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

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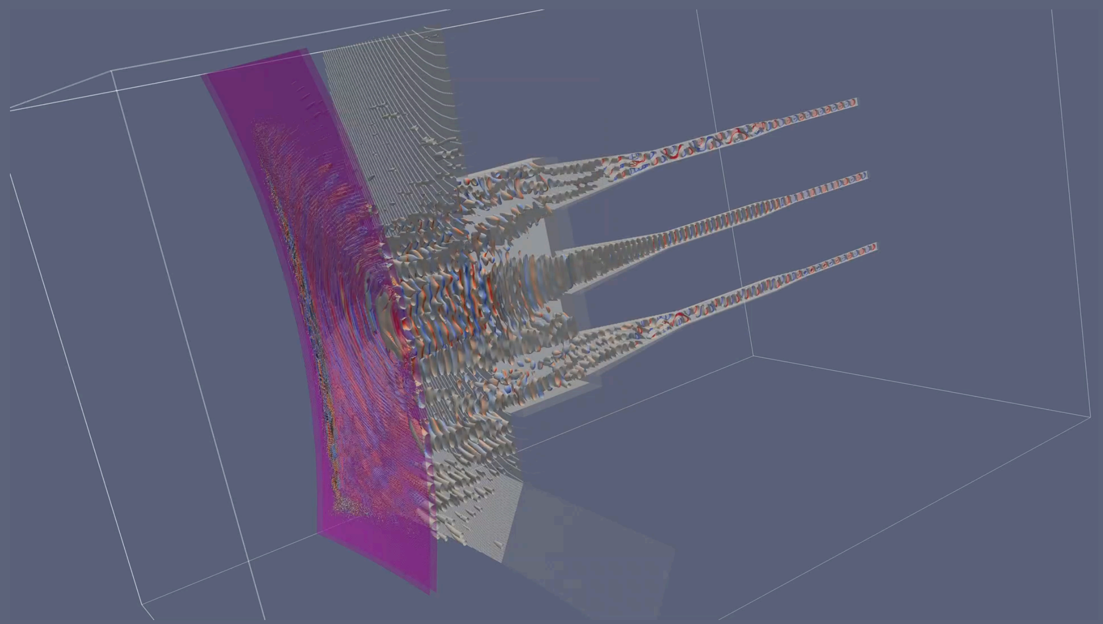


Collaborations:* *Tiago Ribeiro, P. R. Resendes, J.C.C. Abrantes, Raul Luís, Yohanes Nietiadi

Lisbon, 5 February 2024, 7th Scientific Board - Technology & Systems

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

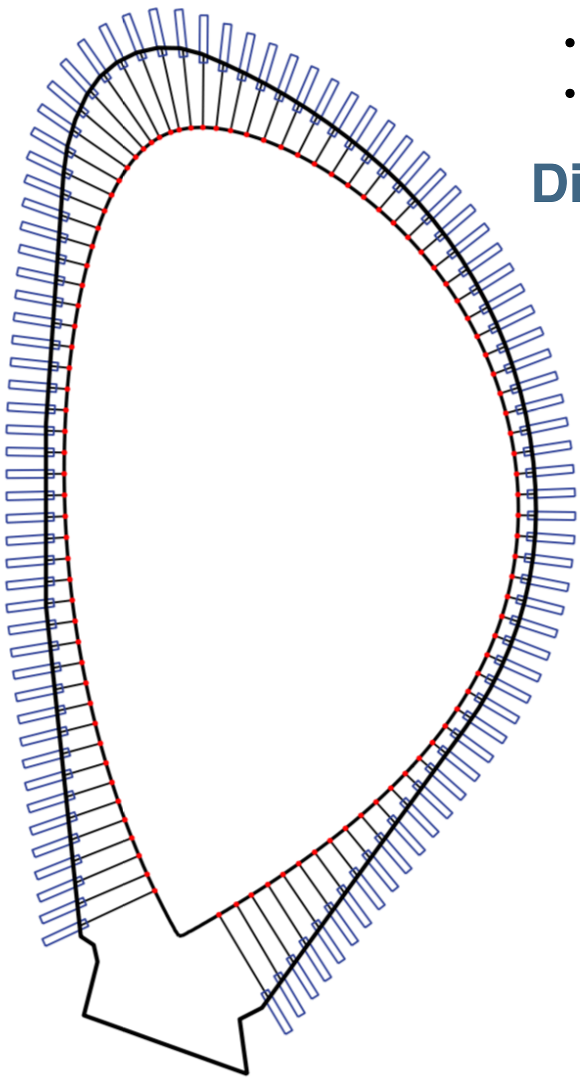
With unprecedented capabilities to diagnose the electronic density and track the position and shape of the plasma column

(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

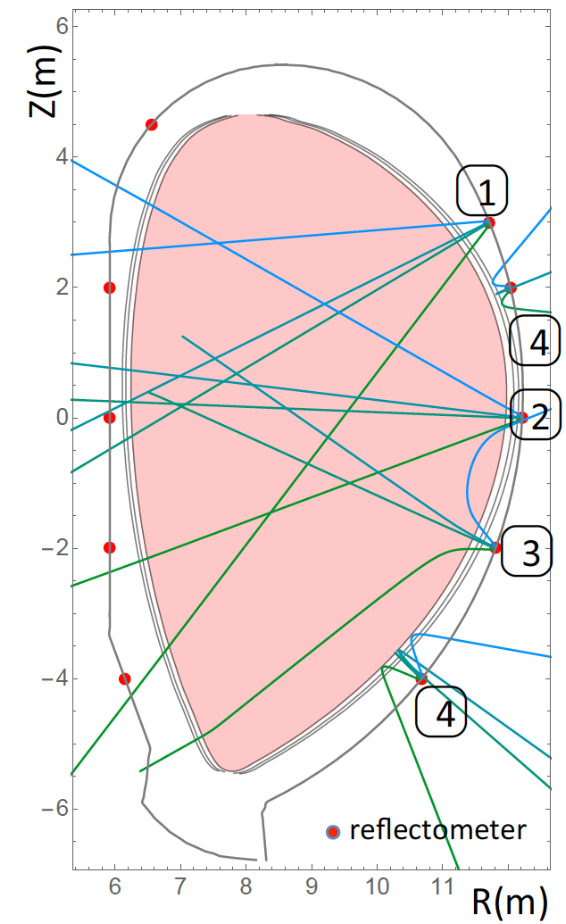
  1 Interferometry

  2 Refractometry

  3 Intensity refractometry

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

  4 Reflectometry



S. Heuraux, September 2022.

Fields being developed

Development of synthetic diagnostics

- DEMO and DTT density inputs for simulation codes - ***On schedule***
- Developments in FDTD codes (+REMUL3) - **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 - **On schedule with work intensifying in the remainder of EnR**

