ENR-TEC.01.IST
Advances in real-time reflectometry plasma tracking for next generation machines: Application to DEMO

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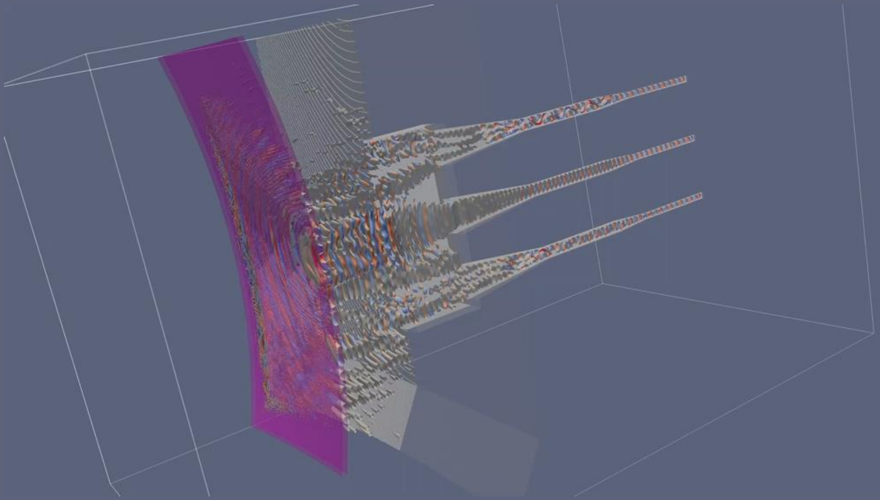

Collaborations: Tiago Ribeiro, P. R. Resendes, J.C.C. Abrantes, Raul Luís, Yohanes Nietiadi

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EUROfusion

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Motivation

- Reflectometry will play a major role in next-generation machines, in particular in DEMO.
- It is expected, for DEMO, to provide plasma positioning, shaping and tracking.
- The first steps already been taken experimentally, theoretically and with simulations.

A great amount of groundwork **remains to be done** and this project aims 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)**.

IN OMNIBUS AUTEM NEGOTIIS PRIUSQUAM ADGREDIARE, ADHIBENDA EST PRAEPARATIO DILIGENS

„Before entering any occupation, diligent preparation is to be undertaken.“
Marcus Tullius Cicero *Book I, section 73 De Officiis* (44 BC)

ENR-TEC.01.IST Objectives

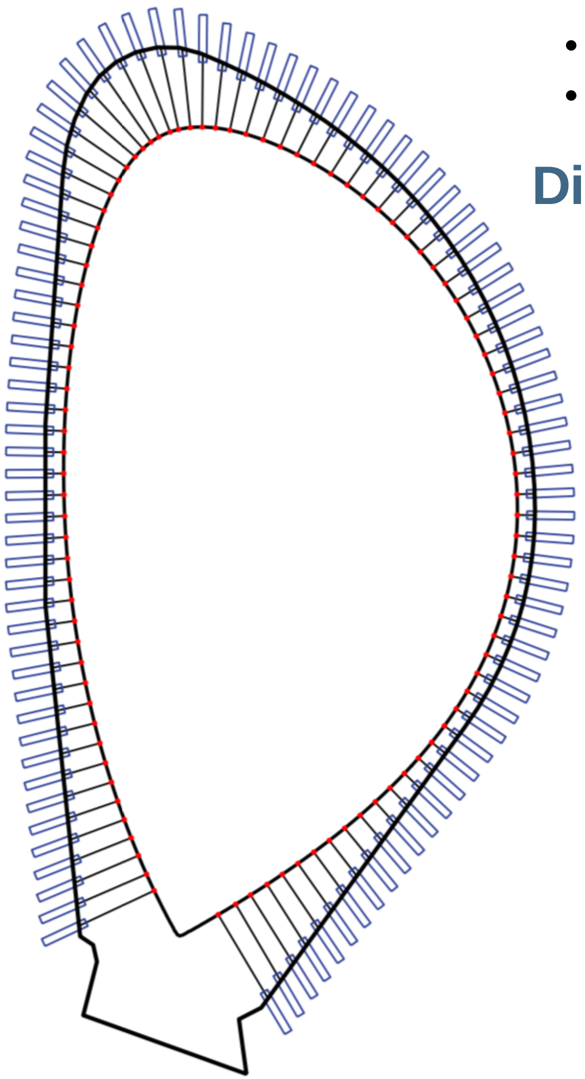
A group was put together to contribute to the conception of a reflectometry system for next generation machines

With unprecedented capabilities to diagnose the electronic density and track the position and shape of the plasma column

(i) The ability to track and monitor the plasma in the initial stage of the discharge, in the start-up phase.

(ii) Improved capability of operation in the stationary phase (flattop).

DEMO's Plasma Position Reflectometry conceptualisation



A set of poloidally equidistributed reflectometers

- Nr. of lines of sight (LOS) remains open
- Dependent on access of waveguides

Different modes of operation with same hardware

This concept brings forward new challenges

- **Ramp-up**
  new concept

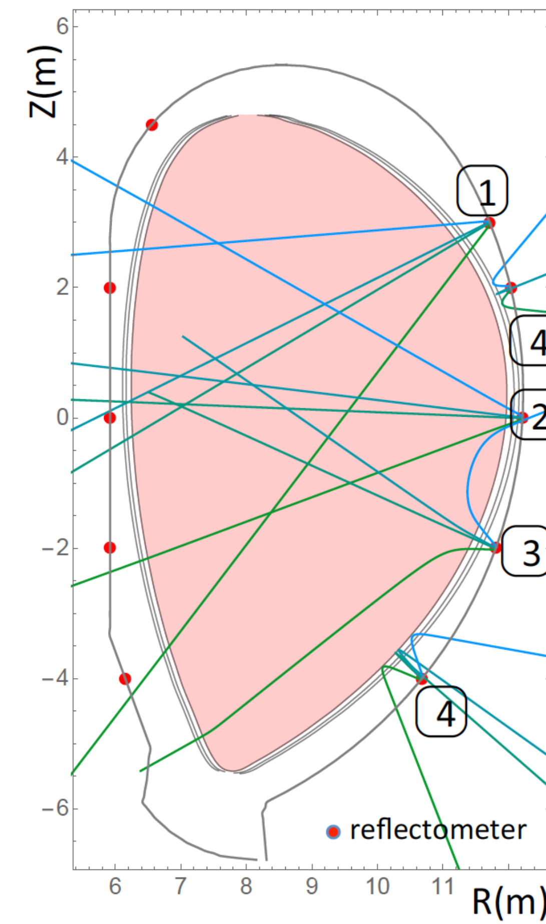
  1 Interferometry

  2 Refractometry

  3 Intensity refractometry

- **Steady state**
  no experience way from equatorial view

  4 Reflectometry



S. Heuraux, September 2022.

Different areas of knowledge involved

Development of synthetic diagnostics

- DEMO and DTT density inputs for simulation codes
- Developments in FDTD codes

Development of new algorithms

- For steady state
- For ramp-up

Synchronisation between different reflectometers

- An experimental validation on the tokamak WEST

Advances on reflectometry hardware are contemplated

- Compact reflectometer prototype using MMIC with DDS signal generation

DTT as a possible testbed for DEMO

- Synthetic diagnostics for simulation and algorithms

Different areas of knowledge involved

Development of synthetic diagnostics

- DEMO and DTT density inputs for simulation codes
- Developments in FDTD codes (+REFMUL3)
- Developments in description of structures
- Developments in description of plasma scenarios

Development of new algorithms

- For steady state
- For ramp-up

Synchronisation between different reflectometers

- An experimental validation on the tokamak WEST

Advances on reflectometry hardware are contemplated

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DTT as a possible testbed for DEMO

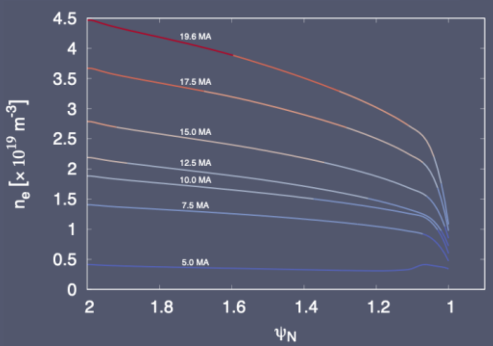
- Synthetic diagnostics for simulation and algorithms
- Design of antennas for a possible PPR implementation

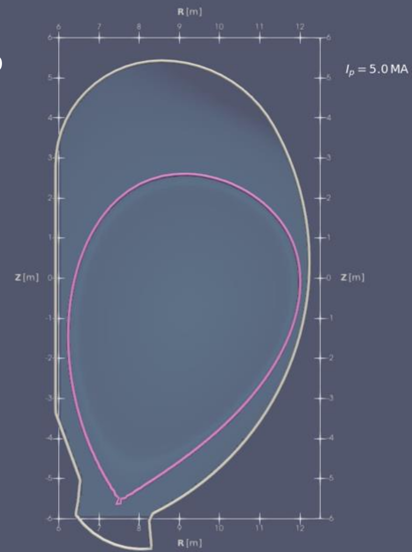
Added to the initial proposal

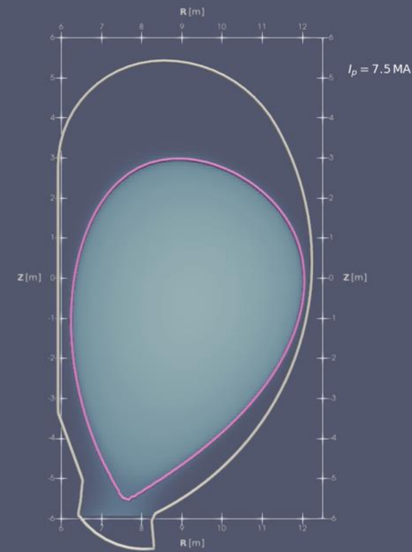
DEMO Ramp Up

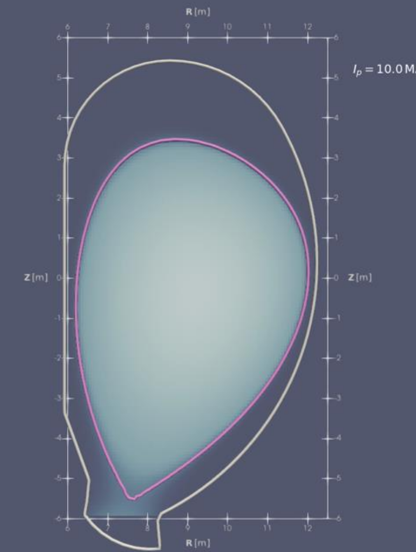
DEMO and DTT density inputs for simulation codes

