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EPJ Web of Conferences **346**, 01007 (2026) https://doi.org/10.1051/epjconf/202634601007
RFPPC2025

Benchmark of the new release of FELICE solver in TOPICA code with the ASDEX Upgrade 3-strap antenna

David Galindo [1*], *Daniele* Milanesio[1], *Giuseppe* Vecchi[1], *Roberto* Bilato[2], *Marco* Brambilla[2], and *Volodymyr* Bobkov[2]

[1]Politecnico di Torino, Torino, Piemonte, Italy
[2]Max Planck Institute for Plasma Physics, Garching, Germany

Abstract. This paper discusses the integration of the latest release of the FELICE code (2023) with the TOPICA code. A comparison is made between the current and previous versions of FELICE, starting from the plasma impedance matrix itself and, eventually, getting to the standard TOPICA outputs as the antenna input parameters, the coupled power and the radiated fields. The ADEX Upgrade (AUG) 3-strap antenna is adopted for this comparison, showing very similar results for the two versions of FELICE.

1 Introduction

The TOrino Polytechnic Ion Cyclotron Antenna (TOPICA) code is an advanced numerical tool for the simulation of ion-cyclotron (IC) radio frequency antennas. This code is based upon an integral equation formulation with the method of moments (MoM) solution [1]. TOPICA solves Maxwell's equations taking into account the entire antenna geometry and an approximate 1D plasma computed by the Finite ELements Ion Cyclotron Evaluation (FELICE) code [2].

The FELICE code was initially developed in the 90s and it was coupled to TOPICA in 2002; that FELICE release has been used along with TOPICA for the past twenty years. It implements single-precision functions and it lacks modern features and advanced functionality such as modules, derived data types, and traditional structures and loops such as "CASE" and "DO WHILE." It is also quite challenging to add new features and to address issues that arise along with new TOPICA upgrades.

1.1 FELICE-TOPICA

The FELICE code solves the FLR (Finite Larmor Radius) full-wave equation in a plane stratified geometry with a spectral decomposition along the equivalent poloidal (y) and toroidal (z) directions and a cubic Hermit finite element method along the radial direction (x) [2]. The FELICE output used by TOPICA is the plasma 2x2 impedance matrix (see equation *1*) whose elements are functions of the components of the wavevector $k = n\,k_0$, parallel and perpendicular to the confining magnetic field [3].

$$\begin{pmatrix} E_y \\ E_z \end{pmatrix} = \widetilde{Z_p} \begin{pmatrix} H_y \\ H_z \end{pmatrix}. \qquad (1)$$

This impedance matrix represents the plasma contribution in TOPICA and is used to express the plasma Green's function [1]. The coupling mechanism of FELICE-TOPICA can be represent using a equivalent transmission-line model illustrated in Fig. 1, which represents the transformation of the plasma admittance $\widetilde{Y_{pl}}$ into magnetic current at the vacuum-plasma interface $z = z_p$.

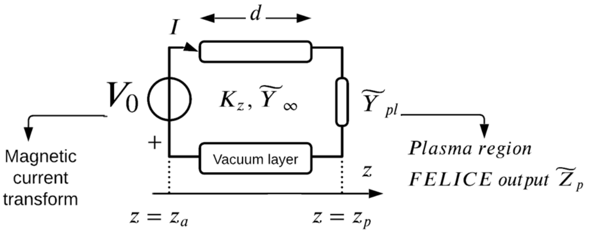

Fig. 1. Equivalent circuit representation. In this model, the magnetic current $\widetilde{M_a}$ passes over into a lumped voltage source, the vacuum region is modeled as a transmission line of length d, and the plasma response is encapsulated in the admittance $\widetilde{Y_{pl}}$, which corresponds to the inverse of the plasma 2×2 impedance matrix computed by the FELICE code.

Then, the entire problem antenna-plasma is represented by replacing physical sources and materials with equivalent surface magnetic and electric currents [4], maintaining the relevant fields while reducing both analytical and computational complexity. Subsequently, using a hybrid spatial–spectral MoM, a reaction integral of the plasma is evaluated directly in the spectral domain to solve fields in the entire geometry (antenna-plasma) [1]. Finally, the antenna circuit parameters (impedance/scattering matrices), the radiated power, and the electric fields (at locations other than the chamber aperture) are obtained. For a comprehensive understanding of the implementation of the plasma

* Corresponding author: david.galindo@polito.it

impedance matrix in TOPICA, readers are referred to [1]–[3].

