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STABILITY, HEATING AND END LOSS OF A 3.5-MEGAJoule
THETA PINCH (SCYLLA IV)

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ABSTRACT

Experiments on stable, high-density, high-temperature, drift-free plasmas produced at initial deuterium filling pressures of 10 to 50 mtorr without bias magnetic fields (low-density regime), as well as at initial filling pressures of 50 to 125 mtorr with negative bias magnetic fields (high-density regime) have been reported. These measurements on the plasma generated by a "primary" capacitor bank of the Scylla-IV theta pinch (570-kJ at 50 kV with a 7.4- μ sec half period) included the following: Mach-Zehnder interferometer measurements of the plasma electron density, shape, stability, and end losses; x-ray absorption measurements of the electron temperature and impurity levels; neutron yields and collimation measurements of plasma length; shadowgraphs showing sharp plasma boundaries; and streak photographs showing gross plasma stability. In the low pressure regime without magnetic bias fields, characteristic plasma parameters are: density, 2 to 4 $\times 10^{16}$ cm⁻³; electron temperature, 300 eV; mean ion energies, 3 to 9 keV; plasma length, 80 cm; plasma volume, 60 cm³; and plasma impurities < 0.1%. Plasma end losses were found to be the predominant loss mechanism. We report here the extension of these measurements to the higher magnetic field and longer half-period provided by a 3-MJ, 20-kV "secondary" capacitor bank of Scylla IV. In this case the plasma containment is no longer limited by the duration of the applied field. The end loss proceeds as indicated by the loss rates measured in the earlier experiments, and all plasma disappears by ~ 17 μ sec. During this time no flute instability or appreciable drift of the plasma core are observed. Some effects, attributed to cold plasma diffusing in from the ends, are seen during the longer compression times. Closed, theta-pinches without end loss are discussed as a means of reaching the long containment times in which the eventual stability limitation can be tested.

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1. Introduction

The heating and confinement of plasma by rapidly-rising, longitudinal magnetic fields in theta pinches have been studied in many laboratories, and it has been established that dense, high-energy plasmas are produced in these devices. A review of the experiments through 1960 has been given by Quinn [1]. Two plasma regimes may be distinguished: the high-density regime of the early experiments, corresponding to deuterium filling pressures between ~ 70 and 250 mtorr, in which high ion energy and neutron emission occur only when magnetic field, directed oppositely to the compression field, is initially trapped in the plasma [1-6]; and a low-density regime, corresponding to filling pressures between ~ 5 and 50 mtorr, in which high ion energy and readily observable neutron production occur without trapped field [7-10]. The Scylla theta-pinch experiments pursued at Los Alamos are characterized by comparatively large (~ 1.1 kV/cm) induced, vacuum, azimuthal electrical fields at the inner surface of the discharge tube and typically produce plasma densities n of a few times 10^{16} cm $^{-3}$, electron temperatures T_e between 200 and 1300 eV, ion temperatures T_i (strictly, two-thirds of the mean, random ion energy) between 1000 and 9000 eV, and plasma diameters between approximately 1 and 3 cm.

A rotating flute instability in the high-pressure regime with two-fold azimuthal symmetry has been extensively investigated [2,4,11,12]. In the Los Alamos Scylla III experiment using coil lengths between 10 and 26 cm, the growth rate and amplitude of the instability were observed to decrease with increasing coil length (and decreasing average curvature of the magnetic lines). The possibility of obtaining greater plasma stability in its longer compression coil was a main reason for constructing the large Scylla IV theta pinch. Its basic properties have been reported by Jahoda *et al.* [6] and Little *et al.* [10]. We report here on an extension of its operation to longer periods and higher magnitudes of its magnetic field.

2. The Scylla IV Experiment

2.1 Apparatus

The Scylla IV apparatus consists basically of a 1-m compression coil of 10-cm inside diameter, driven by two capacitor banks. The primary bank is comprised of 50-kV capacitors with a total energy storage of 570 kJ and with sufficiently small inductance so that 82% of the energy is transferred to the compression coil. The secondary bank has a maximum of 3 MJ at 20 kV and consists of a portion of a large bank (the "Zeus" bank) constructed earlier for general-purpose energy storage [13]. The overall system has been described by Jahoda *et al.* [6] and by Putnam and Kemp [14]. In addition to these banks there is a 10-kJ, 40-kV preionization bank and a 280-kJ, 10-kV bank for

furnishing bias magnetic field. All four capacitor banks are indicated in the circuit diagram of Fig. 1. The sequence of operation is to fire the bias bank (if used), followed by the preionization bank whose 330 kc/sec oscillating magnetic field is allowed to decay. The "afterglow" of this discharge is nearly fully ionized and provides the initial plasma to which the field of the primary bank is applied. When used, the secondary bank is fired before the maximum of the first half cycle of the primary magnetic field. The half period of the primary bank alone is 7.4 μ sec, and that of the secondary bank is 52 μ sec.

