HYPHEN:
A multi-thruster simulation platform

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EP2 uc3m

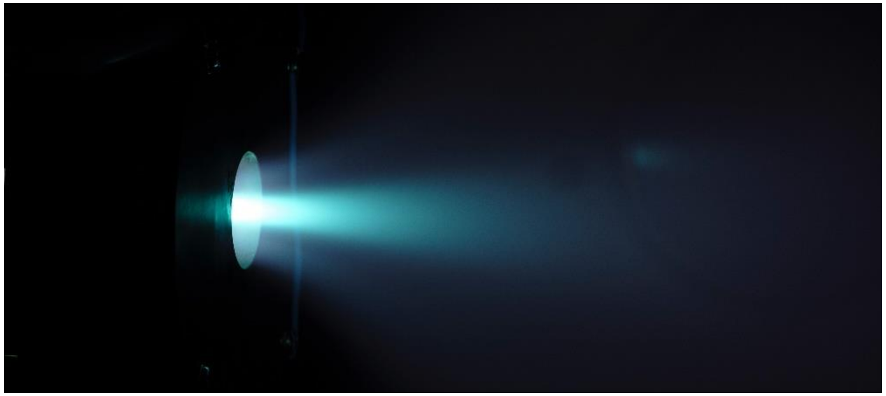
EPIC Workshop
London, October 15-17, 2018

Plasmas and Space Propulsion Team (EP2)

- ~20 year R&D experience
  - Modeling
  - Code development
  - Testing (since 2016)
- ~15 Researchers
- ~ 40 R&D projects
  - FP7 and H2020
  - ESA, US-AFOSR
  - National R&D Plans
- ~60+120 papers, 1 patent
- Large background in teaching EP physics
- Large experience in international & industrial collaborations

- Modeling and simulation
  - Hall-effect thrusters
  - Electrodeless thrusters (HPT, ECRT)
  - Propulsive magnetic nozzles
  - Hollow cathodes, AF-MPDT (incipient)
  - Plasma plume characterization (unmagnetized & magnetized)
  - Contactless Debris Removal & Plume-Spacecraft interaction
  - Electrodynamic Tethers
  - Plasma-surface interaction
  - Plasma instabilities and turbulence
- Plasma diagnosis (theory & design)
- Thruster design, development, testing

