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Advancing Fusion Research: Synthetic VOPOO Diagnostics and Plasma Scenario Modelling for the SPEKTRE Platform

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Abstract. SPEKTRE is a new research platform dedicated to plasma physics and nuclear fusion, designed to investigate magnetised plasmas. The platform will be relevant to edge physics in fusion devices and will offer extensive diagnostic coverage, enabling comprehensive measurements. One of the diagnostics being designed is the Variable Oblique Probing on O-mode (VOPOO) to study normal to tangential wave propagation at the edge of a plasma and to contribute to the development of novel analysis tools for experimental data, with applications to intensity refractometry and innovative tomographic approaches for next-generation fusion machines such as DEMO. This study introduces a method for constructing plasma descriptions for a VOPOO synthetic diagnostic. It accommodates a broad range of plasma scenarios, including instabilities and various turbulence regimes, which are evaluated across multiple antenna configurations and injection angles. The implemented synthetic diagnostic is crucial for interpreting the results of the experiment, especially for treating intensity refractometry data, and for driving the development of advanced processing techniques, including Machine Learning (ML)-based methods. This is a first step towards the final goal of having a numerical twin of VOPOO.

1. Introduction to the project

SPEKTRE (Sheaths, Plasma Edge & Kinetic Turbulence Radiofrequency Experiment) is a new research platform dedicated to plasma physics and nuclear fusion. It is designed to investigate magnetised plasmas, both cold and hot, with a unique experimental setup capable of confining a large plasma column (6 m long, 40 cm in diameter) within a static magnetic field of up to 0.5 T. The platform will achieve ion temperatures relevant to edge physics in fusion devices, using a heating system in the range of ion

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cyclotron frequency and offering extensive diagnostic access through 42 ports, enabling comprehensive measurements [1, 2].

A key diagnostic tool is the Variable Oblique Probing on O-mode (VOPOO). Following the completion of its pre-design study, hardware procurement is underway. VOPOO will advance the understanding of oblique and tangential wave propagation at the edge of a plasma and contribute to the development of novel analysis tools for experimental data. Its impact will span intensity refractometry, such as the MILS diagnostic [3], and innovative tomographic approaches for next-generation fusion machines such as DEMO, helping in plasma shape and position tracking during the discharge ramp-up and ramp-down phases. The principles of this novel idea have been established in the EUROfusion Enabling Research (EnR) project, ENR-TEC.01.IST [4].

Preliminary simulations using ray tracing and the Finite-Difference Time Domain (FDTD) code REFMULF have demonstrated their potential. The present work extends the characterisation of VOPOO to a broader range of plasma scenarios, including instabilities and various turbulence regimes. By exploring different antenna configurations (variable angle of injection), VOPOO aims to validate the concept of tomography for DEMO. Synthetic diagnostics are crucial for interpreting the results of the experiment, especially for treating intensity refractometry data, and for driving the development of advanced processing techniques, including Machine Learning (ML)-based methods.

2. Methodology for electron density perturbation construction

SPEKTRE plasma column transverse cut has a circular shape and can be *naturally* described by polar coordinates, as depicted in Figure 1-(a). The 2D synthetic diagnostic of VOPOO is implemented using REFMULF, a FDTD full-wave code, where the simulation grids, including the plasma description, resort to a Cartesian description $n_e(i, j)$. There is a need to convert the polar description to a Cartesian one in a manner that is both simple and numerically efficient. The method also needs to be flexible enough to allow for modelling enlarged plasma scenarios and to permit temporal evolution, such as the rotation of the plasma. This necessity of passing from a polar description or polar grid to a Cartesian grid has been addressed in previous works, for instance, in 2D full-wave simulations of reflectometry using the Global Electromagnetic Gyrofluid Relativistic (GEMR) [5] plasma turbulence, where the output of the gyrofluid code GEMR was employed as input for the FDTD full-wave code REFMUL [6], a 2D O-mode code from the REFMUL* family. The method used for the GEMR-REFMUL coupling was a Delaunay interpolation [7]. VOPOO simulations require a more flexible solution than the ones used before, with the plasma being rotated during the simulation, and consequently, these modifications have to be done within the REFMUL* codes, written in C language, during runtime.

