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3D microwave simulation in fusion plasmas

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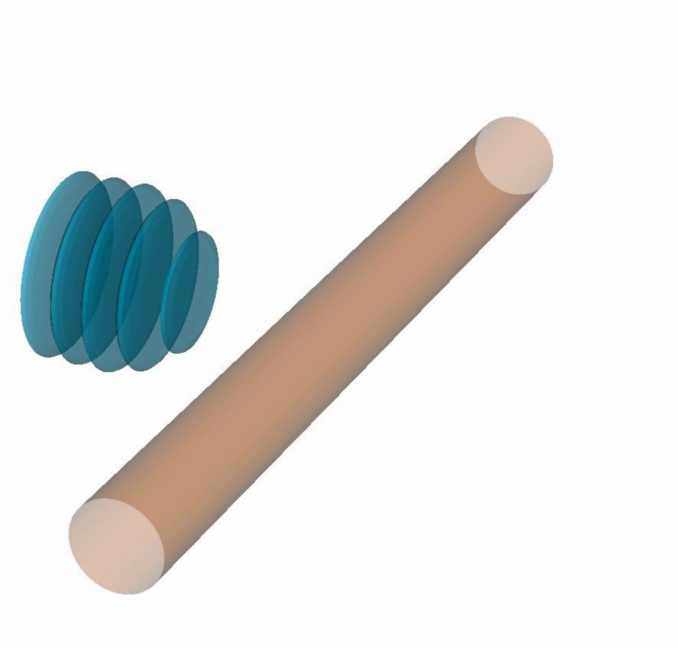
Outline

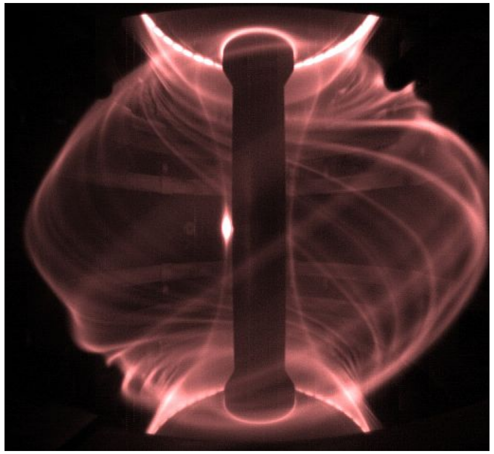
1. Experimental motivation
2. The EMIT-3D code
3. Filament scattering: methodology
4. Filament scattering: results
5. Conclusions & current work

Motivation: Filaments

- Filamentary density perturbations observed on MAST during all modes of operation

- **Interactions with microwaves must be understood for EC emission diagnostics e.g. Synthetic Aperture Microwave Imaging (SAMI), heating and current drive (for EBW, the effect on mode conversion)**

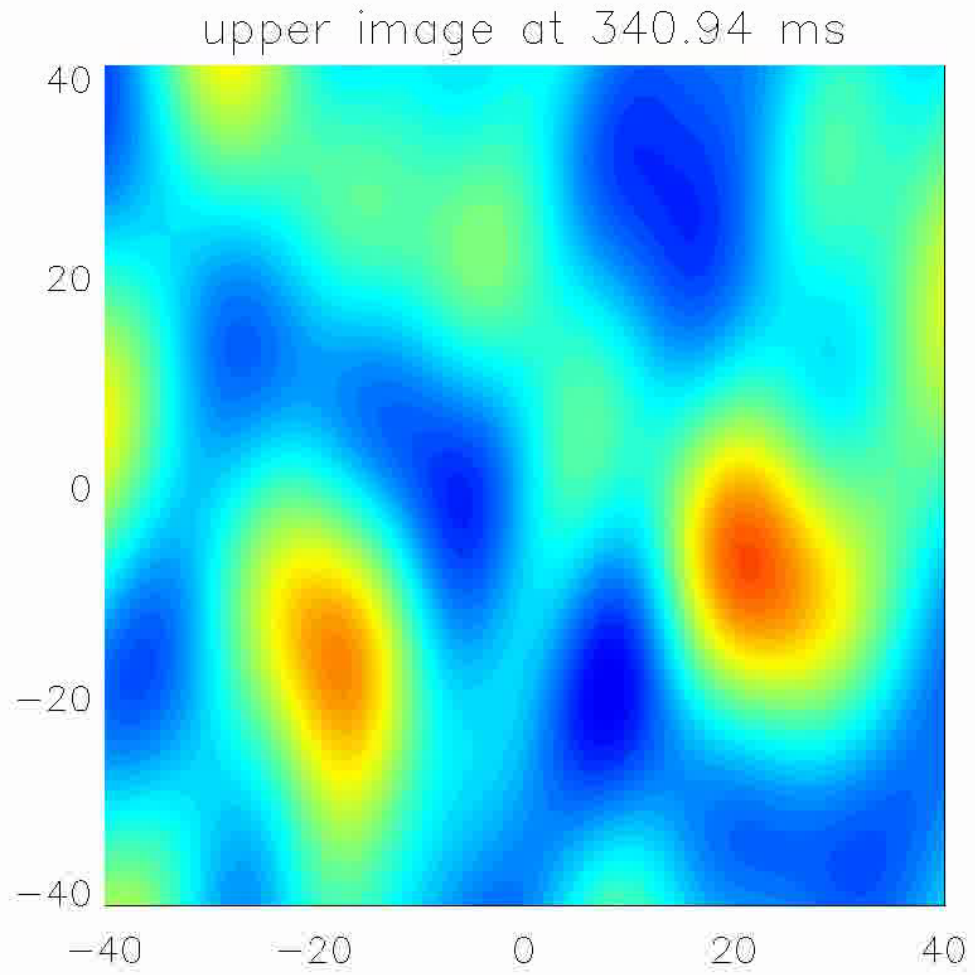




- Full-wave modelling necessary to explore interactions in detail since filament width ~ wavelength

- Explain fluctuations in experimental data: potential 3D effects

SAMI fluctuations



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The EMIT-3D code

- New 3D code developed in support of experimental project (SAMI)

- Cold plasma model: solve Maxwell's equations + linearised cold fluid equation of electron motion to include effect of plasma on wave

$$\frac{\partial \mathbf{E}}{\partial t} = c^2 \nabla \times \mathbf{B} - \frac{1}{\varepsilon_0}\mathbf{J}$$

