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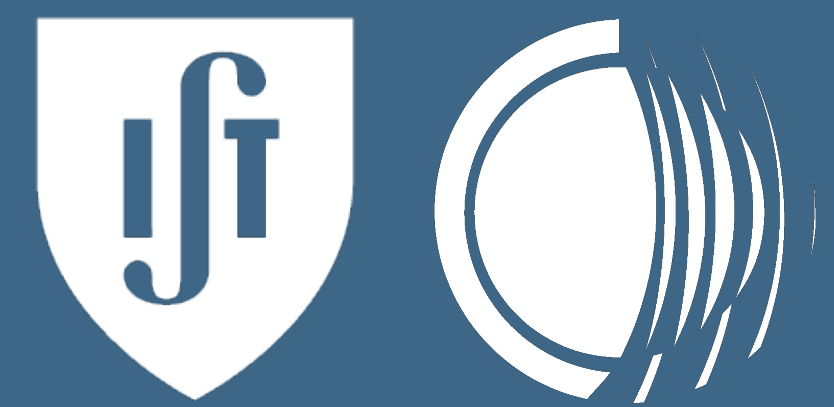
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Assessment of Measurement Performance for Low Field Side IDTT Plasma Position Reflectometry System

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Summary...

- The Italian Divertor Test Tokamak (IDTT) 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 IDTT OPERATING IN THE LOW FIELD SIDE

- A set of 3 O-mode LFS FMCW reflectometers
- On the equatorial plane **gap 0°**
- On the upper torus midplane **gap 45°**
- On the lower torus midplane **gap -60°**

ASSESSMENT MADE USING SYNTHETIC REFLECTOMETERS IMPLEMENTED USING A 2D FULL WAVE FDTD CODE

REFMULF

REFMUL* code family available for simulations

- 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
 - 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
 - All field components included
 - Parallel hybrid implementation (OpenMP+MPI) with 3D domain decomposition
 - XMDF/HDF5 compressed binary output (big data output)

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

$$\nabla \times \mathbf{H} = \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \sigma \mathbf{E} + \mathbf{J}$$

$$\nabla \times \mathbf{E} = -\mu_0 \frac{\partial \mathbf{H}}{\partial t} - \sigma^* \mathbf{H}$$

- This results in a system coupling Maxwell equations with a LDE for $\mathbf{J} = \sigma \mathbf{E}$

$$\frac{d\mathbf{J}}{dt} = \epsilon_0 \omega_p^2 \mathbf{E} + (\omega_x + \omega_y + \omega_z) \times (\mathbf{J}_x + \mathbf{J}_y + \mathbf{J}_z)$$

- The curl equations are discretised following the Yee schema
- A time integrator is used to solve — the sensitive part...

Expressions for 2 & 3 Dimensions

Full polarisation e.g. REFMULF

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

$$\mu_0 \frac{\partial H_x}{\partial t} + \sigma^* H_x = -\frac{\partial E_z}{\partial y}$$

$$\mu_0 \frac{\partial H_y}{\partial t} + \sigma^* H_y = +\frac{\partial E_z}{\partial x}$$

$$\epsilon_0 \frac{\partial E_z}{\partial t} + \sigma E_z = -\frac{\partial H_x}{\partial y} + \frac{\partial H_y}{\partial x} - J_z$$

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

$$\epsilon_0 \frac{\partial E_x}{\partial t} + \sigma E_x = \frac{\partial H_z}{\partial y} - J_x$$

$$\epsilon_0 \frac{\partial E_y}{\partial t} + \sigma E_y = -\frac{\partial H_z}{\partial x} - J_y$$

$$\mu_0 \frac{\partial H_z}{\partial t} + \sigma^* H_z = \frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x}$$

3D Full polarisation e.g. REFMUL3

$$\frac{\partial E_x}{\partial t} = \frac{1}{\epsilon_0} \left(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} \right) - \frac{\sigma}{\epsilon_0} E_x - \frac{1}{\epsilon_0} J_x$$

$$\frac{\partial E_y}{\partial t} = \frac{1}{\epsilon_0} \left(\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} \right) - \frac{\sigma}{\epsilon_0} E_y - \frac{1}{\epsilon_0} J_y$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\epsilon_0} \left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} \right) - \frac{\sigma}{\epsilon_0} E_z - \frac{1}{\epsilon_0} J_z$$

$$\frac{\partial H_x}{\partial t} = -\frac{1}{\mu_0} \left(\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} \right) - \frac{\sigma^*}{\mu_0} H_x$$

$$\frac{\partial H_y}{\partial t} = -\frac{1}{\mu_0} \left(\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z} \right) - \frac{\sigma^*}{\mu_0} H_y$$

$$\frac{\partial H_z}{\partial t} = -\frac{1}{\mu_0} \left(\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} \right) - \frac{\sigma^*}{\mu_0} H_z$$

