TBM torque scaling with β_N in DIII-D

A. Salmi[1], M. Lancot[2], N.C. Logan[3], T. Tala[1], J.S. deGrassie[2], B.A. Grierson[3], C. Paz-Soldan[2] and W.M. Solomon[3]

[1]VTT Technical Research Centre of Finland, PO Box 1000, FI-02044 VTT, Espoo, Finland
[2]General Atomics, San Diego, California 92186, USA
[3]Princeton Plasma Physics Laboratory, Princeton, New Jersey 08453, USA

Abstract Experiments at DIII-D have been conducted to validate models of the scaling of Test Blanket Module (TBM) torque with the normalised plasma pressure, β_N, and to extrapolate DIII-D results to ITER. The TBM generated torque was determined experimentally and found to increase with β_N in good qualitative agreement with the IPEC-PENT [1] calculations of the neoclassical toroidal viscosity (NTV) torque. However, the measured torque was found to be roughly a factor of 3 smaller.

Experimental arrangement The ITER TBM fields are simulated in DIII-D using a set of purpose-built coils [2]. TBM torque modulations were induced by modulating the coil currents (see Figure 1). A modest 5-10% modulation was measured in the C^{6+} rotation while temperature and density were nearly unaffected confirming time independent transport and enabling the experimental determination of the TBM generated torque.

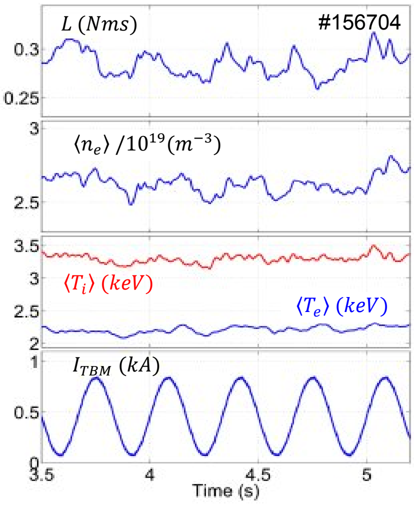

Figure 1. Time traces showing the response of the volume integrated toroidal angular momentum, plasma temperature and density to the TBM current.

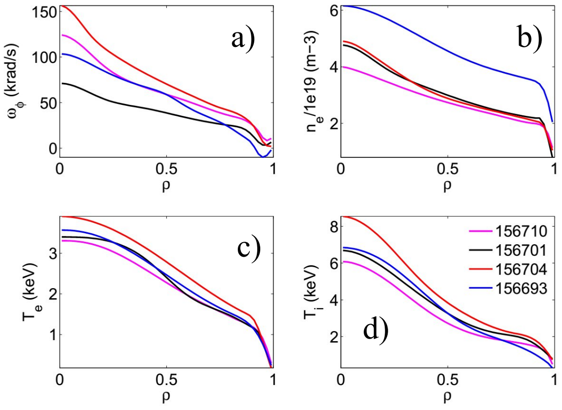

Figure 2. Plasma profiles across the normalized minor radius within the β_N scan. a) Toroidal angular rotation frequency, b) electron density, c) electron temperature and d) ion temperature. Each color corresponds to a shot from Table 1, as labeled in (d).

Table 1. Operation space covered in the β_N scan. Electron cyclotron heating, especially in the high β_N discharges, keeps the plasmas MHD stable.

shot #	156710	156701	156704	157893
β_N	1.5	1.9	2.4	2.6
I_p	1.2 MA	1.2 MA	1.2 MA	1.4 MA
B	1.7 T	1.7 T	1.6 T	1.6 T
P_{EC}	1.5 MW	0.6 MW	1.6 MW	2.9 MW
P_{NBI}	3.2 MW	4.6 MW	5.7 MW	8.1 MW

Table 1 shows the heating, plasma current and magnetic field used in the β_N scan while Figure 2 plots the plasma profiles. Plasma pressure is dominantly increased by additional heating which simultaneously leads to more NBI torque and higher rotation. The 4-point β_N scan does have some variation also in dimensionless quantities such as collisionality and Ti/Te ratio but β_N is expected to be the dominant contributor to TBM torque changes.

Theory The TBM torque is modeled as Neoclassical Toroidal Viscosity (NTV) using the Perturbed Equilibrium Nonambipolar Transport (PENT) code [1]. The model calculates the nonambipolar ion flux across flux surfaces (generating a toroidal JxB torque) induced by perturbative 3D fields that break the toroidal symmetry. The ideal plasma response to the 3D TBM vacuum perturbation is taken into account using the IPEC model [3]. The TBM torque is generally found to be strongly edge localized (see Figure 3) concentrating in the region where the radial electric field crosses zero. Calculations also find the TBM torque to scale quadratically with the TBM error field, as expected, and to increase roughly linearly with normalised plasma pressure β_N, although the magnitude of the modeled torque is roughly 3 times larger than the value found in the experimental analysis (see below). The sharp modeled profiles might be expected to be shielded and broadened when including the kinetic damping self consistently in the perturbed equilibrium, and a General Perturbed Equilibrium Code (GPEC) is being developed to test this hypothesis.

