Toroidal Current Drive by Intense Relativistic-Electron Beams

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An experimental study of the injection of a intense relativistic electron beam into a plasma confined in a toroidal magnetic field is described. An increase in toroidal current after beam injection was observed and is argued to be the result of both beam-induced and additional Ohmic-heating-driven plasma currents. Typical current-drive efficiencies (beam net current to injected-beam current) of (10–30)% were observed.

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To ensure economic viability as a commercial reactor the tokamak may need to be operated in a steady-state mode. This would require some form of current drive other than the Ohmic heating scheme which is presently used and which makes the tokamak inherently a pulsed device. Experiments attempting to demonstrate current drive with microwaves are under way.[1-3] Intense particle beams have been proposed for the same purpose.[4,5] Relativistic-electron-beam–Ohmic-heating hybrid schemes using the relativistic electron beam (REB) for start up have also been considered.[6] This would allow significantly longer Ohmic-heating (OH) pulses than presently possible. Experimental efforts using REB current drive in toroidal devices have been initiated by Mohri *et al.*,[7] Proulx, Bailey, and Helava,[8] and Gilad, Kusse, and Lockner.[9] Here we present a summary of the current-drive results of the experiment recently completed at Cornell.

The experiment was performed in an aluminum racetrack vacuum vessel, 6.3 cm minor radius, 8 m circumference; see Fig. 1. A toroidal magnetic field of up to 5 kG was applied by means of a 550-μF, 100-kJ capacitor bank with a quarter-cycle rise time of 200 μsec followed by a 1-msec crowbarred decay. This field penetrated through a toroidal slit. The plasma was produced by an Ohmic heating system (OH) where the field penetrated through a poloidal slit. Breakdown was facilitated by some initial preionization provided by a hot tungsten filament in the limiter shadow. The stainless-steel limiter had a 3.8-cm radius. The toroidal electric field was induced by an iron–air-core transformer driven by a 56-μF, 11-kJ capacitor bank. The iron core had a 0.04-V·sec rating which was enough to initiate the discharge. The iron saturated at 150 μsec after which time the air core was able to sustain the loop voltage and plasma current for another 300 μsec.

Plasma currents in the range of 400 to 1000 A were observed with q's at the limiter of 3.5 to 1.5. The plasma density ranged from 10^{12} to 2×10^{13} cm^{-3}. The bell-shaped distribution had a Gaussian width $r_p = 1.7$ cm. Plasma temperatures ranged from 10 to 20 eV. Discharges were run in hydrogen, argon, and nitrogen. The energy confinement time (τ_E) observed varied from about 3 to 30 μsec. τ_E showed no dependence on toroidal field or plasma current. The energy confinement time did, however, increase as $M_i^{1/2}$ and showed a steady, almost linear increase with plasma density. The discharges were relatively turbulent with (10–50)% density and temperature fluctuations. The unmagnetized nature of the plasma was attributed to ion-acoustic turbulence since $v_s < v_D < v_{Te}$ (where v_s is the ion acoustic velocity, v_D is the electron drift velocity, and v_{Te} is the electron thermal velocity).

The intense relativistic electron beam was produced by a 3.5-kJ Marx-Blumlein accelerator and injected in one of the straight sections. Typically, injected beams of 10 kA, 400 keV, and 50 nsec were used. Injection was accomplished by a combination of field diversion and drift techniques which have been described elsewhere.[9,10]

Several diagnostics were used to monitor the beam and the plasma. Plasma currents were

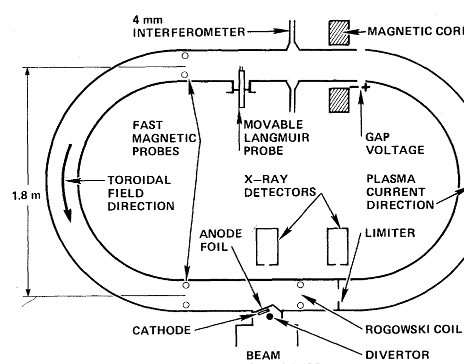

FIG. 1. Overhead view of the experimental setup.

measured by Rogowski coils and localized magnetic probes. Plasma densities were determined by Langmuir probes and a 4-mm microwave interferometer. Plasma temperatures were measured by Langmuir probes and diamagnetic loops. Beam diagnostics consisted of magnetic probes, transparent witness meshes, and collimated hard-x-ray detectors.

