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

Jorge M. Santos[1], Emanuel Ricardo[1], Filipe J. da Silva[1], Tiago Ribeiro[2], Stephane Heuraux[3], and António Silva[1]
(jsantos@ipfn.tecnico.ulisboa.pt)

[1] Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal
[2] Max-Planck-Institut fuer Plasmaphysik, 85748 Garching, Germany
[3] Institut Jean Lamour, UMR 7198 CNRS-Université de Lorraine BP 50840, F-5401 Nancy, France

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MOTIVATION

The **design** and performance assessment of **microwave reflectometry diagnostics** for future fusion reactors **relies heavily on** the results produced by **synthetic diagnostics**.

- To fully simulate the main effects that influence the diagnostic measurements, **realistic 3D representations of all system components**, such as waveguides, tapers, antennas, as well as vessel wall and access to the plasma structures, **are needed**.

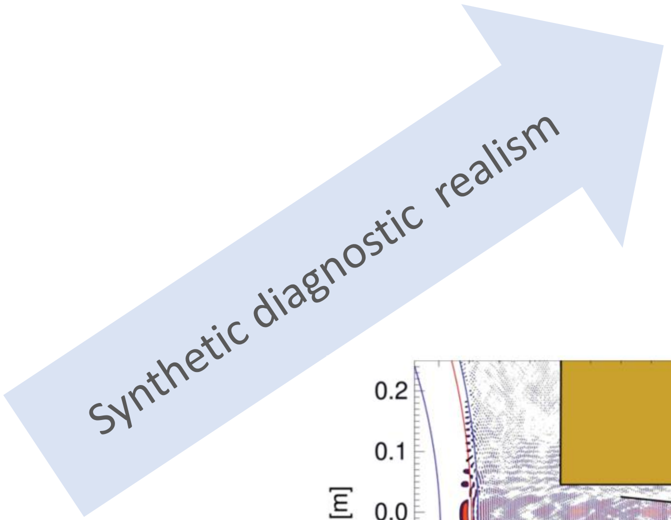
- **The quality of** the obtainable **measurements**, in the proposed reflectometer configurations and target plasma scenarios, **can** then **be realistically assessed using advanced 3D FDTD** microwave propagation **simulations.**

This often-neglected step requires the adaptation of tessellated mesh CAD models of the various components to the input VOXEL descriptions required by full wave 3D Maxwell FDTD parallel codes such as **REFMUL3***. **We herein present a fully automated pipeline that adapts these realistic 3D CAD models to a format that can be fed to REFMUL3 3D simulator.**

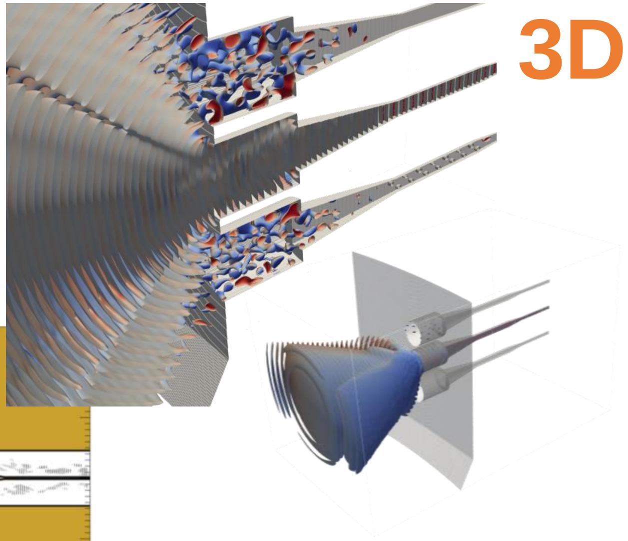
* F. da Silva et al. – Journal of Computational Physics, 2015, vol. 219, pp 24-45 / J. Inst., 2019 (08), pp C08004

FDTD FULLWAVE REFLECTOMETRY SIMULATIONS

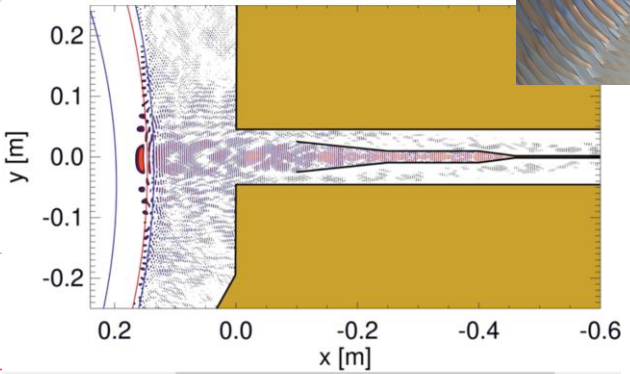
IPFN developed the REFMUL family of FDTD simulators to improve the interpretation of the complex measurements generated by its numerous deployed reflectometry diagnostics.



2020's

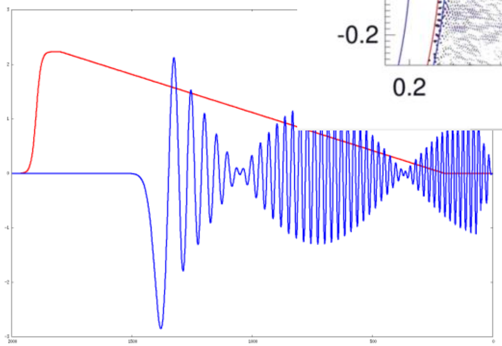


3D Provides a realistic volumetric simulation that incorporates the full 3D effects affecting the waves propagating in the plasma, and their interaction with the more or less complex geometries of the launcher and receiver antennas, vessel wall antenna access cutouts, and other surrounding plasma facing structures.



2D Provides a simulation along the poloidal plane, incorporates 2D effects and allows the use of more detailled 2D structures and antenna designs (3D -> 2D simplification).

2000's

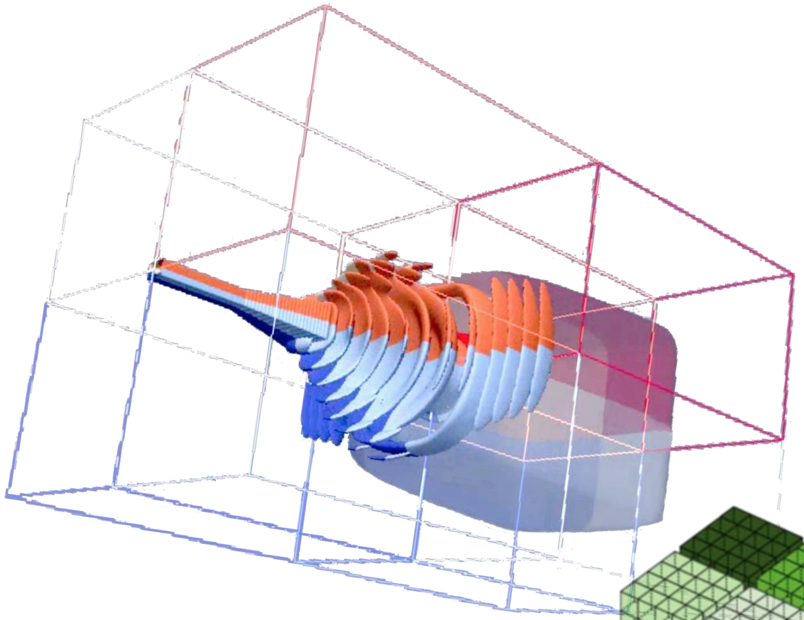


1D Provides a simulation along the line-of-site, no geometric effects are included.

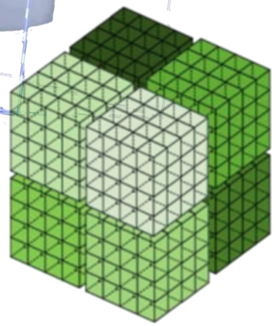
REFMUL3 – A 3D FDTD CODE

Solves Maxwell's equations + constitutive relation (current)

$$
\begin{aligned}
\nabla \times \mathbf{H} &= \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \sigma \mathbf{E} + \mathbf{J} \\
\nabla \times \mathbf{E} &= -\mu_0 \frac{\partial \mathbf{H}}{\partial t} - \sigma^{\star} \mathbf{H} \\
\frac{\partial \mathbf{J}}{\partial t} &= \varepsilon_0 \omega_p^2 \mathbf{E} + \vec{\omega}_c \times \mathbf{J}
\end{aligned}
$$



numerically using the Finite Difference Time Domain (FDTF) method



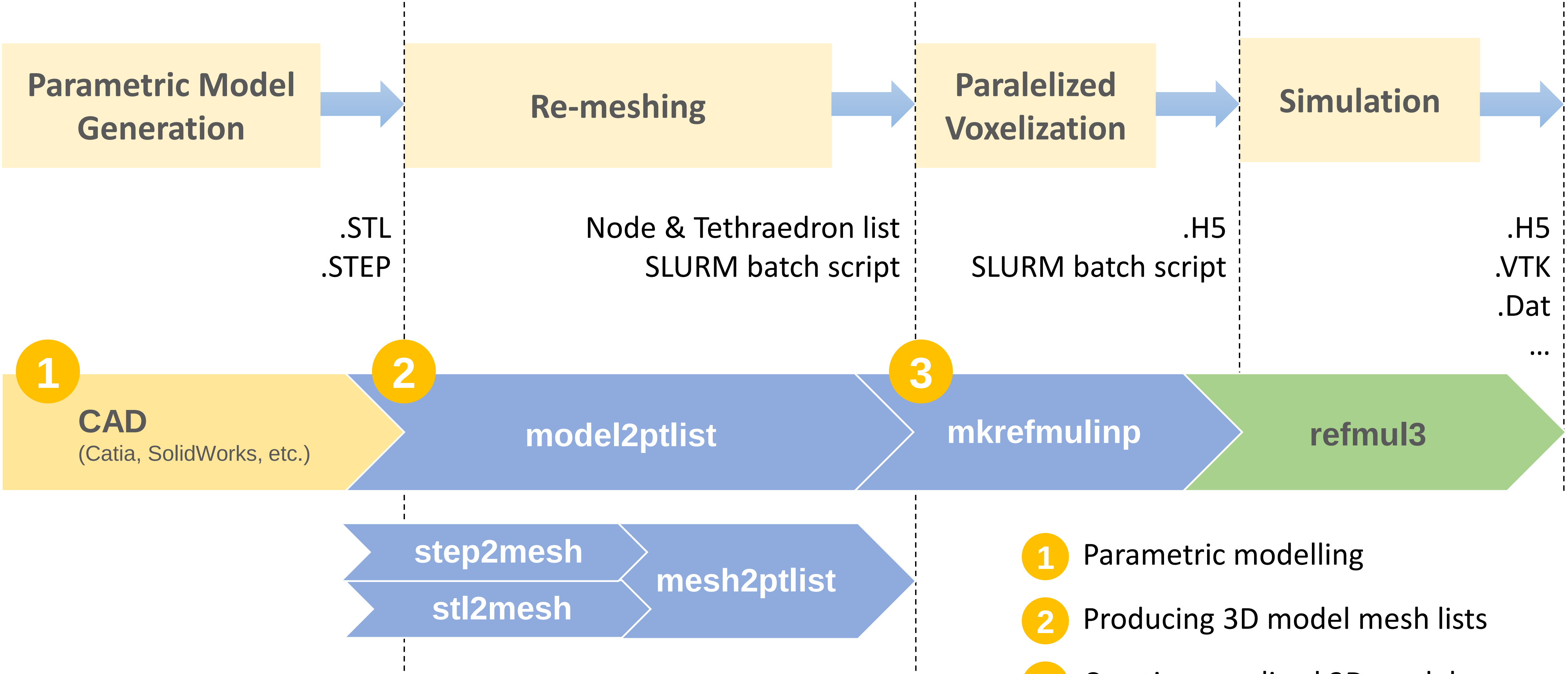
K.S. Yee, IEEE Trans. on Antennas and Propagation 14 (1966) 302

