2D EBW Emission Studies in MAST

Vladimir F Shevchenko

EURATOM/CCFE Fusion Association, Abingdon, OX14 3DB, UK

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Outline

- Use of EBW thermal emission (EBE) for plasma diagnostics.
- EBE spectrum in spherical tokamak.
- B-X-O mode conversion. Effect of the magnetic shear.
- EBE observation with the fast rotating mirror.
- Pitch angle reconstruction from EBE.
- EBE imaging – edge q-profile diagnostic
- Summary

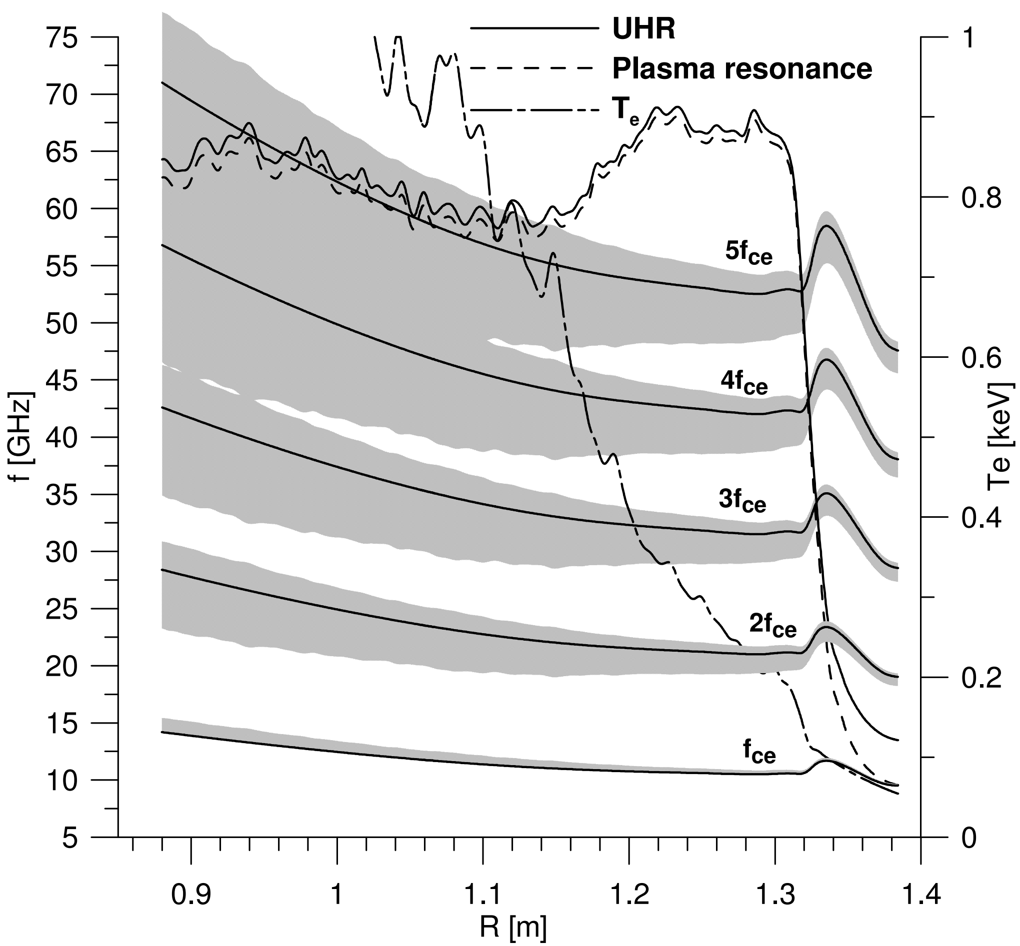
EBWs for Plasma Diagnostics

- Thermal EBWs are emitted from the EC resonance and its higher harmonics.
- Unlike O and X modes the EBW mode is trapped inside the plasma.
- EBWs are electrostatic waves. They cannot propagate in vacuum.
- EBE can escape plasma via B-X-O mode conversion (MC).
- B-X-O MC is highly anisotropic. It is efficient within a narrow angular window determined by the magnetic field at the O-mode cut-off ($\omega = \omega_{pe}$) layer.
- This fact can be used for magnetic pitch angle measurements.
- The $\omega = \omega_{pe}$ layer position depends on n_e only. It can be obtained from Thomson Scattering measurements.
- EBE spectral measurements can provide estimates of the total magnetic field.

EC Harmonics Visibility with EBE

- ❑ Even high EC harmonics are optically thick ($\tau \sim 200$ at $5\omega_{ce}$) in MAST
- ❑ Higher EC harmonics partially shadow the lower EC harmonics
- ❑ Doppler broadening of EC harmonics decreases central accessibility
- ❑ Edge current can block the access to the second harmonic as observed in EBW emission studies
- ❑ Fundamental EC resonance is less affected by edge currents and Doppler broadening

broadening of is given by the factor $\mathbf{1/(1 \pm 3N_{||}(v_T / c))}$



Midplane resonance topology with Doppler broadening. Edge magnetic field reconstructed from the EBE spectral measurements, shot #8694.

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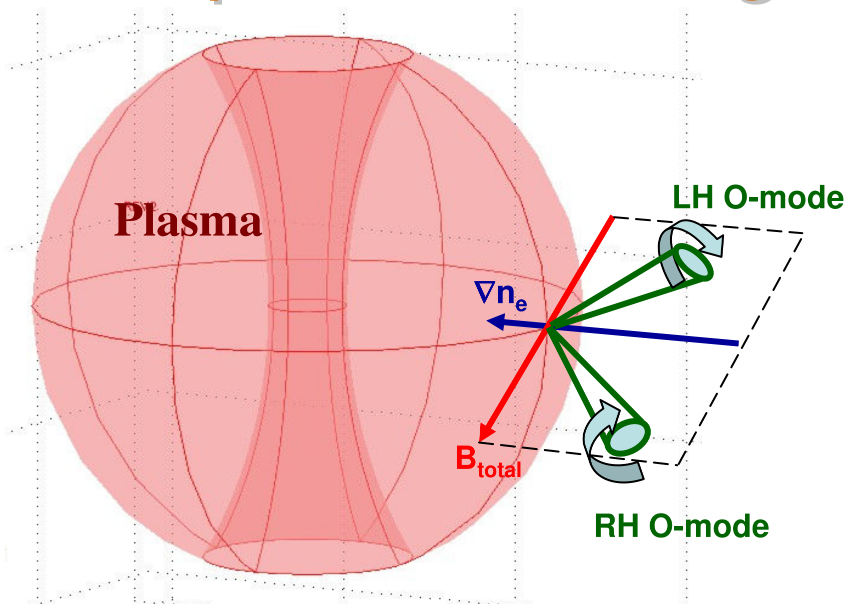
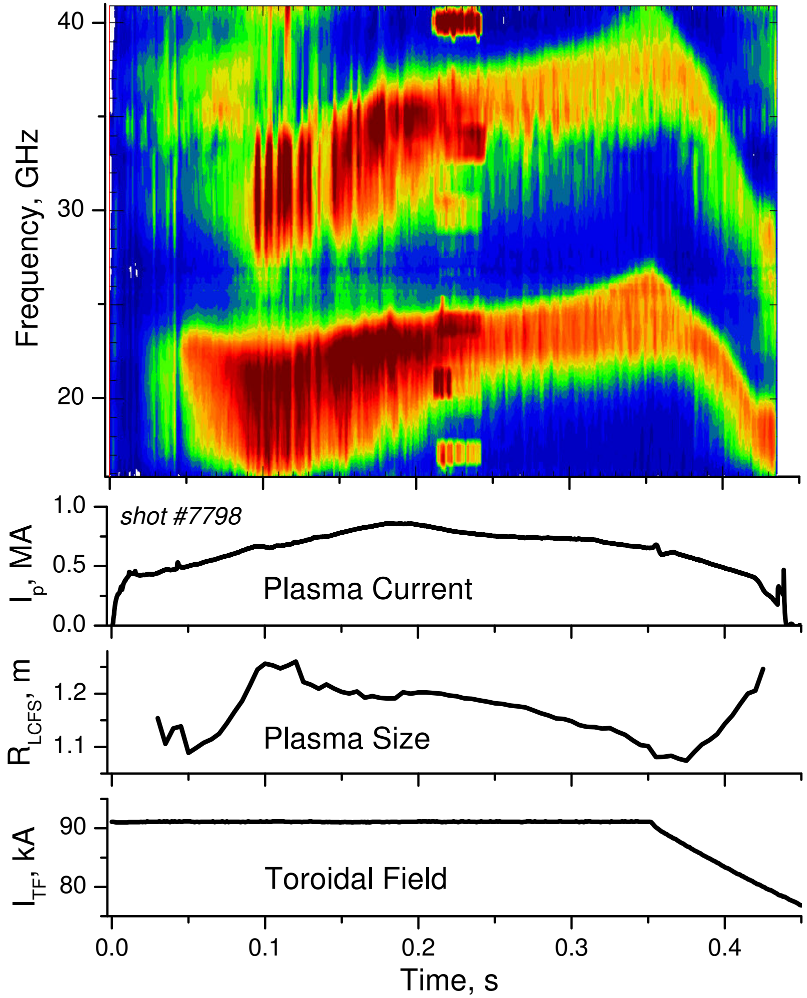
Optimal Aiming for B-X-O Conversion



