Isotope Effects on Intrinsic Toroidal Rotation and Rotation Reversals

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Introduction. Recent experimental campaigns at the tokamak JET performed a series of experiments with different hydrogen isotopes, designed to clarify the impact that isotope mass has on plasma physics, and in particular transport and confinement questions, relevant for reliable predictions for ITER [1]. JET experiments are important for predictions for ITER due to the JET size, the ITER-like wall and, the only tokamak that operates with Tritium. This paper reports on experimental results from a study of density and isotope effects on the intrinsic rotation of JET Ohmic plasmas where rotation measurements in Hydrogen (H), Deuterium (D) and Tritium (T) were compared. One of the aims of the experiments was the study of rotation reversals in Ohmic plasmas [2], a well-known observation in smaller tokamaks, previously not seen at JET. The study for the first time includes measurements of intrinsic rotation in T plasmas [3]. Both peaked and hollow rotation profiles were observed for the first time in JET Ohmic plasmas, confirming that rotation reversals can also occur at JET.

Experimental set-up. Low triangularity Ohmic plasmas with q_{95}=3.5 (I_p= 2.7 MA and B_T=2.7T), were repeated in H, D and T for the study of isotope effects. The average line density was varied between 0.8-3x10^{19} m^{-3}. Charge exchange measurements of main ion toroidal rotation was obtained during short pulses of Neutral Beam Injection (NBI) (Fig. 1). These are the first JET rotation measurements for the main ion obtained from the analysis of spectra of Hα, Dα and Tα. The charge exchange data shown below is from the first 10 ms of data measured after NBI is switched on. With the ITER-Like wall and care to avoid contamination from impurities, very pure Ohmic plasmas, with effective charges, Zeff, close to unity where obtained.

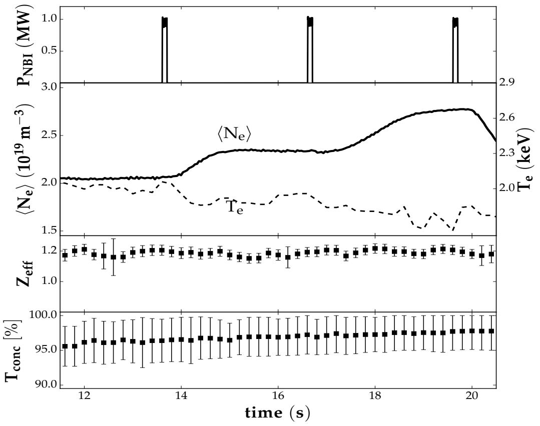

Figure 1 (a) – Experimental set up, for Tritium plasma (#99262), I_P=2.3 MA and B_T=2.7 T. The boxes show: (i) NBI blips for charge exchange measurements; (ii) $<N_e>$ is the line-averaged electron density from far-infrared interferometer, and T_e is the central electron temperature measured with high resolution Thomson scattering (iii) Effective charge, Z_{eff}, from visible Bremsstrahlung, (iv) Tconc=nT/(nH+nD+nT) is the Tritium concentration.

Observations. Both peaked and hollow rotation profiles were observed for the first time in JET Ohmic plasmas. As the density increased a similar sequence of rotation profile changes was observed for H, D and T. Two rotation reversals were observed for each isotope mass (Fig. 2). Here reversal is defined as a change in the sign of the gradient of rotation (as in [2]). At the lowest densities, rotation profiles were flat or peaked with the central plasma rotating in the co-current direction. As the density increased co-rotation decreased and, the rotation profiles become hollow (Fig. 3a, Fig. 4b). For D and T, hollow profiles with the core rotating counter-current were obtained, that is the core rotates on the opposite direction from the edge that is always co-current. H rotation profiles were hollow but remained always co-rotating. A second branch of co-rotation with peaked profiles was observed as the density was further increased (Fig. 3b).

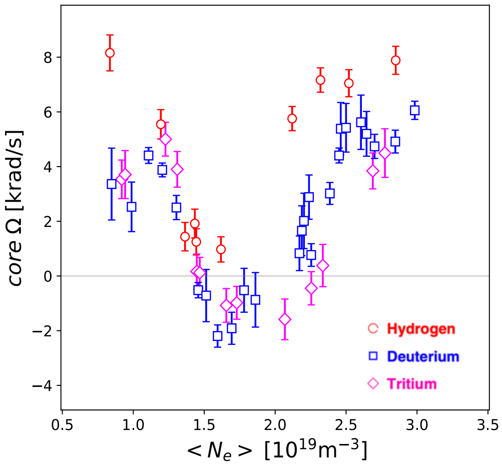

Figure 2 -Central main ion toroidal rotation (r/a=0.2) versus average line density. Positive sign is co-current.

