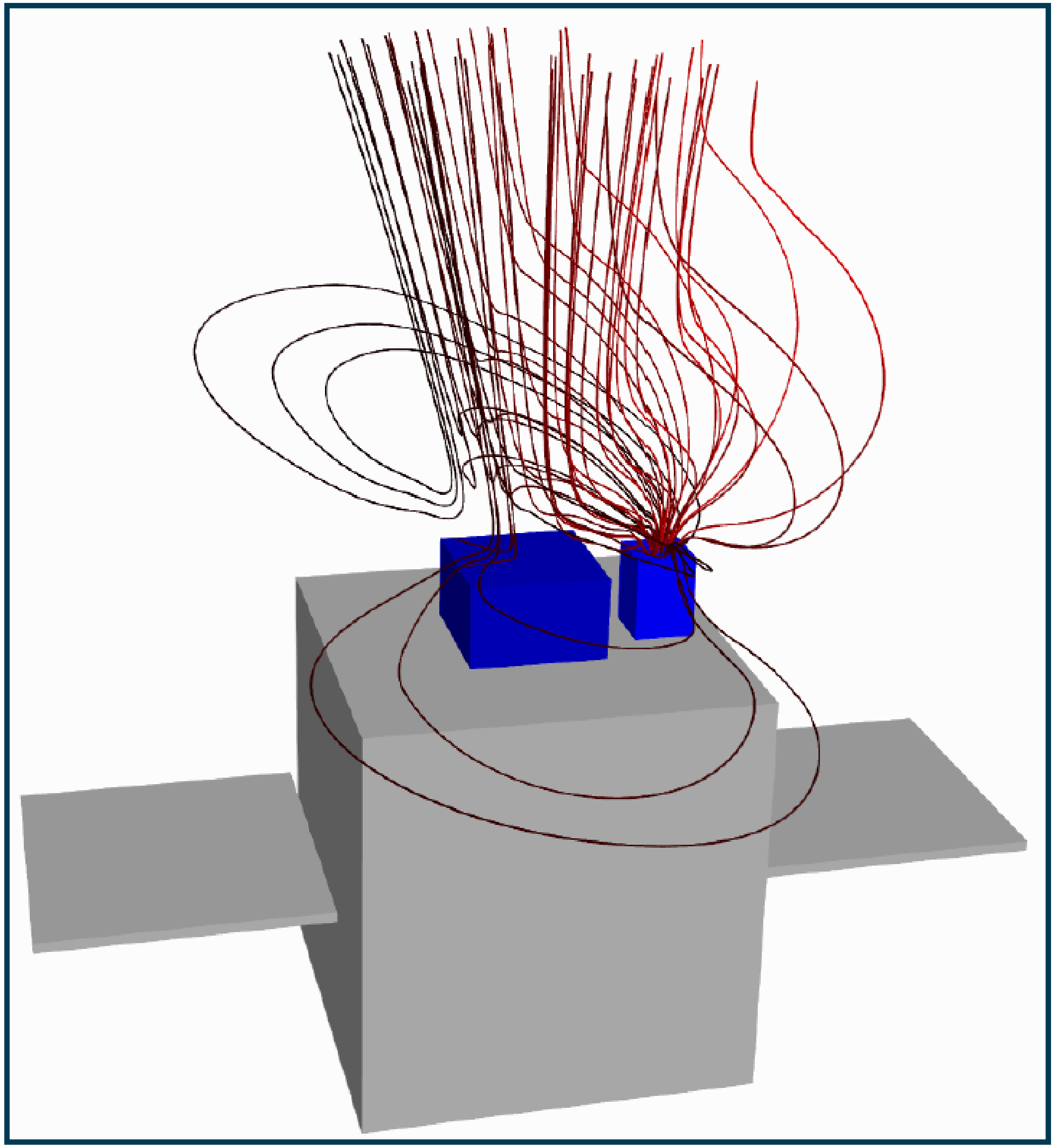


S/C-plume interaction (4)

ELECTRON CURRENT DENSITY

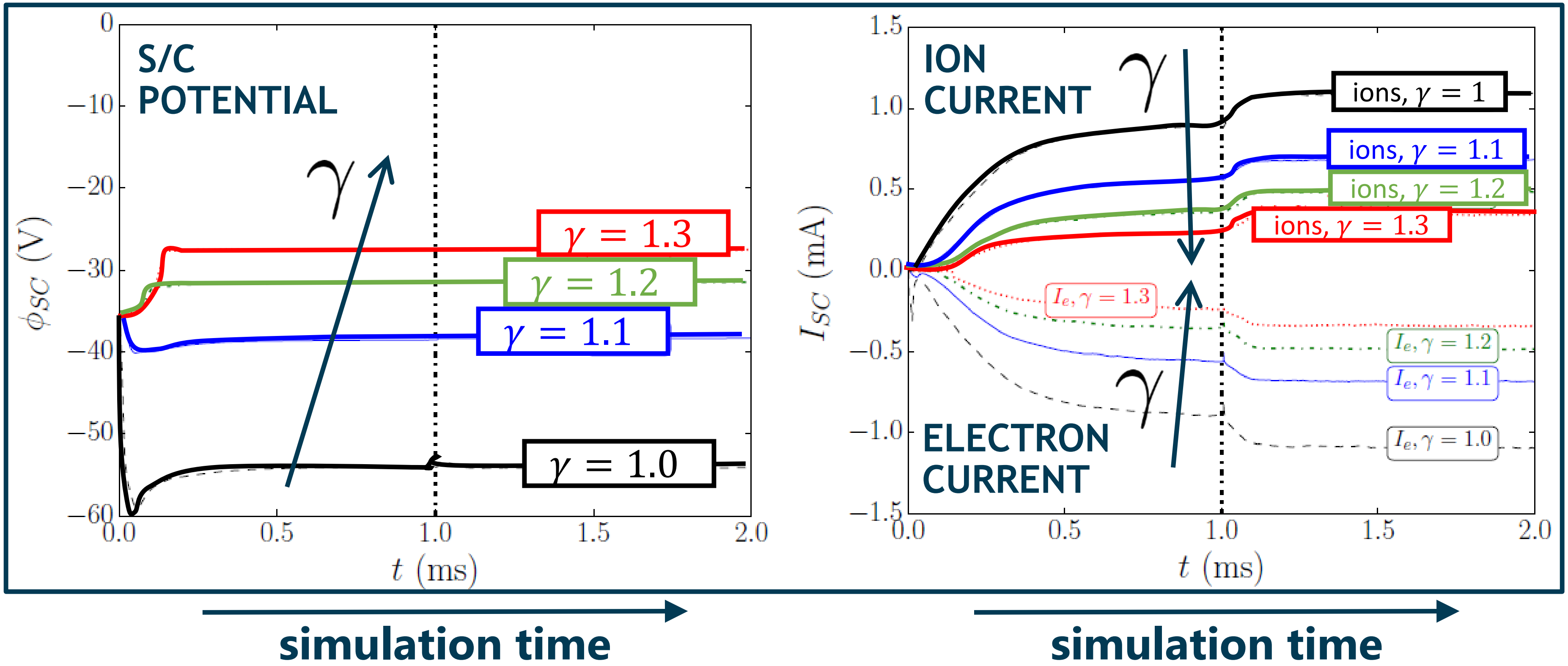


3D ELECTRON STREAMLINES



- Electron streamlines are 3D
- Electrons follow the minimum resistance path

S/C-plume interaction (5)

