Journal of
Instrumentation

Overview of the studies towards a Plasma Position Reflectometry system for Divertor Test Tokamak (DTT)

To cite this article: F. da Silva *et al* 2025 *JINST* **20** C09004

Jinst
Published by IOP Publishing for Sissa Medialab
Received: *February 28, 2025*
Accepted: *July 16, 2025*
Published: *September 5, 2025*

7th International Conference Frontiers in Diagnostic Technologies
INFN research center of Frascati, Italy
21–23 October 2024

Overview of the studies towards a Plasma Position Reflectometry system for Divertor Test Tokamak (DTT)

F. da Silva,[a,*] **J. Santos**,[a] **A. Silva**,[a] **J. Ferreira**,[a] **S. Heuraux**,[b] **T. Ribeiro**,[c] **G. De Masi**,[d] **R. Cavazzana**,[d] **G. Marchiori**[d] **and O. Tudisco**[e]

[a]*Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal*
[b]*Institut Jean Lamour UMR 7198 CNRS-Université de Lorraine, BP 50840, F-5401 Nancy, France*
[c]*Max-Planck-Institut für Plasmaphysik, Garching D-85748, Germany*
[d]*Consorzio RFX, C.so. Stati Uniti, 4, 35127 Padova, Italy*
[e]*Associazione EURATOM-ENEA-CR Frascati, 00044 Frascati, Italy*

E-mail: tanatos@ipfn.tecnico.ulisboa.pt

Abstract: Plasma Position Reflectometry (PPR) is taking an important role in next-generation fusion machines, such as DEMO, as a diagnostic to monitor the position and shape of the plasma, complementing magnetic diagnostics. The Divertor Test Tokamak (DTT) facility is the perfect machine to implement, develop, and test PPR systems. Important work is being done to evaluate the performance of a tentative PPR system in DTT, including assessment efforts integrated into the EUROfusion Enabling Research Project (ENR-TEC.01.IST). These efforts involve designing two- and three-dimensional synthetic diagnostics for the Low (LFS) and High Field Sides (HFS), using Finite-Difference Time-Domain codes. This simulation assessment works in parallel with the design of antennas for the LFS and HFS. Their integration in synthetic diagnostics is done through a CAD conversion pipeline. An overview of the progress achieved, together with future work planned, is provided in the present work devoted to the accuracy of the separatrix localisation at different positions around the vessel.

Keywords: Nuclear instruments and methods for hot plasma diagnostics; Simulation methods and programs

*Corresponding author.

https://doi.org/10.1088/1748-0221/20/09/C09004

2025 JINST 20 C09004

Contents

1 Introduction

Plasma Position Reflectometry (PPR) is taking an important role in next-generation fusion machines, such as DEMO, as a diagnostic to monitor the position and shape of the plasma, complementing magnetic diagnostics. The possibility of positioning the plasma for control in real time was validated on ASDEX Upgrade using one reflectometer [1] and on COMPASS [2]. This proof of principle is a basis for support for the assessment studies concerning the possibility of having PPRs in future fusion machines [3, 4]. The Divertor Test Tokamak (DTT) facility presents itself as the perfect machine to implement, develop, and test PPR systems, contributing to the gain of a knowledge database in position reflectometry needed for DEMO. The benefits of having a PPR installed at DTT go beyond this long-term application to DEMO. As in all fusion machines, diagnostics insensitive to neutron flux, such as those based on reflectometry, will be necessary to gather knowledge of the physical processes that occur in the plasma for engineering needs and control. This makes reflectometry an important asset for DTT. These reasons have driven important assessment work to evaluate the performance of a tentative PPR system in DTT, both for Low Field Side (LFS) [5] and High Field Side (HFS) [6] and this paper presents a short review of the efforts that lead to a relevant initial proposal for a PPR for DTT, handling mechanical, thermal and electromagnetic constraints. These assessments involved the setup of synthetic diagnostics using Finite-Difference Time-Domain (FDTD) full-wave codes, REFMULF, for 2D simulations and REFMUL3, for 3D simulations, capable of simulating the propagation in the plasma but also describing the system location in the vacuum vessel and characterising its access to the plasma (waveguides and antennas). The assessment of the LFS PPR included the study of three lines-of-sight (LOS) and was initially conducted integrated in the EUROfusion PEX DTT Topic2 IST 02/T006 [7], being later incorporated in the EUROfusion Enabling Research (EnR) Project, *Advances in real-time reflectometry plasma tracking for next-generation machines: Application to DEMO-ENR-TEC.01.IST*, and further developed with an initial 3D assessment [8] with REFMUL3, resulting in a proof of principle of the viability of the PPR system for the HFS [6].

