Internally Generated Currents in a Small-Aspect-Ratio Tokamak Geometry

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Pressure driven currents are observed in an electron cyclotron resonance (ECR) heated, small-aspect-ratio toroidal plasma in the CDX-U device. A toroidal current of 1.05 kA was generated with ~8 kW of ECR power. At this current level, the poloidal field created by these currents is significantly larger than the vacuum field and produces closed flux surfaces in a small-aspect-ratio tokamak geometry. After flux surface formation we hypothesize that bootstrap currents are driven to maintain the discharge. This internally driven current may offer an attractive method to start up and maintain the tokamak discharge.

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Recently the idea of an extremely small-aspect-ratio ($A=R/a$) tokamak has been advanced [1]. This low field configuration features very large currents for a given edge q_a (high β and good confinement); hence a reactor based on this geometry has many advantages over more conventional designs. These advantages are offset by difficulties in the engineering of such a device, the main difficulties being the design of the toroidal field coils and sustainment of the large steady-state current in the device. The conventional method of driving toroidal current using a flux core is limited to a small volt times second product compared to large-aspect-ratio geometries. The concept is thus reduced to a geometry which can support large currents, but has no simple way of driving currents.

The current drive problem is not unique to small-aspect-ratio tokamaks. A fundamental shortcoming of the tokamak reactor concept is the requirement of some form of external current drive to maintain a steady state. The most successful methods thus far have been lower hybrid and neutral beam current drive. Although the efficiencies of these methods may be marginally acceptable for a reactor, they represent an up-front energy and equipment cost to the reactor. A much more desirable approach is to exploit the ubiquitous self-generated currents found in toroidal geometries (e.g., the bootstrap current) [2]. Transport analysis of high-β_p discharges in most large tokamaks has shown that a large fraction of the current can be driven by the pressure gradient [3,4]. Given that these geometric currents exist, it is worthwhile to consider ways of exploiting them in the tokamak configuration. In this Letter we demonstrate that with a proper choice of geometry, e.g., a small aspect ratio, a tokamak plasma can be maintained entirely by pressure driven currents, the method requiring only some form of heating power [5].

A newly constructed toroidal facility, CDX-U, has been built to study the physics of small-aspect-ratio, toroidally confined plasmas and methods of driving current in this configuration [6]. In the present experiment, the poloidal field whose flux contours are shown in Fig. 1 was imposed on a much stronger toroidal field. Initially, the poloidal field provides single particle confinement by guiding the particles to regions of high toroidal field where magnetic reflection occurs. The orbits are then banana orbits similar to those in tokamaks. After applying electron cyclotron resonance (ECR) heating (≈ 8 kW into a neutral gas filled vacuum vessel) to ionize and heat the plasma, significant net toroidal (up to 1050 A) currents were observed, and with appropriately weak external fields, low-aspect-ratio tokamak formation was observed.

The CDX-U device consists of a toroidally continuous Al vacuum vessel of very low aspect ratio ($A \geq 1.3$). In practice, carbon limiters confine the plasma to a volume defined by 10 cm $\leq R \leq$ 56 cm, -38 cm $\leq Z \leq$ 38 cm, with R and Z being conventional cylindrical coordinates. A steady-state toroidal field is generated by currents flowing in a 6.35 cm radius center stack which forms the inner wall of the vacuum vessel. For these experiments, a net axial current of ~90 kA provided an 875 G toroidal field at 15 cm. The steady-state poloidal magnetic field is generated by two sets of "mirror" coils centered at $(R,Z)=(9$ cm, ± 49 cm) and (40.5 cm, ± 84 cm) each carrying 3000 A turns of current (this generates a B_z of ~10 G at the center of the device). Two 2.45 GHz magnetrons provide <5 kW each with pulse durations up to

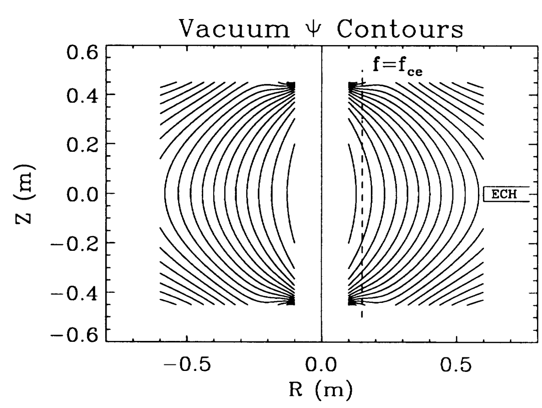

FIG. 1. The vacuum poloidal flux contours. The total field is a combination of $\nabla\psi\times\nabla\phi$ (ψ being the poloidal flux function) and a toroidal field $B_\phi=B_0R_0/R$.

