Magneto-Inertial Fusion

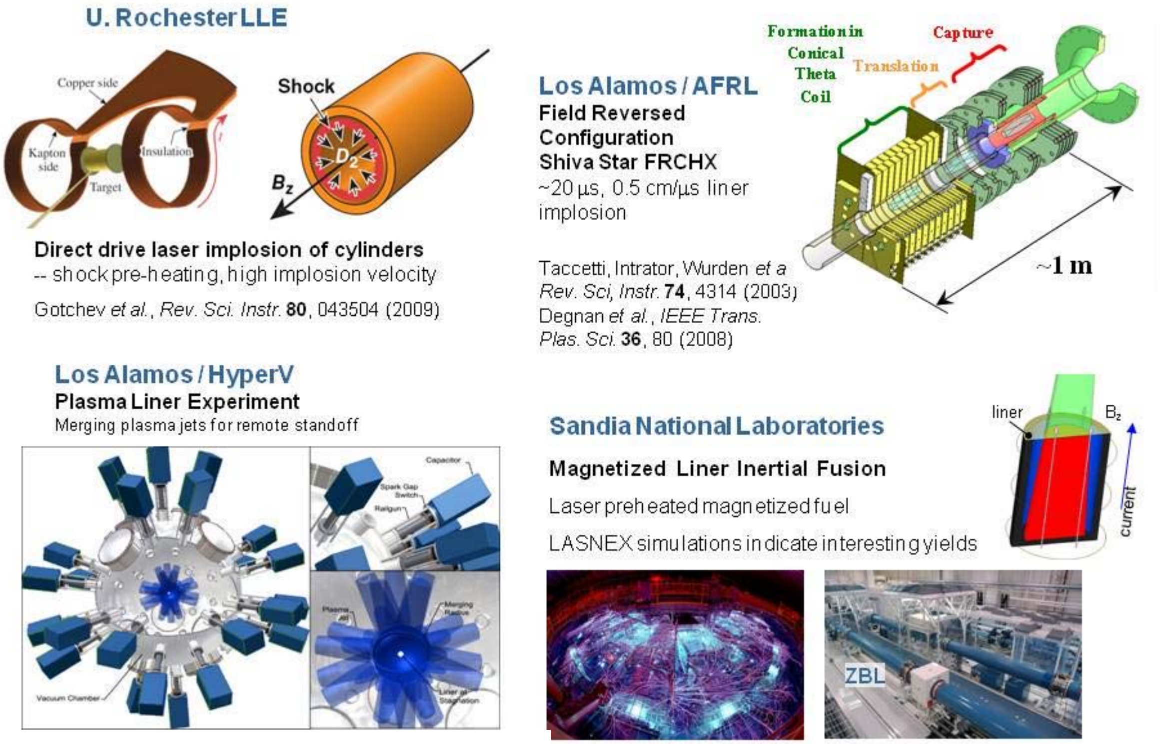
LA-UR-14-23844

G. Wurden, S. Hsu, T. Intrator (LANL), C. Grabowski, J. Degnan, M. Domonkos, P. Turchi (AFRL),
M. Herrmann, D. Sinars, M. Campbell (Sandia), R. Betti (U Rochester), D. Ryutov (LLNL),
B. Bauer, I. Lindemuth, R. Siemon (UNV, Reno), R. Miller (Decysive Systems),
M. Laberge, M. Delage (General Fusion)

Description

Magneto-inertial fusion (MIF) (aka, magnetized target fusion, or MagLIF) is an approach to fusion that combines the compressional heating of ICF with the magnetically reduced thermal transport and magnetically enhanced alpha heating of MCF [1]. From an MCF perspective, the higher density, shorter confinement times, and compressional heating as the dominant heating mechanism reduce the impact of instabilities. From an ICF perspective, the primary benefits are potentially orders of magnitude reduction in the difficult to achieve ρr parameter (areal density), and potentially significant reduction in velocity requirements and hydrodynamic instabilities for compression drivers. In fact, ignition becomes theoretically possible from $\rho r \leq 0.01$ g/cm^2 up to conventional ICF values of $\rho r \sim 1.0$ g/cm^2, and as in MCF, Br rather than ρr becomes the key figure-of-merit for ignition because of the enhanced alpha deposition. Within the lower-ρr parameter space, MIF exploits lower required implosion velocities (2–100 km/s, compared to the ICF minimum of 350-400 km/s) allowing the use of much more efficient ($\eta \sim 0.3$) pulsed power drivers, while at the highest (*i.e.*, ICF) end of the ρr range, both higher gain G at a given implosion velocity as well as lower implosion velocity and reduced hydrodynamic instabilities are theoretically possible. To avoid confusion, it must be emphasized that the well-known conventional ICF burn fraction formula does not apply for the lower-ρr "liner-driven" MIF schemes, since it is the much larger mass and ρr of the liner (and not that of the burning fuel) that determines the "dwell time" and burn-up fraction. In all cases, MIF approaches seek to satisfy/exceed the IFE figure-of-merit $\eta G \sim 7$-10, which implies an economical plant recirculating power fraction. A great advantage of MIF is indeed its extremely wide parameter space which allows it greater versatility in overcoming difficulties in implementation or technology, as evidenced by the four diverse approaches and associated implosion velocities shown in Figure 1.