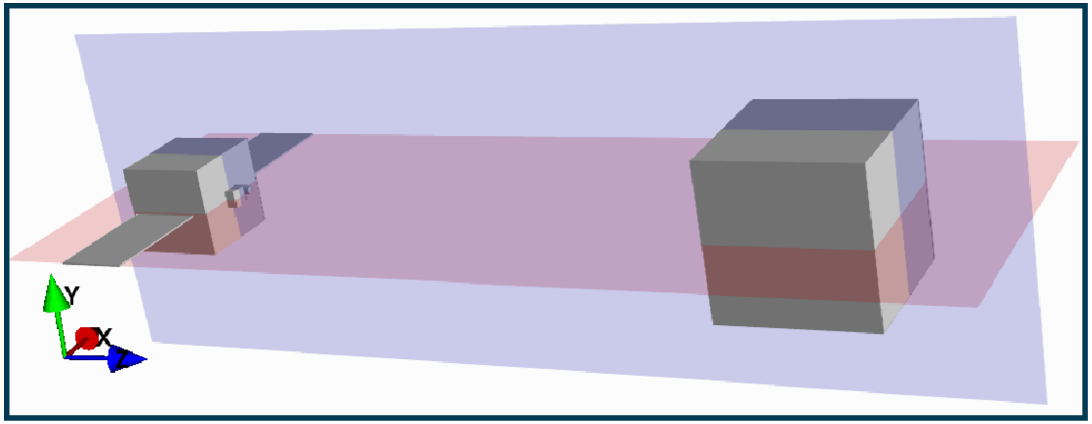


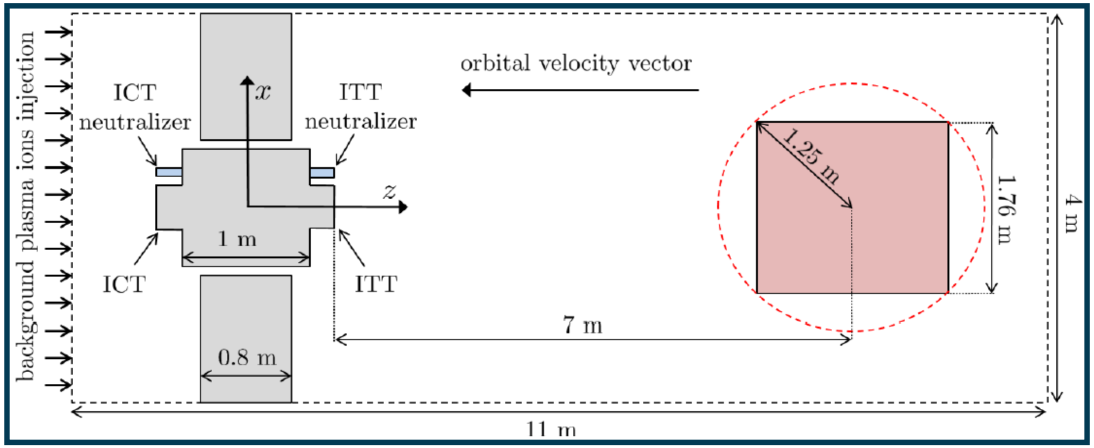
- The higher γ, the more positive the S/C floats, and the lower the collected ion/electron current
- Solving for non-neutral regions close to S/C yields a current increase (20-30%)

Application to an IBS scenario (1)

➢ Application to the ion beam shepherd scenario

- ❑ Modeling of sputtering on target debris (with **SRIM/TRIM**)
- ❑ Evaluation of critical phenomena (ion and sputtered neutral contamination, relative charging, etc…)



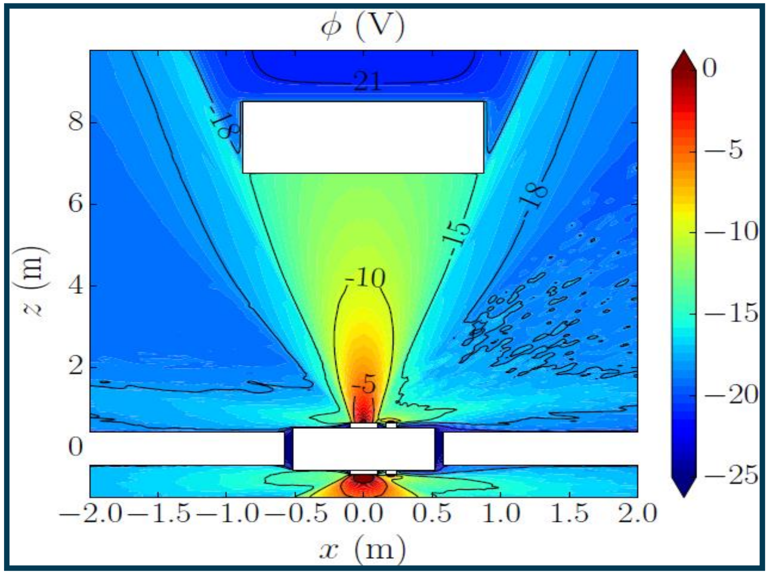


SIMULATION CHARACTERISTICS

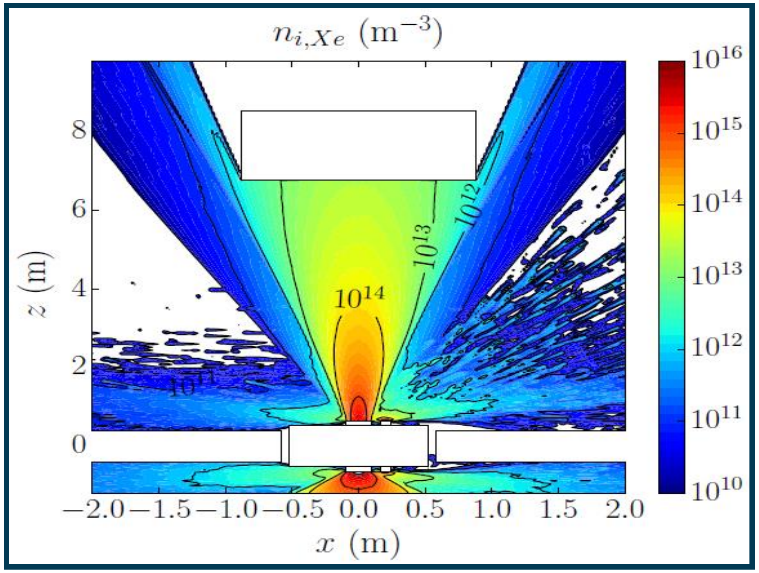
- ❑ Both thrusters with neutralizers
- ❑ Sun direction normal to solar arrays
- ❑ Arrays surface aligned with TG direction
- ❑ Ambient plasma ions
- ❑ Polytropic coefficient 1.15
- ❑ Target made of aluminium

Application to an IBS scenario (2)

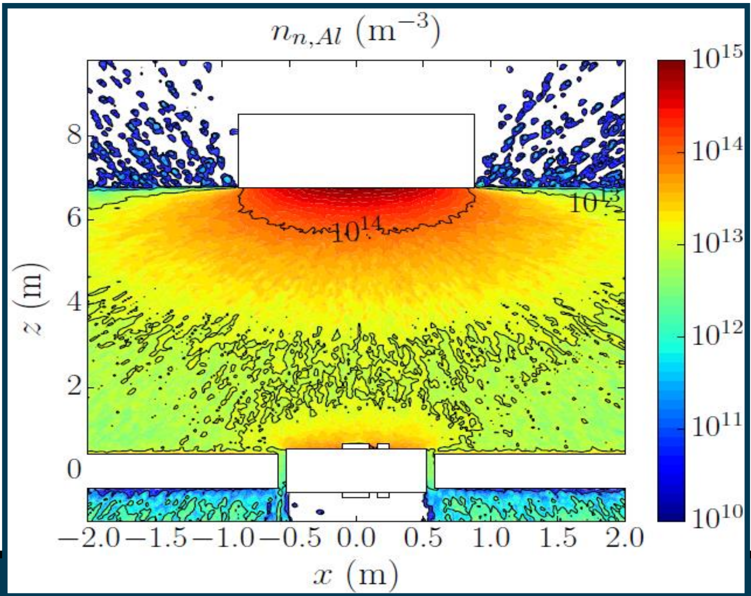
ELECTRIC POTENTIAL



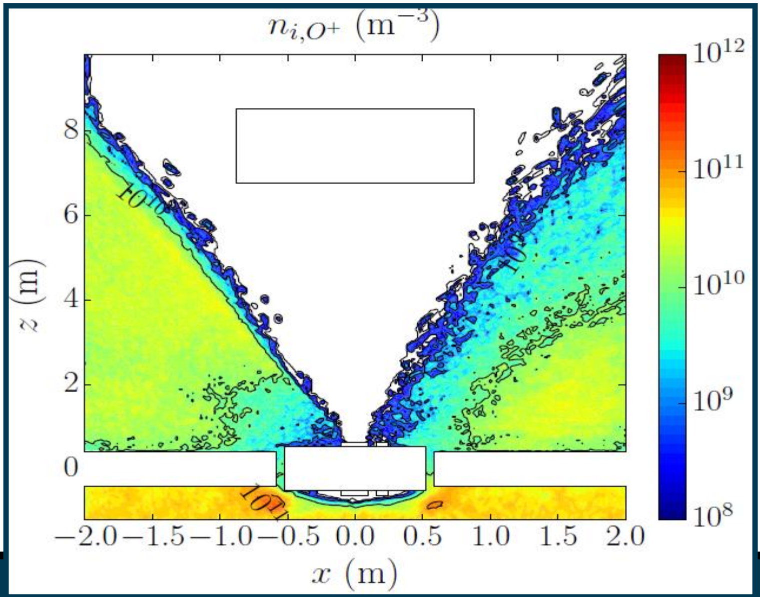
TOTAL Xe ION DENSITY



SPUTTERED ALLUMINIUM DENSITY

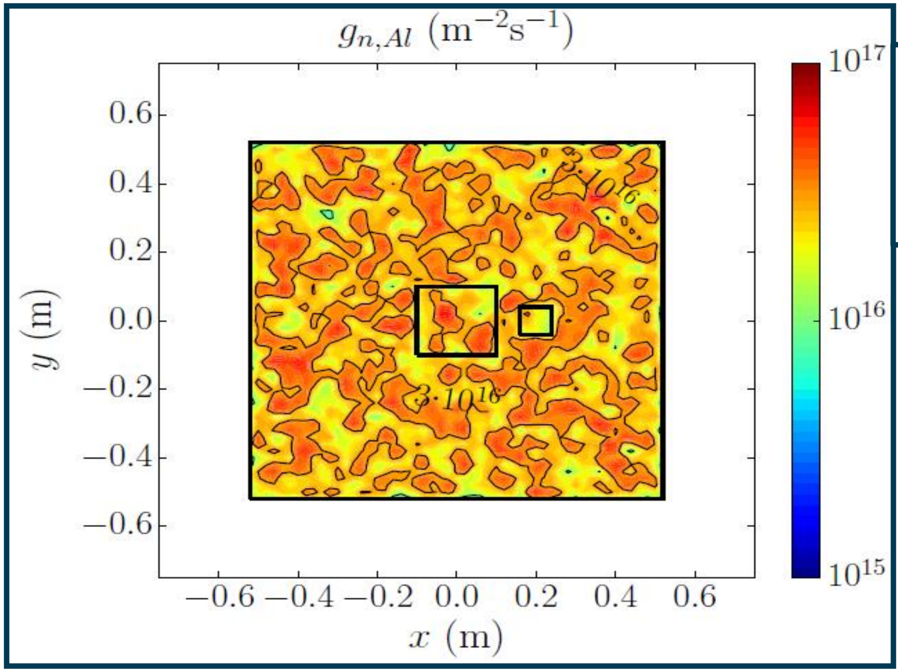


AMBIENT ION DENSITY



Application to an IBS scenario (3)

