NBI Modulation Experiments to Study Momentum Transport and Magnetic Field Induced Ripple Torque on JET

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* *See the Appendix of F. Romanelli et al., Fusion Energy 2010 (Proc. 23rd Int. Conf. Daejeon, Korea), paper OV/1-3*

Abstract. Several parametric scans have been performed to study momentum transport on JET. NBI modulation technique has been applied to separating the diffusive and convective momentum transport terms. The magnitude of the inward momentum pinch depends strongly on the inverse density gradient length, with an experimental scaling for the pinch number being $-Rv_{pinch}/\chi_\phi = 1.2R/L_n + 1.4$. There is no dependence of the pinch number on collisionality. The Prandtl number was not found to depend either on R/L_n, collisionality or on q. The gyro-kinetic simulations show qualitatively similar dependence of the pinch number on R/L_n, but the dependence is weaker in the simulations. Gyro-kinetic simulations do not find any clear parametric dependence in the Prandtl number, in agreement with experiments, but the experimental values are larger than the simulated ones. The extrapolation of these results to ITER illustrates that at $R/L_n>2$ the pinch number becomes large enough (> 3–4) to make the rotation profile peaked provided that the edge rotation is non-zero. And this rotation peaking can be achieved with small or even with no core torque source. The absolute value of the core rotation is still very challenging to predict partly due to the lack of the present knowledge of the rotation at the plasma edge, partly due to insufficient understanding of 3D effects like braking and partly due to the uncertainties in the extrapolation of the present momentum transport results to a larger device.

1. Introduction

Plasma rotation and momentum transport are currently very active areas of research, both experimentally and theoretically. It is well-known that sheared plasma rotation can stabilise turbulence [1] while the rotation itself has beneficial effects on MHD modes, such as resistive wall modes or neo-classical tearing modes [2]. Although the importance of rotation has been recently recognised, predicting or extrapolating the toroidal rotation profile has turned out to be extremely challenging and several key issues remain.

The NBI torque source is relatively well established, and a lot of work has been done recently to compare and benchmark different codes [3,4]. The validation of the NBI torque calculation in plasmas with large toroidal magnetic ripple is presented also in this paper in section 3. Besides NBI, other core torque sources and sinks are less understood. Intrinsic rotation in ICRH, ECRH and Ohmic plasmas still requires clarification [5,6,7]. Another unknown torque source in the core plasma, probably also being very important in ITER rotation predictions, is seen as a strong toroidal rotation braking in plasmas with application of an *n*=1 magnetic perturbation field on JET [8].

The second major issue in giving large uncertainties in ITER rotation predictions is the lack of the knowledge of the edge rotation as well as edge torque sources. While the core and edge torque sources and the edge rotation question are crucial in order to be able to predict the rotation profile in future tokamaks, in this paper we concentrate on core momentum transport studies. The best and most clean way of identifying separately diffusive and convective transport is by means of NBI modulation in JET [9]. The existence of momentum pinch has been reported on JET in references [10,3], however, no systematic studies have been experimentally carried out to study the parametric dependencies of the momentum pinch and diffusive terms. This needed for extrapolation of the pinch and diffusive terms to ITER.

2. Experimental Scans to Study the Parametric Dependencies of Momentum Transport

A 3-point collisionality scan to study momentum transport coefficients has been performed on JET. The main idea is to vary collisionality while keeping the other dimensionless quantities, such as ρ^*, β_N, q and T_i/T_e, as well as density as constant as possible. Within the 3-point scan, collisionality spans over almost a factor of 4.

The resulting Prandtl number and momentum pinch number profiles from the detailed transport analysis are shown in figure 1 (left frame). It can be easily seen within the error bars that neither the Prandtl nor the pinch number depends on collisionality. This scan was carried out in L-mode in plasmas because the collisionality scan, while simultaneously keeping R/L_n constant, is not viable to carry out in H-mode plasmas due to the well-known density peaking dependence on collisionality. The dependence of the momentum pinch and Prandtl number on collisionality was also studied in linear gyro-kinetic simulations using the GS2 code using the input data from the same scan. The most important conclusion is that neither momentum pinch nor the Prandtl number depends on collisionality, shown in figure 1 (right frame).

