



Simultaneous O- and X-mode plasma probing with a shared dual-polarisation reflectometer front-end: a full-wave feasibility study

Filipe da Silva¹, A. Silva¹, J. Santos¹, T. Ribeiro², S. Heuraux³

¹*Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal*

²*Max-Planck-Institut für Plasmaphysik, Garching D-85748, Germany*

³*Institut Jean Lamour, UMR 7198 CNRS-Université de Lorraine, Nancy, France*



This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

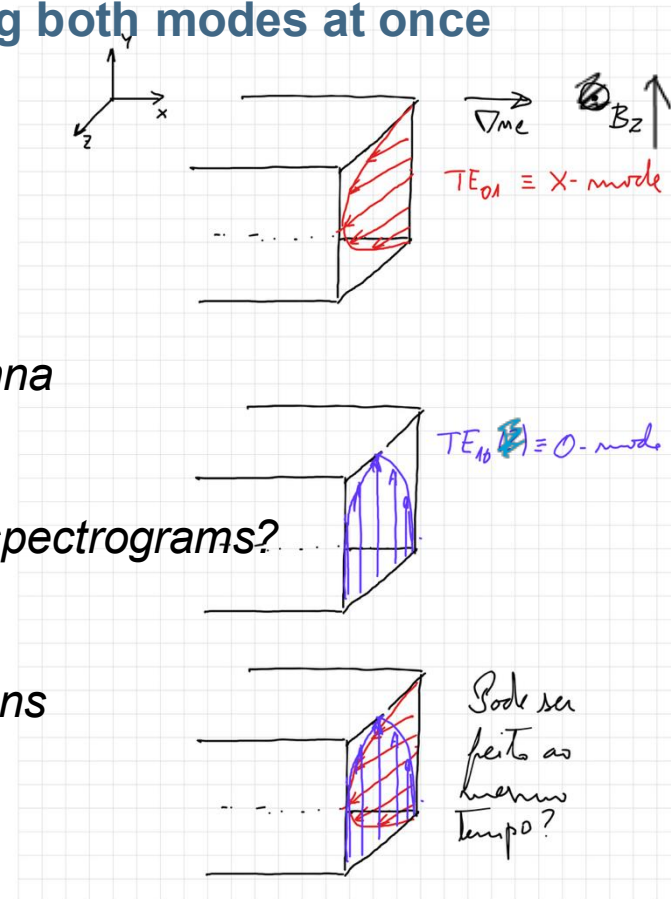


- **O- and X-mode reflectometry are complementary**
 - **O-mode:** density profile, independent of B_0
 - **X-mode:** can reach from low-density edge till the core, but depends on B_0
- **Port space in ITER, DEMO and DTT limits the number of antennas**
- **Proposal: one dual-polarisation front-end probing both modes at once**

This talk: a full-wave feasibility study

- **2D full-wave simulations with REFMULF**
 - O- and X-mode excited separately and together
 - Mode coupling when B_0 is not aligned with the antenna
- **Ka-band (26–40 GHz) frequency sweep**
 - Can O- and X-mode reflections be told apart in the spectrograms?
- **3D full-wave studies were planned**
 - An A.C. malfunction prevented running the simulations

Original sketch of the idea →



Reflectometry in a nutshell

Reflectometry is a spin-off of the radar techniques used in the study of the ionosphere.

- Signal sent through the plasma

$$s_{src}(t) = A_{src} \cos(\omega t)$$

- It propagates until being reflected at cut-off position r_c , where the refraction index is zero, $N(x_c)=0$

$$s_{rcv}(t) = A_{ant} \cos(\omega t + \varphi)$$

- The reflected wave shows a phase shift ϕ due to the microwave circuit ϕ_μ , the propagation in a vacuum ϕ_0 and to the propagation in the plasma ϕ_p .

$$\varphi_p = \frac{4\pi f}{c} \int_0^{r_c} N(r) dr - \varphi_k$$

- The phase ϕ_p reflects the propagation of the wave along a path described by a refraction index $N(r)$ and contains information on the electronic density n_e

- O-mode** $\varphi_p = \varphi_p[f, N_O(n_e)]$

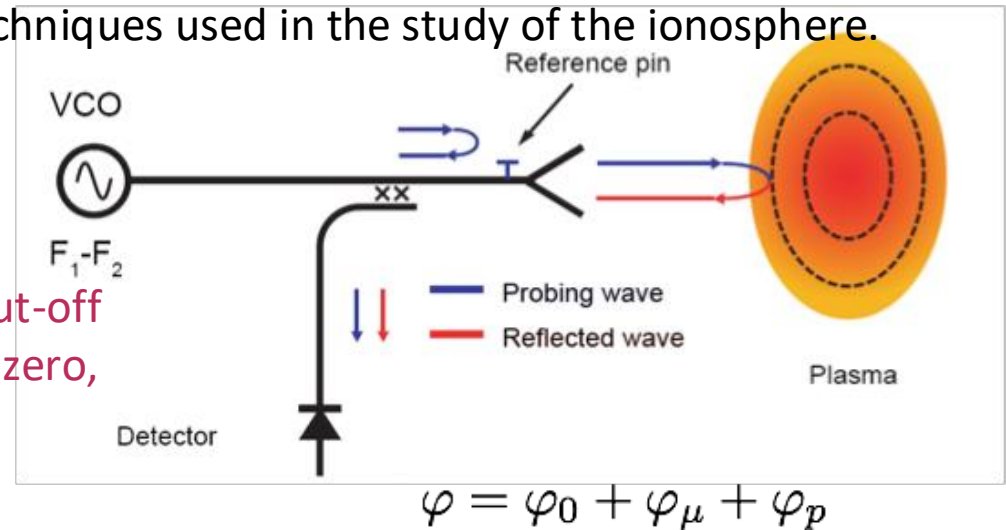
$$N^2 = 1 - X$$

$$X=1 \Rightarrow f = f_{pe} = \frac{1}{2\pi} \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}}$$

- X-mode** $\varphi_p = \varphi_p[f, N_X(n_e, B_0)]$

$$N^2 = 1 - \frac{X(1-X)}{1-X-Y^2}$$

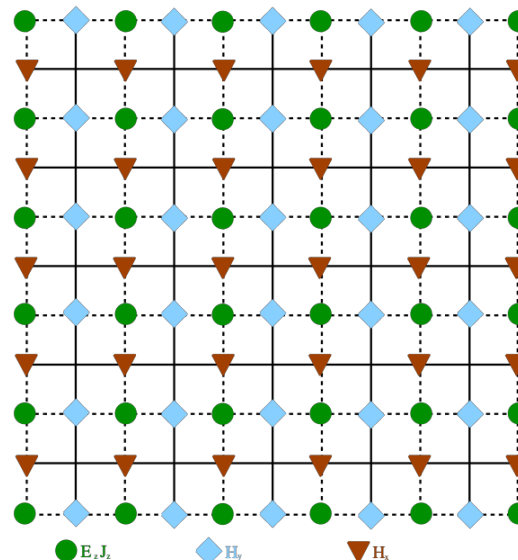
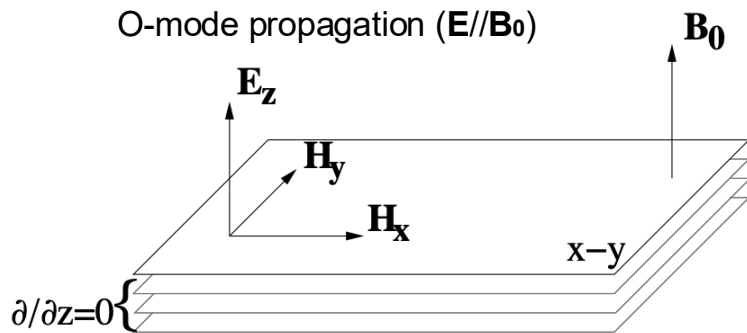
$$X=1 \mp Y \Rightarrow f_{R,L} = \frac{1}{2} \left[\sqrt{f_{ce}^2 + 4f_{pe}^2} \pm f_{ce} \right], \quad f_{ce} = \frac{eB_0}{2\pi m_e}$$