We point out that lower-ρr based MIF approaches occupy an attractive region in thermonuclear ρ-T parameter space, as elegantly shown in a paper by Lindemuth and Siemon from physics first principles [2]. The center of the attractive region, which extends to more than an order of magnitude higher and lower densities, is at a density value that is approximately the geometric mean of ICF and MCF. A key point here is that burning plasma class MIF driver facilities, which already exist (e.g., Z/Z-Beamlet, or perhaps ATLAS), cost ≤US $200M compared to the multi-US $B ITER and NIF. These facilities can address much of the physics critical to MIF concepts, and may even be able to show fuel gains of order unity. For this reason alone, MIF warrants serious attention given our budget-constrained politico-economic climate. Furthermore, the density regime of MIF is in a relatively unexplored area of magnetized plasma physics and plasma/material interactions, thereby allowing a multitude of opportunities in plasma research in the HEDP Discovery Science.



S. C. Hsu et al., IEEE Trans. Plasma Sci. 40, 1287 (2012)

S. A. Slutz, et al., Phys. Plasmas 17, 056303 (2010)

Figure 1: MIF concepts presently being explored in the lab, in the USA

Status

The USA is a world leader in magneto-inertial fusion research. In the last ten years, there have been substantial advances and growing interest in MIF research and concepts. A team led by Los Alamos National Laboratory and the Air Force Research Laboratory has been investigating solid liner compression of magnetically confined field-reversed configuration (FRC) plasmas to achieve kilovolt temperatures [3-5]. The University of Rochester has introduced seed magnetic fields into the center of targets at the OMEGA laser facility, and compressed those fields by imploding a liner with the OMEGA laser to record values of magnetic field and demonstrated increases in neutron yields [6-8]. Sandia has proposed and is testing MagLIF (Magnetized Liner Inertial Fusion), in which a magnetically driven beryllium liner, imploded by the Z-machine, adiabatically compresses a laser-preheated magnetized DT target plasma [9-11]. In the very first series of MagLIF shots last year, > 10^{11}-10^{12} DD neutrons were observed, indicating significant improvement in target performance due to the presence of preheated and magnetized fuel in the target. The experiments also showed a significant DT yield (~10^{-2}) from a pure D_2 fuel, indicating magnetized of DD fusion-produced Tritons. Los Alamos leads a team that is exploring a standoff concept of using a spherically convergent array of gun-driven plasma jets to achieve assembly and implosion of a plasma liner (PLX) without the need to destroy material liners or transmission lines on each shot [12-15]. A private company, General Fusion in Canada, is developing a merging compact toroid plasma source and envisions rep-rated acoustic drivers that would drive a liquid liner through thick liquid walls [16-18].]. Much of the current MIF work can be traced back, at least in part, to the Russian MAGO program first revealed by Russian scientists when the Cold War ended (Lindemuth, *et al*., PRL 75, 1953 (1995)). The USA clearly has world leadership position in MIF research, but fledgling MIF efforts are also underway in China, France, and Russia. Russia has also stated that it is constructing a pulsed power facility at twice the current (~50 MA) and four times the delivered energy than Z to explore MIF concepts. These approaches span implosion time scales ranging from ns to hundreds of μs and all have substantially different “target physics” issues.

Current Research and Development (R&D)

R&D Goals and Challenges

An MIF grand challenge is to determine and quantitatively understand how driven or self generated magnetic fields can facilitate ignition or increase yield for a variety of inertial fusion schemes. For the wide range of plasma compression strategies there are several overarching physics goals that must be addressed. These include 1) whether suitable target plasmas can be formed and subsequently compressed and heated to thermonuclear temperatures; 2) what are the transport mechanisms for particle, energy and flux losses; and 3) characterization of the plasma boundary interface and the robustness and stability of initial target configurations. Each of these broad topics involves engineering and basic science components that overlap conventional MFE and IFE concerns. Since one major justification for pursuing MIF invokes simpler and less expensive implementations compared with conventional fusion approaches, practical cost considerations should be not be overlooked. As with ICF schemes, the cost of material that must be recycled versus consumed for each pulse (the “kopeck” problem) is an important issue.