During the first year of the EnR project, the possibility of having a PPR at the HFS became tangible, and with it, the need to have a concept ready for the HFS, which prioritised HFS to the detriment of LFS endeavours, since the waveguide routing and the way to access the vacuum chamber in the HFS needed to be sorted out quickly to fulfil the assembly timeline of the machine. HFS planning involved the design of 2D and 3D synthetic diagnostics. Such simulation exercises worked in

2025 JINST 20 C09004

parallel with the design of antennas for LFS and HFS, whose integration into synthetic diagnostics was carried out through a CAD conversion pipeline [9]. In the present work, an overview of the progress achieved, together with the planned future work, is offered along with an analysis of the accuracy of the location of the separatrix at different positions around the vessel.

The work done towards an HFS solution during the EnR integrates many of the modules that had been worked on or developed in the EnR project: (1) Strong ameliorations in synthetic diagnostics and simulation codes; (2) Accurate description of the target machine layout and operating scenario; (3) Advances in hardware (compact reflectometer); (4) Use of enhanced signal processing techniques. These tools permitted establishing *an integrated design workflow for a PPR diagnostic system*, which (1) uses common CAD models of antennas and first wall components; (2) incorporates 3D target plasma scenarios obtained from equilibria simulations; (3) includes the design of custom-made antennas; (4) involved the fabrication of laser metal printed prototypes of the antennas; (5) and laboratory tests of these antennas using an EnR developed compact reflectometer. Thermal analysis of plasma-facing components (6) was included in the simulations of the antenna behaviour; and (7) 3D full wave FDTD simulations both in vacuum and with plasma allowed assessing their performance.

2 Plasma Position Reflectometer system for the Low Field Side

During the assessment of measurement performance for an LFS DTT PPR System [5], a complete evaluation was performed, using the 2D full wave FDTD code, REFMULF. It consisted of a set of 3 ordinary mode (O-mode) LFS Frequency Modulated Continuous Wave (FMCW) synthetic diagnostics, one on the equatorial plane (gap 0°), another on the upper torus midplane gap (gap 45°) and finally one on the lower torus midplane (gap −60°). Two operational scenarios were used, the Single Null (SN) scenario and the Double Null scenario (DN), provided by DTT and complemented outside the separatrix with a model extracted from [10] following the model given in [11]. For the antennas, a standard horn was used, similar to the ones used in the synthetic diagnostics for DEMO. The model for the wall was based on the *Limiter* curve (*RLIM, ZLIM*) provided with the G-EQDSK equilibria files, given in *(R,Z)* machine framework. Simulations with just the antennas and with the antennas recessed into the vessel wall were conducted, allowing us to ponder the influence of the wall on the radiation diagram and ultimately on the results. Having the antennas recessed in the wall gives rise to perturbations in the wave pattern and traversal modulation but the effects are small and do not rule out the use of the tested configuration. The effects of the plasma curvature and tilt for both equilibria scenarios do not introduce major deviations from the standard reference case, using a slab plasma model. Synthetic diagnostics were implemented for the K, Ka, Q, V and W (stopping at 95 GHz) bands, covering a total probing frequency of (18 GHz–95 GHz), which corresponds to an electronic density span of ($0.4 \times 10^{19}\,\mathrm{m}^{-3}$–$1.12 \times 10^{20}\mathrm{m}^{-3}$). In figure 1, on the left, we can observe the REFMULF 2D synthetic diagnostic operating in the K band at a frequency of $f = 26.5$ GHz. Simulations showed overall errors within one-centimetre tolerance throughout the bands, and in particular for the position of the separatrix, for both the SN and DN (the *sn* suffix indicates that the antennas were optimized for the SN scenario), as displayed in figure 3 (top-right). From the simulated microwave signals, a numerical In-phase/Quadrature (I/Q) detection is implemented, and the reflectometry signal is obtained. The usual signal processing procedures are then applied, and the phase derivative recovered. With these, the density profiles are calculated using an Abel reconstruction technique. The reconstructed profiles are shown in figure 3 (bottom-right). 3D simulations were repeated for the K and Ka bands, showing that the effects of the wall at the lower bands are higher than those predicted by 2D simulations [8]. In figure 1, on the right, we can observe the REFMUL3 3D synthetic diagnostic operating in the K band at a frequency of $f = 18\,\mathrm{GHz}$.

