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Status of the Enabling Research Project *Advances in real-time reflectometry plasma tracking for next generation machines: Application to DEMO*

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1 Introduction

One of its expected major roles for DEMONstration power plant (DEMO) will be plasma positioning, shaping and tracking, effectively substituting magnetic diagnostics. The first steps to achieve this goal have already been taken experimentally, theoretically and with simulations but a great amount of ground-work remains to be done. An EUROfusion Enabling Research Project (EnR) was built involving a team of experts and developers of reflectometry systems in Europe aiming to tackle many of the still remaining open questions and come out with a coherent and unified approach allowing to implement a reflectometry system able to provide control inputs not only in steady-state operation (flattop) but also during the initial stage of the discharge (ramp-up phase). The objectives and associated outcomes are divided in two main branches with its own specificities and requiring different approaches: (i) The ability to track and monitor the plasma in the initial stage of the discharge, in the start-up phase; (ii) To improve the capabilities of operation in the stationary phase (flattop) in order to provide an accurate and precise substitute to the positioning magnetic diagnostics in real time. An important issue that must be addressed is the synchronisation between all reflectometers. An experimental validation on the Tungsten (W) Environment in Steady-state Tokamak (WEST) will prove the concepts of synchronising several reflectometers sharing the same clock and synchronising triggering events. The project also contemplates advances on hardware with a prototype of a compact coherent fast frequency sweeping Radio Frequency (RF) back-end being developed using commercial Monolithic Microwave Integrated Circuits (MMIC) with Direct Digital Synthesis (DDS), which allows for full control of the signal's frequency and phase, both with very high precision and resolution. After this general overview of the EnR project, in the reminder of the document, we present the first efforts of the project, achieved in the second semester of 2021 in Section 2, together with the work develop in the first half of 2022 at Section 3.

2 Planned and executed tasks in 2021

The first 6 months of the project were intended to the preparation and systematisation of the EnR project, officially Task 1. This task has been informally subdivided in four sub-tasks, T1.1—T1.4, to know:

T1.1 For all relevant scenarios, input datasets for REFMUL will be prepared and made available to properly model DEMO [and Divertor Tokamak Test facility (DTT)].

T1.2 Preparation of FDTD code REFMULF (REFMUL3 added) to handle the specific needs of the simulations.

T1.3 Planning of the clock demonstration. Synchronisation between reflectometers.

T1.4 Planning the compact reflectometers.

A more detailed review of the efforts conducted on these sub-tasks is described below.

2.1 Subtask T1.1 — For all relevant scenarios, input datasets for REF MUL will be prepared and made available to properly model DEMO (and DTT).

An important part of the EnR work will be performed using synthetic reflectometers setup with Finite-difference Time-domain (FDTD) codes, REF MULF (2D) and REF MUL3 (3D). This will permit a comprehensive description of the behaviour of the reflectometers in consideration. To achieve it, a self-consistent description of the density, obtained from equilibria simulations, should be used.

Obtaining the appropriate official scenario to simulate reflectometry in a given machine has proven to be an ordeal in the past. Our efforts on this matter for the present project confirm it.

2.1.1 Data for DEMO density modelling

We have faced major difficulties in obtaining official complete scenarios. For the flattop regime, the most complete scenario available is the 2015 with the equilibria and electronic density associated going only up to the separatrix. Data for the Scrape-Off Layer (SOL) is not available and had to be modelled. In 2021, no information for the ramp-up could be obtained. Nevertheless, some studies on these part of the discharge have been performed, for instance see [1] but they do not seem to be readily available in DEMO data base or ready to distribution. To bridge this obstacle our action plan to 2022 was, (i) first of all, try once more to obtain the needed data officially at DEMO; (ii) for the ramp-up, to try an educated model based on the data published; and for the flattop keep with the 2015 complete model.

2.1.2 Data for DTT density modelling

At the end of 2021, DTT data access, looked slightly more promising with two full scenarios available for the flattop, a single null and a double null scenario. As *usual*, the SOL density was unavailable and had to be completed with a model. For ramp-up, equilibria were available, although without the associated density description. We expected to obtain them by yearly 2022, yet this showed not to be possible.