The solution developed here involves the use of two Cartesian grids: an $\alpha \times R$ *unwrapped* parameter-space domain, as shown in Figure 1-(b), where the polar plasma

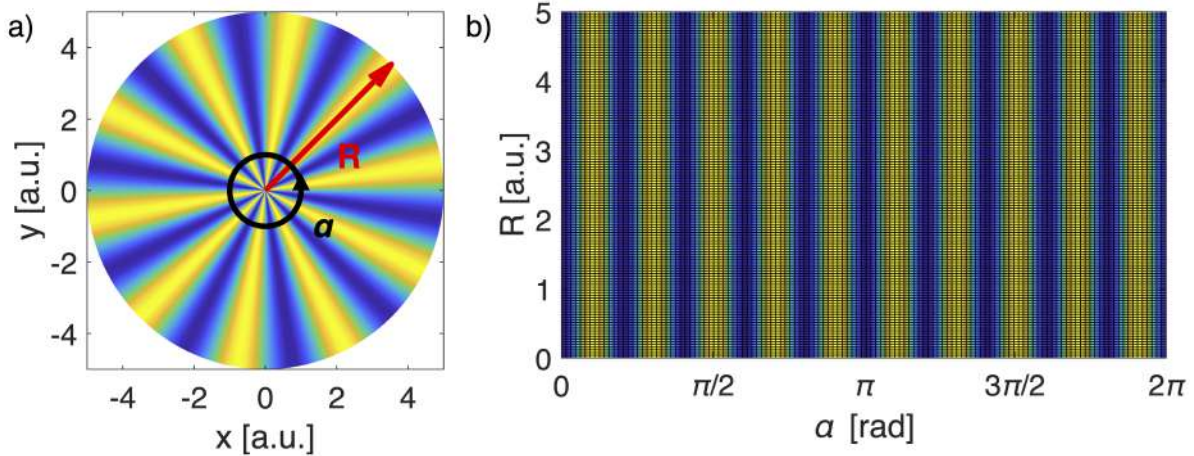


Figure 1. A model for a plasma *naturally* described on a polar domain (a), $n_e(\alpha, R)$ is developed in a Cartesian *unwrapped* parameter-space domain $\alpha \times R$ (b).

description is handled, and all modifications are made before being mapped onto the Cartesian plasma grid used by REFMUL* codes.

For every point of the plasma grid (i, j) that indexes a spatial point $(x_i, y_j) = (i\delta x, j\delta y)$ on the final FDTD code Cartesian grid (see Figure 2-(a), where δx and δy are the spatial discretisation intervals, we must attribute a value of the density perturbation δn_e from the values modelled in the parameter-space domain (α_k, R_k) . In Figure 2-(b), we show examples of the location of plasma Cartesian grid positions (red asterisks) in the parameter space. The *central* example shows a typical point, the most general case inside the parameter space. The others show the cases of the corners and of points lying at the limits of the parameter space. The grid points in the plasma Cartesian grid do not have to correspond to the grid points in the parameter space; a correspondence will be coincidental. Figure 2-(c) details how a cell (light blue) and a grid point of the plasma-parameter space (blue dot) are attributed to each of the points coming from the plasma Cartesian grid (red asterisks). These attributions provide a map linking the plasma Cartesian grid points to the parameter space cell positions (indexed by the corner grid points). It is these locations within the parameter-space domain that will be used to obtain an adequate value δn_e for the plasma grid. This can be accomplished by giving the value of one of the corners of the parameter cell, Figure 2-(d₁), or by performing a bilinear interpolation using all the corners of the cell, as schematized in Figure 2-(d₂). In the first approach, while faster, it results in *digitised* plasma-grid values, while the second provides very smooth values. This process of evaluating the value at an arbitrary position of a grid cell in the parameter space from the grid points (corners) is called *gathering* and is a common operation in Particle-in-Cell (PIC) codes used to deposit particle-based information onto the PIC mesh [8]. To do this, we need to know the positions of the plasma Cartesian grid points in the parameter space. Then, using the points of the parameter space grid (cell corners), we *gather* the value on the Cartesian grid using an interpolation technique, such as bilinear interpolation. First,

