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Plasma Compression by Explosively Produced Magnetic Fields*

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ABSTRACT

Early attempts to apply multi-megagauss fields obtained by cylindrical explosive compression to plasma compression are reported. Two approaches are discussed. In the first method, a slotted liner is used, so that the initial field may be applied rapidly and plasma is produced by a fast θ -pinch, prior to implosion. This method has the advantage that the initial plasma may be made quite hot, i. e. , 200-800 ev, but has the disadvantage of requiring a cylindrical insulator, such as Pyrex, to hold the vacuum, thereby limiting the effective implosion field to the range of $1/2$ to 1 megagauss. In the second method, an unslotted resistive cylinder is used to hold the vacuum, thereby allowing the implosion fields to reach measured values as high as 4 megagauss. Here, the initial magnetic field diffuses through the cylinder so that the initial plasma is heated by a slow θ -pinch with the disadvantage that the initial temperatures have been low, about 5-15 ev. Implosion shots have resulted in very small ($<10^4$) neutron yields for the first method, and zero yields for the second method. Hitherto the first method has been hindered by field asymmetries and by marginally low fields. A review of results and improvements to date is presented, and future plans are indicated.

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PLASMA COMPRESSION BY EXPLOSIVELY PRODUCED MAGNETIC FIELDS

I. Introduction

The achievement¹ of megagauss magnetic fields by explosive compression, together with the early success of the Los Alamos^{2, 3, 4} θ -pinch experiments, led to an effort at Los Alamos to study the properties of hot deuterium plasma compressed by very high axial magnetic fields. This effort began⁵ in 1960 and has been continued on a modest scale since that time.

The first approach has involved the use of a slotted aluminum liner as the implosion chamber. A Pyrex discharge tube is placed inside the liner. Deuterium gas is flowed through the discharge tube and some appropriate form of pre-heating is applied to the gas. The initial magnetic field is applied rapidly through the slotted liner so that a hot neutron-producing plasma is created by a fast θ -pinch. A cylindrical explosive charge placed around the slotted liner is timed to close the slot and implode the liner near the first peak of the initial field cycle with the result that the magnetic field is increased from an initial value of about 50 kilogauss to a final effective value of 1/2 to 1 megagauss in about 6 μ sec. A number of implosion shots of this nature have been fired in an effort to observe the effect of the increasing implosion field on the initial hot plasma. In the first series of shots reported⁶ two years ago, very little increase in neutron yield

was observed due to the implosion field. Extensive laboratory tests have shown that the initial plasma has not been satisfactorily contained, most likely due to marginally low E_θ fields from the condenser bank available at the firing point, and to field asymmetries characteristic of the end-fed coil originally used with the implosion system.

The slotted liner fast θ -pinch system is limited in ultimate magnetic field that can be applied to the plasma. The volume occupied by the Pyrex vacuum chamber, under implosion, limits the peak fields to about 1 megagauss or less in the currently available systems. However, with use of an unslotted resistive cylinder^{7,8,9} for the implosion system, which also can serve as the vacuum chamber, measured fields of four megagauss, have been achieved. Since the initial field must diffuse through the resistive liner, the initial plasma condition that one can achieve with this kind of system will be more characteristic of a slow θ -pinch. With the condenser bank currently available at the firing point, initial fields of about 25 kG with rise times of 20-25 μ sec have been used. The resulting initial plasma has been characterized by good containment and good percentage ionization, but limited in temperature, the highest measured value to date being about 12 eV. Though no neutrons have been observed on any of the preliminary plasma implosion shots fired so far with this system, it does look quite promising as a general long-range approach.

The following sections will include a discussion of both the slotted

liner and unslotted resistive liner implosion systems, the basic results obtained to date with both the fast and slow θ -pinches, and the prospects for the immediate future with each method.

II. Megagauss Fields by Explosive Cylindrical Implosion

A wide variety of implosion systems has been developed at Los Alamos including both those involving slotted liners^{1, 7} and unslotted resistive liners,^{7, 8} both systems giving peak measured magnetic field values most generally in the range of 1/2 to ten megagauss, depending on the design.