2.2 Machine (wall and accesses) and antennas

For DTT, access to a Computer-Aided Design (CAD) file for Sector 10 of the machine was made available allowing for a good modelling of the machine (wall and accesses) and a correct placement of the antennas and waveguides. At the start of DTT reflectometry assessment, the model for the antennas had not yet been considered. Therefore, EnR proposal was to adopt the same design being used in DEMO synthetic reflectometry, a conventional horn [2]. The *proof of principle* simulations for the Low Field Side (LFS) showed this choice to be appropriated. For High Field Side (HFS), the limited access and lack of space imposed the design of a more compact antenna, a hog-horn with a flat mirror. The performance of the HFS antenna is more modest than the LFS one as a consequence. Its design had to be adjusted in 2022, since a more updated CAD description of the Sector 10 revealed that the available space was even scarcer than initially thought. In Subsection 3.6 details of the new design are presented together with the more recent simulation efforts.

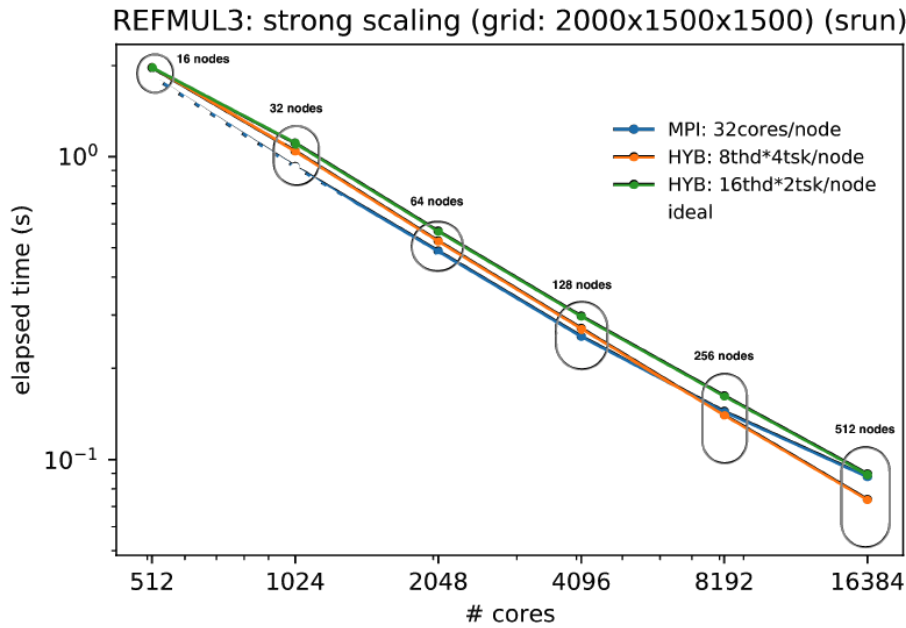


Figure. 1: The Amdahl's law (strong scale behavior) for REFMUL3 is shown in the image for both for MPI and hybrid (MPI+OpenMPI) executables of the code.

2.3 Subtask T1.2—Preparation of FDTD code REFMULF (REFMUL3 added) to handle the specific needs of the simulations.

Synthetic diagnostics will use FDTD codes of the REFMUL* family, REFMULF a 2D full polarization code and REFMUL3, a 3D code. REFMULF stands out from regular 2D codes as is able to treat all components of \mathbf{E} ($\mathbf{E}_x + \mathbf{E}_y + \mathbf{E}_z$) and \mathbf{B} ($\mathbf{B}_x + \mathbf{B}_y + \mathbf{B}_z$) of the wave while supporting a generic external magnetic field \mathbf{B}_0 ($\mathbf{B}_{0x} + \mathbf{B}_{0y} + \mathbf{B}_{0z}$). This code is able to couple the TE Mode (X-mode) with the TM Mode (O-mode) via \mathbf{J} and has an extended variety of sources on both electrical planes: Unidirectional Transparent Source (UTS) with antennas and waveguides, Total Field/Scattered Field (TFSF) plane wave, TFSF Gaussian beam and Periodic Boundary Condition (PBC) plane wave. It extends the capabilities of available 2D codes enabling for instance coupling O/X, Faraday rotation or Cotton-Moutton effect. It can be used in its full polarisation capability or compiled as a *traditional* O- or X-mode code. REFMUL3 is a 3D parallel which includes all field components and has a parallel design, having an hybrid implementation with Message Passing Interface (MPI) and Open Multi-Processing (OpenMP) threading. It shows very good scalability as observed in Figure 1. It has advanced file output capabilities, compatible with big data output, with eXtensible Data Model and Format (XDMF)/Hierarchical Data Format 5 (HDF5) compressed binary parallel output or parallel Visualization Toolkit (VTK). VTK is the native format of the VTK library and is used by visualization programs such as Paraview or VisIt.