Earlier experiments in the racetrack with neutral gas fill observed expected field diversion and beam-drift behavior.[9,10] It was expected that the preionization present in these experiments might degrade the earlier field-diversion results. However, this was not the case and even with preionization it was possible to divert the field and inject well into the plasma column with the proper ratio of toroidal field to beam (divertor) current. This was attributed to either poor conductivity across the field or enhanced turbulence during injection. Figure 2 shows the poloidal position of the center of the beam 18 cm downstream from the injector as a function of the toroidal field for fixed beam (divertor) current. As in the experiments with no preionization, beam penetration increased with decreasing ratio of toroidal field to beam current.

Typically, the beam was launched directly onto the minor axis and was immediately current neutralized. To study beam drifts the toroidal field was increased and the beam was purposefully launched midway between the minor axis and the wall. Here the plasma density was low and as a result the beam was only partially current neutralized. As expected, to zero order the beam interacted with the OH plasma current and followed the rotational transform of the machine. To first order the beam drifted across the magnetic field in the poloidal direction. This first-order drift resulted from an interaction of the beam with a self-induced image current that flowed predominantly in the plasma column.

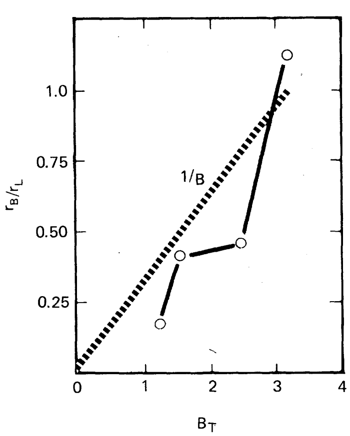

FIG. 2. Beam injection position vs applied magnetic field in kilogauss for fixed beam (350 keV, 10 kA) and plasma ($N_e = 1\times 10^{13}$ cm^{-3}, I_p = 500 A) conditions.

Collimated hard-x-ray detectors were used to determine the lifetime of the beam electrons. With the detector viewing the scrape-off layer at the limiter, the x-ray signal looked as shown in Fig. 3 and indicated the presence of beam electrons for approximately 1 μsec. Since the circulation time was approximately 80 nsec, this corresponded to at least 10 revolutions of the machine.

The net currents which result when an intense beam passes through a preionized plasma column are well understood.[11-13] For conditions of this experiment ($a/\lambda_\epsilon \ll 1$; $10^{-1} \lesssim n_b/n_p \lesssim 10^{-2}$) the beam would be expected to be initially current neutralized with the return current flowing entirely in the beam channel. (Here a is the beam channel radius, $\lambda_\epsilon \equiv c/\omega_{pe}$ is the collisionless skin depth, and n_b/n_p is the beam-to-plasma density ratio.) For a beam that enters a linear system, passes through a preformed plasma, and then exits, the induced plasma return current can be expressed as

$$\begin{aligned} I_r(t) &= -I_b e^{-t/T} \approx -I_b, \quad 0 \le t \le \tau_b, \\ &= I_b[1-\exp(-\tau_b/T)] \\ &\quad \times \exp[-(t-\tau_b)/(L/R^*)], \quad t > \tau_b, \end{aligned} \tag{1}$$

where I_b is the injected beam current, $T = \tau_{col}^*(a^2/\lambda_\epsilon^2)$, τ_{col}^* is the effective collision frequency during the beam pulse for the return-current electrons, τ_b is the beam pulse length, and L/R^* is the effective decay time of the net current remaining after beam passage. This analysis as-

