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Magnetized Target Fusion: A Burning FRC Plasma in an Imploded Metal Can

WURDEN Glen A., SCHOENBERG Kurt F., SIEMON Richard E.,
TUSZEWSKI Michel, WYSOCKI Fred J. and MILROY Richard D.[1]
Los Alamos National Laboratory, Los Alamos, NM 87545 USA
[1]U. of Washington, Seattle, WA 98155 USA

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Abstract

We are designing a compact (r = 5cm, l = 30cm), high density ($n \sim 10^{17}$–10^{18}cm^{-3}) Field Reversed Configuration (FRC) target plasma for Magnetized Target Fusion (MTF) experiments, using theta pinch formation techniques. The resulting FRC will then be translated into an aluminum liner for subsequent compression by implosion of the aluminum “can”. The stored plasma energy will be modest (~ 7.5kJ), with average plasma beta of 1, and an initial external magnetic field strength of 5.4T. Numerical modeling using the MOQUI FRC code shows that the required plasma can be formed using conical theta pinch coils, and our existing 0.25MJ Colt capacitor bank, and then translated in a few microseconds into the aluminum liner, where it is trapped by mirror fields. We hope to demonstrate 10-fold cylindrical compression of the plasma with an imploding liner, which should allow significant burn in the resulting (deuterium) fusion-grade plasma.

Keywords:

magnetized target fusion, liner implosion, pulsed power, field reversed configuration, proof of principle.

1. Introduction

We have proposed a three-year, $6.6 million per year, proof-of-principle (PoP) program to establish the scientific basis of Magnetized Target Fusion (MTF) [1,2] as a faster and cheaper approach to fusion energy. One version of Magnetized Target Fusion uses the kinetic energy of an imploding metal liner to compress a plasma, while the magnetic field in the plasma acts to suppress thermal conduction losses. To explore this truly different fusion concept (proposed initially by Kurtmullaev, et al. [3,4] in Russia in the early 70’s and 80’s), we will take advantage of compact toroid (CT) research developed by the magnetic fusion energy program (MFE) in the past 20 years [5,6]. The CT plasma is the target, which we will implode using well-established liner technology developed by DOE and DoD defense programs research in recent years. The magnetic topology of the CT should provide enough thermal energy confinement to allow compressional heating of the plasma to fusion-relevant conditions. Fusion energy will be generated in a micro-second pulse during which pressure (plasma and magnetic) is inertially confined by the imploding liner wall. This specific CT approach to small-size, high-density fusion (by MFE standards) is intended to prove the principle of MTF by achieving significant performance ($n\tau > 10^{13}$s-cm^{-3}, T ~ 5keV) in just a few years at modest cost using available pulsed-power facilities. Success in understanding will require both experiments and large-scale numerical computation.

Corresponding author’s e-mail: wurden@lanl.gov

Table 1 Summary of experimental research goals, issues, and requirements for FRC-based MTF.

Research Goals	Scientific/Technical Issues	Principal Facility	Principal Diagnostics
FRC formation Suitable for Compression $T \sim 300$ eV $n \sim 10^{17}$ cm^{-3} $\tau_E > 10$ µs	FRC formation at high density Stability for $S^*/E < 3.5$ Confinement $\tau_E \sim 0.5\, R^2/\rho_i$ Impurity Content $Z_{eff} < 2$	Colt (LANL)	Excluded flux B probe array Interferometry Thomson scattering Bolometry Optical spectroscopy
FRC Translation and trapping into a liner with $r_{wall} = 5$ cm, $r_s \sim 3$ cm $l_s = 30$ cm	Maintaining stability Impurity content	Colt (LANL)	B probe array Bolometry Interferometry Spectroscopy
Vacuum liner compression from $r_i = 5$ cm to $r_f = 0.5$ cm with $V > 0.3$ cm/µs	Rayleigh-Taylor and kink stability for $L/D \sim 3$, Convergence $R_i/R_f \sim 10$	Shiva-Star (AFRL)	3-axis radiography end-on framing photos magnetic probe pin arrays
Integrated Compression of FRC in liner to $T \sim 5$ keV, $n \sim 10^{19}$ cm^{-3} $\tau_E \sim 1$ µs	Stability Transport Impurity content (liner mix)	Shiva-Star (AFRL)	3 axis radiography End-on interferometry Spectroscopy Bolometry Neutrons