L.. Xu and N. Yuan IEEE Antennas and Wireless Propagation Let. 5 (2006) 335

REFMUL3: hybrid MPI/OpenMP full-wave code, with a **3D domain decomposition**

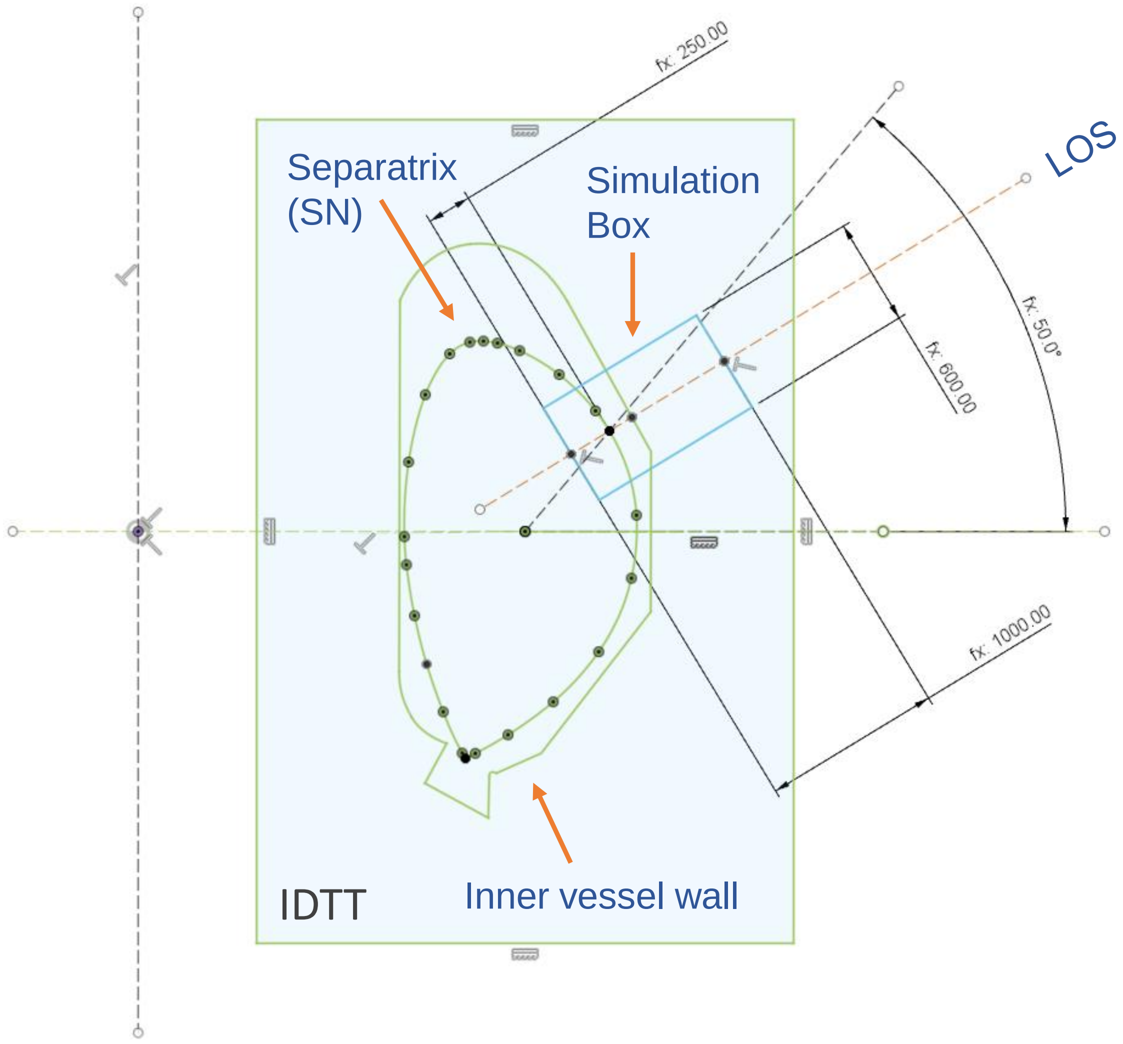
See also **F. da Silva**, *“Status of the Enabling Research Project Advances in real-time reflectometry plasma tracking for next-generation machines: Application to DEMO”* & *“Assessment of the measurement performance for a DTT plasma position reflectometry system - Simulations performed using the 2D REFMULF and 3D REFMUL3 and future efforts”* – in this workshop, for more **refmul3** applications.

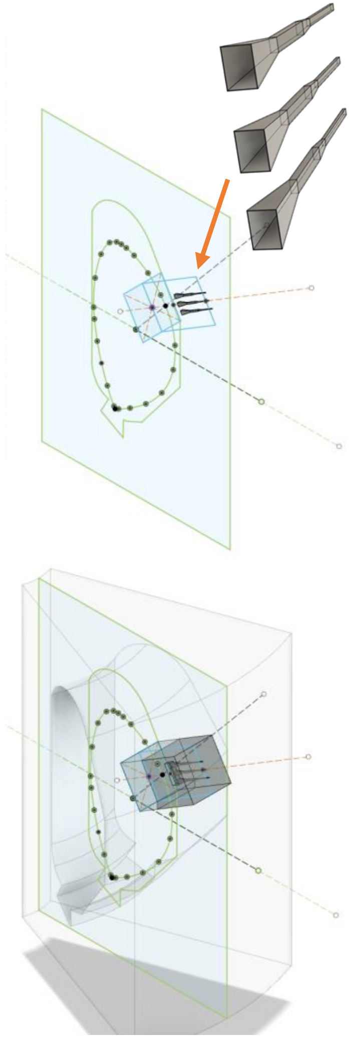
REFMUL3 INPUT MODEL PIPELINE



1. Parametric modelling
2. Producing 3D model mesh lists
3. Creating voxelized 3D model

1. Elaboration of parameterized CAD descriptions





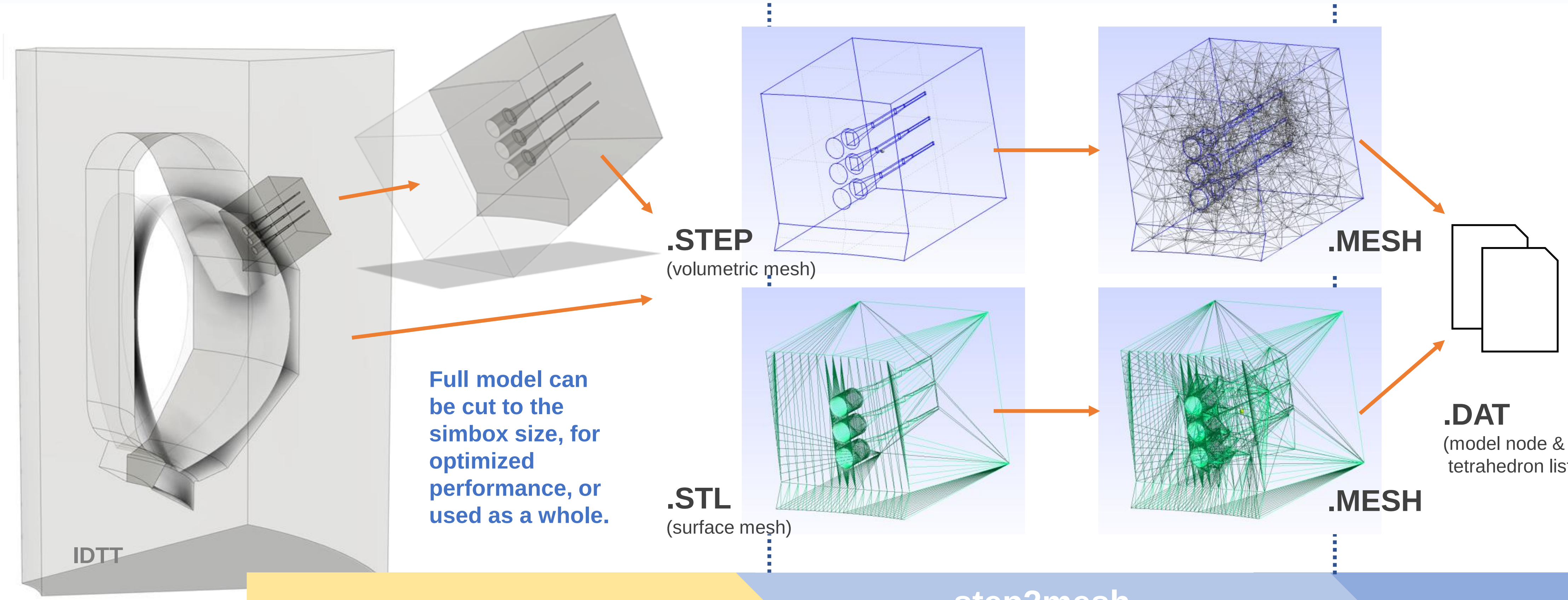
Proposed solutions require validation at various lines-of-sight (LOS)
(e.g., assessment of plasma position reflectometer's design)

⇒ **Parameterized CAD Modelling:**

- Antenna geometry & waveguide dimensions (band dependent)
- LOS definable in respect to facing separatrix configuration
- Simulation box sizes
- Feature rich vessel & antenna access to plasma geometries

A complete description of all relevant diagnostic components and of their actual integration in the tokamak allows for a more realistic simulation of the interaction between the propagating waves and the investigated antenna deployment schemes.

2. AUTOMATED MESH LIST GENERATION (MODEL2PTLIST)



Full model can be cut to the simbox size, for optimized performance, or used as a whole.

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

step2mesh

stl2mesh*

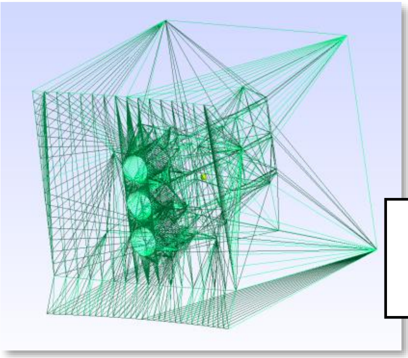
mesh2ptlist

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

Scripted node and tetrahedron extraction

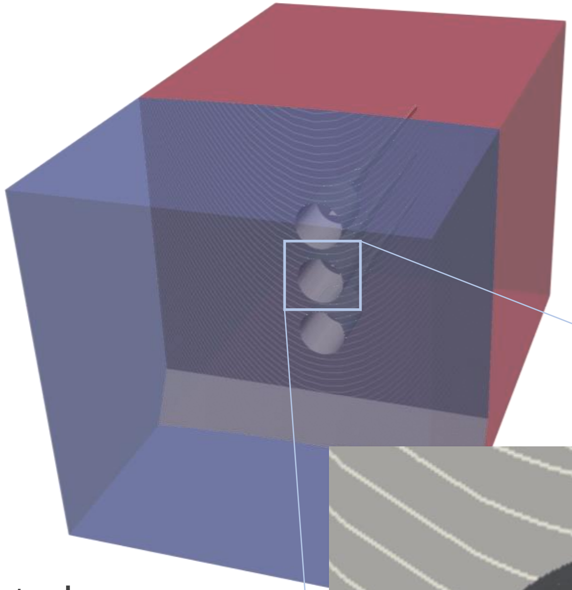
Gmsh © is distributed under the terms of the GPL License

3. Meshed model voxelization – parallel implementation

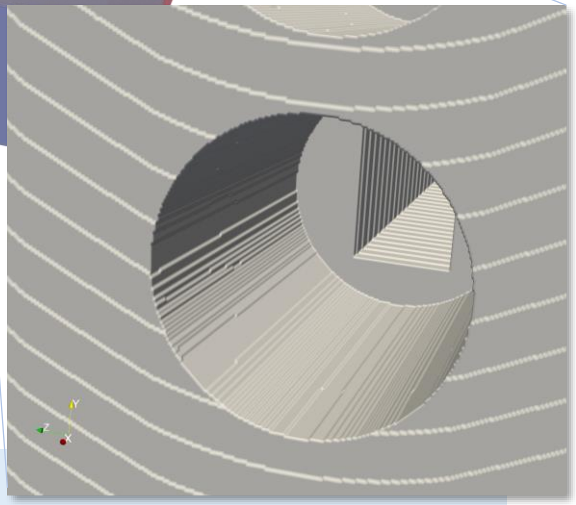


.DAT
(model node & tetrahedron list)

mkrefmulinp



.H5 / .XMF
(voxelized model in target simulation grid)



mkrefmulinp – generates a voxelised version of antenna & structure models in the simulation box volumetric range.

To cope with the complexity of the models and the huge size of the generated matrices, the voxelisation code was written in **C and parallelized using OpenMP**.

model2plist generates Slurm sbatch script to run **mkrefmulinp** in Marconi queues.

mkrefmulinp generates Slurm sbatch script to run **refmul3** in Marconi queues.

Voxelised simulation box of 1m x 0.6 m x 0.6m:

K band ⇒ Dxyz=0.504 mm ⇒ 2000 x 1200 x 1200 grid points ⇒ **~10 GB** (float32)
…
V band ⇒ Dxyz=0.201 mm ⇒ 4975 x 2975 x 2975 grid points ⇒ **~165 GB** (float32)

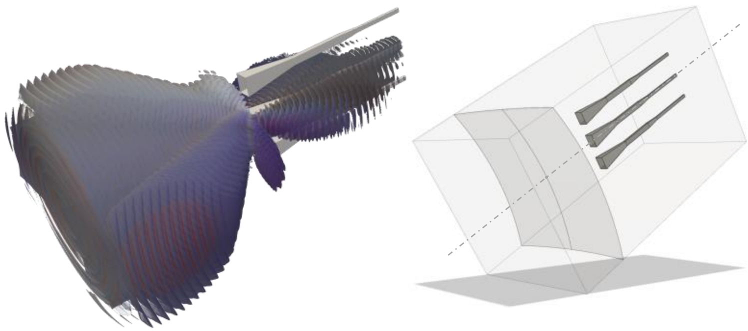
3. Meshed model voxelization – parallel implementation

Average time for the voxelization of a simulation box size of 1.0m × 0.6m × 0.6m,using 1, 24, and 48 cores in a single Marconi node (2 Xeon 8160 at 2.10 GHz, 48 cores, 192 GB DDR4 RAM).

