Magneto-inertial fusion: An emerging concept for inertial fusion and dense plasmas in ultrahigh magnetic fields

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An overview of the U.S. program in magneto-inertial fusion (MIF) is given in terms of its technical rationale, scientific goals, vision, research plans, needs, and the research facilities currently available in support of the program. Magneto-inertial fusion is an emerging concept for inertial fusion and a pathway to the study of dense plasmas in ultrahigh magnetic fields (magnetic fields in excess of 500 T). The presence of magnetic field in an inertial fusion target suppresses cross-field thermal transport and potentially could enable more attractive inertial fusion energy systems. A vigorous program in magnetized high energy density laboratory plasmas (HED-LP) addressing the scientific basis of magneto-inertial fusion has been initiated by the Office of Fusion Energy Sciences of the U.S. Department of Energy involving a number of universities, government laboratories and private institutions.

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1 Introduction

Assuming success in ignition in the National Ignition Facility, inertial fusion still faces substantial scientific challenges for commercial power generation. Economically practical targets and drivers remain to be found. Targets must be fabricated at high repetition rate on the fly and must produce sufficiently high fusion gain to overcome the low wall-plug efficiency of conventional inertial fusion drivers. The drivers must be rep-ratable and of reasonable cost. Magneto-inertial fusion (MIF) provides an additional knob in addressing both these challenges.

The essential ideas behind MIF have existed for a long time[1,2]. The concept involves freezing magnetic flux in the hot spot of an inertial fusion target or embedding magnetic flux in a target plasma bounded by a conducting shell serving as a magnetic flux conserver. In a manner similar to conventional inertial fusion, the hot spot or the conducting shell is imploded. As the shell or the hot spot implodes, the magnetic flux is compressed with it, thus the intensity of the magnetic field is increased. The intense magnetic field suppresses cross-field thermal diffusivity in the plasma during the compression, and thus facilitates the compressional heating of the plasma to thermonuclear fusion temperatures. The extremely high magnetic field created in the hot spot or the target plasma enhances alpha energy deposition in the fusing plasma.

There are two main classes of MIF, the class of high-gain MIF and the class of low-to-intermediate gain MIF. Both attempt to make use of a strong magnetic field in the target to suppress electron thermal transport in the target and thus rely upon the same scientific knowledge base of the underlying plasma physics. However, as we shall see below, their strategies for addressing the above two challenges of IFE, suitable targets and drivers, are different.

In the U.S., magneto-inertial fusion is currently being pursued as a science-oriented research program in high energy density laboratory plasma (HED-LP) by the Office of Fusion Energy Sciences (OFES) of the U.S. Department of Energy (DOE). The OFES HEDLP program aims to provide general stewardship of the field of energy-related high energy density plasma science. Dense plasma in ultrahigh magnetic field, or magnetized HEDLP, is one of the thrust areas of HEDLP[3]. By ultrahigh magnetic fields, we mean magnetic fields exceeding 500 T. Exceedingly strong magnetic fields are also present in astrophysical situations, and present theories suggest that their interactions with plasmas play an important role in many astrophysical processes including gamma ray bursts (GRBs), accretion disks, and astrophysical jets. Magneto-inertial fusion (MIF) is a pathway to create and study dense plasmas in ultrahigh magnetic fields. The OFES program in MIF is designed to be broadly based in order to address the broad spectrum of science in magnetized HEDLP.

In this paper, we begin by discussing the research activities and plans for high-gain MIF which is an evolution from conventional inertial confinement fusion (ICF). This is followed by a discussion of the extension of the MIF concept to the low and intermediate gain regime using pulsed power drivers with far higher driver wall-plug efficiency than conventional ICF drivers based on lasers or particle beams.

2 High-gain MIF

In conventional ICF, un-magnetized, cryogenic targets containing the fusion fuel are compressed to high density and heated to ignition. For ignition in central hot-spot ICF, the heating power into the hot spot must exceed the rate of heat loss from the hot spot[4,5]. Before the onset of significant fusion reactions, increasing heating power by compression implies increasing implosion velocity. Increasing implosion velocity lowers fusion gain for the same driver energy since less cold fuel is assembled, even though higher implosion velocity gives rise to higher hydrodynamic efficiency in converting the laser energy to the kinetic energy of the imploding shell. This is because the hydrodynamic efficiency increases more slowly than the kinetic energy of the shell with velocity. Higher implosion velocity also increases the in-flight-aspect-ratio (IFAR) of the imploding shell, which leads to higher growth rate of Rayleigh-Taylor (R-T) instabilities during the implosion. This impacts the choice of the in-flight adiabat (ratio of the plasma pressure to the Fermi degenerate electron pressure at the same electron density) in order to keep the R-T growth rate down to a reasonable level. A higher in-flight adiabat is needed to suppress the R-T instability. A higher in-flight adiabat lowers the achievable areal density (ρR) at peak compression which directly compromises on the burn fraction and thus further reduces the fusion gain. Laser-plasma interaction (in the case of direct drive) or the interaction of the x-radiation with the target (in the case of indirect drive) further complicates the choice of cryogenically compatible ablator. And finally, all these requirements have to be met in such a way as to allow for repetitive operations at several hertz. Therefore, any physics approach that lowers the implosion velocity for assembling the main fuel would greatly relax many of the design constraints, and is one of the key parameters in optimizing an inertial fusion energy (IFE) system. Fast ignition (FI), using a second pulse of energy to ignite a pre-compressed target to decouple ignition from fuel assembly is one approach to lower the implosion velocity. Magneto-inertial fusion (MIF) presents yet another approach.

