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ABSTRACT

Formation and maintenance of a tokamak discharge utilizing helicity injection via a dc low-energy electron beam has been observed in the Current Drive Experiment (CDX). As the plasma current increases, the discharge changes from a configuration dictated by the externally imposed vacuum poloidal fields into a steady-state configuration dominated by the self-generated poloidal field. This configuration was maintained for 60 msec (the time limited by the cathode bias supply), equivalent to more than 400 resistive decay periods. Viewed tangentially, the plasma spontaneously evolves into a circular shape. Measurement of the poloidal magnetic field reveals a considerably peaked current profile, indicating strong radially inward current pinching. The measured q-profile has a typical value of 10 at the plasma edge and reaches a minimum of 4 at the magnetic axis. The line-averaged density profile is also highly peaked, reaching $\bar{n}_e = 2 \times 10^{13}$ cm^{-3} for the central chord. Measurements of plasma conductivity indicate that T_e rises to ~ 25 eV, while the spectroscopically observed average ion temperature increases from ~ 1 eV to ~ 15 eV as the current increases. These results indicate that the current system evolves toward a tokamak configuration even though the current drive is noninductive.

In order to drive plasma current in a tokamak, it is necessary to inject "helicity" into the plasma (helicity is a quantity closely related to the amount of current in the plasma).[1] Inductive ohmic current drive and noninductive rf current drive[2] are the two major approaches now used for helicity injection into tokamak plasmas. However, the former method is inherently not steady state, and the efficiency of the latter may not be high enough for reactor applications.[3] Recently, other types of helicity injection have been proposed.[4-8] These new ideas, generally referred to as "dc" and "ac" helicity injection, may lead to more efficient methods for driving steady-state current and for controlling the current profile,[9] both of which are crucial for an economic tokamak reactor.

A small toroidal facility, the Current Drive Experiment (CDX), is dedicated to the study of helicity injection based on the nonclassical behavior of radial current diffusion.[7,10] In the present experiment, the CDX helicity source is a steady state low-energy electron beam which produces a current sheath at the surface of the toroidal plasma. Current in the sheath is transported radially inward by nonclassical processes. A low energy beam possesses certain advantages over the high-energy relativistic beam which has been previously used to create a tokamak-like plasma.[11] Current drive efficiency using high energy electrons is predicted to saturate at rather modest electron energies due to relativistic effects.[3] However, the ultimate current drive efficiency for a low energy beam can be quite good, theoretically approaching ohmic drive efficiency within a factor of ten.[12] In the framework of helicity injection theory, it is the injected beam magnetic energy and not the beam kinetic energy that is the important quantity and it is advantageous, therefore, to minimize the energy expended to inject a given amount of current. This suggests that a low energy beam may be desirable since the ratio of beam momentum to beam energy increases as the energy decreases. Other advantages of low energy beam injection include a good efficiency for converting input energy to beam energy and a modest cost of implementation. The potential problem of impurity influx from the beam source cathode material may not arise because of the low beam energy, or may be suppressed by injection through a magnetic divertor.

For both dc and ac helicity-injection schemes, current is generated near the plasma edge and, to be useful, must subsequently diffuse into the interior of the plasma in order to offset resistive current decay. This process conceptually requires a nonclassical mechanism for current diffusion such as a current profile-dependent instability.[7] As an example, a strong edge current can trigger the double-tearing instability only if its direction of flow is parallel to that of the interior current. Magnetic turbulence associated with the instability could then facilitate rapid radial penetration of the edge current.[13,14] Penetration of the edge current is the crucial issue for success of a dc helicity-injection current-drive approach. Spheromak experiments have demonstrated previously a formation of a spheromak plasma using the dc helicity-injection concept, although on shorter time scales.[15] In this letter, we report the first demonstration of formation and maintenance of a steady state tokamak discharge via dc helicity injection and present evidence for strong inward current diffusion.

The CDX machine is a toroidal magnetic confinement device with major and minor radii of 59 and 10 cm, respectively, and a steady state on-axis field of 5 kG. The vacuum vessel, toroidal field coils, and power supplies are composed of the former Advanced Concepts Torus-1 (ACT-1).[16] Major modifications including the addition of internal coils, high-current electron beam injectors, and new diagnostics resulted in a machine specialized for dc helicity injection current drive investigations.

