MAST

Prospects of EBW emission diagnostics and EBW Heating in Spherical Tokamaks

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Acknowledgements

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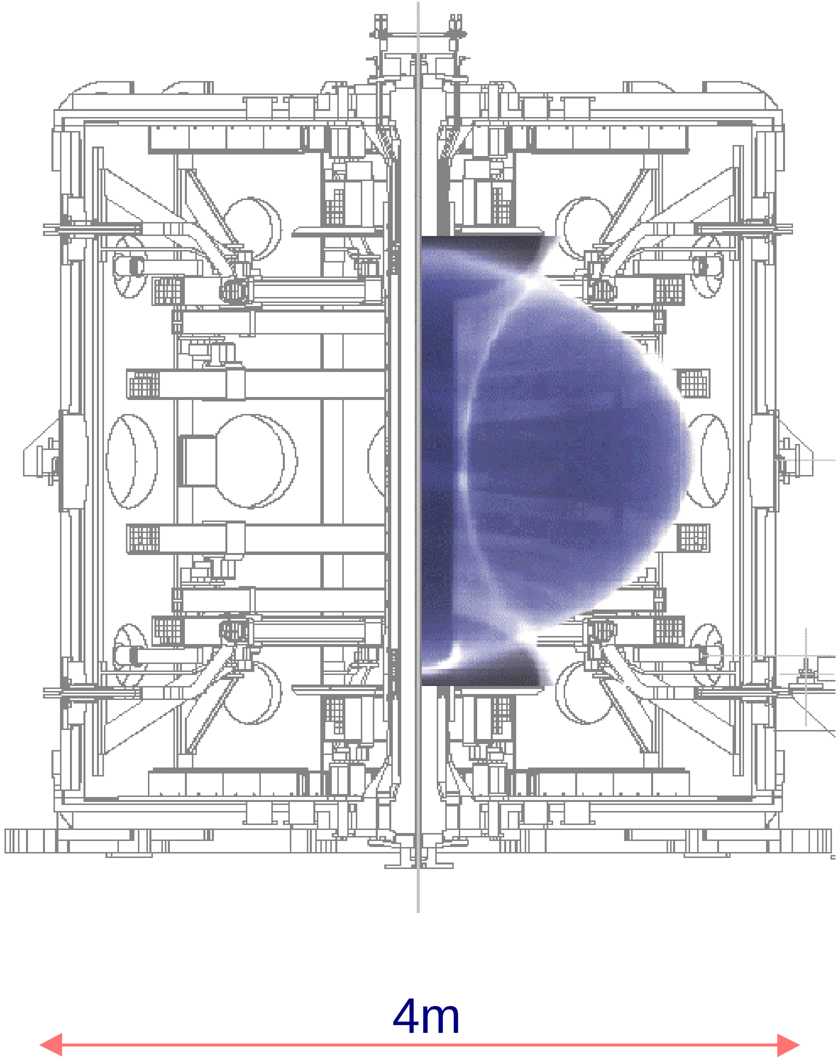
Outline

EBW Emission in ST

EBW Heating Experiments in MAST at 60 GHz

EBWH and EBW CD Modelling in ST

MAST Parameters



	Design	Achieved
Major radius	0.85 m	0.85 m
Minor radius	0.65 m	0.65 m
Plasma current	2 MA	1.3 MA
Toroidal field	0.52 T	0.52 T
NBI heating	5 MW	3.3 MW
RF heating	1.4 MW	0.9 MW
Pulse length	5 s	0.7 s

EBW Emission in Spherical Tokamaks

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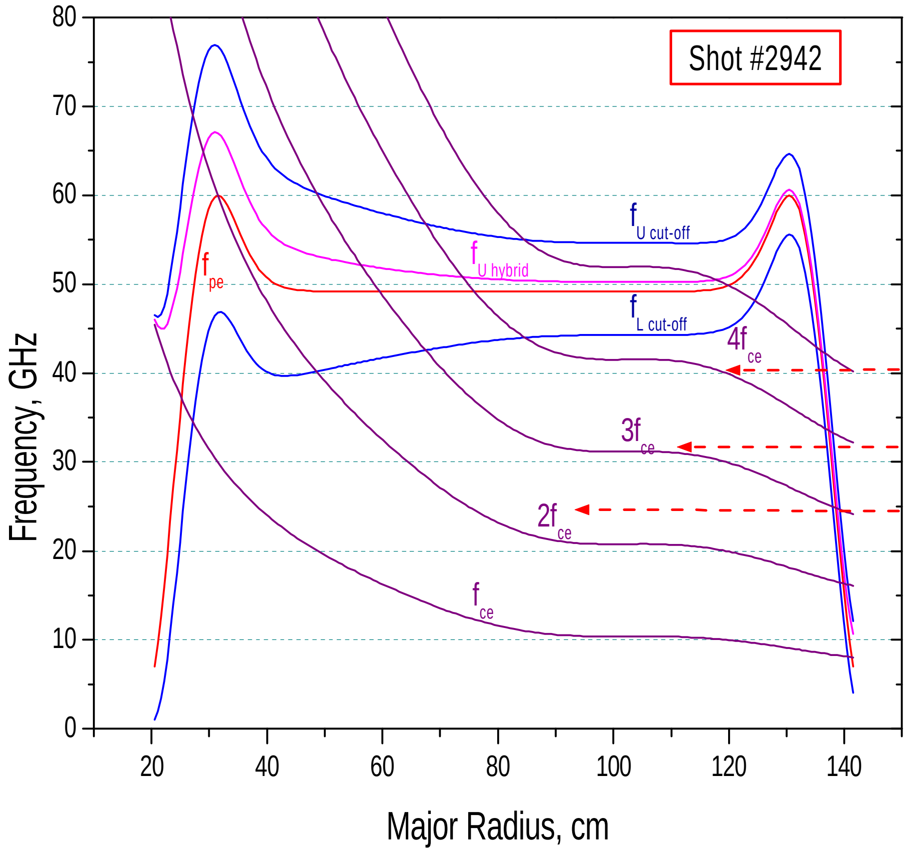
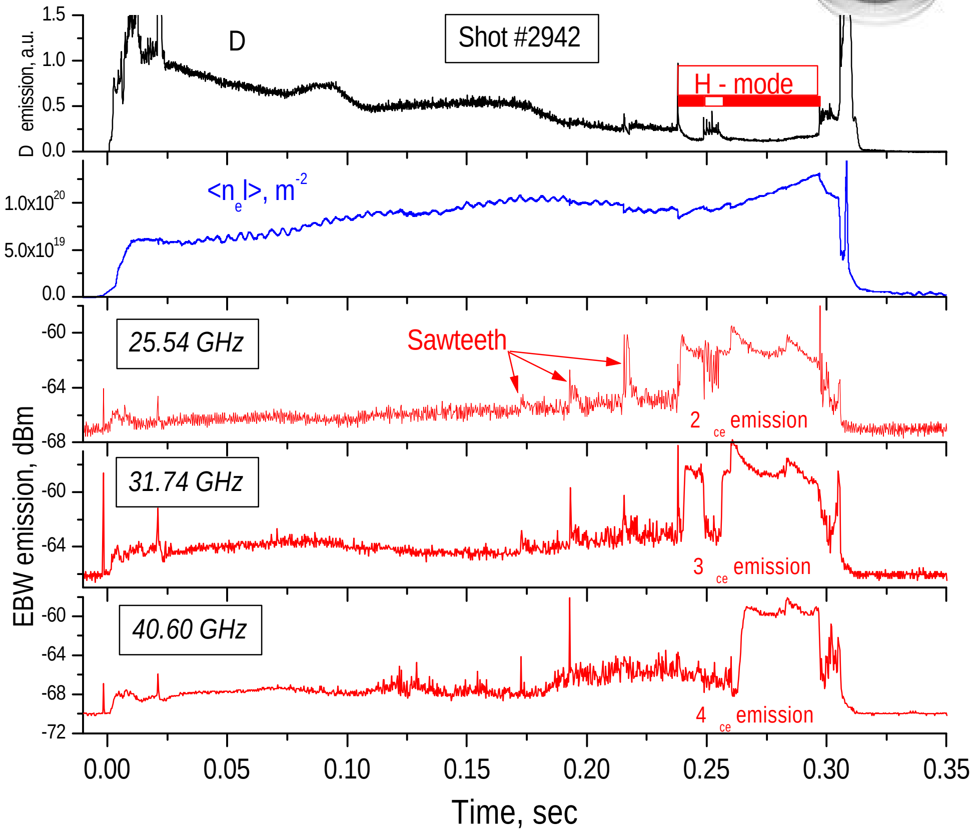
O-X-B EBW emission enhancement in H-mode



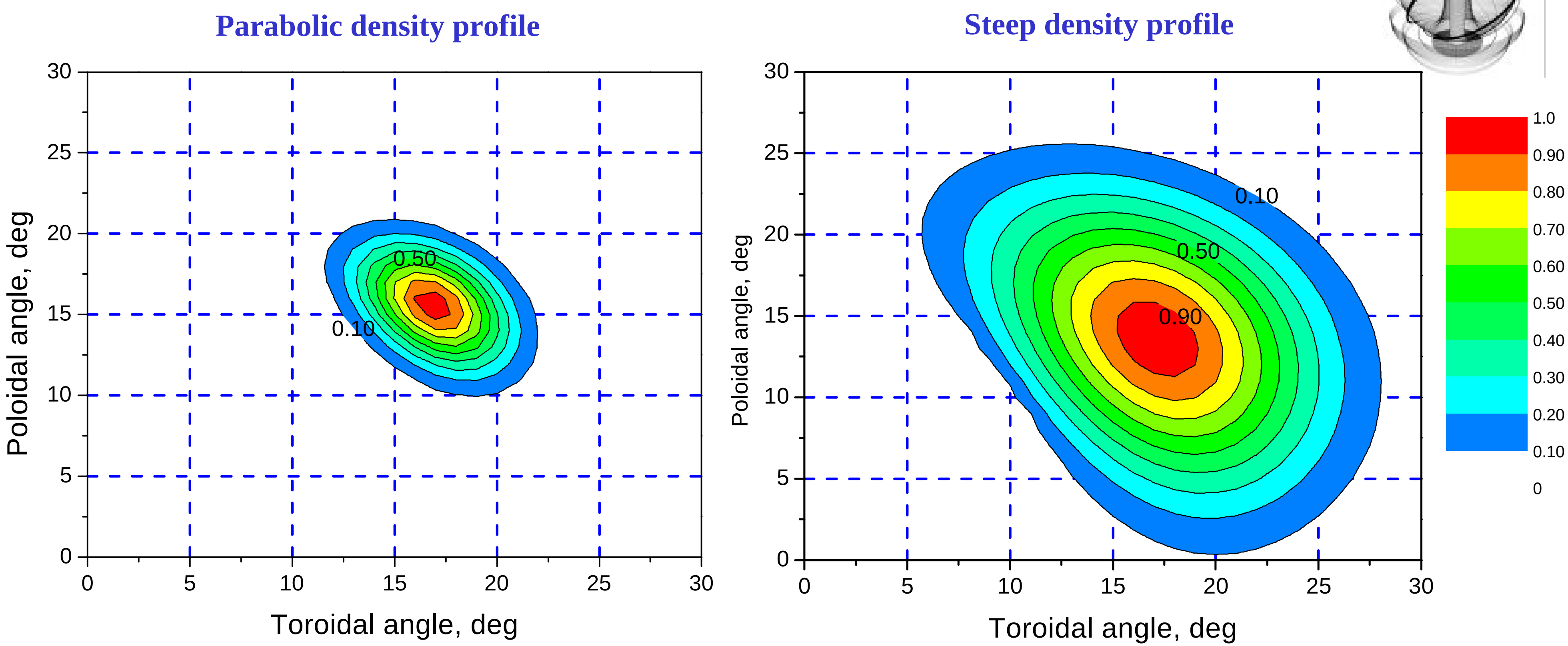
Midplane topology of cut-offs and resonances during H-mode in MAST



EBW signals from different EC harmonics during H-mode in MAST

*** X-B emission enhancement in H-mode, NSTX: G. Taylor et al, 14th Conf. RF Power in Plasmas, 2001**

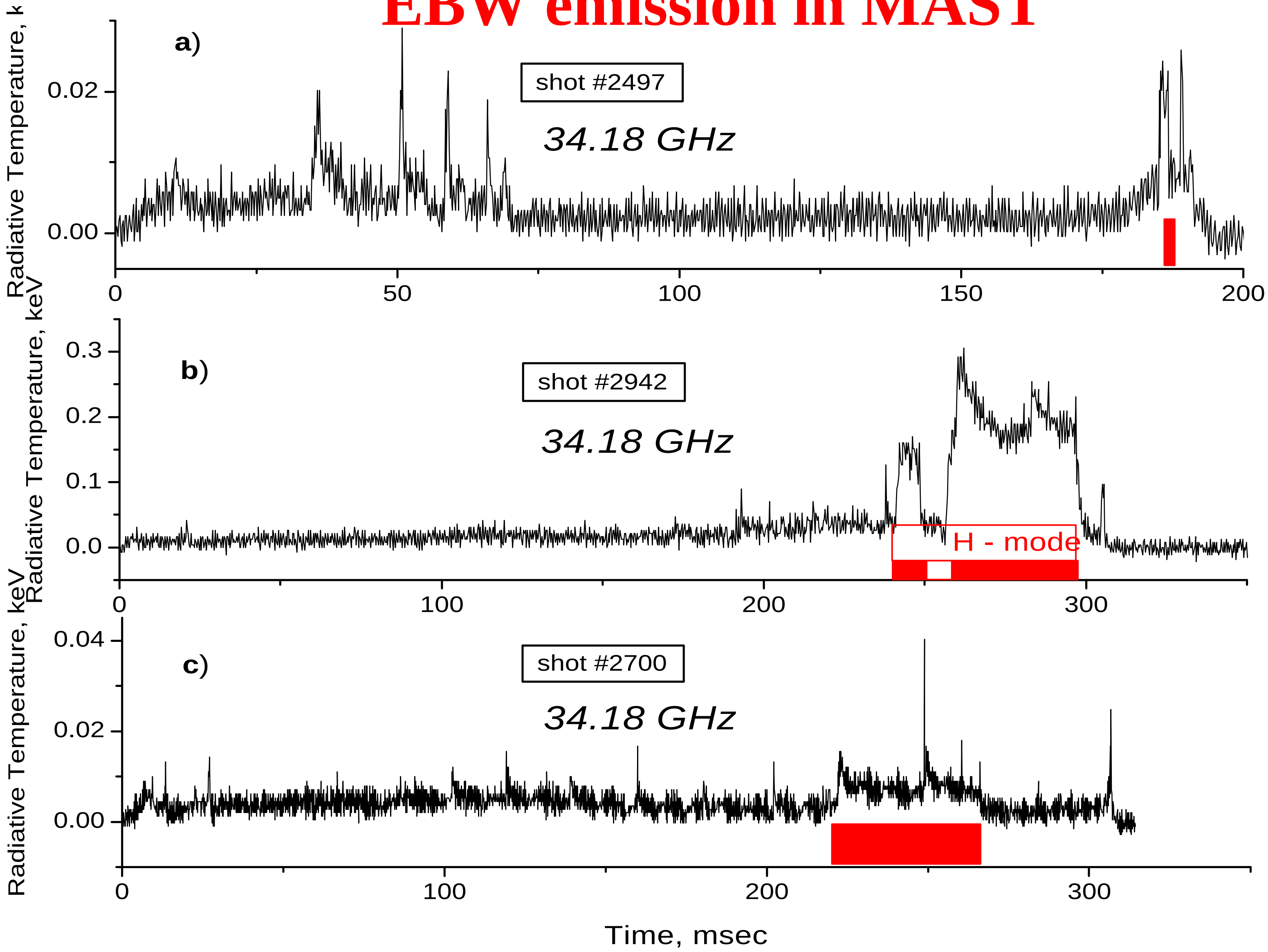
O-X-B mode conversion efficiency



Contour plots of the O-X-B mode conversion efficiency at 37 GHz represented in angular co-ordinates.

