



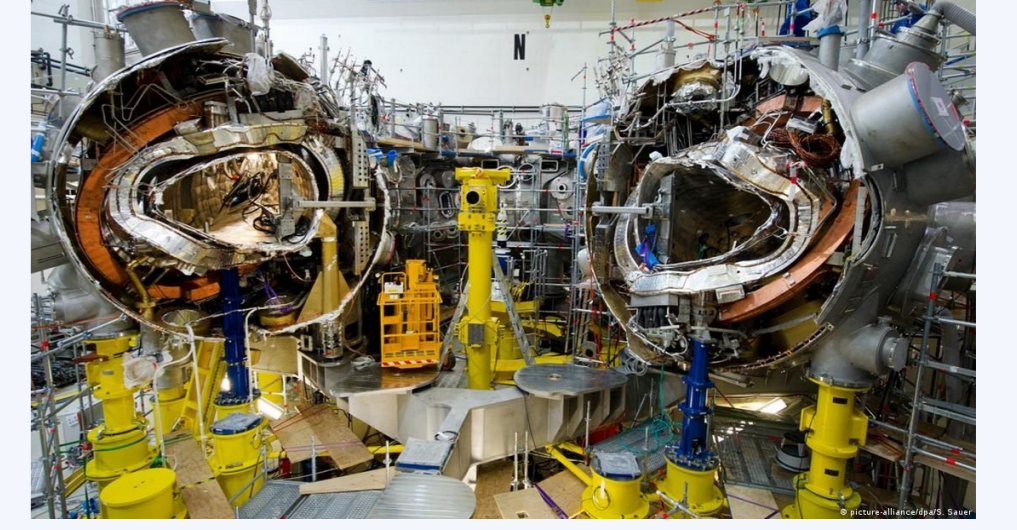
Full-wave modeling in Wendelstein 7-X with Petra-M FEM

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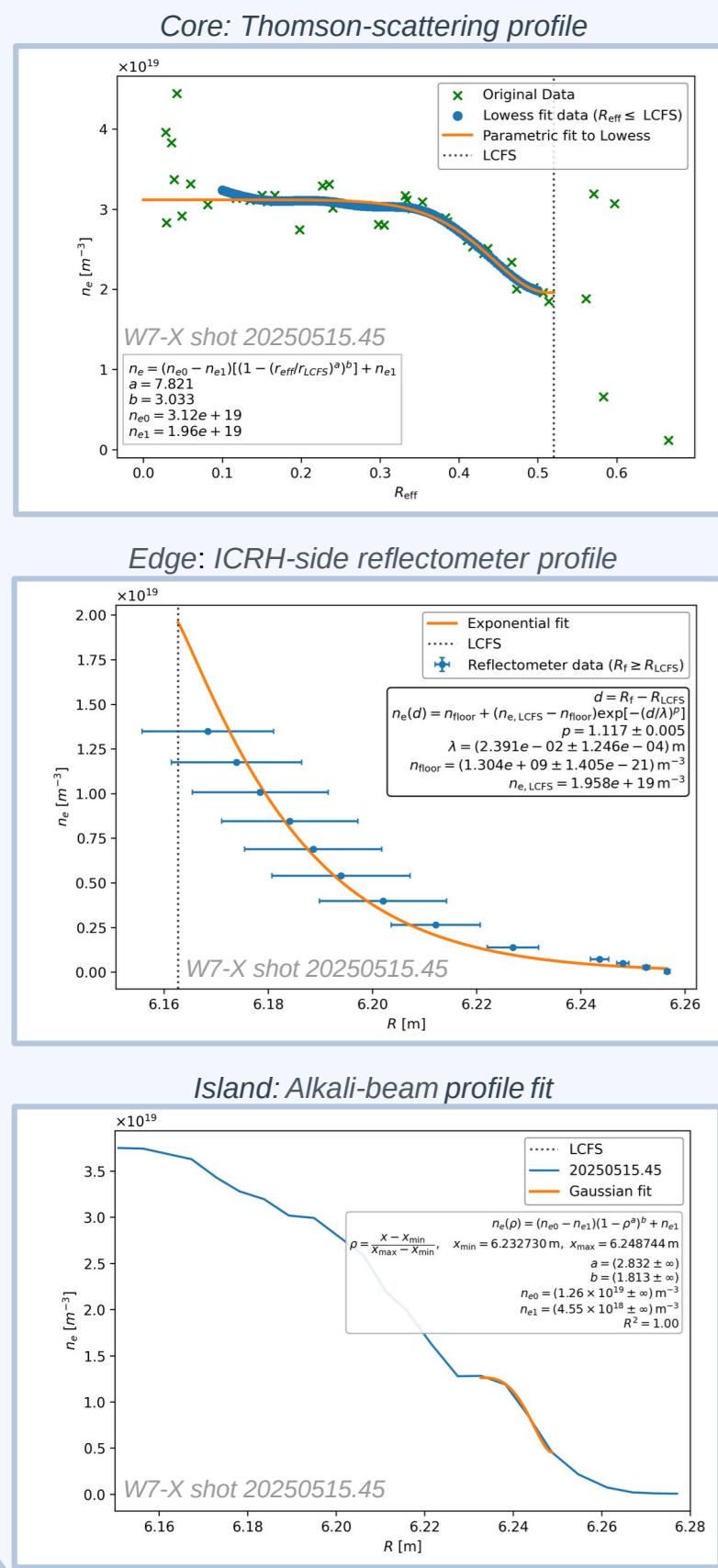


