MASTER

CONF-810364--3

TITLE: LOS ALAMOS COMPACT TOROID, FAST-LINER, AND HIGH-DENSITY Z-PINCH PROGRAMS

AUTHOR(S): R. K. Linford (and the Compact Toroid Staff),
A. R. Sherwood (and the Fast Liner Staff), and
J. E. Hammel (and the High Density Z-Pinch Staff)

SUBMITTED TO: 5th Course on Unconventional Approaches to Fusion,
held in Erice, Italy, March 15-25, 1981

University of California

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos Scientific Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

LOS ALAMOS SCIENTIFIC LABORATORY

Post Office Box 1663 Los Alamos, New Mexico 87545

An Affirmative Action/Equal Opportunity Employer

LOS ALAMOS COMPACT TOROID, FAST-LINER, AND
HIGH-DENSITY Z-PINCH PROGRAMS

R. K. Linford (and the Compact Toroid Staff),
A. R. Sherwood (and the Fast Liner Staff),
and J. E. Hammel (and the High Density Z-Pinch Staff)

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

INTRODUCTION

The Compact Toroid (CT) and High Density Z-Pinch (HDZP) are two of the plasma configurations presently being studied at Los Alamos. The purpose of these two programs, plus the recently terminated (May 1979) Fast Liner (FL) program, is summarized in this section along with a brief description of the experimental facilities. The remaining sections summarize the recent results and the experimental status.

Compact Toroid

Two types of CTs are studied at Los Alamos:¹ Spheromaks and Field Reversed Configurations (FRCs). Spheromaks, which contain both poloidal and toroidal field components, are produced by a magnetized coaxial source (magnetized Marshall gun), as shown in Fig. 1(a). The separated spheromak is trapped and confined in a metal flux conserver not shown in Fig. 1. Coaxial sources, 30 cm in diameter, have been used to form spheromaks in the CTX facility and its predecessor, the Prototype facility.²

FRCs are produced by preionizing a plasma in the presence of an axial "bias" field in a theta-pinch coil, and then by rapidly reversing the current in the coil. This current reversal changes the field direction outside the plasma. This external field reconnects near the ends of the coil with the bias field trapped inside the plasma. The resulting FRC shrinks axially to the equilibrium state (Fig. 1(b)), which contains only poloidal field

and toroidal current. FRC experiments have been conducted in the FRX-A and FRX-B facilities,³ which both have coil diameters of 25 cm and coil lengths ~ 1 m. FRX-C has twice these linear dimensions and should be operational in the summer (1981).

Both FRCs and spheromaks share the common characteristic of CTs; no magnet coil or vacuum vessel links the hole in the toroidal plasma geometry. This feature substantially reduces the engineering complexity of proposed CT reactors. It also allows important flexibility in reactor design. The plasma rings can be translated along guidefields, merged with other ring etc. Moving ring reactors can yield essentially steady-state thermal conditions in the blanket region while avoiding the complexities of proposed steady-state systems such as current sustainment,

Fig. 1. CT formation techniques showing (a) the tearing and reconnection of the fields that separate the spheromak from the radial fields of the coaxial source, and (b) the final equilibrium state of the elongated FRC in the theta-pinch coil.

feedback stabilization, refueling, ash removal, and impurity control.⁴ CTs also have other potential reactor advantages including high engineering beta, natural diverter action, and the possibility of small size and small unit power. These potential advantages motivate the study of both spheromaks and FRCs to determine their stability and confinement properties.

Fast Liner

The Los Alamos FL program explored a portion of the general liner concept in which a previously prepared plasma is adiabatically compressed to thermonuclear temperatures and pressures by an imploding metal liner. The particular aspect of this concept studied at Los Alamos is illustrated in Fig. 2. A prepared plasma having $\beta > 1$ and containing an embedded azimuthal magnetic field to slow the thermal energy losses is in contact with the liner and end plugs. A very large axial current driven through the thin, cylindrical liner shell causes the liner to implode by the pinch effect at a sufficiently rapid rate that the adiabatic heating of the plasma overcomes cross-field thermal losses. Theoretical estimates indicated that liner velocities of at least 10^6 cm/sec were required for this, and achieving such velocities with near-reactor-sized liners was a major goal of the program. The cylindrical geometry shown in Fig. 2 was used in these experiments.⁵ Liner implosion studies were conducted using portions of the large modular capacitor bank previously used for the Scyllac experiment.