OPENMP Voxelization code running time					
Band / Simbox size	Model / #Tetrahedra	IO / Memalloc	1 core	24 cores	48 cores
K	CSH / 15874	45.67 s	1100.50 s	58.07 s	36.07 s
$1999 \times 1199 \times 1199$	SRH / 52617	45.17 s	1103.67 s	54.01 s	38.33 s
10.963 GB	FULL / 595373	45.73 s	1123.94 s	72.34 s	51.05 s
Q	CSH / 15874	160.37 s	4648.26 s	216.04 s	143.08 s
$3277 \times 1967 \times 1967$	SRH / 52617	161.10 s	4691.48 s	220.62 s	146.37 s
47.233 GB	FULL / 595373	161.70 s	4793.22 s	222.83 s	154.58 s

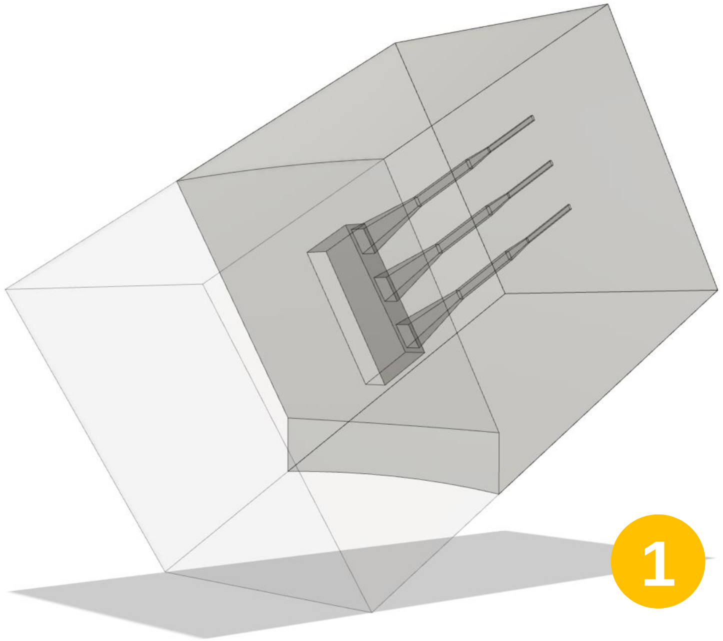
From: Santos, J. M., et al. (2021). A 3D CAD model input pipeline for REFMUL3 full-wave FDTD 3D simulator. *Journal of Instrumentation*, *16*(11), C11013

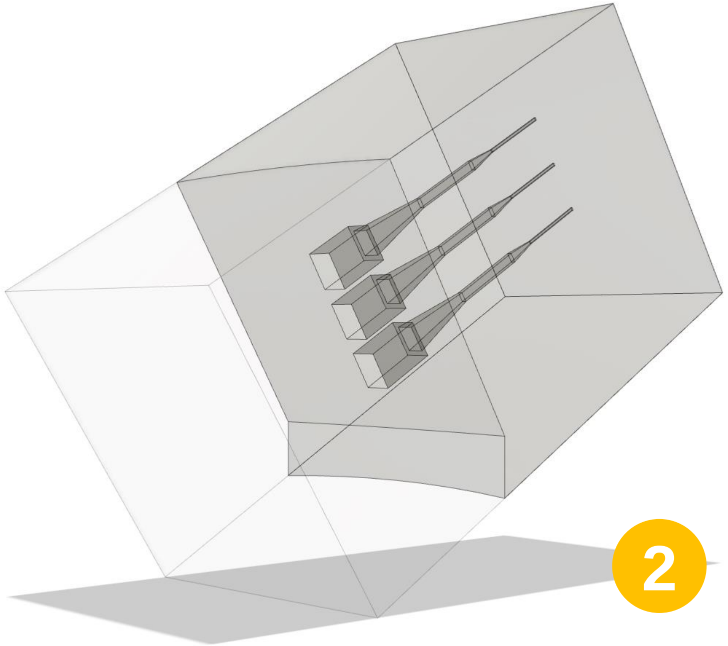
* For reference a K band full sweep FM simulation takes ~9.5 h to run in 64 nodes of 48 cores.

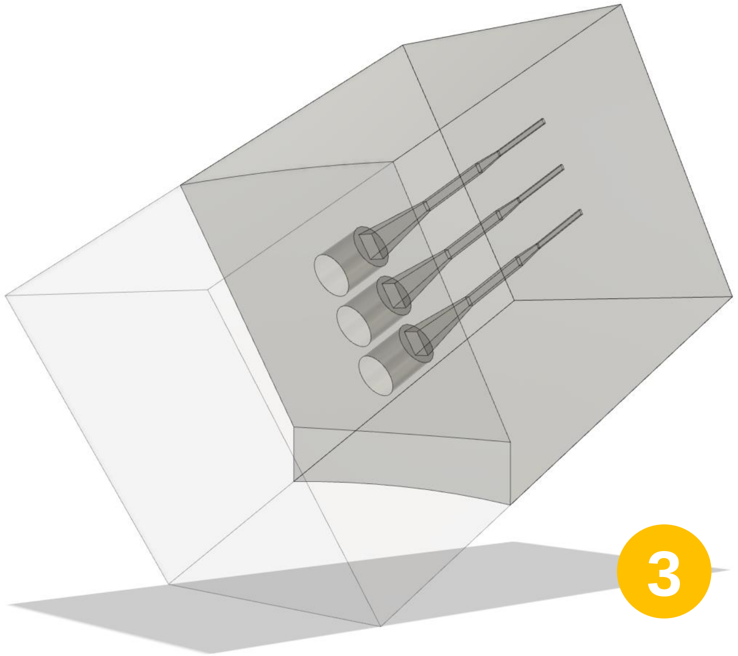


Assessment on the effects of the plasma access geometry for a "DEMO-like" PPR slim-cassette 3 antenna cluster

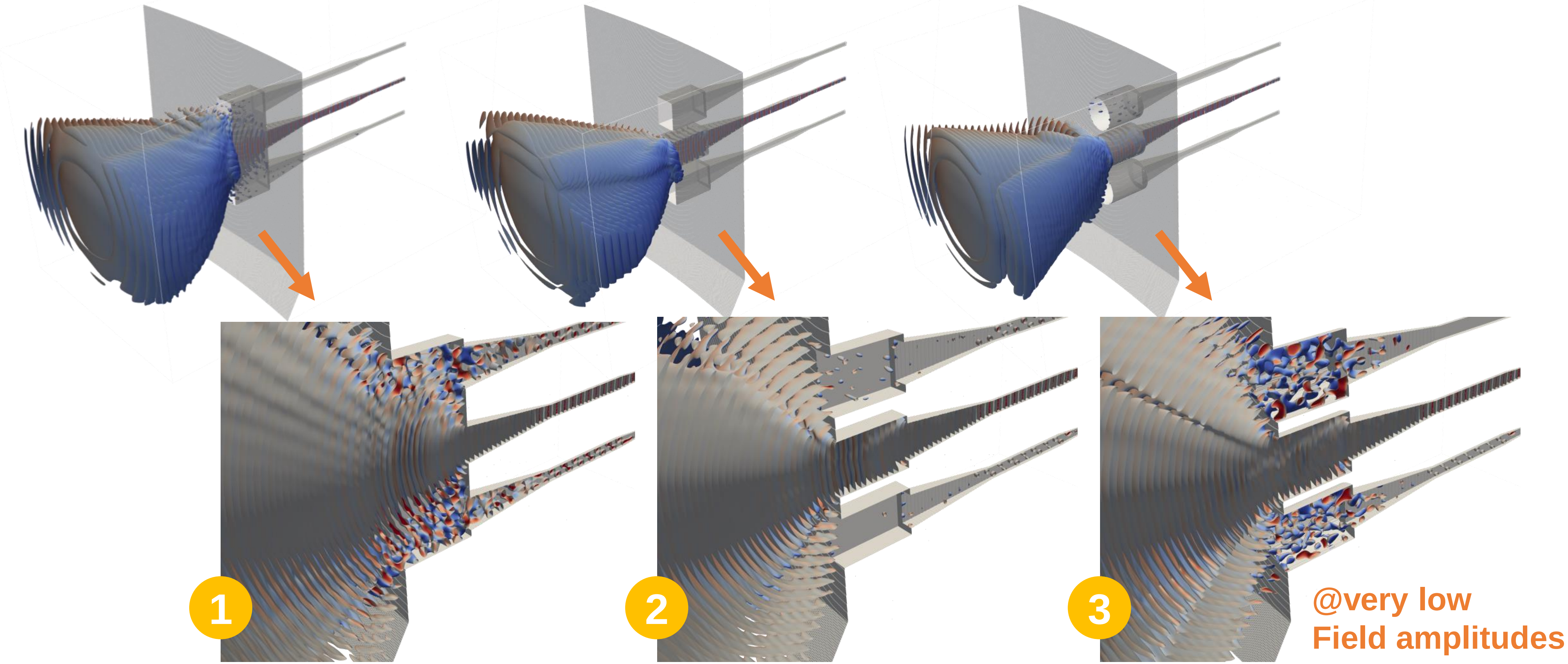
- One emitting / 3 receiving antennas (all LOS //)
- Emitting antenna (central) LOS ⊥ to separatrix
- Cluster recessed 10 cm in the vessel wall





