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Central MHD Modes during High-Power Lower Hybrid and Electron Cyclotron Heating in the FTU Tokamak.

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Introduction: During high-power lower-hybrid (LHCD) and Electron cyclotron (ECCD) heating and current drive on of the FTU Tokamak MHD modes appear in the spectra measured by the soft X-ray (SXR) cameras. The frequency of these modes lies between 10 and 60 kHz. The modes appear on the central SXR channels, typically within a radius of 30% of the plasma radius of 0.3 m. These modes if visible at all have very low amplitude on the Mirnov coils ($\delta B/B \leq 5.10^{-5}$), consistent with the fact that these are modes localised near the plasma centre. Plasma conditions are: B_T=5-7 T, I_p=0.4-1.1 MA, n_e=0.8-1.5 10^{20} m^{-3}, T_e = 5-7 keV. See V.Pericoli. [1]

Tomographic Techniques. The plasma surfaces are defined by the Lao-Hirschman geometry:

$$R = R_0(x) + x \cos\gamma + R_2(x) \cos 2\gamma \qquad (1)$$

$$z = E(x) (x \sin\gamma - R_2(x) \sin 2\gamma) \qquad (2)$$

with $0 < x < a$, a being the plasma radius. γ is the poloidal angle, R_0 is the centre of the plasma surface x in the horizontal plane R, E the ellipticity of the surface and R_2 is its triangularity. z is the vertical axis. Asymmetric terms can be added without foreseeable problems. For the moment E is set to: $E(x) = E_0 + E_2 (x/a)^2$ and $R_2(x) = R_2 (x/a)^4$, in principle these quantities can be obtained from the tomography itself, using both vertical and horizontal pinhole cameras. For carrying out a tomographic inversion the tangent and crossing points of all lines-of-sight with all plasma surfaces have to be calculated. Line-of-sights are defined by: $z = z_s + m (R-R_s)$ (3) with R_s, z_s the coordinates of the slit or pinhole and m the tangent of the angle of the line with the horizontal axis. The tangent point is calculated from the dz/dR of the surface equating it to the slope of the line-of-sight m.

$$dz/dR = -E (\cos\gamma - 2\delta \cos 2\gamma)/(\sin\gamma + 2\delta \sin 2\gamma) = m \quad \text{with} \quad \delta = R_2(x)/x << 1.$$

This results in the following equation for γ to be solved:

$$\cos(\gamma + \alpha) = 2\delta \cos(2\gamma - \alpha) \quad \text{with} \quad \alpha = \text{atan}(-m/E) \qquad (4)$$

This is readily solved by iteration since $\delta<<1$. In fact always: $\gamma + \alpha \approx \pm\pi/2$. The sign depends on position of the line-of-sight with respect of the line connecting the plasma centre and the pinhole of the camera. The crossing points are calculated by substituting the R,z values of equations (1) and (2) into line-of-sight equation (3):

$$E(x)\,(x \sin\gamma - R_2(x) \sin 2\gamma) = z_s + m\,(R_0(x) - R_s + x \cos\gamma + R_2(x) \cos 2\gamma)$$

This can be written as:

$$\sin(\gamma+\alpha) = U + \delta \sin(2\gamma-\alpha) \quad \text{with} \qquad (5)$$

$U = (z_s + m\,(R_0-R_s)) \cos\alpha / (E\,x) = ((R_s-R_0)/x) \sin(\theta_0+\alpha)$ and $\theta_0 = \mathrm{atan}(z_s / (E\,(R_s-R_0)))$

Again because $\delta \ll 1$ this equation is readily solved for γ. There are 2 solutions: γ and $\pi-\gamma-2\alpha$, except when $\gamma+\alpha = \pm\pi/2$ in that case we have the tangent point.

It is now possible to calculate the line segments for each line-of-sight and the poloidal angles associated with these. A 2nd order scheme has been used to calculate the matrix elements for the tomographic inversion [2] and the rotation of the MHD modes is used to map the modes on the poloidal plane, where it is assumed that the modes phase lock, so that modes with the same toroidal mode number n show up with the same frequency. It seems that at higher mode amplitudes this is always the case. In particular n=2 modes will have a frequency of twice that of the n=1 modes.

