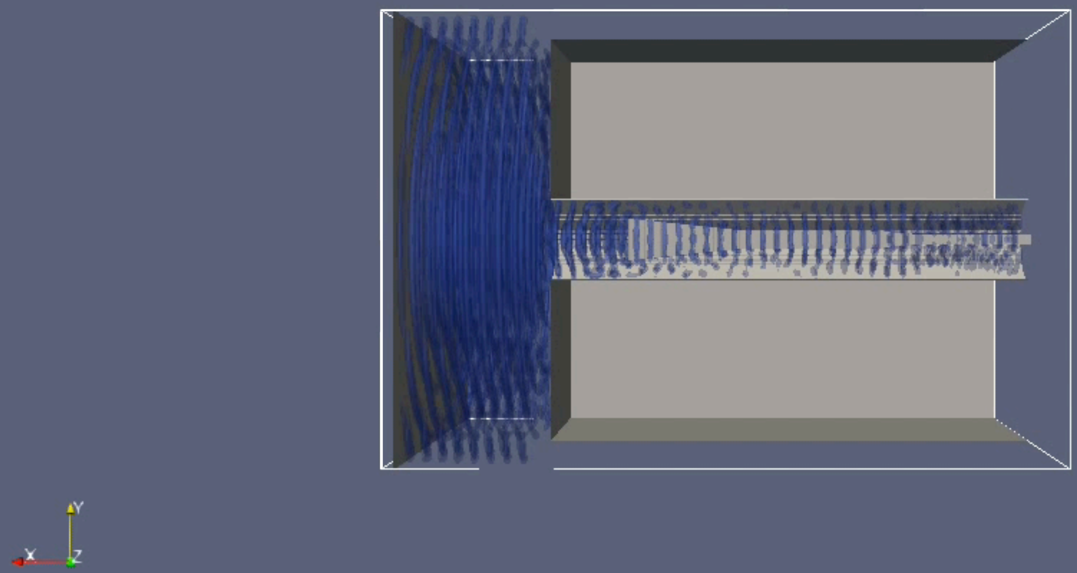
Assessment of the measurement performance for a DTT plasma position reflectometry system— Simulations performed using the 2D REFMULF and 3D REFMUL3 and future efforts



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EUROfusion

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The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Summary...

- **The Divertor Test Tokamak (DTT) aims to study exhaust solutions on tokamaks.**
  - Special look on DEMO.

- **ITER is operating in detached condition. What if it proves inadequate?**
  - Sound alternatives must be made available.

As in all fusion machines there will be a need for diagnostics to gather knowledge about the physical processes occurring in the plasma, for engineering needs and control

- **Reflectometry is one of the most important techniques to diagnose fusion plasmas**
  - Foreseen in the coming generation of machines such as ITER and DEMO.

ASSESS THE PERFORMANCE OF A PLASMA POSITION REFLECTOMETRY SYSTEM FOR DTT OPERATING IN THE LOW FIELD SIDE

ASSESSMENT MADE USING SYNTHETIC REFLECTOMETERS IMPLEMENTED USING A 2D AND A 3D FULL WAVE FDTD CODES

REFMULF & REFMUL3

- **A set of 3 O-mode LFS FMCW reflectometers**
  - On the equatorial plane **gap 0˚ 2D (from K to W band) and 3D (K & Ka bands)**
  - On the upper torus midplane **gap 45˚ (from K to W band)**
  - On the lower torus midplane **gap -60˚ (from K to W band)**

Synthetic diagnostics/Simulations

- **Synthetic diagnostics using FDTD time-dependent codes offer a comprehensive view of reflectometry:**
  - ***Propagation in the plasma***
  - ***System location within the vacuum vessel***
  - ***Assess the plasma signal processing techniques.***

- **Reflectometry simulation computational demanding due to:**
  - ***Large volumes*** *spatially discretised using a* ***small fraction of the wavelength****.*
  - ***Short time discretisation*** *of wave period to comply with CFL condition.*

- **Computational demands are the reason to mainly use 2 dimensional codes, such as REFMULF.**

- **REFMUL3, a newly performing parallel code gives access to 3D simulations, although much more costly than 2D ones.**

- **Included in this work, an effort to benchmark the two types of codes, dimensionwise, to assess the main differences and compromises done when using 2D versus 3D.**

Maxwell curl equations
Auxiliary linear differential equation for *J*

- FDTD most commonly applied to Maxwell's curl equations (Wave equation possible)
- Usual to write the curl equation in a vacuum(with ε_0 and μ_0)
- Condense the plasma physics in the density of current **J**

$$\begin{aligned}\nabla \times \mathbf{H} &= \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \sigma \mathbf{E} + \mathbf{J} \\ \nabla \times \mathbf{E} &= -\mu_0 \frac{\partial \mathbf{H}}{\partial t} - \sigma^\star \mathbf{H}\end{aligned}$$

- This results in a system coupling Maxwell equations with a LDE for **J=σE**

$$\frac{\mathrm{d}\mathbf{J}}{\mathrm{d}t} = \varepsilon_0 \omega_p^2 \mathbf{E} + (\boldsymbol{\omega}_x + \boldsymbol{\omega}_y + \boldsymbol{\omega}_z) \times (\mathbf{J}_x + \mathbf{J}_y + \mathbf{J}_z)$$

- The curl equations are discretised following the Yee schema
- A time integrator is used to solve the LDE

REFMUL* code *family*

- All REFMUL* are full-wave FDTD Maxwell codes
- REFMUL: 2D O-mode simulation code
- REFMULX/REFMULXp: 2D X-mode simulation codes (serial/ parallel)

- REFMULF is a 2D Full polarization code ☚ 2D simulations in this work
  - *Treats all component of* E (E_x+E_y+E_z) *and* B (H_x+H_y+ H_z)*of the wave*
  - *Supports a generic external magnetic field* B_0 (B_{0x}+B_{0y}+ B_{0z})
  - *Couples the TE Mode (X-mode) with the TM Mode (O-mode) via J*
  - *Sources on both planes: UTS (antennas et alia…), TFSF plane wave, PBC plane wave*

  Extends capabilities of available 2D codes

  - *e.g. Coupling O/X, Faraday rotation, Cotton-Moutton effect,..*

- REFMUL3 is a 3D parallel code ☚ 3D simulations in this work
  - *All field components included*
  - *Parallel hybrid implementation (OpenMP+MPI) with 3D domain decomposition*
  - *XDMF/HDF5 compressed binary output or parallel VTK (big data output)*

Expressions for 2 & 3 Dimensions

2D Full polarisation e.g. **REFMULF**

2D TMz (O-mode) e.g. **REFMUL**

$$
\begin{aligned}
\mu_0 \frac{\partial H_x}{\partial t} + \sigma^\star H_x &= -\frac{\partial E_z}{\partial y} \\
\mu_0 \frac{\partial H_y}{\partial t} + \sigma^\star H_y &= +\frac{\partial E_z}{\partial x} \\
\varepsilon_0 \frac{\partial E_z}{\partial t} + \sigma E_z &= -\frac{\partial H_x}{\partial y} + \frac{\partial H_y}{\partial x} - J_z
\end{aligned}
$$

2D TEz (X-mode) e.g. **REFMULX/REFMULXp**

$$
\begin{aligned}
\varepsilon_0 \frac{\partial E_x}{\partial t} + \sigma E_x &= \frac{\partial H_z}{\partial y} - J_x \\
\varepsilon_0 \frac{\partial E_y}{\partial t} + \sigma E_y &= -\frac{\partial H_z}{\partial x} - J_y \\
\mu_0 \frac{\partial H_z}{\partial t} + \sigma^\star H_z &= \frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x}
\end{aligned}
$$

3D Full polarisation e.g. **REFMUL3**

$$
\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon_0}\left(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z}\right) - \frac{\sigma}{\varepsilon_0} E_x - \frac{1}{\varepsilon_0} J_x
\qquad
\frac{\partial H_x}{\partial t} = -\frac{1}{\mu_0}\left(\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z}\right) - \frac{\sigma^\star}{\mu_0} H_x
$$

$$
\frac{\partial E_y}{\partial t} = \frac{1}{\varepsilon_0}\left(\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x}\right) - \frac{\sigma}{\varepsilon_0} E_y - \frac{1}{\varepsilon_0} J_y
\qquad
\frac{\partial H_y}{\partial t} = -\frac{1}{\mu_0}\left(\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x}\right) - \frac{\sigma^\star}{\mu_0} H_y
$$

$$
\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon_0}\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}\right) - \frac{\sigma}{\varepsilon_0} E_z - \frac{1}{\varepsilon_0} J_z
\qquad
\frac{\partial H_z}{\partial t} = -\frac{1}{\mu_0}\left(\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y}\right) - \frac{\sigma^\star}{\mu_0} H_z
$$

2D Full polarisation / 3D Full polarisation

2D TMz (O-mode)

$$\frac{\mathrm{d}J_z}{\mathrm{d}t} = \varepsilon_0 \omega_p^2 E_z + \omega_x J_y - \omega_y J_x$$

2D TEz (X-mode)

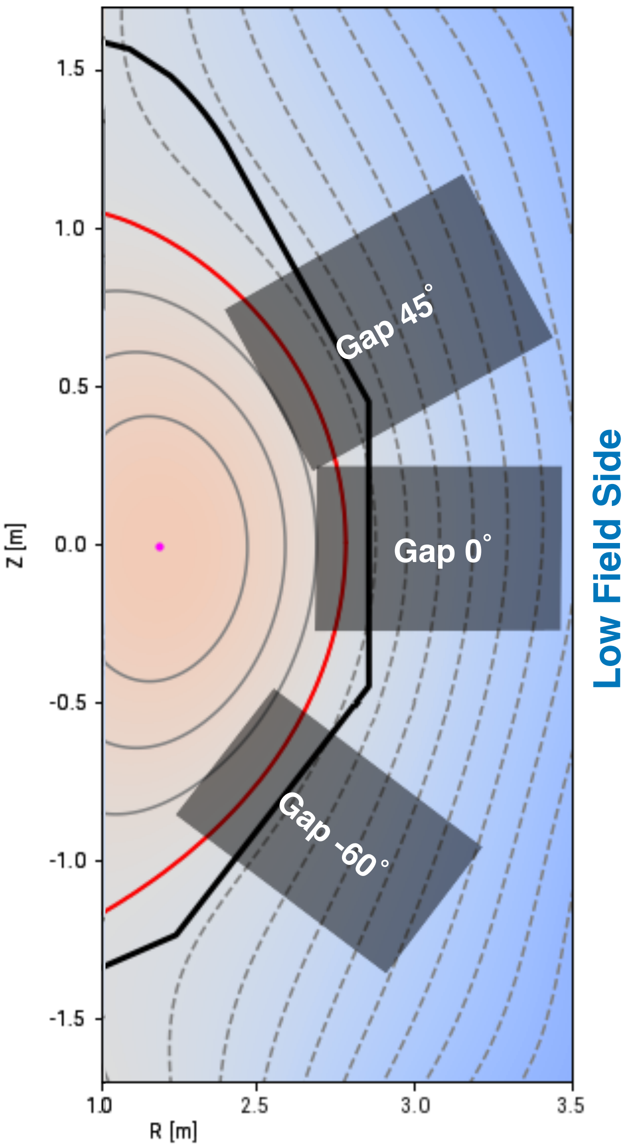
$$\frac{\mathrm{d}J_x}{\mathrm{d}t} = \varepsilon_0 \omega_p^2 E_x - \omega_z J_y + \omega_y J_z$$

