

# Measurements of Solid Liner Implosion for Magnetized Target Fusion

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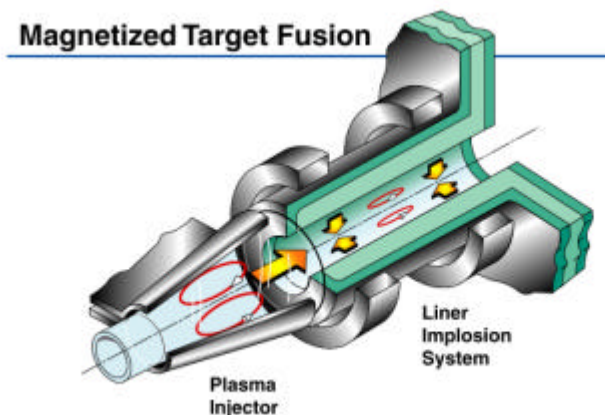
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**Abstract** Data are presented on the implosion symmetry of a 1-mm-thick 10-cm-diameter 30-cm-long solid aluminum cylinder (called a liner.) At the moment when radial compression of more than 10:1 is achieved, the inward velocity of the inner liner surface is 5 km/sec and liner symmetry is excellent (rms variation in radius of about 6%). This technology is important for Magnetized Target Fusion, the approach being developed where magnetically insulated plasma is compressed to fusion conditions by means of an imploded liner. The construction of a theta pinch to inject a high-density field-reversed configuration ( $n \sim 10^{17} \text{ cm}^{-3}$  with  $T \sim 300 \text{ eV}$ ) into the liner is presently underway.

## 1. Introduction

Magnetized Target Fusion (MTF), shown in Fig. 1 is a promising alternative concept because of its potential for low-cost development [1-5]. MTF is closely related to the “liner” fusion idea that was investigated in the 1970s [6]. The basic concept is to preheat and embed a magnetic field in fusion fuel to suppress electron thermal conduction, and to compress it by liner implosion to megabar pressures where energy gain is produced in microsecond pulses.



*FIG. 1. As a demonstration of MTF principles, a field-reversed configuration could be formed in a conical theta pinch on the left and injected into a cylindrical liner geometry on the right. Then pulsed current of 10 MA or more in the liner would drive a z pinch implosion to produce thermonuclear conditions.*

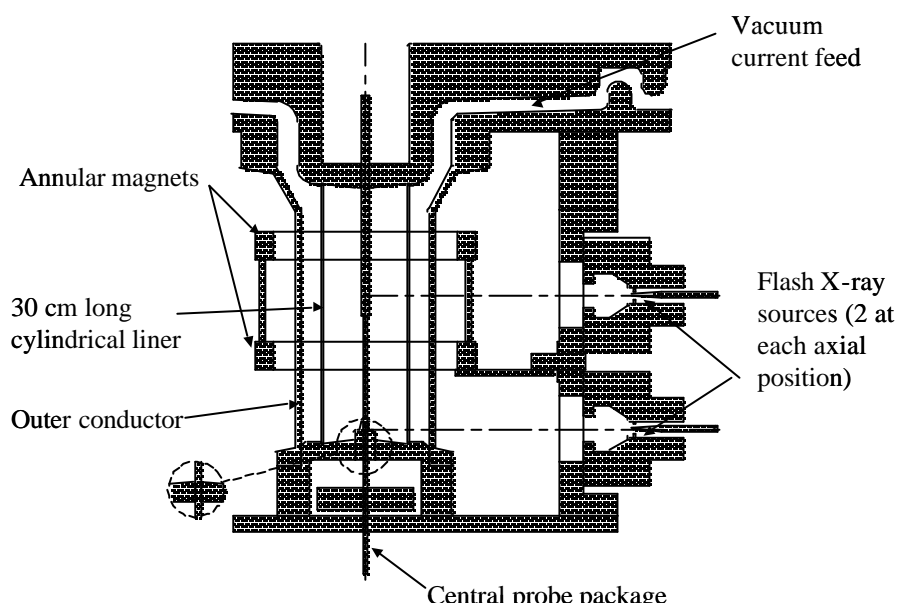
Progress since the 1970s in understanding compact toroids, especially the field reversed configuration (FRC) [7], shows how a target plasma can be inserted into a liner for implosion. Separately, liner technology has been advanced in recent years as a tool for high-energy-density physics studies of interest to U. S. Department of Energy Defense Programs. Early work by Kurtmullaev showed promise that this approach is technically feasible [8].