1.2 Updated version vs. old version

The 2023 release of FELICE code offers several enhancements with respect to the 2002 one. A notable feature is the upgrade to the numerical linear algebra library LINPACK functions [5] used for solving cubic finite elements, now employing double-precision arithmetic to enhance numerical accuracy and stability.

A second key improvement is its ability to use a fully numerical plasma profile. In contrast, the previous version relied on a numerical profile only up to the separatrix, beyond which it transitioned to a parametric model. The updated version of FELICE now requires the complete electron density profile n_e and the temperature profiles for both electrons and ions, all as functions of radius. If measured profiles are not available, parameter-based profiles can still be used as an alternative. Moreover, the algorithm retains three waves: fast, shear Alfven, and ion Bernstein.

Additionally, the latest version of FELICE includes modern programming features that greatly enhance code readability, maintainability, and computational efficiency. By incorporating advanced programming practices, this update offers improved clarity and performance. Moreover, its modular design increases flexibility and ensures compatibility with both the default configuration of FELICE and the FELICE-TOPICA mode. This makes it easier to perform checks and benchmarks between the two modes.

1.3 FELICE modifications

To enable the integration of the two codes, several modifications were implemented in the 2023 release of FELICE, which was not originally designed to be coupled to TOPICA. These adjustments were crucial to ensuring compatibility in the generation of the plasma impedance matrix. In the following lines we describe the most relevant modifications coded to FELICE.

First, the workflow within the FELICE was adjusted to ensure that only the functions responsible for generating the impedance matrix are executed. In other words, the code was adapted to operate in "TOPICA mode". Further adjustments were necessary to allow for the reading of the complex spectral n_y, n_z grid (see equation 2) and plasma profiles, which include electron density and electron-ion temperature, as inputs. A MATLAB-based [6] preprocessing tool was also developed to generate the input data required by FELICE. It is also important to note that this modified version of FELICE can still produce the standard outputs associated with the original version.

Beyond the internal workflow adjustments, the FELICE code was also configured to implement outward radiation conditions. This configuration ensures that electromagnetic waves propagating outward from the plasma do not reflect back into the simulation domain. These outward radiation conditions are numerically equivalent to Perfectly Matched Layers (PML) and act as boundary constraints within the plasma, where the WKB approximation is applicable.

To mitigate numerical instabilities during integration in TOPICA, a complex spectral mesh was also introduced to address the polar singularity that arises in the numerical integration of Green's functions at a specific location, namely where the wavenumber is equal to the vacuum wavenumber $k = k_0$. The integration path was therefore deformed into the complex spectral plane as explained in [7]. This adjustment ensures numerical stability and convergence by regularizing the singular behavior, allowing for accurate computation of Green's functions while preserving the physical validity of the solutions.

$$n_y = \frac{k\, co\, s(\emptyset)}{k_0}, \qquad n_z = \frac{k\, sin(\emptyset)}{k_0}. \tag{2}$$

Finally, the updated version of FELICE has been modified to output the plasma impedance matrix in complex form for both n_y and n_z at any radial point within the integration region of the profile. By using the electric and magnetic field outputs computed by TOPICA at the final point of the integration profile, it is also possible to calculate the equivalent fields at selected locations within the plasma profile. This is accomplished by using the impedance matrix saved by FELICE at those specific points. As a result, one of the new features of TOPICA is the ability to visualize the fields at any point within the plasma profile.

2 Simulation methods and setup

In TOPICA, the ASDEX IC launcher was modeled as a single-cavity antenna comprising three straps, a Faraday screen, and two ports (see Fig. 2). The workflow began with construction of the antenna geometry—typically imported from technical drawings—followed by geometric optimization and mesh generation. The model was exported as a three-dimensional triangular mesh. A total of 63,357 Rao–Wilton–Glisson (RWG) basis functions [8] were used to discretize the equivalent electric and magnetic surface currents over the mesh, which was then loaded into TOPICA. The frequency was set to 30 MHz for all simulations.