Synchronisation between different reflectometers

- An experimental validation on the tokamak WEST - **Advancing**

Advances on reflectometry hardware are contemplated

- Compact reflectometer prototype using MMIC with DDS signal generation - **On schedule**

DTT as a possible testbed for DEMO

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

Added to the initial proposal

Main Scientific output in 2023 (I)

- **One of the main objectives of the project, to follow the plasma position and shape during the ramp up.**
  - *The basic physics of the diagnostic and operational principles established.*
  - *The different operational cases and regimes identified.*
  - ***The numerical tools and procedures thoroughly evaluated and ratified.***
  - ***Feasibility of the diagnostic promising.***

- **Adaptation of the 3D fullwave code REFMUL3 to run on GPU.**
  - *Associated to a Enabling Research call of Advanced Computing Hub support.*
  - *Runs on GPU using OpenMP offloading.*
  - *Successfully tested on Leonardo, a pre-exascale HPC.*
  - *Used by third party as a for testing purposes at LEONARDO, before its official production phase.*

Main Scientific output in 2023 (II)

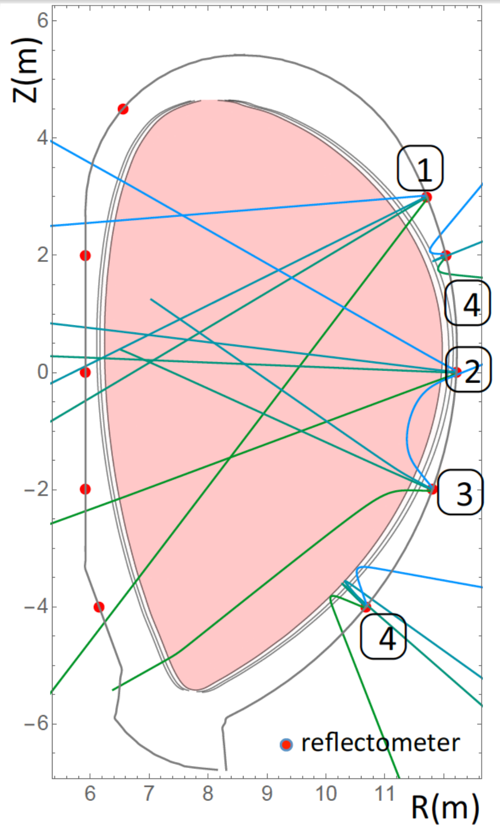
- **Application of an integrated design workflow for a PPR diagnostic system.**
  - *Uses common CAD models of antenna and first wall components.*
  - *Incorporates 3D target plasma scenarios obtained from equilibria simulations.*
  - *Design of custom made antennas.*
  - *Laser metal printed prototypes of the antennas.*
  - *Laboratorial tests of the antenna prototype using the compact reflectometer*
  - *Thermal analysis of plasma facing components*
  - *3D full wave FDTD simulations both in vacuum and with plasma assessed the performance.*

This effort integrates many of the modules that have been worked or developed in this 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;*
4. *Use of the enhanced signal processing techniques;*
5. *Advances in numerical simulation codes;*

Different modes of operation with different interpretative models

Algorithms for ramp-up



0 Vacuum

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

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

3 Intensity refractometry

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

0 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:

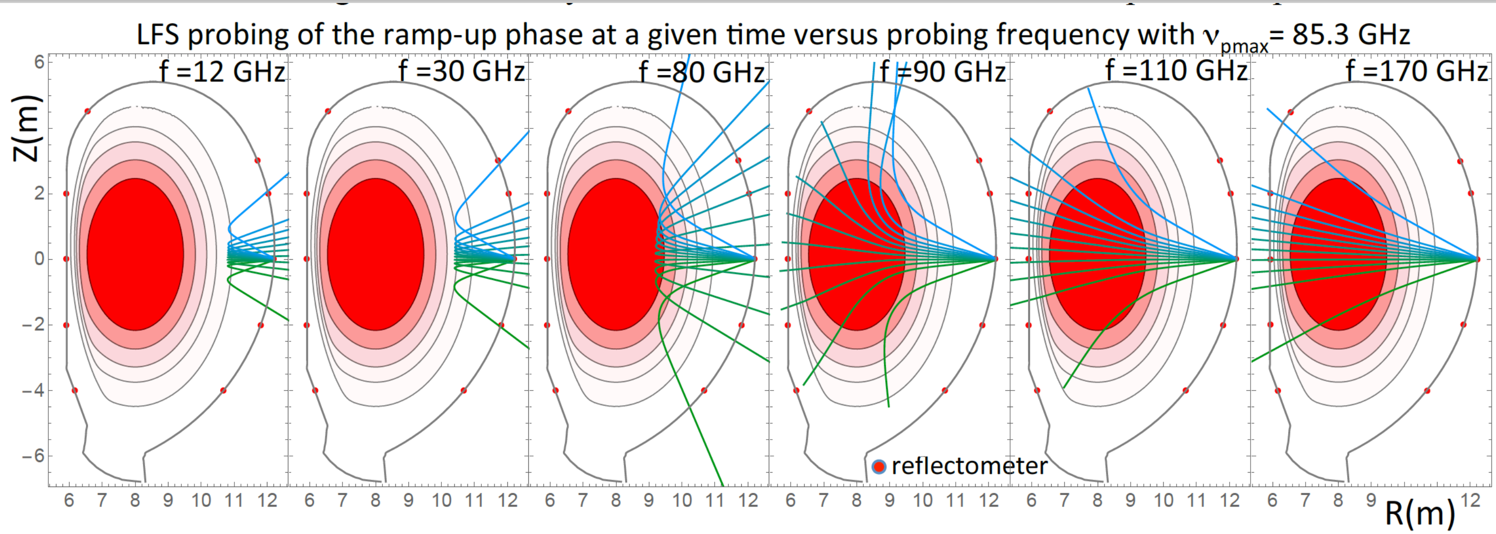
4 Reflectometry ➡ **3** Intensity refractometry ➡ **2** Refractometry ➡ **1** Interferometry