A variety of diagnostics was used to study the CDX discharge (Fig. 1a). A primary indication of the overall plasma shape was provided by time-resolved imaging of a tangential view of the plasma using "boxcar photography,"[17] in which a fast electro-optic shutter provides photographic sampling and a number of successive shots are integrated to produce each image. The total toroidal current was measured with an electrostatically shielded Rogowski coil located inside the vacuum chamber. A radially scanning magnetic probe was used for the poloidal field measurements. Chord-averaged electron density measurements were obtained with an 8 mm radially scannable microwave interferometer, and a radially scannable FIR dual beam laser interferometer[18] was installed for density and fluctuation measurements. Ion temperatures were determined from the Doppler broadening of a He II line (λ = 4686 Å), measured with a Fabry-Perot interferometer.

Plasma is created in the CDX device by injection of an electron beam from a cathode at the bottom of the machine (Fig. 1b). The cathode consists of lanthanum hexaboride (LaB_6) tubes, about 1 cm in diameter and 1 cm in length, placed over electrically heated carbon rods; LaB_6 was utilized for its high emissivity at relatively low temperature.[19-21] Also shown in Fig. 1b are the positions of the divertor coils and the LaB_6 cathode. The cathode is biased with respect to the limiter and chamber wall, and in vacuum the electron beam spirals gently upward following the magnetic field lines. The poloidal field is strong near the divertor coils (7-10 G) and enables the electron beam to avoid the cathode as it travels upward. As the beam drifts into the main plasma region, the poloidal field decreases rapidly and is typically ~ 2 G at the plasma center. The electron beam path and radial current penetration to the main plasma are sketched in Fig. 1b.

A two-dimensional simulation code was developed to model the experiment. A transport algorithm computes the current throughout the plasma cross section given the plasma resistivity together with current diffusion[10] and ad hoc current pinching coefficients (which are chosen to match the experimental observation). It is assumed that electrons in the primary beam follow single particle trajectories for a single 90° scattering distance. The code steps in time until a steady state solution is reached. Figures 2a-c show the poloidal field configurations and the partition of beam and plasma current resulting from three simulations with increasing injected current. In Fig. 3a, the injected current is sufficiently low that the vacuum poloidal fields dictate the electron beam path. As the beam current increases, Fig. 3b, the self-generated poloidal fields become comparable to the vacuum poloidal fields and some current is carried by the plasma (as is evident from the bent beam trajectory). When the injected current has increased sufficiently that the self-generated poloidal fields dominate the vacuum poloidal fields, a dramatic change in the magnetic field structure takes place, shown in Fig. 3c. In this configuration, the injected electron beam circulates around the main current-carrying plasma while helicity associated with the beam is transferred to the main plasma which now displays a field structure similar to that of a conventional tokamak. Laboratory confirmation of this computed tokamak configuration was one of the goals of the experiments described here.

The experiments were conducted with hydrogen or helium as a working gas, at a typical prefill pressure of 3×10^{-4} torr. The LaB_6 cathodes were heated continuously, and the discharge was created entirely by the electron beam, pulsing the cathode bias for 30-60 msec. The cathode bias voltage, typically 300 V, produced injected electron beam currents up to ~ 50 A, and the discharge could be repeated at a rate of 2-4 Hz.

Time-resolved images of the discharge formation obtained with the boxcar photography system are shown in Figs. 2d-f. Each photograph, taken during the flat top of the discharge, displays structure similar to the corresponding case shown in Figs. 2a-c. The first picture, Fig. 2d, is of a low current discharge where the total toroidal current, I_T, was less than 10 A. The second picture (Fig. 2e) is of an intermediate current case where $I_T \approx 50$ A, and the third picture (Fig. 2f) is the high current case where $I_T \approx 330$ A. In this last case, the discharge has a sufficiently high current that the resulting plasma is constrained primarily by its own magnetic fields. As predicted by the simulation result (Fig. 2c), a tokamak-like circular discharge was observed in Fig. 2f. The minor radius of the steady state discharge inferred from the photograph was about 3 cm, and the resulting safety factor (q) at the plasma edge was ~ 10. When the cathode bias was pulsed off, the plasma current decayed with a L/R time typically $\tau_{res} \sim 130$ μsec. Assuming a 1.2 μH inductance for the 3-cm radius current channel and $Z_{eff} = 1.5$, the implied space-averaged conductivity temperature is $kT_e \approx$ 25 eV. The high current discharge was maintained for several hundred resistive time periods and, therefore, was essentially steady state. The limit to the duration of the discharge in this experiment was the capacity of the cathode bias supply.

