An advanced simulation code for Hall effect thrusters

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uc3m | Universidad Carlos III de Madrid

EP2

Contents

UC3M EP2 BACKGROUND

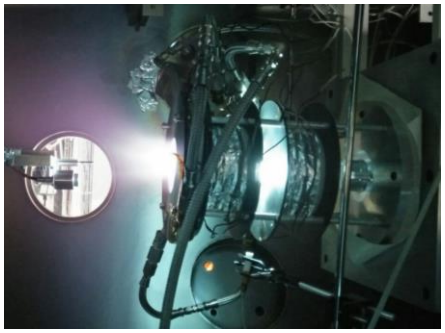
Equipo de Propulsión Espacial y Plasmas EP2

- *16 researchers (~50% are PhD students)*

EP2 ***main research lines****:*

- *Theoretical and numerical modelling of Electric Space Propulsion: Hall thrusters, RF-based thrusters*
- *Modelling of Plasma-wave interaction*
- *Plasma-wall interaction analyses. Erosion studies. Plume-SC interaction*
- *Modelling of Magnetic Nozzles and electron cooling*
- *Active Debris removal*
- *Experimental characterization of EP and Plasma jets. Development of EP Thrusters*

Main ongoing activities



- *Helicon Plasma Thruster Development:*
  - *Based on Helicon waves (generation) & Magnetic nozzle (acceleration)*
  - *FP7-HPHCOM*
  - *HPT05: Joint EP2-SENER Design & Manufacturing (1kW)*
- *H2020-MINOTOR: ECR accelerators*
  - *Based on ECR (generation and heating) & Magnetic nozzle (acceleration)*
  - *Goal: to advance on the theoretical & technical development of the thruster*
  - *EP2 developing a full model of ECRA physics: Microwave-plasma interaction (i.e. heating), ionization, heating, flow, wall interaction, supersonic expansion, final beam energy, thruster performance*
- *H2020-CHEOPS: Hall Effect Thrusters*
- *Modexval-ESA (Plasma Cooling)*
- *National Research plans (Electric Propulsion)*

H2020-CHEOPS: Hall Effect Thrusters

CONSORTIUM FOR HALL EFFECT IN ORBIT PROPULSION SYSTEM

Motivation: *HETs are the technological main solutions in near-earth EP*

CHEOPS (coord. SAFRAN): *large project aimed for development of next generation low-to-high power HET required simulation and testing tools*

Simulation tools: *Reduce development time/costs, reveal optimization opportunities,*

EP2 large experience in modeling/simulating HET

EP2 is leader of WP on simulation activities. Main tasks:

- *Development of advanced hybrid (PIC/fluid) code for HET*
- *Code validation with Safran prototypes*

Main challenges:

- *Full-2D fluid model of magnetized electrons*
  - *generic magnetic topologies*
  - *non-Maxwellian features*
- *Assessment on magnetic shielding physics*
- *Operation with alternative propellants & non-conventional conditions*
- *Scaling strategies for very low and very high power*

H2020-CHEOPS: Hall Effect Thrusters

CONSORTIUM FOR HALL EFFECT IN ORBIT PROPULSION SYSTEM

WP1 – Coordination, dissemination & exploitation (SNECMA)
- Task 1.1 Project coordination (SNECMA)
- Task 1.2 Project level dissemination (S4S)
- Task 1.3 Market analysis and specification (SNECMA)
- Task 1.4 Final synthesis & recommendations for Phase 2 (SNECMA)

WP2 – Strategies for value cration & cost reduct. (SNECMA)
- Task 2.1 Strategies for VC & CR (CHALMERS)
- Task 2.2 Industriali. and COTS (CHALMERS)
- Task 2.3 Model HET EPS as a funct. breakdown in prep.for Value and Cost studies (CHALMERS)
- Task 2.4 Value and Cost Assessment (CHALMERS)

WP3 – HET system for GEO/NAV (SNECMA)
- Task 3.1 System & AIT (SNECMA)
- Task 3.2 Thruster dual mode >5KW (SNECMA)
- Task 3.3 PPU (TAS B)
- Task 3.4 PMS (BRADFORD)

WP4 – HET system for LEO (SNECMA)
- Task 4.1 System & AIT (SNECMA)
- Task 4.2 Thruster 200-700W (SNECMA)
- Task 4.3 Cathode (SITAEL)
- Task 4.4 PPU (SITAEL)
- Task 4.5 PMS (BRADFORD)

WP5 – HET system for Exploration (SITAEL)
- Task 5.1 System & AIT (SITAEL)
- Task 5.2 Thruster 20KW (SITAEL)
- Task 5.3 Cathode (SITAEL)
- Task 5.4 PPU (SITAEL)
- Task 5.5 PMS (AST)

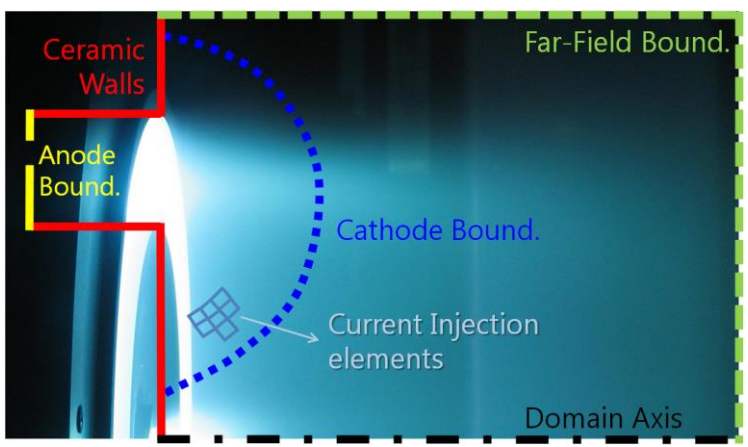
WP6 – Modelling and transverse activities (UC3M)
- Task 6.1 Alternative propellents (CNRS-LPP)
- Task 6.2 Plasma/thruster modelling (UC3M)
- Task 6.3 Platform / plume interaction (SITAEL)
- Task 6.4 Advanced diagnostics (SITAEL)
- Task 6.5 Standardisation of accept. tests (CNRS-ICARE)

