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Plasma Stream Interactions through
Polarization Electric Fields

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Jay E. Hammel
Ralph W. Kewish, Jr.

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PLASMA STREAM INTERACTIONS THROUGH POLARIZATION ELECTRIC FIELDS

by

Jay E. Hammel and Ralph W. Kewish, Jr.

ABSTRACT

An experiment is being conducted using two plasma streams with opposing velocities in a transverse magnetic field to observe the interaction of the two opposing polarization electric fields. The technique is a possible means of loading a closed-field geometry. The two similar streams are not directly opposed but are displaced from one another along the magnetic field to increase the possibility of a significant interaction. The fast plasma produced by coaxial guns has a density up to $5 \times 10^{14} \text{ cm}^{-3}$ and a directed velocity of 50 to 70 cm/ μsec . The resultant polarization field in kilogauss magnetic fields is of the order of kilovolts per centimeter. The lateral stream separation is 54 cm, and at magnetic fields below 3.0 kG the streams have a negligible effect on each other. At high fields (7.0 kG), the streams have a larger interaction under certain conditions, and an increase in density is observed. The effects when the two streams differ widely in density and arrival time are discussed.

I. INTRODUCTION

Because a Marshall gun produces a deuterium plasma whose density and energy are in the thermonuclear range, it is important to determine experimentally whether this plasma can be injected and held in magnetic geometries. The technique of transverse injection into a magnetic field gives two possible means of loading a field, depending on depolarization of the polarized transverse stream by (1) self-depolarization of one stream along re-entrant field lines that cross the stream twice, or

(2) by the interaction of one stream on an oppositely directed stream. In addition to providing information on loading of magnetic geometry, these experiments will be useful in observation of the polarization field interactions.

The use of two opposing streams is a possible technique for loading toroidal geometries with azimuthal fields. The self-depolarization technique requires a geometry with re-entrant field lines over a short distance such as multipoles with little or no shear.

Fig. 1. Field plot, two-gun experiment, 55-cm-diam coils.

II. TWO OPPOSING GUNS

An experiment with two opposing guns is being performed in the geometry shown in Fig. 1. The guns are not directly opposed but are offset 55 cm along the field direction. From previous measurements on streams entering a shorted region of a transverse field,¹ it is predicted that two directly opposed streams will interact to give a deflection one from the other while both remain transverse to B. This direct encounter would not leave an appreciable amount of plasma in the field.

If the streams are offset along the field direction, the buildup of depolarization currents is delayed by inductive effects until the streams pass each other, and a more complicated and efficient depolarization and trapping is possible. The characteristic time for this current buildup under very simplifying assumptions¹ is:

$$\tau = \rho v w L / B^2 h, \quad (1)$$

where

ρ = density of streams before encounter

v = directed velocity of stream

w = stream dimensions along B

L = inductance of current path, assumed time-dependent

h = height of stream.

τ is adjusted through L (function of offset) and B to the same magnitude as the transit time of the stream across most of the diameter of the field. Previous experiments indicate that an offset of a few 10's of centimeters is about right for kilogauss fields.

III. DENSITY AND ELECTRIC FIELD FOR SINGLE STREAM

Three features of the plasma are measured in the experiment by methods which do not place objects directly into the plasma stream. The electric field orthogonal to v and B is measured by probe pairs placed outside the coils as shown in Fig. 1. In Fig. 2 a usual electric probe signal is shown for each gun fired separately. The impedance of the electric probe pairs must be $> 1000 \Omega$ if the far probe signal is not to be measurably degraded. This impedance value is probably given by the limiting electron current set by the density of the plasma which connects the plasma stream to the probe. An estimate of this density from the required probe impedance is made by estimating the area of the probe connection to the plasma as $\pi \rho_{ion}^2$. This estimate gives a density of $\sim 10^{11} \text{ cm}^{-3}$ for the plasma outside the main stream. Most of the signal appears on two probe pairs; this indicates a stream height of about 5 cm. The peak signal makes an $E/B = 6.0 \times 10^7$ cm/sec.

The plasma density is determined by a laser interferometer² operating at 3.39μ . The peak cross-sectional density for each stream alone is 0.1 to 0.2 fringe ($3 \times 10^{15} \text{ cm}^{-2}$).

