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Effect of Sawteeth on the Spontaneous TCV Plasma Rotation

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Introduction

Toroidal rotation is observed to help stabilise the Resistive Wall Mode (RWM) instability, yet in larger machines such as ITER, externally applied sources of toroidal torque, such as high power neutral heating beams (NBI), are not thought sufficient to externally determine the toroidal rotation velocity [1]. The scaling of Intrinsic or Spontaneous toroidal rotation (i.e. in the absence of an external torque) is thus of strong present day investigation but is often complicated by the use of strong torque injecting NBI in many of the Charge Exchange Spectroscopy (CXRS) rotation measurements. This paper presents rotation profiles measured with the TCV diagnostic CXRS system whose toroidal torque may be neglected [2,3]

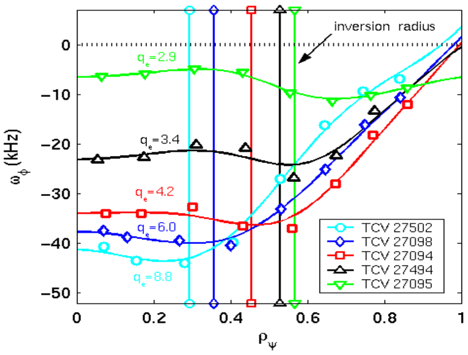

Fig 1 *Toroidal rotation profiles for limited TCV discharges at low plasma density. Note the velocity gradient in the outer plasma is mostly independent of the plasma current.*

Toroidal Rotation Scaling

The rotation profiles from an initial plasma current scan, at low plasma density (Fig 1) demonstrates the main toroidal rotation profiles' features. The rotation profiles, for these limited discharges (δ~0.4, κ~1.5) , are divided into an edge zone with close to zero rotation velocity, an intermediate gradient, with the inner plasma increasingly rotating in the counter-plasma current direction, and a core region where the toroidal rotation is relatively flat. The radius of the flat core region was found to be close to the sawtooth inversion radius (q= ~1) so the effect of sawteeth is to redistribute toroidal momentum inside the q=1 radius. With increasing plasma current ($q_e \approx$ 3 and below) the toroidal rotation profile is more complicated, which will be further discussed below.

By taking the highest observed toroidal rotation values, (which from the above description implies the toroidal rotation close to q=1), an empirical toroidal rotation scaling was deduced with a linear dependence on the ion temperature and an inverse-linear dependence with plasma current [3]. It is to be stressed that, for these discharges, the ions are heated solely by electron-ion collisions so the ion temperature dependence has yet to be independently exercised. With increasing plasma current, there is an increase in the ohmically heated electron temperature resulting in an increased ion temperature. This dependence was found to be identical for positive and negative plasma current directions with the plasma always rotating in the counter-current direction [2,3]. The TCV observations are in qualitative agreement with those from other machines although it must be said that the rotation direction and amplitude between the reported devices is not always consistent [3,4 and refs therein]

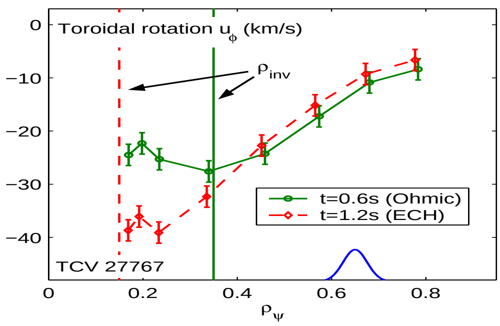

Fig 2 *Toroidal rotation profiles with and without the injection of ECH current drive (shown in blue). With the q=1 radius (vertical lines) displaced inwards, the toroidal rotation extends to higher values.*

Sawteeth inversion radius

Using TCV's second harmonic Electron Cyclotron beams (X2) to generate plasma current, it was possible to decrease the sawteeth inversion radius. Fig 2 shows the toroidal rotation profile without and during X2 power injection. The toroidal rotation profile gradient from the plasma edge continues, with approximately the same gradient, up to the displaced sawtooth inversion radius where, as before, it flattens. In this paper it is proposed that, if the maximum toroidal rotation is determined by the sawteeth radius, then its value in the absence of sawteeth may be extrapolated from the rotation gradient outside the sawteeth inversion radius. (This implicitly requires that there is no other mechanism that would limit the toroidal rotation which has not yet been demonstrated for all the configurations described here).