Related R&D Activities

MIF reactor systems tend toward larger yields and lower repetition rates than conventional unmagnetized ICF, and most likely as a result will need to (and are able to) use liquid-walled chamber systems, which are also relevant for other ICF targets and drivers especially heavy-ion beam driven fusion. Liquid “fusion facing” walls have the potential to significantly reduce the “first wall” material challenges common for most mainline approaches to fusion energy. Present MIF work falls under the category of Magnetized High Energy Density Laboratory Plasmas, and its science is well documented in the recent FESAC HEDLP Basic Research Needs Report (2010) and the National Academy of Sciences Inertial Confinement Fusion report from 2013.

Recent Successes

At Rochester LLE, a fusion yield enhancement due to a compressed magnetic field that was externally introduced into the fusion fuel prior to the test has been unequivocally demonstrated experimentally using the OMEGA laser. The results are consistent with 1-D modeling estimates. In spherical implosions of solenoidal magnetic field with open field lines, a statistically significant neutron yield increase of 30% was obtained, and proton deflectometry measured a compressed magnetic field of 23 Megagauss in similar spherical implosions. If magnetic field with closed field lines could be introduced in the same target plasma, calculations show a factor of 2 to 4 increase in neutron yields is expected. In previous cylindrical implosions, magnetic field in excess of 70 Megagauss was detected. In all of these experiments the initial applied axial magnetic field is ~10 Tesla (0.1 MG). The density in these experiments is not optimum but serves as an example of the wide range of densities over which MIF might operate.

A deformable liner system has been developed and tested at the Air Force Research Laboratory (AFRL) on Shiva Star, and a field-reversed configuration (FRC) plasma target has been developed at Los Alamos and ported to AFRL. Modeling by NumerEx, LLC with MACH2 of the overall system, from plasma formation through compression within the liner, has been guiding the experiments. The first integrated plasma/liner engineering test of the Field-Reversed Configuration Heating Experiment, or FRCHX, on Shiva Star was performed in April 2010, but for this test the plasma lifetime was too short compared to the compression time. After extensive diagnostic studies and a series of improvements were implemented, most notably the inclusion of a longer capture region, the lifetime of trapped flux within the FRC was improved such that it was now comparable to the implosion time [19], and an integrated compression test was conducted in Oct. 2013. The FRC was compressed cylindrically by more than a factor of ten, with density up more than 100x, to $>10^{18}$ cm^{-3} (a world FRC record), but temperatures were only in the range of 300-400 eV, compared to the expected several keV. Although compression to megabar pressures was inferred by the observed time and rate of liner rebound, we learned that heating rate during the first half of the compression was not high enough compared to the normal FRC decay rate. Principal diagnostics for this experiment were soft x-ray imaging, soft x-ray diodes, and neutron measurements.

The 80-terawatt Z facility at Sandia National Laboratories is the world's largest stationary pulsed power facility, capable of generating up to 26 million Amperes of current in a ~100 ns pulse. These large currents can be used to create large magnetic fields (~5000 Tesla) and pressures (~100 Mbar) in mm-scale targets. The Z facility supports a wide variety of stockpile stewardship experiments, including measuring the equation of state of materials under extreme conditions, developing intense radiation sources for testing, and inertial confinement fusion research. The particular form of magneto-inertial fusion being tested at the Z facility is a relatively new concept known as Magnetized Liner Inertial Fusion (MagLIF). Sandia Z experiments and 2D and 3D modeling with small solid liners for MagLIF, an NNSA supported project, have begun. MagLIF uses a low aspect ratio (liner outer radius/liner thickness ~ 6) beryllium liner to compress a laser-initiated axial plasma embedded in an axial magnetic field. In the MagLIF concept, a magnetically imploded, cylindrical metal liner is used to compress fusion fuel that has been magnetized by an externally applied axial field (10-30 Tesla) and preheated to ~100-300 eV using a laser (other preheating concepts are also being explored). Simulations indicate it is possible to achieve 100 kJ DT fusion yields on the Z facility, a yield comparable to the energy coupled to the fusion fuel, at fuel pressures of about 5 Gigabar. To do this will require a 26-MA drive current, about 6-10 kJ of 0.532 μm laser energy delivered over 8-10 ns, an applied magnetic field of 30 T, and DT fuel. Scaling studies suggest that gains of relevance for fusion energy may be possible on a future > 61 MA pulsed power facility using similar preheat and magnetic field parameters. A smaller facility (~ 47 MA) could produce fusion yields from volume DT burning in the tens of MJ range. Success with Z experiments is essential for moving forward. Over the past six months, the first fully integrated MagLIF experiments were conducted using deuterium fuel, a drive current of about 18-20 MA, external field coils delivering up to 10 Tesla magnetic fields over a several cm^3 volume, and 2-2.5 kJ of laser in about 2 ns using the Z-Beamlet laser irradiating a 3 μm thick foil covering the laser entrance hole. The foil is necessary to keep the 0.8 mg/cc D_2 gas in the Be liner. Off-line experiments showed that only 100-300 Joules of the laser and was transmitted thru the foil to preheat the fuel. These experiments successfully produced significant DD fusion yield (~ $5x\ 10^{11}$ to $2x\ 10^{12}$), high ion temperatures (> 2-2.5

