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Status of the US program in magneto-inertial fusion

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Status of the U. S. program in magneto-inertial fusion

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Abstract. A status report of the current U.S. program in magneto-inertial fusion (MIF) conducted by the Office of Fusion Energy Sciences (OFES) of the U.S. Department of Energy is given. 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. The program is part of the OFES program in high energy density laboratory plasmas (HED-LP).

1. Introduction

The essential ideas behind magneto-inertial fusion (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 heating of the plasma to thermonuclear fusion temperatures. The extremely high magnetic field created in the hot spot or the target plasma also enhances alpha-particle energy deposition in the plasma when fusion reactions occur.

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, their strategies for addressing the 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). Dense plasma in ultrahigh magnetic field (> 500 T), or magnetized HEDLP, is one of the thrust areas of HEDLP [3]. Magneto-inertial fusion (MIF) is a pathway to create and study dense plasmas in ultrahigh magnetic fields.

We give here a brief status report of the U.S. program in magneto-inertial fusion (MIF). A more detailed overview of the program giving its technical rationale, scientific goals, vision, research plans, needs, and the research facilities in support of the program is given elsewhere [4].

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 [5,6]. 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.

It was shown by Kirkpatrick et al [7]. that ignition is possible with lower implosion velocity with magnetized targets. Magnetic fields from 1,000 T to 10,000 T are required for typical ICF scenarios, 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.

Experiments are in progress at the University of Rochester to compress a seed magnetic field in surrogate ICF targets using the OMEGA laser facility [8]. The apparatus for generating a seed magnetic field of the order of 10 – 15 T has been developed and tested successfully. The magnetic field is generated by a large current flowing in small external coils surrounding the target. Compression of the magnetic flux using a high-temperature conductive plasma will be attempted next. If successful, the flux will be compressed to produce a plasma with an embeded magnetic field of 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 [9].

3. Low and intermediate gain MIF

Low-gain MIF 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 [5]. The lower fusion gain required 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 target 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.

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. Plasma liner might prove to be more attractive for energy applications eventually, and are being explored for its potential for achieving intermediate fusion gain up to about 50.

3.1. Solid-liner driven MIF

In solid-liner driven MIF [7,10,11,12,13], a magnetized target plasma (plasmoid) is formed in a plasmoid generator, and is then translated and captured in a metallic solid liner (Figure 1). The solid liner is imploded by the magnetic pressure of a large pulsed current in a suitable configuration. The imploding liner compresses and heats the target plasma.

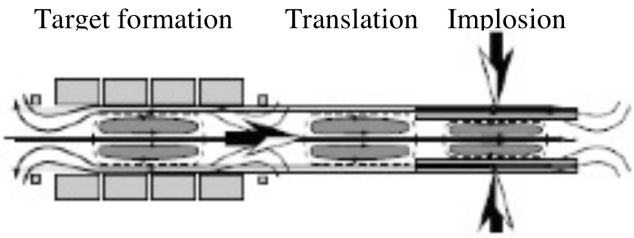

Figure 1 Schematic of solid-liner driven MIF

Because a sufficiently large database in FRC exists [14,15], 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. Other target plasmas such as the z-pinch, the diffuse pinch and spheromaks are possible [16,17] and will be considered in future experiments. Research is required to develop predictive understanding of the heating of a magnetized plasma compressed by a metallic liner.

Some theoretical results have been obtained for the transport properties of dense plasmas in high magnetic fields for MIF applications [18,19]. However, experimental data for benchmarking the theoretical results and for guiding further development of the theoretical and computational models are few and far between. 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.

Both 2D and 3D compression of the FRC are possible [20,21]. To keep the experimental configuration simple, 2D compression is first chosen in the current experiment to advance our understanding of compression-heating of a magnetized plasma by a solid liner. The research needs are being met using existing experimental facilities at the Los Alamos National Laboratory and the Air Force Research Laboratory at the Kirtland Air force Base (AFRL-Kirtland) in Albuquerque, New Mexico.

At the Shiva Star pulsed power facility at AFRL-Kirtland, we have 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].