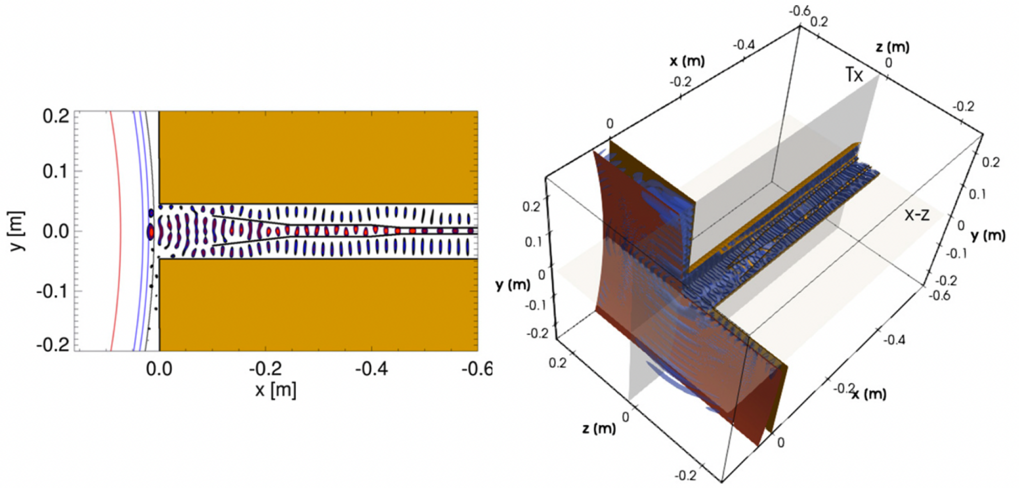

Figure 1. Snapshots of simulations of the probing wave in the case of the LFS reflectometer. On the left, a 2D K band simulation taken at a frequency of $f = 18\,\mathrm{GHz}$. On the right, a 3D K band simulation taken at the same frequency, with part of the 3D volume removed to reveal the inner structure of the electric field E_z. Reproduced with permission from [8]. © 2022 IOP Publishing Ltd and Sissa Medialab.

3 Antenna design for the High Field Side

The starting point for the HFS efforts was the need to find a viable engineering solution that took into consideration the difficulty of routing the waveguides at the HFS of the machine, including the design of antennas that could fit in the reduced space available, and also the restrictions involved in the removal of cooling pipes to give way to the waveguides and antenna. The contemplated design uses a single waveguide shared between all bands, fundamental in the K and oversized in the remaining ones (Ka-W). Two hoghorn antennas have been designed: one monostatic and the other bistatic, occupying the same volume. That said, the small footprint of these custom-designed antennas resulted in moderate gains when compared with the standard horn considered for LFS, especially for the bistatic design. The bistatic antenna was manufactured using 3D metal additive printing, and the prototype was tested in the laboratory. The results were compared with 3D simulations made with REFMUL3. This comparison [6] offers a good agreement between the laboratory tests and the 3D simulation results. The use of the *CAD import pipeline* [9] allowed integration of the waveguides and the antennas in the CAD design of the machine, allowing for a complete description of the hardware environment of the machine, resulting in improved 3D synthetic diagnostics. During the EnR project, three different wall designs were used. The first two were based on the first wall limiter modules. One, where the antennas were at the face of a tile-covered wall; the second, used in the simulations referenced in [6], with the antennas embedded in a vertical submodule 1 cm recessed with respect to the rest of the wall. In the third design, based on a standard first wall module, the antenna was adapted to be cooled by neighbouring cooling tubes [12]. This design was considered in the thermal analysis done to complement the system assessment [6]. These changes reflect the evolution of the wall design during the project.

