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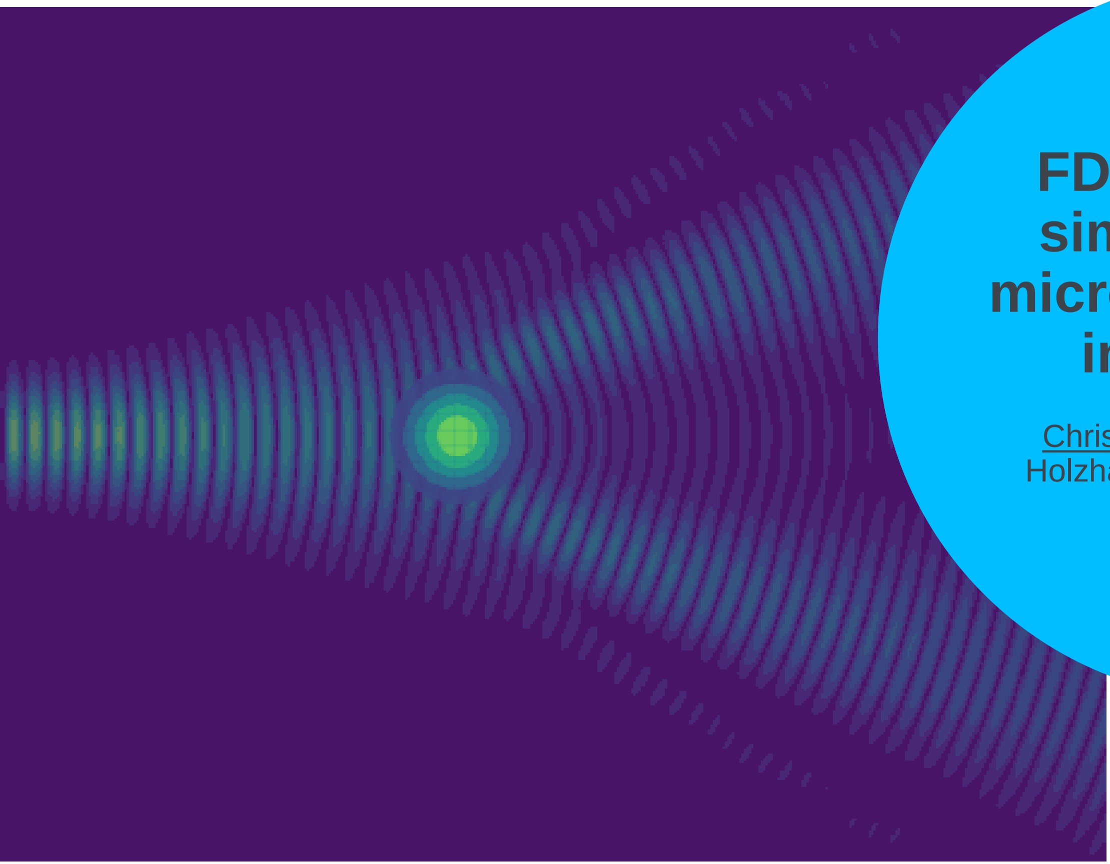

FDTD full-wave simulations for microwave-plasma interactions

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Overview

1. Motivation
2. The Yee algorithm
3. The FDTD code
4. Challenges and code design
5. Results and discussion

Motivation

- Diagnostic tools
  - **Interferometry** (measures line – integrated electron density)

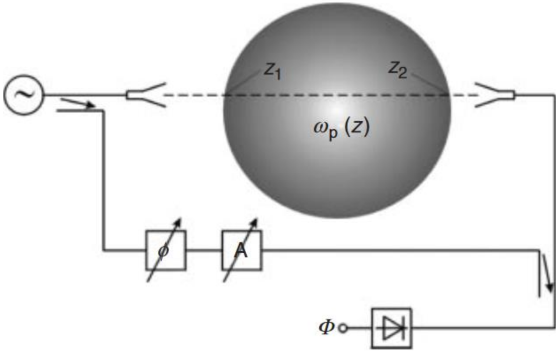

Figure 1: Mach-Zehnder interferometer [1]

- Heating mechanism in nuclear fusion devices (ECRH heating)

