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PRELIMINARY STUDY OF CROSS-FIELD PLASMA INJECTION IN 2XIIB

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PLASMA INJECTION IN 2XIIB

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ABSTRACT

Preliminary results are presented of a study of cross-field plasma injection in the 2XIIB mirror machine. Plasma accelerated by a coaxial deflagration gun was observed to pass 3.5M across the vacuum field, and some trapping was observed when the gun plasma intersected a plasma streaming along B at the center of the magnetic well. Parameters for the experiment are: gun plasma kinetic energy 50-200eV, $n_{\text{gun}} = 3 \times 10^{13} \text{ cm}^{-3}$, streaming plasma 25 to 50 eV and $n_{\text{streaming}} = 6 \times 10^{11} \text{ cm}^{-3}$, duration of both 100-200 μsec . For the trapped plasma, $n = 2.4 \times 10^{12} \text{ cm}^{-3}$, and the decay time is $t_{1/2} = 400 \mu\text{sec}$ consistent with Coulomb scattering loss at 100eV mean ion energy.

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A PRELIMINARY STUDY OF CROSS-FIELD PLASMA INJECTION IN 2XIIB

(I) Introduction

The experiments discussed herein were motivated by the possibility of supplementing neutral beam driven field reversal in 2XIIB by transverse plasma gun injection. A recent reassessment⁽¹⁾ of the requirements to obtain field reversal in 2XIIB by neutral beams alone, taking into account electron effects, suggests that either the neutral beam current or the confinement time must be increased by about a factor of 3 over present 2XIIB values. Alternately, auxiliary injection of approximately 6 kilojoules energy such as by transverse plasma gun injection might substantially reduce the required neutral beam current.

The 2XIIB experiment⁽²⁾ provides a high quality environment in which to study cross-field injection using a plasma gun. Two important environmental aspects are the minimum B magnetic mirror field configuration, and the high vacuum, fast pumping technology made possible by large, gettered surfaces located near the containment region. Furthermore, the experiment has a complement of plasma diagnostics. Since accelerated plasmas having 10 kilojoules of energy or more are available from guns, as compared with 1 kJ plasma energy in a typical 2X-experiment, a preliminary experiment was started using a deflagration mode, coaxial gun developed at the University of Santa Clara.⁽³⁾

This report describes preliminary experiments, conducted for roughly 5 days on the 2XIIB experiment, to assess the feasibility of cross-field injection using the University of Santa Clara plasma gun. Although the gun operated poorly during these experiments, the results are sufficiently encouraging to continue these investigations to assess further the potential of plasma gun injection. In these preliminary cross-field experiments, only low beta plasmas were trapped, and field reversal was not achieved. The results however indicate the potential of the plasma gun-type source in that no special field contour appears to be required for plasma penetration and trapping.

(II) Experimental Configuration and Apparatus

A horizontal section of the 2X experimental device is shown in Fig. 1. The plasma gun was located in the south-side neutral beam tank. During the course of the experiment, the gun was located in two nearby port locations, each of which gave a nearly horizontal traverse of 350 cm to the magnetic well minimum. Fig. 2 shows the magnetic field along the traverse for typical operating conditions. The field is provided by a D.C. solenoid and the pulsed Yin Yang coil. In addition to the deflagration plasma gun, two streaming guns located in the west end plate were used.

The coaxial plasma gun is shown in Fig. 3. The gun was connected to the driving capacitor bank ($C = 60 \mu\text{fd}$) by 30 RG 8 u coaxial cables, each roughly 20 feet long. Under normal operating conditions, the bank is charged to 15-19 kV, the fast-acting gas valve opened to admit $1 \text{ atm-cm}^3 \text{ D}_2$, and the gun self-switches during the pressure rise. Self-switching selects the deflagration mode of acceleration which, under nominal conditions, leads to a fast component plasma output in the $3 \mu\text{sec}$ current rise of several kilojoules (out of 10 kJ max input), with mean kinetic energy in the range 5-10 keV. For the experiments reported here, only 0.4 atm-cm^3 gas input could be obtained.

Diagnostic measurements were performed using a segmented calorimeter which could be raised to the center of the magnetic well, and a 2 mm interferometer which passed nearly vertically through the magnetic well minimum.

