

## Toroidal Rotation Reversals in JET Plasmas

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**Abstract:** Recent experiments at JET studied the effect of density on the rotation of Ohmic divertor plasmas. As the density increased, two core rotation reversals were observed, showing two regimes of peaked co-current rotation. The experiment was done with hydrogen and deuterium plasmas, critical densities for reversal appear to be independent on isotope type.

Intrinsic rotation is expected to play a key role in the performance of future tokamak power plants where the momentum input will be small. However, understanding how momentum originates and how it is transported in the plasma remains a challenge. Increasing rotation shear in the core is valuable for increasing thermal confinement, and yet what determines the shape of the rotation profile remains unclear. This question was addressed in recent experiments at JET that studied the effect of density on the shape of the core rotation profiles of Ohmic divertor plasmas.

The density was varied in steps and toroidal rotation measured during density plateaus (fig 1), with average line densities in the range  $0.8\text{--}3 \times 10^{19} \text{ m}^{-3}$ ; with  $q_{95}$  in the range 3.2 to 4.8. Conditions were matched in Hydrogen and Deuterium plasmas for the study of isotope effects. The rotation measurements were done by Doppler scattering reflectometry and by using neutral beam injection blips and analyzing the  $H_\alpha$  and  $D_\alpha$  charge exchange spectra at the beginning of beam blip. These are the first measurements of the main ion intrinsic rotation from JET plasmas. Here we show experimental results for H and D plasmas with a fixed plasma current  $I_p=2.25 \text{ MA}$  and  $B_T=2.60$ ,  $q_{95}=3.5$  as the density was varied in steps (fig. 1).

Both peaked and hollow rotation profiles were observed (figures 1-2). As the density was increased two rotation reversals were observed (fig. 2-3). At the lowest densities, rotation profiles were peaked with the plasma rotating in the co-current direction. As the density increased co-rotation

decreased, then in a narrow range of densities, average densities of  $1.1\text{-}1.6 \times 10^{19} \text{ m}^{-3}$ , the profiles became hollow. The hollow profiles, have central angular frequencies typically less than 2 krad/s. In some cases, central counter-current rotation was measured. A second branch of co-rotation with peaked profiles was observed as the density was further increased.

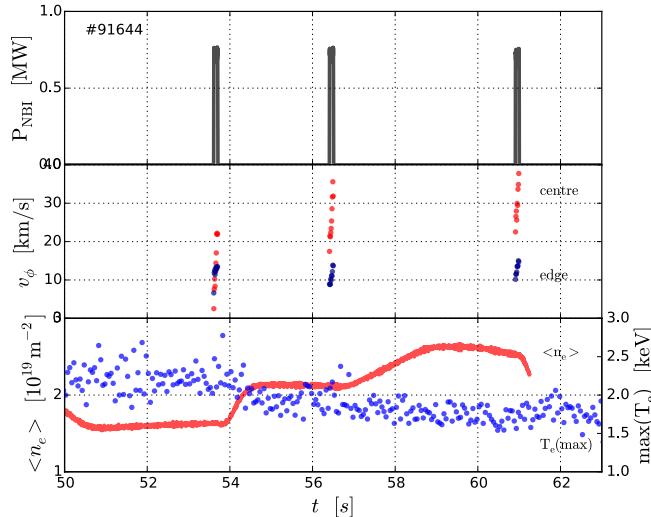


Figure 1 (a) – Experimental set up. Hydrogen plasma,  $I_p=2.25$  MA and  $B_T=2.60$  T, (i) NBI blips for charge exchange measurements; (ii) Toroidal velocity of H at the centre (red) and edge (blue); (iii) average line density and maximum electron temperature.