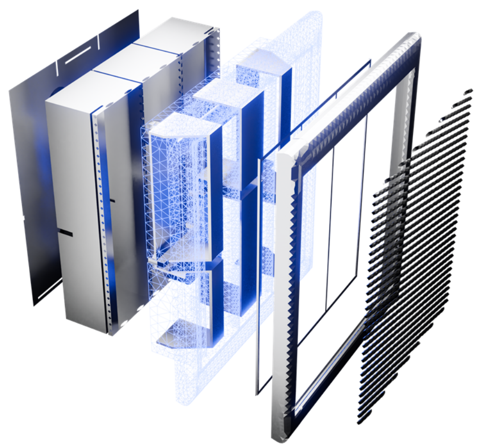

Fig. 2. Three-strap ASDEX flat antenna.

Regarding the plasma profile, an AUG discharge 31515 was used (see Fig. 3). The profile consisted predominantly of deuterium (D) with a minor hydrogen (H) fraction. The central magnetic field was 2 T, and the field lines at the antenna–plasma interface were tilted 169° relative to the toroidal direction. Outward-radiation boundary conditions were applied 30 cm from the plasma edge, beyond the separatrix; therefore, no power is expected to be reflected past this radial point. This discharge was simulated with the 2002 and 2023 versions of FELICE.

To evaluate the impact of the FELICE updates on field distributions, we defined a surface that coincides with the front face of the antenna (0 cm offset). By analyzing the electric field |Efield| in |V/m| across this surface, we can visually assess the field distribution differences and compare the maximum and minimum values of the electric field.

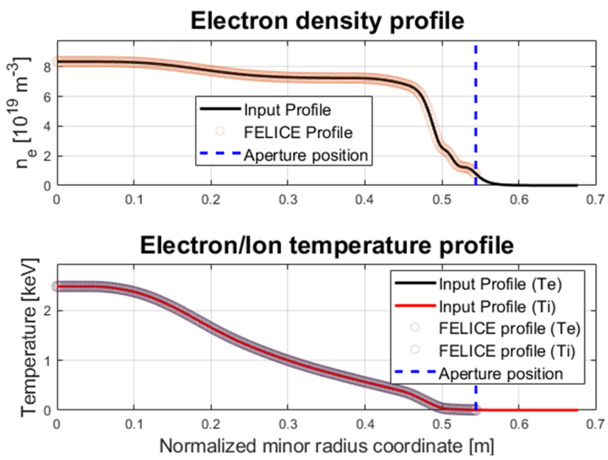

Fig. 3. Electron density & temperature profile (31515) vs. radius.

3 Results

The results include a comparison of the plasma impedance matrix obtained with the two code versions and an evaluation of the effect of the differences on TOPICA outputs—antenna input characteristics, power transfer to the plasma, and the distributions of the electric fields in front of the IC launcher.

To begin, we compared the plasma impedance matrix calculated at the endpoint of the plasma profile—the last point in the integration region—using both versions of the FELICE code. This four-component matrix characterizes the plasma in terms of wave propagation contributions, including fast waves, two mixed terms, and slow waves. The components of the plasma impedance matrix are presented for the ranges of -30 to 30 for both k_z/k_0 and k_y/k_0 in Fig. 4 to Fig. 6. The 2002 and 2023 versions of FELICE produced very similar results, with only slight differences in magnitude. Fig. 7 to Fig. 9 illustrate the relative difference calculated as $(Z_p^{old} - Z_p^{new})/Z_p^{old}$ between the previous and current versions of the code, highlighting that the differences are minimal. These discrepancies stem from the implementation of double-precision functions for the LU-decomposition routines, which enhance matrix accuracy compared to the single-precision functions used in the earlier release of FELICE.