Introduction

Ion cyclotron resonance frequency (ICRF) heating¹ is an important auxiliary heating method for stellarators, yet understanding RF wave propagation and power absorption in the complex three-dimensional magnetic geometry of stellarators remains challenging. This work presents progress on a full-wave modeling capability for ICRF heating in Wendelstein 7-X (W7-X)² using the Petra-M finite element method (FEM) code³ developed at the Princeton Plasma Physics Laboratory, combining realistic antenna/vessel CAD, VMEC magnetic equilibria, plasma profiles and experimentally constrained RF matching. The resulting launched wave fields will support the interpretation of W7-X heating experiments, and provide future inputs for transport and turbulence studies in W7-X's magnetic configuration.



Plasma Density Reconstruction

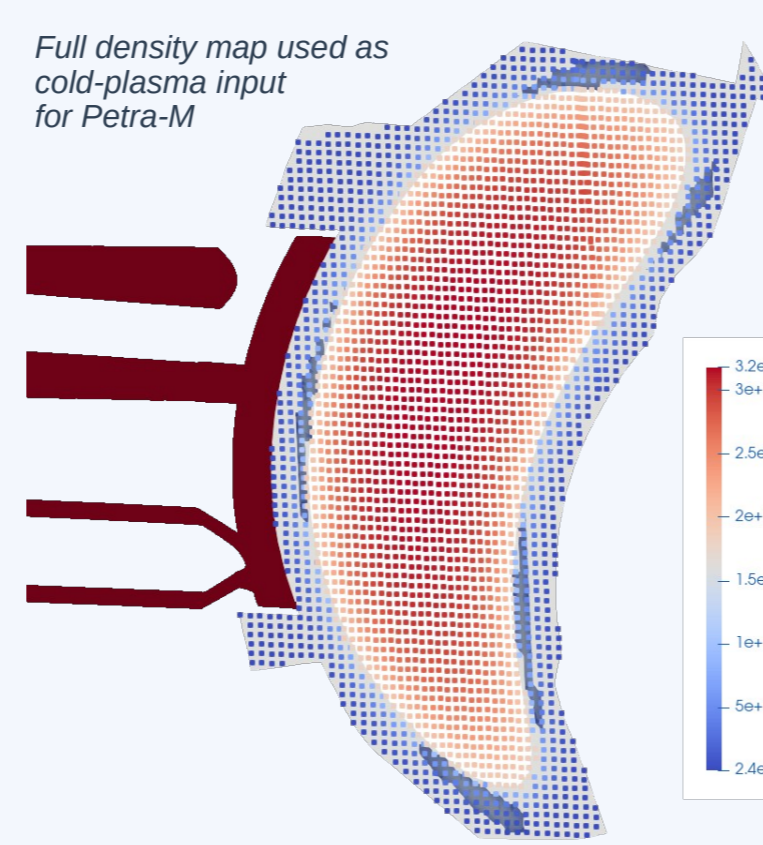


Density profile measurements from different diagnostics are converted into one 3D density input for the FEM model. Profiles are extended to the full complex volume via $n_{\text{eff}} = \sqrt{\frac{A}{\pi}}$, which stays constant over flux surfaces.