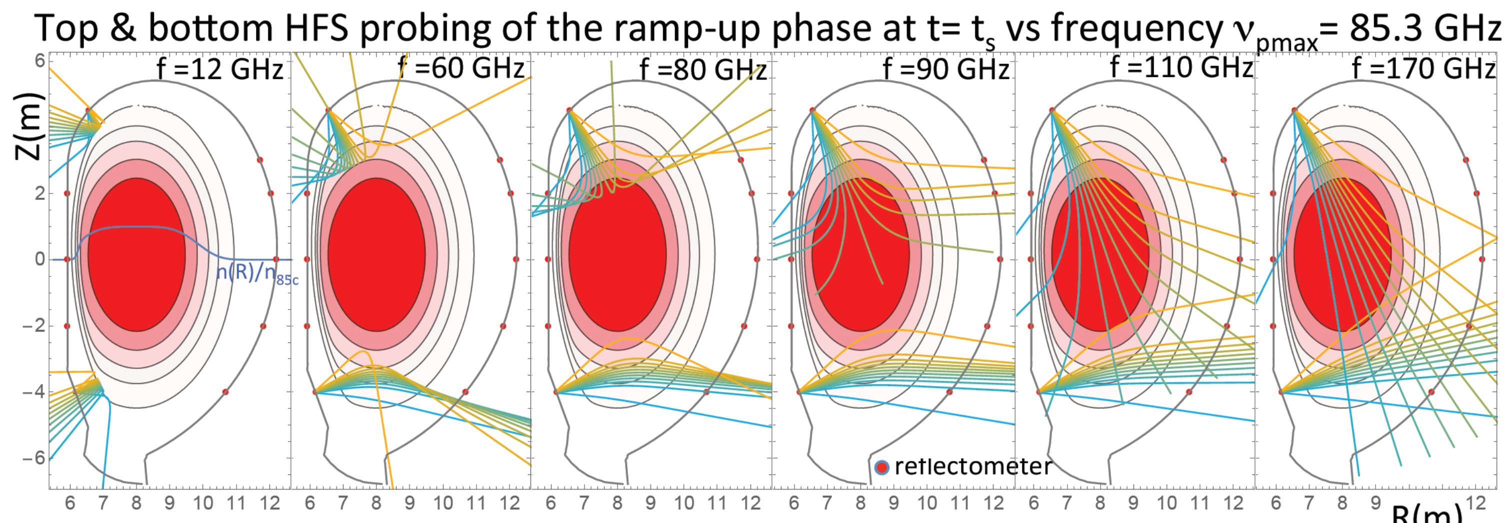
N=1 ***N>N_{vac}*** ***N=N_{vac}*** ***N=N_{vac}***

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

Identification of operational cases: *devising procedure algorithms*

Algorithms for ramp-up





4 Reflectometry ➡ 3 Intensity refractometry ➡ 2 Refractometry ➡ 1 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.*

  } **Evaluated @Antenna mouth**

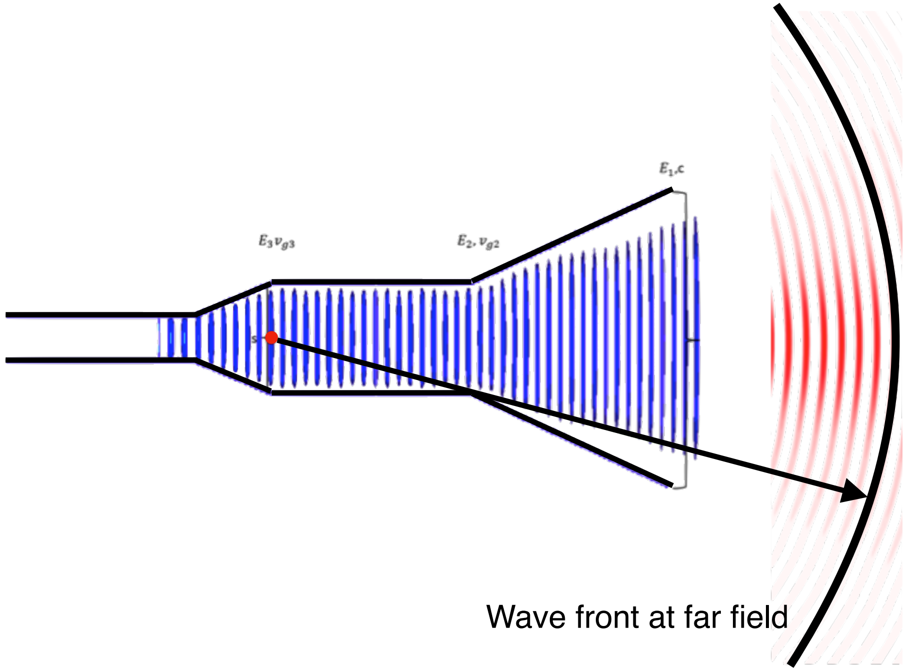
- **Amplitude knowledge essential**
  - *Determine if enough power can be detected after a long path (**feasibility**)*
  - *Interpret data in intensity refractometry*

