Confinement, Transport and Turbulence Properties of NSTX Plasmas

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Introduction

Data from dedicated parameter scans and statistical studies in the National Spherical Torus Experiment (NSTX) [1, 2] have been used to study the confinement and transport trends in H-mode plasmas at low aspect ratio. NSTX operates at a nominal aspect ratio of 1.3, a factor of two lower than that for conventional aspect ratio devices, and also at high beta, with achieved toroidal beta values of over 35%. NSTX data therefore provides a good testbed in which to study the effects of extreme toroidicity, kinetic effects and high beta. In addition, it is the electrons in NSTX that are predominantly heated by up to 7 MW of 90 keV D^0 neutral beams, and thus NSTX is an excellent laboratory in which to study electron physics. This is underscored by the fact that in H-mode plasmas the ion transport is often close to neoclassical while the electron transport is anomalous. The data to be presented in this paper is taken from experimental campaigns during 2004 to 2007 in which R=0.83 to 0.89 m, a=0.57 to 0.66 m (R/a~1.3 to 1.45), I_p = 0.6 to 1.2 MA, B_T = 0.3 to 0.55 T, elongation κ = 1.7 to 2.5, triangularity δ=0.4 to 0.85 and n_e = 1.5 to 7.0 x 10^{19} m^{-3}. Results from dedicated I_p, B_T and power scans will be presented that will include both global and local analysis. The data from the power scans are used to study the beta dependence of confinement. Furthermore, results from statistical studies of momentum diffusivity will be presented.

B_T and I_p Dependence of Confinement

Dedicated parameter scans, one at fixed plasma current and one at fixed toroidal field were used as a basis to determine the dependence of thermal and global confinement on B_T and I_p respectively in NSTX [3]. These scans were carried out at similar densities and fixed injected power (4 MW) in Lower Single Null deuterium H-mode discharges. The results of these scans are shown in Figs. 1 a and b for a toroidal field scan at I_p=0.7 MA and a plasma current scan at B_T=0.55 T respectively. The results show a much stronger toroidal field scaling than plasma current scaling for both the thermal and total (including fast ion contribution) confinement times. The results from these dedicated scans confirmed earlier results from statistical analysis [4]. These dependences, with $\tau_E \sim B_T^{0.9} I_p^{0.4}$ are quite different than those at conventional aspect ratio, as typified by the ITER98pby,2 scaling [5] and given by $\tau_E \sim B_T^{0.15} I_p^{0.93}$. A B_T scan was performed also at I_p=0.9 MA, and this showed a weaker dependence, with $\tau_E \sim B_T^{0.6}$, indicating a possible non-linear dependence on q or I_p.

Local transport analysis was carried out to determine the source of the underlying transport giving rise to these confinement trends. As was reported in [3,6],

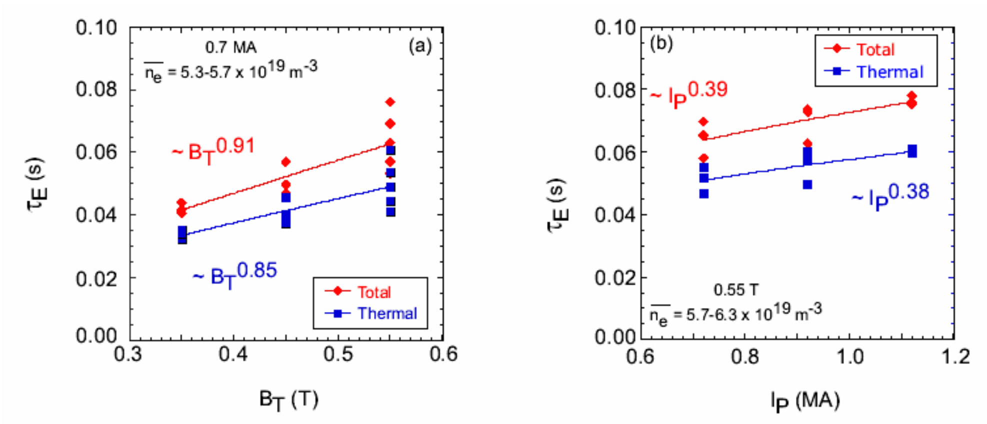
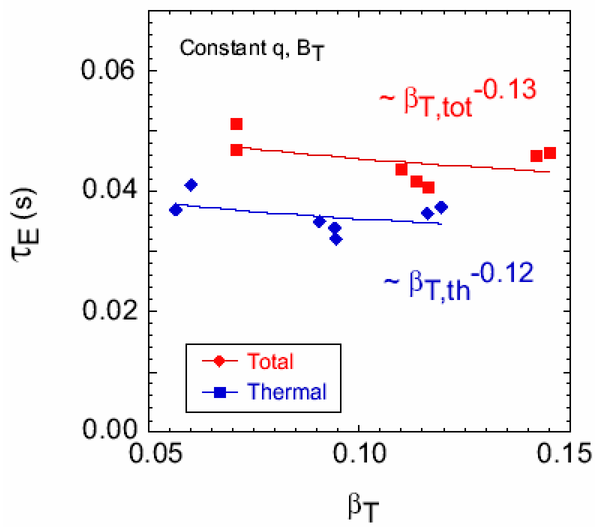