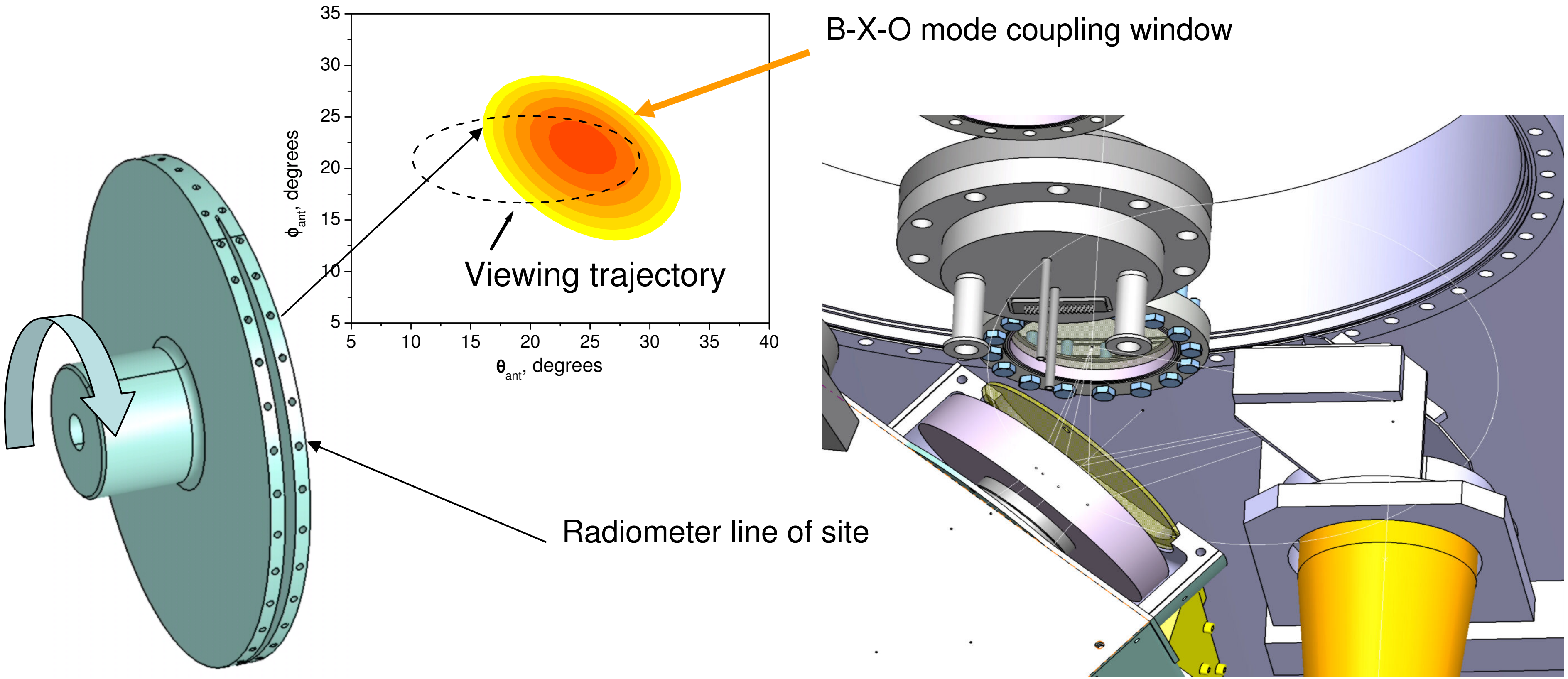
$$\sin^2\phi = N^2_{\|,opt} = Y/(Y+1), \quad Y = \omega_{ce}/\omega$$

- Launch / viewing plane is determined by B_{tot} and ∇n_e in the layer where $\omega_{RF} = \omega_{pe}$
- Angle between ∇n_e and optimal direction depends only on $|B_{tot}|$
- Magnetic pitch angle can be deduced from EBE and density profile measurements



EBE spectrum at optimal viewing angle. Note the effect of TF ramp down at 0.35 s.

EBE Observation with Rotating Mirror



Mirror design

Fast rotating mirror (FRM) is installed in front of the radiometer antenna on MAST.

Shear Effect on X-O Coupling

❑ Full wave modelling of B-X-O mode coupling (MC) revealed strong sensitivity of MC to the magnetic shear.
❑ The main effect of magnetic shear on MC is a tilt of the MC window around optimal direction.
❑ Shear effect can be taken into account within the framework of the WKB approximation

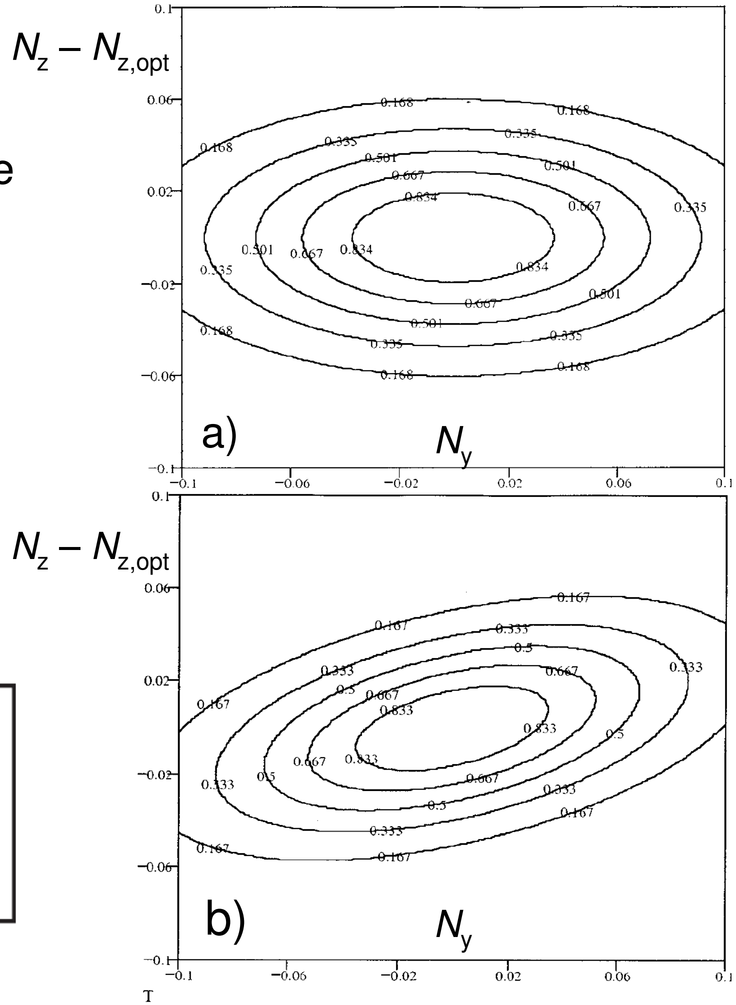
R. A. Cairns, C. N. Lashmore-Davies, Phys. Plasmas, vol. 7, No 10, Oct. 2000, p. 4126.