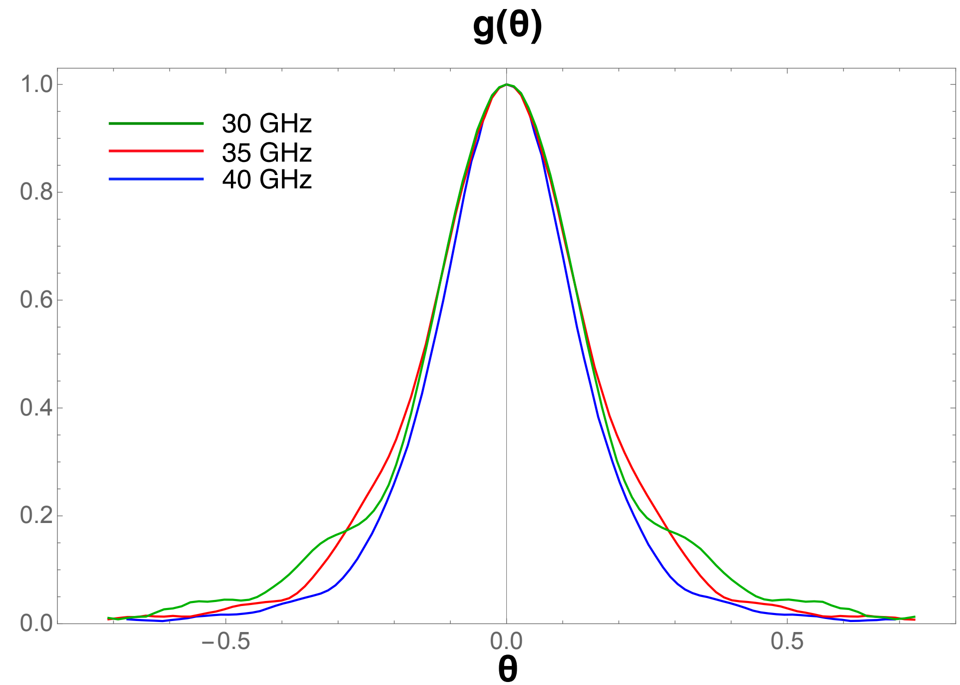
Full wave results, obtained with FDTD code, are evaluated at the fundamental wave guide, taking into account the receiving structure.

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

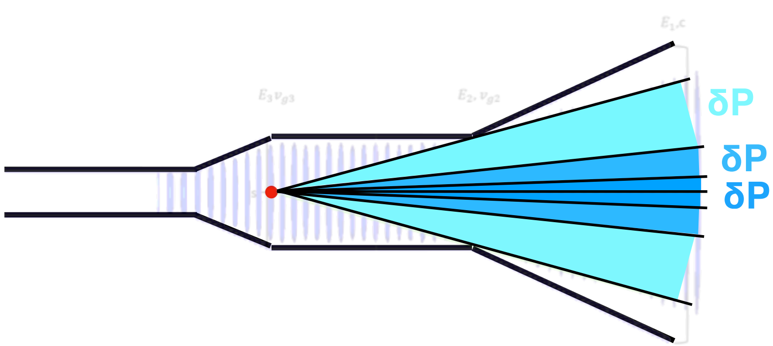
- **Reconstruction of the complex electromagnetic field @antenna mouth**
- **Detection on the fundamental waveguide**
  - *Rejection associated with radiation pattern.*
  - *Projection of the into fundamental mode.*
  - *Access the amplitude and phase of the detected wave.*

Radiation pattern needed to RT emission



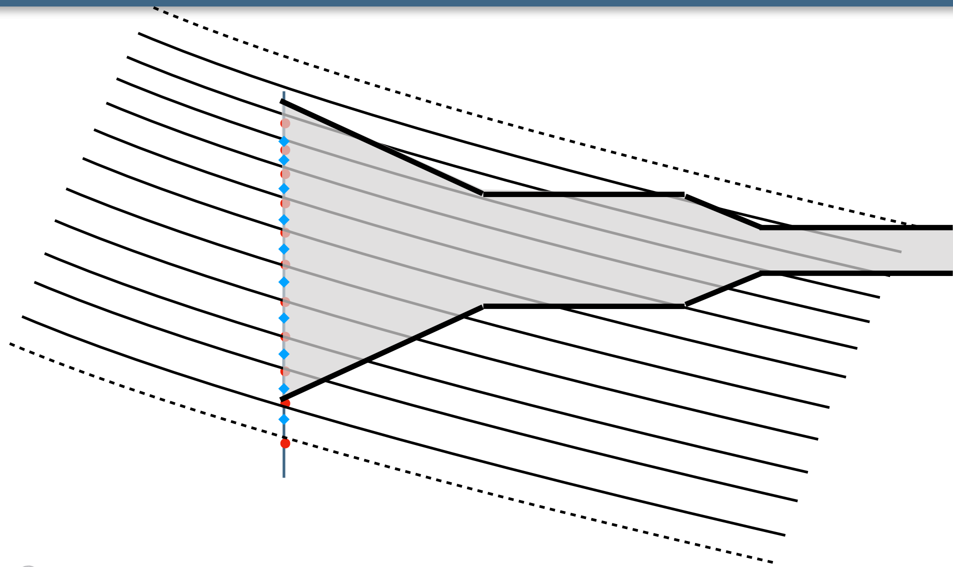


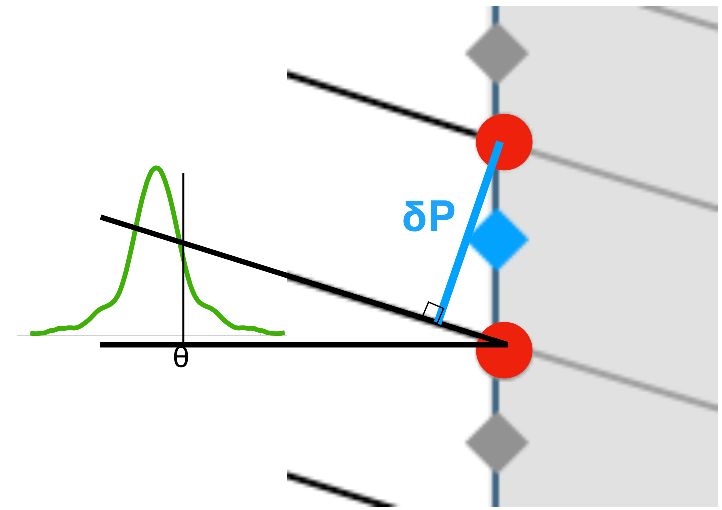
- **Exact** *radiation pattern g(θ) is essential.*
- *Evaluated from **full wave** simulation for each frequency.*
- *g(θ) interpolated from sampled (θ,E/E_{max}).*



- *Total emitted power calculated from* **∫g(θ)dθ.**
- **δP** elementary power between adjacente rays constant.
- Injection angles ***θ_j*** *calculated.*