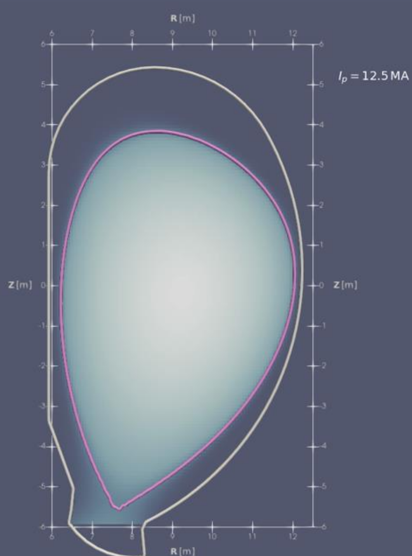
Managed to obtain a description for DEMO Ramp Up
NOT DEMO Official, yet already used in several studies and published works

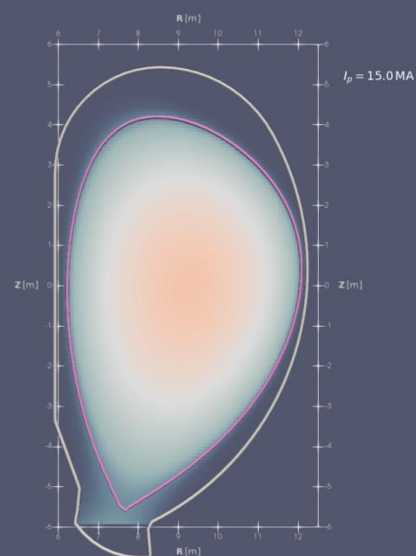


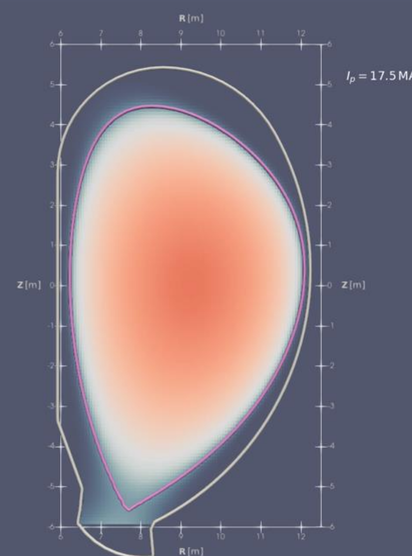


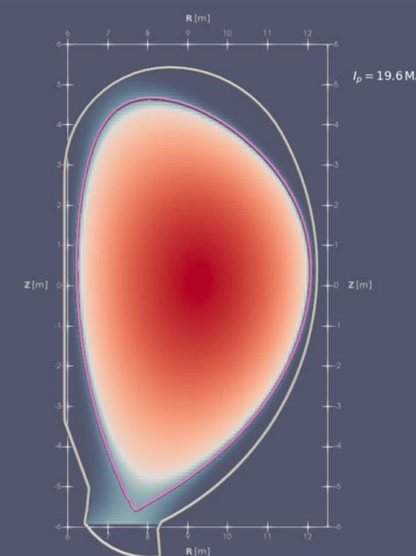












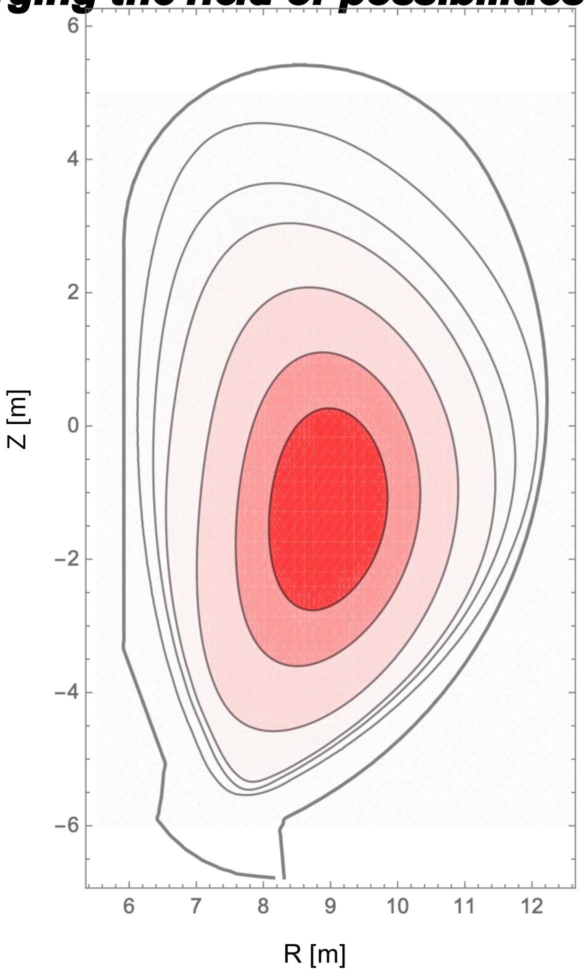
Data kindly supplied by Francesco Maviglia and Mattia Siccinio

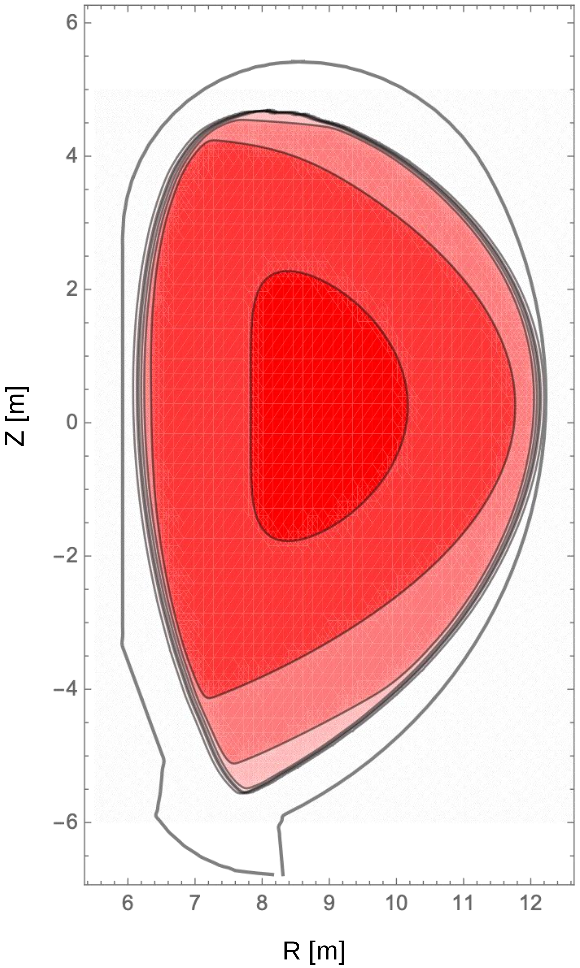
Analytical poloidal density maps

DEMO and DTT density inputs for simulation codes

Educated Analytical models for density, developed to mitigate the scarce available equilibria data for ramp up

- ***Enlarging the field of possibilities to study***

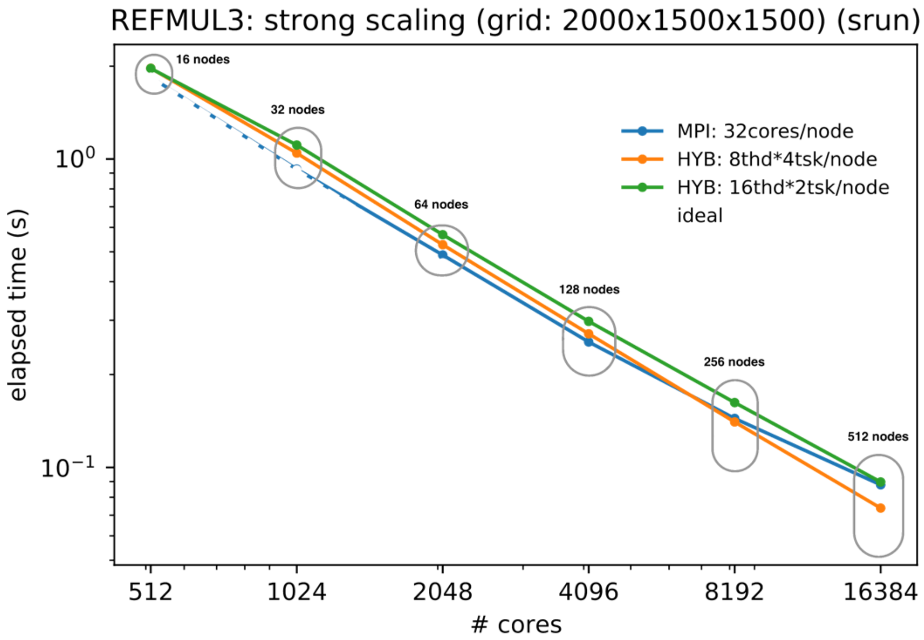




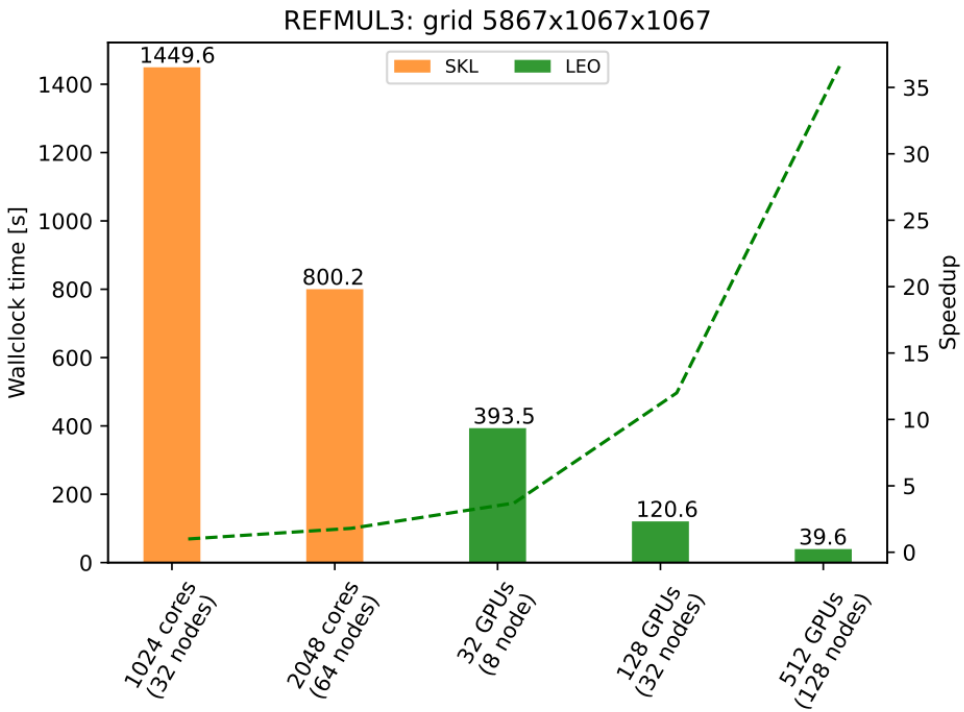
S. Heuraux, private communication, 26 April, 2022

