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Rotation Frequencies of MHD Modes in ASDEX Upgrade

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Introduction Plasma rotation plays an important role for understanding and controlling MHD activity in fusion devices. It is believed that plasma rotation influences the stability of MHD modes and may also prevent disruptions. It is still debatable which physics mechanisms determine the rotation frequency f_o of different MHD modes in the plasma rest frame. Various assumptions include:

$$f_o = f_{lab} - n f_{tor} \tag{1}$$
$$f_o = f_{lab} - n f_{tor} - m f_{pol} \tag{2}$$
$$f_o = f_{lab} - n f_{tor} + m f_{dia} \tag{3}$$
$$f_o = f_{lab} - n f_{tor} - m f_{pol} + m f_{dia} \tag{4}$$
$$f_o = f_{lab} - m f_{E\times B} \tag{5}$$

where n and m are the toroidal and poloidal mode numbers and f_{lab} is the frequency of the mode in the lab frame of reference measured by the Mirnov pick-up coils. f_{tor} $[= v_{tor}/(2\pi R)]$, f_{pol} $[= v_{pol}/(2\pi r)]$, f_{dia} $[= v_e^*/(2\pi r)]$ and $f_{E\times B}$ $[= v_{E\times B}/(2\pi r)]$ are the frequencies derived from the toroidal velocity v_{tor}, poloidal velocity v_{pol}, electron diamagnetic velocity v_e^* and the $E \times B$ velocity $v_{E\times B}$ respectively at the major radius R (and minor radius r) where the mode is localized.

The frequency f_o is often associated with the plasma toroidal rotation at the modes' rational q surface (i.e. assumption (1)) since this rotation dominates in the plasma core. However, recent measurements at JET imply that the poloidal rotation may also contribute and therefore assumption (2) is relevant. Previous analysis in ASDEX Upgrade considered assumption (3) [1]. In addition, it is predicted that certain modes, such as ideal and resistive MHD modes, rotate with the ExB velocity, giving assumptions (4) and (5) [2]. These two assumptions are identical and differ only in the methods in which they are measured. The rotation and mode frequency of various MHD modes, such as neoclassical tearing modes (NTM) and toroidicity induced Alfven eigenmodes (TAE), are investigated here in co-NBI injected discharges and used to test these various assumptions.

Technique In the calculation of f_o, the toroidal rotation is measured by Charge Exchange Recombination Spectroscopy (CXRS), where the carbon impurity velocity is assumed to be the main ion velocity. The poloidal rotation is determined by the neoclassical code NEOART [3], the diamagnetic velocity is computed from the electron density and electron temperature (both provided by the Thomson scattering diagnostic) and the $E \times B$ velocity is measured by Doppler reflectometry, assuming that the phase velocity of the turbulence is small [4]. The errors in f_o are calculated using the partial derivatives of the various rotation terms.

Two methods are presented for assessing the f_o assumptions. For NTMs, the frequencies of the modes are compared with the frequencies of their harmonics, where f_o is the mode frequency, $2f_o$, the frequency of the second harmonic, $3f_o$, the frequency of the third harmonic and so forth. In addition, the magnitude and sign of the frequencies are investigated. Here, + (-) f_o corresponds to the mode rotating in the ion (electron) diamagnetic direction. For TAEs, the frequencies f_o may be compared with theoretical predictions, in which the TAE moves with a frequency $f_o = v_A/(4\pi qR)$, where $v_A = B/(\mu_o \rho_m)^{0.5}$ and $q = (2m+1)/2n$ [5].