The above reasoning has been made quantitative by Betti and Zhou[6] and Gotchev et al.[7] Following these authors, for unmagnetized direct drive using 0.35 μm laser light, Betti and Zhou[6] obtain a numerical fit for the hydrodynamics efficiency for the conversion of laser energy E_L to the kinetic energy E_k of the imploding shell as,

$$\eta_h = \frac{0.049}{I_{15}^{0.25}}\left(\frac{v_{imp}\left(cm/s\right)}{3\times10^{7}}\right)^{0.75},\quad E_k = \eta_h E_L \qquad (2.1)$$

and the areal density at stagnation as,

$$\rho R\left(\text{g/cm}^2\right) = \left(\frac{1.3}{\alpha^{0.55}}\right)\left(\frac{E_L(kJ)}{100}\right)^{1/3}\left(\frac{v_{imp}\left(cm/s\right)}{3\times10^{7}}\right)^{0.06} \qquad (2.2)$$

where I_{15} is the laser intensity in 10^{15} W/cm^2, and α is the in-flight adiabat. The numerical simulations were carried out for ten direct-drive cryogenic targets with 0.35 μm laser energies varying from 25 kJ to 1.5 MJ, in-flight adiabats from 0.7 to 3, implosion velocities from 1.7×10^7 to 5.4×10^7 cm/s and initial aspect ratios from 2 to 6, with the laser intensities around 10^{15} W/cm^2 (hence the intensity scaling is not numerical). The targets are either all DT ice or wetted foam CH(DT)$_6$ capsules with a 2 μm CH overcoat filled with DT gas at 2×10^{-4} g/cc. The laser pulse shapes vary from continuous to picket pulses and they are optimized to achieve maximum areal density. Substituting expression (2.1) into the generic definition for the fusion gain, $G = \frac{\varepsilon_f M\theta}{m_i E_L}$ where ε_f is the energy release per fusion reaction (17.6 MeV), M and m_i are the total mass and mean atomic weight of the fusion fuel respectively, and θ is the burn fraction, and using $E_k = \frac{1}{2} M v_{imp}^2$, Betti and Zhou[6] obtain an expression for fusion gain for unmagnetized direct-drive ICF under the above conditions as,

$$G = \frac{E_{fusion}}{E_L} \approx \frac{73}{I_{15}^{0.25}}\left(\frac{3\times10^{7}}{v_{imp}\left(cm/s\right)}\right)^{1.25}\left(\frac{\theta}{0.2}\right) \qquad (2.3)$$

where the burn fraction may be approximated as[5],

$$\theta \approx \frac{\rho R}{7+\rho R} \qquad (2.4)$$

with ρR given by (2.2). The above expression for burn fraction is valid only for a pusher-less target, and assumes that a rarefaction wave works its way from the outside of a bare sphere of burning DT fuel to the center quenching the burn.

For the same laser energy and intensity, the ratio of the fusion gains for two different design choices of the implosion velocity (v_{imp}) and the in-flight adiabat (α) can be obtained from the above expressions as,

$$\frac{G_1}{G_2} = \left(\frac{v_{imp,2}}{v_{imp,1}}\right)^{1.19} \left(\frac{\alpha_2}{\alpha_1}\right)^{0.55} \left(\frac{7+(\rho R)_2}{7+(\rho R)_1}\right) \qquad (2.5)$$

where the subscripts 1 and 2 correspond to the two design choices of (v_{imp}, α) respectively. The last factor is not a sensitive function of v_{imp} and α within the design range of interest. The expression shows that a lower implosion velocity significantly increases the fusion gain. Furthermore, for the same growth rate of the Rayleigh-Taylor instability, a lower adiabat can be chosen for a lower implosion velocity. This follows from the fact that stability of the implosion is governed mainly by the in-flight aspect ratio for which Betti and Zhou[6] give the following numerical fit from the same simulations as,

$$A_{if} = \frac{51}{\alpha^{0.6}} \left(\frac{v_{imp}(cm/s)}{3\times10^7}\right)^2 \frac{1}{I_{15}^{4/15}} \qquad (2.6)$$

For example, in the point design for a direct drive on NIF[8] using 1.5 MJ of 0.35 μm laser energy and with the design choices of $v_{imp} = 4 \times 10^7$ cm/s and an adiabat $\alpha = 3$ for stability, the above expressions give a fusion gain of 52 and an in-flight aspect ratio of 47. The fusion gain is not sufficient for IFE purposes. For IFE with conventional drivers, fusion gain of at least 100 is required[4]. Now, *if ignition can be made to occur* at a lower implosion velocity, say, 2.25×10^7 cm/s, then a lower adiabat $\alpha = 2$ can be used which results in an in-flight aspect ratio of 19, giving an implosion of much greater stability. Using only 0.75 MJ of laser energy, a fusion gain of 103 can be obtained from the above expressions. The challenge is to produce ignition with the lower implosion velocity. Without using a second fast pulse of energy as in fast ignition, one way to overcome this is to suppress the thermal loss rate from the hot spot with a sufficiently strong magnetic field in the hot spot.