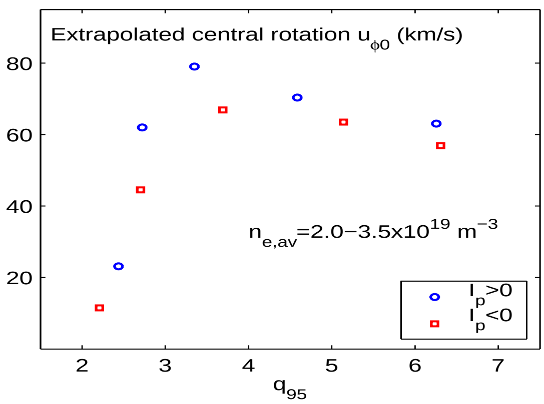

Fig 3a *Extrapolated value of the rotation at the plasma centre from the rotation gradient outside the sawteeth inversion radius.*

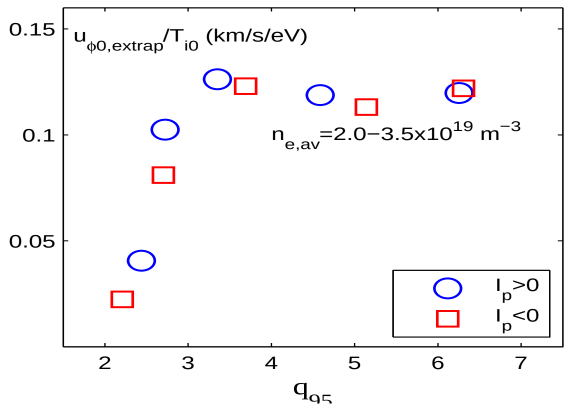

Fig 3b *Extrapolated central toroidal rotation normalised to the measured ion temperatures. Above q=3, there is little remaining evidence of a plasma current dependence.*

Fig 3a shows this extrapolated maximum rotation as a function of q_{95}. For q_{95} >3, this rotation appears to be independent of the plasma current. The remaining slope, with the rotation increasing with plasma current (from $q_{95} \approx 8$ to 3), can be removed by normalising to the measured ion temperature (Fig 3b). The data from the original current dependent scaling (i.e. the rotation at q =1), [3], in shown in Fig 4, with the same axes, for comparison.

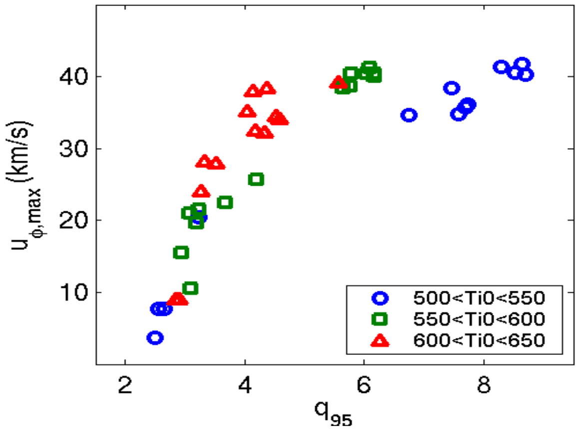

Fig 4 *Uncorrected core rotation as a function of the edge safety factor for comparison with Fig 3a). The points are coded according to the measured ion temperature.*

This implies that the plasma current scaling of the intrinsic toroidal rotation velocity is only an artefact of the effect of sawteeth. Furthermore, if there is a direct "intrinsic" toroidal torque on the plasma, Fig 2 shows that there is less total toroidal momentum with an increasing sawtooth inversion radius. Unless there is a change in the momentum transport outside the q=1 surface, this in turn implies that there is a reduction in the intrinsic toroidal torque inside the sawteeth inversion radius (since otherwise by momentum conservation, there would be an increase in the rotation outside the sawteeth radius).