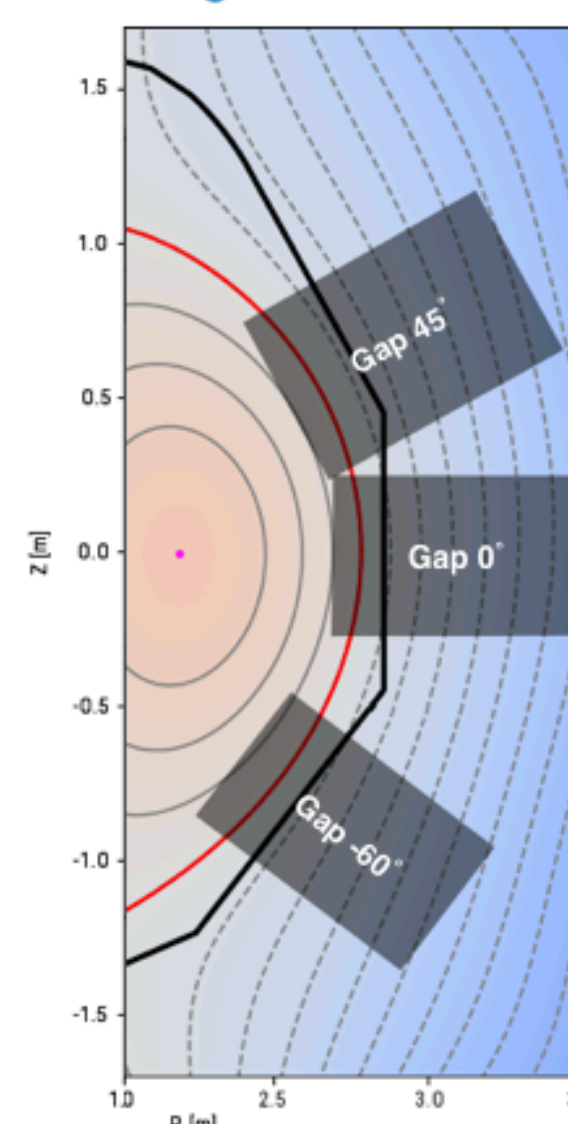
$$\frac{dJ_x}{dt} = \epsilon_0 \omega_p^2 E_x + \omega_x J_y - \omega_y J_x$$

$$\frac{dJ_y}{dt} = \epsilon_0 \omega_p^2 E_y - \omega_x J_x + \omega_y J_z$$

$$\frac{dJ_z}{dt} = \epsilon_0 \omega_p^2 E_z + \omega_x J_z - \omega_y J_z$$

Density profiles

Single Null Scenario



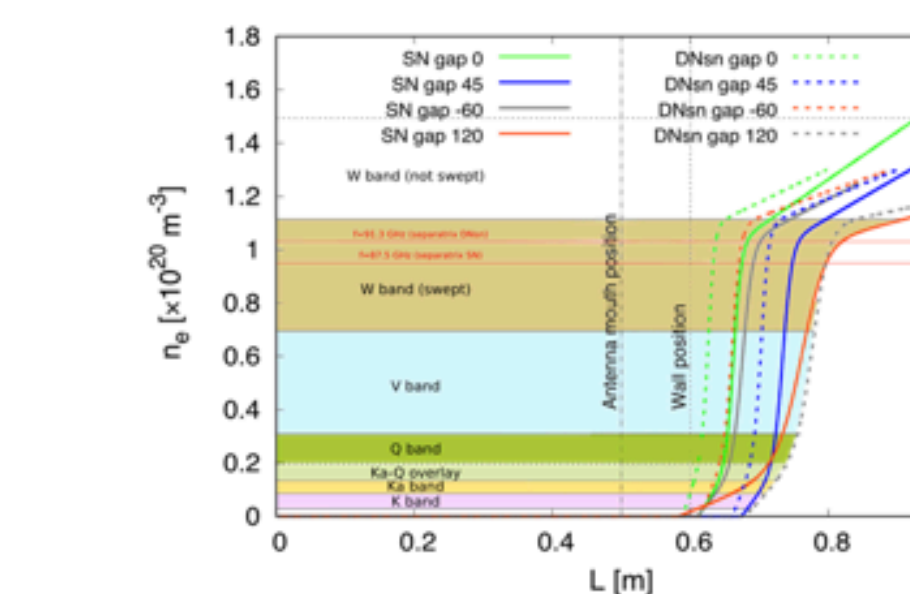
We used an educated guess model based on the density profiles appearing in R. Martone et alia, DTT Divertor Tokamak Test facility—Interim Design Report, April 2019, using a fit on the extracted data with the expression proposed in L. Frassinetti et alia, Nuclear Fusion 57 (2017) 016012.

$$n_{\text{max}}^{SN}(r) = \frac{n_0}{2} \left[\frac{1 + e^{-(r-r_0)/\Delta r}}{1 + e^{-(r-r_0)/\Delta r}} + 1 \right]$$

Having n_0 as a function of real space along a line of sight, e.g. $n_0(r, \theta)$ or as a function of a flux radial variable, such as the poloidal flux $\psi_{pol} = \psi_{pol}(R, Z)$ and having the 2D maps of the flux in machine coordinates (R, Z)