In order to measure the generated poloidal magnetic field, a special radially scanning magnetic probe was developed. To withstand the heat flux and discharge repetition at ~ 2 Hz, the probe is water cooled. Water flows through a 3.2 mm o.d. thin-wall stainless steel tube at the end of which is a 200-turn coil wound with #40 AWG insulated wire. This tube is concentric with a 6.3 mm o.d., closed-end thin-wall stainless tube that provides the vacuum seal and the water return path. The resistivity of the metal tubing is sufficiently high, and the tubing sufficiently thin, that magnetic flux diffusion through the probe is rapid compared to the time scales of interest. A boron nitride tube (9.5 mm o.d.) over the probe provided electrical and thermal insulation from the plasma, while the probe signal was processed through a low-noise high-gain integrator to yield an output proportional to the magnetic field linking the coil.

The poloidal magnetic field measured during a radial probe scan which passed through the plasma axis is shown in Fig. 3a. The points are plotted for a time during the discharge when the current had reached its full steady state value. As expected, the poloidal field reversed near the center of the discharge. The measured poloidal field at the plasma edge of 20-25 G (much larger than the vacuum poloidal field of ~ 2 G) was consistent with the measured plasma current of 330 A and the observed discharge radius of 3 cm (assuming circular symmetry). The field was typically 10-15% larger on the high field side, consistent with the toroidal geometry. The current density and q-profile obtained from this measurement, $q = (B_t/B_p)(r/R)$, are shown in the inset of Fig. 3a. The value of q decreases monotonically with the plasma radius, from $q = 10$ at the edge to $q = 4$ at the center while the current profile indicates not only that current flows inside the plasma core, but that the current density is higher on axis than at the edge. This centrally peaked current profile is somewhat surprising in that the current source in this experiment is purely external. This observation may be a confirmation of self-rearrangement of the plasma current toward a preferred state,[1] in this case toward a tokamak configuration.

A comparison of the experimental measurements with the simulation shows a presence of very strong current diffusion and an inward current pinch. In the code, these diffusion and pinch terms are adjusted until the results agree sufficiently with the experimental observations. One can qualitatively see from the picture that, in order for the poloidal projection of the beam path to be circular, it is necessary to have a large circulating current present in the plasma interior to provide the necessary poloidal field. In fact, in order to produce the circular discharge shown in Fig. 2c, it is necessary in our code to introduce anomalous current diffusion and pinch terms of $D_j \approx 4\ cm^2/\tau_{res}$ and $V_j \approx 12\ cm/\tau_{res}$. This indication of anomalous current penetration may be related to recent theoretical investigations in which a resistive MHD instability-driven anomalous current diffusion was obtained.[8,22]

The density measured in the high current, tokamak-like discharge by the FIR laser interferometer is shown in Fig. 3b. The plot shows the temporal evolution of the vertical chord-averaged electron density as a function of the tangency radius of the chord. A region of high plasma density is seen lying within 3 to 4 cm of the plasma axis position, in close agreement with the magnetic probe and boxcar photography observations. The central chord-averaged density of $\bar{n}_e = 2 \times 10^{13}\ cm^{-3}$, with a fall-off length of 3-4 cm, is a significant departure from the relatively flat profile previously observed in the unconfined ACT-1 plasma where the line-averaged density was in the range of $10^{12}\ cm^{-3}$. The steepened profile suggests an improved particle confinement in this tokamak regime. Average ion temperatures, determined by the Doppler broadening measurement, increased from ~ 1 eV in the low current discharge to ~ 15 eV in the tokamak discharge. These observations appear to support an increased plasma confinement in the tokamak mode compared to the case when the field lines are open and intersect the vacuum vessel. The FIR laser system has also revealed coherent long-wavelength modes in the edge region which have been tentatively identified as drift waves.[18] Although one can conjecture that these modes may be responsible for the anomalous current penetration observed in this experiment, more detailed investigations are needed for a definitive confirmation. Finally, we wish to emphasize that the tokamak-like discharge observed in the CDX is formed and maintained with no ohmic transformer action. The loop voltage is essentially zero during the discharge except for positive and negative spikes during the current start-up and termination.

