# AN ANALYSIS OF PLASMA ION TOROIDAL ROTATION DURING LARGE AMPLITUDE MHD ACTIVITY IN JET

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Introduction A detailed study of plasma ion toroidal rotation in JET during large amplitude MHD activity has revealed a strong viscous force that couples plasma ions to MHD modes. Depending on the MHD modes present, this force can couple across all of the plasma cross section, across only the central region, roughly within the q=1 surface, or across only the outer region outside the q=1.5 surface. The force acts to flatten the ion toroidal rotation frequency profile, measured by the JET active charge exchange spectroscopy diagnostic [1], across the coupled region of plasma. The frequency of rotation in this region agrees with the MHD oscillation frequency measured by magnetic pick-up coils at the wall. The strength of the force between the ions and modes becomes evident during high power NBI when the mode locks [2] and drags the ion toroidal rotation frequency to zero, within the errors of the measurements. The present theories of plasma rotation either ignore MHD effects entirely [3], consider only moderate n toroidal field ripple [4], or low n ripple effects [5].

Sawtooth Related MHD Modes As observed previously on JET [6] and on ISX-B [7], the measured MHD frequency of m=1, n=1 modes agrees well with the central plasma ion toroidal rotation frequency. Sawtooth precursor and postcursor oscillations driven by m=1, n=1 modes at the q=1 surface are toroidally coupled to n=1 modes near the plasma boundary with higher m numbers also with n=1. These coupled modes maintain the same oscillation frequency as the m=1, n=1 mode, but have $m/n \approx q_\psi(a)$. That is, modes at the plasma edge take on the rotation frequency of the driving mode from the q=1 surface. Thus, even for very peaked ion toroidal rotation profiles, the measured MHD oscillation frequency at the edge agrees with the plasma ion rotation frequency measured in the center during NBI.

Figure 1a shows an example of a reasonably peaked ion toroidal rotation frequency profile during sawtooth related MHD activity. Note that, during sawtoothing, the ion rotation profile is always flat across the central region, which is roughly the extent of the q=1 radius. In the top traces, the central ion rotation frequency closely follows the peaks of the MHD oscillation frequency. The measurement of the MHD frequency is made by a zero crossing frequency to voltage converter with an n=1 combination of poloidal field pick-up coils as input. The rapid collapses in the MHD frequency are partly real changes in the oscillation frequency (that are to rapid to be observed by the charge exchange diagnostic due to its 50 msec integration time and 50 msec dead time) and partly due to the MHD signal dropping below the threshold of the frequency to voltage converter.

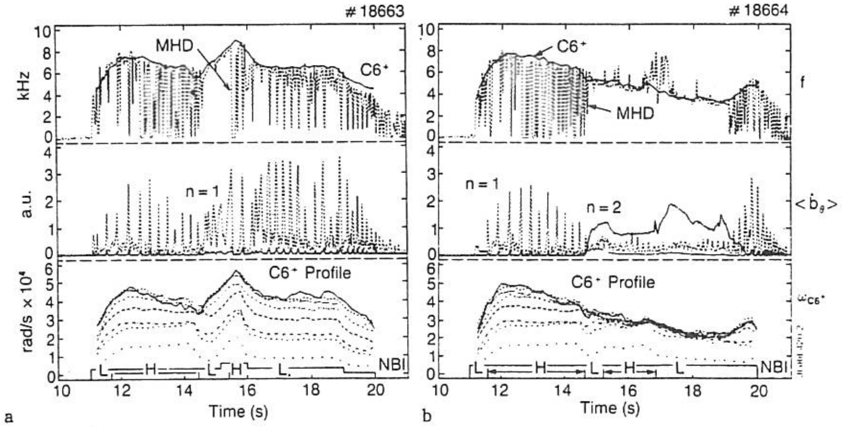

Figure 1. a) A discharge with sawtooth related MHD activity showing good agreement between the central charge exchange toroidal rotation frequency and the n=1 MHD frequency at the edge, together with the n=1, 2 and 3 rectified and smoothed MHD amplitudes and the C 6$^+$ rotation profile. b) A similar discharge but with a large n=2 mode that flattens most of the C 6$^+$ rotation profile. The times during H and L mode are indicated during the NBI. The spacing between the charge exchange channels is 10 - 15 cm.

Persistent Rotating MHD Modes When the MHD oscillations persist for more than about 300 msec, the ion toroidal rotation frequency profile flattens over an even larger region than the q=1 radius, sometimes flattening as much as 70% of the plasma cross section. Figure 1b shows an example with an oscillating predominantly n=2 mode that persists for about 5 sec. The discharge begins much like the previous one in Figure 1a with a peaked rotation profile during sawtooth related activity, then during the persistent n=2 mode, the rotation profile flattens out to roughly the q=1.5 radius. The spacing between channels of the charge exchange diagnostic is about 10 - 15 cm. The measured m number at the edge was found to be a mixture of 4 and 5, so linear toroidal coupling to the m=3, n=2 mode is expected. Note that the profile begins to peak up again as the n=2 mode decays away after about 19 sec. Similar rotation profile flattening is also observed during persistent n=1 or n=3 oscillations. Note, however, that while the MHD frequency increases proportional to n, the ion rotation frequency agrees with the n=1 oscillation frequency.

