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Normalised Ion Gyroradius Scaling of Intrinsic Torque in JET

S-P. Pehkonen[1], T. Tala[1], A. Salmi[1], B. Duval[2], C. Giroud[3], J. Ferreira[4], J. Hillesheim[3], S. Menmuir[3], M. Tsalas[5], M. Maslov[3], H. Weisen[2], E. Delabie[6] and JET contributors *

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK

[1]VTT, Espoo, Finland, [2]CRPP-EPFL, CH-1015, Lausanne, Switzerland, [3]CCFE, Culham Science Centre, Oxon. OX14 3DB, United Kingdom, [4]IST, Instituto de Plasmas e Fusao Nuclear, 1049-001 Lisbon, Portugal, [5]FOM Institute DIFFER, Edisonbaan 14, NF-3439MN, Nieuwegein, Netherlands, [6]Oak Ridge National Laboratory, Tennessee, USA

Introduction

Plasma turbulence and MHD fluctuations can be stabilised by $E \times B$ shearing as a result of plasma toroidal rotation [1]. In JET and other medium-to-large sized tokamaks, toroidal rotation is mostly provided externally to the plasma by neutral beam injection (NBI). With the increased device size of ITER, the relative amount of external rotation is drive to the plasma inertia thus compromising the stabilising effect of rotational shearing [2]. Plasma intrinsic torque, potentially originating from steep pedestal gradients and serving as the source of intrinsic rotation, may aid in breaching the gap between lost external rotation drive and the required velocity shear for turbulence reduction. As a part of an ITPA multi-machine intrinsic torque rho* scaling of intrinsic torque, four JET discharges were analysed for their intrinsic torque magnitudes and profiles. The results were normalised and extrapolated to ITER baseline ρ_*-value of 0.001 for a preliminary estimate its intrinsic torque magnitudes.

Experimental Data

A three-point normalised ion gyroradius scan, with volume-averaged ρ_*-values ranged between 0.0028-0.0063, was obtained on JET by altering the toroidal magnetic field, NBI power, plasma current and density (Table.1). Plasma shape along with the dimensionless parameters, β, ν_*, and q, were matched between the discharges (Fig. 1). Parameter β for discharge #87315 deviated slightly from the other plasmas.

Discharge	$\langle \rho_* \rangle$	P_{NBI} [MW]	I_P $[MA]$	B_T $[T]$	$\langle n_e \rangle$/1e19 [m^{-3}]	$\langle T_i \rangle$ $[keV]$
#87309	0.0063	7.15	1.12	1.31	2.24	2.29
#87320	0.0041	14.2	1.91	2.34	3.78	1.57
#87314	0.0028	21.1	2.43	2.96	2.73	1.00
#87315	0.0028	20.8	2.43	2.94	2.56	0.98

Table 1. Plasma parameters for the analysed JET discharges and their volume-averaged ρ_* values.

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

In order to solve for intrinsic torque, the NBI power was modulated by 5-10 % at a 2 Hz frequency. A subsequent modulation of similar proportion was observed in the plasma angular momentum, while the temperature and density time traces showed little to no modulation thus retaining the pedestal conditions at a relative steady-state. The time traces of the relevant plasma parameters as shown below.