2.3.1 REFMULF enhancements

The project prospective simulation requirements anticipated the need of some enhancements to REFMULF. REFMULF was being design as serial code and the need of parallelism has not been one of the priority development issues. This EnR foresees some large Region of Interest (ROIs), specially for the ramp-up, thus the need to increase the code performance in an expeditious way. REFMULF was threaded

using OpenMP with satisfactory results up to $\times 12$ for a strong scaling 1000×1000 case on a MARCONI Skylake partition node. Another tool added to the code was the implementation of a pitstop/restart file, a capability first implemented on REFMUL3. Its main use on a 2D code is to allow running large jobs divided in several submission runs as detailed in next subsection. These amelioration prepared REFMULF for bulk running in an High Performance Computer (HPC).

2.3.2 Addition of REFMUL3 to the EnR FDTD toolkit

REFMUL3 was given the pitstop/restart file capability. This feature allows two important things: (i) from time to time save the state of the running code on disk which, in the case of a malfunction on one of the nodes allows to recover the run without having to restart from scratch, saving user time and perhaps more important, allocated node hours, already too scarce. This was the original intend of the pitstop/restart; (ii) an additional use of this capability, which acquired perhaps more importance than the first is the capability of using it to divide a simulation in several runs. On a HPC there is a maximum run time that can be asked at a time by an user, which depends on the partition, queue and quality of service required. Any run exceeding this preset limit is terminated by the system. The pitstop/restart file permits an overrun of this time limit. The running code, as it approaches this limit saves a state file and executes a clean exit and on a subsequent job submission one can to retake calculations from were they were left left. The process can be repeated several times allowing an effective simulation time far greater than the limit of a given HPC. A VTK output format was added to the code. An ancillary CAD import pipeline tool developed and included in our toolkit offers now a unprecedented description of the vessel walls, accesses and antennas giving much more integrated and accurate synthetic diagnostics [3] and [4].

2.3.3 CAD import pipeline

A considerable part of the work of the EnR project relies on the results produced by synthetic diagnostics. Those should simulate the main effects that influence the diagnostic measurements requiring a realistic 3D representations of the different system components, such as waveguides, tapers, antennas, as well as the vessel wall structures access the plasma, a fact often-neglected. A fully automated pipeline that adapts realistic 3D CAD tessellated mesh models of the various components to the input VOXEL description format required by REFMUL3.

2.4 Subtask T1.3—Planning of the clock demonstration. Synchronisation between reflectometers.

During this initial stage of the works three improvement steps have been identified to reduce the time shift between WEST reflectometers [5]

Step 1: distribute a single 10 MHz reference clock to the 3 reflectometers. The WEST chronology is already based on a 10 MHz chock. Only a downsampled clock at 1 MHz is distributed to all diagnostics. With optical fibers and new receivers this 10 MHz clock will be distributed to the three WEST reflectometers.

Step 2: ensure that WEST events are received at exactly the same time in each reflectometer cubicles. The propagation time from the chronology board to the reflectometer boxes will be measured with synchronisation tools. Calibrate and adjust round trip latencies on all three connections.