keV), high electron temperatures (~3.5 keV), and significant secondary 14.1 MeV neutrons arising from triton burnup. Additional imaging and time resolved x-ray measurements show strong stagnation of the fusion fuel, all occurring with implosion velocities of only ~70km/second. The data is consistent with significant flux compression and magnetized electrons and tritons.

To test the possibility of a standoff driver (one without physical leads to the liner thus avoiding repetitive hardware destruction), a plasma liner formed from multiple plasma jets [12] is being pursued at Los Alamos. A 9’ (2.7 m) diameter spherical vacuum chamber is the centerpiece of the Plasma Liner Experiment (PLX) facility at LANL[13], which is presently conducting basic plasma shock experiments [14,15] using two plasma railguns that were developed by HyperV Technologies Corporation. The PLX team has and is continuing to refine a 36-60 gun experimental design that aims to address the key MIF relevant scientific issues of spherically imploding plasma liners as a standoff driver. The near-term objectives of plasma liner experiments, if funding can be secured, would be to (i) obtain experimental data on the scaling of peak liner ram pressure with initial plasma jet parameters, (ii) characterize liner uniformity and explore methods to control uniformity, and (iii) explore techniques to form liners with the needed thickness and profiles to enable reactor-relevant energy gains for the plasma liner driven MIF concept.

The Canadian private company General Fusion has been exploring the compression of spheromak plasmas via sonically driven shock waves into a fluid lead-lithium liner. The company has constructed and tested elements of their acoustic system, achieving milestones for the energy input (125 kJ/piston) and timing control required on their driver (+/-5 us). General Fusion is also operating a relatively large (100 kg/s) molten lead loop for liner formation. In the near term they have successfully injected 200-300 eV magnetized spheromak plasmas into their capture region, and kept these plasmas confined there for over 500 μs, more than 3x the implosion timescale. Most recently, they have begun high-explosive driven liner tests at a contractor facility. During compression, only a 3x increase of the initial magnetic field was observed. Analysis indicates this disappointing result was most likely due to plasma impurity problems. They are trying to resolve these impurity problems (due to delamination of gettering coatings on the inside surface of the liner). While no measurable neutron yields have been achieved to date, work is continuing.

Budget

Historically MIF budgets under FES auspices were recently as large as $7M per year nationally, out of a $25M/year HEDLP effort. Due to recent FES reprioritization towards ITER and tokamaks in FY14, this funding level has been zeroed. We would like to see this decision, which was taken without review or community input, reversed, so that FES continues to steward MIF research, even at Discovery Science levels.

Anticipated Contributions

- ***Energy Concepts*** — Given the limited funding, the long-term application of MIF to energy production has not been examined at a systems level as extensively as conventional magnetic or inertial fusion, and the metrics are less well defined. At a high level, MIF yields in the gigajoule range would allow operation at a lower repetition rate than conventional ICF, though the plasma liner-driven MIF concept is somewhat intermediate and aims for yields well below 1 GJ but with a ~1 Hz rep-rate. Physics challenges in designing and testing target concepts that can achieve these fusion yields and gains have been identified. Much of the work on recyclable transmission lines contained in the Z-IFE four year reactor design effort, led by Sandia, is applicable to several of the pulsed power MIF concepts. Several energy approaches are being studied. Pulsed compression using a circulating liquid metal similar to the early LINUS concept is one approach. Low-cost re-fabrication of electrical leads together with a liquid blanket as proposed in the 1978 Conceptual Fast Liner Reactor Study is another. Stand-off delivery of power by plasma jets, lasers, ion beams, or electron beams is a third.

