ENR-TEC.01.IST

Advances in real-time reflectometry plasma tracking for next generation machines: Application to DEMO

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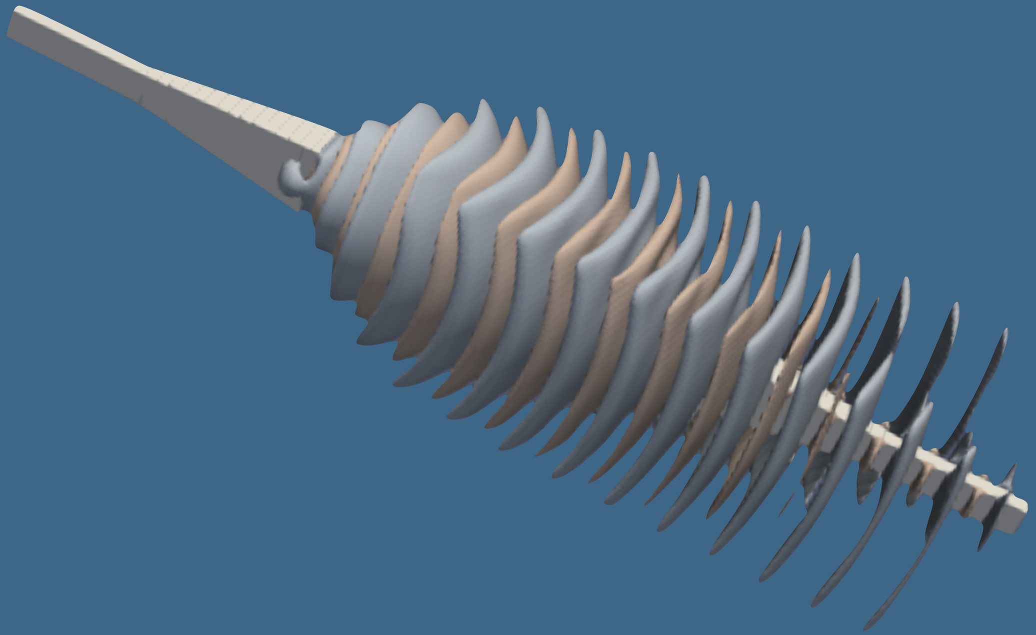

Lisbon, 29 November 2021, 2nd Scientific Board Technology & Systems

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- 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)**.

Planned tasks

Task 1 – Preparation and systematisation of the project

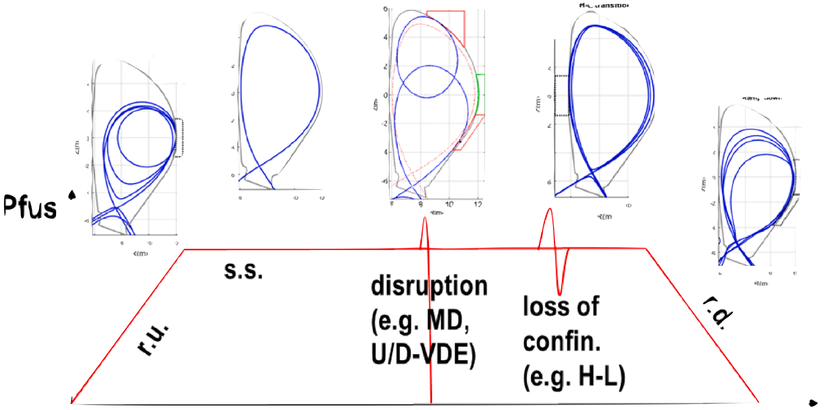
- **T1.1** For all relevant scenarios, input datasets for REFMUL will be prepared and made available to properly model DEMO (and IDTT).
- **T1.2** Preparation of FDTD code REFMULF (REFMUL3 added) to handle the specific needs of the simulations.
- **T1.3** Planning of the clock demonstration.
- **T1.4** Planning the compact reflectometers.

Subtask T1.1: Data for DEMO density modelling

- **T1.1** For all relevant scenarios, input datasets for REFMUL will be prepared and made available to properly model DEMO (and IDTT).

- For DEMO some difficulty in obtaining official complete scenarios.
  - The most complete scenario is the 2015, just up to the separatrix.
  - SOL data unavailable.
  - SOL had to be modelled.
  - Data for only the Flattop. No data for ramp-up obtained.

There are models *available*:



E.g.: F. Maviglia et alii, Impact of plasma-wall interaction and exhaust on the EU-DEMO design

Nuclear Materials and Energy 26 (2021) 100897

Action plans for early 2022

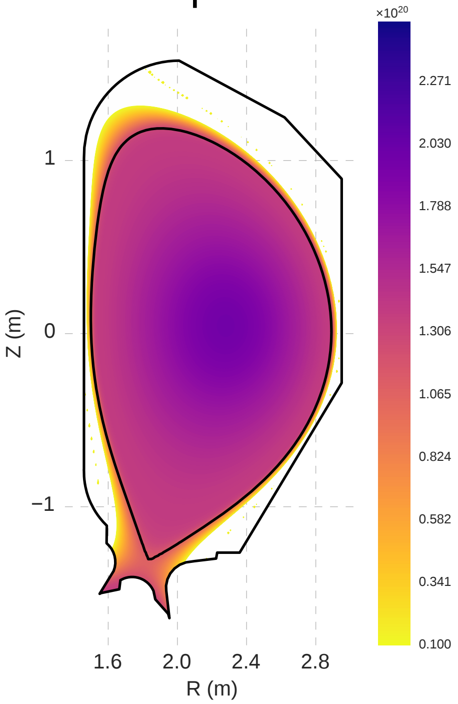
[1] Try to obtain them officially from DEMO

[2a] Educated model from published data (rump-up)
[2b] Follow with the 2015 model (flattop)

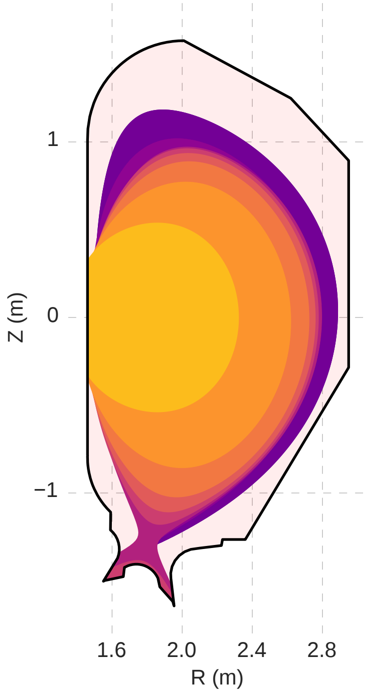
Subtask T1.1: Data for IDTT density modelling

- For IDTT the endeavour is almost complete.
  - The most recent scenario available (Single null scenario).
  - SOL data unavailable.
  - SOL had to be modelled.
  - Data for the Flattop and equilibria for ramp-up obtained (density missing).

Density for IDTT flattop simulated with JINTRAC with extrapolation for the SOL.



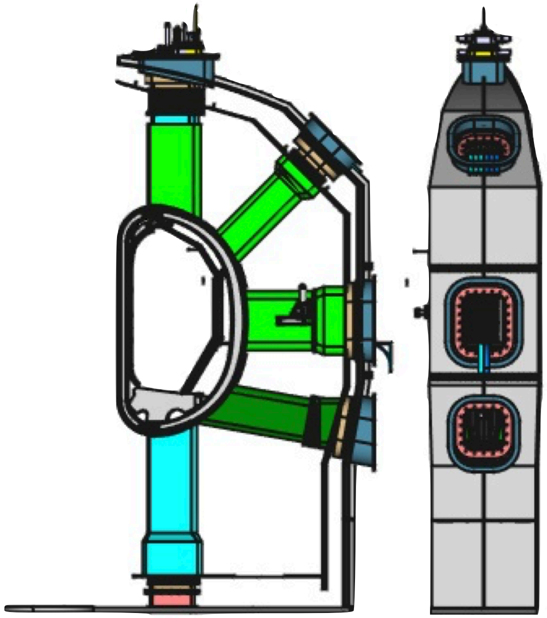
Evolving magnetic equilibria during the ramp-up.



