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LOS ALAMOS SCIENTIFIC LABORATORY

OF THE UNIVERSITY OF CALIFORNIA o LOS ALAMOS NEW MEXICO

QUARTERLY STATUS REPORT OF THE LASL
CONTROLLED THERMONUCLEAR RESEARCH PROGRAM
FOR PERIOD ENDING MAY 20, 1962

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PICKET FENCE IIB

The experimental results observed for a deuterium plasma injected and contained in the Picket Fence IIB are consistent with an average density of 2×10^{12} deuterons/cm^3 and a mean energy of ~ 5 keV, confined in a volume of $\sim 10^4$ cm^3, with an electron temperature of ~ 1.4 keV. The time dependence of the confined plasma is evaluated from the decay of the neutron signal produced by the energetic deuterons escaping out along cusp field lines and producing D-D reactions on the wall. This signal generally rises to a peak about 100 μsec after injection, starts to fall with roughly a $1/t^2$ dependence, then changes to a relatively long exponential slope, and terminates in a small long-lived linear tail. The exponential part of the slope follows (on the average) a B^3 dependence up to 1 msec at 7.4 kG cusp field (for the previously described plasma gun powered by 6 μF at 25 kV).

Preliminary attempts to increase the confined plasma density by adding a second plasma blob to an already confined plasma have been unsuccessful. The system used for this experiment was a second gun injecting axially from the cusp opposite to the first gun. Briefly the data indicate that injection from the second gun abruptly spills out any previously trapped plasma,at least for time delays between the firing of the two guns of 50 to 400 μsec.

PICKET FENCE III

The duration of the neutron signals produced by the trapped fast ions increases with the magnetic field up to the maximum field strength available (2300 G at the ring cusp). Assuming that all of the neutrons are produced on the tank walls, these signals may be integrated to find the number of contained particles as a function of time; this assumes that the losses are not strongly energy dependent. The decay of the contained particles is exponential (within 10%) and the e-folding time is proportional to the field strength. At 2300 G this e-folding time is 35 msec.

The base pressure before the shot was raised by admitting air; as the pressure increased the duration of the neutron signal decreased. At pressures of 6-9 x 10^{-5} torr, lifetimes are as much as 10^3 greater than the time for charge exchange. This clearly demonstrates that the background gas has been burnt out by the injected plasma.

The energy spectrum of the injected plasma was measured with an electrostatic energy analyzer. The most probable ion energy is 7 keV and the average ion energy is 15-25 keV. The average was not accurately determined since the analyzer will not operate above 34 keV.

COAXIAL GUN EXPERIMENTS

In order to account for the large deuteron energies inferred from neutron production, greater than expected from the bank voltage, some process must be invoked whereby the plasma can generate large voltages and hence fast ions. This process would produce the large transient voltages which are measured at the gun terminals as well as downstream during the passage of the plasma. An azimuthal array of B_θ probes shows that the B_θ magnetic field in the annulus and to 7 cm downstream varies spatially and with time. Two neutron sources are distinguished, one associated with the fast deuterium ions striking a metal plate 1 meter downstream and the other in the vicinity of the gun muzzle (center electrode end). From the time of onset of neutrons, the process producing the fast downstream ions appears to originate in the vicinity of the end of the outer electrode some 35 cm from the center electrode end. By closing the end of the outer electrode with a metal stopper, no fast ions are observed impinging (assumed from no neutron production) on the metal stopper. This result implies either that the metal stopper prevents the occurrence of a current breaking phenomenon which could account for high transient accelerating voltages or that the metal stopper is not a good deuterium target. The shape of the current signal, measured within and external to the plasma, exhibits a starvation of current carriers at $\sim 1\ \mu$sec in the current cycle. This phenomenon, it is thought, is associated with magnetic field penetration into the plasma causing partial shredding of the current layer which goes to make up the complicated process of high-energy acceleration of ions.