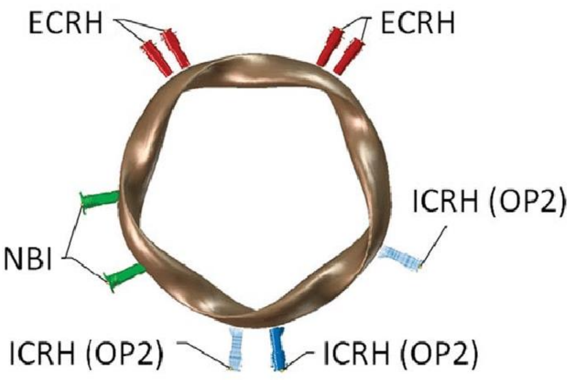

Figure 2: Port allocation for plasma heating mechanisms in W7-X [2]

[1] H.J. Hartfuß and T. Geist, "Fusion Plasma Diagnostics with mm-waves, An Introduction", Wiley-VCH Verlag GmbH & Co, Weinheim (2013).
[2] H.S. Bosch *et al*, Nucl. Fusion **53**, 126001 (2013).

The Yee algorithm

- Faraday's law
  - $\frac{\partial}{\partial t}\boldsymbol{B} = -\boldsymbol{\nabla} \times \boldsymbol{E}$
- Ampere's law
  - $\frac{\partial}{\partial t}\boldsymbol{E} = c^2\boldsymbol{\nabla} \times \boldsymbol{B} - \frac{1}{\epsilon_0}\boldsymbol{J}$
- Replace derivatives with finite differences
- Discretise space and time
- Evolve fields with leapfrog method

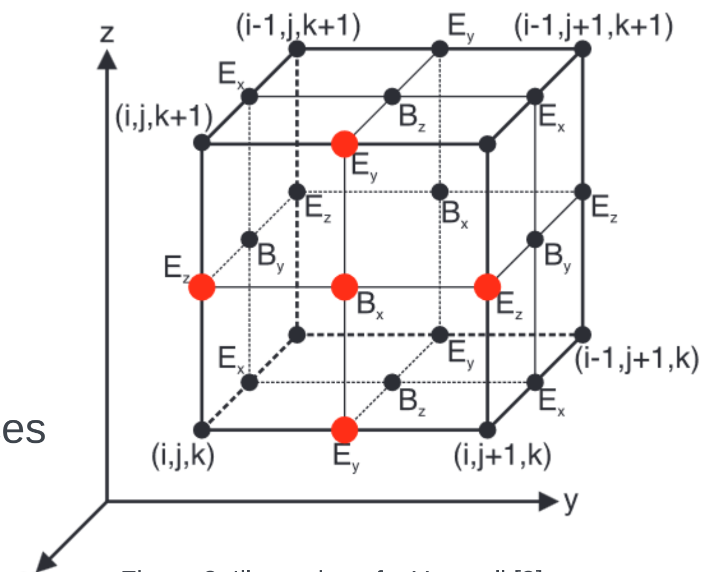

Figure 3: Illustration of a Yee cell [3]

$$B_x^{n+1/2}\left(i,j+\frac{1}{2},k+\frac{1}{2}\right) = B_x^{n-1/2}\left(i,j+\frac{1}{2},k+\frac{1}{2}\right)$$
$$+\frac{\Delta t}{\delta}\left[E_y^n\left(i,j+\frac{1}{2},k+1\right) - E_y^n\left(i,j+\frac{1}{2},k\right)\right.$$
$$\left. - E_z^n\left(i,j+1,k+\frac{1}{2}\right) + E_z^n\left(i,j,k+\frac{1}{2}\right)\right]$$

[3] A. Köhn, (2010). *Investigation of microwave heating scenarios in the magnetically confined low-temperature plasma of the stellarator TJ-K*. University of Stuttgart, Stuttgart, Germany.