According to present thinking about FRCs, the MHD instabilities otherwise expected for the magnetic configuration are suppressed provided the size parameter  $S^* = \text{separatrix radius} / (c/\omega_{pi})$  is less than about  $3.5xE$ , where the elongation  $E$  is separatrix length relative to separatrix diameter [1]. Thus an elongated cylindrical liner geometry is preferred for FRC compression to maintain stability during compression.

## 2. Implosion of an elongated cylindrical liner

In proposed proof-of-principle MTF experiments, a liner with initial length-to-diameter aspect ratio of 3:1 appeared suitable for anticipated FRC properties [1]. Recent liner experiments by Defense Programs have focused mainly on smaller aspect ratios, typically 1:2. Therefore, Los Alamos and Air Force Research Laboratory (AFRL) conducted a liner-stability experiment with MTF-relevant geometry using the Shiva Star facility at Kirtland Air Force Base in Albuquerque.

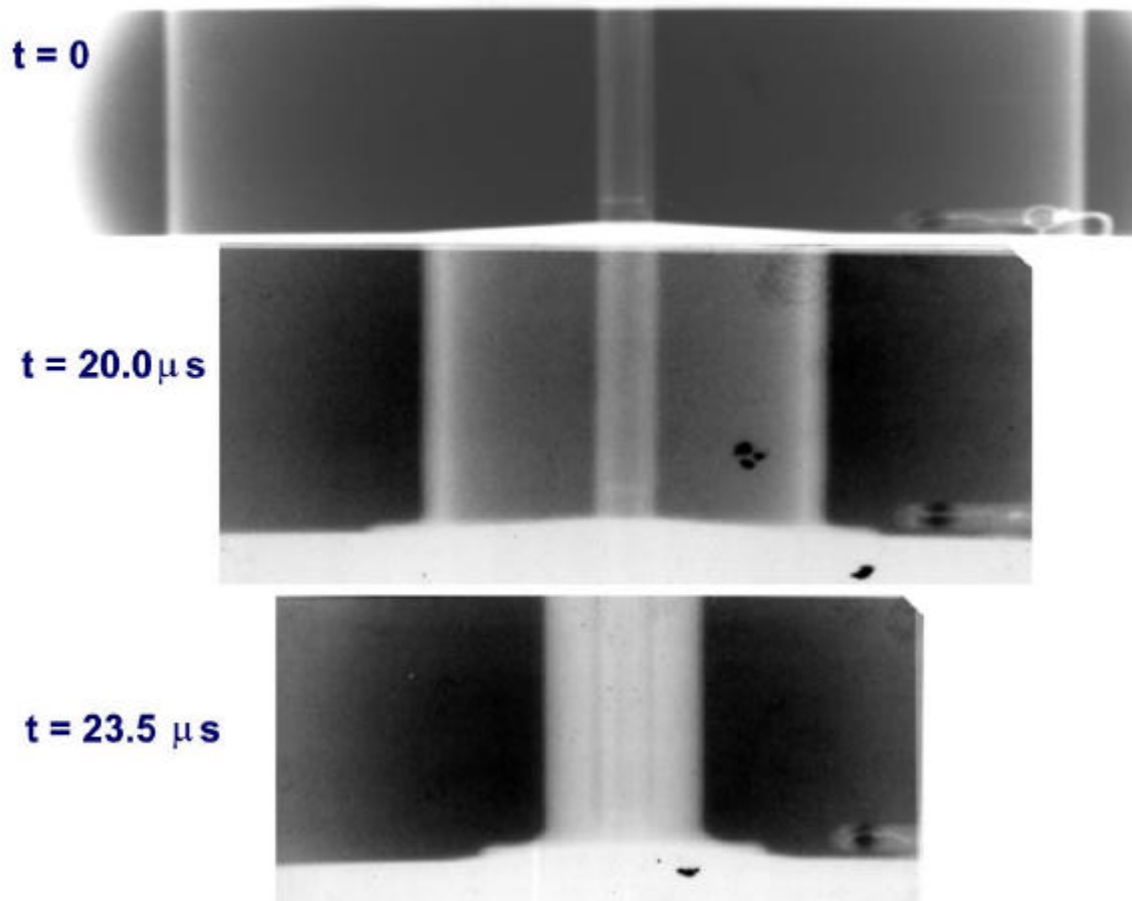
These initial experiments involved no plasma and only a small magnetic field for diagnostic purposes. A 30-cm-long, 10-cm diameter, 0.11-cm thick aluminum liner (alloy 6061-T6) was imploded on two occasions using the 1300 microfarad Shiva Star capacitor bank charged to 80 kilovolts (stored energy 4.2MJ) using current feeds configured as shown in Fig. 2. The liner was press fit between upper and lower conical glide planes that provide electrical contact during implosion. For FRC injection the current feed arrangement would be different. The initial total inductance was 44 nanohenries, and the initial system resistance was approximately 1 milliohm plus that due to a series safety fuse that grows in resistance as the current flows. Diagnostics included electrical parameters, flash radiographs, and an on-axis probe package: fiber optic impact probes mounted at 1-cm radius (top half of liner) and magnetic probes inside a 0.64-cm tube (lower half).