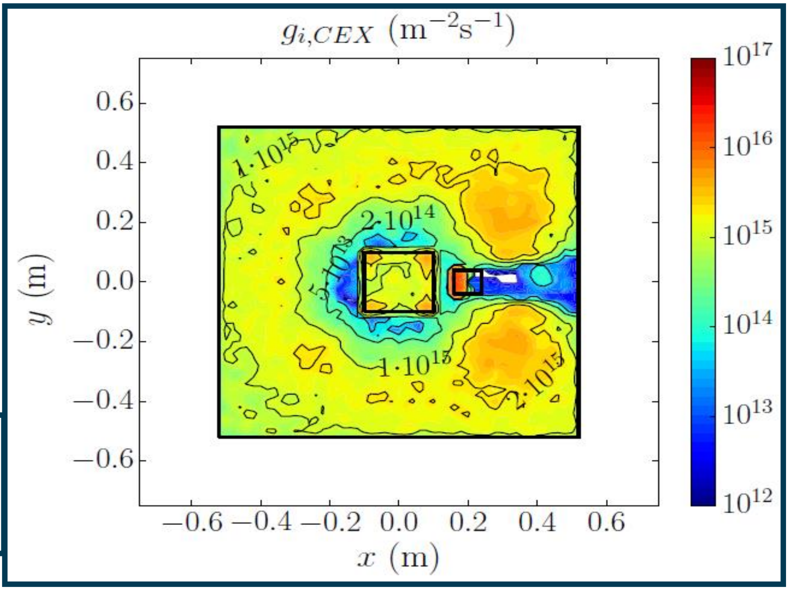
SPUTTERED ATOMS FLUX ON S/C



WORST CASE ALUMINIUM THICKNESS IN 170 DAYS:

$\approx 3\ \mu\mathrm{m}$

CEX ION FLUX ON S/C



PEAK ION FLUX:

$\approx 4 \cdot 10^{15}\ \mathrm{m}^{-2}\mathrm{s}^{-1}$

Application to an IBS scenario (4)

- Considered cases:
  - Nominal ($\gamma = 1.15$)
  - Higher polytropic coefficient ($\gamma = 1.25$)
  - No CEX collisions
  - No ambient ions
  - Off axis target (+0.44/-0.44 m along x/y)

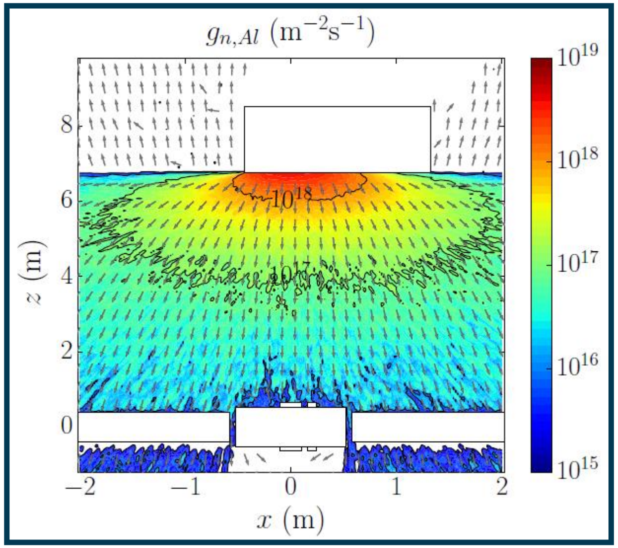
NOMINAL CASE MOMENTUM TRANSFER

$$\eta_m = 107\% \begin{cases} 91.7\% & \text{EMITTED Xe}^{+} \text{ IONS} \\ 3.4\% & \text{EMITTED Xe}^{++} \text{ IONS} \\ 8.6\% & \text{RECOMBINED Xe} \\ 3.0\% & \text{SPUTTERED Al} \end{cases}$$

	nominal	higher γ	Off-axis	no CEX	No amb.
ϕ_{plume}(V)	+26.3	+22.9	+26.3	+27.8	+26.3
ϕ_{TG}(V)	+9.7	+9.9	+9.5	+11.2	+9.7
$I_{i,S/C}$ (mA)	1.59	1.31	1.58	0.24	1.46
η_m	106.7%	107.9%	83.5%	106.7%	106.7%

POTENTIALS WITH RESPECT TO S/C GROUND

SPUTTERED ATOMS FLUX IN OFF AXIS TARGET CASE



- An off-axis TG yields:
  - Lower ion current and transferred force to TG
  - Non-negligible torque on the target debris
  - Minor changes in backsputtered atoms flux to the S/C

Conclusions and future work

- EP2PLUS main features presented with relevant simulation results
- Generalization of the electron model:
  - By retaining the magnetic field in the electron momentum balance equation → new elliptic equation for H_e

NEW TERMS

$$\bar{\bar{\sigma}}_e : \mathrm{Hess}(H_e) + \nabla H_e \cdot (\nabla \cdot \bar{\bar{\sigma}}_e) = -Y \qquad \boldsymbol{j} = \frac{\bar{\bar{\sigma}}_e}{e}\nabla H_e + \bar{\bar{\sigma}}_e/\sigma_{e\parallel}\left(\boldsymbol{j}_d + \chi \boldsymbol{j}_i \times \hat{\boldsymbol{b}}\right)$$

CONDUCTIVITY TENSOR

INPUTS FROM PARTICLE IN CELL MODEL AND MAGNETIC TOPOLOGY

HALL PARAMETER

$$Y = \frac{1}{e}\nabla\cdot\left[\frac{\bar{\bar{\sigma}}_e}{\sigma_{e\parallel}}\left(\boldsymbol{j}_d + \chi \boldsymbol{j}_i \times \hat{b}\right)\right] \quad , \quad \bar{\bar{\sigma}}_e = \sigma_{e\parallel}\begin{bmatrix} 1 & \chi b_z & -\chi b_y \\ -\chi b_z & 1 & \chi b_x \\ \chi b_y & -\chi b_x & 1 \end{bmatrix}^{-1} \quad , \quad \chi = \omega_{ce}/\nu_e$$

- Other modeling improvements:
  - Finer modeling of sputtering
  - More effective population control (re-normalization)
  - Inclusion of other surface effects (photo-emission, electron and ion bombardment emission, etc...)
  - More complex structured meshes (for different object geometries)