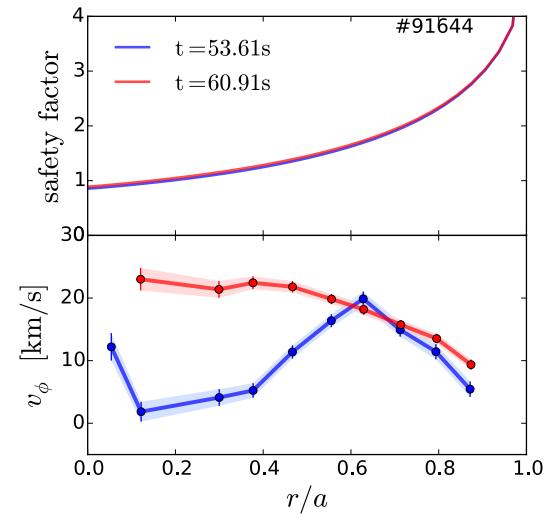


Figure 1 (b) – (i) safety factor, from EFIT using magnetic data only; (ii) CXRS Hydrogen toroidal velocity profiles. Hollow profile for  $\langle n_e \rangle = 1.6 \times 10^{19} \text{ m}^{-3}$ , peaked profile for  $\langle n_e \rangle = 2.5 \times 10^{19} \text{ m}^{-3}$ . Rotation measured by CXRS at the beginning of the NBI blip.

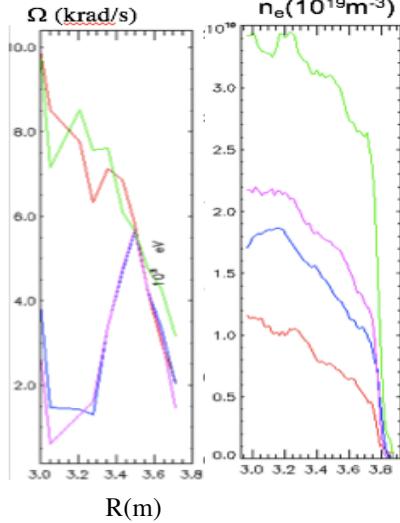


Figure 2 – Rotation and plasma profiles for Hydrogen plasmas, with  $I_p=2.25$  MA and  $B_T=2.60$  T. (a) toroidal angular frequency of H ions; (b) electron density.

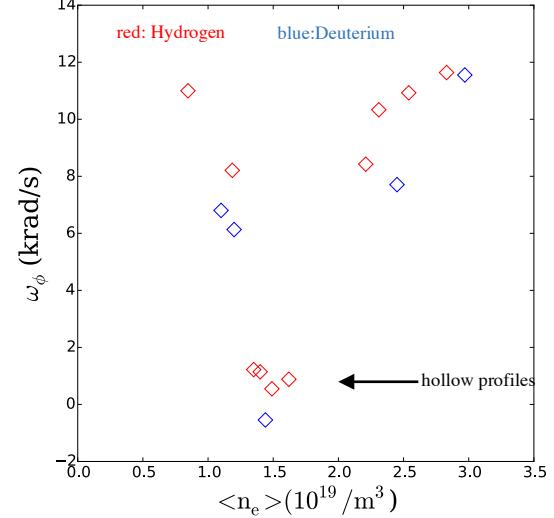


Figure 3 – Central angular velocity ( $R=3.1\text{m}$ ) versus line average density for Deuterium (blue) and Hydrogen (red) plasmas with  $I_p=2.25$  MA and  $B_T=2.60$  T. Hollow profiles have  $\omega < 2\text{ krad/s}$ .

This was the first time rotation reversals were observed in JET Ohmic plasmas. The rotation flip at low densities is similar to observations, extensively studied in medium size machines, like TCV [1-2], C-Mod [3] and ASDEX [4] and DIII-D [5]. The second rotation bifurcation at higher densities has been seen in limiter experiments in TCV [1] and Tore-Supra [6]. (For a recent review of rotation bifurcations with density and plasma current in medium size tokamaks see [7].)

Figure 3 shows the central toroidal angular frequency versus density for H and D plasmas. The rotation reversals were observed with both isotopes. The range of densities for hollow profiles is the same for both types of ions. These is confirmed by inversions from co- to counter-current observed in the turbulence velocity profiles measured with the Doppler reflectometer.

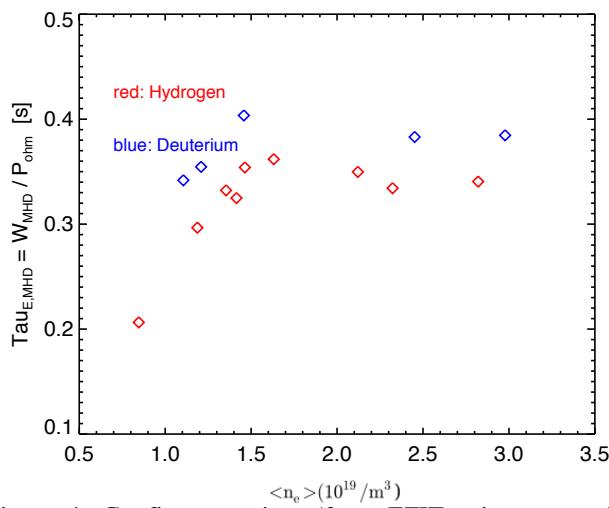


Figure 4- Confinement time (from EFIT using magnetic measurements only) versus the average line density.

