Effect of Radial Electric Field Shear on Tokamak Transport: Flow Shear and Magnetic Field Scaling

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I. Introduction

Numerous recent tokamak experiments using reversed magnetic shear have renewed interest in the connection between reduced energy and particle transport and large shearing rates of the radial electric field.[1,2] A simple criterion has been suggested[3] for turbulence and transport suppression. Transport is suppressed when the shearing rate, γ_{ExB}, is larger than the linear growth rate, γ_{max}, of the fastest growing mode involved in the transport. The shearing rate is defined as $\gamma_{ExB} \equiv RB_p/B_t \partial(E_r/RB_p)/\partial r$ where B_p and B_t are the poloidal and toroidal magnetic fields, respectively.[4] Force balance determines the radial electric field to be $E_r = \quad P/nZe + V_t B_p - V_p B_t$. In plasmas with small pressure gradients, such as in L-mode discharges, the ratio $\gamma_{ExB}/\gamma_{max}$ is expected to scale as MB_p/B_t where M is the toroidal Mach number ($M = V_t/C_s$ and C_s is the ion sound speed).

Although complete turbulence suppression requires $\gamma_{ExB} \approx \gamma_{max}$, nonlinear numerical turbulence calculations have indicated that transport could be reduced even when $\gamma_{ExB} < \gamma_{max}$. Thus, shear-flow effects could potentially affect confinement in a variety of plasma regimes including L-mode and the H-mode core. For this reason, the dependence of the shearing rate on the toroidal velocity may be a concern for the validity of ρ^* and other scaling experiments that use only uni-directional beam injection. The results of those scaling experiments may be confused by a favorable scaling of transport with increased flow shear. Also, empirical expressions for the global energy confinement time, τ_E, typically do not explicitly account for rotation effects. Scalings deduced from rotating plasma experiments could be misleading for extrapolating to devices such as ITER where the external momentum input is small.

II. Experimental Results

Experiments were performed on TFTR to examine the effects of both toroidal rotation and magnetic field on transport in L-mode plasmas with monotonic q profiles. The toroidal velocity was varied by changing the net torque applied to the plasma using neutral beam heating directed in either the same (co-) or opposite (ctr-) direction to the plasma current. For the analysis presented here, the plasma rotation is assumed to track linearly with the mix of co- and ctr-injected power. More detailed analysis using measured carbon velocity profiles is in progress.

The magnetic field scaling was determined by changing simultaneously the plasma current and the toroidal field at fixed edge q.

The plasmas were formed at a major radius of 2.52 m with a minor radius of 0.87 m. The line-averaged density during the discharge was kept to a programmed level of 5.5 x 10^{19} m^{-3} (Fig. 1) by puffing deuterium gas. The plasmas were heated with 11 to 15 MW of neutral beam injection (NBI) power for two seconds. The directionality of the heating power was changed from all co- to balanced and then to all ctr- by substituting individual sources on successive discharges. The plasma current and toroidal field were either 2.0 MA and 4.8 T or 1.0 MA and 2.4 T, respectively. The confinement times were typical of L-mode discharges on TFTR, 100 - 120 ms for the high-field discharges and 50 - 90 ms for the low-field discharges. All of the discharges had sawteeth.

Global plasma performance on TFTR is critically dependent on edge conditions (edge density and particle influx). The transition from low-performance L-mode discharges to high-performance supershots is a smooth function of edge conditions. Examination of the edge density and electron temperature show that these quantities were well matched. Therefore, a variation in edge conditions was not responsible for the observed confinement variations.

The radial profiles achieved in the high-field discharges are shown in Fig. 2. The discharges were well-matched in density, beam deposition, and electron temperature profiles. Toroidal velocities between +1.5 x 10^5 and -1.0 x 10^5 m/s were obtained, corresponding to Mach numbers between +0.3 and -0.3.

It was found that global energy confinement was the highest for pure co-injection compared to balanced or pure ctr-injection, i.e., it took less co-injected power to match the same stored energy at the same line-averaged density as it took either balanced or ctr-injected power. Figure 1 shows that this was true for both high- and low-field discharges. However, to conclude that plasma rotation is favorably affecting energy confinement for co-rotation, it is necessary to