The profiles can be mapped into the machine coordinates

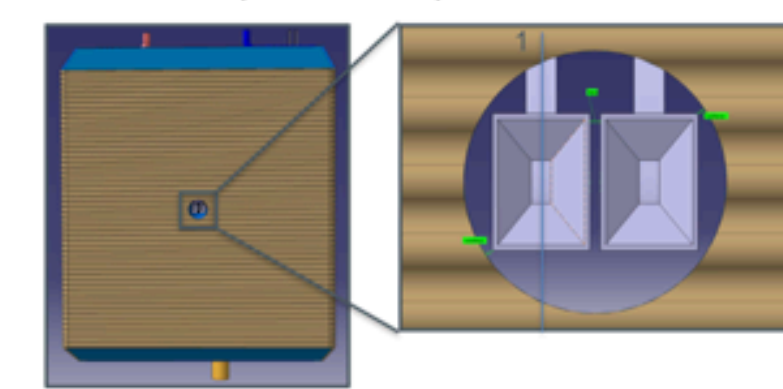
$$n_e(r, \theta, z) \rightarrow n_e(r_{pol}, \theta) \rightarrow n_e(R, Z)$$



Synthetic Diagnostics setup

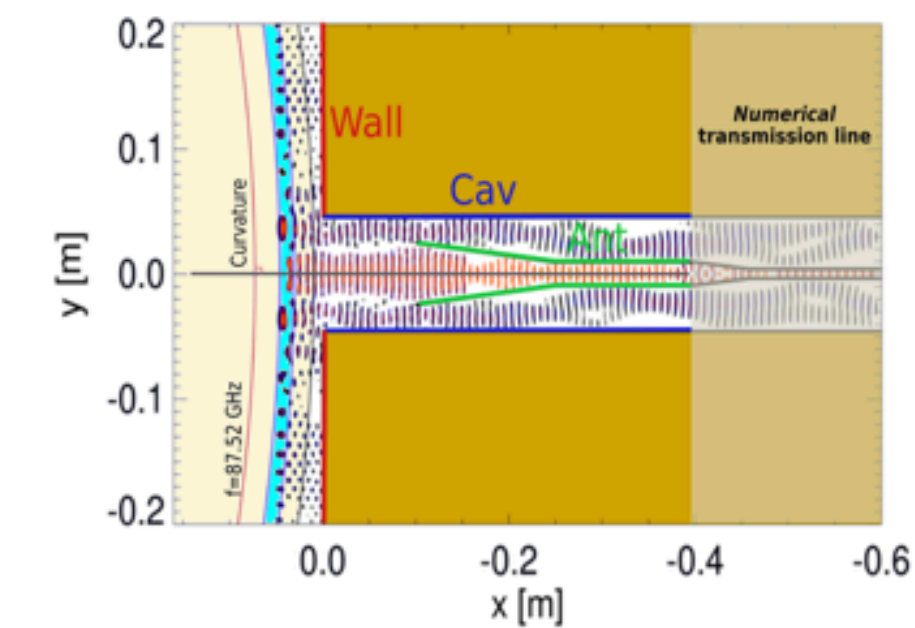
- Synthetic diagnostics using FDTD time-dependent codes offer a comprehensive view of reflectometry:
 - Propagation in the plasma
 - System location within the vacuum vessel
 - Access to the plasma
 - Signal processing techniques.

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.