EP2 vacuum facility



HYPHEN: A multi-thruster simulation platform

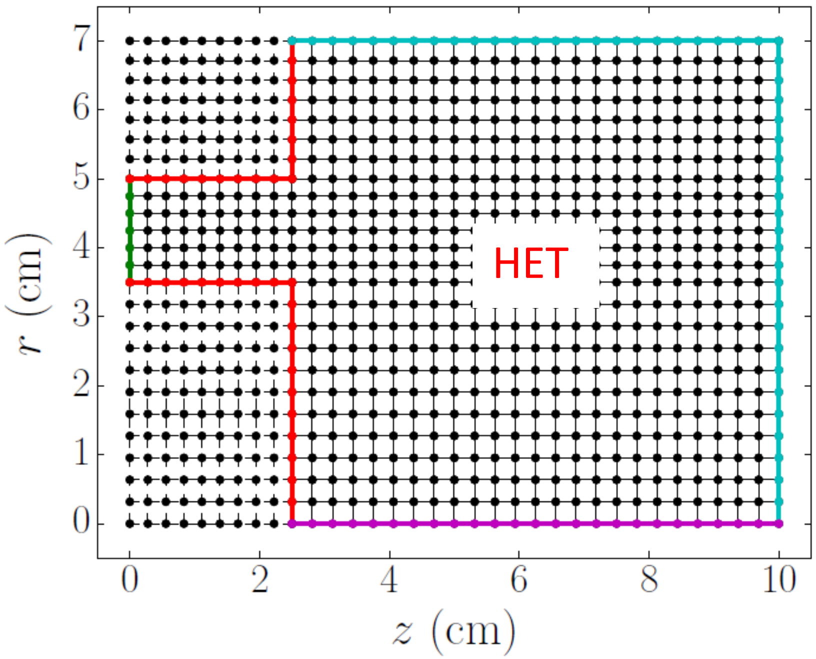
HYPHEN: A multi-thruster simulator

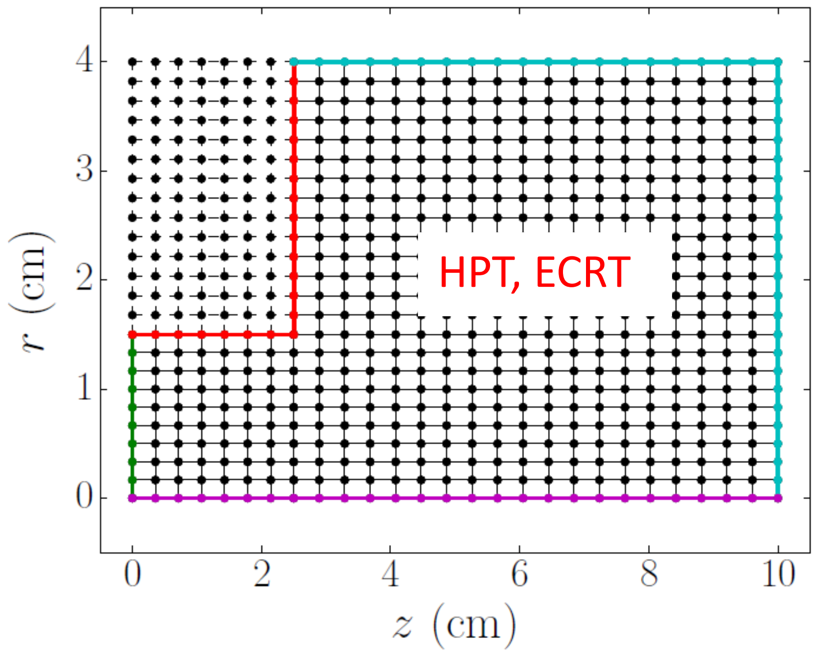
- Project to be developed along 2019
- Multi-thruster simulation platform for electromagnetic thrusters (EMT) operating with rarefied (i.e. weakly-collisional) plasmas
  - EMT with electrodes: HET, HEMPT, AF-MPDT
  - EMT with EM emission: HPT, ECRT, VASIMR
- From converging ongoing EP2 developments for individual thrusters:
  - NOMADS within H2020-CHEOPS
  - SURFET within H2020-MINOTOR
  - HELPIC within AirbusDS (F) funded project
- Improves thruster physics understanding, optimize code development
- Axisymmetric (2D), hybrid (PIC-MC/fluid), modular, OMP-parallelized
- HYPHEN will share structure and algorithms with EP2PLUS (3D hybrid code, focused on plumes)
    - EP2PLUS presentation on Wednesday 17 at 5:30 PM
- HYPHEN will include our Magnetic Nozzle Physics models
    - Magnetic Nozzles presentation on Wednesday 17 at 2:00 PM

Code modular structure

- **Ion-module**
  - PIC-MC, multi-species
- **Electron-module**
  - Highly-magnetized, weakly-collisional fluid
  - Will include pressure anisotropy & magnetic mirror effects
  - Needs turbulent transport models !
  - Auxiliary full-PIC code will provide ‘kinetic’ information
- **Wave-module** (only for electrodeless HPT, ECRT,…)
  - Maxwell eqs + dielectric tensor → strong coupling with E-module
  - Provides heating and other wave effects to E-module
- **Sheath-module**
  - By default plasma is quasineutral (but Poisson solver can be added)
  - Admits different wall types (dielectric, metallic, emissive,…)
- **Circuit-module**
  - Essential in HPT, ECRT for overall performance calculation
  - Simplifies numerical convergence when different wall-types are present

Ion Module





- Operates on a **structured mesh** (ad-hoc PIC mesh generator)
- Possibility of including **inner active surfaces** (conducting or dielectric walls)
- 3D Cartesian particle mover: provides accuracy **symmetry axis**
- **Improved PIC statistics:**
  - **Independent multiple populations**
  - Generation weight-based **population control**
  - **Cylindrical corrections**

Electron Module

Continuity & Momentum Eqs.

$$\nabla \cdot (\mathbf{j}_e + \mathbf{j}_i) = I_d$$

$$\mathbf{j}_e = \mathcal{K}_\sigma \cdot \left(-\nabla\phi + \frac{1}{en_e}\nabla p_e - \sum_Z \eta_{iZ}\mathbf{j}_{iZ} \right)$$

$$\mathcal{K}_\sigma = \begin{bmatrix} \sigma_\top & -\sigma_H & 0 \\ \sigma_H & \sigma_\top & 0 \\ 0 & 0 & \sigma_\parallel \end{bmatrix} \quad \sigma_\parallel = \frac{e^2 n}{m_e \nu_e} \quad \sigma_H = \chi_e \sigma_\top$$

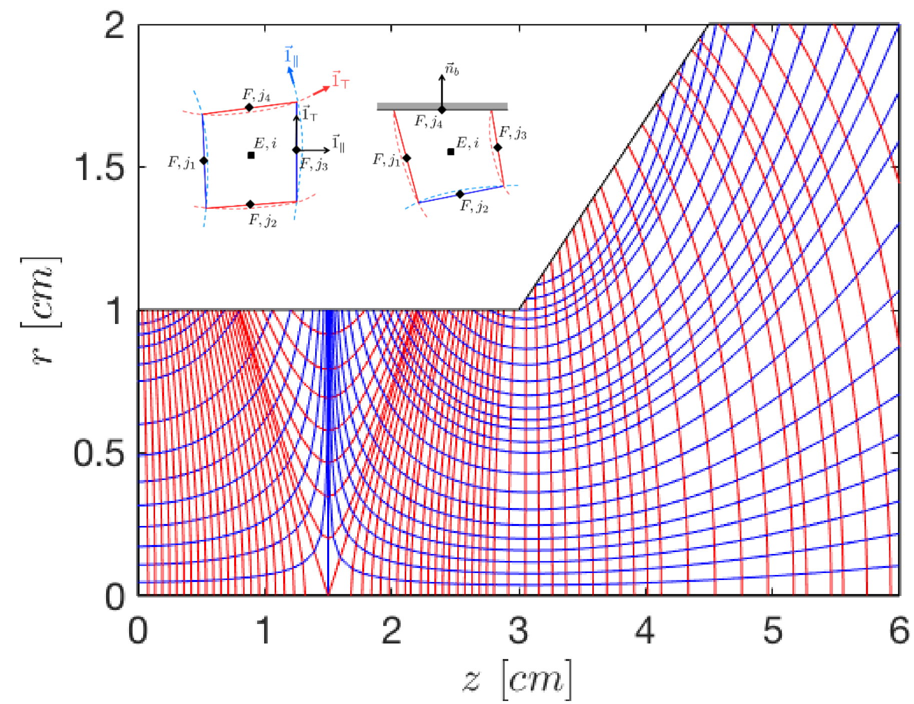
$$\sigma_\top = \frac{\sigma_\parallel}{1+\chi_e^2} \quad \chi_e = \frac{\omega_{ce}}{\nu_e}$$