References

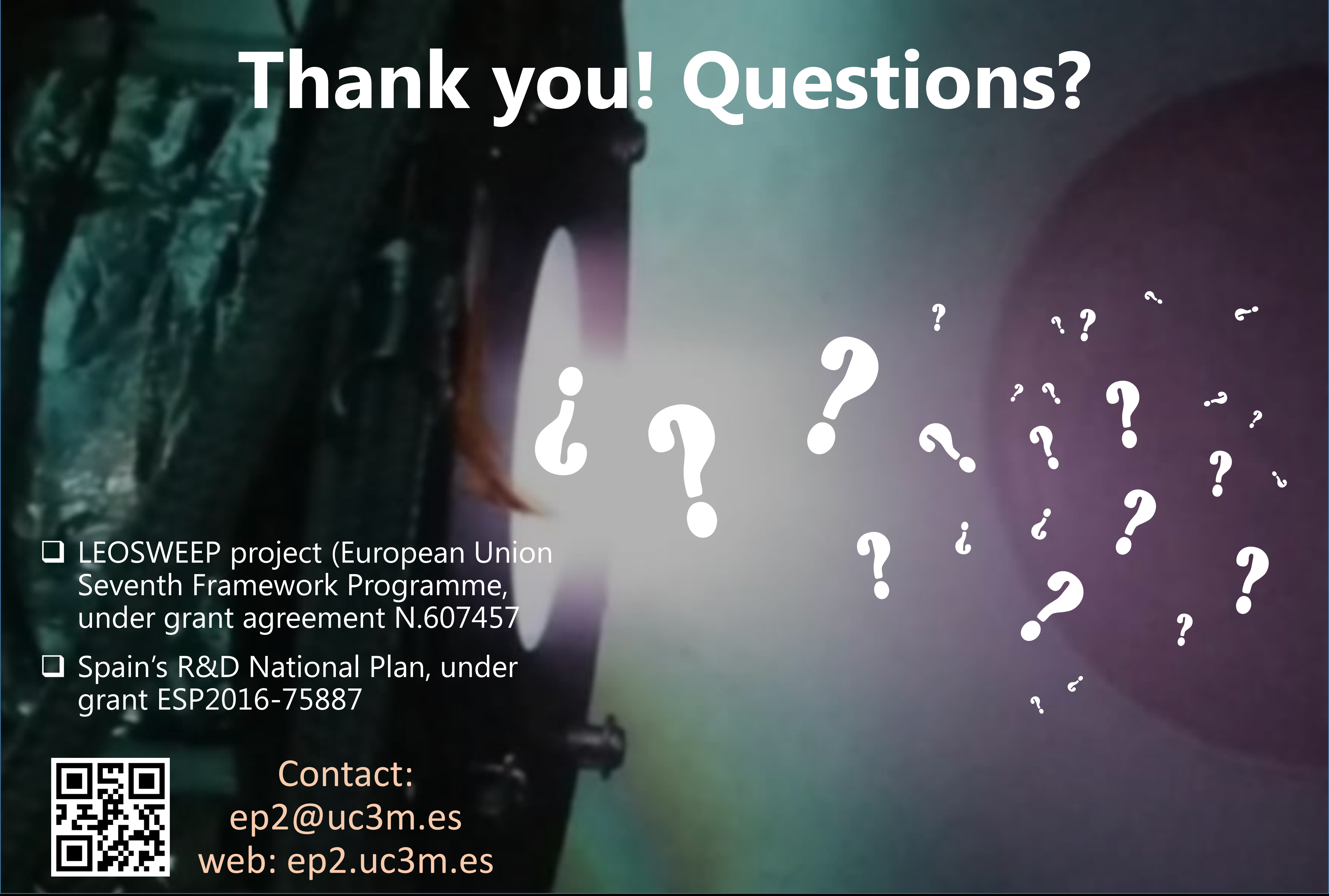
- F. Cichocki, PhD Thesis: **Analysis of the expansion of a plasma thruster plume into vacuum**, defended on September 26th, 2017, University "Carlos III de Madrid"

- F. Cichocki, A. Domínguez, M.Merino and E. Ahedo: **Hybrid 3D model for the interaction of plasma thruster plumes with nearby objects**, submitted to Plasma Sources Science and Technology, 2017

- F. Cichocki, M. Merino, E. Ahedo: **Spacecraft-plasma-debris interaction in an ion beam shepherd mission**, being submitted to Aerospace Science and Technology

- M. Merino, J. Mauriño, and Eduardo Ahedo: **Direct-Vlasov study of electron cooling mechanisms in paraxial, unmagnetized plasma thruster plumes**, International Electric Propulsion Conference 2017

Thank you! Questions?



- LEOSWEEP project (European Union Seventh Framework Programme, under grant agreement N.607457
- Spain’s R&D National Plan, under grant ESP2016-75887

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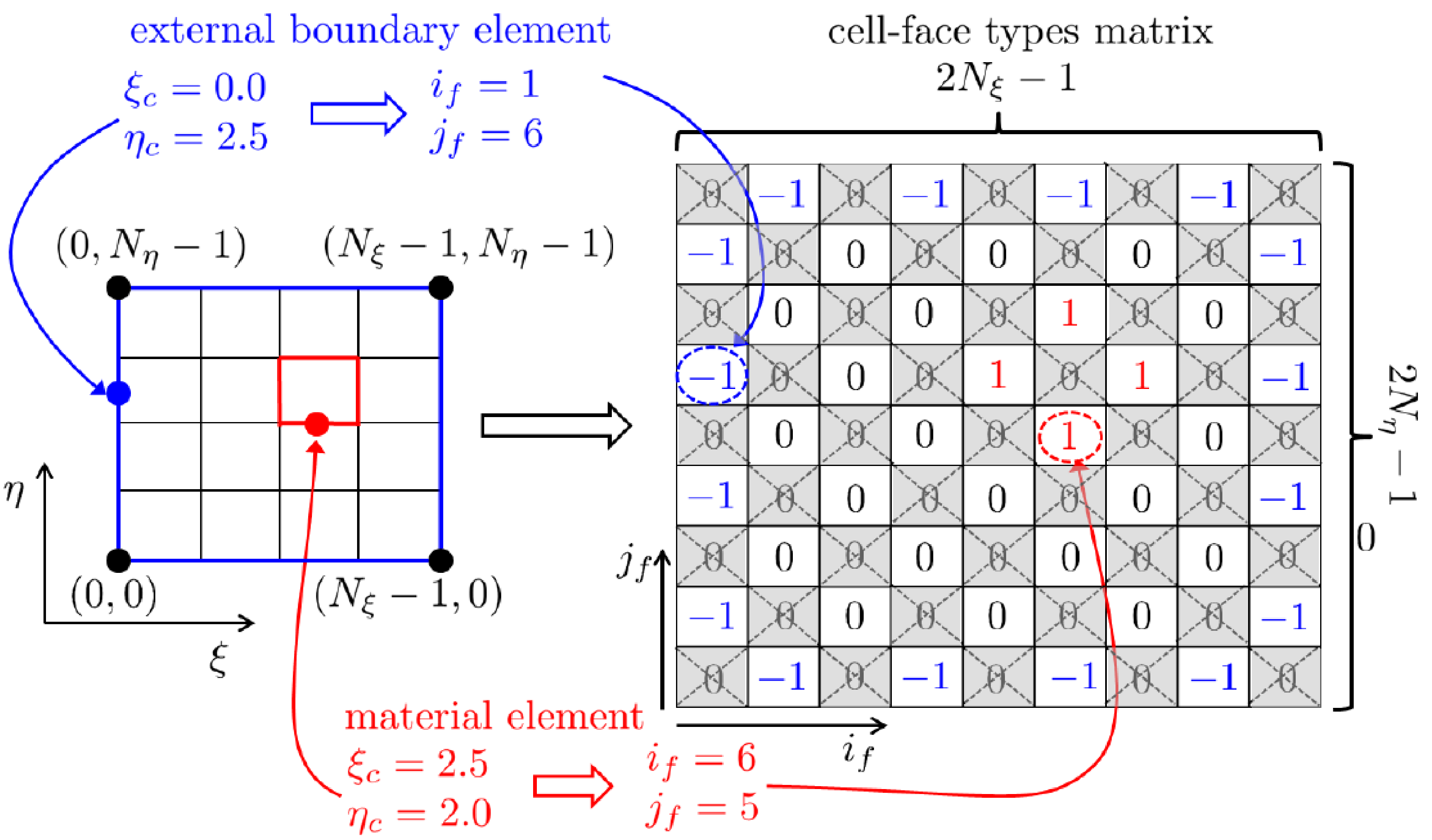
INDEXING LOGIC OF CELL-FACES



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PIC sub-model and Bohm’s condition forcing

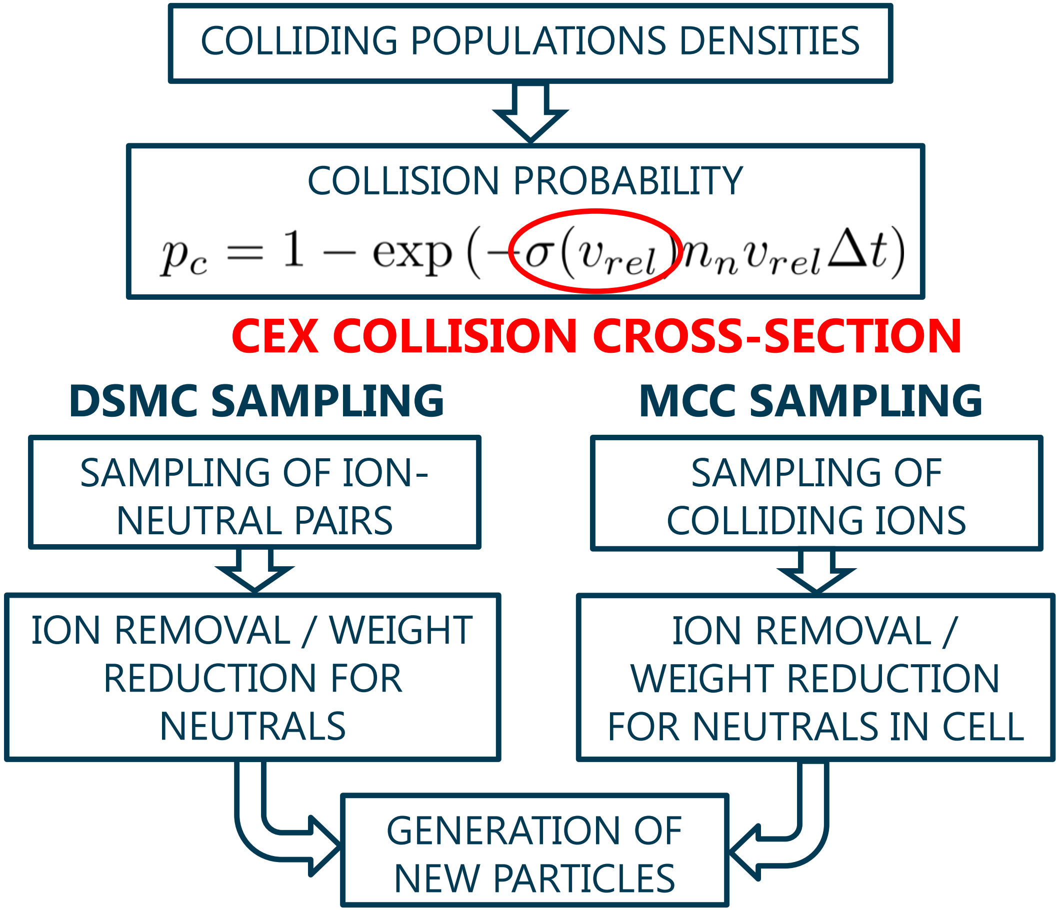
- Ions and neutrals are modeled as macro-particles
  - Standard injection, moving and weighting algorithms
  - Collisions include CEX and ionization
  - Interaction with walls: reflection, recombination and sputtering
- Different computational lists for macro-particles in terms of:
  - Elementary mass and charge
  - Origin/energy content
- Population control:
  - Controlled generation weight
  - Use of deformed meshes
- Surface-weighting at material boundaries
  - Accurate properties at sheath edges
- Bohm’s condition forcing at quasineutral boundaries