IV. DENSITY, ELECTRIC FIELD, AND CURRENT WITH TWO STREAMS

The experiment requires that both plasma streams intersect the same flux tube near the axis of the magnetic field. The streams are quite narrow (5 cm)

Fig. 2. Single-gun electric field signals.

at high B values, and a small refraction by the transverse field causes the streams to miss. By mounting one gun in a bellows and allowing movement of the gun direction, the intersection is controlled within the variation in the stream direction. When the guns are fired, the current flowing between the two streams is measured by three Rogowski loops placed midway between the streams. The three loops are placed relative to the plasma guns as shown in Fig. 1. The currents through the Rogowski loops and the electric fields are dependent upon the displacement in time and the ratio of the energy density of the two streams.

A. Simultaneous Streams of Equal Energy Density.

When the two streams are simultaneous within the arrival time jitter of $\approx 0.2 \mu\text{sec}$ and are of similar energy density, the electric field probes give signals which oscillate rapidly between nearly peak field values of the two streams. Compare the two-gun E-field shown in Fig. 3 with that of the individual guns shown in Fig. 2.

The current in the Rogowski loops is presented in Fig. 3 with peak currents of more than 6 kA. The top and bottom loop currents are not symmetrical because exact placement of the loops with respect to

the stream is impossible. The current is of a magnitude that would halt the streams when the known stream parameters are put into the equation of the momentum flow

$$\rho v^2 = \frac{I \cdot B}{wk} \quad (2)$$

I is the measured current, and k is a number between 1 and 2 depending on whether the stream is halted or reflected.

Fig. 3. Two-stream depolarization current and electric field.

$k = 1$ is assumed which is the case if the streams are halted. An important feature of the current trace is that it is nonoscillatory and appears to be heavily damped. Since, classically, the collisionless plasma would not cause such a damping, the energy might be dissipated through instability and turbulence. The rapidly oscillating voltage signal would indicate a turbulence or plasma wave caused by the two-stream interaction shown in Fig. 3. An alternate explanation suggested by Don A. Baker (Group P-18)³ is that self-expansion of the depolarization current loop path might look like damping. However, damping even at high B_0 when the depolarization currents are not large (Eq. 2) makes this explanation seem unlikely.

The cross-sectional density measured by the laser interferometer gives a general idea of the density of plasma involved in this experiment, about 0.1 to 0.2 fringe at 3.39μ ($\approx 3 \times 10^{15} \text{ cm}^{-2}$). The shot-to-shot variation in signal is large, primarily owing to the angular variation in the direction of the narrow streams. This makes it difficult to measure the increased density caused by interaction of the two streams. Also, the solenoid magnetic field is not a bottle that can contain a large buildup of density. On certain favorable shots the stream density after the first fast plasma pulse greatly exceeds the density produced by a single gun. An example of this increased density after the first pulse is shown in Fig. 4.

Fig. 4. One- and two-gun laser interferometer measurements.

B. Simultaneous Streams of Unequal Density. If both streams arrive at the same time but are very different (by factor of two or more) in density, the high-density stream completely dominates the E-field. The dominant stream sweeps up the low-density stream

with it by means of its depolarization E-field. Current measurements for this case have not yet been made.

C. Equal Streams Slightly Displaced in Time. When the timing of the two guns is not simultaneous but is within $2 \mu\text{sec}$, E-field characteristics of both guns are present in sequence. The current and E-field for this case will be investigated further.

D. Streams Greatly Displaced in Time. A tenuous background plasma was placed in the magnetic field prior to the arrival of one stream by firing one gun at low voltage very early ($> 6 \mu\text{sec}$). Even with the density of the background plasma less than 0.2 fringe, the normal density stream will not enter the field to a detectable level. This is most surprising since, from the simple momentum transfer point of view, the dense fast stream should easily pick up the background gas and enter the transverse field. The low-density background must have some large effect as the stream tries to enter the field. We hope to investigate this point using Franz Jahoda's (Group P-15) Moire pattern technique.

V. CONCLUSIONS

Simultaneous streams of equal energy density interact strongly with measured currents that are of the right magnitude to stop the streams. A damping mechanism is present which could put a large part of the energy into the plasma (a form of turbulent heating). Further investigations of the currents and electric fields in various combinations of timing and density are needed to clarify the disposition of the plasma and energy after the encounter.

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