A. Slotted Liner Systems

The most straightforward type of slotted liner for plasma applications has been a one-turn, thin-walled cylinder with an insulated tangential slot. The continuous cylinder of HE needed around the outside of the coil for good implosion has required that the coil be end-fed. The energy source condenser bank discharges directly through the liner by means of cable tabs at the ends.

These systems have worked quite well during implosion, and Fig. 1 shows plots of field versus time for an implosion probe shot. The tangentially slotted dural liner was 10.5 inches long, and has an i. d. of 2.69 inches and a wall thickness of 0.125 inches. To better simulate plasma shot conditions, a 2 mm wall glass tube was placed inside the liner. The cylindrical charge was 7 inches long. The initial central field was about 40 kG, and the implosion field at probe destruction (probe diameter about 8 mm) was somewhat over 400 kG. A

characteristic of these end-fed coils is the occurrence of a natural magnetic mirror. It can be seen from this figure that a mirror ratio greater than one was maintained throughout the implosion. Such mirror fields have generally been useful or necessary in the early² fast θ -pinches.

The end-fed coil was extensively probed electrically to establish the initial magnetic field distribution. Axial field (B_z) probes were used to determine the mirror ratio and basic circuit characteristics.

B_θ probes were used to determine the tangential fields originating from the end current feed. Figure 2 shows plots of B_θ (normalized to the central axial field) as a function of the angle, θ , measured from the liner slot. It can be seen that for this system, used for all the fast θ -pinch explosive shots fired so far,⁶ the asymmetries are quite large near the liner slot.

Since asymmetries of this magnitude are believed to cause gross plasma drifts, an effort was made to reduce the B_θ fields. The system that evolved consists of two concentric slotted liners properly insulated and fed inductively at the ends by a closely-coupled coil pair. The slots of each liner are placed about 180° from each other so that each liner tends to shield out the effects of B_θ fields due to axial currents which flow along the slot of the other coil. The use of the coil-pair inductive feed in place of the axial feed tabs of the earlier single-liner coil, reduces the effect of axial currents at the ends. The flux concentrator action of the double slotted liner results in a nearly

constant axial field along the entire z axis for this compensated double liner end-fed coil. It can be seen that the B_{θ} asymmetries have been reduced by an order of magnitude or more making this coil system much more suitable for future plasma implosion shots.

A primary limitation of insulated slotted liners for plasma applications is the need of a separate, non-conducting vacuum chamber. Even when thin wall (1 mm) Pyrex is used for the chamber, the volume of the glass is quite appreciable as the liner is imploded around it. The final effective field is limited to the value existing at the point for which the discharge tube occupies all the volume inside the liner, thus leaving no room for plasma. For initial fields of 50 kG, an upper limit of around one megagauss is placed on effective implosion fields for the past⁶ and presently planned slotted liner geometries.

B. Resistive Liner Systems

The resistive liner system presently in use has gradually evolved to that shown in Fig. 3. The inner unslotted liner shown on Fig. 3 is approximately 4 inches in diameter, is made of a 0.030 inch wall titanium alloy (Ti-6Al-4V), and also will serve as the plasma chamber. This alloy is approximately twice as resistive as 18-8 stainless steel and has a density of about 4.5 gm/cm³. An alternate design was a tapered wall about 0.030 inch thick at the ends and 0.040 inch thick in the center. The total span of the tapered section is 5 inches. The tapered wall serves to produce a magnetic mirror both in the initial field, because of the

greater diffusion time, and in the implosion phase, because the thicker central section eventually lags the thinner sections during implosion.

The assembly is completed by two external concentric, tangentially-slotted thin aluminum liners (wall thickness, 0.055 inch) as seen in Fig. 3, and heavy brass single-turn drive coils at the ends of the assembly, which are connected to the main energy source condenser bank (1430 μ F, 20 kV). Mylar sheets 0.006 inch thick, serve to insulate the concentric cylinders from each other and the drive coils and, also, serve as insulation in the slots of the dural liners. The dural liners serve to concentrate the flux inside the entire liner assembly, more than doubling the central field obtained within the liners and at the same time greatly reducing the undesirably large fields that would normally be under the feed coils.