REFMUL3 ported to GPU

- **REFMUL3 is a 3D hybrid MPI/OpenMP full-wave code written in C (≈20k lines)**
  - **Some EnR ameliorations:**
    - *Pitstop/restart file implementation*
    - *VTK format output (big data output)*
    - *Ancillary CAD import pipeline*
- **Ported to GPU using OpenMP offloading**
  - ***Shows excellent performance on Leonardo while maintaining CPU (MPI/OpenMP) efficacy***



This scales a grid of 4 500 000 000 grid points on Marconi Skylake partition



A grid of 6 679 514 963 grid points Marconi Skylake partition & Leonardo

Filipe da Silva, ENR-TEC.01.IST

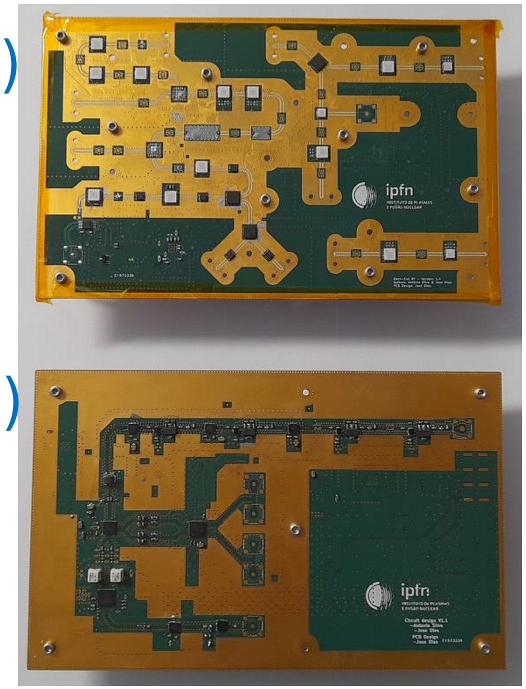
Status of the compact reflectometer

- The compact reflectometer board had to be **redesigned** due to the **obsolescence** of three MIMIC chips.

New version of the compact reflectometer board

a)

b)



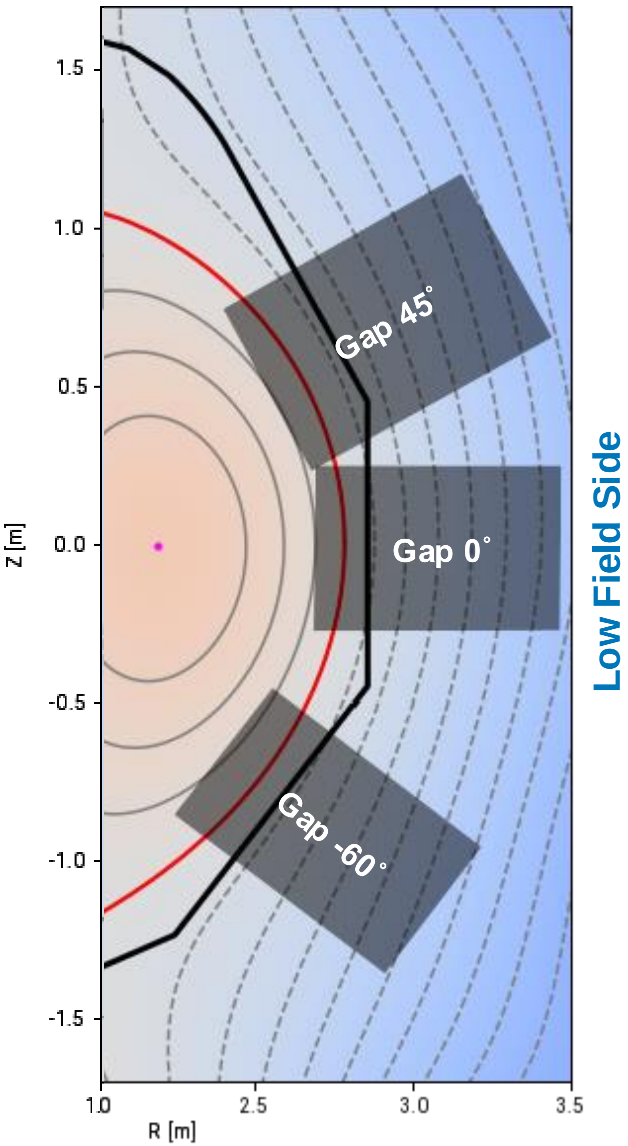
A new version of the Compact Reflectometer PCB has been designed and is currently undergoing assembly and testing. The components include:

- Signal Generation Board: Responsible for creating the necessary signals for reflectometry measurements **(a)**.
- IF Processing and IQ Detection Board: Handles intermediate frequency (IF) processing and in-phase/quadrature (IQ) signal detection **(b)**.

- The **DDS development progressed** exploring on the possible ways implement it, but due to the world present conflicts the access to the necessary high-end electronics like ultra-fast FPGA is limited, with high lead times and high prices.
- *We are trying to purchase the critical components – Wake of EnR*

Density description

Single Null Scenario



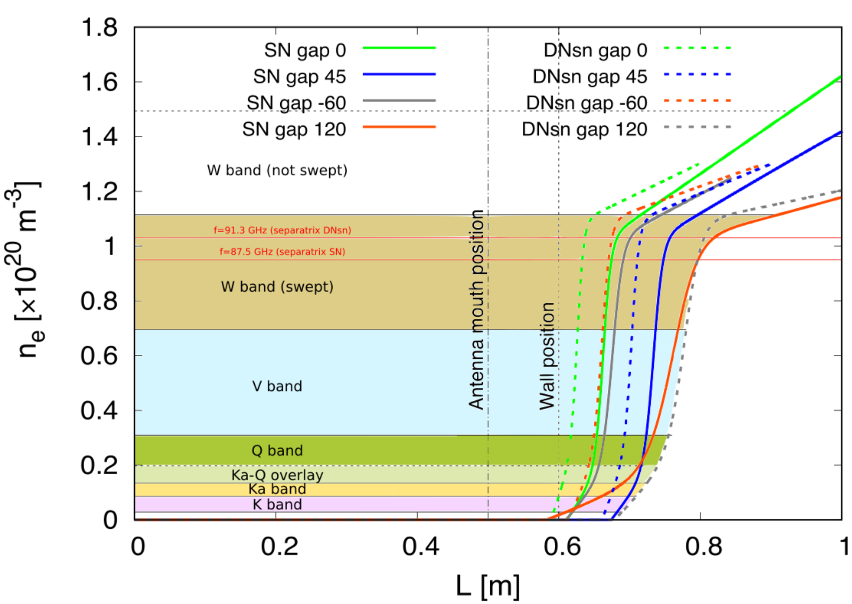
We used an educated guess model based on the density profiles appearing in
R. Martone et alia, DTT Divertor Tokamak Test faciliy—Interim Design Report, April 2019.
using a fit on the extracted data with the expression proposed in
L. Frassinetti et alia, Nuclear Fusion 57 (2017) 016012.

$$\mathrm{mtanh}^{SOL}(r) = \frac{h}{2}\left[\frac{(1+s^{core}x)\mathrm{e}^{x} - (1+s^{sol}x)\mathrm{e}^{-x}}{\mathrm{e}^{x}+\mathrm{e}^{-x}} + 1\right], with \quad x = \frac{p_{pos}-r}{2\omega_r}$$

Having n_e as a function of real space along a line of sight, e.g. $n_e(r_{LOS})$
or as a function of a flux radial variable, such as the poloidal flux $\rho_{POL} = \sqrt{\Psi_N}$,
and having the 2D maps of the flux in machine coordinates ***(R,Z)***

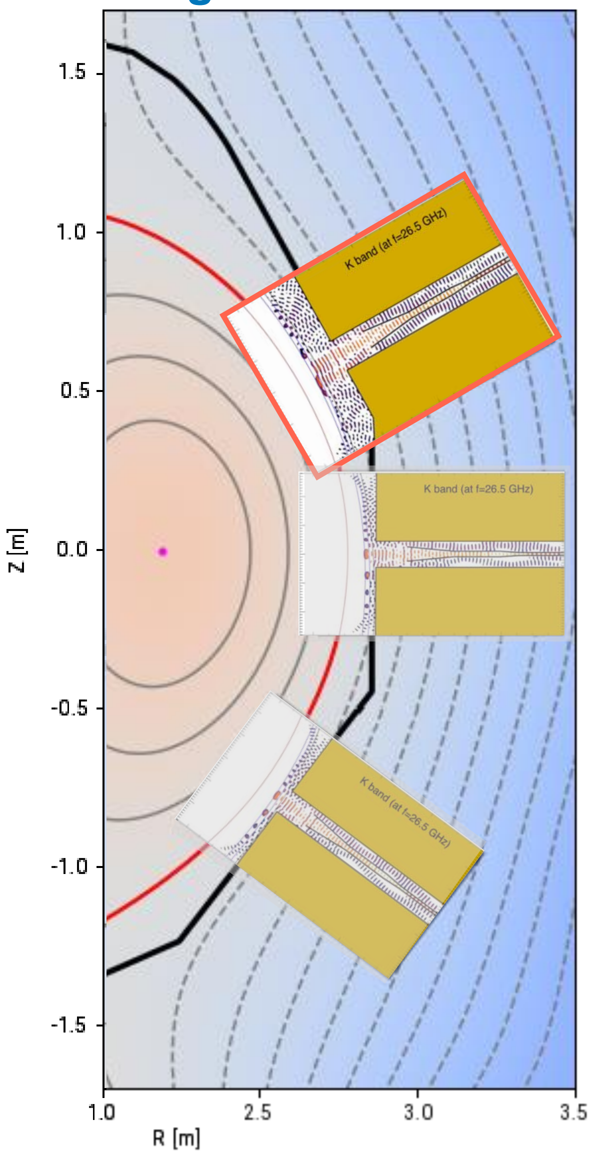
The profiles can be mapped into the machine coordinates

$$n_e(r_{LOS}) \xrightarrow{r_{LOS}(\rho_{pol})} n_e(\rho_{pol}) \xrightarrow{\rho_{pol}(R,Z)} n_e(R,Z)$$