In H-mode the O-X-B mode conversion angular window becomes broader for all frequencies below the O-mode cut-off.

EBW emission in MAST



Perpendicular X-mode

Close to optimum for B-X-O

Optimum for B-X-O with opposite Ip

Radiometer signals during H-mode for different viewing angles.

EBW emission during high density H-mode

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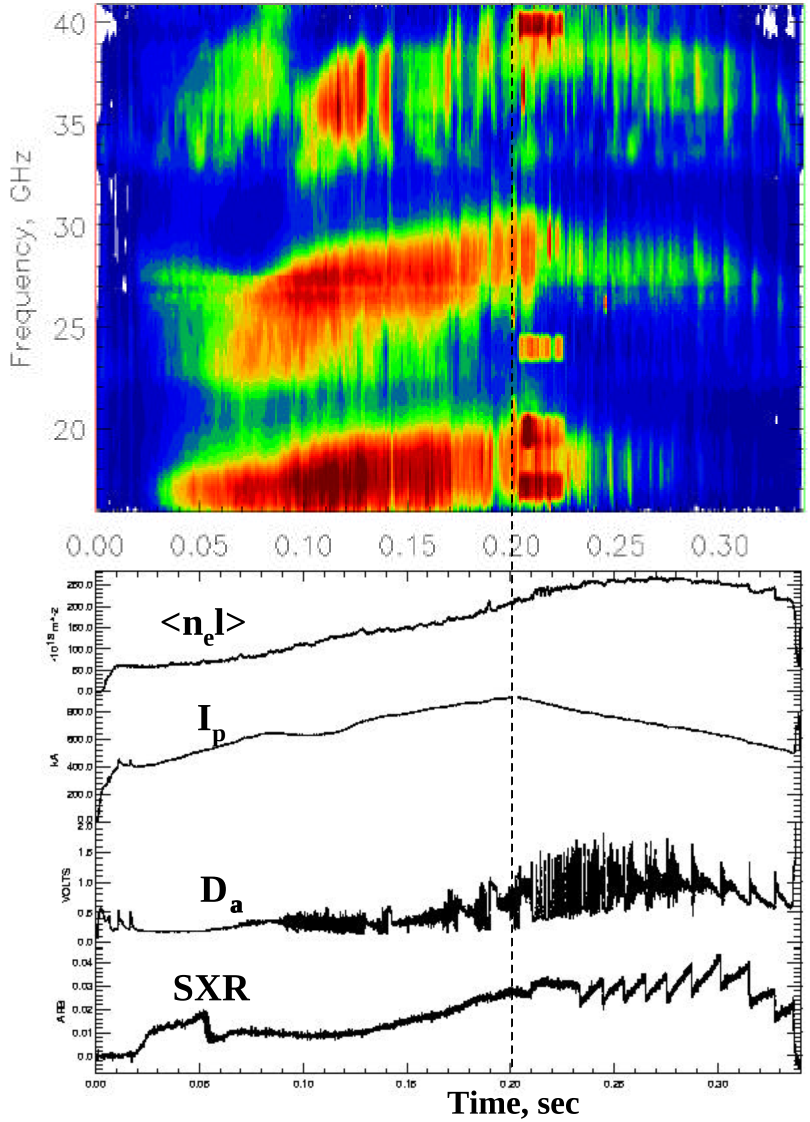
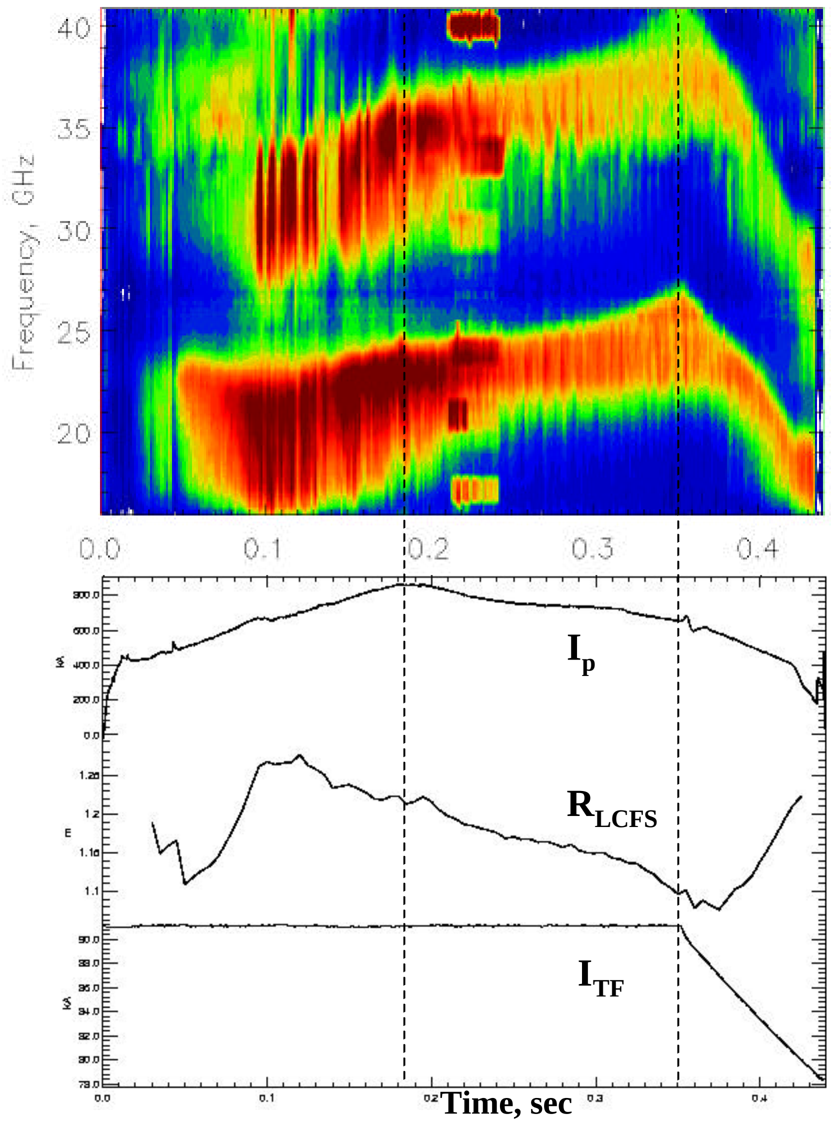


Shot #7680 EBW spectrum in low TF (I_{TF} =77 kA) with plasma current ramp down



Shot #7798 EBW spectrum measured during H-mode at high TF (I_{TF} =92 kA)

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EBW emission suppression in H-mode

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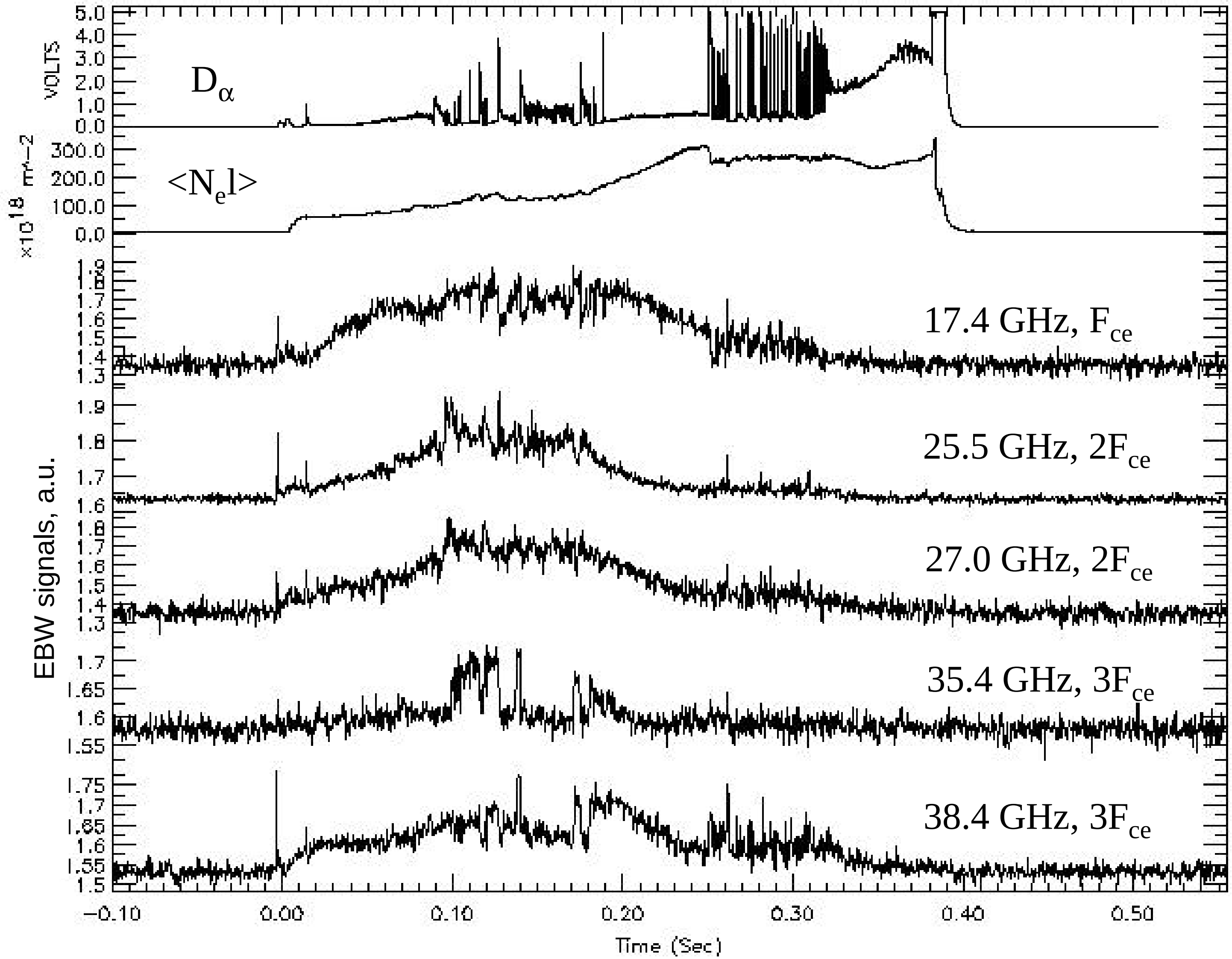

EBW signals suppression during high density H-mode in MAST

EBW Spectra in L-mode and in H-mode

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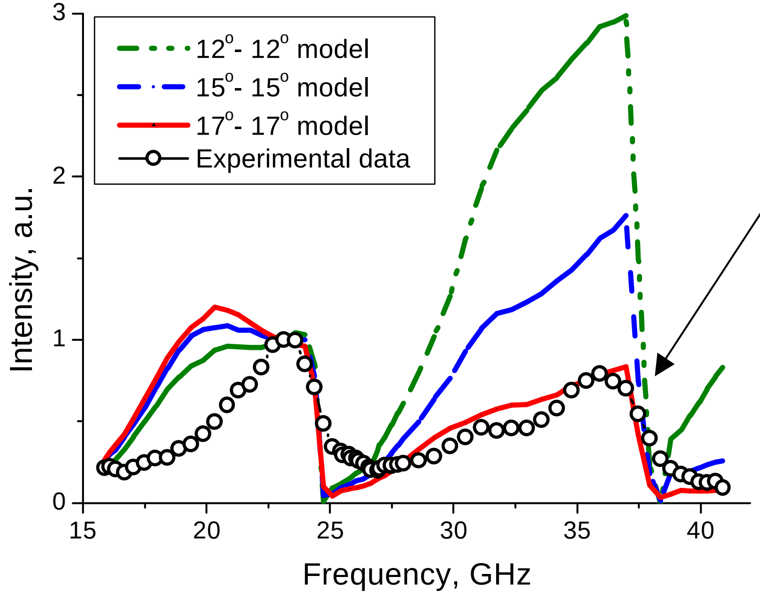
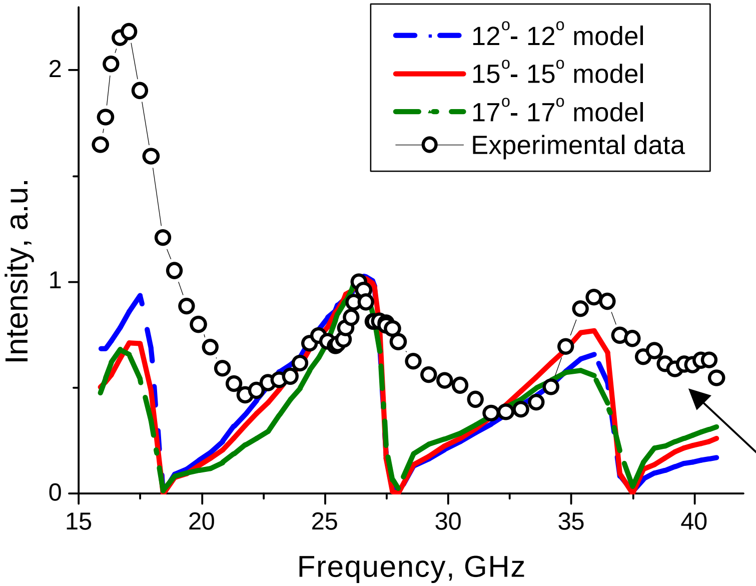