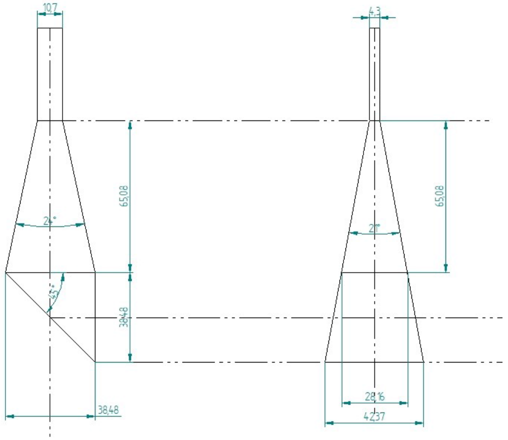
Plasma model for IDTT will be completed in the beginning of 2022

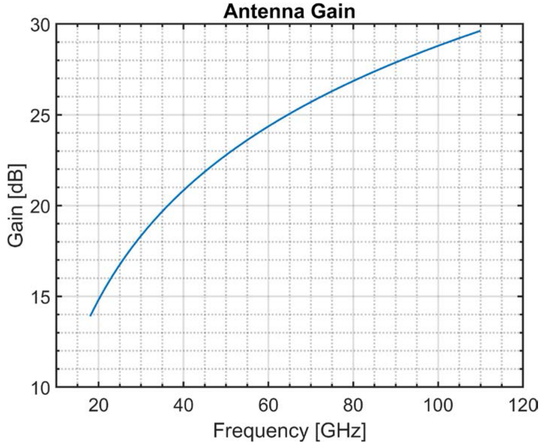
Subtask T1.1: Machine (wall and accesses) and antennas

IDTT Sector 2

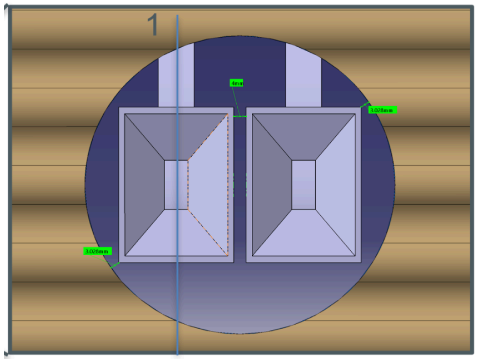


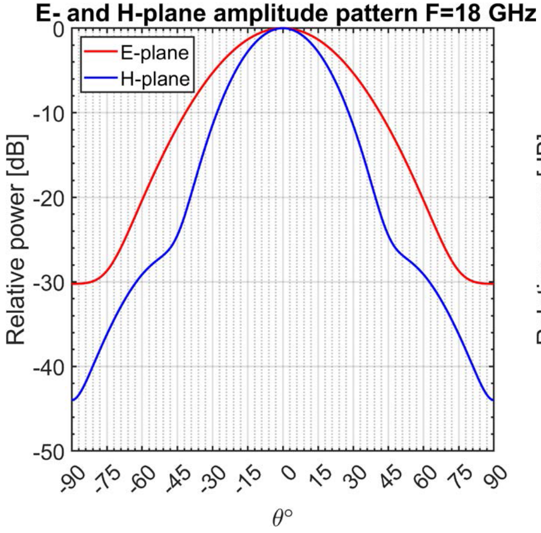
A new HFS antenna designed for the HFS IDTT