2D TEz (X-mode)

$$\frac{\mathrm{d}J_y}{\mathrm{d}t} = \varepsilon_0 \omega_p^2 E_y + \omega_z J_x - \omega_x J_z$$

Density description

Single Null Scenario



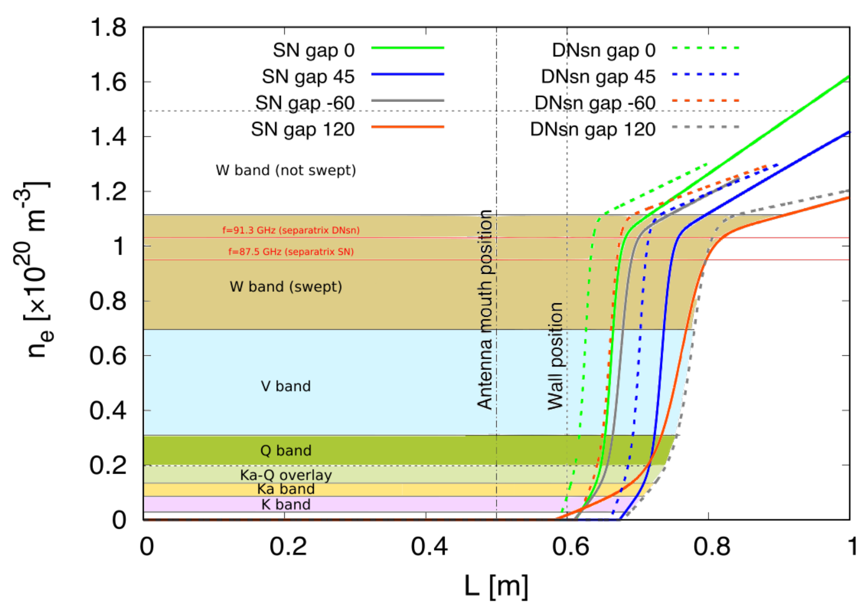
We used an educated guess model based on the density profiles appearing in
R. Martone et alia, DTT Divertor Tokamak Test faciliy—Interim Design Report, April 2019.
using a fit on the extracted data with the expression proposed in
L. Frassinetti et alia, Nuclear Fusion 57 (2017) 016012.

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

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

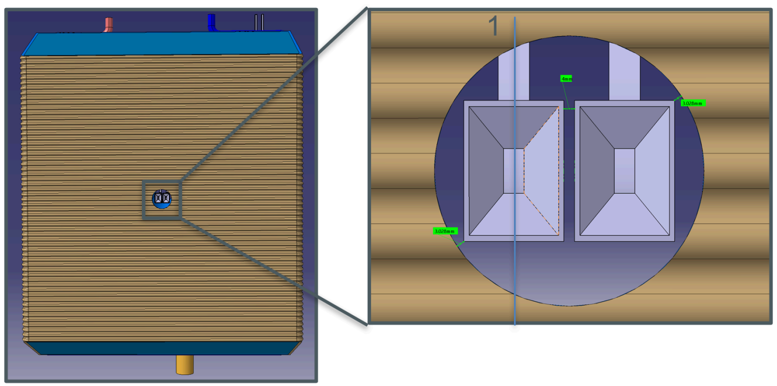
The profiles can be mapped into the machine coordinates

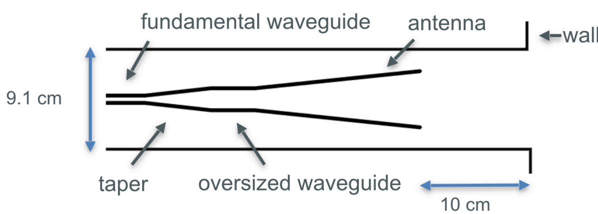
$$n_e(r_{LOS}) \xrightarrow{r_{LOS}(\rho_{pol})} n_e(\rho_{pol}) \xrightarrow{\rho_{pol}(R,Z)} n_e(R,Z)$$



Synthetic Diagnostics setup

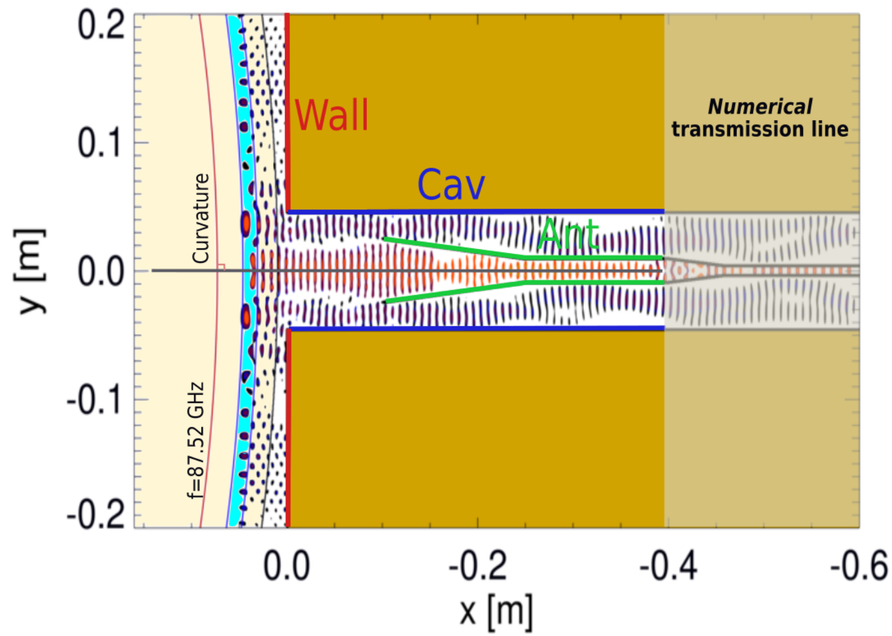
CAD of one of the antenna models adopted for the present work.





2D schematic of the antenna

Synthetic reflectometer of **gap 0°** for **Ka** band operating at a frequency of **40 GHz**.



Blue-shaded region: iso-density region corresponding to the frequency limits of the Ka band.

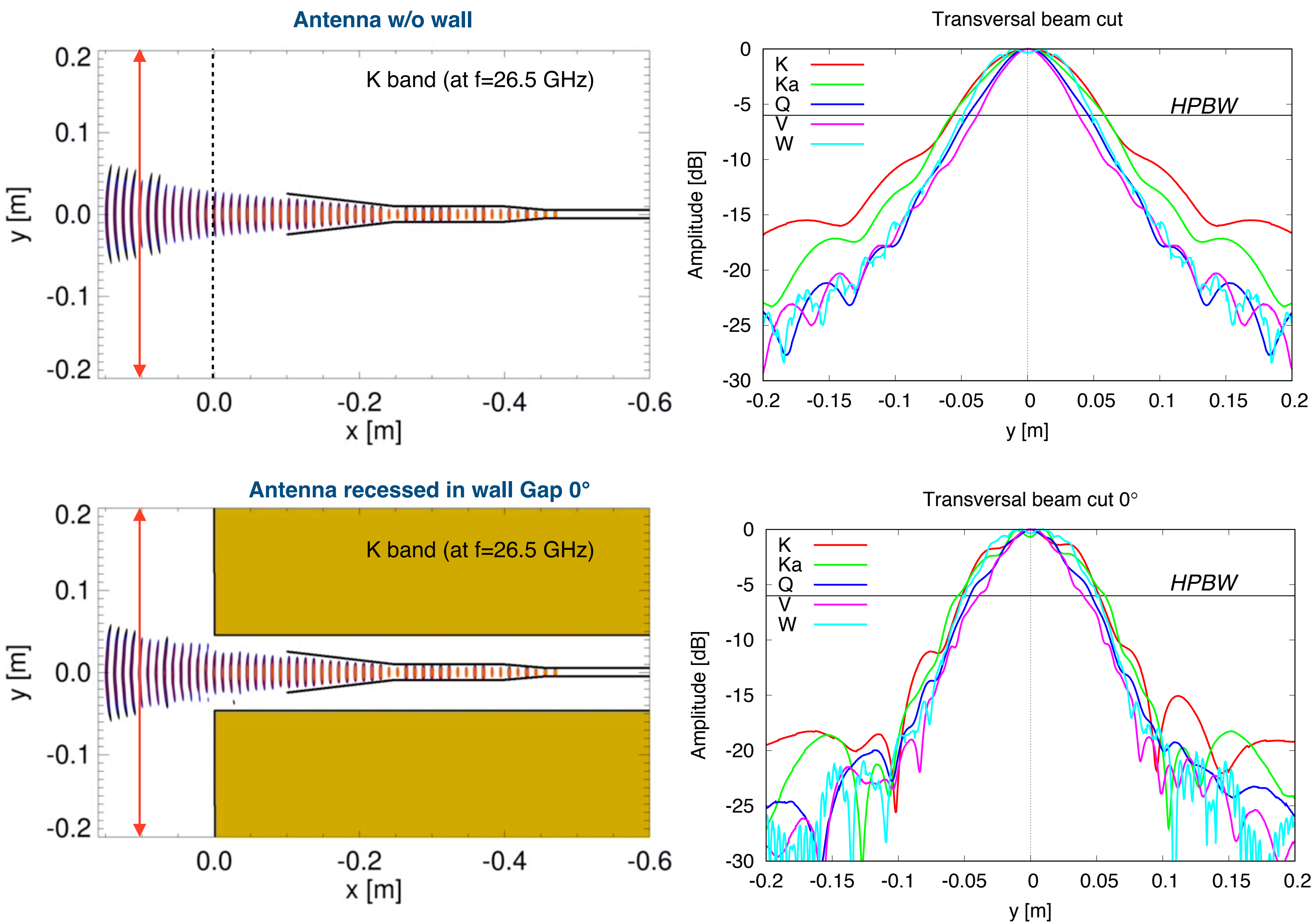
Shaded part between [-0.4,-0.6] [m] in the simulation box provides a termination to the antenna giving a boundary to the oversized antenna and waveguide numerically equivalent to a well behaved transmission line.