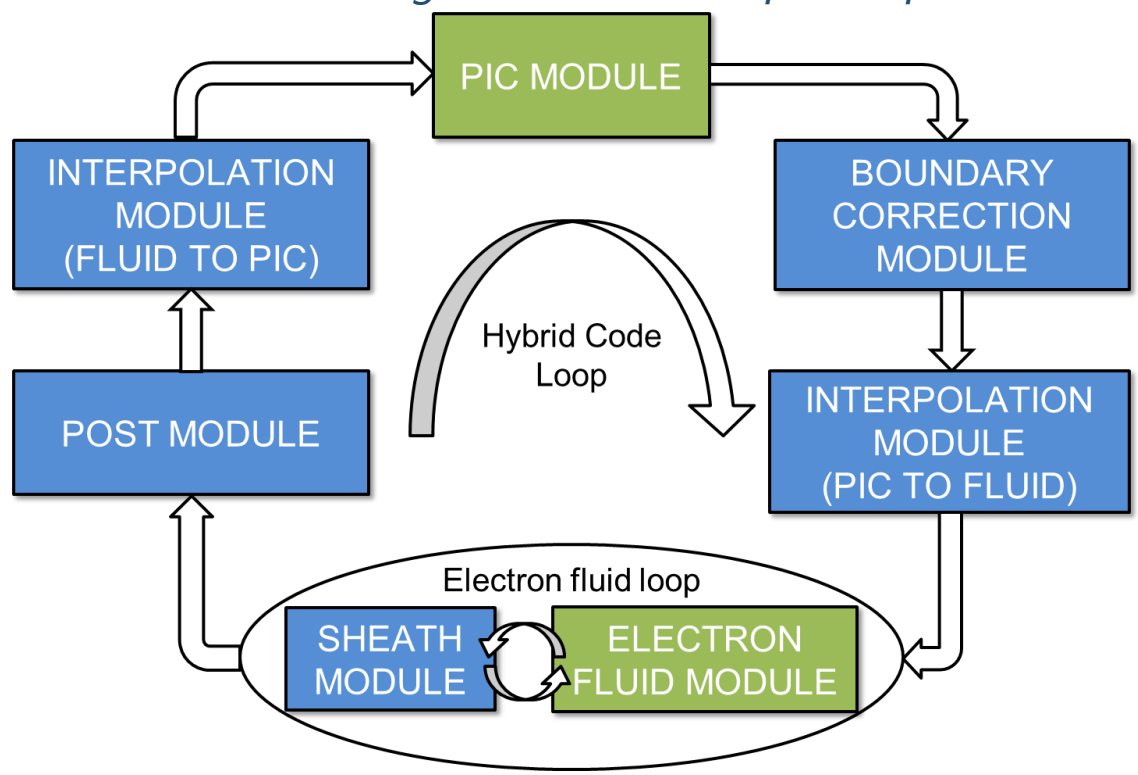
NOMADS: 2D hybrid code for Hall-effect thrusters

- ***Hybrid:*** *PIC (ion and neutral heavy species) + Fluid (electron population)*
- ***2D Axisymmetric*** *(z-r) plasma simulator of chamber & plume*
- *Heritage from HALLMA and EP2PLUS, but designed with extended capabilities*

Main Design Architecture:

- *Pre and post simulation tools (matlab, python)*
- *Mesh generators for ion (PIC) and electron modules Magnetic mesh accepts cusps, zeros,…*
- *CORE: FORTRAN*
  - *PIC module*
  - *Electron module + Sheath*





Particularities of PIC segment

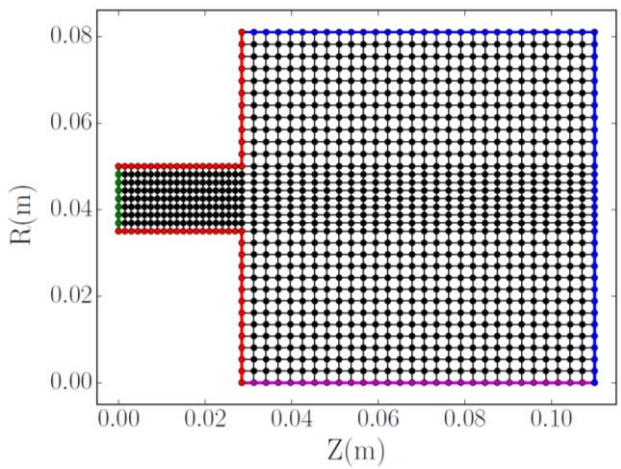
Algorithms:

- *Particles stored in individual lists, under population control (PIC noise, controls computational resources)*
- *Macroscopic variables obtained by particle weighting (modifications in axis)*
- *Collisional processes carried out on cell-wise algorithm:*

$$\left.\begin{aligned} Xe + e &\rightarrow Xe^{+} + 2e \\ Xe^{+} + 2e &\rightarrow Xe^{++} + 3e \end{aligned}\right\} \text{Drawin}$$

$$\left. Xe^{+} + e \rightarrow Xe^{++} + 2e \right\} \text{Bell}$$

- *Particle-surface interaction, extended surface weighting (time averaging, reduce noise)*



Surface type	Effects on ions	Effects on neutrals
Transparent	None	None
Free loss	Removal	Removal
Injection	Stochastic injection	Stochastic injection
Material wall	Recombination	Reflection
Sheath*	Normal velocity shift	None

$$n_{sw}^{(k)} = \frac{1}{\Delta t \Delta S} \sum_{p=1}^{N_{hit}} \frac{W_p}{v_{\perp,p}}$$

$$\vec{g}_{sw}^{(k)} = \frac{1}{\Delta t \Delta S} \sum_{p=1}^{N_{hit}} \frac{W_p \vec{v}_p}{v_{\perp,p}}$$

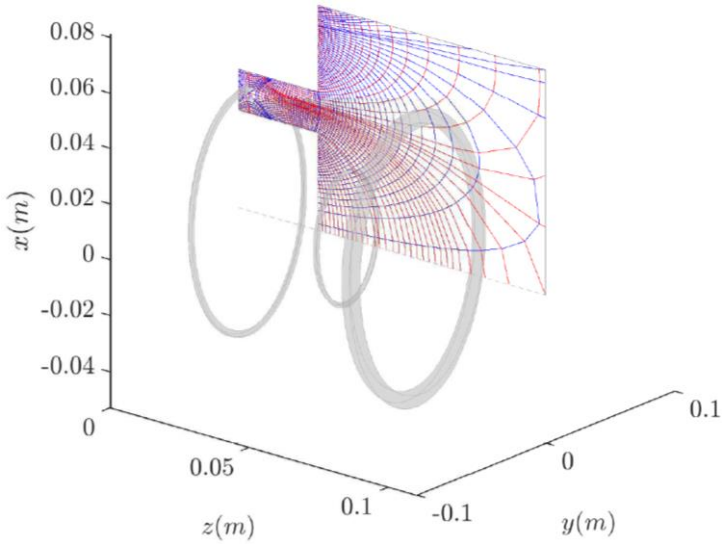
$$\overline{n}_{sw}^{(k)} = \frac{(\Delta k_{avg} - 1)\overline{n}_{sw}^{(k-1)} + n_{sw}^{(k)}}{\Delta k_{avg}}$$

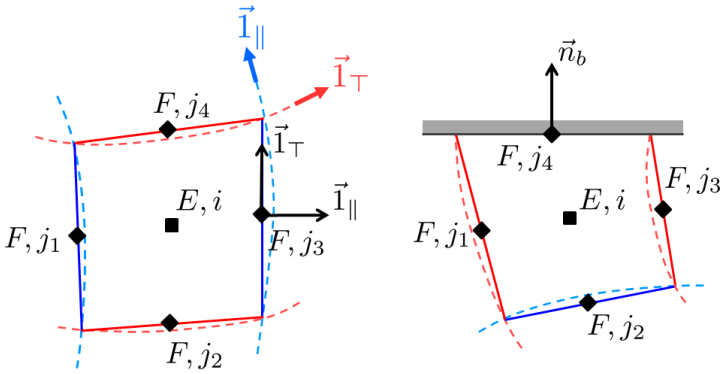
- *Kinetic Bohm correction: algorithmic density reduction forces a response from the electric potential within the domain, prompting sonic or supersonic ions*

