

# Implosion of Solid Liner for Compression of Field Reversed Configuration

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**Abstract**—The design and first successful demonstration of an imploding solid liner with height to diameter ratio, radial convergence, and uniformity suitable for compressing a field reversed configuration is discussed. Radiographs indicated a very symmetric implosion with no instability growth, with  $\sim 13\times$  radial compression of the inner liner surface prior to impacting a central measurement unit. The implosion kinetic energy was 1.5 megajoules, 34% of the capacitor stored energy of 4.4 megajoules.

**Index Terms**—Capacitor bank, field reversed configuration, FRC, implosion, magnetized target fusion, megamp, MTF, radiography, solid liner.

**WE REPORT ON** experiments that successfully imploded a cylindrical Al shell, or liner, with size, implosion velocity, uniform symmetry, and convergence suitable for compressing field reversed configurations (FRCs) to magnetized target fusion (MTF) conditions. FRCs are a version of magnetized plasma rings, or compact tori, that have closed poloidal field lines, and relatively little or no azimuthal field [1]. The work reported here represents a new combination of high convergence, good uniformity, and high ratio of length to initial radius in an electromagnetically imploded liner.

Multiple diagnostics indicated good quality implosions, with full current delivery, with good symmetry and lack of observable instability growth, within the radiographic measurement precision of  $\sim 0.2$  mm. These diagnostics include radiographs (shown here), interior magnetic field compression, fiber optic impact probe arrays, Faraday rotation probe and current delivery probes. The inner surface implosion velocity exceeded 4 km/s, and the mass averaged implosion velocity exceeded 3

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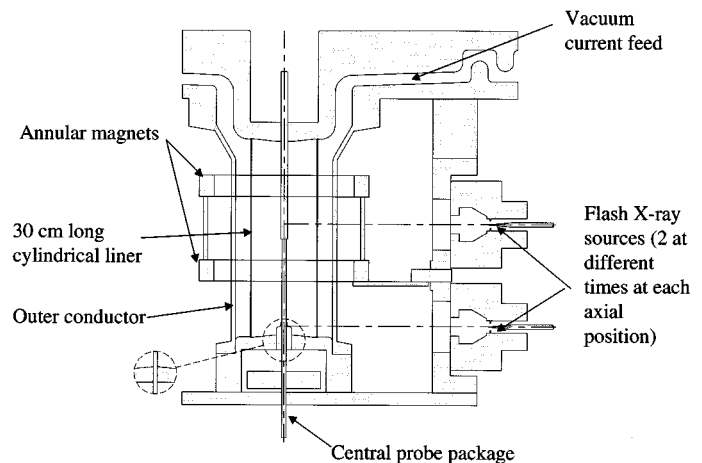


Fig. 1. Configuration of long liner implosion experiment. The central probe package has an outer diameter of 1.0 cm in its upper half and 0.64 cm in its lower half. The initial liner outer diameter is 10 cm. The mounting fixture for the central probe package is modified for the second shot.

km/s. Radiography indicated that the inner surface convergence ratio was  $\sim 13$  at  $23.5 \mu\text{s}$  after start of the implosion discharge. This performance is suitable for compression of FRCs to MTF conditions, as described by Schoenberg, Siemon *et al.* [1]. The premise of MTF is that fusion gain can be produced inexpensively by using “liner” compression of a magnetized plasma, because of magnetic inhibition of electron thermal conduction losses [1], [5], [6]. For adiabatic compression of an FRC, 10 : 1 radial compression is predicted to give impressive heating: 10 keV from an initial temperature of 250 eV [1].