Case Study 1 - NTMs In ASDEX Upgrade, NTMs are triggered by rapidly stepping NBI heating power up to high power levels at the start of the discharge as seen in figure (1). Once the NTM is established, ECRH heating is applied during a ramp in the magnetic field to hit the resonance surface and stabilize the mode. In discharge #20774, a (2,1) NTM and its harmonics are detected on a frequency spectrogram of the magnetic pick-up coils. The mode is localized at normalized radius $\rho_{pol} \approx 0.70$, determined by electron cyclotron emission (ECE) and soft-Xray diagnostics. At this radial position, the rotation and mode frequencies

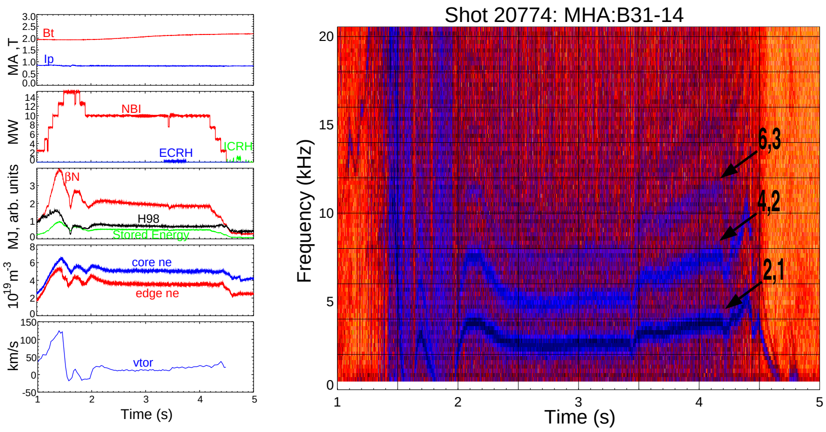

Figure 1: *Time traces of plasma parameters in discharge #20774. On the right hand side is the spectrogram from the mirnov pick-up coils, showing the onset of a (2,1) NTM and its harmonics at 2s.*

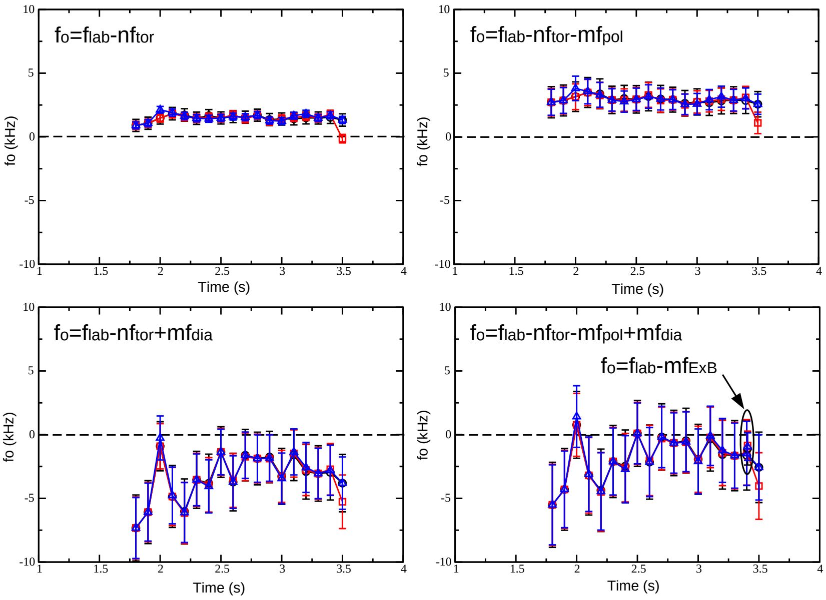

Figure 2: *Frequencies of a (2,1) NTM mode (black ◯), its 4,2 harmonic (red □) and 6,3 harmonic (blue △) in discharge # 20774.*

are calculated using assumptions (1) to (5) and are shown in figure (2) for the mode and its harmonics.

In all cases, the f_o calculated for the mode and its harmonics agree as expected. Using assumptions (1) and (2), f_o is small and the mode is moving in the ion diamagnetic direction. This has been reported previously on other fusion devices [6, 7]. However, when the diamagnetic velocity is also included, the mode appears to be at rest at 0kHz. The single measurement from Doppler reflectometry at 3.4s confirms this. Assumptions (3) and (4) give similar frequencies since the poloidal velocity is small and negligible here. Note the error bars are larger when including v_e^* due to the uncertainty in the electron density and temperature profiles.