Considered macro-particle collisions

RESONANT SYMMETRIC CHARGE EXCHANGE

$$\mathrm{A}^{+}(\mathrm{fast}) + \mathrm{A}(\mathrm{slow}) \rightarrow \mathrm{A}^{+}(\mathrm{slow}) + \mathrm{A}(\mathrm{fast})$$

$$\mathrm{A}^{++}(\mathrm{fast}) + \mathrm{A}(\mathrm{slow}) \rightarrow \mathrm{A}^{++}(\mathrm{slow}) + \mathrm{A}(\mathrm{fast})$$



COLLIDING POPULATIONS DENSITIES

COLLISION PROBABILITY

$$p_c = 1 - \exp\left(-\sigma(v_{rel}) n_n v_{rel} \Delta t\right)$$

CEX COLLISION CROSS-SECTION

DSMC SAMPLING

SAMPLING OF ION-NEUTRAL PAIRS

ION REMOVAL / WEIGHT REDUCTION FOR NEUTRALS

MCC SAMPLING

SAMPLING OF COLLIDING IONS

ION REMOVAL / WEIGHT REDUCTION FOR NEUTRALS IN CELL

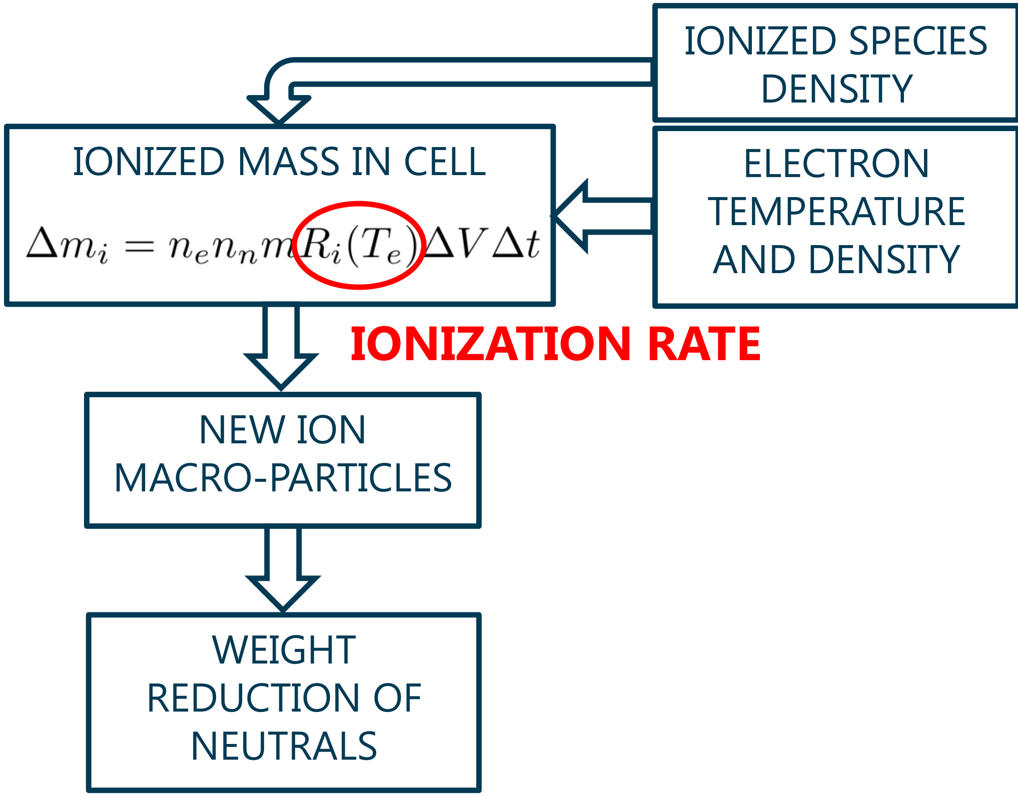
GENERATION OF NEW PARTICLES

IONIZATIONS

$$\mathrm{A} + e \rightarrow \mathrm{A}^{+} + 2e$$

$$\mathrm{A} + e \rightarrow \mathrm{A}^{++} + 3e$$

$$\mathrm{A}^{+} + e \rightarrow \mathrm{A}^{++} + 2e$$



IONIZED SPECIES DENSITY

ELECTRON TEMPERATURE AND DENSITY

IONIZED MASS IN CELL

$$\Delta m_i = n_e n_n m R_i(T_e) \Delta V \Delta t$$

IONIZATION RATE

NEW ION MACRO-PARTICLES

WEIGHT REDUCTION OF NEUTRALS

EP2PLUS: Surface weighting and Bohm

➢ Surface-weighting at material walls:

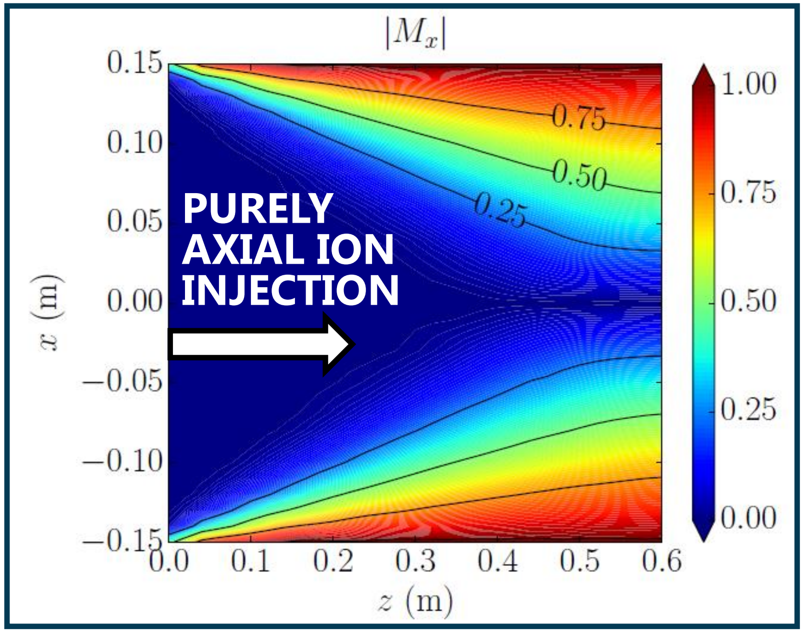
- ❑ More accurate evaluation of fluid properties
- ❑ Based on counting macro-particles that cross a given surface element of surface ΔS in the time interval Δt

CROSSING MACROPARTICLE WEIGHT

$$n^{(sw)} = \frac{1}{\Delta t \Delta S} \left(\sum_{j=1}^{N_{hit}} \frac{W_j}{|v_{\perp,j}|} + \sum_{j=1}^{N_{emi}} \frac{\boxed{W_j}}{|v_{\perp,j}|} \right)$$

➢ Bohm's condition forcing:

- ❑ Ions must be supersonic at quasineutral material boundaries (not automatically fulfilled in hybrid codes)
- ❑ A supersonic criterion (based on surface weighting) is evaluated → a density correction is applied, if not supersonic



Boundary conditions for electron model

- Simulation objects in EP2PLUS are of 2 types:
  - ❑ Conductive: iso-potential
  - ❑ Dielectric: zero electric currents, locally
- Collisionless, unmagnetized sheath model obtains:
  - ❑ Electron currents at conductive walls
  - ❑ Electric potentials at dielectric walls

ELECTRON CURRENT TO THE WALL

$$\boxed{\phi_W} = \boxed{\phi_S} - \frac{T_e}{e} \ln \left(\frac{\boxed{j_{e,W}}}{e n_e} \sqrt{\frac{2\pi m_e}{T_e}} \right)$$