The explosive system finally used also has some innovations. The basic cylindrical lens consists of two hemicylindrical halves. Separate hemicylindrical inner charges whose outer diameters mate with the fixed lens inner diameter complete the assembly. The inner charge inside diameters are cut to size for the particular liner system in question. This also allows for use of different types of explosive. It was discovered earlier that the presence of the radial inner-charge junctions produced severe jetting through thin-walled liners (≤ 0.040 inch). This problem was finally solved by angling the inner charge surfaces such that the junction planes intersected the liner surface

approximately 30° from normal, and by applying a quick drying glue between these surfaces. K. J. Ewing of our explosives fabrication group, was largely responsible for these improvements. Framing camera photographs show that jetting is absent with this explosive configuration. Although past experience has shown that this technique is not necessary for thicker liners, we will use this technique in the future for all untested systems that have thin liners, even when bolstered by additional liners as in Fig. 3. Figure 4 shows typical framing camera pictures of an implosion which produced jetting, and an implosion using all the improvements to prevent jetting.

Figure 5 shows the plot of central magnetic field buildup versus time measured for the implosion shot with the setup of Fig. 3. The initial field rises from 0 to 22.5 kG in $19.5 \mu\text{sec}$. A peak field of about 4 MG was obtained at probe destruction $10.5 \mu\text{sec}$ later. A subsequent double-probe shot with a tapered liner showed that a mirror field at least 20% greater than the central field persisted through the implosion up to the peak fields of somewhat over 3 MG.

The system of Figs. 3 and 5 takes full advantage of the maximum magnetic fields available from cylindrical implosions for θ -pinch applications by using the continuous resistive liner, instead of Pyrex, for the vacuum chamber. This system obtained as rapid as possible a rise time of the initial field, such rapid rise being necessary for θ -pinch pre-heating. This system, with and without tapered liners to

produce mirrors, is the best so far available for the purpose of studying the θ -pinch in the multi-megagauss region.

III. Fast θ -Pinch Studies and Implosions

Early experiments¹⁰ at Los Alamos indicated that if an axial magnetic field was applied to an independently preheated plasma, then radial compression and adiabatic heating of the stable plasma would result. Then results of the Scylla fast θ -pinch experiments^{2, 3, 4} demonstrated that very hot ($T \approx 1$ keV) deuterium plasma could be produced by fast-rising axial magnetic fields and contained sufficiently long ($> 1 \mu\text{sec}$) to produce substantial neutron yields of thermonuclear origin.

The implosion experiments represent an effort to obtain a neutron-producing θ -pinch ($T \approx 500$ eV) contained by a 55 kG field as an initial condition in an end-fed slotted liner and to implode the system to increase the field to about 1 MG. If good containment and ideal adiabatic compression of the plasma followed, neutron yields of the order of 10^9 to 10^{11} should be observed with deuterium.

Figure 6 shows idealized calculations for a wide range of plasma conditions, and includes the parameters of these experiments. The calculations assume, $\beta = 1$, an ideal gas, $\gamma = 5/3$, and no losses. Neutron emission rates are shown by the dotted regions. For the implosion systems of IIA, realistic estimates for the final plasma volume are about 0.1 cm^3 , so that shots starting from an initial

condition of states A would give maximum yield rates of 10^{10} - 10^{11} neutrons per μsec .

A. Plasma Characteristics in a Side-Fed Coil

Thin-walled coils suitable for implosion are destroyed by electrical forces on one full-current condenser bank discharge; thus parameter studies of the initial plasma condition have been made first in heavy, side-fed Scylla type coils. Figure 7 shows oscilloscope traces of a typical discharge with a side-fed coil of length 8-1/2 inches, an i. d. of 3 inches, and a mirror ratio of 1.2 to 1.0. The discharge tube was 64 mm o. d. Pyrex, and the deuterium was weakly preionized by a 1 kW r. f. supply. These data were taken indoors with a low-inductance 20 kV condenser bank of 360 μF similar to the low-inductance bank available at the firing point. The soft x-rays are observed with a two-channel detector designed on the two-foil signal ratio method developed by Sawyer¹¹ et al. Thin aluminum foils are used for the soft x-ray attenuator foils. Neutron yields of the order of 10^3 to 10^5 per shot were observed over a range of deuterium base pressures of 20 to 125 microns. The neutron yields are seen to occur on second half cycle, and later. Radial smear pictures show a cold plasma on first half cycle, and on second half cycle show a hot plasma that is well contained for 3-4 μsec , after which it seems to break into two filaments which appear to rotate, much like the rotations reported by Kolb¹² and others.