- ***Science*** — The intermediate density and pressure regime in which MIF resides, which differs by several to as much as 5 to 6 orders of magnitude from both MCF and ICF, requires a detailed understanding of the behavior of energy, particle, and field transport in high beta plasmas. Flux compression enables the generation of extreme magnetic field values in systems with currents presently available. Can we compress fields to >100 Megagauss? Ultrahigh magnetic fields change the properties of the matter in surprising and often hard-to-predict ways. The Magneto-Rayleigh Taylor instability is a key issue which we address in liners. Magnetized High Energy Density Laboratory Plasma physics (MHEDLP) is a relatively unexplored and intellectually rich plasma regime, which is ripe for near-term discoveries, and has also been identified as one of four "cross cutting areas of HEDP of interest to the missions of Federal agencies" [20]. In addition, significant overlap exists with other areas of inquiry, including materials science at high pressures, and the basic science of astrophysics. MHED plasmas that are large compared to the ion gyroradius, at multi-keV temperatures, are enabled in the laboratory by MIF. Recent experiments on MagLIF at Z/Z-Beamlet have seen DT/DD fusion yield ratios suggestive of magnetized ions in the compression DD plasma.

Near Term (≤5 years)

Near-term research should focus on continuing to explore the science of MIF and to demonstrate quantitative understanding of plasma lifetime, heat and field loss, and implosion physics. Research is also needed on efficient drivers capable of both peak and average power performance, such as Linear Transformer Drivers (LTDs). Magnetized targets need continued improvements in pre-compression lifetime and density for virtually all MIF concepts with microsecond-scale or slower implosions. For robust performance, the energy confinement time of the pre-compression target should be an order of magnitude longer than the implosion time. While dedicated and focused efforts are needed for improving target parameters, any effort must also consider compatibility of the target formation and delivery with the specific driver, at all steps of the R&D effort. There is renewed interest in magnetized ICF by both LLE and LLNL, and finally a standoff plasma liner driver concept has received much theoretical/modeling attention in recent years and is ready for experimental investigations.

For the more mature integrated concepts such as the LANL/AFRL solid liner/FRC or Sandia's MagLIF, the highest priority near-term scientific issues are well-defined. The highest priority for the LANL/AFRL effort is to improve the target lifetime and density by factors of 2–3 for better mating with the ~20-µs implosion time of the solid liner on the Shiva Star capacitor bank. For MagLIF, integrated implosions with meaningful neutron yield have already been carried out, and a more quantitative understanding of the physics, especially target pre-heat, B field and thermal energy loss during implosion and acceleration/deceleration-phase interfacial instabilities/mix, is needed. It will also be important to see how target performance behaves with increased laser preheat energy, gas density, axial B field and Z current for continued performance improvement.

Although no experiments have been performed to date, simulations indicate that if NIF implosions are to achieve ignition, magnetizing the fuel may be beneficial. At the high-density regimes of ICF, the main benefits differ from those of lower-density MIF concepts. For magnetized ICF, a magnetic field provides modest benefits simultaneously in several respects, such as thermal insulation and reduction of instability driven mix. Dedicated efforts to explore a much larger target design space and focused experiments to validate the beneficial physics, are needed to fully exploit these physics benefits in integrated shots. Magnetic field coils already exist at LLE/OMEGA and a prototype is under design/construction at LLNL/NIF, thus there are good prospects for near-term advances in magnetized ICF. Limited experiments on Omega where hohlraums have been "magnetized" have also shown improved laser coupling and a reduction in laser-plasma instabilities (LPI) such as Stimulated Raman Scattering. These improvements are likely due to modifications in the electron density and temperature of the under-dense plasma within the hohlraum.

MIF would also benefit significantly from a standoff, high-repetition-rate driver, which would improve the chances for an economic MIF-based fusion reactor. The use of a dynamically formed imploding spherical plasma liner has received attention recently [21]. The science and technology are ready for initial experiments to demonstrate the feasibility of forming imploding plasma liners via merging supersonic plasma jets, and to explore the ram pressure scaling and uniformity of these liners in order to assess their potential as a standoff MIF driver. The Plasma Liner Experiment (PLX) facility at LANL has the needed infrastructure, including a 9' diameter spherical vacuum chamber, multiple diagnostics, and a good portion of the needed capacitors, to carry out 36-60 jet experiments. Accompanying studies on standoff-driver compatible targets could also be initiated, e.g., laser beat-wave magnetization [22]. As mentioned above, further development and demonstration of LTD's would also be appropriate.