MC efficiency including magnetic shear can be estimated by:

$$T=\exp\left[-\pi\frac{L_n\omega}{c}\frac{\left(\frac{2\delta}{n_{cr}}-rn_yn_{cr}\right)^2+n_y^2\left\{\frac{2\omega}{(\omega+\Omega_e)}\frac{1}{n_{cr}^2}-r^2n_{cr}^2\right\}}{\left(\frac{2\omega}{(\omega+\Omega_e)}\frac{1}{n_{cr}^2}-r^2n_{cr}^2\right)^{3/2}}\right]$$

where $N_{opt} = n_{cr}$, $\delta N_y = n_y$, $\delta = N_z - N_{z,opt}$, $\Omega_e = \omega_{ce}$
$L_\theta = \theta / x$ and $r = L_n / L_\theta$.

Note at r = 0 the formula converts into *Mjølhus's* formula



Contour plots of the X–O MC, both axes vary between ±0.1. 15 GHz, L_n=0.2 m. ***a)*** *no shear r = 0,* ***b)*** *shear included r = 1.*

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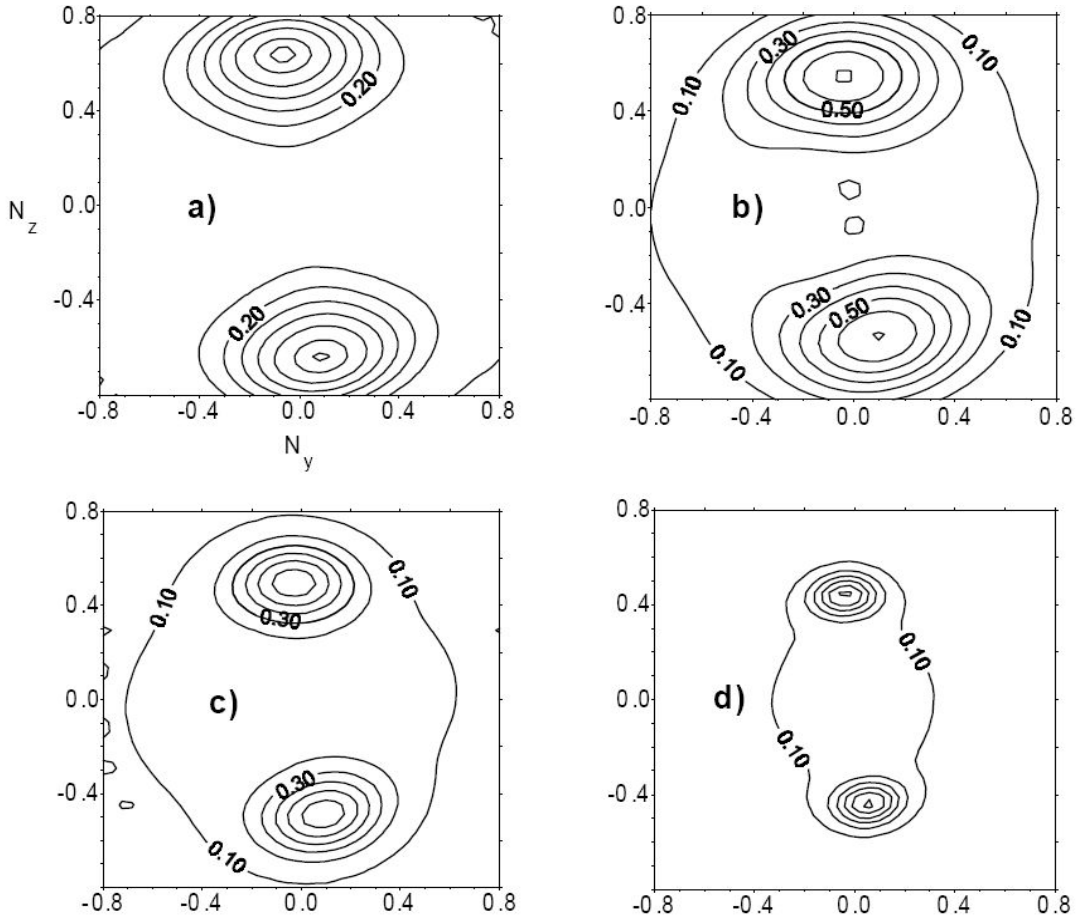
Shear Effect in Full Wave Treatment

❑ It is clear that X-O MC windows are not elliptical in full wave treatment.

❑ The effect of magnetic shear on MC is not only a tilt of MC window around optimal direction but also a tilt around $N_z = 0$, $N_y = 0$.

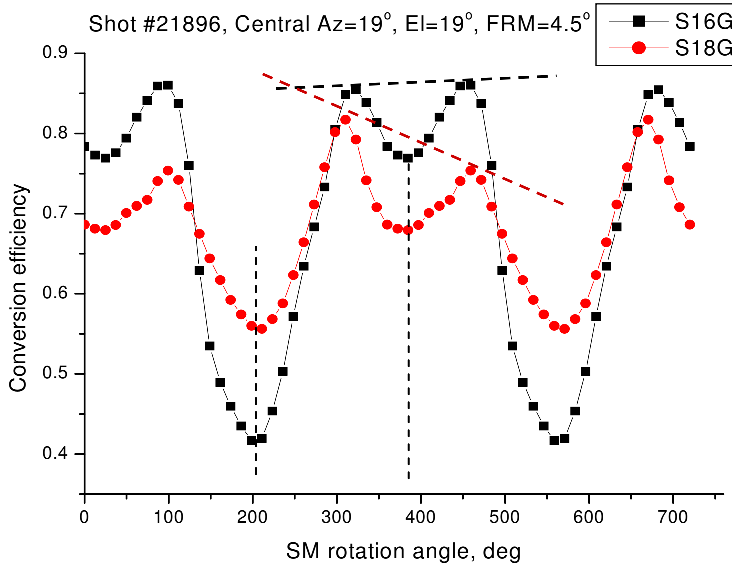
❑ In the presence of steep density and magnetic field gradients the full wave solutions may be very different from the WKB estimates.