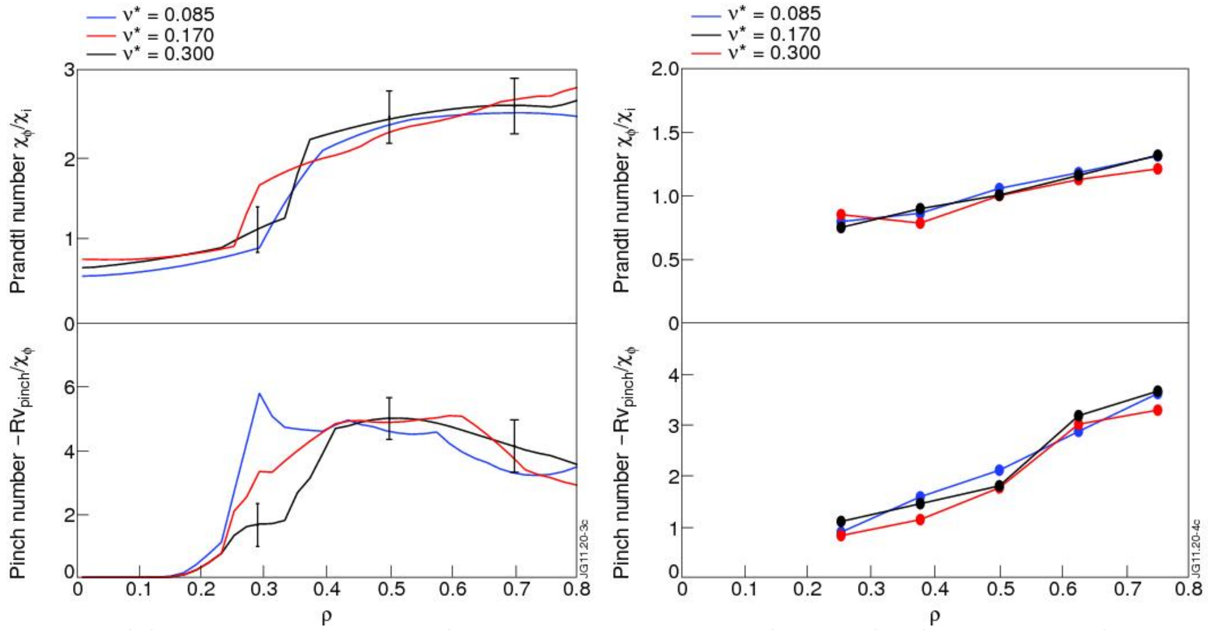

Figure 1. (left frame) Prandtl number (upper frame) and pinch number (lower frame) profiles for the discharges forming the 3-point collisionality scan. (right frame) As in left frame, but the data is from linear GS2 simulations using the actual input data from each shot. The GS2 runs have been performed at five radial locations for each shot.

There is no simple way to perform a clean R/L_n scan in a tokamak without changing some other dimensionless parameter simultaneously. Since no dependence of momentum transport coefficients on collisionality was found in the collisionality scan experiment, it is possible to scan R/L_n by varying collisionality and assign the possible changes in momentum transport to be caused by variations in R/L_n rather than by variations in collisionality.

The dependence of the Prandtl number on R/L_n is illustrated in figure 2 (left frame). The single value of P_r attached to each shot is based on the average value of P_r between $0.4<\rho<0.8$. Also, R/L_n reflects the average value from the same radial range. The large range in R/L_n among the shots has been achieved mainly by varying collisionality, density and the amount of the NBI heating power. It is evident that the Prandtl number does not depend on R/L_n as the scatter of the points is uniform. Typical error bars have been added for two of the shots. The red points in figure 2 are from linear GS2 simulations using the input data from 9 of the 12 experimental shots. More details of all these scans can be found in reference [11].

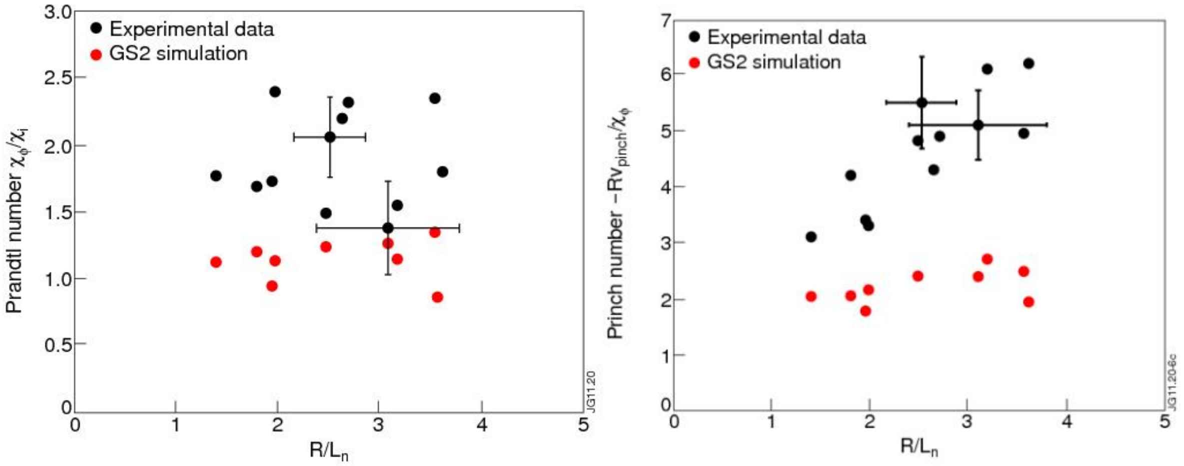

Figure 2. (left frame) Experimental (black dots) and simulated (red dots) Prandtl numbers $P_r=\chi_\phi/\chi_i$, averaged over the range of $0.4<\rho<0.8$. (right frame) As in left frame, but for pinch numbers $-Rv_{pinch}/\chi_\phi$.