Step 3: ensure that all 3 reflectometers perform measurements at exactly the same time. Each reflectometer has its own electronics and microwave set-up. Moreover out-vessel waveguide length are different: 20 cm for the core reflectometer, 2 m for the edge reflectometers and 4 m for the Lower Hybrid (LH) antenna. Once the triggers are received at the same time in all reflectometers control board, delays between will be adjusted in each reflectometers so all reflectometer wave reach the plasma edge at the same time.

The goal is to reach a synchronisation about few ns, i.e. better than the plasma propagation time and a thousandth of the reflectometer sweeping time. A plan for the execution of these steps has been layout with prospective timeline.

2.5 Subtask T1.4—Planning the compact reflectometers.

During the EnR, we intent to develop a compact coherent Frequency-Modulated Continuous-Wave radar (FMCW) microwave reflectometer with applications in plasma diagnostics with back-end covering directly 10 to 20 GHz and, with full band frequency multipliers, have its frequency extended up to 140 GHz [6]. For improved linearity, a key feature to guarantee high precision on a FMCW radar, analog oscillators can be replaced by DDS generators. In this initial stage the objective was to plan its development but the work has passed far beyond this point with two prototype Printed Circuit Board (PCB) boards being develop with very encouraging first tests, see Figure 2—left. The back-end prototype can generate full band signals exceeding 8 dBm, enough to drive external multipliers. All undesirable harmonics are 15 dBc bellow the desired output, in all frequency range. The output must be the 2nd harmonic of the Hyperabrupt Tuning Oscillator (HTO), as we are measuring the output of the active frequency doubler. The frequency multiplier rejection of the input frequency (blue line) is always 20 dB bellow the output, see Figure 2—right (red line).

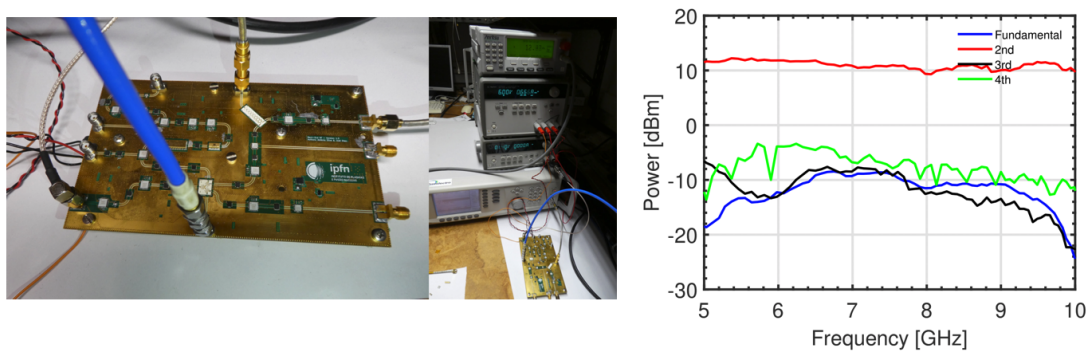


Figure. 2: On the left, the first test performed on a prototype of the compact reflectometer and on the right the output power of the back-end.

2.6 Scientific output in 2021

Although the main objective of 2021's work was to prepare and systematise the EnR project, this has produced already scientific output with one oral communication and a poster in the *1st European Conference on Plasma Diagnostics* (ECPD2021) and two peer reviewed publications [4], [7]. More scientific

output is expected for the duration of the project, contributing to the knowledge database available to the community to aid the preparation of next generation reflectometry systems.

3 Activities in the first semester of 2022

Following 2021's initial activity kickoff, the first half of 2022 has seen a fair amount of work parted in the following non-exclusive categories.

- DEMO Steady state comprehensively studied
- DEMO Ramp Up data from equilibrium and from analytical modelling
- Preliminary ray tracing analysis for ramp up of DEMO
- CAD model input pipeline advancing and entering production stage
- Substantial advances in the compact reflectometer project
- Work on DTT HFS PPR Reflectometer
- Complementary activities

3.1 DEMO Steady state comprehensive study

During the EnR proposal evaluation, and ongoing effort of DEMO fullwave simulations in the framework of a PhD work [3] was integrated in EnR project and during 2021, a major effort of evaluation of DEMO steady state concluded. Its results were also important for EUROfusion WPDC and included in its reports [2]. This effort resulted in one of most extensive simulation enterprise for simulation of a reflectometry system and involved a major undertaking in modelling, SOL densities turbulence and plasma dynamics to bridge the limited plasma description for the flattop, remembering that only the 2015 was available inside the separatrix. Several signal processing procedures were proposed during this study and the initial code for one of the components of the *CAD pipeline* first developed together with an ancillary modeller for density whose use will be important during the remaining of the EnR.