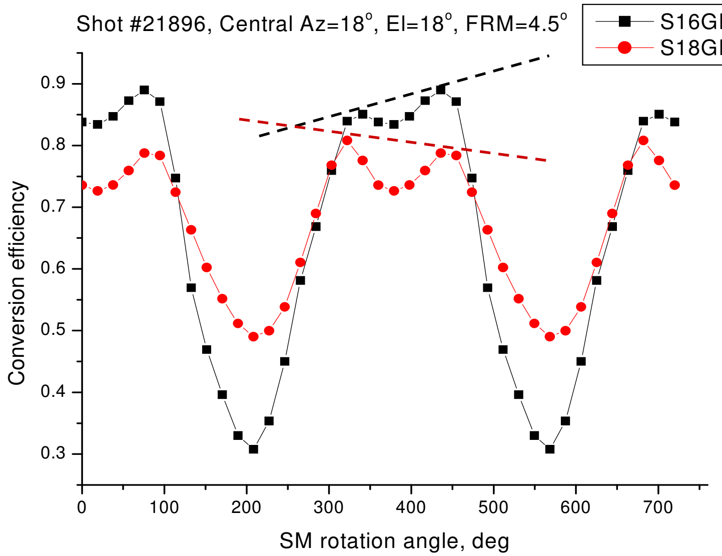


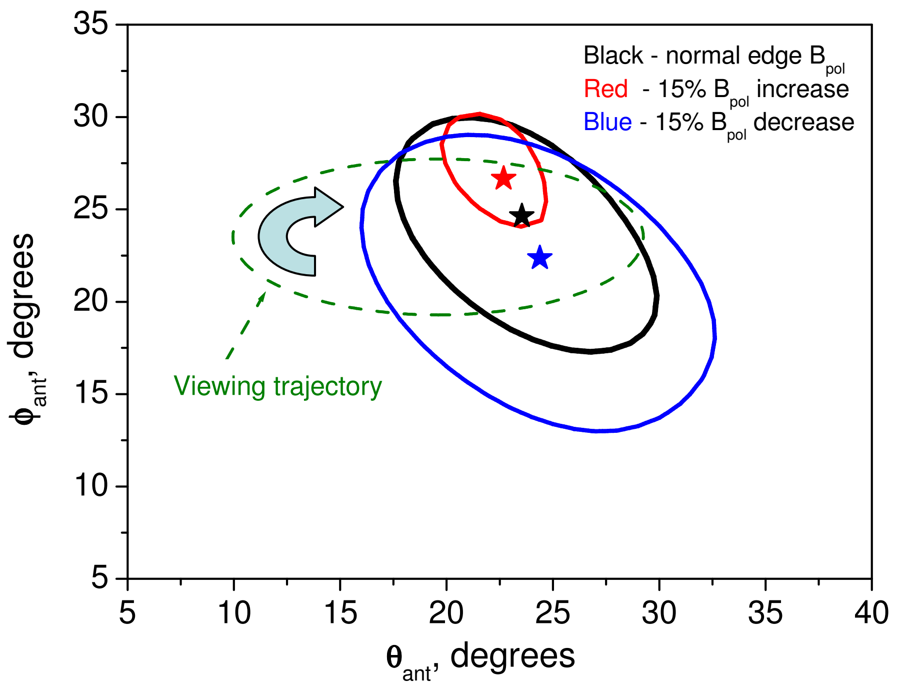
J. Preinhaelter et al, Rev. Sci. Instrum., Vol. 72, No. 1, January 2001

Contour plots of the B-X-O MC in N_y – N_z plane for linearly polarized wave. H-mode plasma (small L_n) in MAST, shear included. ***a)*** *18 GHz,* ***b)*** *30 GHz,* ***c)*** *40 GHz,* ***d)*** *60 GHz .*

Simulated Signals from Radiometer with FRM



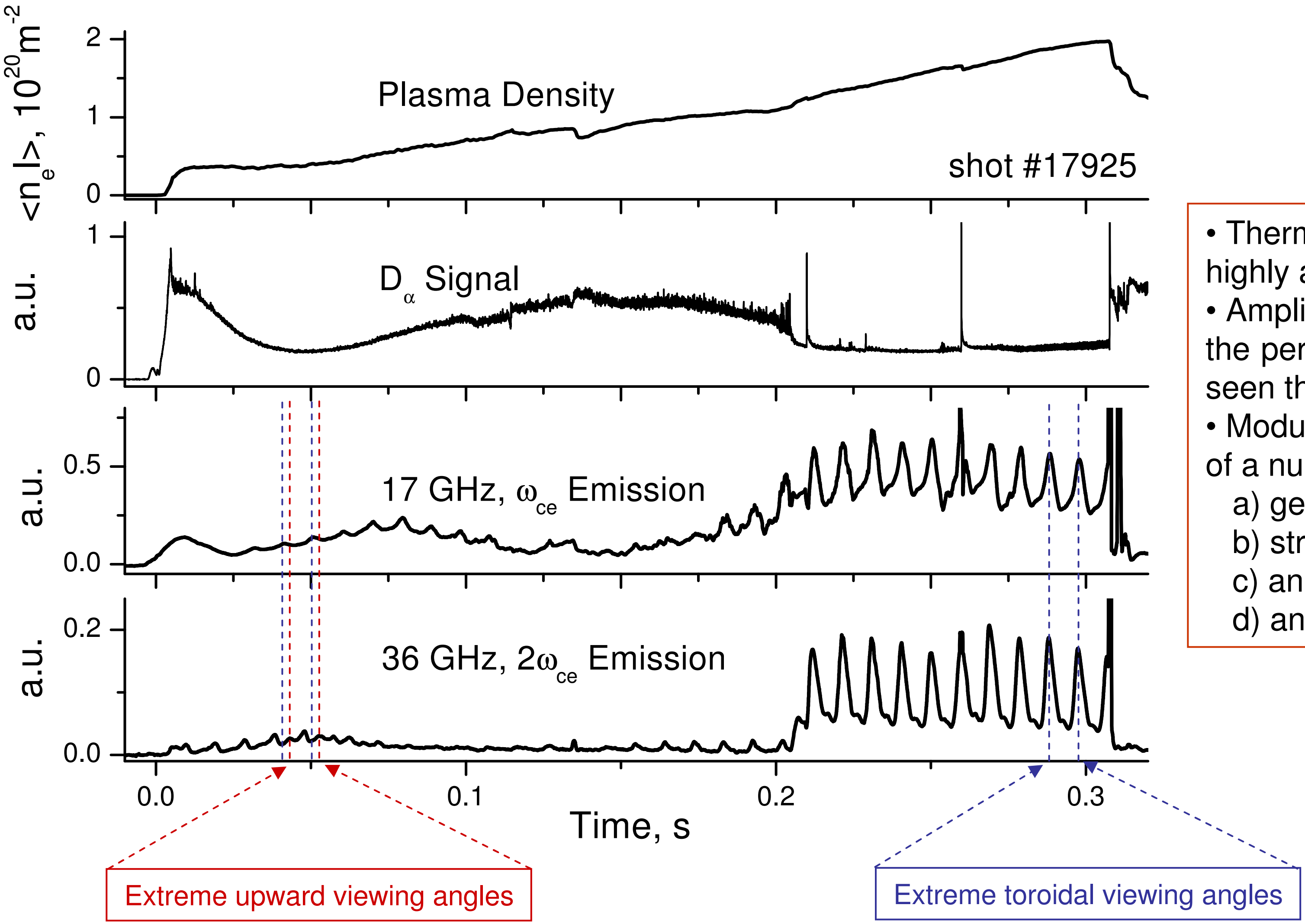




Full wave B-X-O mode conversion (MC) 50% windows at 18 GHz for various pitch angles of the magnetic field in the conversion layer – various colours. Angular range covered by 4.5º FRM.

