Bootstrap-Current Experiments in a Toroidal Plasma-Confinement Device

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The toroidal current observed during electron cyclotron heating in the Advanced Toroidal Facility torsatron is identified as bootstrap current. The observed currents, ranging between +4 and −2 kA, agree well with predictions of neoclassical theory in magnitude and parametric dependence, as determined by systematic scans of quadrupole (shaping) and dipole (magnetic axis shift) moments of the poloidal magnetic field. It has been shown that the bootstrap current in a stellarator can be externally controlled, and zero-current operation can be achieved.

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The existence of bootstrap current—a toroidal plasma current produced by density and temperature gradients—is predicted by theory.[1,2] It is caused by viscosity of the trapped and untrapped particles that tends to relax the diamagnetic flow velocity, and, as a consequence, produces a current. This current is important for steady-state operation of toroidal confinement devices, because it would reduce current-drive needs in tokamaks and jeopardize current-free operation in stellarators. Therefore, in both devices it is necessary to understand the physics of the bootstrap current and to find ways to control it. The existence of bootstrap currents has been confirmed in several toroidal devices.[3-9] Recent experiments in the Advanced Toroidal Facility (ATF) have gone one step farther and shown that the measured bootstrap current agrees with predictions of neoclassical theory[10-12] by changing the neoclassical viscosity through variations of the magnetic-field structure. This demonstration is feasible because of the flexibility in controlling the magnetic configuration in ATF and the absence of other current sources.

Neoclassical theory predicts that, in the low-collisionality limit, the bootstrap current density is given by $j_b = -3(f_t/f_c)G_b B_P^{-1}\nabla p$, where f_t (f_c) is the fraction of trapped (circulating) particles, ∇p is the gradient of plasma pressure, B_P is the poloidal field, and G_b is the magnetic geometry factor, which is normalized to that in the axisymmetric tokamak ($G_b = 1$).[11] The geometry factor depends on the magnetic-field structure—in particular, on the harmonic content of $|\mathbf{B}|$ along a magnetic-field line. In a stellarator, the magnetic field contains axisymmetric, helical, and mixed components, whose mode-number spectrum can be externally controlled. Therefore, by varying the $|\mathbf{B}|$ harmonics, the bootstrap current can be externally controlled. In a plasma of finite collisionality, the bootstrap current decreases with increasing collision frequency. The collisionless regime for the helically trapped particles is more easily accessible than that for toroidally trapped particles because of the shorter helical connection length. The direction of the bootstrap current associated with helically trapped particles is opposite to that of the usual bootstrap current, because the viscous force caused by these trapped particles damps primarily the toroidal (rather than the poloidal) flow and admits a residual approximately poloidal (rather than toroidal) flow, which makes a negative (rather than positive) contribution to the parallel current.[11] The reversal of current direction has been observed in the experiment described here.

The ATF device[13] is a torsatron with two continuous helical coils, twelve field periods, major radius $R_0 = 2.1$ m, average minor radius $\bar{a} = 0.27$ m, and magnetic field on axis $B_0 \leq 2$ T. In the standard configuration, the rotational transform $\iota\!\!\!-$ $(=1/q)$ varies radially from 0.3 to ≈ 1.0. The flexibility of controlling the magnetic configuration is provided by three independently driven pairs of axisymmetric coils [inner, mid, and trim vertical-field (VF) coils]. Variations of the dipole and quadrupole moments of the poloidal magnetic field change the flux-surface position and shape, respectively.[14] This occurs in nearly-fixed-$|\mathbf{B}|$ surfaces which are primarily determined by the helical field coils, thereby changing the $|\mathbf{B}|$ harmonic content on a given flux surface and producing significant variations in the geometry factor G_b. The present studies are carried out with electron cyclotron heating (ECH) only, in order to avoid the uncertainties resulting from beam-driven current with neutral-beam injection. Up to 0.4 MW of ECH power from two 53.2-GHz gyrotrons is used for plasma initiation and heating.