3.2 DEMO Ramp up from equilibrium and from analytical modelling

One of the primary challenges felt in 2021 was to obtain DEMO data for the ramp-up. Following the steps of our mitigation plan (see 2.1) and unable to obtain official DEMO information we turned to the literature in the hope to build an educated model and fortunately we could go a step further. Contacting one of the main authors studying DEMO, Francesco Maviglia, we managed to obtain EQUILIBRIA DiSK (EQDSK) files with a ramp-up scenario together with the associated density profiles. In Figure 4 shows the evolution of the electronic density and associated equilibria for during for several raising current instants $I_p = 5.0$ MA, $I_p = 7.5$ MA, $I_p = 10.0$ MA, $I_p = 12.5$ MA, $I_p = 15.0$ MA, $I_p = 17.5$ MA, and $I_p = 19.6$ MA, this last one very close to the flattop situation. This description for DEMO ramp-up, although not DEMO official, has already been used in several studies and published works, giving its use in EnR a certain continuity and consistence with the work developed by the larger DEMO community. Despite its usefulness in relaunching the EnR ramp-up efforts, it represents just one scenario of evolution of the plasma and the initial available equilibrium displays already a fairly high density. With the insight

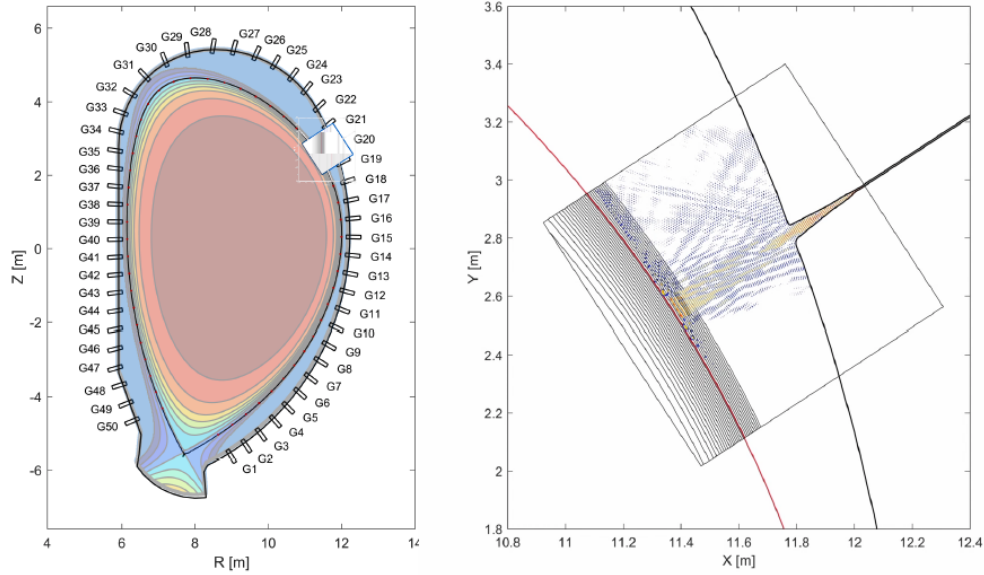


Figure 3: On the left a poloidal section of DEMO with a HFS equatorial reflectometer ROI is marked. A snapshot of the electric field in this ROI (G20), for a frequency of $f = 43$ GHz, appears on the right.

given by these equilibria and to enlarge the possible scenarios available the strategy of designing *educated* analytic models continued, mitigating the scarcity of ramp-up data. The development of this analytical scenarios also ease the use of analytical ray trace codes, as done for obtaining the first ramp-up analysis presented below.