Fig. 1 (a) Total (red) and thermal (blue) confinement dependence on toroidal magnetic field (b) on plasma current from dedicated parameter scans

the analysis showed that it is the electron transport outside r/a=0.5 that is responsible for the B_T scaling, with the ion transport being in the neoclassical range. The ions, on the other hand, were the controlling species for the I_p scaling. In this case, the ion thermal diffusivities outside r/a=0.5 were in the neoclassical range for all three current levels, with the variation of neoclassical transport with I_p being responsible for the confinement dependence on this parameter. For both the B_T and I_p scans, linear gyrokinetic calculations using GS2 indicated that long-wavelength (low-k) modes, such as ITGs, could be stabilized easily by the large ExB shearing rates typical of NSTX plasmas. Microtearing and ETG modes, however, could be unstable in some cases, leading to the anomalous electron transport (and possibly its scaling with B_T) in NSTX. Measurements of high-k turbulence using a recently implemented microwave scattering diagnostic [7] have been taken to further help in determining the source of the electron transport.

Beta Scaling of Confinement

Because of the low toroidal magnetic field in NSTX plasmas, the range of accessible toroidal beta is typically a factor of five greater than that in conventional aspect ratio tokamaks. This large range of beta potentially allows for high leverage in determining the scaling of confinement with this parameter, an important issue for the performance of the advanced operating scenario in ITER. The results of a power/beta scan at constant q, B_T in strongly shaped plasmas (κ~2.1, δ~0.8) is shown in Fig. 2. In this scan, density was adjusted so that the variation in collisionality ν^*_e and normalized gyroradius ρ^*_e was kept constant to within 20% across the scan. Only small ELMs were present in the discharges in this scan. The beta scaling of both total and thermal confinement resulting from this scan is seen to be quite weak, if not zero.



It has been suggested, however, that plasma shaping can play an important role in the beta scaling [8], and to test this effect, the scan was performed again, but this time in more weakly-shaped plasmas (κ~1.8, δ~0.4). Unlike the strongly-shaped plasma scan, the nature of the ELMs seen in the weaker-shaped plasmas changed from Type III to Type I, with power losses from 2 to 5%, as the power increased from the 2 MW level up to the 4 MW level and beyond, as can be seen in Fig. 3. This change in ELM behavior complicates the analysis. It is seen, however, that there is a clear degradation of confinement with increasing beta; shown in Fig. 4 is the total confinement time vs the total toroidal beta (fast ion component included), along with a fit to the data. Time periods during which Type III ELMs were present, just after the L-H transition (see Fig. 3) were not included in this plot, as the discharges were still evolving. There is a strong degradation of confinement with beta in these plasmas in the total toroidal beta as; such a strong degradation cannot be ruled out for the thermal beta scaling, although the range of thermal betas was smaller than that for total beta, making a determination of the scaling more uncertain. The strong beta degradation is no doubt linked to the increasing ELM severity with increasing power.

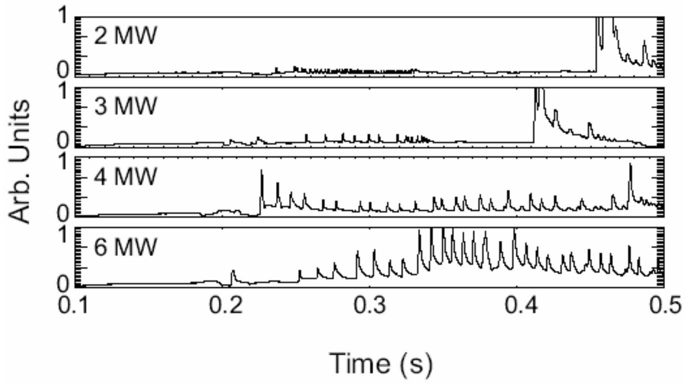


Fig. 3 ELM behavior in the power/beta scan in weakly-shaped plasmas.