Internal Energy & Heat Flux Eqs.

$$\frac{\partial \frac{3}{2} p_e}{\partial t} - \nabla \cdot \left(\frac{3}{2} p_e \frac{\mathbf{j}_e}{en_e} \right) - p_e \nabla \cdot \left(\frac{\mathbf{j}_e}{en_e} \right) + \nabla \cdot \mathbf{q}_e =$$

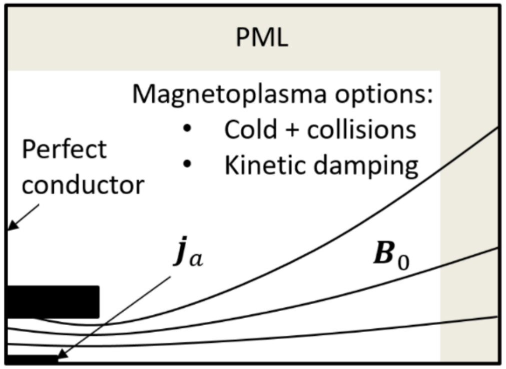
$$E_{coll} + \frac{\mathbf{j}_e}{en_e} \cdot \left(\mathbf{M}' - \frac{\mathbf{j}_e}{2en_e} m_e S_e \right) + Q_a$$

$$\frac{5}{2} p_e \nabla \left(\frac{p_e}{m_e n_e} \right) + \omega_{ce} \left(\mathbf{q}_e \wedge \mathbf{1}_\parallel \right) = \mathbf{H}_{coll} - \frac{5}{2} \frac{p_e}{m_e n_e} \mathbf{M}'$$

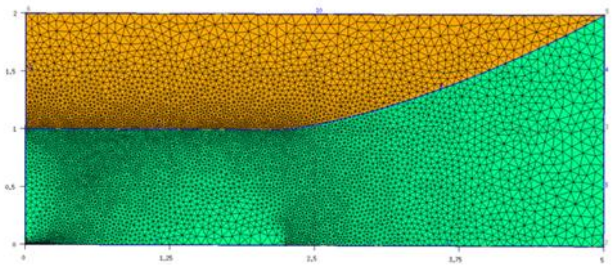


- Finite volume method on Magnetic Field Aligned Mesh
- Limits impact of numerical diffusion.
- Very irregular cells, specially at boundaries and null points
- Accuracy issues

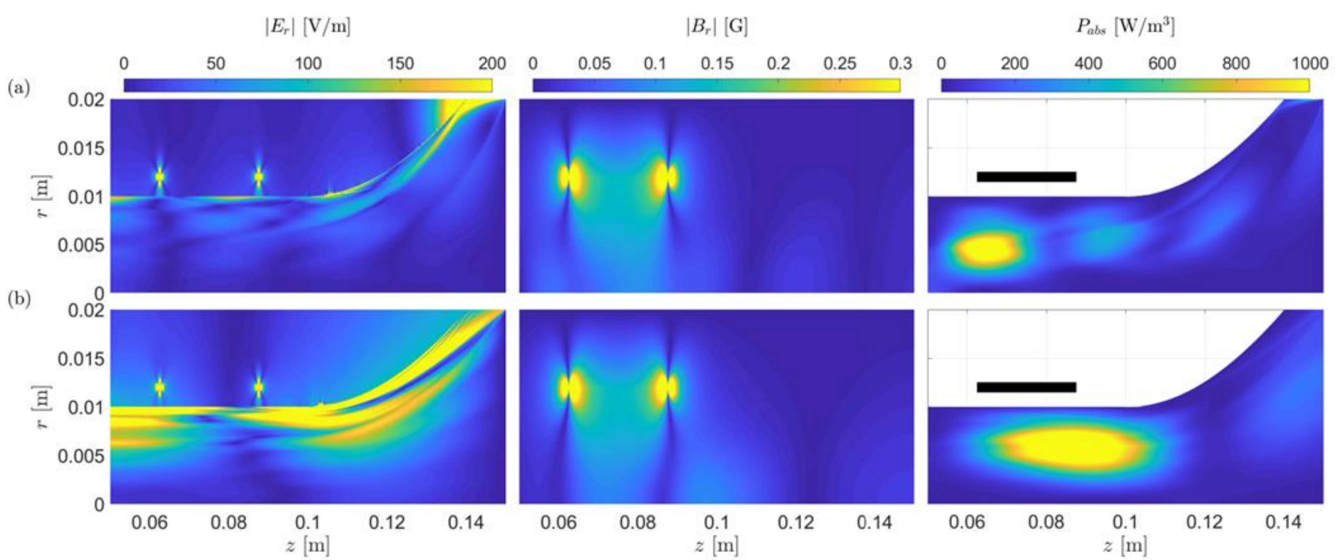
Wave Module



- Wave-plasma interaction module for HPTs, ECRTs provides
  - wavefields,
  - power deposition maps
  - plasma impedance
- Maxwell eqs. + dielectric tensor in the ω-domain
  - HPT: Finite Differences
  - ECRT (MINOTOR): Finite Elements