*FIG. 2. Current feed configuration from the Shiva Star capacitor bank. Tapered electrodes at the top and bottom provide current to the imploding liner.*

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Early in the 11-MA current pulse (peak current at 10  $\mu\text{s}$ ) the yield strength of aluminum is exceeded and the liner deformation is elastic plastic. Discharge parameters are chosen to avoid bulk melting and vaporization of the liner. Raleigh-Taylor instabilities are expected to reach small amplitude during implosion provided initial imperfections in the liner's shape are sufficiently small [9].



*FIG. 3. Radiographs near the lower glide plane of initial liner and at two times during implosion. The 0.64-cm stationary probe jacket is visible on axis. Because the aluminum is approximately incompressible, conservation of mass implies the increase of liner thickness observed in these data.*

Radiographs (Fig. 3) show excellent symmetry of the implosion within the  $\sim 0.02$  cm resolution of the diagnostic. Note the 0.05-cm gap between the inner surface of the liner and the stationary probe jacket at 23.5  $\mu\text{s}$ . This indicates acceptable symmetry even with a final radial compression ratio of 13:1, which exceeds the 10:1 design goal for MTF compression. These radiographs do not show the axial and azimuthal array of 16 optical impact probes located above the liner midplane. The optical probe data show that the final cylindrical shape was distorted to an oval, but symmetry was better than  $\pm 0.03$  cm at the 0.5-cm probe radius.

Liner radius versus time is measured independently by magnetic field measurements (assuming the liner conserves flux during implosion), radiographs, and impact probes. After correcting for the time-dependent magnetic diffusion through the stainless steel probe jacket, all data are in excellent agreement as shown in Fig. 4. The inner surface implosion velocity exceeded 4 km/s, and the mass averaged implosion velocity exceeded 3 km/s. The kinetic

energy of the 0.27-kG liner was 1.6 MJ. With modest engineering effort the efficiency could be improved, but even in this initial experiment the transfer efficiency from stored electrical energy to kinetic energy was 33%.