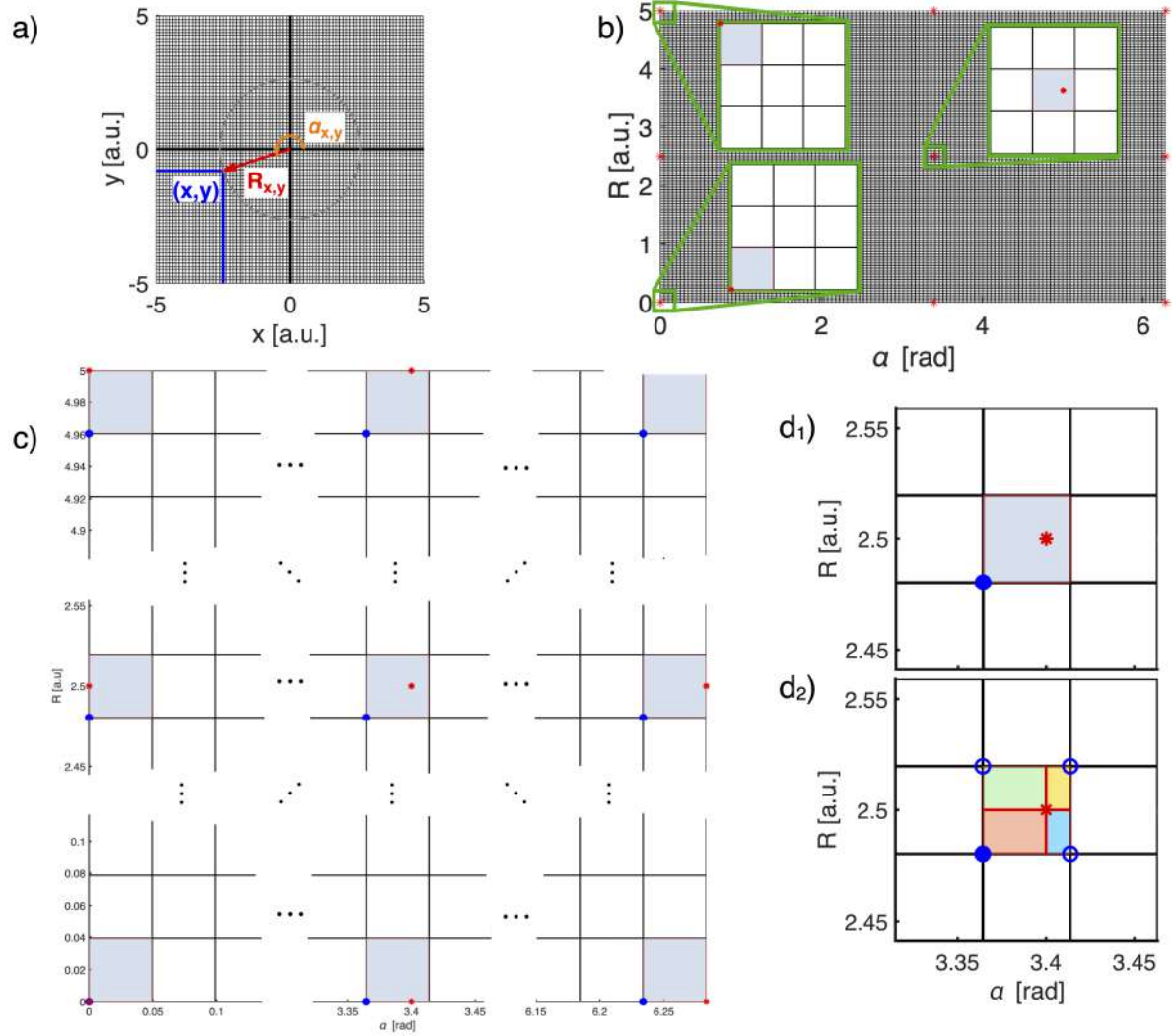


Figure 2. Mapping the *unwrapped* $\alpha \times R$ space domain into the simulation Cartesian grid domain $i \times j$. (a) Projection of (R, α) in (x, y) ; (b) Location of different cases to consider, detailed in (c), where the cell attributions and corresponding grid points are shown. Two weighting methods can be used: attribution of the value of the lower cell corner (d_1) or with an interpolation using the four corners of the cell (d_2).

for each Cartesian grid point, the *logical coordinates* — the floating-point counterpart of (α_k, R_k) — are used to perform the interpolation. Unlike the gathering in a PIC code, which must be done at every iteration step, for the present purpose, this operation is done only once at initialisation, before the main cycle, to obtain the mapping between the two grids and the interpolation coefficients.

