Wave propagation and absorption in a Helicon plasma thruster source, plume and surroundings

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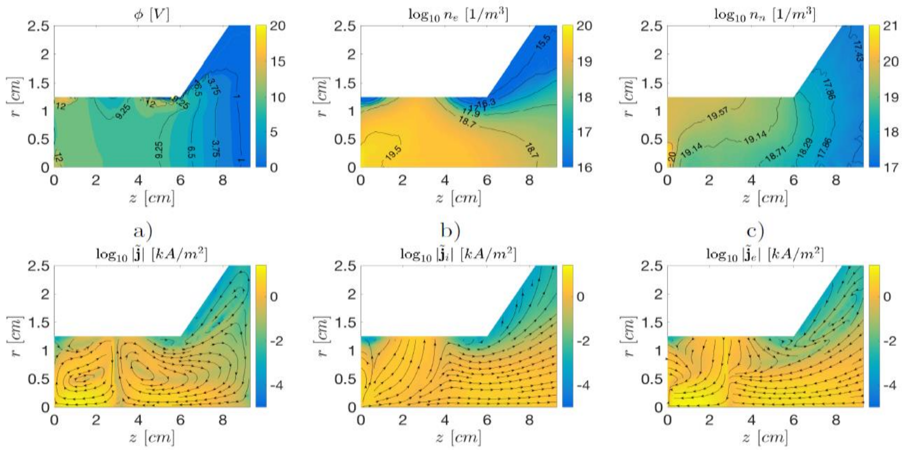
Previous Works in HPTs

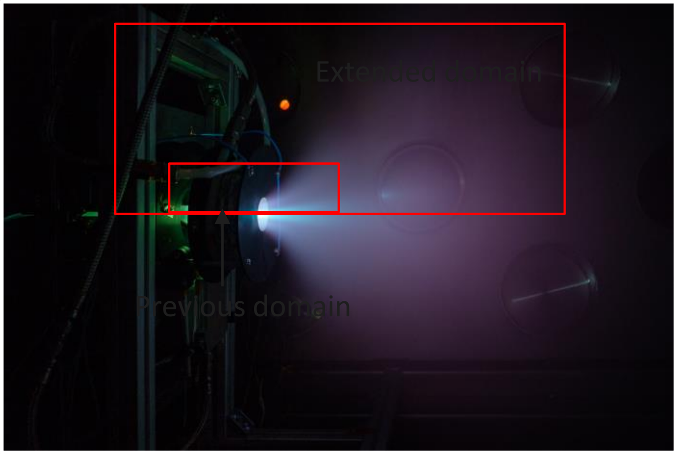
- Self-consistent coupled simulations. Plasma transport (HYPHEN)+ Plasma Wave Interaction (PYEE)
  - J. Zhou, P. Jimenez, M. Merino, P. Fajardo, and E. Ahedo, “Numerical simulations of the plasma discharge in a helicon plasma thruster," in 36th International Electric Propulsion Conference, paper IEPC, vol. 330, 2019.
  - Sanchez-Villar, A., Zhou, J., Ahedo, E., & Merino, M. (2021). Coupled plasma transport and electromagnetic wave simulation of an ECR thruster. Plasma Sources Science and Technology.
- HYPHEN -> Hybrid PIC (heavy species) + fluid (electrons) 2D multithruster simulation platform
- Full physics for the steady state operation of the thruster
- Process:
  1. Initial guess for the plasma profiles (density, temperature, collisions)
  2. Wave module is called, and the **power deposition computed**
  3. **Plasma dynamics advanced in time** assuming power deposition map remains unchanged
  4. After some time steps the **wave module is recalled** to update the power distribution
  5. The process is repeated until a stationary solution is achieved