Radiation diagram

Antenna recessed in the wall gives rise to perturbations in the wave pattern and traversal modulation

Effects are kept small and do not rule out the use of this configuration

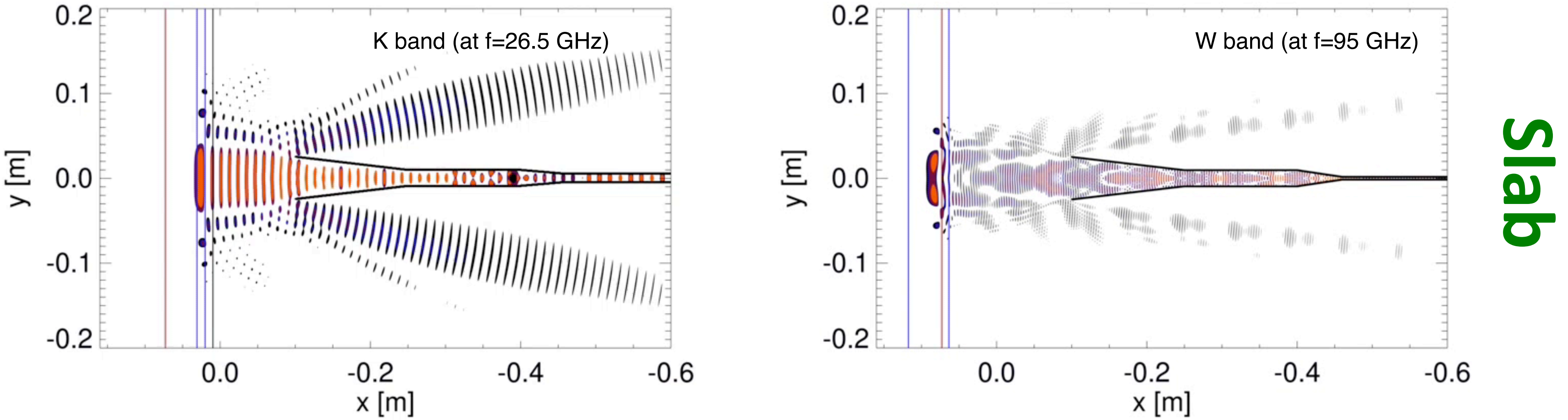
Poloidal cuts of Ez are representative of the antenna radiation diagram



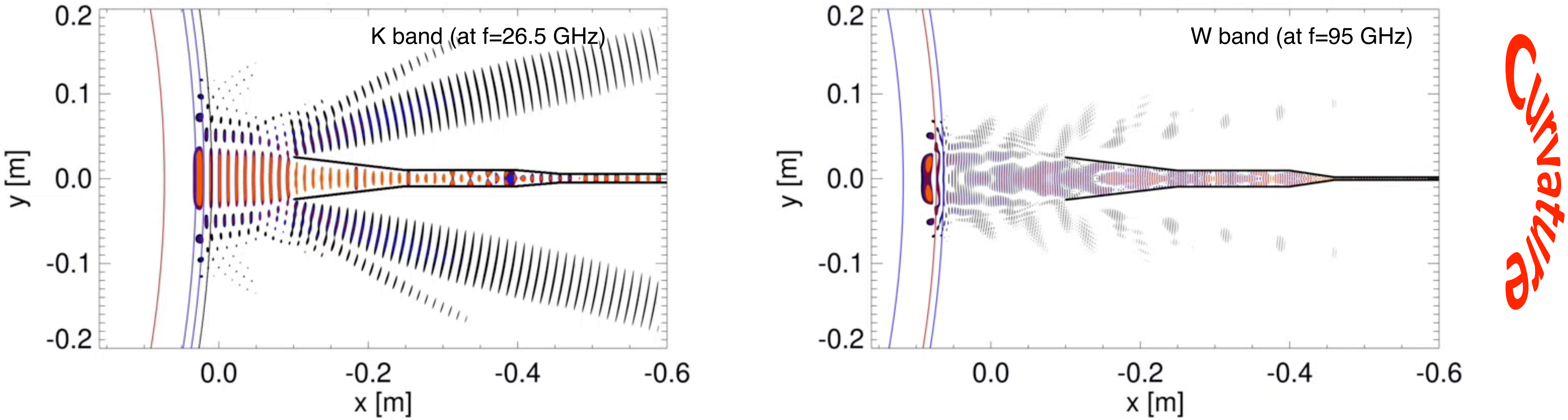
Effects of curvature

The curvature on both plasma scenarios (SN & DN) do not introduce major deviations from the standard reference case

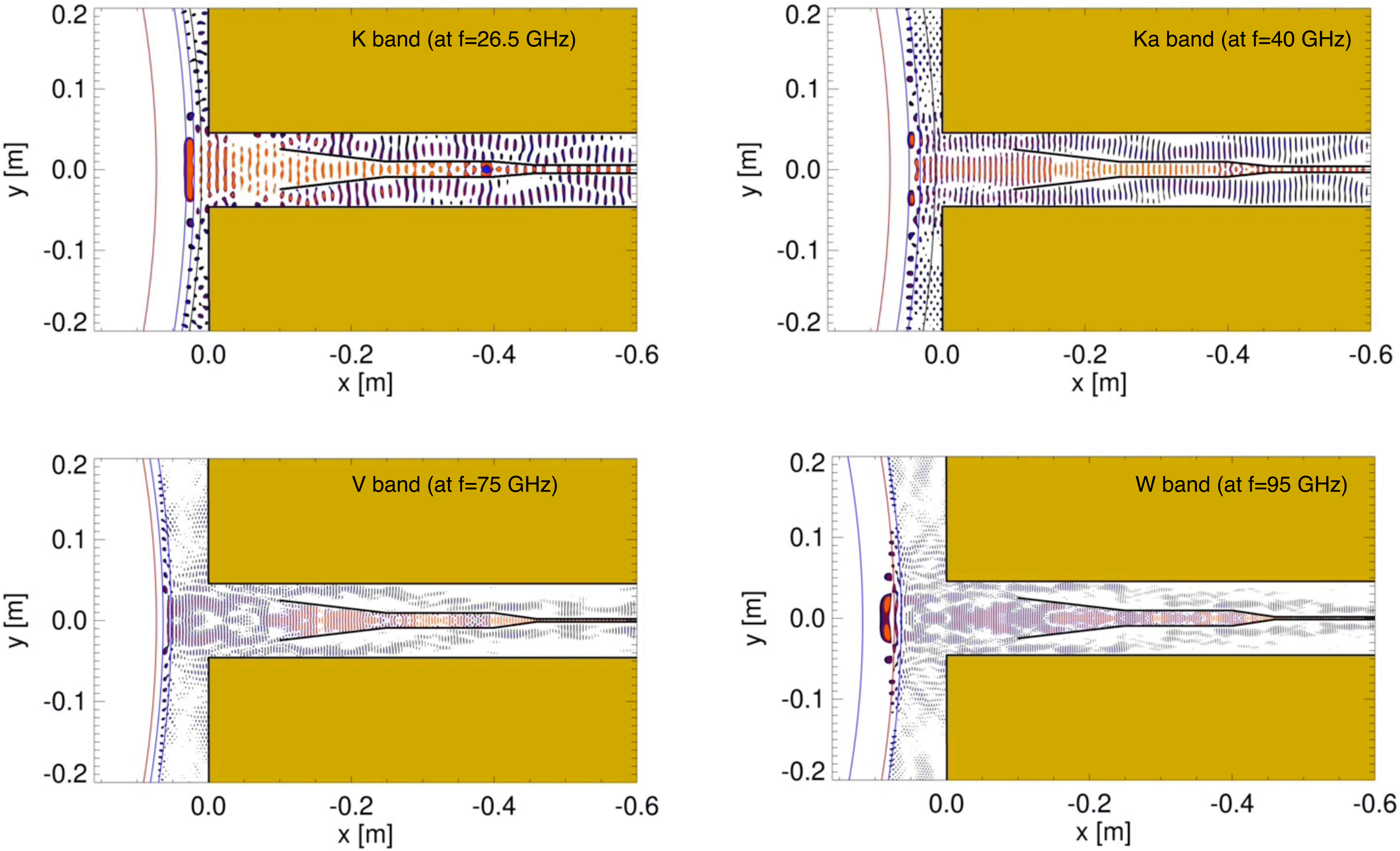
Slab plasma (reference case)



