Conf-761012-14

LA-UR-76-1843

TITLE: PLASMA EXPERIMENTS ON THE STAGED THETA PINCH, THE IMPLOSION HEATING EXPERIMENT, AND SCYLLAC FEEDBACK-SECTOR EXPERIMENT

AUTHOR(S): R.R.Bartsch, C.J.Buchenauer, E.L.Cantrell, J.N.Downing, B.L.Freeman, K.B. Freese, R.F. Gribble, I. Henins, F.C.Jahoda, T.R.Jarboe, R. Kristal, G. Miller, W. E. Quinn, F. L. Ribe, A.R.Sherwood, R.E.Siemon, K.S.Thomas

SUBMITTED TO: To be presented by F.L.Ribe at the Sixth IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, FRG October 6-13, 1976.

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

MASTER

Form No. 836
St. No. 2629
1/75

UNITED STATES
ENERGY RESEARCH AND
DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

IAEA-CN-35/E-10

PLASMA EXPERIMENTS ON THE STAGED THETA PINCH, THE IMPLOSION HEATING EXPERIMENT, AND SCYLLAC FEEDBACK-SECTOR EXPERIMENT*

by

R. R. Bartsch, C. J. Buchenauer, E. L. Cantrell, J. N. Downing, B. L. Freeman, K. B. Freese, R. F. Gribble, I. Henins, A. R. Jacobson, F. C. Jahoda, T. R. Jarboe, R. Kristal, G. Miller, W. E. Quinn, F. L. Ribe, A. R. Sherwood, R. E. Siemon and K. S. Thomas

University of California, Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

This paper summarizes results of the Los Alamos theta-pinch program in three areas of investigation. (1) In the Staged Theta Pinch results are reported on the effects of magnetic field amplitude and time history of plasma formation. (2) In the Implosion Heating Experiment density, internal-magnetic-field and neutron measurements yield a consistent picture of the implosion which agrees with kinetic computations and with a simple dynamic model of the ions and magnetic piston. (3) In the Scyllac Feedback-Sector Experiment the $\ell = 1,0$ equilibrium plasma parameters have been adjusted to accommodate the feedback stabilization system. With a uniform toroidal discharge tube the $m = 1$ instability is feedback-stabilized in the vertical direction, and confinement in the toroidal direction is extended by feedback control. We also report results with a helical discharge tube.

*Work performed under the auspices of the U. S. Energy Research and Development Administration.

PLASMA EXPERIMENTS ON THE STAGED THETA PINCH, THE IMPLOSION HEATING EXPERIMENT, AND SCYLLAC FEEDBACK-SECTOR EXPERIMENT

R. R. Bartsch, C. J. Buchenauer, E. L. Cantrell, J. N. Downing, B. L. Freeman, K. B. Freese, R. F. Gribble, I. Henins, A. R. Jacobson, F. C. Jahoda, T. R. Jarboe, R. Kristal, G. Miller, W. E. Quinn, F. L. Ribe, A. R. Sherwood
R. E. Siemon and K. S. Thomas
University of California, Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

1. THE STAGED THETA-PINCH EXPERIMENT

1.1 Introduction. The Staged Theta Pinch (STP) is a 4.5-m-long, 22-cm-bore theta pinch designed to study the physics and technological problems associated with using separate capacitor banks for shock heating and adiabatic compression. Energy is fed to the shock-compression coil from two collector plates. Each plate is connected to half of the two high-voltage (125 kV) and one low-voltage (40 kV) capacitor banks. The STP uses one of the low-energy (47 kJ), high-voltage capacitor banks (PFN I) to produce the plasma and the lower-voltage, higher-energy (500 kJ) capacitor bank to provide a variable amount of adiabatic compression. A second low-energy (94 kJ), high-voltage capacitor bank (PFN II) is available to shape the implosion magnetic field and/or to assist in containing the plasma before it contacts the wall of the discharge chamber. A more complete description of the experiment may be found elsewhere [1,2].