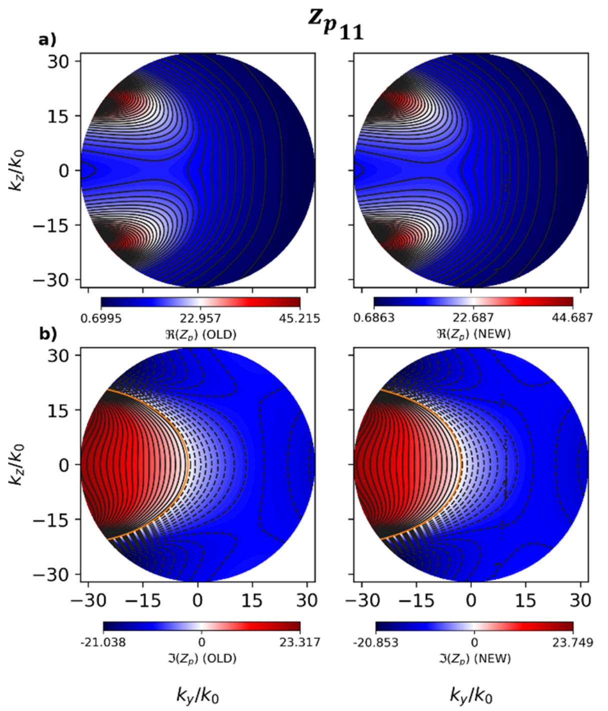

Fig. 4. Fast wave component of the plasma impedance matrix at 30 MHz: (a) Real part computed with the old and new versions of FELICE. (b) Imaginary part computed with the old and new versions of FELICE.

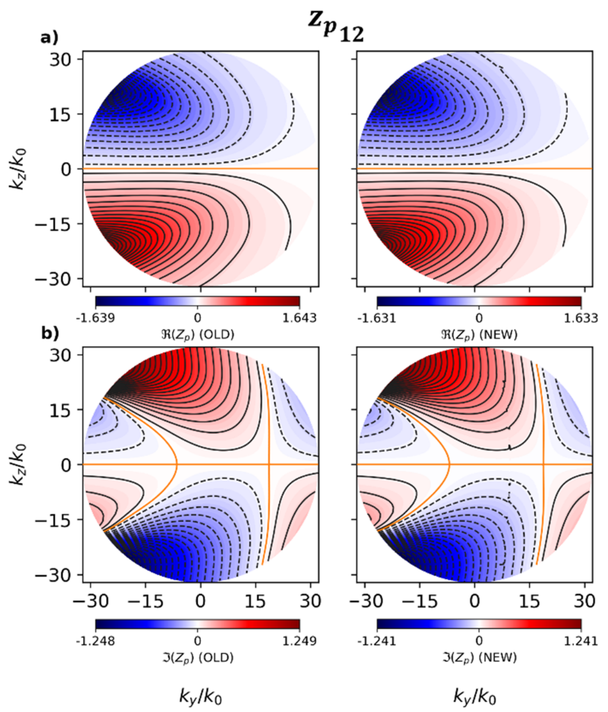

Fig. 5. Mixed component (fast wave, slow wave) of the plasma impedance matrix at 30 MHz: (a) Real part computed with the old and new versions of FELICE. (b) Imaginary part computed with the old and new versions of FELICE.

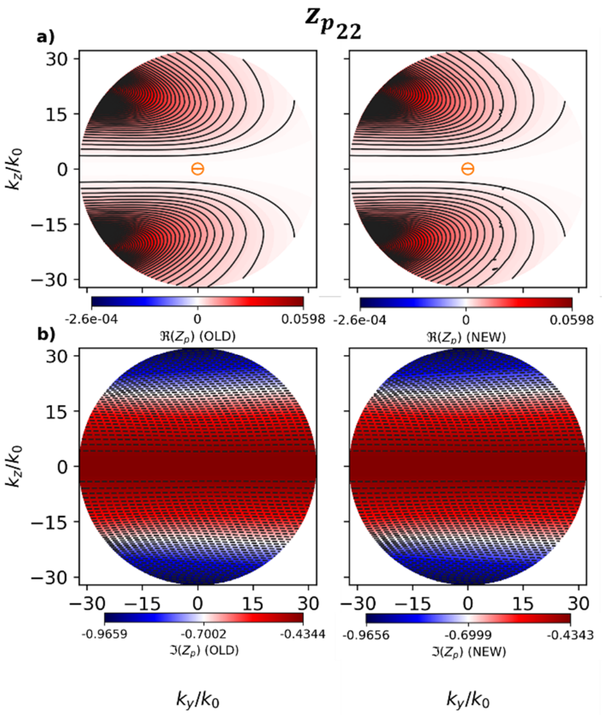

Fig. 6. Slow wave component of the plasma impedance matrix at 30 MHz: (a) Real part computed with the old and new versions of FELICE. (b) Imaginary part computed with the old and new versions of FELICE.