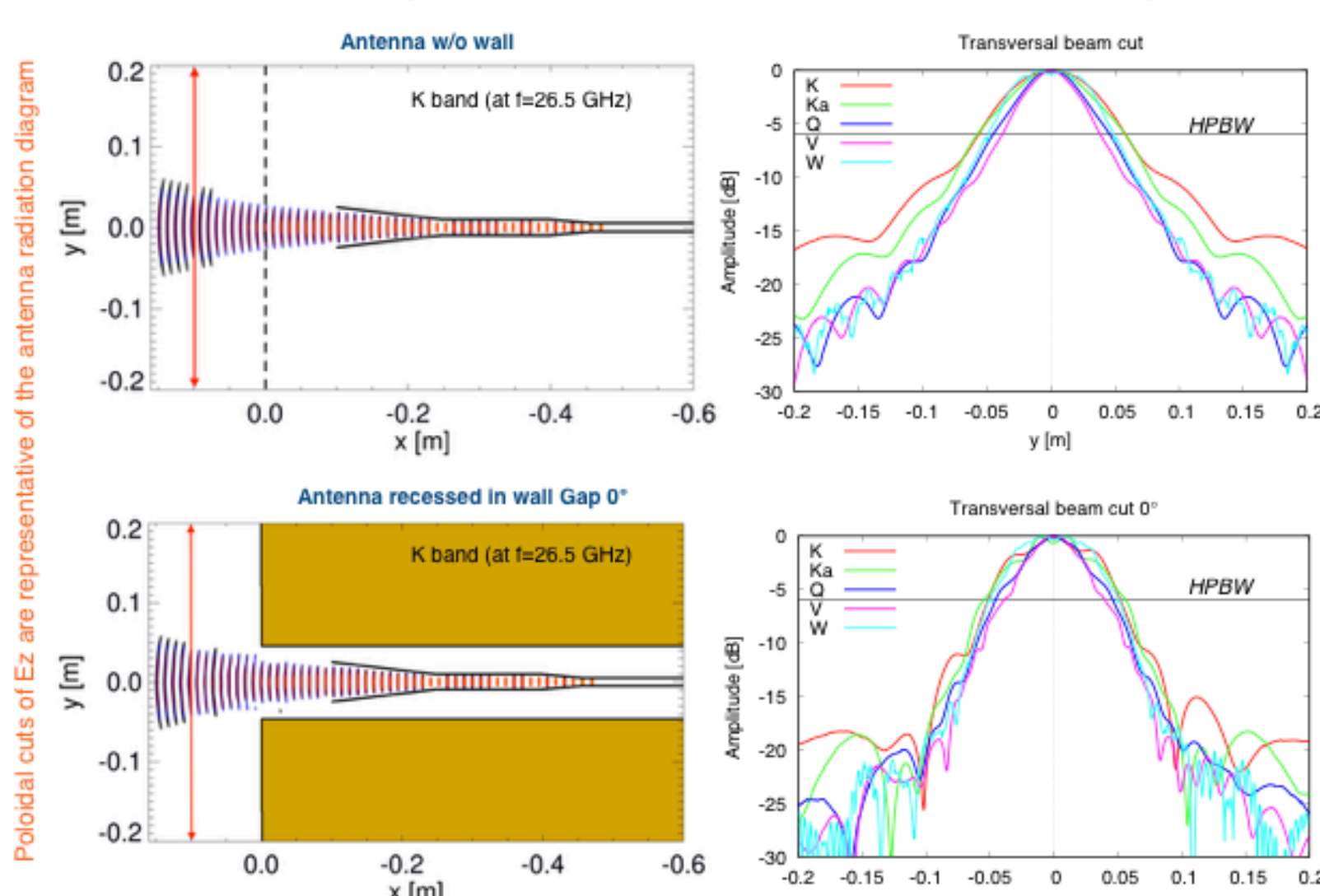


Blue-shaded region: iso-density region corresponding to the frequency limits of the Ka band.