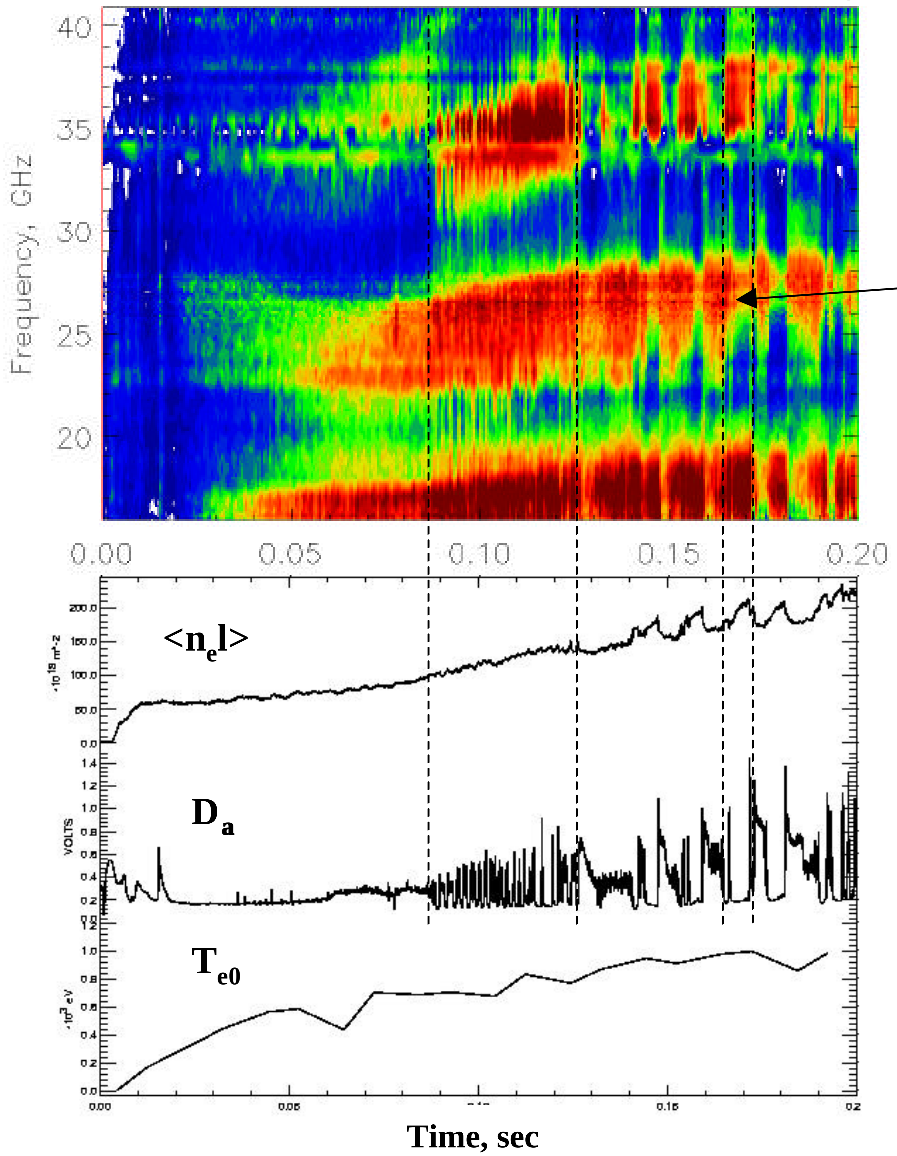
Measured and simulated EBW spectra in high density L-mode in MAST, shot #7798 at 0.24 s.

- **Model: 1D full wave mode coupling, EBW ray-tracing including collisional and non-collisional damping, radiative transfer for non-local wave damping.**
- **Good agreement in L-mode plasma**
- **Disagreement is strong in high beta plasmas and in a long sustained high density H-mode.**

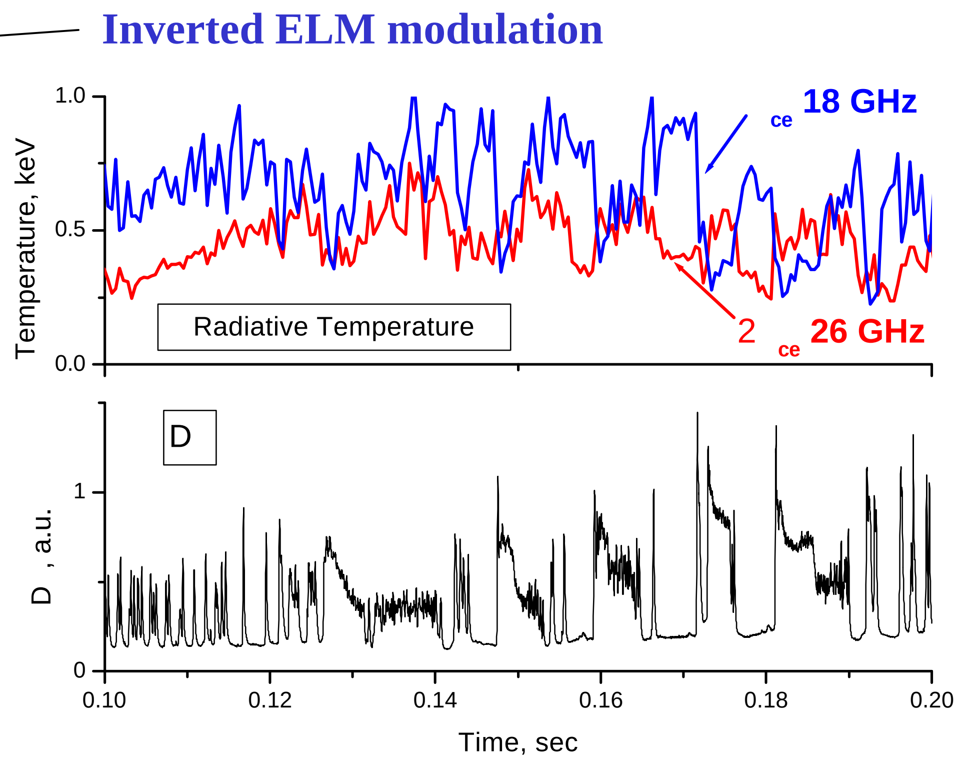


Measured and simulated EBW spectra in high density H-mode in MAST, shot #7786 at 0.24 s.

Inverted behaviour of $2\omega_{ce}$ EBW emission



Shot #7695 EBW spectrum measured during H-mode in low TF (I_{TF} =77 kA)



Fundamental and second harmonic EBW emission and Dα signal

Effect of Magnetic Well in High Beta Plasma

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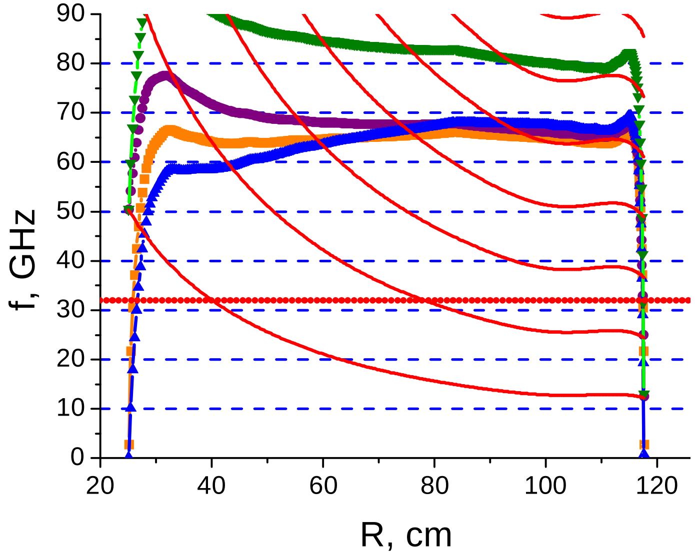
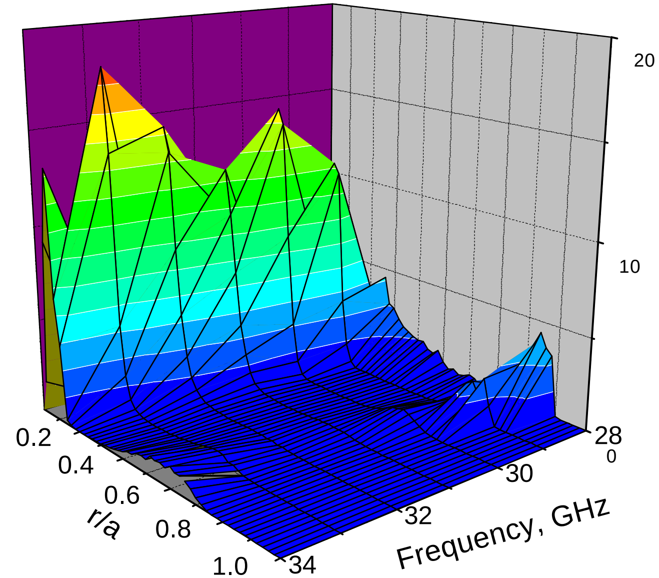
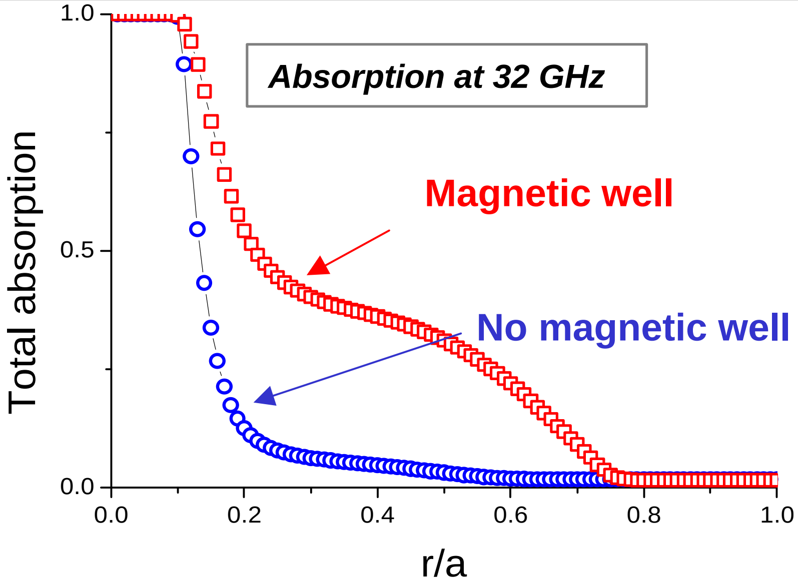
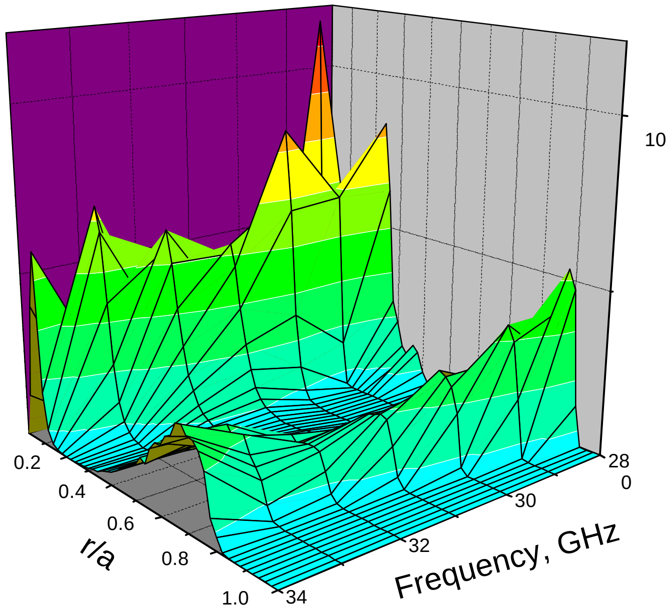


Midplane topology of cut-offs and resonances in high beta plasma in MAST. Magnetic well is formed at R=105cm



No magnetic well





Second harmonic absorption

Magnetic well

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Magnetic Well Effects

- Magnetic wells observed in MAST can explain only ~50% of EBW radiative temperature reduction in high beta plasma

- In experiment radiative temperature can be suppressed by an order of magnitude

- However, magnetic well can appear near the plasma edge due to the edge currents (bootstrap, P-S and diamagnetic) generated during H-mode

- Such current (density of 1-2 MA/m^2) has been recently measured on DIII-D by Zeeman polarimetry with Li beam (A.W. Leonard et al, Bull. Am. Phys. Soc. 48, 184 (2003).

- Edge current of the similar value in MAST could cause a 5^o pitch angle increase because of lower toroidal field.

