Trapping of Gun-Injected Plasma by a Tokamak

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It is shown that a plasma produced by a Marshall gun can be injected into and trapped by a tokamak plasma. Gun injection raises the line-averaged density and peaks the density profile. Trapping of the gun-injected plasma is explainable in terms of a depolarization current mechanism.

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Recent results with pellet injectors in tokamaks have shown that improved discharges can result from proper refueling and profile tailoring.[1,2] Higher densities and energy-confinement times are thus achieved. A possible scheme for refueling is the injection of a space-charge–neutralized beam of plasma across the magnetic field to the center of a tokamak.[3] Previous work on the Wisconsin levitated octupole has shown that such refueling by use of a coaxial Marshall gun may be possible.[4] In this Letter we describe experiments demonstrating the injection and trapping of a gun-created plasma in a tokamak.

A moving plasma can cross vacuum magnetic field lines provided it meets the condition[5] $1+\omega_{pi}^2/\omega_{ci}^2 \gg 1$, where ω_{pi} and ω_{ci} are the plasma and ion cyclotron frequencies, respectively. As a plasma moving with velocity $\mathbf{V}$ encounters a magnetic field, electrons are deflected in one direction and ions in the other. This process continues until a polarization electric field is set up such that $\mathbf{E}=-\mathbf{V}\times\mathbf{B}$. Thereafter the interior of the plasma beam can move across the magnetic field with its original velocity $\mathbf{V}=\mathbf{E}\times\mathbf{B}/B^2$.

It has also been seen that such plasmas can be stopped while crossing a magnetic field by shorting out of the polarization electric field with an external conductor.[6] In this case the plasma stream tries to reestablish the polarization field with a polarization current that is perpendicular to $\mathbf{B}$ and $\mathbf{V}$ such that $\mathbf{J}\times\mathbf{B}$ is in the $-\mathbf{V}$ direction. If the current path has a low enough impedance, current will flow such that the $\mathbf{J}\times\mathbf{B}$ force will stop the plasma.

This has also been observed in toroidal devices with only a poloidal magnetic field, such as a toroidal octupole.[7] Here plasma is injected perpendicularly to the torus and magnetic field lines, as shown in Fig. 1. The injected plasma can initially cross the magnetic field by the polarization drift, but once halfway across it encounters field lines in the opposite direction. This change of direction sets up an electric field in the direction of travel such that currents flow to short out the polarization field. If enough current flows, $\mathbf{J}\times\mathbf{B}$ forces will stop the plasma.

The tokamak has both poloidal and toroidal fields. A plasma injected into a purely toroidal field will cross the magnetic field unimpeded, because there is no way to short out the polarization field. However, added poloidal field due to plasma current will cause a shift in the direction of field lines along the path of the injected plasma. Electric fields are then set up in the direction of travel which allow depolarization currents to flow. Injected plasma might then be stopped in the center of a tokamak discharge, with the tokamak plasma current being the most important controlling parameter.

Tokapole II is a four-node poloidal-divertor tokamak with a major radius of 0.5 m and an average radius to the separatrix of 10 cm. For these experiments the toroidal field was 5 kG, plasma current ~ 20 kA, and line-averaged density $\sim 5\times10^{18}/\mathrm{m}^3$. The central electron temperature was approximately 100 eV, with an energy-confinement time of about 0.5 msec. The coaxial Marshall gun[8] has a 5-cm-diam outer barrel and a 1.5-cm-diam inner barrel with a length of 55 cm. The gun discharge was created by application of high voltage to the electrodes 500 μsec after the gun had been filled with 60 mTorr of hydrogen gas. The 15-kV high-voltage pulse had a period of 20 μsec and drew 150 kA between the electrodes. The characteristics of