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

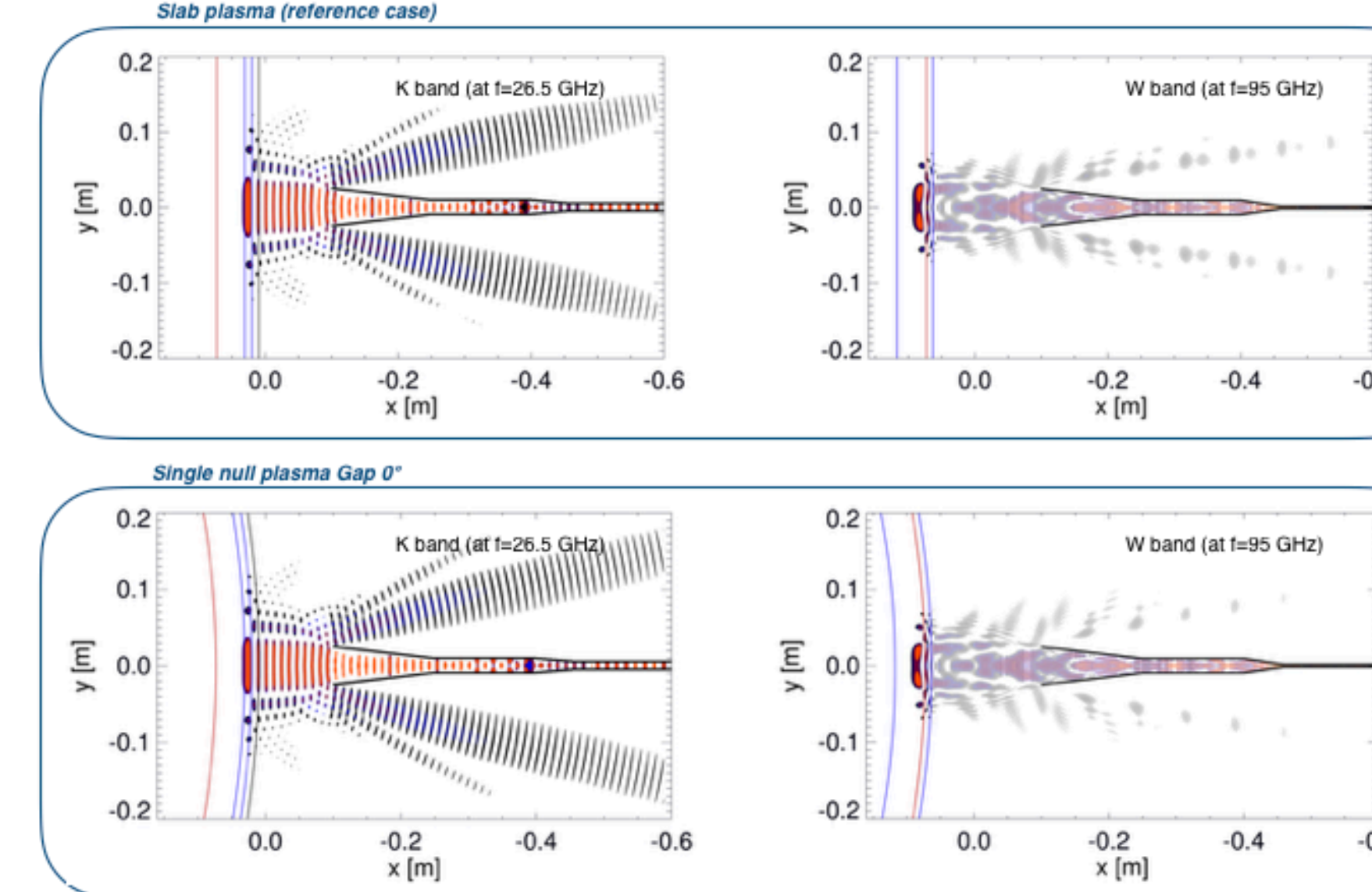
Radiation diagram

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

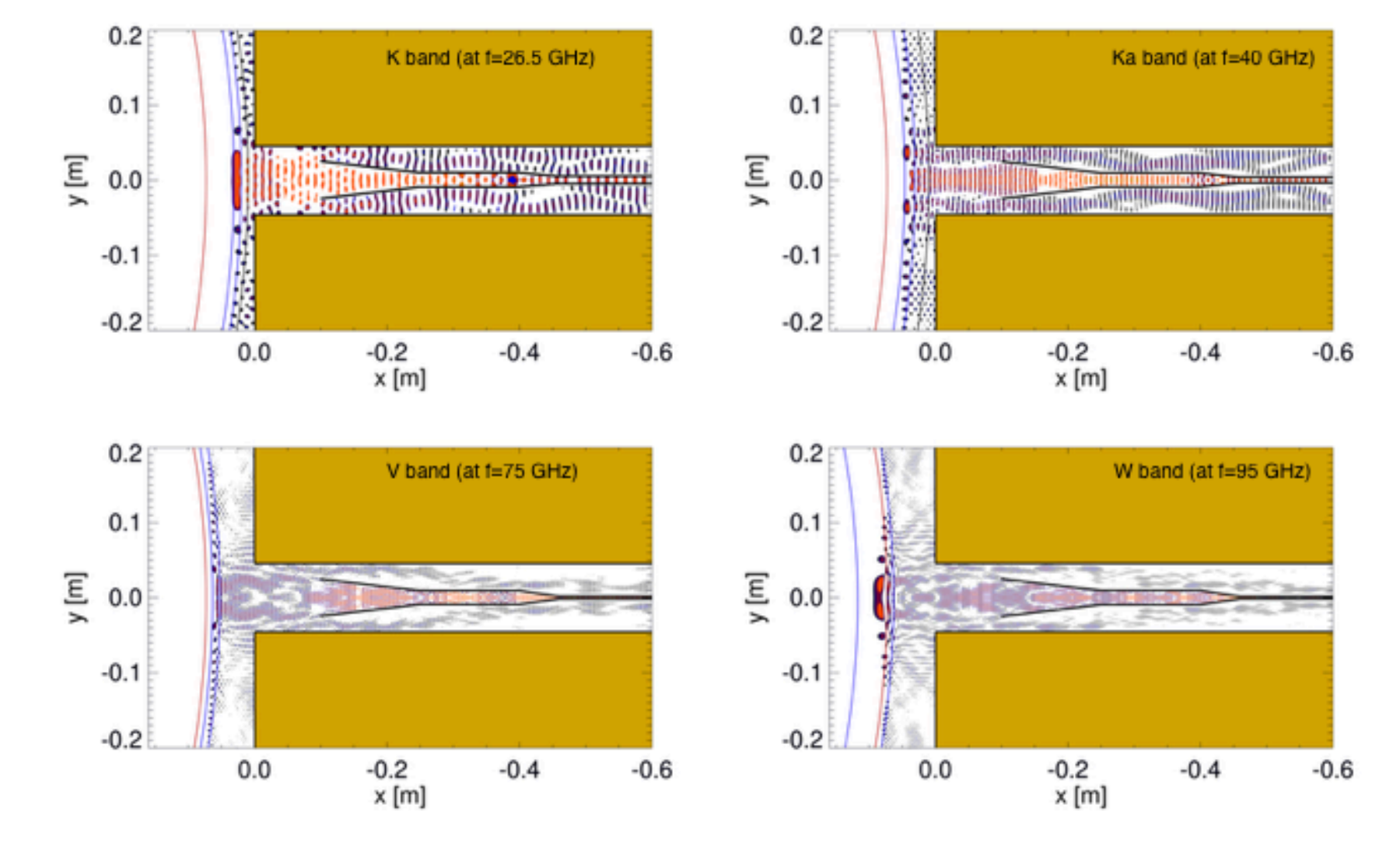


Effects of curvature