(III) Experimental Results

Initially the gun was located on a port in the south neutral beam tank east of the neutral beam ports (Location A of Fig. 1). In order to obtain a straight traverse to the well center, it was necessary to locate the gun off center in the tank port so that, immediately after exiting the gun, the plasma passed near the side walls of the 6 inch diameter by 30 inch long pipe within the beam vacuum tank shown in Fig. 1. After tune-up, firing the gun gave no detectable signal on the calorimeter. The gun was re-aimed through the use of a vacuum gimbal, and for all adjustments no signal was obtained.

During a subsequent shutdown, visual observation showed that considerable sputter damage had occurred at the entrance aperture to the main chamber. The damage pattern was elliptical in cross-section, and roughly 6 inches to the east of the aperture. It was concluded that distortion and deflection of the accelerated plasma column had occurred because of the off-center positioning of the gun within the pipe. On disassembly, the end of the gun center electrode was found to be off center about 3/16 inch, and a film deposit was found on the center electrode near the breach. The deposit was later identified to contain Au, Cu, Ca, Mg, and Si, the latter three elements presumably coming from the insulator. Insulator material could have been ablated because of insufficient gas input.

Next, the gun was installed in a neutral beam port, again about at the midplane. A moveable paddle and viewport were also installed in the gun flange for diagnostic purposes. This time, calorimeter signals were observed at the center of 2XIIB. After some sighting in to optimize the calorimeter signal, it was determined that a plasma beam having a cross-sectional dimension of 10's of cm was reaching the center of the well. It was further determined that with the D.C. field on, the plasma continued to reach the center, but was deflected upward consistent with slightly insufficient polarization.

The profile of energy deposition on the calorimeter is shown in Fig. 4. This measurement suggests that, with a magnetic field present, a broad beam along B with roughly 10 cm half-width transverse to B is injected. The peak energy per cm^2 indicated by the calorimeter is 0.5 joules/cm^2 .

Following the calorimeter measurements, the calorimeter was lowered and the study continued using the 2 mm wavelength microwave interferometer. Fig. 5 shows the $\int n d l$ values obtained vs time for $B_{DC} = 0$ and 1 kG. It is seen that the transverse magnetic field does not appreciably affect the leading edge of the plasma stream, but it does prevent the slower lower energy plasma from entering, in agreement with results obtained earlier.⁽⁴⁾ Similar penetration across the field was observed with the Yin Yang field only (Fig. 6a), and with both the Yin Yang and D.C. field (Fig. 6b). Time-of-flight measurements indicate that the earliest component has $v = 1.4 \times 10^7 \text{ cm/sec}$, and at peak line

density $v = 7.0 \times 10^6$ cm/sec, corresponding to deuterium ion kinetic energies of 200 eV and 50 eV, respectively.

Having established that the gun plasma penetrates across the field, trapping by interaction with a plasma streaming along B was investigated. It is anticipated⁽⁵⁾ that the streaming plasma would short out the polarization electric field, thereby trapping the gun plasma. Streaming guns Nos. 10 and 11 were used. These two guns are positioned in the west end flange such that the cross section of the plasma emitted maps into an ellipse with vertical major axis in the well bottom. The ellipse has a major axis of 10 cm and a minor axis of 2 cm.

Figs. 7a, 7b, and 7c show interferometer traces (2 phase shift is equivalent to a line density of 1×10^{14} cm⁻²) of the streaming plasma alone, the transverse gun plasma alone, and the two combined. The duration of the streaming gun's voltage pulse was reduced to obtain the relatively low $\int nd\ell$ shown in Fig. 7a. Approximate time-of-flight measurements indicate that the mean deuterium ion kinetic energy of the streaming plasma guns is in the range up to 50 eV.

The plasma line density vs time derived from Fig. 7 is shown in Fig. 8. It is clear that some trapping does occur. The trapped plasma $\int nd\ell$ lies above the sum of the streaming plasma and the gun plasma. After obtaining the above data, the experiment was interrupted by planned down time on experiment.

(IV) Discussion of the Results

Taking the plasma width along the interferometer beam path to be $L = 10$ cm, the peak gun plasma density at the well bottom is 3.0×10^{13} cm⁻³ while the peak streaming plasma density is about 7.0×10^{12} cm⁻³. The coulomb mean-free-path for gun ions in the streaming plasma with, say, 50 eV energy, is 10^3 cm. This suggests that collisions are unimportant in the trapping process. It appears likely therefore, that trapping takes place by some depolarization of the gun plasma, similar to earlier observations.⁽⁵⁾

The trapped plasma (assuming $L = 10$ cm) has an average density of about $1.2 \times 10^{12} \text{ cm}^{-3}$, and it decays with a time constant $t_{1/2} = 400 \text{ } \mu\text{sec}$ (see Fig. 8). Decay of the plasma by coulomb scattering on the mirror with $n = 1.2 \times 10^{12} \text{ cm}^{-3}$ and $t_{1/2} = 400 \text{ } \mu\text{sec}$ would require a mean ion energy of about 100 eV. This is about the value inferred from the time-of-flight measurements, suggesting the trapped plasma decay is nearly classical.