First-half-cycle operation¹³ has also been studied with this coil using a 27 kA linear discharge fired 25 μ sec before the main compression field. A reverse field of about 1000 gauss was used and the peak magnetic field was 56 kG. Smear pictures showed containment similar to that of Fig. 7, over the same range of pressures. No neutrons were observed, but first-half-cycle soft x-ray signals indicated a maximum electron temperature of 285 eV at 25 microns deuterium pressure.

B. Plasma Characteristics in Single-Liner End-Fed Coils

The thin walled end-fed coils used for the explosive shots were sufficiently weak as to require starting the liner implosion on the first half cycle to prevent excessive slot separation due to the electrical forces.

In early studies of the plasma initial condition, it was found that first-half-cycle neutrons could be produced in the end-fed coil if a 30 kA linear discharge current was carefully timed to start one to four μ sec before the start of the initial compression field. Reverse field was necessary but its value was not critical if above 500 gauss. A Pyrex discharge tube of 64 mm o. d. was used for the plasma chamber. First-half-cycle neutrons were produced over a deuterium pressure range of about 20 to 40 microns. The yields ranged in magnitude from 10^3 to 10^5 , and exhibited considerable shot-to-shot variation. Figure 8 shows oscilloscope traces and a smear picture typical of this type of first-

half-cycle operation. As may be seen from the smear picture, the plasma hits the discharge tube wall as early as $2 \mu\text{sec}$ after the start of the magnetic field, although neutrons are still being produced as late as 3 or 4 μsec after the start.

Discovery of the poor containment evidenced in Fig. 8 was followed by a long series of parameter variation studies in an effort to find a more satisfactory plasma initial condition. For these laboratory studies a heavy-walled end-fed coil was used to simulate the one-shot flimsy end-fed coil used with implosion shots. The heavy coil was 10-1/2 inches long with an i. d. of 2.75 inches. Discharge tube o. d. 's of 64, 51, and 38 mm were used. Delay time, between the start of preheater current and main field current, was varied from "short" (1-4 μsec) to "long" (20-30 μsec). Reverse field was varied from 0 to 2900 gauss, and the deuterium pressures were varied from 10 to 500 microns. Over this range of parameters, the only condition that gave a hot neutron producing plasma was the "short" delay, narrow pressure range, case of Fig. 8. The conditions that indicated best containment were "long" delay, low or zero reverse field cases. Best containment was obtained with the 38 mm tube diameter, perhaps due to the fact that less plasma saw B_θ asymmetries in this case. The good containment cases were verified by use of stereographic photography, in which simultaneous side and top views of the plasma were obtained. For all cases showing good containment,

the plasma was "cold," i. e., no neutrons or soft x-rays were observed. Figure 9 shows a collection of radial smear pictures characteristic of these "cold" plasma conditions. None of the end-fed coil, fast θ -pinch conditions reported here gave really satisfactory initial plasma conditions suitable for subsequent implosion. A combination of the following factors are believed to be responsible. The fast condenser bank is inadequate, in that higher initial voltages should be delivered to the coil, and the waste inductance should be reduced thus allowing for more favorable energy transfer to the coil. The tangential field asymmetries are too large. The linear discharge preheater, when operated at "short delay" also appears to contribute to poor containment.

C. Results of Implosion Shots

In the past few years, several full scale implosion shots with plasma have been fired⁶ using the parameters of Fig. 8, even though the initial plasma containment was poor.