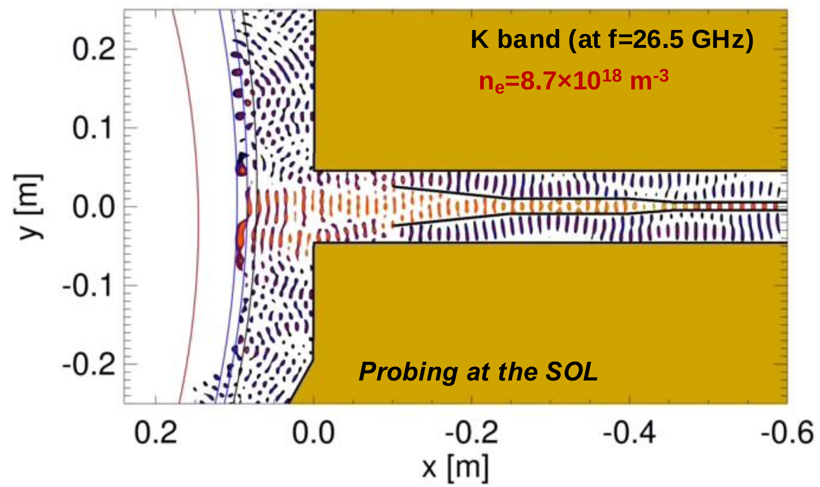
Full System for Gap 45° SN scenario probing

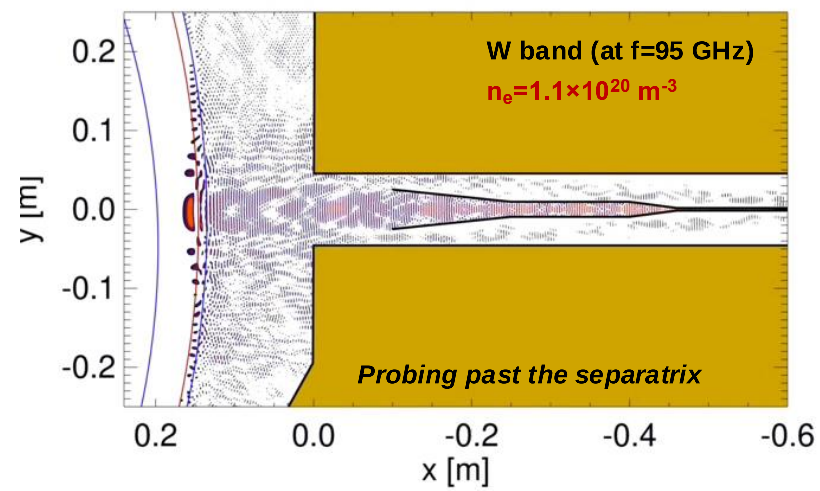
Single Null Scenario



Low Field Side

Simulated with REFMULF code





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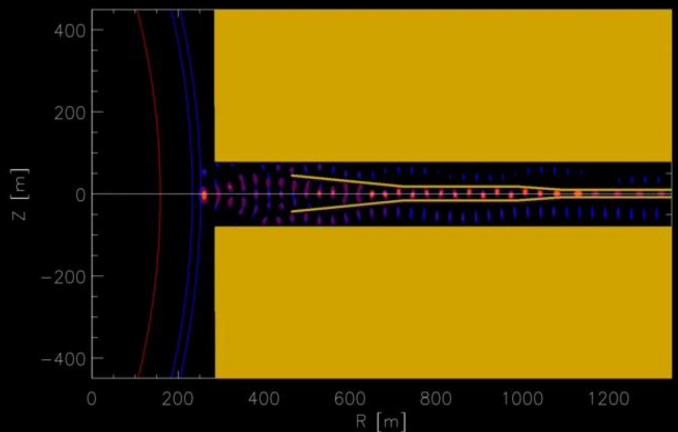
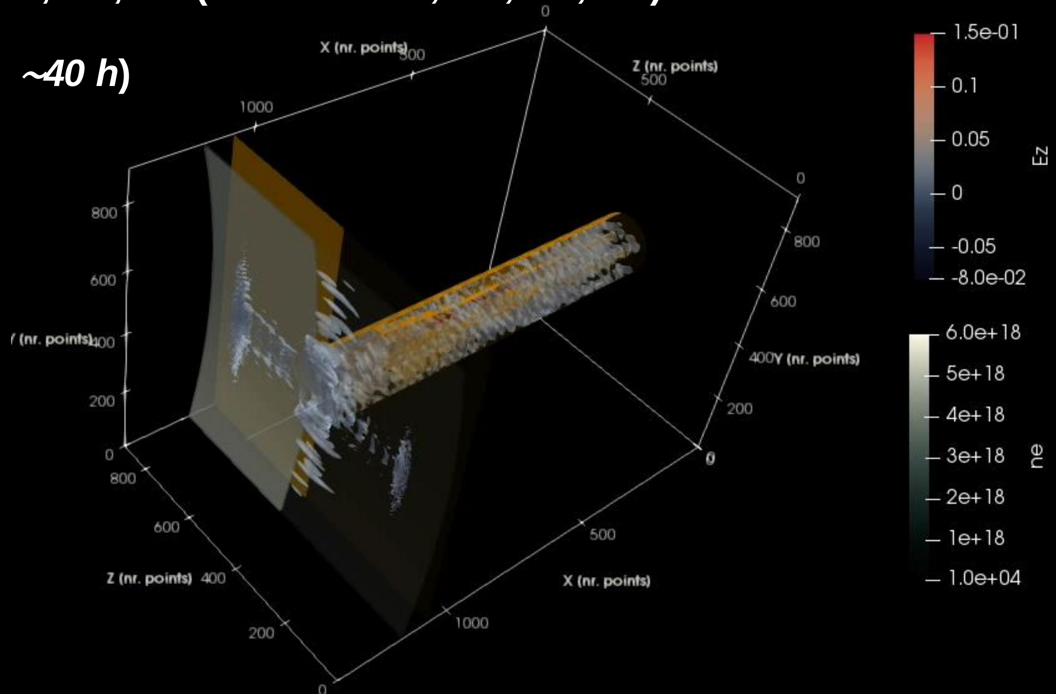
Gap 0° LFS K (&Ka) band(s) for LFS DTT PPR

3D

Grid size: K band — 1348×899x899 (*Ka band — 2033×1356×1356*) Nr. of iterations: 120,000
Total nr. Grid points: K band —1,089,454,948 (*Ka band — 3,738,150,288*)
Nr. of iterations: 120,000
Wallclock: K band ~ 7h (*Ka band: ~40 h*)

Ran on Marconi Skylake
Nr. Nodes: 64 nodes (3,072 cores)
Nr. Tasks/node (MPI tasks/node): 4
Total nr. MPI tasks: 256
Nr. OpenMP threads/task: 12





Simulated with REFMULF (2D) & REFMUL3 (3D) codes

2D

Grid size: K band — 1348×899 (*Ka band — 2033×1356*) Nr. of iterations: 120,000
Total nr. Grid points: K band —1,211,852 (*Ka band — 2,756,748*)
Nr. of iterations: 120,000
Wallclock: K band ~ 7min (*Ka band: ~18min*)

Ran on Marconi Skylake
Nr. Nodes: 1 node (48 cores)
Nr. OpenMP threads/task: 48

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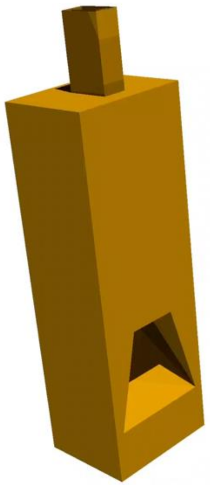
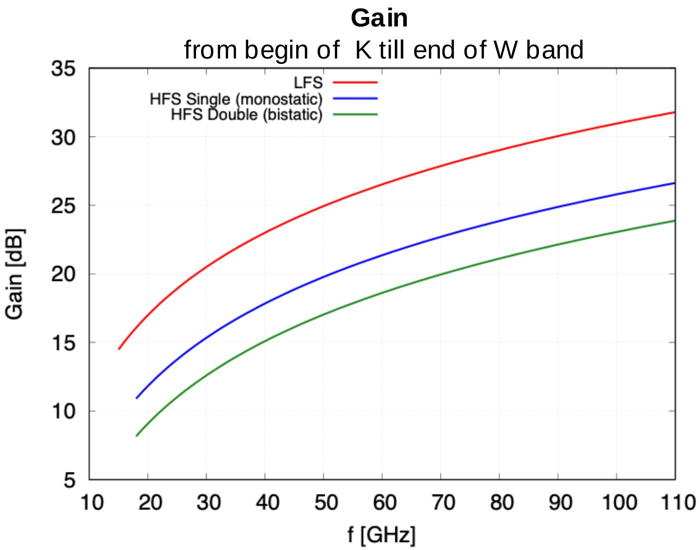
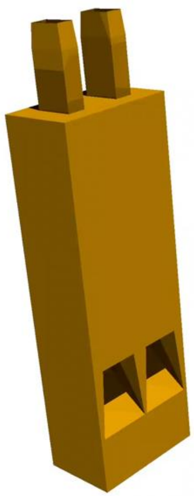
Design of antennas for HFS PPR implementation

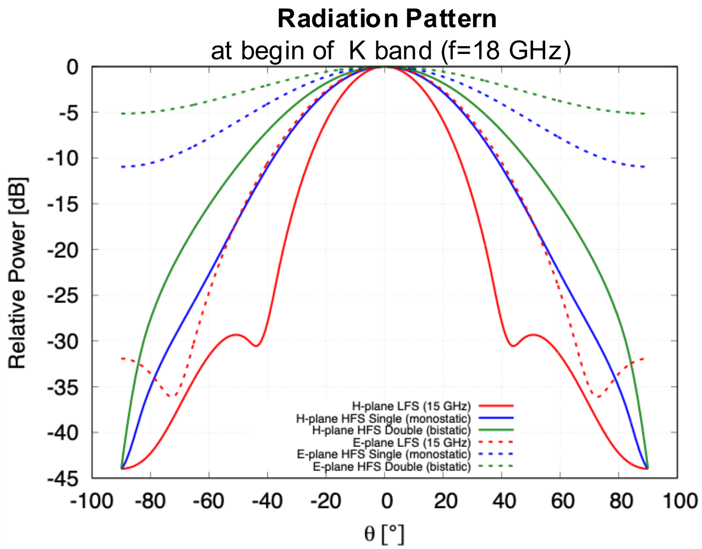
Newly designed HFS antenna (single)