Modelling the reception

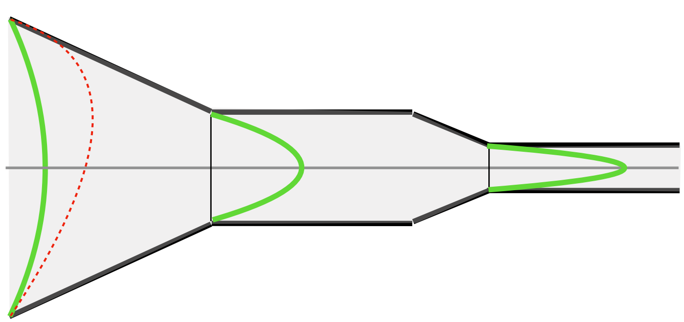




- Identification of the rays used to compute the amplitude
- *Compute normal distance between adjacent rays.*
- *EM flux conservation to determine amplitude* ◆
- *Weighting of the amplitude from the incident angle **θ***
- *Amplitude **A(s)** along an antenna mouth coordinate **s***
- *Phase (●) and time of flight (●) referred to **s, φ(s) τ(s)***

Computation of the complex electric field

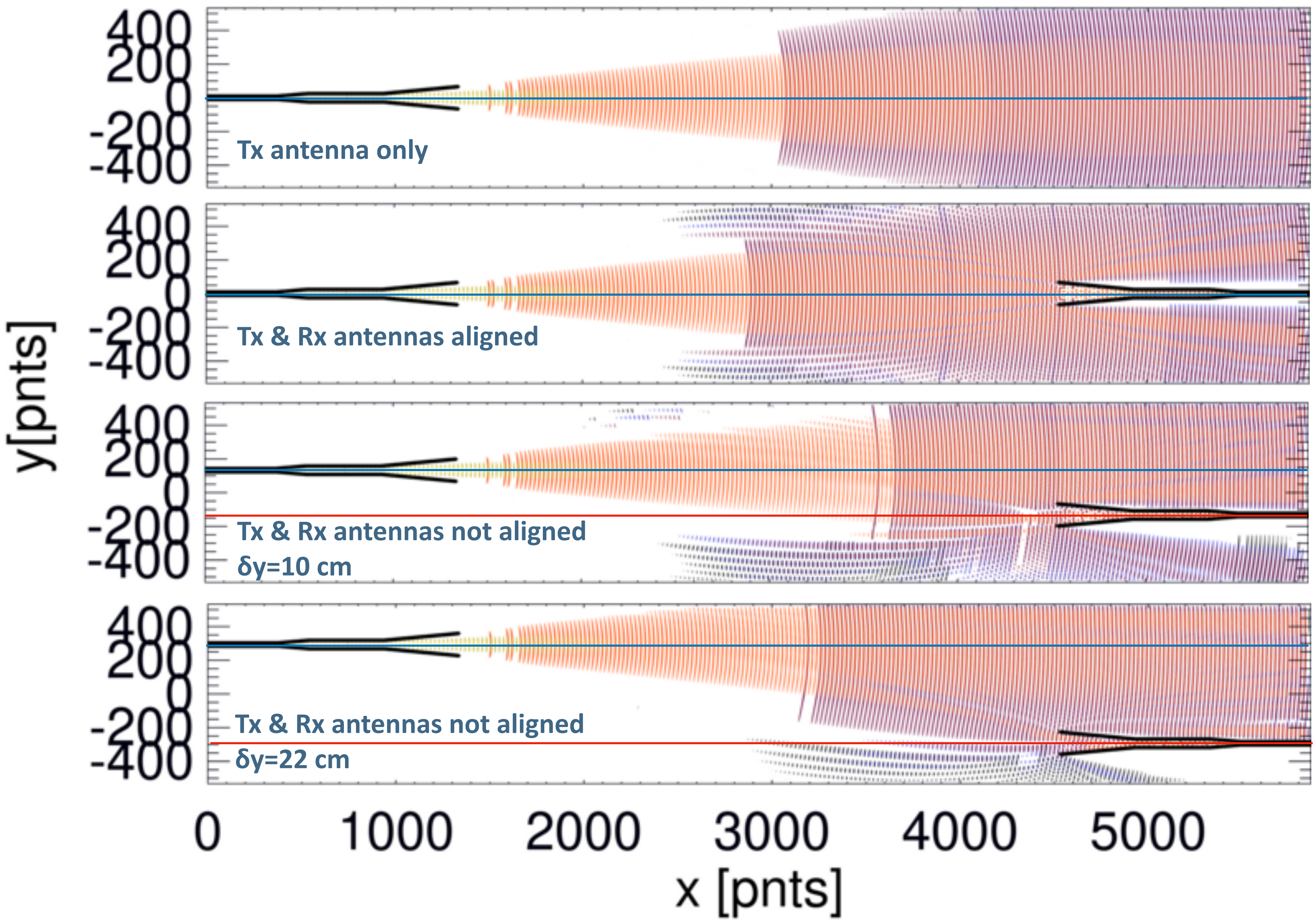
$$E(s)=A(s)\, e^{i\varphi(s)}$$



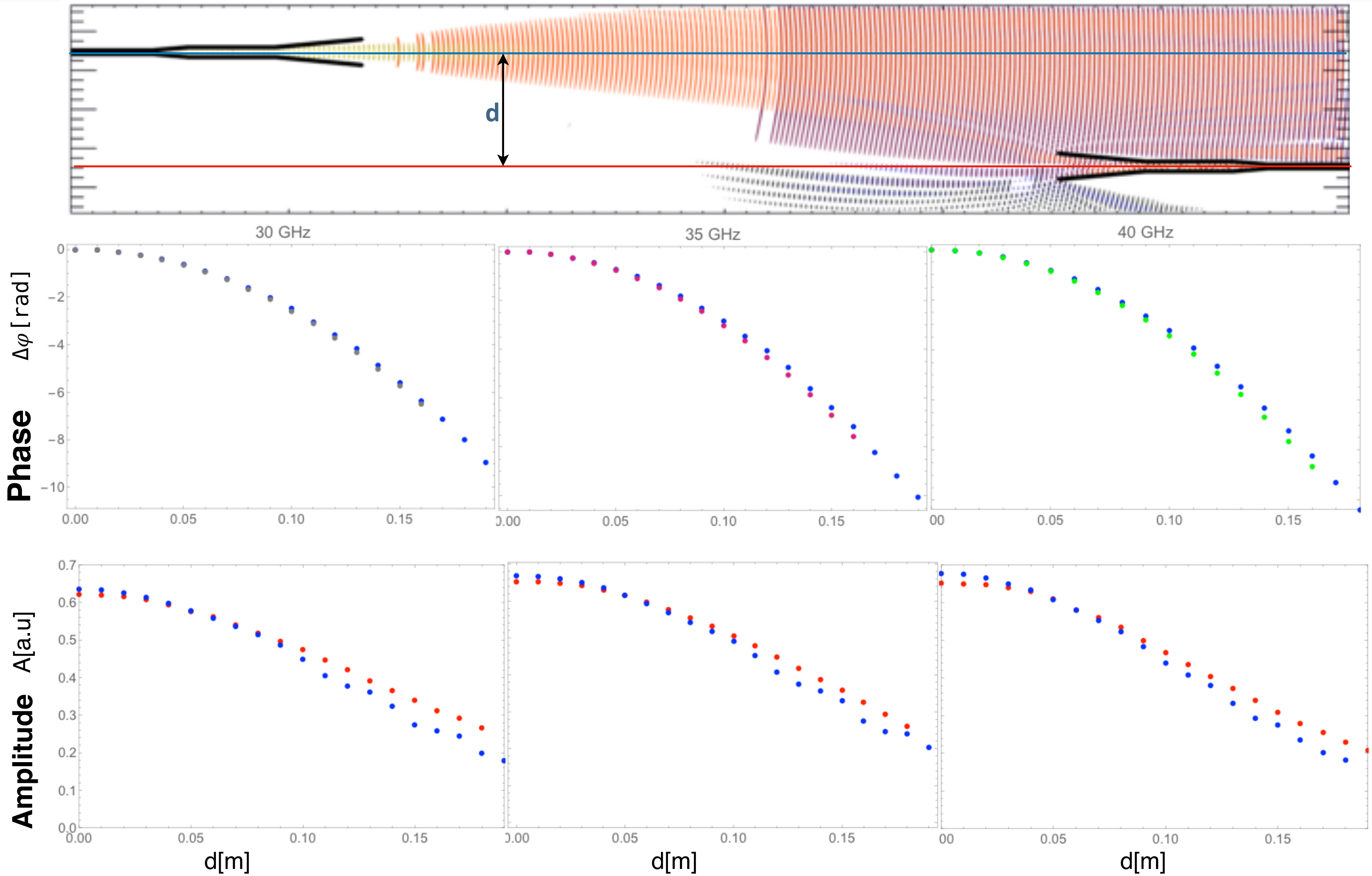