A warmup procedure was developed for explosive shots which involved firing the pre-heater at full voltage and the compression field at reduced voltage through a heavy coil, to condition the discharge tube. After the warmup shots, the heavy coil was quickly removed from around the thin-walled implosion coil, the cables transferred from the heavy coil to the implosion coil, the explosive placed in position, and the implosion shot fired all within one hour of the last warmup shot. This procedure was found to be reliable for producing neutrons on the

first full energy discharge through the implosion coil, which, due to the electrical forces alone, could survive only one such shot.

Figures 1 and 10 show the results of the two implosion shots which produced neutrons. In both cases, the parameters used essentially were those which produced the plasma initial conditions of Figure 8. Initial implosion magnetic fields were about 50 kG. In both shots, there was a neutron yield prior to liner closure typical of that observed during electrical tests of these conditions. In both shots, there is an additional neutron yield after liner closure but the additional yields are disappointingly small. In Figure 1 the additional yield is less than the initial yield; in Fig. 10, it is somewhat greater. In the latter case, a Mg liner was used instead of Al, with a resulting faster implosion-field buildup. The poor yields observed for these shots following liner closure and implosion are attributed to poor containment of the initial plasma, as mentioned above, although there remains the possibility that debris from the imploding discharge tube may have poisoned the plasma.

An additional explosive shot was fired, using the parameters of the last picture of Fig. 9 for which the initial plasma was well contained but "cold". This shot resulted in a zero neutron yield and a zero soft x-ray yield, indicating a final temperature of less than 100 ev.

D. Future Plans

Through collaboration with J. L. Tuck,¹⁴ G. A. Sawyer, K. S. Thomas, E. Dolnick, E. L. Kemp, and other members of the Los Alamos

Sherwood groups, a fast condenser bank is being built which will double the voltage at the coil and decrease the rise time of the initial field. The bank will be transferred from Sherwood to our firing point by late fall of 1965. It is expected that our initial plasma conditions will be greatly improved with use of this bank in conjunction with the compensated, double liner, end-fed coils described in section II.

IV. Studies with a Four Megagauss θ -Pinch System

A. Characteristics of a θ -Pinch Induced within a Resistive Liner

As mentioned in section II, the achievement of magnetic fields of several megagauss or greater by implosion requires use of an unslotted resistive liner for the plasma vacuum chamber. The rate of rise of the magnetic field inside such liners is greatly reduced from that characteristically used with fast θ -pinches. We have, consequently, referred to θ -pinches produced in this manner as "slow θ -pinches". Plasma formation in this manner, generally suffers from a lack of E_θ , slow initial sheath formation, and poor radial shock heating, as compared with those produced from the fast θ -pinches discussed in section III.

In the present work, the axial initial field available at the firing point, such as shown in Fig. 5, has been simulated in the laboratory to study characteristics of the slow θ -pinch. These laboratory studies have involved compression fields of 6 to 14 kG, with rise times (developed

inside a 0.016 inch wall stainless steel liner) of 6 to 15 μsec . First-half-cycle operation is used, with and without reverse field. Preheating has been obtained with a pair of conical θ -pinch shock coils located one at each end of the discharge tube. The dimensions of the conical coils, based upon results of earlier work,¹⁰ have had maximum diameters of 100 mm, minimum diameters of 38 mm, and lengths of 6 inches. In our first studies,⁹ the shock coils were driven by 150 μF at 16 kV, and produced average first-front deuterium shock velocities of 3 to 4 cm/ μsec . More recently, the shock coils have been driven by 360 μF at 12-14 kV, giving first-front velocities of about 5 cm/ μsec . This latter shock velocity corresponds to a deuterium temperature of 2 eV, before collision, as predicted by the calculations of Venable and Stein,¹⁵ and Kolb.¹⁶

Figures 11 and 12 summarize the best results of the slow θ -pinch studies to date. In Fig. 11, a loop signal shows the shock-coil current, the reverse field, and the axial field drive current, all taken with a system used to mock-up the "initial condition" compression field to be used at the firing point. This laboratory field peaked at 13.9 kG in 6-1/2 μsec . Figure 11 also shows a typical D_{β} (4861 $\text{\AA}$ line) signal taken with a JACO monochromator and EMI 6256 B quartz-window photomultiplier. The monochromator views the axial center of the discharge tube.