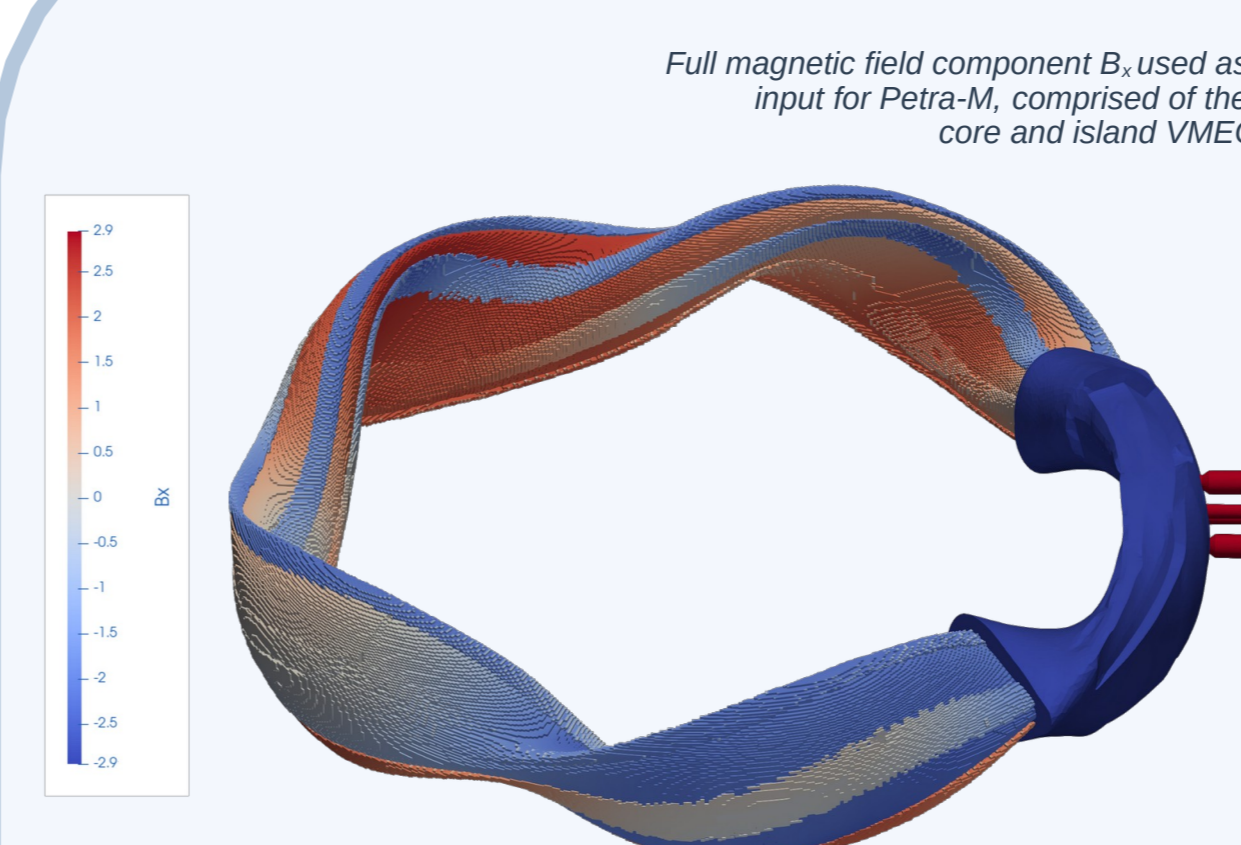
Core: inside the last closed flux surface (LCFS) a parametric fit to the Thomson reflectometer profile is performed

Edge: outside the LCFS an exponential fit to the ICRH reflectometer profile is performed, with the LCFS density fixed by the first fit

Island: in the magnetic islands a Gaussian fit to the bump of the Alkali-beam profile is performed