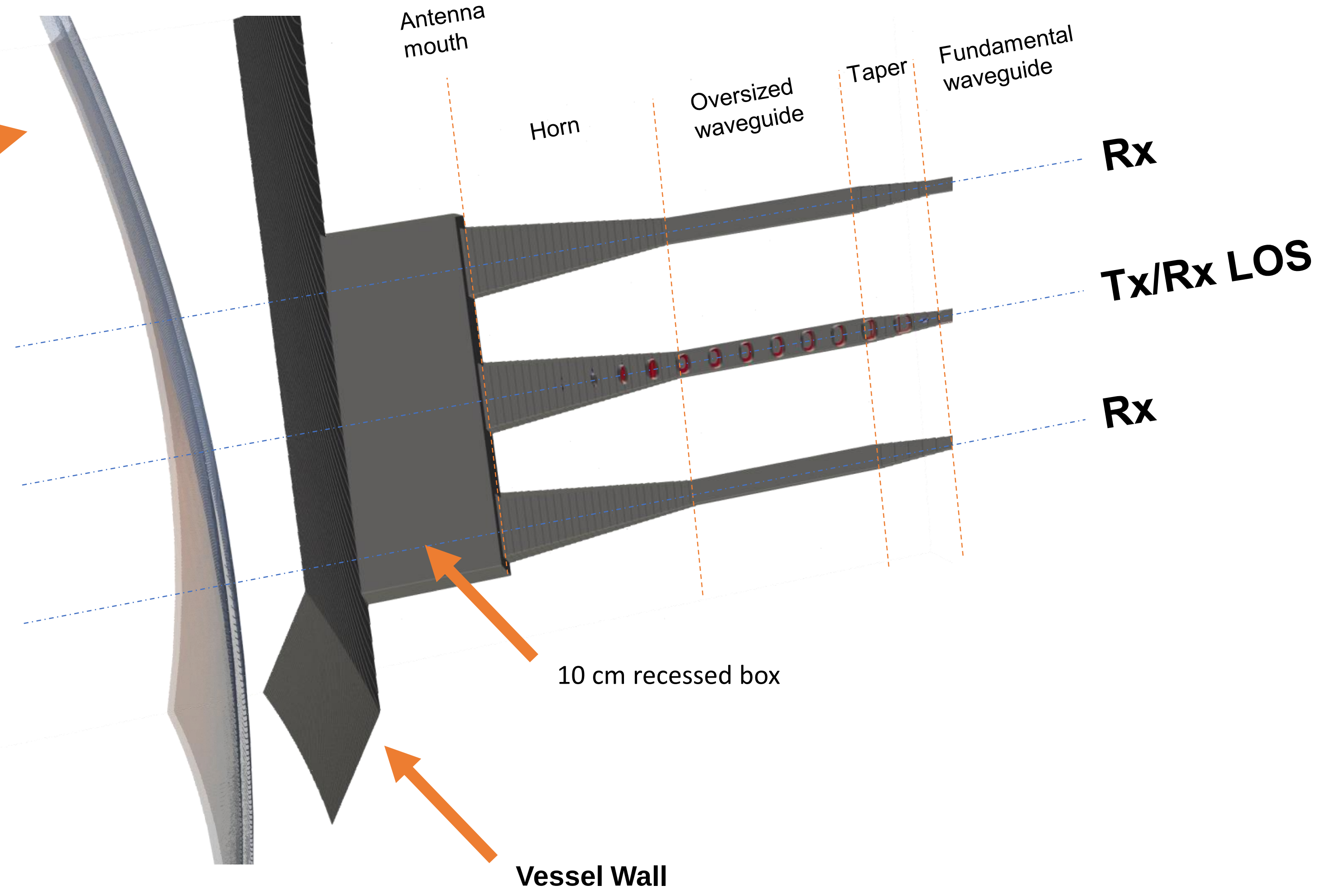


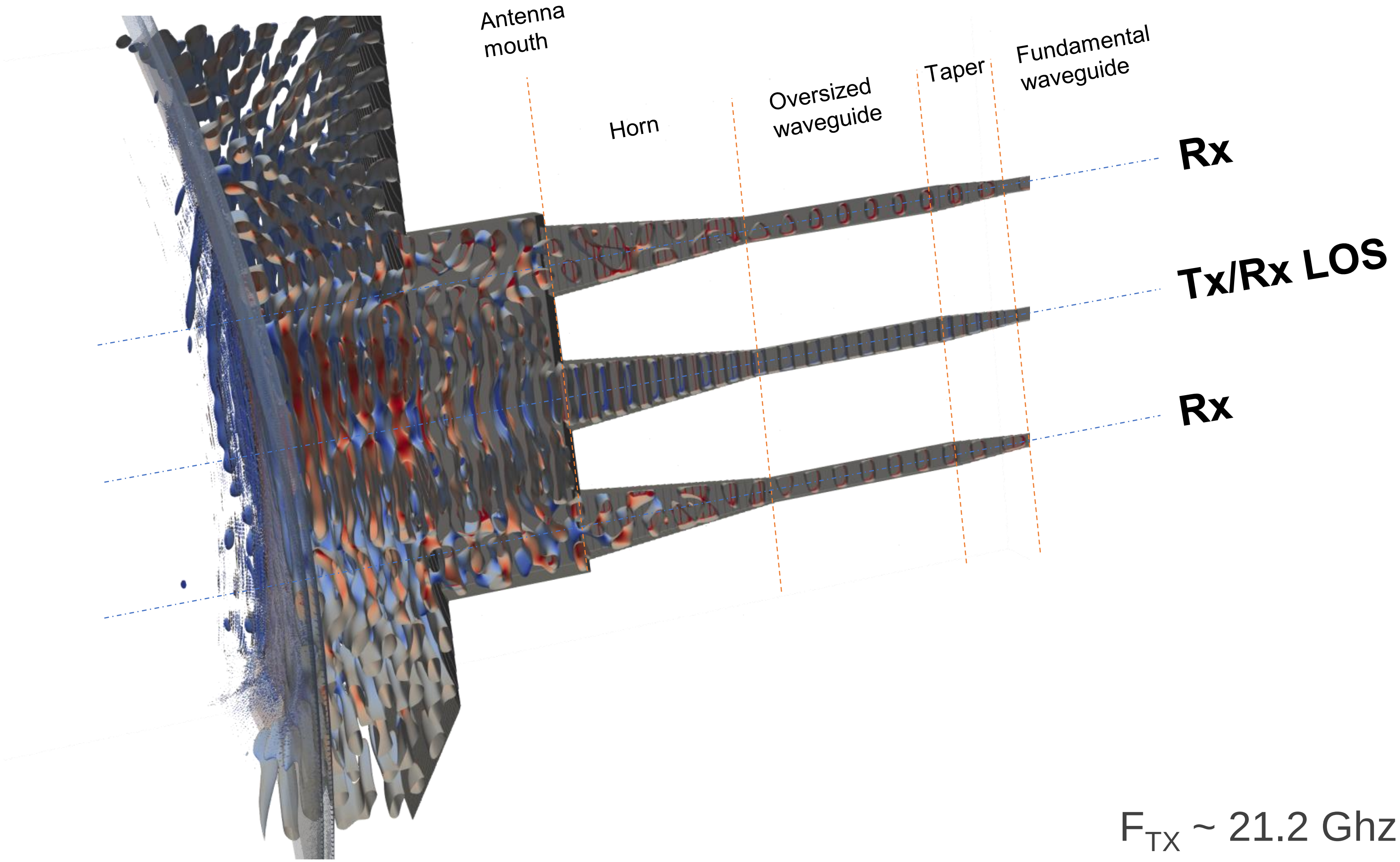
CASE STUDY 1 – 3 ANTENNA CLUSTER: PROPAGATION IN VACUUM



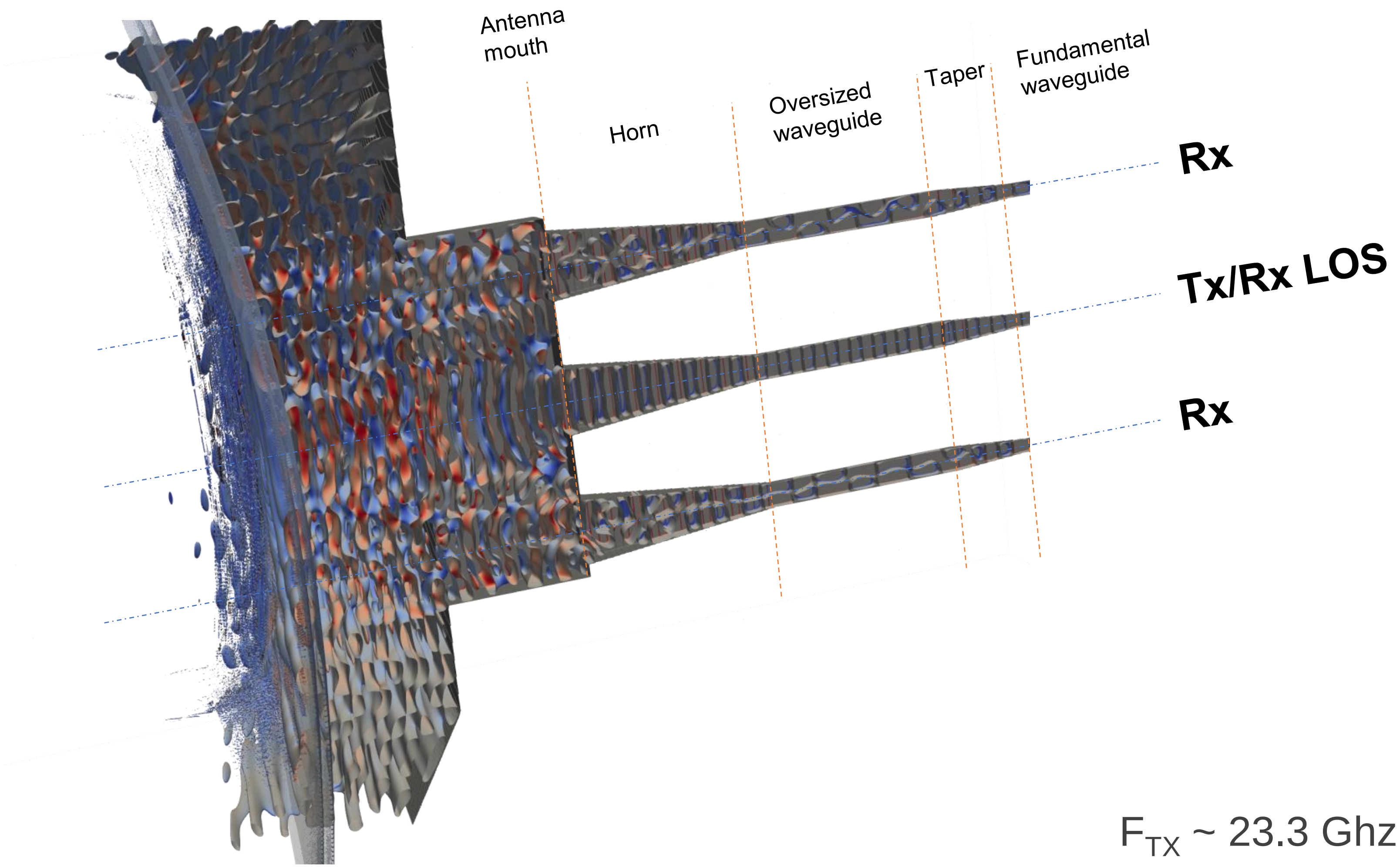
IDTT Single Null (SN) config.:

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

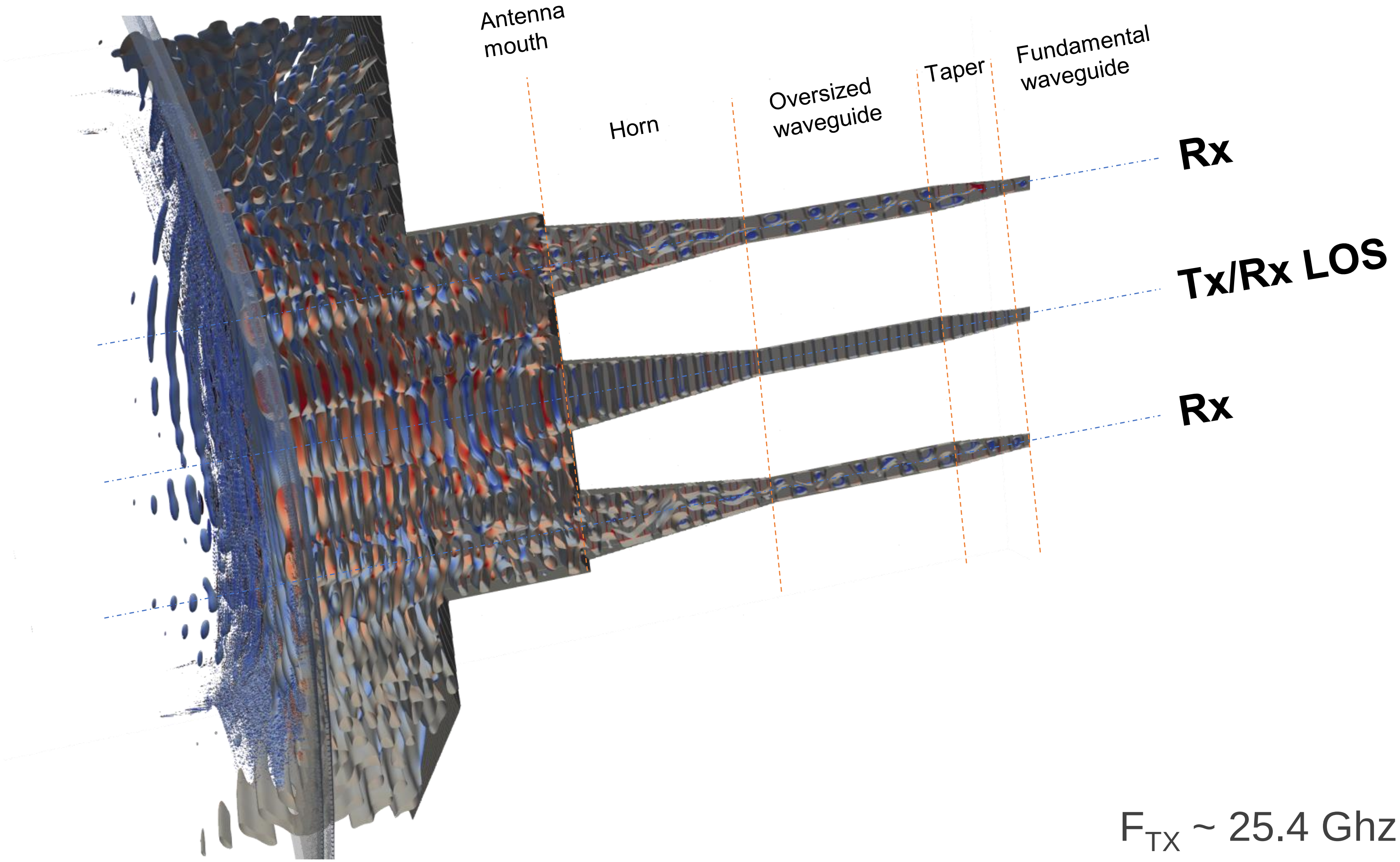



Antenna mouth
Horn
Oversized waveguide
Taper
Fundamental waveguide
Rx
Tx/Rx LOS
Rx

F_{TX} ~ 21.2 Ghz

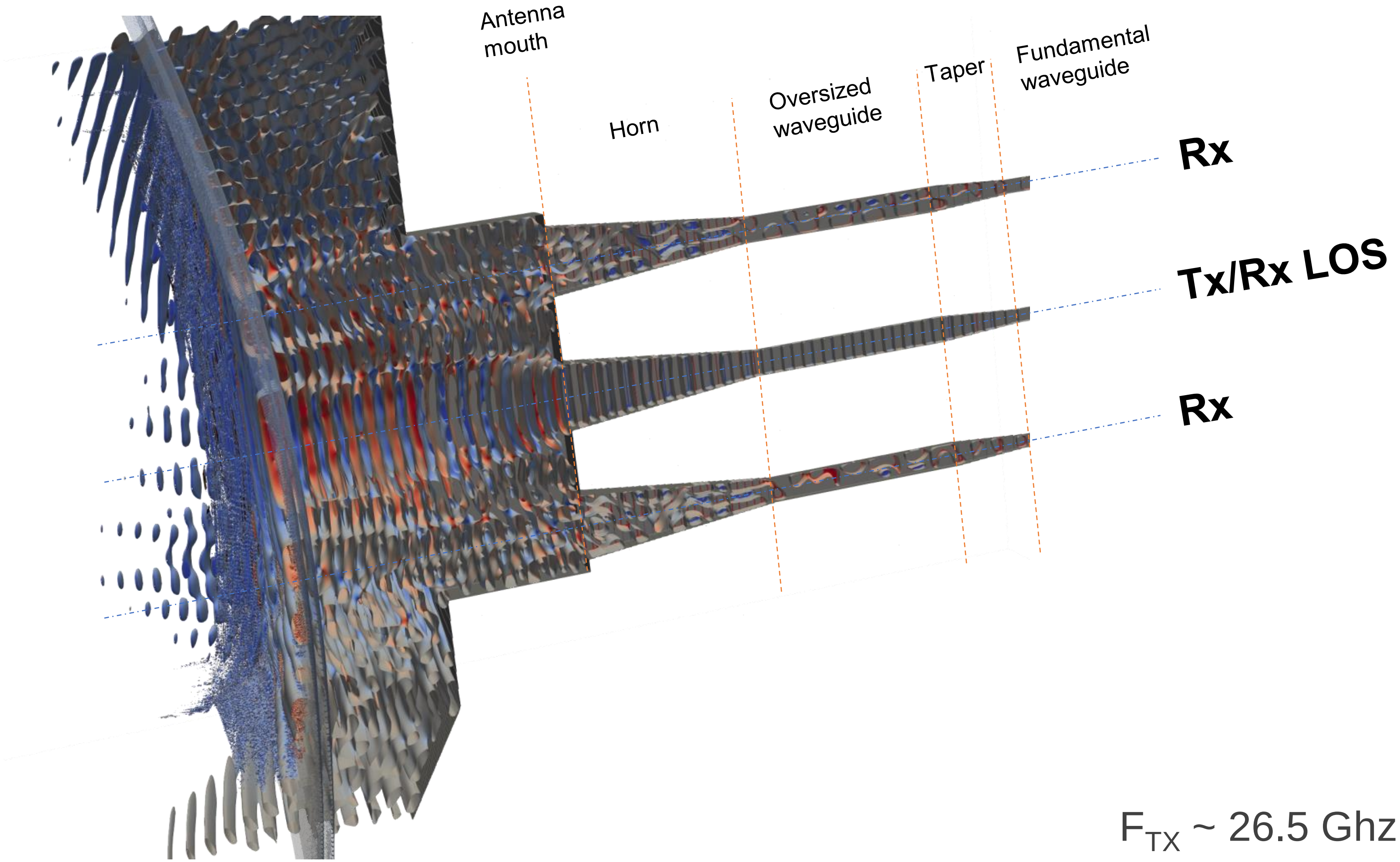

Antenna mouth
Horn
Oversized waveguide
Taper
Fundamental waveguide
Rx
Tx/Rx LOS
Rx

