Physics Division Research Review

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FRX-L: A Plasma Injector for Magnetized Target Fusion

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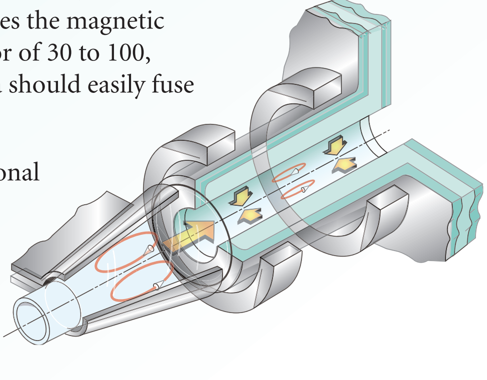
Since the early 1950s, Los Alamos National Laboratory (LANL) has conducted research into ways to achieve controlled thermonuclear fusion to eventually create a new energy source[1] for the benefit of mankind. In the last decade, LANL has largely focused on collaborating with other experimenters around the world to build and diagnose the most advanced (and usually quite large) experimental fusion machines. In the background, several scientists and very small teams at LANL have been developing a new fusion concept that could lead to a faster, better, and cheaper approach to fusion energy.[2] This concept, generically called "magnetized target fusion" (MTF), lies somewhere in-between the more established approaches of magnetic fusion energy (MFE), which uses large magnetic bottles to confine hot plasma for long periods of time, and inertial fusion energy (IFE), which uses lasers or ion beams to implode tiny fuel capsules in a few nanoseconds.

A Different Approach to Generating Fusion Energy

MTF offers the possibility of achieving useful thermonuclear fusion conditions with a radically different approach—combining features of both MFE and IFE. MTF has the potential of operating at higher fuel density and of being more compact than MFE while at the same time alleviating the huge power requirements needed for IFE. As such, MTF will enable the use of slower (and therefore cheaper) pulsed power that has (literally) been around for decades. This innovative method basically begins with the production of an initial "warm" plasma embedded in a magnetic field (Figure 1). This plasma is then injected into an adjacent region where it is compressed to thermonuclear conditions using pulsed-power technology developed by the Department of Energy's Defense Programs (DP) to study materials under very high-pressure conditions. The DP technology essentially "moves metal fast"—that is, a solid metal "liner" is imploded at extreme speeds. The region into which the MTF plasma is injected is surrounded by a thin aluminum cylindrical liner, which is then crushed in about 20 μs. The compression rapidly increases the magnetic field and the density and temperature of the plasma by a factor of 30 to 100, establishing thermonuclear conditions. As a result, the plasma should easily fuse and therefore release significant amounts of energy.

The ultimate goal of this research is to develop a fully operational pulsed-power fusion machine. The effort will combine 30 years of work at LANL to develop a class of plasmas called "compact tori," including one type, in particular, called the "field-reversed configuration" (FRC),[3] with 20 years of pulsed-power-technology development. To address this goal, we began an effort about four years ago to combine the required initial plasma and the liner implosion technology into a scientific effort that will hopefully lead to the first MTF physics demonstration.



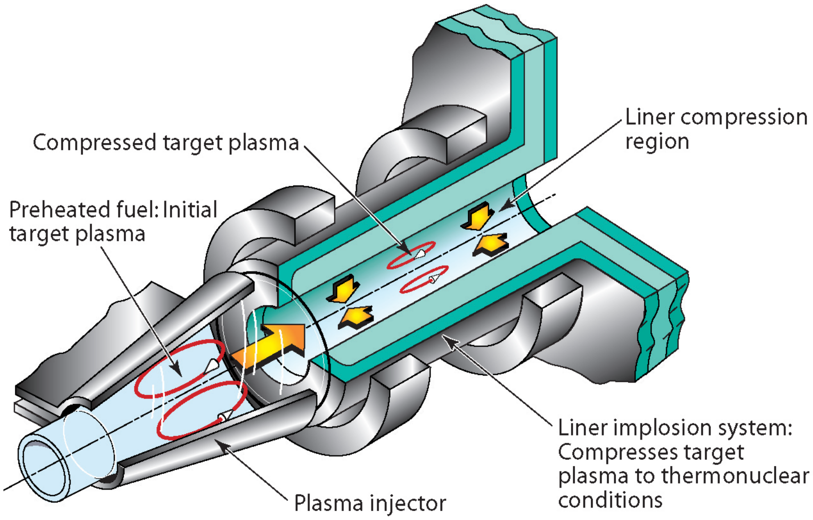


Figure 1. Rendering of MTF elements, including the initial target plasma, which is then injected into a liner compression region where the plasma can be compressed to thermonuclear conditions.