2. MTF Regime

The density regime and time scale of MTF is intermediate between MFE and inertial-confinement fusion (ICF). Three technical considerations explain why the regime is important. First, fusion reactivity scales as density squared, which can be increased by many orders of magnitude over conventional MFE. Second, all characteristic plasma scale-lengths decrease with density. Hence, system size is naturally reduced at a high density. Third, magnetic insulation greatly reduces the required power and precision to compressionally-heat plasma to fusion-relevant conditions compared with ICF, and brings the pulsed-power requirements within reach of existing facilities. Thus, we conclude the intermediate density regime holds promise as a new low-cost avenue to fusion energy. The future path for engineering development of MTF as an economic power source is less well defined than for the more mature approaches of MFE and ICF. However, a number of possibilities are being discussed, and our research program will include scoping studies to identify the most promising approaches.

Our research will be focused on several critical issues for application of a CT target plasma to MTF: formation of a target plasma at required density (~10^{17}cm^{-3}) and temperature (~300eV), stability during formation and compression, energy confinement adequate for fast liner compressional heating, and plasma impurity content and the general consequences of high-energy-density plasma-wall interactions. In pursuit of these research goals, Los Alamos will lead a multi-institutional team formed to elucidate the physics underlying these technical challenges. Our near term experimental efforts are outlined in Table 1. Los Alamos and the Air Force Research Laboratory in Albuquerque (Phillips site) form the experimental team who will develop the FRC plasma target and conduct liner experiments using primarily LANL experimental facilities for FRC target development and the AFRL Shiva-Star facility for energetic liner implosions.

3. Target Plasma

Our principal target plasma candidate is the field-reversed-configuration (FRC) [5]. The FRC offers the promise of robust, closed flux surfaces, capable of maintaining their topology during compression. Past experiments have demonstrated that an FRC can be translated and trapped in a liner implosion geometry [7]. Most importantly, formation of an FRC using high-voltage theta-pinch technology is well established, and appears likely to extrapolate to the required target requirements. The existing database for energy confinement scaling suggests the FRC will work well in an MTF application. The cylindrical geometry of the

FRC allows end-on diagnostic access even during energetic liner implosions. Finally, the FRC has the interesting property that when you squeeze on it radially, it actually contracts axially, due to field-line tension at the ends [8,9], hence a simple 2D implosion geometry effectively yields almost a 2.5D compression. All together, the physics base developed by over twenty years of FRC research gives confidence that FRC targets have a reasonable chance of being compressed to fusion-relevant conditions.

The experimental effort will consist of three phases: (1) the FRC is formed in a conical theta pinch, (2) the FRC is translated and trapped in a liner suitable for implosion, and (3) the FRC is compressed by the liner to high temperature and density. We are confident that we can form, translate, and trap the FRC in a region under the liner.

Initially, to quantify the plasma parameters desired, we use a Zero-D model for FRC performance. This 0-D model for cylindrical FRC liner (or wall) compression is based on past FRC research [10] and is very similar to that used in an earlier evaluation of FRC liner compression [11]. The calculation starts with an FRC at rest inside a liner and ends when a radial compression of 10 is achieved. The main assumptions of the model are that we have a 2-D elongated FRC equilibrium at all times, there is a thin liner with constant radial velocity v_L, that $S^*/E < 3.5$ at all times for stability, (where S^* is the ratio of the FRC separatrix radius to the average ion skin depth (c/ω_{pi}), and E is the FRC elongation parameter), FRC transport goes as $\tau_E \sim 0.5R^2/\rho_i$, $\tau_N \sim \tau_\phi \sim R^2/\rho_i$, (where τ_E, τ_N, τ_ϕ are the energy, particle, and flux decay times respectively, ρ_i is the ion gyro radius), and that liner resistivity and heating are included.

Table 2 Zero-D calculations of FRC parameters

Parameter	**Before compression**	**After compression**
coil radius (cm)	5	0.5
Separatrix radius (cm)	2.3	0.2
coil length (cm)	30	30
Separatrix length (cm)	30	4.2
B external (T)	5.4	520
peak density (10^{17} cm^{-3})	1.2	350
T_e (keV)	0.3	8.6
T_i (keV)	0.3	10.6
plasma energy (kJ)	7.4	80
τ_E (μs)	28	4
particle inventory (10^{19})	5.0	1.7
internal flux (mWb)	1.0	0.64
S*	23	35
E	6.7	11
S*/E	3.5	3.3