- *Project E(s)* on the fundamental mode ∫E cos().
- *Use conservation of EM flux to have amplitude at detection*
- *Evaluate wavenumber evolution along optical axis of receiver.*

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

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

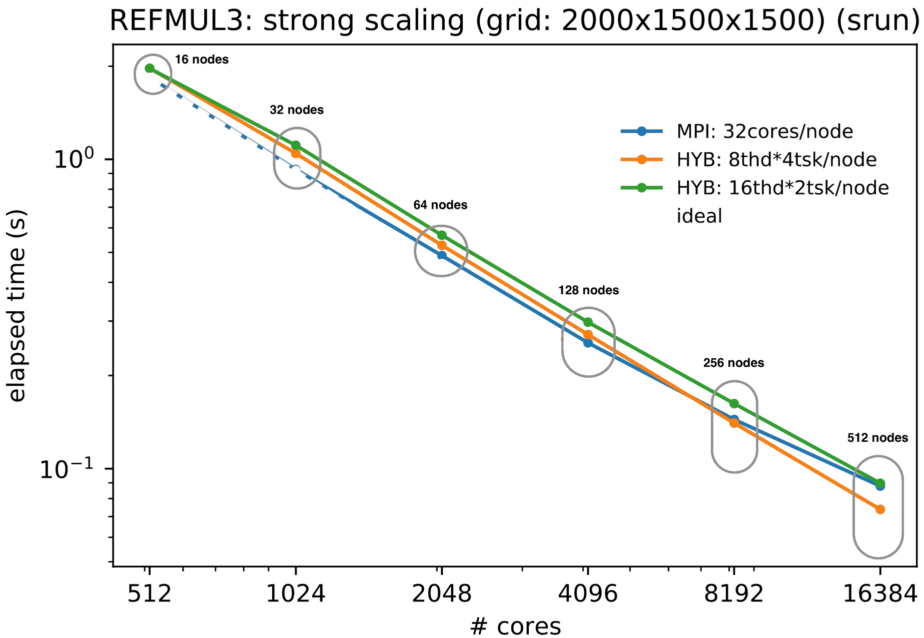
REFMUL3 ported to GPU

3D hybrid MPI/OpenMP full-wave code written in C (≈20k lines)

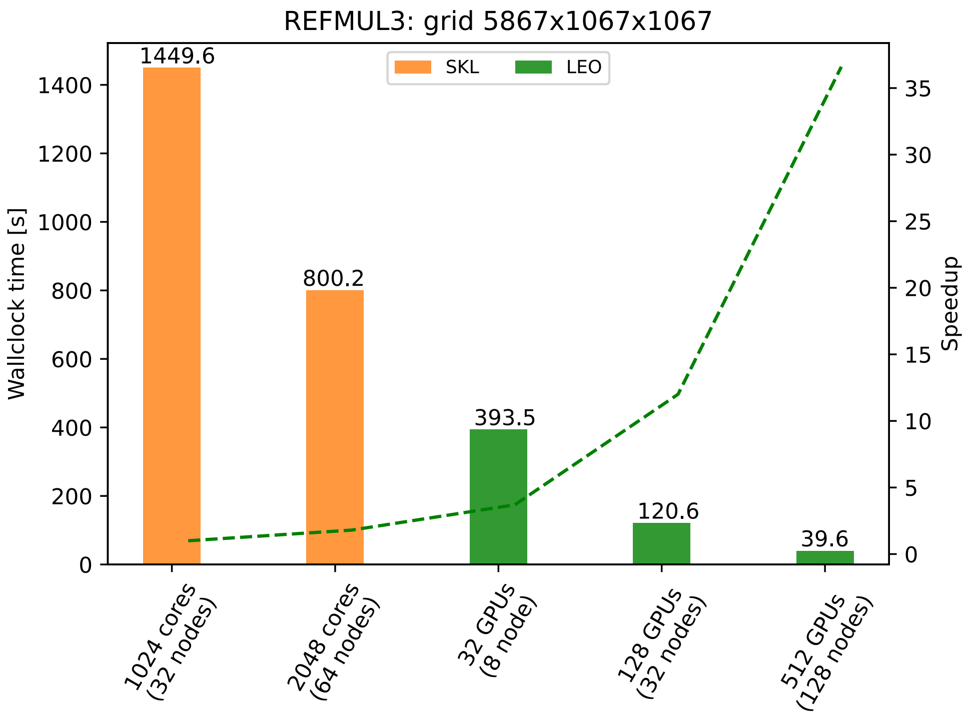
- **Former** **EnR ameliorations:**
  - *Pitstop/restart file implementation*
  - *VTK format output (big data output)*
  - *Ancillary CAD import pipeline*