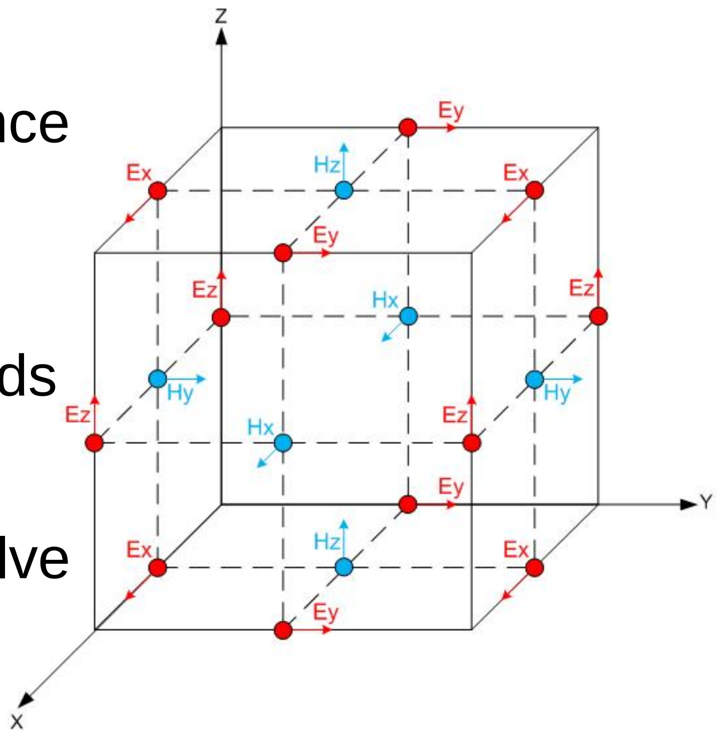
$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

$$\frac{\partial \mathbf{J}}{\partial t} = \varepsilon_0 \omega_{pe}^2 \mathbf{E} - \omega_{ce}\mathbf{J} \times \hat{\mathbf{b}}_0 - \nu \mathbf{J}$$

- Static background n_e & $\boldsymbol{B_0}$ assumed over propagation timescale

Finite-Difference Time-Domain (FDTD) method is employed in 3D

- Discretise field components to staggered grid
- Substitute in 2^{nd} order centred difference formulae in both space and time
- Leapfrog update equations for ***E*** and ***B***-fields
- Conductivity not scalar: in addition, solve fluid equation for ***J*** in phase with ***B***



Solving for current density

- Fluid equation for ***J*** solvable as a matrix equation:

$$\mathbf{J}\big|^{n+\frac{1}{2}} = e^{A\Delta t}\mathbf{J}\big|^{n-\frac{1}{2}} + \varepsilon_0\omega_{pe}^2 A^{-1}\left(e^{A\Delta t} - I\right)\mathbf{E}\big|^{n}$$

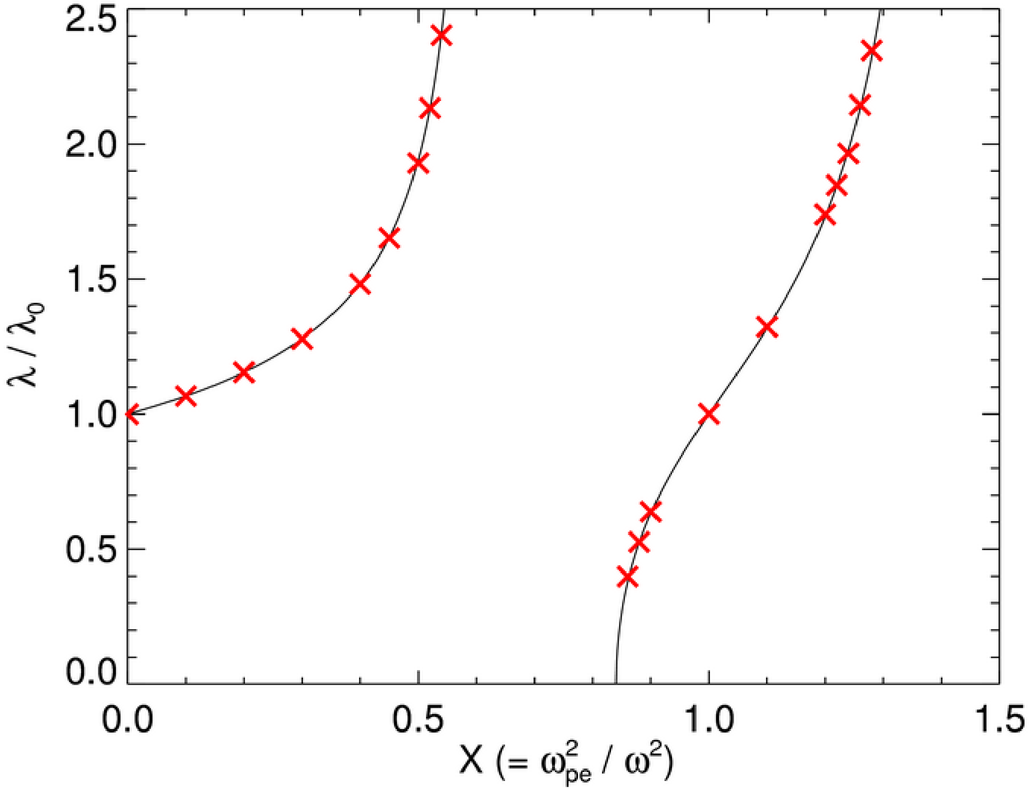
$$A = \begin{pmatrix} -\nu & -b_z\omega_{ce} & b_y\omega_{ce} \\ b_z\omega_{ce} & -\nu & -b_x\omega_{ce} \\ -b_y\omega_{ce} & b_x\omega_{ce} & -\nu \end{pmatrix} \quad , \quad \hat{\mathbf{b}}_0 = (b_x, b_y, b_z)$$

- Static backgrounds so update coefficients calculated only once at start of run: arbitrary n_e & $\boldsymbol{B_0}$ profiles

- Code written in C++. Data-level parallelisation using MPI

Benchmarking: the X-mode dispersion relation is reproduced

- Results shown at Y = $|\omega_{ce}|/\omega = 0.4$



Black line – analytical, red crosses - numerical

- For 2D cases, excellent agreement with 2D code (IPF-FDMC)