Full density map used as cold-plasma input for Petra-M

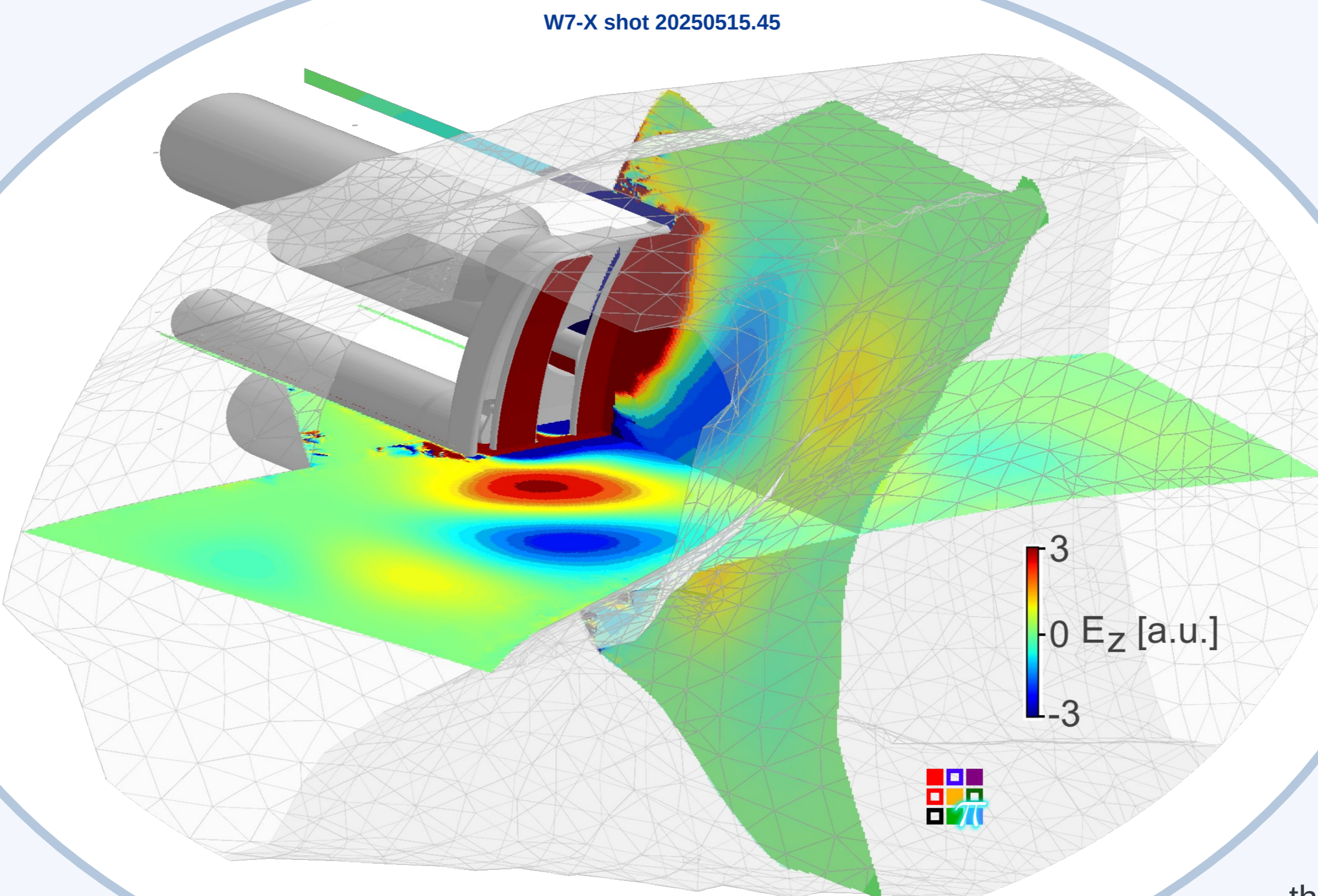
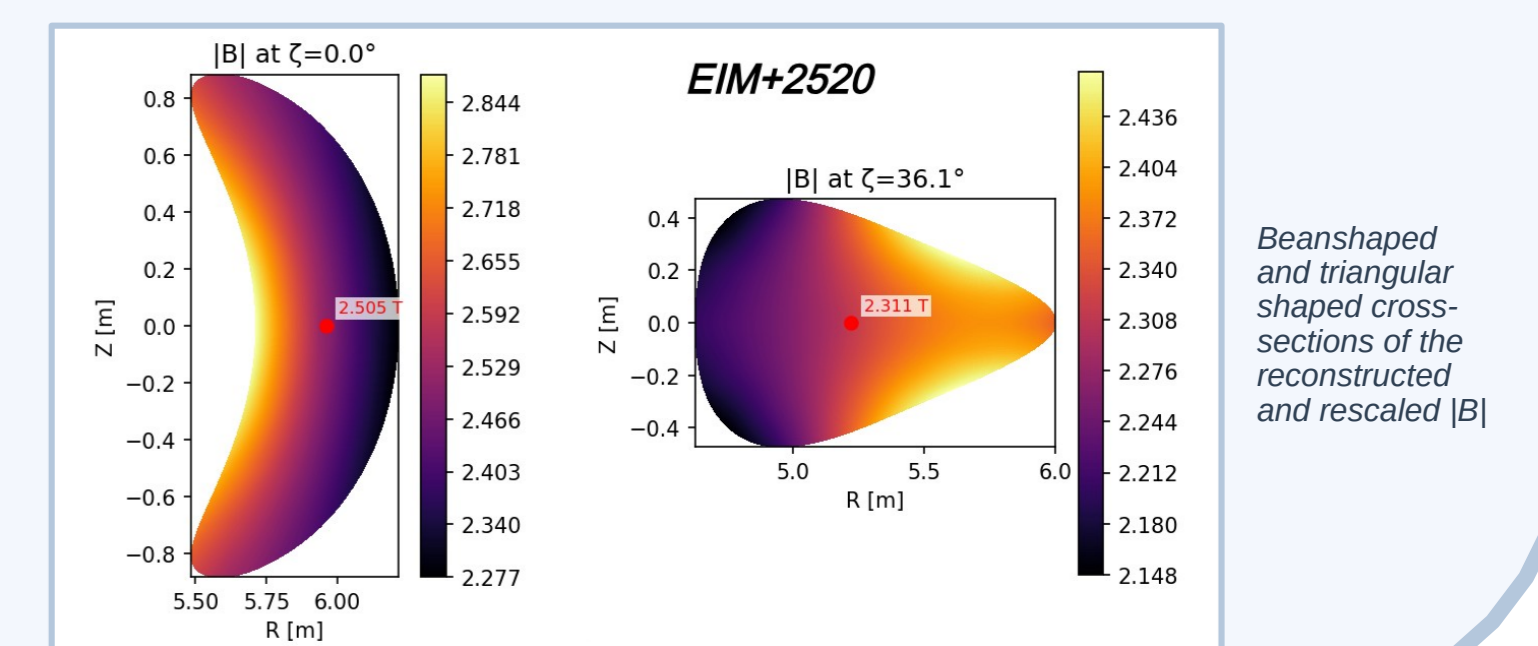


Full magnetic field component B_z used as input for Petra-M, comprised of the core and island VMEC

3D Magnetic Equilibrium

The 3D design of the ICRF antenna is aligned with the LCFS of the standard magnetic field configuration (EIM). VMEC, the Variational Moments Equilibrium code, provides plasma equilibrium configurations for the W7-X EIM configurations used during ICRF experiments.

Fourier synthesis reconstructs the 3D flux-surface geometry and the VMEC field components on full poloidal and toroidal angle grids; the field is converted to Cartesian B_x, B_y, B_z . The reconstructed field is interpolated from flux coordinates onto a regular (R, Z, ϕ) grid. The magnetic-field magnitude is rescaled to the experimental B-axis value. For the island case, 5-fold toroidal periodicity is imposed in the reconstructed input fields.