Rotation During Quasi-Stationary Modes (QSM) The agreement between the ion rotation frequency and the n=1 frequency becomes particularly apparent during high power NBI when mode locking occurs, which brings the mode to rest. Under most conditions, the ion toroidal rotation profile collapses

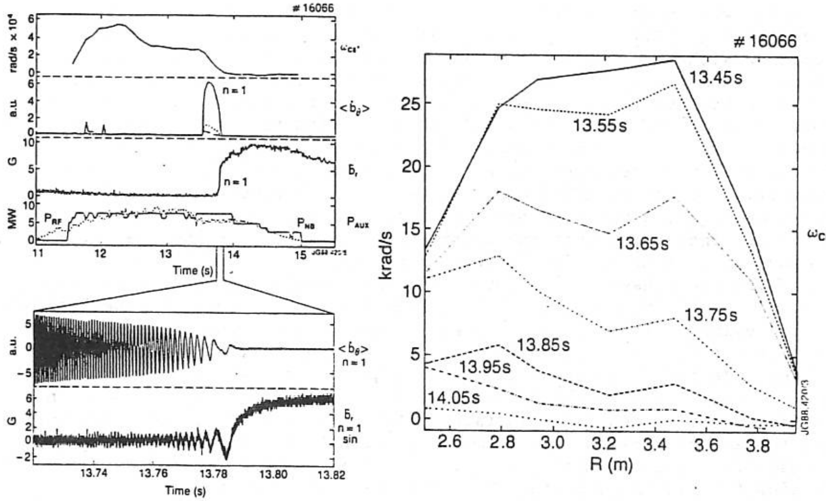

Figure 2. Mode locking during NBI + ICRH showing the subsequent collapse of the C $6^+$ ion toroidal rotation profile. The time traces are the ion rotation near the center; the rectified amplitude of the n=1, 2 and 3 oscillations; followed by the locked mode radial field amplitude; and the NB and ICRH power. The expanded time traces show the n=1 oscillations slowing down and locking together with the sine component of the QSM.

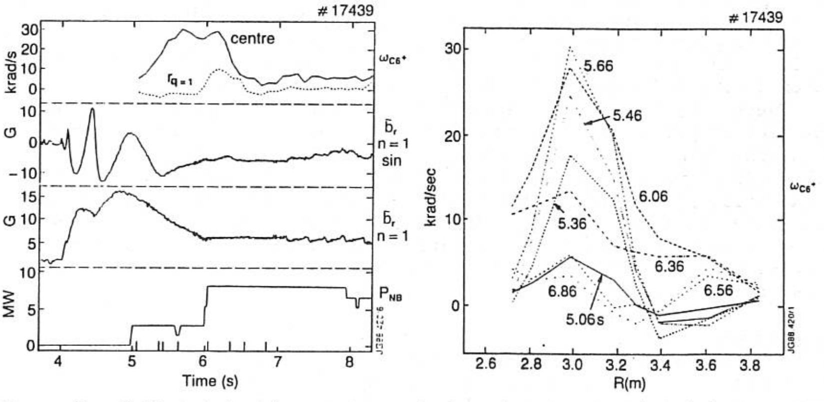

Figure 3. Pellet injection at 3 sec during the current rise drives an MHD mode that becomes a QSM at 4 sec and remains locked during NBI. Plasma ion rotation occurs within the q=1.5 surface despite the QSM at the boundary until a q=1 surface emerges in the plasma at about 6.5 sec, after which the central rotation also comes to rest, within the errors of the measurements.

to zero, within the errors of the measurements, within 100 - 300 msec of mode locking. Figure 2 shows an example of mode locking during NBI combined with ICRH. A monster sawtooth collapse at about 13.5 sec drives a large predominantly n=1 mode unstable. Almost immediately, the central rotation frequency begins to drop as the mode frequency slows down. The mode locks at about 13.79 sec and the entire ion toroidal rotation profile comes to rest, within the errors of about ± 5 krad/sec, in about 200 msec. This time lag is believed to be due to the inertia of the ions. Note, however, that the Ni XXVII ion toroidal rotation from the central region of the plasma, which has a sampling rate of 20 msec, comes to rest in about 120 msec, indicating that the 100 msec sampling rate of the charge exchange diagnostic is artificially increasing the time delay.

While the behavior in Figure 2 is what normally happens, there are special cases with NBI after pellet injection in the current rise where the outer region of the plasma is locked by the QSM, but the inner region, roughly within the q=1.5 surface, is allowed to rotate (Figure 3). A pellet injected at 3 sec drove an oscillating mode, which becomes a QSM at about 4 sec with a dominant mode number of m=2, n=1. The ion rotation continues within the q=1.5 surface despite the presence of the QSM, until a q=1 surface emerges in the plasma at about 6.5 sec, according to equilibrium code calculations, after which time the rotation profile remains flat at approximately zero despite continued NBI.

Conclusion and Comparison with Theory Plasma ion toroidal rotation is strongly coupled to MHD activity through a viscous force between the ions and the modes that equilibrates the plasma rotation and MHD oscillation frequencies. Sawtooth related modes flatten the ion rotation profile within the q=1 surface. Persistent modes lasting for more than about 300 msec can flatten the ion rotation profile across more than 70% of the plasma cross-section. Quasi-stationary modes that come to rest can also bring the plasma rotation to rest, within the errors of the measurements, in 100 - 300 msec despite NBI. Nonetheless, central plasma rotation can occur during QSM's near the plasma boundary when $q(0) > 1$.

These results indicate that MHD effects should be taken into account in theories of plasma rotation to obtain a more accurate description of the rotation. The observed time required for the ions to lock to the mode is 100 - 300 msec, and appears to be independent of the mode amplitude for the cases studied, suggesting that it may be fundamentally due to the plasma inertia. The extent of flattening of the ion rotation profile, however, seems to be well correlated with rational q surfaces, indicating that toroidally coupled MHD modes are indeed responsible for flattening the rotation profile.

## References

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