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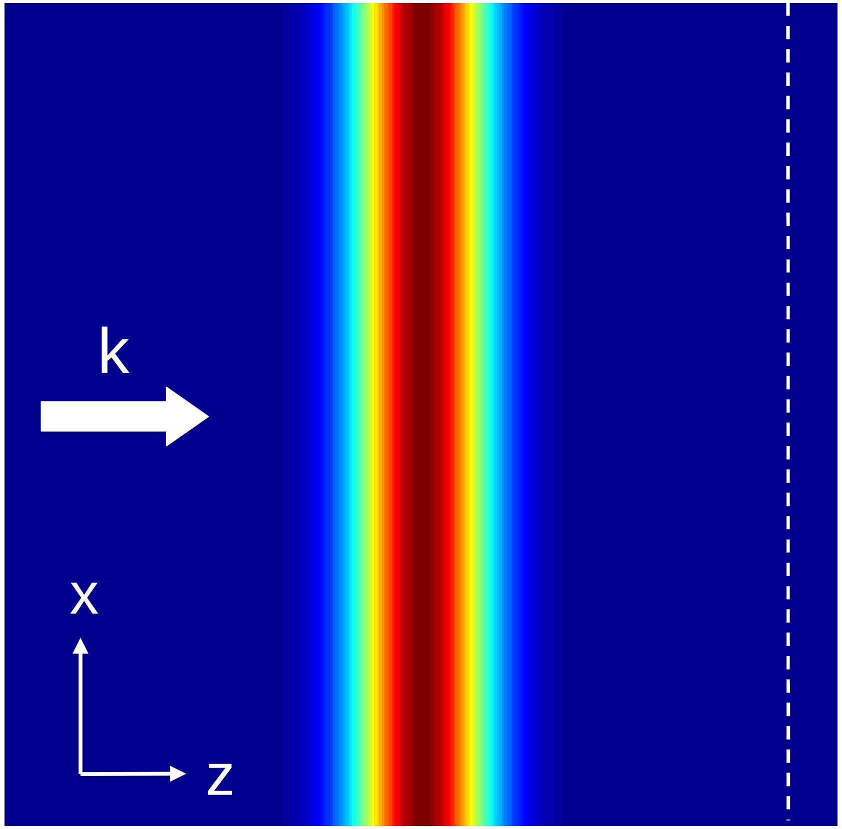
How do the filament scattering simulations look?

- Gaussian-profiled filament, peak $n_e < n_{crit}$, on vacuum background
- Scan physical parameters through experimentally relevant values

Plot of n_e :

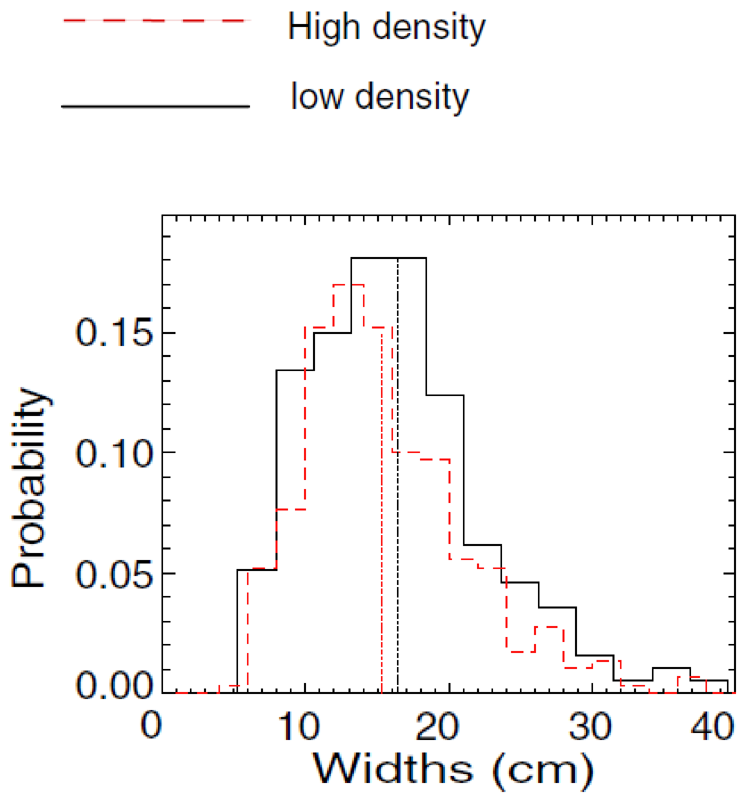
Incident beam



Backplane:

- Calculate RMS electric field here over several cycles.
- Record point of maximum emission.

Parameters chosen from experiment



N. Ben Ayed *et al.*
PPCF **51** (2009)

- SAMI: 10 – 35 GHz (first 2 EC harmonics) so λ = 0.85 – 3.00 cm
- MAST inter-ELM filament relevant scalings from Langmuir probe data
- Filament Gaussian widths 1.25 – 7 cm (~¼ of widths between minima)
- Filament peak densities range 5×10^{17} – 2×10^{18} m^{-3}
- Parameter $n_{e,peak} / n_{e,cutoff}$ = 0.03 – 1.61