F_{TX} ~ 23.3 Ghz



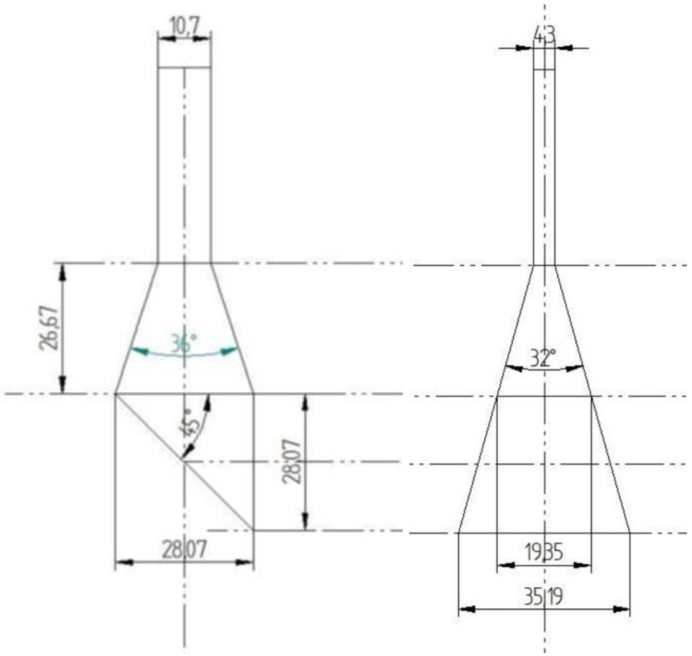
$F_{TX} \sim 25.4$ Ghz

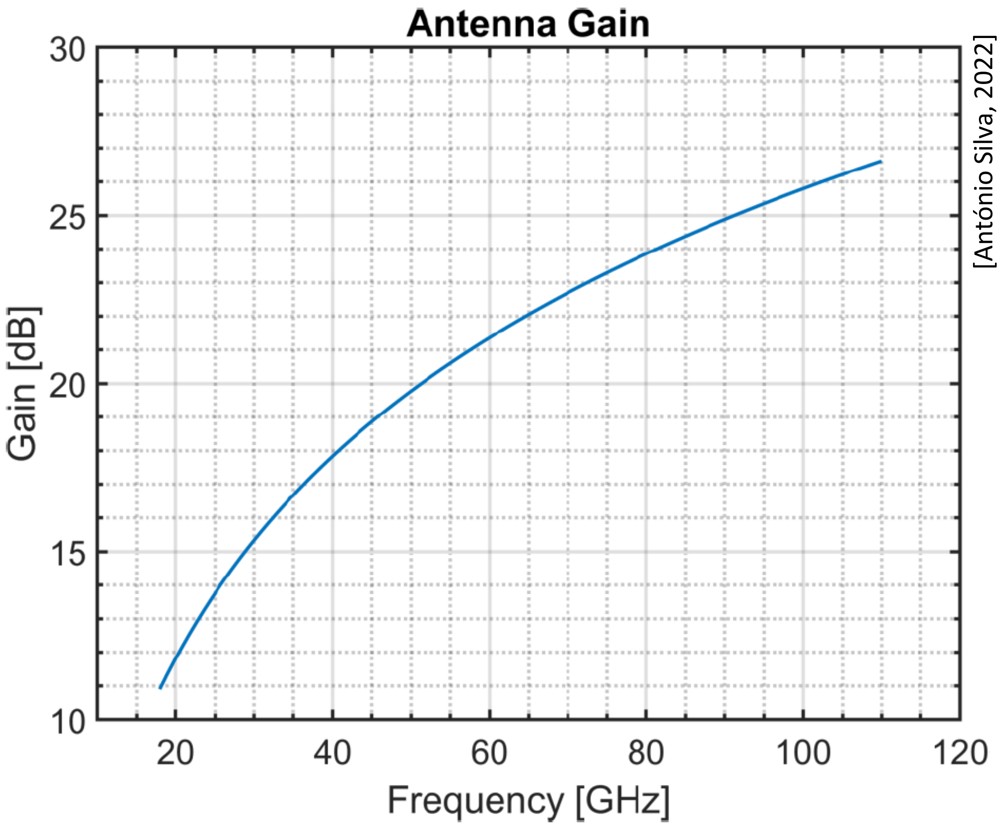
Case study 1 – 3 Antenna cluster: propagation in plasma - case 1