Efforts Toward a Field-Reversed Configuration Machine

The research program at LANL involves efforts (1) to demonstrate a suitable plasma injector, called the "FRX-L,"[4] where FRX refers to "field-reversed experiment," and the "L" refers to "liner," (2) to develop the "can crusher" at the Air Force Research Laboratory (AFRL) in Albuquerque, NM, and mate it to the plasma injector, and (3) to predict and model the plasma implosions using sophisticated computer codes with data from fast-plasma diagnostic tools.

FRX-L is designed to produce compact, high-density, field-reversed plasma configurations with parameters compatible with what is needed to serve as a MTF target (deuterium) plasma that has a density of ~ 1×10^{17} cm^{-3} and a temperature of ~ 200 eV at magnetic fields of ~ 3 to 5 T and a lifetime of ~ 20 µs. The FRX-L uses four high-voltage capacitor banks (up to 100 kV, storing up to 1 MJ of energy, see Figure 2) to drive a 1.5-MA current in one-turn magnetic-field coils that surround a 10-cm-diam quartz tube (Figure 3) where the target plasma is formed. We use a suite of sophisticated plasma diagnostics to ensure that the target plasma has the correct density, temperature, lifetime, and purity needed for use in MTF. Multi-chord laser interferometry measures the plasma density; high-power laser scattering (Thomson scattering) is used to measure the plasma temperature and density; a variety of plasma spectroscopy measurements are taken to determine the plasma purity; sets of external magnetic probes measure the plasma shape and pressure; bolometers measure the power radiated from the plasma; and fast imaging cameras view the plasma symmetry and wall interactions.

The entire FRX-L experiment is controlled from a shielded screen room, and data from approximately 100 channels of measurements are acquired on high-speed digitizers before being transferred to a database for display after each shot. During a day of operations, 20 to 30 shots (each lasting about 100 µs) can be fired under computer control. A blast door/wall separates the researchers from the high-voltage and high-energy conditions in the experiment. Red and yellow warning lights indicate the status of the experiment; meanwhile, experienced researchers often plug their ears when they hear the building announcement "Main bank is charging"!

Presently, plasma parameters at a density of ~ 2 to 4×10^{16} cm^{-3}, temperatures of 100 to 250 eV, magnetic fields of 2.5 T, and lifetimes of 10 to 15 µs are within a factor of 2 to 3 of our desired endpoints for the starting target plasma. In the coming year, while also improving the pulsed power and plasma performance, we will begin translating these plasmas into a test-liner chamber to confirm the plasma cleanliness and lifetime and our ability to trap the plasma in the close-fitting aluminum liner.

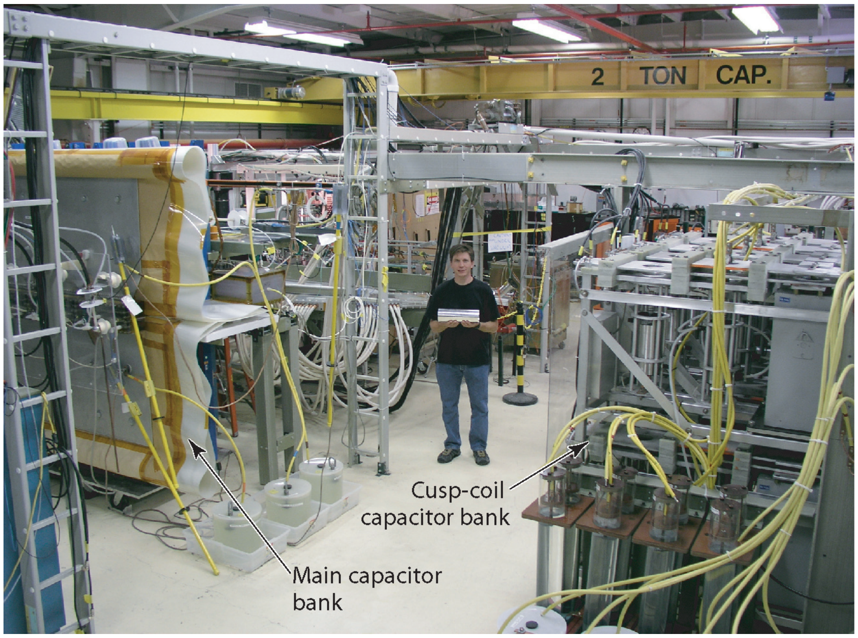


Figure 2. The FRX-L experimental bay, showing the pulsed-power electrical systems that supply energy to the plasma injector. Martin Taccetti (P-24) holds a full-scale aluminum liner in his hands. The main capacitor bank (to the left), delivers 1.5 MA of current to the theta pinch coils. Another bank (on the right) provides energy to the cusp coils.