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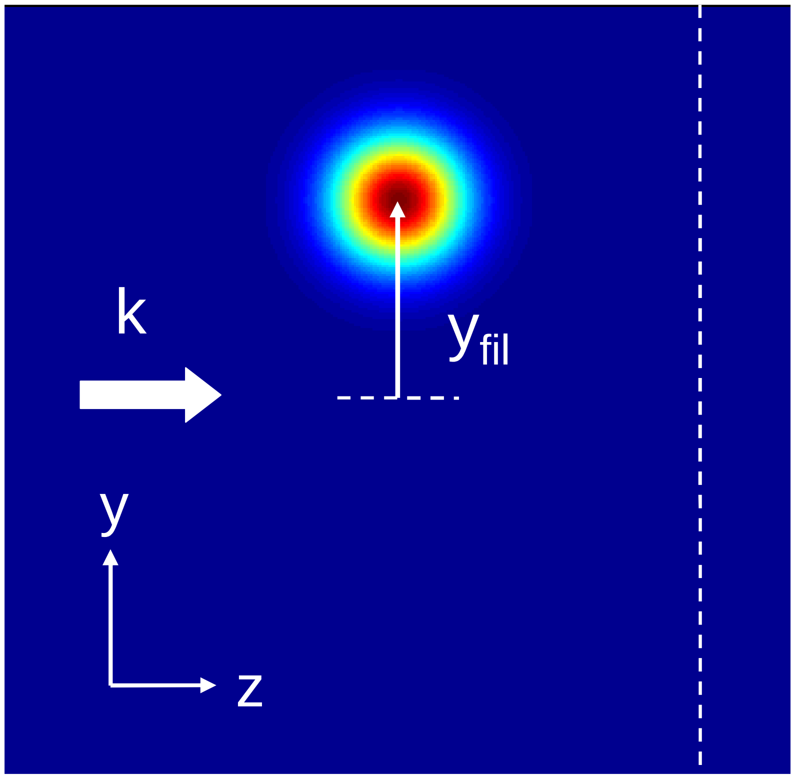
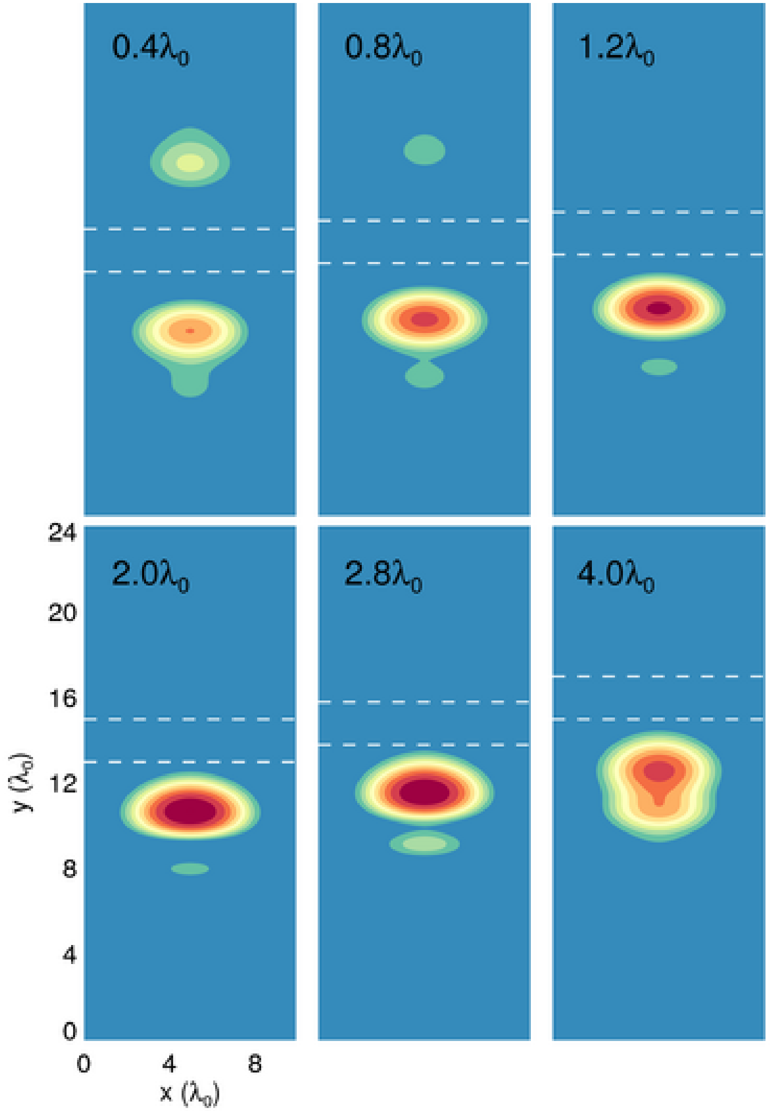
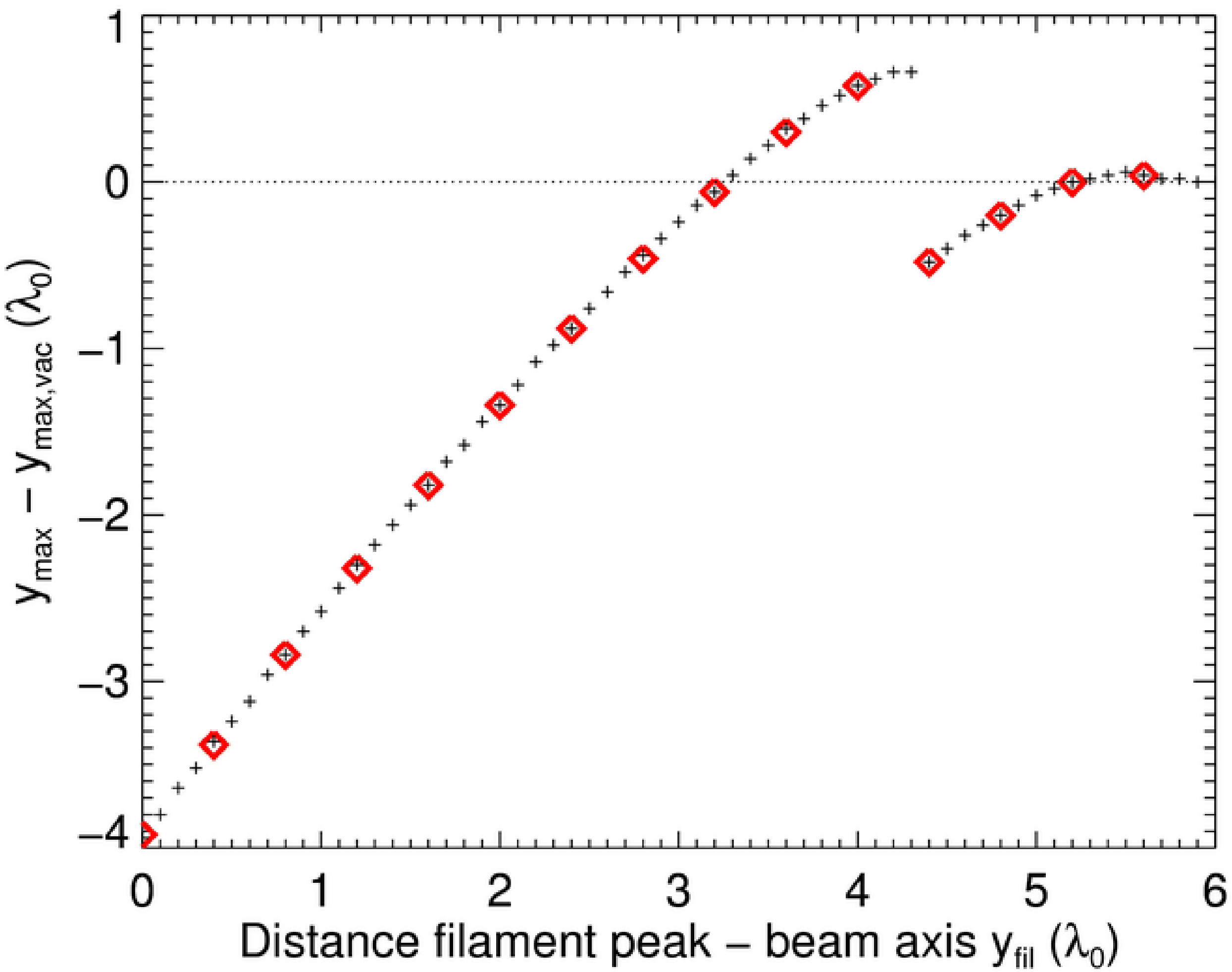
Position scan: shows effect of filament transiting beam





- Maximum scattering angle (y_{fil} = 0) of 26° : e.g. normal incidence on a filament of $n_{e,peak} = 2\times10^{18}\ m^{-3}$ for a 14 GHz beam