The FDTD code

- 2D FDTD simulation code (written in C), based on the Yee algorithm
- Solves Faraday and Ampere's law
- Plasma effects are taken into account from current density equation:
  - $\frac{\partial}{\partial t}\boldsymbol{J} = \epsilon_0 \omega_{pe}^2 \boldsymbol{E} - \omega_{ce} \boldsymbol{J} \times \widehat{\boldsymbol{B_0}}$

    $\widehat{\boldsymbol{B_0}} = 0$ (unmagnetized plasma)

    - $\omega_{pe} = \sqrt{e^2 n_e / (\epsilon_0 m_e)}$
    - $n_e \rightarrow$ can be of arbitrary shape
- Different plasma profiles can be explored
- Code similar to IPF-FDMC [4]

[4] A. Köhn *et al*, Plasma Phys. Control. Fusion **50**, 085018 (2008).

The FDTD computational details

- Stability criterion for 2D domain [5]:
  - $c\Delta t \leq \left(\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2}\right)^{-1/2}$
  - $\boxed{{}^{\Delta t}/_{\delta} = {}^{1}/_{2c}}$, where $\delta = \Delta x = \Delta y$
- Computational grid
  - $50\lambda_o \times 38\lambda_o$, ($\lambda_o = 1.441$ mm for $f = 208$ GHz)
- OpenMP parallelised, in order to simulate large domain to keep experimental relevance

No parallelis.	2 threads	4 threads	8 threads	16 threads
~ 20 minutes	~ 10 minutes	~ 6.5 minutes	~ 4.5 minutes	~ 4 minutes

[5] A. Taflove and M.E. Brodwin, IEEE Tans. Microwave Theory Tech. **MTT-23**, 623 (1975).

Experimental set-up

- Atmospheric plasma, confined in glass quartz tube
- Novel interferometry design
- Move receiving antenna of interferometer
- Measure intensity of the wave electric field
- Obtain full plasma profile

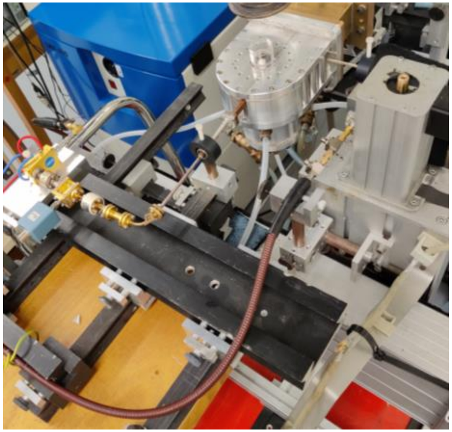

Figure 4: Interferometer's antennas mounted on the plasma torch

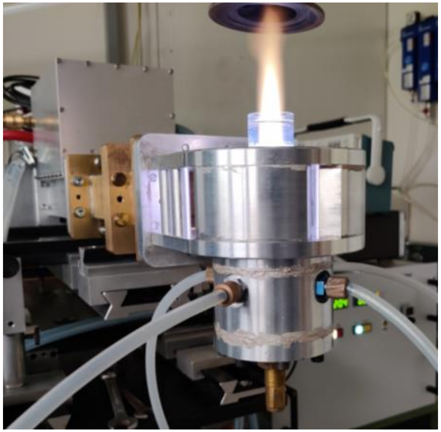

Figure 5: Ignited plasma

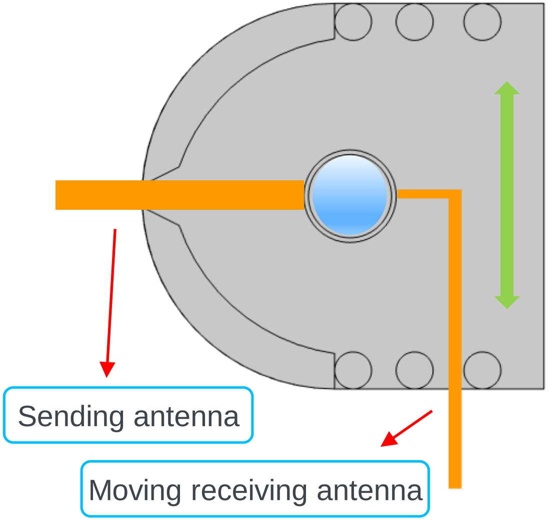

Figure 6: Atmospheric plasma torch set-up

Wave excitation

- Wave excited inside two waveguides
- Waveguides act as sending antenna
- Simulate waveguides as Perfect Electric Conductors (PECs)
- For every Bz component inside PEC, four surrounding E-field components are set to zero (TE mode) [6]