The plasma modelling is done in the parameter space, including the base plasma $n_e(x, y, t)$ and the density perturbation $\delta n_e(x, y, t)$. In Figure 3 we show a poloidal $m = 10$ mode, delimited by a Gaussian frame $G(x, y)$, represented in the parameter-space domain (a); this same perturbation appears in the plasma Cartesian domain (b). The correspondence between one period of the mode, which covers an angle of $\pi/5$ rad, is shown in both domains.

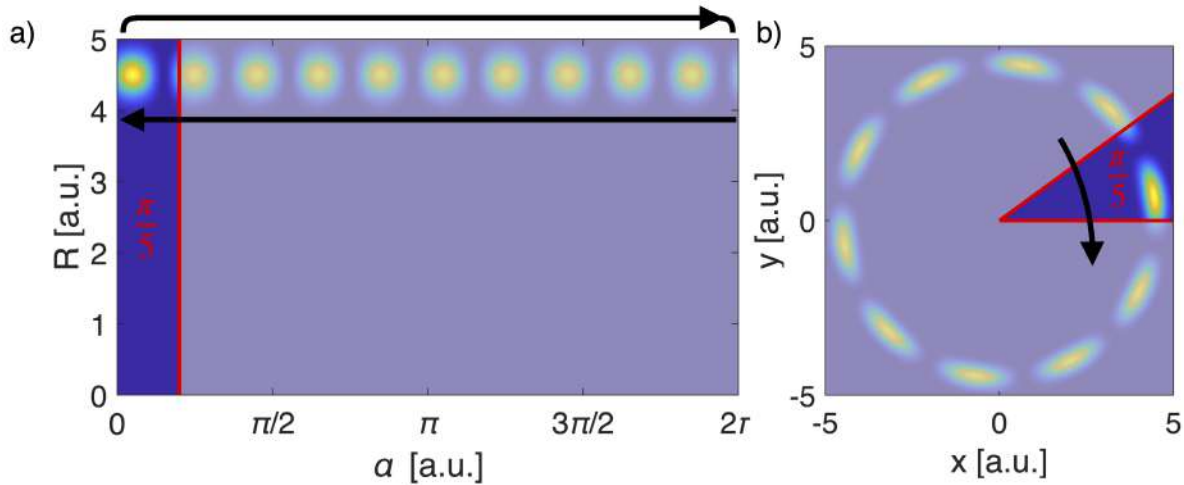


Figure 3. Generation of the plasma in the $\alpha \times R$ domain (a) and its projection in the (x,y) space (b), applied to a rotation of an $m = 10$ structure. Sliding the columns along α in the parameter space brings forth a rotation in the plasma Cartesian domain.

During the simulation, the temporal evolution of the plasma is computed in the parameter space and remapped into the physical plasma space, using the locations and weights stored at initialisation of the run. We are particularly interested in rotating the full structure, which can be achieved by sliding the columns in the parameter space along α , with those that slide off the domain being reintegrated at the other extremity as schematised in Figure 3. Choosing the direction of the slide determines the direction of rotation. A slide to the left of the parameter-space domain gives rise to a clockwise rotation in the plasma Cartesian domain, while a slide to the right brings about a counterclockwise rotation.