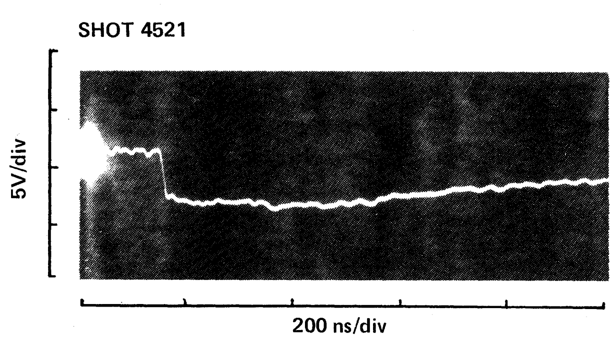

FIG. 3. Hard-x-ray signal produced at the limiter after beam injection and trapping.

sumes that the beam is not subject to effects such as the electron-electron two-stream instability, and that I_b remains essentially constant. Then

$$I_{\rm net}(t) = I_b + I_r(t). \qquad (2)$$

The result is that the net current starts from zero, rises to a peak which occurs at a time equal to the beam pulse length, and then decays to zero. The rise time and subsequent decay time are not the same. Anomalies affecting $\tau_{\rm col}{}^*$ during the beam pulse can be quite different from those affecting R^* after the beam pulse. Even if we assume a small value for $\tau_{\rm col}{}^*$, due, for example, to ion acoustic turbulence, the short beam-pulse length inevitably results in beam net currents which are small compared to I_b.

This is not the case, however, for a beam trapped in a toroidal device. Here the net current can rise for a time equal to the trapping time of the beam. Analysis of such a configuration is somewhat more complicated because of geometrical considerations and because, on the longer beam-trapping time scale, I_b can no longer be assumed constant. This general effect was observed on our net current signals with the peak occurring 1–2 μsec after injection ($\tau_b = 50$ nsec). This was consistent with the 1-μsec hard–x-ray signals discussed in the previous section. The toroidal current signals were complicated further by the effects of the incremental change in the Ohmic heating current, $\delta I_{\rm OH}$:

$$I_{\rm net}(t) = I_b(t) + I_p(t) + \delta I_{\rm OH}(t). \qquad (3)$$

The decays of the net currents for coinjection and counterinjection were not the same. Coinjection and counterinjection were accomplished by switching the polarity of the OH supply and thus the direction of $\delta I_{\rm OH}$. Net current signals are shown in Fig. 4. The net-current response up to and including the peak is the same for both cases. The signals differ, however, in their subsequent time dependence. For coinjection the net-current signal stays positive. For counterinjection the net current switches sign. Since the beam is injected in the same direction in both cases, beam effects should be the same for both cases. The OH effects, however, should be of opposite polarity. Figure 5(c) shows half the sum $[I_b(t) + I_r(t)]$ and Fig. 5(b) half the difference $[\delta I_{\rm OH}(t)]$ of the signals in Fig. 4. The sum signal behaves as one would expect, implying the 1–2-μsec lifetime of the beam and a simple L/R decay of induced plasma currents. Figure 5(b) shows the additional toroidal current induced by the OH system after beam injection. Not the subject of this Letter is the fact that the beam also heated the plasma as evidenced by long-term diamagnetic signals, thus reducing the effective plasma resistivity. The rate of rise of this current compares favorably with $V_l/L_p \simeq 7$ μsec, where V_l is the applied loop voltage and L_p is the calculated plasma column

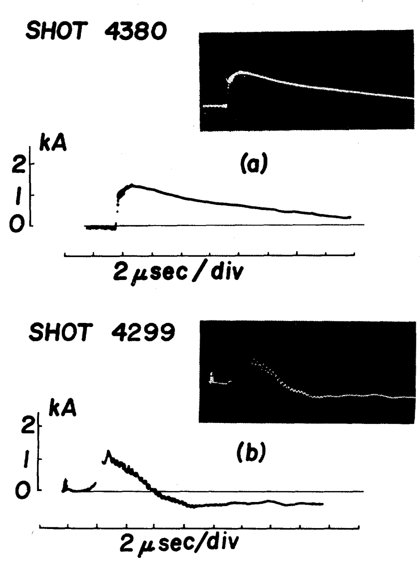

FIG. 4. Additional net toroidal current generated by the beam injection and trapping process for (a) coinjection and (b) counterinjection.