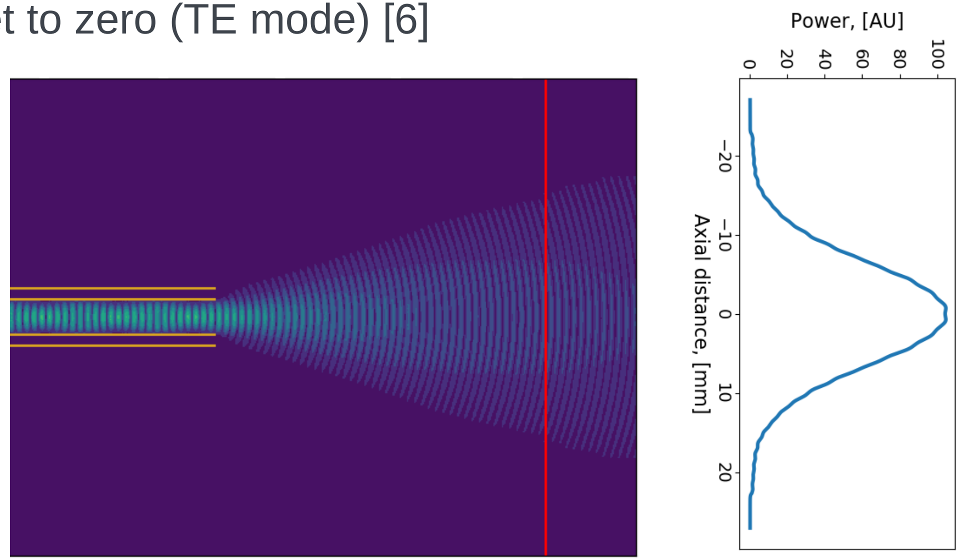

Figure 7: Unperturbed microwave beam with $w_0 = 1.208 \times \lambda_o$, and wave electric field intensity

[6] J.B. Schneider, *Understanding the Finite-Difference Time-Domain Method*, www.eecs.wsu.edu/~schneidj/ufdtd (2010).

Gaussian plasma

- Include plasma through current density equation
- Density profile: 2D Gaussian distribution
- Leads to strong beam scattering