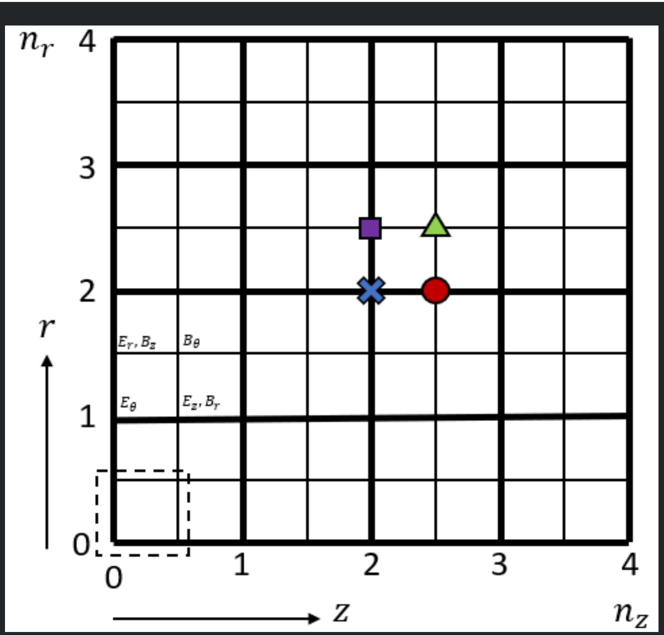
Objectives and methodology

- Study the electromagnetic fields in the plume region and vacuum chamber
  - The fields in those regions can affect the effective power distribution
  - Improvement in the modeling that reproduces much better the vacuum chamber shape and walls
  - Addition of internal PEC conditions to model metallic parts

- Methodology
  - Focused on the electromagnetic solution and power deposition -> not coupled simulations
  - Enlarge the wave domain from previous works (about 3 x Length and 4 x Radius)
  - We use stationary profiles from coupled simulations in the source and near plume
  - We use a different methodology to estimate plasma density and temperature at the far plume



Electromagnetic model and discretization



- Frequency Domain Maxwell's equations in integral form for a non-isotropic linear material

$$\tilde{\boldsymbol{D}} = \varepsilon_0 \bar{\bar{\kappa}} \cdot \tilde{\boldsymbol{E}}$$

$$\omega \int i\tilde{\boldsymbol{B}} \cdot \mathrm{d}\boldsymbol{s} - \oint \tilde{\boldsymbol{E}} \cdot \mathrm{d}\boldsymbol{l} = 0$$

$$\mu_0 \omega \int i\tilde{\boldsymbol{D}} \cdot \mathrm{d}\boldsymbol{s} + \oint \tilde{\boldsymbol{B}} \cdot \mathrm{d}\boldsymbol{l} = \mu_0 \int \tilde{\boldsymbol{j}}_a \cdot \mathrm{d}\boldsymbol{s}$$

$$S \equiv \frac{1}{2}(R + L)$$

$$D \equiv \frac{1}{2}(R - L)$$

$$P \equiv 1 - \sum_s \frac{\omega_{ps}^2}{\omega(\omega + i\nu_m)}$$

$$R \equiv 1 - \sum_s \frac{\omega_{ps}^2}{\omega(\omega + i\nu_m + \omega_{cs})}$$

$$L \equiv 1 - \sum_s \frac{\omega_{ps}^2}{\omega(\omega + i\nu_m - \omega_{cs})}$$

- The circulation and flux integral terms are conveniently discretized thanks to the staggered (Yee) grid layout.
- Perfect Electric Conductor (PEC) boundaries can be introduced with ghost nodes at the boundaries.
- The axial boundary conditions must be considered depending on the azimuthal mode number m.
- Interpolation needed to obtain the value of E at every node due to full dielectric tensor $\bar{\bar{\boldsymbol{\kappa}}}$

- **Dielectric tensor** from Plasma Dynamics with static B_0 and cold plasma assumption (no pressure term)