- Severe numerical difficulties
  - Numerical dispersion
  - Resonances
  - Short wavelengths
- Perfectly matched layers for radiation to free space

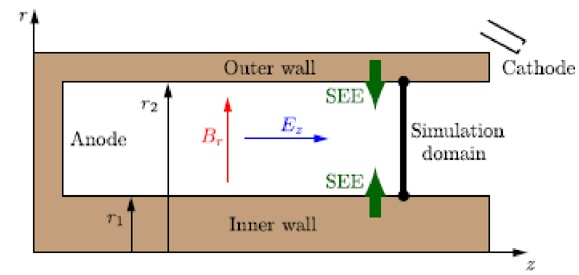


2D wavefields and absorbed power maps in a HPT under two operating conditions

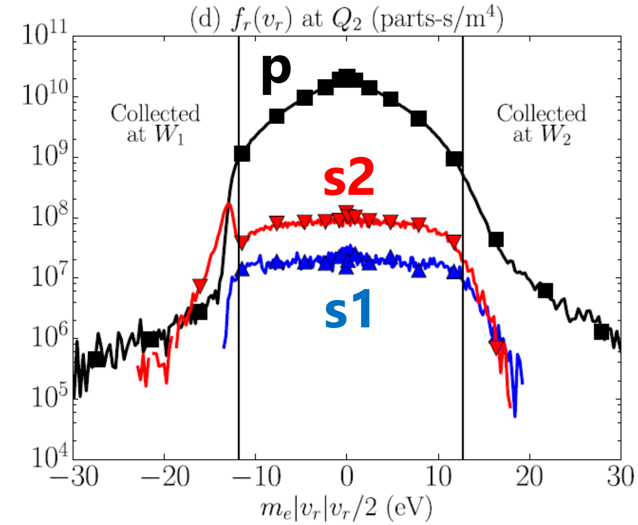
Auxiliary full-PIC code for EVDF

1Dradial full-PIC code for HET

- Study of electron VDFs with strong wall SEE
- T-anisotropy → magnetic mirror effects
- Primary and secondary electrons behave differently
- SEE is partially thermalized, partially recollected
- Cylindrical effects are significant
- Information on macroscopic magnitudes and eqs.
  - Correction to Boltzmann-Maxwell equilibrium
    - Up to 30% in our simulations
  - Correction factors to energy fluxes to the wall
  - Ways to include SEE in single-fluid equations



EVDFs at outer wall sheath edge



$$e\phi - e\phi_M - T_{rpM}\ln\frac{n_p}{n_{pM}} = \left[T_{rp} - T_{rpM} + \int_{r_M}^{r} dr\,(T_{rp} - T_{rpM})\frac{d\ln n_p}{dr}\right] + \int_{r_M}^{r} dr\frac{T_{rp} - T_{\perp p}}{r} - \int_{r_M}^{r} dr\frac{m_e u_{\theta p}^2}{r}$$

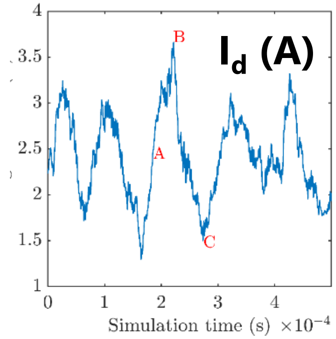
Boltzmann relation terms — **Non-uniform radial temperature** — **T-anisotropy+ magnetic mirror** — **Centrifugal force**

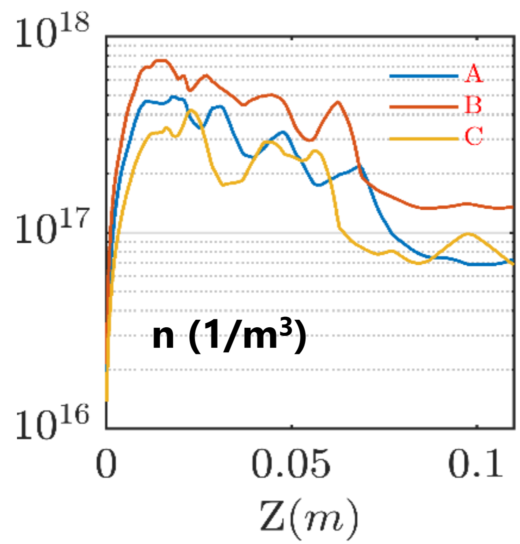
Results for CHEOPS

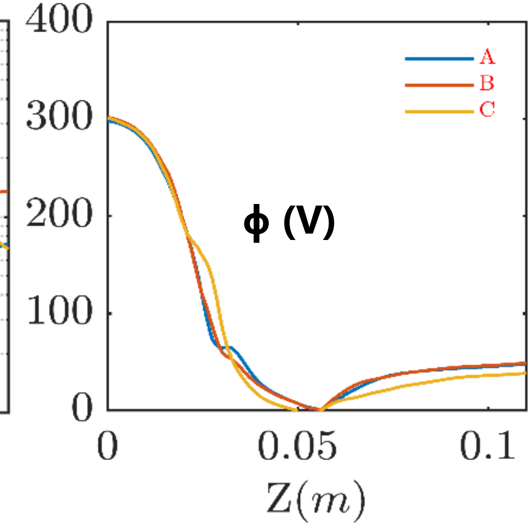
Base SPT-100 configuration

PPU control	V_d	$\dot{m}$ (Xe)	PIC Δt	NOMADS Δt
Constant voltage	$300V$	$5\frac{mg}{s}$	$10^{-8}s$	$10^{-10}s$