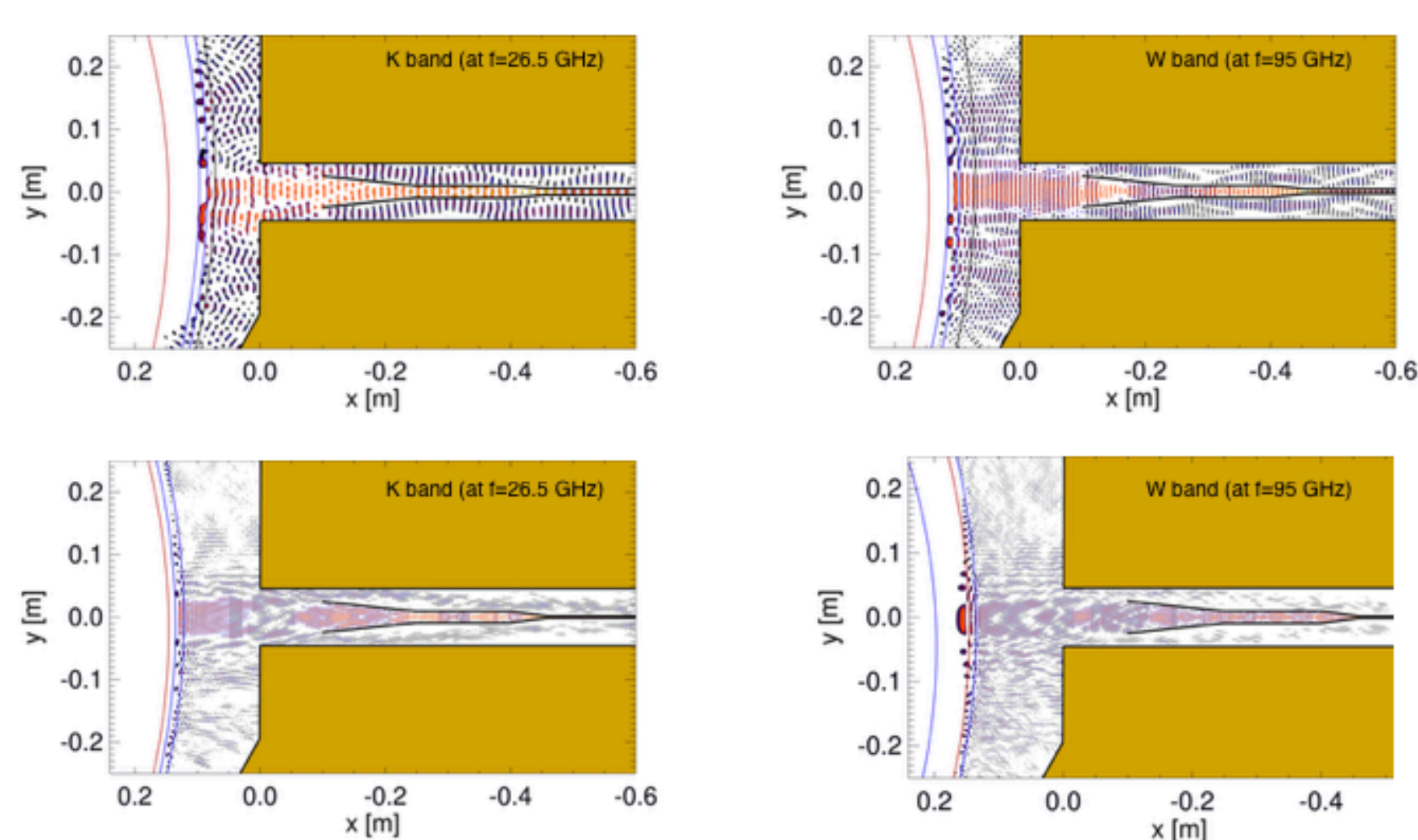
The curvature and tilt of both plasma scenarios (SN & DN) do not introduce major deviations from the standard reference case



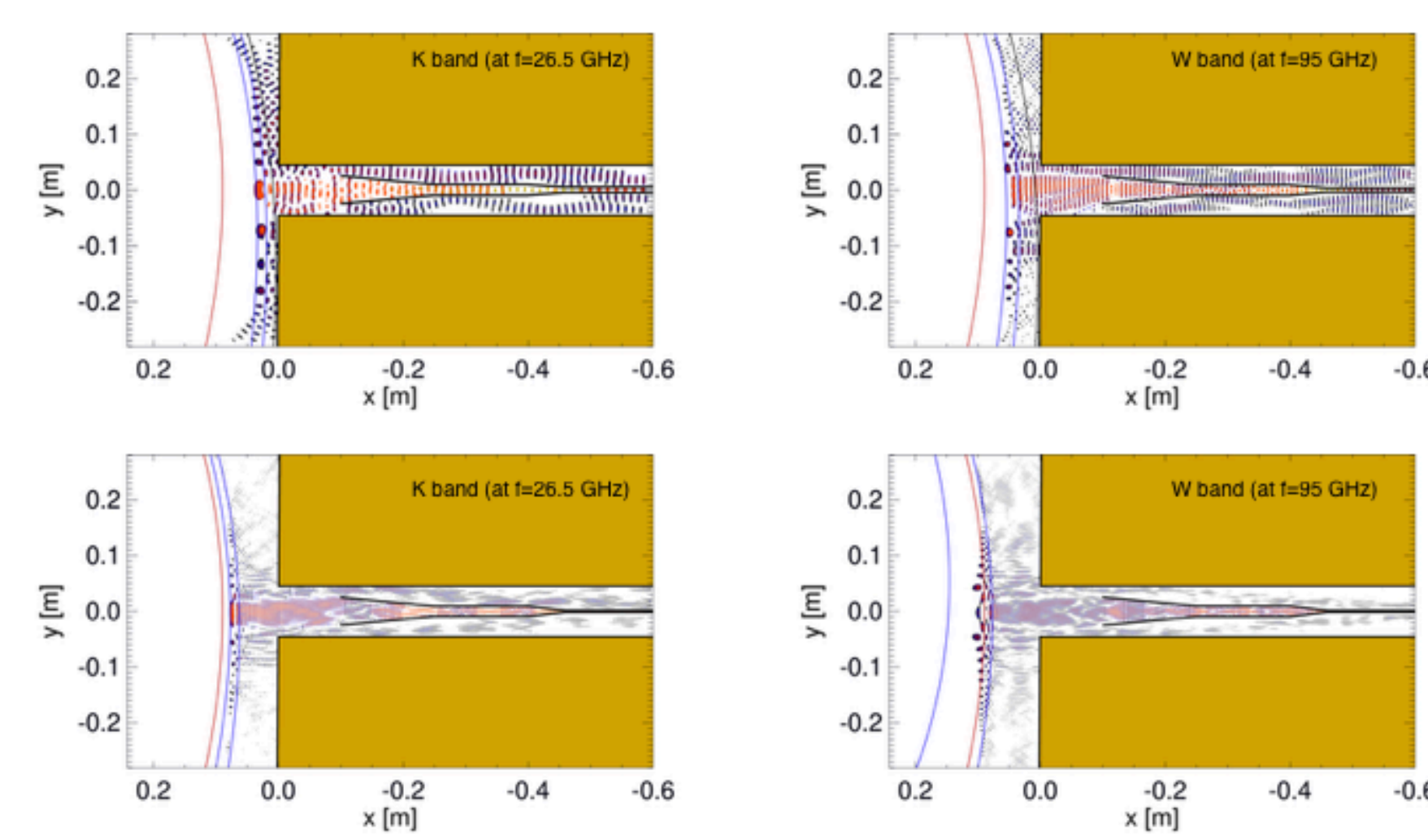
Full System for Gap 0° SN scenario probing