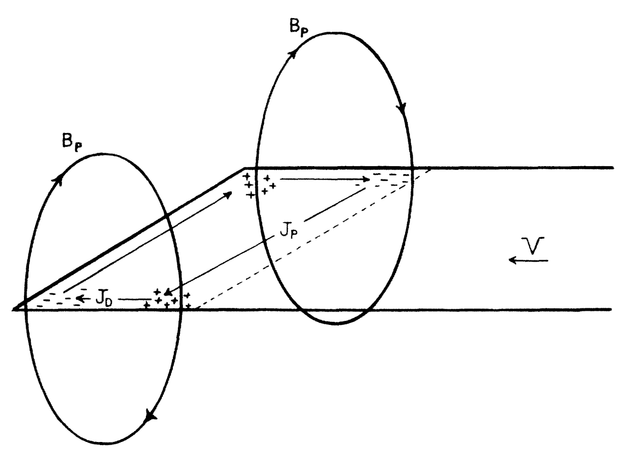

FIG. 1. Trapping mechanism for plasma injected into poloidal magnetic field. The polarization current (J_p) provides a $\mathbf{J}\times\mathbf{B}$ force to plasma moving with velocity $\mathbf{V}$. The depolarization current (J_D), resulting from field reversal, drains charge buildup due to J_P and allows J_P to continue flowing until plasma is stopped.

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the plasma ejected from the gun were determined by measurement of the time of flight and ion saturation current of the plasma with Langmuir probes. The density and velocity of the plasma were adjusted by variation of the gas fill and the voltage on the capacitors which energize the gun. Typical parameters useful for refueling yield a plasma beam at a velocity of 5×10^4 m/sec with 3×10^{18} particles ejected.

The trapping of the gun-injected plasma leads to a rapid rise in density, with most of the injected plasma being deposited in the center of the discharge. The average density change and density profile change were measured with a 70-GHz interferometer sensitive to the line-averaged density on a chord through midcylinder, and Langmuir probes that measure the edge density. The characteristics of a typical Tokapole II discharge without and with gun refueling are shown in Fig. 2. The signal from the interferometer showed an immediate increase upon firing of the gun. Since the density rises quickly (< 50 μsec), changes due to refueling are measured at 50 μsec after injection. This is done to discount any effects of un-ionized gas from the gun entering the vacuum chamber and contributing density to the edge region 2–3 msec after injection. The typical increase in the average density of a Tokapole II discharge was (2 to 3)$\times10^{12}$/cm^3. This represents trapping of 60%–70% of the injected plasma as determined by comparison with results obtained by firing of the gun into the poloidal vacuum fields created by the divertor rings, which efficiently trap the injected plasma.

To measure the density profile a Langmuir probe, which can be inserted to within 10 cm of the axis, was used in combination with the interferometer. The inferred density profile, before and after injection, is shown in Fig. 3. The Langmuir-probe data were subtracted point by point from the line-integrated signal. The remaining line-integrated signal was then used to form a continuation of the edge profile to the center. This procedure does not uniquely specify the profile, but indicates that significant plasma was added to the center creating a more peaked profile.

Another indication of central plasma conditions is the soft x-ray (SXR) emissivity. This signal is proportional to the electron density, with a strong dependence on the electron temperature. A typical SXR sig-