Figure 1 shows the time evolution of plasma parameters in two discharges with different quadrupole moments of the vertical field. Both the helical and VF coil currents reach flattop at least 0.4 s before the ECH plasma is formed. The discharge becomes quasistationary before the measurement are made, usually at 0.48 s. The total toroidal current is measured by a Rogowski coil wound on the inner wall of the vacuum vessel. There is negligible Ohmic voltage (time- and shot-average resistive voltage less than 0.01 V), so Ohmic current is much less than 1 kA. Furthermore, ECH current drive is negligible because (1) the microwave power is launched perpendicularly to the magnetic field,

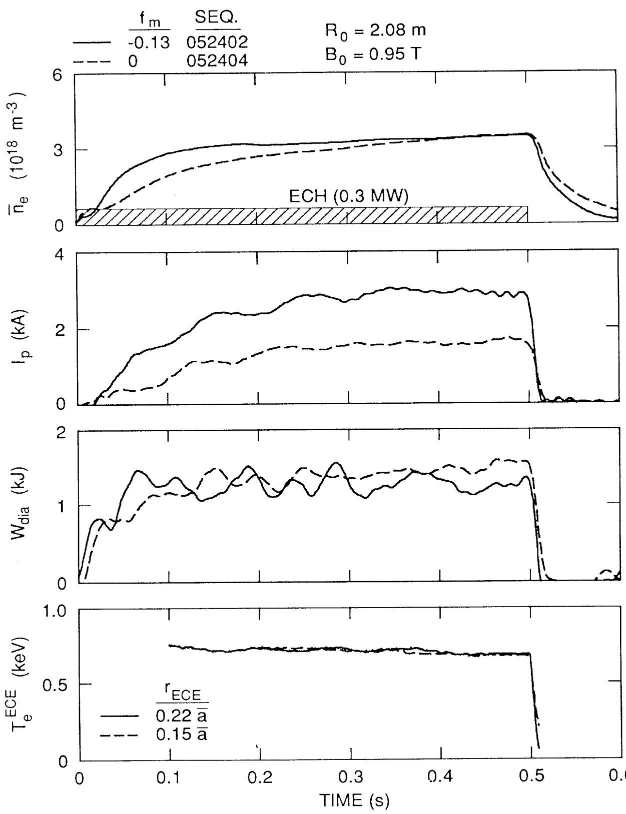

FIG. 1. Time histories of plasma parameters in discharges with two different quadrupole fields.

and (2) the observed current responds to reversal of the helical coil current and to changes in $-ne$ in manners opposite to those expected for an ECH-driven current. In the quadrupole scan, the mid-VF coil-current ratio

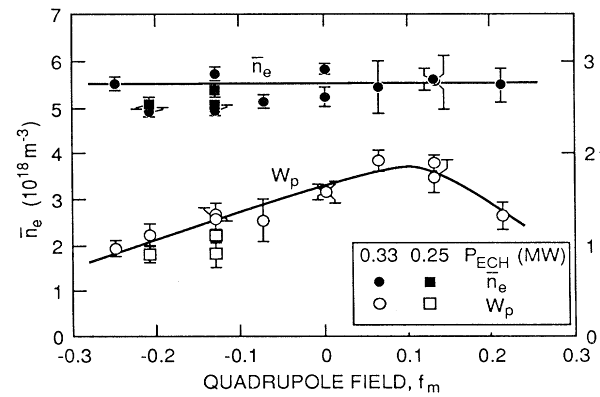

FIG. 2. Variation of line-averaged electron density and plasma stored energy as functions of the quadrupole field.

(f_m, the ratio of ampere-turns in the mid-VF coil and in the helical coil) is varied to change the toroidally averaged plasma shape from horizontally elongated ($f_m < 0$) to vertically elongated ($f_m > 0$). Throughout the scan the line-averaged electron density is kept constant, as shown in Fig. 2. The stored energy peaks at about $f_m = +0.10$. Electron temperature and density are measured from Thomson scattering at fifteen different positions along a single vertical chord. The data are further analyzed by mapping the real-space electron-temperature and density profiles onto the vacuum flux surfaces using the flux-surface coordinate ρ. The flux-surface coordinate is defined as $\rho = (\Phi/\Phi_a)^{1/2}$, where $\Phi(\rho)$ is the vacuum toroidal magnetic flux enclosed at surface ρ and Φ_a is the toroidal flux enclosed by the outermost surface $\rho = 1$. Representative profiles are shown in Fig. 3. The density profile broadens in going