Magnetic field suppresses electron thermal transport by causing the electrons to gyrate about the magnetic field lines with a gyro-radius that is inversely proportional to the magnetic field. If the magnetic field is sufficiently strong, even the ion gyro-radius becomes smaller than the electron collision mean free path and sets the spatial scale for cross-field thermal diffusion. With the smaller thermal diffusion length of the ion gyro-radius, thermal diffusion is slowed down. With the help of the Lindl-Widner diagrams and using Braginskii's expressions for the thermal conductivities in magnetized plasma and a model for the confinement of the alpha particles, Kirkpatrick et al.[9], show that ignition is possible with lower implosion velocity with magnetized targets, and produce estimates for the magnetic fields required. Magnetic fields from 1,000 T to 10,000 T (10 MG to 100 MG) are required for typical ICF scenarios. The extremely high magnetic field required is due to the high burn-time density in typical ICF targets.

Research is required to develop the scientific knowledge base on the physics of dense plasmas in ultrahigh magnetic fields and the capabilities in creating and applying ultrahigh magnetic fields to facilitate ignition in conventional ICF with lower implosion velocity and driver energy. Specifically, present research is directed at answering the following scientific questions:

- *How can strong magnetic fields be created in the hot spot of a conventional ICF target and what limits the intensity of the field that can be created?*
- *How strong a magnetic field is required in the hot spot of conventional ICF in order to suppress the thermal transport sufficiently to allow the implosion velocity to be significantly lowered while achieving ignition?*

In answering these questions, benchmarking computer prediction against experiments are required. Experiments are in progress at the University of Rochester to explore the answers to the first question using the OMEGA laser facility[7]. A seed magnetic field of the order of 10 – 15 T is generated by a large current flowing in small external coils surrounding the target. During implosion, the magnetic flux is frozen with the high-temperature conductive plasma within the "hot spot". As the hot spot is compressed, the flux is compressed with it to several thousand Tesla. Another method to create a seed magnetic field in dense plasma is by laser-driven current drive. Theoretical and computational research to explore the concept is underway at Princeton University[10].

3 Low and intermediate gain MIF

High gain MIF is potentially an evolutionary improvement on conventional ICF. Low-gain MIF seeks a completely different strategy. It trades fusion gain in favor of non-cryogenic gaseous targets and high-efficiency low-cost drivers, so that the very high gains and high costs traditionally associated with ICF may not be needed.

Electromagnetic pulsed power has lower power density than lasers or particle beams, but it has much *higher wall-plug efficiency* and much *lower cost per unit energy delivered*. By using both a magnetic field in the target and a lower-density target plasma, the required compression and heating power density is reduced to such an extent as to allow direct compression of the target by electromagnetic pulsed power. With considerably higher wall-plug efficiency, target fusion gain needed for economic power generation can be much lower than for conventional laser driven ICF. For example, if the wall-plug efficiency of the driver is higher than 30%, a fusion gain as low as 30 may be acceptable for IFE purposes[4]. By comparison, wall-plug efficiency of present-day laser drivers is about 1% and projected future laser drivers is typically below 8%. The lower fusion gain required for EM pulsed power driver allows the use of a lower plasma density for the fusion burn. Furthermore, with the lower implosion velocity, a material liner with inertia (mass) much larger than conventional inertial fusion can be used to contain the fusion burn. The greater inertia prolongs the duration of plasma confinement. This allows for a lower fusion burn rate and further lowers the density required for the fusion burn.

The idea is to lower the target density to the extent that gaseous initial targets could be used instead of cryogenic solid targets, allowing targets to be readily prepared and injected on the fly at high rep-rate. The strategy could potentially eliminate altogether the very challenging practical problem of high rep-rate fabrication of precision cryogenic solid targets. This would completely revolutionize IFE.

Solid and liquid shells (called liners) have been proposed for compressing various types of magnetized target plasma for low gain MIF in which fusion gain in the range of 10 – 30 is sought. Solid-liner implosion technology has matured over nearly three decades of defense research to apply magnetically driven metallic liners to create extreme material conditions, and is ready for experimental applications. For this reason, the principal effort in the current OFES program in MIF makes use of a solid liner to implode a magnetized plasma. This serves to open up the physics domain relevant to MIF applications for immediate investigations. Other type of liners such as plasma liner might prove to be more attractive for energy applications eventually, and have been proposed as MIF drivers to achieve intermediate fusion gain up to about 50.