Electrons module

Main Features

- *2D solutions of Electron Temperature and Plasma Potential*
- *Magnetic Field Aligned Mesh (MFAM) - limiting the impact of numerical diffusion*
    - *Gradient reconstruction: Weighted Least Squares Face Interpolation*
    - *Improved by computing in r & z and projecting locally to the field dir.*

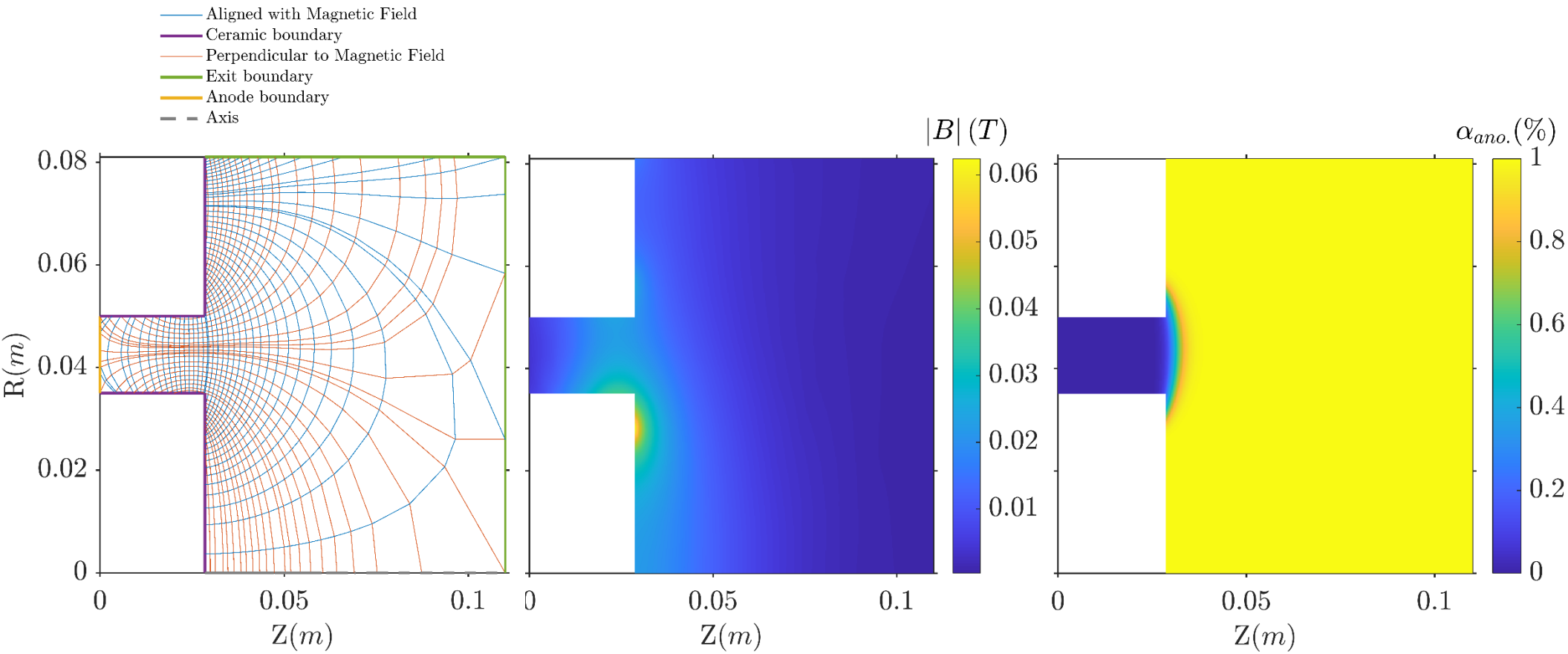




- *Electron population: 12 moment approximation from Bolzmann equation*
    - *Two-temperature description: T_{par} & T_{perp}*
- *Quiasineutral, stationary formulation, Fourier type closure in heat-flow eq.*
- ***Secondary models:*** *Collisions: elastic-Coulomb, innelastic* $Xe + e \rightarrow Xe^* + 2e$
- *Non-classic electron transport modeled as an anomalous transport term*
- *Sheath model: Anode, Ceramic walls*

Preliminary simulation results (I)

Base SPT-100 configuration:



Computational resources:

1 ms = 1-2 days

10 μs = 15-30 min

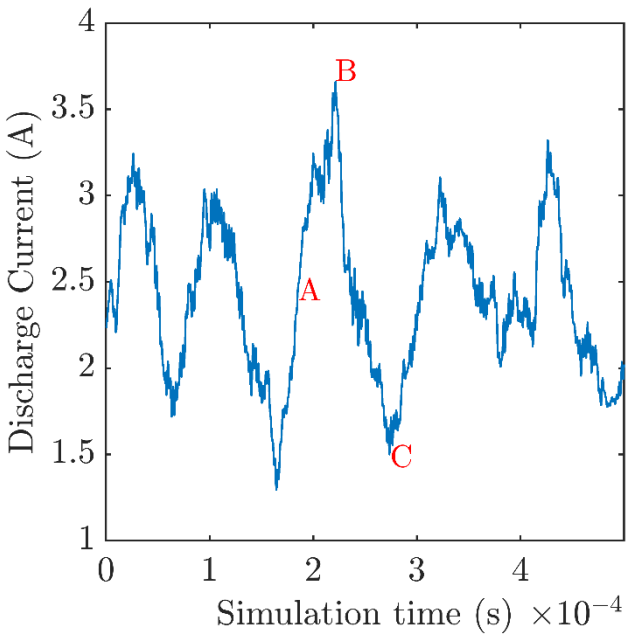
Preliminary simulation results (II)

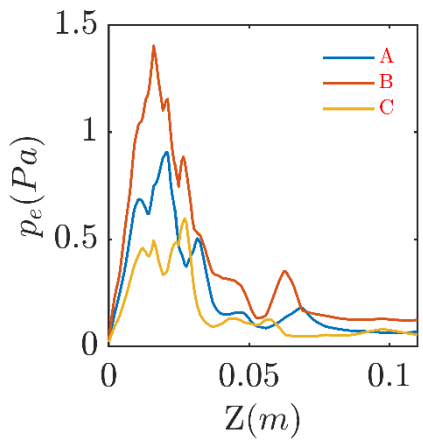
Base SPT-100 configuration:

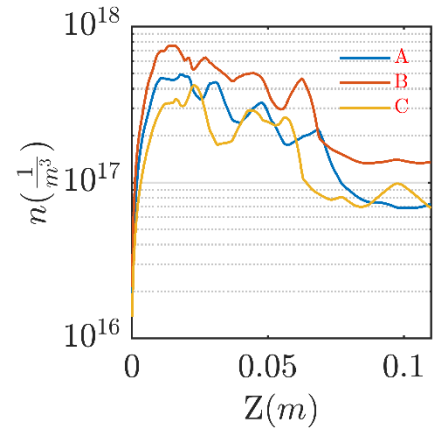
PPU control	V_d	$\dot{m}$ (Xe)	PIC Δt	NOMADS Δt
Constant voltage	$300V$	$5\frac{mg}{s}$	$10^{-8}s$	$10^{-10}s$