No. PIC mesh elements	1080
Avg. No. macroparticles	$\sim 10^5$ Neutrals, $\sim 9\times10^4$ Single Ions, $\sim 9\times10^4$ Double Ions
No. MFAM elements	1326
No. cores	20
Computation time	$7.17\times10^4 s (\sim 20h)$: $4.6\times10^3 s$ in PIC, $6.6\times10^4 s$ in NOMADS



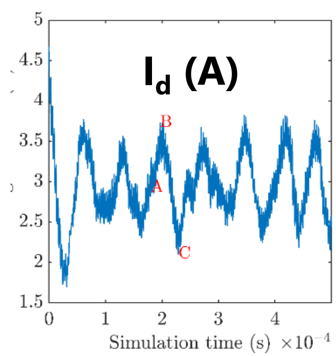


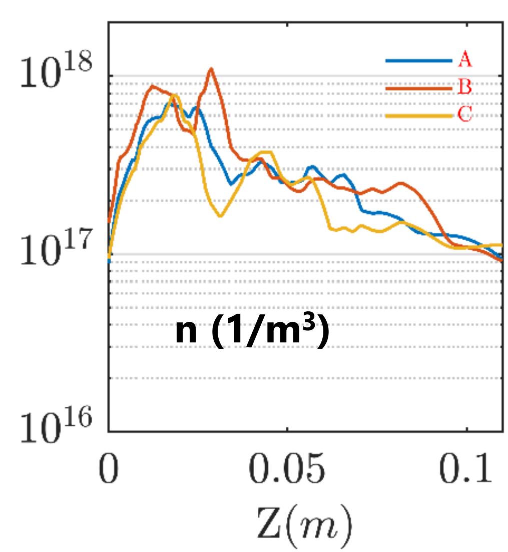


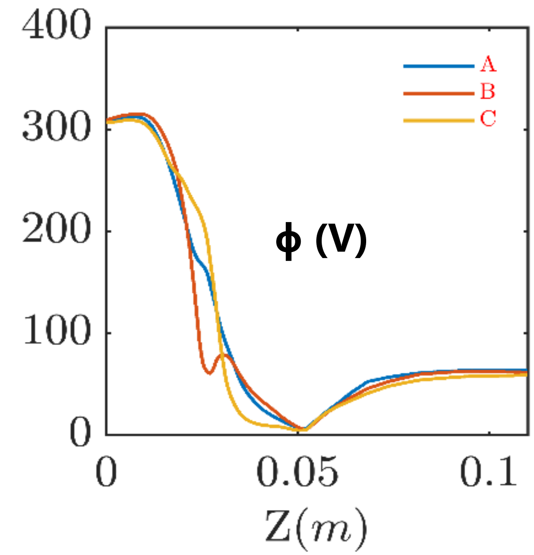
Singular SPT-100 configuration

PPU control	V_d	$\dot{m}$ (Xe)	PIC Δt	NOMADS Δt
Constant voltage	$300V$	$5\frac{mg}{s}$	$10^{-8}s$	$10^{-10}s$

No. PIC mesh elements	1080
Avg. No. macroparticles	$\sim 10^5$ Neutrals, $\sim 7\times10^4$ Single Ions, $\sim 7\times10^4$ Double Ions
No. MFAM elements	2453
No. cores	20
Computation time	$18.8\times10^4 s (\sim 50h)$: $4.0\times10^3 s$ in PIC, $18.4\times10^4 s$ in NOMADS