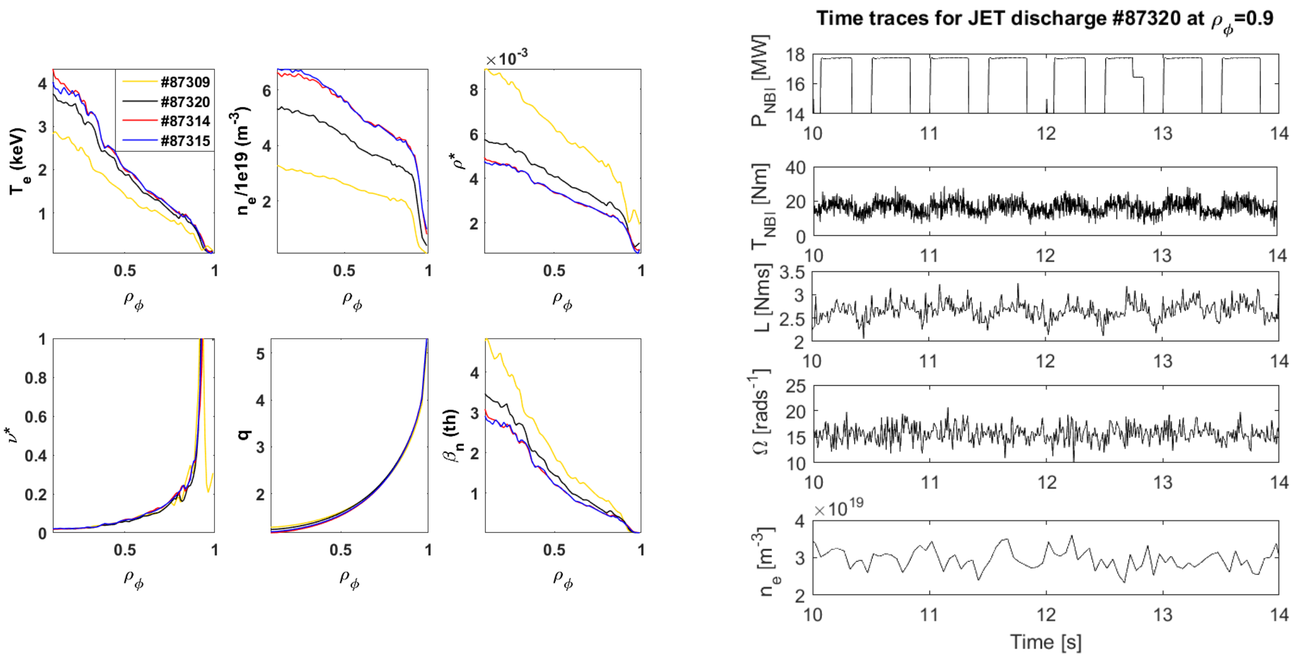

Figure 1. Dimensionless parameter match and electron density and temperature profiles for the four JET discharges (left). Experimental time traces for the relevant data, shown for $\rho_{\phi} = 0.9$ for JET discharge #87320, the medium ρ_* shot (right). Modulation in NBI torque and plasma angular momentum is visible at the 2 Hz frequency NBI power modulation frequency.

Methods

Two methods were used to solve for the missing intrinsic torque and momentum transport variables. The primary source of results was the 1D Onion skin method [2]:

$$\frac{\partial L}{\partial t} = \frac{\partial \langle n_i m_i R^2 \Omega \rangle}{\partial t} = T_{NBI} + T_{int} - \frac{L}{\tau_{\phi}} \qquad (1)$$

In the above, L is angular momentum, n_i and m_i are the ion density and mass, R is the major radius, Ω is the angular velocity, and T_{NBI} is the NBI torque. The two unknowns, toroidal momentum confinement time τ_{ϕ} and intrinsic torque T_{int}, were solved using a direct search optimisation method to minimise the objective function :

$$\chi^2 + 1 = \sum \left(L_{exp} - L_{sim}\right)^2 \qquad (2)$$

The results of the Onion skin model were tested against a simplified 1.5D angular momentum density flux equation:

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

$$V'\frac{\partial\gamma}{\partial t} = \frac{\partial}{\partial\rho}\left(\langle R^2\rangle V'\left[\chi_M\langle|\nabla\rho|^2\rangle\frac{\partial\gamma}{\partial\rho} - \chi_M\langle|\nabla\rho|^2\rangle\frac{1}{\sigma}\frac{\partial\sigma}{\partial\rho}\gamma\right]\right) + V'\langle T^{\phi}\rangle \quad (3)$$

where $\gamma = \Omega n_i m_i$, σ is the ion mass density, V is the volume, and $\langle|\nabla\rho|^2\rangle$ is a geometric term. The transport variable, momentum diffusion χ_ϕ and intrinsic torque, a part of T^{ϕ}, were solved and compared to the solutions of the Onion skin model.

Unfortunately, due to the high noise levels of JET data, the results from the two methods yielded high levels of uncertainty resulting in large error bars. A set of most consistent and realistic results was obtained by directly solving the Onion skin equation by substituting τ_ϕ with the experimentally determined energy confinement time τ_E, which according to previous experiments is expected to be of similar magnitude as the toroidal momentum confinement time [3].

The resulting profiles indicate intrinsic torque presence deep into the plasma core with peaking at the edge pedestal region at $\rho_\phi > 0.85$(Fig. 3). The profile shapes were in agreement with similar results obtained from the other two machines. However, similar analysis on the ASDEX Upgrade data suggested that although the total edge intrinsic torque magnitudes may reflect the true values, the profiles may be skewed by the lack of local transport phenomena, which could produce further edge-peaked profiles. This was observed from the results of equation 3 for some discharged, but due to the very large error limits of the solutions, the Onion skin equation was used for further scaling and extrapolation to ITER.