A similar trend in f_o can be seen in discharge # 20097 in which a (3,2) NTM is localized at $\rho_{pol} \approx 0.73$. The calculations show that when considering purely poloidal and toroidal plasma rotation at this q surface, f_o is about +8kHz, as seen in figure (3). In this particular case, the poloidal rotation is very small. The diamagnetic velocity contribution reduces the f_o to about 0kHz, in agreement with four values of f_o calculated from the $E \times B$ velocity. If

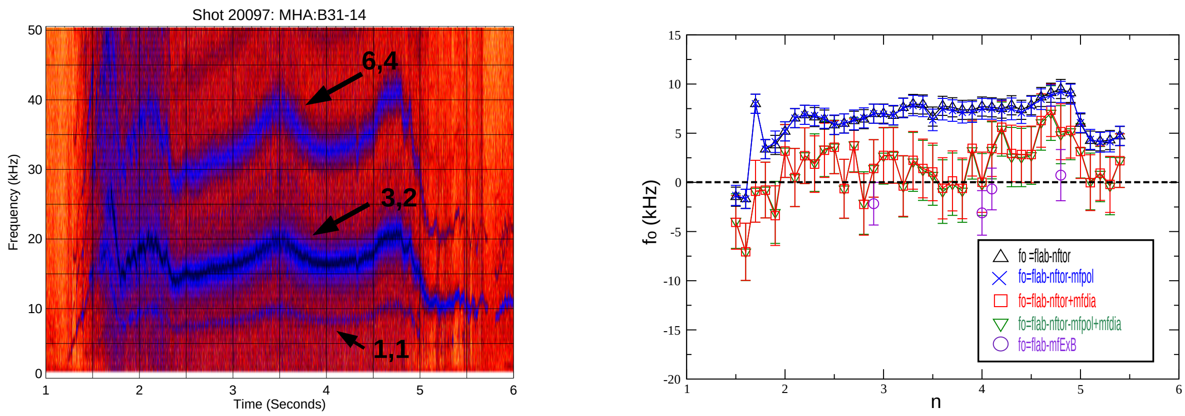

Figure 3:*Frequencies of (3,2) NTM mode in discharge #20097.*

NTMs rotate with the plasma $E \times B$ velocity (assumptions (4) and (5)) as predicted [2], then the modes have a rest frequency of 0kHz. This means that NTMs have no intrinsic rotation.

Case Study 2 - TAE TAE modes are destabilized on ASDEX Upgrade by ICRF heating. In order to measure the toroidal velocity with CXRS, short NBI blips ($\approx$ 50ms) are introduced. Figure (4) shows the frequency spectrogram from the magnetic pick-up coils of a TAE mode with different n numbers and the frequencies f_o calculated at 4.65s, at the time of an NBI blip, and at $\rho_{pol} \approx 0.53$. There is good agreement between the theoretical equation for f_o and assumptions (3) and (4). The f_o calculated by assumptions (3) and (4) show no dependence on the n number, being constant at roughly 134kHz. On the other hand, assumptions (1) and (2) have poorer agreement, indicating that the diamagnetic velocity is not negligible. A possible explanation for the poor agreement might be the underestimation of v_{tor}. A q=1 mode with $f_{lab} \approx f_{tor} \approx$ 4kHz is observed before and immediately after the NBI blip. Taking this extra rotation into account decreases the f_o calculated by assumptions (1) and (2) to frequencies closer to the theoretical frequencies.