F_{TX} ~ 26.5 Ghz

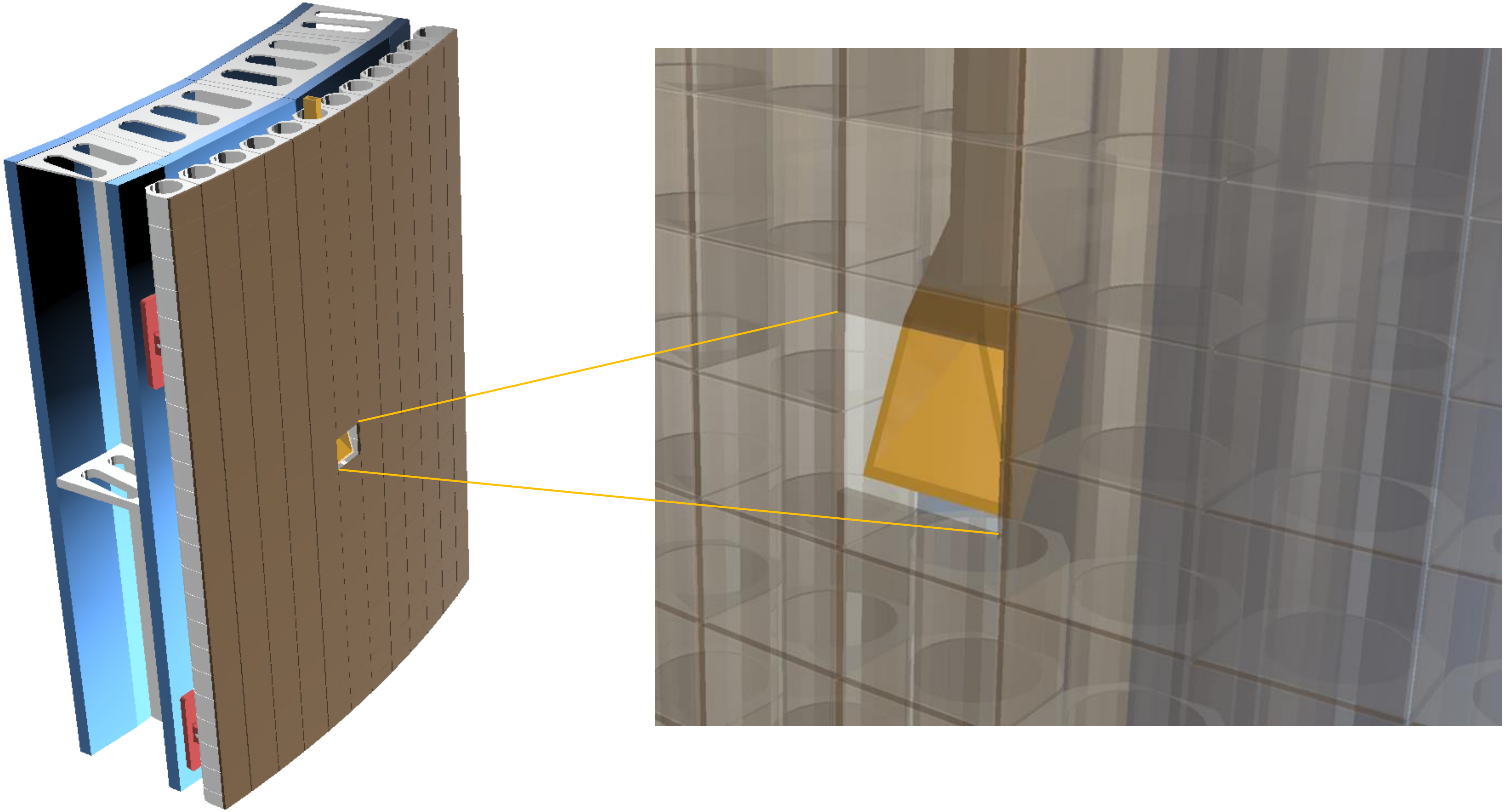
CASE STUDY 2 – HFS PPR ANTENNA FOR DTT



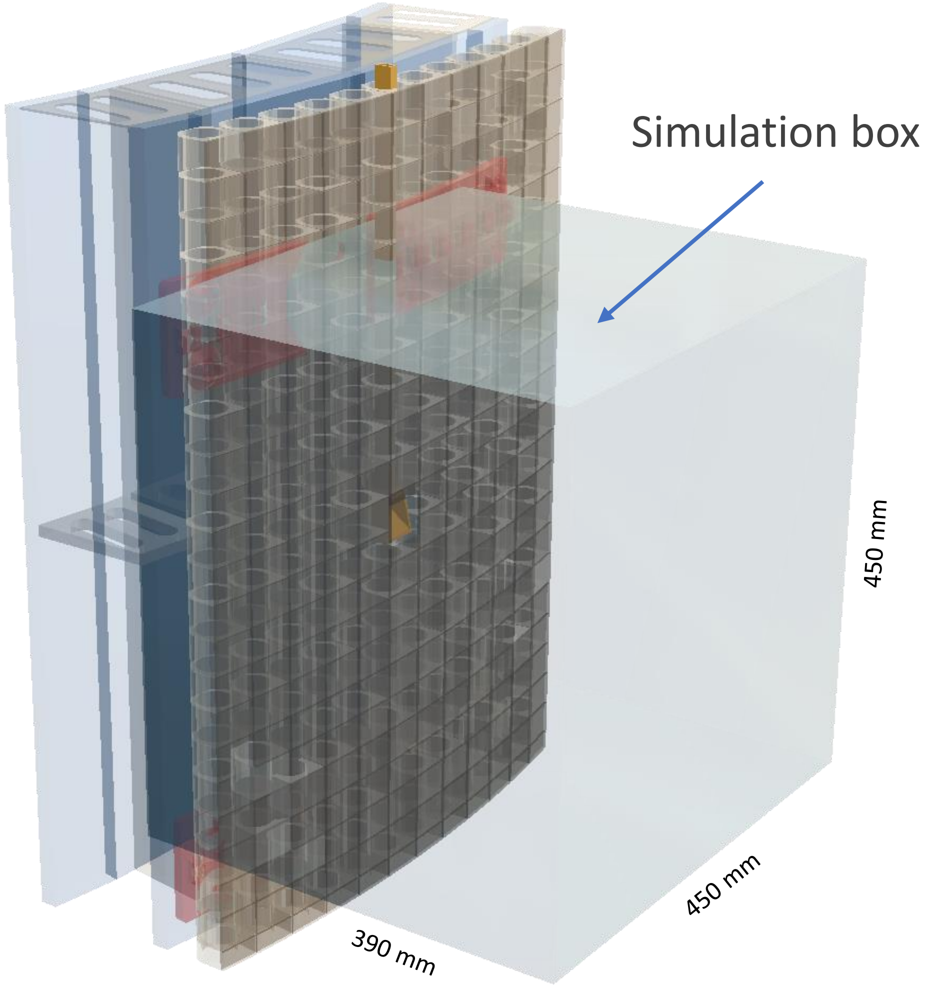


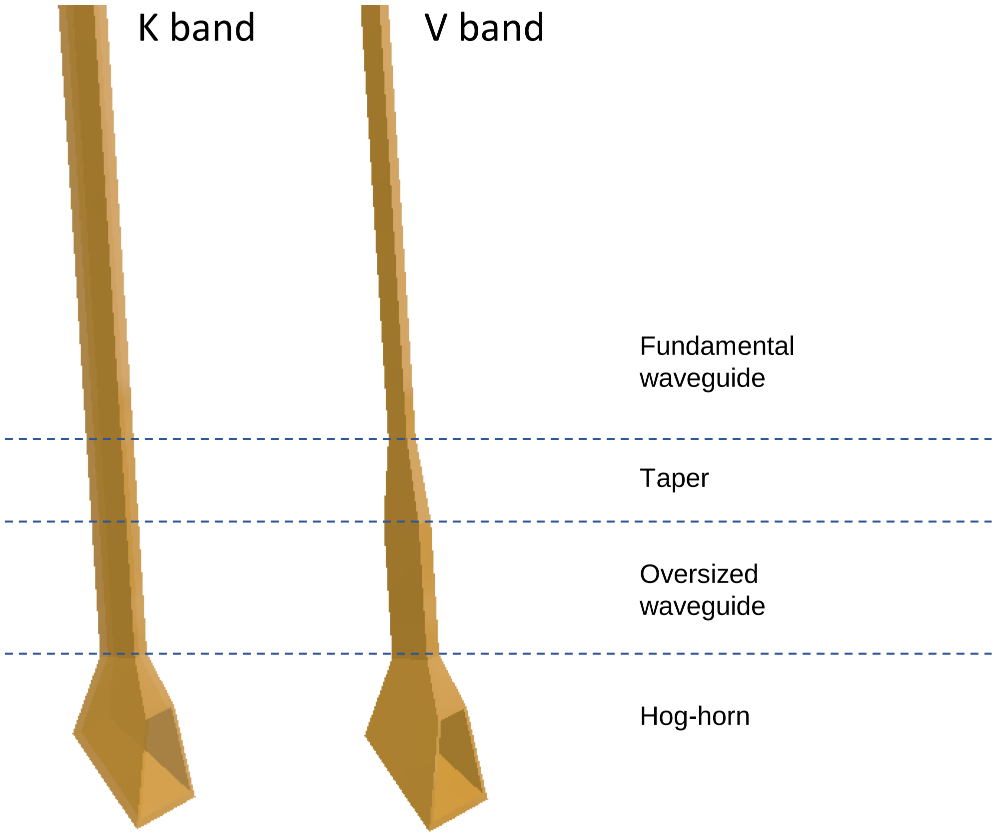
- Monostatic antenna setup
- K-W band range
- Narrow space (<41 mm)