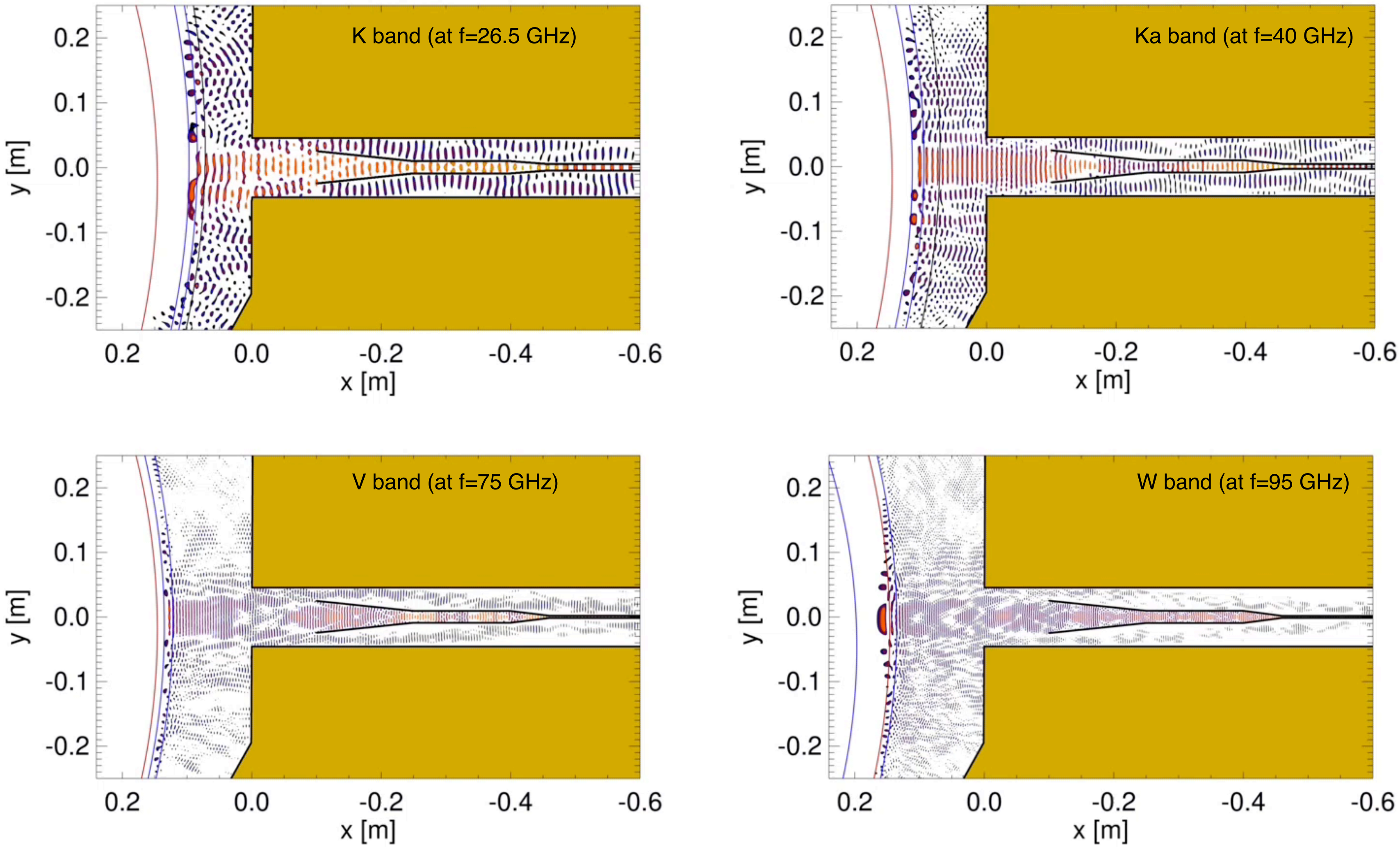
Single null plasma Gap 0°



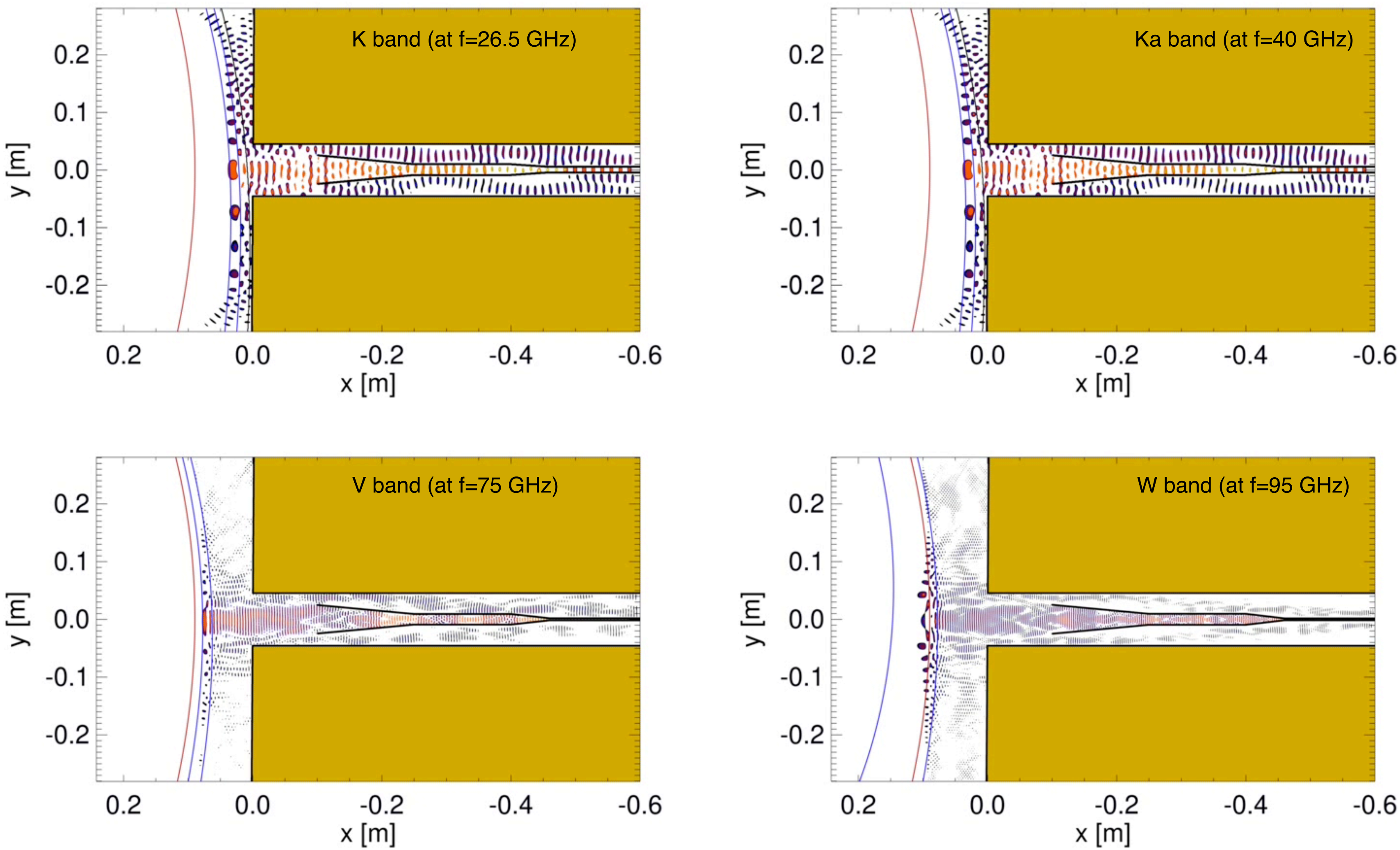
Full System for Gap 0° SN scenario probing



Full System for Gap 45° SN scenario probing

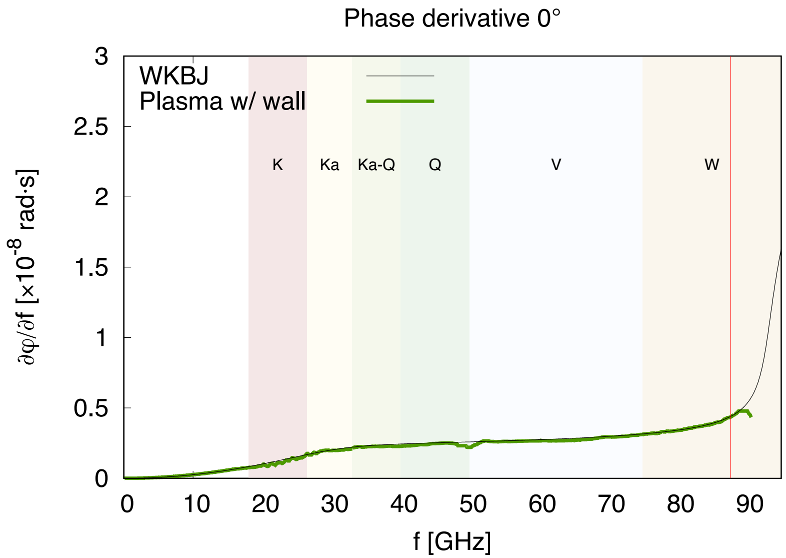


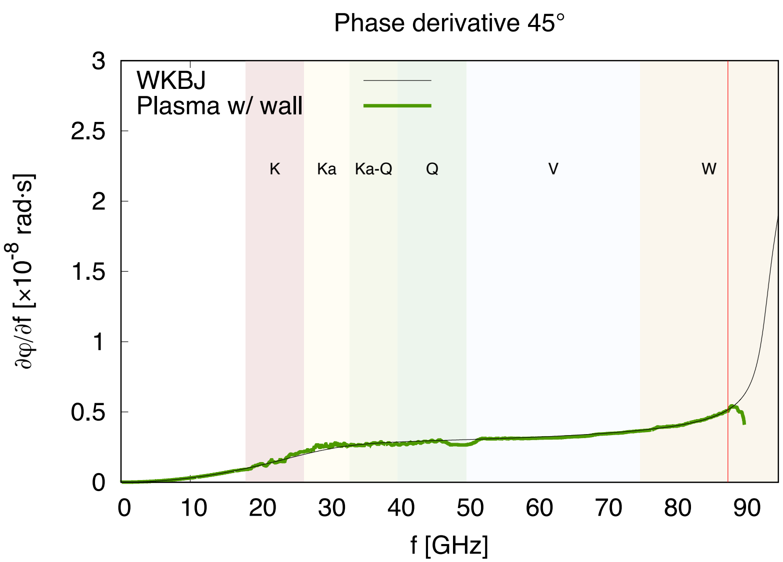
Full System for Gap -60° SN scenario probing

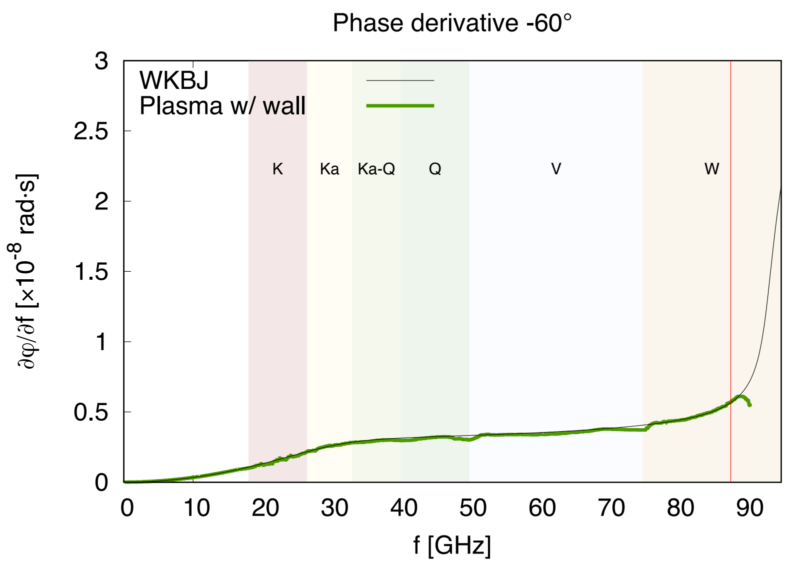


Phase derivative

The **phase derivatives** evaluated from simulation data (SN plasma scenario) represented against the **theoretical WKBJ** (known from input data).
The vertical red line marks the **separatrix frequency**. The vertical shaded areas denote the frequency ranges of the different bands.