3.3 Preliminary ray tracing analysis for ramp up

Some preliminary studies have been performed using an analytical ray trace code [8] with analytical plasma description, exploring different scenarios from the equilibria description available [9]. Examples of such endeavours appear in Figure 5, on the left and central image, during an early stage of ramp-up where the *recently born* forming plasma is not dense enough to reflect the probing beam. The leftmost image shows emission from the LFS while in the middle the plasma is probed from the HFS. In this situation the reflectometry apparatus are operating in an interferometer/refractometer mode. In the right image, the ray tracing simulation illustrate, for higher density and evolved plasma shape, how reflectometers take up their usual *normal reflecting* behaviour. The reflectometer positions are marked with red dots and can be used as emitters and/or receivers.

3.4 Advances model input CAD pipeline

The CAD pipeline has had its proof of principle as a powerful tool to describe the environment of the reflectometry systems under study and is now being used as a production tool. As examples, the new study being carried out for the HFS of DTT makes full use of the CAD pipeline. The 3D full wave studies to be developed for DEMO will exploit it. A more complete review of the advances and applicability of the tool has been presented in the talk *CAD model input pipeline for REF MUL3 fullwave FDTD 3D simulator* given by J. Santos in this workshop.

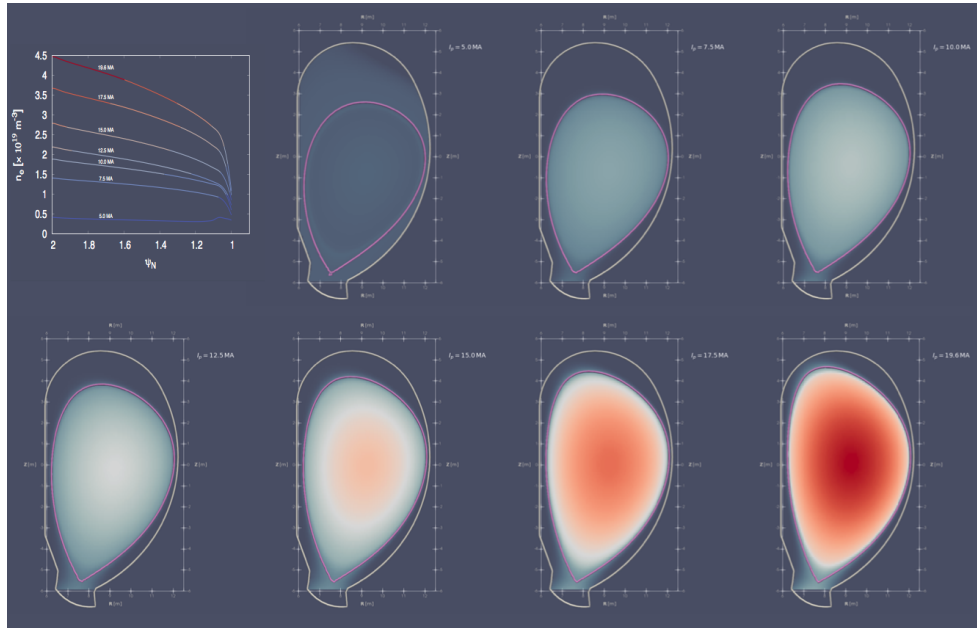


Figure. 4: Demo ramp up densities.

3.5 Substantial advances in the compact reflectometer project

More information on this part of EnR work can be found in the talk *Substantial advances in the compact reflectometer project* given by A. Silva, during this workshop.