Fig. 2. Geometry of Los Alamos FL experiments. Typical dimensions were $R_0 = 2.6$ cm, $\Delta_0 = 0.1$ cm, $L = 6$ cm.

The FI concept leads to a relatively small, high power density, pulsed reactor. A preliminary conceptual reactor design study⁶ indicated a possible economical power system, given favorable solution to several critical engineering problems and physics uncertainties. Perhaps foremost among these was the replacement cost of the liner and current lead structure that would be destroyed on each shot. Although this and other reactor-related engineering issues⁶ were not solved, a major attractive feature of the approach is that, in principal, reactor-like conditions (breakeven) might be achieved in the Laboratory at a relatively early date and at modest cost.

High Density Z-Pinch

The long term objective of the Los Alamos HDZP experiment is to achieve a 10 keV plasma temperature at a particle density of 10^{20} to 10^{21} cm^{-3} with a pulse time of 250 ns. These conditions should be achieved by using a laser beam to initiate a small diameter (~ 0.1 mm radius) plasma channel of deuterium between electrodes fed by a 600 kV transmission line, as shown in Fig. 3. After the initiation, the high-voltage line provides the rapid current rise necessary for the magnetic pressure to balance the pressure generated by the ohmic heating of the dense plasma. The theoretical current profile required for pressure equilibrium is given in Fig. 4. The equilibrium for constant current is reached at about 1.5 MA, the Pease current. At a density of 5×10^{20} cm^{-3} with a channel radius of 0.1 mm, the plasma temperature is

Fig. 3. Z-pinch and electrode assembly.

Fig. 4. Temporal behavior of the current required for radial equilibrium.

predicted to be greater than 10 keV at the 1.5 MA current level. Initial experiments have been performed on Prototype HDZP at the 100 kA level, and a 400 kA facility is under construction. A fusion reactor study based on the HDZP concept has been made by Hagenson, et al.⁷

The reactor study used parameters which are close to those now being used in the Los Alamos HDZP experiment. The length of the plasma is 10 cm with a density of 10^{21} cm^{-3} and a radius of 0.1 mm. The current source is a Marx-driven water line with a current capability of 1.45 MA. The conclusion in the study is that a Marx-bank energy of 140 kJ would produce a fusion yield of 4.4 MJ for a plasma Q-value of 33. These results show that the dense Z-pinch is a dramatic departure from the usual reactor concept, with its much smaller size and high power density capability.

SPHEROMAK

Formation

The formation process shown in Fig. 1(a) results in a spheromak trapped in a flux conserver, as shown in Fig. 5. Field probes measuring all three orthogonal components at several points along the axis of symmetry indicate that field reconnection is complete within less than 50 μs . The axial component of the field

Fig. 5. The flux conserver and spheromak geometry with the axial field profiles along the axis of symmetry as a function of time.

plotted in Fig. 5 also shows that the poloidal field decay in the spheromak (confinement region) is an order of magnitude slower than the reconnection time (entrance region).

Gross Stability

Several different flux conserver shapes and external field conditions have been used to test the gross stability of the spheromak. Some of these configurations are shown in Fig. 6. As predicted by theory,⁸ the prolate spheromaks produced in the first flux conserver in Fig. 6 were unstable to the $n = 1$, $m = 1$ tilting mode (n and m are the toroidal and poloidal mode numbers), but the oblate shape of the other three conservers stabilized the tilt. The addition of external field has a destabilizing influence, but the last flux conserver shown stabilized the plasma even with significant external field.

Further experiments need to be coupled with the continuing theory effort to determine optimum shaping of field and flux conserver for stability, confinement, and access to the plasma. The access issue is not only important for present diagnostic

Fig. 6. Cross sections of four flux conserver shapes and proximity to the coaxial source. The stability of the spheromak to the tilting mode is indicated as a function of shape and presence of external fields.

needs, but also for future auxiliary heating, plasma diverter action, etc.

Equilibrium

The equilibrium properties of the plasma were determined by a variety of diagnostics indicated in Fig. 7. Interferometry indicates that the density decay approximately matches the field decay. The configuration lifetimes of up to $\sim 350 \mu s$, as shown in Fig. 8, are consistent with estimates of the classical resistive decay for the $T_e \sim 10 \text{ eV}$ measured by Thomson scattering. A transport code is being developed with all the geometry effects to model this process more accurately.