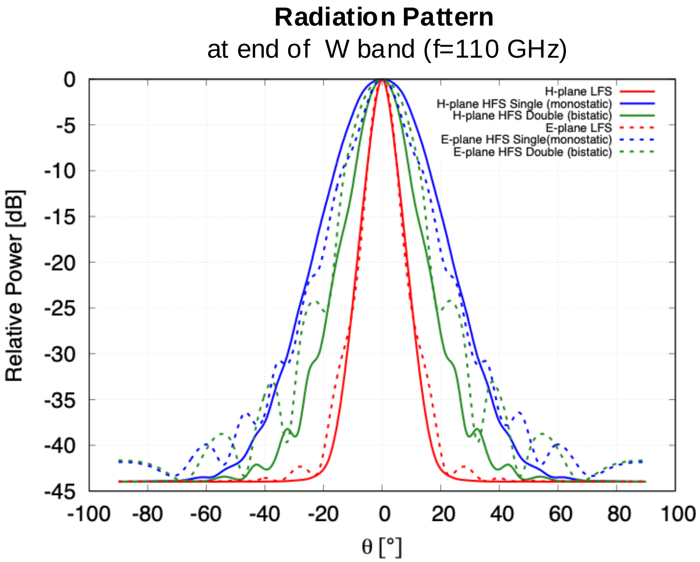




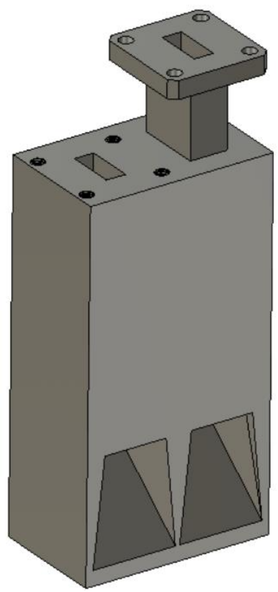
Newly designed HFS antenna (double)

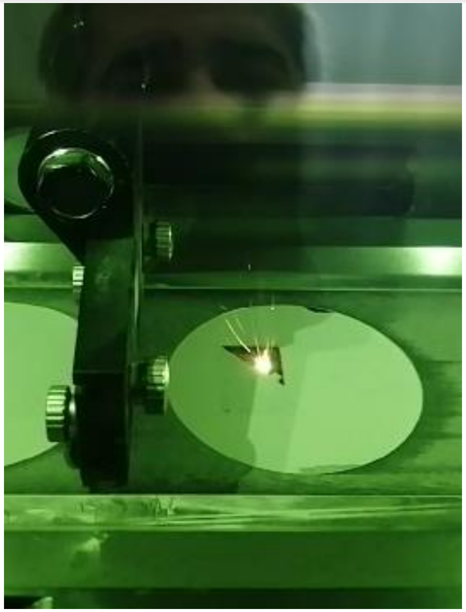




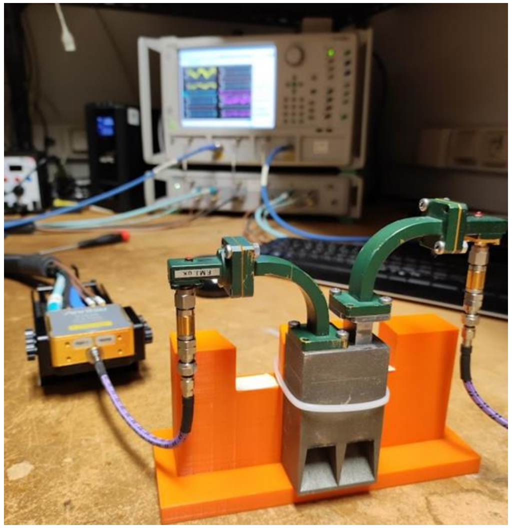


Laboratory measurements of 3D printed metal

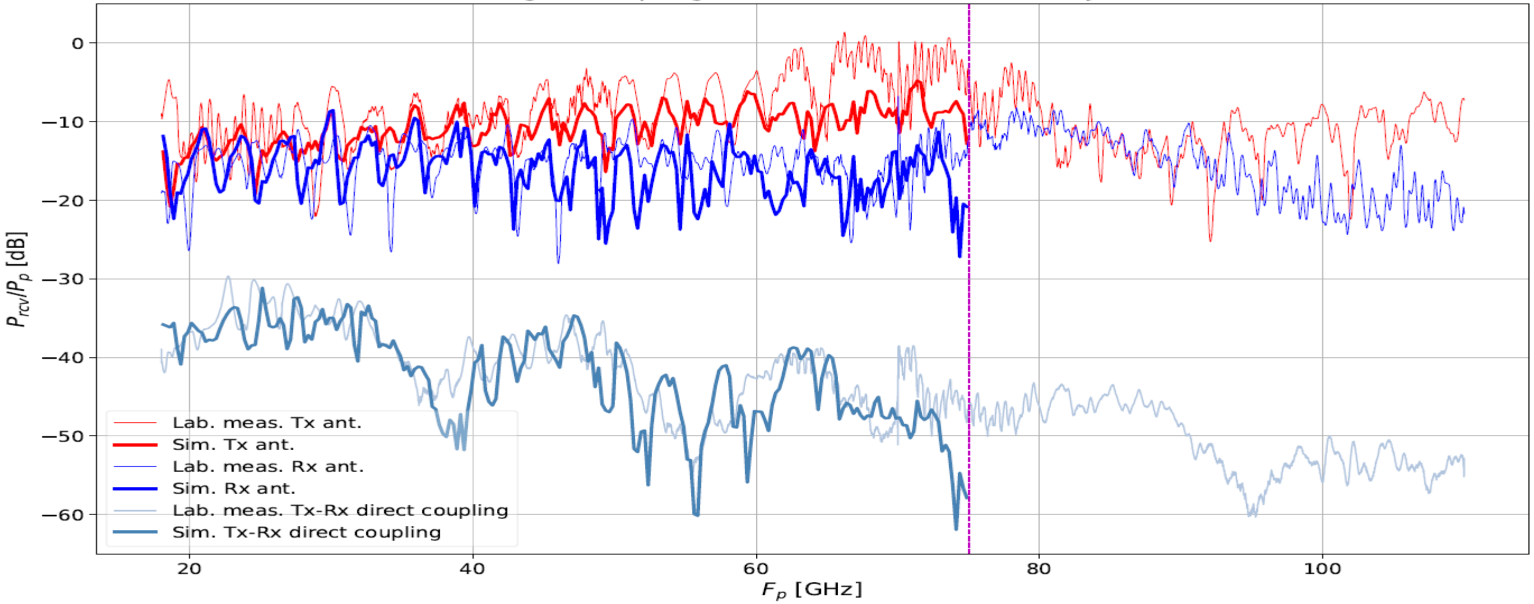




Bistatic antenna mockup



Bistatic antenna signal coupling (mirror at 5cm) - Laboratory Test vs Simulation



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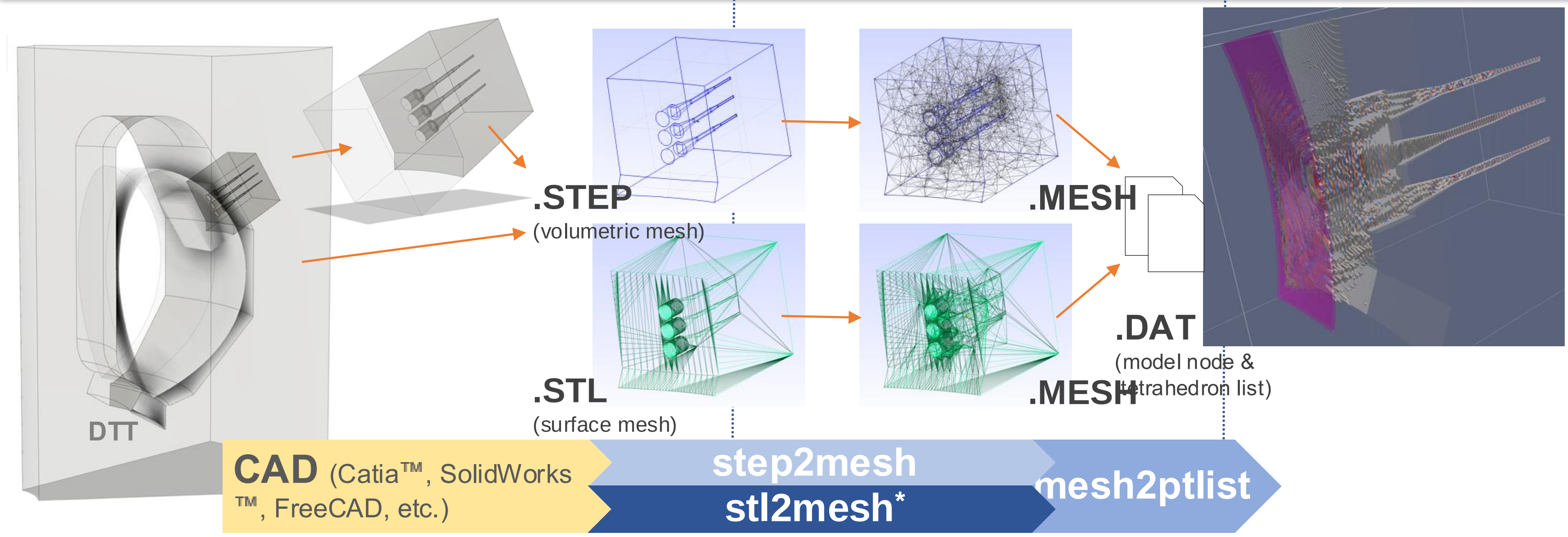
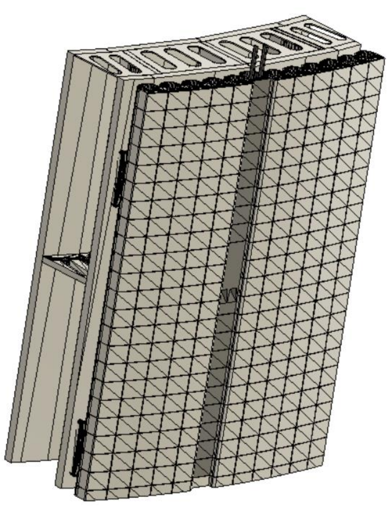
Excellent match to simulation results done with REFMUL3

A CAD import pipeline developed



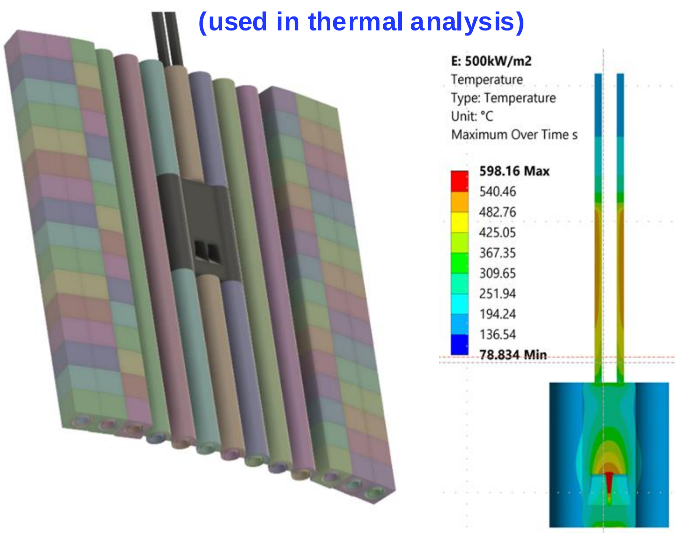
First design concept

Used on EnR bulk studies



DTT current wall design

(used in thermal analysis)