As in other machines the first reversal at low densities is observed near the transition from the linear Ohmic confinement (LOC) to the saturated ohmic confinement (SOC) regime. The LOC-SOC transition occurs at the same density for both H and D. A study of isotope effects on the confinement of these Ohmic experiments is presented in a separate paper in this conference [8].

Figure 5 shows the gradient lengths of plasma density and temperature calculated in the region of largest rotation gradients inside of the rotation reversal radius ( $R < 3.5\text{m}$ ). It shows that the first transition, from peaked to hollow profiles, occurs when the density gradient length starts to decrease. The ion temperature gradient length changes very slowly with density, while the electron temperature gradient length increases with density. No particular features have been found associated with the second rotation transition.

Gyrokinetic modelling of the effect of turbulence on neoclassical parallel velocity, heat flow and neoclassical poloidal flow have shown that changing collisionality [9] can change the direction of rotation in qualitative agreement with the rotation reversal observed at low densities in medium-size tokamaks. Modelling is being performed to clarify the role of collisionality in the JET observations described here.

In conclusion intrinsic rotation was measured in Ohmic divertor plasmas as a function of density. This was the first measurements of the main ion rotation in JET. It shows that density has a large effect on the core plasma rotation, producing two plasma rotation bifurcations in the plasma core. The experiment was done with hydrogen and deuterium plasmas, the critical densities for reversal appear to be independent on isotope type.

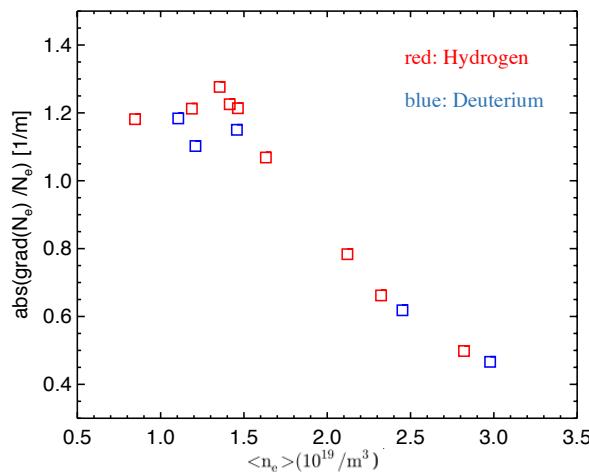


Fig. 5 (a) Density gradient length at  $R=3.4\text{m}$ . Gradients were calculated from 3.3 to 3.5 m, i.e. inside the radii of rotation inversion but outside sawtooth inversion radii.

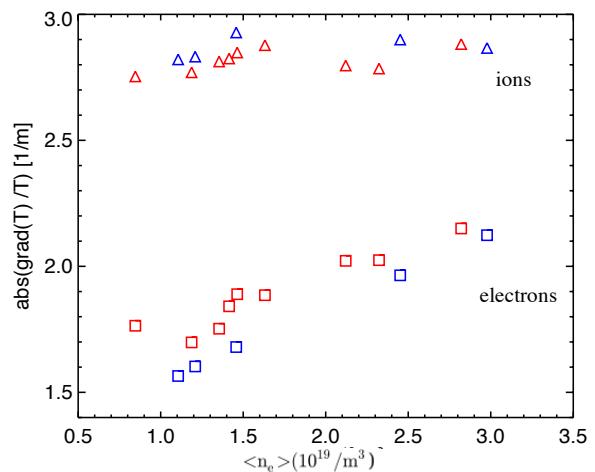


Fig. 5 (b) Temperature gradient lengths at  $R=3.4\text{m}$ .

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\*See the author list of "Overview of the JET results in support to ITER" by X. Litaudon et al. to be published in Nucl. Fusion Special issue: overview and summary reports from the 26th FEC (Kyoto, Japan, 17-22 Oct 2016)