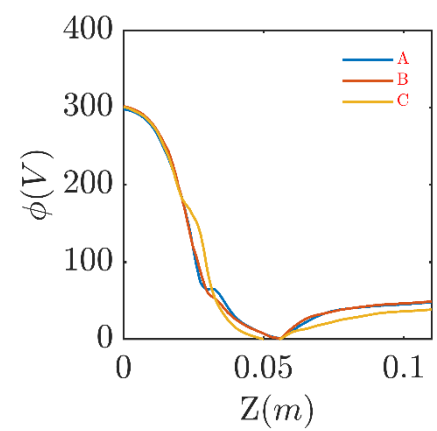
I_d	P_d	Thrust	I_{sp}	η_T	P_{jet}	$P_{sheaths}$	$P_{ioniz.+excit.}$	$P_{cahtode}$
$2.41A$	$723W$	$41mN$	$844s$	0.24	$168W$	$165W$	$57W$	$16W$

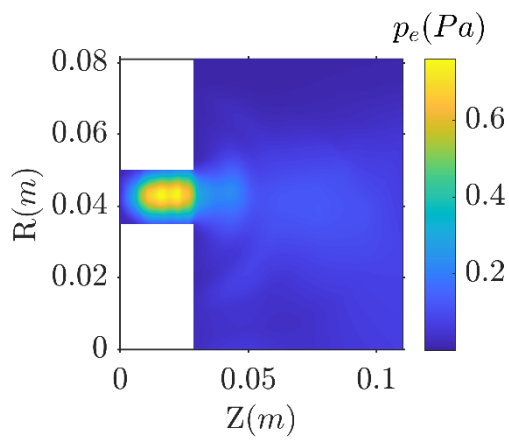
No. PIC mesh elements	1080
Avg. No. macroparticles	$\sim 10^5$ Neutrals, $\sim 9\times10^4$ Single Ions, $\sim 9\times10^4$ Double Ions
No. MFAM elements	1326
No. cores	20
Computation time	$7.17\times10^4 s(\sim 20h)$: $4.6\times10^3 s$ in PIC, $6.6\times10^4 s$ in NOMADS

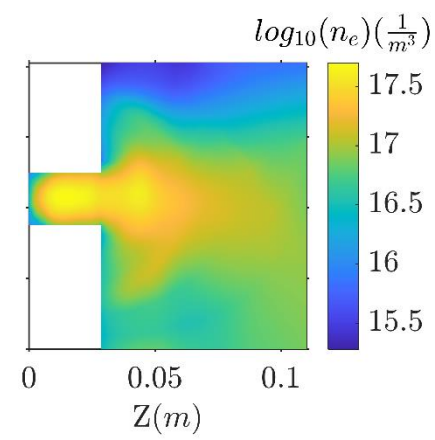


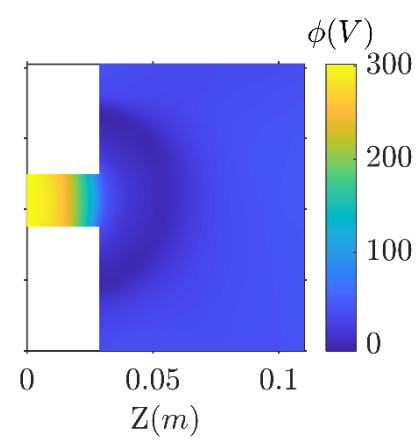












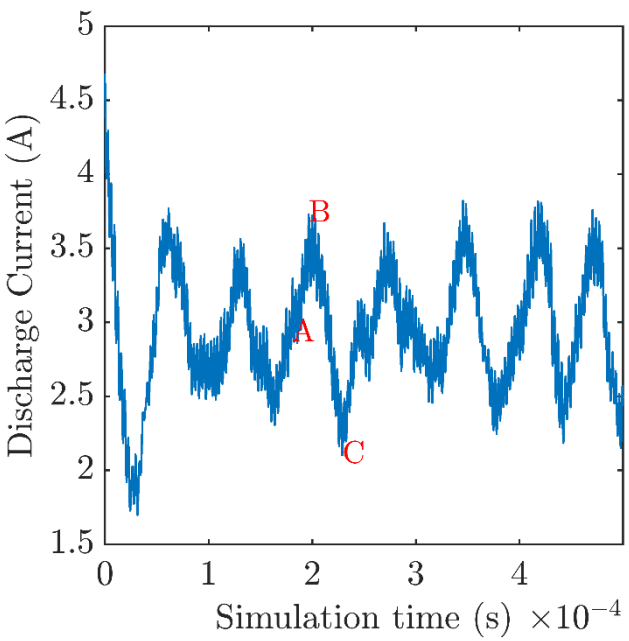
Preliminary simulation results (III)

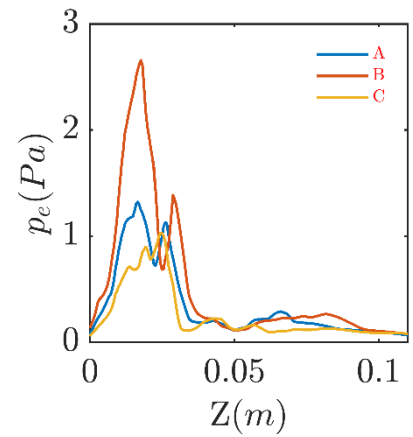
"Singular" SPT-100 configuration:

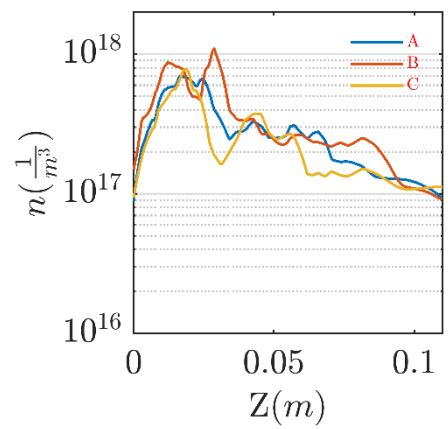
PPU control	V_d	$\dot{m}$ (Xe)	PIC Δt	NOMADS Δt
Constant voltage	$300V$	$5\frac{mg}{s}$	$10^{-8}s$	$10^{-10}s$

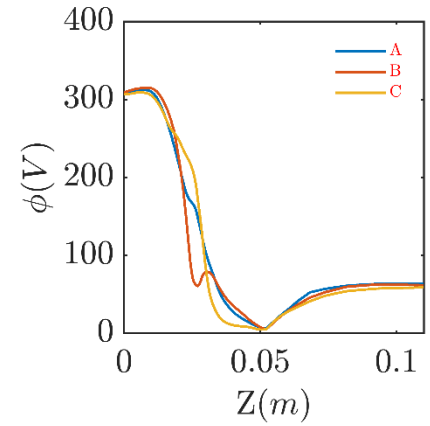
I_d	P_d	Thrust	I_{sp}	η_T	P_{jet}	$P_{sheaths}$	$P_{ioniz.+excit.}$	$P_{cahtode}$
$2.94A$	$881W$	$48mN$	$980s$	0.26	$229W$	$162W$	$72W$	$10W$