In conclusion, a tokamak plasma configuration has been created and maintained in steady state for the first time by means of dc helicity injection via a low-energy electron beam. As the plasma current increased, a circular discharge evolved which was qualitatively similar to the predictions of a numerical code that invoked both current diffusion and current pinching. The poloidal magnetic field measurements demonstrated a centrally peaked current profile with q-values ranging from 10 at the edge to 4 near the center. In addition, a highly peaked plasma density profile with central chord-averaged values of 2×10^{13} cm^{-3} was observed, and ion and electron temperatures were approximately 15 and 25 eV, respectively.

Acknowledgments

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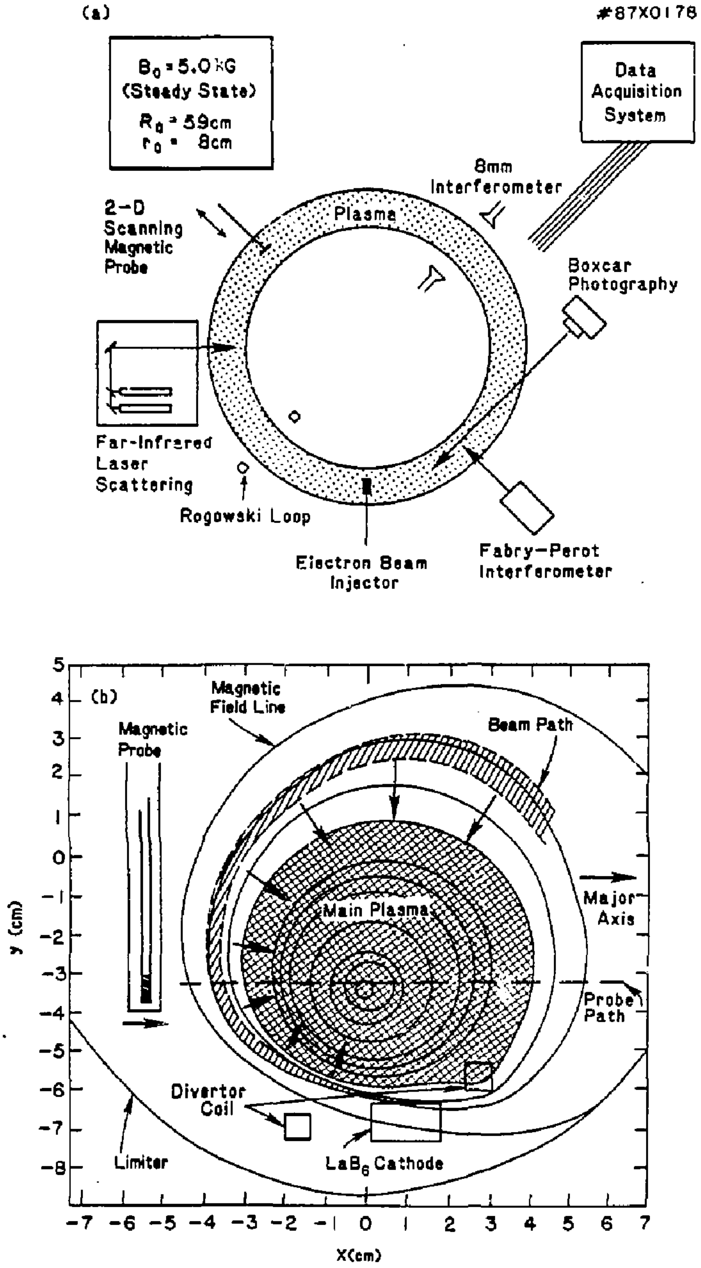
Figure Captions

Fig. 1 Schematic of the experimental setup: (a) CDX experimental facility. (b) Poloidal cross-section for the DC helicity injection experiment.

Fig. 2 Poloidal cross section of the plasma produced by DC helicity injection. (a)-(c) Magnetic field contours computed by a 2-D numerical simulation code. The lightly shaded area shows the electron beam path, and the darker shaded area indicates a region of closed magnetic field lines. (a) Low current case ($I_T < 10$ A) where $B_{plasma} << B_{vac}$; (b) medium current case ($I_T \approx 50$ A) where $B_{plasma} \approx B_{vac}$; and (c) high current case ($I_T \approx 330$ A) where $B_{plasma} >> B_{vac}$. (d)-(f) Photographs of the poloidal view of the CDX discharge. (d), (e), and (f) correspond to the cases shown in (a), (b), and (c), respectively.