Propagation in 2D (x-y plane) External magnetic field, B_0 along z No gradients along z axis ($\partial/\partial z=0$)

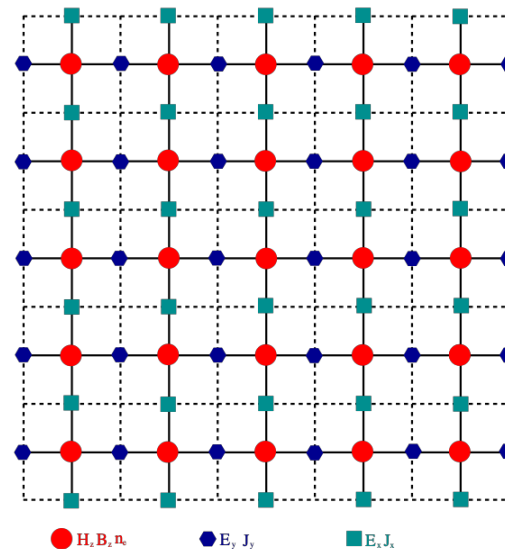
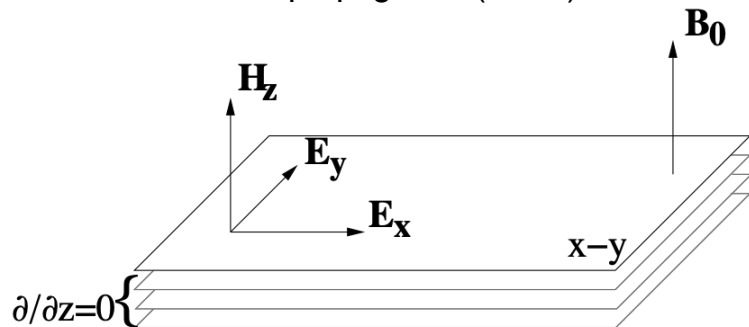
Transverse magnetic mode TMz (E_z, H_x, H_y)

O-mode propagation ($\mathbf{E} // \mathbf{B}_0$)



Transverse electric mode TEz (H_z, E_x, E_y)

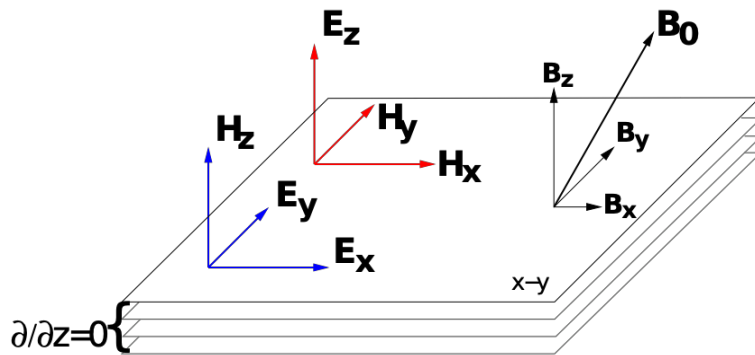
X-mode propagation ($\mathbf{H} // \mathbf{B}_0$)



Propagation in 2D (x-y plane)

No gradients along z axis ($\partial/\partial z=0$)

Generic external magnetic field, $\mathbf{B}_0=\mathbf{B}_x+\mathbf{B}_y+\mathbf{B}_z$



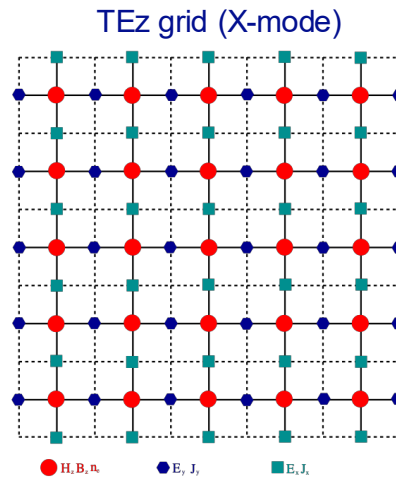
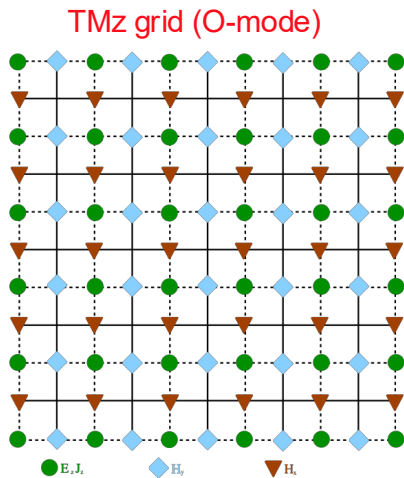
Transverse magnetic mode **TMz** (E_z, H_x, H_y)

O-mode propagation ($\mathbf{E} \parallel \mathbf{B}_0$) if $\omega_x, \omega_y=0$

Transverse electric mode **TEz** (H_z, E_x, E_y)

X-mode propagation ($\mathbf{H} \parallel \mathbf{B}_0$) if $\omega_x, \omega_y=0$

Maxwell curl equations can only couple TMz and TEz modes through $\partial/\partial z$



BUT

$$\omega_c = \omega_x + \omega_y + \omega_z$$

$$\omega_{x,y,z} = |\omega_{x,y,z}|$$

$$\frac{d\mathbf{J}}{dt} = \varepsilon_0 \omega_p^2 \mathbf{E} + \boldsymbol{\omega}_c \times \mathbf{J}$$

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

TEz (X-mode)

$$\frac{dJ_x}{dt} = \varepsilon_0 \omega_p^2 E_x - \omega_z J_y + \omega_y J_z$$

B_x or B_y couples TM_z (J_z) plane to TEz

$$\frac{dJ_y}{dt} = \varepsilon_0 \omega_p^2 E_y + \omega_z J_x - \omega_x J_z$$

TMz (O-mode)

$$\frac{dJ_z}{dt} = \varepsilon_0 \omega_p^2 E_z + \omega_x J_y - \omega_y J_x$$

B_x or B_y couples TEz (J_x, J_y) plane to TMz



REFMULF is a 2D Full polarization code → **2D simulations in this talk**

- Treats **all component of $\mathbf{E}$** ($E_x + E_y + E_z$) and **$\mathbf{H}$** ($H_x + H_y + H_z$) of the wave
- Supports a **generic external magnetic field $\mathbf{B}_0$** ($B_{0x} + B_{0y} + B_{0z}$)
- Couples the **TE (X-mode)** and **TM (O-mode)** planes via $\mathbf{J}$, in both directions

Extends capabilities of available 2D codes

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

Maxwell curl equations

2D TMz (O-mode)

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

2D TEz (X-mode)

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

Auxiliary equation for $\mathbf{J}$

2D TMz (O-mode)

