Magneto-Inertial Fusion

Description

Magneto-inertial fusion (MIF) is a set of pulsed fusion approaches that add a strong magnetic field to the compressed fusion DT fuel. The key physics effects of the magnetic field are that it (i) reduces thermal conduction within and (ii) enhances alpha-particle heating of the compressed burning fuel. The primary features are a significant enlargement of the areal density (ρr) parameter space for inertial fusion ignition, and relaxed requirements for compression schemes. 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 Br rather than ρr becomes the key figure-of-merit for ignition. Within the lower-ρr parameter space, MIF exploits lower required implosion velocities (5–100 km/s) allowing the use of much more efficient ($\eta \sim 0.5$) 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 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 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 $\eta G \sim 10$. 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 approaches and implosion velocities shown in Fig. 1.

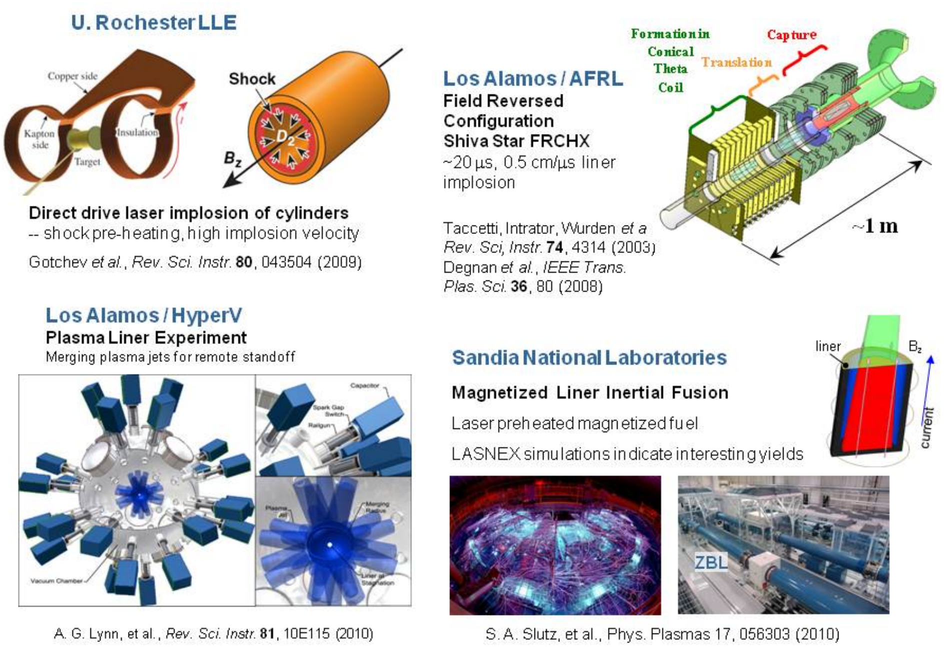

Figure 1: MIF concepts presently being explored in the lab, in the USA

We point out that lower-ρr based MIF approaches occupy a "sweet spot" in thermonuclear ρ-T parameter space, as elegantly shown in a paper by Lindemuth and Siemon from physics first principles (I. R. *Lindemuth*, R. E. *Siemon*, Am. J. Phys., Vol. 77, No. 5, May *2009). The key point here is that breakeven-class MIF driver facilities, which already exist (e.g., ATLAS or Z/Z-Beamlet), cost ≤US$200M compared to the multi-US$B ITER and NIF*. For this reason alone, MIF warrants serious attention given our budget-constrained politico-economic climate.

Status

In the last ten years, there have been substantial advances in MIF research and concepts. A team led by Los Alamos and the Air Force Research Laboratory is investigating solid liner compression of a magnetically confined field reversed configuration (FRC) plasma to achieve kilovolt temperatures. The Univ. 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. Sandia has proposed and is testing a magnetically driven beryllium liner, imploded by the Z-machine, which will compress a laser-preheated magnetized DT target plasma (MagLIF). Los Alamos is also leading a team that is working on a stand-off 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 nor transmission lines on each shot. 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. These approaches span implosion time scales ranging from ns to tens of μs and all have substantially different "target physics" issues.