The appearance of D_{β} shows that the shock preionization occurs tens of μsec ahead of the compression field. Figure 11 further shows a typical radial smear picture of this condition. The radial compression.

and containment appear to be quite good, consistent with data⁹ taken over quite a variety of parameters. The radial sheath during the first inward motion is not as well defined as shown here when the compression field is reduced.

A detailed spectrographic study was made of the D_{β} line with the monochromator set at different values for each discharge. Figure 12 shows typical D_{β} line profiles and the nearby continuum. Table I summarizes the values of electron density (N_e) and temperature (T_e) inferred from the D_{β} profiles of Fig. 12, and calculations given by Griem.¹⁷

TABLE I.

	D_{β} Halfwidth ($\text{\AA}$)	N_e (electrons/cc)	D_{β} /continuum ratio	T_e (eV)
First Strong Shock Front:				
at 35 microns	11.7	1.3×10^{16}	2.8	8
at 100 microns	32.8	5.9×10^{16}	---	--
Compression Signal Peak:				
at 35 microns	11.3	1.2×10^{16}	2	11
at 100 microns	19.6	2.7×10^{16}	1.7	13

B. The Multi-Megagauss Theta Pinch

The resistive liner implosion system of section II-B together with the creation of an initial-condition plasma within the liner by the slow

θ -pinch of section IV-A, may be combined to form a multi-megagauss θ -pinch experiment. The plasma conductivity, as indicated by the temperatures of Table I, is just sufficient to insure fair to good adiabatic compression by the implosion field.

Encouragement for proceeding with this approach stemmed from theoretical calculations by T. A. Oliphant.^{18,19} The calculations indicate that a preionized plasma at a T_e of 2 eV, compressed by a field with a magnitude and rise time as in Fig. 5, should attain a plasma temperature of 1 keV or higher and produce good neutron yields (greater than 10^7 per 10 cm length). The predominant heating mechanisms indicated are joule heating and adiabatic compression. Figure 13 gives results from one of Oliphant's¹⁹ calculations.

Following several explosive probe shots and two preliminary plasma shots, an explosive plasma shot was fired in June 1965. A setup of the shot is shown in Fig. 14. The shot was planned for the magnetic field shown in Fig. 5 and a plasma initial condition similar to those given in Table I. No provisions were made to produce a magnetic mirror. Also, owing to a condenser bank failure, there was no reverse field on the shot. No neutron yield was observed within detection limits ($>10^3$). This may have resulted from an inadequate warmup procedure, excessive impurity radiation, end-losses, or possibly the lack of reverse field. A reverse field may well be necessary for good neutron production,¹³ but is not assumed in Oliphant's calculations.

Future shots are planned in this series which will include a tapered liner for producing mirror fields to reduce end-losses, and will include an initial reverse field.

V. Summary

The results obtained to date in this program justify a considerable confidence in the characteristics of the available implosion systems discussed in II. Most of the difficulties have occurred in the effort to get suitable initial condition plasmas in systems usable for implosion. A continued effort in these directions has the following incentives:

1. Successful implosions and diagnosis with slotted liners of a typical good fast θ -pinch initial condition should yield information on the behavior of kilovolt plasma compressed to fields of 1/2 to 1 MG. Combined with results of Scylla IV,²⁰ and other high energy θ -pinches,^{21, 22, 23} such implosion data could add information that would be useful in the design of the next generation²⁴ of these devices.

2. Observation of neutron yields from a resistive liner multi-MG system should lead to a series of experiments which, if the pre-heating can be substantially improved, * would explore the full potential of these systems for producing very large neutron yields (DD) of the order of 10^{14} - 10^{16} per shot, and for studying the characteristics of the

*For example, by more effective transfer of hot plasma from an auxiliary θ -pinch than obtained with the present shock coils of section IV.

associated very hot dense plasma.

The experiments to date have barely scratched the surface in this effort.