3.1 Solid-liner driven MIF

One possible embodiment of solid-liner driven MIF is illustrated in Figure 1. A magnetized target plasma (plasmoid) is formed in a plasmoid generator, and is then translated and captured in a metallic solid liner. The solid liner is imploded by the magnetic pressure of a large pulsed current flowing axially along the shell (i.e. a z-pinch). The imploding liner compresses and heats the target plasma.

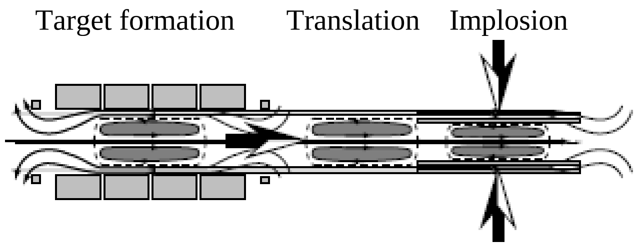


Figure 3.1 Schematic of solid-liner driven MIF

The physics basis for solid-liner driven MIF have been previously reviewed by several authors[9,11,12,13,14]. A variety of plasma configurations have been considered for the target plasma including field reversed configurations (FRC), spheromaks, diffuse pinches, etc.[15,16]. Because a sufficiently large database in FRC exists[17,18], current research in solid-liner MIF concentrates on using the FRC as the test target plasma. However, the FRC might not ultimately be the optimal target plasmas. Most theoretical studies (e.g. Lindermuth et al.[2]) suggest that the optimal density to burn a solid-liner compressed target is in the range of 10^{20} to 10^{22} per cm^3 and might prove to be too high for FRC targets. Other target plasmas such as the z-pinch, the diffuse pinch and spheromaks are possible and should be considered in future experiments.

For FRC as the target plasma, it is shown by Tuszewski et al.[19] that, due to tension in the magnetic field lines, the FRC contracts axially when it is compressed radially. As a result, an adiabatic compression of the FRC that conserves particles within the separatrix yields an average plasma density that scales as $r^{-2.4}$ where r is the radius of the FRC or the liner. If the compression is adiabatic and flux conserving, the following scaling relationships hold for the mean density (ρ), magnetic field (B), pressure

(p), and temperature (T) during implosion: $\rho \propto r^{-2.4}$, $B \propto r^{-2}$, $p \propto r^{-4}$, $T \propto r^{-1.6}$ where the ratio of specific heats γ has been assumed to be 5/3 in evaluating the relationships for the pressure and temperature. For the density and the magnetic field, the scaling expressions are independent of γ.

3D implosions of the FRC and other magnetized target plasmas may also be possible. One way is to use quasi-spherical liners instead of cylindrical liners[20,21]. Another approach is to tailor the thickness of an initially cylindrical liner to produce a cigar-shape implosion[11]. 3D implosion provides even more favorable scaling resulting in more attractive plasma parameters for the same radial convergence (ratio of initial to final radius): density grows as $1/r^3$, temperature grows as $1/r^2$ and the plasma β grows as $1/r$. (B still scales as $1/r^2$ as in 2D implosion since compression of magnetic flux is essentially a 2D effect).

Thus, even in a 2-D liner compression of an FRC in which the density grows as $1/r^{2.4}$ and temperature grows as $1/r^{1.6}$, a radial convergence of 5 to 10 would result in an increase in the FRC density by a factor of about 50 to 250, magnetic field by a factor of 25 to 100, pressure by a factor of 625 to 10,000 and temperature by a factor of 13 to 40. If the FRC has an initial temperature of about 200 eV and a pressure in the range of 6 to 60 bar, a magnetized plasma with a temperature in the multi-keV range and pressure nearly a megabar would be produced at peak compression. The corresponding initial density and magnetic fields are 10^{16} - 10^{17} per cm^3 and 1 to 4 T. Densities and magnetic fields at peak compression up to 10^{19} cm^{-3} and several megagauss (400 T) can be obtained. In the current research, the initial FRC is taken to be about 30 cm long and 10 cm in diameter. With 3-D liner compression, higher temperature, pressure, density and plasma β can potentially be attained.

Such plasmas would be very interesting objects for studies in the field of magnetized high energy density laboratory plasma (MHEDLP). The inner wall of the liner would be exposed to an intense magnetic field in the megagauss range with rise time of a few micro-seconds and a dense plasma with temperature in the multi-keV regime. The abrupt exposure of the conducting inner wall of the liner to the combination of the intense magnetic field and dense and hot plasma would compress a thin layer of the liner to a very high pressure (in the megabar range) and rapidly raise its temperature, possibly creating a layer of warm dense matter between the core of the liner and the FRC plasma. Phase transition of this layer of warm dense matter leading to ablation and ionization will dominate plasma-wall interaction of the compressed FRC plasma. The wall plasma will undoubtedly be strongly coupled. The transport of any impurities from the wall into the FRC plasma is a critical issue affecting the heating of the FRC, and could prevent the compressed FRC plasma from reaching fusion temperature.