Full wave simulations for FRM, based on EFIT and TS

EBE Observation with FRM



- Thermal plasma emission is highly anisotropic
- Amplitude modulation with the period of mirror rotation is seen throughout the shot
- Modulation is a combination of a number of factors:
  - a) geometric modulation
  - b) stray radiation
  - c) anisotropic ECE
  - d) anisotropic EBE

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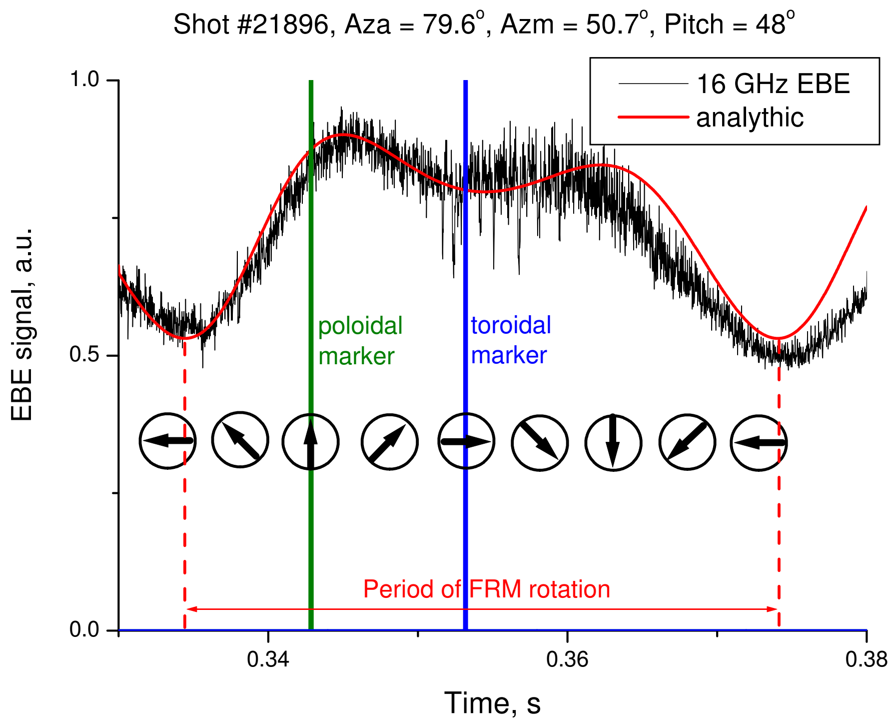
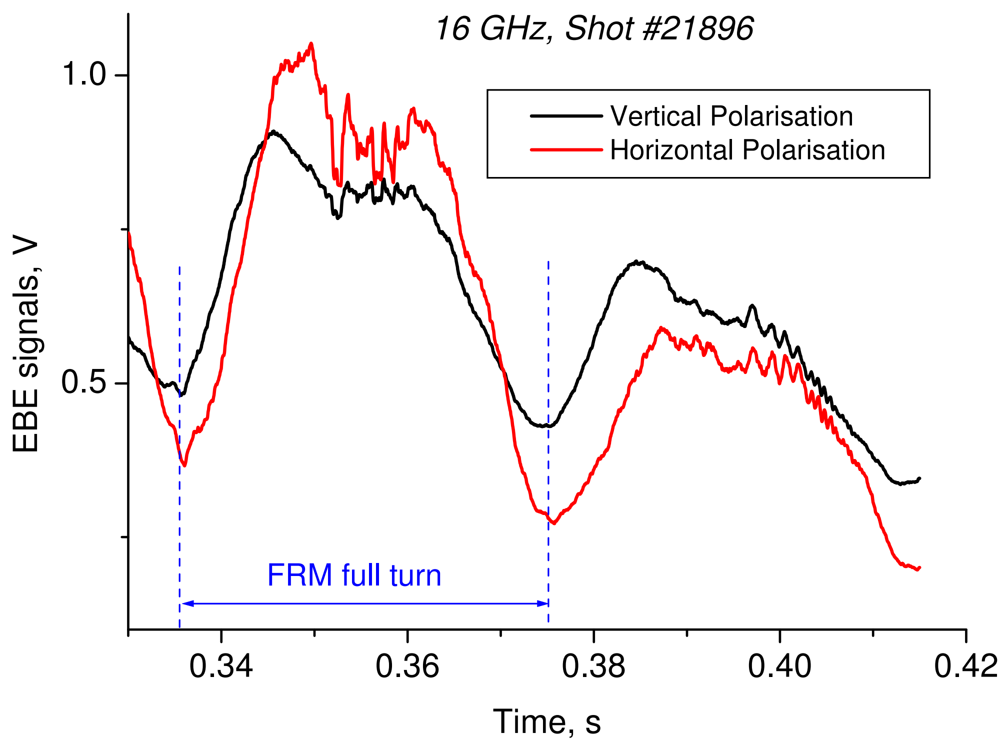
Measurements at Two Polarisations