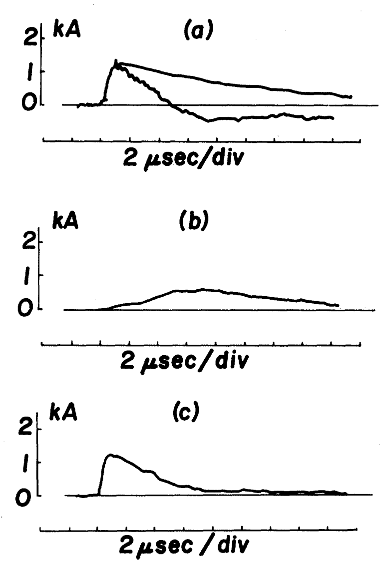

FIG. 5. (a) Signals from Fig. 4 superimposed. (b) $\frac{1}{2}$ the difference of the two signals shown in (a). (c) $\frac{1}{2}$ the sum of the two signals shown in (a).

inductance. The ensuing turnover and decay of this current can be attributed to the poor energy confinement.

In summary, a relativistic electron beam was successfully injected and trapped in a plasma-filled toroidal device by use of a pulsed magnetic field divertor that was naturally time synchronized with beam injection. The divertor was located in the diode region, near the wall and in the shadow of the limiter. Beam trapping was observed with beam electrons circulating in the machine for 1–2 μsec after injection. Additional toroidal currents were observed and were found to be due in early times (1–2 μsec) to beam net current $(I_b + I_r)$ and later in time to additional OH-driven current. Excluding the effects of the OH field, typical current-drive efficiencies $[(I_b + I_r)/I_b]$ of (10–30)% were observed. In contrast to recent lower-hybrid current-drive experiments on Versator,[14] we observe an increase in the current driven by the OH transformer after beam injection.

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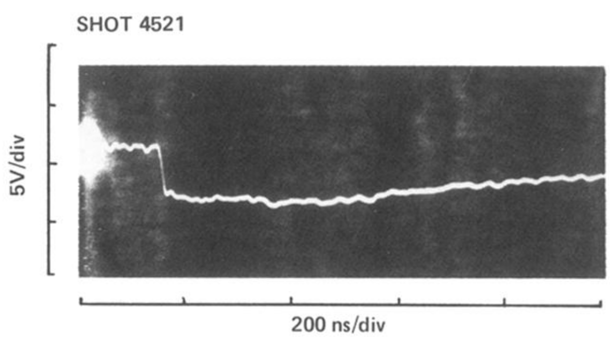

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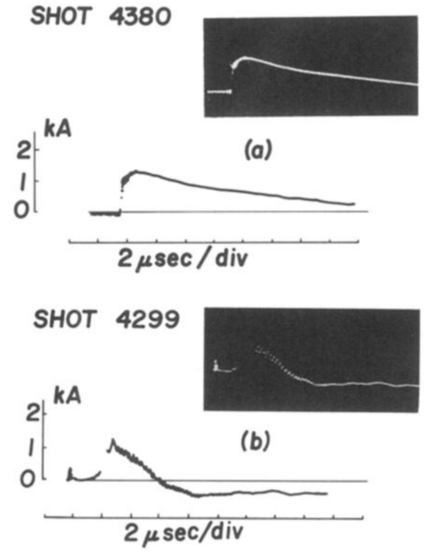

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