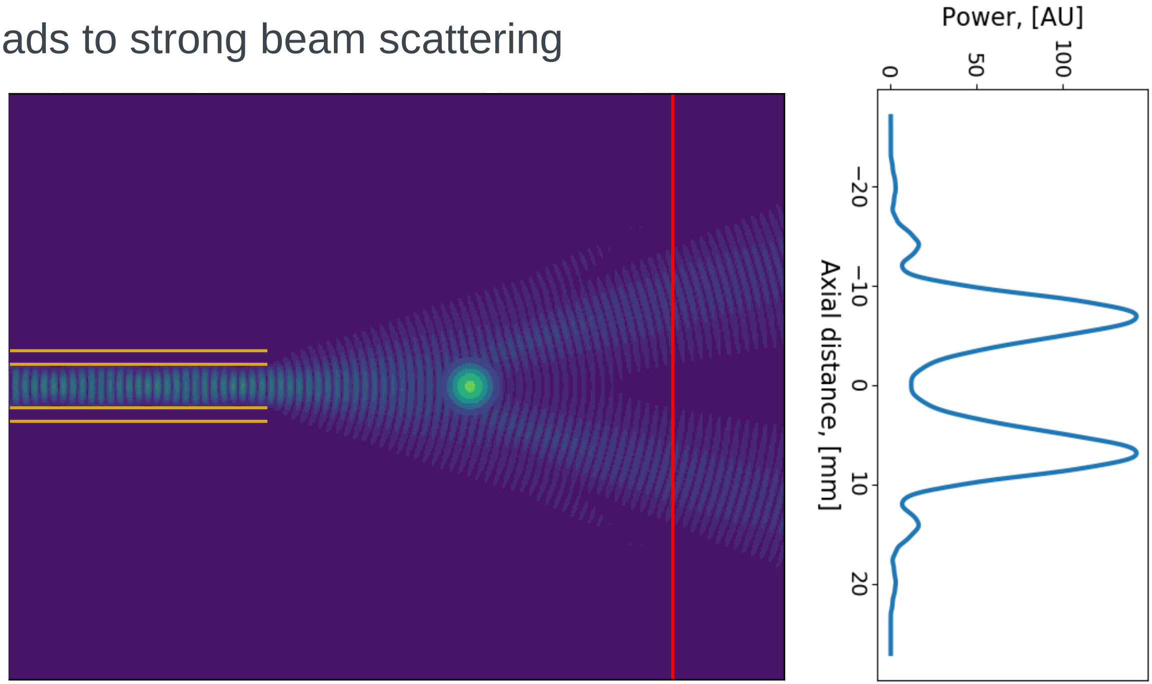

Figure 8:Microwave beam propagating into gaussian plasma ($n_e/n_c = 0.37$), and wave electric field intensity

Glass quartz tube

- Plasma confined inside glass quartz tube
- Change relative permittivity where the quartz tube is located
- Quartz tube induces beam reflections

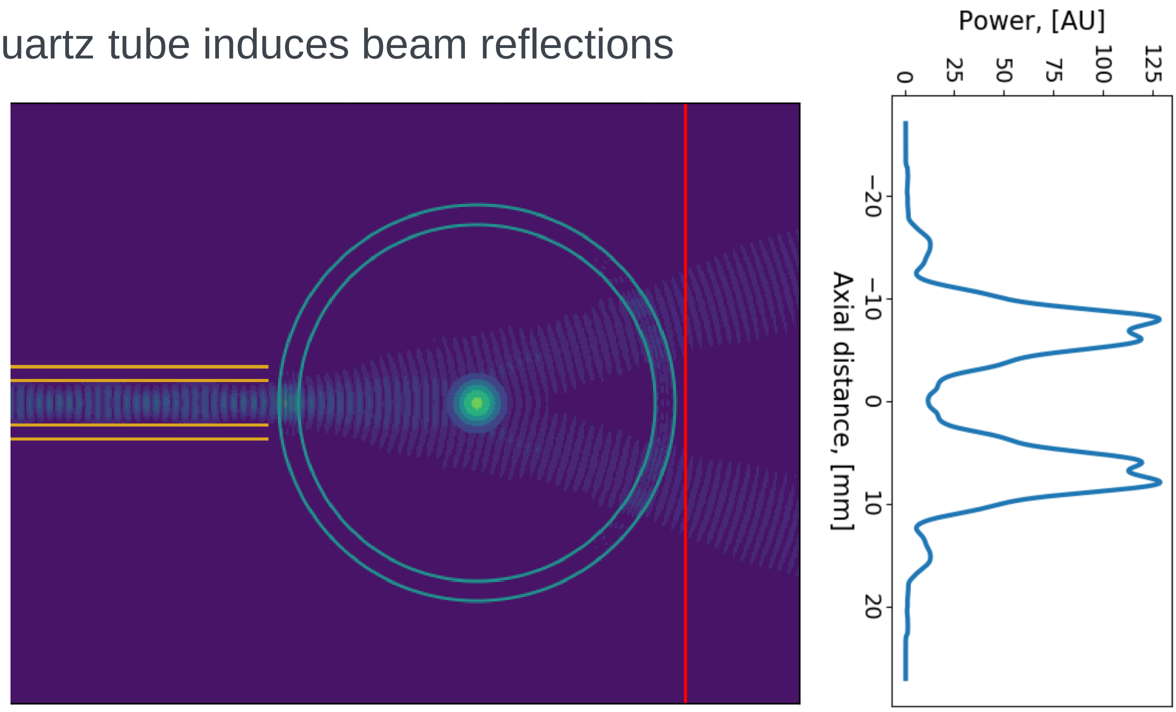

Figure 9:Microwave beam propagating into gaussian plasma ($n_e/n_c = 0.37$) and glass quartz tube, and wave electric field intensity.