W7-X shot 20250515.45

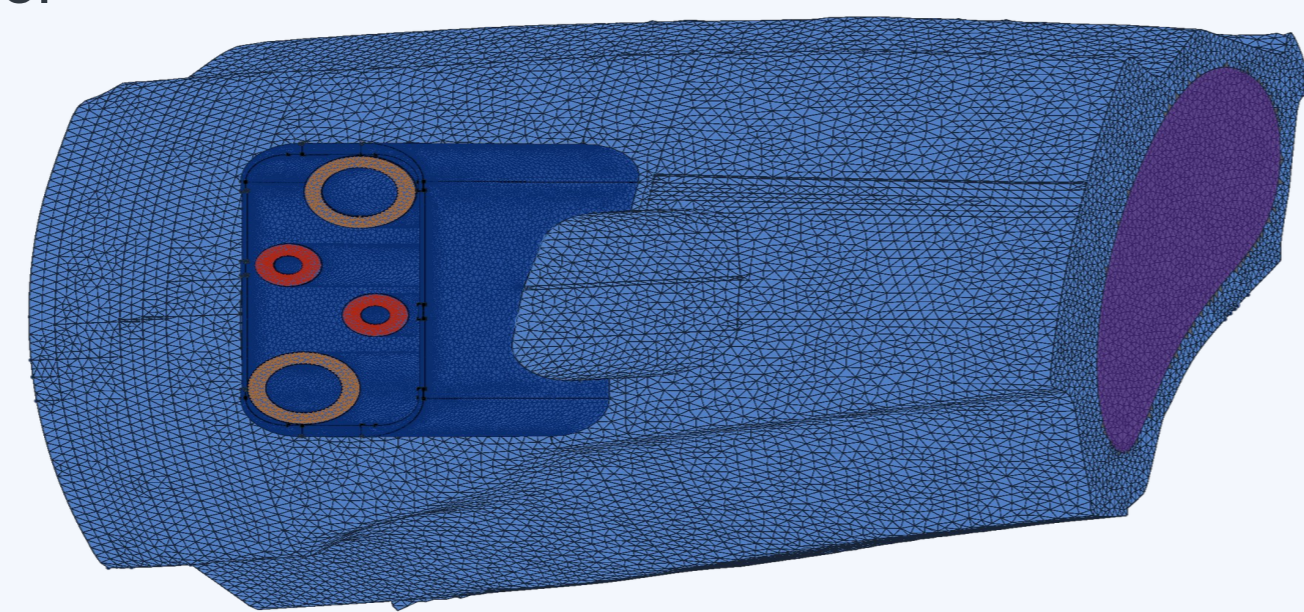
Petra-M full-wave ICRF simulation result for the three-ion-heating scheme, using a cold-plasma model with core and edge density, normalized to unit port excitation (see below)

Petra-M Computational Model

In CATIA, the full 3D surface of the W7-X inner wall and the plasma domain (the VMEC LCFS) are provided as 751 cross-sectional curves in cylindrical coordinates, connected to create smooth surfaces. The detailed ICRF antenna geometry is simplified for the Petra-M finite-element workflow built on PyMFEM/MFEM.

The **computational domain** is separated into physically meaningful regions: vacuum around the **ICRF antenna**, cold-plasma in the **core**, low density and low temperature cold-plasma in the **edge**. Shot-specific datasets are loaded for each region from the pre-processing pipeline.

The **RF solve** is a frequency-domain electromagnetic finite-element problem with material coefficients depending on local plasma quantities and magnetic field. Boundary conditions define conducting vessel / antenna surfaces, interface continuity, driven **RF ports**, and **capacitor ports**. The solver infrastructure supports direct or iterative linear solves and parameter scans.



The computational domain as a Gmsh mesh of 1/10th of the vessel containing plasma and the ICRF antenna.