Opposite of P_r, a clear trend with R/L_n is found for the pinch number. This is illustrated in figure 2 (right frame) where a strong dependence of the pinch number is shown by the black points as a function of R/L_n. GS2 runs also show an increase in $-Rv_{pinch}/\chi_\phi$ with increasing R/L_n although the trend is weaker than in the experimental data. Fitting a line through the experimental cloud of points, one obtains the following relation: $-Rv_{pinch}/\chi_\phi \approx 1.2R/L_n + 1.4$. This strong dependence also has consequences to ITER predictions, i.e. without knowing the inverse density gradient length it will be challenging to estimate the momentum pinch number.

A 3-point q-scan was also performed on JET. It cannot be ruled out that the observed weak q-dependence of the pinch number, i.e. $-Rv_{pinch}/\chi_\phi$ decreasing with q, is just within the error bars and not a real trend. The Prandtl number does not depend on q.

3. Validation of the NBI Torque Calculation in the Presence of Magnetic Field Ripple

Accurate and validated tools for calculating toroidal momentum sources are necessary to make reliable predictions of toroidal rotation for current and future experiments. In this work we present the first experimental validation of the torque profile calculation from NBI heating under toroidal magnetic field ripple. We use discharges from a dedicated experimental session on JET where the NBI modulation technique is used together with time-dependent torque calculations from ASCOT code for making the benchmark.

Figure 3 summarizes the result of the torque evaluation for the three discharges. It shows the time traces of the volume integrated torque components and the time averaged torque densities for the modulated NBI units only. For better illustration only one NBI modulation cycle is pictured. The total torque is split into three components each with distinct time scale; collisional torque due to Coulomb collisions, instantaneous torque which is essentially the toroidal component of the $j \times B$ force arising from the difference in the initial and bounce averaged flux surface of the ions. Third, the ripple torque is due to the non-ambipolar radial diffusion of the NBI ions in the non-axisymmetric magnetic field. They all have different time scales and must be correctly resolved for simulating the inherently time-dependent NBI modulation experiments. These torque profiles are used in fitting the simulated amplitude, phase and steady-state of the modulated rotation against the experimental ones in the same way as presented in reference [10]. Good agreement between the ASCOT simulations and experimental results is found, therefore validating the ASCOT torque calculation in plasmas with significant magnetic field ripple. More details can be found in reference [4].

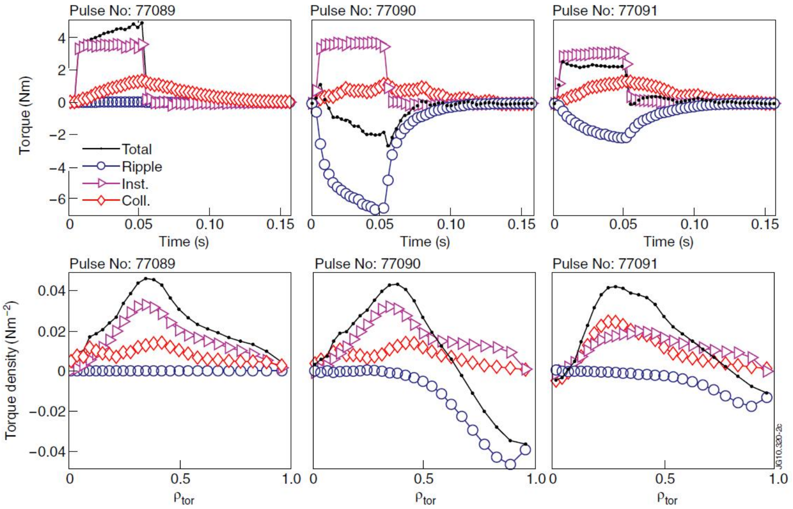

Figure 3. One modulation cycle data for the modulated NBI units only. Top row shows the volume integrated torque separated in ripple, collisional and instantaneous components. Bottom row shows the cycle averaged torque densities for each component. 77089 is the reference, no-ripple case with normal NBI, 77090 is with normal NBI and 1.5% ripple, and 77091 is with tangential NBI and 1.5% ripple. Note that 77091 uses only two modulated NBI units.

6. Summary and Conclusions

The NBI modulation technique has been exploited on JET to study parametric dependencies of both the momentum pinch and the Prandtl number. Within the R/L_n scan, a strong dependence for the pinch number on the inverse density gradient length was observed. This dependence is consistent with the JET rotation database study where a similar dependence of the pinch number on R/L_n is reported in reference [12], and with a statistical approach applied to the JET rotation database [13]. No change in the pinch number was observed when the collisionality was varied by a factor of 4 within the scan. Based on the results from these parametric scans of the pinch and Prandtl numbers, one can conclude that while it seems plausible that the rotation profile will be peaked in ITER, the absolute magnitude of the toroidal rotation remains still challenging to predict with the present uncertainties in the edge rotation, in sources/sinks, in particular the 3D braking effects and finally in the extrapolation of the momentum pinch.

Acknowledgements

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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