With 3-D compression, β as high as 10 may be obtained. In general, obtaining and studying plasmas with say $\beta \sim 10$ is of scientific interest, with a number of connections with solar physics (sub-photospheric convection and reconnections) and astrophysics.

Current two-dimensional MHD simulations are able to reproduce gross dynamical features of liner implosion in reasonable agreement with experimental observation, including effects of the magnetic Rayleigh-Taylor instability and collisions between liners and solid targets, etc., etc.[22]. However, it is not yet known how well existing MHD capability will model the interactions between a liner and a magnetized plasma. 1D numerical study of the plasma-wall interaction has been made for an aluminum liner[23]. More precise and detailed experimental studies and 2-D modeling of the plasma-wall interactions are in progress[24].

Theoretical and computational results are availabvle on the transport properties of dense plasmas in high magnetic fields for MIF applications[23,25]. However, experimental data for benchmarking the theoretical and computational models and for guiding further development are few and far between.

For fusion applications, the ion gyroradius must be significantly smaller than the plasma radius (at least by a factor 15), as otherwise the classical ion thermal conduction makes the energy losses unacceptably high. So, ultimately the optimal target plasma (which might not be an FRC) may not be highly kinetic, especially given that the collision frequency is much higher than the growth rates of drift instabilities[25,23]. For the alpha particles, the kinetic effects are more important, but, due to relatively low electron temperatures in the MIF environment, slowing down times of the alpha particles are much shorter than those in tokamaks, and their relative contribution to pressure is quite small[26]. Therefore alpha particle driven instabilites, such as the TAE (toroidal Alfven eigenmode) instabilities, are unlikely to pose a threat in MIF systems. On the other hand, the global stability of the imploding plasmas (e.g., tilt and rotational instability of FRCs), for the parameter domain of high collisionalities characteristic of MIF plasmas, remains an open issue for MIF.

Research is required to answer the following scientific questions:

- *How does a high-density magnetized plasma behave when compressed by a metallic liner?*
- *What limits liner compression and dwell time?*
- *How do nearby boundaries (walls) affect the heating of the target plasma during the compression?*
- *What are the transport properties of magnetized plasma such as those that can be formed by liner compression?*

3.1.1 Experimental/Computational Facilities

Plasma generators to form magnetized target plasmas with temperatures in the range of 0.1-1.0 keV, and multi-megampere microsecond pulsed power systems for flux compression to generate megagauss magnetic field are required for performing the research. Parallel computer processor arrays and extensive code development are required to develop multi-dimensional numerical simulations of the integrated plasma and liner compression systems accounting for liner phase transitions, plasma stability, boundary plasma interactions, and the effects of radiative and resistive magnetohydrodynamics (MHD).

Figure 3.2 The Shiva-Star pulsed power facility is capable of delivering 12 MA in 10 μs for single-shot integrated MIF experiments.

In the next five years, the research needs are being met using existing experimental facilities with minor upgrades. The research highly leverages the pulsed power facilities and diagnostics capabilities available at the Los Alamos National Laboratory and the Air Force Research Laboratory at the Kirtland Air force Base (AFRL-Kirtland) in Albuquerque, New Mexico. The Shiva-Star pulsed power experimental facility (Figure 3.2) at AFRL-Kirtland includes a variety of capacitor banks, with the largest bank having a stored energy of 9 megajoules. It is capable of delivering current up to 12 MA with a rise time of about 10 μs. There are also substantial diagnostics capabilities including diagnostics for pulsed current, voltage, and magnetic field; rotating mirror and gated micro-channel plate fast photography; RF, optical, vacuum-ultra-violet, X-ray, gamma, and neutron spectroscopy equipment; pulsed radiography equipment; fast closure shutters and shielding to protect and enable use of these diagnostics in extreme blast and debris environments.

The Shiva Star experimental facility has already successfully demonstrated the implosion of an aluminum liner of the required geometry (30 cm long, nominally 10 cm in diameter and 1.1 mm thick) for compressing an FRC in 24 μs, achieving a velocity of 0.5 cm/μs, a kinetic energy of 1.5 MJ from stored capacitor energy of 4.4 MJ, and a radial convergence of 16 without observable Rayleigh-Taylor instability[22].

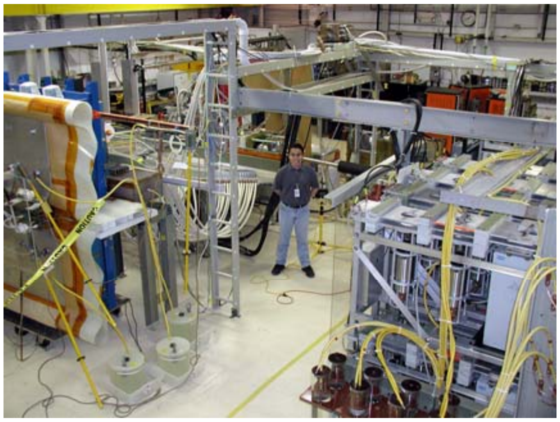


Figure 3.3 The FRX-L facility at the Los Alamos National Laboratory, Los Alamos, New Mexico.