3.6 Work on DTT HFS PPR Reflectometer

Three different sub-systems are to be installed in a dedicated toroidal section (Sector 10). A reflectometer for density profile reconstruction (DPR), a Doppler reflectometer for fluctuation and turbulence studies (TR) and a plasma position reflectometer (PPR) system. The PPR system being investigated for installation on DTT aims to research a possible reactor application as a complement/back-up system of magnetic sensors and should involve four lines-of-sight: (i) One in the low field side midplane; (ii) One in the upper vertical port and (iii) Two in the high field side region. In terms of planing, the HFS PPR is more urgent since the concept is needed by the end of 2022. The initial effort in DTT simulation was for the LFS, nevertheless this urgent time table shifted our immediate attention to the planning of the HFS. Our main effort has been the design an antenna and its integration in the available space reduced and at premium. The initial 2021 design when confronted with the CAD design proved to be too big and had to be redesigned with a smaller footprint and consequently a reduced gain. The configuration of the HFS PPR has also been under analysis as shown in Figure 6. The original setup on the table for discussion reserves space for two tentative bistatic systems, in the proposed design, one near the equatorial plane and a second in upper section of the machine. Unfortunately, this design separates the Transmit (Tx)/Receive (Rx) pair excessively, which almost certainly impairs the operation of the system. A new solution for the configuration of the antennas is paramount. In discussion are different solutions to address the problem (see Figure 6):

A monostatic setup. Using just one antenna will solve the size restrictions and guarantee the same line-of-sight in Tx/Rx. This is, nevertheless a difficult to implement due to the possible presence of

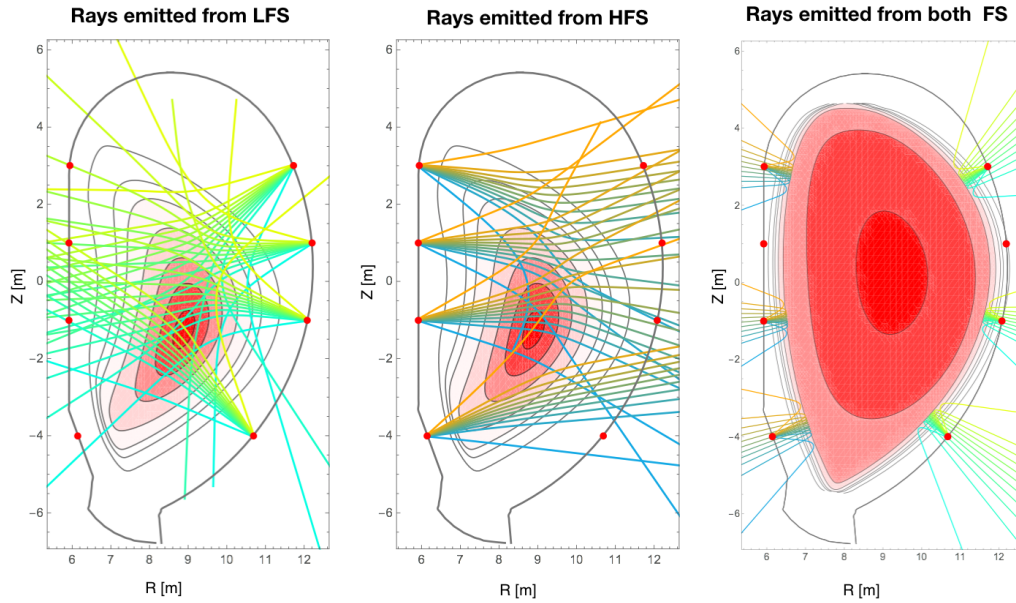


Figure. 5: A preliminary ray tracing study for DEMO ramp-up using a synthetic plasma description.

multiple stray reflections in common RX/TX transmission line path that will mix and dim the plasma signal, reason for the preferred choice of a bistatic system. A further evaluation of this possibility needs to be carried out.

A bistatic setup with “Up/Down” antennas. This solution permits a bistatic system with just one cooling pipe removed. The inverted antenna can act as collector of debris and dust, which with time can lead to a deterioration of the system. Also, the waveguide routing of the inverted antenna ideally should be made by the lower part of the machine since routing the waveguide behind the remaining cooling pipes can be difficult and pose problems during a needed disassembly of the wall.

A bistatic setup with two adjacent cooling pipes removed. This is from the reflectometry point of view the best solution since it allows a bistatic system having the two antennas, Tx and Rx, side by side. It relies on the feasibility and authorization of having one more cooling pipe removed.

A bistatic setup with two non-adjacent cooling pipes removed. Not as effective as previous solution but still a good compromise. As an advantage, the uncooled area is not continuous. Relies as well on the feasibility and authorisation of having one more cooling pipe removed.