Though this kind of implosion behavior has been achieved before for shorter cylindrical liners (2), and for quasi-spherical liners (3), at even higher implosion velocities, it had not been attempted for long liners at these implosion velocities. The effort reported here was done because of concerns over possible buckling or other unanticipated and undesirable three dimensional phenomena that might interfere with good quality, symmetric implosions, for high ratios of length to initial radius. Research relevant to the use of imploding liners to compress magnetized plasmas has also been reported by a number of researchers. This includes suggesting the concept of using imploding liners to compress plasmas, and research on shorter or lower velocity liner implosions, in, e.g., [4]–[17], and implosion of a Cu-W

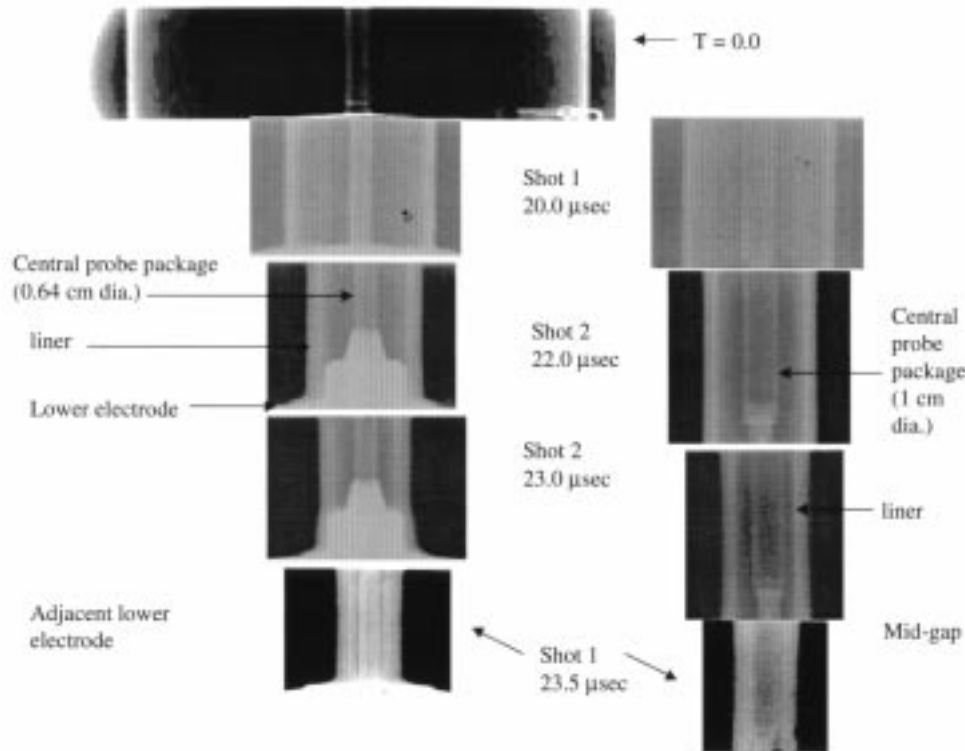


Fig. 2. Radiographs from two implosion experiments with identical liner and discharge circuit parameters. On the left are radiographs observing the axial portion of the liner adjacent to the lower electrode. On the right are radiographs observing the axial portion near the center of the electrode gap.

liner with explosives, resulting in a 200-T field inside via flux compression [18].

In the two experiment shots performed, the liner was imploded by magnetic pressure from an 11-megamp, 10- $\mu$ s rise time, axial discharge. The liners were 30 cm long, 5 cm outer radius, and 0.11 cm thick prior to implosion. The liner material was 6061-T6 Al, and the liner mass was 0.27 kg. The discharge was driven by the 1300-microfarad Shiva Star capacitor bank, charged to 82 kV. The initial total system inductance was 44 nanohenries. The initial system resistance was approximately 1 milliohm plus that due to an Al series safety fuse (0.94 meter long, 2.125 cm<sup>2</sup> cross section). The safety fuse protects the capacitor bank and transmission line, in the event of failure of the insulator-vacuum interface in the current feed. The experiment configuration is illustrated in Fig. 1. The imploding shell is observed by flash radiography, taken through the Al return current conductor (0.64 cm thick, 7.3 cm inner radius), which is the outer conductor. Radiography was taken at two different times, at each of two axial positions, for each implosion shot. The axial positions were near the center of the electrode gap, and near the lower electrode. An instrumented impact probe was installed along the axis of the liner. The lower half had an outer diameter of 0.64 cm and contained an array of magnetic probes (to measure compression of a modest, predominantly axial,  $\sim$ 50 Gauss initial magnetic field, provided by permanent magnets) [19]. The upper half had an outer diameter of 1.0 cm and contained an array of fiber optic impact probes. The X-ray shadow of this probe package provides a useful size scale for the radiographs. The parameters of the radiography source