TABLE I. Dependence of current direction on field direction. Positive is clockwise when viewed from the top.

Field direction	B_t: +	B_t: −
B_{pf}: up	+	+
B_{pf}: down	−	−

30 msec. The power was launched into the vacuum vessel from unterminated WR-284 waveguide at the midplane with $\mathbf{E}_{rf} \parallel \mathbf{B}_t$ and at the top of the vessel at $R=33$ cm with $\mathbf{E}_{rf} \perp \mathbf{B}_t$. After entering the vessel, the power is expected to reflect many times before it is absorbed.

These experiments were performed in He, Ar, and H_2, at pressures of $P_{fill} \leq 3\times10^{-5}$ Torr, in a vacuum with base pressures of $P_0 \leq 3\times10^{-7}$ Torr. After applying the rf power, net toroidal currents were measured by a Rogowski coil encompassing the plasma. The current direction was found to be a function only of the poloidal field direction as indicated in Table I. The magnetic field generated by the plasma current added to the imposed poloidal field on the outside of the plasma, and subtracted on the inside. The dependence of current direction only on the vacuum field eliminates any uncertainties due to asymmetries in the launched rf and confirms the geometric nature of the current. In addition, the limiters were isolated from the vacuum vessel in order to determine the current flowing from the limiters to the plasma (or vice versa) and were found to be negligible ($I_{lim} \leq 0.5$ A). Hence, the toroidal currents are flowing entirely within the plasma.

The magnitude of the current was found to depend upon the rf power, the neutral pressure, the applied poloidal field strength, and the resonance position. Measurements of the total current during scans of these four parameters are shown in Fig. 2. The toroidal current scales with rf power, inversely with neutral pressure and applied poloidal field, and is maximized with the resonance as close to the inner limiter as possible. Typically, the toroidal current was maximized by running at the lowest neutral pressure and poloidal field, provided that rf breakdown occurred. In order to keep all but one of the parameters fixed during these scans, fixed neutral pressures high enough to assure breakdown at the extreme parameters of the scan were used. It appears that a minimum amount of confinement was required to initiate the discharge, and this is where the imposed mirror field played a role. Confinement for these discharges was easily destroyed by inserting probes into the plasma confirming the role of initial electron confinement for breakdown. As seen in Fig. 2(b), the largest currents corresponded to the lowest neutral pressure. A record current of 1050 A was obtained under conditions in which the neutral pressure in the vessel was dropping during the discharge. These conditions existed in H discharges after Ti gettering; before each shot, a small gas puff of H_2 was given by an electronically controlled piezovalve. The pressure was monitored by a fast ionization gauge located at the midplane outside of the magnet coils. The fill pressure prior to ionization was typically 1.5×10^{-5} Torr and would drop by a factor of 2–3 indicating low recycling conditions on the vessel wall. The pressure drop was correlated with a total current increase. In He discharges strong current degradation was also associated with a neutral pressure influx and density rise. The high initial pressure allowed ECR breakdown, while the subsequent pressure drop permitted large currents to be driven. There was no observable difference between He and Ar.

The vector magnetic field (shown in Fig. 3) generated by the plasma currents has been measured on the edge of