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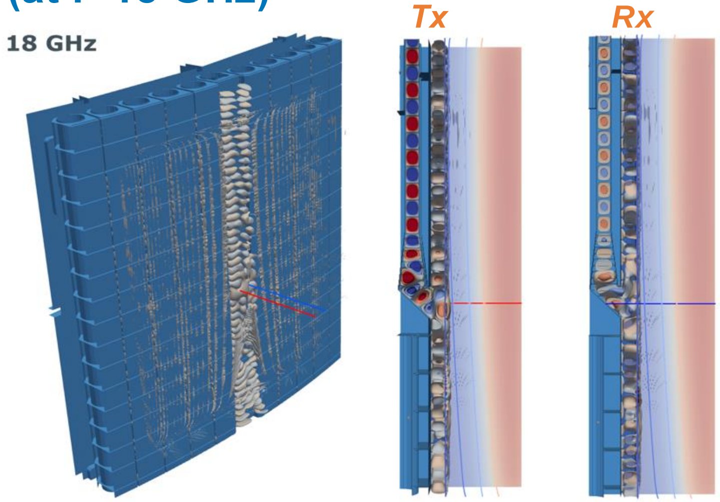
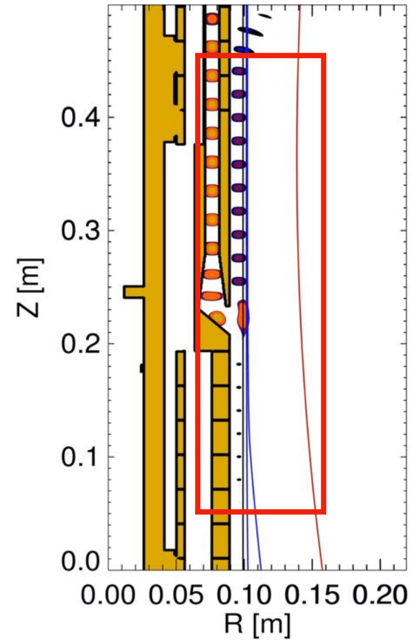
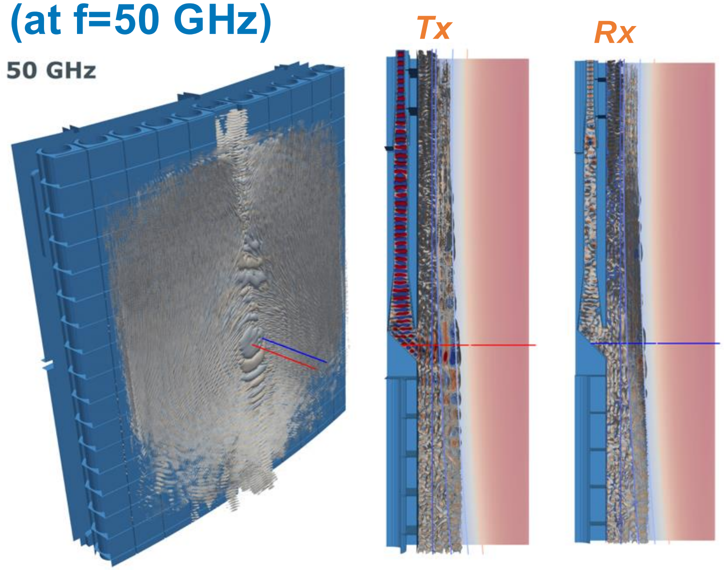
HFS 3D vs 2D qualitative comparison w/ plasma

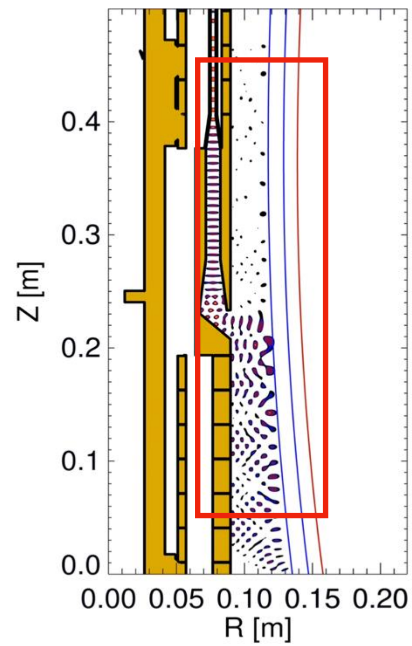
K band (at f=18 GHz)





V band (at f=50 GHz)





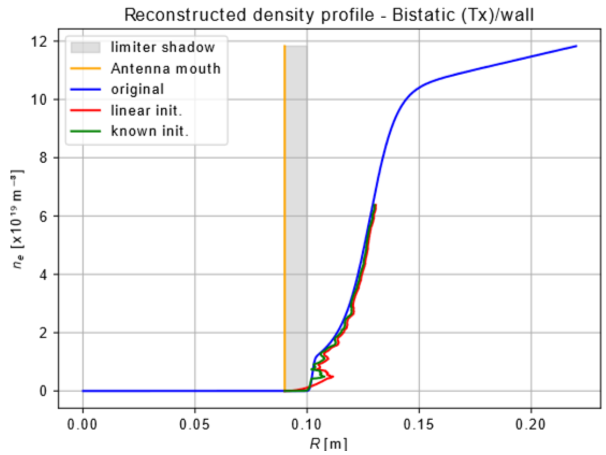
Simulated with REFMUL3(3D) & REFMULF (2D) codes

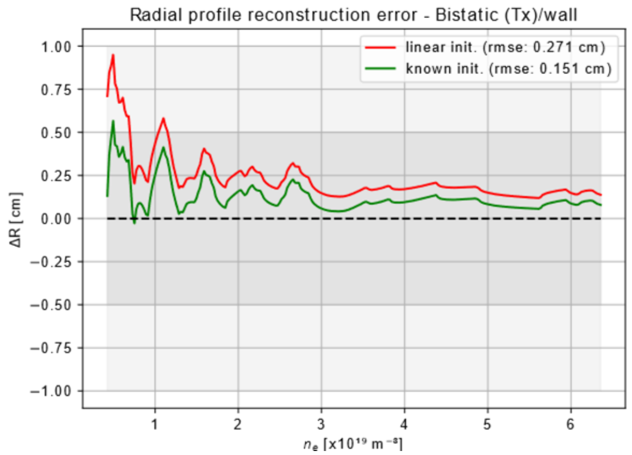
Filipe da Silva, ENR-TEC.01.IST

3D fullwave simulations: Bistatic antenna / Std. Single Null plasma

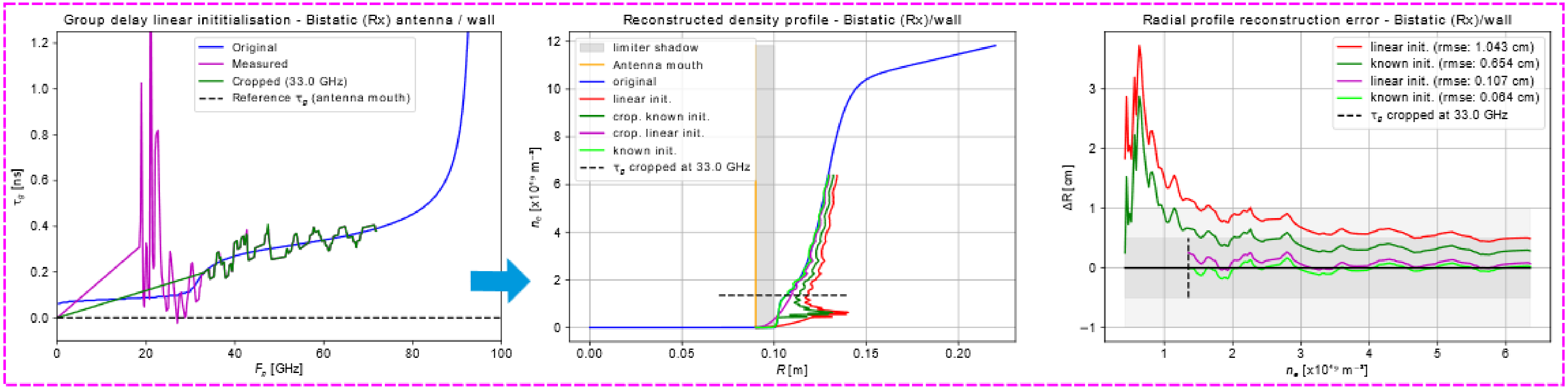
Δ R << 1 cm for n_e > ≈ $1.5\text{x}10^{19}$ m^{-3}