2.2 Plasma Properties with the Primary Bank Alone

The basic features of the discharge in the high-density regime [6] are the following: The rotating flute instability is not observed to occur, and the plasma drift observed and discussed by Reynolds et al. [15] and by Hintz et al. [16] is absent, at least during the magnetic half period. The absence of drift is ascribed to the fact that a tapered and straight section separates the compression coil from the wider (4.6 m) parallel-plate transmission line which carries the current (10 MA) from the coaxial cables leading to the capacitors. The effect of the tapered and straight section is to reduce the bending of the field lines, convex to the feed slot of the coil. Neutron emission with yields per discharge as great as 2×10^9 was observed to correlate with bias field, as was the electron temperature. The plasma cylinder of length ~ 70 cm was observed optically to have a sharp boundary separating it from the magnetic field, as would be expected for a $\beta = 1$ plasma, having no internal magnetic field at peak compression. On the assumption of $\beta = 1$, the measurements of density, magnetic field, and electron temperature yield an ion temperature of 2.6 keV.

In the low-density regime the plasma has quite different properties [10]. The neutron yield with zero bias field is approximately 6×10^8 , almost independent of filling pressure. On the assumption that $\beta = 1$, the measurements yield ion temperatures increasing from 4 to 9 keV, as the deuterium filling pressure is decreased from 50 to 10 mtorr. The electron temperature remains approximately constant at 300 eV. This confirms the high ion temperatures (10 keV) and relatively low electron temperature (300 eV) found in the low-density theta pinch of Goldman et al. [8,9].

A comparison of the plasmas in the high- and low-density regimes is given by the interferograms of Fig. 2, taken from data of Jahoda et al. [6] and Little et al. [10]. These interferograms were made on separate discharges with a 2-m Mach-Zehnder interferometer spanning the discharge tube along its axis. In the high-density case (left-hand side) the cross section of the plasma is typically larger, and the fringes show distortions near the wall, corresponding to the influx of wall impurities. The low-density plasma shows no such wall impurity, since the fringes remain straight to the wall boundary. The relative absence of impurity in the low-pressure regime is borne out by measurements of the absolute intensity of the plasma soft x-rays [10] which show $< 0.1\%$ impurity, whereas the impurity level is typically a few percent in high-density Scylla experiments [1].

An important feature of the low-density discharge in Scylla IV is the rapid loss of plasma out the ends of the discharge. Interferometric measurements show the plasma diameter to decrease with time (as can be seen in Fig. 2) with an accompanying decrease of the total number of ions. The end-loss rate is greater after peak magnetic field than before. At 10-mtorr filling pressure the e-folding time of the decay of the number of ions is 5.9 μ sec before peak field and 2.4 μ sec afterwards. Analysis of the experimental data on the basis of a simple model of plasma leakage through end orifices yields an orifice radius equal to the Larmor radius of the plasma ions [10].

3. Operation of the Secondary Capacitor Bank

The secondary bank consists of twenty-one, 700- μ F modules of capacitors, each capable of furnishing approximately 1 MA of current to the one-meter compression coil when charged to its maximum energy of 1/7 MJ. The problem of switching these large currents has been discussed by Kemp and Quinn [17]. It was decided to use twenty-one of the multiple-electrode vacuum spark gaps shown in Fig. 3, each triggered by a stream of plasma fired through the triggering apertures in the plates from the washer-type plasma guns. In a test of the secondary bank alone, switched at 15 kV, the half period of the current was observed to be 52 μ sec, and the measured magnetic field in the compression coil was 121 kG. From the logarithmic decrement of the current wave, a bank resistance $R_s \approx 2.9 \times 10^{-4} \Omega$ was derived. The bolted, 4.6-m x 4.6-m parallel-plate transmission line (collector plate system) was found to suffer less than 0.02 mm of deflection over its whole area, except at the feed slot of the coil. There the deflection varies linearly with voltage and amounts to 0.96 mm at the full bank voltage of 20 kV, for the clamping arrangement presently in use (described by Jahoda et al [6]).