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

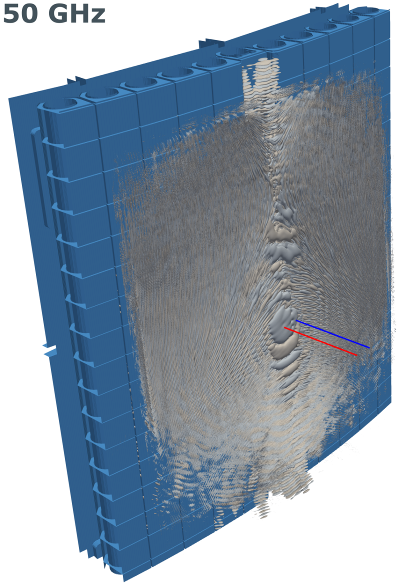


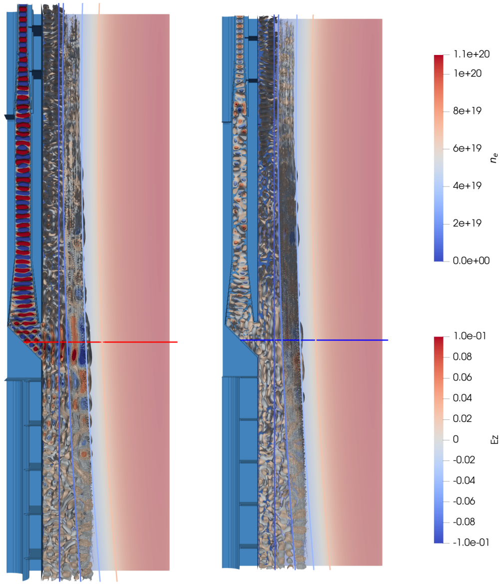
A grid of 6 679 514 963 grid points Marconi Skylake partition & Leonardo

Integrated design workflow for a PPR diagnostic system (DTT HFS)

REFMUL3 fullwave simulations: Bistatic antenna / Std. Single Null plasma

50 GHz





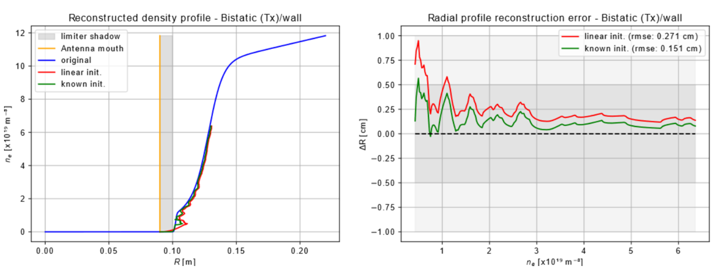
REFMUL3 fullwave simulations validate the use of Bistatic antenna design in Standard Single Null plasma scenario

➡ Excellent accuracy for plasma position purposes

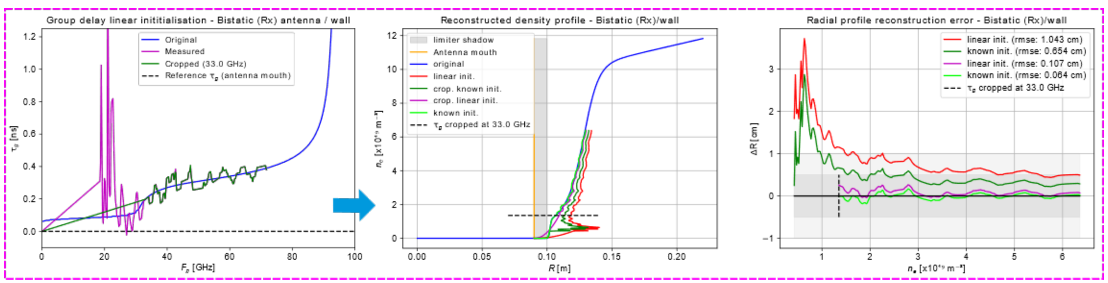
Δ R << 1 cm for n_e > $\approx$1.5x10^{19} m^{-3}

➡ Bistatic Rx signals require improved/ adapted data processing

Bistatic antenna - T**x LOS**

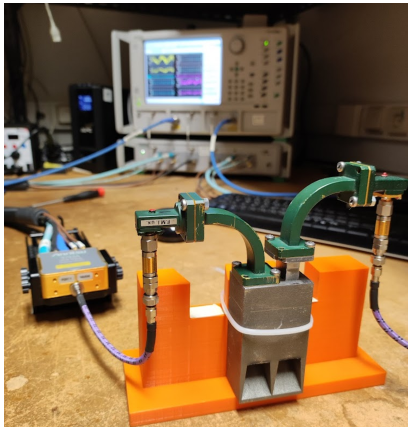


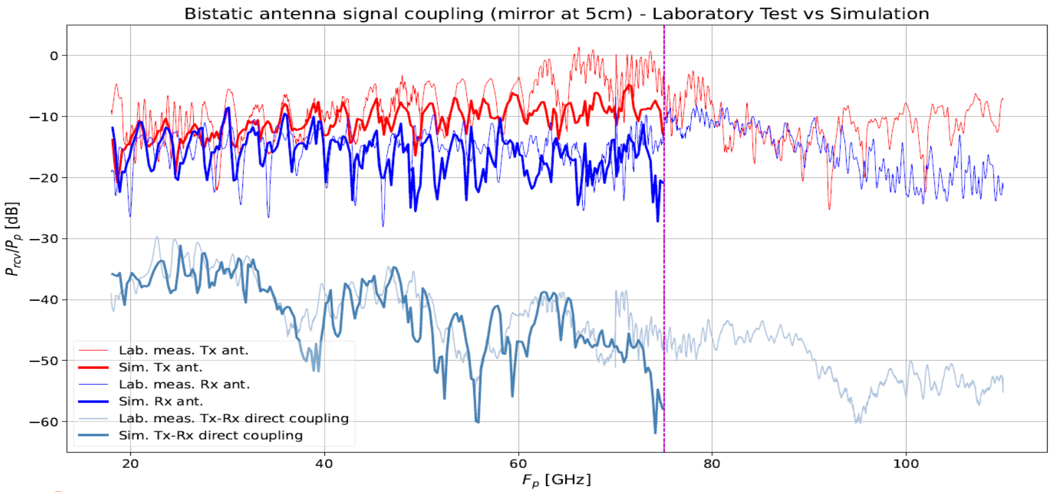
Bistatic antenna - **Rx LOS**



Integrated design workflow for a PPR diagnostic system (DTT HFS)