PLASMA GUN RESEARCH FACILITY

In an attempt to ground the plasma ejected by the gun, the center electrode was shorted to the outer electrode through 9-in. long metallic extensions of various diameters terminating in a set of radial fins at the end of the barrel. The action of the gun was insensitive to this change in terms of output (registered on a thermocouple-calorimeter) and general dynamic behavior. The plasma itself still dominated the inductive behavior of the system. Neutron yield was generally reduced, although the usual peaked dependence on a sharp neutral gas distribution was broadened a factor of four. With or without the shorting bridge, large numbers of 100-keV deuterons were accelerated and bombarded the end plate of the vacuum tank, 125 cm away. Total neutron yield was about 10^5 neutrons per cycle in the unshorted condition.

RESONANT HELIX - COAXIAL GUN INJECTION EXPERIMENT

The work on the interaction of the resonant helix with the plasma from a coaxial plasma gun was terminated this quarter. A paper describing the observed phenomena is now in preparation.

KINETIC THEORY OF PLASMA AND RADIATION

Work is underway to construct a useful kinetic theory of plasmas which includes electromagnetic radiation. One physical limit has already been explored. This is the limit of low particle density in which the effects of the dielectric constant should disappear. Under these conditions, emission, absorption, and scattering processes can be pictured as collisions between photons and electrons (or atoms) with the various radiative transition probabilities given by separate classical or quantum mechanical calculations. As an example, this technique has been applied to a problem arising in connection with the attempt to understand the theoretical limitations standing in the way of designing a cyclotron radiation maser (LAMS-2682). In this problem, it is found that a positive slope in the velocity distribution function, f, of electrons can lead to negative absorption (amplification). As a result of this amplification, the distribution function must change with time. The calculation made utilizes the electron-photon description, and indicates that where the slope of f was originally a maximum it decreases in time to zero. A similar behavior occurs for positive absorption. Here, in the region surrounding the point of maximum (negative) slope, the slope of f also decays to zero with time. The time for this decay process is given by

$$T = \frac{1}{\sqrt{\pi}} \frac{1}{(e^2/mc^2)} \frac{mc^2}{P} \frac{(\Delta\omega)^3}{c\,\omega_B^2} \frac{(1 + x_o^2)^{3/2}}{x_o^2}$$

where

P = magnitude of the Poynting vector

$\Delta\omega$ = line width of the radiation

$\omega_B = \frac{e}{m}B$ = cyclotron radian frequency

$x_o = p_o/mc$

p_o = electron momentum perpendicular to magnetic field, characteristic of electrons populating f at the maximum (positive or negative) slope location of f.

The formula for T was derived for propagation of the extraordinary wave perpendicular to B, and includes interaction with the fundamental cyclotron radiation (n = 1) only. These results cannot be derived from the usual collisionless Boltzmann equation.

PREIONIZATION OF SCYLLA BY MEANS OF RAPIDLY OSCILLATING B_Z FIELD

A $\dot{B}_z$ preionization arrangement has been installed on Scylla III with the objective of producing a clean, ionized deuterium plasma with an appropriate amount of trapped magnetic field. Upon the application of the main magnetic compression field a hot plasma is produced on the Scylla first half-cycle. An additional purpose is to simulate the preionization arrangement which has been designed, but not tested, for Scylla IV.

The fast, low-energy capacitor bank, which is directly coupled to the 18.7-cm compression coil to reionize the deuterium gas, consists of two low inductance, 0.85-μF, 120-kV capacitors connected in parallel. The 120-kV voltage rating is required in order for these capacitors to withstand the transient voltage-doubling from the main 100-kV bank. Two individual 50-kV spark gap switches and 46 RG-17/14 cables connect the preionizer bank to the collector plates and compression coil. At 50 kV on the preionizer capacitors, a magnetic field of 12 kG is produced in the 18.7-cm compression coil. A 3-kV capacitor bank is used to provide an initial bias magnetic field B_o in the compression coil.

The plasma produced by the preionizer, with and without bias magnetic fields, was studied with streak photography and magnetic probes, and after compression by these techniques and also by the observation of soft x-ray and neutron emissions.