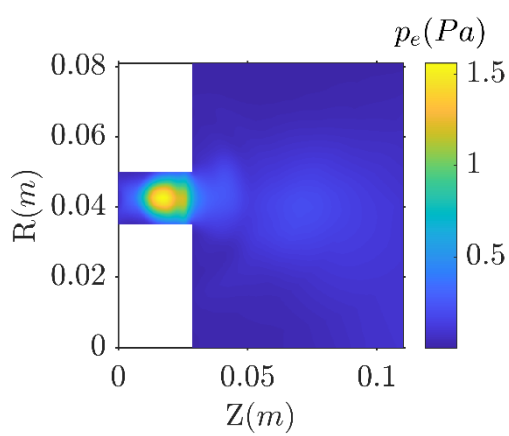
No. PIC mesh elements	1080
Avg. No. macroparticles	$\sim 10^5$ Neutrals, $\sim 7\times10^4$ Single Ions, $\sim 7\times10^4$ Double Ions
No. MFAM elements	2453
No. cores	20
Computation time	$18.8\times10^4 s(\sim 50h)$: $4.0\times10^3 s$ in PIC, $18.4\times10^4 s$ in NOMADS

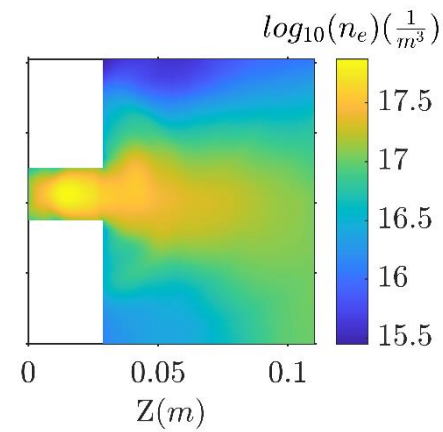


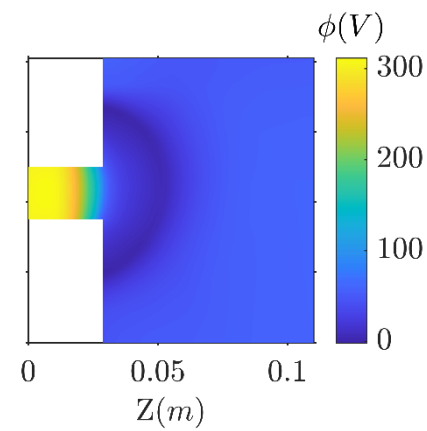












Conclusions

- ***Development of a new 2D Hybrid code for HET***
  - ***In the frame of H2020 and EPIC***
  - ***PIC: for heavy particles + fluid for electrons***
  - ***Potentially expandable to other thrusters***

- ***Main characteristics were described***

- ***Preliminary simulations have been obtained, further improvement is required***

- ***Future simulations will include both parallel and total electron temperature***

- ***Future developments: further paralelization, validation with experimental data, additional models,***

Thank you! Questions?

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BACK-UP

Electron population fluid model (II)

Current continuity + Momentum eq. → Generalized Ohm's law:

$$\{GR\} \cdot \{\phi_E\} = \{D\} + \{GR\} \cdot \{p_{e,E}\} + \{B\} + \{I_{d,E}\}$$

Thermal Energy Density eq. + Semi-implicit temporal discretization:

$$\{p_{e,E}\}^{t+1} = \Delta t \left[\left(\{A\}^t + \{Ex\}^t \right) \cdot \{p_{e,E}\}^{t+1} + \{Q\}^t \cdot \{GR\} \cdot \{p_{e,E}\}^{t+1} + \{CS\}^t \right] + \{p_{e,E}\}^t$$

Parallel Internal Energy eq. $\{...\}$

Ancillary models:

- Collisional models:
  - Elastic collisions (***{D}***): e-n (Hayashi), e-i_Z (Coulomb)
  - Additional inelastic collisions: $Xe + e \rightarrow Xe^* + 2e$ (Hayashi)
  - Non-classic electron transport modelled as an additional *anomalous* collisionality term:

$$\nu_{e^*} = \nu_e + \alpha_{ano} \Omega_{c,e}$$

- Sheath model:
  - Anode: $\vec{j}_e \cdot \vec{n}_b \Big|_{F,j} = f_{sheath,metallic} \left(\Delta\phi_{sheath}, n_e, T_e \right)$; $\Delta\phi_{sheath} = \phi_{F,j} - \phi_{wall}$
  - Ceramic walls (BN): $\Delta\phi_{sheath}|_{F,j} = f_{sheath,dielectric} \left(\sum_{Z=1}^{2,3,...} \vec{j}_{iZ} \cdot \vec{n}_b, n_e, T_e \right)$

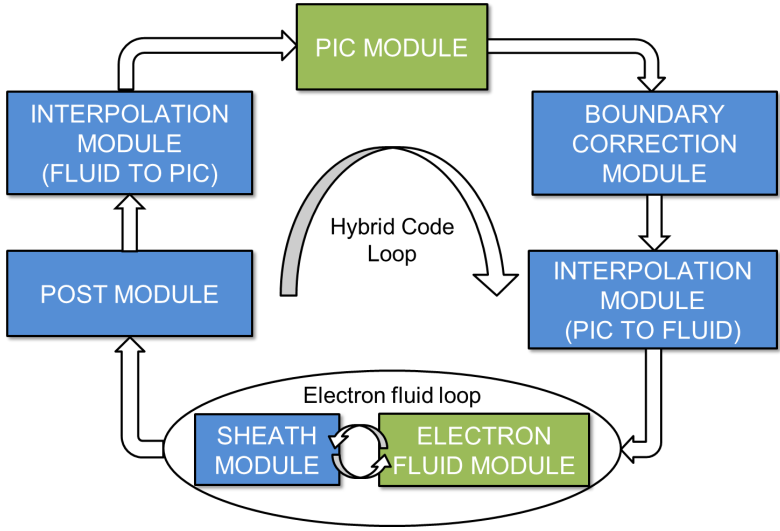
"Far-field" Boundary Conditions: non-homogeneous Neumann based on imposed current and heat-fluxes: $(\vec{j}_e + \vec{j}_i)\Big|_{F,j} \cdot \vec{n}_b = 0$; $\vec{q}_e \cdot \vec{n}_b|_{F,j} = 0$

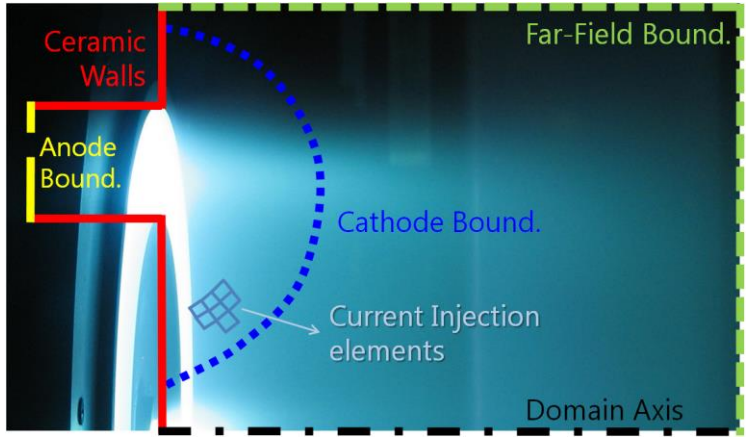
NOMADS: 2D hybrid code for Hall-effect thrusters