WALL POTENTIAL

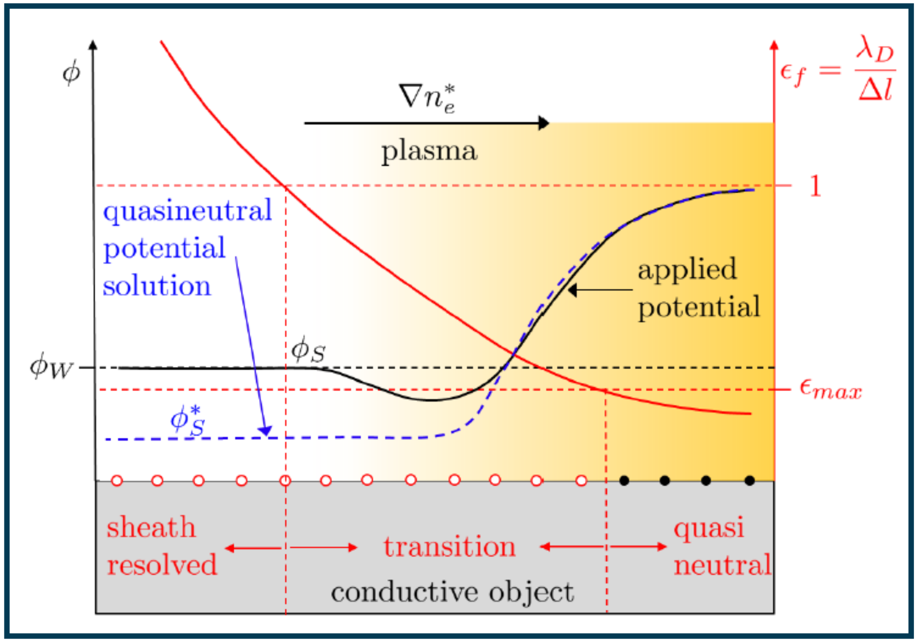
SHEATH EDGE POTENTIAL

- Conductive objects potential from an equivalent circuit
- External boundary conditions:
  - ❑ Zero normal electric field (at non-neutral boundaries)
  - ❑ Zero net-current

Electric potential boundary conditions

- ☐ $\phi = 0$ at the reference point for electron properties
- ☐ Sheath edge potential at quasineutral boundaries
- ☐ Transition conditions at non-neutral boundaries with

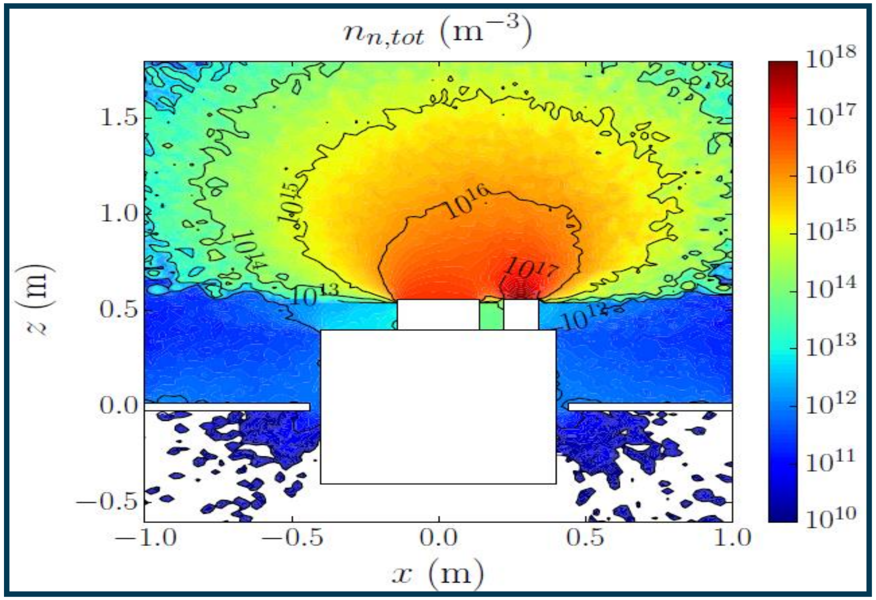
$$\varepsilon_{max} < \varepsilon_f < 1$$



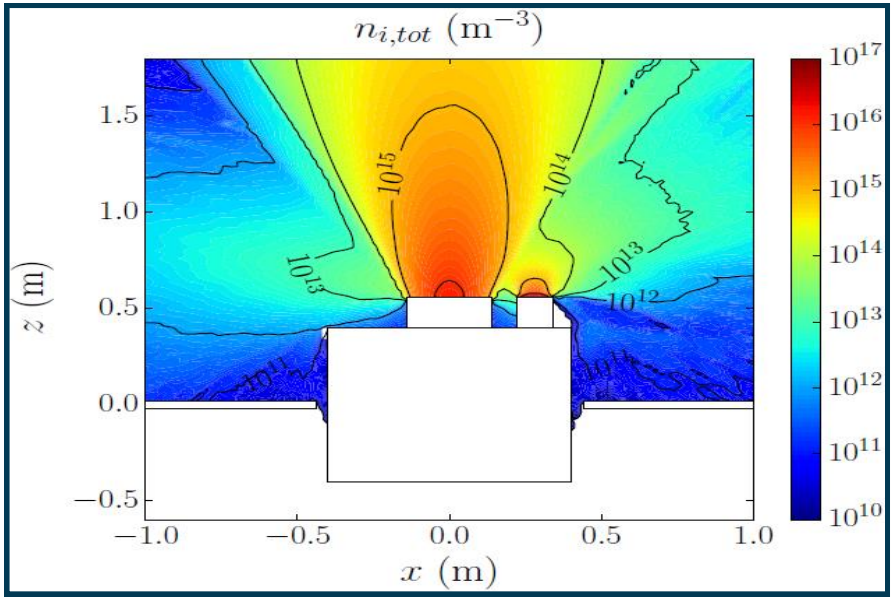
- ☐ Wall potential at resolved sheath boundaries $\varepsilon_f > 1$
- ☐ Zero electric field at non-neutral external boundaries

Plume-SC interaction: additional plots (1)