1.2 Results of Plasma Studies to Date: Plasma columns with ratios (a/b_t) of plasma radius to discharge tube radius of approximately 0.5 and plasma density outside the main column less than 2% of the maximum column density can be produced at 5 to 10 mtorr initial D_2 fill at a PFN I voltage of 75 kV. At 100 kV on PFN I, plasma columns with the same properties can be produced at 7 and 10 mtorr initial D_2 fill. The 100-kV, 7-mtorr case is illustrated in Fig. 1, which shows the plasma density profile at four times during the plasma discharge, along with the magnetic field waveform. At 5 mtorr which has given the maximum T_i to date (T_i > 1000 eV), the results are not quite as favorable. Although a well-defined plasma column is formed which has a profile which decreases in a smooth monotonic fashion to the wall, plasma density near the wall is 5-10% of the peak column density. Plasmas with a/b_t of 0.5 (at the 1/e point in the density profile) would be capable of providing wall stabilization [3] in the proposed Staged-Scyllac Experiment [4].

Figure 2 shows the magnetic-field waveform, a holographic interferogram, and the reduced data from the interferogram for two cases. Figure 2(a) is for a "step-function" waveform where no flux leaves the discharge tube. In

Fig. 2(b) the dip in the magnetic field causes flux to move outward. This flux carries low-density plasma into the wall creating additional plasma. In the field-programming mode of operation of Fig. 2(b) the magnetic field is reduced while the plasma is re-expanding after the initial implosion. Theoretical studies [5] predict that this mode of operation should lead to fatter, hotter plasma columns. The data in Fig. 2 show a 15% increase in plasma area for the "field programming" case. Data at 100-kV PFN voltage and 10-mtorr fill, where the plasma implosion and magnetic field waveform are more nearly in "resonance", show a 25-30% increase in plasma area, and consequently in plasma temperature. However, for the preionization levels (~60%) obtained in the STP, additional plasma is generated outside the main plasma column.

2. THE IMPLOSION HEATING EXPERIMENT (IHX)

In the IHX, an approximate step function of magnetic field is applied to a cylinder of approximately 70% preionized plasma which is 100-cm long and has a radius r_o of 20 cm. The circuit used for the implosion phase and the methods of preionization is described elsewhere [1,6]. In IHX the plasma-laden coil provides a large fraction of the circuit impedance, and therefore the current shape is strongly dependent on the initial fill density. The data presented here were taken with 120 kV on each of the four pulse-forming networks (PFNs) at the initiation of the implosion. With this voltage, 8.2-mtorr filling pressure gives a fairly constant magnetic field during most of the implosion (cf. Fig. 3). Ion energies of 1.6 keV are obtained, and E_θ at the wall during the implosion is 1.3 kV/cm.

The data of IHX are in good agreement with the numerical calculations of Sgro et al. [7] and Hamasaki and Krall [8] and with the simple "bounce" model [5] where the ions are elastically reflected by the current sheath at twice its speed. An important conclusion from the present experiment is that implosion heating can be indeed described by this simple model.

Figure 4 shows density data taken continuously at ten different radial positions using a four-beam Mach Zender interferometer, averaged over four discharges. The circles show the 2 v_s position where v_s is the velocity of the sheath. In a simple bounce model this position would be the maximum and the front edge of the density. In the experiment the finite risetime of B_z causes a velocity spread which tends to smooth and to lower this peak. In the simple bounce model $v_s = B_z/[4\mu_o m_i n_o]^{1/2} = 2.3 \times 10^7$ cm/sec, where n_o is the fill density. This is 5% to 10% higher than observed. The expected density jump is 2 n_o, and in the data from 200 nsec to 500 nsec the jump is within 25% of this value. The density behind the sheath is lower by more than an order of magnitude than the initial fill density. Measurements with probes show the magnetic field taking several centimeters to rise to its wall value. However Faraday-rotation measurements [9] show that the field rises over about the same distance as that of the density decrease, i.e., about 1 cm. In the simple model the minimum radius of the sheath is $r_o/3 = 6.7$ cm. In IHX the minimum occurs between 700 and 750 nsec and has a value of about 7 cm. The velocity and density of the density expansion are also consistent with its being pushed by 2 v_s ions. The neutron production and the value of $\int n^2 d^3r$ are shown in Fig. 3. By using the expression for the D-D cross-section given by Greene [10] and assuming a mono-energetic, isotropic, two-dimensional velocity distribution, these data yield an ion speed of 3.9×10^7 cm/sec. This is within 10% of 2 v_s. In conclusion, the simple bounce model describes the implosion phase of IHX quite well. In addition remarkably good agreement is obtained with much more detailed particle simulation calculations.