Many of the techniques being proposed for "MIF" are Rayleigh-Taylor unstable in the final compression. These include the spherical compressions of General Fusion and plasma liners, and the inner surface of the MagLIF liner. On the other hand, stabilized liquid liner implosions, demonstrated at the Naval Research Laboratory in the seventies [23-24] offer the opportunity to achieve repetitive megagauss-level operation while avoiding the "kopek" problem of replacing solid-density liners and their associated connections. The thick, rotating liquid liners provide the replenished first-wall and blanket in reactor concepts. Advances in material strength since the time of the NRL experiments now offer the opportunity for much higher drive pressure (25 kpsi vs 3 kpsi) and faster speeds for the liner compression of a target plasma.

NNSA sponsors the MagLIF efforts at Sandia. Higher performance MagLIF implosion experiments (after present optimization testing) need the Z-Beamlet laser energy upgrades to 6-8 kJ of 0.532 um light, axial B fields to 30 Tesla, and Z current increased to 26 MA to be completed. Improved diagnostics are also required. Assuming success with the physics tests and an increased funding level, a series of near-break-even (DT equivalent fusion energy release equal to the energy in the imploded fuel) tests could be done in the 2016-2019 timeframe with the Sandia Z-machine for MagLIF or with Los Alamos explosively-driven pulsed power generators using solid liners and FRCs or other suitable plasma formation schemes. The Canadian company General Fusion has accelerated spheromak targets that should be suitable for shockless compression tests. An ignition-class laser driven MIF experiment could be fielded on NIF. An interesting aspect to MIF is that university-scale experiments (such as at the UNR Nevada Terawatt Facility) can test some MIF target physics. Success in the laboratory would give strong incentive for expanded work on technologies needed for economic energy production. We note that in 2013, a white paper was submitted to the FESAC Facilities panel, for a pulsed power test facility called "Prometheus" [25], capable of DD break-even equivalent experiments, at the $100 M scale.

Near Term (≤10 years)

With aggressive progress in the near-term, credible scientific breakeven attempts as described above, could be made with the lower-density concepts, and ignition attempts could be fielded for dedicated magnetized ICF target designs on NIF within 5 years. If these efforts are successful, facility upgrades for the lower density concepts in the 5-10 year timeframe would be justified to reach higher gains.

From a development perspective, MIF can be viewed as a broader class of ICF possibilities that are characterized by reduced demands on drivers and target performance, although with the complication of adding the B-fields. Possible MIF embodiments range from FRC or spheromak target plasmas, to MagLIF, to ICF targets with B-fields, to a class of Z-pinch like wall-confined plasmas represented by the Russian MAGO configuration. Imploding plasma liners offer exciting and untested possibilities such as composite jets/liners carrying the DT fuel and eliminating the need to separately form a target, liners with shaped profiles, and delivery of additional cold fuel for amplified burn and gain. Heating is possible with liner driven implosions or stand-off laser beam or particle beam drivers with reduced power and intensity requirements compared with conventional ICF. Development can proceed rapidly because the necessary scientific studies (including burning plasma physics) require no new billion-dollar-class facilities. *Furthermore, successful implementation of liquid-wall based reactor concepts also eliminates multi-B$ materials research and development requirements.*

Proponents' and Critic's Claims

Proponents are excited because MIF offers a potentially affordable and attractive path to burning plasma experiments and an intriguing and generally unexplored possibility for practical fusion energy. MIF allows the possibility of more compact fusion systems, the use of thick liquid blankets (no neutron damage problem), a fresh plasma/wall interface on each pulse, and a lower cost development pathway. MIF strengthens the ICF fusion portfolio because it represents both an extra knob on existing targets, and enables fundamentally different approaches. So far no physical limitation has been identified that precludes developing MIF as a practical fusion energy system, and several promising development pathways have been identified. Critics argue that pulsed systems (like conventional ICF and MIF) are unlikely to meet the practical requirements for pulse repetition rate and cost per target, especially in the case of MIF, if it involves replacement of liner hardware on every pulse. There are also technical concerns that high-Z liner material will mix rapidly with the relatively low-density fusion fuel, leading to unacceptably large radiation losses. MIF, having far less total funding invested, is understandably less scientifically mature than conventional MFE and ICF approaches.

