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**See the Appendix of F. Romanelli et al., Proc. 25th IAEA Fusion Energy Conference 2014, St Petersburg, Russia*

Introduction - Intrinsic rotation in JET plasmas has been determined from X-ray Crystal Spectroscopy (XCS) [1], Charge eXchange Recombination Spectroscopy (CXRS) [2, 3] and from the observed frequency of Magneto Hydro-Dynamics (MHD) modes [3]. Intrinsic rotation, observed in plasmas with Ohmic, lower-hybrid frequencies and Ion-Cyclotron Resonance Frequencies (ICRF) heating, has quite low amplitude, typically one order of magnitude lower than rotation in plasmas with Neutral Beam Injection (NBI). At JET this turned out to be difficult to measure since often it is at the limit of detection. Data analysis methods for all three diagnostic techniques had to be improved. Careful and dedicated data analysis for JET C-wall' experiments have shown that these three methods of detecting the toroidal rotation give comparable rotation velocities and consistent determination of the direction of rotation.

CXRS - The most common method for obtaining spatial profiles of toroidal angular frequency, as well as ion temperature is through analysis of CXRS of C^{+6} measured during NBI blips (short NBI pulses with P_{NBI}=1-2 MW). The spectral analysis requires the fitting of a 'cold' component, the passive, due to charge exchange between C^{6+} ions and thermal deuterium at the edge, and a 'hot', active, component that arises from the interaction of C^{6+} with the fast neutral beam. The velocity of the toroidal rotation is determined from the Doppler shift of the active charge exchange spectrum of C6+ with respect to the Be^{1+} emission line at 527.063 nm that originates in the cold scrape-off layer (SOL). (A schematic view of JET with indication of the relevant layers for CXRS analysis is shown in fig. 1.) For Ohmic and other low temperature plasmas, the spectral lines of active and passive components are of the same order so can be difficult to separate (fig. 2). In this case the spectra taken during the diagnostic NBI blip are subtracted from the spectrum taken just before the application of beam power. The subtracted spectra are analyzed by fitting them to only one Gaussian component. A recent assessment on how to improve the spectral fitting of the passive component has been performed. Among the questions considered were: improving the passive fitting by adding data from several passive frames; the effect that edge and core MHD events, such as ELMs and sawteeth, occurring during the time interval taken for the passive analysis may have on the measurements of both rotation and ion temperature at the beginning of the blip; and whether the Be^{1+} line rotates. For the later it has been found, that the Be^{1+} does rotate during H-modes with ICRH, with significant effect on the rotation near the edge. Based on this assessment, the intrinsic rotation database is being re-analyzed taking 10 passive frames before the blip and making sure that the Be^{1+} wavelength is always chosen during an Ohmic phase.

Since NBI provides a toroidal momentum source, the question of whether the time resolution of the CXRS measurements, at present 10 ms, was suitable to measure intrinsic rotation has been addressed in two ways: (i) extrapolation of measurements during the NBI to a time before the blip and, (ii) modelling the rotation produced by the NBI blip. An example of linear extrapolation to time t=0 ms is shown in figure 4 for the angular frequency and the ion temperature profiles, that in both cases are very close to the measured profiles at t=10 ms. Modelling was performed with the code JETTO for different models of momentum diffusion, using as input the NBI time dependent torque calculated with the code ASCOT. The NBI rotation was found to be negligible in the first 10-50 ms, confirming that rotation measurements taken at the first 10 ms are indicative of the rotation before the NBI blip.

XCS - The toroidal angular frequency in the plasma core can be obtained with a high resolution x-ray crystal spectrometer (XCS) that observes the spectrum around the resonance line of the helium-like nickel ion Ni^{26+}. This is a passive technique ideal for measuring rotation in plasmas with no NBI momentum; however, it gives information only at one radial position, the localization depending on the plasma temperature, in the range 3-8 keV. As a reference line for Doppler shift measurement is not available, the wavelength scale is calibrated by comparison with the angular frequency derived during NBI from CXRS of C^{6+} [1]. Figure 5 shows a typical discharge used for XCS calibration. In the 3rd box is the intensity of Ni^{26+} measured with an integration time of 30 ms, while in the bottom box are the Ni^{26+} toroidal angular frequencies, determined during NBI and in the Ohmic phase before the NBI. For the Ohmic plasma the spectra has been added over extended phases lasting up to 2 s. The reference wavelength has been determined by comparing CXS and CXRS measurements of 20 discharges with NBI power varying from 2.5 to up to 11 MW (figure 6). The CXS and CXRS measurements were matched at the radii of maximum CXS emission. Figure 5 shows that the Ohmic plasma central rotation is in the direction counter to the plasma current. The NBI phases are co-rotating. The direction and amplitude of rotation measured with XCS and with CXRS in Ohmic and in plasmas with ICRH have been found to be consistent.