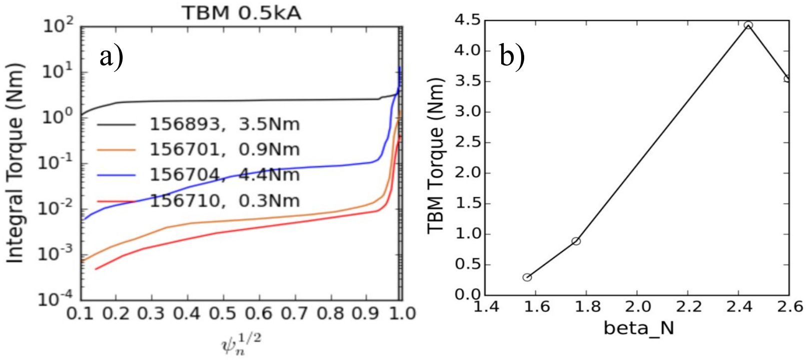

Figure 3. IPEC-PENT calculated TBM torque profiles (a) and the trend as a function of normalised plasma pressure (b). Note that in the experiment the TBM coil current was 0.85kA and thus the actual values are a factor of 3 larger.

Experimental torque determination To model the plasma angular momentum density (i.e. rotation) we use the 1.5D toroidal angular momentum conservation equation where transport is assumed purely diffusive for simplicity:

$$\frac{\partial \gamma}{\partial t}+\frac{1}{V'}\frac{\partial}{\partial \rho}\left(V'\langle|\nabla\rho|^2\rangle\chi_{\phi,eff}\frac{\partial \gamma}{\partial \rho}\right) = T_{NBI}+T_{TBM}$$

Here $\gamma = m_i n_i \langle \mathrm{R}^2 \rangle \omega_\phi$ is the flux surface averaged toroidal angular momentum density, V' is the radial derivative of the plasma volume, $\chi_{\phi,eff}$ is the effective momentum diffusion coefficient and the terms on the right hand side are the NBI driven torque density and the TBM generated torque density. All terms except the T_{TBM} and ω_ϕ are taken to be functions of radius only. T_{TBM} and $\chi_{\phi,eff}$ are unknown while the remaining terms come from either experimental measurements or the EFIT and TRANSP models. To avoid calculating temporal and spatial derivatives of the experimental data, we solve the unknowns iteratively by a least squares approach where T_{TBM} and $\chi_{\phi,eff}$ are varied to minimize the difference between calculated and measured rotation.

To estimate the experimental torque profiles, a simplified model is derived. Firstly, we assume that the TBM torque originates dominantly from the NTV, which has a quadratic dependence on the applied field [4], $T_{TBM} \propto \delta \mathrm{B}^2 \propto I_{TBM}^2$. Furthermore, we assume that the torque induced by the perturbed magnetic field acts instantaneously at all radii. We thus write the TBM generated torque as $\mathrm{T_{TBM}}(\rho, \mathrm{t}) = \mathrm{S}(\rho) \cdot \left[\frac{\mathrm{I_{TBM}}(t)}{\max |I_{TBM}|}\right]^2$ where the time dependence comes directly from the experiment and only the radial dependency needs to be found. We approximate $\mathrm{S}(\rho)$ with two Gaussians whose width, height and location are free (fitted) parameters and with an edge localised torque: $\mathrm{S}(\rho) = a_1 e^{-(\rho - b_1)^2/c_1} + a_2 e^{-(\rho-b_2)^2/c_2} + a_3 \delta(\rho - 1)$.