The FRX-L facility (Figure 3.3) at the Los Alamos National Laboratory is a dedicated experimental facility for developing high-density, compact FRC as targets for MIF, including the translation and capture of the FRC by a metallic liner. The FRC is formed by a field-reversed theta pinch in a quartz tube about 0.5 m long and 10 cm in diameter. The facility is equipped with a number of capacitor banks: (1) to provide the initial bias flux for the FRC, (2) to produce a ringing magnetic field to pre-ionize the pre-filled gas, (3) to generate the reversed field for the theta pinch, (4) to provide the cusp field to seed the reconnection of field lines to form the FRC, and (5) to provide the guide field for translating the FRC. Detailed description of the facility can be found in Taccetti et al.[13] and Intrator et al.[27]. Experiments at FRX-L have produced FRC with densities of about 3 x 10^{16} cm^{-3}, temperature ($<T_e + T_i>$) of about 300 eV corresponding to pressure of about 30 bar with a lifetime of about 10 μs. The facility has been able to field about 800 shots per year on the average over the last four years. It has developed a considerable database for the FRC behavior for various combinations of bank voltages, trigger timing and pre-fill gas pressure. The best settings so far have resulted in about 35% - 50% of the main bank shots being good ones.

The next step is to combine the FRC generation technique developed at Los Alamos with the Shiva Star facility to perform an integrated liner-on-plasma implosion experiment to study and demonstrate compressional heating of the FRC to multi-keV temperatures and to achieve plasma densities in the 10^{18} cm^{-3} range. This experiment will be performed over the next few years.

At the University of Nevada in Reno (UNR), a 2-TW, 1-MA pulsed power generator (Zebra) and a 10-TW laser (Leopard) are available and are being used by the program to investigate the plasma-wall interaction resulting from exposing a conducting wall to intense magnetic fields[24].

3.2 Plasma-Liner Driven MIF

A potential improvement on solid-liner driven MIF is the use of plasma liner in place of the solid liner. Experiments using plasma jets produced by capillary discharges[28] (Figure 3.4) and in wire-array Z-pinch[29] (Figure 3.5) suggested that plasma jets can be merged to form an imploding plasma liner. The plasma jets may be launched in a standoff manner from the periphery of a vacuum chamber using a symmetrical array of plasma guns driven by electromagnetic pulsed power[16,30]. Staged Z-pinch[31,32,33] and theta pinch can also be used to produce cylindrical (2D) plasma liners. Slow, deeply subsonic plasma liners can also be created by electrothermal heating of a plasma shell to drive a cold heavy gas or dusty shell to moderately high velocity with high Mach number. The heavy or dusty shell implodes a conducting shell containing the magnetized target plasma[34].

Plasma liner formed by plasma jets provides an avenue to address three major issues of low-to-intermediate gain magneto-inertial fusion: (1) standoff delivery of the imploding momentum, (2) repetitive operation, and (3) liner fabrication and cost. It can potentially achieve faster compression and higher density for the compressed plasma than solid or liquid liners. It offers the opportunity for burning a thin cold fuel layer on the inner wall of the plasma liner to amplify the fusion burn[16]. The higher fusion gain from using plasma liner results from this intriguing possibility. For applications to HEDLP research, potential opportunities exist for forming strongly coupled and Fermi degenerate plasmas in substantial volume for convenient experimental probing of the plasma.

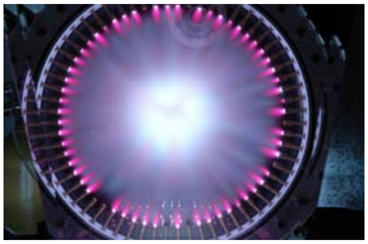


Fig. 3.4 Convergence of plasma jets to form an imploding plasma liner. (Witherspoon et al.[28])

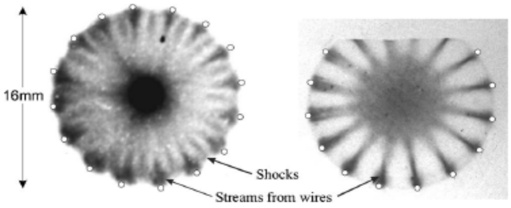


Figure 3.5. Cylindrically converging precursor plasma flow stagnating to form a compact plasma seen in wire-array Z-pinch. (Bott et al.[29])

Because there is no hardware obstruction to the target plasmas with the use of plasma liner, remote current drive by the use of lasers and/or particle beams can be applied to create the seed magnetic field in the target plasma. Plasma liner offers a clear view of both the liner and target plasmas, thus enhances diagnostic access making it easier to study these plasmas.

To produce an efficient target compression, it is essential that the dynamic instabilities during formation and implosion be well understood and controlled. The study of these dynamic instabilities may contribute to the understanding of dynamical processes found in astrophysical plasmas as well.