- ***Hybrid:*** *PIC (ion and neutral heavy species) + Fluid (electron population)*
- ***2D Axisymmetric*** *(z-r) plasma simulator of chamber & plume*
- *Heritage from HALLMA and EP2PLUS, but designed with extended capabilities*

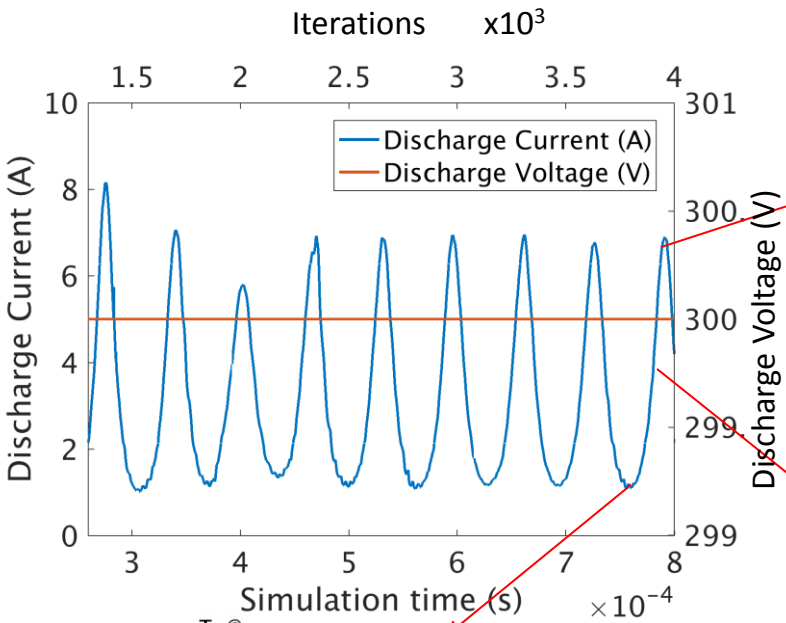
Main Design Characteristics:

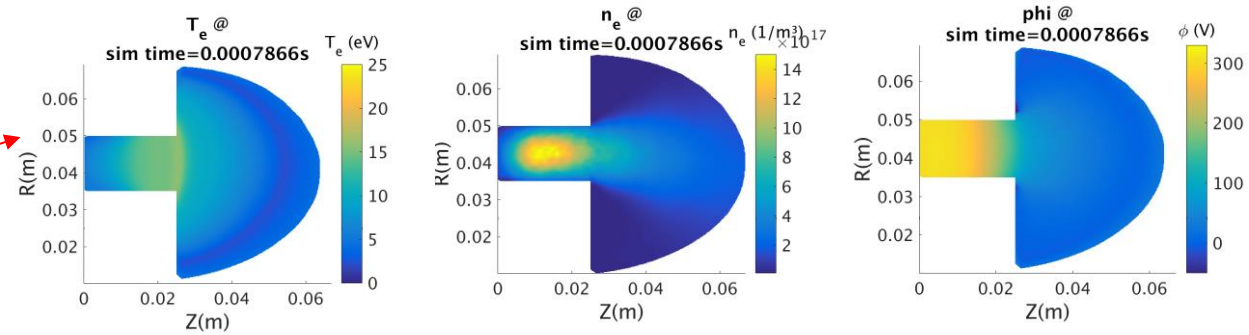
- *Mesh generators for ion (PIC) and electron modules*
  - *Magnetic mesh accepts cusps, zeros,…*
- *Reduced PIC noise:*
  - *multiple independent populations*
  - *cell population control algorithms*
- *Electron + electric module:*
  - *2 Temperatures population:* $T_{parallel}$ *&* T_{perp}
  - *Secondary e-emission*
  - *Accurate sheath/presheath Bohm forcing*
  - *Variety of wall materials/conditions*

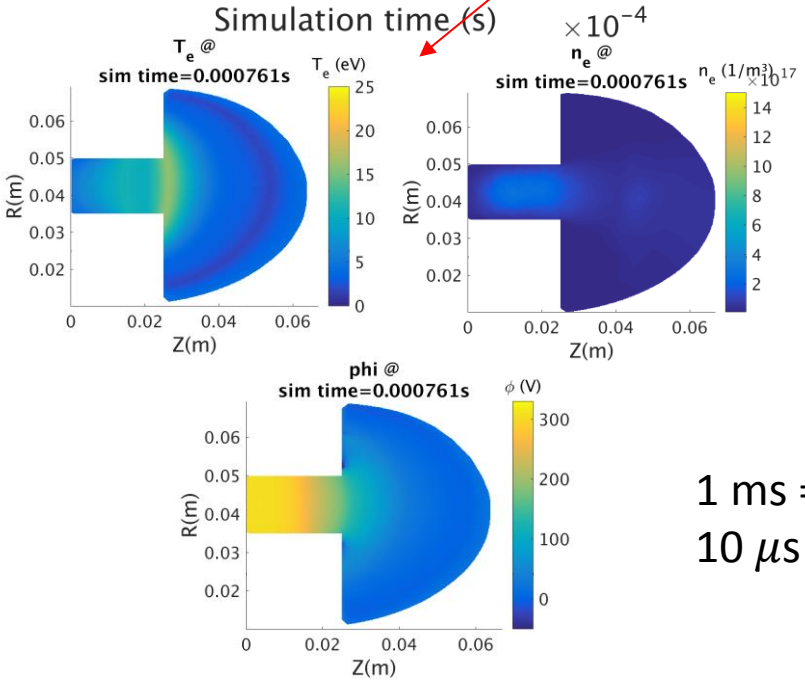


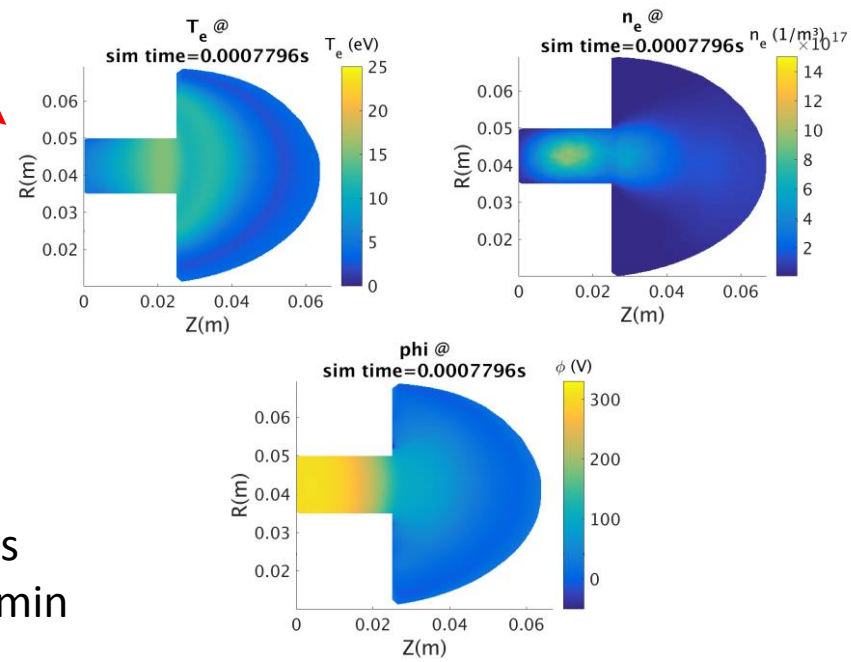


Preliminary results (fluid module)







