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Authors

Nazikian, R
Austin, ME
Budny, RV
et al.

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Fast Ion Redistribution and Implications for the Hybrid Regime

R. Nazikian[1], M.E. Austin[2], R.V. Budny[1], M.S. Chu[3], W.W. Heidbrink[4], M.A. Makowski[5], C.C. Petty[3], P.A. Politzer[3], W.M. Solomon[1], M.A. Van Zeeland[3] and R.B. White[1]

[1] *Princeton Plasmas Physics Laboratory, Princeton, New Jersey, USA*
[2] *University of Texas-Austin, Austin, Texas, USA*
[3] *General Atomics, San Diego, California, USA*
[4] *University of California-Irvine, Irvine, California, USA*
[5] *Lawrence Livermore Laboratory, Livermore, California, USA.*

Abstract. Time dependent TRANSP analysis indicates that radial redistribution of fast ions is unlikely to affect the central current density in hybrid plasmas sufficient to raise $q(0)$ above unity.

The role of neoclassical tearing modes (NTMs) has been central to the discussion of core current density and sawtooth suppression in Hybrid plasmas [1,2]. One hypothesis is that NTMs may redistribute co-injected beam ions, thereby reducing the net current density on axis sufficient to suppress sawteeth. Another idea is that the m/n=3/2 mode couples to a 2/2 sideband that drives counter current in the plasma core through differential rotation when the core rotates faster than the island in the co-beam direction. Yet another notion is that some anomalous resistivity occurs in the core of hybrid plasmas that suppresses the ohmic current density on axis [3]. Other mechanisms have also been proposed. In this paper we address the question whether the radial redistribution of beam ions alone is capable of suppressing the current density on axis sufficient to avoid sawteeth in hybrid plasmas. Our preliminary conclusion is that a broadening of the fast ion distribution is unlikely to affect the central current density in hybrid plasmas. This is due to a reduction in the beam driven current associated with the broadening of the fast ion profile and consequent increase in the centrally peaked inductive current.

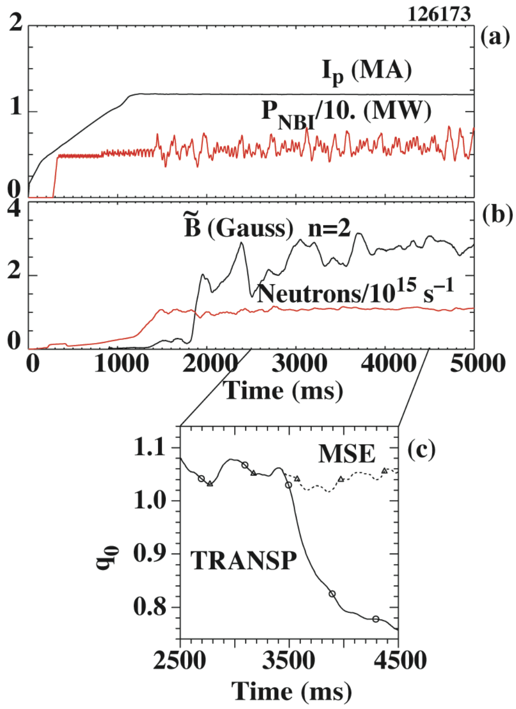

Fig. 1. Time evolution of plasma parameters for hybrid discharge 126173: (a) plasma current and beam power, (b) rms mode amplitude for m/n=3/2 mode and neutron rate, (c) evolution of $q(0)$ from MSE and TRANSP without MSE after 3.5 s. Plasma parameters are: B_T=1.8 T, I_p=1.2 MA, R_0=175 cm, $T_e(0)\approx$ 3.2 keV, $n_e(0)\approx 5\times10^{13}$ cm^{-3}.

Figure 1 shows a hybrid discharge with $q(0)\approx1.05$ from motional Stark effect (MSE) measurements in the period where there is a robust m/n=3/2 NTM observed on external magnetic probes. The neutron signal does not decrease at mode onset, indicating no large losses are associated with the mode, but this does not rule out redistribution. The plasma is heated with co-injected 80 keV deuterium neutral beams. Co-beam injection is expected to drive a centrally peaked co-going current on axis based on classical orbit analysis. Also shown is a time dependent TRANSP simulation of the same discharge constrained by the MSE measured q-profile up to 3.5 s. At 3.5 s the MSE constraint is removed from the TRANSP simulation and the current is allowed to evolve assuming neoclassical resistivity and inductive current feedback to maintain I_p=1.2 MA as in the experiment. The figure shows that the central $q(0)$ decays to ≈0.75, consistent with the general understanding that some anomalous mechanism is required to maintain $q(0)>1$ in hybrid plasmas.