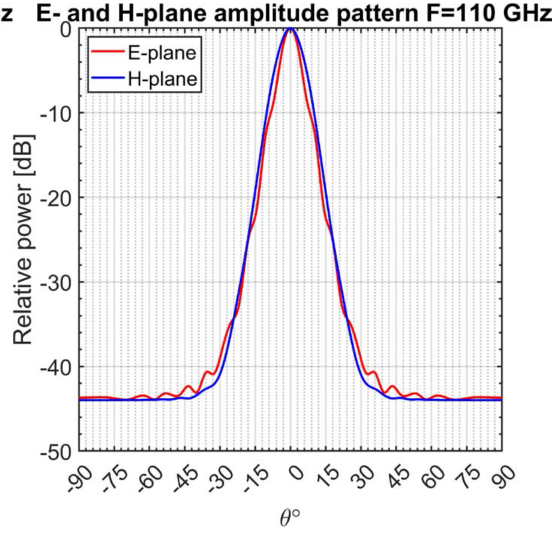




DEMO antenna model
Dubling as LFS IDTT antena

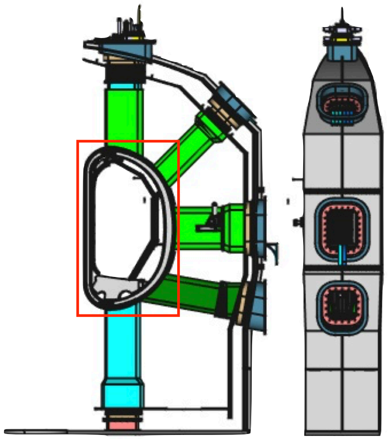




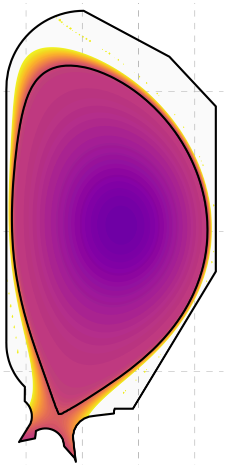


Subtask T1.1: From n_e and CAD models to a synthetic diagnostic

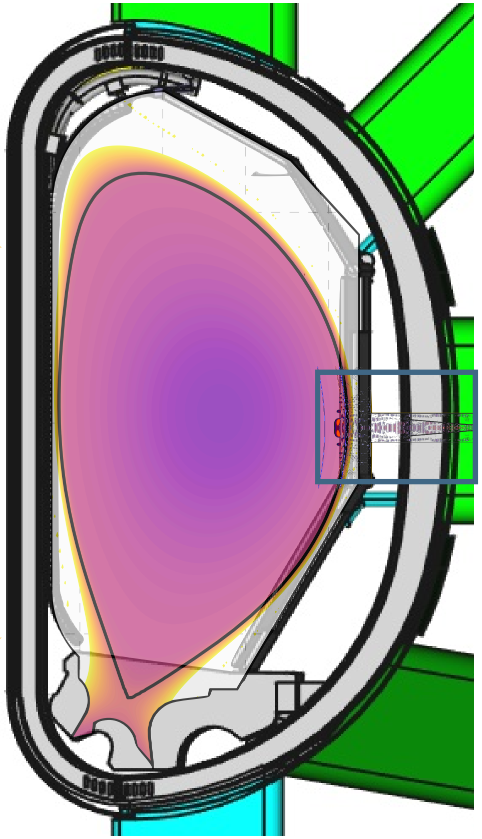
IDTT Sector 2



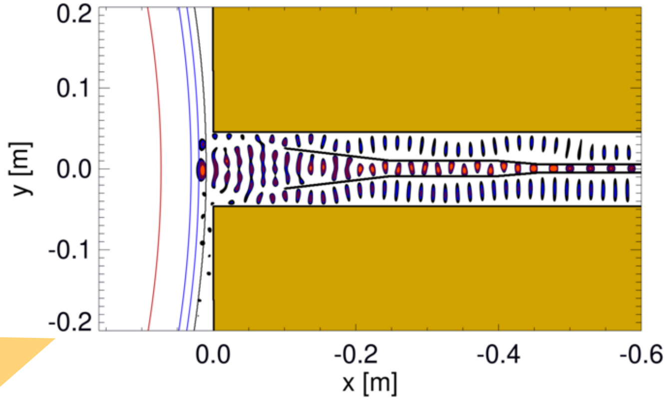
IDTT Flattop $\mathbf{n_e}$



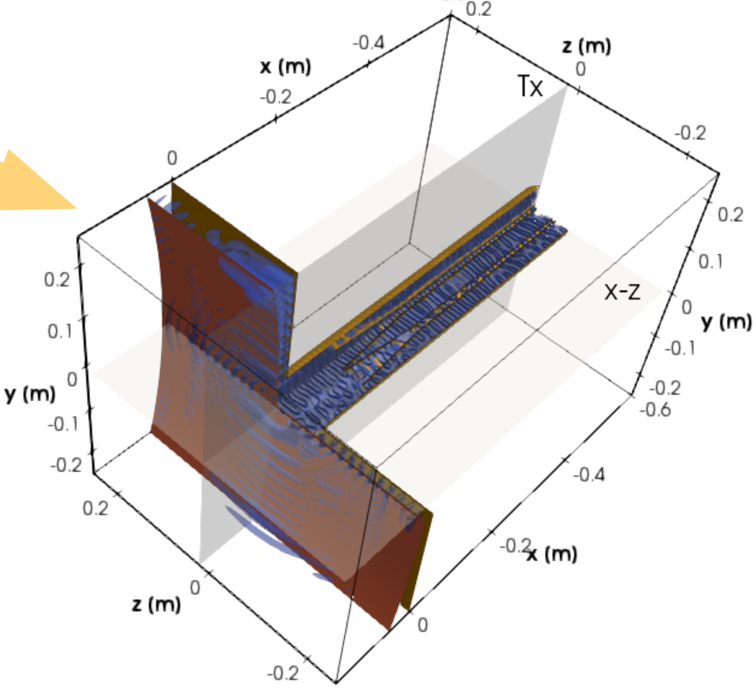
ROI selected



2D simulation using **REFMULF**
Preliminary synthetic diagnostic for IDTT K band



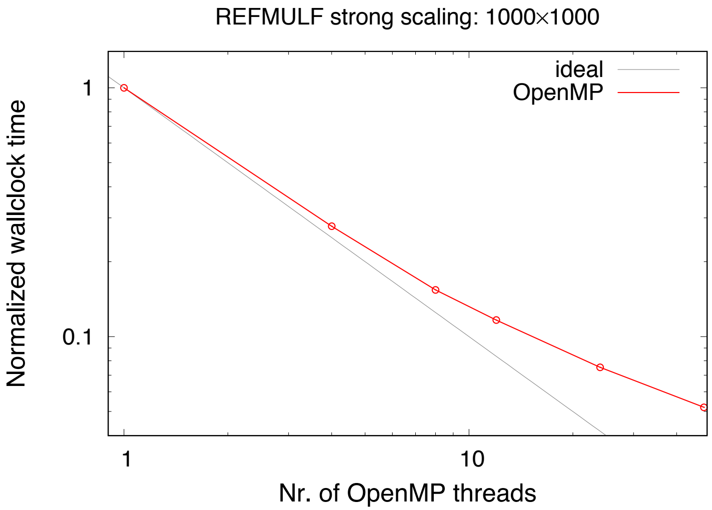
3D simulation using **REFMUL3**
Preliminary synthetic diagnostic for IDTT K band



Subtask 1.2: REFMULF *enhancements*

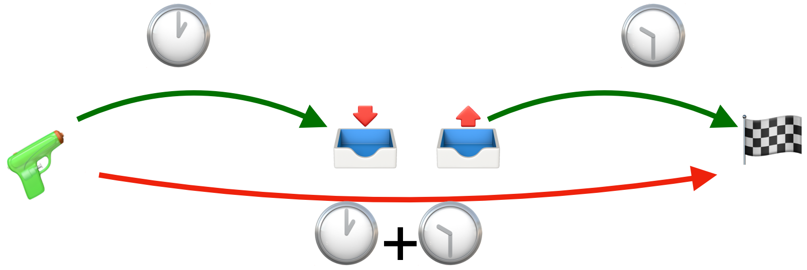
- **T1.2** Preparation of FDTD code REFMULF to handle the specific needs of the simulations.

REFMULF has been parallelised using OpenMP.

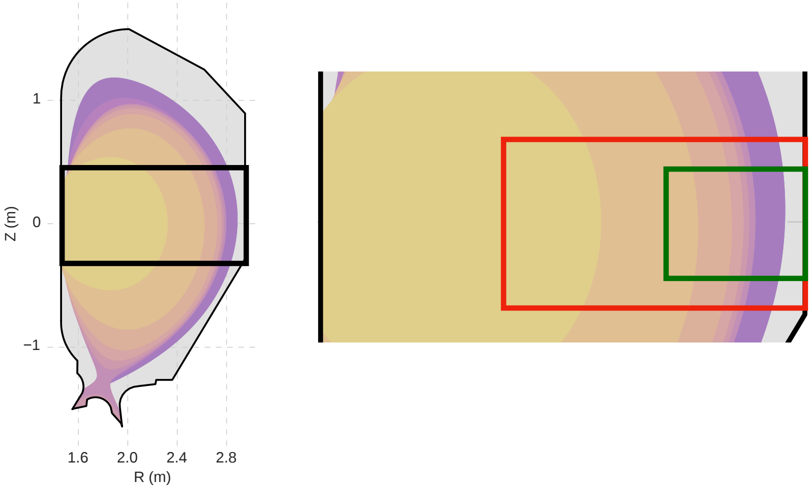


Prepared for bulk running in HPC

REFMULF is being implemented a pitstop/restart file



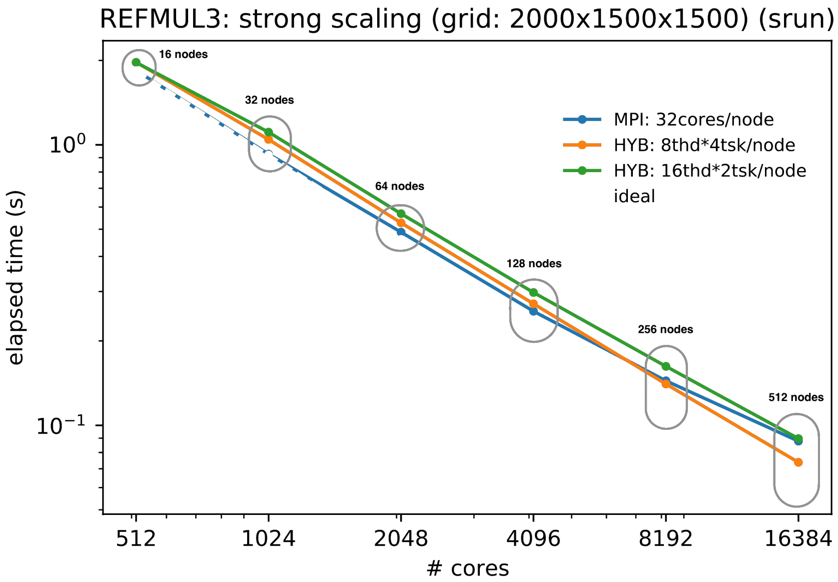
Allows to run with several job submissions for large grids