$$\frac{dJ_z}{dt} = \varepsilon_0 \omega_p^2 E_z + \omega_x J_y - \omega_y J_x$$

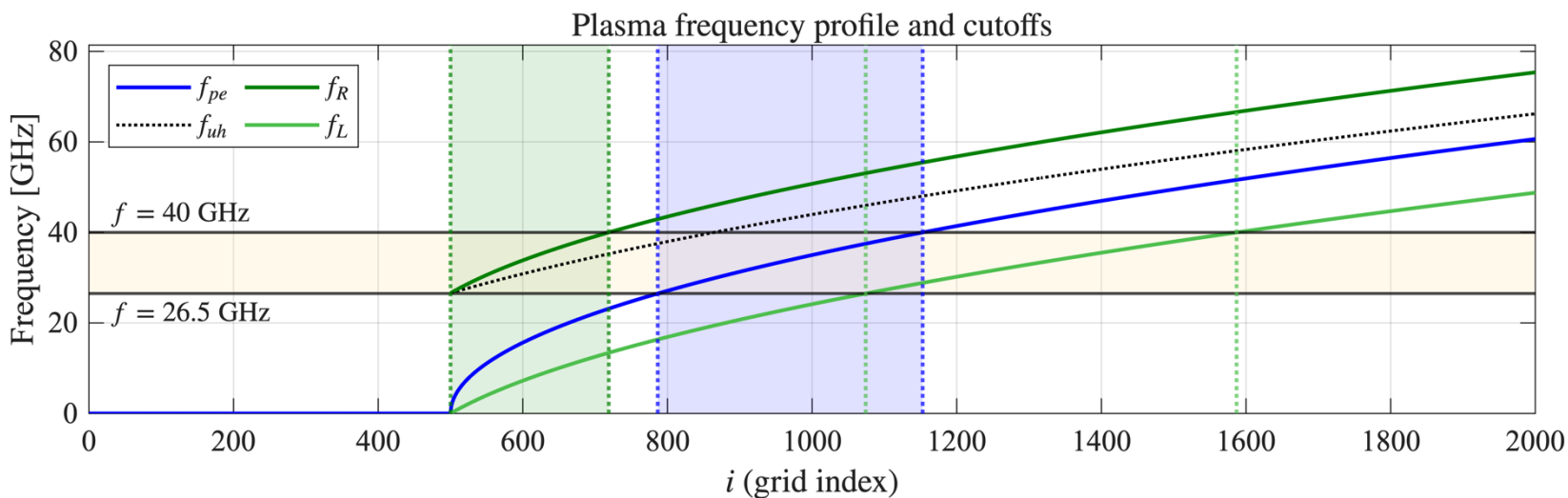
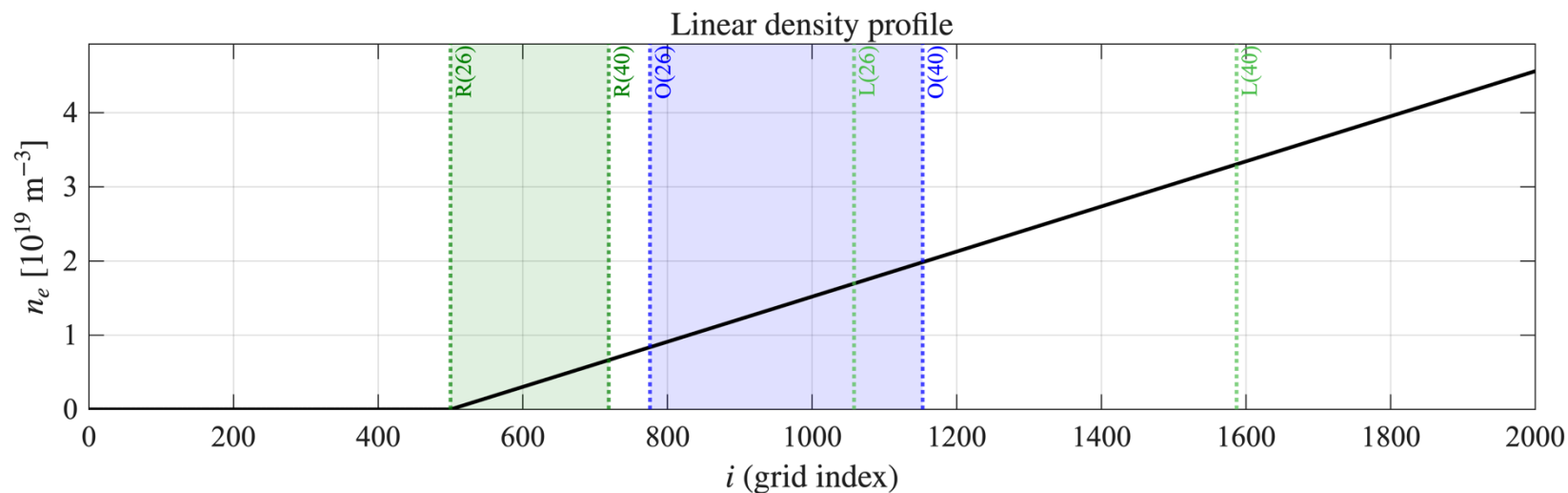
2D TEz (X-mode)

$$\frac{dJ_x}{dt} = \varepsilon_0 \omega_p^2 E_x - \omega_z J_y + \omega_y J_z$$

$$\frac{dJ_y}{dt} = \varepsilon_0 \omega_p^2 E_y + \omega_z J_x - \omega_x J_z$$

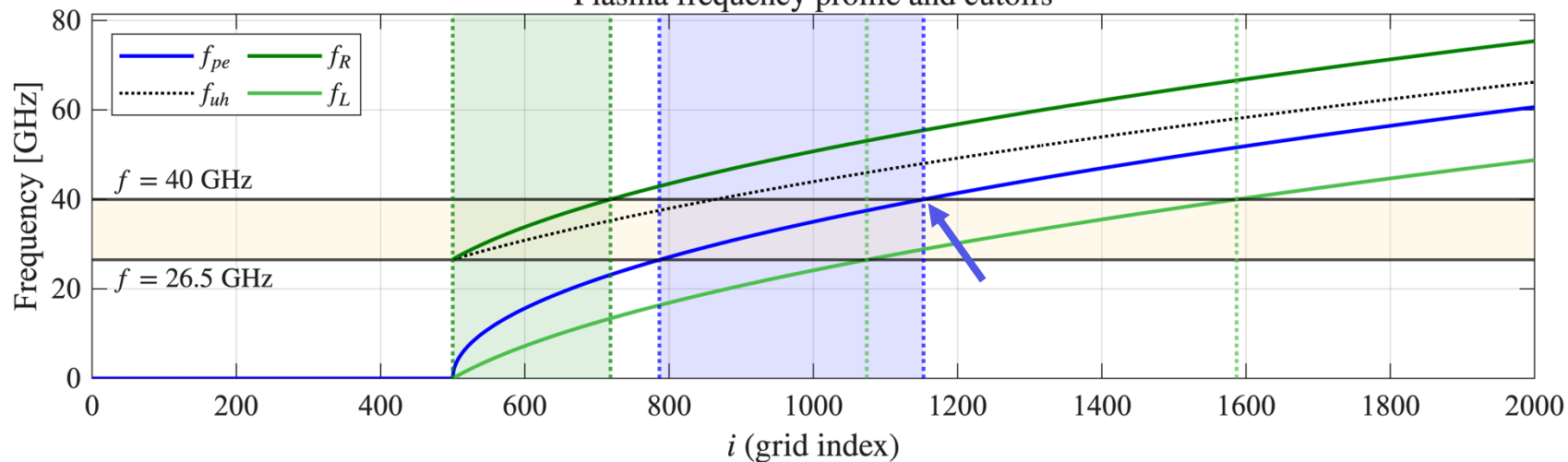
Linear slab plasma with constant B_0

$n_{ec} = 1.52 \times 10^{19} \text{ m}^{-3}$, $x_0 = 500$, $x_c = 1000$, $B_z = 0.95 \text{ T}$, CWFM [26, 40] GHz