Edge Current Effects at Second Harmonic

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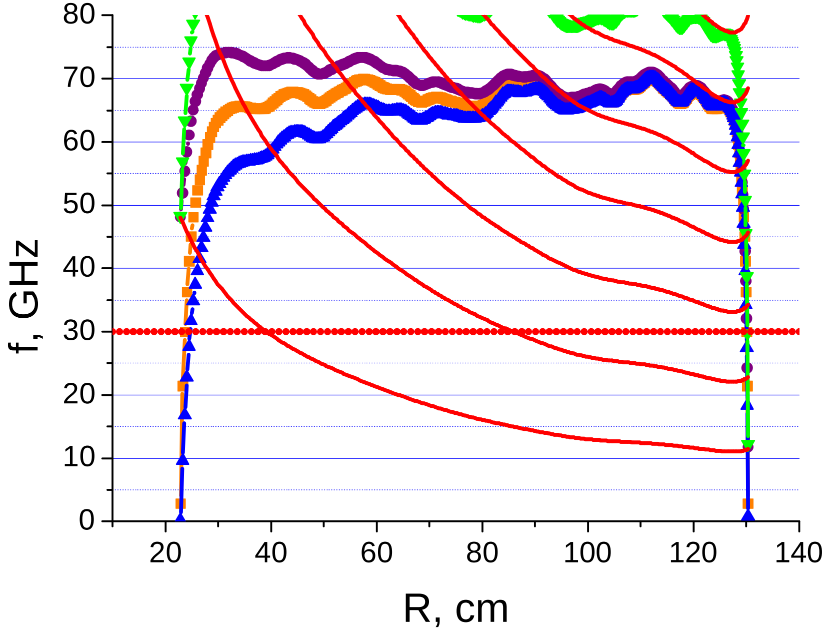
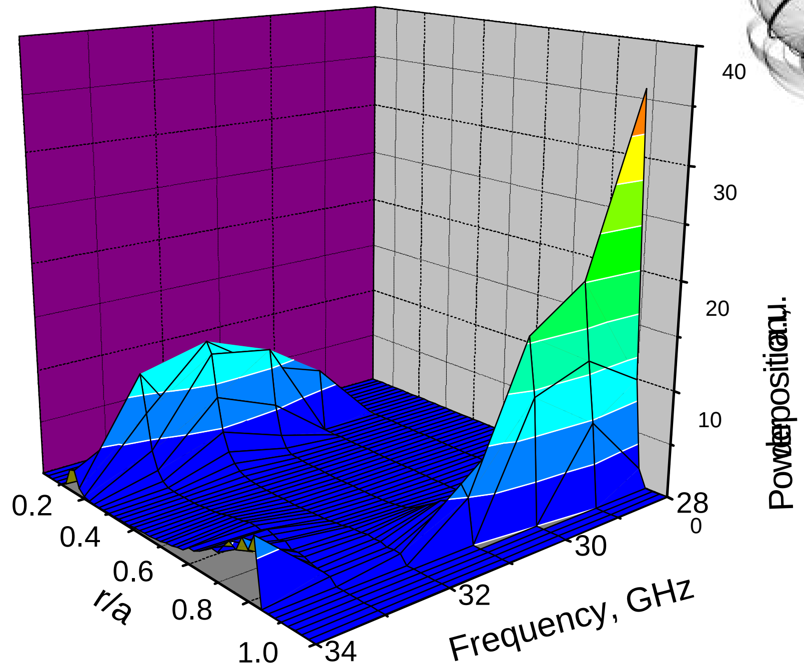


Midplane topology of cut-offs and resonances for shot #6141 in MAST. Edge magnetic well was formed by edge current of 2 MA/m^2



Power deposition at second harmonic with edge current

- **Edge current causes two effects: mode conversion efficiency reduction due to the pitch angle increase and enhanced peripheral absorption**
- **Both effects are local in frequency space**
- **Both effects result in radiative temperature reduction**
- **Edge current in principle explains all observed peculiarities of EBW emission**
- **Experimental proof is required for this hypothesis**

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Prospects of EBW emission diagnostics

- Electron temperature only for low beta and in L-mode.

- EBW emission can be used for reconstruction of the outer part of q profile in plasmas exhibiting sawtooth-like spectrum.

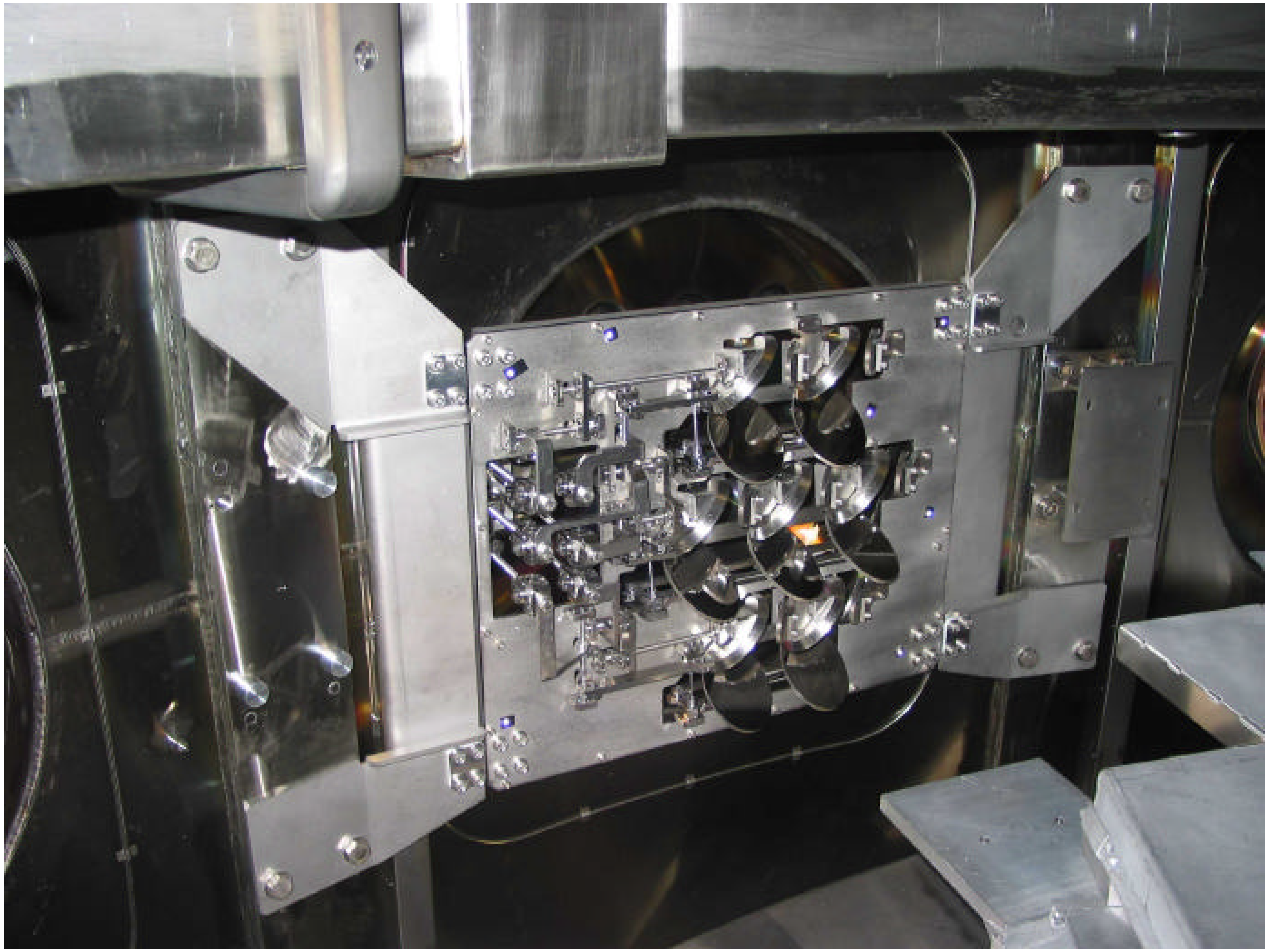
- EBW propagation is highly sensitive to edge plasma currents. The inverse problem must be solved for correct data interpretation.

- Edge pitch angle can be measured directly in the range of frequencies (at different depth in the pedestal) with angular scanning EBW radiometer or EBW imaging system.

- Magnetic well itself is an interesting physical phenomenon. EBW radiometry is a valuable tool in its investigation.

First EBW Heating Experiments in MAST at 60 GHz

EBW Steerable Launcher in MAST



21 mirrors
7 beams
60 GHz

- **Final polarisation can be chosen from linear to circular**
- **Resultant beam divergence is less than +/-2.5º (w = 25 mm)**
- **Poloidal steering range of +/-13º, toroidal +/-24º, accuracy of 0.5º**

O-X-B Heating in High Density H-mode

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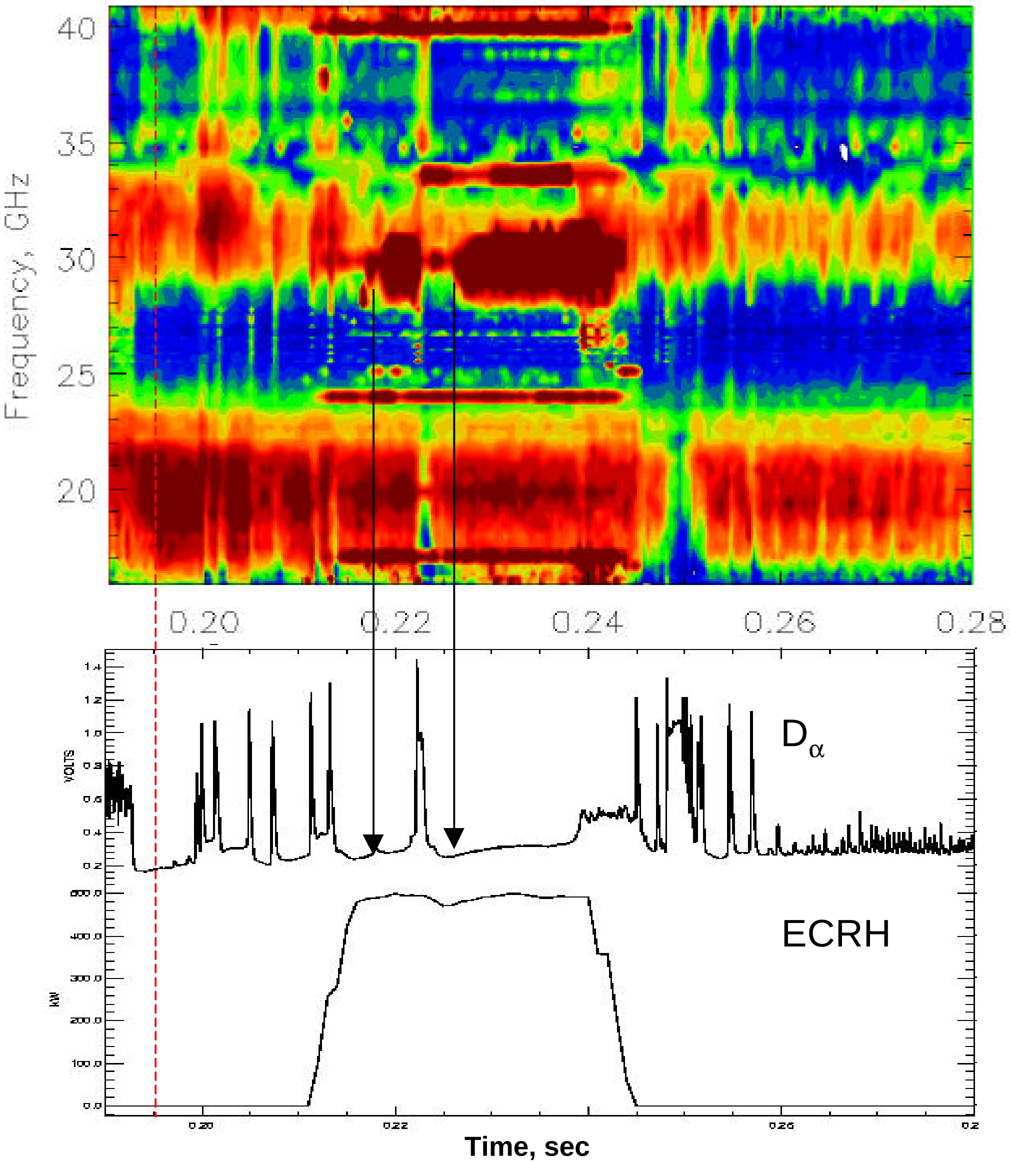
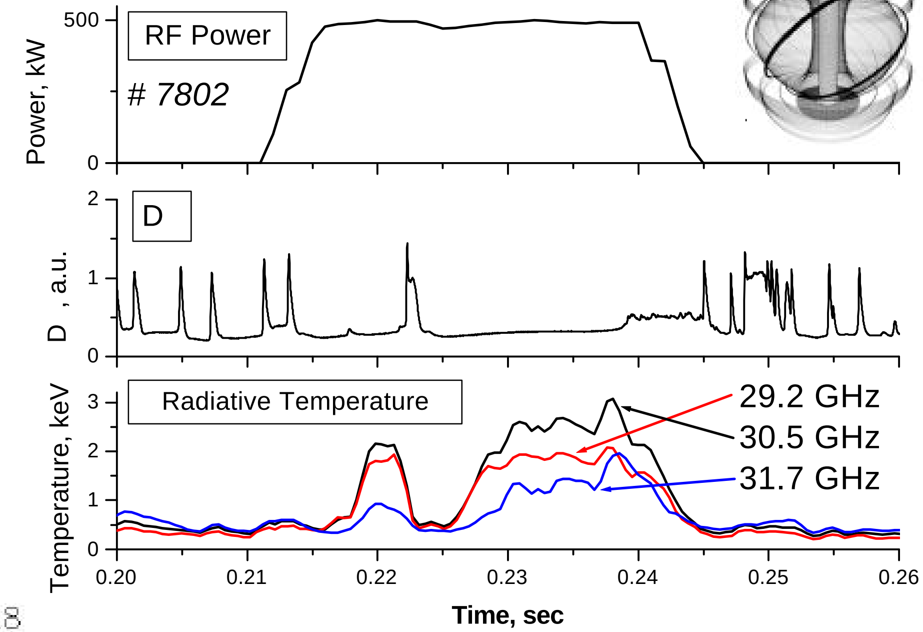