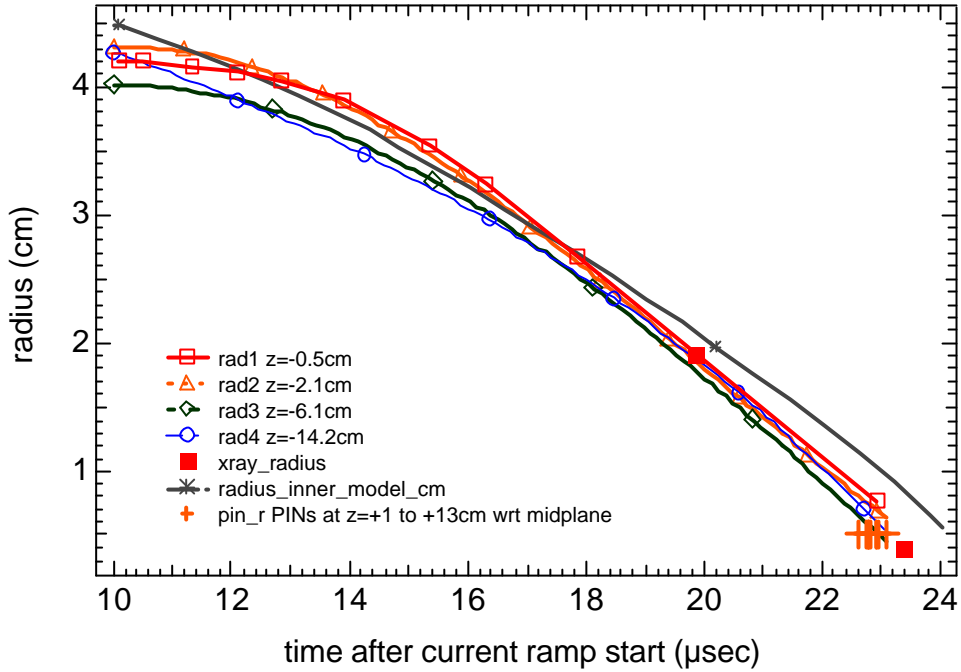


FIG. 4. Liner radius vs. time from magnetic probe data (rad1-rad4), radiographs, and impact probes showing agreement between all measurements.

### 3. Design of a high-density FRC target plasma injector

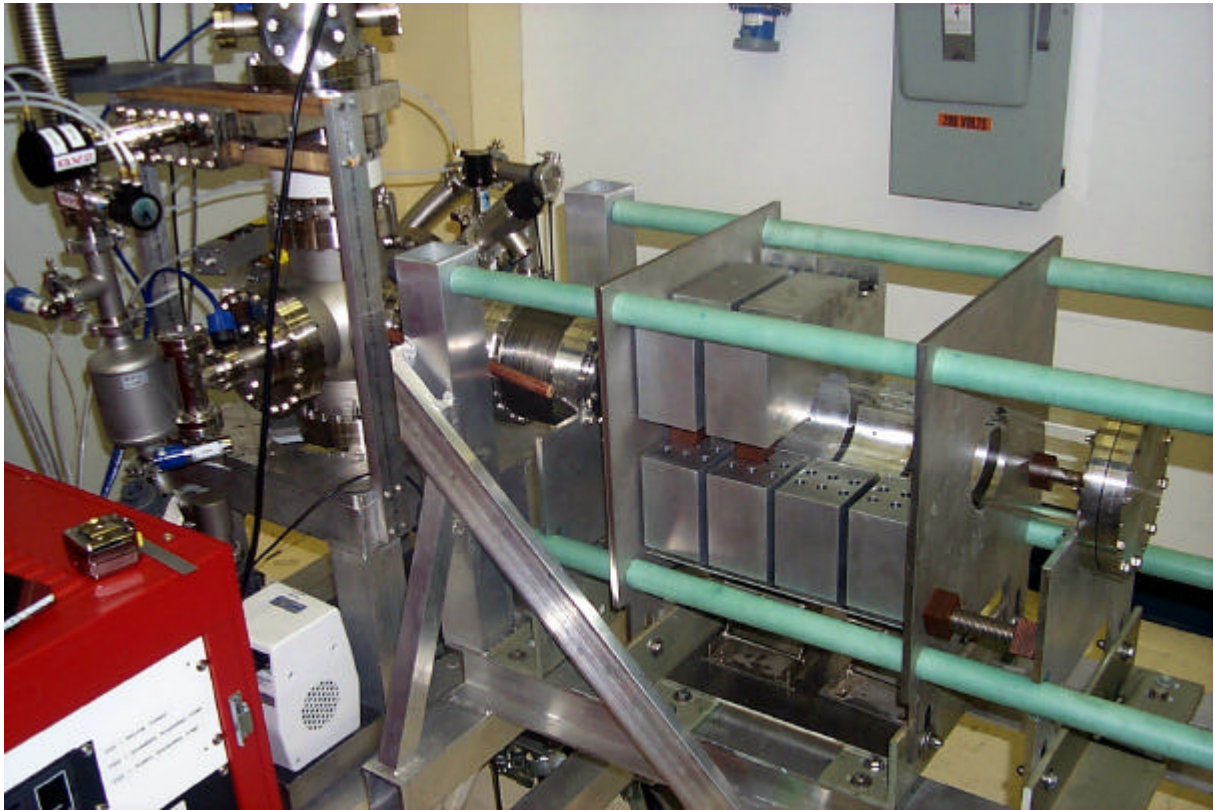
Adiabatic compression by a liner is an impressive means of plasma heating. Radial compression of 10:1 should increase FRC temperature from 250 eV to 10 keV. A zero-dimensional model that includes realistic losses [1] gives the predictions in Table I.