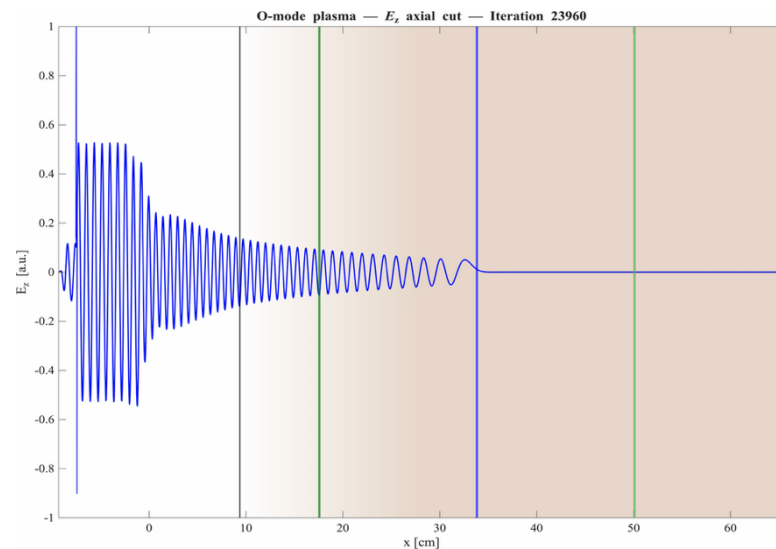
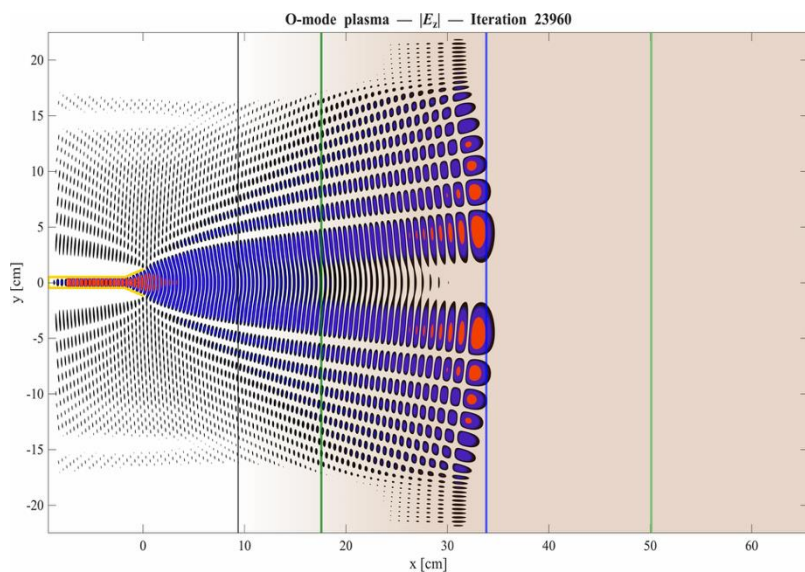


REFMULF compiled as pure O-mode code

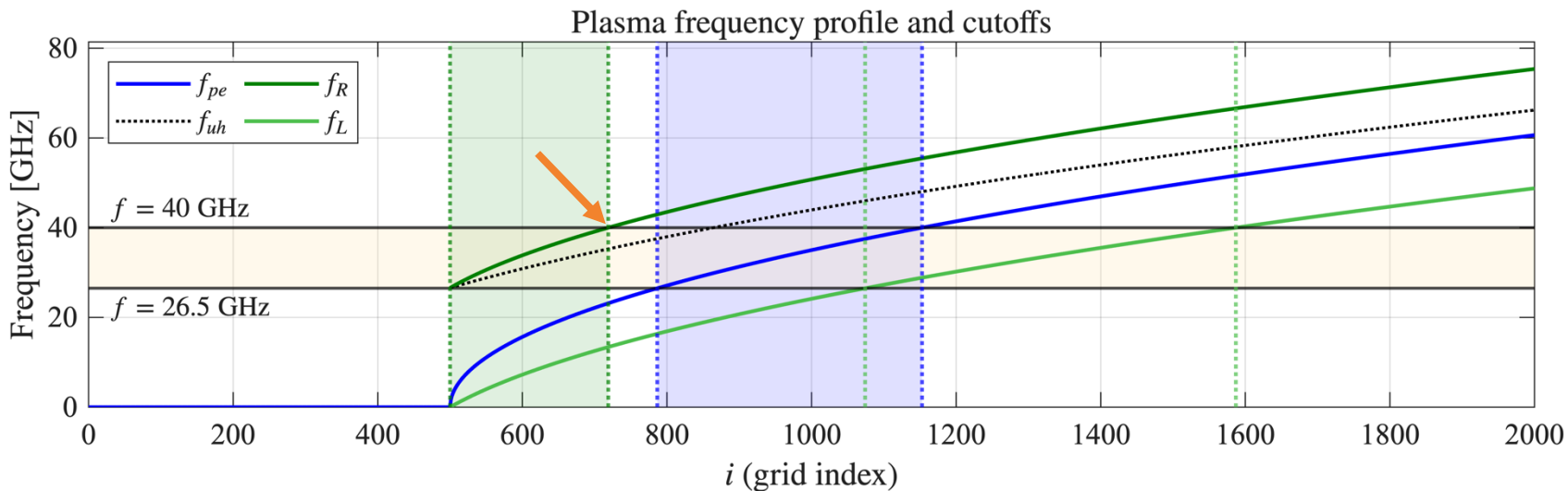
Plasma frequency profile and cutoffs



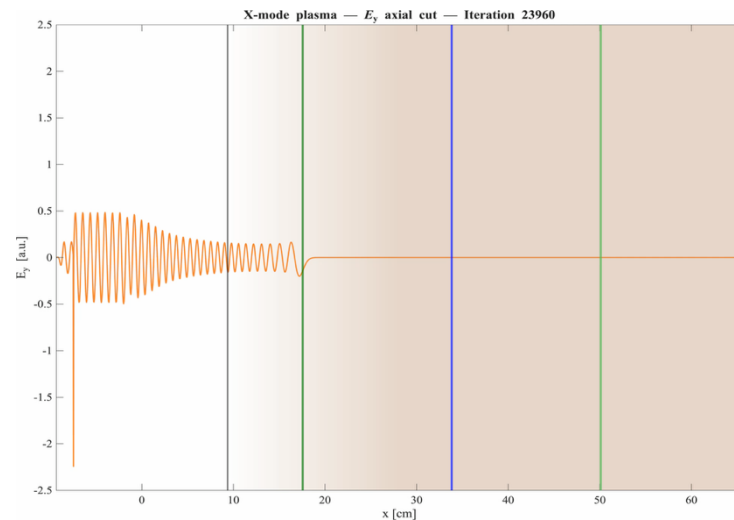
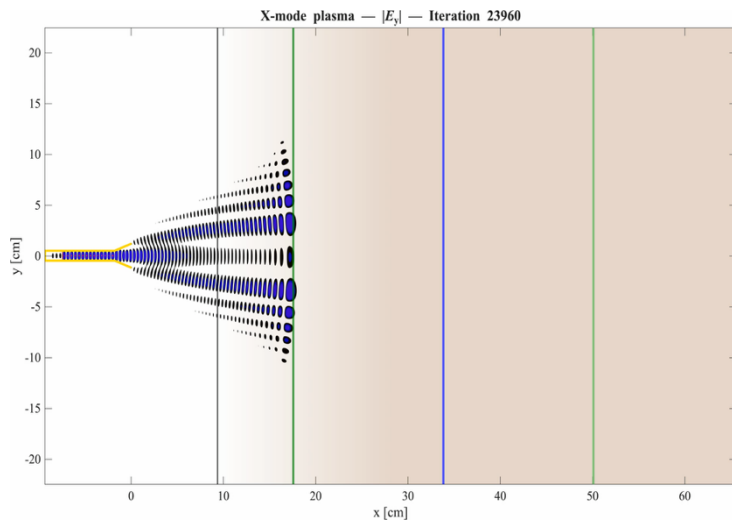
O-mode probing with $f=40$ GHz, $B_z=0.95$ T