Fig. 3 (a) Midplane poloidal magnetic field as a function of radial position. $I_T = 330$ A, $B_0 = 4.5$ kG, and $R_0 = 59$ cm. Inset: Corresponding deduced q-values as a function of the minor radius. (b) Temporal evolution of the vertical chord-averaged density as a function of radial position, $r = R-R_0$, where R_0 is the major radius of the plasma axis.


(a)
#87X0178
$B_0 = 5.0$ kG
(Steady State)
$R_0 = 59$cm
$r_0 = 8$cm
Data Acquisition System
8mm Interferometer
2-D Scanning Magnetic Probe
Plasma
Boxcar Photography
Far-Infrared Laser Scattering
Rogowski Loop
Electron Beam Injector
Fabry-Perot Interferometer
(b)
Magnetic Field Line
Magnetic Probe
Beam Path
Main Plasma
Major Axis
Probe Path
Divertor Coil
Limiter
LaB_6 Cathode
y (cm)
X(cm)
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-7
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6
7

Fig. 1

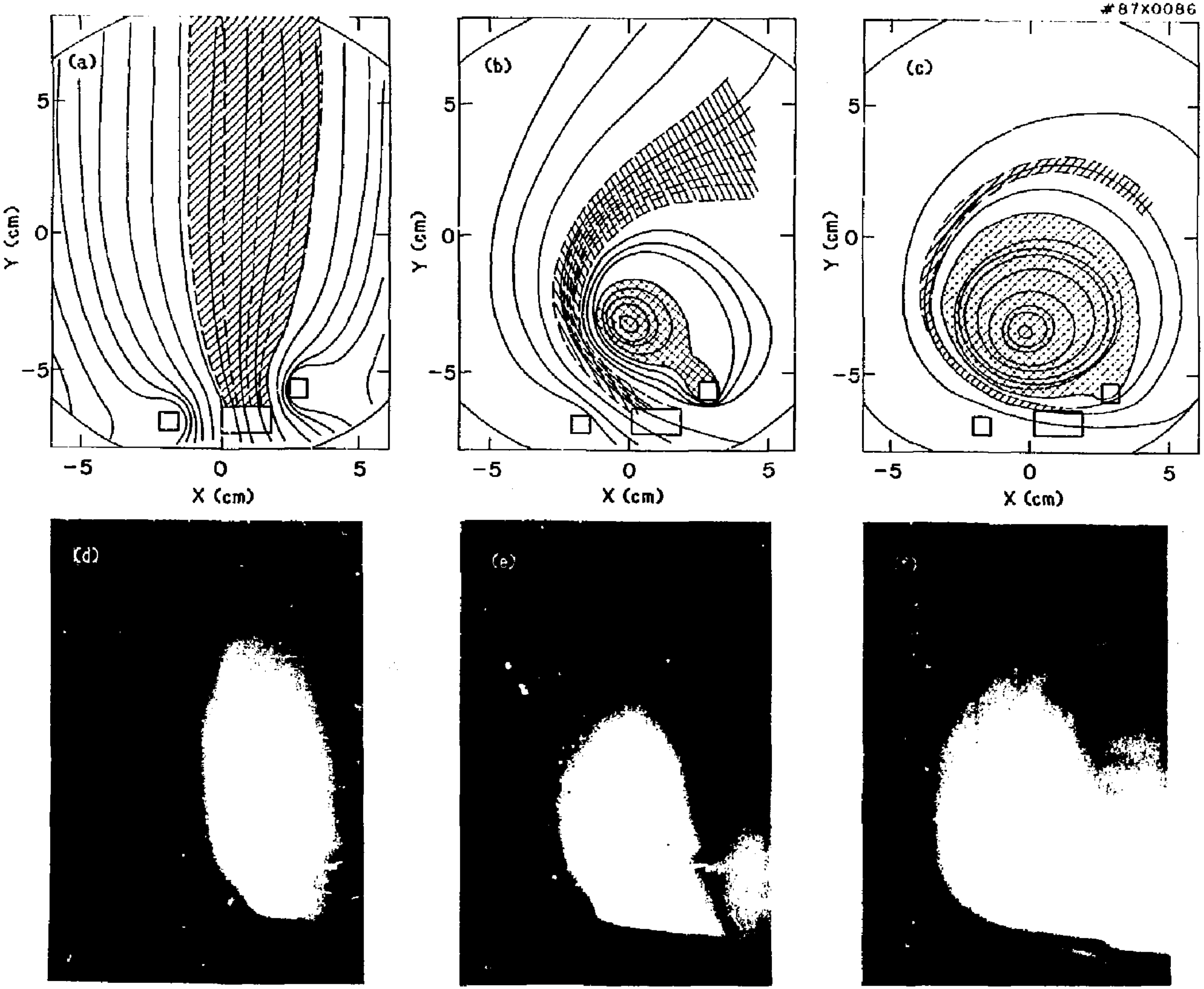

Fig. 2

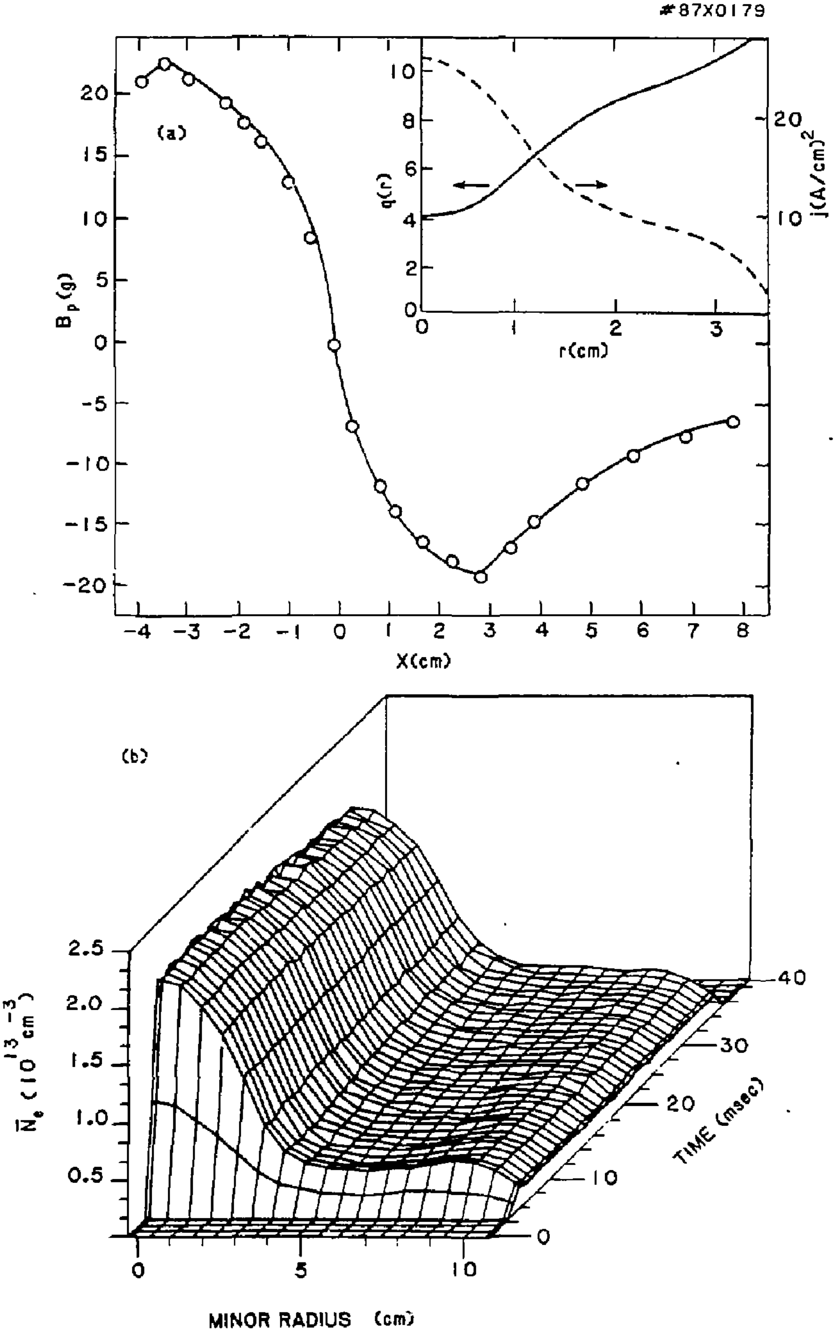
#87X0179
(a)
$B_p(g)$
20
15
10
5
0
-5
-10
-15
-20
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
X(cm)
q(r)
10
8
6
4
2
0
0
1
2
3
r(cm)
20
10
j(A/cm)^2
(b)
$\bar{N}_e$ (10^{13} cm^{-3})
2.5
2.0
1.5
1.0
0.5
0
5
10
MINOR RADIUS (cm)
0
10
20
30
40
TIME (msec)

Fig. 3

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