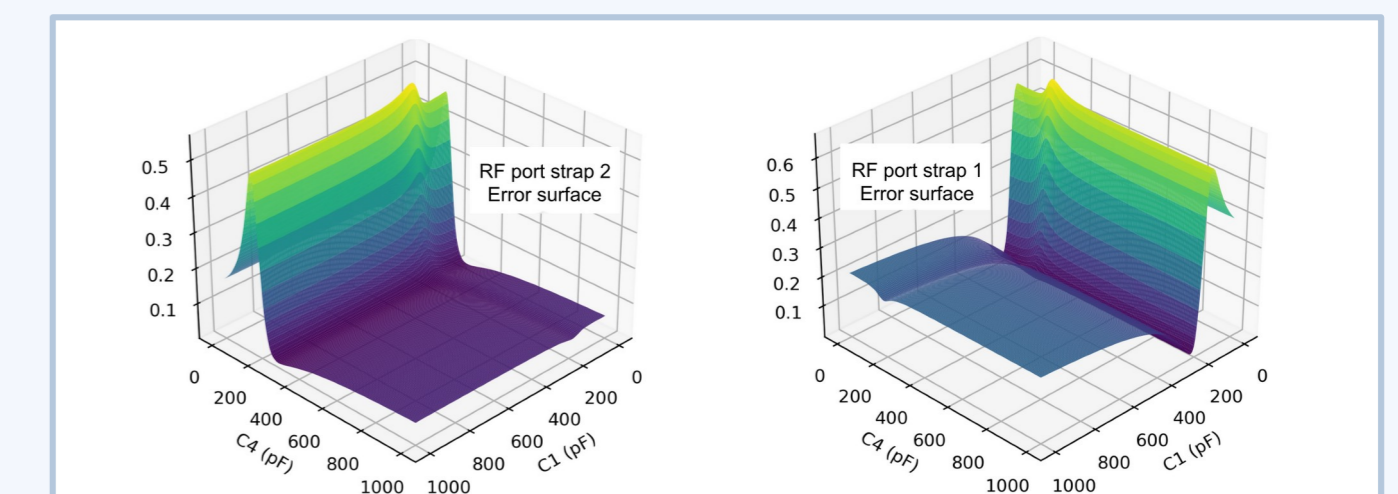
Experimental RF reconstruction

The experimental RF matching state is reconstructed from calibrated ICRF measurements rather than generator settings. The measured reflection coefficient $\Gamma = |\Gamma|e^{i\phi_\Gamma}$, is de-embedded/translated to the antenna reference plane using $\Gamma_{\text{ant}} = \Gamma e^{2\gamma L}$. The matching capacitors are fitted by comparing measured active reflection coefficients with those predicted from the Petra-M four-port S-matrix. Capacitor ports are terminated by