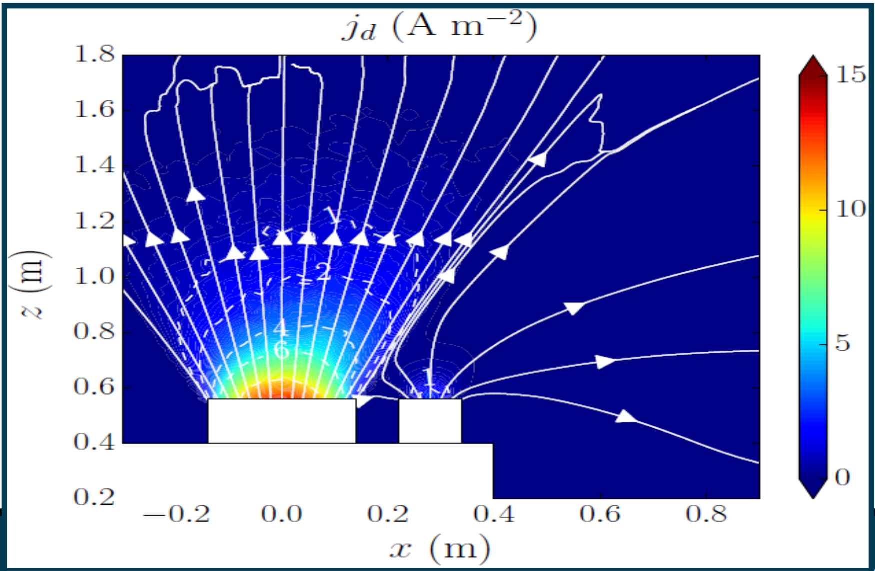
TOTAL NEUTRAL DENSITY



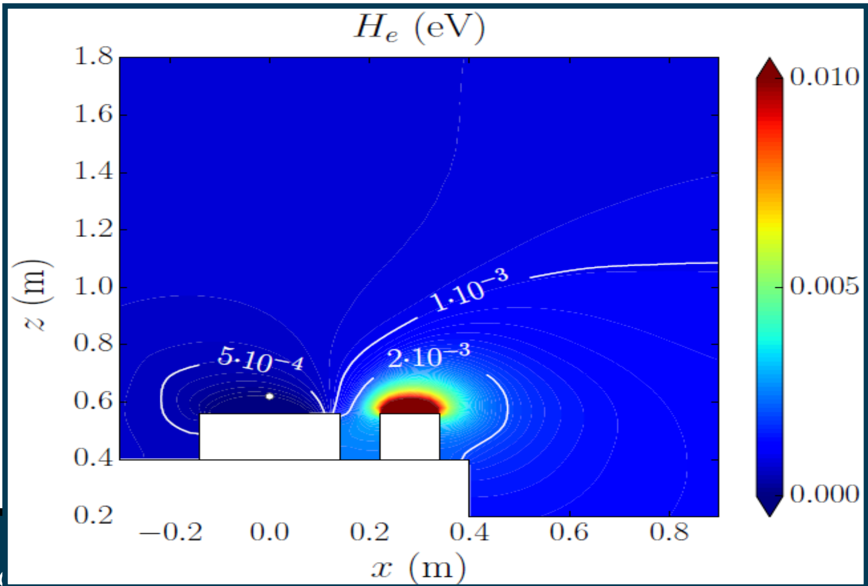
TOTAL ION DENSITY



DRIVING CURRENT

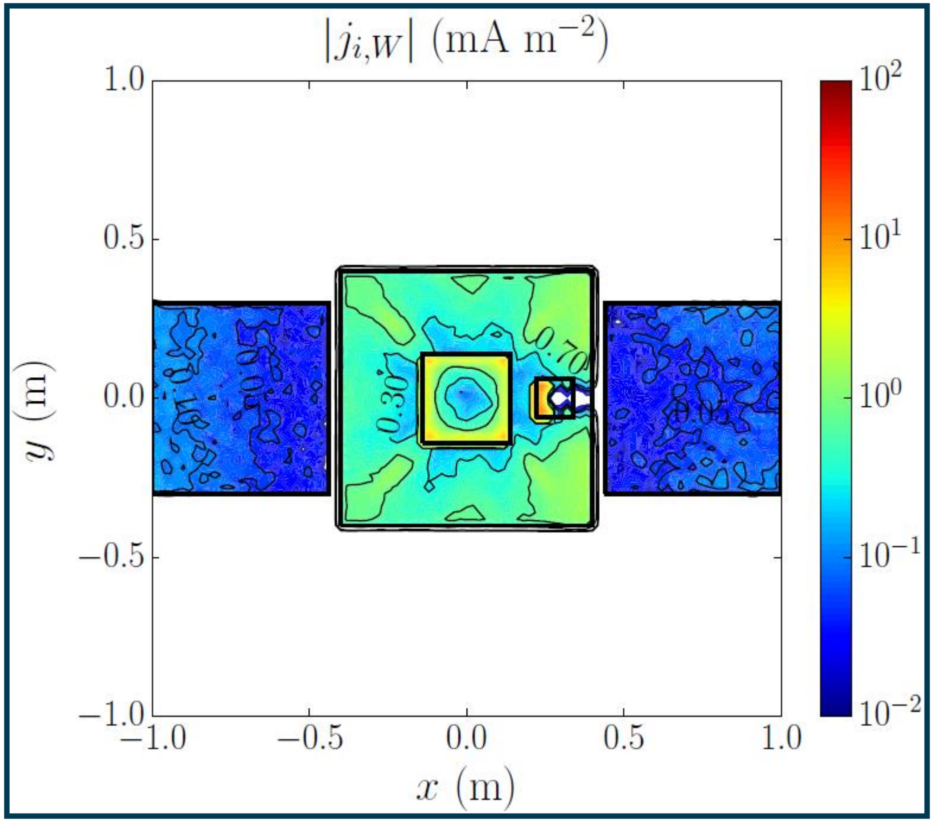


BERNOULLI'S FUNCTION

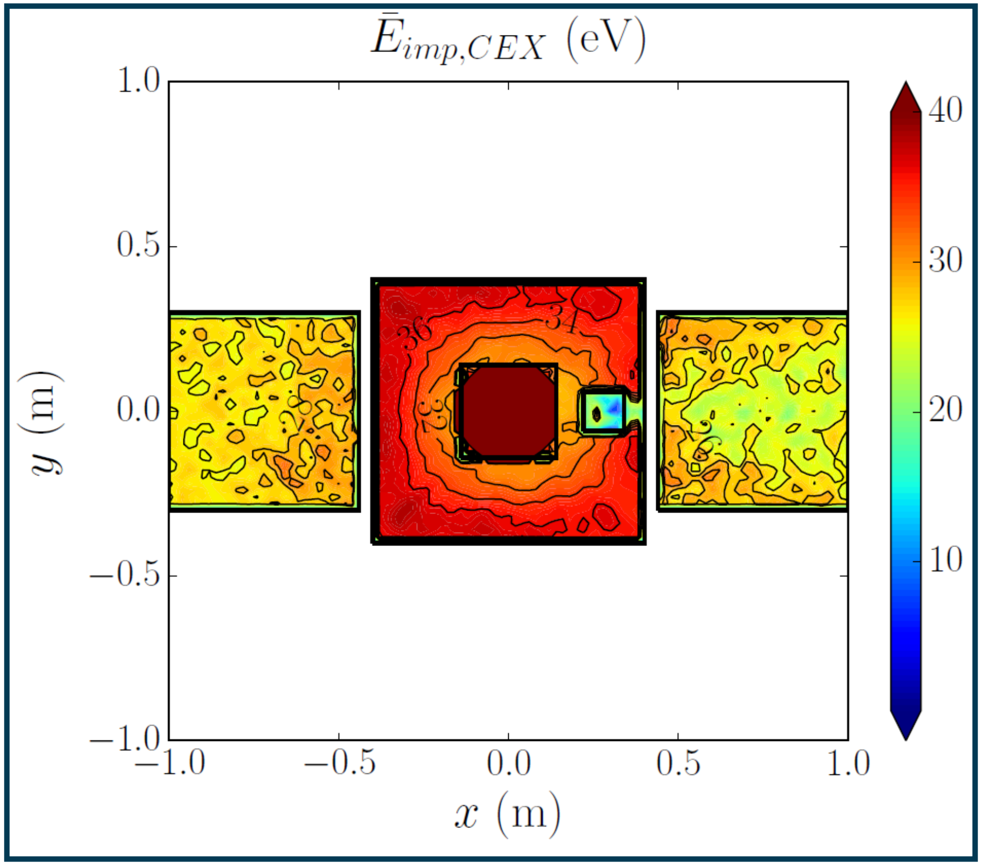


Plume-SC interaction: additional plots (2)

ION CURRENT TO S/C WALLS

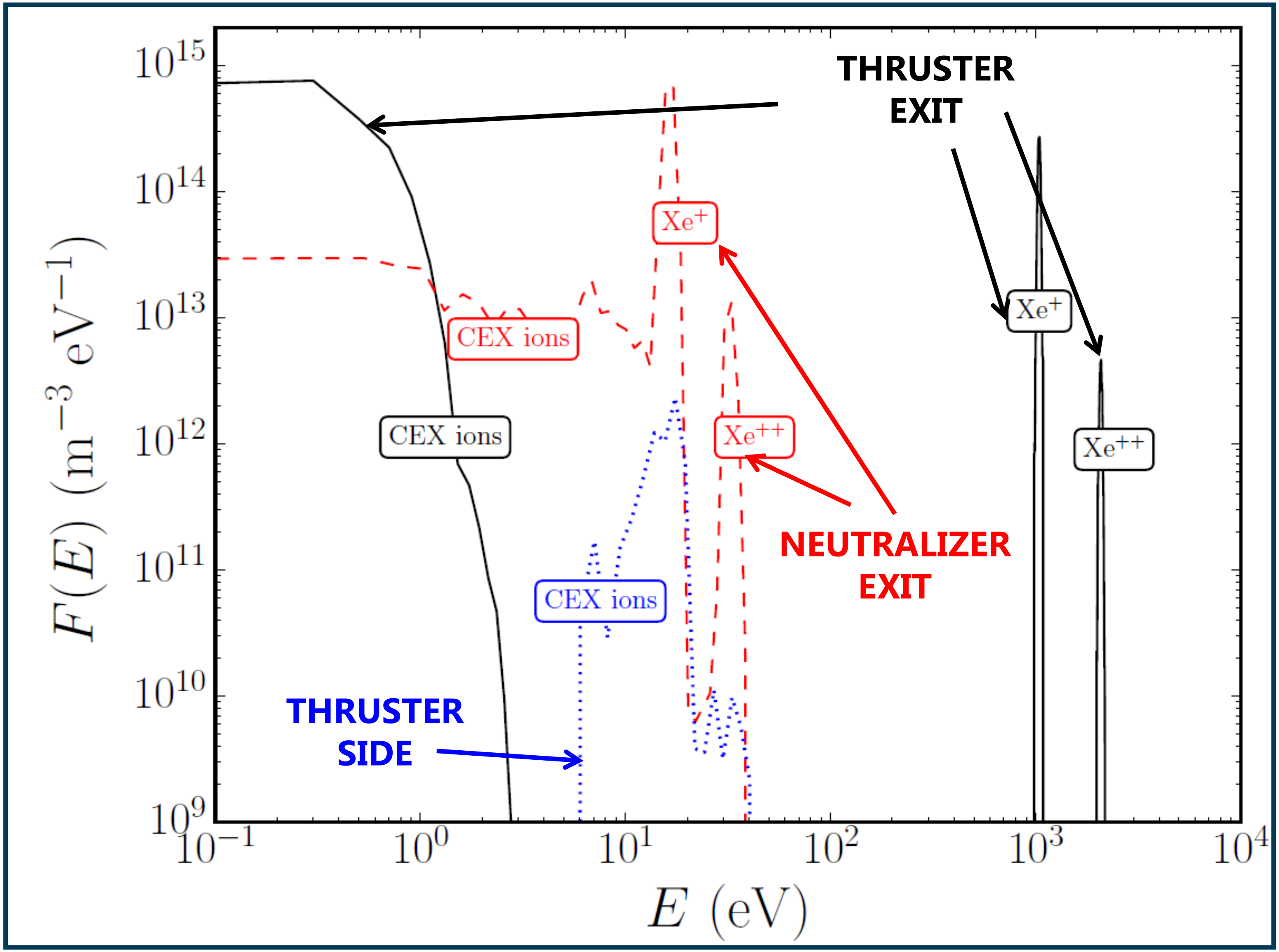


CEX ION MEAN IMPACT ENERGY



Plume-SC interaction: additional plots (3)