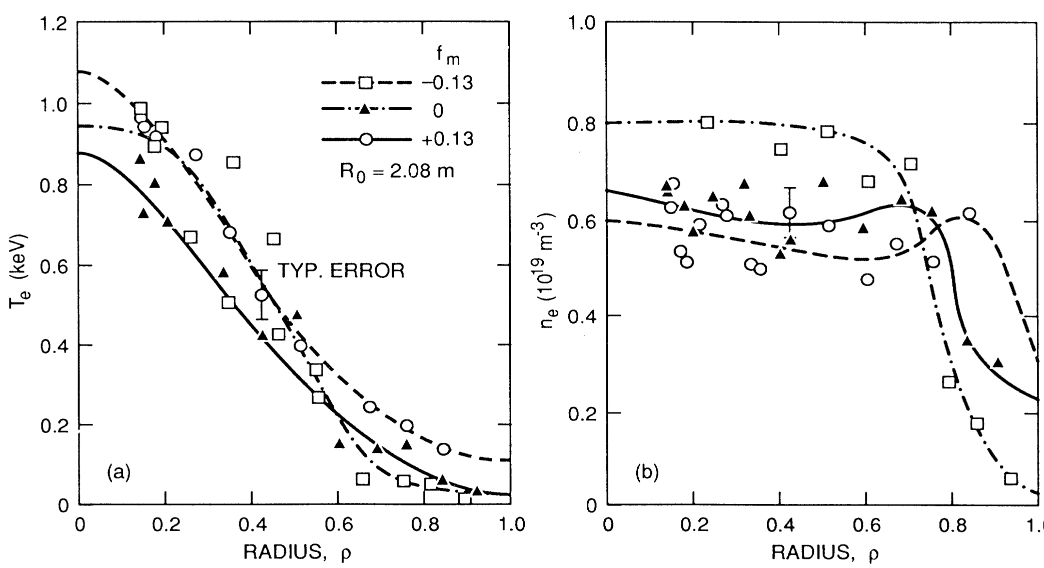

FIG. 3. Electron-temperature and density profiles measured from Thomson scattering for three different quadrupole fields.

from the negative- to the positive-f_m configuration. The fast turn-off of the current seen in Fig. 1 is due to a rapid increase in collisionality with decreasing electron temperature.

Figure 4 shows the measured toroidal current (shown by solid symbols) plotted as a function of the quadrupole field with the magnetic axis position kept constant ($R_0=2.08$ m). Also plotted are theoretical predictions (shown by open symbols) for the bootstrap current based on the experimental electron-temperature (T_e) and density (n_e) profiles as inputs. The ion-temperature profile is calculated from the local power balance with the assumption of neoclassical ion conductivity. The calculated values of central ion temperature [$T_i(0)=0.1$–0.2 keV] agree well with those determined from neutral-particle analysis. The ion contribution to the total pressure (and thus to the bootstrap current) is very small because $T_i \ll T_e$. In the low-collisionality limit the geometry factor G_b can be calculated as in Ref. 15. However, at finite collisionality, the geometry factor needs the finite-collisionality corrections. This is achieved with an analytical expression that interpolates between different collisionality regimes. The expression for the geometry factor G_b consists of the axisymmetric and helically symmetric parts. For the axisymmetric part, we take the interpolation formula in terms of the tokamak collisionality ν_{*t} given in Ref. 16. For the helically symmetric part, we use a similar functional dependence on the helical collisionality $\nu_{*h}=\nu_{*t}(\varepsilon_t/\varepsilon_h)^{3/2}/Mq$ [where ε_t is the inverse aspect ratio, ε_h is the helical ripple, and M $(=12)$ is the number of field periods]. Values for the bootstrap current calculated with the expression agree well with the numerical results of the drift kinetic equation solver (DKES) code[17] obtained for the ATF configuration and at different collisionalities.[18] For the present experimental results and in the region where the pressure gradient is significant, the collisionality ranges are $5 \geq \nu_{*t} \geq 1$ and $0.25 \geq \nu_{*h} \geq 0.05$. The agreement between experiment and theory for the bootstrap current is good; the uncertainty is probably caused by uncertainties in the profiles (Fig. 3) and in the value of $Z_{\rm eff}$, which we have taken to be 1 for all the theoretical estimates, while $Z_{\rm eff}=2$ is used to calculate the ion contribution to the total pressure.

The agreement of the experimental and theoretical trends with the quadrupole moment is more clearly seen in Fig. 5, where measured toroidal current is plotted as a function of quadrupole moment ($\Delta\hat{Q}_{20}$) for a number of quadrupole scans. Use of the quadrupole moment[14] instead of the mid-VF field (f_m) permits including other combinations of currents in the three VF coils. The figure includes data from dynamic configuration scans in which the VF currents were varied during two long (20-s) ECH discharges, changing the vertical elongation (in the $\phi=0°$ toroidal plane) from 1.9 to 2.4 in one discharge and from 1.9 to 1.4 in the other, both with the magnetic axis fixed at $R_0=2.08$ m and a constant linked flux (so that no loop voltage was driven). The results are similar to those from quasistationary discharges. Also shown are theoretical estimates of bootstrap current with two fixed-pressure profiles (in the flux coordinate, at two extreme cases that bracket the experimental profiles). This shows that the basic dependence on the quadrupole moment is through the geometrical factor G_b, rather than through changing plasma parameters. The agreement of the experimental and theoretical trends with the quadrupole-moment variation supports the neoclassical description of the observed current. The current decreases with increasing vertical elongation and goes negative at maximum elongation.