REFMULF compiled as pure X-mode code

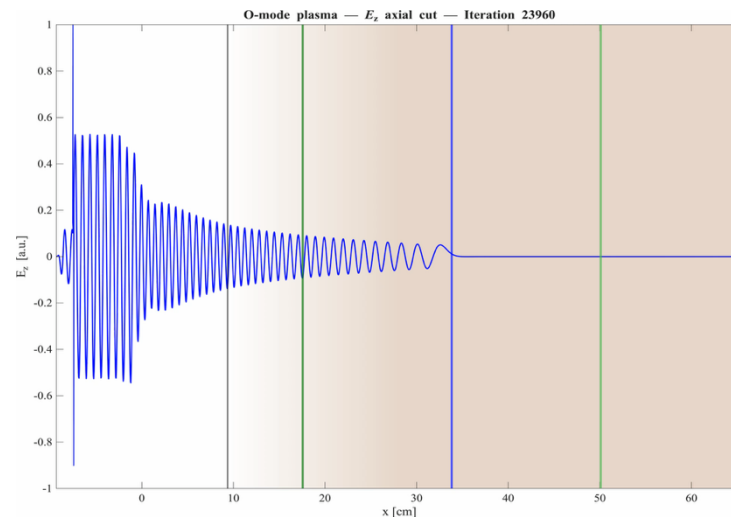
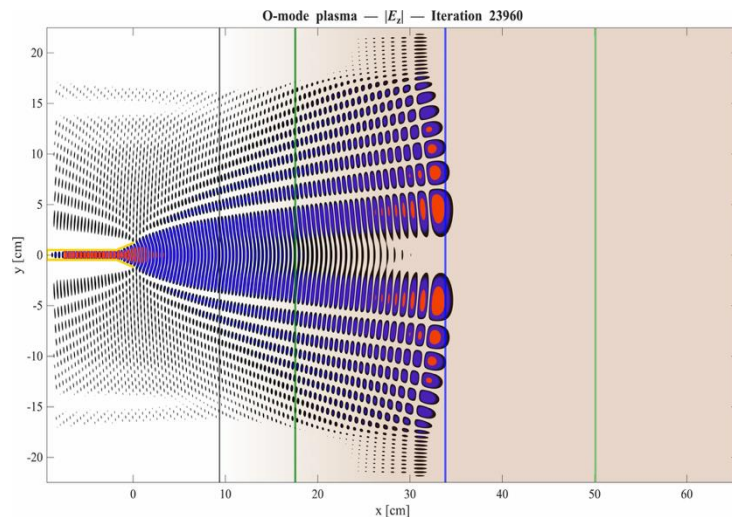


X-mode probing with $f=40$ GHz, $B_z=0.95$ T

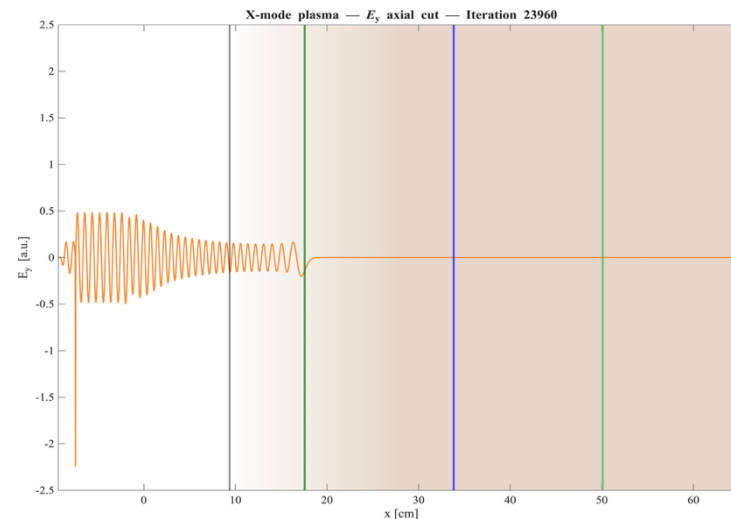
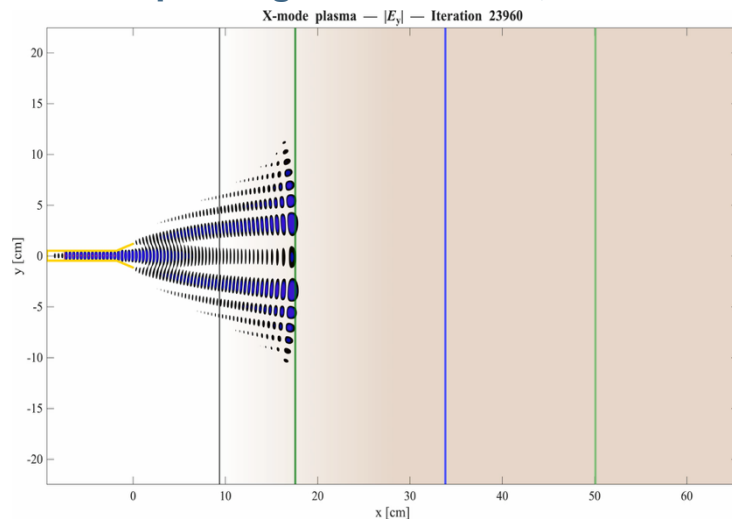


REFMULF compiled with full polarization (“*F-mode*”)

O-mode probing with $f=40\text{GHz}$, $B_z=0.95\text{T}$



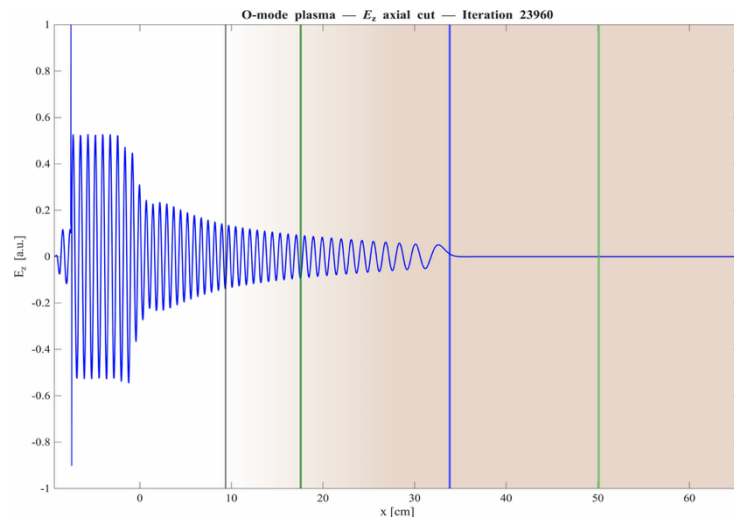
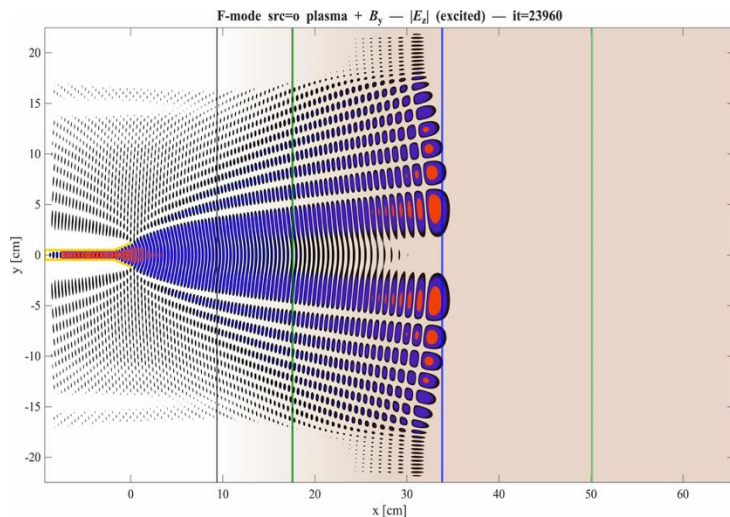
X-mode probing with $f=40\text{GHz}$, $B_z=0.95\text{T}$



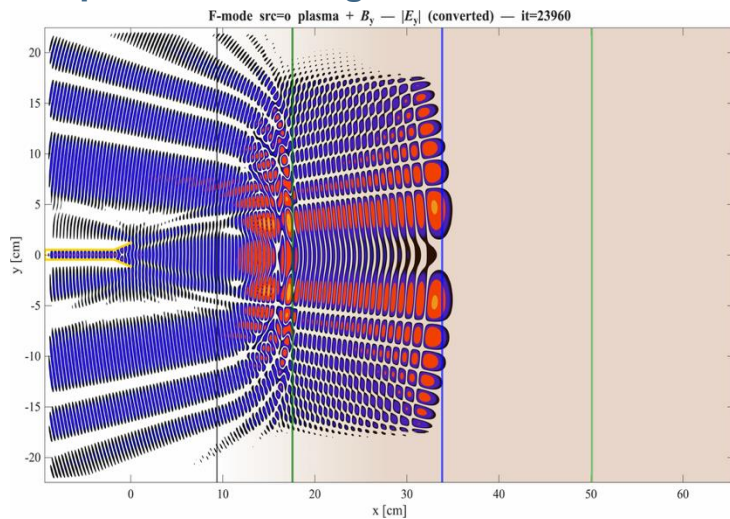
O-mode/TE_z excitation ($E_z // B_z$ & $E_z \perp B_y$)