The operational sequence was as follows: (1) A bias magnetic field B_0, whose magnitude is variable between 1.0 and 20 kG, is produced in the compression coil with a rise time of approximately 75 μsec. (2) The preionizer field B_{PI} is applied to the compression coil at a time such that $|B_0| < B_{PI}$. (3) The main compression field is produced in the same single-turn coil at a time interval in the range of 5 to 65 μsec after the initiation of the preionizer. The operation of the main Scylla capacitor bank was limited to 75 kV because of prefires of the 100-kV spark gaps produced by the preionizer voltage. At 75 kV a maximum compression field of 125 kG was produced in the 18.7-cm coil with a rise time of 2.5 μsec.

Without a bias magnetic field ($B_0 = 0$) the streak photographs show a shock at the beginning of the main compression field which implodes to the axis of the discharge tube without any subsequent "bounce." Radial plasma oscillations, which are characteristic of an annulus of plasma oscillating between two parallel magnetic fields, occur after the initial implosion. There was no neutron emission during the first half-cycle of the main compression field. Some soft x-ray emission was observed through the "thin" absorber foil (18.75 mg/cm^2 Be) of the dual soft x-ray detector. However, the emission was quite erratic and since it did not penetrate the "thick" absorber foil (49.45 mg/cm^2 Be) an electron temperature was not obtained, although an upper limit of 200 eV applies.

With a parallel bias magnetic field, a somewhat slower implosion occurs followed by rapid plasma oscillations which are characteristic of a plasma containing parallel trapped magnetic field. There is no neutron emission with $+B_0$. Some soft x-ray emission, which was erratic and nonreproducible, was observed through the thin absorber foil of the dual soft x-ray detector.

With antiparallel bias magnetic field in the range 4 to 7 kG and B_z applied after the sixth half-cycle of the preionizer, a "shock" implosion occurs at the beginning of the first half-cycle of B_z which does not reach the axis of the discharge and is not followed by a "bounce." A compressed plasma column results, which contains a hollow core. This hollow core is quite reproducible and is believed to consist of trapped B_0 field similar to that observed in other, less dynamic, θ pinches. The flute-type instability develops after or in the vicinity of the maximum compression field and is independent of the existence of the hollow-core plasma structure. Results from streak photography indicate that the hollow core is unrelated to the development of the instability.

As B_0 is increased to 7 kG, the normal "second half-cycle" shock and double bounce begin to occur and the hollow core in the compressed plasma disappears. The flute-type instability develops at the usual time. With B_0 values between 7 and 16 kG, streak photographs show on the first half-cycle an initial shock implosion and bounce structure characteristic of the usual second half-cycle operation.

Appreciable first half-cycle neutron emission requires an antiparallel bias magnetic field in excess of 4 kG. In addition, the high neutron emission rates are favored by a relatively long time delay of the order of 30 μsec between the initiations of the preionizer and B_z. As the antiparallel bias magnetic field is increased from 4 kG to 16 kG, the neutron yield increases and the time distribution of the neutron emission becomes symmetrical with respect to the compression field.

The highest neutron yields were produced at an initial deuterium pressure of approximately 140μ. However, appreciable neutron emissions, greater than 10^7 per discharge, were obtained over the range of 85 and 250μ. Such emission ($> 10^7$ neutrons per discharge) occurs over a relatively wide range of time intervals (10 to 65 μsec) between the initiation of the preionizer and B_z circuits. The highest neutron yields are observed when the time interval is ~ 30 μsec. The maximum neutron yields of about

2×10^8 were observed with an antiparallel bias field of approximately 16 kG and with the preionizer capacitor bank charged to 35 kV and applied to the deuterium gas at a time when the bias field had a value of about 8 kG.