Other experiments in ATF support the neoclassical description of toroidal current flow with ECH alone. Figure 6 shows the bootstrap current measured in a dipole-field scan where the magnetic axis position is varied with the quadrupole field fixed at $f_m=-0.13$.

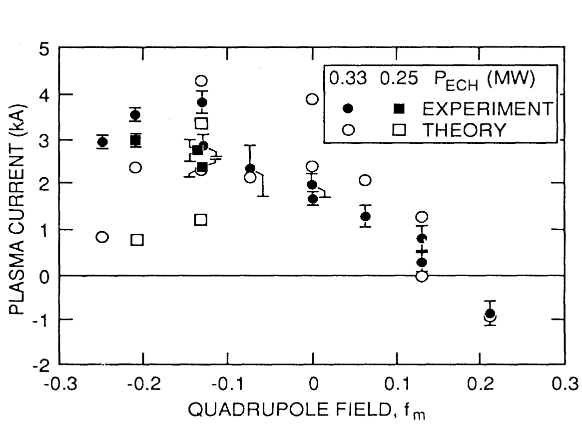

FIG. 4. Measured toroidal currents and neoclassical predictions for the bootstrap current as a function of the quadrupole field.

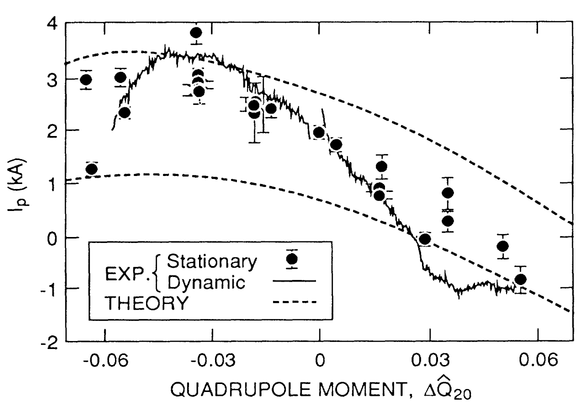

FIG. 5. Current as a function of the quadrupole moment. Experimental values are from stationary discharges (closed circles) and dynamic configuration scans during long ECH discharges (continuous curves). Theoretical estimates (dashed curves) are based on two fixed-pressure profiles that bound the measured profiles.

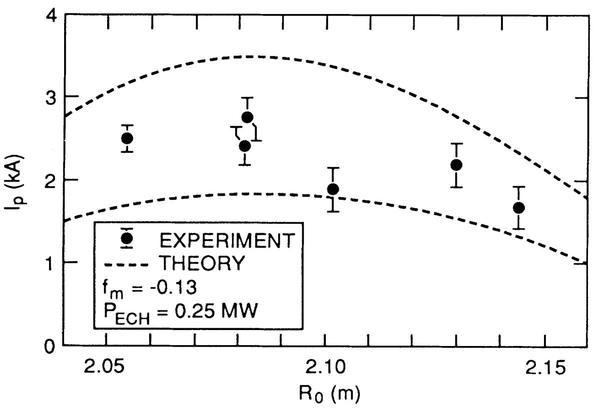

FIG. 6. Measured toroidal currents and neoclassical predictions for bootstrap current as a function of magnetic axis position in the dipole-field scan. Theoretical estimates (dashed curves) are based on two fixed-pressure profiles that bound the measured profiles.

This result is also consistent with neoclassical theory, whose predictions are based on two fixed-pressure profiles. Both experimental and theoretical current values tend to increase as the magnetic axis is shifted inward. In operation at 1.9 T the observed current is lower by about a factor of 2 than that at 0.95 T for the same quadrupole moment, supporting the assertion that the bootstrap current is inversely proportional to B_0.

These results show that toroidal currents flowing in ATF with ECH alone are adequately described by neoclassical theory in magnitude and dependence on magnetic-field structure, as determined by scans of dipole and quadrupole moments, field intensity, and total pressure. This conclusion is obtained in the regime where both particle and heat transport substantially exceed (by a factor of 10 to 100) neoclassical predictions,[19] supporting the common observation that, while parallel (to field lines) transport is approximately neoclassical, perpendicular transport is substantially anomalous.[20] The present results also verify the ability to control the bootstrap current through the quadrupole and dipole components of the vertical field, demonstrating the feasibility of currentless operation of stellarators in the low-collisionality regime with no need for current drive.

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