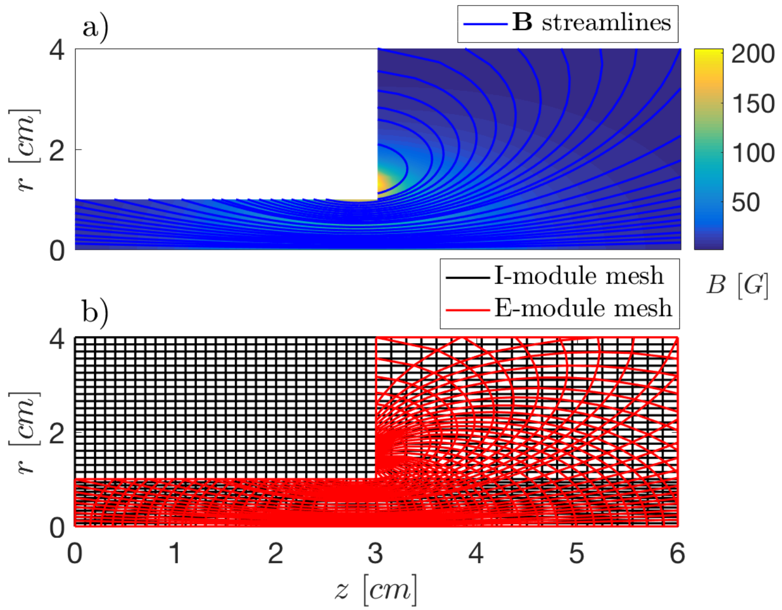


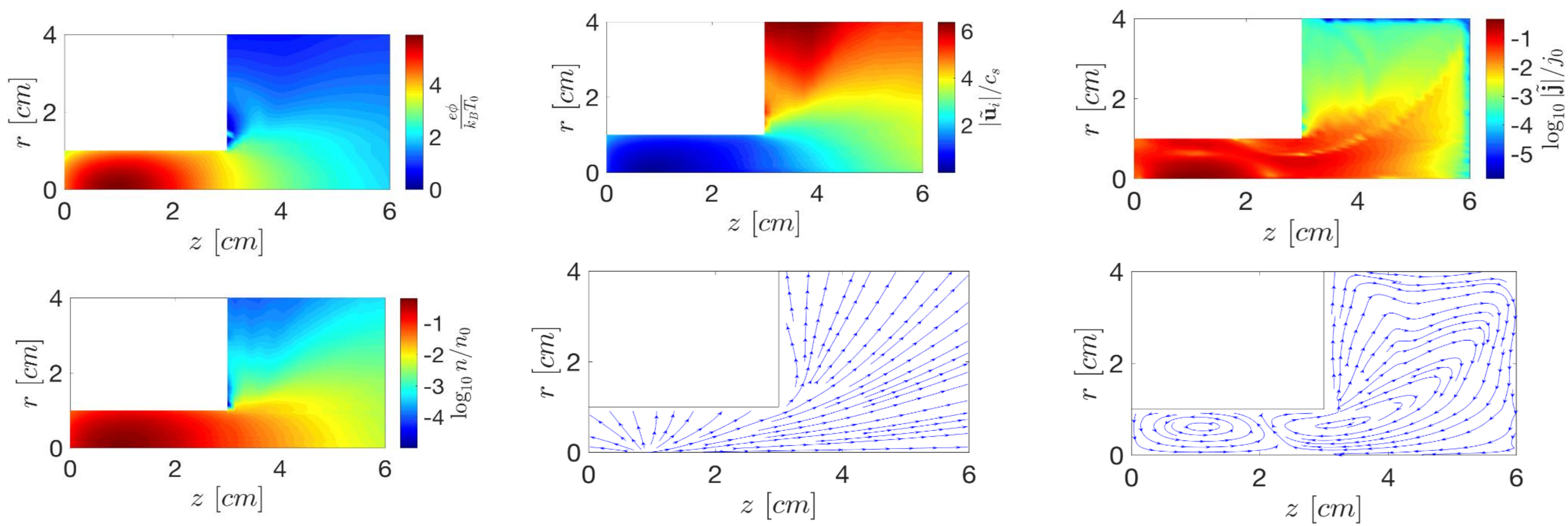




Results for HPT

- Partial results without Wave module
- Simulation here for $T_e \propto n_e^{\gamma-1}$
- In progress: simulation with prescribed map of energy deposition
- Adaptation to ECRT (MINOTOR) in progress





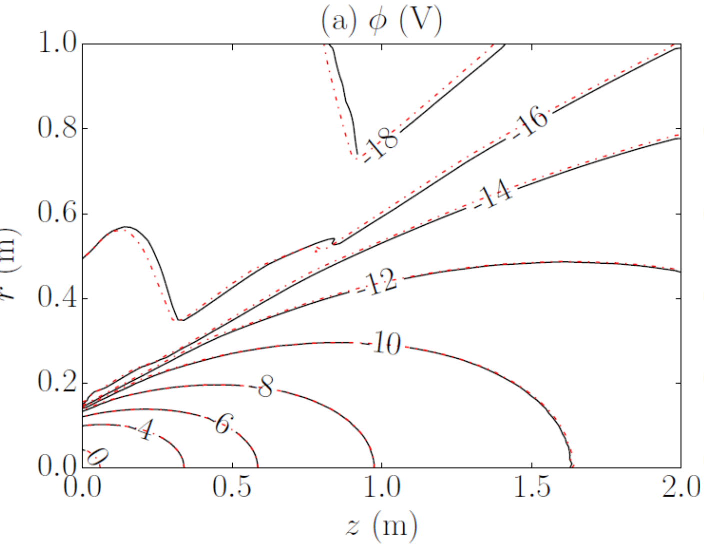
Benchmarking 2Dcyl and 3D codes

- Excellent agreement between 2Dcyl NOMADS and 3D EP2PLUS
  - Electron module reduced to polytropic electron closure
  - 6 heavy species treated separately
  - Weighting more complex in 2D

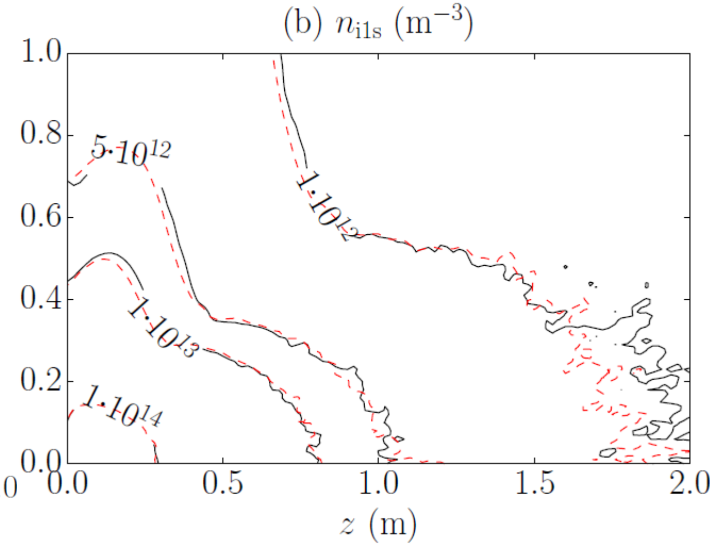
Total N. parts. 2D	6.5M
Total N. parts. 3D	143M