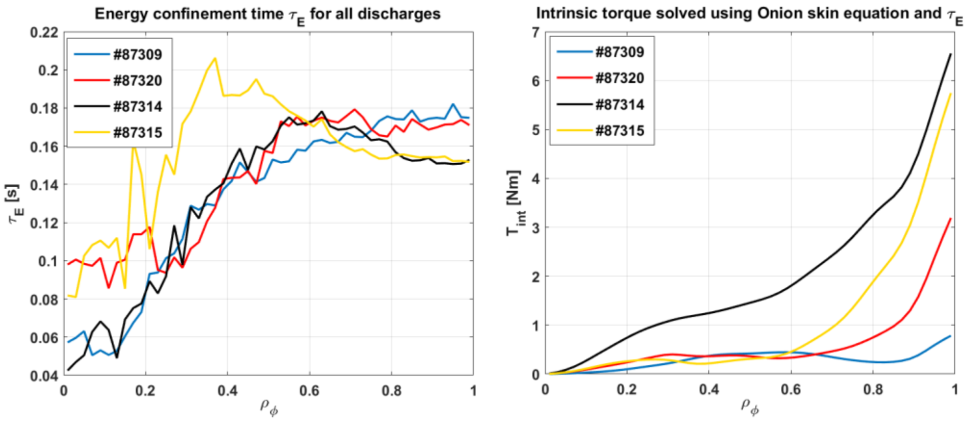

Figure 3. The obtained intrinsic torque profiles (right) by directly solving the Onion skin equation using the experimental energy confinement time profiles (left). The edge intrinsic torque values follow inverse scaling with the discharge volume-averaged ρ_*.

Results

The edge values of the obtained intrinsic torque profiles were normalised according to three methods suggested by theory or by matching dimensions. The intrinsic torque predictions for ITER were calculated assuming baseline scenario values: B_T=5.3 T, n_e=20 × 10^{19} m^{-3}, V=840 m^{-3}, and T_i=15 keV. Fits to the data for each normalisation suggested approximately equal validity of linear and exponential scaling of intrinsic torque with the normalised ion gyroradius. However, combined plots using preliminary results from the other two devices support the further use of normalisation

** See the Appendix of F. Romanelli et al., Proc. 25th IAEA Fusion Energy Conference 2014, St Petersburg, Russia* with the ion temperature along with an exponential scaling for ITER. Similarly, the combined results reduce the extrapolated ITER values from those shown in figure 4.

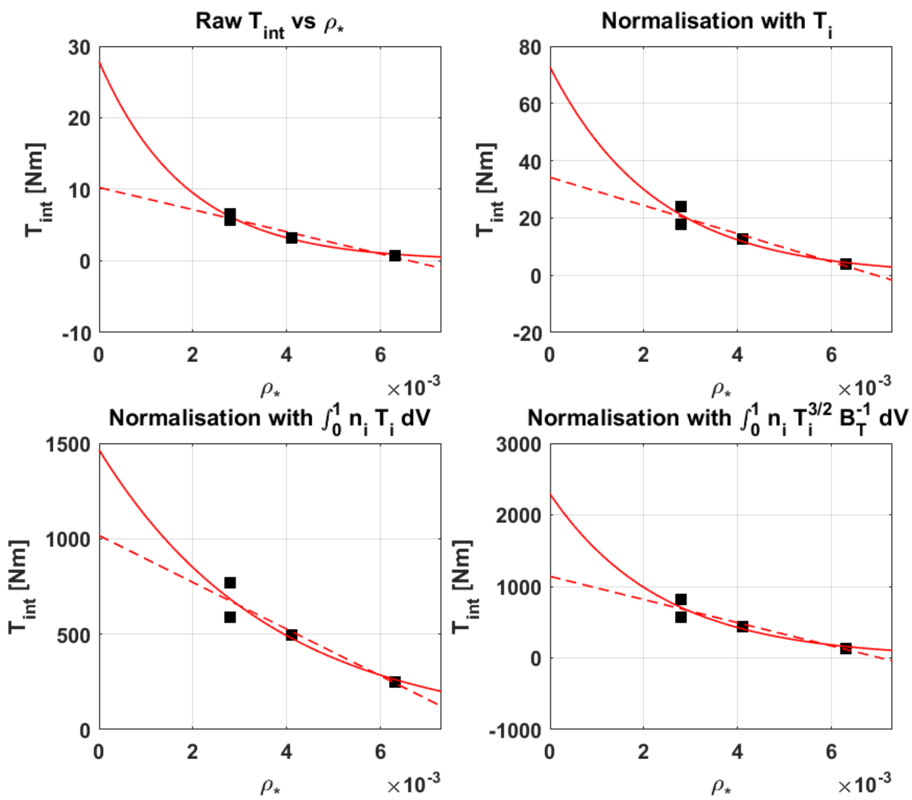

Figure 4. JET intrinsic torque results, scaling, and extrapolation to ITER. a) Raw edge ($\rho = 1$) torque values for the four discharges. b) Scaling using the plasma centre ($\rho = 0$) ion temperature. c) Scaling using volume integrated plasma thermal energy. d) Scaling using volume integrated residual stress.

Depending on the selected normalisation and ability to further improve result from the transport equation, the JET results indicate intrinsic torque edge magnitudes ranging by two orders of magnitude for ITER. The JET data alone appears insufficient for reliable ITER estimates, both due to the small number of data points and large error bars following the high noise of the experimental data. Additional data points from ASDEX and DIII-D are necessary in order to clarify the best normalisation and scaling for future ITER predictions.

References

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