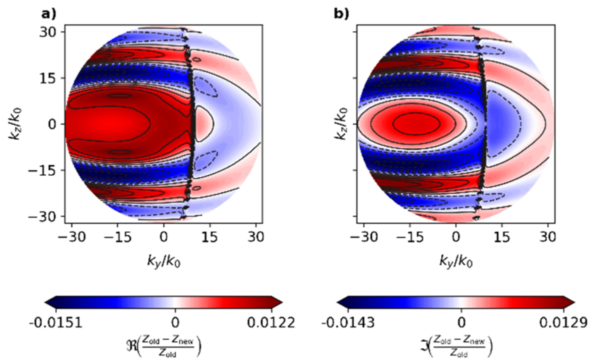

Fig. 7. Difference in the fast wave component of the plasma impedance matrix at 30 MHz (old version - new version).

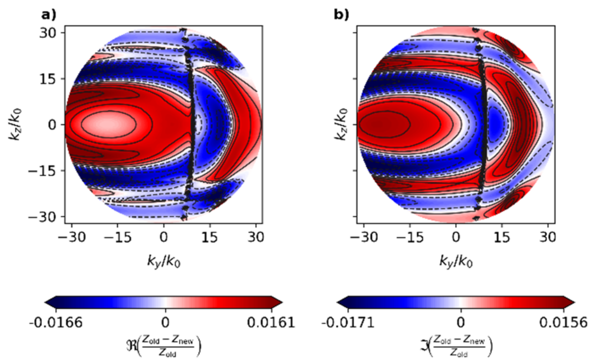

Fig. 8. Difference in the mixed component (fast wave, slow wave) of the plasma impedance matrix at 30 MHz (old version - new version).

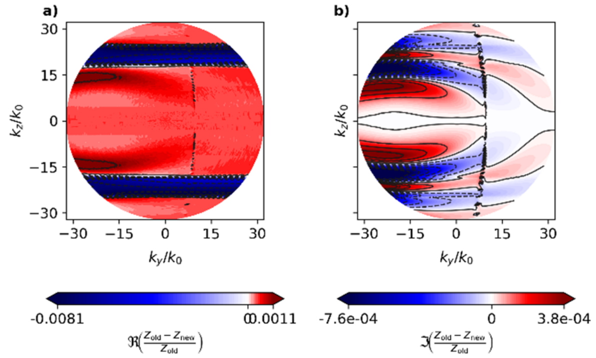

Fig. 9. Difference in the slow wave component of the plasma impedance matrix at 30 MHz (old version - new version).

Regarding input impedance, Fig. 10 shows a small difference for self-terms, while a larger variation is observed for non-diagonal terms (which are intrinsically smaller). In terms of radiated fields at 30MHz, the distribution of the electric field using the two versions of FELICE is identical, and the difference in maximum and minimum values is minimal (see Fig. 11 a/b).

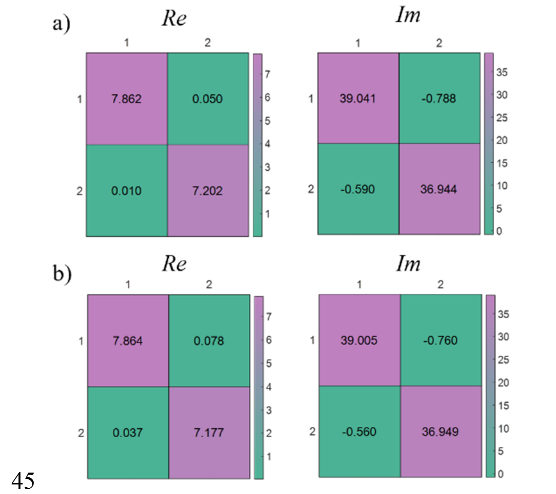

Fig. 10. Antenna input impedance: a) Old FELICE b) New FELICE.