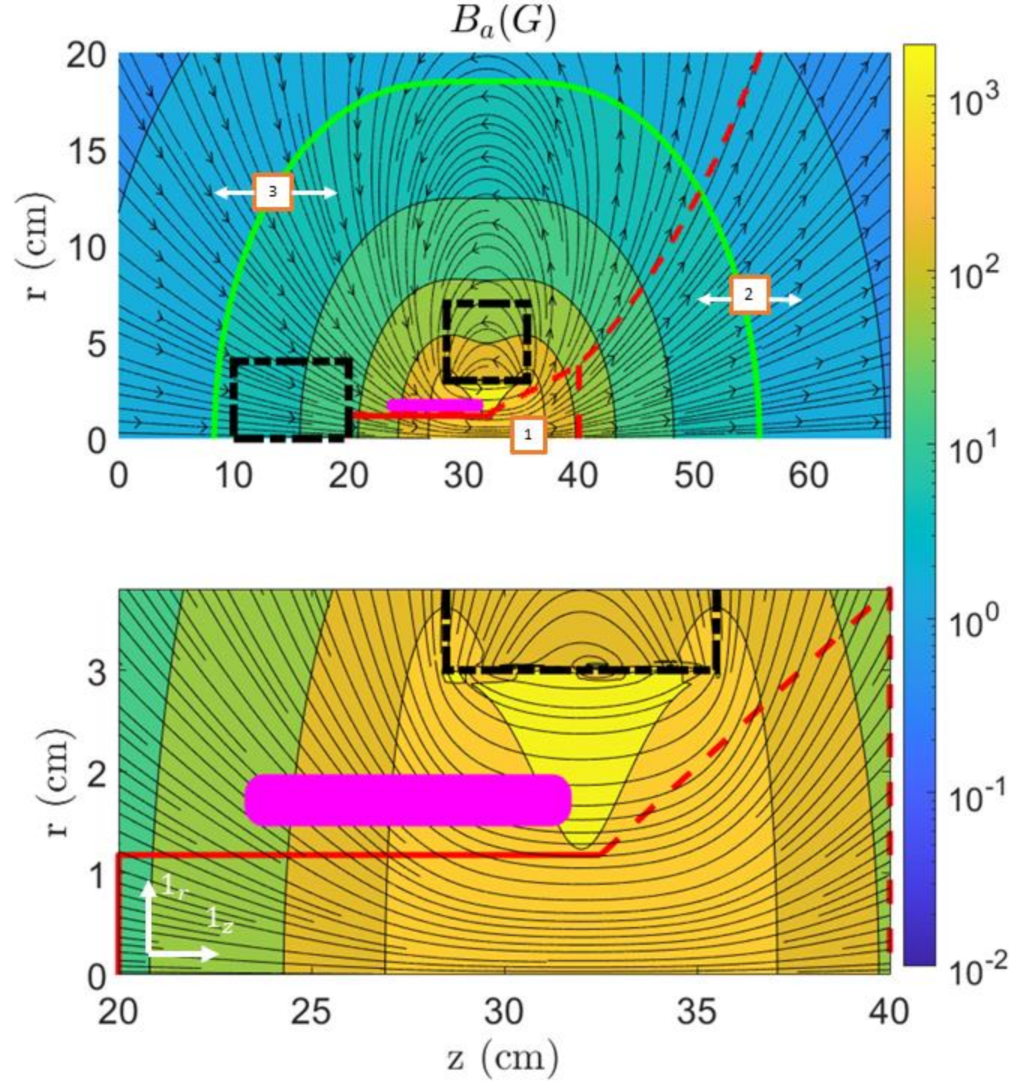
$$\bar{\bar{\kappa}} = \begin{pmatrix} S & -iD & 0 \\ iD & S & 0 \\ 0 & 0 & P \end{pmatrix}$$

- Governing parameters:
  - Applied magnetic field
  - Plasma density
  - Effective collision frequency