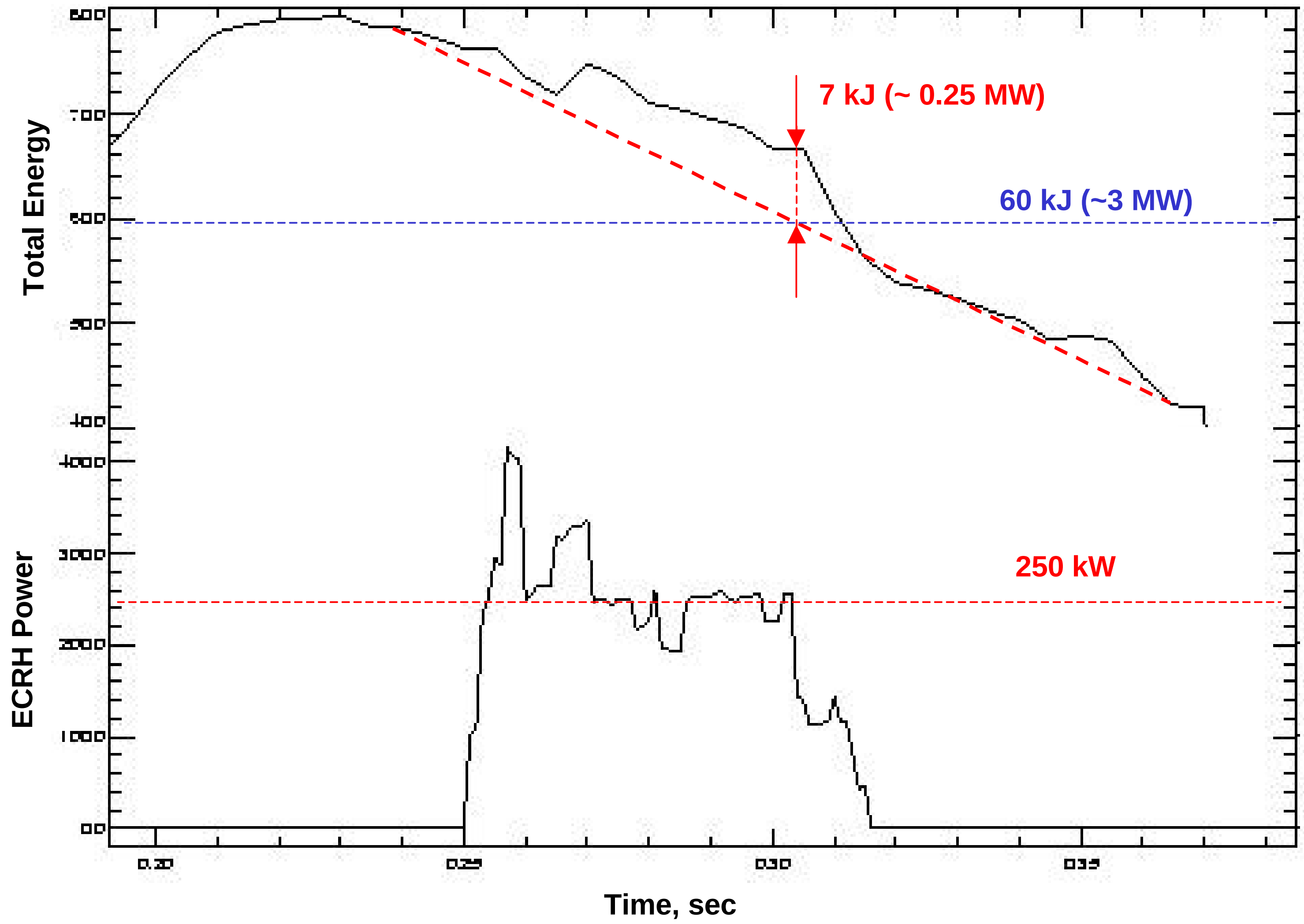
EBW emission from w_{ce} and $2w_{ce}$ harmonics during ECRH



EBW emission during ECRH pulse in ELM-free phase

- **Radiative temperature exceeds T_e by factor of 3-4 during ECRH pulse**
- **TS shows broadening of the scattered spectra at radii where power deposited**

EBWH in High Density ITB-like Plasma



Shots #9262, #9263, #9267. Overage heating result.

EBW modelling in MAST

- 1D full wave mode coupling solution
- EBW ray-tracing uses a fully e/m hot plasma dispersion relation
- Magnetic equilibrium was obtained from the equilibrium code SCENE
- EBW wave propagation and damping was studied with the aim of EBWH and EBW CD optimisation
- Modelling was conducted over a range of frequencies and launch configurations for one particular high beta plasma scenario

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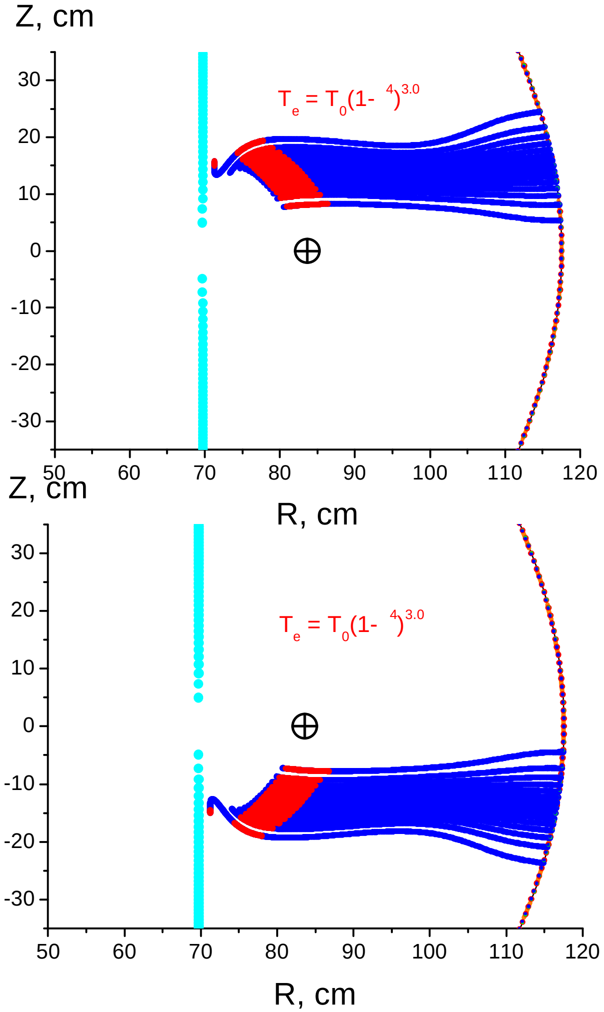
Symmetry

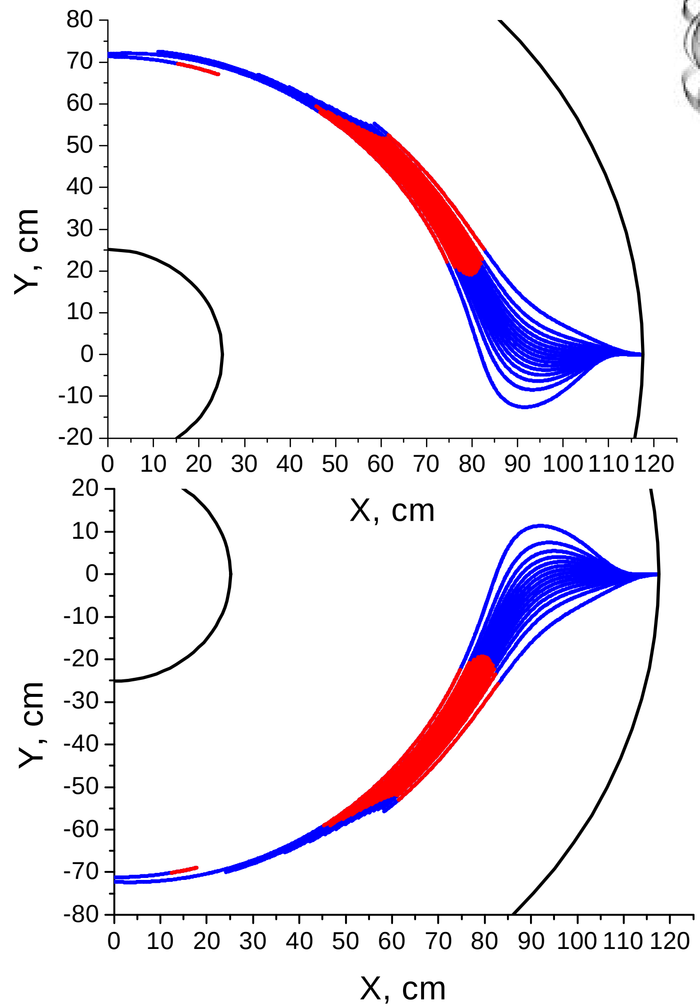
Side View



Right

Left

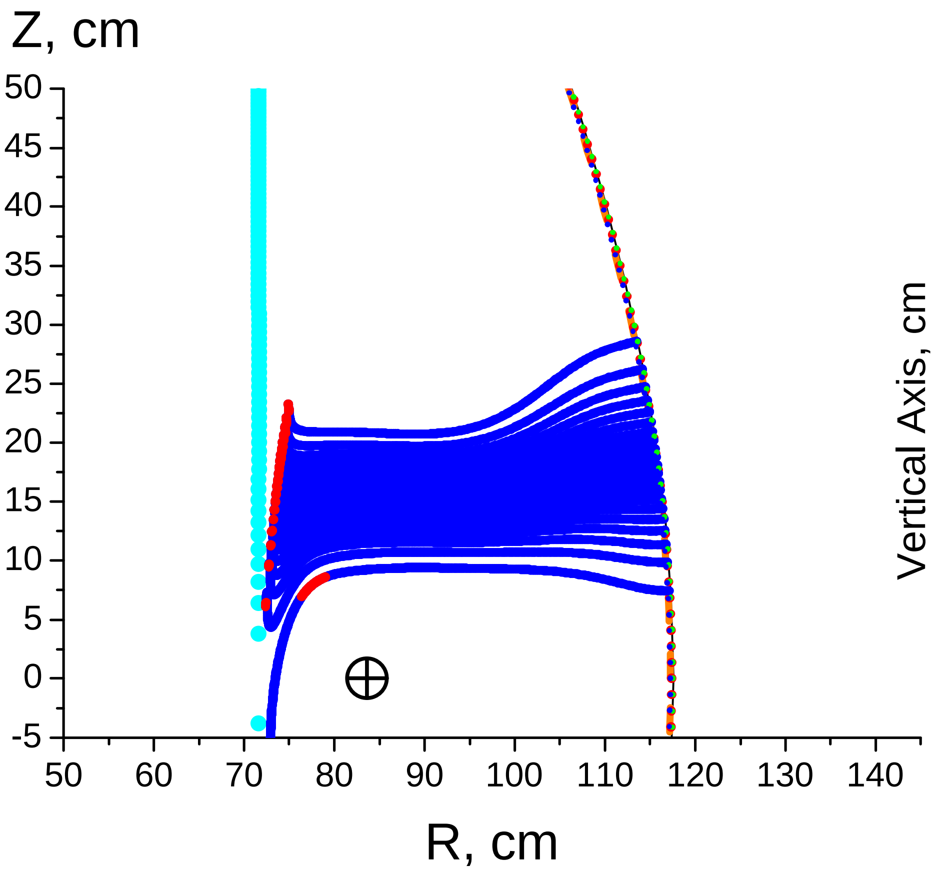
Top View

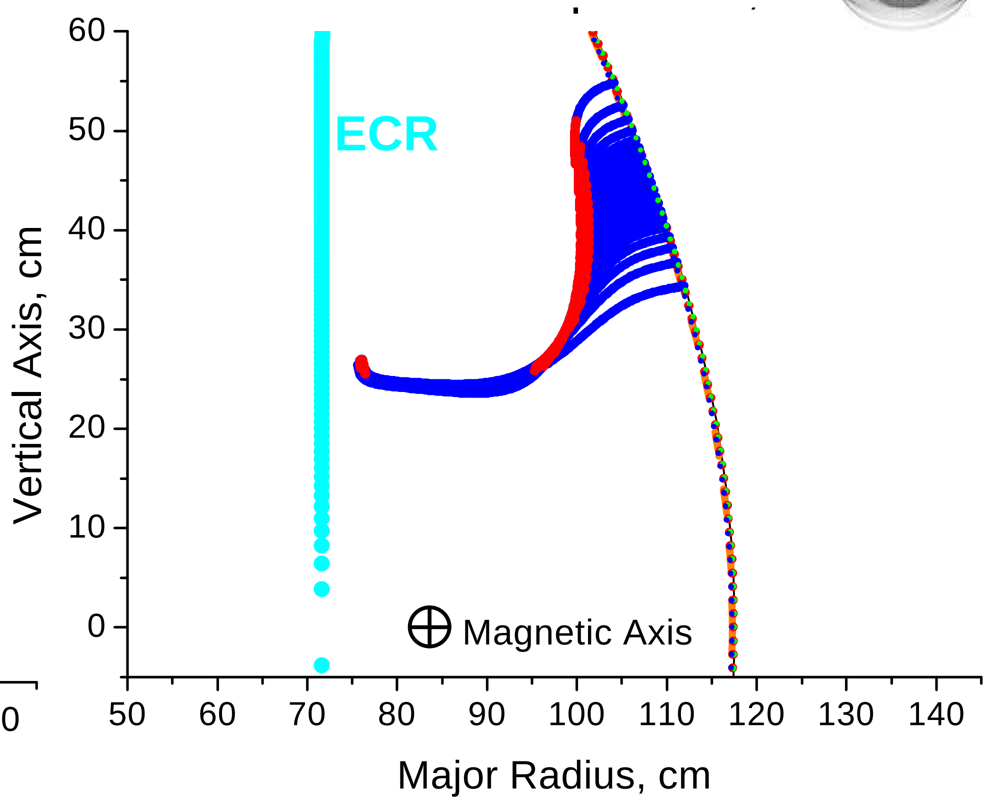


Symmetry of EBW ray-tracing with respect to the midplane. 18 GHz, midplane launch, right (top) and left (bottom) polarisation

Same launch. Note, $k_{||}$ has opposite sign for above and below midplane absorption.