Subtask 1.2: Addition of REFMUL3 to the FDTD toolkit

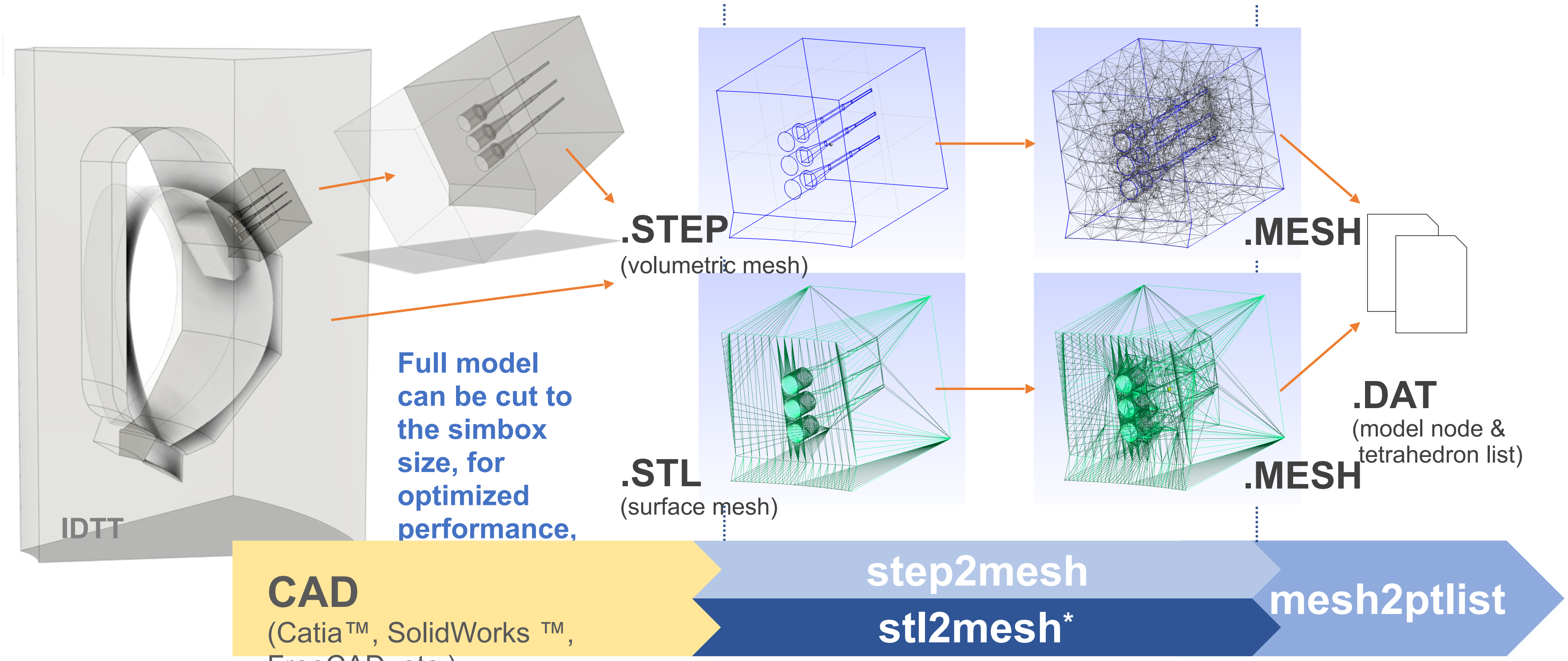
REFMUL3 entered a production stage

- **REFMUL3 is a 3D parallel code ☚ making 3D simulations available**
  - ***All field components included***
  - ***Parallel hybrid implementation (OpenMP+MPI) with 3D domain decomposition***
  - ***XMDF/HDF5 compressed binary output***



- ***Pitstop/restart file implementation ☚ Subtask 1.2***
- ***VTK format output (big data output) ☚ Subtask 1.2***
- ***Ancillary CAD import pipeline ☚ Subtask 1.2***

Subtask 1.2: CAD import pipeline



Full model can be cut to the simbox size, for optimized performance,

.STEP
(volumetric mesh)

.STL
(surface mesh)

.MESH

.MESH

.DAT
(model node & tetrahedron list)

CAD
(Catia™, SolidWorks ™, FreeCAD, etc.)

step2mesh

stl2mesh*

mesh2ptlist

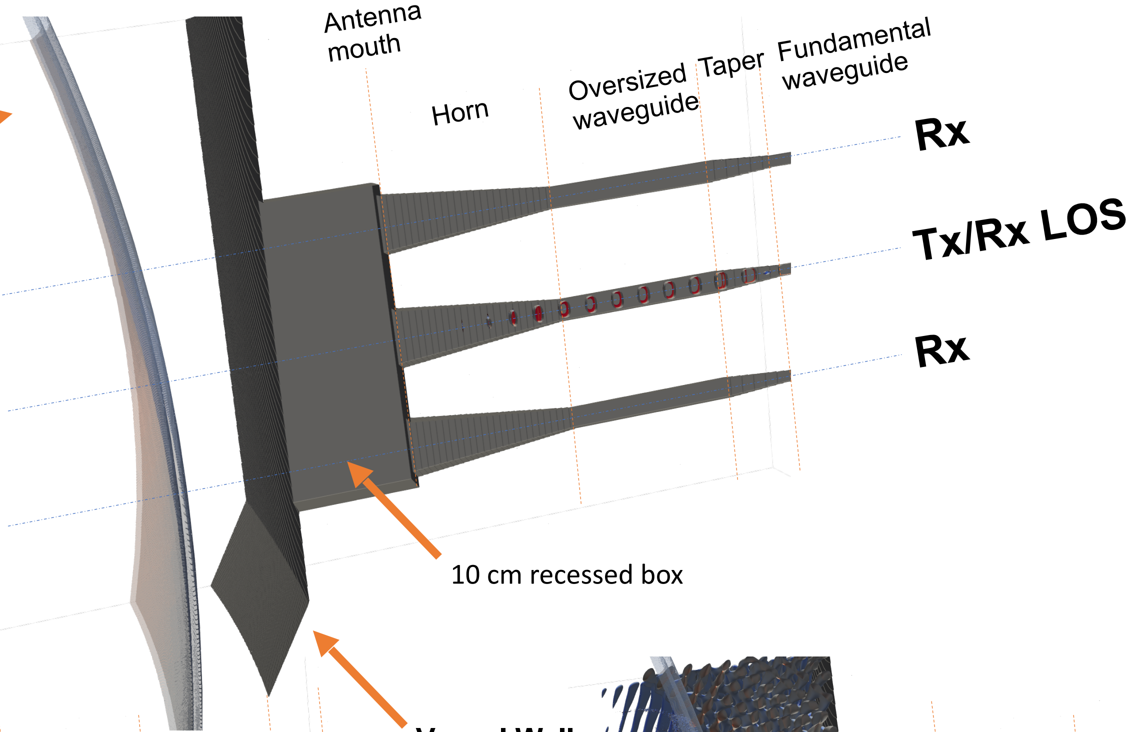
Scripted Gmsh© model optimized re-meshing or* volume generation+meshing.

Scripted node and tetrahedron extraction

Subtask 1.2: CAD design offers unprecedented description

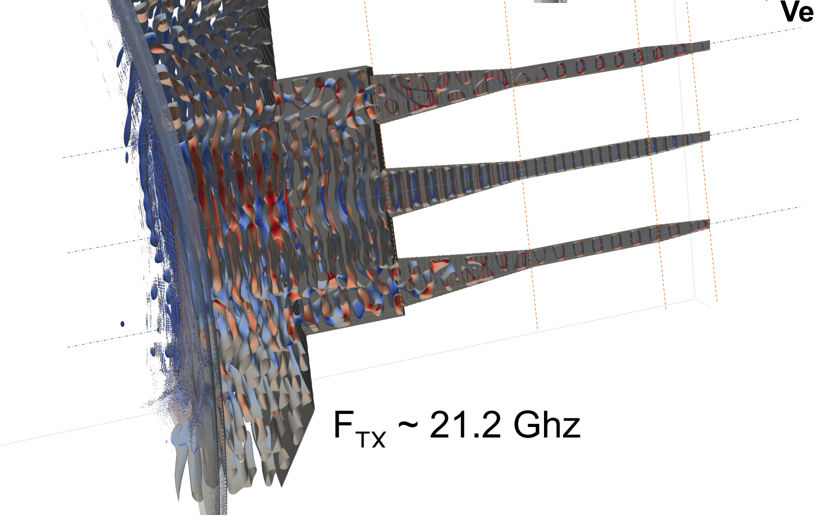
IDTT Single Null (SN) config.:

Cutoff density layers corresponding to the first and last frequency probed in the simulated K band (18 – 26.5 GHz) frequency sweep

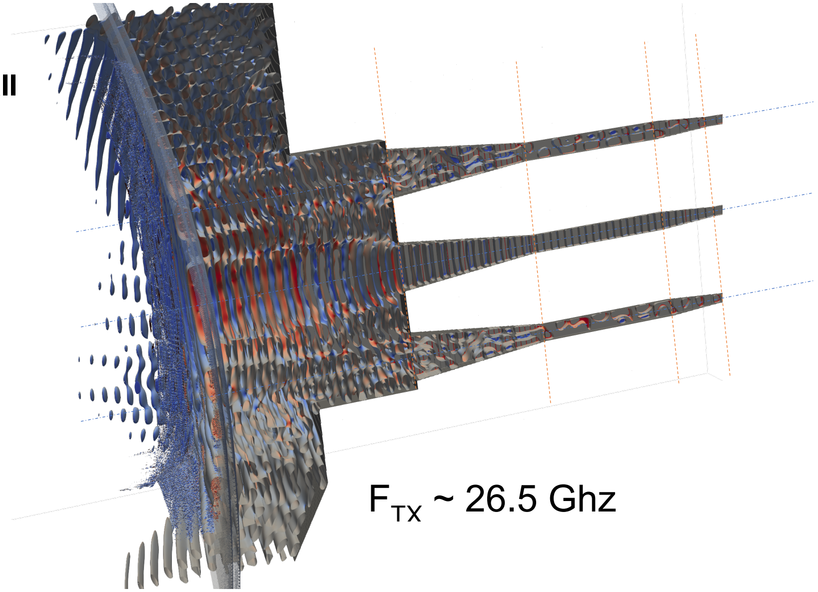


10 cm recessed box

Vessel Wall



F_{TX} ~ 21.2 Ghz



F_{TX} ~ 26.5 Ghz

Subtask 1.2: 3D simulations — Example for the K band

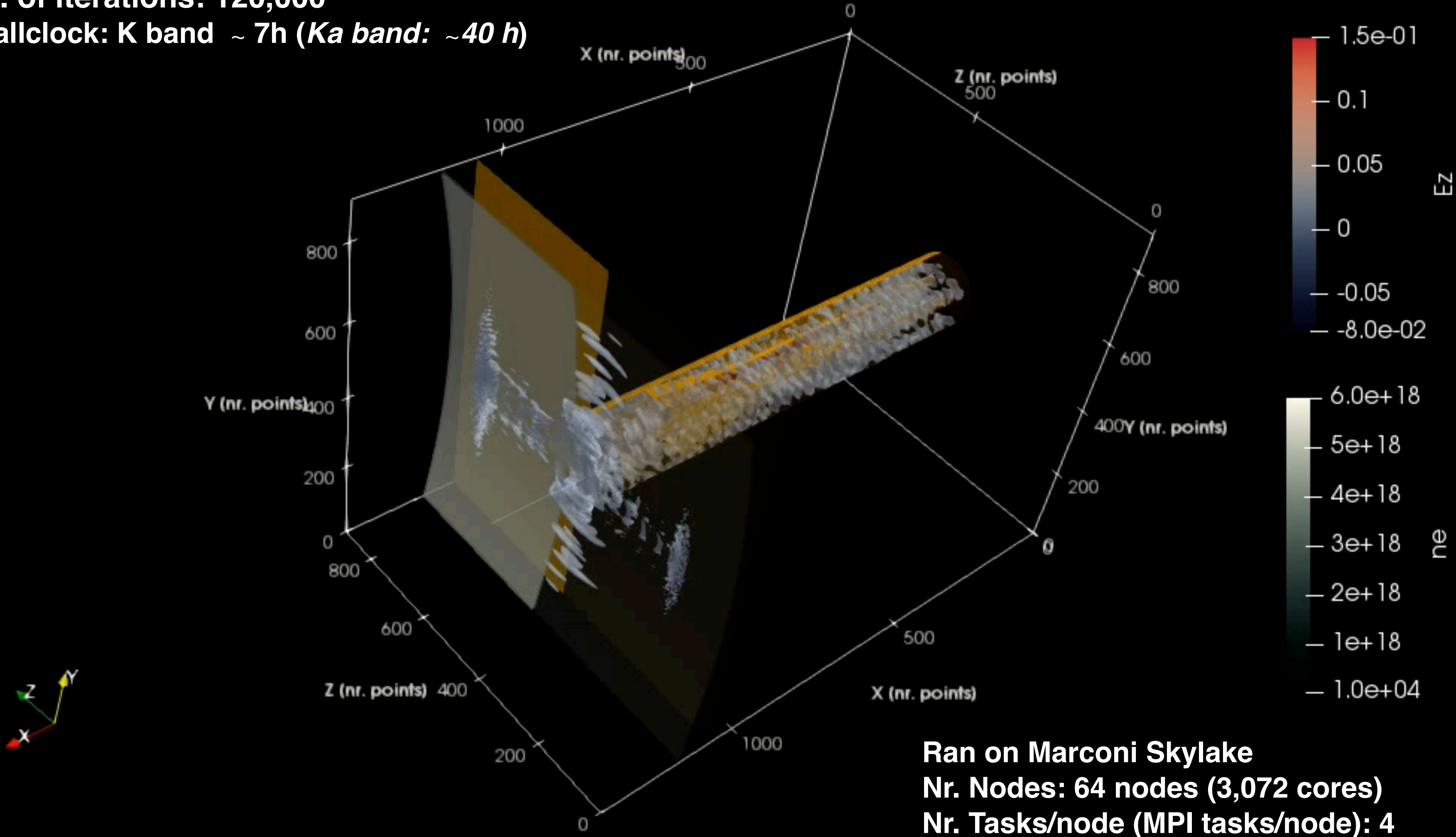
Grid size: K band — 1348×899x899 (*Ka band — 2033×1356×1356*)