The major concern with these observations is the low electron temperatures. In an effort to increase the temperature, a "snipper" coil was added to the entrance region to speed up the field reconnection. Faster reconnection would reduce the time for parallel electron thermal conduction back to the source and would also reduce the possibility that metallic impurities evolving late

Fig. 7. Cross section of the CTX facility showing the source (gun) and flux conserver geometry and the diagnostic access. The flux conserver is 90 cm in diameter.

in the discharge could stream into the confinement region. The coil successfully increased the reconnection rate up to a factor of three, but no significant change occurred in either the lifetime or the temperature as indicated in Fig. 9. The shot-to-shot nonrepeatability of these T_e data is apparently not due to nonrepeatability in the source behavior. Shots exhibiting more than a factor of 3 difference in T_e had virtually identical magnetic field behavior. These observations are similar to the temperature and density fluctuations observed in small, cold, impurity-dominated Reversed Field Pinches (RFP). When the impurities are reduced, allowing T_e to increase ~ 100 eV, these fluctuations are greatly reduced.⁹ Because of the similarities between the spheromak and the RFP, such as field profiles, gross stability requirements, etc., it is possible that a reduction in impurities in the spheromak will have the same favorable result. The major effort now is to initiate impurity measurements with bolometers and spectrometers, and then begin an impurity reduction program if impurity radiation is consistent with the energy decay rate of the spheromak fields.

Fig. 8. Comparison of the average density through a diameter with the axial component of the field on the axis of symmetry.

Fig. 9. Comparison of the temporal history of T_e with and without the sniper coil energized. The data were obtained one point per plasma shot at the location indicated in Fig. 7.

Fig. 10. Temporal field behavior compared with the Taylor state (dashed line).

Another similarity between the spheromak and the RFP is the concept of the Taylor minimum energy state.¹⁰ In Fig. 10 the toroidal field just outside the magnetic axis and the poloidal field on the major axis are plotted as a function of time. Their ratio is then compared with the calculated ratio for the Taylor state (dashed line). It appears that when the spheromak deviates too far from the Taylor state some relaxation process restores it back to this minimum energy state. These relaxation processes need to be studied more carefully, particularly when the resistivity and fluctuations are reduced under higher temperature conditions.

FIELD REVERSED CONFIGURATION

Gross Stability

Since an FRC contains no toroidal field, $q = 0$ everywhere and the field has no shear. Simple MHD arguments would then predict that FRCs should be very unstable. However, when proper pressure profiles, elongated (prolate) geometry, and a conducting wall are included in the calculations, most modes have been shown to be stable.³

The only ideal MHD modes that are still predicted to be unstable are shown in Fig. 11. The first mode is the same tilting mode predicted and observed in spheromaks. However, this mode has not been observed in highly prolate FRCs with the separatrix radius at least half of the wall radius. The observed stability may be due to kinetic or finite Larmor radius (FLR) effects, or may be a result of the equilibria found in the experiments. The computations have been done for elliptical equilibria (see Fig. 12) while the experiments appear to be more racetrack-like. Attempts are being made to compute racetrack equilibria to determine the importance of this difference.

The second type of unstable mode is the axial or radial kink. Only the radial form is shown in Fig. 11. Again this mode is not

Fig. 11. The two ideal MHD modes that are theoretically predicted to be unstable. Both the undisturbed equilibria and the growing modal distortions are shown.

Fig. 12. Comparison of elliptical and racetrack equilibria.

observed experimentally. FLR stabilization is a possible explanation.

The only gross mode that is normally observed is the rotational $n = 2$ instability. The observed stable period before the mode onset is consistent with the FRC increasing in angular velocity until it crosses a threshold for instability predicted by a Vlasov fluid code.¹¹ The angular acceleration could be due to an external torque perhaps applied by plasma outside the separatrix through viscosity.¹² Another cause of acceleration could be net angular momentum carried by particles diffusing across the separatrix.¹³ This particle loss model predicts that the onset of the instability should occur when about half the particles are lost. This prediction is consistent with the experiment. Since the external torque or other sources of rotation are also possible, better correlation between experiment and theory is needed to properly understand this issue. However, if the FRC stable period τ (time before mode onset) continues to scale with the time required to lose half the particles, then particle transport, not the rotational mode, will limit the reactor potential of the FRC.