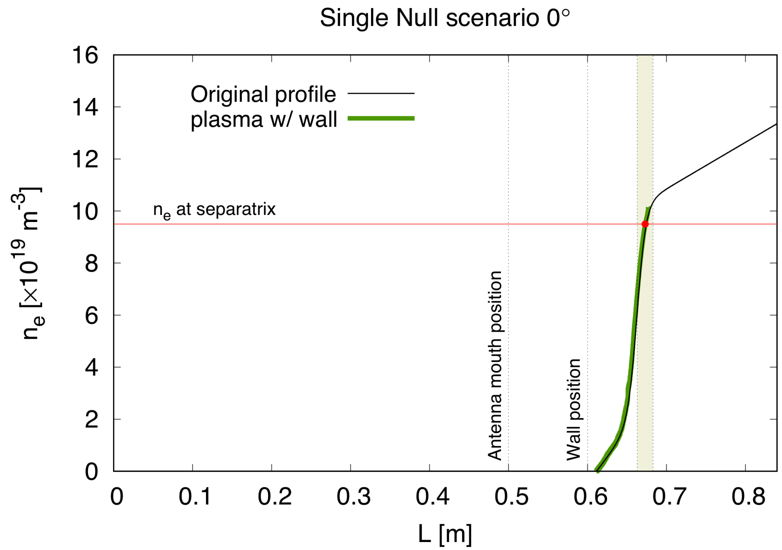


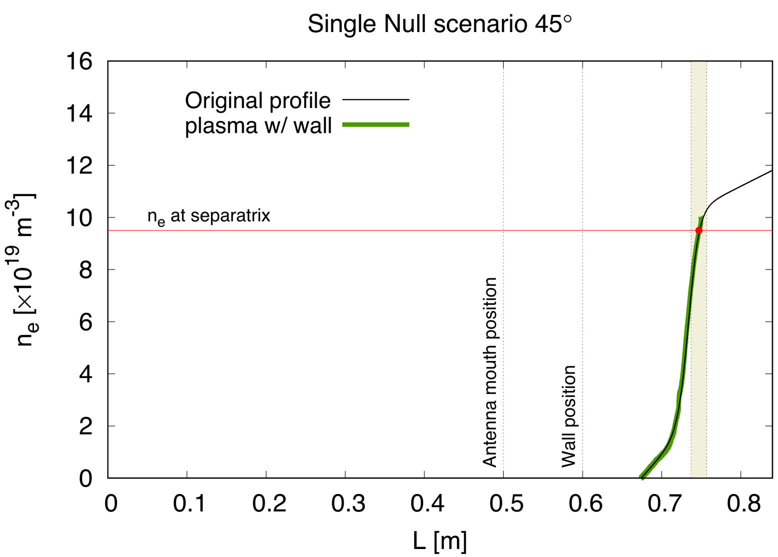
Profile reconstruction

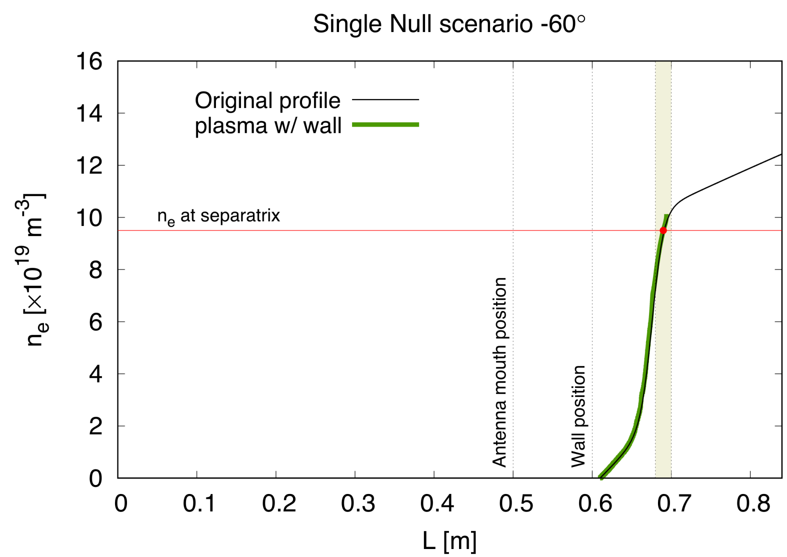
The phase derivative allows us to calculate the position of a given reflecting layer ***r(nₑ)*** and recover the electronic density profile using

$$r(F) = \frac{c}{2\pi^2} \int_0^F \frac{\partial\varphi}{\partial F} \frac{\mathrm{d}f}{\sqrt{F^2 - f^2}}$$

The **profiles reconstructed** from the phase derivatives, for the SN plasma scenario. The horizontal red line marks the separatrix density. The vertical shaded band shows the error tolerance of **1cm** in the position of the separatrix.





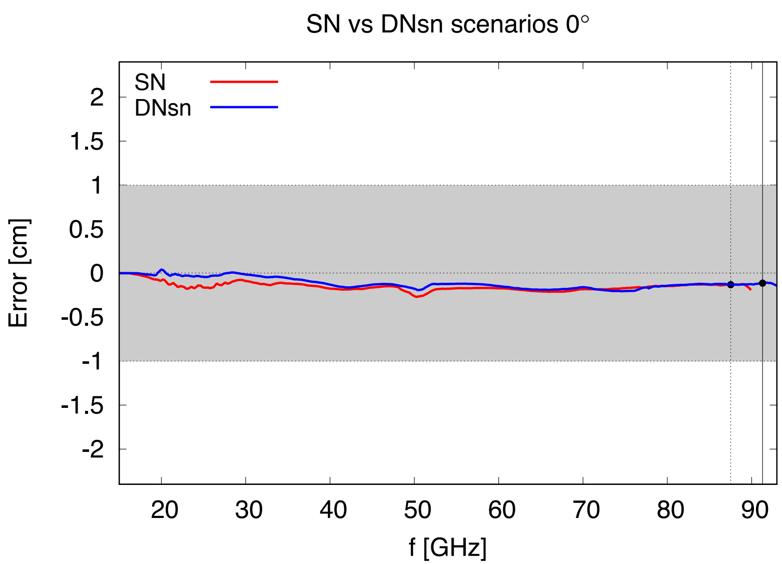


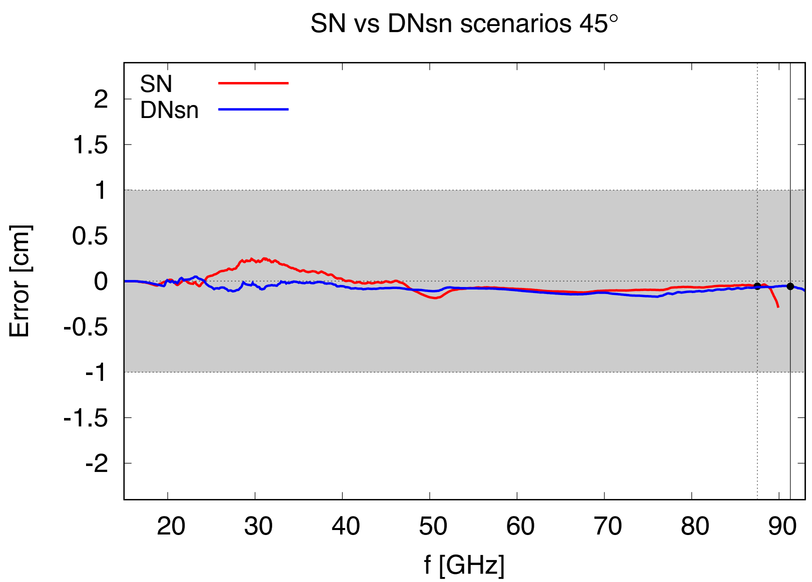
Position error at the separatrix

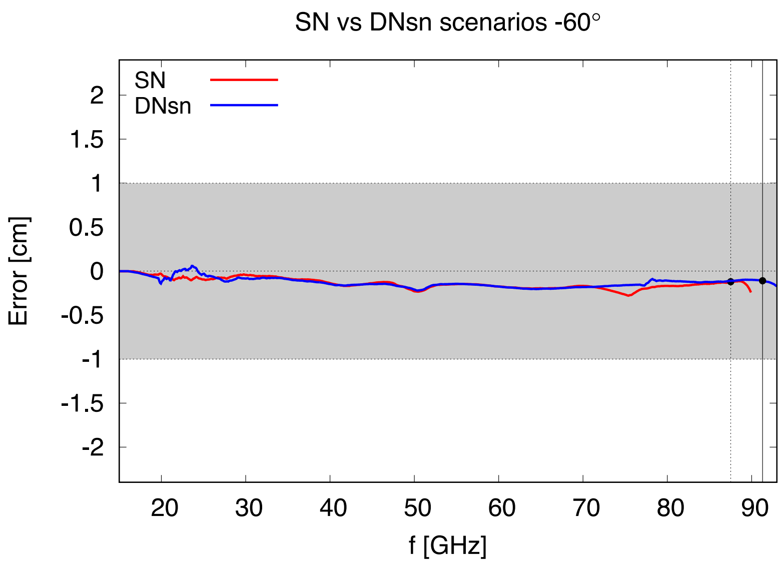
The error in the reflectometry measurement of a given position in the plasma can be evaluated as:

$$\mathrm{Error}(F) = \frac{c}{2\pi^2}\int_0^F \left(\frac{\partial\varphi}{\partial F} - \frac{\partial\varphi_0}{\partial F}\right)\frac{\mathrm{d}f}{\sqrt{F^2 - f^2}}$$

where $\partial\varphi/\partial F$ is the phase derivative of the measurement and $\partial\varphi_0/\partial F$ is the phase derivative of the reference measurement. Evaluating at the cut-off frequency corresponding to the electronic density at the separatrix, the error at the separatrix is obtained $\mathrm{Error}_{sep} = \mathrm{Error}\left[F(n_e)\right]$