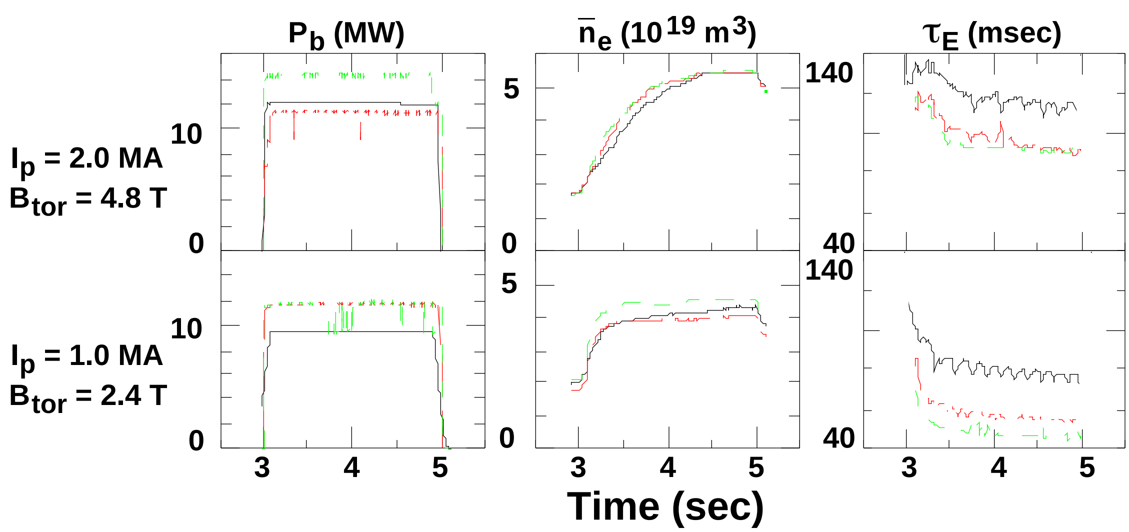

Figure 1. Energy confinement is better with co-injection for both toroidal fields. The discharges had ratios of co- to total injected neutral beam power of 1.0 (solid line), 0.4 (dashed), or 0.2 (dotted).

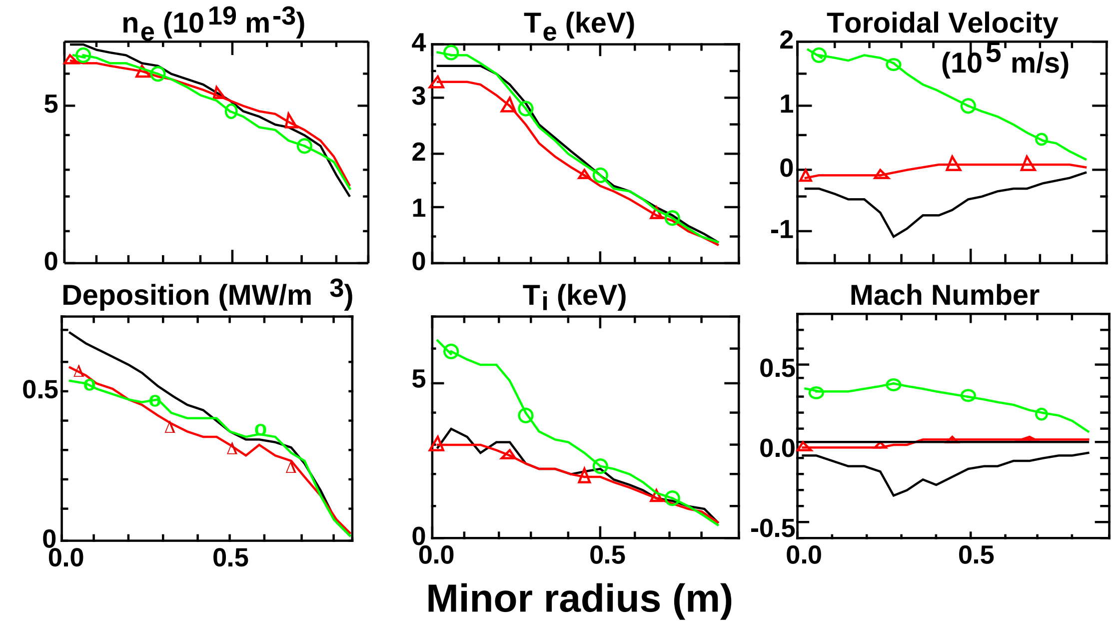

Figure 2. Profile information for the high-field discharges of Fig. 3 at 4.15 sec. The discharges had ratios of co- to total injected neutral beam power of 1.0 (o), 0.4 (Δ), or 0.2 (solid line).

include beam-orbit effects which reduce the effectiveness of ctr-injected beams. But as shown in Fig. 2, even when the orbit effects are taken into account, the co-injected plasma achieved a higher ion temperature.

Kinetic analysis shows that improvement of the ion energy transport accounts for the increase in global confinement. This is shown clearly in Fig. 3 in the elevated ion temperature 25 cm from the magnetic axis ($r \approx a/3$) for the pure co-injected plasma. There is no increase in the density or central electron temperature. The density, T_e, and T_i at the edge of the plasma showed no systematic change due to rotation.