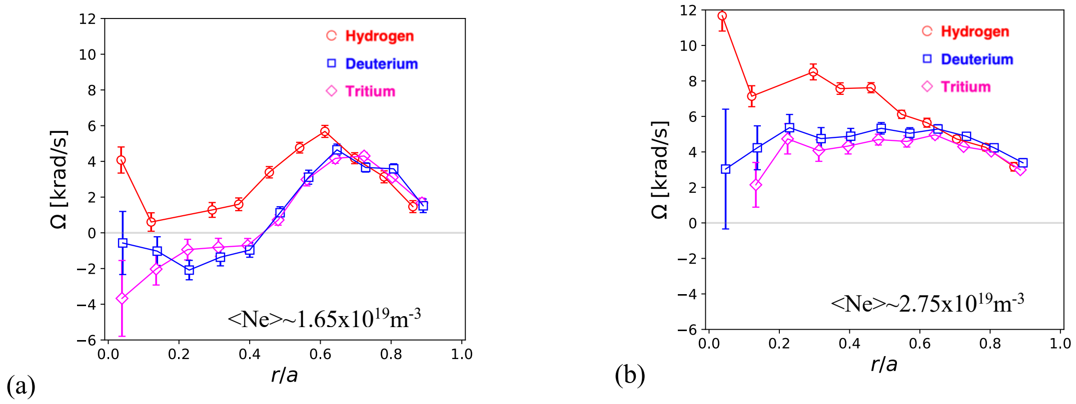

Figure 3 – H, D and T toroidal angular frequency profiles with the same density, for two densities.(a) Intermediate density <Ne>~1.65 x $10^{19}m^{-3}$ showing hollow profiles; (b) As the density increases, co-rotation increases, at <Ne>~2.35 x $10^{19}m^{-3}$ peaked rotation is observed.

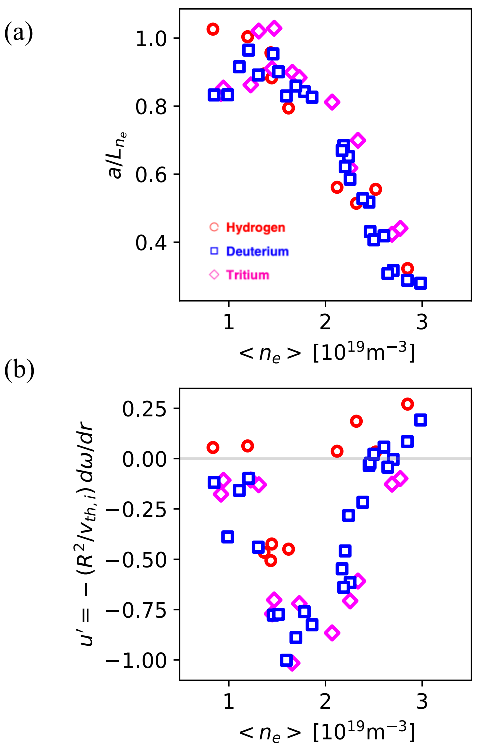

Figure 4 –(a) Inverse density scale length; (b) rotation shear normalized to the thermal ion velocity, at r/a=0.5, versus average line density.

The strong effect of the density on the core rotation seen for each isotope mass and the observation of rotation reversals are similar to observations from other tokamaks [2]. The core rotation change at low densities was extensively studied in medium size machines, like TCV [5-5], C-Mod [6] and ASDEX [7] and DIII-D [8]. The second rotation bifurcation at higher densities is similar to observations from ASDEX [7] and also in limiter experiments in TCV [4] and Tore-Supra [9].

Isotope mass has a strong effect on intrinsic rotation. The magnitude of the core rotation was found to depend on isotope type, stronger co-current rotation observed in H (Fig. 3). Core counter-rotation was observed with D and T but not with H. A comparison of rotation profiles at the same density shows that the isotope effect is only in the plasma core, r/a<0.6, since for outer radii the rotation is the same for all ion masses (Fig. 3). Within the experimental uncertainties, the critical density for the first reversal at low density, is the same for all isotope masses. However, the critical density for the second reversal increases with ion mass (Fig. 2).

The density range for the experiment spanned over both the Linear Ohmic Confinement (LOC) and the Saturated Ohmic Confinement (SOC) phases. The density of the LOC-SOC transition was observed to shift to a higher density for higher ion mass [10]. As in other machines the first rotation reversal at low densities is observed close to the LOC-SOC transition, however it does not coincide with it. D and T rotation profiles are already hollow at the LOC-SOC transition [3]. This is similar to a recent study in TCV in H, D and He plasmas where the LOC-SOC transition was also found to depend on isotope ion mass [11].

Ion mass effects were observed in ion and electron temperature, as well as density profiles. Fig. 4 shows the density scaling length together with the rotation shear normalized to the thermal ion velocity, $u'=(R^2/v_{th,i})d\Omega/dr$, at mid radius, r/a=0.5, showing a strong correlation between the two as observed in ASDEX [7]. Further parametric studies and ongoing modeling will be discussed elsewhere.

Summary. The isotope mass effect on intrinsic rotation was investigated in JET Ohmic plasmas matched in H, D and T. This was the first time that accurate measurements of main ion rotation were obtained in Tritium plasmas. It was concluded that intrinsic rotation is affected by ion mass. Counter-current rotation increases with ion mass, which is a core effect. With respect to density scans, that covered both the linear and the saturated Ohmic confinement regimes, the observations can be summarized as follows. As the density increases, two rotation reversals are seen for each isotope mass. Within the experimental uncertainties the first reversal, from peaked/flat to hollow rotation profiles, occurs at the same density. The critical density for the second reversal, from hollow to peaked/flat rotation profiles, is shifted with ion mass. This results in Tritium requiring a higher density for access to the second regime of co-current rotation.

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