3. Worked example: density perturbations in simulation

In Figure 4-(a), we observe a radial cut of the complete density matrix (plasma Cartesian grid) used in our full-wave simulation. The total electron density is, in the present case, $n_e(x, y, t) = n_{e_0}(x, y) + G(x, y)\delta n_{e_0}(x, y, t)$, where $n_{e_0}(x, y)$ is the background plasma to which the perturbation is added, and $G(x, y)$ is a Gaussian envelope selecting the location of the $m = 10$ mode perturbation $\delta n_e(x, y, t)$. The base plasma has a flattop with a step gradient at the edge, the region where the mode is superimposed. The grey lines show the evolution of the full density over a period of the $m = 10$ mode, along the radial cut. A surface visualisation of the complete density is offered (b). We can also observe that, for the particular case depicted, the value of the density was set to have its maximum to coincide with the O-mode density cutoff for a 12 GHz probing wave. A snapshot of a full-wave simulation using the finite-difference time-domain code REFMULF appears in (c), showing the amplitude of the positive values of the electric field E_z . The transmission antenna (Tx) is at the bottom of the simulation box, and the receiving antenna (Rx) is at the top. The antennas used are 2D H-plane synthetic

versions of the Narda WR75 20 dB horn, which were used in the first simulations of VOPOO [10]. Signals are picked up at the middle of the Tx and Rx waveguides. At the Tx waveguide, the received signal is separated from the main emission through a numerical decoupling performed with a Unidirectional Transmission Source [9]. In Figure 4-(d), we can observe the modulation in phase (φ) and amplitude of the detected signal at the Tx antenna, corresponding to the backscattered signal during a turn of one period, $1/10$, of the full $m = 10$ mode *extension*. The sampled signals can be analysed directly. Nevertheless, to mimic the experiments, a detection procedure, such as homodyne or heterodyne detection, is implemented, and the resulting signals can be subjected to the signal-processing techniques usually used in the diagnostic in question or serve as an instrument for the development of new ones.

4. Flexibility of the proposed methodology

Previously, in the presentation of the method, the density perturbation used was a poloidal $m = 10$ mode framed by a Gaussian envelope and added to a *base* profile. The density perturbation chosen for this *proof of principle* is relevant for some of the studies previewed with VOPOO, but it is nevertheless just one of the many models and plasma scenarios allowed by the procedure. In Figure 5, we illustrate some of the possibilities allowed. While this illustration clearly shows the plasticity of the procedure, it does not exhaust the possibilities that can be explored. Some of the options include the possibility of using the approach of a *spiral perturbation* or simulating a density propagation front, in a similar manner to what was done in [11] for measuring plasma filaments with radial and poloidal velocity components. Column two presents the tools to describe a hollow density profile. It can also be used as a frame to spatially circumscribe a perturbation, as done in the $m = 10$ example. The last two columns illustrate the use of turbulence with high and low wavenumbers \mathbf{k} . The setting of the turbulence follows the one proposed in [12] and used, for instance, in [13]. Here, it is developed in the parameter space as a sum of modes in the (α, R) parameter space, with $\delta n_{e_{TRB}}$ being defined by

$$\delta n_{e_{TRB}} = \sum_{i=i_m}^{i_M} \sum_{j=j_m}^{j_M} A(i, j) \cos[k_\alpha(i)\alpha + k_R(j)R + \varphi(i, j)], \quad (1)$$

before being mapped into the plasma Cartesian domain, where $A(i, j)$ is a chosen amplitude spectrum and $\varphi(i, j)$ is a randomly generated phase, combining all possible wavenumbers. Many of the plasma modelling scenarios developed over the years for slab plasmas directly on an (x, y) Cartesian grid can be treated in the (α, R) parameter space and remapped onto the plasma Cartesian grid. For instance, taking the plasma rotation procedure described above, if the sliding columns are moved non-uniformly with a *velocity* profile along R , meaning that some of the lines are slid non-uniformly, this allows the implementation of a shear layer to study its Doppler signature [14].