When both the primary and secondary banks of Fig. 1 are used in sequence, the switching problem is particularly severe. The primary bank voltage $V_p \approx 50$ kV is applied first, and nearly all of this voltage must be held off by the vacuum spark gaps. The optimum time at which to switch the secondary bank is when V_p has decreased to the value V_s to which the secondary bank is charged. This would provide an uninterrupted rise of the coil current in the absence of inductance in the secondary branch of the circuit. If the secondary bank is switched too early, it absorbs energy from the primary bank, causing the current in the compression coil to fall short of the nominal primary bank maximum. When the secondary bank is switched too late, it must supply current both to the compression coil and the primary bank, allowing a decrease in the compression coil current. If the secondary bank should fire when the primary bank is first switched, it removes a large fraction of V_p from the compression coil and spoils the initial implosion of the pinch.

The secondary-bank spark gaps were essentially identical with one which was used about 1000 times in the previous Scylla IV experiments [6,10] in order to short circuit the coil near the maximum of the current half wave of the primary bank. The central triggering apertures of the multiple electrodes had a diameter of 6.3 mm, and the gap was embedded in the collector plates. However, when the twenty-one spark gaps were connected with cables between the secondary bank and the collector plates, the additional voltage caused by doubling of the suddenly applied voltage wave V_p at the open cable ends caused the spark gaps to fire simultaneously with the application of the primary bank. Rather than making the extensive corrections required to eliminate this voltage doubling, the cure for this prefiring was provided inside the gaps. As shown in Fig. 3, the holes in the 4th and 8th plates were constricted to a diameter of 1.7 mm. It was then found that the spark gaps would stand the application of V_p without breaking down at their operating pressure of ~ 2 mtorr of argon. They could furthermore be fired at voltages less than 1 kV. It is planned later to modify the gap structure to eliminate the voltage doubling, thereby allowing all of the central apertures to retain their large diameters. In that case the spread of firing times (jitter) of the gaps should be smaller than at present.

In order to minimize the jitter in the firing of the spark gaps it was necessary to monitor the individual gap currents and to adjust their operating pressures individually. The pressures were adjusted such that the gaps did not fire appreciably before the time at which $V_s = V_p$. After this time 75% of the gaps fired within a total jitter of about 5 μ sec. Under these conditions the

decrease in coil current after the first maximum of the component from the primary bank is due to the inductance in the secondary branch of the circuit. This can be seen by comparing the observed waveform of Fig. 4(b) with the computed waveform of Fig. 4(c), in which all of the secondary spark gaps are approximated by a single switch with series inductance and resistance.

4. Plasma Experiments with both the Primary and Secondary Banks

4.1 Apparatus

The basic measurements were those of relative neutron emission rate and of plasma density and cross-sectional shape as functions of time. The density and shape measurements were made with a 2-m Mach-Zehnder interferometer, illuminated by a cooled, continuously-emitting ruby laser, as described by Little, et al [10]. Time-resolved interferograms were made with a 2.6×10^6 frame/sec, $f/4.0$, rotating-mirror framing camera [18], as well as a 3-frame, high-speed image converter. The framing camera allowed measurements to be made for 25 μ sec (56 frames) after initiation of the pinch. The measurements reported here were made in a mirrorless, 1-m coil at a deuterium filling pressure of approximately 15 mtorr.

4.2 Results

The fringe pattern of each interferogram yields $\int ndl$ as a function of fringe diameter d_i . Therefore the total number N of plasma electrons (ions), assuming a uniform plasma density, is closely approximated by $1.26 \times 10^{17} \sum_i d_i^2$, where the numerical coefficient is $\pi/4$ times the value of $\int ndl$ corresponding to one-half fringe [6]. Typical interferograms are given in Fig. 5 and corresponding graphs of the reduced data showing the fringe shifts vs distance across the discharge tube diameter are given in Fig. 6. These are typical of many discharges in which fairly good simultaneity of firing the vacuum spark gaps was obtained. Graphs of the total number N of plasma electrons vs time are given in Fig. 7. The time variation of N for the central core of plasma is typified by a steady decrease with a characteristic (e-folding) time of $\sim 2 \mu$ sec. A thin core of plasma is retained for longer times and disappears completely (within experimental error) approximately 17 μ sec after initiation of the pinch. At later times there is a distortion of the fringes outside the central region, corresponding to motion of new plasma outside the original core. The plasma core does not show the interchange instability seen in earlier Scylla experiments with short compression coils [2, 12]; nor does it drift appreciably during its 17 μ sec of existence.