Vertical Position Effect

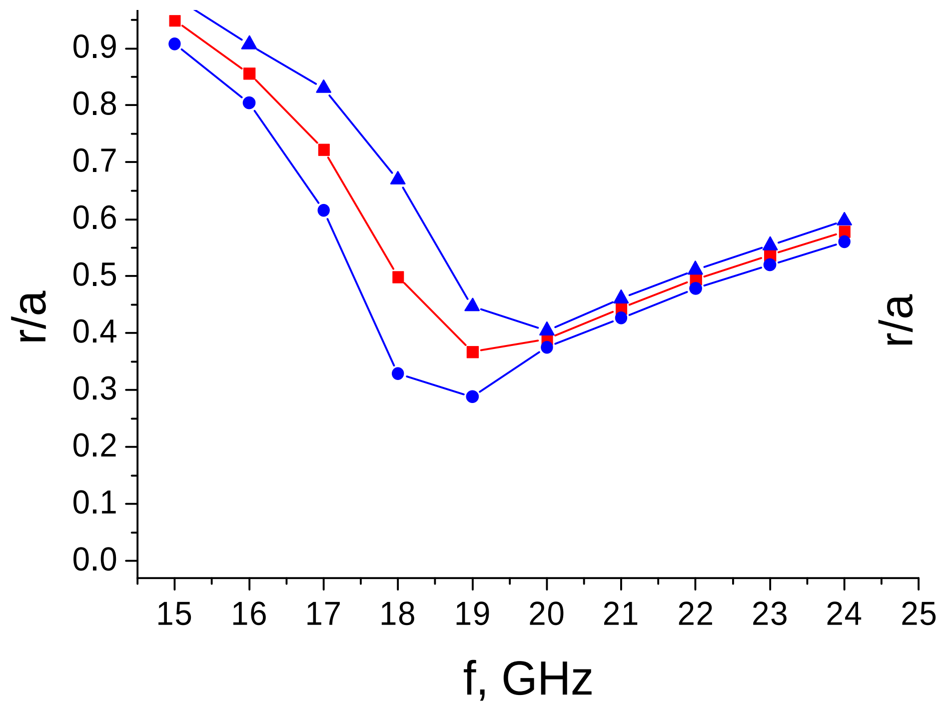


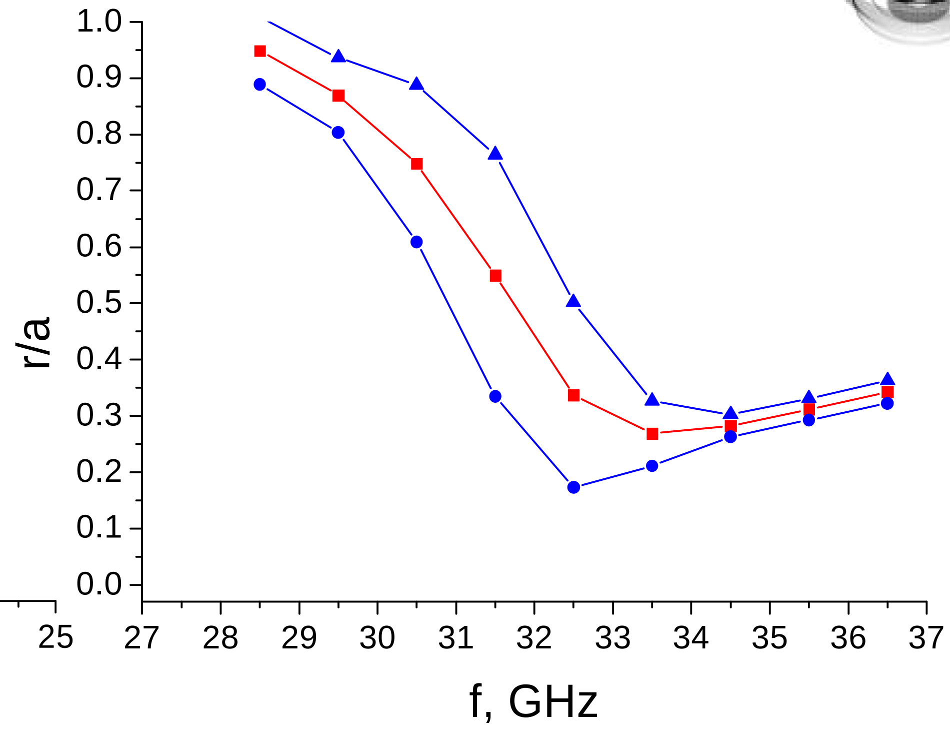


Poloidal view of ray trajectories. Midplane (right polarisation) launch at 17.5 GHz.

Poloidal ray trajectories. 40 cm above midplane (right polarisation) launch at 17.5 GHz.

EBW Ray-tracing Frequency Scan



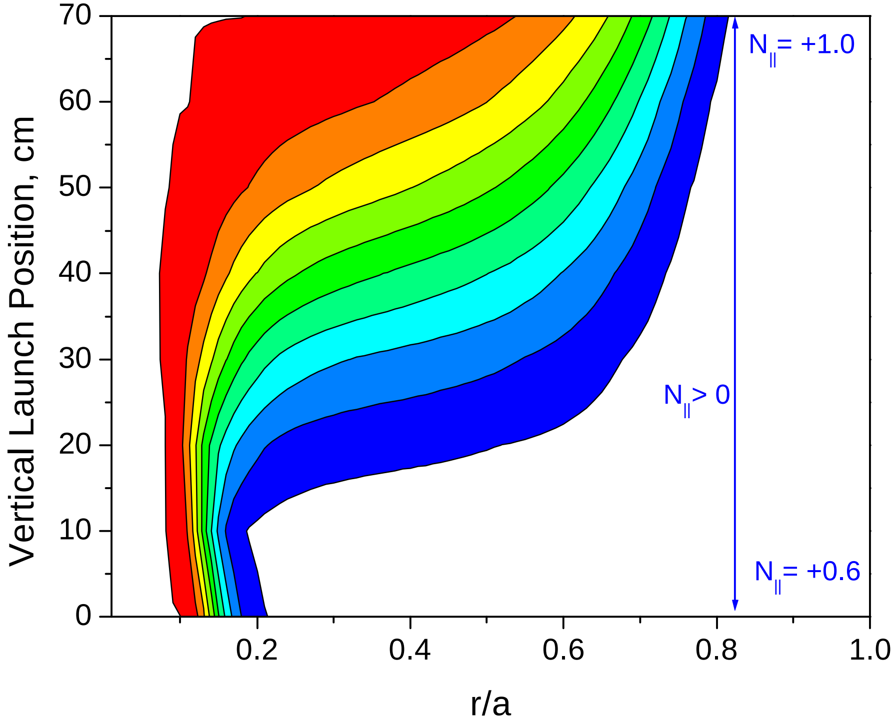


Power deposition at fundamental resonance in the range of frequencies. 40 cm above midplane launch, right polarisation

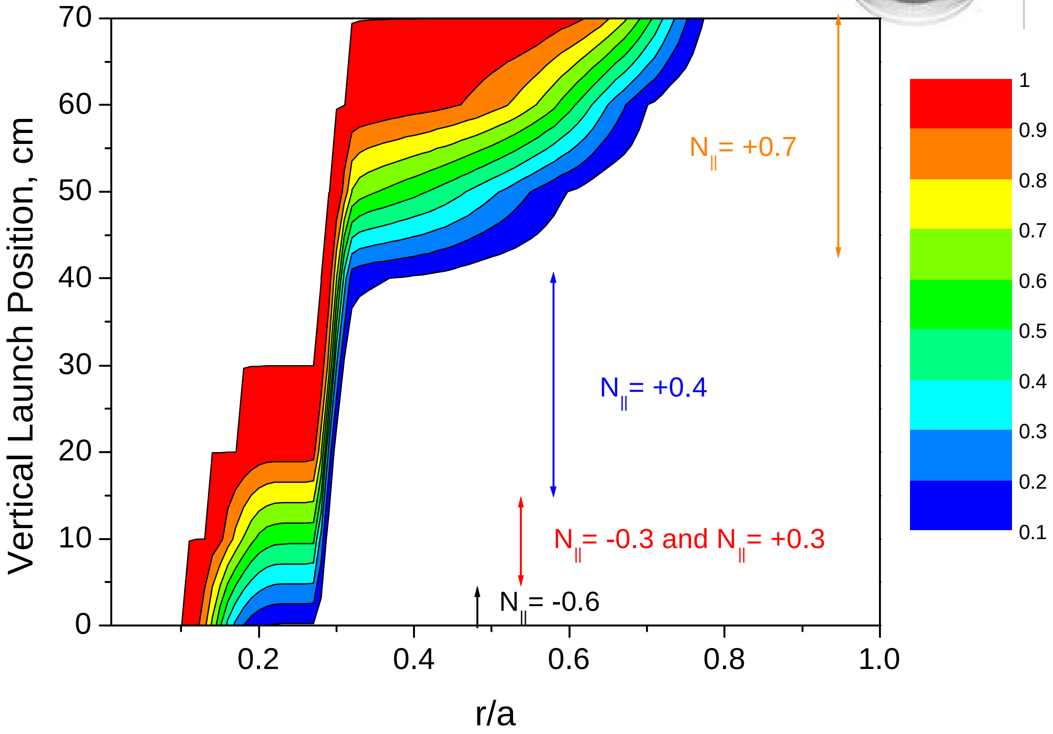
Power deposition at $2w_{ce}$ in the range of frequencies. Comparison of 30 cm above midplane launch, right polarisation

- **Note the radial position of the absorption zone against the frequency.**

Vertical Scan



Left polarisation, 18 GHz vertical scan



Right polarisation, 18 GHz vertical scan.

Note the Right polarisation can continue the Left polarisation graph (with inverse sign of $N_{||}$) to negative values of launch positions and vice versa.

Benchmarking of Fokker-Planck codes
- preliminary EBW CD calculations do not agree

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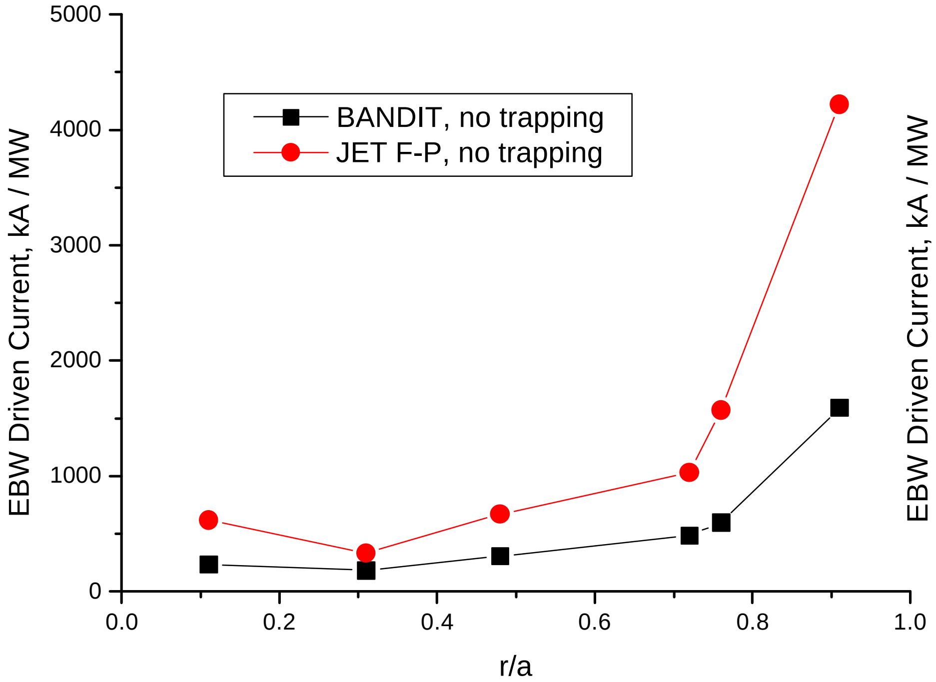
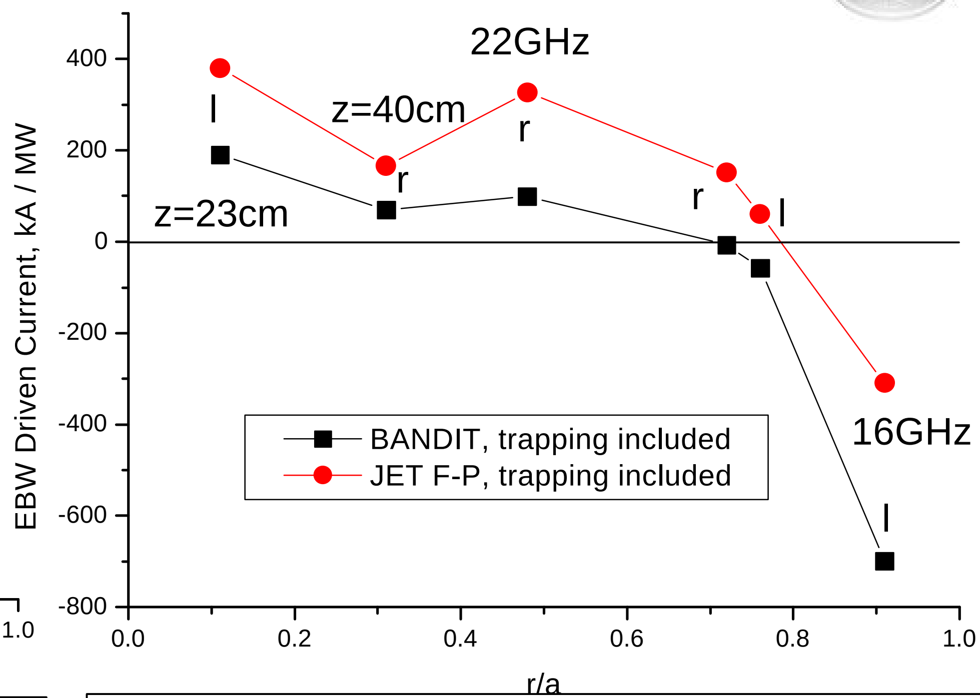


Predicted EBW CD with 1 MW injected power over radius without trapping (preliminary results).