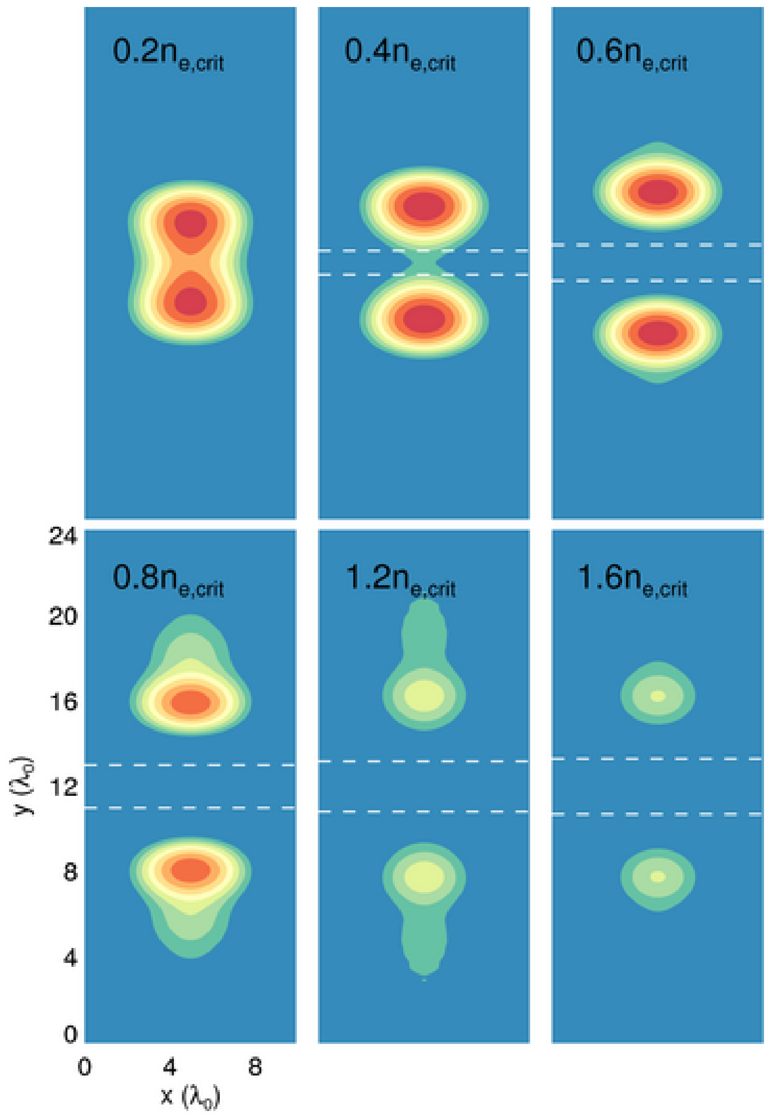
Position scan: Location of maximum



- More complex effect of filament transit on maximum than simple linear displacement

- Discontinuity at $y = 4.3\lambda_0$

Density scan: forward scattering angle saturates above cutoff



- Even at lower end of peak density range (e.g. 5×10^{17} m^{-3} for a 14 GHz beam), dual emission lobes still present
- As peak density increases above cutoff, maximum scattering angle of 32° is not exceeded
- Power reaching backplane is diminished due to backscattering
- Dense filaments / long wavelengths

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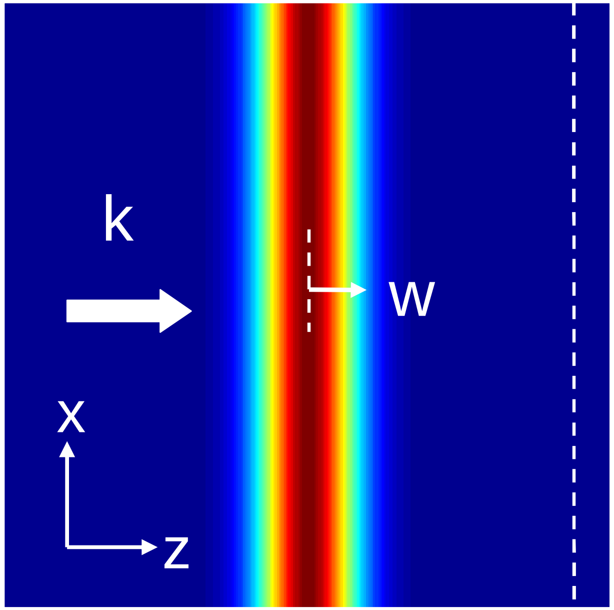
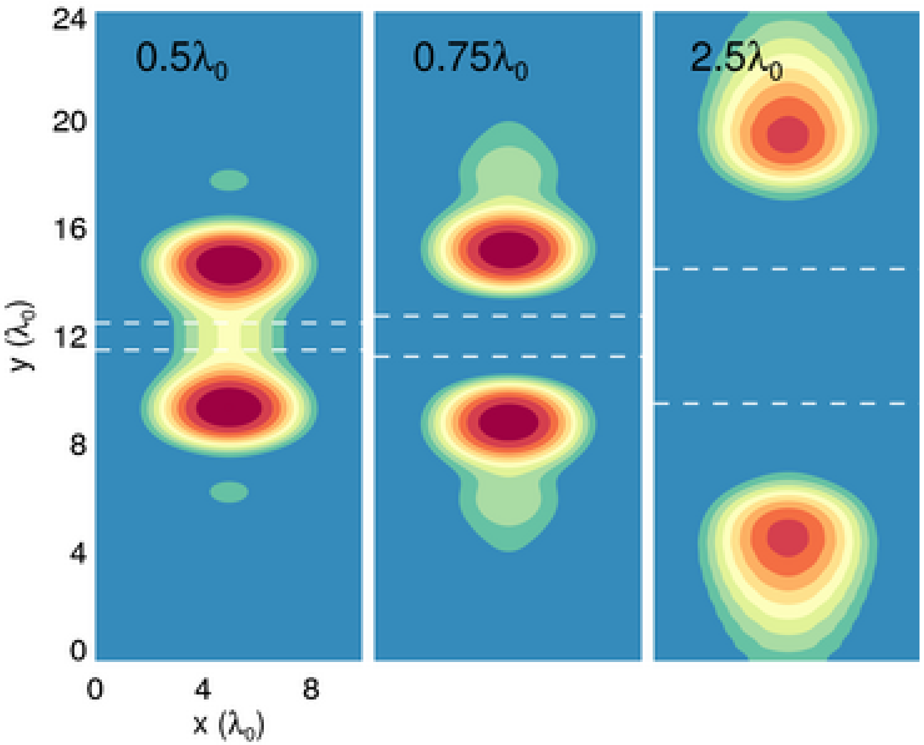
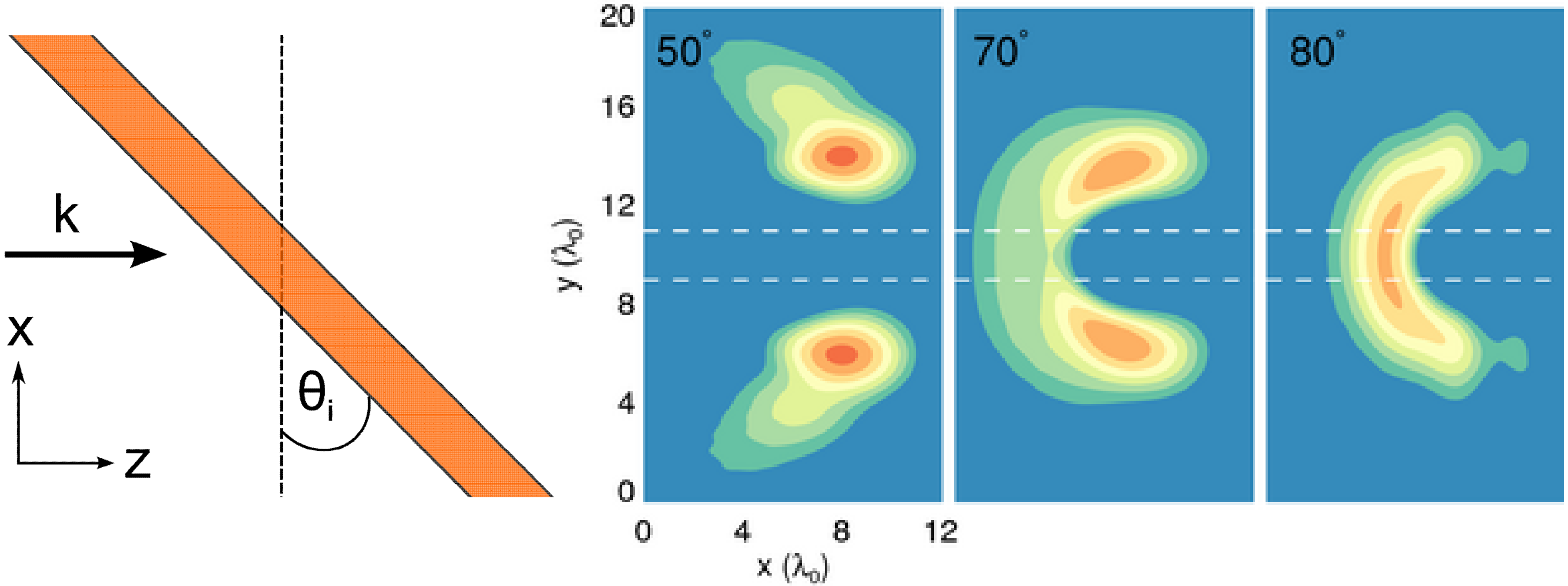
Width scan: large scattering angles observed for high w / λ_0