The electron temperature appears to be independent of the magnitude of the antiparallel bias magnetic field so long as it exceeds a few kilogauss. Under the conditions which produced high neutron yields, the intensity of the soft x-ray emission is reduced in the vicinity of the maximum compression field, whereas the time distribution of the neutron emission is approximately symmetrical about the field. This suggests that the discharge may be burning through the impurities, in particular, completely stripping the oxygen impurity to O IX. With antiparallel bias magnetic fields, higher electron temperatures (~ 850 eV) were observed than any heretofore in the Scylla experiments. This result was anticipated since the particular preionization arrangement used should result in a plasma with lower impurities.

PLASMA ANALYSIS OF INJECTED SCYLLA III

The apparatus has been constructed for attempting to "spill" the trapped and compressed plasma in the injected Scylla III experiment (LAMS-2682, p. 8). Measurements of the magnetic field show that a connection has been achieved between the compression and spill fields, which is smooth to within 13%.

The operational sequence of the experiment is supposed to be as follows: (1) The gun hammer is released and upon striking the anvil sends a compression wave through the sonic transmission line to the fast-acting valve and an electrical pulse to start the timing sequence of the various capacitor banks. (2) The capacitor banks which energize the gun guide fields, and spill coil fields, the plasma guide fields, and the 100-kV bank are fired at appropriate times so that they obtain their maximum values simultaneously. (3) The coaxial gun injects plasma through the guide fields into the compression coil at its entrance end. (4) The rapidly rising compression field is applied and traps a portion of the injected plasma which possesses the appropriate ratio of transverse to axial energy. (5) Ideally, the compressed plasma particles spill out over the disappearing mirror of the spill coil I (at the exit end of the compression coil) as the compression field attains its maximum value. The transverse energy of this radially compressed plasma is adiabatically transformed into axial energy in spill coils I and II. The "spilled" plasma is then in the constant guide field awaiting analysis.

Experiments were performed with the coaxial plasma gun injecting into the axial magnetic field configuration in the absence of the main Scylla compression field. Neutron signals from the heavy-ice targets indicated that 10-keV deuterons were penetrating the 70-kG field of the spill coil. These particles must therefore possess and/or gain very little transverse energy as they traverse the system.

With the rapidly rising compression field applied to the injected plasma, the signals from the heavy-ice targets and from the ion and secondary emission detector are appreciably increased. Time of flight measurements give a mean deuteron energy of 17 keV. Extrapolation of the corresponding axial velocity backwards in time indicates that these deuterons left the main compression coil when the compression field was rising and had a value of approximately 0.5 B_{max}.

With the compression field, the ion and secondary emission detector signal is enhanced with the majority of the signal arriving at a later time than the deuteron velocities from the heavy-ice targets would predict. This discrepancy is explained by assuming that the ion and secondary emission detector is collecting mostly slow ions which do not make appreciable neutrons on the heavy-ice targets.

These preliminary results suggested the following changes in the apparatus: (1) Since the plasma does not appear to be spilling from the compression coil in the desired manner, the inside surface of the compression coil is being bored to a 5% taper, i.e., a conical surface. The magnetic field between the injection and spill coil ends of the compression coil should thus be decreased by 10%, so that (a) spilling of the plasma out the spill coil end should be aided and (b) the mirror ratio at the injected end should be increased and this should improve the initial trapping and reduce losses. (2) Since the ion and secondary emission collector gives an appreciable signal (~ 0.5 V) with a 3-mm collimated aperture, it appears feasible to replace it with either an energy or momentum analyzer. Because of its simplicity, a cylindrical electrostatic analyzer is being constructed, which should greatly facilitate the ion energy analysis.

SCYLLA I SPECTROSCOPY

The Zeeman effect measurement of the magnetic field breakthrough has not been successful with the present instrumentation. The failure of the experiment up to now can be attributed to a shortcoming in the two quartz-fluorite achromats which are the collimating and camera lenses of the spectrometer and are not capable of the 0.1 Å resolution (5μ spot size) required in this application. Computer calculations gives a minimum spot size of 50μ. Further, the wavelengths of achromatization are so far apart that in the vicinity of the C V line the effective focal length changes the permissible amount of 80μ (f/8 cone) in only 13 Å.