Full System for Gap 45° SN scenario probing

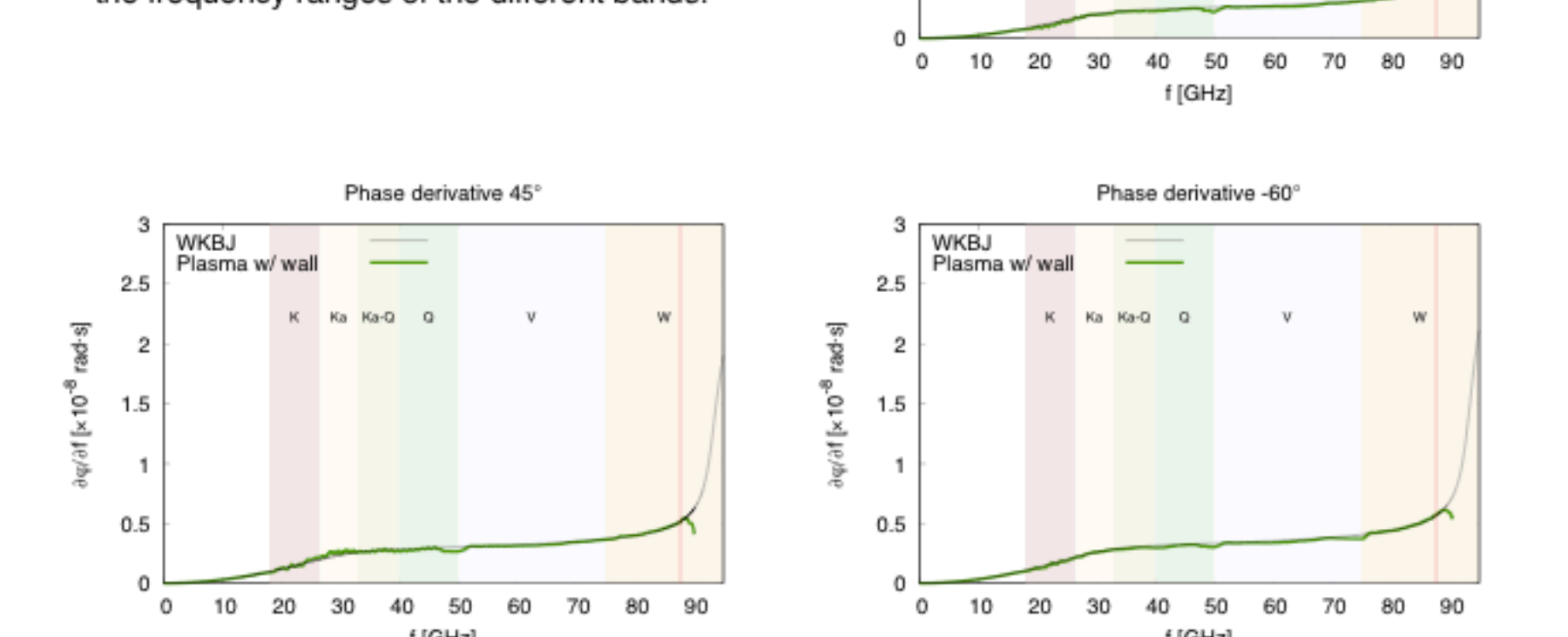


Full System for Gap -60° SN scenario probing



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.