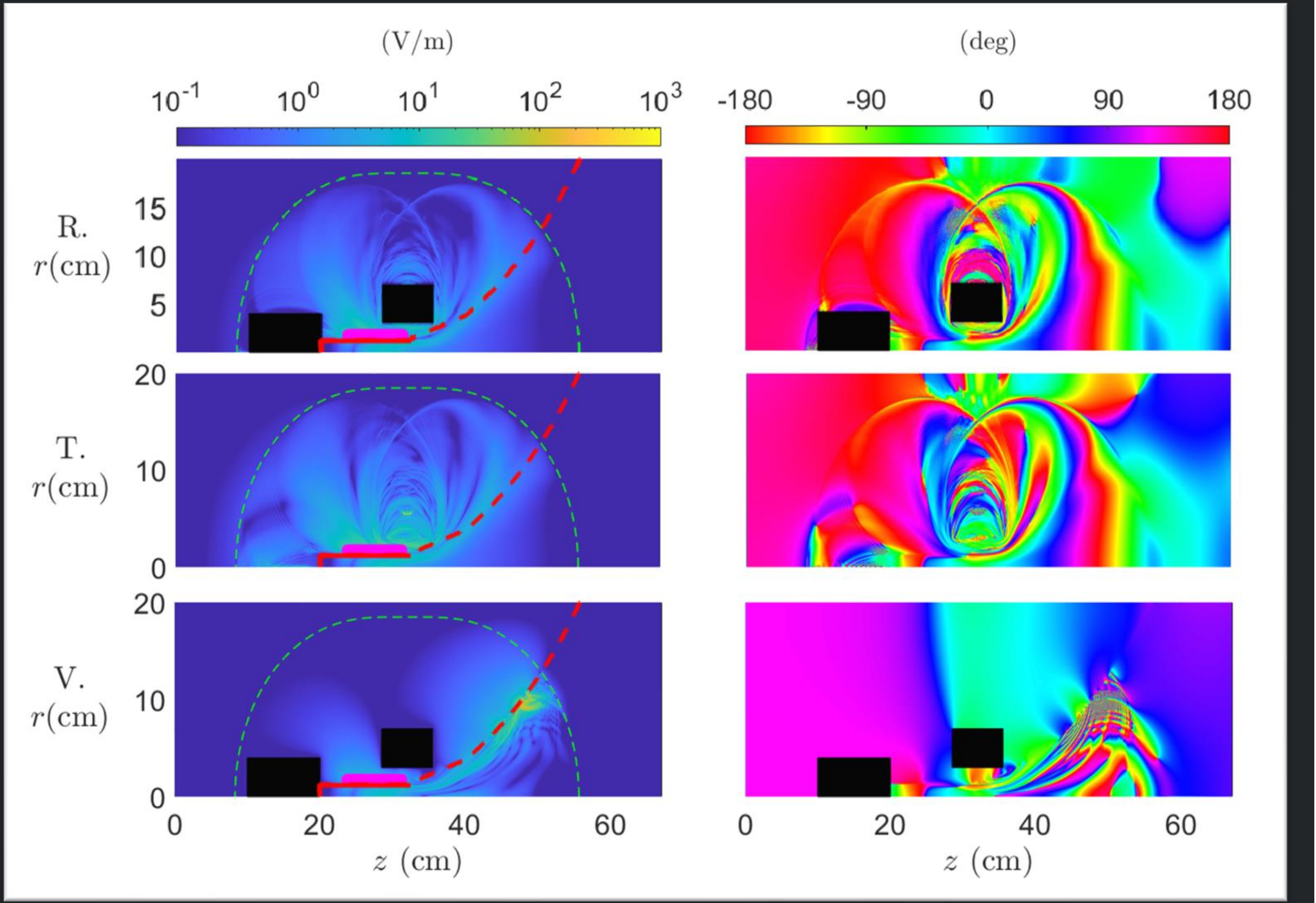
$$\omega_{ce}(z,r) = \frac{eB_a}{m_e}, \quad \omega_{pe}(z,r) = \sqrt{\frac{ne^2}{m_e \varepsilon_0}}$$

Setup

- Frequency domain full-Maxwell Finite Difference (FDFD) code.
- Electron Cyclotron Resonance downstream.
- Realistic plasma density and collision frequency profiles coming from transport codes.
- New interpolation algorithm.
- 3 study cases:
  - Reference: Overdense conditions, the vacuum chamber (region 3) is filled with a tenuous plasma $n \approx 10^{14}\ \mathrm{m}^{-3}$
  - Transparent: Same as reference but metallic boxes (corresponding to the magnetic coils and thruster support equipment) are excluded.
  - Vacuum: Simulates the operation in full vacuum, no plasma in region 3.