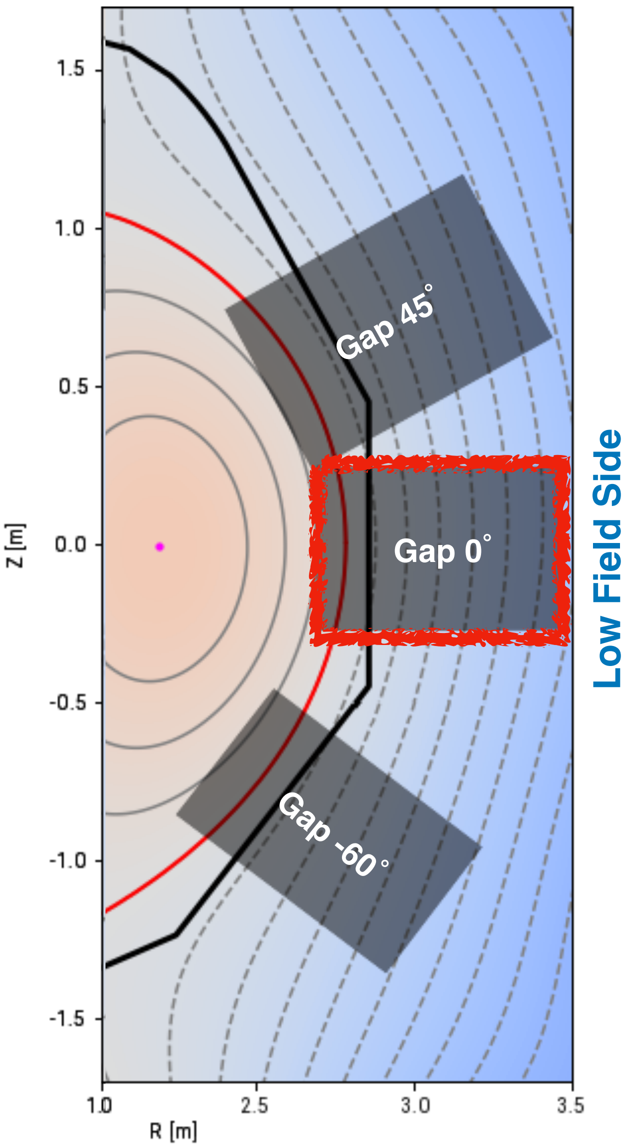


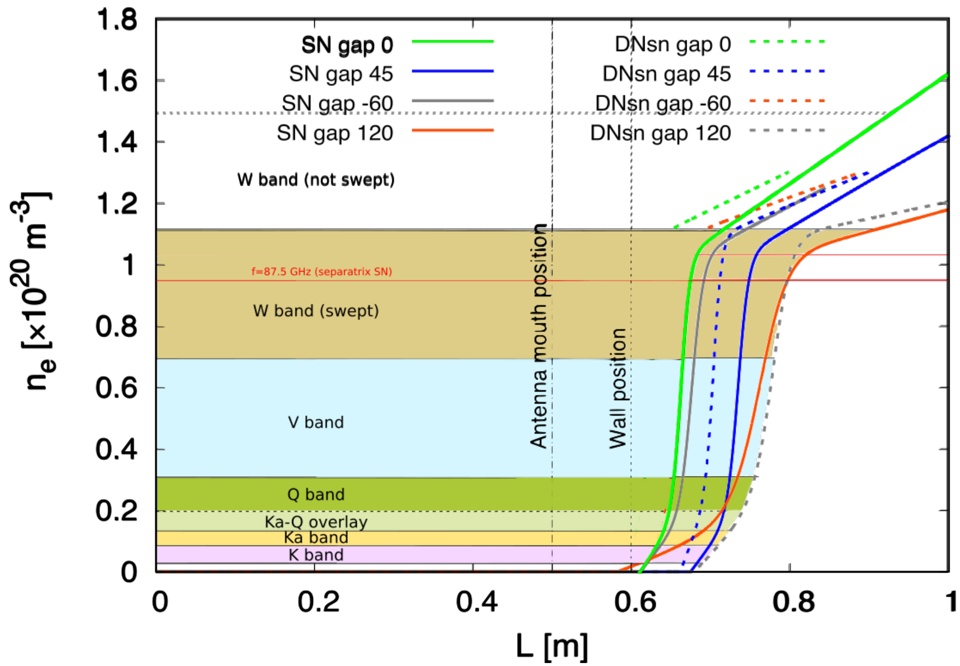




For the 3D simulations…

Single Null Scenario



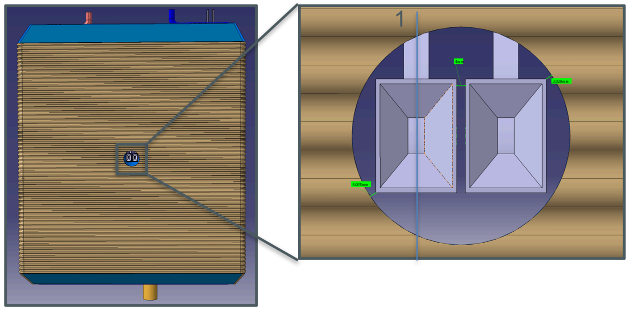


3D simulations focus on Gap 0° — SN Scenario

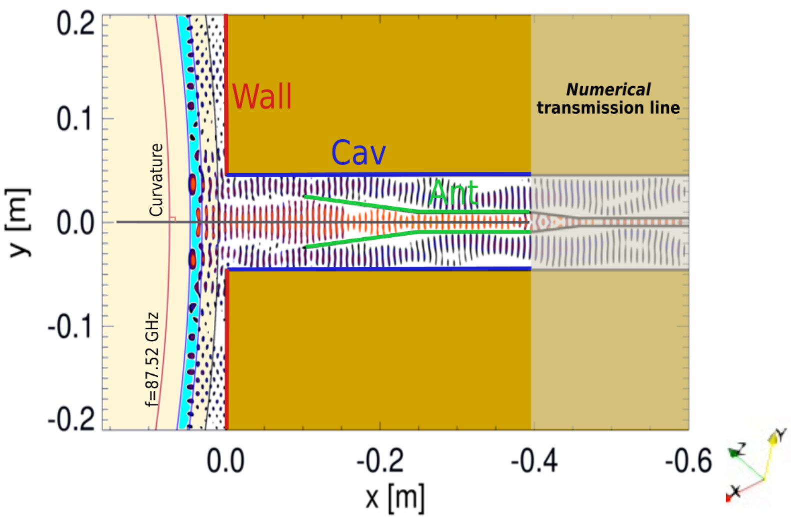
- **2D** simulations span over **K, Ka, Q, V** and **W** bands:
- **3D** simulations:
  An ongoing work…
  Bands **K** and **Ka** ready…

3D Synthetic Diagnostics setup

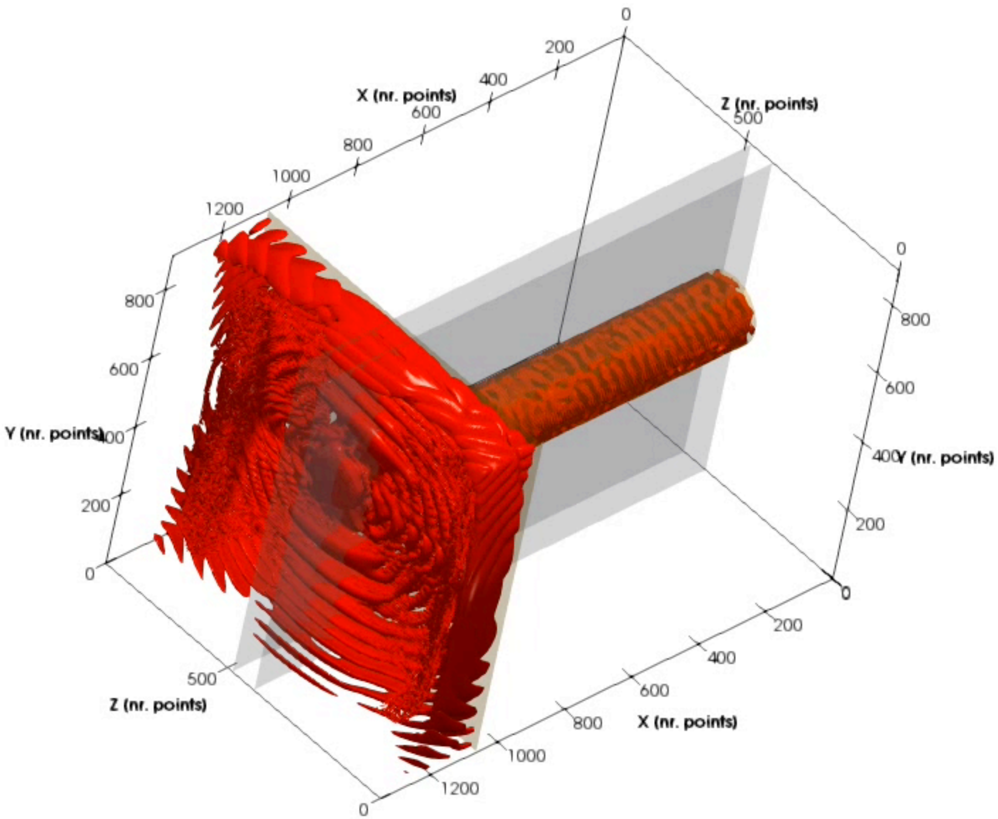
CAD of one of the antenna models



Recalling the 2D Synthetic reflectometer of **gap 0°** for **Ka** band operating at a frequency of **40 GHz**.



Synthetic reflectometer of **gap 0°** for **K** band operating at a frequency of **18 GHz**.



3D simulations — Example for the K band

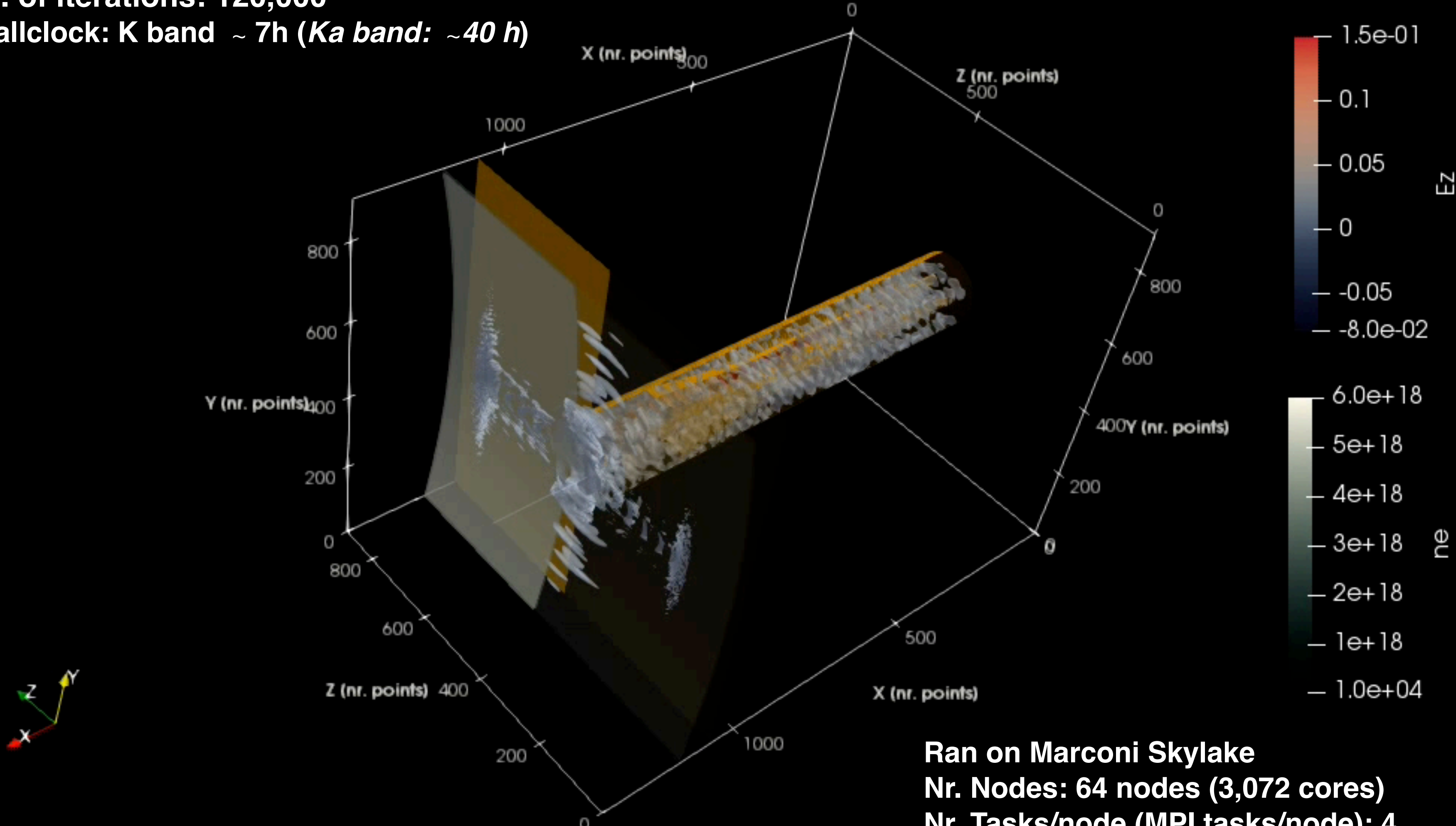
Grid size: K band — 1348x899x899 (*Ka band — 2033×1356×1356*)