General MHD Behaviour during high-power LHCDand ECCD heating and current drive.

The modes appear when the LHCD power gets over 1 MW and appear stronger in better plasmas with higher pressure gradients. The LH power then drives a substantial part of the plasma current and leads to substantial changes in the central safety factor q_0. The value of q_0 increases as a function of time during the heating phase as calculated with the JETTO code. And q-profiles can become hollow, in this case we observe a time-sequence of central modes at different frequencies.

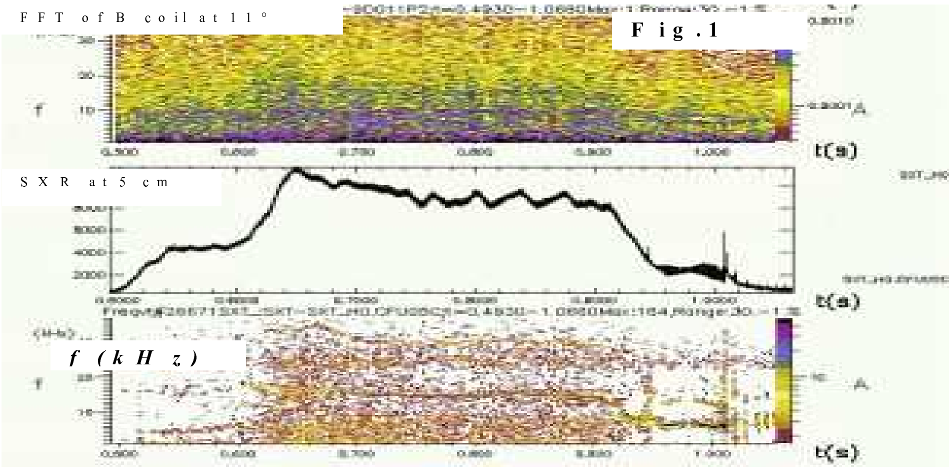
Various modes are likely to become unstable when rational q values are passed.

In discharges with ECCD in counter-current drive the changes in q_0 are more immediate leading to the appearance of a continuous mode at 15 kHz of an odd parity.

This mode is believed to be a (3,2) mode consistent with the fact that q_0 is above unity (sawteeth disappear).

The mode is just visible on the Mirnov coils with $\delta B/B \leq 5.10^{-5}$. See fig.1. The toroidal n-number is difficult to determine and has a value of 2±1. Its m-number is 3 at the low field side and higher elsewhere.

It can be seen that apart from the MHD activity on the Soft X-rays (lower part of thfig.1) at 15 kHz and its harmonic plus weaker modes at roughly half that frequency (n=1) and some other activity roughly 1.5 times faster (n=3) are present.