- Comparable noise level: typical ten-times computational cost gain in 2D
- CEX ions: generated in near plume, accelerated sidewards of plume core
  - Characterization of their density & energy (for S/C sputtering, …)

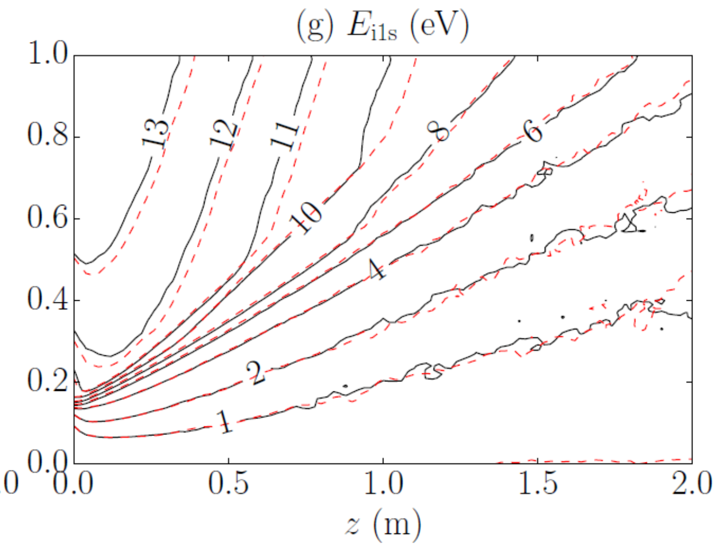
Electric potential



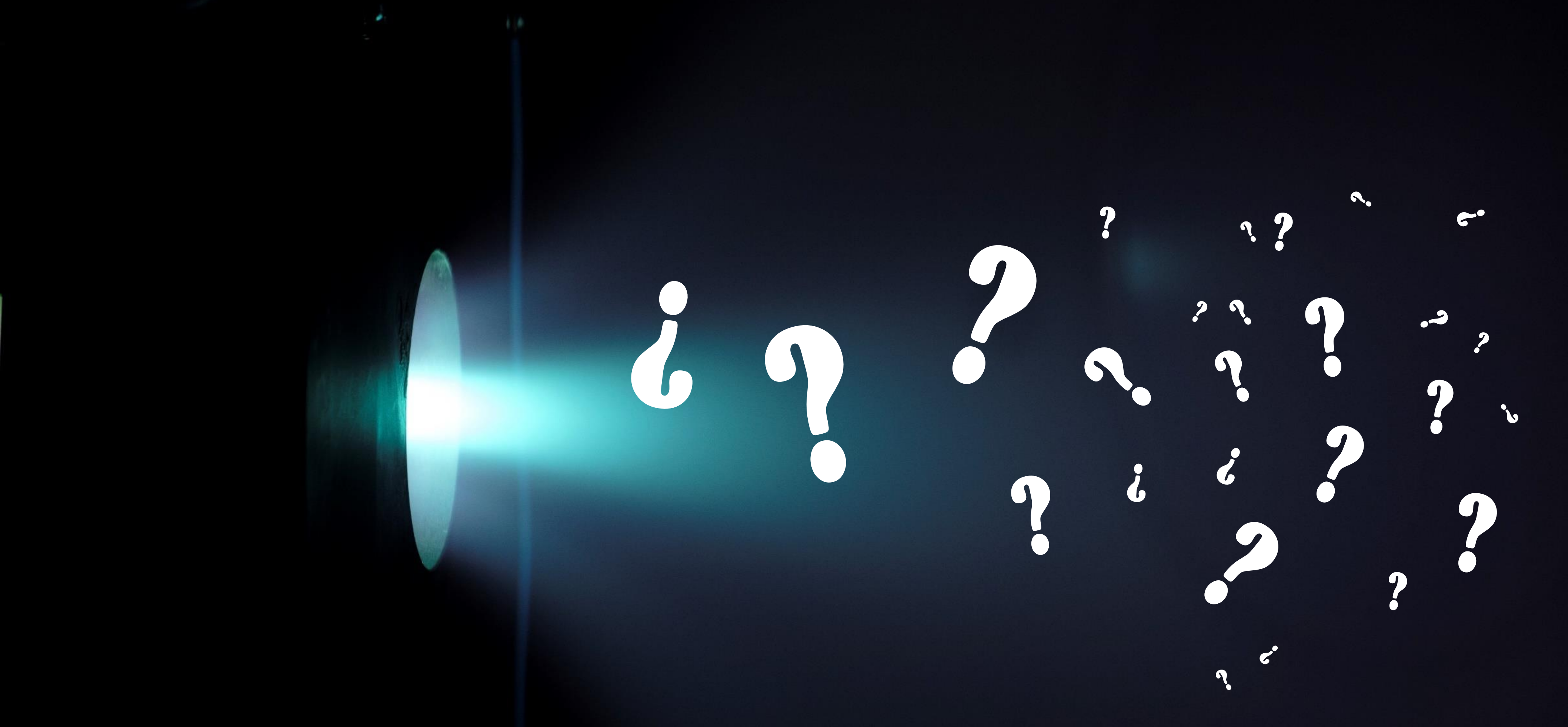
Slow singly-charged ions density



Slow singly-charged ions energy



Thank you! Questions?