Lens prescriptions have been computed for the required resolution and achromatized for wavelengths only 16 Å apart, namely the C V wavelength and the strongest line of cadmium, which can serve for finding the best focus. New achromats having this prescription have been obtained. The spectrometer front end itself has been redesigned to permit fine focusing adjustment, along with other improvements.

Previous measurements of the Doppler broadening of x-ray spectral lines indicate a nonequilibrium nature of the ion energy distributions. The Doppler temperature of a trace of Ne X ions was found to be 8.4 keV. This compares with the previously established 1.3 keV (nuclear) Doppler temperature of the deuterons.

Using the Zeeman ultraviolet spectrometer, the broadening of the λ2271 C V line has also been measured. After a correction for the instrumental line width, the Doppler temperature of this line is found to be approximately 6.4 keV.

The three measurements are consistent with a model in which ion motion arises from a common true temperature of 0.5 keV and a common "turbulent" velocity of 2.8 x 10^7 cm/sec.

TRANSVERSE MAGNETIC FIELD INJECTION

Beam Splitting as an Injection Method

In the preceding quarterly report (LAMS-2682, p. 8) plans were mentioned for using the splitting of a plasma stream as it enters a transverse magnetic field to attempt to inject from the side of a mirror. The experiment involves a Pyrex T-tube as the vacuum vessel. One branch of the tube lies inside the mirror coils spaced by 25 cm as shown in Fig. 1. Plasma is injected from a coaxial gun through the Pyrex inlet tube.

Photographic observations have revealed that the injected plasma strikes the walls of the 8-in. inlet tube at positions marked A in Fig. 1. The fringing magnetic field is apparently too great in the inlet tube region to allow the plasma to split at such a position that it misses the corner at the junction of the limits of the T-tube. In order to reduce the fringing field in this region, two 1/2-in. thick copper shims were placed near the glass, as indicated in Fig. 1. With the shims in place, a portion of the plasma did travel past the corner and followed the field lines until they intersected the vacuum chamber. The plasma struck the walls where the field lines left the chamber (at points B in Fig. 1) forming luminous spots.

Magnetic probe measurements were made with the arrangement shown in Fig. 1; the pickup loops were oriented to pick up the axial components of ΔB