The experimental results are summarized by Fig. 4. Both pure co- and pure ctr-injection led to improved global confinement compared to balanced injection (non-rotating plasmas). The figure of merit is the energy confinement time compared to standard L-mode scaling. Confinement is improved by 20% for the high-field discharges and by 50% for low-field discharges. Simple models of flow-shear stabilization would suggest that the effects of rotation

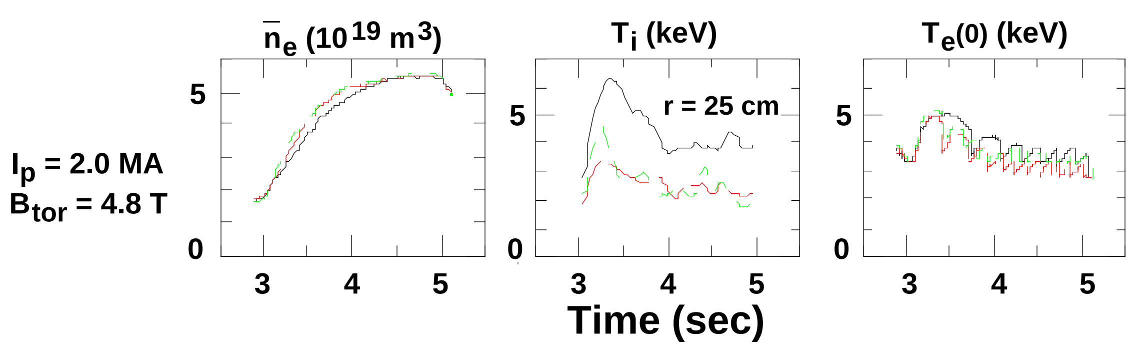

Figure 3. The core ion temperature increases greatly with co-injection. There is little effect on the electron temperature. The discharges had ratios of co- to total injected neutral beam power of 1.0 (solid line), 0.4 (dashed), or 0.2 (dotted).

should be symmetric with respect to co- or ctr-rotation. The data, however, clearly show that the minimum confinement occurs for moderate values of ctr-rotation. Detailed analysis, accounting for beam-orbit effects, will modify the shape of these curves but will not affect the overall conclusion that rotation improves confinement.

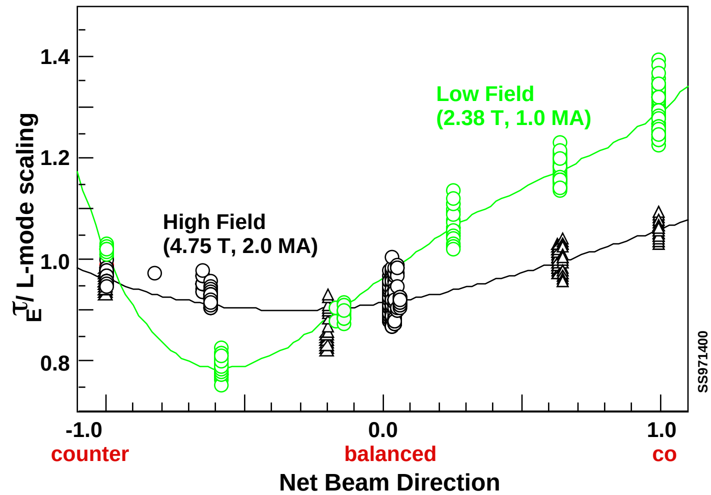

Figure 4. Both high-field (Δ) and low-field (o) data sets show that rotation improves energy confinement.

These L-mode experiments were limited to rotation velocities of Mach ±0.3. Mach numbers up to +0.8 and -0.6 have been produced in supershot discharges which have large pressure gradients, $T_i >> T_e$, and peaked density profiles. The co-injection discharges exhibited significantly improved core ion heat confinement compared to balanced or ctr-injection, with local χ_i (r=a/3) decreasing an order of magnitude in some cases. The effect on global energy confinement was masked by several classical effects of rotation on beam deposition and thermalization which made global τ_E a maximum for slight co-injection rather than pure co-injection.

III. Conclusion

The effect of rotation on global energy confinement was clearly observed in discharges with $T_i \approx T_e$ and weak pressure gradients. Increased confinement was observed for both strong co- and strong ctr-rotation. Kinetic analysis indicates that ion energy confinement was affected most by rotation. The effect was stronger at lower toroidal magnetic field ($B_t \approx 2.4$ T). Suppression of transport by radial electric field shear is supported by both of these observations.

These results suggest that shear-flow effects should be considered in the analysis of empirical global τ_E scaling and dimensionless scans for estimating τ_E in next-step tokamaks.

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