Bistatic antenna - Tx **LOS**





Bistatic antenna - **Rx LOS**



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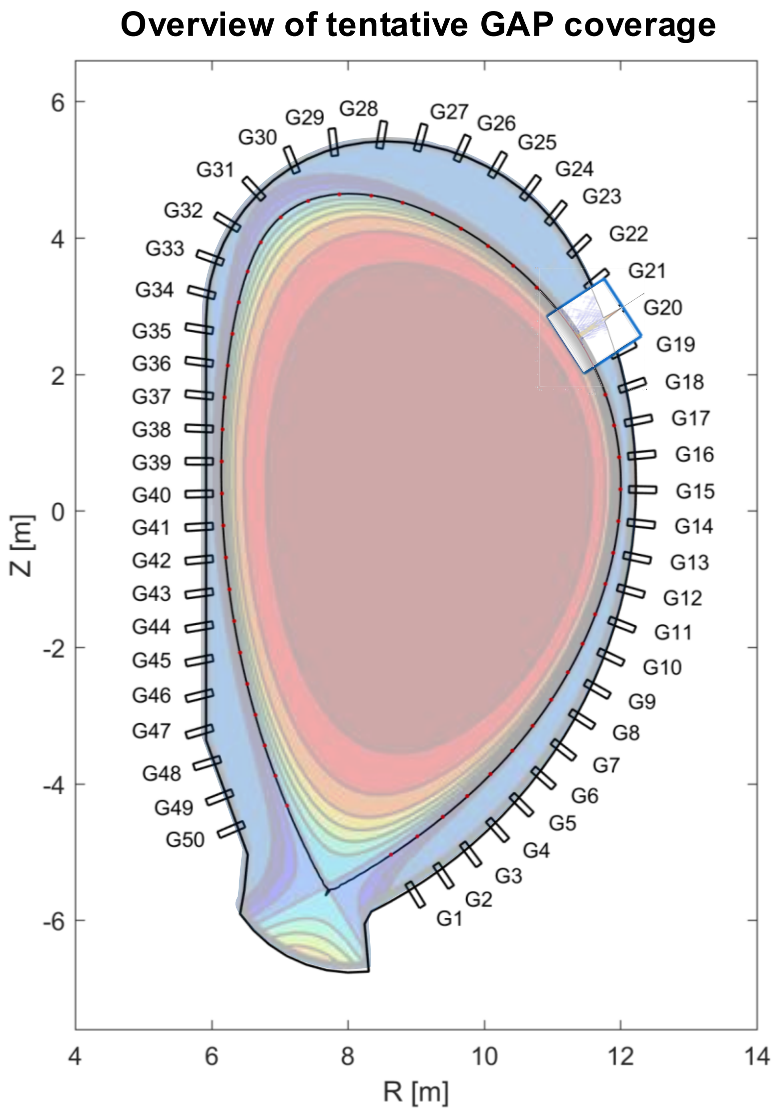
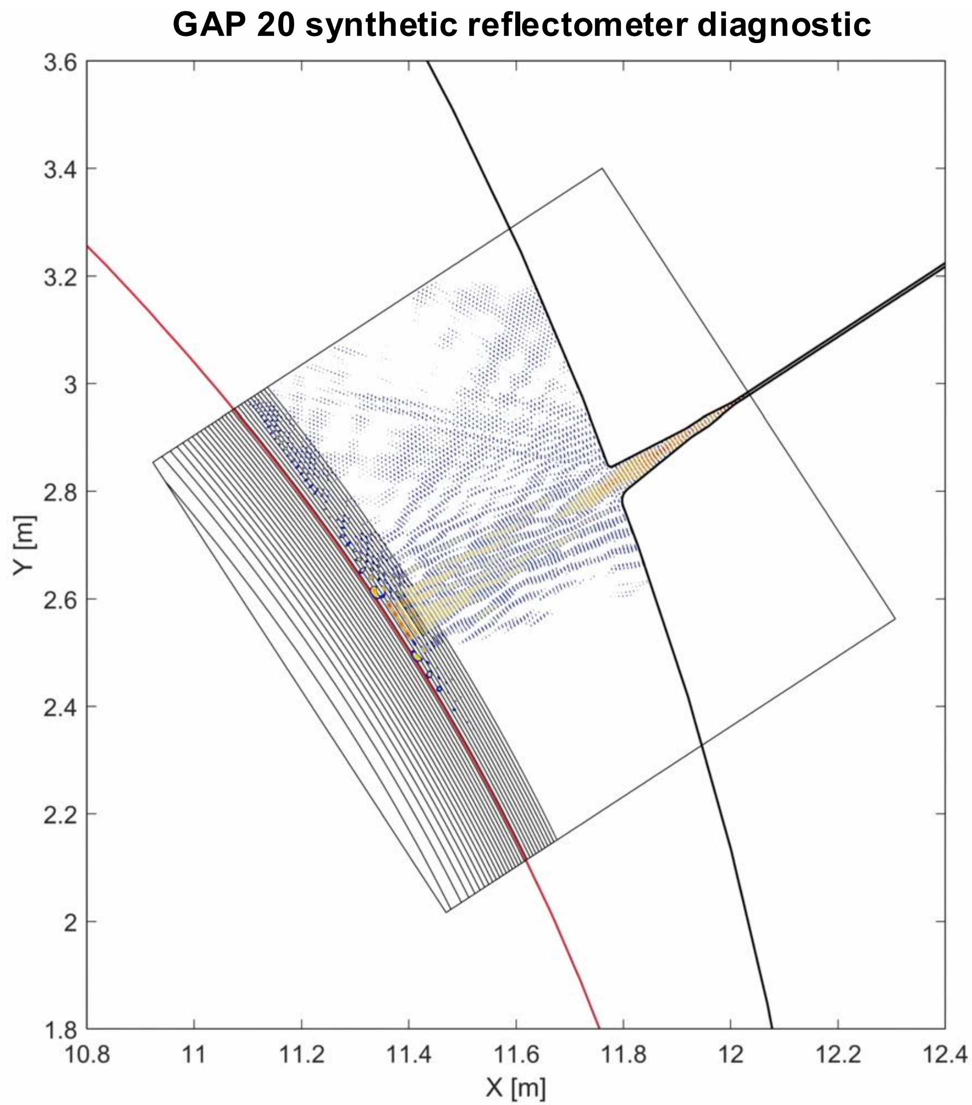
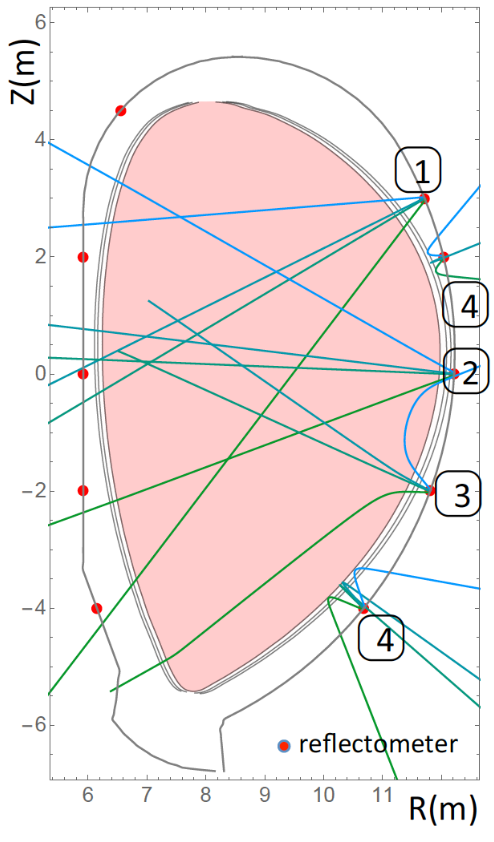
DEMO Steady state comprehensively studied

Algorithms for steady state





E. Ricardo, PhD Work/ENR



0 Vacuum

1 Interferometry $f_{prob} > 5 f_{p_{max}}$

2 Refractometry $f_{prob} > 3 f_{p_{max}}$

3 Intensity refractometry

4 Reflectometry $f_{prob} < f_{p_{max}}$

Vacuum necessary to calibrate the system

N**vac* ***- Nr. of receivers N with signal in vacuum

When sweeping the frequency from a lower to a upper frequency, the order of the interpretative models is:

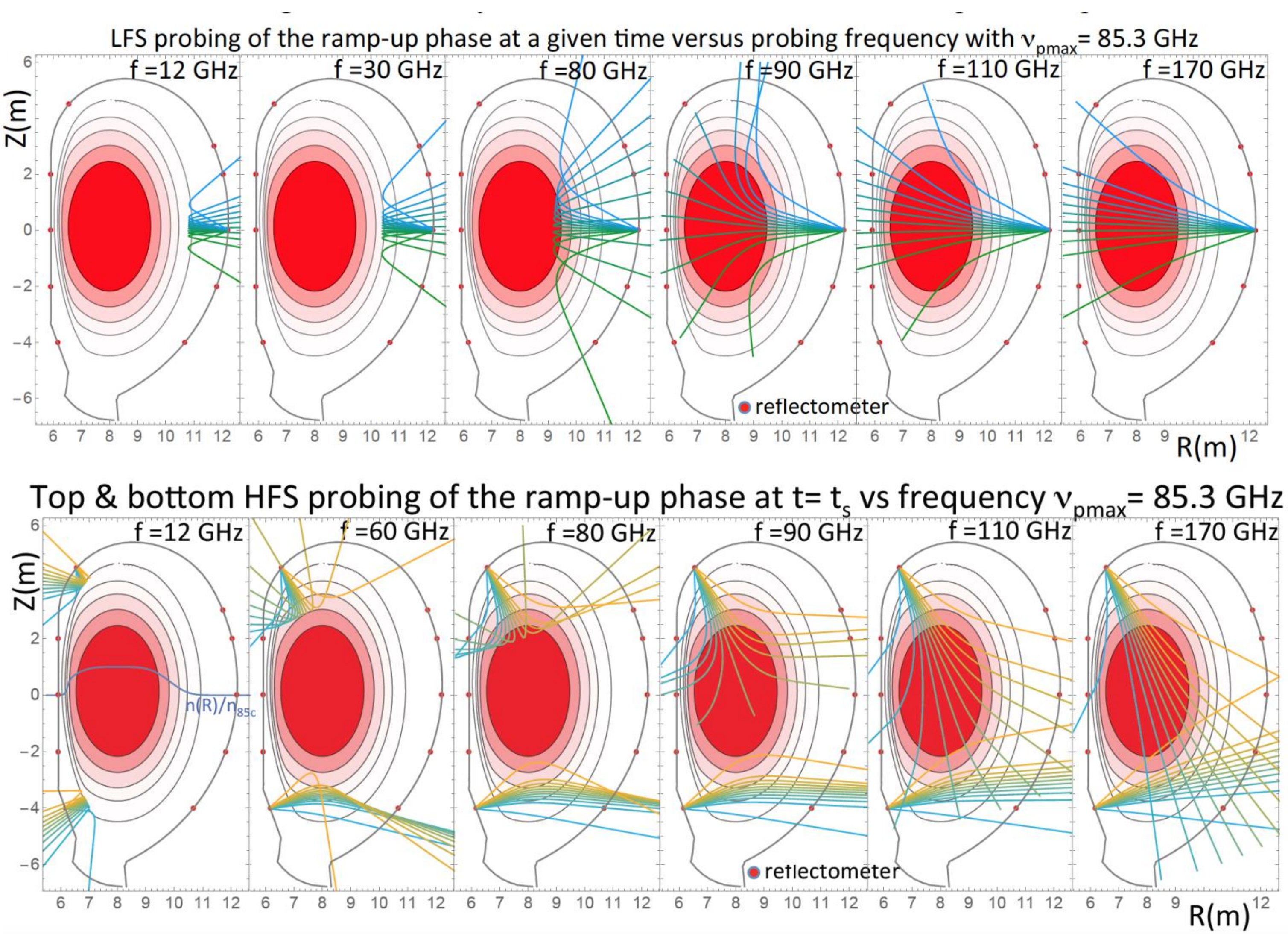
Reflectometry → Intensity refractometry → Refractometry → Interferometry

N=1 ***N>Nvac*** ***N=Nvac*** ***N=Nvac***

Initial interpretative model $f(f_{p_{max}})$

Identification of operational cases: *devising procedure algorithms*

Algorithms for ramp-up



Reflectometry → Intensity refractometry → Refractometry → Interferometry

S. Heuraux, Report on the microwave tomography-reflectometry based on plasma positioning reflectometry system to control the ramp-up phase of DEMO, September 2022