Conclusion – Careful analysis of data from charge exchange spectroscopy and X-ray crystal spectroscopy have provided information of intrinsic toroidal velocities of JET plasmas with C-wall. CXRS intrinsic rotation measurements have been routinely compared with the observed frequency and direction of propagation of MHD modes with low n-mode numbers, such as sawtooth precursors and NTMs, which have confirmed the direction of rotation and measured rotation frequencies in the core of the plasma. A benchmark of XCS, CXRS and MHD observations for ICRF L-mode plasmas has shown that all three methods give comparable angular rotation velocities. CXRS measurements of C-velocities with the JET ILW are more demanding to analyse as the available C has been reduced. Measuring Neon rotation is being considered and experiments with Ne puffs for CXRS analysis are planned for the re-start phase of the next JET experimental campaign later in 2015. A new tool for measuring rotation in JET is Doppler backscattering (DBS), which has recently started being used [5]. DBS measures the lab frame perpendicular propagation velocity of turbulent structures, which in the core of tokamaks is often dominated by the D toroidal velocity -- even when there is no external momentum input. Commissioning and cross-checking against CXRS measurements is also planned for the re-start of the next JET campaign.

References

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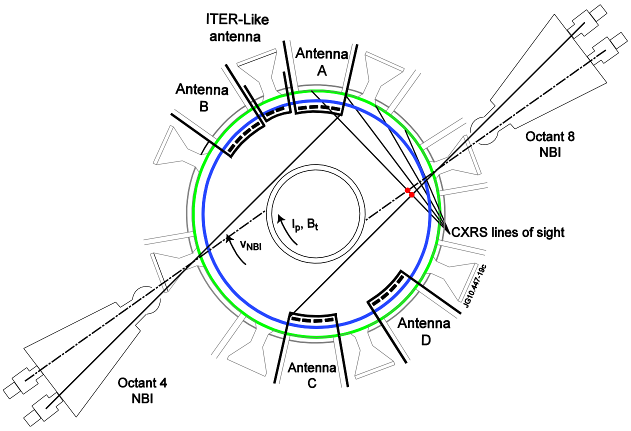


Fig 1. Schematic view from the top of JET showing the two NBI injectors, NBI lines and, the CXRS lines of sight. (also shows the ICRH antenas). CXRS emission layers which contribute to the measured spectra are indicated as the cold non-rotating SOL in green being the zone of the reference B^{1+} line, the passive warm and slowly rotating layer in blue and the active hot and strongly rotating region which is shown by red dots in the intersection of beam lines and CXRS lines of sight. Also indicated in the figure are the usual directions of the toroidal field B_T, the plasma current I_p and the usual direction of the rotation induced by NBI, v_{NBI}.

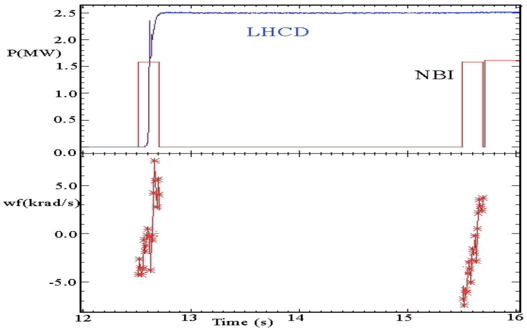


Fig. 2. NBI setup for CXRS measurements (pulse # 74866) with NBI blips lasting 200 ms in an Ohmic phase (beginning of 1st blip) and a phase with 2.5 MW of Lower Hybrid (2nd blip). On the bottom, the time evolution of C angular frequency from a central channel (R=3.1 m).

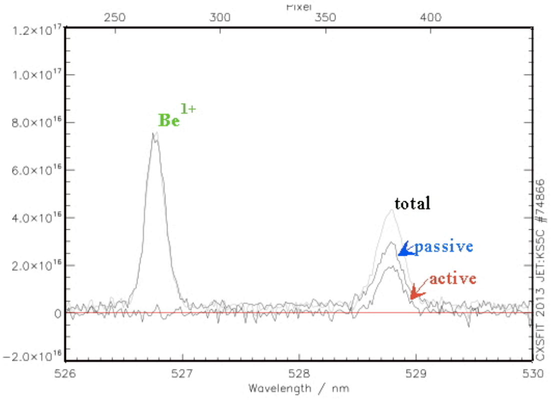


Figure 3. Measured Spectral line at beginning of 2nd blip, compared with passive line measured immediately before the blip. Active line, i.e. total with passive subtracted.