A bistatic setup with a Tx/Rx “mono-bloc” antenna. This solution implies the design of a new antenna able to *squeeze* two antennas, for Tx and Rx in the same volume occupied by the original one. This new antenna will forcibly have a worse performance than the original one. Its design should minimise cross talk, which may occur, given the geometry and dimensions involved.

3.7 Complementary activities

Some complementary tasks have been performed being such as keep-in-touch activity with the Microwave Intensity refractometer in the Limiter Shadow (MILS) [10], [11] developments in particular with the setup

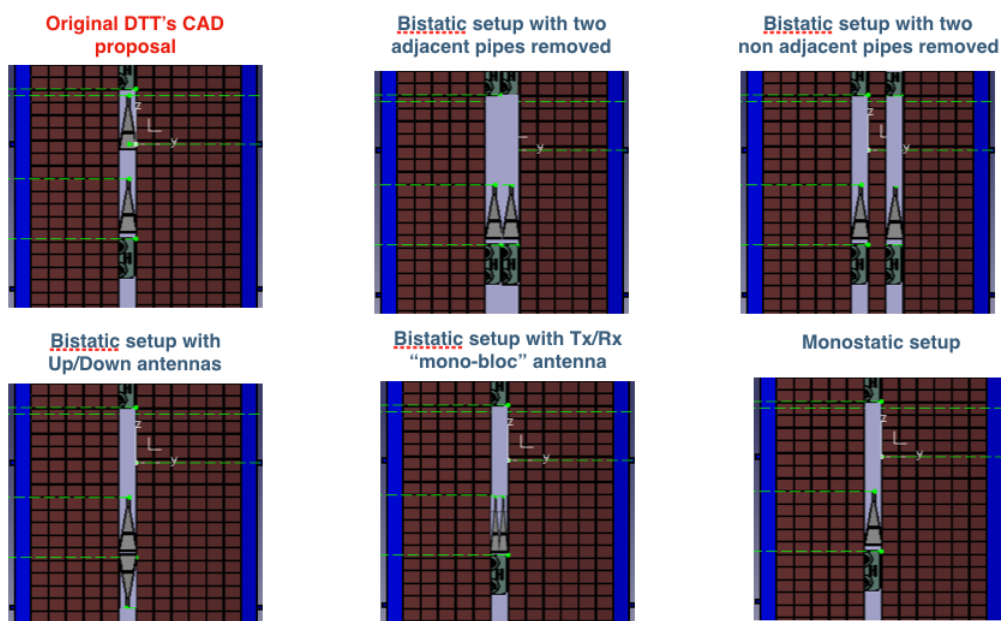


Figure. 6: DTT HFS antenna configurations and accesses under appraisal.

and use of the RIC [12] reflectometer as interferometer and in the analysis of the results obtained. Also an WIKI of the EnR project is being kept for future memory.

4 Discussion

The efforts developed during these first 12 months of the project have been quite positive. The main difficulties faced so far have been exterior to the project and have to do in what simulation and modelling are concerned with scarce data available for our input models. The obtaining of the bare minimum of information to proceed as added a considerable *extra dead time* to some tasks of the project and required an additional effort of modelling to complement the needed knowledge. On the hardware front, a problem is looming, which may impact in the development of the DDS, which is the scarcity of some electronic components, the new extended delivery times and above all the very inflated prices due to COVID-19. All that considered, the compact reflectometer development is well advanced and ahead of schedule with a functional prototype available and hopefully to be tested at WEST in 2023 in conjunction with the synchronisation efforts. The PPR plans for DTT evolved from a wishful hypothesis at the time of writing of the EnR proposal to a possible implementation on DTT and the EnR is giving its contribution to this. Clear advances have also been achieved in the numerical codes for reflectometry simulation. A major effort on the evaluation of DEMO steady state was finished giving a valuable contribution for DEMO comprehension. Our main efforts should now be turned to the ramp-up stage where the bulk of the work remains to be done, in general within the community and in particular in this EnR.

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