4 Plasma Position Reflectometer for the High Field Side

The cubic voxel description of the physical system, combined with a 3D toroidal volume account of the electronic density, for the SN scenario, was used to set up the HFS synthetic diagnostic at the equatorial position. Simulations were conducted across the K, Ka, Q, and V bands for both antenna designs. In figure 2, on the left, we can observe the REFMUL3 3D synthetic diagnostic operating in the Q band at a frequency of $f = 50\,\text{GHz}$. Following a methodology similar to that employed for the LFS, we evaluated the impact of the wall against the case using isolated antennas. A signal processing analysis, similar to the one used for the LFS, was done, and simulations showed overall errors within one-centimetre tolerance requirements, as displayed in figure 3 (top-left). The density profiles were calculated by Abel inversion. Two initialisation techniques were used, resorting to the known profile (known init.) and with a linear initialisation (linear init), see figure 3 (bottom-left). The results shown are for a bistatic antenna operating in transmission/receiving mode. These 3D simulations were repeated in 2D as part of an ongoing comparative effort to compare 2D and 3D approaches [8, 13]. In figure 2, on the left, we can observe the REFMUL3 3D synthetic diagnostic operating in the Q band at a frequency of $f = 50\,\text{GHz}$ while on the right, a 2D version of the synthetic diagnostic operating at the same frequency is shown.

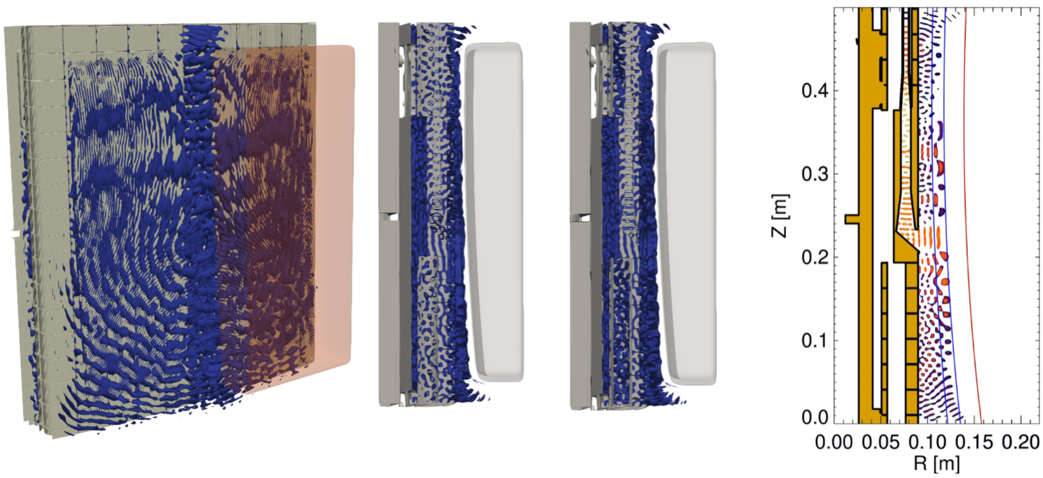

Figure 2. Snapshots of simulations of the probing wave in the case of the HFS reflectometer. On the left, a 3D Q band simulation taken at a frequency of $f = 50\,\text{GHz}$. In the middle, 2D plans for the transmission (Tx) and reception (Rx), obtained has cuts from the 3D volume. On the right the 2D synthetic diagnostic using has Tx/Rx structure a 2D version (cut) of the 3D hardware.

5 Discussion and conclusions

The promising results of the DTT PPR assessment for the LFS advocate for the development and installation of a system in DTT. The LFS PPR evaluation should be followed by an integrated design workflow similar to the one deployed in the HFS.