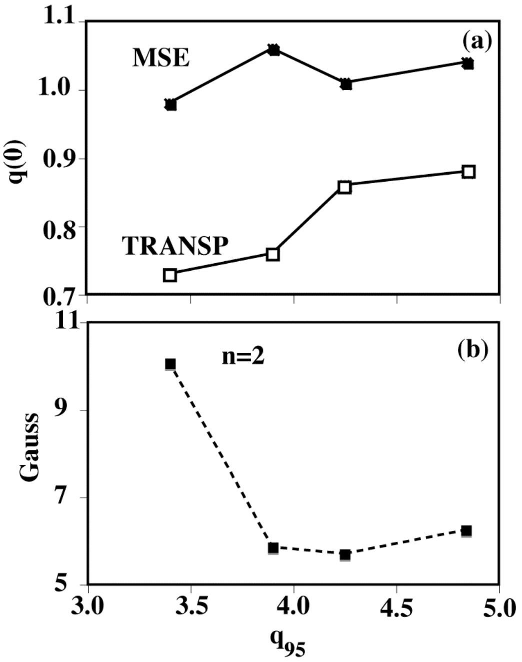

Fig. 2. (a) Measured $q(0)$ from MSE and simulated $q(0)$ form TRANSP at 4.5 s. into the discharge vs q_{95} for a reproducible set of hybrid discharges with a strong m/n=3/2 mode. (b) Estimate of the n=2 RMS poloidal magnetic field at the q=3/2 surface.

Figure 2 shows the result of an experiment where q_{95} was scanned in a sequence of hybrid plasmas by varying the toroidal field from 1.55 T to 2.15 T, keeping the plasma current constant at 1.2 MA. The MSE measurements indicate $q(0)\approx1$ over the scanned range of q_{95}, however the TRANSP simulations suggest that $q(0)$ should fall below unity for all the discharges according to neoclassical resistivity. The estimate of the rms poloidal field amplitude of the n=2 mode at the q=3/2 rational surface is shown in Fig. 2(b) assuming m=3 is the dominant poloidal harmonic. More detailed analysis is underway based on the local displacement inferred from ECE measurements.

Figure 3 shows a plot of the various plasma current components for the relaxed q-profile at 4.5 s with $q(0)$=0.75 in Fig. 1 according to the TRANSP analysis based on neoclassical resistivity and classical ion orbits. The edge bump in the plasma current density (j_p) is attributed to the bootstrap current in the edge pedestal. Both the relaxed ohmic current and the beam driven current are centrally peaked and the central beam driven current density is of the order of 20% of the total current density.

Figure 4 shows TRANSP analysis of the fast ion current density profiles (j_{NBCD}) for different levels of fast ion diffusion applied to the TRANSP simulation in Fig. 3. Two fast ion diffusivities are used in Fig. 4; D_{fast} = 0.01 and 4.0 m^2.s^{-1} and the enhanced diffusivity is switched on at the start of beam injection in the simulation. The enhanced diffusivity extends to r/a=0.7 in order to minimize losses, consistent with the observation that the neutron emissivity is unaffected by the onset of the NTM. The profiles of the beam driven current are shown at 3.4 s just before the MSE constraint is switched off, and do not vary significantly through the current flat top region of the discharge. In order to affect the axial beam current in the TRANSP simulation without dramatically reducing the neutron rate, it was necessary to enhance the beam ion diffusion inside r/a=0.7 with classical confinement beyond this radius. For D=0.01 no noticeable effect is seen on the classical prediction as expected, while at 4.0 there is a complete flattening of j_{NBCD}. However the enhanced diffusion of the beam ions for the case D_{fast}=4.0 also results in a reduction of the net beam-driven current by about 20% due to charge exchange at the plasma edge, leading to an increase in the on-axis inductively driven current.

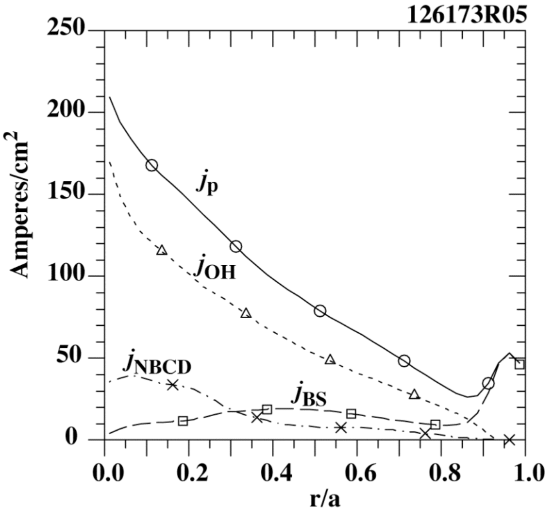

Fig. 3. Current density profiles vs normalized minor radius from TRANSP for 126173 at 4.5 s. Plasma current (j_p), Ohmic current (j_{OH}), neutral beam current (j_{NBCD}), bootstrap current (j_{BS}).