are 300 kV, 5 kA, 30 ns pulse, with a tungsten anode (further discussed in [3]). The spatial resolution is  $\sim$ 0.2 mm. Radiographs for two implosion experiments, taken at 20.0 and 23.5  $\mu$ s after start of the implosion discharge for the first shot, and at 22.0 and 23.0  $\mu$ s for the second shot, are shown for both axial positions in Fig. 2. These indicate that the liner imploded symmetrically, without instability growth, within their  $\sim$ 0.2-mm precision.

The time history of the radial implosion inferred by measuring the compression of a small magnetic field agrees with computer models of the implosion and is consistent with the radiography results reported here [19], [20], and with fiber optic impact probe array data [20]. Detailed discussion of these additional diagnostics, which corroborated the radiography results on implosion timing and behavior, is given by Taccetti *et al.* [19] and by Intrator *et al.* [20]. A comparison of the data on the liner radius versus time, for the different diagnostics, is shown in Fig. 3.

To mitigate instability growth, we chose discharge parameters that avoided the onset of bulk melting and vaporization. That is, we chose the liner thickness so that resistive heating would not cause such onset. We used analytic criteria such as those used by Maisonnier *et al.* [21] and by Knoepfel [22] to avoid the onset of melting, and checked the results using 1D-MHD and 2D-MHD simulations, using the magnetohydrodynamics code MACH2 [23]. As long as the liner remains solid, material strength can stabilize the liner against instability growth (at least in the  $r$ - $z$  plane), provided initial imperfections in the liner's initial geometry are sufficiently small [24]. Simpler calculations of the implosion treat the finite thickness of the liner,

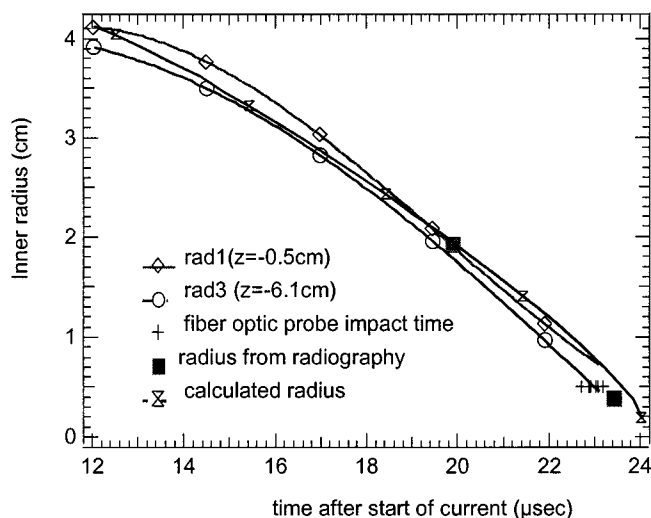


Fig. 3. Comparison of data on liner inner radius versus time for different diagnostics, and for calculation. Data includes radiography, diagnostic magnetic field compression (rad1 and rad3 curves), and time of arrival from fiber optic impact probes. A possibly generous estimate of the error in the inner radii obtained from diagnostic field compression is  $\pm 10\%$ . The estimated errors in the radiograph and fiber optic data are less than the symbol sizes. Plot also includes calculated inner radius, assuming 1 milliohm series resistance plus standard safety fuse, 44-nanohenry initial total inductance, 1300- $\mu$ F capacitance, and 82-kV initial capacitor voltage.

assume incompressibility of the liner, and use discharge circuit solution with interactive inductance and safety fuse resistance [2]. This agrees sufficiently well with experimental (and MHD simulation predicted) performance, to enable *a priori* timing of the contact between the liner and central instrumented impact probe to  $\sim 100$  ns precision, for a 24- $\mu$ s implosion. Comparison of radiograph timing with MHD and simpler calculations indicates that the liner implosion kinetic energy was 1.5 megajoules, which is 34% of the initial capacitor bank stored energy of 4.4 megajoules.