3. EXPERIMENTS ON 8-m SCYLLAC FEEDBACK-SECTOR EXPERIMENT

3.1 Previous Experiments. At the Tokyo IAEA Conference experiments were reported on the Scyllac full torus [11] and 8-m sector [12] with a compression field of 40 kG. The plasma behavior showed good agreement with sharp-boundary theory of the $\ell = 1,0$ helical equilibrium and the $m = 1$ growth rate ($\gamma \approx 0.7$ MHz), which was too large to be compatible with the delay time ($\tau \approx 1.5$ μsec) of the feedback stabilization amplifiers. Following these experiments the 8-m sector (major radius R = 4.0 m) was modified as follows: the $\ell = 1,0$ wavelength was increased from 41.9 to 62.8 cm; the compression field reduced from 40 kG to 17 kG; beta decreased from 0.8 to 0.65; and δ_1 increased from 0.7 to 1.4 [13]. This resulted in the expected decrease in growth rate to 0.3 MHz [14,15] and an acceptable value of $\gamma\tau = 0.4$. It was also found that the toroidal equilibrium is affected by initial $\ell = 1$ oscillations of the plasma helix (period = 3 μsec) and especially $\ell = 0$ longitudinal oscillations of plasma between the periodic-mirror maxima and minima (period = 10 μsec), leading to plasma motions in the toroidal plane which are difficult to stabilize. It was also shown that $\ell = 2$ feedback fields are preferable to $\ell = 0$ fields.

Here we report plasma stabilization experiments in the 8.4-m Feedback Sector Experiment consisting of five 1.7-m compression coils having $\ell = 1,0$ internal surfaces with (1) a uniform toroidal quartz discharge tube, and (2) a helical tube. In both cases the equilibrium is characterized by $\delta_1 = 1.4$, $\delta_0 = 0.2$, $T_i \approx 120$ eV, $T_e \approx 120$ eV, $\beta = 0.6$-0.7 and $n = 2$-4×10^{16} cm^{-3}. The feedback stabilization system is described in Refs. [15] and [16].

3.2 Results with Closed-Loop Feedback Stabilization in a Uniform Toroidal Discharge Tube. Initial experiments with the closed-loop feedback system showed successful stabilization of the $m = 1$ instability in the vertical plane perpendicular to the plane of the torus, as shown in Fig. 5. The $m = 1$ motion in the horizontal plane of the torus was dominated by loss of equilibrium and was not controllable by feedback. Derivation of the net force on the plasma column in the horizontal plane from the observed accelerations of the plasma trajectories shows that the equilibrium loss results from transient effects in setting up the equilibrium plasma displacements δ_0 and δ_1, particularly oscillations of δ_0. Experiments were next performed with $\ell = 2$ fields of 4-8 μsec duration and 30-60 G amplitude applied to the plasma during the preionization phase. This resulted in improvements in the plasma equilibrium and confinement as shown in the upper streak photographs of Fig. 6, where the compressed plasma column remained nearer the axis of the discharge tube. Under these conditions the $m = 1$ instability was feedback-stabilized during the main discharge in the vertical plane and plasma confinement in the horizontal plane was extended by feedback control as shown in the lower streak photographs of Fig. 6. This resulted in plasma confinement times of 25 μsec. The lower plots of Fig. 6 show the average of the feedback output currents and the plasma trajectories obtained from the five plasma position detector stations approximately equally spaced around the sector. The streak photographs of Fig. 6 also show: initial δ_1 helical oscillations which damp; the helical plasma distortion δ_1 which is proportional to the separation of the dual plasma trajectories taken one-half helical wavelength apart; the bumpy plasma distortion δ_0, which is proportional to the difference in the plasma diameters in the horizontal plane; and the unstable $m = 1$ motion terminating the plasma confinement.