Beam propagation comparison

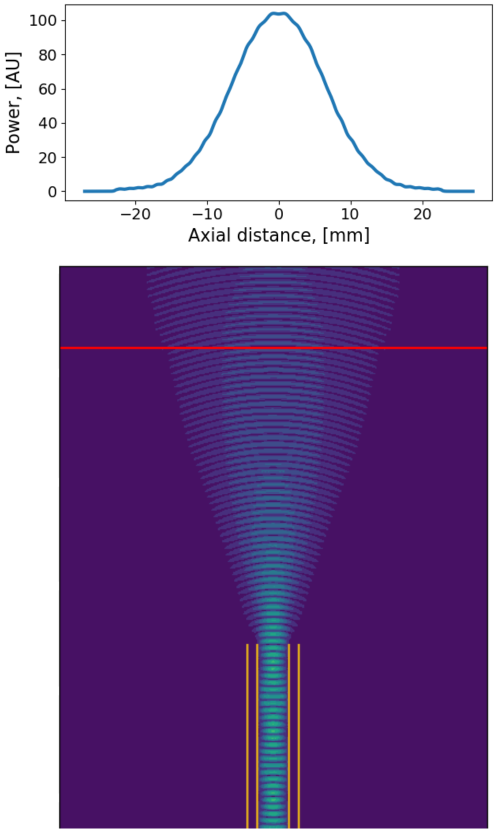

Figure 10: Unperturbed microwave beam

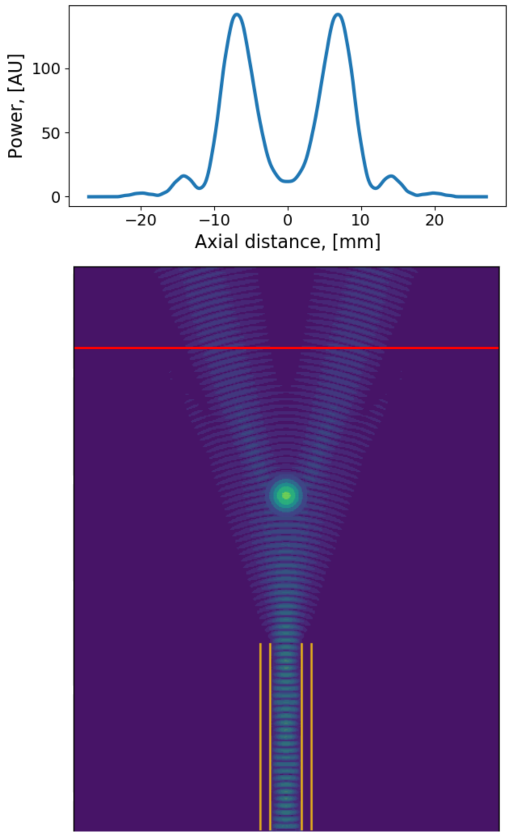

Figure 11: Microwave beam propagating into plasma

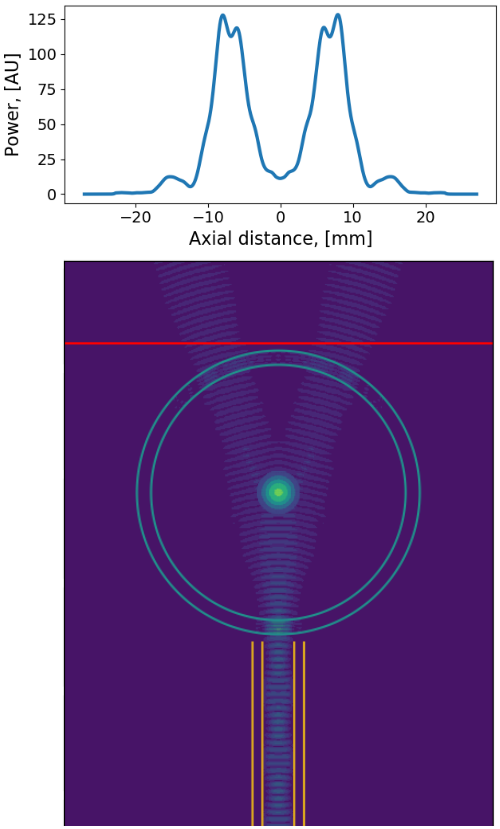

Figure 12: Microwave beam propagating into quartz tube and plasma

Comparison against COMSOL

- Code benchmarked with COMSOL Multiphysics software (results without waveguides)
- $n_{e,max} = 2 \times 10^{20} m^{-3}$ ($n_e/n_c = 0.37$)
- Good agreement without quartz tube
- Similar behaviour with quartz tube
- Aluminium plates not included