Predicted EBW CD over radius with 1 MW injected power including trapping (preliminary results).

f = 18GHz, z= 70cm, except where indicated.
r,l indicate right & left polarisation respectively

Ohkawa effect dominant for r/a > 0.7

EBW can provide both Core and Edge CD

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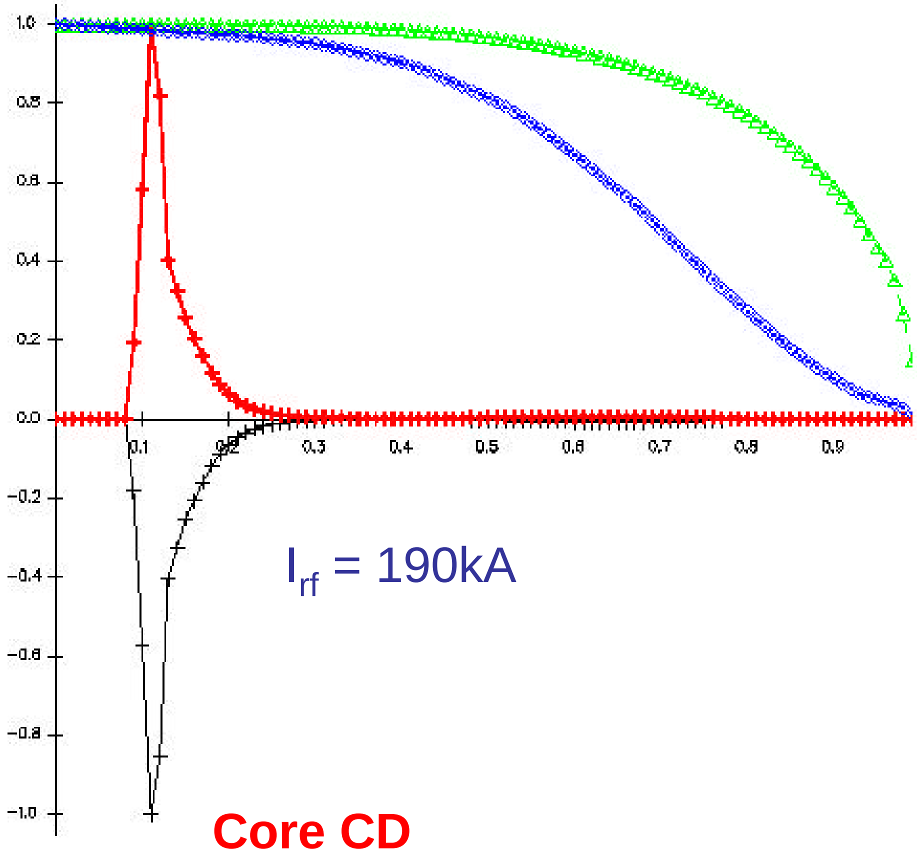
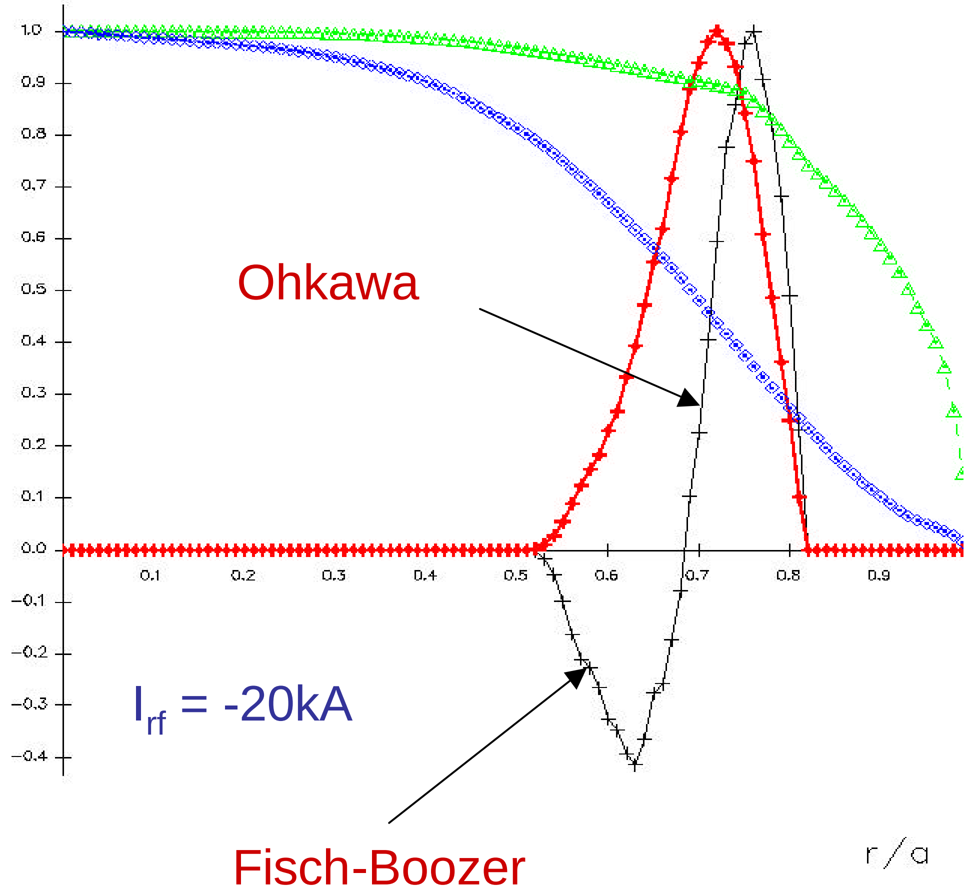
P_{rf} = 1MW, f = 18GHz

z=23cm, left polarisation



Core CD

z=70cm, right polarisation



Edge CD

Summary

EBW offers potential for localised electron heating and current drive

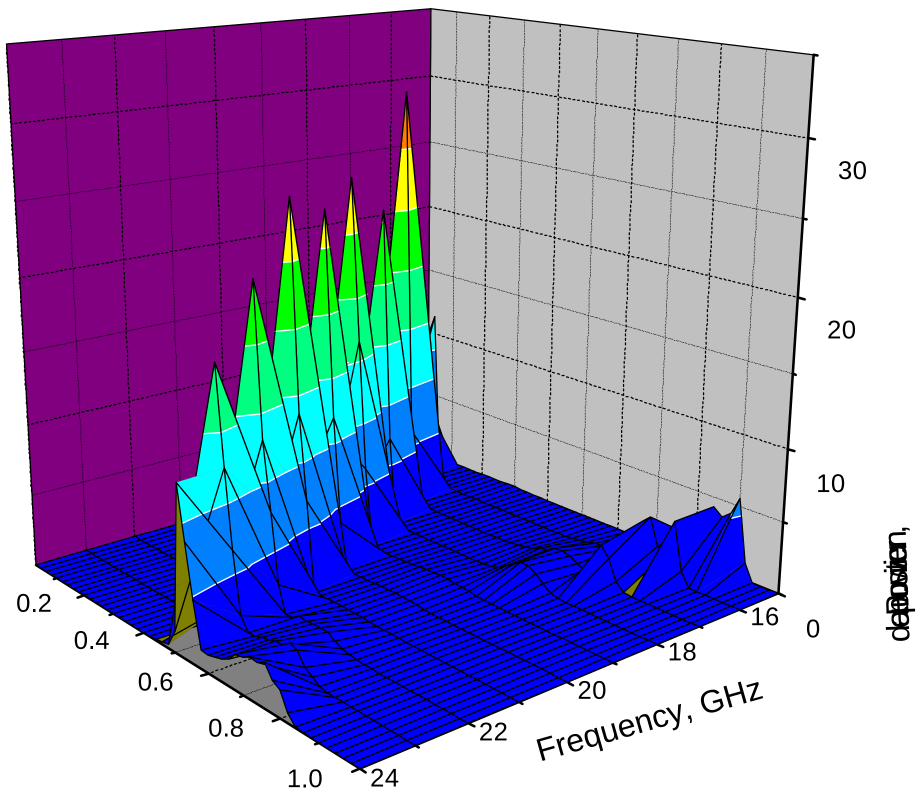
Radial power deposition can be controlled by vertical launcher position and polarisation at a fixed frequency

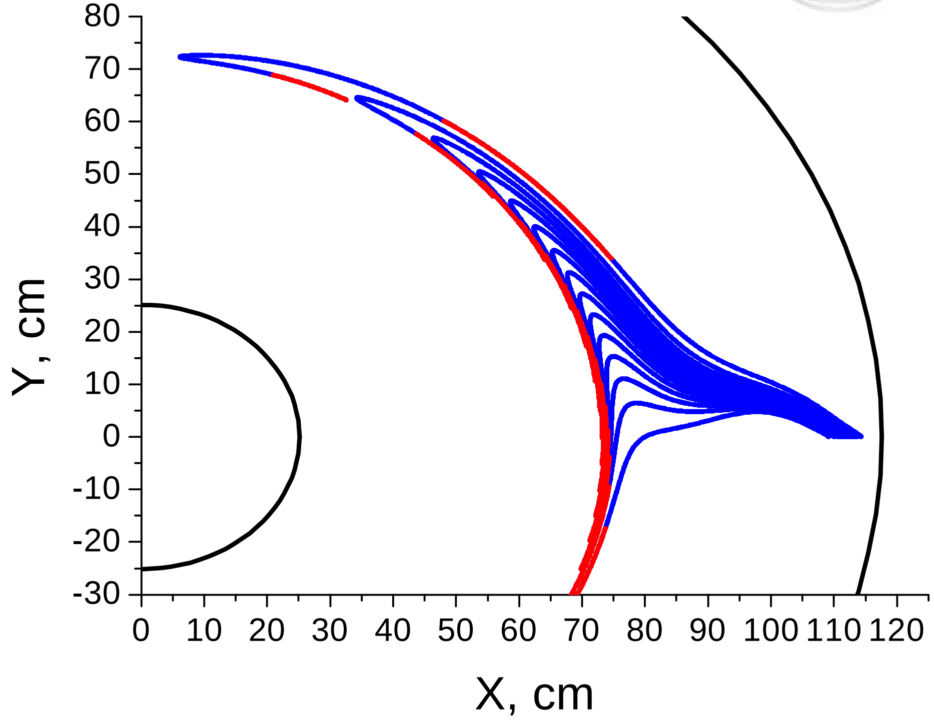
EBWH and EBW CD are beneficial at fundamental resonance, but antenna design will be a challenge ($\phi_{beam} \geq$ 30cm at 18GHz)

Ohkawa effect likely to limit EBW CD efficiency at r/a ~ 0.7 but might provide efficient far off-axis CD

Back-up Material

Frequency Scan

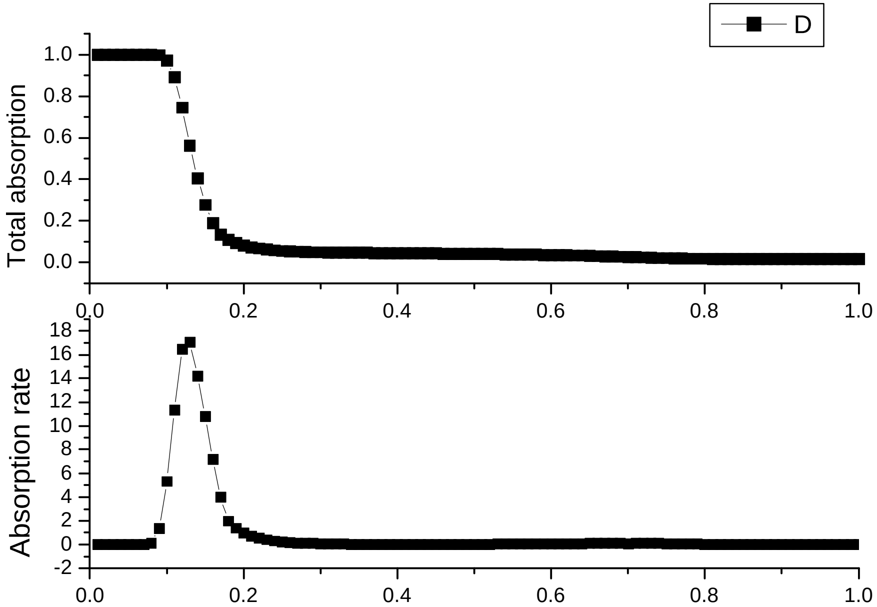


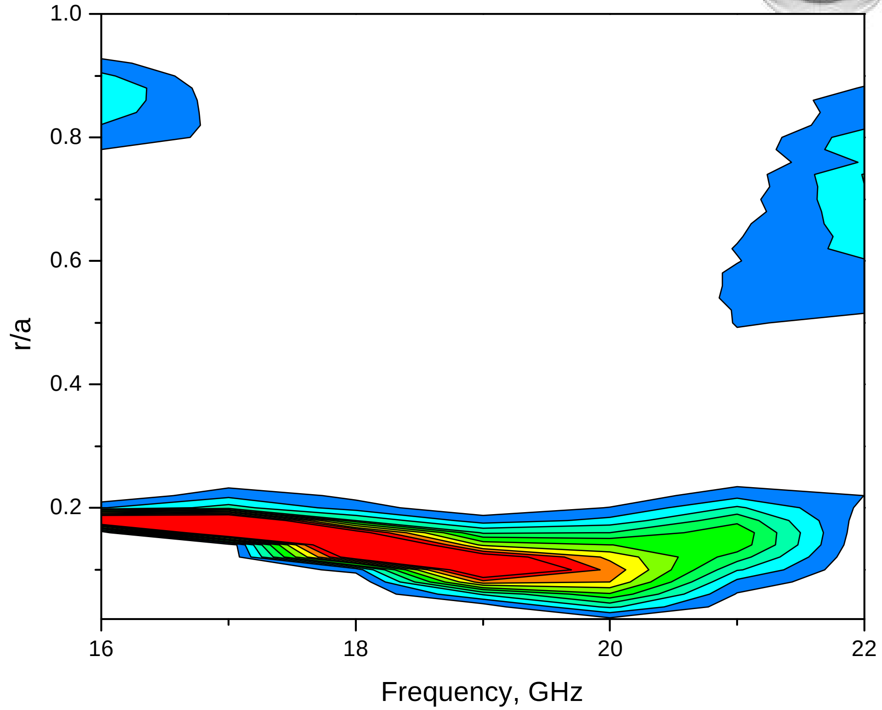


First harmonic frequency scan. Perpendicular launch X-mode

Toroidal projection of EBW rays for 20 cm above midplane launch. 18 GHz, right polarisation = launch against the edge magnetic field Red indicates strong absorption of EBWs.