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

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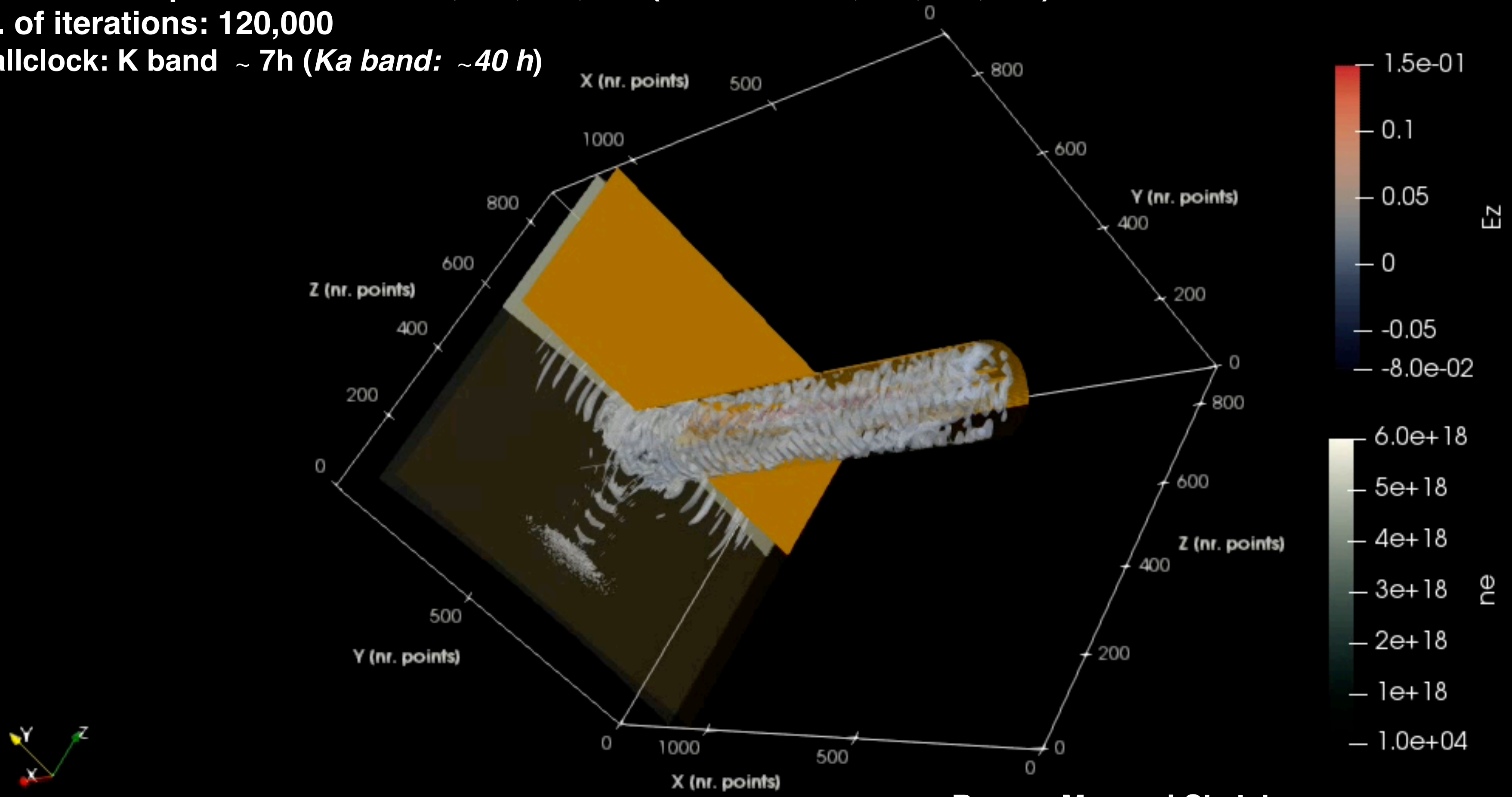

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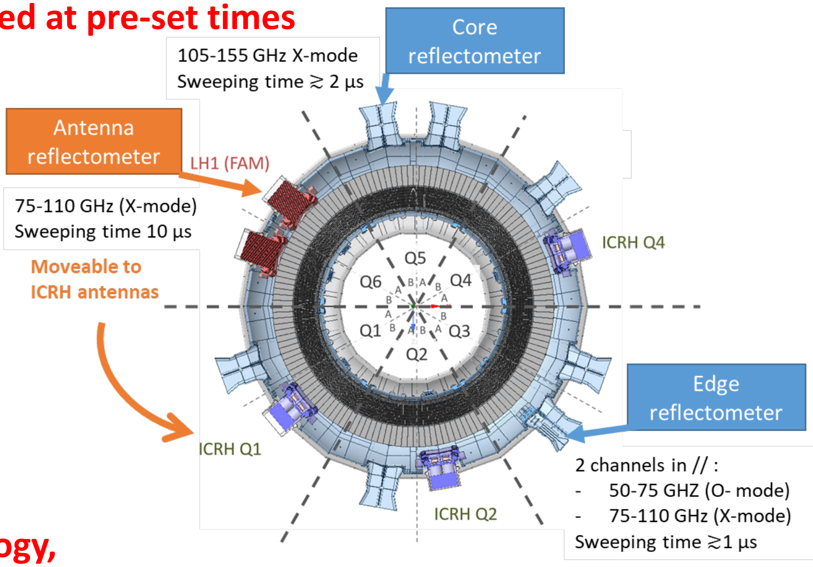
On Task 1.3: WEST reflectometer timing

T1.3 Planning of the clock demonstration.

WEST is equipped with 3 profile reflectometers implemented around the torus.
The reflectometers are swept continuously, but profiles are recorded at pre-set times

- **Each reflectometer has its own 10 MHz reference clock used :**
  - As a reference for microwave equipment
  - To synchronize the acquisition card with the sweep generator
    ➔ avoid any time drift between the sweeps and the acquisition

- **The WEST central chronology sends to each reflectometer**
  - A 1 MHz clock to date the trigger events
  - the discharge event codes (plasma start, end …)
  - The codes that trigger a density profile measurement



Core reflectometer

105-155 GHz X-mode
Sweeping time ≳ 2 µs

Antenna reflectometer

75-110 GHz (X-mode)
Sweeping time 10 µs

Moveable to ICRH antennas

Edge reflectometer

2 channels in // :
- 50-75 GHZ (O- mode)
- 75-110 GHz (X-mode)

Sweeping time ≳1 µs

Although the 3 reflectometers are connected to the WEST chronology, they are not perfectly synchronised

- They have their own 10 MHz chock
- They received the WEST events at slightly different time (10s to 100s ns time differences ?) as
  - They are not connected to the same chronology sub-board
  - They are implemented at different toroidal positions so the connection length to the chronology board are different (~4ns /m)
- The delay between the sweep trigger and the time the wave reaches the plasma edge are different:
  - The electronics, the waveguide lengths and the propagation time from the reflectometer antenna to the plasma edge are all different

On Task 1.3: Synchronisation of WEST reflectometers

Three improvement steps have been identified to reduce the time shift between WEST reflectometers

- **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, microwave set-up. Moreover out-vessel waveguide length are different : 20 cm for the core reflectometer, 2 m for the edge reflectometers, 4 m for the 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, ie better than the plasma propagation time and a thousandth of the reflectometer sweeping time.**

On Task 1.3: Prospective Timeline

- **Step 1 : distribute a single 10 MHz reference clock to the 3 reflectometers**
  - Q4 2021 : Modification of existing hardware to provide 10 MHz Clock output
  - Q1 2022 : Installation and cabling of boards on the three reflectometers
  - Q2 2022 : Tests during WEST experimental campaign C6

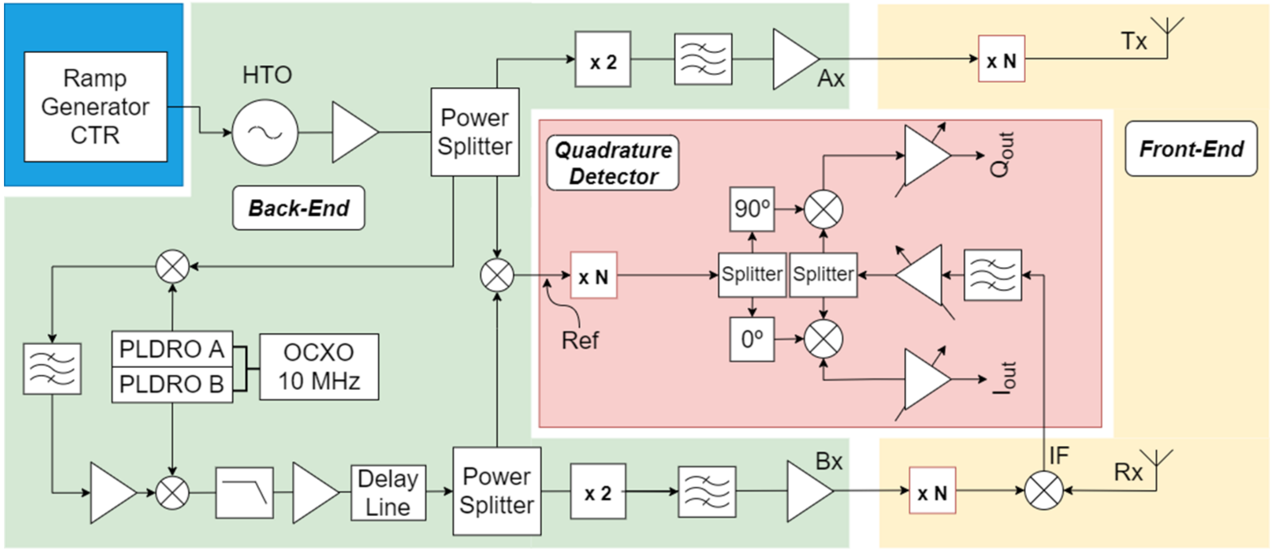
- **Step 2 : ensure that WEST events are received at exactly the same time in each reflectometer cubicles**
  - Q3 2022 : Connect in full duplex all three reflectometers to a single “master” board in the WEST “chrono” clock distribution network **(~10 kE)**
  - Q4 2022 : Calibrate and adjust round trip latencies on all three connections
  - Q4 2022 : Monitor possible latency variations over time.