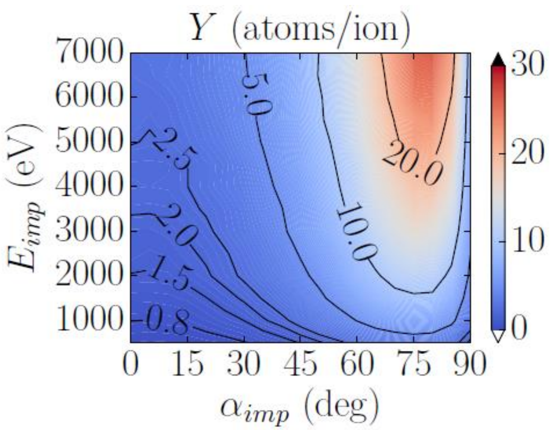
ION ENERGY DISTRIBUTION FUNCTION



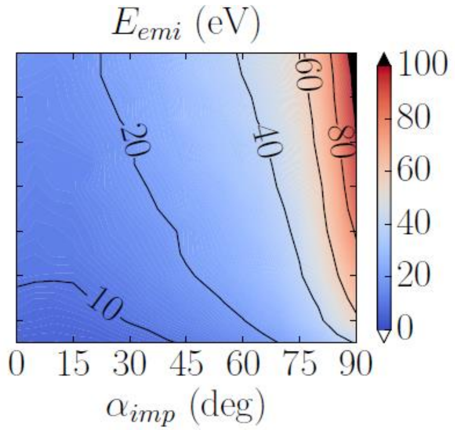
Application to IBS: sputtering and equivalent circuit

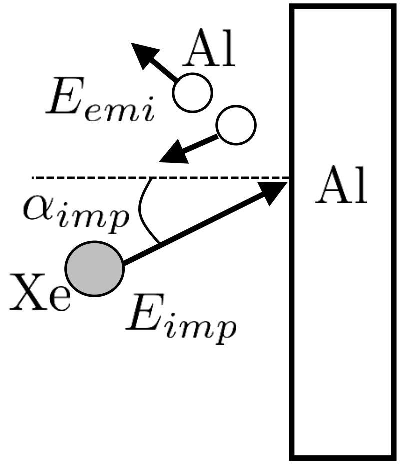
- Sputtering properties for impact of Xe ions/atoms on aluminium (from SRIM-TRIM open software)

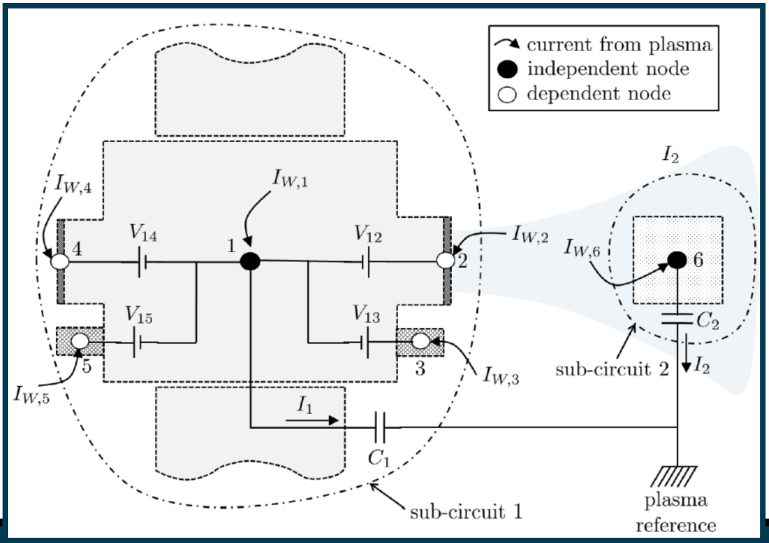
PARTICLE YIELD



MEAN Al ATOMS ENERGY



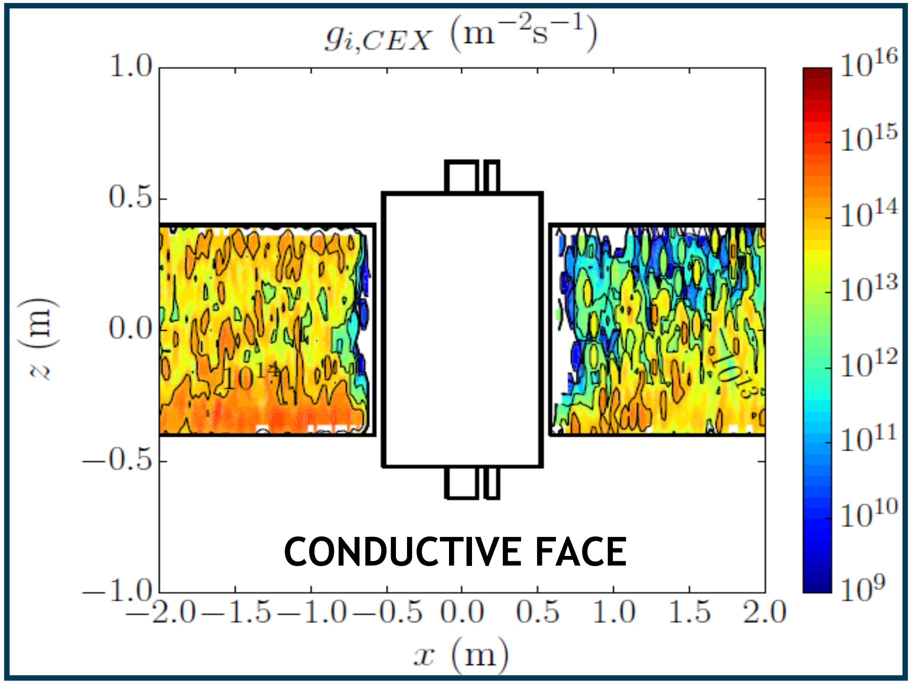




- Electric circuit of the IBS:
  - ❑ A conductive TG connected to the S/C only through the plasma plume
  - ❑ S/C circuit is similar to the one already presented

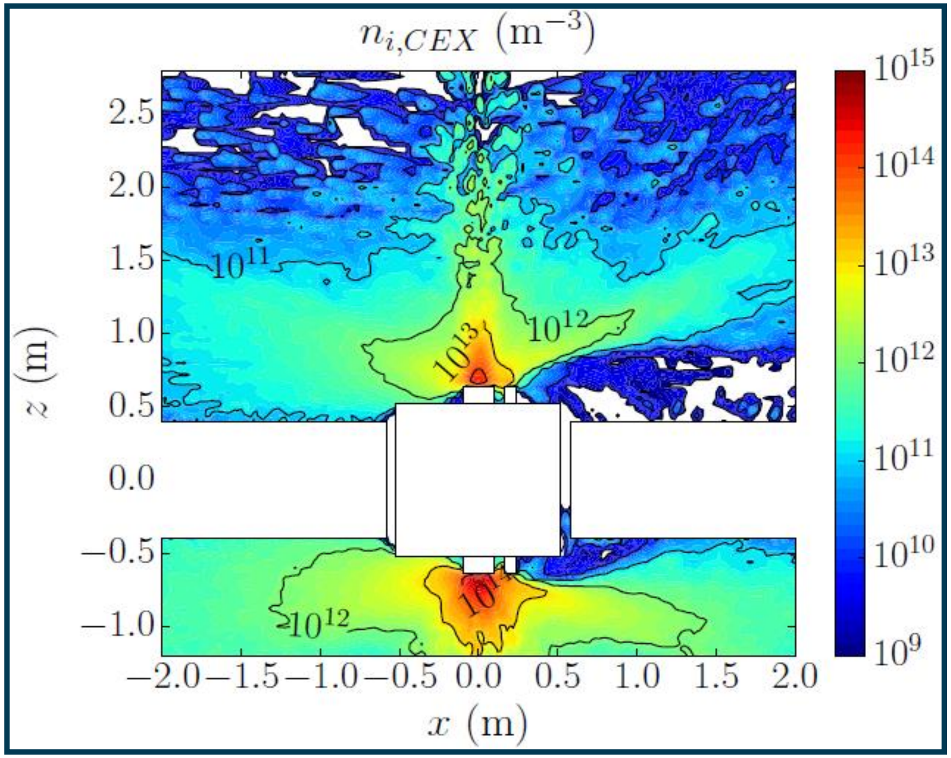
Application to IBS: additional plots (1)

CEX ION FLUX ON SOLAR ARRAYS



CONDUCTIVE FACE

CEX IONS DENSITY



Application to IBS: additional plots (2)

ELECTRIC POTENTIAL AT $z = 0$