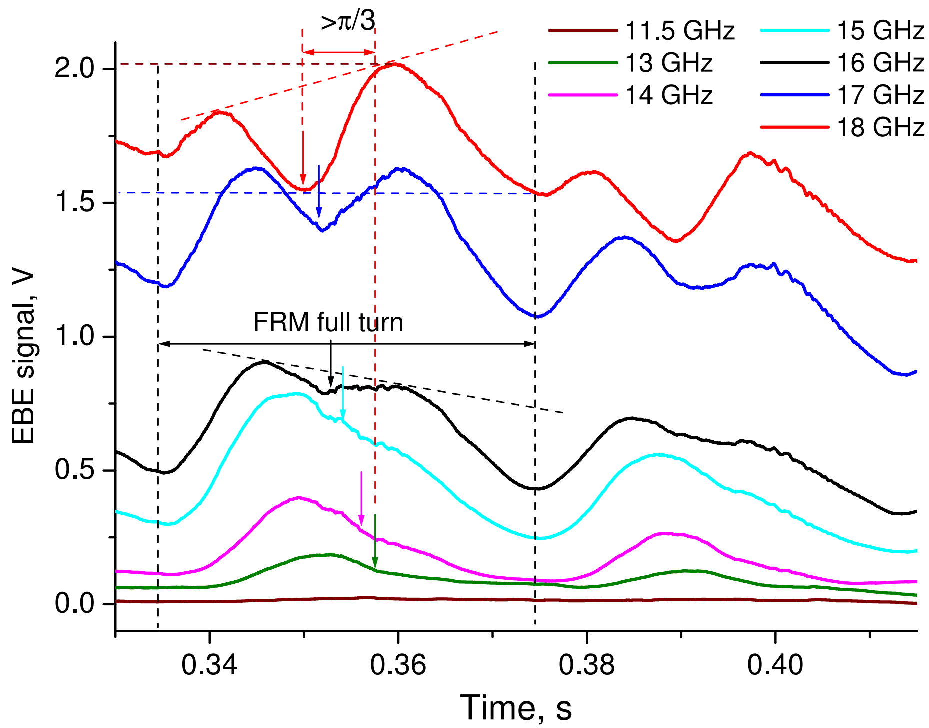


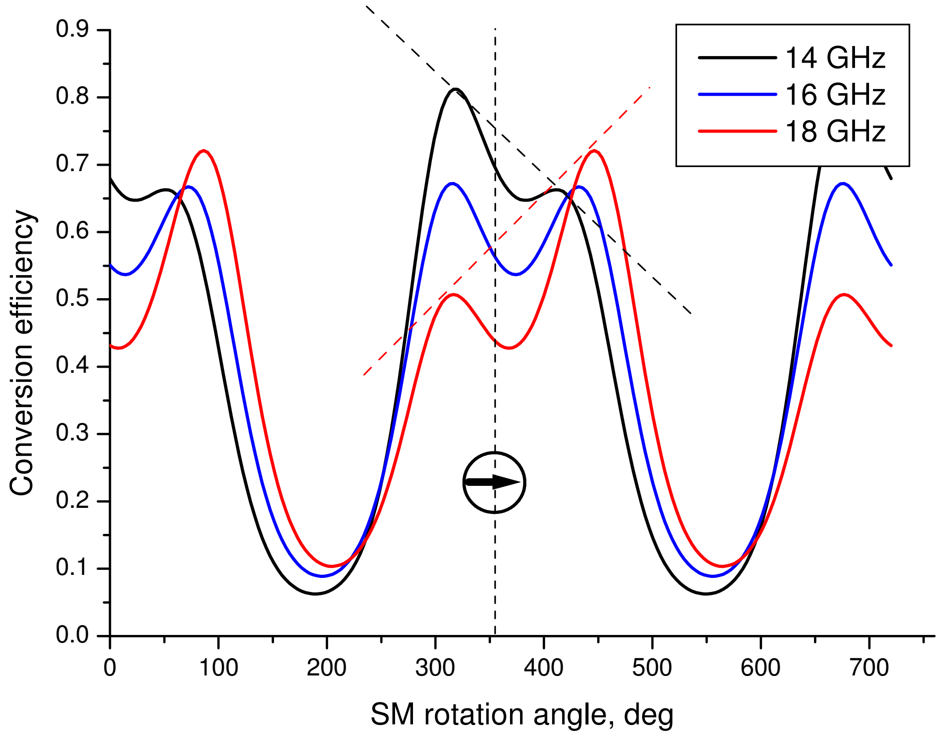


One FRM period of EBE signal at 16 GHz during ELM-free H-mode – black. Analytic EBE signal – red. Best match was achieved at n_e / grad(n_e) ~ 5 mm and magnetic pitch angle of 48°.

16 GHz EBE signal measured simultaneously at perpendicular polarisations. Signals have similar amplitudes indicating close to circular polarisation.

EBE in a Range of Frequencies

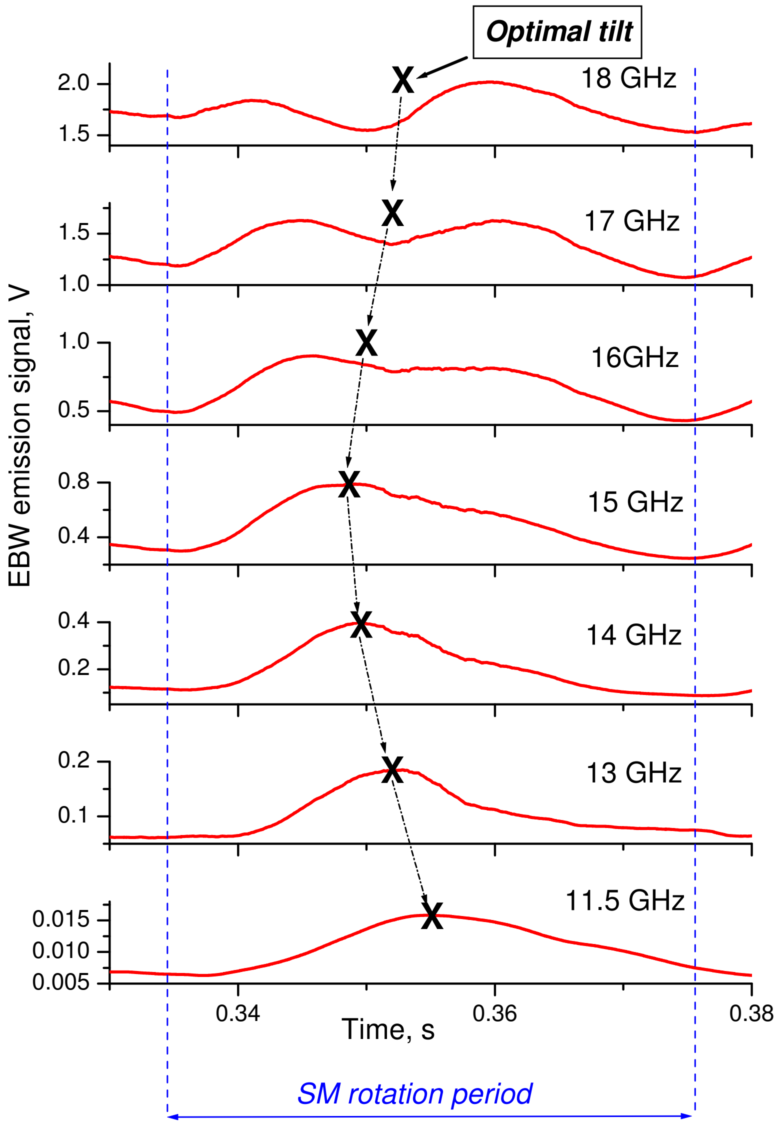




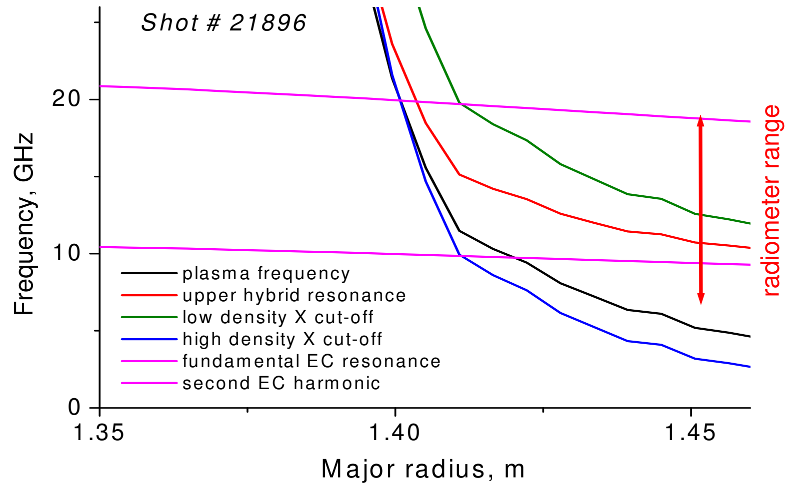
EBE signals with FRM during ELM-free H-mode, shot # 21896. Note the delay of the dip in EBE signals with the frequency decrease ➔ Magnetic pitch angle quickly decreases toward the edge. Modulation depth of EBE is smaller than predicted by full-wave modelling by factor of 2. ➔ The MC window is wider ➔ Local density gradient may be higher than estimated from TS. ➔ The delay of the dip typically is larger than π/3 between 18 and 13 GHz EBE which requires pitch angle decrease ~20º in less than 2 cm layer.

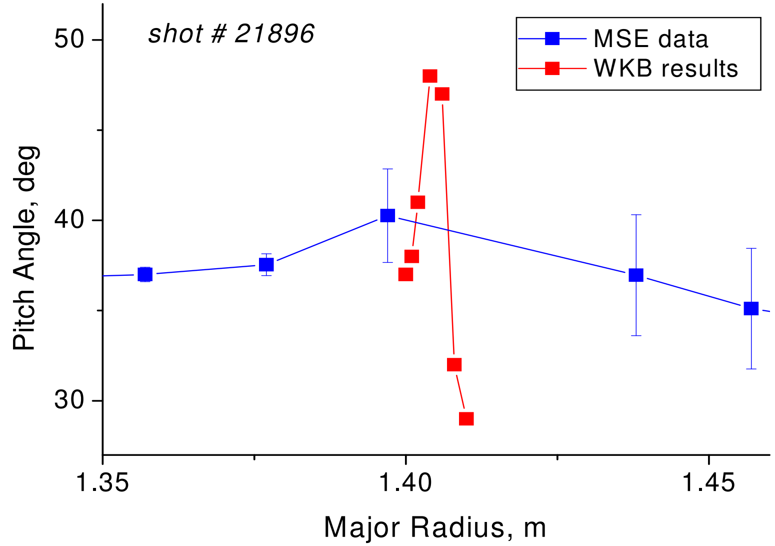
MC efficiency calculated analytically. The delay of the dip can be explained only by a decrease of the magnetic pitch angle towards the plasma edge. Required pitch angle gradient is about 1 degree/mm. Distance between 18 GHz and 14 GHz MC layers is about 8 mm from TS.