TAB. I: PREDICTED PARAMETERS FOR A PROOF-OF-PRINCIPLE MTF EXPERIMENT.

Parameter	Before compression	After compression
Liner radius (cm)	5	0.5
Separatrix length (cm)	30	4.2
B (T)	5.4	520
Density (cm <sup>-3</sup> )	$1.2 \times 10^{17}$	$3.5 \times 10^{19}$
Te (keV)	0.3	8.6
Ti (keV)	0.3	10.6
$\tau_E$ ( $\mu$ s)	28	4
S*/E	3.5	3.3

Experiments with FRCs in recent years have concentrated on large-dimension, millisecond time scales and low density ( $n \sim 10^{15} \text{ cm}^{-3}$ ). The higher-density higher-field parameters of Table I resemble early field-reversed theta-pinch experiments [10,11], which were not as well diagnosed as modern experiments. Therefore, a new high-density FRC formation experiment is under construction at Los Alamos to investigate FRC properties in the MTF regime of

parameters. An existing capacitor bank (Colt facility) is being modified to provide a 2.5- $\mu$ s-quarter-period 2-MA current pulse into a reverse biased 10-cm-diameter 30-cm-long coil. The coil and vacuum system is shown in Fig. 5. The FRC parameters of Table I are expected according to FRC formation models developed in recent years [6].



*FIG. 5. High-field FRC formation coil and vacuum system. A magnetic guide field allows the FRC formed in this coil to translate into a liner (not shown) [12]. Current feed plates from the capacitor bank to the coil are not shown.*

#### **4. Conclusions**

Experiments with the AFRL Shiva Star facility have now demonstrated most aspects of the necessary liner technology for MTF-relevant implosions. A new experiment at LANL will explore the properties of a high-density FRC injected into a liner with parameters needed for a proof-of-principle MTF experiment. In just a few years it appears that significant fusion energy gain (equivalent DT fusion yield between 1 and 10% of liner kinetic energy) could be produced by combining the FRC formation system with the liner implosion system on existing facilities. A  $Q \approx 1$  experiment would require more liner energy, but would not be expensive compared with conventional fusion approaches, and if successful, would pave the way for a qualitatively different and exciting pathway to practical fusion energy.

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