Some further development of the liner implosion technique is needed before liner-on-plasma experiments begin. This development will include tests of the effects of compressing larger magnetic fields, and the replacement of the sliding liner-electrode contact (used in the present tests) with deformable liner-electrode contacts, to enable convenient injection of an FRC into the liner interior. The presence of an interior plasma and a significant interior magnetic field can be expected to result in the onset of Raleigh Taylor instability growth once the inner surface of the liner, if liquefied, starts to decelerate. However, compression of a magnetized plasma to MTF conditions can be achieved before such deceleration starts. There is a trade off in energy efficiency vs amount of instability growth, which we are attempting to investigate computationally.

For the immediate future, emphasis in MTF research has shifted to preparation of a suitable plasma target. Using models based on previous FRC experiments [1], LANL and AFRL are designing an experiment at Los Alamos that can generate a 5-T pulse of magnetic field in 2.5  $\mu$ s, providing an FRC with density  $\sim 10^{17}$  cm $^{-3}$  and  $T \sim 250$  eV (1, 25). The FRC dimensions (separatrix radius  $\sim 2.5$  cm and length  $\sim 30$  cm)

allow the FRC to be translated and trapped in a liner that is the same size as that used for the liner implosion experiments reported here.

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#### REFERENCES

- [1] K. F. Schoenberg and R. E. Siemon, *et al.*, "Magnetized target fusion, a proof of principle research proposal," LA-UR-98-2413, 1998.
- [2] J. H. Degnan *et al.*, "Multimegajoule electromagnetic implosion of shaped solid density liners," *Fusion Technol.*, vol. 27, no. 115, 1995.
- [3] —, "Electromagnetic implosion of spherical liner," *Phys. Rev. Lett.*, vol. 74, p. 98, 1995.
- [4] I. Lindemuth and R. Kirkpatrick, "Parameter space for magnetized fuel targets in inertial confinement fusion," *Nucl. Fusion*, vol. 23, no. 263, 1983.
- [5] I. Lindemuth *et al.*, "Target plasma formation for magnetic compression/magnetized target fusion," *Phys. Rev. Lett.*, vol. 75, p. 1953, 1995.
- [6] V. K. Chernyshev and V. N. Mokhov, "On the progress in the creation of powerful explosive magnetic energy sources for thermonuclear target implosion," in *Dig. Tech. Papers 8th IEEE Int. Pulsed Power Conf.*, 1991, pp. 395-410.
- [7] C. M. Fowler, "Intense magnetic fields," in *Atomic Energy Research in the Life and Physical Sciences*, 1960, (AEC Special Report, Jan. 1961), p. 104.
- [8] J. G. Linhart, H. Knoepfel, and C. Goullan, "Amplification of magnetic fields and heating of plasma by a collapsing metallic shell," in *Nucl. Fusion*, 1962, Supplement 2:733.
- [9] N. K. Winsor, J. P. Boris, and R. A. Shanny, "Plasma heating by flux compression," in *Proc. Symp. Plasma Heating and Injection*, Varenna, Italy, 1973, pp. 227-231.
- [10] E. P. Velikhov *et al.*, "Generation of megagauss magnetic fields using a liner compressed by high pressure gas," *Sov. Phys.-Tech. Phys.*, vol. 18, p. 274, 1973.
- [11] V. Goloviznin *et al.*, "Numerical simulation of dynamics of quasispherical metallic liner," in *Megagauss Physics and Technology, Second Int. Conf. Megagauss Magnetic Field Generation and Related Topics*, P. J. Turchi, Ed. New York: Plenum Press, 1980, p. 415.
- [12] P. J. Turchi *et al.*, "Review of the NRL liner implosion program," in *Second Int. Conf. Megagauss Magnetic Field Generation and Related Topics*, p. 395.
- [13] A. E. Sherwood *et al.*, "Results from the Los Alamos fast liner experiment," in *Second Int. Conf. Megagauss Magnetic Field Generation and Related Topics*, p. 391.
- [14] J. A. Kareev *et al.*, "Liner thermonuclear system with superhigh magnetic field and  $\beta > 1$ ," in *Second Int. Conf. Megagauss Magnetic Field Generation and Related Topics*, p. 399.
- [15] A. M. Andrianov *et al.*, "Production of megagauss magnetic fields by compression of a magnetic field with a metallic liner," in *Second Int. Conf. Megagauss Magnetic Field Generation and Related Topics*, p. 479.
- [16] V. Mokhov *et al.*, "Possible solution of the controlled thermonuclear fusion problem based on magnetogasdynamic energy storage," *Sov. Phys. Dokl.*, vol. 24, p. 557, 1979.
- [17] V. K. Chernyshev *et al.*, "Cylindrical liner: Implosion dynamics under EMG magnetic pressure," in *Sixth Int. Conf. Megagauss Magnetic Field Generation and Related Topics*, 1994, p. 815.
- [18] W. T. Armstrong and J. A. Morgan, "Liner compression of magnetically confined FRC plasmas," in *Megagauss Technology and Pulsed Power Applications, Fourth International Conference on Megagauss Magnetic Field Generation and Related Topics*, C. M. Fowler, R. S. Caird, and D. J. Erickson, Eds. New York: Plenum Press, 1987, p. 683.
- [19] J. M. Tacetti *et al.*, to be published.
- [20] T. P. Intrator *et al.*, to be published.
- [21] C. Maisonnier *et al.*, "Rapid transfer of magnetic energy by means of exploding foils," *Rev. Sci. Instrum.*, vol. 37, no. 1380, 1966.
- [22] H. Knoepfel, *Pulsed High Magnetic Fields*. Amsterdam: North Holland Publishing Co., 1970, p. 87.
- [23] R. E. Peterkin Jr., M. H. Frese, and C. R. Sovinec, "Transport of magnetic flux in an arbitrary coordinate ALE code," *J. Comp. Phys.*, vol. 140, p. 148, 1998.