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)

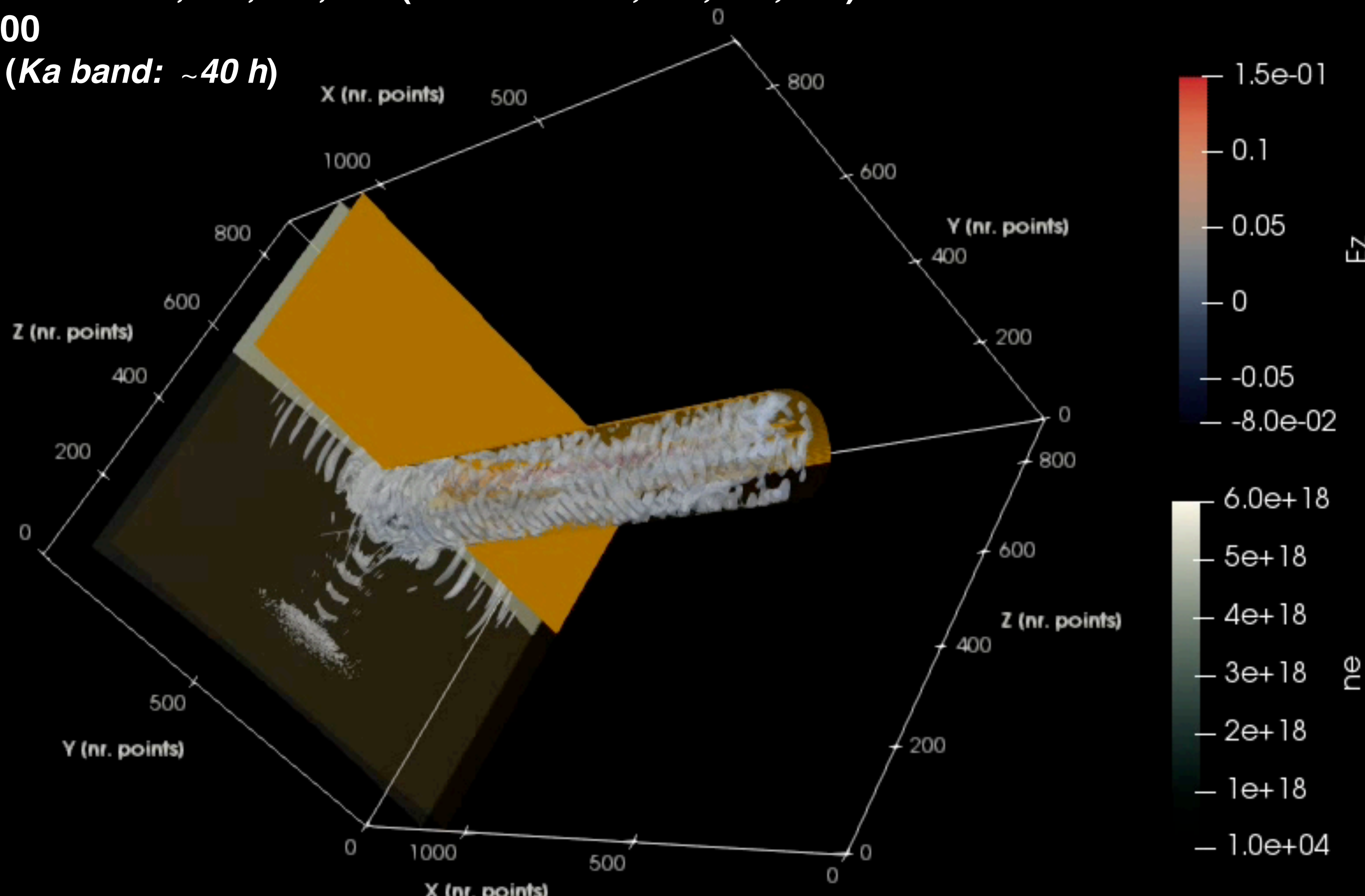
Nr. Tasks/node (MPI tasks/node): 4

Total nr. MPI tasks: 256

Nr. OpenMP threads/task: 12

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*)



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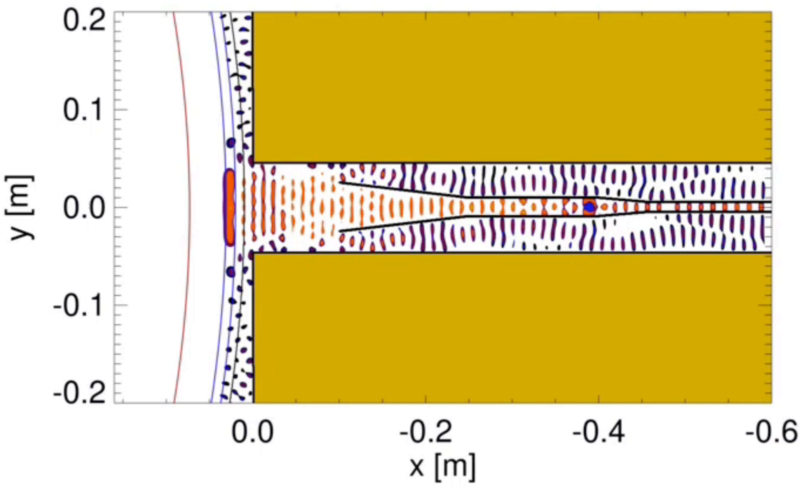
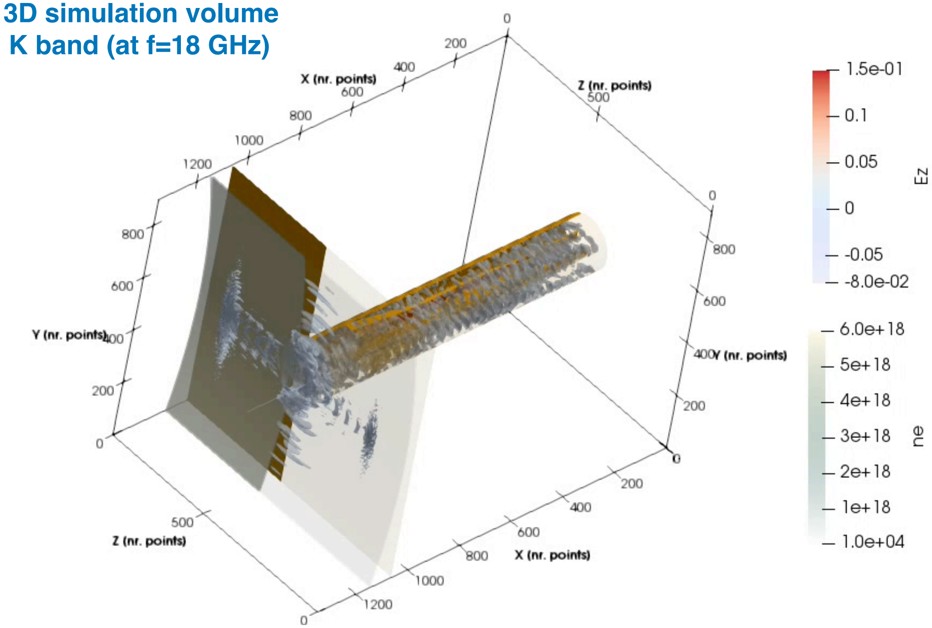
2D E_z field map vs. 2D Tx & Rx cuts of 3D

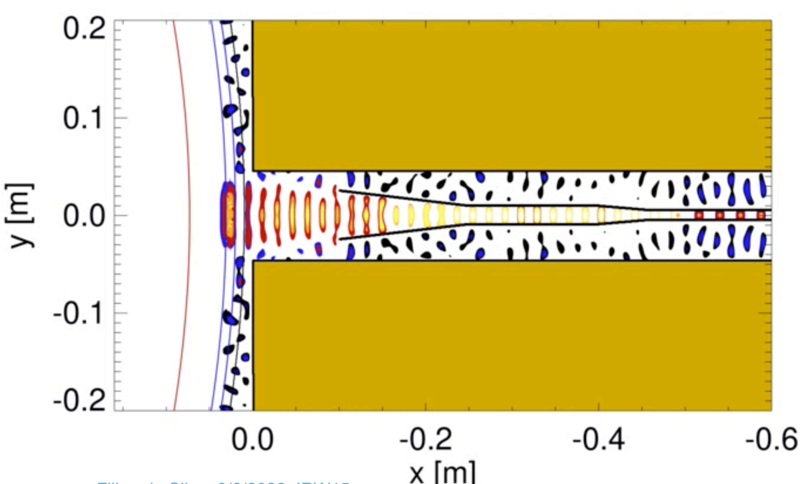
2D simulation
K band (at f=26.5 GHz)



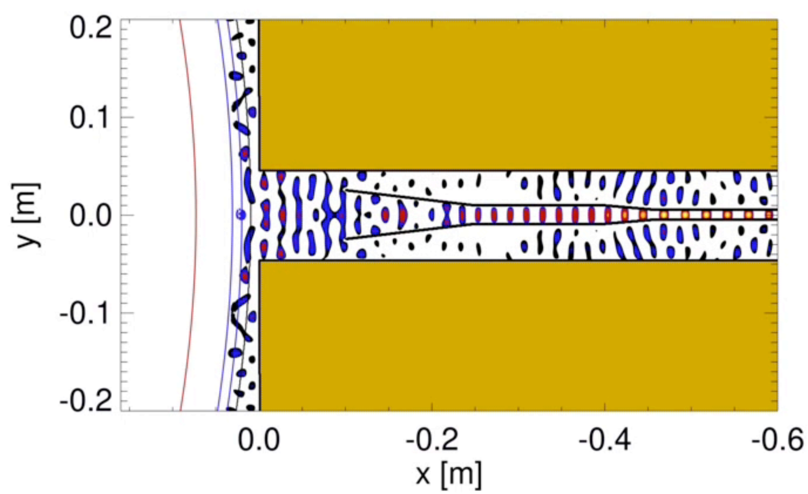
3D simulation volume
K band (at f=18 GHz)



3D simulation— Tx plane
K band (at f=18 GHz)