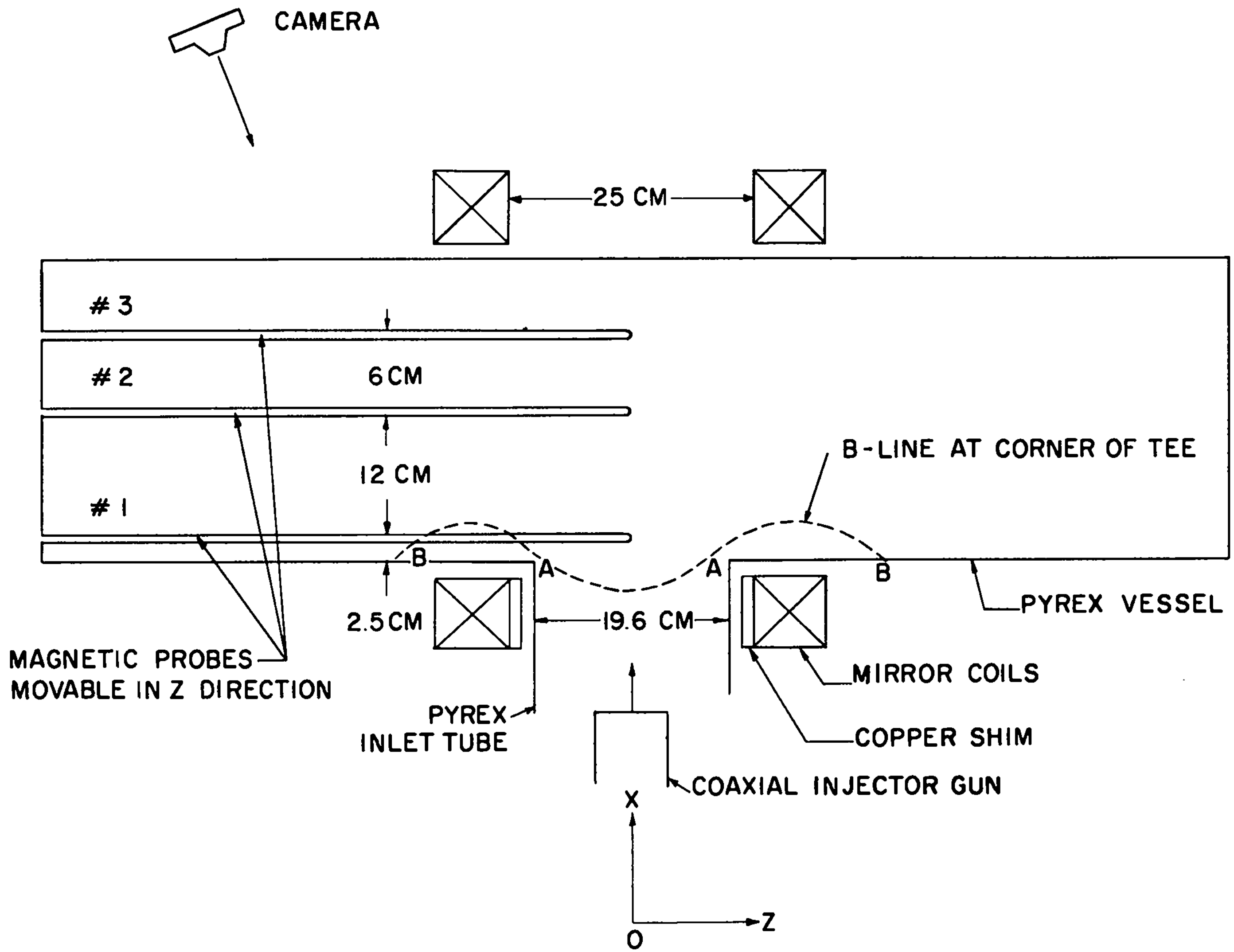

Fig. 1. Transverse Magnetic Field Injection

as the plasma entered the field. Probes 2 and 3 situated well into the field gave either small or no signals from shot to shot. The ΔB_z distribution obtained from probe 1 as it was moved axially across the mouth of the inlet tube is shown in Fig. 2. On the axis of the inlet tube ($z = 0$) the signals were single paramagnetic pulses ~ 5 μsec long. As the wall of the inlet tube was approached, the signals reversed sign, becoming diamagnetic. In the transition region ($z \sim 5$ cm), two pulses were often observed, the first paramagnetic and the second diamagnetic. A possible explanation of the field distribution is that the paramagnetic signal is due to a polarization current which appears as the plasma enters the applied transverse field and the reversed signals near the wall result from the discharge of the polarization at the wall. The wall evidently becomes a conductor under these conditions of plasma bombardment.

To examine the role played by the plasma striking the inlet tube walls and possibly producing conducting surfaces and preventing the plasma from penetrating the field, collimators were inserted in the inlet tube, with the copper shims removed. The collimator consisted of two mica discs having 2-in. diameter apertures. With these in place the signal on the inlet tube axis became diamagnetic, whereas the signals near the tube walls were nearly zero. In addition, the signals on the interior probes (2 and 3) increased, thus giving evidence of enhanced penetration.

All of the foregoing discussions concern injection with the plasma gun operating with a 400-μsec delay time between hammer and voltage triggers. For short delays (~ 140 μsec), the gun very often injects a jet of plasma (probably of lower density) which transverses the field and strikes the opposite wall of the vacuum chamber.