Case study 2 – HFS PPR antenna for DTT

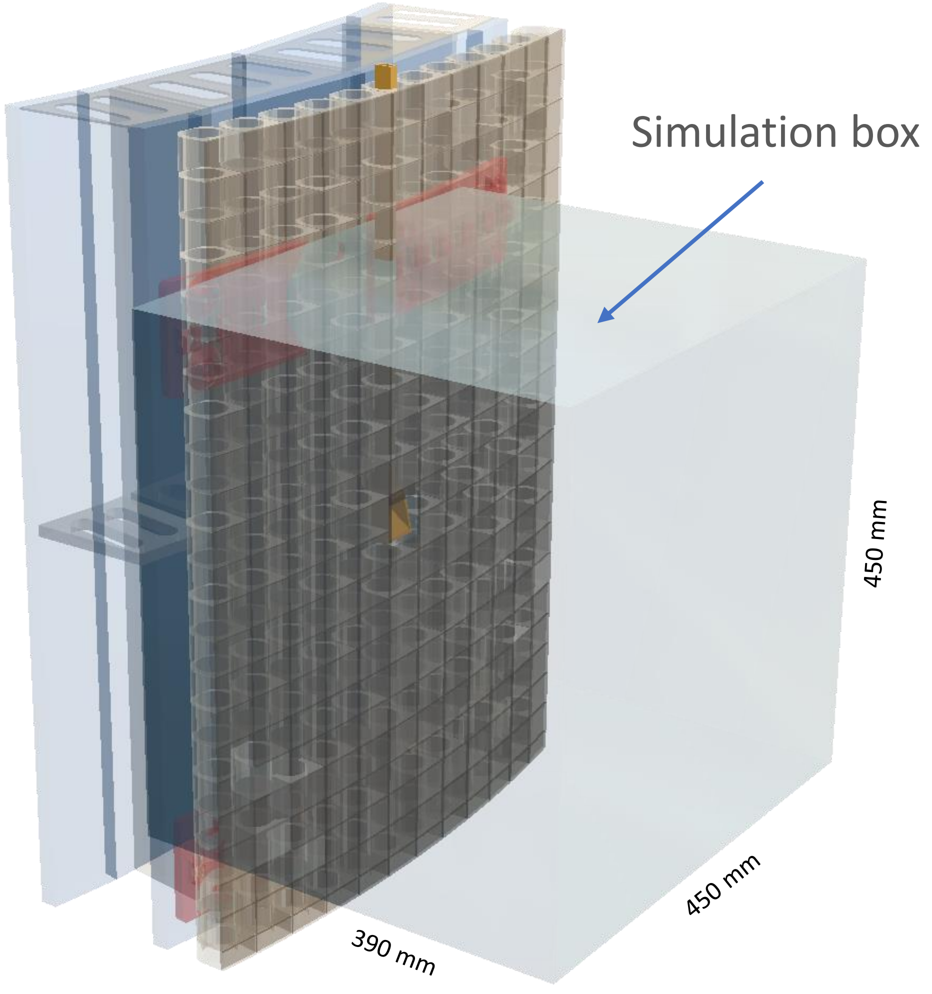


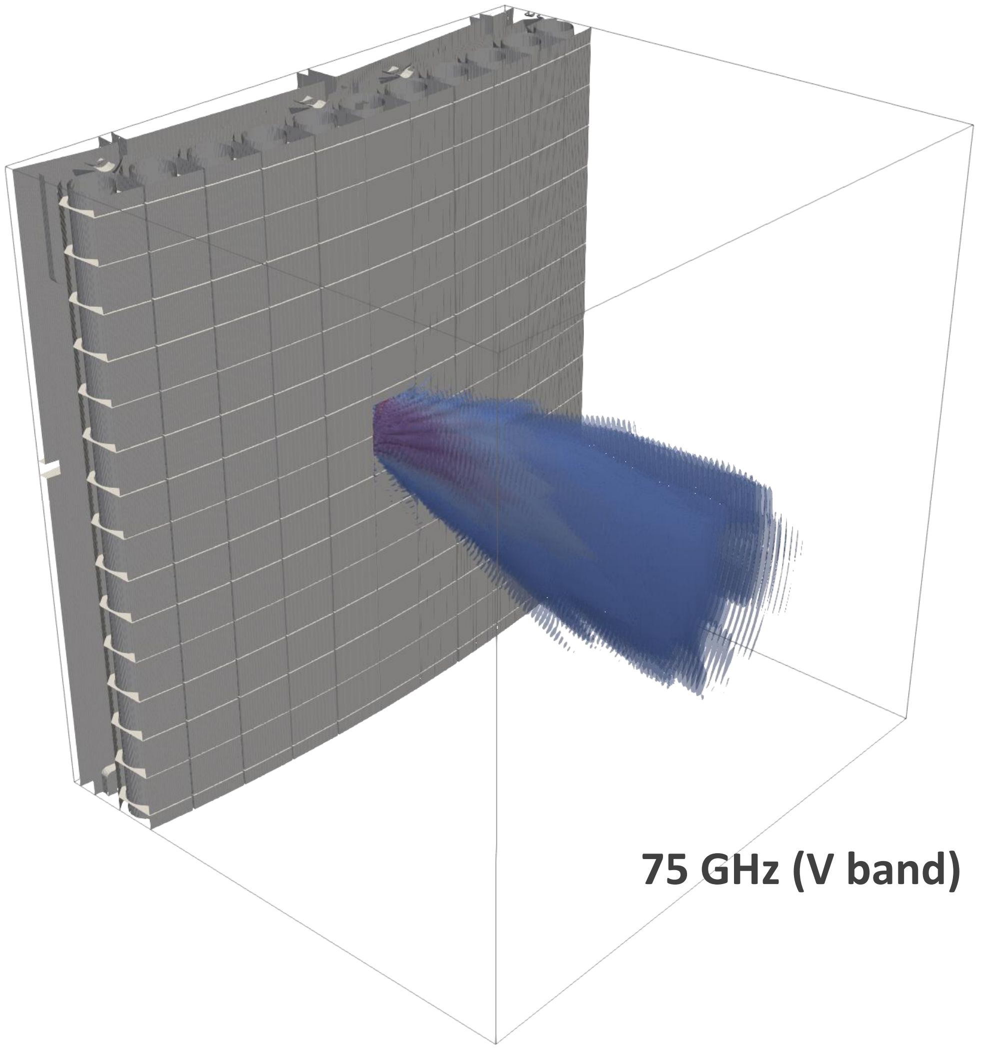
CASE STUDY 2 – HFS PPR ANTENNA FOR DTT



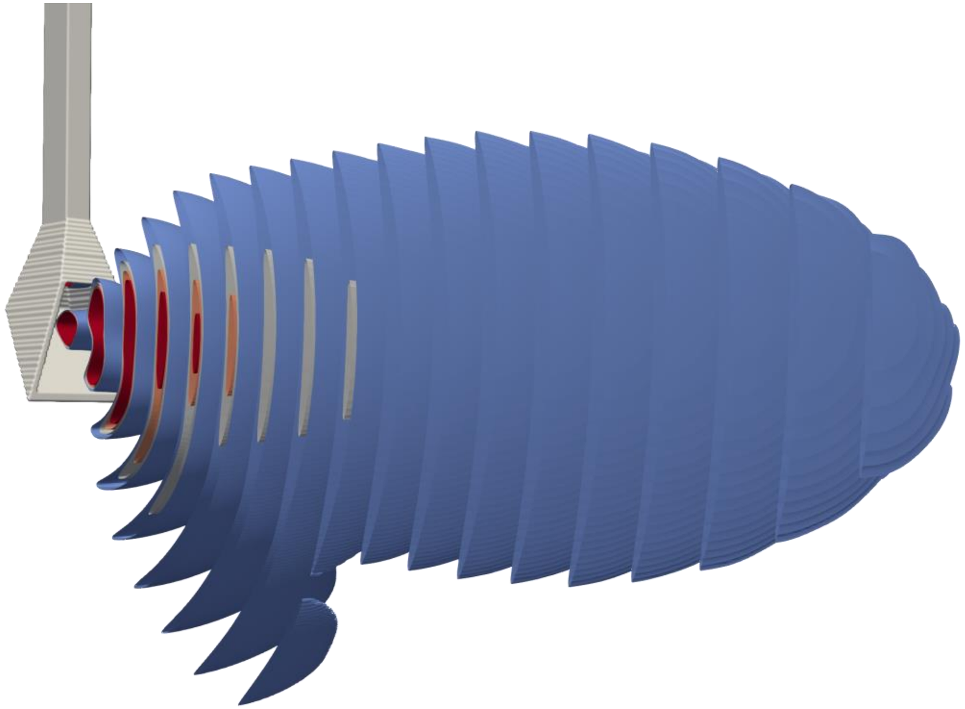


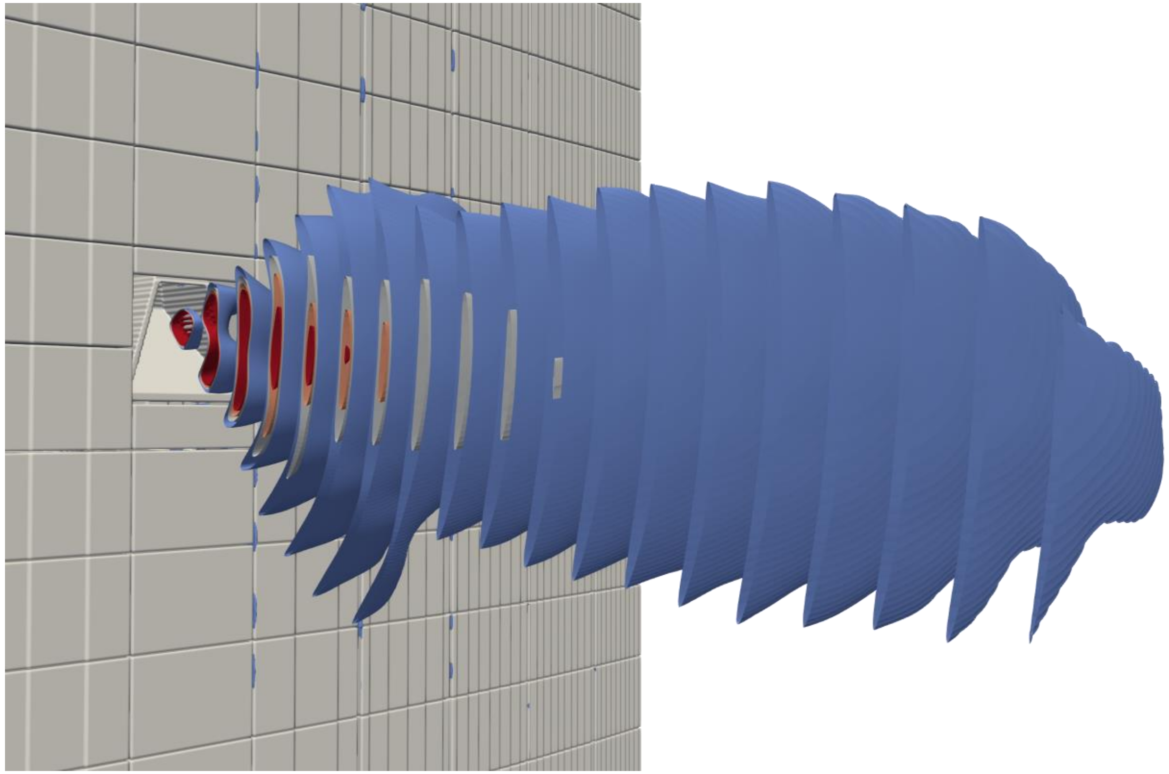
Case study 2 – HFS PPR antenna for DTT





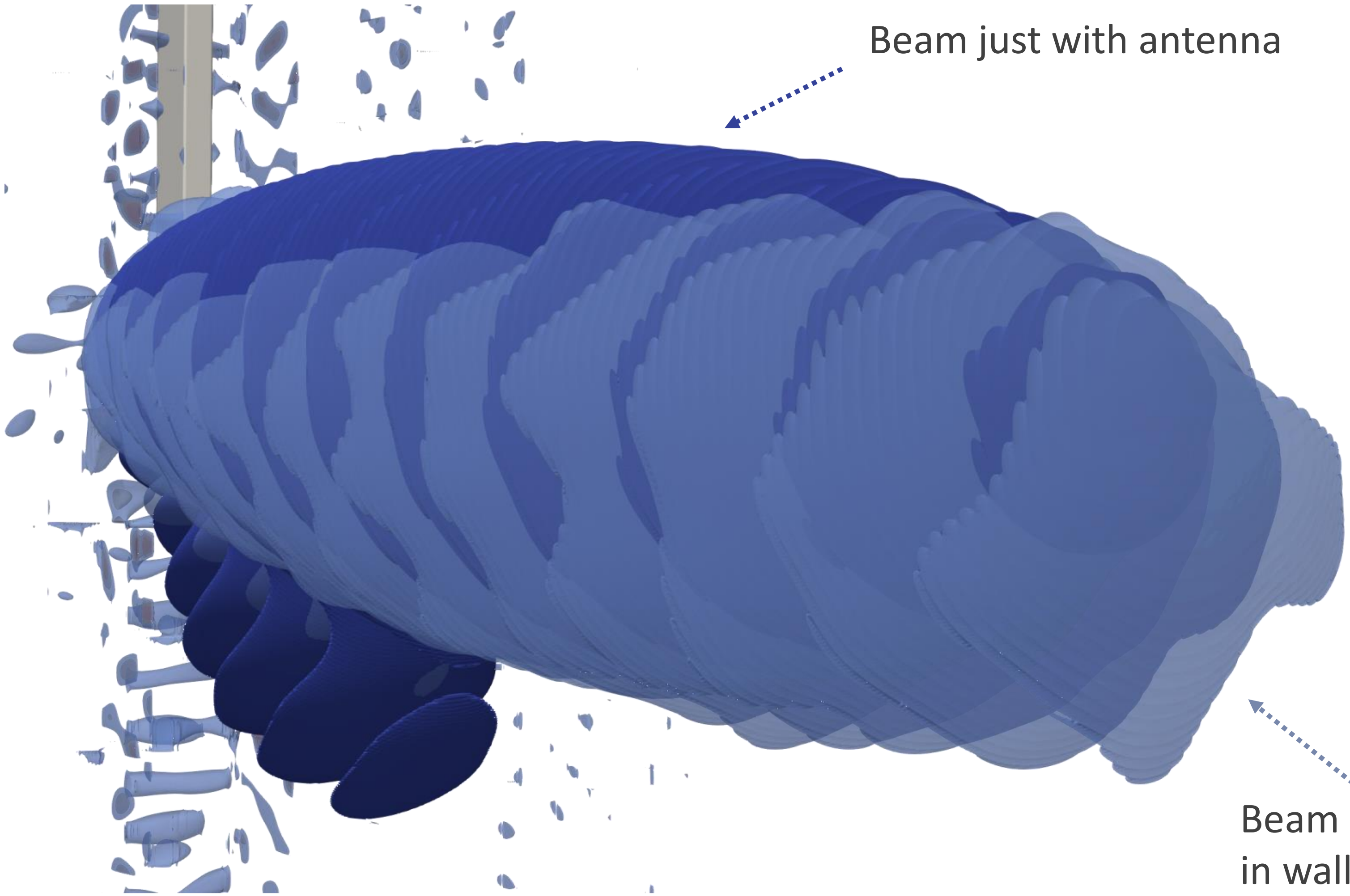
WALL VS NO-WALL 18 GHZ BEAM

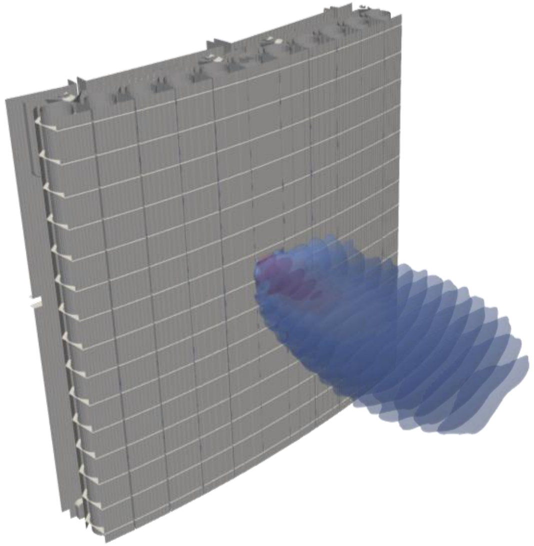




WALL VS NO-WALL 18 GHZ BEAM

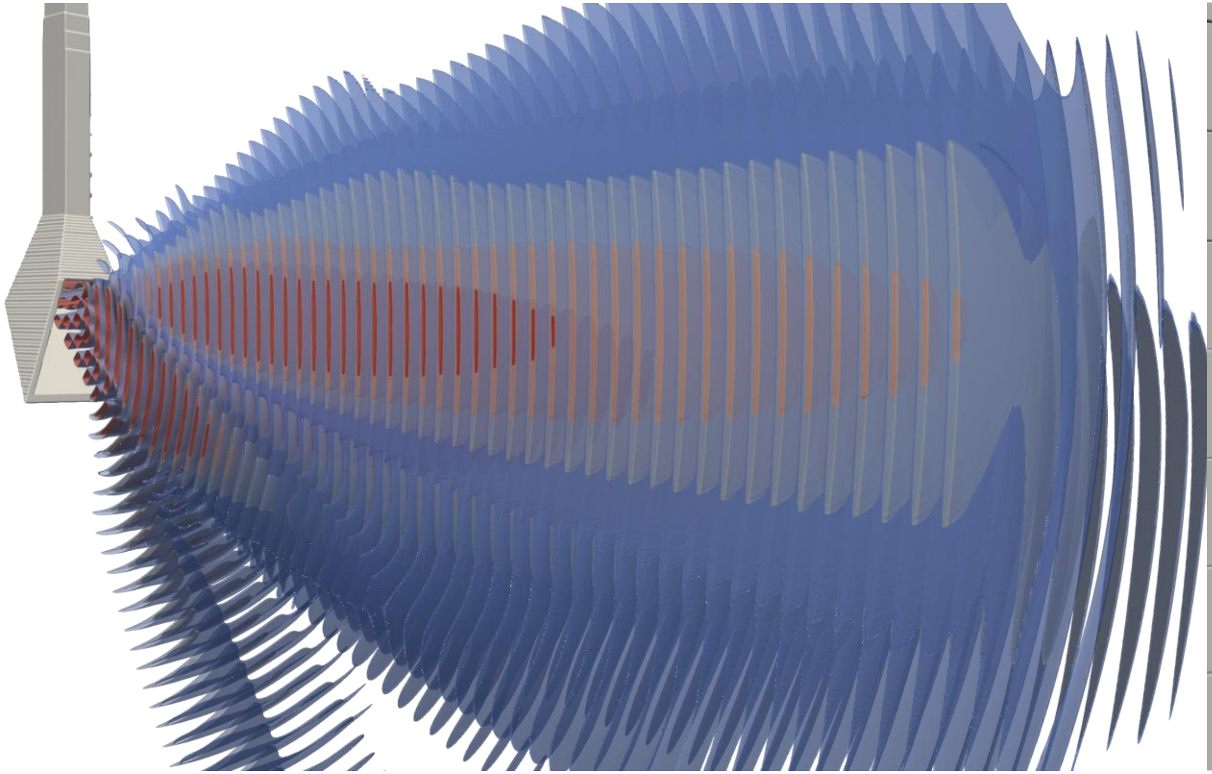
Beam just with antenna

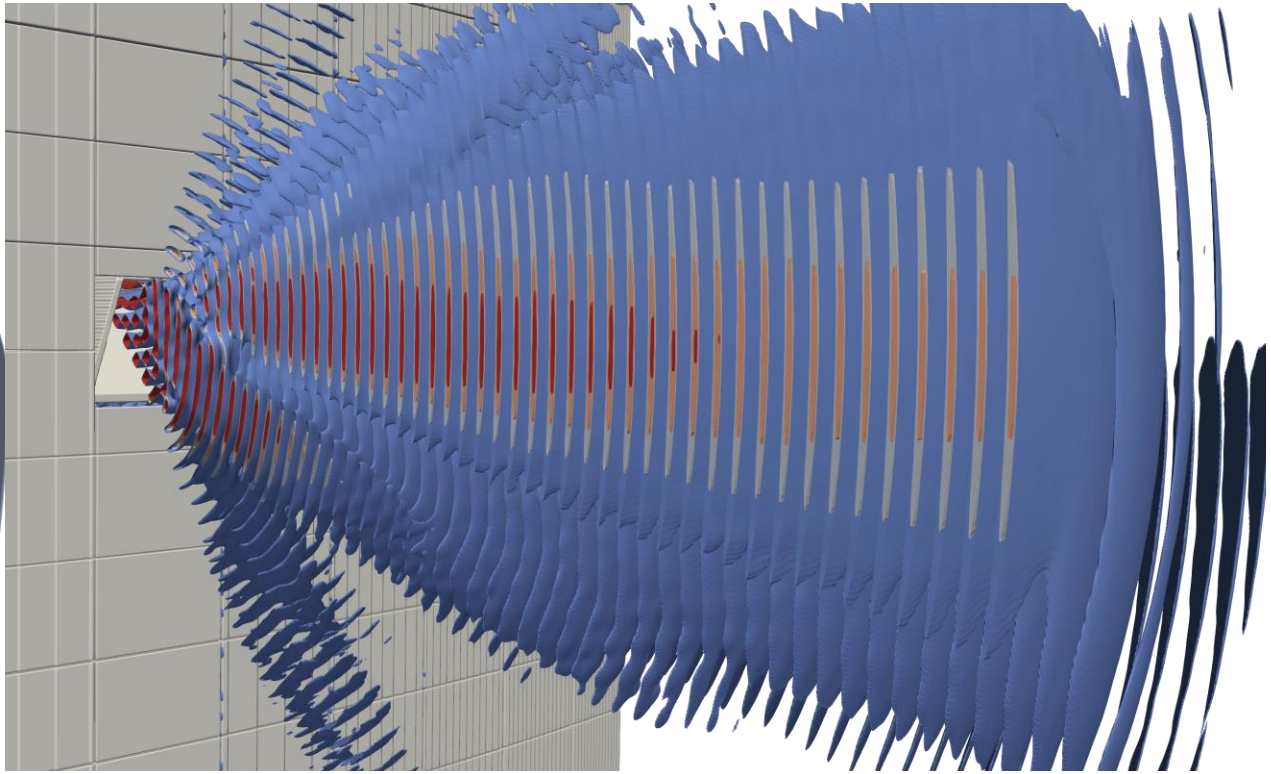




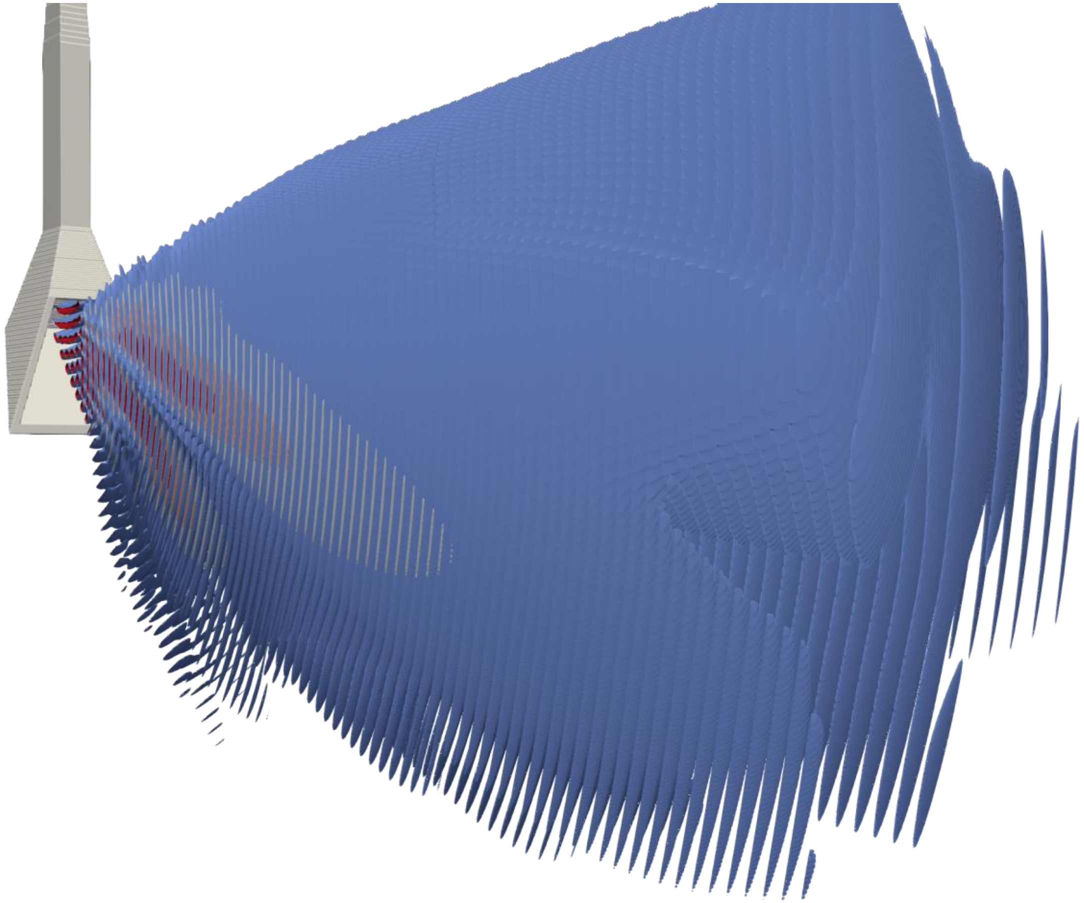
Beam with antenna integrated in wall structures