References

[1] K. F. Schoenberg, R. E. Siemon, R. J. Bartlett, R. R. Bartsch, C. A. Ekdahl, R. J. Faehl, J. Finn, R. A. Gerwin, R. Kirkpatrick, I. R. Lindemuth, R. W. Moses, R. E. Reinovsky, K. F. Schoenberg, P. T. Sheehey, J. S. Shlachter, M. G. Tuszewski, G. A. Wurden, and F. J. Wysocki, J. Degnan, G. F. Kiuttu, E. L. Ruden, and P. Turchi, P. Parks, J. H. Hammer, R. Moir, D. Ryutov, Y. C. F. Thio, R. D. Milroy, L. Green, "Magnetized Target Fusion, A Proof of Principle Research Proposal", Los Alamos National Lab, Los Alamos, NM, Rep. LA-UR-98-2413, 1998. Available: http://wsx.lanl.gov/Proposals/mtf_pop_proposal.pdf.

[2] I. R. Lindemuth, R. E. Siemon, “The fundamental parameter space of controlled thermonuclear fusion," *Am. J. Phys.* 77, pp. 407-416, May 2009.

[3] J. M. Tacetti, T. P. Intrator, G. A. Wurden, S. Y. Zhang, R. Aragonez, P. N. Assmus, C. M. Bass, C. Carey, S. A. deVries, W. J. Fienup, I. Furno, S. C. Hsu, M. P. Kozar, M. C. Langner, J. Liang, R. J. Maqueda, R. A. Martinez, P. G. Sanchez, K. F. Schoenberg, K. J. Scott, R. E. Siemon, E. M. Tejero, E. H. Trask, M. Tuszewski, and W. J. Waganaar “FRX-L: A field-reversed configuration plasma injector for magnetized target fusion,” *Rev. Sci. Instr.* **74**, pp. 4314-4323, Oct. 2003.

[4] J. H. Degnan, D. J. Amdahl, A. Brown, T. Cavazos, S. K. Coffey, M. T. Domonkos, M. H. Frese, S. D. Frese, D. G. Gale, T. C. Grabowski, T. P. Intrator, R. C. Kirkpatrick, G. F. Kiuttu, F. M. Lehr, J. D. Letterio, J. V. Parker, R. E. Peterkin, Jr., N. F. Roderick, E. L. Ruden, R. E. Siemon, W. Sommars, W. Tucker, P. J. Turchi, and G. A. Wurden, “Experimental and Computational Progress on Liner Implosions for Compression of FRCs,” *IEEE. Trans. Plasma Sci.* **36**, pp. 80-91, Feb. 2008.

[5] J. H. Degnan, D. J. Amdahl, M. Domonkos, F. M. Lehr, C. Grabowski, P. R. Robinson, E. L. Ruden, W. M. White, G. A. Wurden, T. P. Intrator, J. Sears, T. Weber, W. J. Waganaar, M. H. Frese, S. D. Frese, J. F. Camacho, S. K. Coffey, V. Makhin, N. F. Roderick, D. G. Gale, M. Kostora, A. Lerma, J. L. McCullough, W. Sommars, G. F. Kiuttu, B. Bauer, S. R. Fuelling, R. E. Siemon, A. G. Lynn, and P. J. Turchi, "Recent Magneto Inertial Fusion Experiments on the Field Reversed Configuration Heating Experiment," *Nucl. Fusion* **53**, 093003, 2013.

[6] O. V. Gotchev, N. W. Jang, J. P. Knauer, M. D. Barbero, R. Betti, C. K. Li, and R. D. Petrasso, “MagnetoInertial Approach to Direct-Drive Laser Fusion,” *J. Fusion Energ.* **27**, pp. 25-31, (2008).

[7] O. V. Gotchev, J. P. Knauer, P. Y. Chang, N. W. Jang, M. J. Shoup III, D. D. Meyerhofer, and R. Betti, “Seeding magnetic fields for laser-driven flux compression in high-energy-density plasmas,” *Rev. Sci. Instrum.* **80**, 043504, (2000).

[8] J. P. Knauer, O. V. Gotchev, P. Y. Chang, D. D. Meyerhofer, O. Polomarov, R. Betti, J. A. Betti, J. A. Frenje, C. K. Li, M. J.-E. Manuel, R. D. Petrasso, J. R. Rygg, and F. H. Seguin, “Compressing magnetic fields with high-energy lasers,” *Phys. Plasmas* **17**, 056318, (2010)

[9] S. A. Slutz, M. C. Herrmann, R. A. Vesey, A. B. Sefkow, D. B. Sinars, D. C. Rovang, K. J. Peterson, and M. E. Cuneo, “Pulsed-power-driven cylindrical liner implosions of laser preheated fuel magnetized with an axial field,” *Phys. Plasmas* **17**, 056303, (2010).