The neutron emission shows an initial rise, as in the experiments with the primary bank alone [10], and decays to a low level before the end of the first relative maximum of the current, as shown in Fig. 4(a) and (b). This correlates with the rapid decrease of N . Both phenomena are attributed to end loss.

5. Discussion and Conclusions

5.1 Plasma End Loss

The rapid loss of plasma observed in these experiments bears out the earlier measurements of rate of end loss made in experiments with the primary bank alone [10]. The plasma essentially disappears by the middle of the second half cycle of the primary component of the coil current. At these longer compression times the interferograms also show the possible effects of cold plasma entering the coil from its ends. This is the interpretation given to the distorted outer fringes at later times in Fig. 5, since the compression time approaches the time for plasma at the preionizer temperature to diffuse into the active coil region. The plasma has more wall contaminant than in

the experiments with the primary bank alone, as can be seen by the distortion of fringes near the wall at early times (in contrast to Fig. 2). This is probably because discharges with the large system are much less frequent than those with the primary bank alone, where discharge cleaning is more effective.

5.2 Possible Closed Systems

There is now considerable evidence that the basic limitation on plasma containment in straight compression coils of the Scylla IV theta pinch is end loss, rather than drift or flute instability, at least for the low density regime. These plasmas do not have the excessive, wall-derived impurity found when the high-voltage Scylla experiments are operated in the high-density regime, and their ion energies are considerably higher. It can be inferred from the scaling of ion energy with plasma parameters [19] that the ion energy in the low-density regime would be increased by decreasing the gas filling pressure or increasing the pinch voltage. It appears, therefore, that low-density theta pinches can provide a means of extending the high-temperature plasma studies.

Clearly, a closed system will be required to determine the limit of the confinement times in which the eventual instability limitation can be tested. (A toroidal system would also eliminate the colder plasma outside the ends of the present linear systems). Consequently, investigations are presently underway [20] to determine the feasibility of constructing a toroidal theta pinch. In the systems under consideration gross equilibrium and interchange stabilization would be provided by spatially-alternating, multipole magnetic fields, superimposed on the basic toroidal compression field, using principles similar to these proposed by Furth and Rosenbluth [21].

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Fig. 1. Schematic circuit diagram of the Scylla IV theta pinch. The inductances are given in nanohenries (10^{-9} H).

$P=70\text{mtorr}, B_0=5.0\text{kG}$

$\Delta t = 1.6\mu\text{sec}$

3.2

$P=25\text{mtorr}, B_0=0$

2.4

4.9

Fig. 2. Interferograms of the Scylla IV plasma in a 1-m, mirrorless coil excited by the primary bank alone. The data on the left represent the high-density regime, and those on the right the low-density regime. B_0 is the bias magnetic field, applied before the theta pinch is formed and Δt is the time lapse after application of the primary bank.

Fig. 3. Diagram of one of the twenty-one vacuum spark gaps, used to switch the secondary bank of Scylla IV.

Fig. 4. Waveforms of the compression coil current and the neutron emission when both the primary and secondary banks are used. (a) Coil current waveform (upper trace) with $V_p = 48$ kV and $V_s = 15$ kV, and the neutron signal (lower trace) from a plastic scintillator. Total neutron yield: 2.6×10^8 . Time scale: $2 \mu\text{sec/div}$. (b) Same signals as (a) on a time scale of $5 \mu\text{sec/div}$. (c) Computed compression coil current waveform using the indicated circuit parameters of Fig. 1, the voltages of (a) and switching the secondary bank into the coil when $V_s = V_p$. Time scale: $5 \mu\text{sec/div}$. Vertical scale: 5.1 MA/div .

$\Delta t = 0.4 \mu\text{sec}$

3.8

5.9

7.1

9.7

16.8

Fig. 5. Interferograms of the Scylla IV discharge corresponding to the current waveform of Fig. 4 with an initial deuterium pressure of 15 mtorr. A few of the 56 photographs taken by the framing camera are shown for illustration and identified by the time Δt after application of the primary bank. Exposure time per frame: $0.42 \mu\text{sec}$.

Fig. 6. Graphs of the reduced data of Fig. 5, showing the fringe shifts produced by the plasma vs the discharge tube diameter and identified by the time Δt after application of the primary bank.

Fig. 7. Total number of plasma electrons vs time for four typical discharges of the primary and secondary banks of Scylla IV. The different symbols correspond to interferometric data obtained on separate discharges. The solid triangular symbols correspond to the current waveform of Fig. 4(a) and (b), the interferograms of Fig. 5 and the reduced data of Fig. 6.