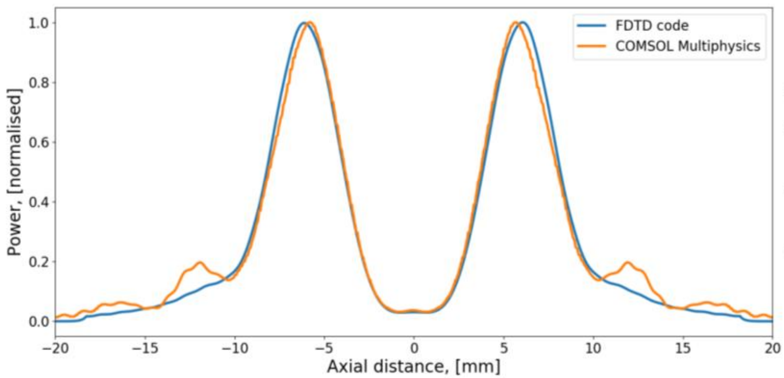

Figure 13: Microwave beam propagating into plasma

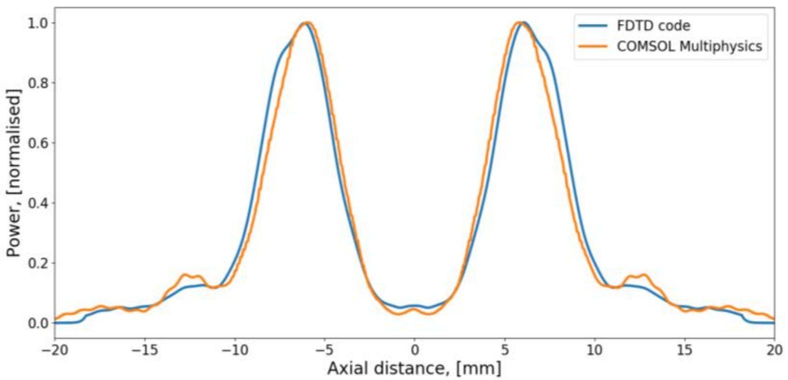

Figure 14: Microwave beam propagating into quartz tube and plasma

Comparison against experimental results

- More noisy result from experiment
- Aluminium pillars and plates induce further strong beam reflections
- Similar beam scattering

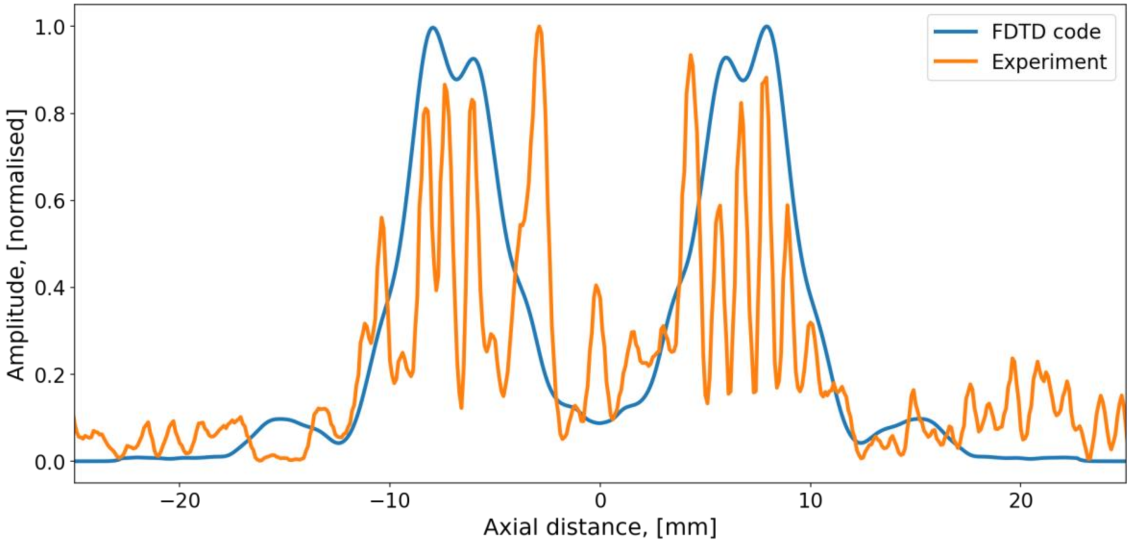

Figure 15: Comparison of the FDTD code against the experimental result

Summary and future work

SUMMARY

- 2D FDTD code applied to simulate microwave beam propagation to glass quartz tube and plasma
- High plasma density leads to strong beam scattering
- Glass quartz tube induces beam reflections
- Comparison against COMSOL demonstrates correct behaviour
- Cannot successfully predict experimental result