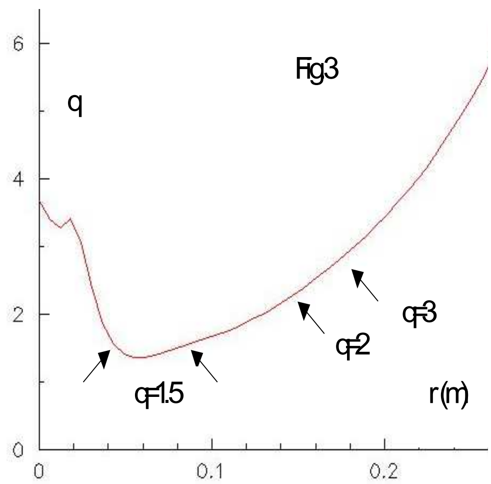


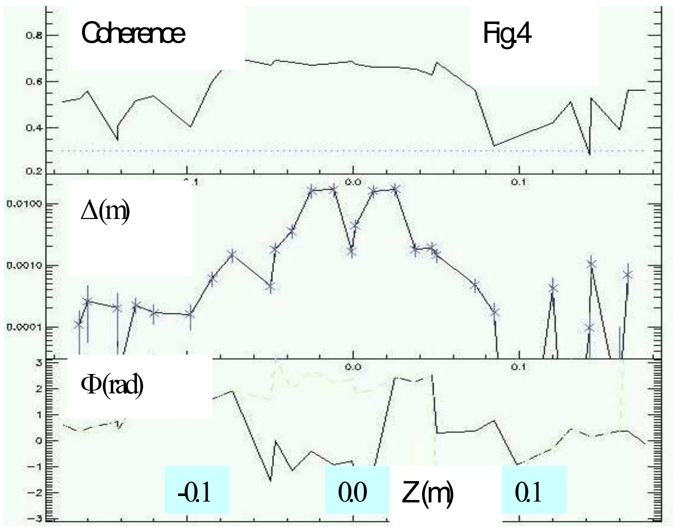
Results from the Tomography using the horizontal cameras.

The horizontal cameras have been calibrated in space and sensitivity by taking a simple mode (a central m=1 snake located at r=10 cm), which rotates before the line-of-sights of the cameras.

The result for the high power LH and ECRH discharge is less simple, because there are more modes present. In the outer plasma weak (3,1) and (2,1) are present and possibly also a (5,2). Somewhere on the inside of this starts the steep gradient of the ITB. This is also the position of the q=2 surface as calculated from the JETTO code (fig. 3).

Further inwards there is an odd mode with two π phase jumps as function of radius (at 5 and 8-9 cm) as seen from the line-integrated data (fig.4). An estimate of the displacement profile from these data yields a value of 2 cm in the centre. Indeed this has also been found by the tomography as shown in fig.5.





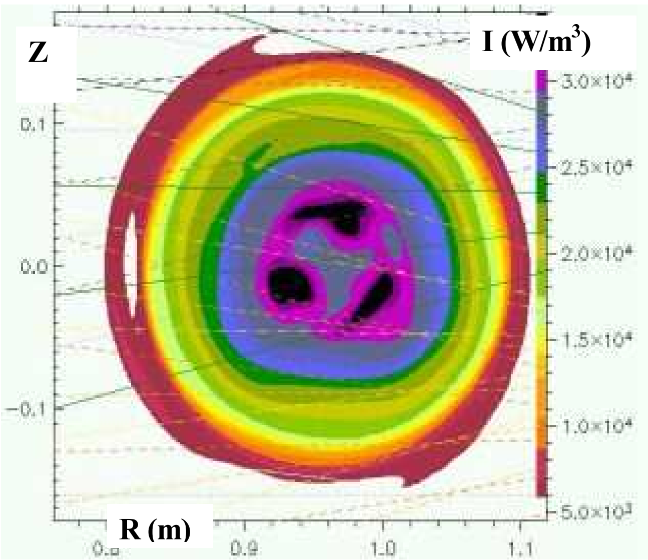


Fig.5. Plasma cross-section at t=0.85 sec using the rotating tomography code and the horizontal Soft-X-Ray cameras.

Also seen in figure 5, is that the likely (3,2) modes are no so clean:
They are deformed by other even and odd components: expected to be (2,2) in the centre and in particularly by a (4,2) mode at the radial position of 8 to 9 cm.
The positions of the MHD activity are in good agreement with the calculated q = 1.5 positions of the q profile.
It is clear from this analysis that the information of the vertical cameras is necessary to unravel the many modes present in an unambiguous way. This will be discussed further on.

Discussion and Conclusions.

The tomographic analysis has given direct evidence of the changes in the radial safety profile q, supporting the JETTO calculations. Tomographic techniques can give direct measurements too of the plasma equilibrium by determining the Lao-Hirschman coefficients.
Future developments are planned. These are:
- Use the vertical and horizontal cameras together to get the full plasma equilibrium.
    - Incorporating vertical and horizontal cameras together to obtain a higher mode separation.
    - Use the tomographic technique on a single Fourier component. This should allow a much higher signal to noise separation as in the present case where only one or two cycles are used. It also should give a much clearer mode separation of modes that have frequencies close to each other or to their harmonic overlaps.

References:
[1] V.Pericoli et al, “High density internal transport barriers for burning plasma operation”,this conference.
[2] P.Smeulders.”A fast Plasma Tomography Routine with second order Accuracy and Compensation for spatial Resolution”, Max-Planck-Institut fuer Plasmaphysik,Garching, IPP 2/252 (July 1983)