Experiments with Plasma Shorting Plates

Since it was not found possible to use the beam splitting as an injection method, the next step was to attempt to use the effect noted earlier (LAMS-2651, p. 10) of stopping a plasma by removing its polarization

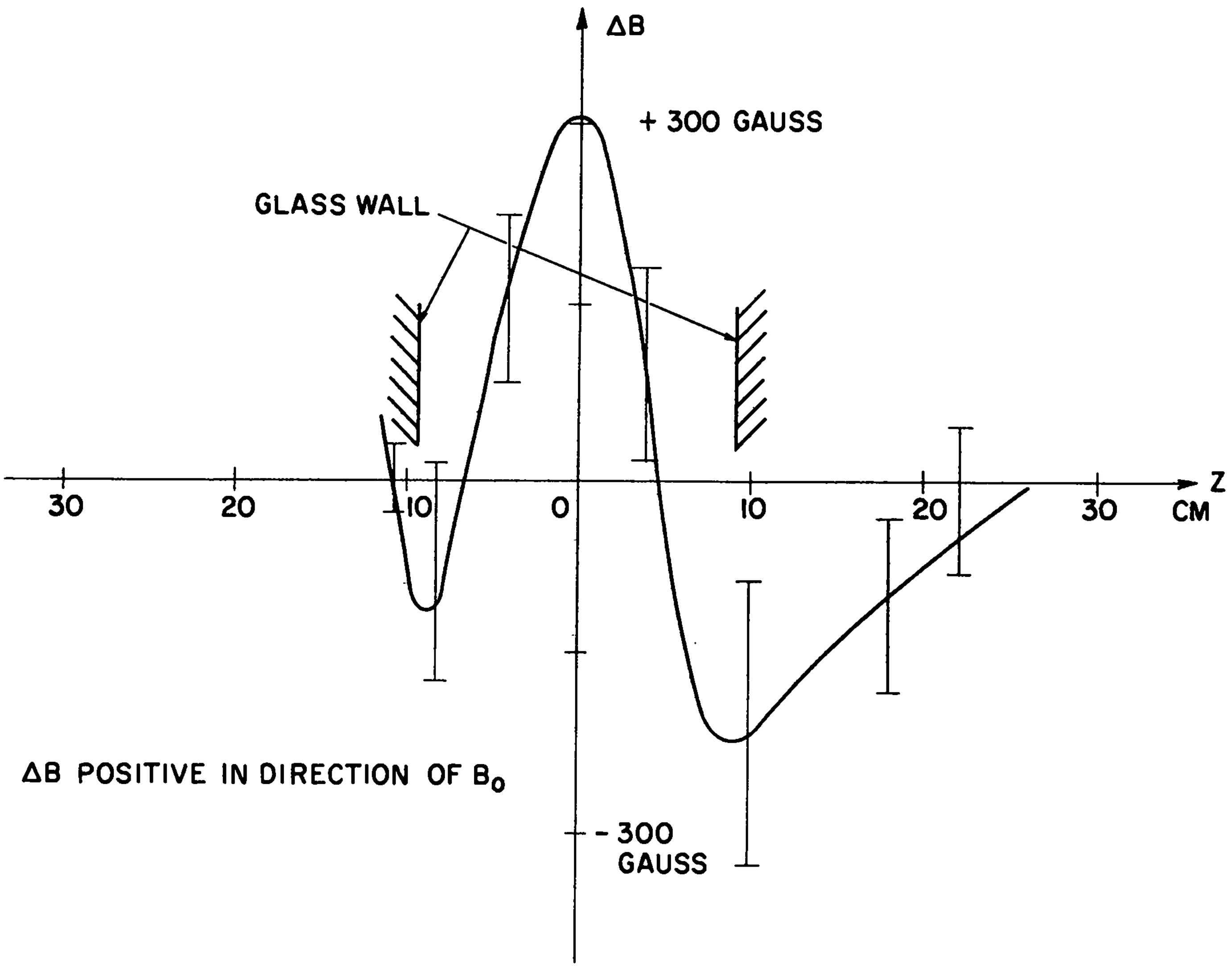

Fig. 2. ΔB_z Distribution Indicated by Magnetic Probes

electric field. A conducting shorting plate was placed perpendicular to the field lines just behind one of the mirrors of Fig. 1. It removes the polarization charge from the plasma in such a manner that current flows from the top of the plasma along the B-lines to the plate, then downward along the plate, and back to the bottom of the plasma stream. Five current pickup loops immediately behind the plate detect this current in the shorting plate. With the coaxial gun triggered 150 μsec after gas injection and the B-field at 9 kG, the current signals indicate a very short 1.5 kA spike of current with duration < 1 μsec at the time of peak gun current. This is followed by a long current signal 7-10 μsec later, persisting approximately 10 μsec. The latter current has a peak value of about 1.5 kA.

