FAST WAVE HEATING AND CURRENT DRIVE IN DIII–D IN DISCHARGES WITH NEGATIVE CENTRAL SHEAR*

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Discharges with negative central shear (NCS) in DIII–D are characterized by access to improved performance: normalized beta reaches 4.0 while the confinement remains very high, $H \approx 4.5$, with high power neutral beam heating [1]. These discharges have been generated in DIII–D by injecting neutral beams during the current ramp. This technique is inherently transient, and the hollow current profiles eventually evolve into monotonically decreasing profiles.

The high performance of NCS discharges motivates development of noninductive means, such as fast wave current drive (FWCD), to help sustain the desired current profiles. Low power NCS discharges make excellent target plasmas for current drive, since they are characterized by high electron temperature, typically 5 keV, and low density, typically $n_e(0) \approx 2 \times 10^{19}$ m^{-3}, conditions which facilitate effective current drive. Additionally, they are free of sawteeth, so that central FWCD may be expressed without interference. The experiments were performed with toroidal field 1.6 to 2.1 T, with 0.8 to 1.6 MA of plasma current, and about 2.5 MW of rf power at 83 MHz and 1 MW of power at 60 MHz.

The first step with FWCD is to demonstrate that the waves are interacting directly with the electrons through observation of heating. The high initial electron temperature of NCS discharges improves the match of the thermal velocity of the electrons with the phase velocity of the wave, which has a parallel index of refraction of about 5. This enhances the damping of the wave and reduces the mild density rise and impurity production which can accompany ICRF power under conditions of weaker damping in DIII–D. Electron temperatures as high as 8 keV have been attained with 2.0 MW of coupled fast wave power combined with 3.7 MW of neutral beam power. At the same time the ion temperature is 11 keV and the density is 3×10^{19} m^{-3}.

These plasmas with high temperature and low density are particularly interesting for analysis of transport, since the electron heating is nearly exclusively from the FW power and the ion heating is exclusively from the beams. Ohmic heating and ion-electron heat transfer are nearly negligible. This makes transport analysis particularly clear and provides opportunity for unique experiments on transport, since the temperature of either species can be independently changed.

Plasma currents are driven by the fast waves when the phasings of the antenna straps are set to launch a toroidally traveling wave. The driven currents are determined from the profiles of the loop voltage, although the current profile varies only on the rather long resistive time scale. The loop voltage is determined from the local time derivative of the poloidal flux using the process developed by Forest [2].

The total plasma current driven by FWCD in DIII–D exceeds 250 kA, and the current drive figure of merit is consistent with theory, in particular with the ITER scaling for FWCD. The linear scaling of the figure of merit with central electron temperature which was found in earlier work [3] has been extended to higher temperature.

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Both the magnitude and the profile of the inferred current driven by fast waves agree well with theory. The experimental determination of the current profile is shown in Fig. 1, along with results from a ray tracing code CURRAY, a full wave code PICES, and a code FASTCD in which the rays are assumed ergodic. Agreement between the codes and experiment is excellent.

Shear reversal can be enhanced by counter-current drive with fast waves, and this can improve both the stability and the confinement. Counter-FWCD maintains reversed shear for 500 ms longer than co-FWCD, and the improved current profile with counter-FWCD is stable to m/n = 3/2 MHD activity which becomes unstable with co-FWCD when the minimum in the safety factor q is 1.5 or less. Figure 2 shows the profile of the measured safety factor for the two cases 400 ms after the start of 2.3 MW of coupled fast wave power. Counter-FWCD clearly has a beneficial effect on maintaining the NCS configuration, although the effect of the ohmic currents induced in opposition to the driven currents decay slowly.

A mode of improved confinement spontaneously appears during counter-FWCD in discharges with mildly negative shear. This mode is characterized by a rapid increase in electron and ion temperatures and plasma density. Transport analysis shows that thermal diffusivities for both electrons and ions decrease near the axis. A hypothesis is that the increase in E×B shear flow due to changes in both E_r and B_p causes the improved confinement.

[1] LAZARUS, E.A., “Higher Fusion Power Gain With Pressure Profile Control in Strongly-Shaped DIII–D Plasmas," submitted to Phys. Rev. Lett.

[2] FOREST, C.B., et al., Phys. Rev. Lett. **73,** 2444 (1994).

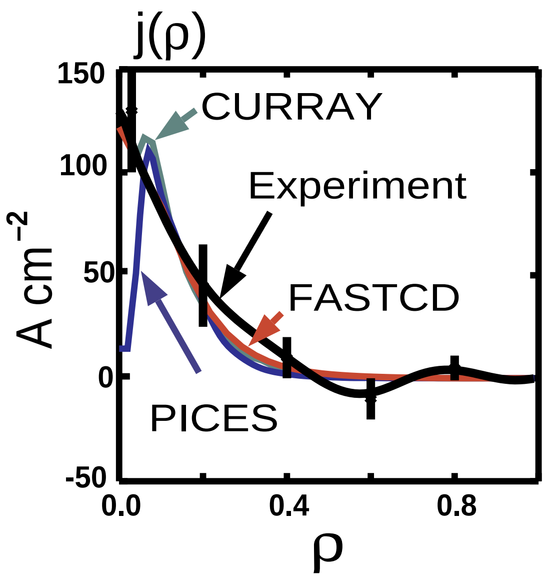

Fig. 1. Comparison of the current density determined from experiment with that from three computer codes. P_{FW} = 1.4 MW, P_{NBI} = 3.5 MW, $n_e(0)$ = 2.9 × 10^{19} m^{-3}, $T_e(0)$ = 4.5 keV, B_t = 2.1 T, and I_p = 1.4 MA. The current from FWCD is 135 kA.

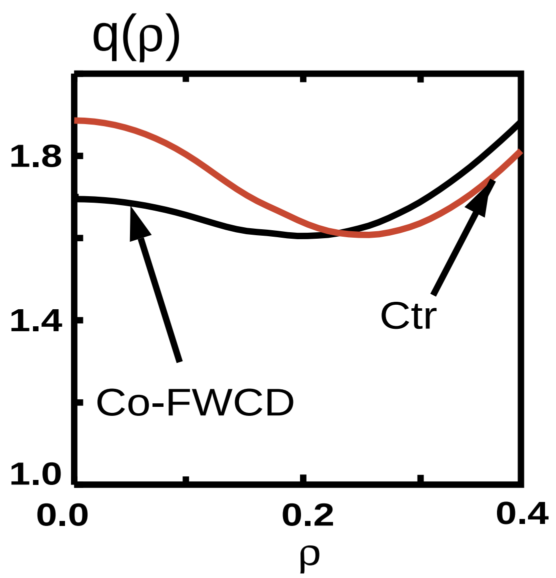

Fig. 2. Profile of safety factor q for 2.4 MW of co- and counter-FWCD.