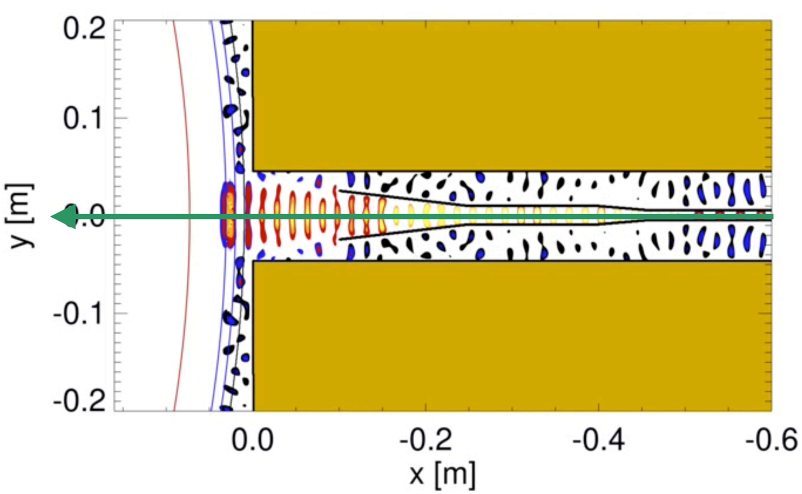


3D simulation— Rx plane
K band (at f=18 GHz)

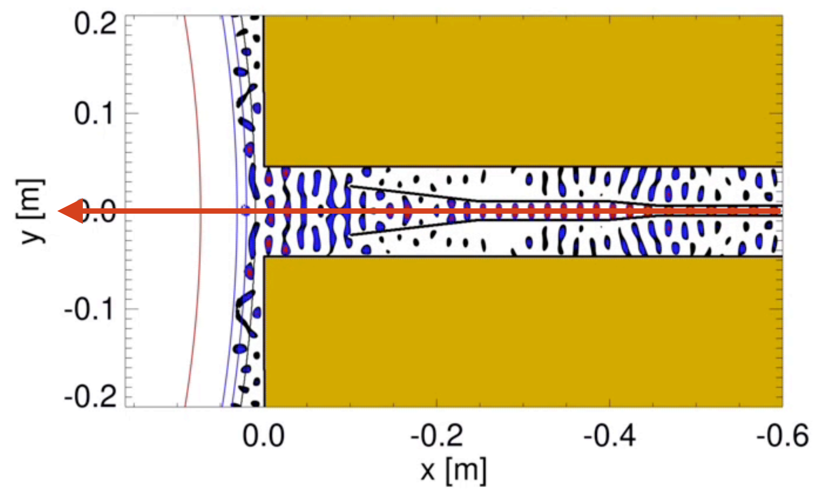


Amplitude of E_z @ LOS — 3D vs. 2D

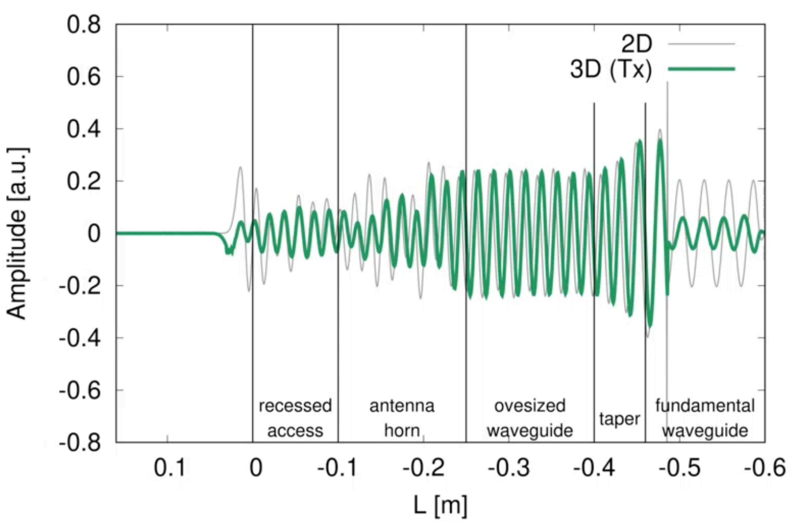
3D simulation— Tx plane
K band (at f=18 GHz)



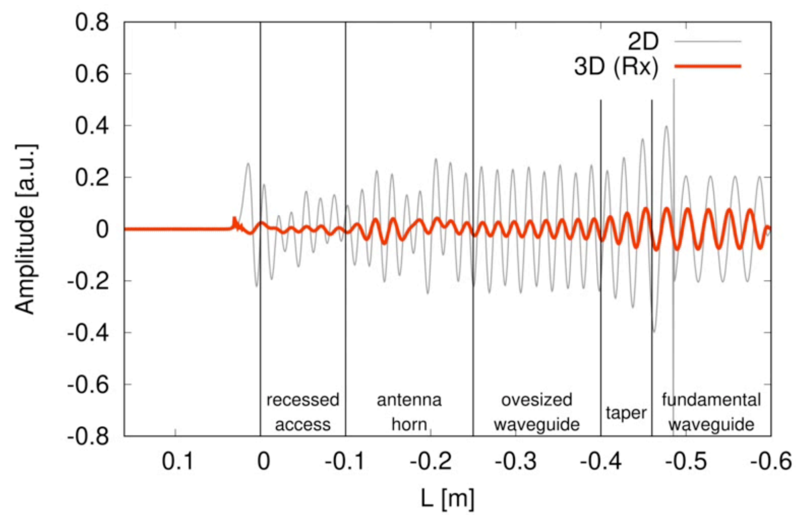
3D simulation— Rx plane
K band (at f=18 GHz)



Tx antenna LOS



Rx antenna LOS



Discussion: *Main assessment results*

- The alignment of the antennas, optimised for the SN scenario, proved to equally performing for the DN scenario.
- For the LSF reflectometers simulated, the impact of probing the plasma away from the midplane does not impose major difficulties.
- Simulations of the full systems, which include the effects of the plasma and structure and their interplay, confirm a good performance with measurement errors well within the ±1cm error requirements, and with deviations of the order of some millimetres at the separatrix.

The main conclusion to take from this exercise is that the proposed positions (or any small variation) for the LFS are suitable for the placement of reflectometry systems and encourage to continue the efforts towards an actual implementation on IDTT.

That would be a major step for reflectometry in general, and for IDDT and DEMO in particular, since a profile measuring system away from the midplane has never been tested before.

Present & Future Work

The transition from 2D to 3D simulation is progressing slowly but steady. It presents some parallels with the change from 1D to 2D that arrived ~20 years ago.

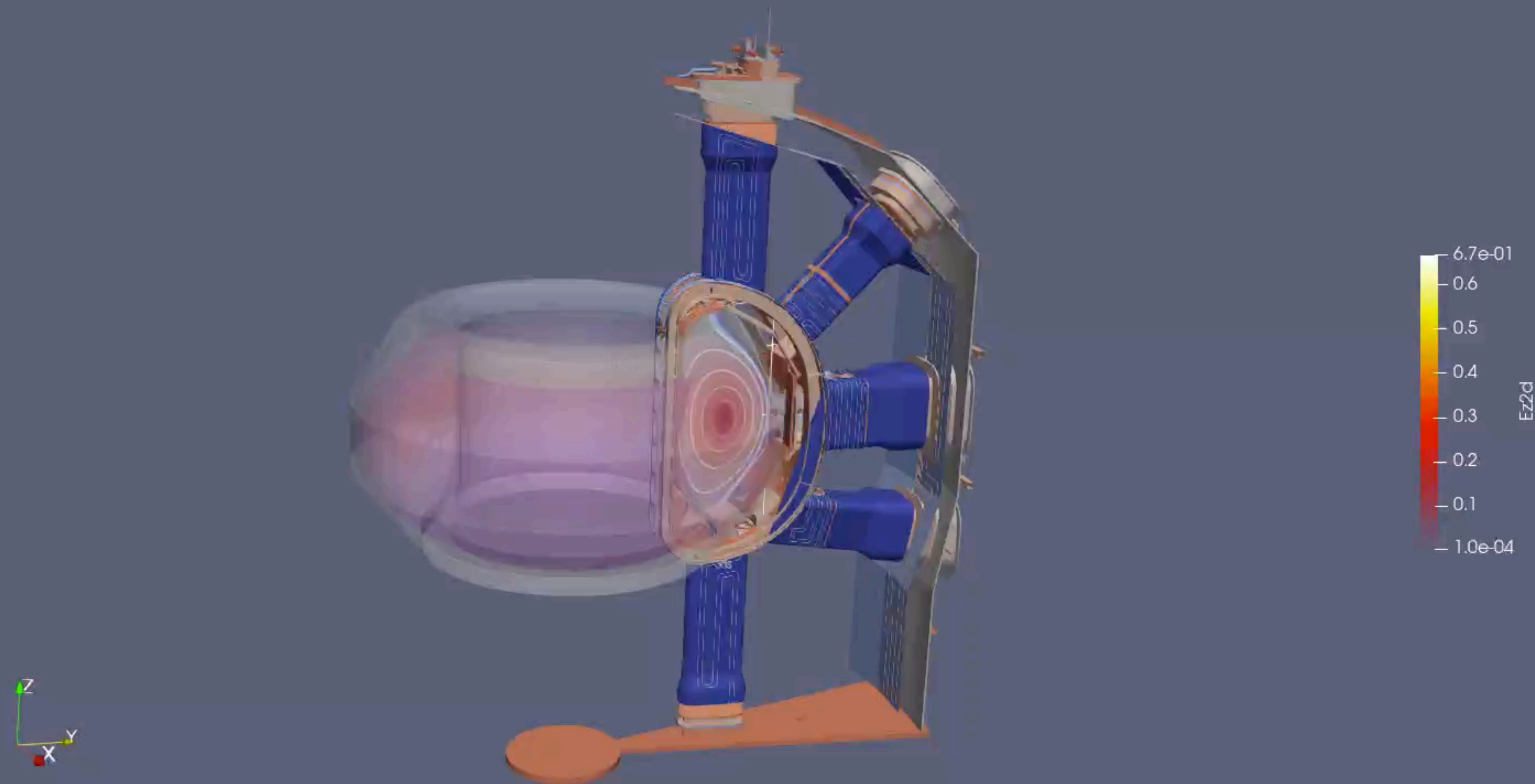
- **3D gives more realistic amplitude values**
  - ***Of major importance to have a proper signal-to-noise ratio (S/N).***
  - ***To infer the true impact of turbulence signatures in S/N***
  - ***Important in the amelioration of profile initialisation.***
- **3D simulations are extremely computationally expensive**
  - ***Should be channelled to the cases where 2D is unable to provide an correct answer.***
  - ***As an aid to help setting up or calibrate a 2D case study.***
  - ***As a complement to the main 2D simulations.***

Present & Future Work appear in talks:

Thursday 9th June [25] Jorge Manuel Santos, *CAD model input pipeline for REFMUL3 full-wave FDTD 3D simulator*

Thursday 9th June [23], F. da Silva, *Status of the Enabling Research Project Advances in real-time reflectometry plasma tracking for next generation machines: Application to DEMO*

Thank you



Thank you