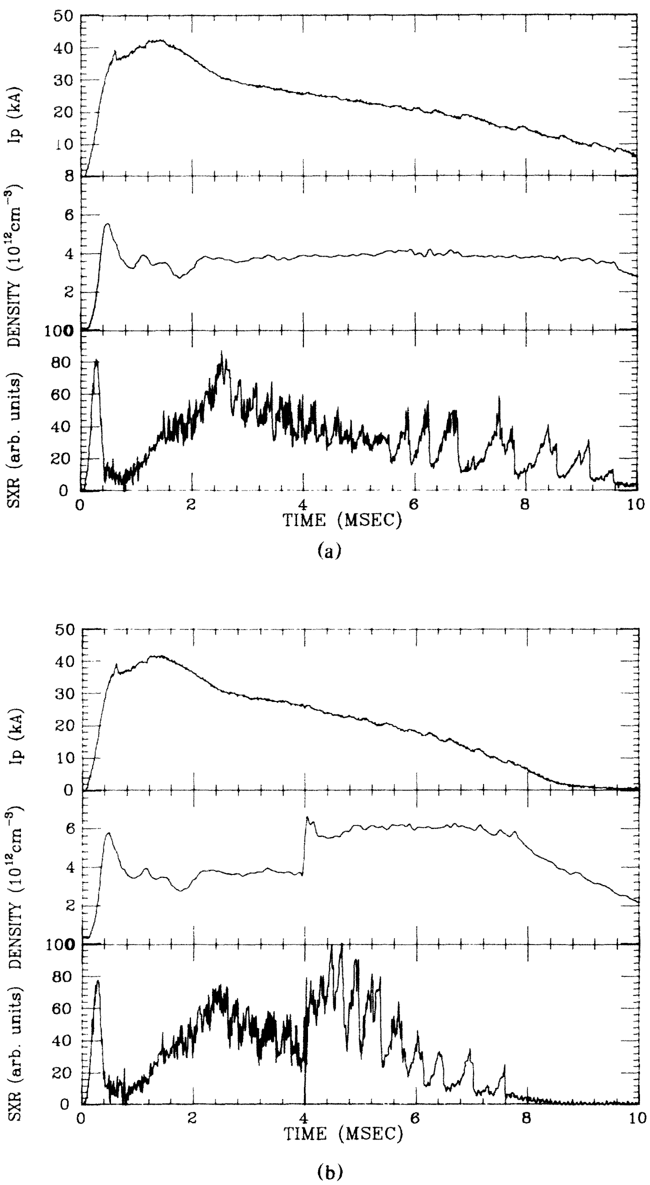

FIG. 2. Characteristics of Tokapole II discharge (a) without and (b) with gun refueling. Shown are the plasma current (I_p), line-averaged electron density (N_e), and central-chord soft x-ray emissivity (SXR).

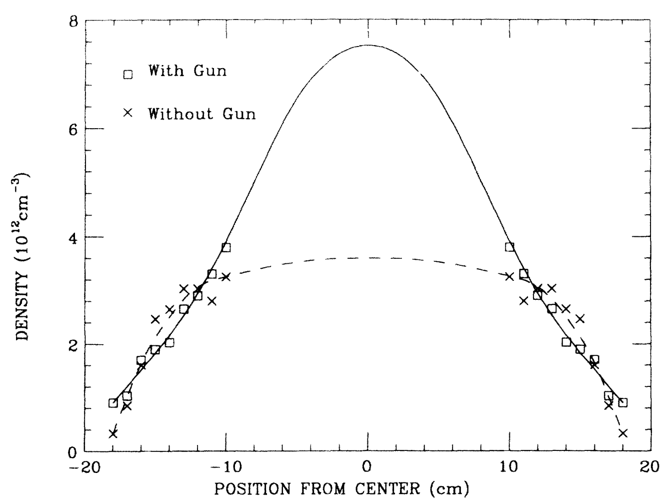

FIG. 3. Density profile found by use of Langmuir probe at edge and line-integrating interferometer.

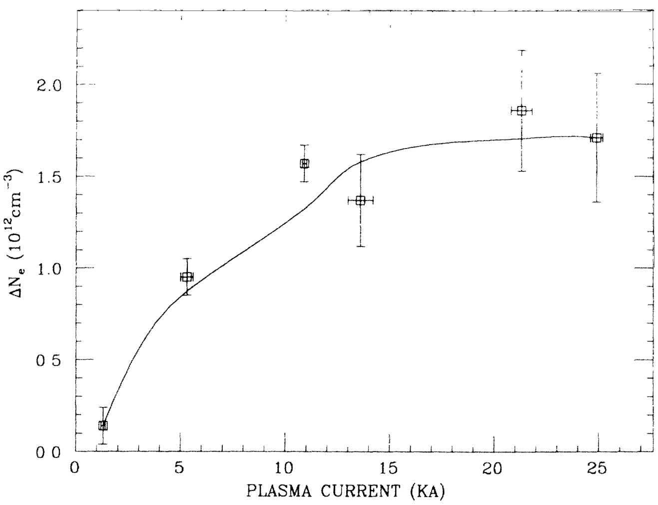

FIG. 4. Trapping efficiency (ΔN_e) shows strong correlation with plasma current.