[10] S. A. Slutz and R. A. Vesey, “High-Gain Magnetized Inertial Fusion,” *Phys. Rev. Lett.* **108**, 025003, (2012).

[11] R. D. McBride, M. R. Martin, R. W. Lemke, J. B. Greenly, C.A. Jennings, D. C. Rovang, D. B. Sinars, M. E. Cuneo, M. C. Herrmann, S. A. Slutz, C. W. Nakhleh, D. D. Ryutov, J. P. Davis, D. G. Flicker, B. E. Blue, K. Tomlinson, D. Schroen, R. M. Stamm, G. E. Smith, J. K. Moore, T. J. Rogers, G. K. Robertson, R. J. Kamm, I. C. Smith, M. Savage, W. A. Stygar, G. A. Rochau, M. Jones, M. R. Lopez, J. L. Porter, and M. K. Matzen, “Beryllium liner implosion experiments on the Z accelerator in preparation for magnetized liner inertial fusion,” *Phys. Plasmas* **20**, 056309, (2013).

[12] S. C. Hsu et al., “Spherically Imploding Plasma Liners as a Standoff Driver for Magneto-Inertial Fusion,” *IEEE Trans. Plasma Sci.* **40**, 1287 (2012).

[13] S. C. Hsu et al., “Experimental characterization of railgun-driven supersonic plasma jets motivated by high energy density physics applications,” *Phys. Plasmas* **19**, 123514 (2012).

[14] E. C. Merritt, A. L. Moser, S. C. Hsu, J. Loverich, M. Gilmore, “Experimental characterization of the stagnation layer between two obliquely merging supersonic plasma jets,” *Phys. Rev. Lett.* **111**, 085003, (2013).

[15] E. C. Merritt, A. L. Moser, S. C. Hsu, C. S. Adams, J. P. Dunn, A. M. Holgado, M. Gilmore, “Experimental evidence for collisional shock formation via two obliquely merging supersonic plasma jets,” *Phys. Plasmas* **21**, 055703, (2014).

[16] M. Laberge, “An Acoustically Driven Magnetized Target Fusion Reactor,” *J. Fusion Energ.* **27**, pp. 65-68, (2008).

[17] S. Howard, M. Laberge, L. McIlwraith, D. Richardson, J. Gregson, “Development of Merged Compact Toroids for Use as a Magnetized Target Fusion Plasma,” *J. Fusion Energ.* 28, pp. 156-161, (2009).

[18] M. Laberge, “Experimental Results for an Acoustic Driver for MTF,” *J. Fusion Energ.* 28, pp. 179-182, (2009).

[19] C. Grabowski, J. Degnan, et. al, “Addressing Short Trapped-Flux Lifetime in High-Density Field-Reversed Configuration Plasmas in FRCHX”, IEEE Trans. Plasma Science, 42(5), 1179 (2014).

[20] *NNSA FES Interagency Task Force on HEDP, Aug. 2007, http://www.whitehouse.gov/sites/default/files/microsites/ostp/report_of_the_interagency_task_force_on_high_energy_density_physics.pdf*

[21] C. E. Knapp and R. C. Kirkpatrick, “Possible Energy Gain for a Plasma Liner-Driven Magneto-Inertial Fusion Concept,” accepted by *Phys. Plasmas* (2014); http://arxiv.org/abs/1403.4314

[22] D. R. Welch et al., “Simulations of Magnetic Field Generation in Unmagnetized Plasmas via Beat-Wave Current Drive,” PRL **109**, 225002; D. R. Welch et al., “Particle-in-cell simulations of laser beat-wave magnetization of dense plasmas,” *Phys. Plasmas* **21**, 032704 (2014)

[23] P.J. Turchi, et al, "Review of the NRL Liner Implosion Program," in Megagauss Physics and Technology, P.J. Turchi, ed., Plenum Press, NY, pg. 375 (1980).

[24] P.J. Turchi, "Imploding Liner Compression of Plasma: Concepts and Issues," IEEE Trans. on Plasma Science, 36, 1, 52 (2008).

[25] “The Prometheus Magneto-Inertial Fusion Research Facility”, a white paper for FESAC Facilities Panel, 2013 *https://www.burningplasma.org/web/fesac-fsff2013/whitepapers/Wurden_G.pdf*