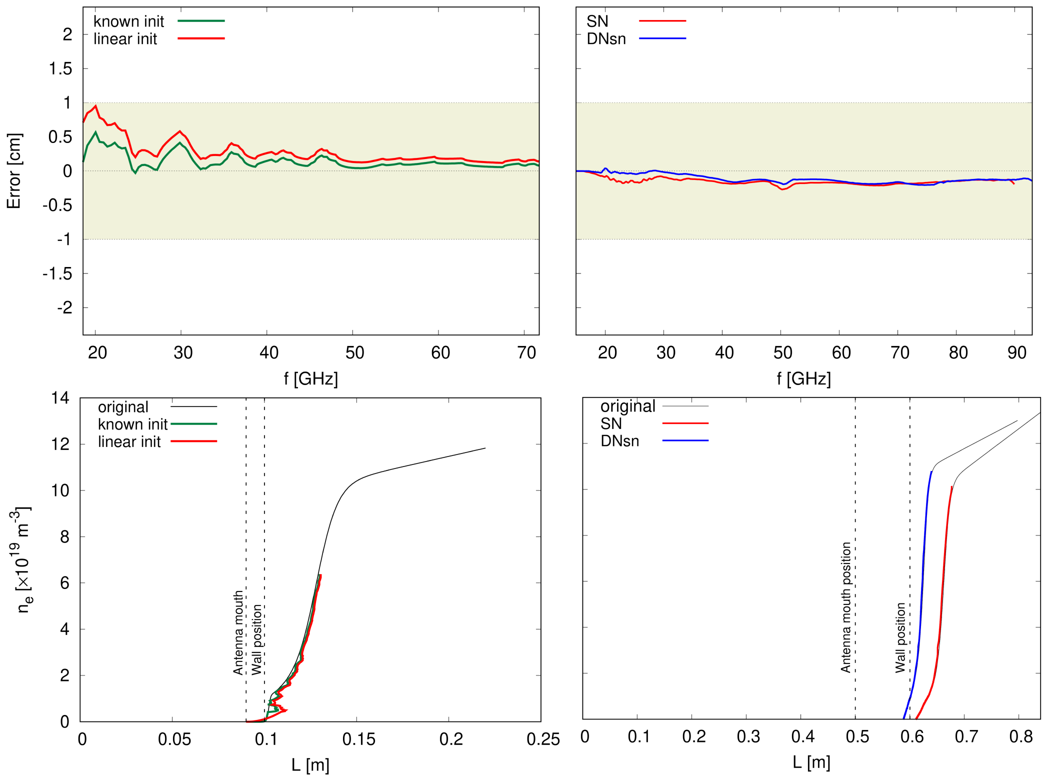

Figure 3. Position errors (top row) and reconstructed density profiles (bottom row). In the first column, the results for the HFS reflectometer system were obtained using 3D REFMUL3 synthetic diagnostic. In the second column, the results for the LFS were obtained using a 2D REFMULF synthetic diagnostic.

Results for the HFS are closer to reality since they were made in 3D, with a realistic description of the machine and plasma, and taking into full consideration the system integration in the machine. The completion of the W band is already underway, in the wake of the EnR project associated with this work. This working proposition offers a complete startup solution and a solid blueprint to start a formal proposal for the implementation of an HFS system or to serve as a guide for exploring another solution. If adopted, the integration of the design antennas in the new wall design will be employed, and the first studies, strongly based on the HFS blueprint presented here [6] are already underway [12] using many of the tools and procedures in our EnR project. To name a few, the microwave access reasoning; the custom-made antennas; the use of the CAD pipeline; the REFMUL3 code; or the signal processing procedures for profile evaluation. The thermal evaluation of the system has already used this new wall design.

3D simulations provide more realistic amplitude values, which are crucial for accurately determining the signal-to-noise ratio (S/N) [13, 14]. This, in turn, is essential for understanding the true impact of turbulence on S/N and for improving the initialisation of profiles. In the presented studies, the influence of the wall/antenna structures is more impactful for the lower bands, especially for the K band, where the ratio of the size of the emitting structure to the wavelength considered is lower. Also, the multiple reflections between the plasma and the wall and the plasma are more intense at the lower bands. As the frequency increases and the radiation patterns of the antennas become narrower, some of these effects decrease. A universal answer does not exist to determine whether using 2D synthetic diagnostics is sufficient, as this must be evaluated for each specific general problem.