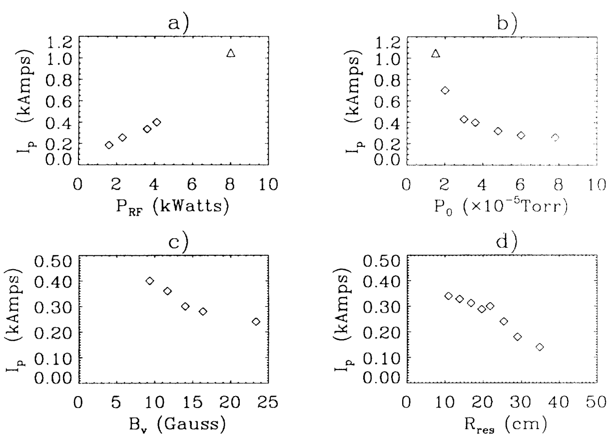

FIG. 2. Parameter scan showing phenomenological dependencies of open field line currents: I vs (a) ECR power, (b) neutral pressure, (c) mirror field strength, in terms B_z at $Z=0$ cm, $R=30$ cm, (d) ECRH resonance radius (i.e., B_ϕ). Unless varied, values are 4 kW, $P_0=3\times10^{-5}$ Torr, $B_z=10$ G, $R_{ECH}=10$ cm. The 1.05-kA point (△ shown for reference), was at 8 kW, $P_0=1\times10^{-5}$ Torr.

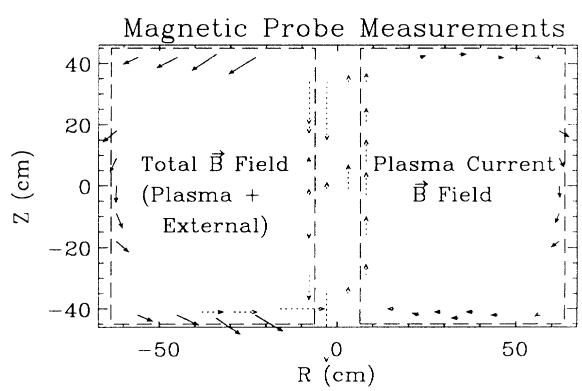

FIG. 3. $\mathbf{B}_p$ field as measured on vacuum vessel wall. The right half is the field due to I_{plasma} and the left the total field which includes the field from external coil. Measurement on the top, bottom, and outside walls are by 2D pickup loops (B_r and B_z), and the inner wall measurements are ψ and B_z loops. The origin of each vector indicates the probe position.

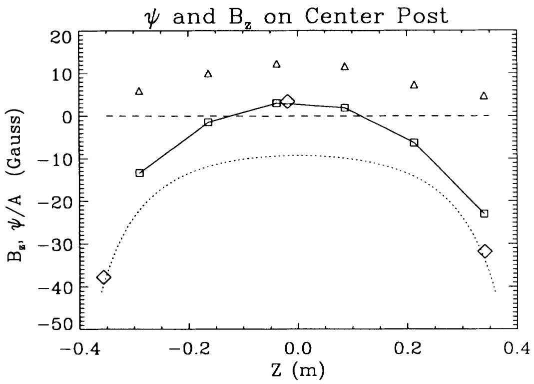

FIG. 4. Measurements on the center post of the device ($R=8$ cm). □, total B_z (plasma and external coil current) showing field reversal; △, B_z of plasma current; ◇, total flux ($\psi_{\text{vac}}+\psi_{\text{plasma}}$); and the dotted line, ψ_{vac}.

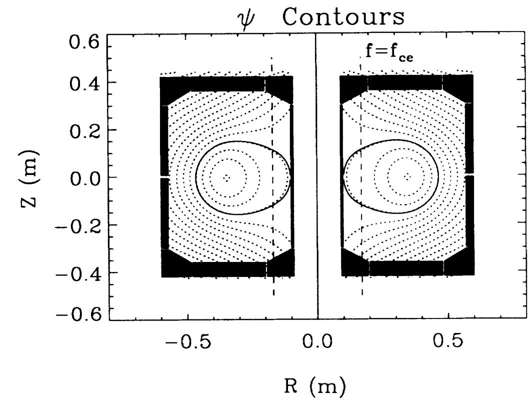

FIG. 6. ψ contours as modeled by filament currents matched to the boundary magnetic field measured by magnetic pickup and flux loops. Also shown is the isolated limiter array defining the outermost closed flux surface and measuring currents flowing from the plasma to the vessel.