Pitch Angle Reconstruction from EBE



EBE signals from fundamental EC resonance





Pitch angle from MSE and EBE measurements.

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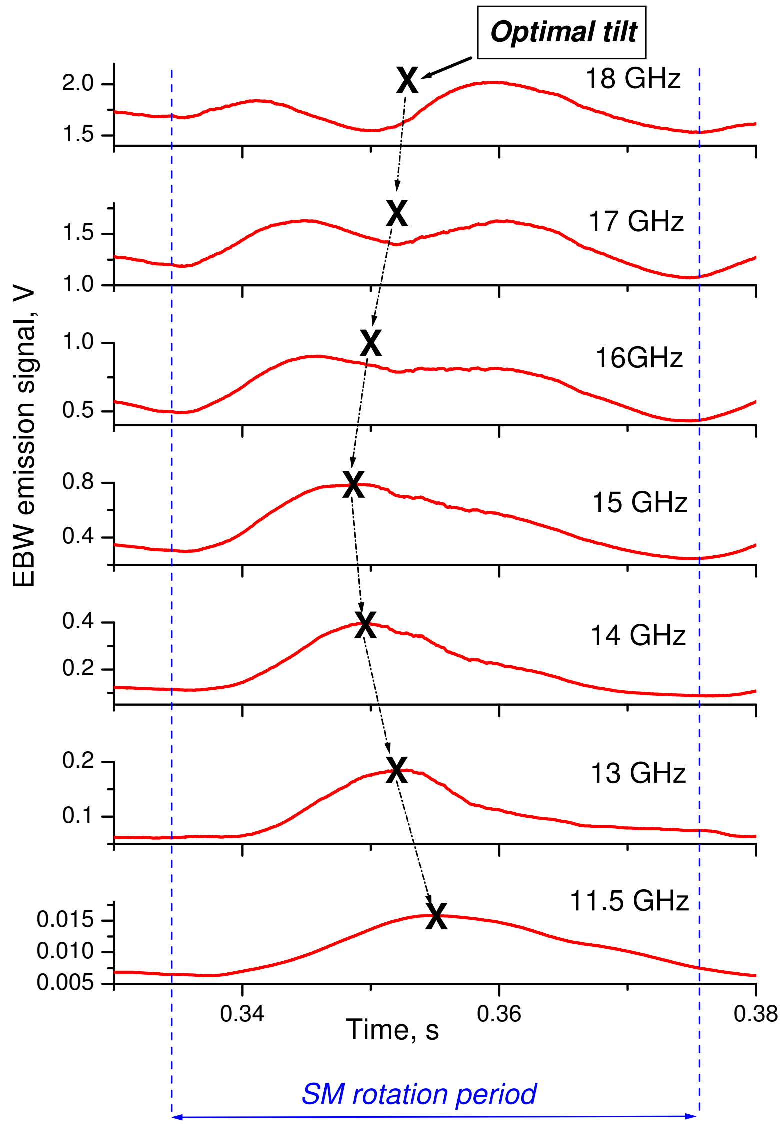
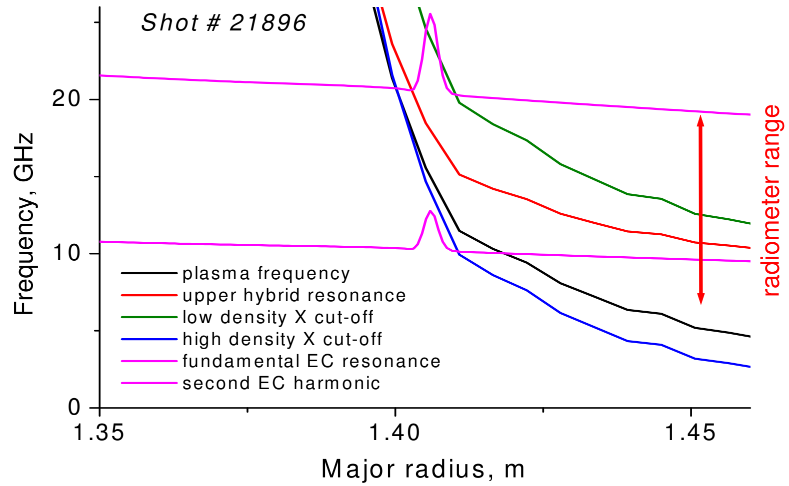
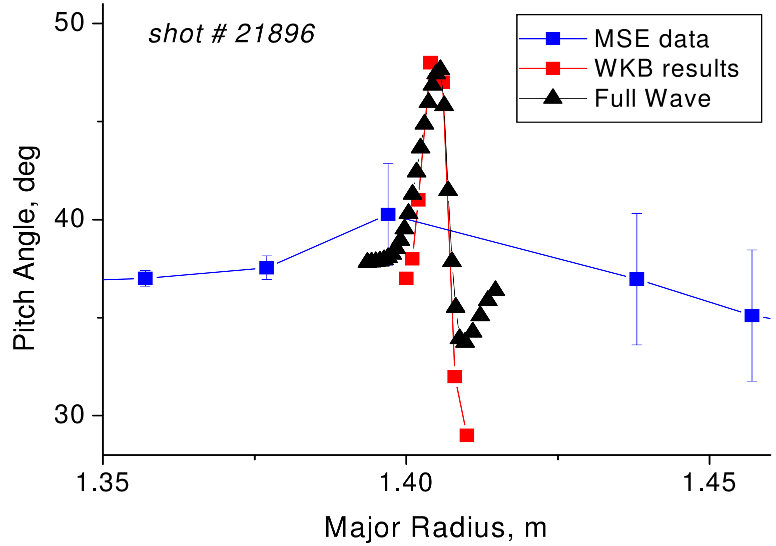
Pitch Angle Reconstruction from EBE