$$Z_C = -\frac{1}{i\omega C}, \quad \Gamma_C = \frac{Z_C - Z_0}{Z_C + Z_0},$$

reducing the 4-port system to an effective 2-port system $S_{\text{eff}} = S_{BB} + S_{BA}(I - \Gamma_{SA})^{-1}\Gamma_{AB}$.

The fitted (C_1, C_2) minimize the phase error between measured and modeled Γ . **Disclaimer:** Solution only available after port reordering. Port-mapping ambiguity under investigation.



Preliminary results and outlook

Result 1: Minority-heating scenario

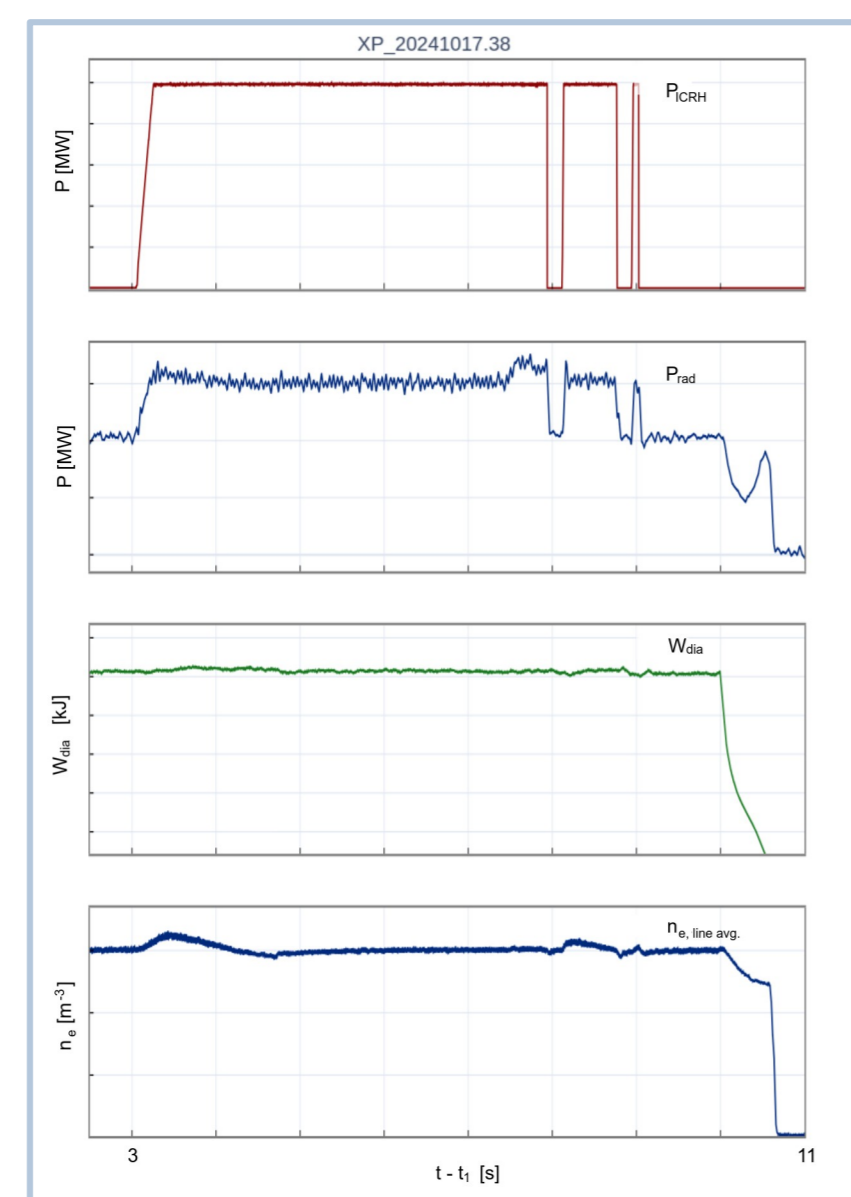
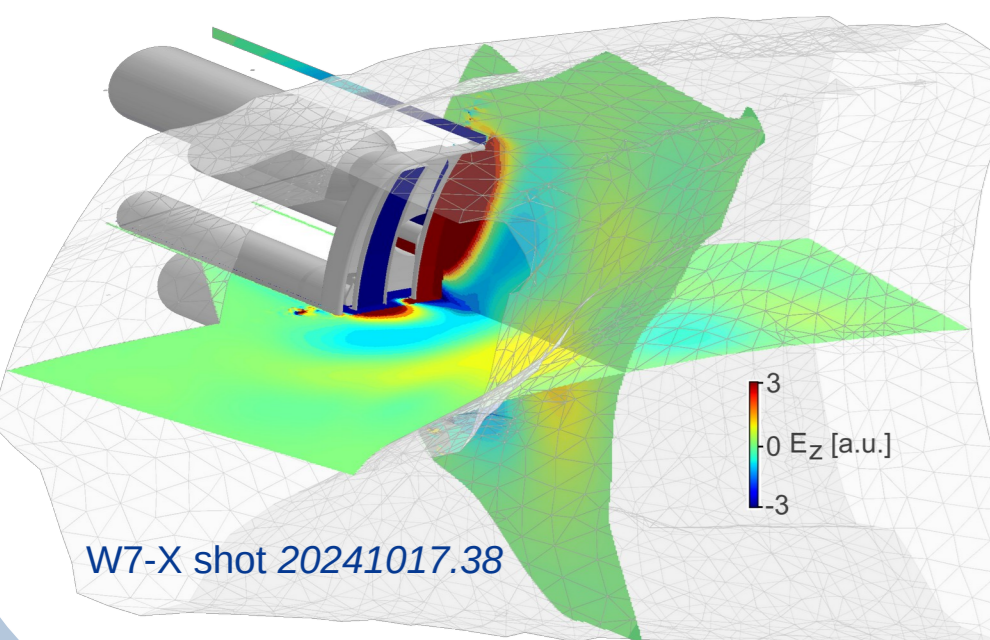
H-(³He) in W7-X shot 20241017.38