EBW Absorption and Power Deposition



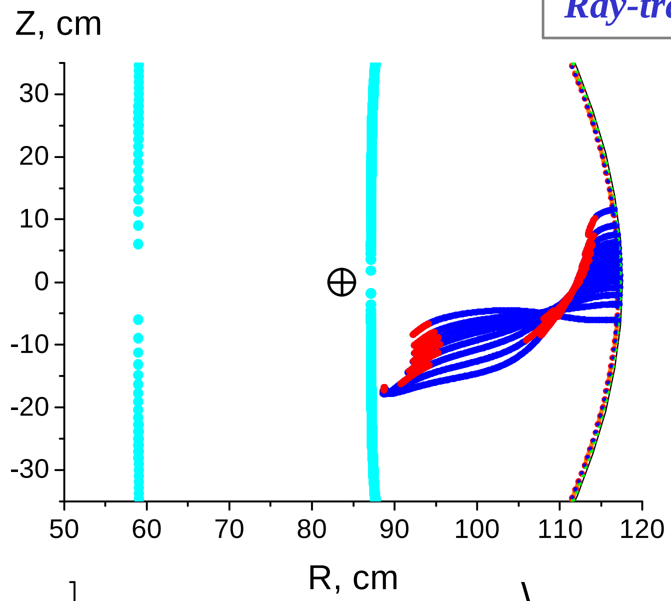


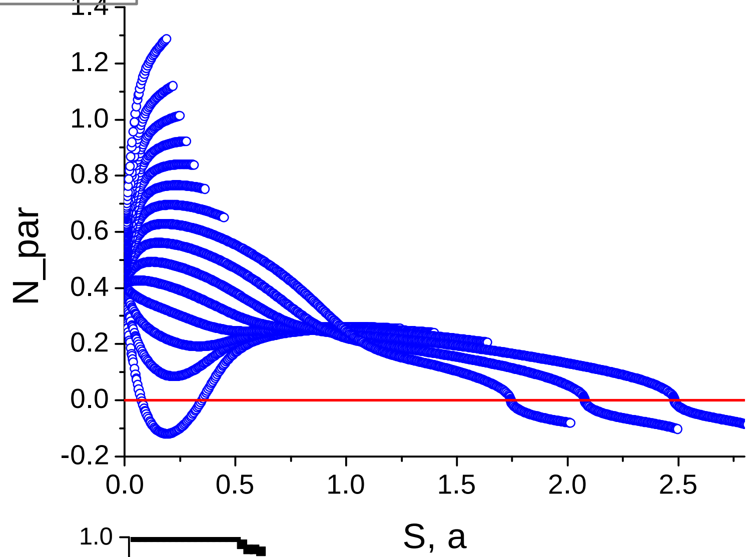
EBW power absorption and absorption rate for 10 cm above midplane launch, 18 GHz, left polarisation

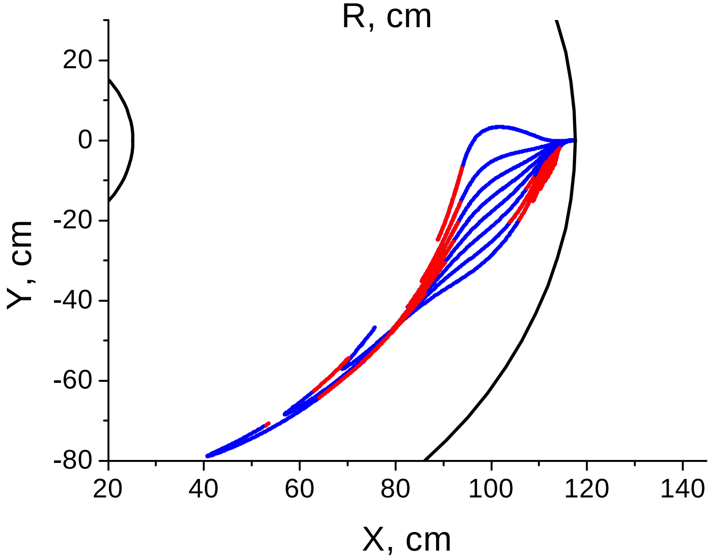
Contour map of power deposition profiles over the range of frequencies at fundamental EC resonance. 10 cm above midplane launch, left polarisation.

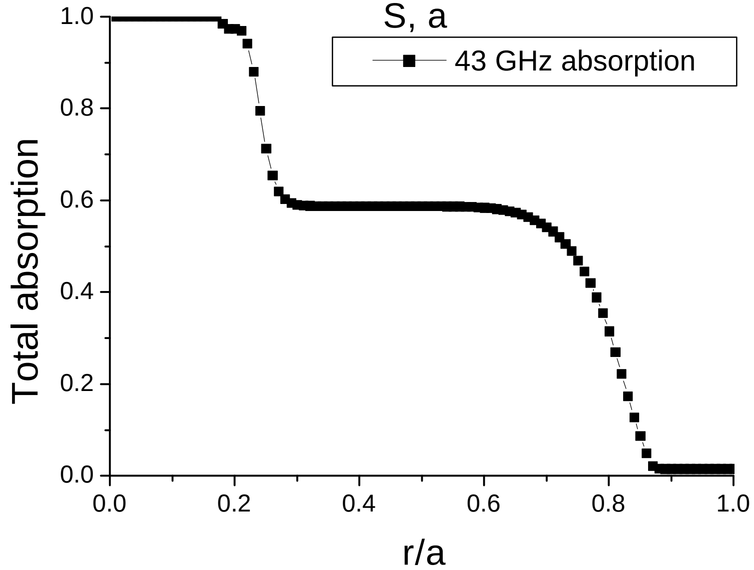
Effect of Magnetic Well at $3w_{ce}$

Ray-tracing at 43 GHz









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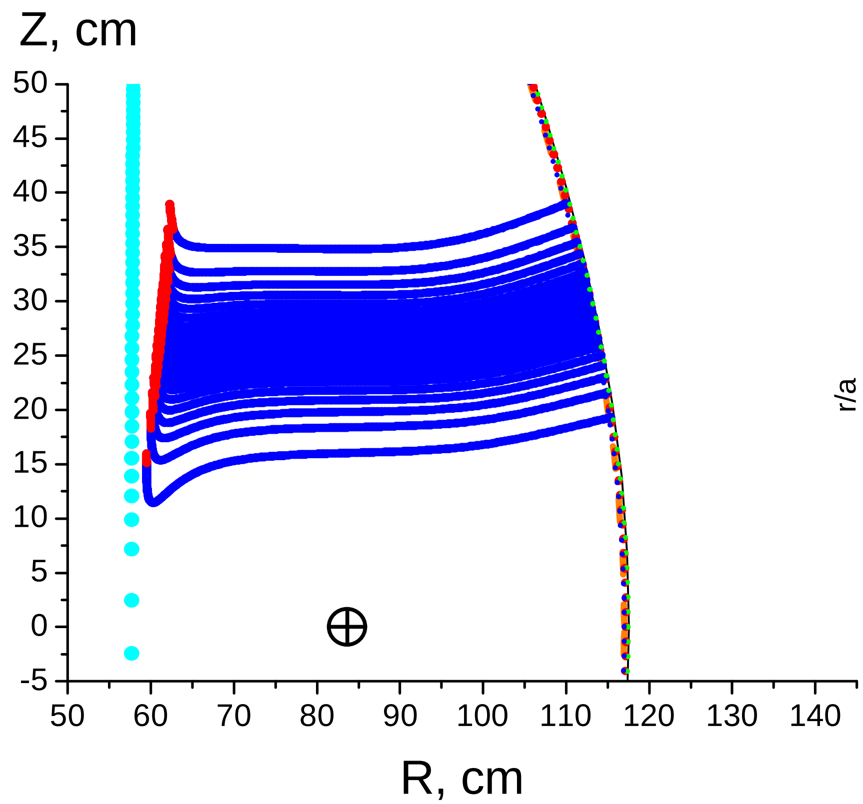
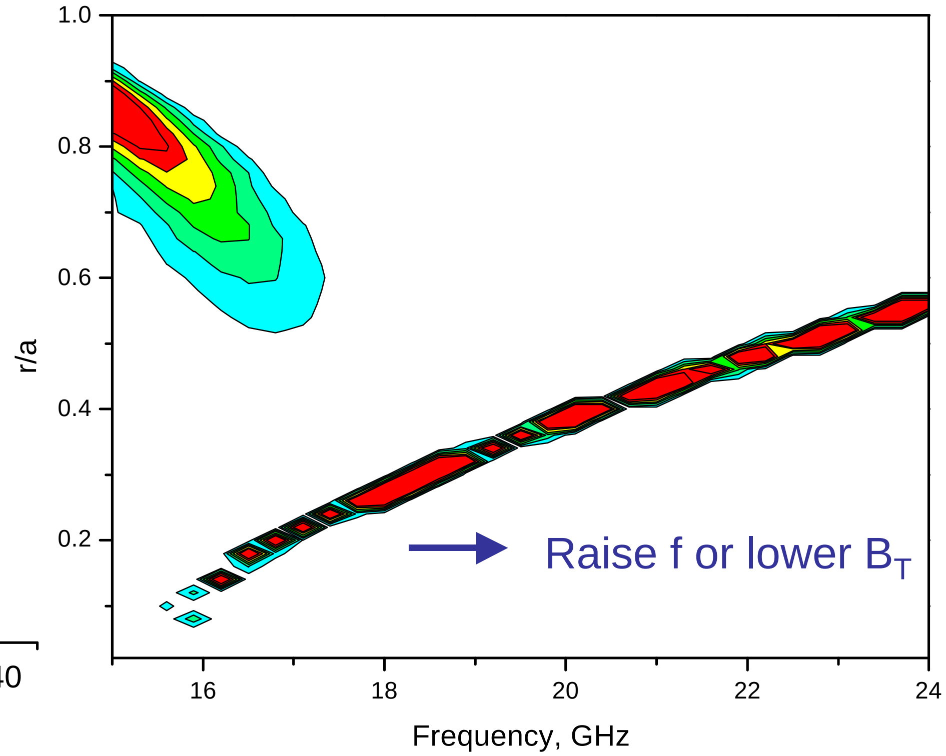
EBW Ray-tracing & Frequency Scan

Right polarisation - launch 20cm above midplane





Poloidal view of ray trajectories at 17.5 GHz.

Power deposition in a range of frequencies (fundamental harmonic).

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Mode Conversion Window and Antenna Alignment

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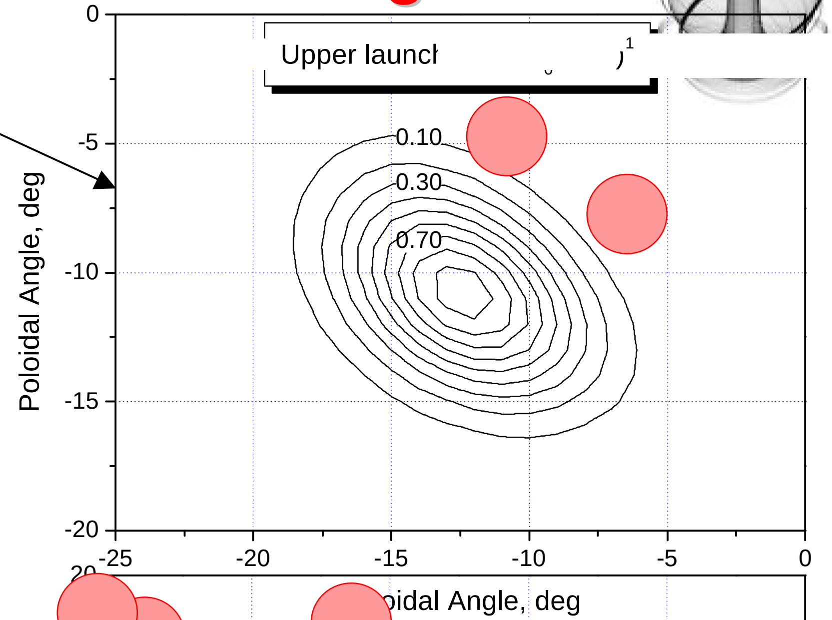
Mode conversion angular windows estimated for Upper Bank of the EBW launcher. Beam patterns are superimposed assuming 'optimal' launch configuration.



- **Even in the H-mode scenario-1 (widest coupling window) the mode coupling cannot exceed 10% for the Upper and Lower Banks and 5% for the Middle Bank.**
- **EBWH results presented above were obtained with 0.3 - 0.6 MW power and coupling efficiency <10%**
- **Power up to 1 MW is expected in M4. With aligned launcher the coupling efficiency must reach 80-90%**
- **EBWH effects must be stronger by an order of magnitude**

Mode conversion windows estimated for Middle Bank in the high density H-mode scenario.