- [24] E. L. Ruden and D. E. Bell, "Rayleigh-Taylor stability criteria for elastic-plastic solid plates and shells," *J. Appl. Phys.*, vol. 82, p. 163, 1997.
- [25] G. A. Wurden *et al.*, "Diagnostics for a magnetized target fusion experiment," *Rev. Sci. Instrum.*, to be published.

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He has performed research in the area of high energy density states of matter for the Air Force Research Laboratory's High Power Microwave Division, and its predecessor organizations. He has developed several interferometric systems for the diagnosis of plasma using coherent radiation sources across a broad spectrum: millimeter wave, far infrared, visible, and ultra violet. In addition, he has extensive experience in experimental, analytic, and computational efforts involving continuum dynamics of all phases of matter. His theoretical work in the high velocity elastoplastic flow of metals has led to improvements in the theoretical treatment of the Rayleigh-Taylor instability of strongly accelerated solids.

**Jack S. Schlachter**, photograph and biography not available at the time of publication.

**Kurt F. Schoenberg**, photograph and biography not available at the time of publication.

**Richard E. Siemon** received the Ph.D. degree in physics from the University of California, San Diego in 1968.

He is the program manager for the \$7-million fusion energy research program at Los Alamos. The research includes a growing effort on qualitatively new fusion ideas: electrostatic confinement, including the Penning Fusion concept, and magnetized target fusion. He serves on the board of directors for Fusion Power Associates, and the steering committee for VLT, the virtual laboratory for technology under Charles Baker at UCSD. In past years, he was appointed by the Secretary of Energy to serve on the Magnetic Fusion Advisory Committee (1986–1990) and the Fusion Energy Advisory Committee (1990–1994). He led a Los Alamos group in the 1980s that studied the Field-Reversed Configuration. Prior to that, he worked on various concepts including high-beta stellarators (Scyllac) linear theta pinches, and multiple magnetic mirrors. His laboratory research included advances in plasma diagnostics such as holographic interferometry and innovations for Thomson scattering. At the present time he is enthused about the MTF concept, which has potential for being a more affordable system for practical development than either tokamak or laser fusion systems.