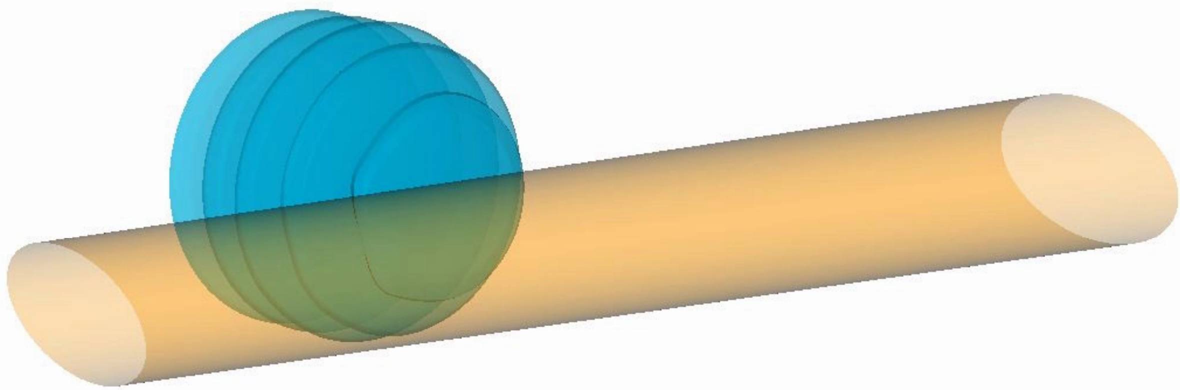
- Large scattering angles observed for greater width, up to 47°
- Wide filaments / short wavelengths

Angular scan: 3D effects observed



- In practice, oblique incidence is the norm; these effects are important
- 3D movie aids visualisation…

3D movie – incident angle 50°



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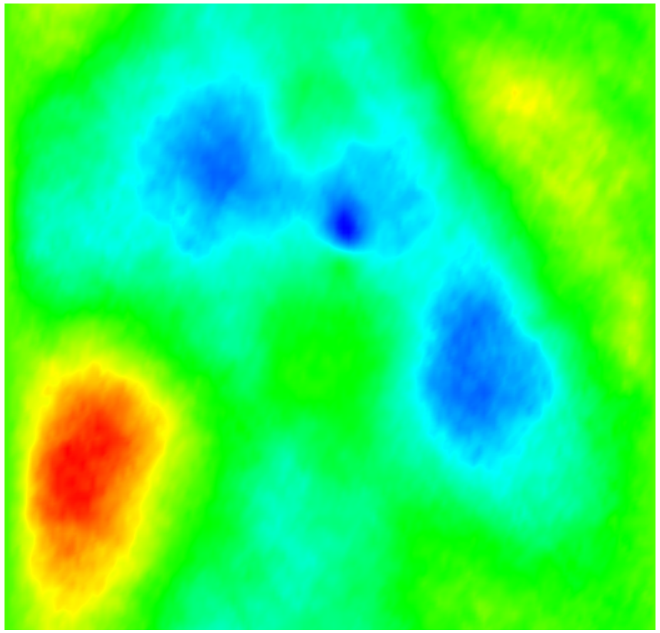
Filament study summary

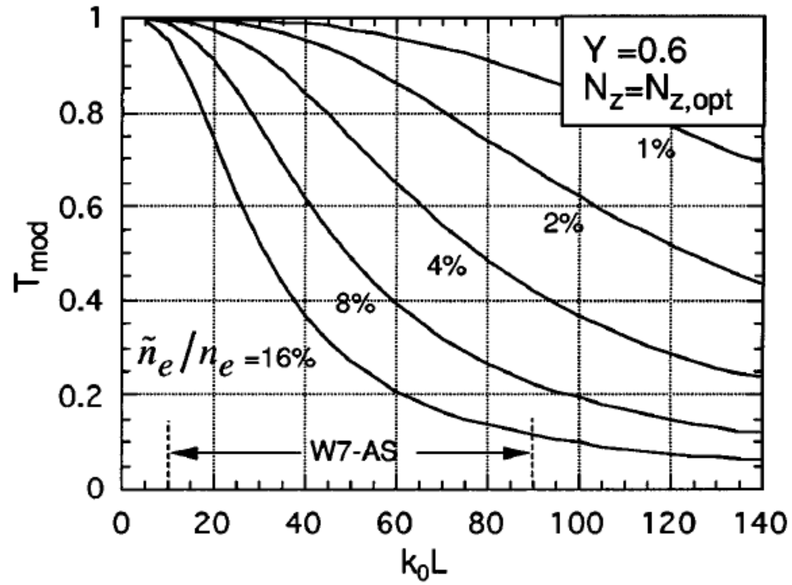
- A new 3D FDTD code (EMIT-3D) has been developed to simulate microwave propagation in a fusion plasma.
- Simulations have shown that inter-ELM filaments at the tokamak edge can have a greater effect on microwave propagation than previously assumed.
- These effects are noticeable across a wide frequency spectrum.
- 3D effects have been observed for obliquely incident beams.