REFMULF compiled with full polarization (“*F-mode*”)

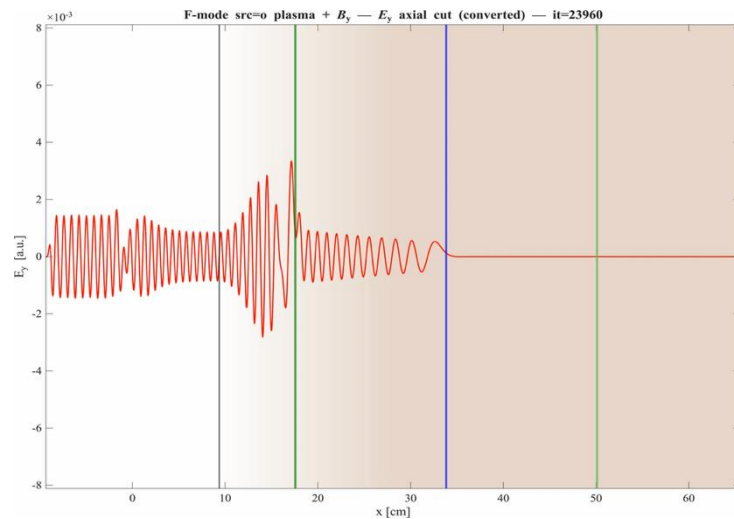
O-mode probing with $f=40\text{GHz}$, $B_z=0.95\text{T}$, $B_y=0.01\text{T}$, $B_y/B_z \sim 1\%$



Coupled X-mode signal

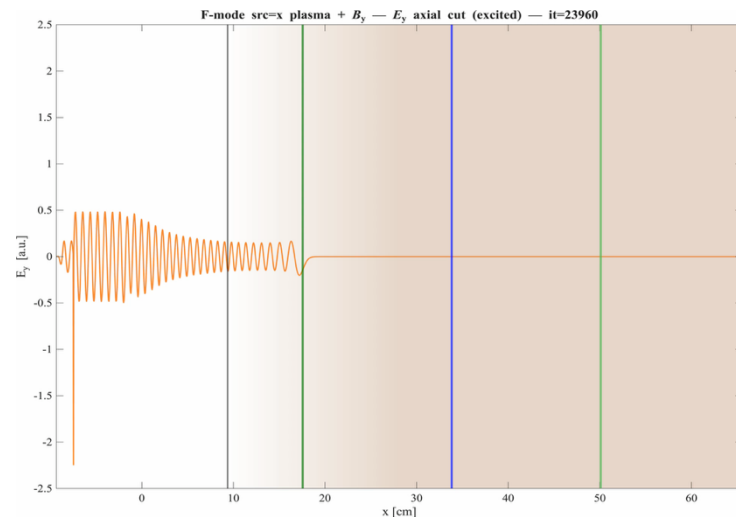
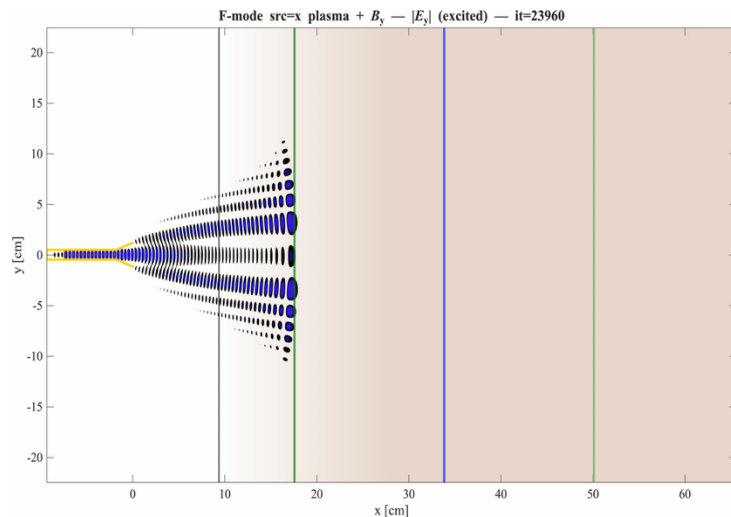


Ratio $E_z/E_y \sim 159$ (maxima)

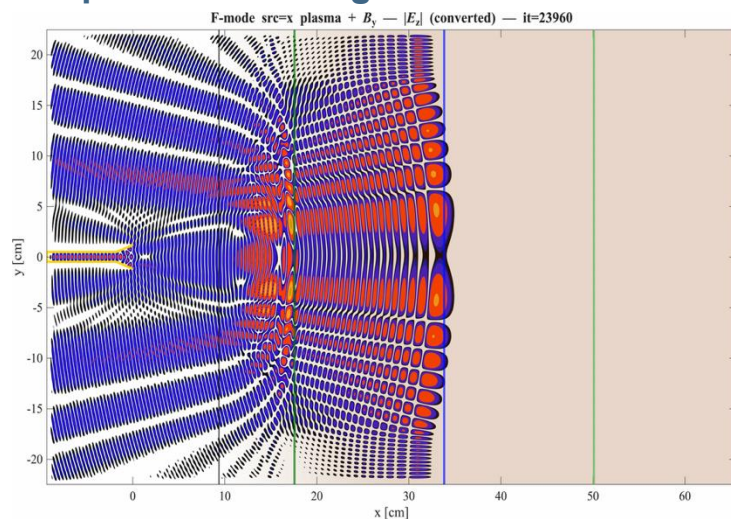


REFMULF compiled with full polarization (“*F-mode*”)

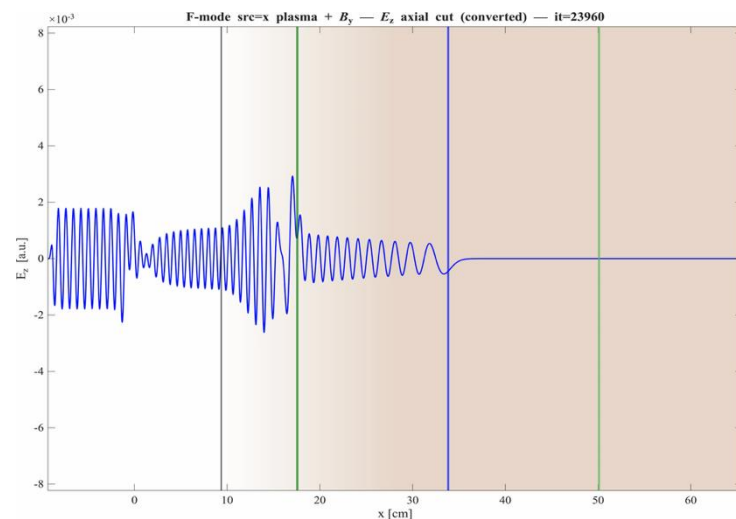
X-mode probing with $f=40\text{GHz}$, $B_z=0.95\text{T}$, $B_y=0.01\text{T}$, $B_y/B_z \sim 1\%$