Validation of the use of ray tracing…

- **The exercises previously shown, can provide:**
  - *Good proxy of the **time of flight**.*
  - *A idea of the **phase**.*
  - ***Amplitude** far from full wave response.*
- **Amplitude knowledge essential**
  - *Determine if enough power can be detected after a long path (**feasibility**)*
  - *Interpret data in intensity refractometry*

Evaluated @Antenna mouth

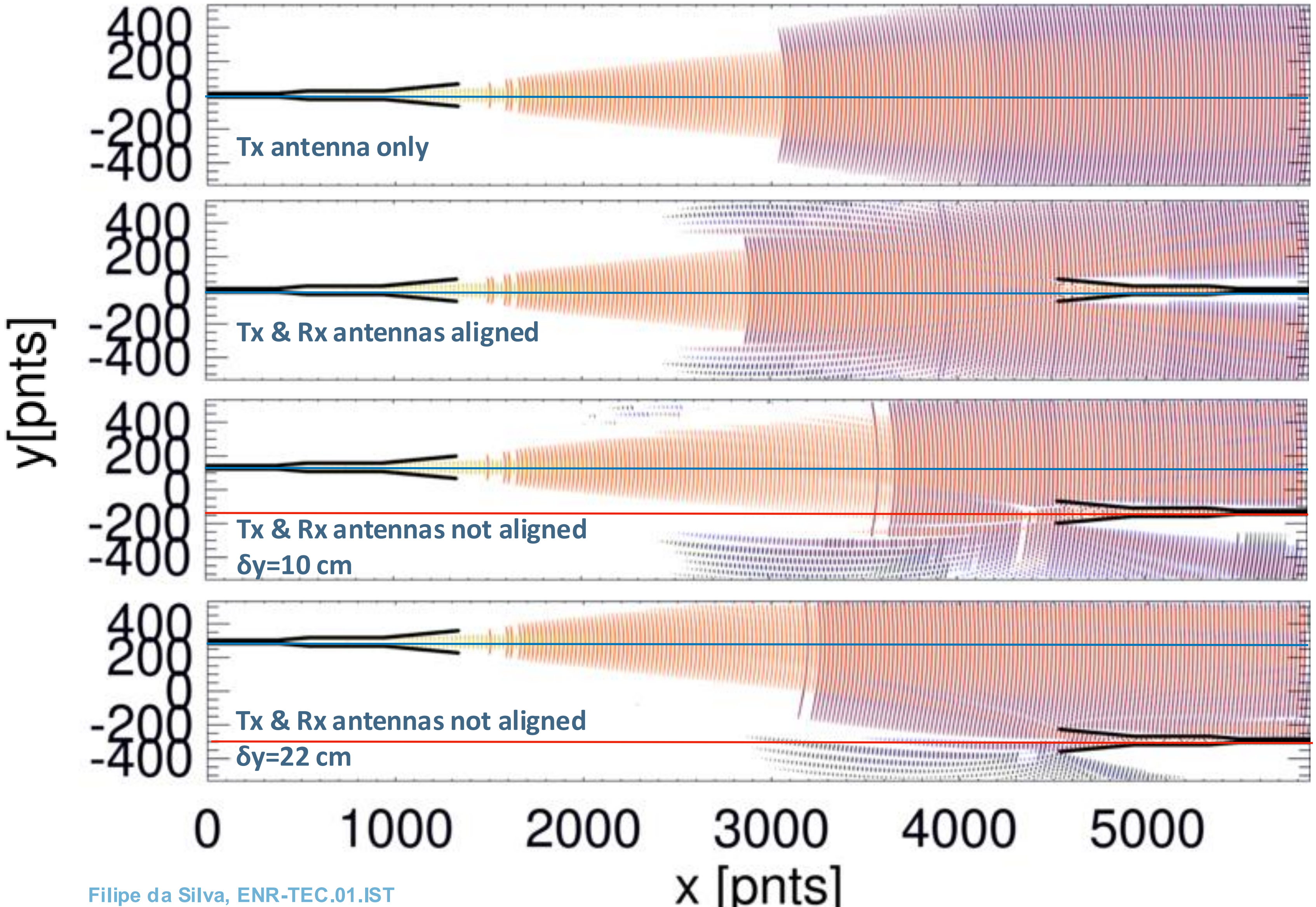
Full wave results, obtained with FDTD code, are evaluated at the fundamental wave guide, taking into account the receiving structure.

Deeper modelling of the receiver is needed to close the gap between ray tracing and full wave

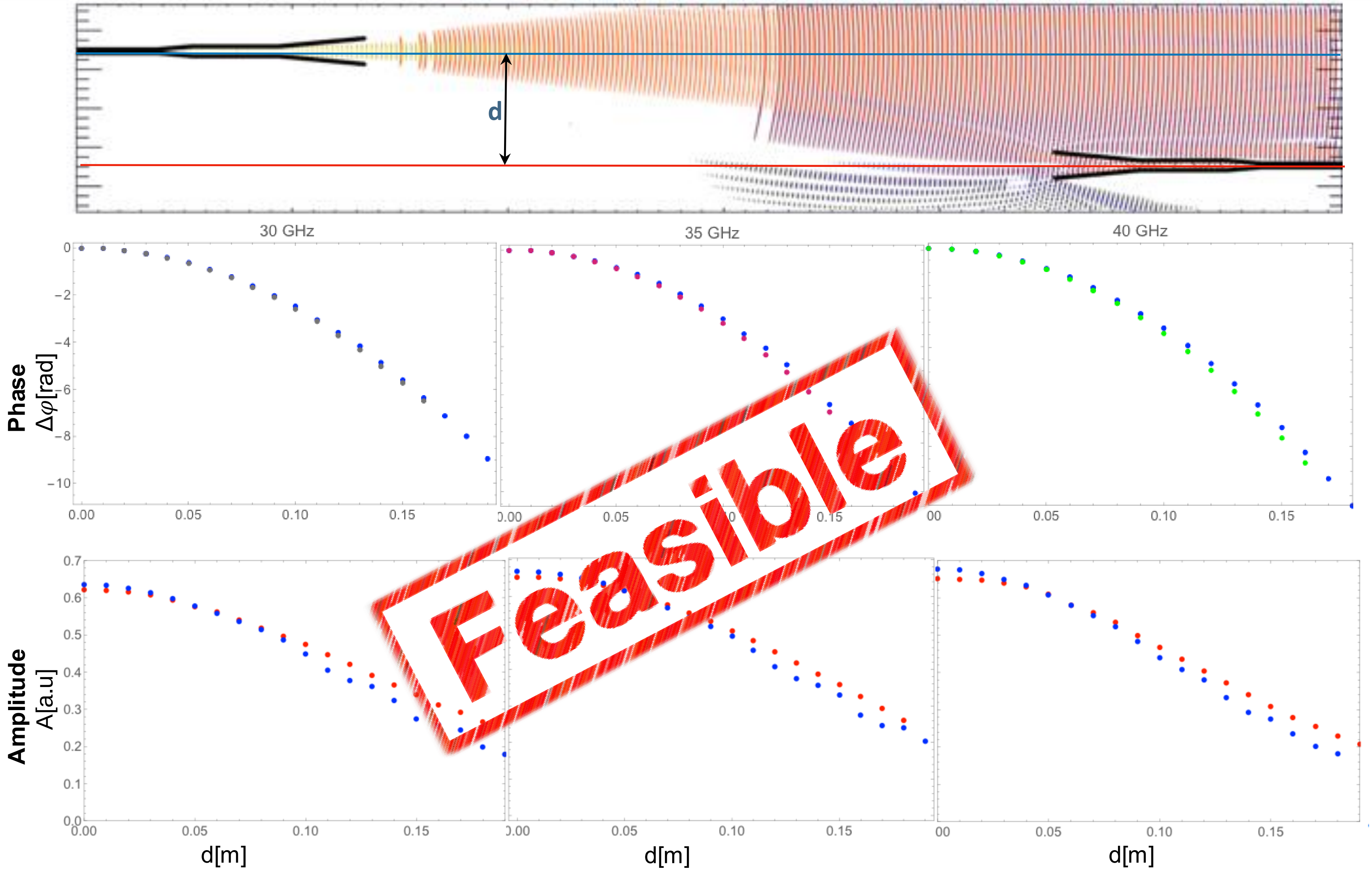
- **Reconstruction of the complex electromagnetic field @antenna mouth**
- **Detection on the fundamental waveguide**
  - *Rejection associated with radiation pattern.*
  - *Projection of the into fundamental mode.*
  - *Access the amplitude and phase of the detected wave.*

Full wave model to assess RT enhanced detection

Full-wave support for ray trace studies of ramp up



Full wave vs. Ray tracing with *improved detection*



●Full wave ●● Ray tracing

Filipe da Silva, ENR-TEC.01.IST

S. Heuraux, Report on the microwave tomography-reflectometry based on plasma positioning reflectometry system to control the ramp-up phase of DEMO, Part II, December 2023

Scientific output under ENR-TEC.01.IST in 2023

Summing up…

These add to an EnR total output of:

- **10 Communications to Conferences and workshops**

- **5 Papers in peer reviewed journals**

…more output is expected in the wake of EnR

Associated EUROfusion HPC Projects and ACH support

TEN Projects under the EUROfusion HPC Project in past cycles

Three new projects running on **EUROfusion HPC** Project **8th cycle** *(started the 15th March 2024)*

- **EnR4DEMO** *Advances in real-time reflectometry for next generation machines.*
  - 1,849,920 node-hours asked. ☛ *24,167 node hours*
- **PPRclust** 3D reflectometry simulations for DEMO PPR antenna clusters
  - 1,000,000 node-hours asked. ☛ *29,000 node hours*
- **DTT_HPPR** 3D reflectometry simulation for DTT HFS PPR
  - 1,000,000 node-hours asked. ☛ *29,000 node hours*

An EUROfusion **Advanced Computing Hub** support for the EnR successful completed in 2023

- Adaptation of **REFMUL3** to run on **GPU HPCs**

Summary of the work achieved

Development of synthetic diagnostics

- DEMO and DTT density inputs for simulation codes – **Available information collected**
- Developments in FDTD codes (+REFMUL3) - **Completed (surpassed objectives)**
- Developments in description of structures - **Completed (surpassed objectives)**
- Developments in description of plasma scenarios - **Completed (surpassed objectives)**

Development of new algorithms

- For steady state - **Completed**
- For ramp-up - **Completed**

Synchronisation between different reflectometers

- An experimental validation on the tokamak WEST – **Continuing on the wake of EnR**

Advances on reflectometry hardware are contemplated

- Compact reflectometer prototype using MMIC with DDS signal generation – **Completed**

DDS Continuing on the wake of EnR

DTT as a possible testbed for DEMO

- Synthetic diagnostics for simulation and algorithms - **Completed**
- Design of antennas for a possible PPR implementation - **Completed**

Added to the initial proposal