Figure 3. The initial field-reversed configuration (FRC) target plasma is formed inside a small (10-cm-diam) quartz tube. One of our AFRL collaborators, Chris Grabowski, provides the scale for the target plasma by looking through the tube.

Conclusion

Recently we have submitted a proposed extension of the MTF project to the Department of Energy, which will authorize the goal of combining our plasma injector with the AFRL "Shiva Star" (Figure 4) liner-implosion system. With partners from the University of New Mexico, the University of Wisconsin, the University of Washington, and the AFRL, we plan to demonstrate fusion-relevant plasma conditions within this decade. The fusion plasma that we hope to produce (at a rate of about 1 shot per week in the laboratory) would be a clean deuterium plasma that will be confined by an enormous magnetic field of 500 T for about 1 μs and will reach a temperature of 5 to 8 keV and a density of $\sim 1 \times 10^{19}$ cm^{-3}! Success could lead to the first demonstration of break-even plasma conditions using magnetized targets in the Atlas liner-implosion facility at the Nevada Test Site in later follow-on experiments.

References

1. See http://fusionenergy.lanl.gov/
2. R.E. Siemon, I.R. Lindemuth, and K.F. Schoenberg, "Why MTF is a low cost path to fusion," *Comments Plasma Physics Controlled Fusion* **18**(6), 363–386 (1999).
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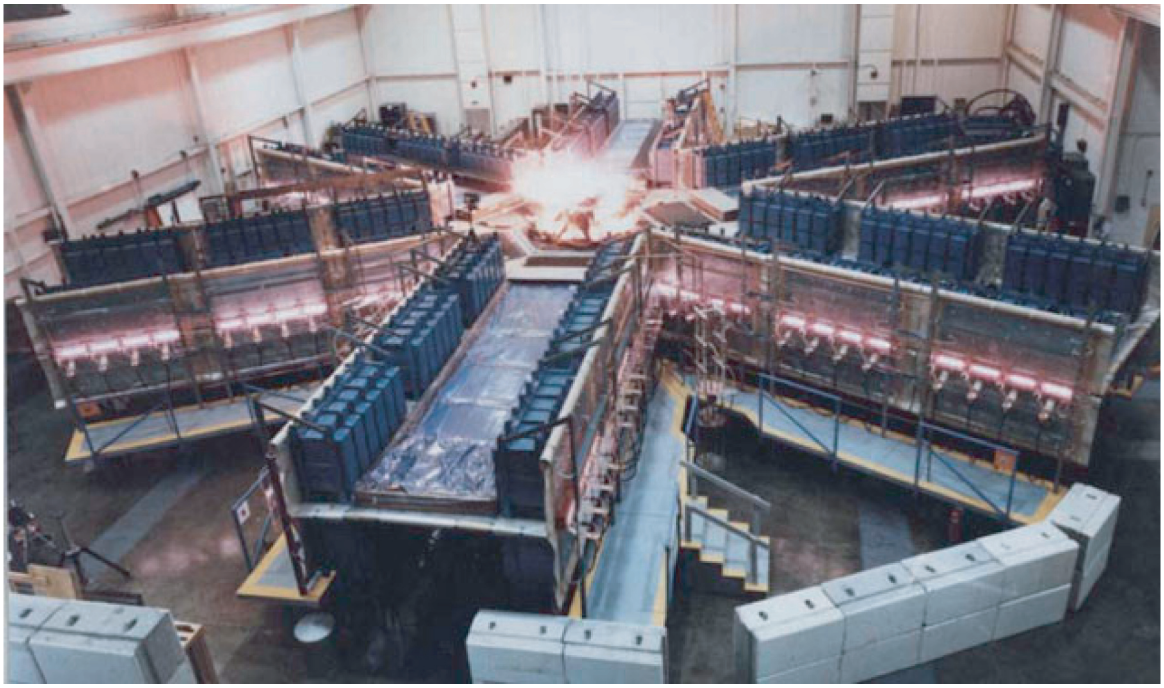

Figure 4. The AFRL pulsed-power machine "Shiva Star," which is about the size of two basketball courts, will be the site for the first combined LANL plasma injector and AFRL Shiva Star liner-implosion experiments earmarked for the 2006–2007 timeframe.

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