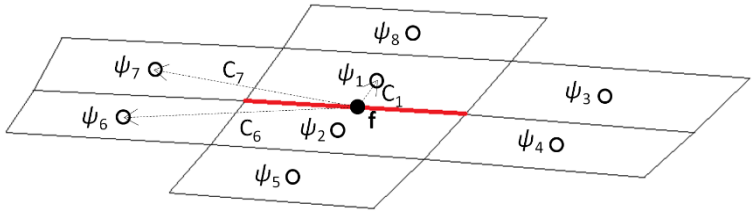


1 ms = 1-2 days

10 μs = 15-30 min

Updates on Gradient Reconstruction (I)

GR based on the Weighted Least Squares Face Interpolation:



$$\left.\frac{d\psi}{dx}\right|_{F,j} = \sum_i c_i \psi_i$$

- Based on magnetic coordinates ***λ*** (magnetic stream function) & ***σ*** (magnetic scalar potential), for gradients in the parallel and perpendicular directions to the magnetic field:
  - Singular for ***B=0***
  - Depends on a good previous calculation (numerical integration) of magnetic coordinates (not defined analytically for the domain)

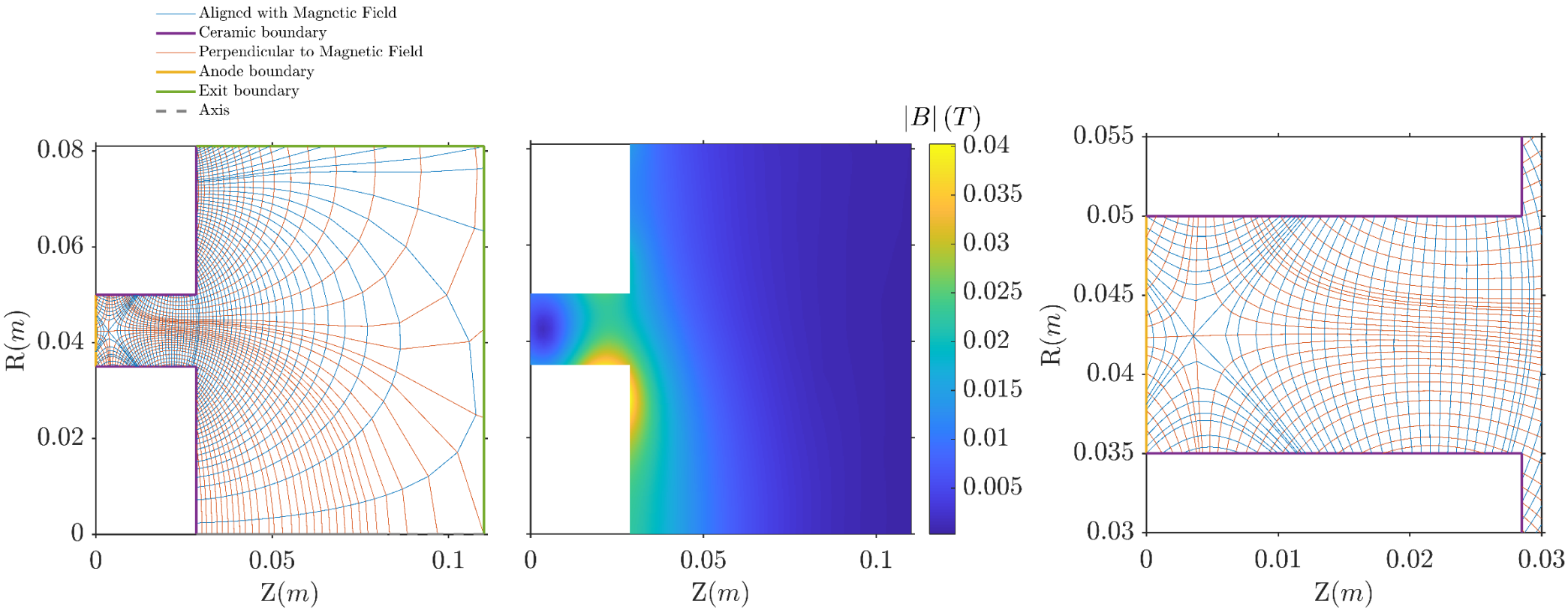
$$\frac{\partial \lambda}{\partial r} = -rB_z, \quad \frac{\partial \lambda}{\partial z} = rB_r \qquad \nabla_{\parallel} \equiv B\frac{\partial}{\partial \sigma}$$

$$\frac{\partial \sigma}{\partial r} = B_r, \quad \frac{\partial \sigma}{\partial z} = B_z \qquad \nabla_{\top} \equiv rB\frac{\partial}{\partial \lambda}$$

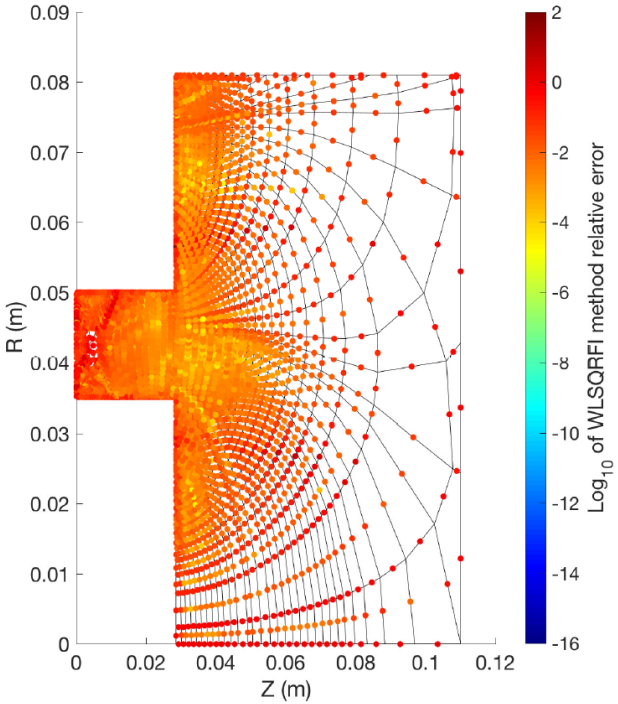
- Alternatively, it is possible to derive spatially (with respect to **r** & **z**) and project locally to the perpendicular and parallel directions…

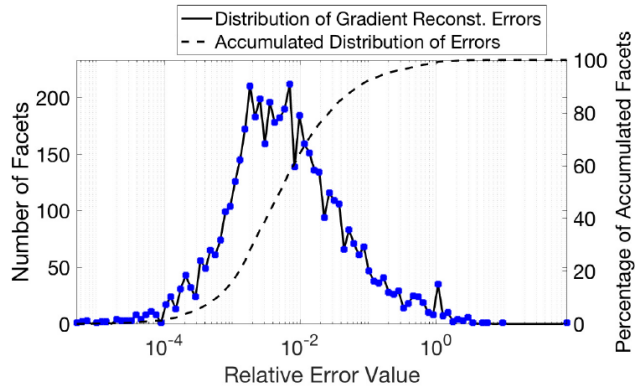
Updates on Gradient Reconstruction (II)