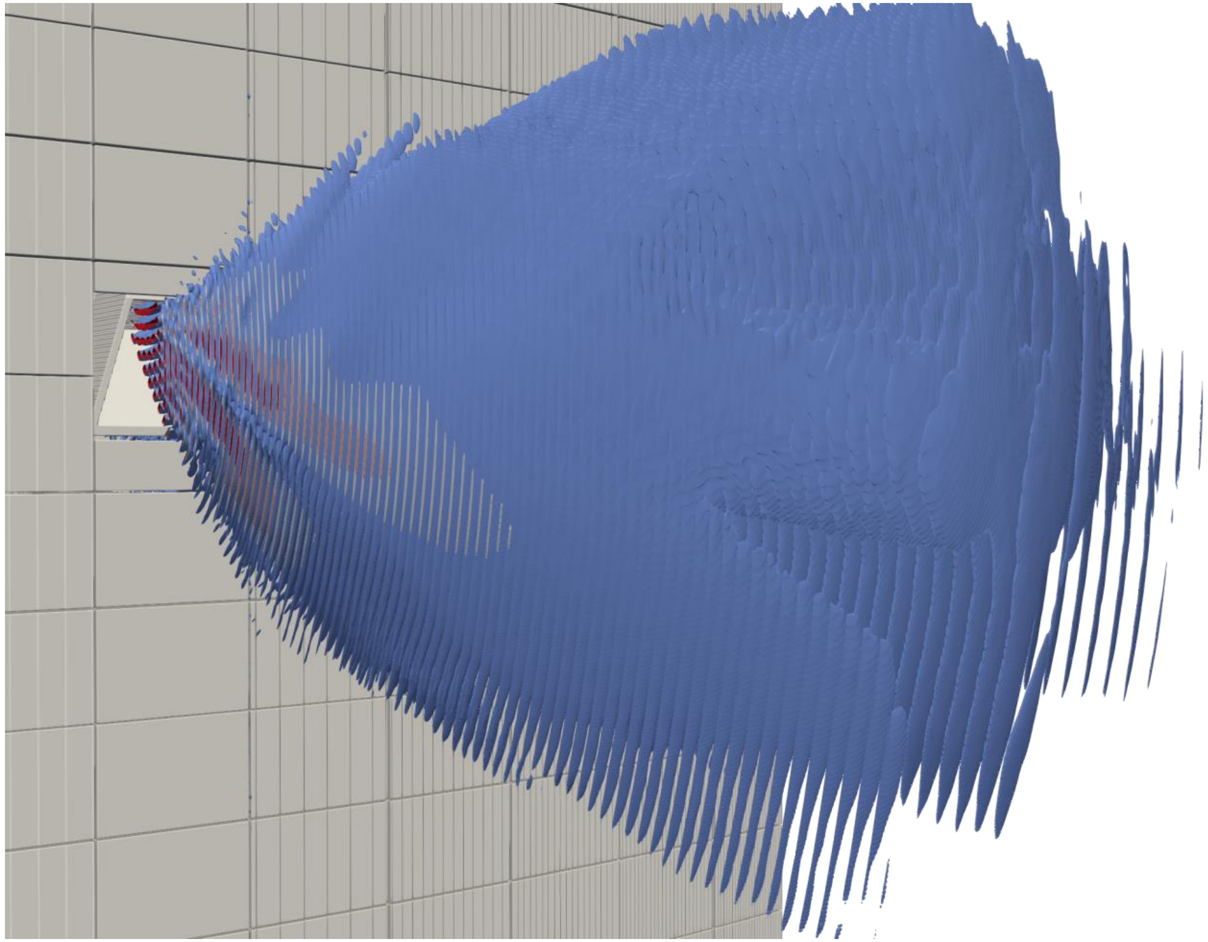
WALL VS NO-WALL 50 GHZ BEAM



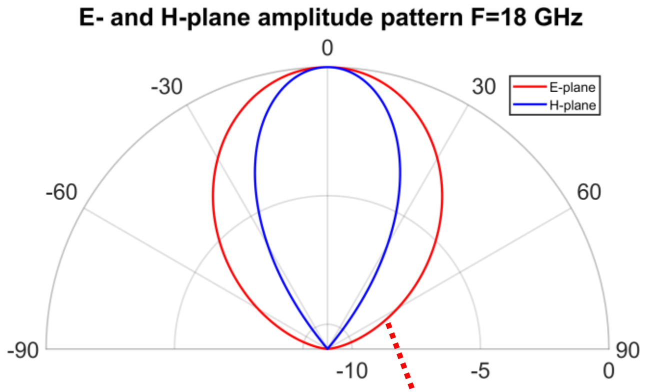


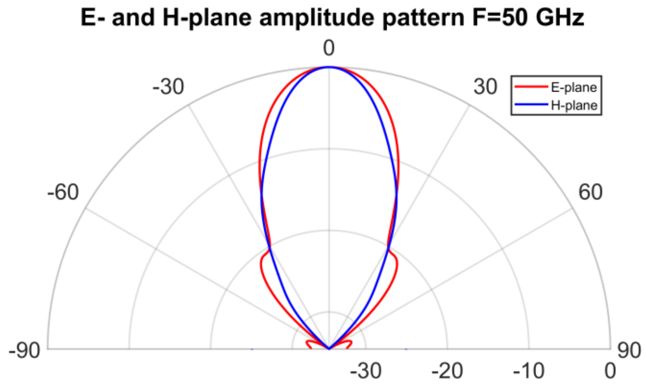
WALL VS NO-WALL 75 GHZ BEAM

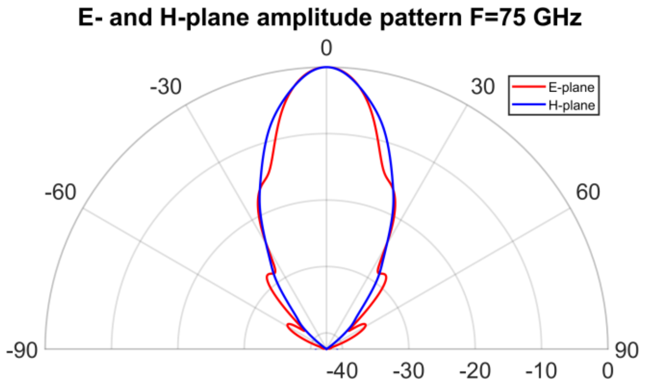


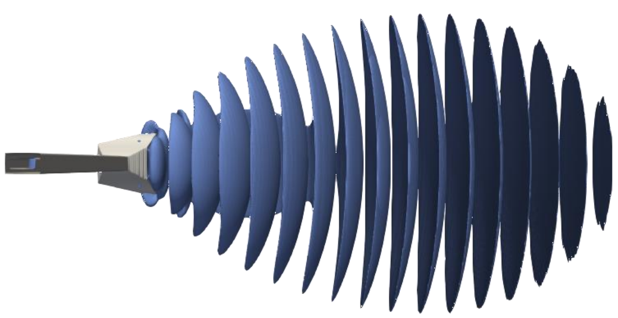


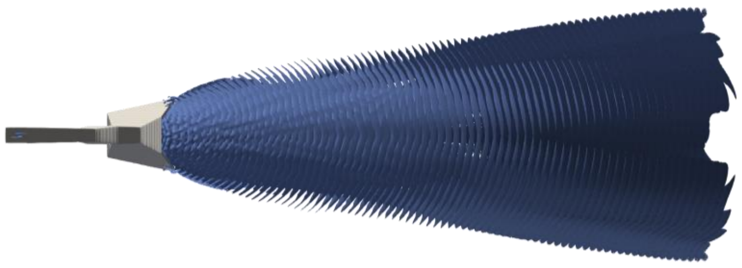
ANTENNA RADIATION PATTERN – E-PLANE



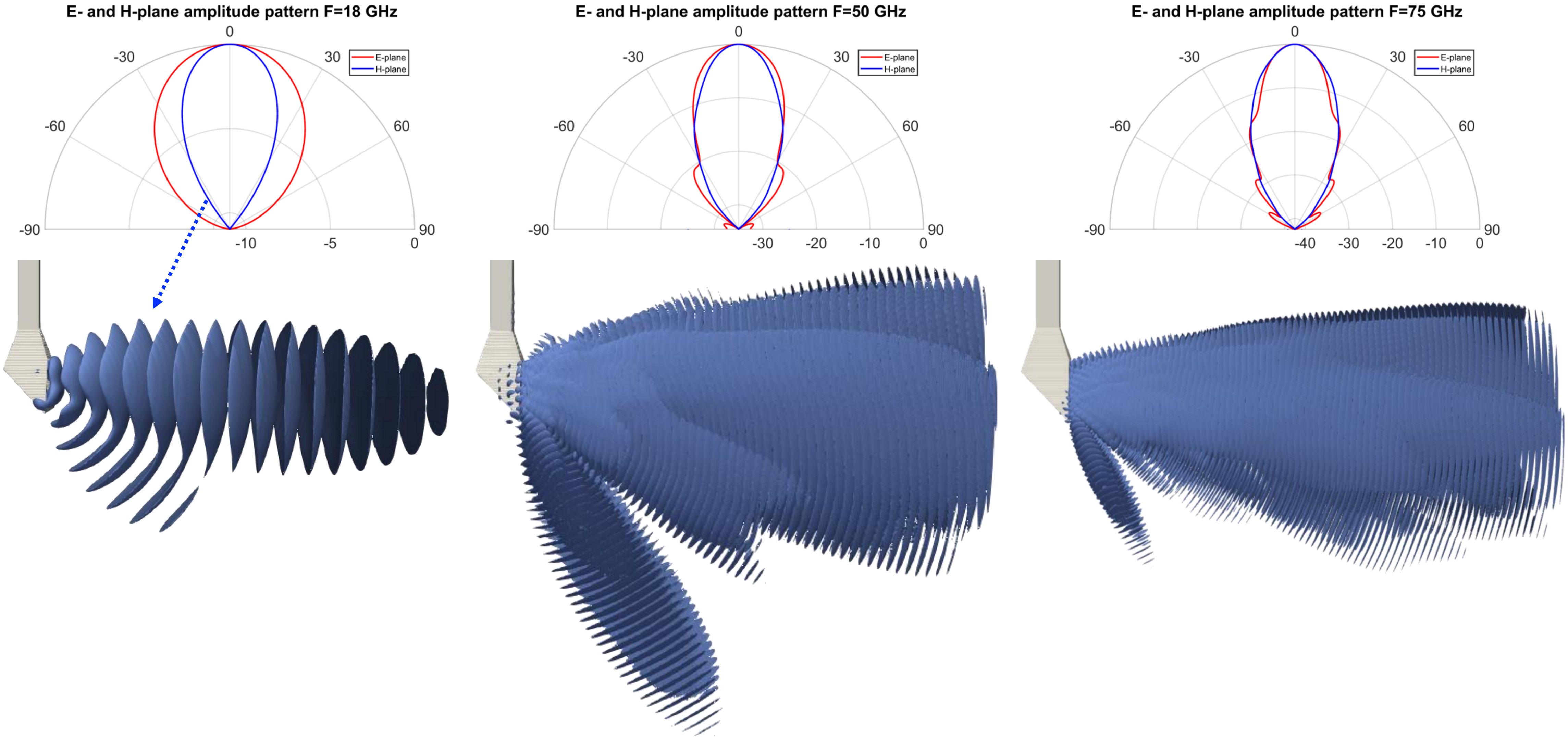








ANTENNA RADIATION PATTERN – H-PLANE



SUMMARY

- **REFMUL3** is now capable of using **realistic** and **detailed CAD models** of emitting and receiving multi-antenna clusters, and complex vessel wall structures and plasma access geometries.

- Adapted profile inversion algorithms can be developed/tested using controlled simulated signals for specific antenna (cluster) arrangements.

- Pipeline automation capabilities are being continuously improved and extended.

- **The same assessed models can be shared with existing codes for the simulation of neutronics, material stress, thermal analysis, etc. for further validation and integrated tokamak engineering design.**

EUROfusion

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