The last assumption affects diffusion of the magnetic field in the sheath separating the liner from the FRC into the liner. The FRC formation requirements are calculated a posteriori, assuming identical FRC parameters after formation and before compression. This implies translation at constant external pressure and equal dimensions for the formation and initial liner regions. Similar translation has been demonstrated [7]. An example of the initial and final FRC parameters obtained from the 0-D model is given in Table 2. Modeling of the formation and translation with the MOQUI code [12], which has previously been benchmarked with experimental data, is shown in Fig. 1. For the liner, we assume initial dimensions: 1-mm-thick aluminum, 30-cm-length, 10-cm-diameter; liner mass 250 g; liner velocity v_L= 0.3 cm/ms; liner kinetic

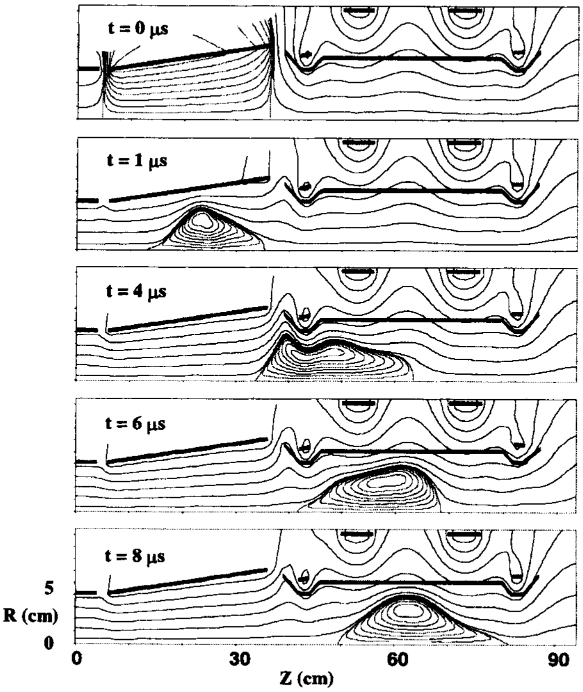

Fig. 1 MOQUI code simulation of FRC formation, translation, and trapping. The conical theta pinch coil is represented by the tilted line on the left, and the trapping (conducting liner) region is on the right. An axial guide field (shown by magnetic field contours) is present. The confined FRC plasma is automatically translated from the formation to trapping region by magnetic forces in less than 10 microseconds. The whole configuration is under 1 meter in length, and the bottom of each diagram is a cylindrical axis of symmetry.

energy: 1MJ; time to compression: 15μs; dwell time (r_f/v_L): 2μs. The FRC can be formed with a conical theta pinch coil of radius 4–6cm; length 30cm, using the LANL COLT capacitor bank, having a single feed at 32kV; with a corresponding electric field of 1kV/cm under the coil. The main field rise-time will be 2.5μs, and we would use a deuterium gas fill pressure of 300 mTorr, and a lift-off bias field of 0.8T. From (probably) optimistic Zero-D code (Table 2) parameters, the equivalent DT fusion yield is estimated at 0.1MJ, (or a neutron yield 3×10^{16} DT neutrons), corresponding to a Q (fusion/liner energy) ~ 0.1. Conservatively, this performance represents more than a ten-fold increase of the ntT triple product compared to the best existing FRC data.

4. Liner

High-speed liners (0.3–2.0cm/msec), composed principally of aluminum, are the best candidates to compress the FRC target plasma. We desire a solid (not liquid or plasma) metal liner during most of the implosion, as the strength of solid materials helps delay liner instabilities during its flight. Defense-program-developed imploding liners have demonstrated the speed and convergence required for MTF PoP experiments [13]. This knowledge base, coupled with well-benchmarked analytic and computational models of liner physics [14], provide confidence that liner performance suitable for an MTF program is in hand.

5. Summary

MTF embodies an exciting new direction for fusion energy development at small scale and low cost. It enables the study of plasma confinement physics over a relatively unexplored region of density and magnetic field strength with a view to advancing CT physics in particular, and fusion energy research in general. The readiness for an MTF Proof-of-Principle program is predicated on the maturity of compact toroid physics and liner implosion technology, as well as the potential to achieve significant plasma performance with existing facilities at modest cost. Given the present circumstances that have led to a restructured fusion program in the USA, in which innovations with lower-cost development are encouraged, we believe the logic of investigating MTF is both propitious and compelling. On the Web, click http://fusionenergy.lanl.gov for more details.

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