Toroidal rotation reversal

With sufficiently high plasma density, discharges for which $q_e \approx 3$, (and lower), can exhibit a rotation profile reversal with the plasma now rotating in the co-plasma current direction [2,5]. The toroidal velocity scalings described above do not well match these configurations. Furthermore, the discrepancy between experiment and the extrapolated scaling, (Fig3), increases with increasing plasma current reflecting the increasing strength of a roll-over in the toroidal rotation profile outside the sawteeth inversion radius for these discharges (Fig 1). This implies that, with the q=3 surface close to the edge or outside the plasma, there is a change in one of the processes driving the intrinsic rotation that eventually results in the toroidal rotation reversal.

Sawteeth and Mhd Effects

Sawteeth are observed to increase toroidal momentum transport, at least within the sawteeth inversion radius, thus limiting the observed core toroidal rotation velocity. The above results would, however, indicate that they are not directly concerned with the toroidal velocity reversal phenomena since the profile discontinuity occurs well outside the sawtooth inversion radius. This is, partially, supported by the absence of an observed change in either the sawteeth amplitude or phase across the rotation reversal.

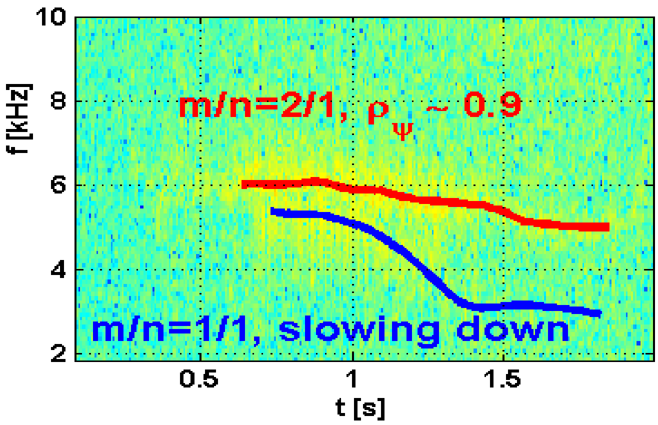

Fig 5 *Mhd modes observed across a toroidal rotation change at ~1.3s. There is a strong change in the rotation velocity of the (n=1,m=1) precursor mode associated with the sawteeth. These is also a change in the character of an (m=2,n=1) mode located in the outer plasma region where there is a discontinuity in the toroidal rotation profile (see Fig 1).*

As reported in [3], a sawteeth precursor mode (m=1, n=1) sometimes is observed from the boundary magnetic pickup coil (and soft X-ray emission) that changes frequency when the core rotation reverses. For the experimental observations to date, a (m=2, n=1) mode is observed that is stronger after the toroidal rotation reversal and sometimes present, at reduced amplitude, before the reversal. This mode, that resides at a magnetic normalised radius of 0.8 – 0.9, is close to the radius at which the discontinuity in the rotation profile changes the most.

Conclusions

By extrapolating the core plasma rotation from the gradient outside the sawteeth inversion radius, most of the plasma current dependence in the previously reported toroidal velocity scaling is removed. By further normalising to the measured ion temperature, the residual scaling decreases except for $q_e \approx 3$ and below where the toroidal rotation strongly decreases with plasma current. It is for these discharges that the toroidal velocity reversal with increasing plasma density is observed on TCV. Although sawteeth are seen to redistribute momentum within the sawtooth radius, and possibly reduce the total toroidal torque, they do not seem to directly determine the toroidal rotation itself. Experiments on other Tokamaks, using similar magnetic configurations, are underway with the goal of reproducing, and possibly extending, these observations. Further experiments on TCV with more constant plasma parameters, where Mhd mode amplitudes and behaviour are constant, will be performed to ascertain whether other Mhd modes are possible momentum drive candidates.

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References

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