3.3 Results With a Helical Toroidal Discharge Tube. A helically-shaped quartz discharge tube (helical displacement = 1.4 cm) was fabricated and installed in the $\ell = 1,0$ equilibrium coil configuration. An additional slow-rising, capacitor-driven $\ell = 2$ field (10-30 G), which can be nulled during the main implosion by a fast "notch" circuit, is used for fine adjustment of the plasma equilibrium. The streak photographs of Fig. 7 show the plasma column imploding to the equilibrium helical axis and the elimination of the δ_1, helical plasma oscillations observed previously (Fig. 6). The slower δ_0 axial oscillation remains and appears in the horizontal-plane streak photographs as a time variation of the plasma diameter and the slow inward-outward oscillation. The small $\ell = 2$ equilibrium trimming field improves the plasma confinement (lower streak photograph of Fig. 7) which is terminated by an $m = 1$ motion in the vertical plane. Feedback stabilization experiments on the plasma in the helical discharge tube will be reported.

REFERENCES

[1] GRIBBLE, R. F., et al., in Plasma Physics and Controlled Nuclear Fusion Research 1974, (Fifth Conf. Proc. Tokyo) IAEA, Vienna 3 (1975) 13.

[2] LINFORD, R. K., et al. To be published.

[3] BERGE, G. and FREIDBERG, J. P., Phys. Fluids 18, 1362 (1975).

[4] RIBE, F. L., Compiler, Los Alamos Scientific Laboratory Report, LA-5026-P (1972).

[5] FREIDBERG, J. P., MORSE, R. L., RIBE, F. L., in Technology of Contr. Therm. Fus. Experiments and the Engineering Aspects of Fusion Reactors, (Conf. Proc. Austin, Texas) USAEC Tech. Ref. Center. Conf. -721111 (1974) 812.

[6] HENINS, I., et al., Proc. of the Third Topical Conference on Pulsed, High-Beta Plasmas, Culham, England, 1975. Plasma Physics (1976).

[7] SGRO, A. G., and NIELSON, C. W., Phys. Fluids 19, 126 (1976).

[8] HAMASAKI, S., and KRALL, N. A., Phys. Fluids (1976). To be published.

[9] JARBOE, T. R. To be published.

[10] GREENE, S. L., Jr., University of California Radiation Laboratory Report UCRL 70522 (May 1967).

[11] CANTRELL, E. L., et al., Plasma Physics and Controlled Nuclear Fusion Research 1974, (Fifth Conf. Proc. Tokyo) IAEA, Vienna 3 (1975) 13.

[12] ELLIS, W. R., et al., Nucl. Fusion 14 (1974) 841.

[13] CANTRELL, E. L., et al., Proc. of the Third Topical Conference on Pulsed, High-Beta Plasmas, Culham, England, 1975. Plasma Physics (1976).

[14] FREESE, K. B., et al., Ibid.

[15] CANTRELL, E. L., et al., Seventh European Conf. on Controlled Fusion and Plasma Physics, Lausanne, 1975. Ecole Poly. Fed. de Lausanne (1976) p. 48.

[16] KUTAC, K. J., et al., Proc. Symposium on Engineering Problems of Fusion Research, San Diego, 1975. IEEE Publication No. 75 CH 1097-5-NPS (1976) p. 705.