- **Step 3 : ensure that all 3 reflectometers perform measurements at exactly the same time**
  - Q4 2022 : modification of reflectometer electronics to work with external trigger and clock
  - 2023 : calibration and adjustment of propagation delays within the reflectometers

On Task 1.4: Compact reflectometer

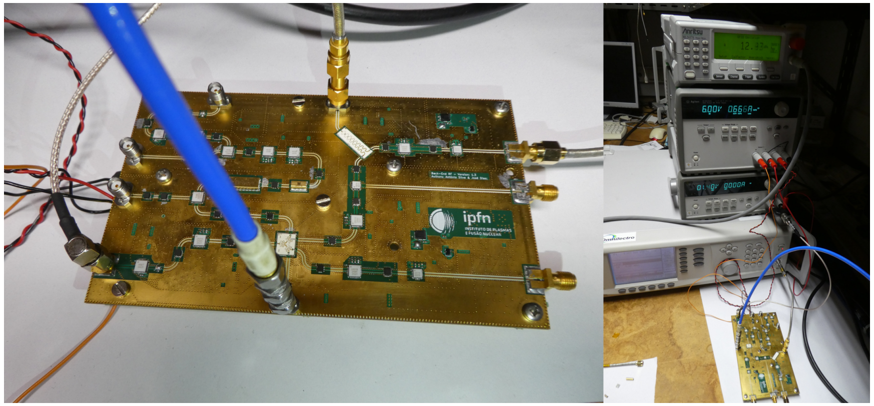
T1.4 Planning the compact reflectometers.

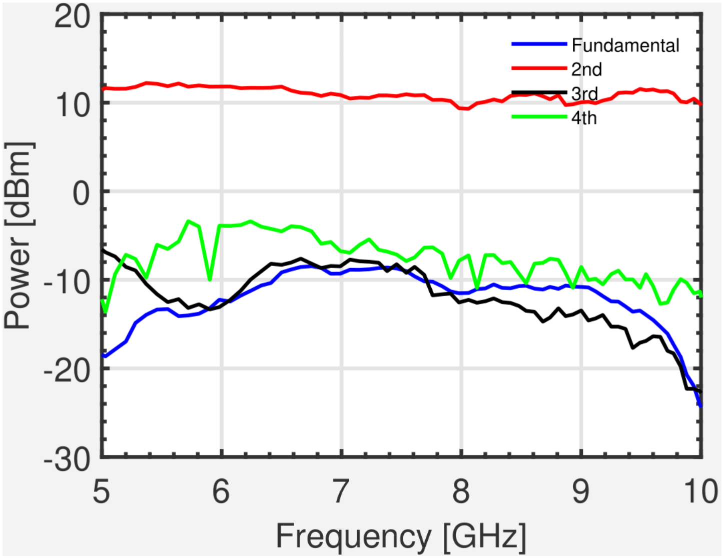
- Develop a compact coherent FMCW microwave reflectometer with applications in plasma diagnostics.
- Back-end covers directly 10 to 20 GHz
- With full band frequency multipliers can be extended to 140 GHz
- For improved linearity, a key feature to guarantee high precision on a FMCW radar, analog oscillators can be replaced by DDS generators.
- Two prototype PCB boards were developed and build:
  - ➢ The back-end (green region)
  - ➢ The quadrature detector (pink region)



On Task 1.4: Compact reflectometer testing

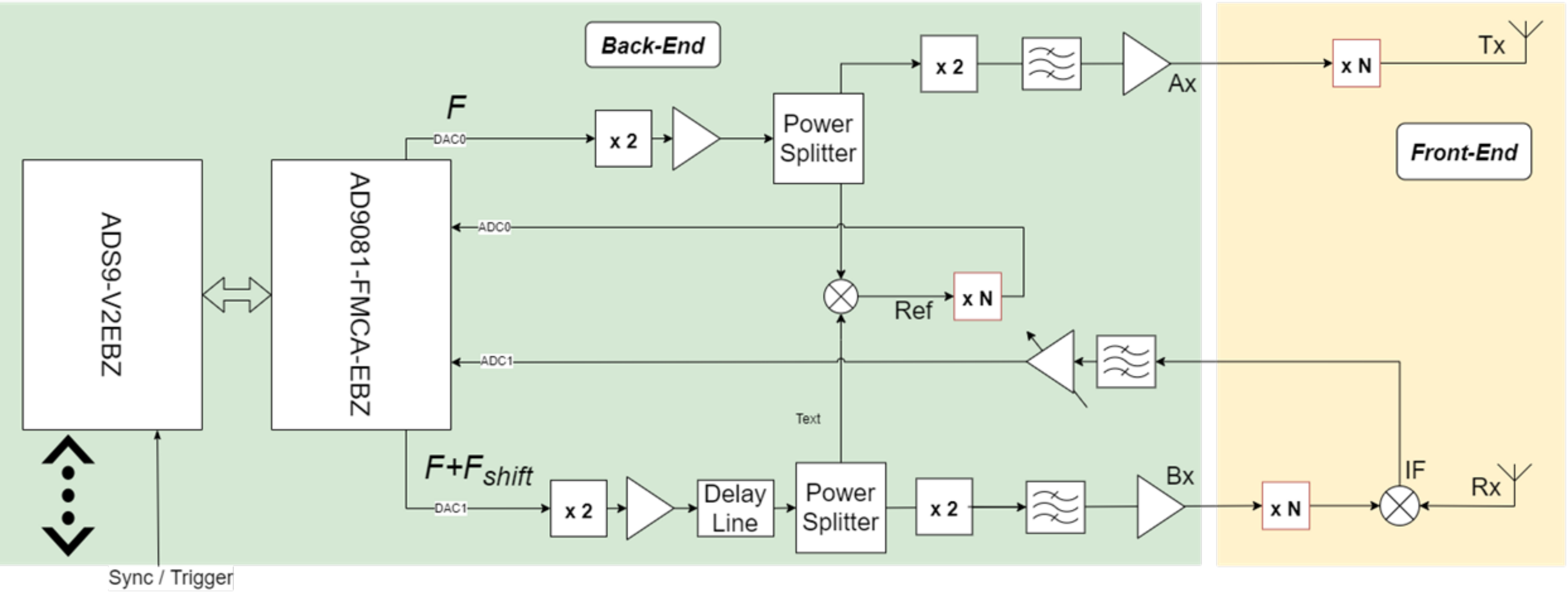
- The back-end prototype can generate full band signals exciding 8 dBm, enough to drive external multipliers.
- All undesirable harmonics are 15 dBi bellow the desired output, in all frequency range.
- The output must be the 2nd harmonic of the HTO, as we are measuring the output of the active frequency doubler.
- The frequency multiplier rejection of the input frequency (blue line) is always 20 dB bellow the output (red line).
- Testing the quadrature detector will follow.