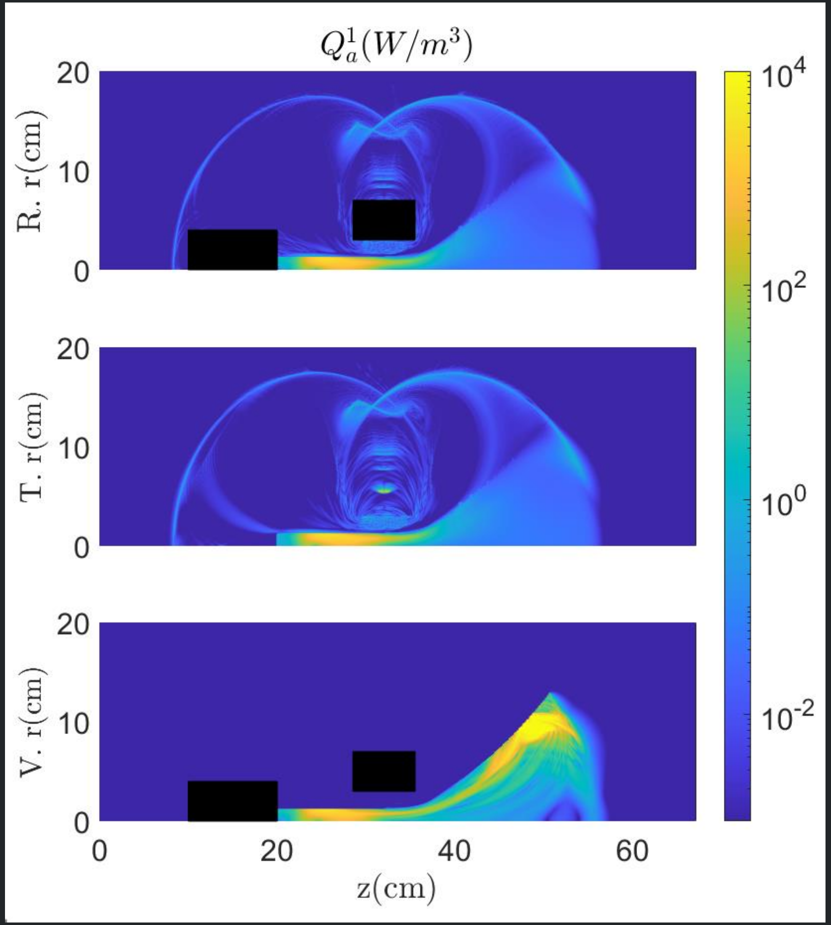


Electromagnetic solution

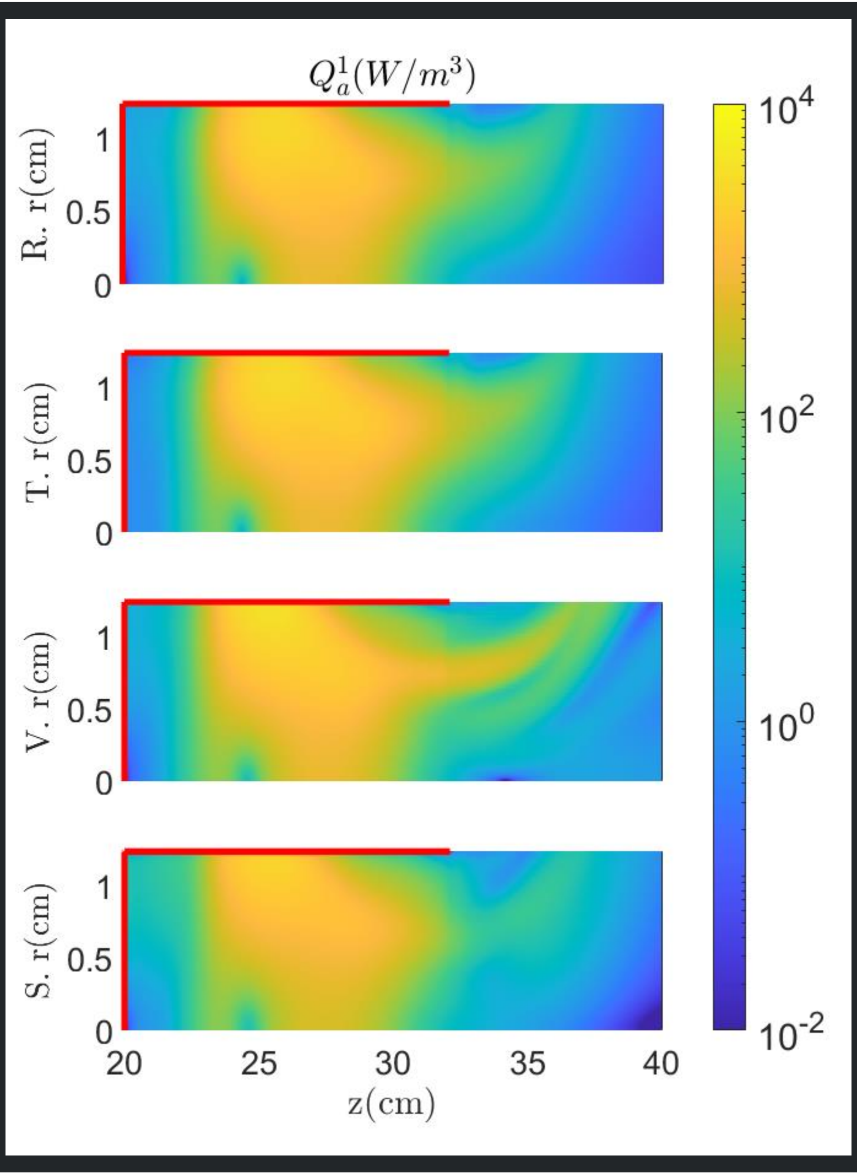


- Internal conductors affect very little the solution.
- The presence of an overdense plasma radically changes the propagation in the far plume but not in the source.
- Evidence of Helicon modes in the source and TG modes in the border of the plume (see phase vacuum case).
- The ECR prevents any free space loss in the overdense case. The fields are evanesced downstream.