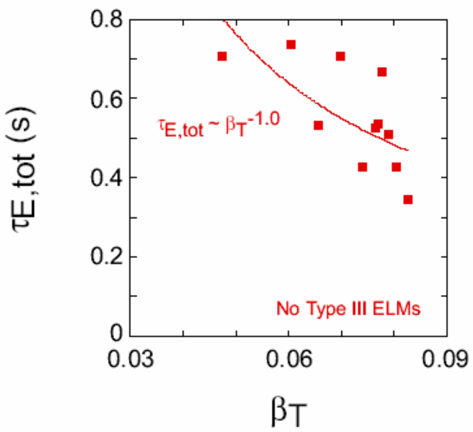


Fig. 4 Scaling of total confinement with beta for weakly-shaped discharges.

Momentum Confinement and Rotation Physics

Rotation physics and the effect of rotation on transport is of particular importance in NSTX due to the relatively high rotation velocities, with central rotation speeds reaching 300 km/s, and due to strong ExB shearing rates, in the 0.1 to 1 MHz range.

Indeed, as to the ExB shearing rate, it is the magnitude of this rate, in addition to geometric effects, that is partly responsible for the believed suppression of long-wavelength ITG and possibly TEM modes [6].

An interesting question arises as to the source and scaling of the momentum diffusivity if these long wavelength modes are indeed suppressed. In conventional aspect ratio tokamaks, the momentum diffusivity generally scales with the ion thermal diffusivity and the magnitudes of the two are within a factor of a few. It is generally believed that the source of this relationship, and thus the source of the physics controlling the momentum diffusivity, is the long-wavelength ITG mode [9]. In NSTX, then with the low-k modes suppressed, a different scaling might be expected. In Fig. 5, χ_i is plotted as a function of χ_ϕ at r/a=0.4, and it is seen that these two parameters do not exhibit a linear relation as in conventional aspect ratio tokamaks.

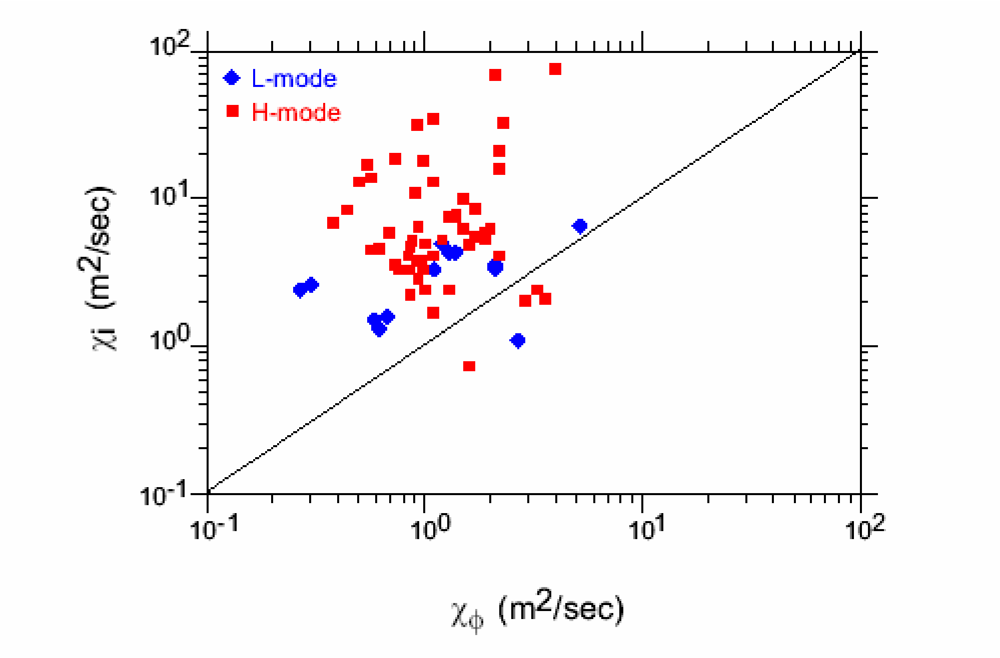


Fig. 5 χ_i plotted as a function of χ_ϕ at r/a=0.4 for L- and H-modes

The momentum diffusivity is typically a factor of several to a factor of ten, but can be up to a factor of 40, greater than the ion thermal diffusivity. The low value of the experimental χ_ϕ may be in the range expected for neoclassical momentum transport. In the dedicated B_T and I_p scans discussed above, it is seen that the χ_ϕ also does not scale with χ_i, but interestingly, seems to decrease monotonically with increasing B_T similar to the scaling of χ_e in that case. Consequently, in these plasmas, it appears that χ_ϕ scales more with the electron thermal diffusivity rather than the ion thermal diffusivity. A more comprehensive study of the momentum confinement physics is underway. This study is based on results from dedicated scans that use applied n=3 fields to magnetically brake the plasma rotation. Both perturbative and steady-state power balance determinations of the momentum confinement time, τ_ϕ, indicate τ_ϕ in excess of 100 ms, consistent with the inference of low χ_ϕ.

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