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Figure 1. Results obtained with the fast θ -pinch implosion system first used in 1961. The upper curves show results of a magnetic axial probe shot with one probe at the center and another mirror probe 3-1/2 inches away from the center, along the liner axis.

The lower curves show the total neutron yield rate for the first such yield-producing plasma shot with explosive fired in August 1961. The first dotted curve shows the typical neutron yield rate obtained electrically with the same system if the explosive is not used. The total yield rate minus the electrical yield rate gives the HE yield rate.

Figure 2: Tangential field asymmetries for the end-fed coil used in the shots of Figs. 1 and 10, the heavy end-fed coil used for the data of Figs. 8 and 9, and the double liner compensated end-fed coil discussed in section II-A. The tangential fields are normalized to the central, axial field, $B_z(0,0)$.

B_θ PROBE DATA FOR END FED COILS ($10\frac{1}{2}$ INCH)

Figure 3. The multi-megagauss implosion system discussed in section II-B, and used for the shot of Fig. 5. The upper picture shows in detail the inner .030 inch titanium alloy cylinder, the two aluminum slotted liners which serve as flux concentrators, and the drive coil-pair, before the Mylar insulation has been added. The lower picture shows the final assembly, complete with field probes and ready for firing, just prior to the addition of the explosive charge.

Figure 4. Framing camera pictures comparing the cylindrical implosions of two four-inch i. d. diameter cylindrical systems.

(a) Frame taken before first liner motion.

(b) Frame taken midway through implosion with a 0.040 inch thick titanium alloy liner, with an unglued and non-angled inner charge, as used in the earlier⁹ resistive liner plasma shots. Note the severe jetting.

(c) Frame taken midway through implosion with a 0.030 inch stainless steel liner enclosed within two 0.050 inch slotted aluminum liners, similar to Fig. 3. The innercharge surfaces are angled, and are glued just before final assembly.

(d) Frame from the same shot as in (c), taken 0.84 μ sec later. Note the absence of obvious jetting.

A

B

C

D

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Figure 5. A plot of the magnetic field versus time measured in the first probe shot using the system of Fig. 3. The two curves refer to different scales and are both for the central probe which gave a field signal up to 3.93 MG.

Figure 6. Graph of idealized neutron yield rates and equilibrium magnetic field versus plasma particle density and temperature. It is assumed that thermal equilibrium prevails, that the ideal gas law holds, that there are no loss mechanisms, and that $\beta = 1$. Region A indicates the range of plasma initial conditions, and region B gives plasma conditions obtained by adiabatic compression of states A, when the confining field is increased by a factor of 20. The regions a and b indicate corresponding neutron yield rates.

REGION A: INITIAL CONDITIONS
FROM $\oplus$ PINCH

B: CONDITIONS OBTAINED
BY 20/1 FIELD COM-
PRESSION, $\gamma = 5/3$

a,b: NEUTRON YIELD
RATES FOR ABOVE
REGIONS

IONS / CM³

10²⁰

10¹⁹

10¹⁸

10¹⁷

10¹⁶

10¹⁵

10¹⁴

10⁷ GAUSS

10⁶ GAUSS

10⁵ GAUSS

4 x 10⁴

2 x 10⁴

10⁴ GAUSS

A

B

b

NEUTRON YIELD RATE PER CM³ μ SEC

10¹⁸

10¹⁶

10¹⁴

10¹²

10¹⁰

10⁸

10⁶

10⁴

10²

TEMPERATURE, ev

10¹⁵

100

1,000

10,000

100,000

Figure 7. Typical fast θ -pinch characteristics in a side-fed coil. The field at the peak of the neutron producing second half cycle is 53 kG. Weak r.f. preionization is used. For this shot the neutron yield was 6×10^3 and the deuterium pressure was 48 microns.

Top -- Radial smear picture. The arrows indicate the time relationship with the oscilloscope traces.

Second -- Main field current.

Third -- Integrated neutron yield.

Fourth -- Soft x-ray yield rate, through 0.25 mil Al foil.

Bottom -- Ten and one μ sec markers.