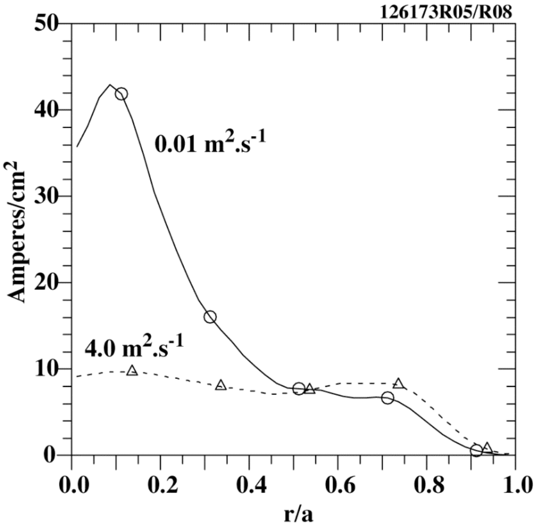

Fig. 4. Beam driven current density profiles from TRANSP for D_{fast}=0.01 m^2.s^{-1} and D_{fast}=4.0 m^2.s^{-1}. The enhanced diffusivity extends to 0.7 minor radius.

Figure 5 shows the time evolution of $q(0)$ and the current drive components inside r/a=0.1 for the two cases in Fig. 4 corresponding to D_{fast}=0.01 and D_{fast}=4.0 m.s^{-2}. After t=3.5 s the q-profile is allowed to evolve according to neoclassical resistivity while maintaining constant total current through inductive feedback. Note that the relaxation of $q(0)$ and the central I_{p} is rather insensitive to the different values of the central I_{NBCD} inside r/a=0.1. The simulation loop voltage increased form the measured 0.11 V at 3.5 s to 0.16 V by 4.5 s. The ohmic current is clearly compensating for the difference in the central j_{NBCD} well after the MSE constraint is removed. This is not unlike an earlier result obtained on DIII-D with fast wave current drive (FWCD) where a similar ohmic compensation of the FW current was obtained [4] owing to the similarity in the central peaking of the FW and OH currents. The conclusion is that even a very strong monotonic redistribution of beam ions leads to a minimal effect on the central current density and $q(0)$ due to ohmic compensation of the missing NB current.

At this point, we need to make clear that our conclusions are dependent on a rather primitive model of beam ion redistribution based on a constant diffusivity. If there is some physical mechanism that can efficiently convert the centrally peaked beam driven current into a strongly peaked off-axis current then our conclusions may need to be modified. To determine if this is possible, the radial displacement associated with an NTM has been inferred on DIII-D from electron cyclotron emission (ECE) measurements and used to simulate the beam ion interaction with the mode using the ORBIT code. The latest results are that the redistribution associated with reasonable values of the displacement (1-3 cm) is negligible and that larger amplitudes (by a factor of three) only lead to a broadening of the fast ion profile, similar to the modeling used in the TRANSP analysis [2]. There are indications from fast ion D_α measurements [5,6] that little or no fast ion redistribution is observed in these plasmas, consistent with ORBIT modeling, however additional measurements are needed to draw a definitive conclusion from this diagnostic. The overall conclusion based on the presently available data and modeling indicates that the interaction of fast ions with NTMs is unlikely to play a significant role in raising $q(0)$ above unity.

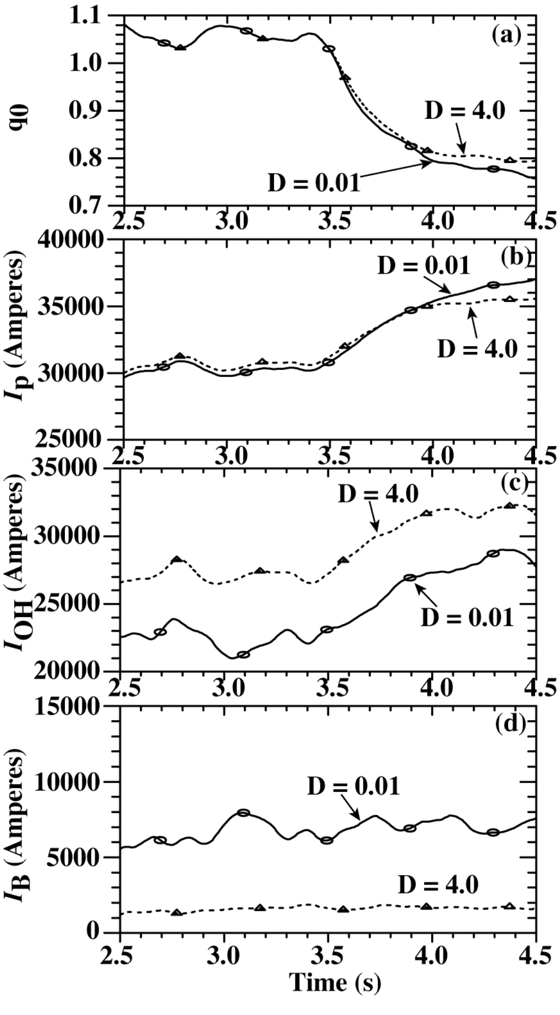

Fig. 5. Time evolution from TRANSP for $q(0)$ (a) and plasma current inside r/a=0.1: I_p (b) I_{OH}, (c) I_{NBCD} (d). D_{fast}=0.01 $m^2.s^{-1}$ (solid) and D_{fast}= 4.0 $m^2.s^{-1}$ (dashed). The TRANSP loop voltage increases from the measured 0.11 V at 3.5 s to 0.16 V by 4.5 s.

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