Equilibrium

The equilibrium conditions of the FRC were measured by field probes, excluded flux loops, HeNe interferometry, etc. Thomson scattering and Doppler broadening of the CV 2271 Å line were used to measure T_e and T_i . Figure 13 shows the temperature dependence on initial fill pressure as well as the classical equilibration between T_e and T_i . A self-consistent set of parameters is $T_i \sim 200$ eV, $n \sim 4 \times 10^{15} \text{ cm}^{-3}$, $B_0 \sim 8$ kG, the energy confinement time $\tau_e \sim 50 \text{ } \mu\text{s}$, and the average beta inside the separatrix exceeds 80 percent. This example corresponds to an $n_i \sim 2 \times 10^{11} \text{ cm}^{-3}$ in a toroidal confinement geometry with a minor radius of less than 2 cm.

Fig. 13. Temporal behavior of the electron and ion temperatures for four initial D_2 fill pressures.

Confinement Scaling

As is indicated in Fig. 14, the observed stable period scales with R^2/ρ_{i0} , where R is the major radius and ρ_{i0} is the ion gyro radius in the external field. This scaling was first suggested Hamasaki, who observed the same particle confinement scaling in a 1-D transport code.¹⁴ The code predicts not only the observed scaling, but the observed particle confinement time. This remarkable agreement is obtained by using a lower-hybrid-drift transport coefficient¹⁵ in the code. Unfortunately, assumptions made in the derivation of the coefficient have been questioned, i.e., no temperature gradient, wave-energy-bound saturation mechanism, etc. Thus, more theory and experiments are needed to understand the scaling.

The major purpose of the FRX-C device, now being completed, is to explore this confinement scaling to larger sizes. Figure 15 illustrates some of the major issues of this scaling study. Here

Fig. 14. The scaling of the stable period observed in two experiments with several bank energies over a period of several years.¹⁶

Fig. 15. Possible confinement scaling with R/ρ_i .

confinement time is plotted against the ratio of plasma size to ion orbit size. The region tested by FRX-A and FRX-B is indicated by the solid line between $R/\rho_i = 5$ to 18. FRX-C may extend that

as high as 40. The dashed lines are just speculated behavior. Will confinement time continue to scale with τ_g ? Will the scaling improve when the macroscopic density scale length becomes long compared with ρ_1 as is indicated by the dashed line? Will MHD activity degrade confinement when the FLR effects become weak as is indicated by the lower dashed curve? These are some of the questions that the FRX-C should begin to answer.

FAST LINER

Liner implosion experiments were conducted at Scyllac bank energies ranging from 1.4 to 2.8 MJ. The emphasis was on liner dynamics, and a plasma load was not present. Other experiments to produce a suitable plasma load in an appropriate geometry have been described elsewhere.⁵ Figure 16 illustrates the experimental arrangement. The diagnostics used included measurements of the driving current and voltage, flux compression of a 1 kG axial seed field, contact probes and flash x rays. The driving current and voltage were used to determine an average radial position of the driving current as a function of time (i.e., an average liner trajectory). This was compared with point measurements of the liner position obtained from the contact probes and with the position at a given time determined from the flash x-ray picture. A separate estimate of a portion of the liner trajectory was obtained from the flux compression diagnostic.

Fig. 16. Schematic drawing of Fast Liner implosion experimental configuration.

The results of these experimental measurements of the liner trajectory were compared with a numerical model for the implosion obtained from a 1-D, Lagrangian, hydrodynamic code containing a detailed treatment of the equation-of-state of the liner material. Figure 17 shows such a comparison for a 1.4 MJ shot. The point labeled as "abrupt current change" marks the discontinuity in the slope of the current trace caused by the sudden ending of the IL contribution to the voltage when the liner hits the axis. The dimensions of the cylindrical aluminum liner were 10 cm length, 5 cm diameter, and 1 mm thickness. On this shot a liner velocity of $\sim 5 \times 10^5$ cm/sec was achieved.

Figure 18 shows the computed trajectory and the experimental data for a 2.4 MJ shot. The velocity inferred from the discrete experimental points is 10^6 cm/sec, in agreement with the calculation. Thus, a major goal of the liner implosion program was achieved.

An x-ray shadowgraph taken on the shot presented in Fig. 18 is shown in Fig. 19. The reproduction is negative, so white areas indicate mass. The liner (white annulus) has an inner radius at 0.6 cm and is traveling at 10^6 cm/sec. (The initial radius was 2.8 cm.) The white spots on axis and the white radial streaks are magnetic probes, contact probes, and signal wires. The liner implosion is seen to be azimuthally symmetric, and the fuzzy appearance of the outer edge of the liner is caused by vaporization of the material there due to ohmic heating from the

Fig. 17. Comparison of theoretical and measured liner trajectories for a 1.4 MJ shot.