Potentially strong gradients and strong asymmetries in the plasma flow may arise from using discrete plasma jets to implode compact toroids or other magnetized targets. Computer modeling of the plasma dynamics requires the use of 3D meshless Lagrangian techniques, discrete particle-in-cell codes, adaptative mesh refinement (AMR) or some combination of these techniques. Extension and refinement of existing 3D SPH and hybrid PIC codes (LSP) to include resistive and radiative magnetohydrodynamics with appropriate transport properties, atomic physics and equation of states are required.

If the plasma liner is used to compress the magnetized plasma directly, very high Mach number (> 15) is required of the plasma liner in order to reach fusion conditions.

Research is required to address the following motivating scientific questions:

How can plasma be formed, accelerated and focused to form dense, high Mach number, high velocity plasma jets and plasma liner suitable for compressing a magnetized plasma to thermonuclear temperatures and for magnetized HEDLP research?

Do instabilities in the compression of a magnetized plasma by a plasma liner behave as predicted and how can they be controlled?

Coordinated research involving experimentation, diagnostic development, theoretical analyses and computational modeling are required to address these questions.

Preliminary theoretical analysis and computational modeling indicates the promise of using a plasma liner to compress a magnetized plasma based on analytical and semi-analytical models[16], 3D meshless Smooth Particle Hydrodynamics[30] (LANL SPHINX code), and extended MHD code[35] (Mach2).

Analytical studies of the concept are being extended at General Atomics, Lawrence Livermore National Laboratory and the University of Alabama in Huntsville. Further computer modeling studies of the concept using the 3D hybrid PIC code LSP are in progress at Far-Tech, Inc. and HyperV Technologies, Inc., the 2D MHD (MACH2) code at HyperV, and the 1D Lagrangian radiation-hydrodynamics ICF code (BUCKY) at the U. Wisconsin.

3.2.1 Experimental Facilities

To enable the formation of plasma liner by merging plasma jets, plasma accelerators (guns) capable of launching un-magnetized plasma jets with high momentum flux density and high Mach number are required. A pulsed power facility (Figure 3.6) is available at the HyperV Technologies Corp., Virginia, USA for developing new coaxial plasma guns with shaped electrodes[36] (Figure 3.7) based on the new mode of plasma acceleration proposed by Thio et al.[37]. The facility has successfully launched an un-magnetized plasma jet with a total mass of 157 μg at 70 km/s[28]. The facility has also a 2π array of miniature plasma jets produced by capillary discharges for studying jet interaction (Figure 3.4). Diagnostics include magnetic and light probes, high resolution spectroscopy, visible light imaging using a fast gated PI-MAX camera, pressure probes, and laser interferometry.

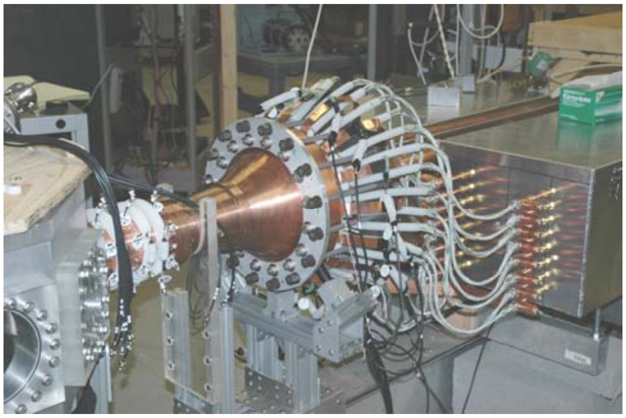
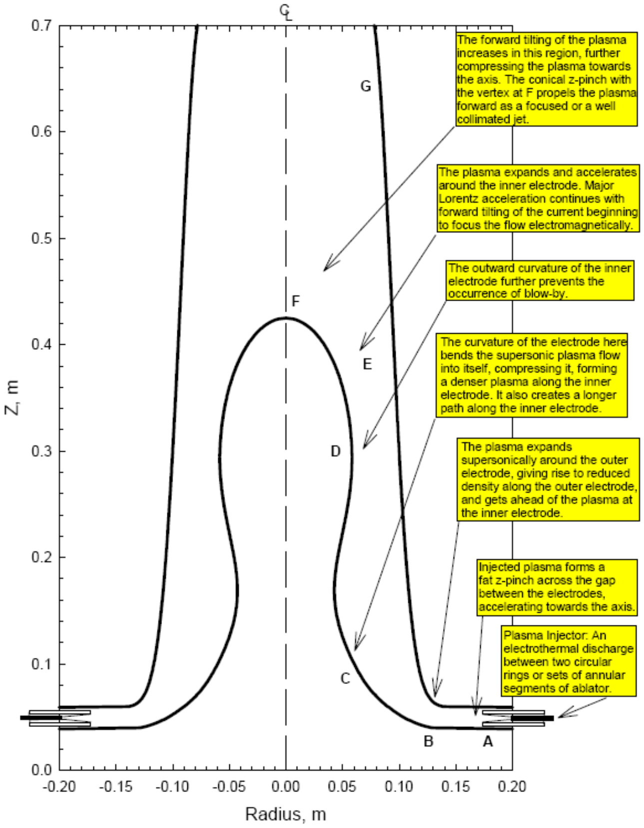


Figure 3.6 Facility at HyperV Technologies Corp. for developing advanced plasma guns to launch high Mach-number, high flux density plasma jets[28].