Current Research and Development (R&D)

R&D Goals and Challenges

A MIF grand challenge is to determine 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 characterization of the plasma boundary interface 3) robustness and stability of initial target configurations. Each of these broad topics involves engineering and basic science components that overlap conventional 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 considered. As with ICF schemes, the cost of material that must be recycled vs consumed for each pulse (the "kopeck" problem) is an issue.

Related R&D Activities

MIF systems tend toward larger yields and lower repetition rates, 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. Present MIF work falls under the category of Magnetized High Energy Density Laboratory Plasmas, and its science is well documented in the recent HEDLP Basic Research Needs Report (2010).

Recent Successes

At Rochester LLE, fusion yield enhancement by a compressed magnetic field externally introduced into a fusion fuel has been unequivocally demonstrated experimentally using the OMEGA laser, consistent with 1-D modeling estimates. In spherical implosions of solenoidal magnetic field with open field lines, a neutron yield increase of 30% was obtained. 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, 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. A deformable liner system has been developed and tested at AFRL on Shiva Star, and a plasma target has been developed at Los Alamos, and ported to AFRL. Modeling with MACH2 at NumerX of the overall system has been guiding the experiments. The first integrated plasma/liner engineering test of the LANL/AFRL FRCHX experiment on Shiva Star was April 16, 2010. Sandia Z experiments and 2D and 3D modeling with small solid liners for MagLIF have begun. A large 9' spherical vacuum chamber is the centerpiece of the Plasma Liner Experiment (PLX) facility at LANL, which is under construction, and plasma guns are being developed for PLX at HyperV Technologies Corp. in Virginia.

Budget

(HEDLP + LDRD) FY2010: $5M; FY2011: $5M; FY2012 $5M anticipated

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Anticipated Contributions Relative to Metrics

Metrics

- ***Energy Concepts***—The long-term application of MIF to energy production has not been examined at a systems level as extensively as for conventional magnetic or inertial fusion, and metrics are less well defined. With MIF, yields in the gigajoule range would allow advantages at a lower repetition rate than conventional ICF, although the plasma liner driven MIF concept is somewhat intermediate and aims for yields well below 1 GJ and a ~1 Hz rep-rate. 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 with circulating liquid metal similar to the early LINUS concept is one approach. Low-cost refabrication of electrical leads that deliver 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 regime, which differs by 5 to 6 orders of magnitude from both MCF and ICF, allows many tests of scientific understanding. Extreme magnetic field values are possible in small 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" [NNSA/OFES Interagency Report 2007]. 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.

Near Term (≤5 years)

More physics tests of FRC implosions will occur within the year. MagLIF implosion experiments need the Z-Beamlet laser energy upgrades to be completed, and funding from NNSA/OFES after LDRD is finished. Assuming success with the physics tests and an increased funding level, a near break-even (DT equivalent) tests could be done in 2015-2017 timeframe in the Sandia Z-machine for MagLIF or with Los Alamos explosive pulsed-power with solid liners and FRC's. PLX will have provided important first results on the feasibility of imploding plasma liner formation via convergent plasma jets, as well as fleshed out its many advanced reactor visions during that time. The Canadian General Fusion company will have accelerated spheromak targets that might be suitable for explosively driven compression tests. An ignition-class laser driven MIF experiment may be fielded on NIF. An interesting aspect to MIF is that university-scale experiments can fully test MIF targets, and the community-based MIF research program assumes a multi-institutional campaign of testing targets developed on small-scall experiments in the large-scale defense program facilities. Success in the laboratory would give strong incentive for expanded work on technologies needed for economic energy production.

Mid Term (≤20 years)

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 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 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 development requirements.*

Long Term (>20 years)

If MIF is successful, the development phase for fusion energy should be accelerated, and the ultimate cost of electricity should be reduced in accord with reduced development costs.

Proponents' and Critic's Claims

Proponents are excited because MIF offers an affordable path to burning plasma experiments and an intriguing and generally unexplored possibility for practical fusion energy. 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 is less scientifically mature than conventional MFE and ICF approaches.