Figure 8. Typical fast θ -pinch characteristics in the heavy end-fed coil used to simulate the plasma initial conditions of the shots of Figs. 1 and 10. The deuterium pressure was about 37 microns. The first-half cycle peak magnetic field is about 50 kG. The reverse field is about 2 kG.

Top -- Linear discharge preheater current, about 22-1/2 kA.

Second -- Main field current.

Third -- Integrated neutron yield, about 4,000.

Fourth -- One μ sec time markers.

Bottom -- Typical radial smear picture showing the plasma hitting the tube wall before peak yield.

B_z SECOND HALF CYCLE
PEAK NEUTRON YIELD
 B_z FIRST HALF CYCLE
 I_z PREHEATER

Figure 9. Typical radial smear pictures of first-half-cycle compression of the fast θ -pinch in the heavy 2.75 inch i. d. end-fed coils used to simulate the shot conditions. For these pictures, the peak field is 55 kG in the 10.5 inch long coil, and 44 kG in the 14.5 inch long coil. The quarter period is approximately 5 μ sec. The linear-discharge preheater current (about 40 kA) is similar to that in Fig. 8, but starts about 30 μ sec before the compression field.

	<u>Tube o. d.</u> (mm)	<u>Deuterium</u> (microns)	<u>Reverse Field</u> (gauss)	<u>Coil Length</u> (inches)
Top	64	53	0	10.5
Second	64	12	870	10.5
Third	51	14	0	10.5
Fourth	51	46	870	10.5
Fifth	64	25	1740	14.5
Bottom	38	17	0	14.5

Figure 10. Results obtained with the fast θ -pinch implosion system using the same dimensions and parameters as in Fig. 1. For this shot, magnesium was used for the slotted liner, and the explosive was timed to close the slot while the neutron yield rate was increasing. The total yield was about 10^4 .

Figure 11. Typical characteristics of the slow θ -pinch induced within a resistive cylinder (.016 inch wall stainless steel). The discharge chamber has a 4 inch o. d. and is 10 inches long. The compression field rises from 0 to 13.5 kG in $6.5 \mu\text{sec}$, and rises in a manner similar to that shown on Fig. 5. The reverse field is about 500 gauss. The deuterium pressure is 100 microns.

Top. Typical radial smear picture showing the preheating shock fronts and the θ -pinch compression. The time sequence is indicated by arrows. Note the good radial containment.

Second. Pickup loop signal showing the shock coil field and the compression field.

Third. D_{β} signal (monochromator set at $4861 \text{ \AA}$, photomultiplier at -1.3 kV).

Fourth. Continuum signal near the D_{β} line (monochromator set at $4820 \text{ \AA}$, photomultiplier at -1.3 kV).

Fifth. Carbon IV impurity line signal (monochromator set at $2531 \text{ \AA}$, photomultiplier at -1.6 kV).

Bottom. Ten μsec marks. Oscilloscope sweep speeds were identical for all traces.

Figure 12. Deuterium line profiles (D_β) obtained with the system operated as in Fig. 11, at deuterium pressures of 35 and 100 microns. The dashed curve is for the signal peak corresponding to the first strong shock front. The solid curve corresponds to the signal peak midway through the first compression rise.

Figure 13. Typical theoretical calculations obtained by T. A. Oliphant, reference 18 and 19, of the behavior of a θ -pinch under implosion-produced megagauss compression. The figure shows the programmed magnetic field, and the code predictions for the ion temperature and the neutron yield. The calculation includes joule heating, hydrodynamic shock heating, and adiabatic compression, but does not account for end losses or impurity radiation. An initial preheat temperature of 2 eV, and an initial density of 10^{15} ions/cc, were assumed. It can be seen that the time behavior of the magnetic field programmed into the code is similar to, but not identical to, the measured field of Fig. 5.

Figure 14. Photograph of the plasma shot assembly of June 3, 1965, ready to fire just before the explosive charge was installed. The liner system is similar to that of Fig. 3. The plasma initial conditions were similar to those of Figs. 11, 12, and Table I, but with no reverse field. The applied compression field was similar to that drawn in Fig. 5. There was no observable neutron yield.

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