The forward tilting of the plasma increases in this region, further compressing the plasma towards the axis. The conical z-pinch with the vertex at F propels the plasma forward as a focused or a well collimated jet.

The plasma expands and accelerates around the inner electrode. Major Lorentz acceleration continues with forward tilting of the current beginning to focus the flow electromagnetically.

The outward curvature of the inner electrode further prevents the occurrence of blow-by.

The curvature of the electrode here bends the supersonic plasma flow into itself, compressing it, forming a denser plasma along the inner electrode. It also creates a longer path along the inner electrode.

The plasma expands supersonically around the outer electrode, giving rise to reduced density along the outer electrode, and gets ahead of the plasma at the inner electrode.

Injected plasma forms a fat z-pinch across the gap between the electrodes, accelerating towards the axis.

Plasma Injector: An electrothermal discharge between two circular rings or sets of annular segments of ablator.

Figure 3.7. Advanced coaxial plasma accelerator for launching plasma jets of high momentum flux density and high Mach number.

At UC-Davis, the acceleration of plasmas in the form of compact toroids is being studied in the CTIX facility. CTIX is a switch-less accelerator with the repetitive rate currently limited only by the gas injector[38]. Magnetized plasma with a density of 10^{16} per cm^3 has been accelerated to 150 km/sec in the 1.5m long accelerator at a repetition rate of 1 Hz. It is a reliable experimental facility supported by a suite of baseline plasma diagnostics, including sub-microsecond 2D imaging, and is currently capable of producing up to a thousand plasmas per day, without the need to replace or refurbish machine parts[39].

At Caltech, an experimental facility is available for addressing the fundamental science issues governing magnetic reconnections, MHD-driven jets and spheromak formation[40,41]. The research emphasizes experimental reproducibility, diagnostics, and achieving agreement between observations and first-principles theoretical models. The inter-shot time is 2 minutes, and a large number of shots can be taken without hardware damage.

The plan for the next 3 years is to demonstrate acceleration of plasma to form jets with velocity exceeding 200 km/s and Mach number greater than 10 and to conduct experiments to explore the physics of merging jets. Concurrently standoff methods to produce seed magnetic fields will be explored conceptually. If successful, research will continue in the next 5 years to increase the Mach number to 20 and to develop a user experimental facility with an array of plasma jets to form plasma liners for a variety of research. The research will include creating high energy density matter and compressing magnetized plasmas to reach keV temperatures and high magnetic fields.

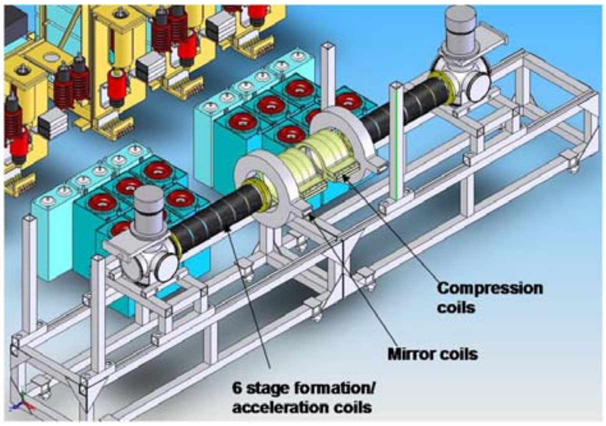


Figure 3.8 Schematic of the IPA experimental facility at MNSW, Inc. and U. Washington, Seatle, WA.

At MSNW Inc. and the University of Washington in Seatle, WA, an experimental facility is being established to generate a database on plasma-liner compression of a magnetized plasma (Figure 3.8). Two inductive plasma accelerators (IPA) have been constructed and tested forming a stable, hot (400 eV - 800 eV) target FRC with density 5 x 10^{14} cm^{-3} for compression[42]. 2D cylindrical imploding plasma shell will be created by theta pinch and will be available in the near future for experimental campaigns to compress the FRC. If successful, research will continue in the next five years to create high-density (> 10^{17} per cm^3) and keV magnetized plasmas for further research at the facility.

4 Summary

A program in magnetized high energy density laboratory plasmas (HEDLP) to address the scientific knowledge base of magneto-inertial fusion (MIF) has been initiated by the Office of Fusion Energy Sciences of the U.S. Department of Energy. The research addresses the main motivating scientific question:

- *How can an ultrahigh (>500 T) magnetic field be created in the dense target plasma of inertial fusion to lower the ignition requirement for implosion velocity and power density?*

The research involves a number of universities (U. Rochester, Princeton U., U. Nevada in Reno, U. Wisconsin in Madison, U. Washington, California Institute of Technology, U. California in Davis, U. Alabama in Huntsville, U. New Mexico), government laboratories (Los Alamos National Laboratory, Air Force Research Laboratory, Lawrence Livermore National Laboratory), and private companies (General Atomic, HyperV Technologies, Far-Tech, Voss Scientific, Prism).

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