On Task 1.4: DDS signal generation

- The analogue oscillator will be replaced by a fast RF DAC.
- Frequency translation will be accomplished by a second RF DAC.
- The Reference (Ref) and IF signals will be acquired by fast ADC's.
- Digital I/Q detection.
- The AD9081 Demo board include 4 RF DAC's (12 GSPS, analog BW 8 GHz) and 2 fast ADC's (4 GSPS, analog BW 7.5 GHz).
- ADS9-V2EBZ works as a data capture/transmit board. Designed to support the highest speed JESD204B/C data converters, the FPGA on the ADS9-V2EBZ acts as the data receiver for high-speed ADC's, and as the transmitter for high-speed DAC's.
- The DDS testing will start as soon as all the necessary parts are procured and purchased.



Papers under ENR-TEC.01.IST

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Jorge Santos
"A 3D CAD model input pipeline for REFMUL3 full-wave FDTD 3D simulator"
Submitted: 15 September 2021
Accepted: 14 October 2021

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Filipe da Silva
"Benchmarking 2D against 3D FDTD codes for the assessment of the measurement performance of a low field side plasma position reflectometer applicable to IDTT"
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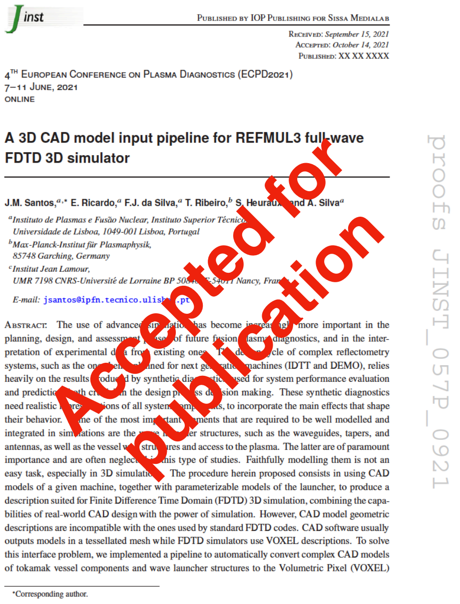
Accepted: 22 November 2021



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

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Abstract: The use of advanced simulation has become increasingly more important in the planning, design, and assessment phases of future fusion plasma diagnostics, and in the interpretation of experimental data from existing ones. The design cycle of complex reflectometry systems, such as the ones being planned for next generation machines (IDTT and DEMO), relies heavily on the results produced by synthetic diagnostics used for system performance evaluation and prediction, both crucial in the design process decision making. These synthetic diagnostics need realistic representations of all system components, to incorporate the main effects that shape their behavior. Some of the most important elements that are required to be well modelled and integrated in simulations are the wave launcher structures, such as the waveguides, tapers, and antennas, as well as the vessel wall structures and access to the plasma. The latter are of paramount importance and are often neglected in this type of studies. Faithfully modelling them is not an easy task, especially in 3D simulations. The procedure herein proposed consists in using CAD models of a given machine, together with parameterizable models of the launcher, to produce a description suited for Finite Difference Time Domain (FDTD) 3D simulation, combining the capabilities of real-world CAD design with the power of simulation. However, CAD model geometric descriptions are incompatible with the ones used by standard FDTD codes. CAD software usually outputs models in a tessellated mesh while FDTD simulators use VOXEL descriptions. To solve this interface problem, we implemented a pipeline to automatically convert complex CAD models of tokamak vessel components and wave launcher structures to the Volumetric Pixel (VOXEL)

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Accepted for publication

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7-11 June 2021
Salamanca, Spain

Benchmarking 2D against 3D FDTD codes for the assessment of the measurement performance of a low field side plasma position reflectometer applicable to IDTT

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Abstract: O-mode reflectometry, a technique to diagnose fusion plasmas, is foreseen as a source of real-time (RT) plasma position and shape measurements for control purposes in the coming generation of machines such as DEMO. It is, thus, of paramount importance to predict the behavior and capabilities of these new reflectometry systems using synthetic diagnostics. Finite-difference time-domain (FDTD) time-dependent codes allow for a comprehensive description of reflectometry but are computationally demanding, especially when it comes to three-dimensional (3D) simulations, which requires access to High Performance Computing (HPC) facilities, making the use of two-dimensional (2D) codes much more common. It is important to understand the compromises made when using a 2D model in order to decide if it is applicable or if a 3D approach is required. This work attempts to answer this question by comparing simulations of a potential plasma position reflectometer (PPR) at the Low Field-Side (LFS) on the Italian Divertor Tokamak Test facility (IDTT) carried out using two full-wave FDTD codes, REFMULF (2D) and REFMUL3 (3D). In particular, the simulations consider one of IDTT's foreseen plasma scenarios, namely, a Single Null (SN) configuration, at the Start Of Flat-top (SOF) of the plasma current.

Keywords: Nuclear instruments and methods for hot plasma diagnostics, Plasma diagnostics—reflectometry, Simulation methods and programs

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[1] Corresponding author.

Accepted for publication

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Document title	Benchmarking 2D against 3D FDTD codes for the assessment of the measurement performance of a low field side plasma position reflectometer applicable to IDTT
Author	F da Silva (tanatost@ipfn.tecnico.ulisboa.pt)
Leader	EUROfusion Programme Manager (T.Donne)
Workpackage	_FP8_1.4 WPISA (R.Hatzky), _FP8_Facility-HPC (K.Gal), 3.CfP-FSD-AWP21-ENR-04/IST-01 (F.da Silva)
Co Authors	E.Ricardo, J. Ferreira, J. Santos, S. Heuraux, T.Ribeiro, A.Silva, G.De Masi, O.Tudisco, R.Cavazzana, O.D'Arcangelo

Conference	European Conference on Plasma Diagnostics ECPD 2021, Online
Document title	Benchmarking 2D against 3D FDTD codes for the assessment of the measurement performance of a low field side plasma position reflectometer applicable to IDTT
Author	F da Silva (tanatost@ipfn.tecnico.ulisboa.pt)
Leader	EUROfusion Programme Manager (T.Donne)
Workpackage	_FP8_1.4 WPISA (R.Hatzky), _FP8_Facility-HPC (K.Gal), 3.CfP-FSD-AWP21-ENR-04/IST-01 (F.da Silva)
Co Authors	E.Ricardo, J. Ferreira, J. Santos, S. Heuraux, T.Ribeiro, A.Silva, G.De Masi, O.Tudisco, R.Cavazzana, O.D'Arcangelo

3.CfP-FSD-AWP21-ENR-04/IST-01

EUROfusion HPC Project

Four proposals for the EUROfusion HPC Project 6th cycle
(running from 15th March 2022 to 28th February 2023)
*These are of **paramount importance** for the execution of the project*

- **EnR_RTOP** *Advances in real-time reflectometry for next generation machines.*
  - 950,960 node-hours asked.
- **EnR_RRMP** Reflectometry plasma tracking during ramp-up: Application to DEMO.
  - 950,960 node-hours asked.
- **DTTSimul3** 3D reflectometry simulation for DTT PPR.
  - 1,000,000 node-hours asked.
- **DPPRTRB** Effect of turbulence in the DEMO PPR measurements.
  - 950,782 node-hours asked.

Previous allocations HPC hosted under EUROfusion, range from about 250,000 (average) to 1,000,000 (maximum) node-hours.

On last cycle IST obtained 25,000 to 32,500 node hours (2.5% to 4% of the asked allocation).

A low allocation for the 6th cycle can be a **problem**.

Budget execution

- **Travel** No missions have been performed within the project due to the travel restrictions and sanitary situation arising from COVID-19.
  - *Work had to be bridged with remote meetings and through e-mail.*

- **Development costs** initially previewed for 2021 could not be executed.

Sub Category	Description	Costs (k€)	Beneficiary	Year	Costs Revised
Eq./OGS 40% standard	Development of compact reflectometer, including DDS	4.000	IST	2021	4.000
Eq./OGS 40% standard	Installation of a fiber network between the central clocking system	3.000	CEA	2021	3.000
Eq./OGS 40% standard	Development of custom electronic boards for clock emission and reception	12.000	CEA	2021	12.000

- **A demand** has been done to transfer them to **2022**