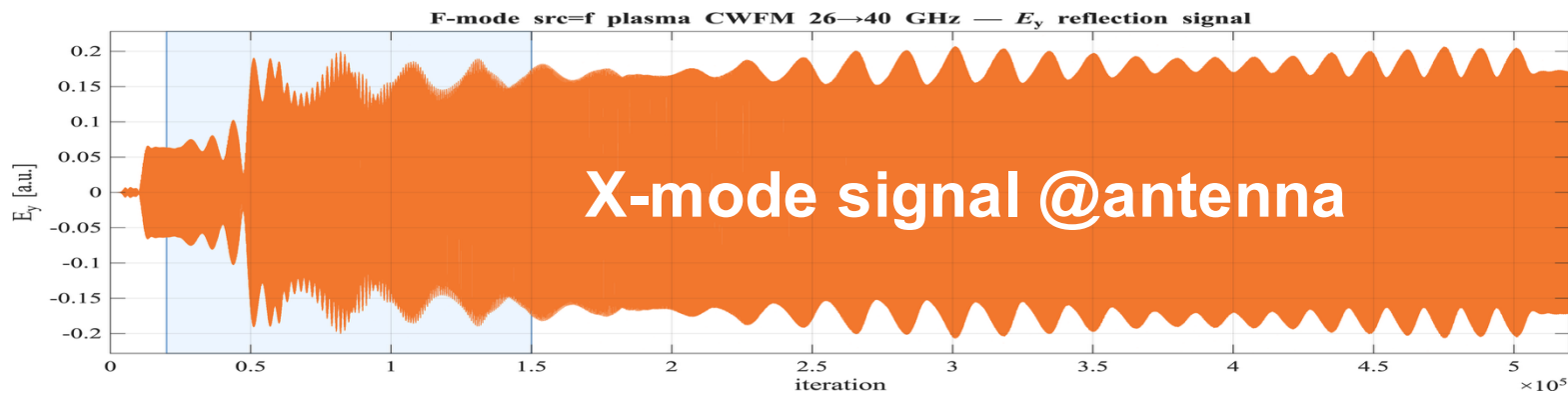
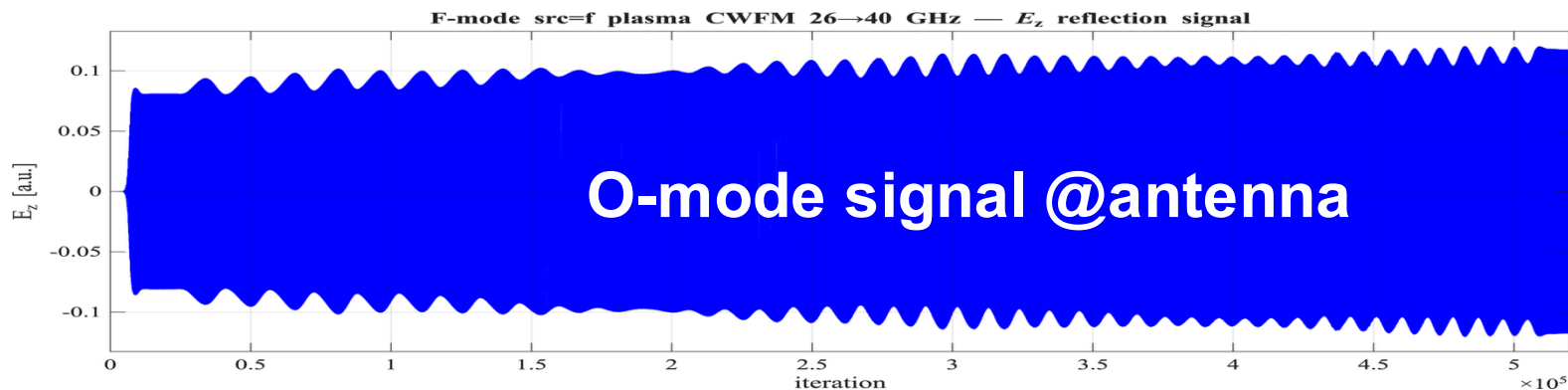
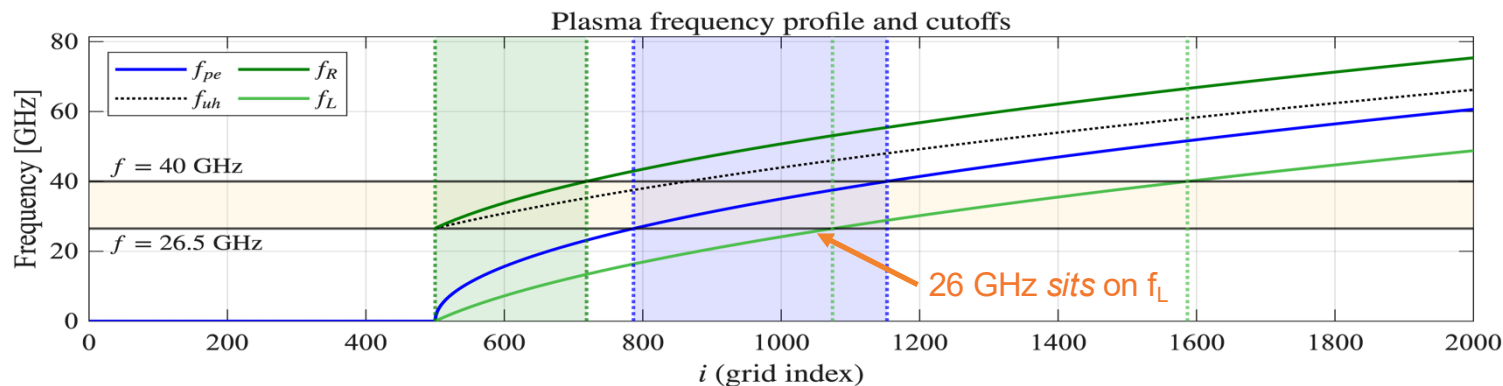
Coupled O-mode signal