6 s long pulse of 400 kW ICRF in H with 2% ³He discharge, using two straps at 25 MHz in dipole phasing.

Right: Plasma parameters during ICRF discharge. Most power is radiated.

Bottom: Petra-M full-wave ICRF simulation result, using a cold-plasma model with core and edge density, normalized to unit port excitation.

Capacitor fit: See dedicated frame.



Result 2: Three-ion-heating scenario

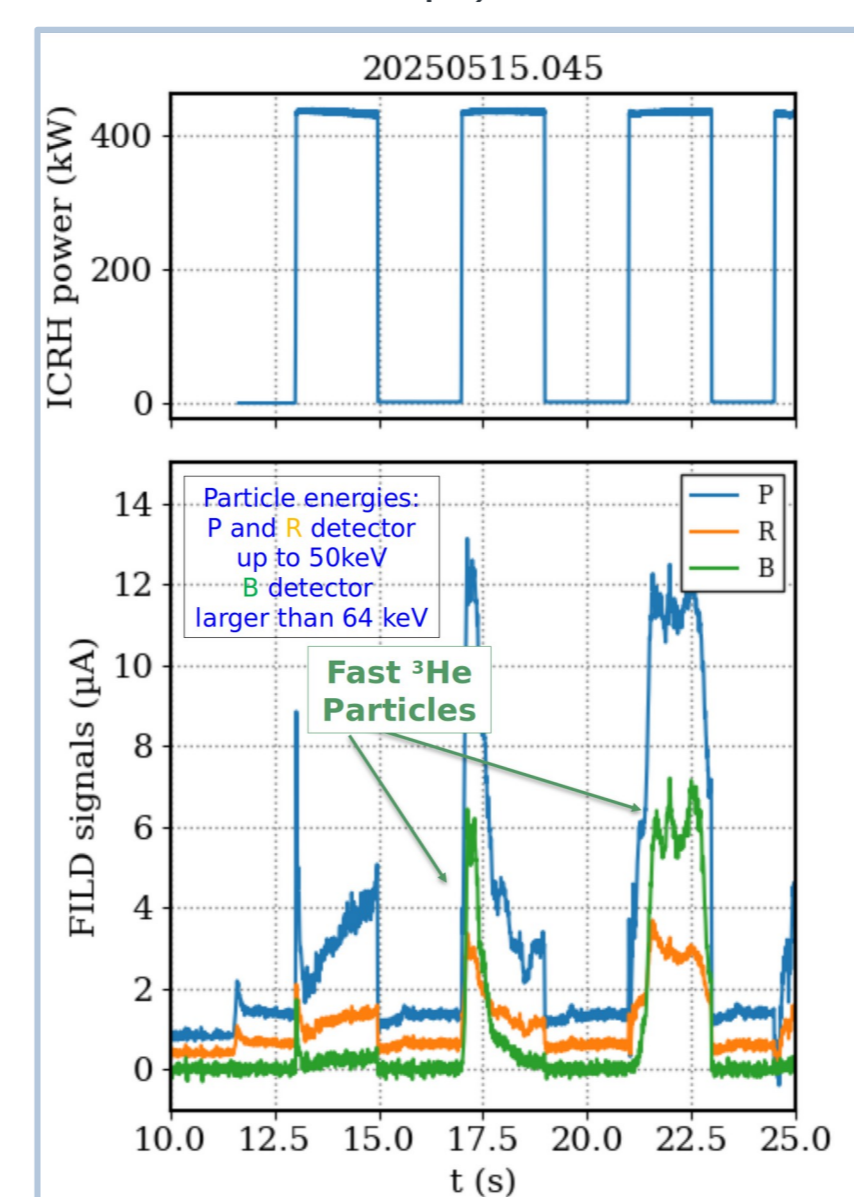
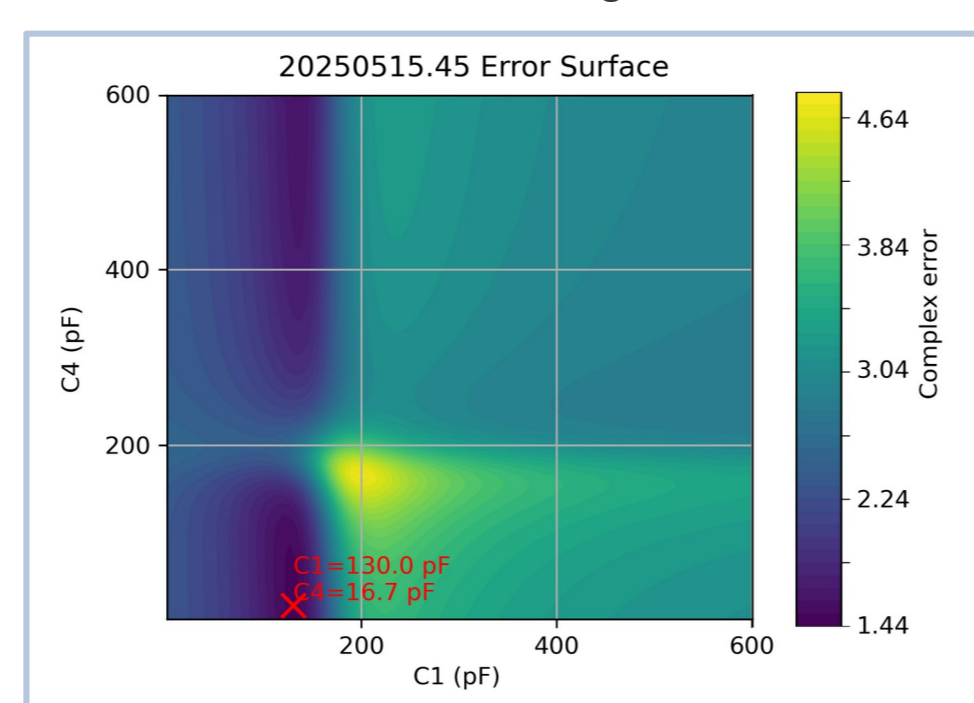
H-(⁴He)-³He in W7-X shot 20250515.45

Modulated 400 kW ICRF in H with ~15% ⁴He and ≤ 1% ³He discharge, using one strap at 25 MHz in monopole phasing (simulation with two straps).

Right: Fast particles detected with FILD detector, aligned with ICRF pulses.

Bottom: Fitting the capacitor values proved challenging, as strap 1 was disconnected during the measurements.

Result: See central image



Outlook

Analysis: For specific heating scenarios, examine antenna coupling, RF field structure and the localization of cold-plasma absorption. Compute a first estimate of the local absorbed-power density from the solved RF field using the anti-Hermitian part of the dielectric response from the enabled cold-plasma damping model, with separate electron and ion Stix contributions where available.

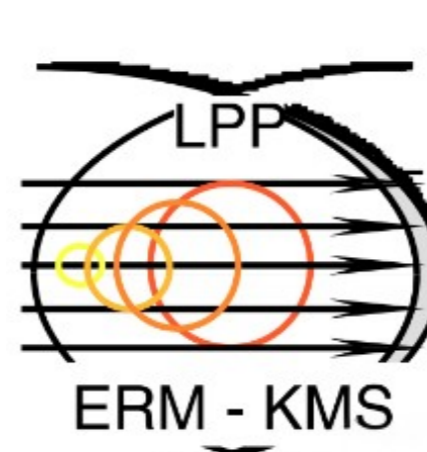
Sensitivity: Assess the sensitivity of the heating scenarios to variations in plasma profiles, magnetic configurations, and antenna position, to identify the dominant sources of uncertainty and the most robust operating scenarios.

Validation: Benchmark simulation results against experimental data and compare RF field localization with parallel W7-X ICRF simulation efforts, notably SCENIC-LeMan (Dr. Slaby, IPP) and AORSA (Dr. Mantsinen's group, CIEMAT).

Integration: For a quantitative heating interpretation and fast-ion generation, couple the RF fields and cold-plasma absorbed-power proxy to kinetic/transport tools, such as the ASCOTS suite.

References

- [1] J. Ongena et al., Phys. Plasmas 21, 061514 (2013)
- [2] O. Grulke et al., 30th Fusion Energy Conf., IAEA-CN-336/3257 (2025)
- [3] S. Shiraiwa, et al., EPJ Web of Conferences 157, 03048 (2017)



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