One can observe that even with the simple parametrization used here for the TBM torque profile the best fitting calculated angular momentum is within the error bars of the experiment (see Figure 4). The minimum of the phase (~40deg) is below what one obtains from a 0d model, $\dot{L} = T - L/\tau_E$, with 3 Hz modulation frequency and energy confinement time $\tau_E = 80ms$ (~56deg) suggesting slightly inferior momentum confinement. The phase minimum

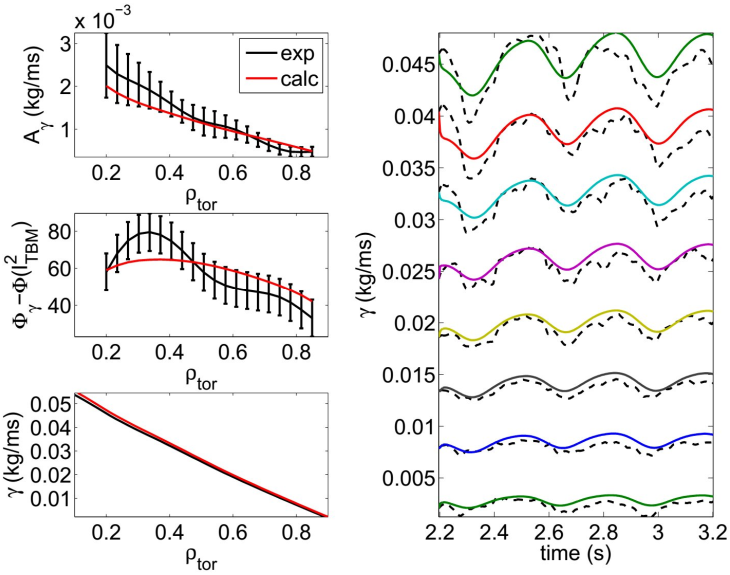

Figure 4. Best fitting simulated angular momentum density (red) and experimental data (black). The left frames show the 3 Hz modulation amplitude (top) and phase profiles and the average angular momentum (bottom). The right frame gives the time traces at various radial locations.

indicates that the position of the strongest torque perturbation is near the edge as predicted by the IPEC-PENT calculations.

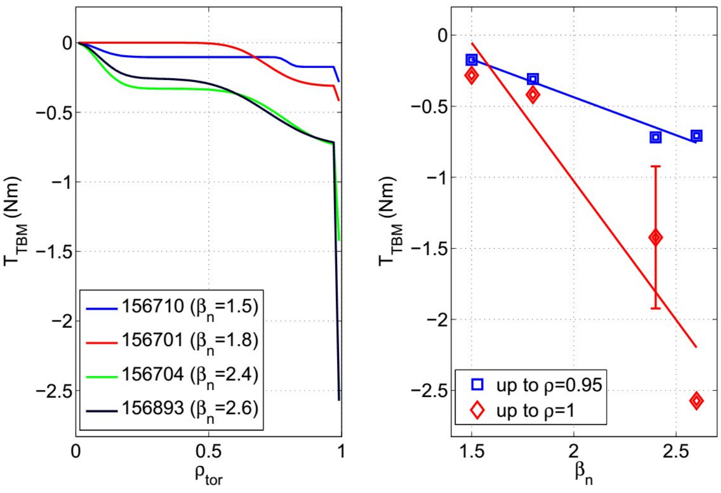

Figure 5. Experimental estimates of the TBM torque for the β_N scan. Volume integrated TBM torque profiles (left) and the total torque up to rho=0.95 (blue squares) and up to the separatrix (red diamonds) as a function of the normalised plasma pressure (right).

Figure 5 shows the summary of the experimental estimates of the TBM generated torque for the 4-point β_N scan. The relatively small rotation perturbation obtained even with the largest technically achievable TBM field results in a fairly modest counter-current torque. The χ^2 goodness of the fit between the measured and the modeled toroidal rotation is relatively sensitive even to the magnitude of the edge localised torque component. However, the radial resolution and the noise in the experimental measurements do not allow transport estimation in pedestal width scale and thus a narrow diffusion barrier and/or outward convection layer could prevent very edge localised torque sources from affecting the core rotation, masking larger edge localised torques.

Conclusions We have found a good qualitative (factor ~3 off in absolute terms) agreement between the experiment and IPEC-PENT calculated torque both in profile shape and in scaling with normalised plasma pressure. At ITER $\beta_N = 1.8$ the experimental TBM torque was observed to be small, barely generating rotation perturbation outside the measurement noise thus suggesting weak effect in ITER. However, the extrapolation of these results to ITER is not straightforward as ITER plasmas are likely to be rotating less and operate in lower collisionality thus influencing the plasma response to the TBM field. Additional effort both in experiments (to reduce error bars) and in code development is desirable to improve the agreement in DIII-D plasmas and to increase the confidence in absolute TBM torque magnitude predictions for ITER.

*Work supported by the US Department of Energy under DE-FC02-04ER54698 and DE-AC52-07NA27344.

[1] N.C. Logan *et al* 2013 Phys. Plasmas **20** 122507

[2] M.J. Schaffer *et al* 2011 *Nucl. Fusion* **51** 103028

[3]. J.-K. Park *et al* 2007 *Phys. Plasmas* **14** 052110

[4] K.C. Shaing 2003 Phys. Plasmas **10** 1443