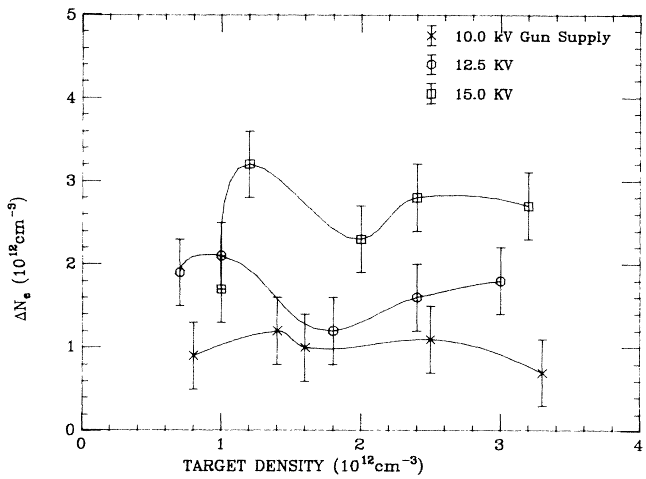

FIG. 5. The trapping of gun-injected plasma depends very little on line-averaged Tokapole II electron density (target density).

nal through the central chord is shown in Fig. 2. The central SXR signal showed an increase at the peak of the oscillations above that of the nonrefueled case, reaching a maximum approximately 0.5 msec after injection, in agreement with the energy-confinement time. The increase in signal indicated an increase in central density. Impurities injected by the gun could also raise the SXR signal, but routine monitoring of impurity radiation from N, O, C, and Cu indicated no substantial increase in these impurities. A chordal profile of the SXR emissivity showed a similar peaking to that of the density profile.

Figure 4 shows that the trapping of injected plasma is a strong function of plasma current. For this plot toroidal field, divertor ring current, and plasma density were held constant. The plasma temperature varied with plasma current, but should have little or no effect on the stopping of injected plasmas. The density and temperature of the tokamak plasma should not influence trapping, because at these parameters the collisional slowing-down distance is greater than 4 m. To verify this, the density was varied while other parameters were held constant. Figure 5 shows no significant change in trapping with variation in Tokapole II plasma density.

To show that plasma current was responsible for trapping, instead of the poloidal field due to the divertor rings, a trapping experiment was done with vacuum fields. With no plasma in Tokapole II the divertor rings produced a poloidal octupole magnetic field which efficiently traps gun plasmas. When the toroidal field is increased relative to the octupole field, the trapped density decreases because of the lessened reversal of the polarization electric field. This trend is shown in Fig. 6. Also shown in Fig. 6 is the trapped density with plasma and plasma current added to the corresponding vacuum fields. While the divertor fields may contribute to trapping, it is primarily the plasma current that is responsible for reestablishment of enough of the polarization electric field reversal to stop the injected plasma.

In conclusion, we have successfully refueled a tokamak using gun injection. Significant plasma has been deposited in the central current channel of the discharge. All of the scaling results agree with a depolarization current mechanism for trapping of the injected plasma. Measurement of the depolarization current and better modeling of the trapping mechanism would be helpful for designing refueling systems for larger tokamaks.

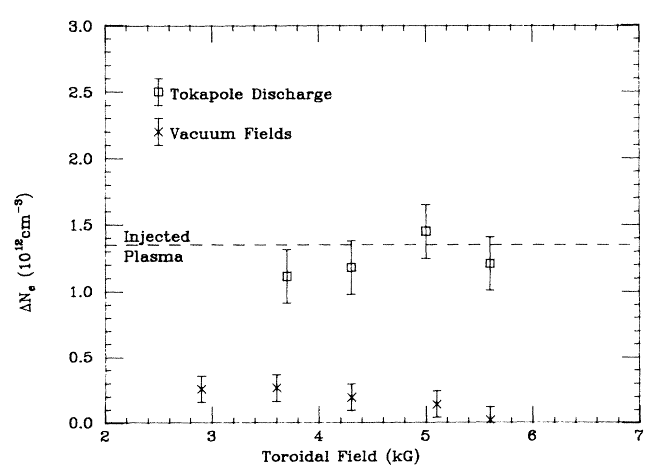

FIG. 6. Trapped density for tokamak discharge is greater than for corresponding vacuum-field case.

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