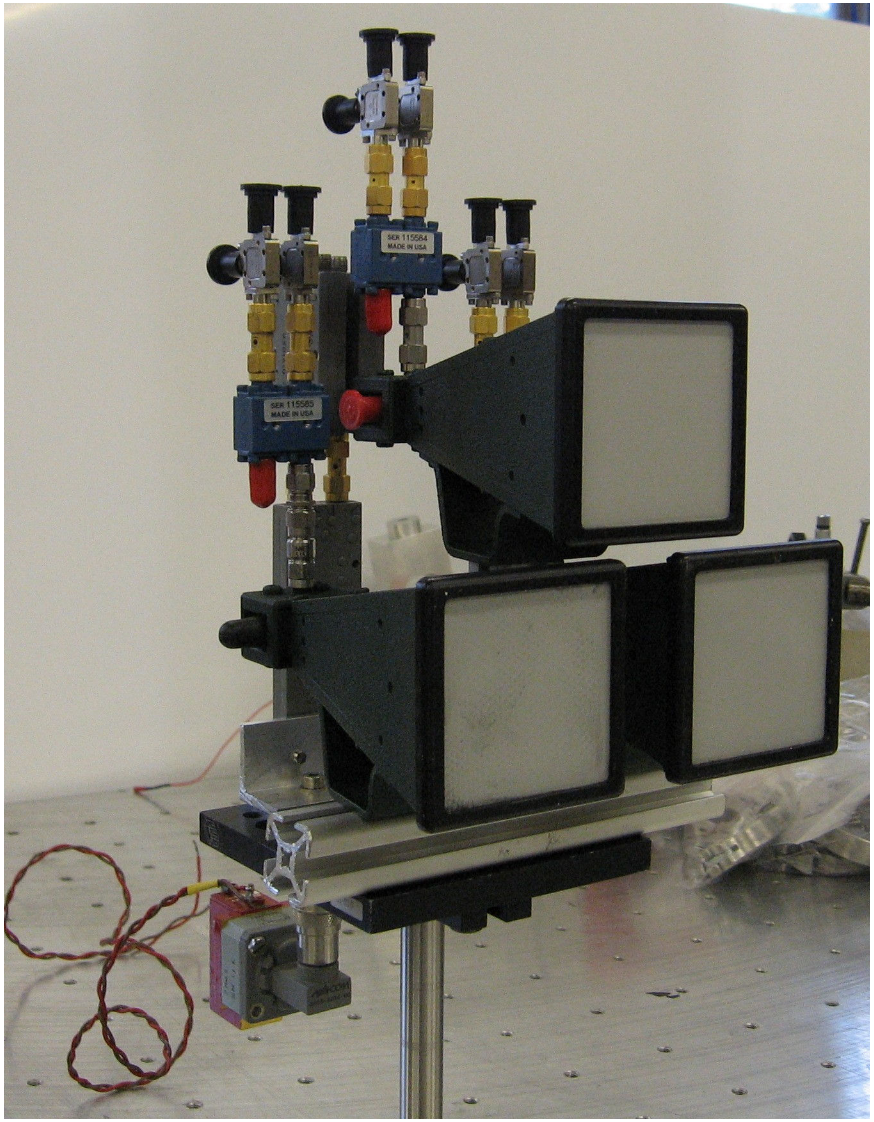
EBE signals from fundamental EC resonance





Full wave analysis of EBE measurements.

EBE Imaging – Edge q Diagnostic



3 antenna array assembled for laboratory tests.

Figure 2.3: The Very Large Array in New Mexico. Image: NRAO/AUI/NSF. http://www.nrao.edu

- ❑ MC processes are intrinsically 2D
- ❑ Angular structure and position of MC windows are strongly related to the edge current distribution
- ❑ EBE imaging is based on the phased array image reconstruction and aperture synthesis technique
- ❑ Two polarizations are simultaneously recorded from each antenna
- ❑ Antennas cover the range from 6 to 40 GHz
- ❑ IF signals are digitized directly in a full vector form with digitization rate of 250 Msps
- ❑ First experiments are planned in 2010

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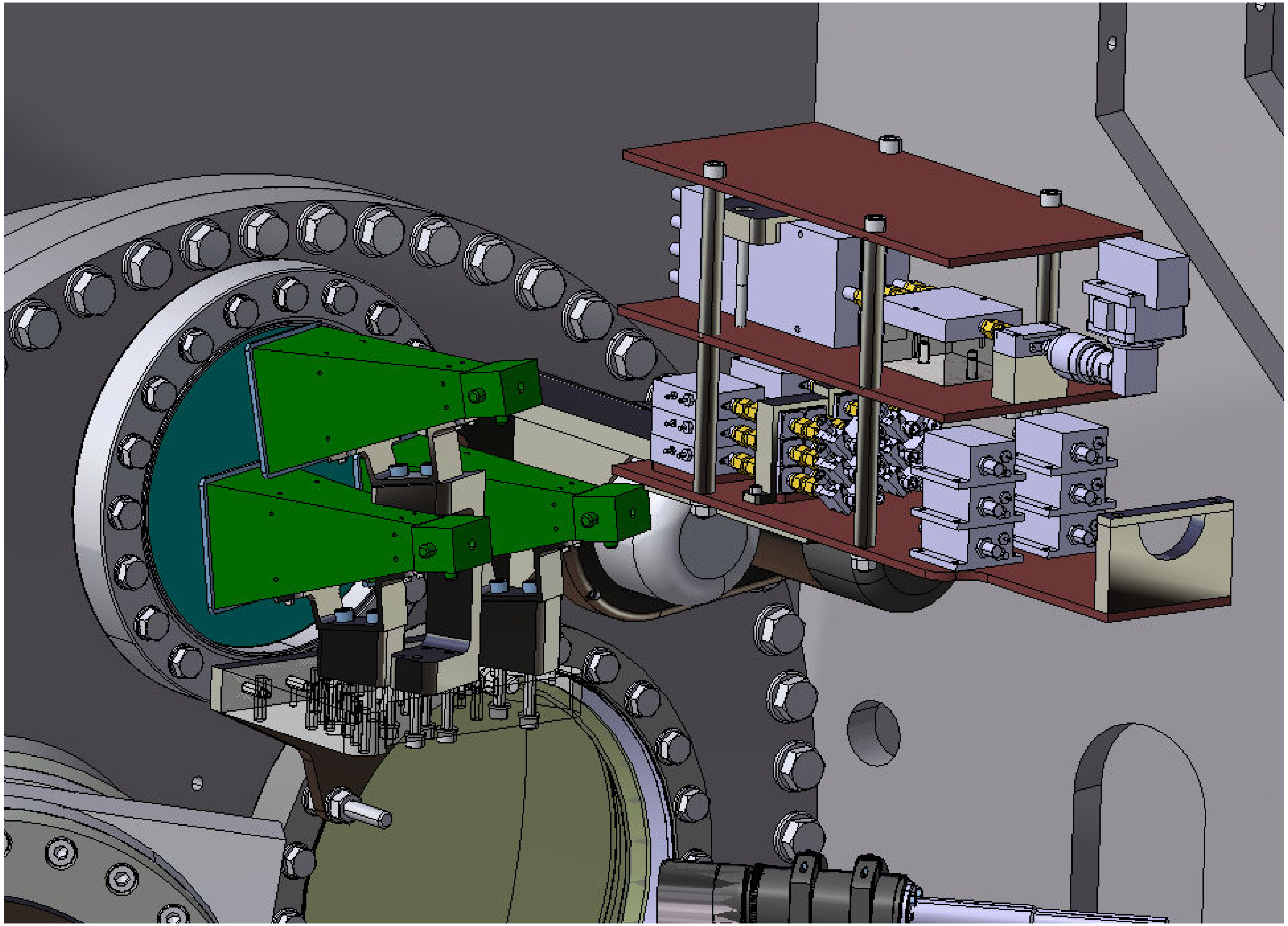
EBE Imaging – Trial Experiment on MAST



3 antenna array installed in sector 7 on MAST.

Summary

- Feasibility studies of thermal EBW emission as a potential edge current diagnostic have been conducted on MAST with the fast rotating mirror.

- In H-mode the magnetic pitch angle, estimated from EBE, has a narrow maximum near the bottom of the $2\omega_{ce}$ resonance. This agrees well with earlier EBE spectral observations.

- Pitch angle variations (WKB analysis) at the plasma edge are stronger than measured by MSE. Full wave EBE analysis is in agreement with WKB results.

- Spatial resolution of the FRM technique is limited by TS space resolution.

- Temporal resolution is limited by the FRM speed, typical 10 ms and 5 ms at maximum FRM speed.

- EBE imaging based on a phased array imaging technique is under development.