Fig. 18. Computed trajectory and experimentally determined positions for a 2.4 MJ shot.

Fig. 19. Flash x-ray photograph of an imploding liner.

~ 15 MA driving current. The inner edge of the liner is still solid. The slight fuzziness of the image there is due to resolution effects.

In general, the x-ray shadowgraphs and the other diagnostics showed symmetric liner implosions having velocities in the 5×10^5 cm/sec range for the lower bank energies and velocities of 10^6 cm/sec for the 2.4 MJ bank energy case.

HIGH DENSITY Z-PINCH

Channel formation experiments have been conducted with a small Prototype machine. This machine is a 600 kV, 5 Ω , 60 ns water transmission line charged with a Marx generator. With fill pressures of 1 to 4 atmospheres, these experiments have created channels of 0.1 mm radius at currents up to 100 kA. The density distribution of a channel is measured by a Moire-Schlieren technique with illumination by a short pulse N_2 laser (3373 Å). An example of such a channel photograph is shown in Fig. 20. In these experiments no sausage or kink instabilities have been observed out to 120 ns.

The reason for the stability against the $m = 0$ could be a favorable plasma pressure profile which satisfies the adiabatic lapse rate. The density measurements show a peak density on axis and a bell-shaped distribution which would go along with this explanation. The kink stability could be produced by finite Larmor radius effects, as well as by reduced growth rates because of the gas blanket.

A larger experiment driven by a lower impedance line is now operational. This line will operate at 600 kV with an impedance of 1.6 Ω and a line length of 100 ns. At the 400 kA peak current,

Fig. 20. Moire-Schlieren photograph of pinch channel at 100 kA current and peak density of $3 \times 10^{19} \text{ cm}^{-3}$.

the pinch temperature for 0.1 mm radius and $2 \times 10^{20} \text{ cm}^{-3}$ density scales to 1.5 keV.

References

1. W. T. Armstrong, et al., "Compact Toroid Experiments and Theory," Proc. of the Eight International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Brussels (1980), IAEA-CN-38/R-3-1, Vol. I, 481.
2. T. R. Jarboe, et al., Phys. Rev. Lett. 45, 1267 (1980).
3. W. T. Armstrong, et al., "Field Reversed Experiments (FRX) on Compact Toroids," to be published in Phys. Fluids.
4. R. L. Hagenson and R. A. Krakowski, "A Compact Toroid Fusion Reactor (CTOR) Based on the Field Reversed Theta Pinch," Third IAEA Technical Committee and Workshop on Fusion Reactor Design and Technology, Tokyo (1981), to be published in the Proceedings.
5. A. R. Sherwood, et al., "The LASL Fast Liner Experiment," Proc. of the Eight International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Brussels (1980), IAEA-CN-38/AA-1-1, Vol. II, 691.
6. R. A. Krakowski, et al., "Fusion Power from Fast Imploding Liners," Fusion Reactor Design Concepts, Vienna (1978), IAEA-TC-145/21, p. 357.
7. R. L. Hagenson, et al., "The Dense Z-Pinch (DZP) as a Fusion Power Reactor: Preliminary Scaling Calculations and Systems Energy Balance," Los Alamos Scientific Report LAUR-80-904, to be published in Nuclear Fusion.
8. M. N. Rosenbluth and M. N. Russac, Nucl. Fusion 19, 489 (1979).
9. A. Buffa, et al., "Eta-Beta II: Reversed-Field Pinch Plasmas with Improved Confinement," Proc. of the Eight International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Brussels (1980), IAEA-CN-38/L-1, Vol. II, 275.
10. J. B. Taylor, Phys. Rev. Lett. 33, 1139 (1974).
11. C. E. Seyler, Phys. Fluids 22, 2324 (1979).
12. L. C. Steinhauer, Phys. Fluids 24, 328 (1981).
13. D. C. Barnes and C. E. Seyler, "Rotation of a Field Reversed Theta Pinch," Proceedings of the Sherwood Meeting, Tucson (1980) 2C22.
14. S. Hamasaki and N. A. Krall, "Anomalous Diffusion Calculations in Field Reversed Configurations," Conference Record of the IEEE International Conference on Plasma Science, Montreal (1979) 143.
15. R. C. Davidson and N. A. Krall, Nucl. Fusion 17, 13. (1977).
16. J. Lipson, et al., Appl. Phys. Lett. 39, 43 (1981).