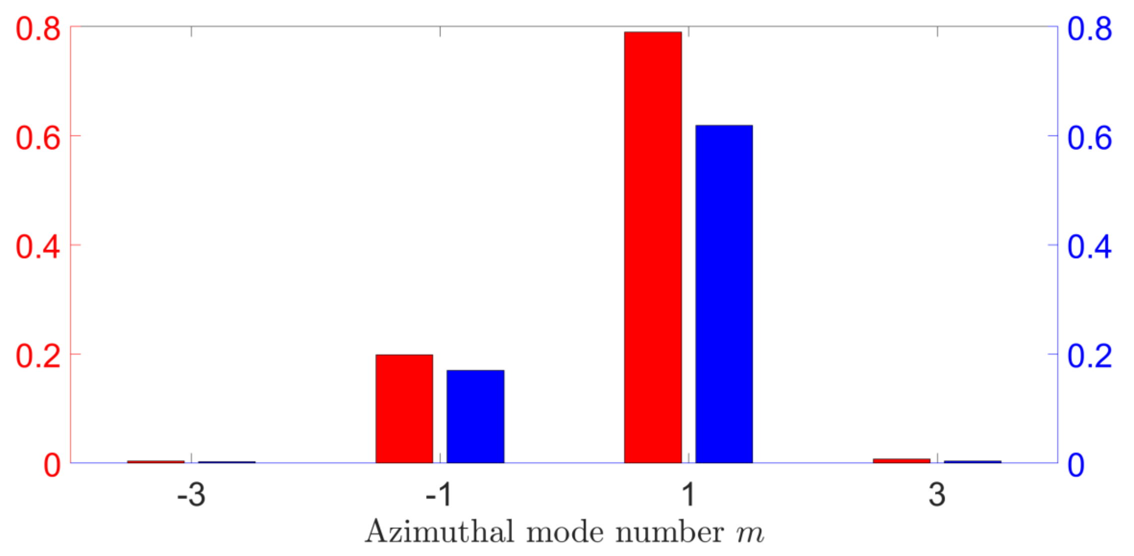
Power Absorption



- The ECR plays a fundamental role in confining the antenna power.
- Most of the power is deposited in the source. The validity of the solution in the outer plume for the vacuum case is uncertain.
- The conditions outside the plasma source and near plume affect very little the power deposition inside.

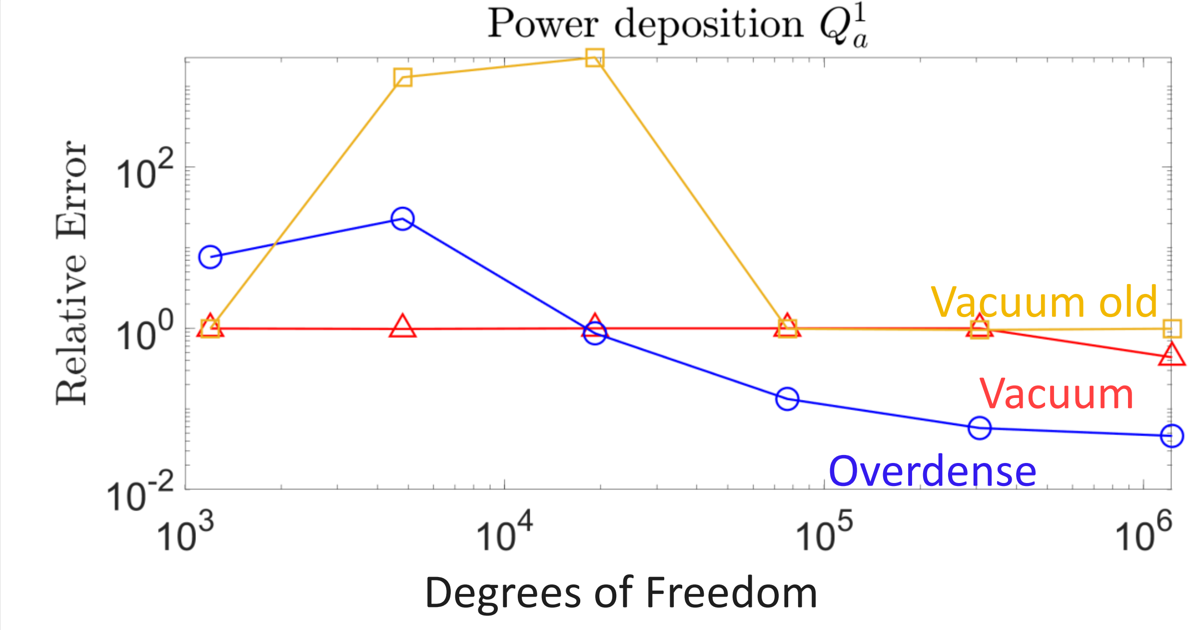


Azimuthal modes and convergence



Fraction of total power (red) and fraction of power deposited inside the source (region 1, blue) for different azimuthal mode numbers.

- The azimuthal mode $m = 1$ accounts for the bulk of the plasma resistance with some minor contribution from $m = -1$ and negligible higher modes.



- For case Vacuum -> Numerical issues and high noise in the interface between the under-dense to overdense transition and the ECR. The critical transition from vacuum to an overdense plasma (P=0) presents a locally ill-posed problem at the border of the plume. We have found that mesh alignment and the interpolation algorithm play a key role.

Acknowledgments

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