FUTURE WORK

- Include aluminium pillars and plates to match experimental results
- Explore more plasma profiles
- Extend code to 3D

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Thank you!

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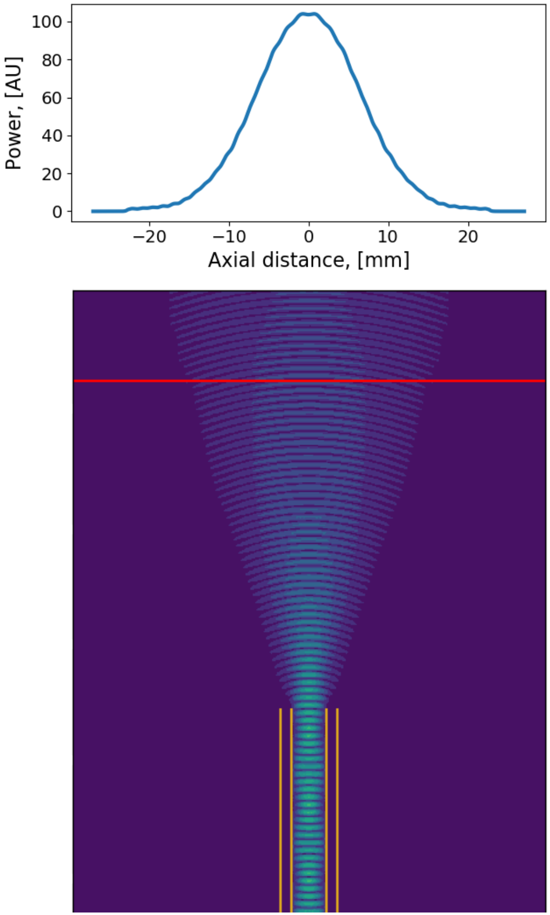
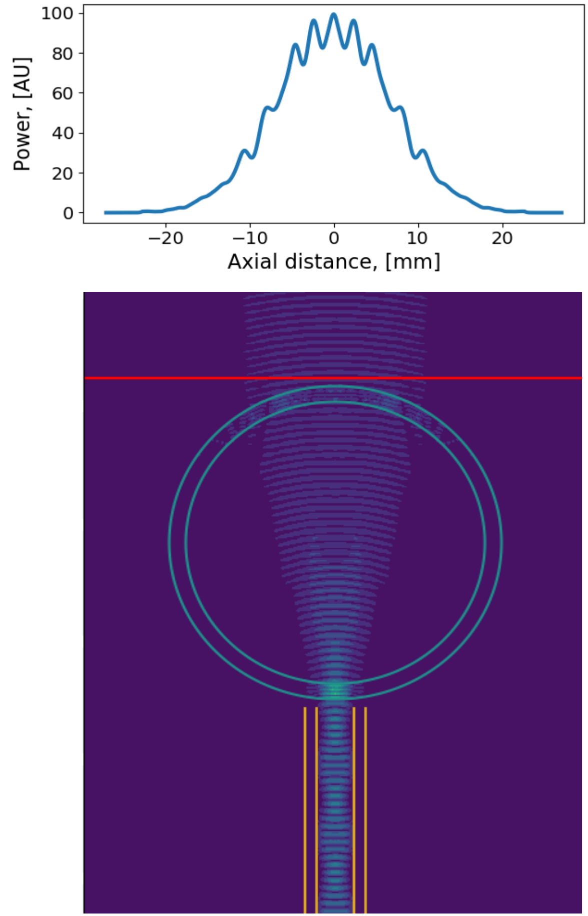
Appendix – The quartz tube effect



<u>Figure 16</u>: Unperturbed microwave beam



<u>Figure 17</u>: Microwave beam propagating into glass quartz tube