In a coordinate system with the plasma flow in the x-direction, and the B-field in the z-direction, the force due to the current flowing from the plasma into the shorting plate will be

$$F = I \times B \text{ per unit length in the y-direction,}$$

where I is the current in the shorting plate. Assuming that the impulse $F\,\Delta t$ is equal to the momentum flow of the plasma, then

$$F\,\Delta t = nmv_x . v_x\,\Delta t . \Delta z,$$

with Δz being the extent of the plasma in the z-direction; hence,

$$I = \frac{nmv^2\,\Delta z}{B} .$$

Thus the current is a measure of the kinetic energy density of the plasma stream. Using time of flight measurements, the velocity of the plasma stream has been found to be 5×10^6 cm/sec for the component that penetrates the B-field. With a typical measured plate current of 10^3 A and using the gun collimator diameter as the stream width, the density of the plasma stream is determined to be

$$n = \frac{I . B}{mv^2\,\Delta z} = 2 \times 10^{15} \text{ deuterons/cm}^3 .$$

This is very close to other determinations of the density of the plasma stream from the gun.

The five current loops were able to give a rough idea of the beam width in the y-direction and it was usual to find the largest signal on two adjacent probes 4-cm apart. These probes also indicated large changes in the position of the beam in its y-coordinate.

Data were taken with the plate placed both inside and outside the mirror in order to determine the effectiveness of a shorting plate outside a magnetic mirror. When the coaxial gun was operated with a short (150 μsec) delay after gas injection, the plate was as effective outside the mirror as it was inside. With the coaxial gun operating at 400 μsec delay (a lower velocity condition), the shorting current was roughly twice as great inside as it was outside the mirror.

These experiments indicate the possibility of using the shorting technique for transverse injection. However, the plasma from the present gun is of high density and sufficiently low temperature that it should escape in a few microseconds. The experiment will be repeated with a low-density, high-velocity gun, so that the plasma should be contained longer, if it becomes trapped.

ZEUS

An experiment was conducted to assess the voltage hold-off ability of the Zeus header and ignitrons when subjected to a high-voltage pulse similar to that which they will receive when attached to Scylla IV. It was shown that the ignitrons are unable to hold off the pulse and that satisfactory operation of Scylla IV will not be possible unless these ignitrons can be replaced. Steps have been taken to obtain better tubes.

SCYLLA IV

High-pot testing has been completed on 1300 load cables. Charge resistor and trigger assemblies have been delivered and installation has begun.

The evaluation of the 2-μF, 50 kV capacitors has continued. Both companies mentioned in the preceding report (LAMS-2682, p. 12) have improved their products, but neither has been able to produce 5000-shot units. Since these capacitors are needed urgently, it has been proposed to split the order equally between the two companies and to continue evaluation.

SPECIAL PROBLEMS

An improved single-capacitor ignitron header has been developed. The inductance of this header is approximately a factor of three lower than the model currently in use.

An evaluation of castor oil as a capacitor impregnant is being carried out. Reports from continental Europe and the United Kingdom indicate that castor oil impregnated capacitors have extremely long lives. It also appears that incipient failures can be detected easily and removed from service before a disastrous explosion occurs, and this eliminates the need for fusing.

PUBLICATIONS

"The Energy Storage System for a 3.5-Megajoule Magnetic Compression Experiment - Scylla IV," IRE Transactions on Nuclear Science, NS-9, 74 (1962).

"Trapping and Prolonged Confinement of an Energetic Deuterium Plasma in a Static Cusped Magnetic Field," Phys. Rev. Letters 8, 305 (1962).