These examples highlight the flexibility of the proposed methodology, which can accommodate diverse plasma scenarios and perturbation models, thereby extending its

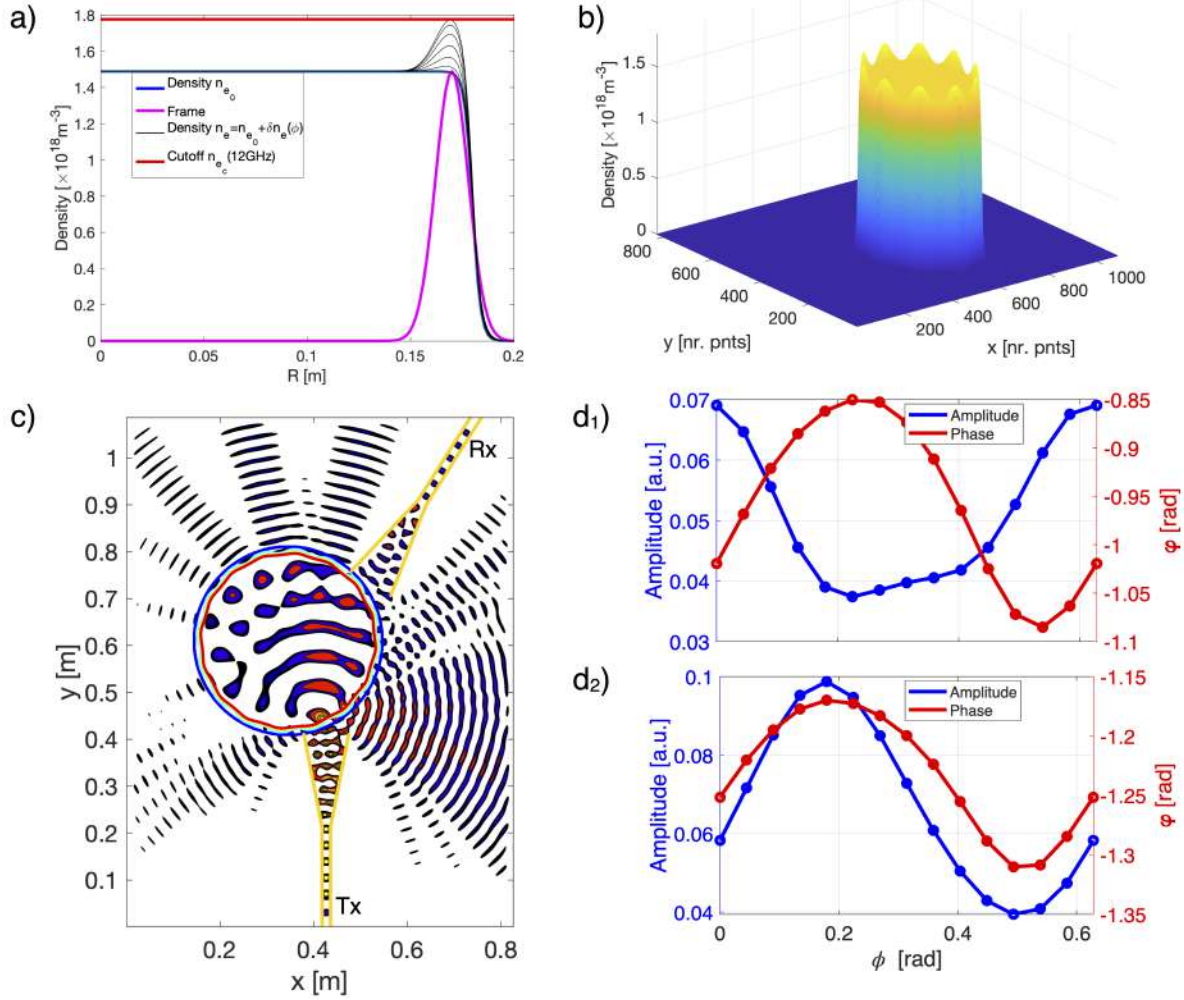


Figure 4. The complete plasma and the full-wave simulation. (a) shows a radial cut of *full* plasma comprising a *base* plasma n_{e0} with the density perturbation $G \cdot \delta n_e$ (see Figure 3) added. A 3D view of the density n_e is depicted in (b). (c) presents a snapshot of the full wave simulation, including the plasma, the contours of the positive electric field E_z , and the emitter (Tx) and receiver (Rx) antennas. From the results of the simulation run of one period rotation of the $m = 10$ mode, the phase and amplitude of the signals backscattered into the Tx antenna (d₁) and picked-up at the receiver Rx (d₂), can be calculated.

applicability to future diagnostic developments.