2025 JINST 20 C09004

One of the most important outcomes of these efforts goes beyond the exploration of these particular DTT solutions. It consists of a general approach put together to develop a diagnostic, in the present case, reflectometry, taking into account the conceptualization of the hardware, its integration in the machine, with a full account of the access to the plasma, the fabrication of mockup parts to test them in laboratory, the realistic plasma scenarios, the evaluation of this joint framework through the setup of realistic synthetic diagnostics, and the inclusion of thermal analysis. This framework and work organisation can be applied to other machines in the fusion community, namely in the continuation of the DEMO planning and to JT60SA, following the European Union and Japan Broader Approach activities.

Also in the case of implementation of an HFS/LFS PPR at DTT, the developed simulation tools and the synthetic diagnostic counterpart can be of major interest to help in the interpretation of the results, help put together specific experiments, or guide the tuning and development of specific signal processing procedures.

As a final plus, the 3D CAD input pipeline was used in 2D, providing the hardware description used in the HFS 2D complementary simulations. This extends the accuracy of 2D simulations, allowing 2D cuts of complex geometries to be taken into account.

Acknowledgments

IPFN activities received financial support from "Fundação para a Ciência e Tecnologia" through projects UIDB/50010/2020 and UIDP/50010/2020. This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No. 101052200 — EUROfusion) and under the EUROfusion Enabling Research project ENR-TEC.01.IST. Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

References

[1] J. Santos et al., *Reflectometry-based plasma position feedback control demonstration at ASDEX Upgrade*, *Nucl. Fusion* **52** (2012) 032003.

[2] P.D. Lourenço et al., *Real-time plasma position reflectometry system development and integration on COMPASS tokamak*, *Fusion Eng. Des.* **160** (2020) 112017.

[3] W. Biel et al., *Development of a concept and basis for the DEMO diagnostic and control system*, *Fusion Eng. Des.* **179** (2022) 113122.

[4] E. Ricardo et al., *Simulation and data processing techniques to design optimized PPR systems on plasma fusion devices*, *Comput. Phys. Commun.* **294** (2024) 108945.

[5] F. da Silva et al., *Assessment of measurement performance for a low field side IDTT plasma position reflectometry system*, *Fusion Eng. Des.* **168** (2021) 112405.

[6] J.M. Santos et al., *Design and performance analysis of a High Field Side antenna for Plasma Position Reflectometry control on DTT*, *Fusion Eng. Des.* **201** (2024) 114275.

[7] F. da Silva, J. Santos and J. Ferreira, *Assessment of the Measurement Performance of a PPR system for IDTT Full Wave simulations*, Deliverable PMI-2.3-T006-IST-02, EUROfusion report EFDA_D_2N4ZAT (2020).

[8] F. da Silva et al., *Benchmarking 2D against 3D FDTD codes for the assessment of the measurement performance of a low field side plasma position reflectometer applicable to IDTT*, 2022 *JINST* **17** C01017.

[9] J.M. Santos et al., *A 3D CAD model input pipeline for REFMUL3 full-wave FDTD 3D simulator*, 2021 *JINST* **16** C11013.

[10] R. Martone et al., *DTT Divertor Tokamak Test facility — Interim Design Report*, ENEA Italian Agency for New Technologies Energy and Sustainable Economic Development (2019). [ISBN: 978-88-8286-378-4].

[11] L. Frassinetti et al., *Global and pedestal confinement and pedestal structure in dimensionless collisionality scans of low-triangularity H-mode plasmas in JET-ILW*, *Nucl. Fusion* **57** (2016) 016012.

[12] F. Ruffini et al., *Performance assessment and integration of the High Field Side Plasma Position Reflectometry system on DTT*, 2025 *JINST* **20** C05030.

[13] F. da Silva et al., *Benchmarking 2D against 3D FDTD codes in the assessment of reflectometry performance in fusion devices*, 2019 *JINST* **14** C08004.

[14] F. da Silva et al., *An overview of the evolution of the modeling of reflectometry diagnostics in fusion plasmas using finite-difference time-domain codes*, *Fusion Eng. Des.* **202** (2024) 114354.

2025 JINST 20 C09004