Continuing work using EMIT-3D (1)

- Including turbulent profiles for ST edge plasma (generated from BOUT++ simulations). Average results over a set of perturbed profiles for statistical measure of beam decoherence

- Investigate effects on both propagation and mode conversion for comparison against analytic, numerical and experimental work

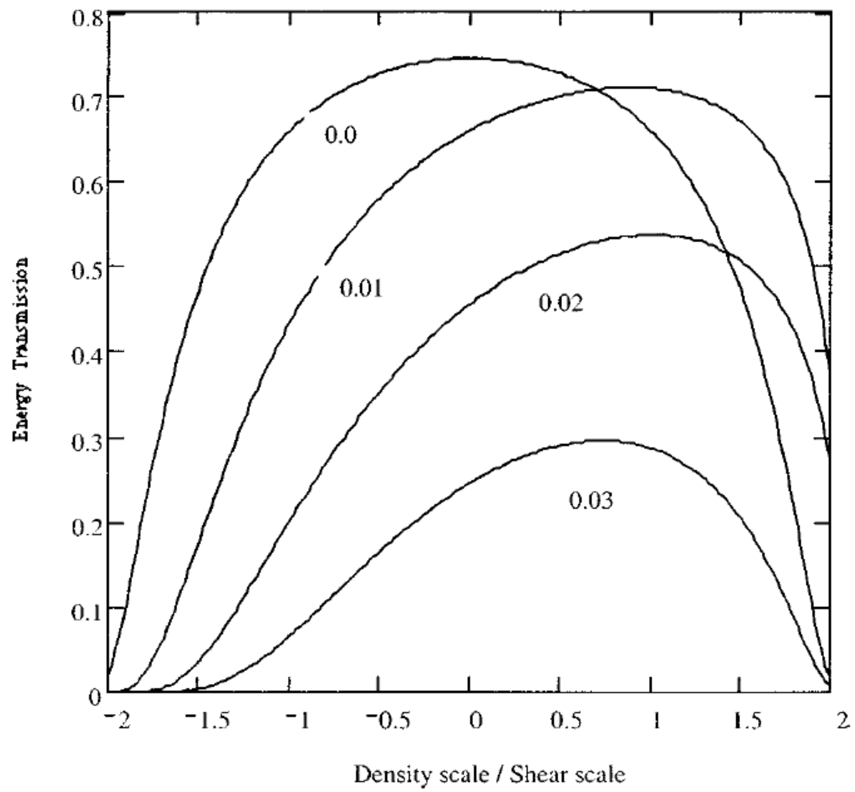




H. Laqua *et al.* PRL **78** 18 (1997)

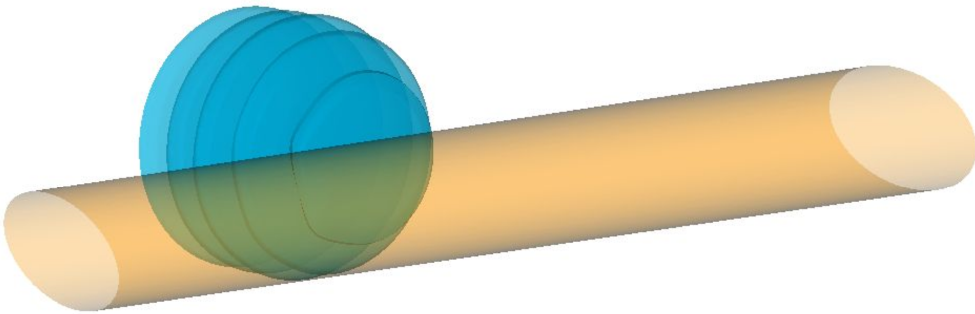
Continuing work using EMIT-3D (2)

- Further investigation of mode conversion problem
- Investigating the influence of other edge inhomogeneities such as magnetic shear on mode conversion efficiency – comparison with analytic work
- High shear at edge of ST plasma makes this relevant



R.A. Cairns & C.N. Lashmore-Davies Phys. Plasmas **7** 10 (2000)

Appendix: 3D movie stills



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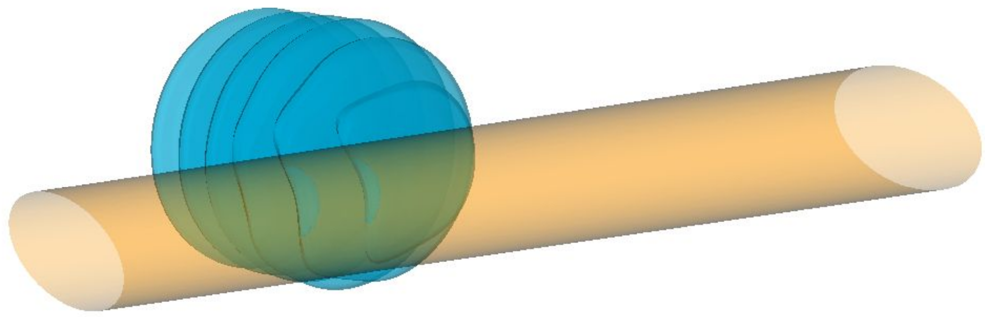

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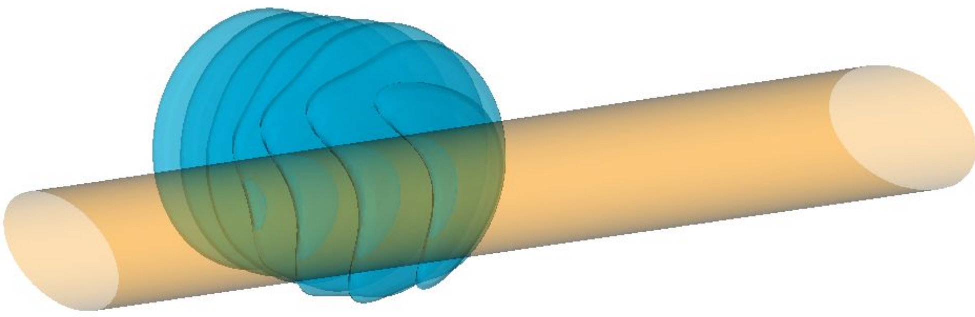

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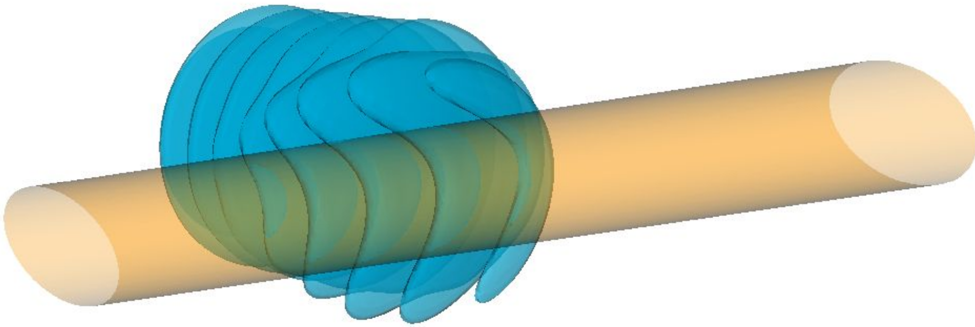