Case Study 3 - Disruptions by (2,1) NTMs

A plasma disruption can be preceded by the growth of a tearing instability resonant at the $q = 2$ surface. Figure (5) shows plasma parameters during discharge # 21363, in which

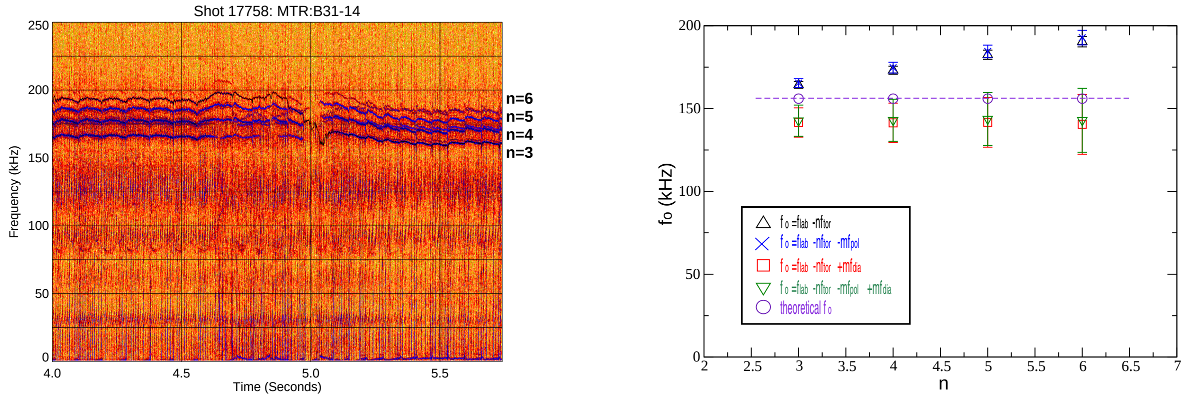

Figure 4:*Frequencies of TAE modes in discharge #17758.*

a (2,1) NTM mode grows, locks and causes a plasma disruption at 4.2s. The frequencies f_o are calculated at the onset of the mode at 1.1s and right before the disruption at 4.1s. For all f_o assumptions, the frequency drops before the disruption and in some cases the mode rotation changes from the ion to the electron diamagnetic direction. For example, $f_o = f_{lab} - n f_{tor} - m f_{pol} + m f_{dia}$ =2.6kHz at 1.1s and -3.6kHz at 4.1s. Likewise, f_{lab} decreases from 15.4kHz to 2.7kHz and f_{tor} decreases from 3.3kHz to -0.9kHz. This implies that to avoid a disruption, an increase in the plasma toroidal velocity is necessary. On other fusion devices, this technique has proven to work [8, 9].

Summary Several assumptions for f_o have been tested for NTM and TAE modes in co-NBI injected discharges. The rest frame frequencies during an NTM are small and the rotation is in the ion diamagnetic direction when considering only toroidal and poloidal fluid velocities. However, with the inclusion of the diamagnetic velocity as required [2], f_o decreases to roughly 0kHz, indicating that NTMs have no intrinsic rotation. Assumption (3) is identical to assumptions (4) and (5) when the poloidal velocity is small, which is typically the case in the plasma core. In the case of TAE modes, when comparing the f_o assumptions with f_o predicted from theory, assumptions (3) and (4) agree best. Hence, the diamagnetic velocity is not negligible and should be included in f_o calculations.

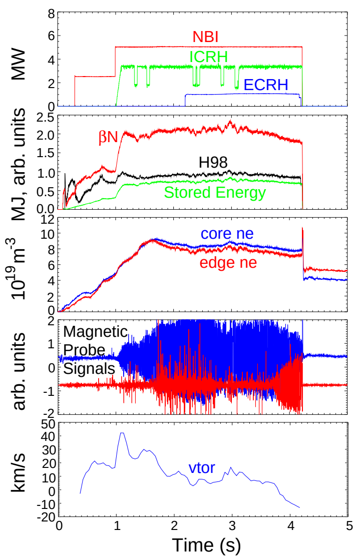

Figure 5: *Time traces of plasma parameters in discharge #21363.*

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