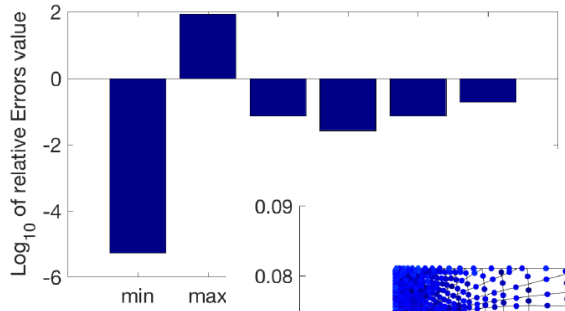
Gradient and integration errors for trial function $\psi = z + r$ on a MFAM with a singular point using WLSQRFI 1st Order method:



Updates on Gradient Reconstruction (III)

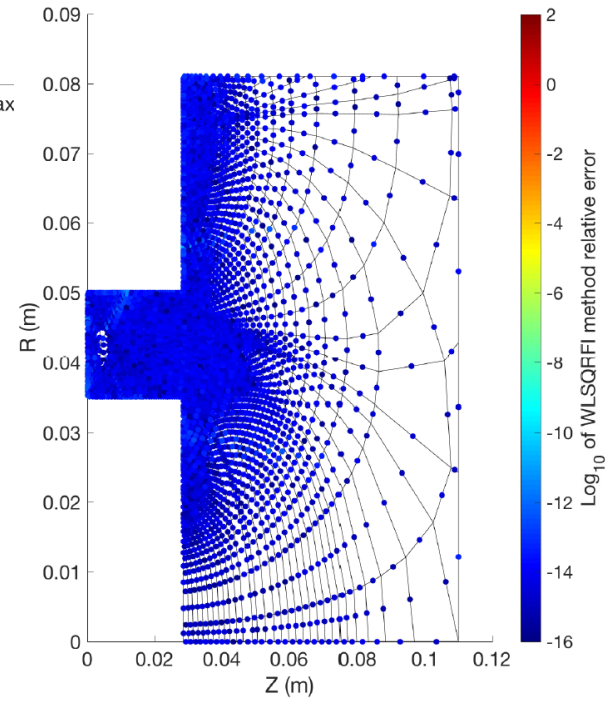


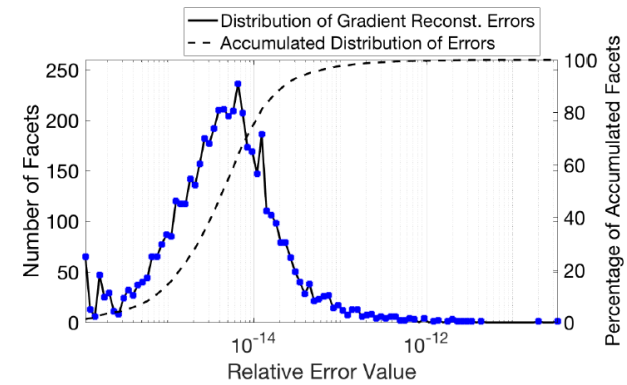


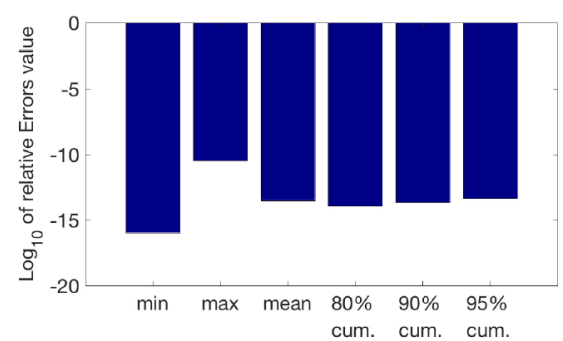


1st Order derivative errors:

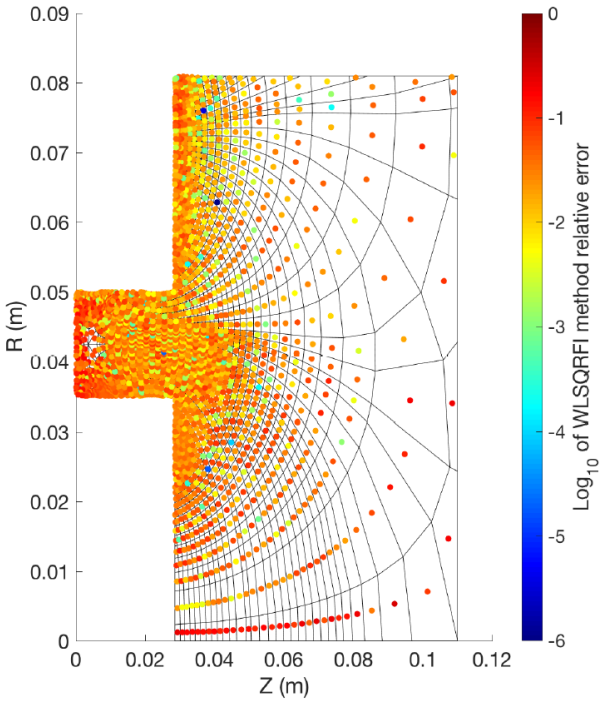
Analytical derivatives for magnetic coordinates are obtained through the Inverse Jacovian

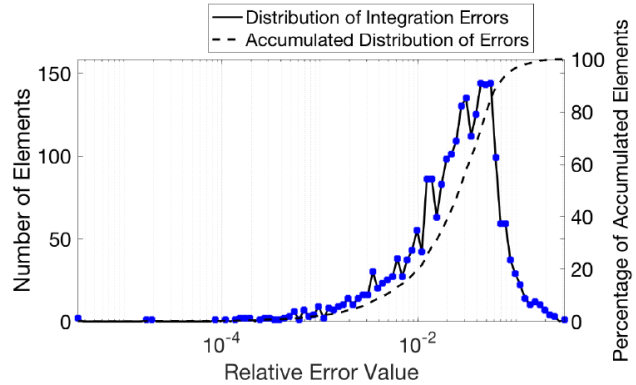


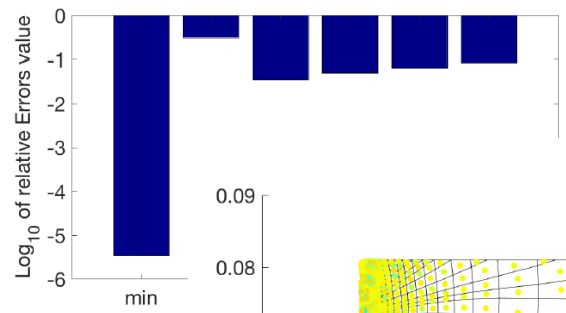




Updates on Gradient Reconstruction (IV)







Errors after integration of 1st Order derivatives