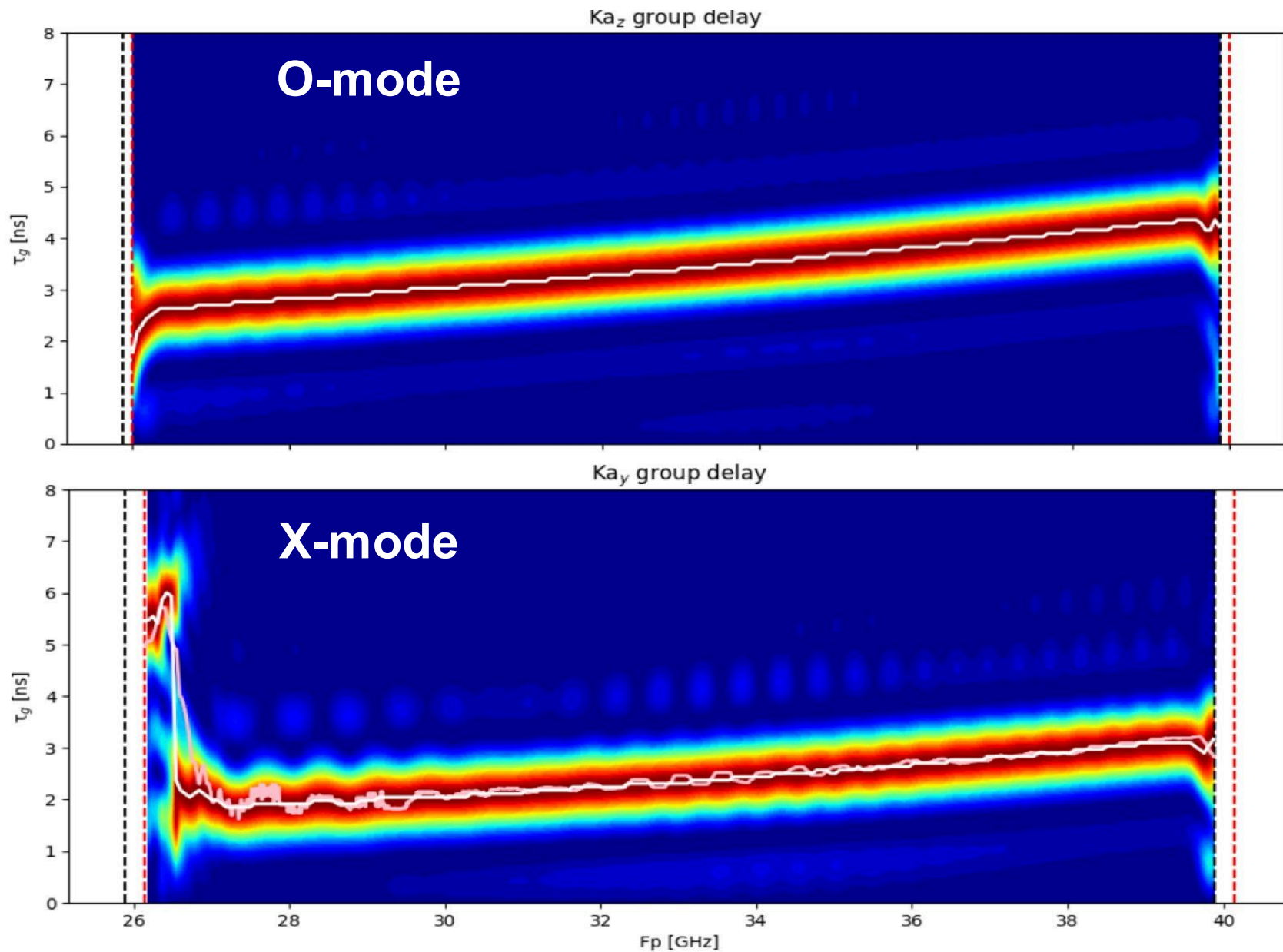


Ratio $E_y/E_z \sim 334$ (maxima)



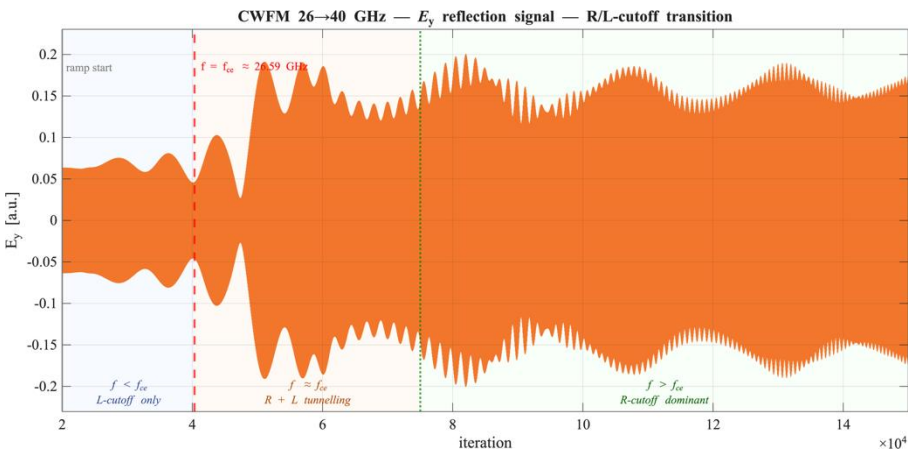
CWFM frequency sweep, Ka band [26,40] GHz



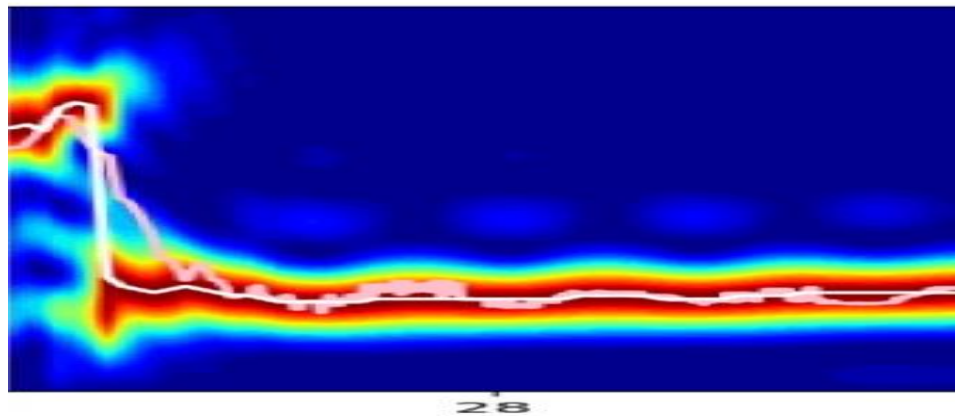


X-mode signal reflection passage from $f_L \rightarrow f_R$

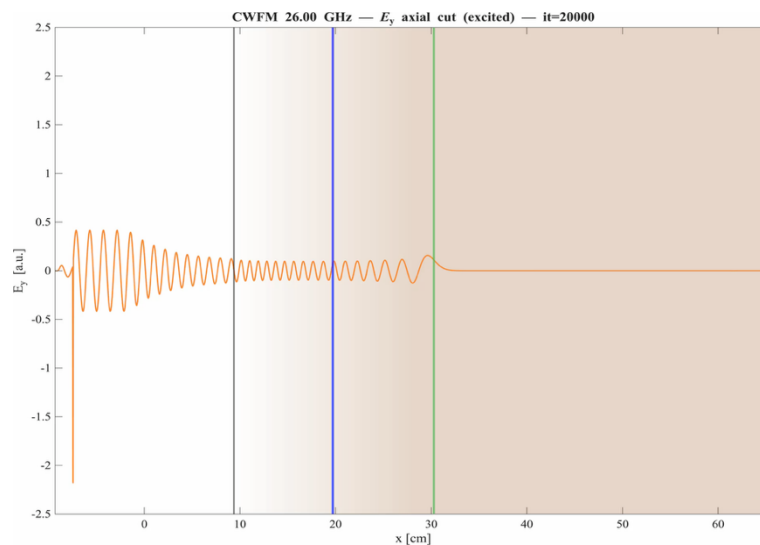
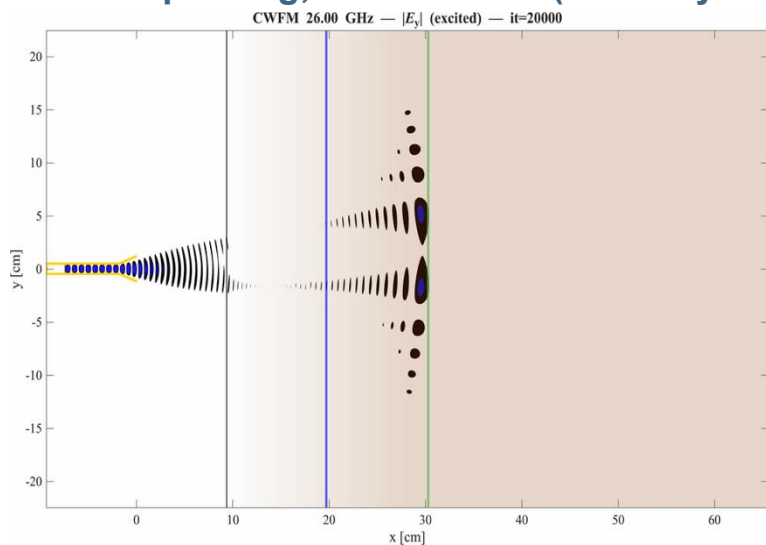
$f_L \rightarrow f_R$ signal window



$f_L \rightarrow f_R$ spectrogram ROI



X-mode probing, 26–29.6 GHz (coarsely sampled)



- **Shared front-end works when B_0 is aligned with the antenna**
 - *O- and X-mode propagate independently, even when launched together*
 - *Each reflects at its own cut-off: f_{pe} for O-mode, f_R for X-mode*
- **A tilted B_0 couples the two polarisations**
 - *A small fraction of the launched power converts to the other mode through J*
 - *In the simple case simulated, **no real impact appeared***
- **O- and X-mode stay separable in a Ka-band sweep**
 - *Distinct group-delay traces in the spectrograms*
 - *X-mode shows the $f_L \rightarrow f_R$ cut-off transition near 26 GHz*

Next steps

- **Find the misalignment angle a shared front-end tolerates**
- **Deploy the planned 3D simulations (the way is paved)**
- **Use different frequency bands for O- and X-modes to optimise and extend coverage of realistic scenarios**
- **Case study on a real machine, e.g. DTT**