Laboratory measurements of 3D printed metal Bistatic antenna mockup

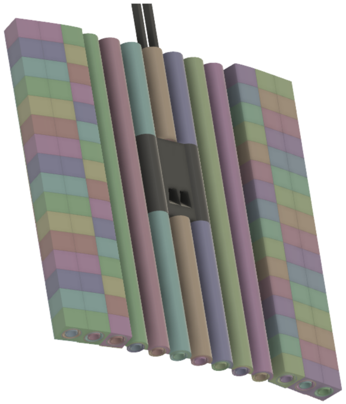


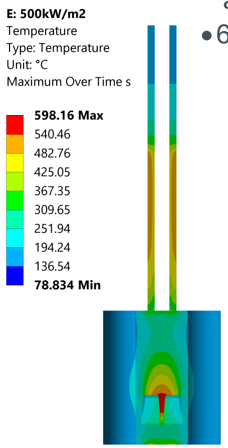


Excellent match to simulation results

Thermal analysis

DTT current wall design





- 0.5 MW/m2 plasma thermal load
- 10 mW/cm3 nuclear load in the ant. block
- 60° C water cooling

Simulations performed with ANSYS Mech. & CFX

Hotspot between Tx and Rx antenna **<= 600° C**
(addressable with antenna and cooling design changes)

➡ Antenna block **redesign required**, with cooling in the antenna axis

Status of the compact reflectometer

- The compact reflectometer board had to be **redesigned** due to the **obsolescence** of three MIMIC chips.
- New PCBs were designed and send for production and new electronic components acquired. Assembly will take place beginning of 2024.
- The **DDS development progressed** on the way on how to better 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.
- In 2024 we will try to purchase the critical components.

Scientific output under ENR-TEC.01.IST

Presence in conferences in 2023

ECPD 2023-5th European Conference on Plasma Diagnostics, Rethymno, Greece.

Oral and a communication in the proceedings:

●F da Silva, J. Santos F. da Silva, A. Silva, J. Ferreira, E. Ricardo, S. Heuraux, R. Sabot, F. Clairet, Y. Moudden, G. De Masi, R. Cavazzana, G. Marchiori, R. Bianchetti Morales, P. R. Resende, J.C. Abrantes, R. Luís, Y. Nietiadi (2023). Status of the EUROfusion Enabling Research Project Advances in real-time reflectometry plasma tracking, for next generation machines.

ISFNT-15-15th International Symposium on Fusion Nuclear Technology, Las Palmas De Gran Canaria, Spain.

Poster:

●J. M. Santos, A. Silva, F. da Silva, Y. Nietiadi, R. Luis, J. Ferreira, G. De Masi, O. Tudisco, R. Cavazzana, P. R. Resende, J. C. C. Abrantes, S. Heuraux, E. Ricardo, T. Ribeiro (2023). Design and Performance analysis of a High Field Side antenna for Plasma Position Reflectometry control on DTT.

Oral:

●F. da Silva, S. Heuraux, T. Ribeiro, E. Ricardo, J. Santos, A. Silva, J. Ferreira, J. Vicente, G. De Masi, O. Tudisco, R. Cavazzana, G. Marchiori, R. Luís, Nietiadi (2023). An overview of the evolution of the modelling of reflectometry diagnostics in fusion plasmas using finite-difference time-domain codes.

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


4th European Conference on Plasma Diagnostics (ECPD2021)
7–11 June, 2021
Online

A 3D CAD model input pipeline for REFMUL3 full-wave FDTD 3D simulator

2021 JINST 16 C11013

Peer reviewed publications in 2023

- J. M. Santos, A. Silva, F. da Silva, Y. Nietiadi, R. Luis, J. Ferreira, G. De Masi, O. Tudisco, R. Cavazzana, P. R. Resende, J. C. C. Abrantes, S. Heuraux, E. Ricardo, T. Ribeiro. Design and Performance analysis of a High Field Side antenna for Plasma Position Reflectometry control on DTT. Fusion Engeneering and Design (Under revision).

- F. da Silva, S. Heuraux, T. Ribeiro, E. Ricardo, J. Santos, A. Silva, J. Ferreira, J. Vicente, G. De Masi, O. Tudisco, R. Cavazzana, G. Marchiori, R. Luís, Nietiadi. An overview of the evolution of the modelling of reflectometry diagnostics in fusion plasmas using finite-difference time-domain codes. Fusion Engineering and Design (Under revision)

- E. Ricardo, F. da Silva, S. Heuraux, A. Silva, J. Santos (2024). Simulation and data processing techniques to design optimized PPR systems on plasma fusion devices (2023). Computer Physics Communications.

These add to an EnR total output of:

- **9 Communications to Conferences and workshops**
- **5 Papers in peer reviewed journal (2 under revision)**

…more output is expected this year

Associated EUROfusion HPC Projects and ACH support

Running Two projects under the EUROfusion HPC Project 7th cycle
(running from 15th March 2023 to 28th February 2024)
*These have been **importante** for completion of the project*

- **EnR4DEMO** *Advances in real-time reflectometry for next generation machines.*
  - 1,849,920 node-hours asked. ☛ *50,000 node hours*
- **DTTsimul4** 3D reflectometry simulation for DTT PPR
  - 650,00 node-hours asked. ☛ *20,000node hours*

Three new proposals submitted the EUROfusion HPC Project 8th cycle
(starting running on the 15th March 2024)

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

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