Reconciling the calorimeter data and the interferometer data of $\int n dL$ and time-of-flight presents some difficulties. From the interferometer data of Fig. 5, at $B_{DC} = 1$ kG, the plasma stream has a peak density $n = 3 \times 10^{13} \text{ cm}^{-3}$ ($L = 10$ cm) with mean kinetic energy of 200 eV and a length corresponding to the flowthrough time of 50 μsec of ≈ 250 cm. The total energy per cm^2 carried by the plasma is therefore about $6.7 \times 10^{-2} \text{ joules/cm}^2$. This is to be compared to the calorimeter data of Fig. 4 which indicates a peak deposition of 0.5 joules/cm^2 - about 7 times higher. A possible explanation is that most of the calorimeter signal results from a low density, higher kinetic energy plasma not detected by the interferometer.

A rough estimate of the gun injection efficiency may be made by assuming a 10 cm transverse scale length. In this case, 50 joules were intercepted by the calorimeter, whereas the capacitor bank energy was 10 kilojoules. Thus the injection efficiency for these experiments was about 1/2%.

Finally, it should be noted that in these experiments the gun plasma energy and ion kinetic energy are both much lower than that produced under normal gun operation. It appears that near-normal operation occurred early in the run, since appreciable ablation damage was observed near the entrance aperture. After the gun was moved to a neutral beam port, where the data presented here were taken, very little high energy plasma was produced by the gun. This was verified by firing the gun at the stainless steel paddle described earlier. With the paddle roughly 70 cm in front of the gun, no appreciable temperature rise or ablation damage was observed for 10 shots. Among possible reasons for poor gun operation are that the gas valve did not open properly, which causes gas starvation and insulation ablation. This was verified by the analysis of the material coated on the center electrode.

(V) Summary and Conclusions

The preliminary experiments described here have demonstrated that it is possible for a gun plasma to cross the field and enter the confinement region of 2XIIB under conditions feasible for neutral beam injection. It has also been demonstrated that streaming plasma leads to some trapping of the gun plasma, probably by depolarization because of low beta. The trapped plasma decays with a nearly classical 400 usec decay rate.

The results indicate that further study is warranted, especially under conditions of normal gun operation and possibly with a gun having higher energy output. Such investigations could be carried out in the Beta II facility at an early date, since neither neutral beams nor a full complement of diagnostics is required. It is also of significance that the 2XIIB magnetic field is a rather complex geometry. Plasma penetration and trapping in this geometry gives encouragement to injection in other configurations.

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FIGURE CAPTIONS

- Fig. 1 Horizontal cross section of the 2XIIB apparatus showing the initial deflagration gun location A, final location B, and streaming plasma source location.
- Fig. 2 Magnetic field components along the gun traverse; B_{yy} is the pulsed Yin-Yang field and B_{dc} is the steady solenoid field. The coordinates n, z are measured from the center of the magnetic well as shown in Figure 1.
- Fig. 3 Coaxial, deflagration mode gun.
- Fig. 4 Segmented calorimeter signals for $B_{DC} = 1$ kG. Figure 4 (a) shows the horizontal distribution for $y = 4.5$ cm and Figure 4 (b) shows the vertical distribution for $x = 4.4$ cm. The y coordinate is measured upward from the center of the magnetic well.
- Fig. 5 Interferometer density measurements of the gun plasma for $B = 0$ and $B_{DC} = 1$ kG. $\Delta\phi = 2\pi$ corresponds to $\int n dl = 1 \times 10^{14} \text{ cm}^{-2}$.
- Fig. 6 (a) Gun current and $\Delta\phi$ vs t for quadrupole fields only, $B_{yy} = 2.43$ kG at the bottom of the magnetic well.
(b) Same with added $B_{DC} = 2$ kG.
- Fig. 7 Interferometer signals for:
(a) The streaming sources only.
(b) Transverse gun only.
(c) Both stream source and transverse gun.
- Fig. 8 Plasma density vs time for the three cases of Fig. 7.

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Fig. 1.

Fig. 2

Fig. 3

Fig. 4

(a)

(b)

Fig. 7

Fig. 3