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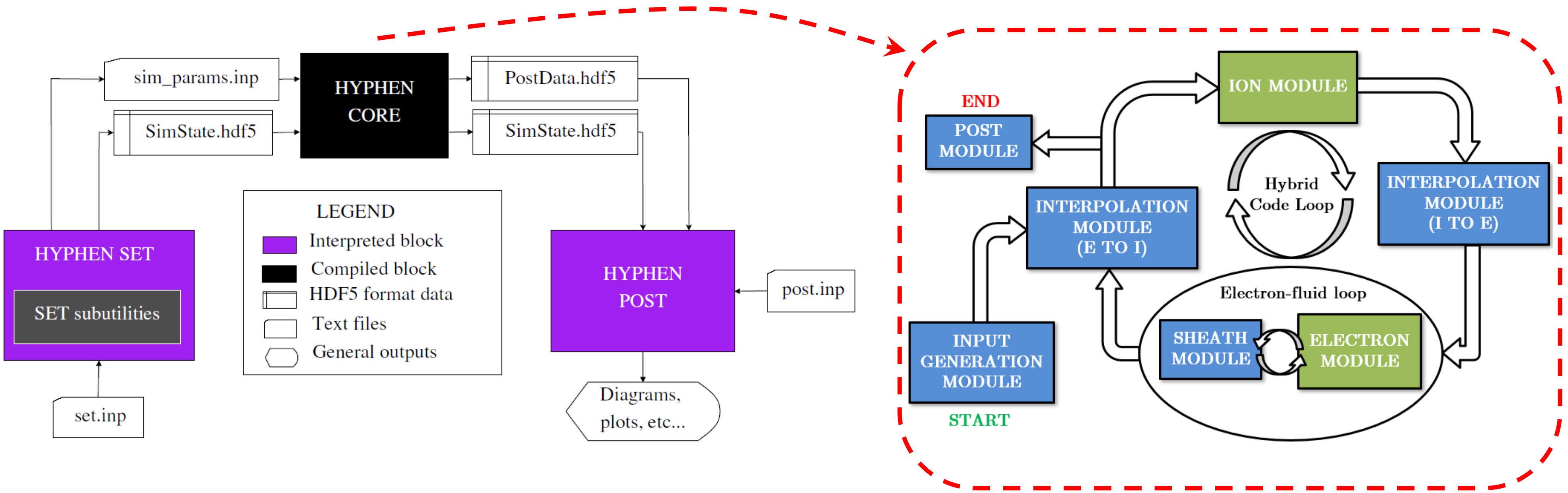
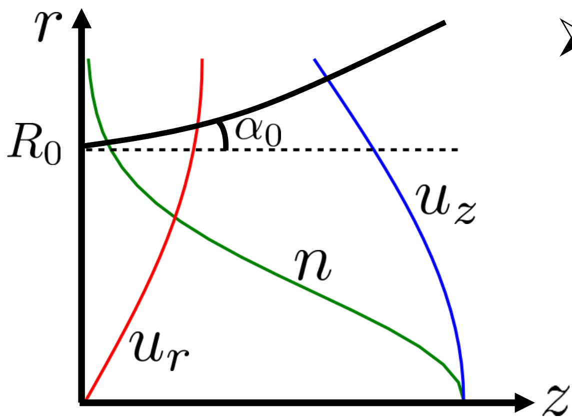
Code structure



- **3 INDEPENDENT UNITS**:
  - SET: Pre-processing tasks (Python/Matlab)
  - CORE: Main simulation tasks (Fortran)
  - POST: Post-processing tasks (Python/Matlab)
- HDF5 for I/O data management

- Open-MP parallelization
- Test Driven Design (TDD) development philosophy
- Version control through a Mercurial online repository

Benchmarking 2D and 3D codes



Ions injection: Generalized Parks-Katz SSM profiles (Parks & Katz, 1979, Merino et al 2015)

$$R_0 = 14 \text{ cm}, \gamma = 1.2$$

- NASA's NSTAR GIT plume simulation (Brophy 2002):
  - 3D simulation domain: 2m side cubic
  - 2D simulation domain: cylinder 1m radius 2m long
  - Circular injection area with radius R = 14 cm

N. cells 3D	-	$4 \cdot 10^6$
N. cells 2D	-	$1 \cdot 10^4$
$\Delta x = \Delta y \equiv \Delta r$, Δz	cm	1, 2
Δt, N. steps, Sim. time	s, N/A, ms	$3 \cdot 10^{-7}$, $5 \cdot 10^4$, 15
T_{e0}, γ	eV, -	3.5, 1.2

Population	**Type**	**Origin**
$i1s$	Xe^+ Slow	Ionization and CEX $0 \to 1$ collisions
$i1f$	Xe^+ Fast	Injected SSM: $\alpha_0 = 20.5$ deg, $T = 0.1$ eV
$i2s$	Xe^{++} Slow	Ionization $0 \to 2$ and $1 \to 2$ and CEX $0 \to 2$ collisions
$i2f$	Xe^{++} Fast	Injected SSM: $\alpha_0 = 30$ deg, $T = 0.2$ eV
ns	Xe Slow	Injected flat profile: sonic conditions at $T = 0.05$ eV
nf	Xe Fast	CEX $0 \to 1$ and $0 \to 2$ collisions