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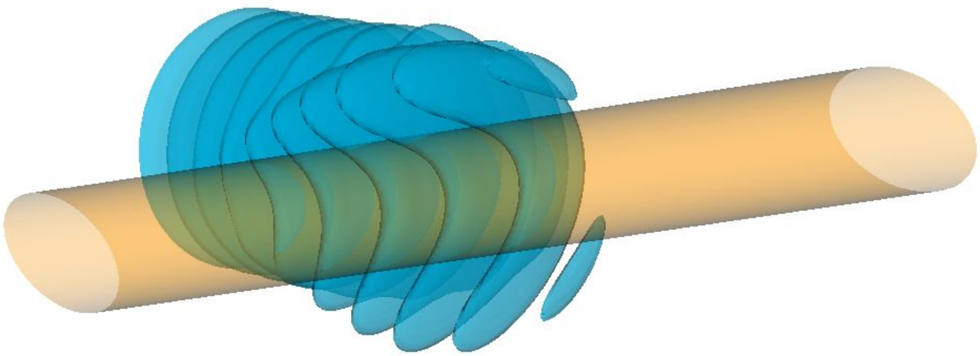

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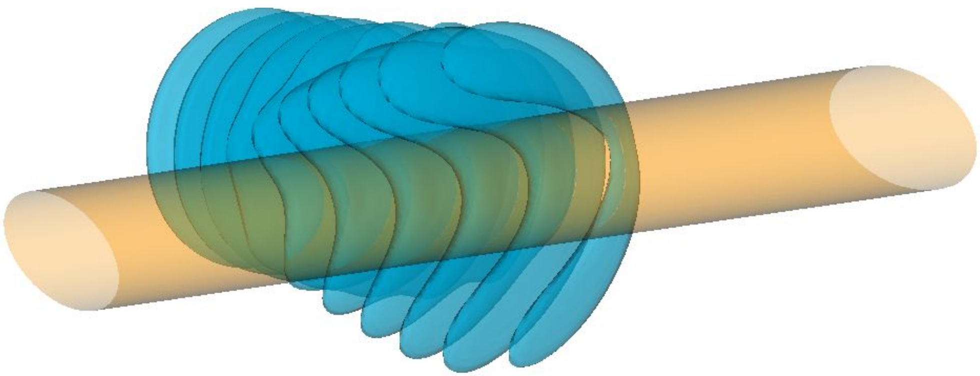

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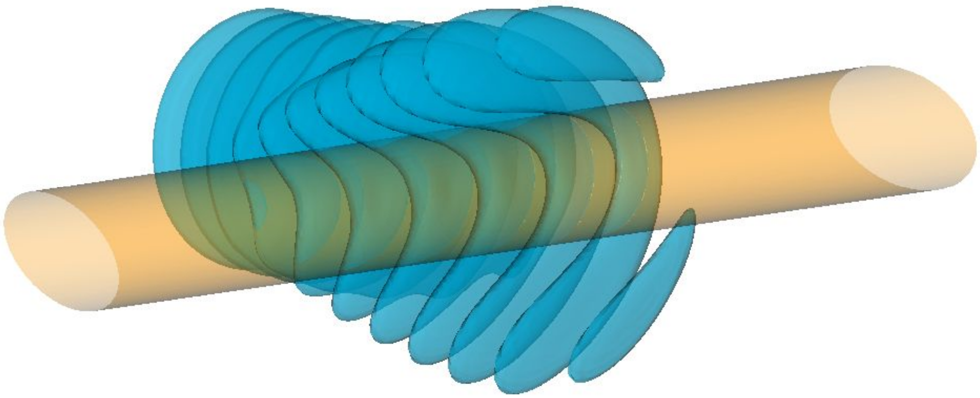

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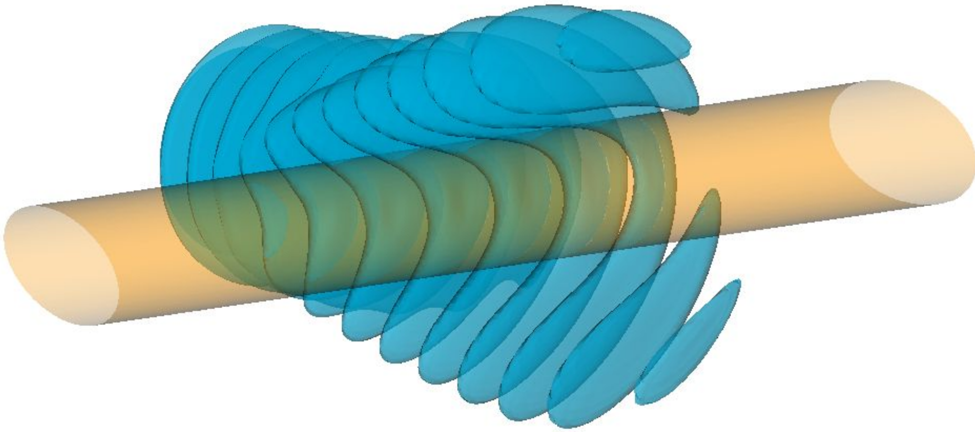

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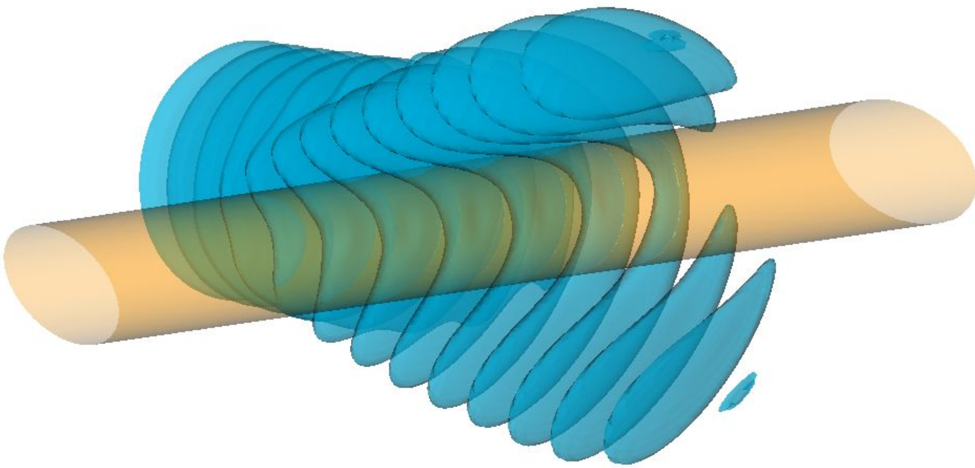

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