5. Summary and future perspectives

In this work, we implemented a flexible method for constructing a dynamic plasma with a circular shape on a Cartesian grid to be used in microwave synthetic diagnostics. The immediate target is to simulate the VOPOO experiment at SPEKTRE; however, it can also be used in a machine with a similar geometry. The code used is a full-wave FDTD one, REFMULF, but the plasma description can easily be adapted to another computational electromagnetic code, such as ray-tracing. The construction and handling

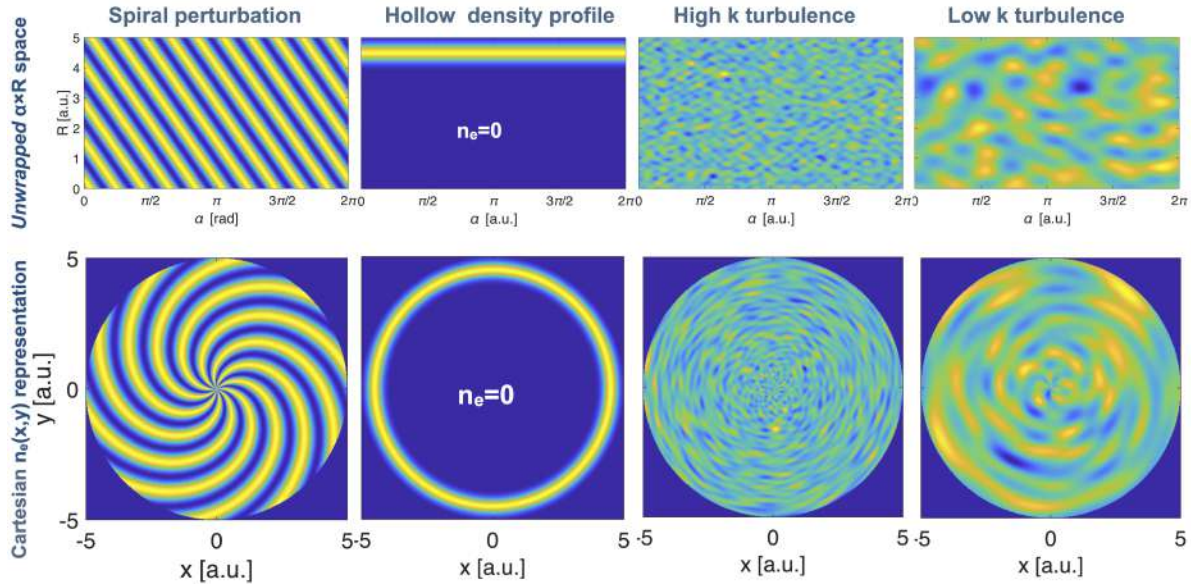


Figure 5. Examples of the density perturbations that can be explored using the method presented.

of the plasma in the parameter space can utilise many of the techniques that have been developed in slab plasma simulations. We resorted to a model of a poloidal $m = 10$ mode to exemplify how the code density matrix is constructed and to illustrate the full simulation pipeline up to the signal processing of the results. For this demonstration purpose, any of the possibilities explained above could be used. The choice made was based on the simulation of these modes as outlined in the future simulation plans.

Also, the shape of the base plasma n_{e0} covers one of three major scenarios previewed in SPEKTRE, the others being a parabolic profile, already used in the preliminary VOPOO simulations [10], and a hollow profile, whose construction was suggested above.

The present work forms part of a broader effort to build a digital twin of the VOPOO diagnostic, initially in 2D using the REFMULF code as the foundational tool, and later extending it to a full 3D implementation supported by REFMUL3. This final 3D step will be crucial for obtaining accurate phase-amplitude values from the twin. Such information is essential for interpreting intensity refractometry measurements since the reconstruction of the radial density profile relies on the measured phase shift and the power alteration of the probing wave. Intensity refractometry underpins an emerging diagnostic technique used at ASDEX Upgrade [3] and tentatively proposed for DEMO [4], a method that VOPOO will explore and help to consolidate.

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