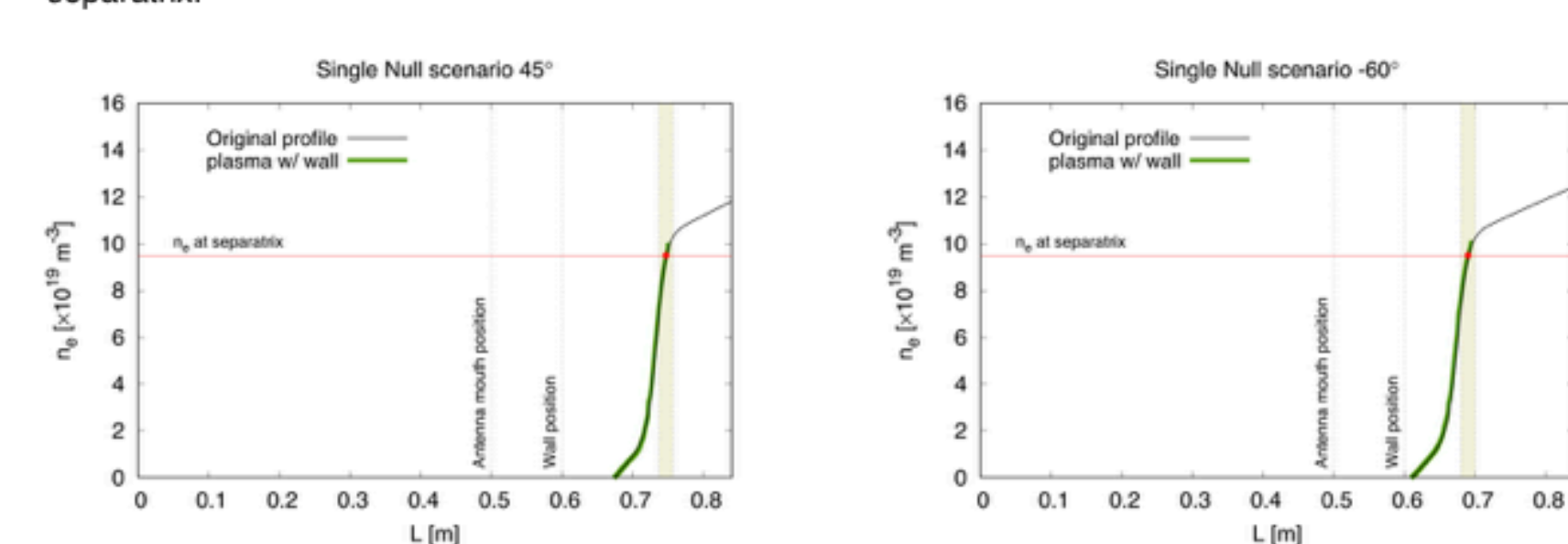


Profile reconstruction

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

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

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.

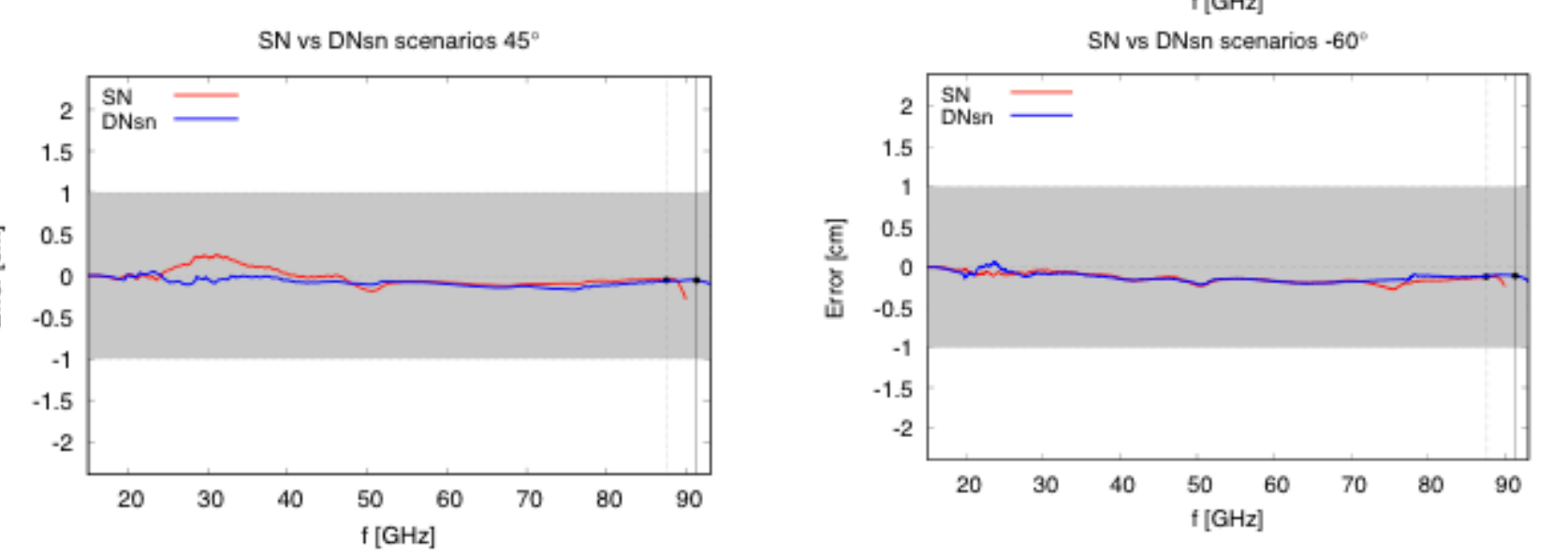


Position error at the separatrix

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

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

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 $\text{Error}_{sep} = \text{Error}(F(n_e))$



Discussion...

- The alignment of the antennas, optimised for the SN scenario, proved to equally performing for the DN scenario.
- For the LFS 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 f measurement errors well within the ± 1 cm 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 IDTT and DEMO in particular, since a profile measuring system away from the midplane has never been tested before.