Dr. Siemon is a Fellow of the American Physical Society.

**Wayne Sommars** received the M.S. degree in electrical engineering from the Air Force Institute of Technology, Wright Patterson AFB, OH.

He is a senior scientist/engineer, Maxwell Technologies, Inc., as the Operations Manager, Site Manager, and Technical Group Leader managing research and development efforts in support of Air Force High Energy Plasma and High Power Microwave customers. He oversees all engineering, drafting, and technician activities relative to the design, analysis, fabrication, assembly, operation and maintenance of up to eleven experiments at three geographically separate facilities and one remote outdoor test site. During his Air Force career, he participated in a joint US/Canadian operational test and evaluation of the US/Canada North Warning System radar network. He also wrote a discrete FORTRAN model to simulate operational maintenance of the systems' reliability, maintainability and availability. He was the US liaison to Korean Air Force counterparts for scheduled maintenance, technical interpretations, assessing problems, and implementing solutions. He was hand picked to participate in the Air Force Innovation Study, a long-range planning effort to identify new and developing communications systems and technologies for use in advanced Air Force systems. As a graduate student he specialized in digital systems engineering and semiconductor device technology.

**Peter J. Turchi** (SM'84–F'00) received the B.S.E., M.A., and Ph.D. degrees in aerospace and mechanical sciences from Princeton University, Princeton, NJ, in 1967, 1969, and 1970, respectively.

As an Air Force officer at the Air Force Weapons Laboratory, Kirtland AFB, NM, in 1971, he initiated (with W. L. Baker) the Shiva program for generating megajoules of soft x-rays by electromagnetic implosion of plasma shells. From 1972 to 1980, as a civilian scientist at the Naval Research Laboratory, he designed and operated imploding liner systems for controlled thermonuclear fusion (NRL Linus program), culminating in demonstration of repetitive, stabilized implosions of liquid-metal liners. From 1977 to 1980, he served as Chief of the Plasma Technology Branch. From 1980 to 1989, he was a Senior Research Scientist at R&D Associates, Inc., Overland Park, KS. As Director of its Washington Research Laboratory, he led the successful effort to switch megajoules of magnetic energy at twelve megamperes using pulsed plasma flows. From 1989 to 1999, he was Professor of Aerospace Engineering at Ohio State University, Columbus, OH, during which time he also served as visiting Chief Scientist for Advanced Weapons and Survivability at the Phillips Laboratory, Kirtland AFB, Albuquerque, NM. In 1999, he joined Los Alamos National Laboratory, Albuquerque, NM, where he leads activities in hydrodynamics and pulsed power physics. He re-established the International Conference on Megagauss Magnetic Field Generation and Related Topics in 1979.

Dr. Turchi has served as Technical Program Chairman and General Chairman for the Fifth and Sixth IEEE Pulsed Power Conferences, and as a member of the Executive Committee of the Plasma Science and Applications Committee. In 1999, he received the IEEE Erwin Marx Award. He is President of the Electric Rocket Propulsion Society, a member of the AIAA Electric Propulsion Technical Committee, and Chairman of the IEEE Standing Committee on Pulsed Power Science and Technology.

**Glen A. Wurden** (M'95) was born on September 9, 1955, in Anchorage, AL. He received the Ph.D. degree in astrophysical sciences from Princeton University in 1982.

He is a staff physicist and team leader for magnetic fusion experiments at Los Alamos National Laboratory, Los Alamos, NM, specializing in plasma physics and plasma diagnostics. He has had experiments at TFTR, Alcator C-Mod, JT-60U, ASDEX, NSTX, SSPX, and used to work on alternate plasma confinement concepts (reversed field pinches and field reversed configurations). Research interests include: high-speed imaging; FRC plasmas; steady-state bolometers; and rad-hard plasma diagnostics.

Dr. Wurden is a member of the APS and Phi Beta Kappa.

**F. Wysocki**, photograph and biography not available at the time of publication.