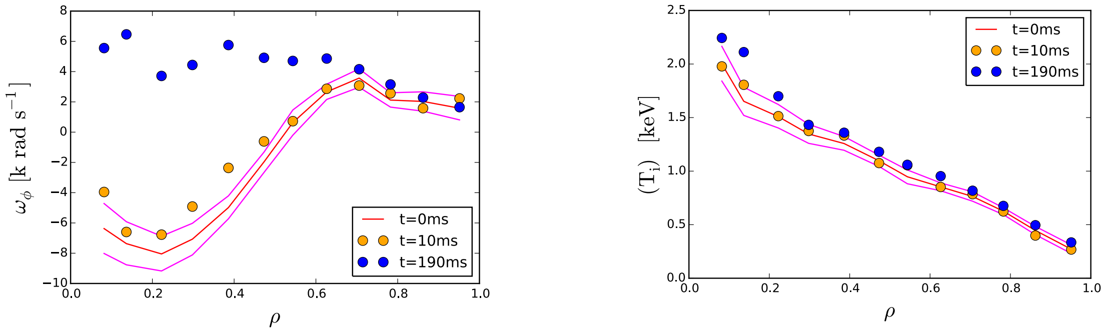
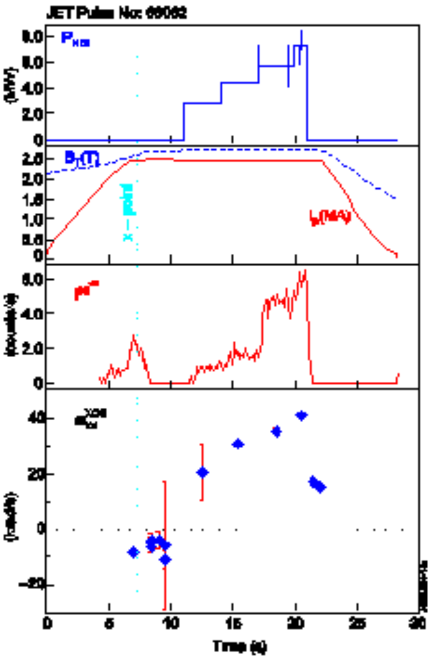


Figure 4- Profile measurements of (a) toroidal angular frequency and (b) ion temperature for the 2nd blip in fig. 2. Orange dots for measurements at the beginning of NBI at 10 ms, blue dots at the end of the blip at t=190 ms, red lines are the linear extrapolation to time t=0 ms. Magenta lines are the linear extrapolation of statistical errors in the spectral fitting, determined from the error in the least-squares fit [4].



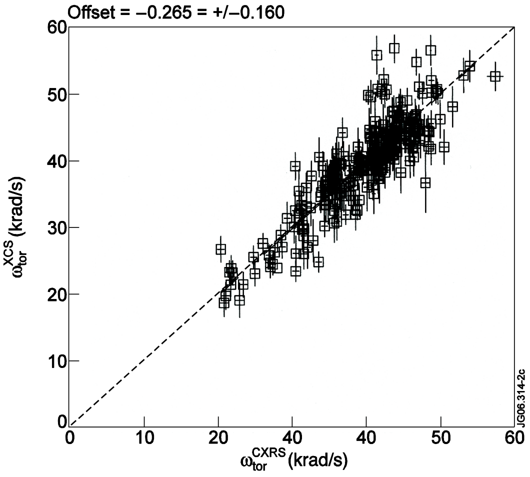


Fig. 5 -Typical discharge used for XCS calibration. (a) P_{NBI}, (b) I_p and B_T, (c) Intensity of Ni^{26+} with integration time 30 ms; (d) Ni core toroidal angular frequency, w_f, versus time determined from XCS (spectra added over extended phases lasting up to 2 s)

Fig. 6 The XCS wavelength scale was calibrated by comparison with the angular frequency obtained during NBI with CXRS using 20 discharges (B_T =2.7T, I_p=2.5 MA) with NBI heating (P_{NBI}=2.5-11 MW)

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