the plasma by an array of magnetic pickup coils. Unfortunately, the breakdown of the discharge is extremely sensitive to internal probes, which has allowed only measurements external to the plasma. Nonetheless, this information is sufficient to conclude flux surface formation, the centroid, and some moments of the current. Specifically, the magnetic measurements on the inner wall show field reversal as indicated in Fig. 4. During plasma formation, a high-β_p plasma is formed with an x point inside the vessel. As the current increases, the x point moves outside the vessel and field reversal is observed on the inner wall. A topological winding number theorem proves the existence of a magnetic axis inside the measurement boundary and tokamak formation is demonstrated [7]. In all cases, the centroid of the current was well outside the resonance layer, typically $R_I=30$–40 cm. This position corresponds approximately to the position of the density maximum as measured by a two-dimensional scanning interferometer [8]. Figure 5 shows line integral density profiles, showing that the plasma is localized in the horizontal direction to ± 15 cm and is peaked at a major radius near the centroid of the current. Inversions of these data show peak densities of $(1\text{-}2)\times 10^{11}$ cm^{-3}. We should note that the plasma is overdense ($\omega_{pe}^2 > \omega_{ce}^2$), and that the ECH absorption appears to take place near the $2\omega_{ce}$ layer as evident from

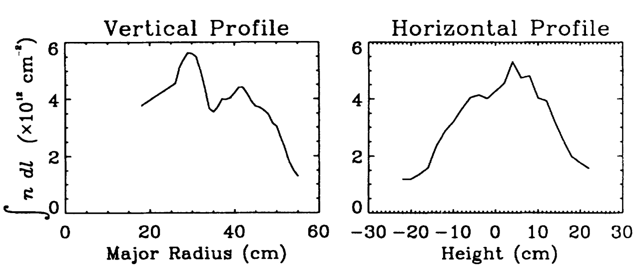

FIG. 5. Line integral density profiles as provided by a 2D interferometry system.

the density and current measurements.

To determine the plasma boundary, the currents have been modeled by a finite-element set of distributed toroidal currents matched by a least-squares-error fit. Although the internal structure is not uniquely determined by this method, the outermost flux surface can be accurately determined if a large fraction of the current is internal to this surface. Flux contours inferred from this fit, and the limiter configuration, are shown in Fig. 6. For the highest current discharge (1.05 kA) the discharge is limited on the inner wall and has a geometric aspect ratio of $A\approx 1.5$ ($R=27$ cm, $a=18$ cm). Checking the consistency of this approach, we find that the model locates 80% of the current inside the calculated boundary. For these geometric parameters, the cylindrical edge safety factor is $q\approx 24$.

To explain the driven current, two different topologies must be considered. Initially, the field lines are open and the current cannot be carried by the passing particles described in the bootstrap current theory. In this phase, two mechanisms have been identified. First, the field-aligned currents from the Pfirsch-Schlüter effect maintaining quasineutrality are in the same direction on the inside and outside of the plasma. In this case a net toroidal current in the required direction can flow to generate flux surface closure. Another mechanism is the toroidal precession of the trapped electrons. Both of these mechanisms scale with the plasma pressure and should scale with input power. It is fortuitous that both of these currents are in a direction which tends to add to the imposed poloidal field on the outside of the plasma and subtract on the inside. Once tokamak formation has occurred, the current drive mechanism may be different. In this case, the Pfirsch-Schlüter current on the inside tends to cancel the current on the outside generating no net toroidal current. The presence of passing particles allows the bootstrap current to be considered.

To estimate these effects, this plasma has been modeled by a plasma approximately the same size, a density of $n_e = 10^{11}$ cm^{-3} (measured by interferometer), an electron temperature $T_e = 20$ eV (edge T_e is 15–20 eV as measured by Langmuir probes), and a net current of 200 A is predicted, peaking where the density peaks. A single particle orbit code has been used to estimate the precession current. For the same parameters as above, a net current of ~ 150 A is found. The precessional current is thus of the same order as the Pfirsch-Schlüter currents, and the sum of the two may be sufficient to form a small closed flux surface.

These experiments have demonstrated that a low-aspect-ratio tokamak magnetic geometry can be formed and maintained by pressure driven currents alone. The high current discharge described herein suggests that a new experimental approach may be pursued. Namely, with appropriate poloidal field control and plasma heating, high-q plasmas (and high β_p) with relatively high currents can be created and self-maintained. This offers a new way of starting up and possibly sustaining tokamak discharges which may have significant reactor implications.

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