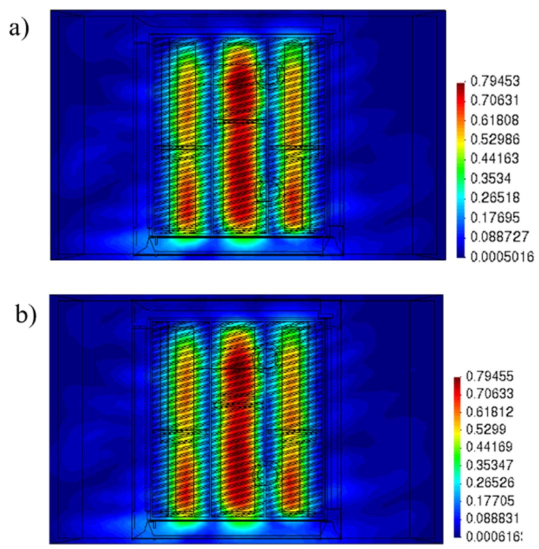

Fig. 11. Electric field (V/m) at 30 MHz at the vacuum-plasma interface: a) old FELICE, b) new FELICE.

Eventually, the assessment of coupled power (see Table 1) reveals only a minor discrepancy between the two versions of FELICE, assuming a maximum of 30 kV applied along infinite transmission lines at 30 MHz.

Table 1. Coupled power at 30 MHz for the 31515 profile, comparing the two versions of the FELICE code.

Frequency	Total power [MW]	
30 MHz	3.12048	Old FELICE
	3.10961	New FELICE

Finally, one of the latest updates to TOPICA introduces a significant enhancement: the capability to plot electric fields at various radial position within the plasma. Fig. 12 illustrates the total electric field magnitude computed within the plasma at radial positions of 0, 0.05, 0.1 and 0.15 m from the antenna aperture, given an input $0\pi0$ phasing.

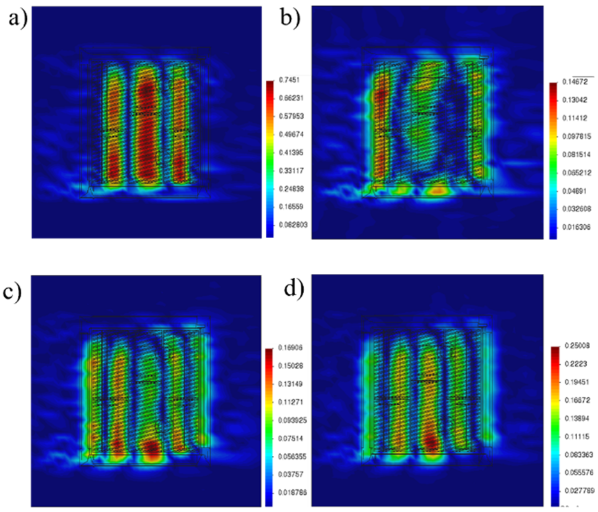

Fig. 12. Electric field (V/m): (a) at 0 m from the aperture, (b) at 0.5 m, (c) at 0.1 m, and (d) at 0.15 m from the aperture.

4 Conclusions

A more recent FELICE release is now fully integrated in TOPICA, reducing the complexity of the code in terms of writing and organization. This improvement will lead to more efficient development in the future due to the updated code version, which encourages better collaboration among the various authors involved who are working with the last version of the code. For instance, the code is undergoing thorough testing to enhance our understanding of the effects of lower hybrid resonance in TOPICA. The findings from this research will be published in the first author's thesis. With respect to simulation results, i.e. testing with different frequencies and plasma profiles (see also for a further test with a preliminary version of the DTT IC launcher) [9], the results obtained with the new version of FELICE are very similar to those obtained with the old version, hence providing a sound code benchmark.

The updated version of the code is currently being used to evaluate future real antenna plasma scenarios, specifically for DTT, and new features for TOPICA are under development.

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