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Current two-dimensional MHD simulations are able to reproduce global dynamical features of liner implosion in the absence of a magnetized target plasma, in reasonable agreement with experimental observation, including effects of the magnetic Rayleigh-Taylor instability and collisions between liners and solid targets, etc [22]. However, it is not yet known how well existing MHD capability will model the interactions between a liner and a magnetized plasma. When a metallic liner compresses a magnetized target plasma, the inner wall of the liner is 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. A layer of warm dense matter may be formed at the wall. The transport of any impurities from the wall into the FRC plasma is a critical issue affecting the heating of the FRC. 1D numerical study of the plasma-wall interaction has been made for an aluminum liner [18]. More precise and detailed experimental studies and 2-D modeling of the plasma-wall interactions are in progress led by the University of Nevada in Reno [23].

A dedicated experimental facility (FRX-L) for developing high-density, compact FRC as targets for MIF, including the translation and capture of the FRC by a metallic liner, has been developed at the Los Alamos National Laboratory [12,24]. The FRC is formed by a field-reversed theta pinch in a quartz tube about 0.5 m long and 10 cm in diameter. 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. It has also developed a considerable database for the FRC behavior for various combinations of bank voltages, trigger timing and pre-fill gas pressure.

The experiment is now ready to combine the FRC generation technique developed at Los Alamos with the Shiva Star facility to perform an integrated liner-on-plasma implosion experiment. The integrated experiment will advance our predictive understanding on the compression heating of the FRC to multi-keV temperatures and 10^{19} cm^{-3} plasma densities. This experiment will be performed over the next few years.

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 [25] (Figure 2) and in wire-array Z-pinch [26] (Figure 3) 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 [17,27].

Figure 2. Convergence of plasma jets to form an imploding plasma liner. (Witherspoon et al. [25])

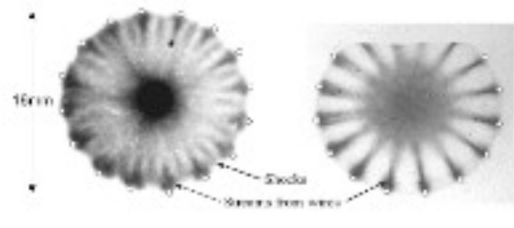

Figure 3. Cylindrically converging precursor plasma flow stagnating to form a compact plasma seen in wire-array Z-pinch. (Bott et al. [26])

Staged Z-pinch [28,29] and theta pinch can also be used to produce cylindrical (2D) plasma liners. Slow, deeply subsonic plasma liners may also be created by electrothermal heating of a plasma shell to drive a cold heavy gas or dusty shell to moderately high velocity and high Mach number. The heavy or dusty shell is used to implode a conducting shell containing the magnetized target plasma [30].

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. 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 develop a predictive understanding of the formation of 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.

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 [17], 3D meshless Smooth Particle Hydrodynamics [27] (LANL SPHINX code), and extended MHD code [31] (Mach2). These studies are being extended at General Atomics, Lawrence Livermore National Laboratory and the University of Alabama in Huntsville, Far-Tech, HyperV and at the U. Wisconsin.

New concepts for coaxial plasma guns with shaped electrodes [32] based on a new mode of plasma acceleration [33] are required to create un-magnetized plasma jets with the required high momentum flux density and high Mach number. An experimental facility has been established at the HyperV Technologies Corp., Virginia, USA for undertaking this development. The facility has successfully launched an un-magnetized plasma jet with a total mass of 157 mg at 70 km/s [25]. It has also a 2p array of miniature plasma jets produced by capillary discharges for studying jet interaction (Figure 2). Diagnostics include magnetic and light probes, high resolution spectroscopy, visible light imaging using a fast gated PI-MAX camera, pressure probes, and laser interferometry.

At UC-Davis, the acceleration 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 [34]. 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. Up to a thousand plasmas per day may be formed without the need to refurbish machine parts [35]. At Caltech, an experimental facility is available for addressing the fundamental science issues governing magnetic reconnections, MHD-driven jets and spheromak formation [36,37]. 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.

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. 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. 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.

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 annual funding for the whole program is about US$4.7M in FY 2008. 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 experiment at AFRL/LANL is poised to use a solid liner to compress an FRC to advance our understanding of the heating of a magnetized plasma by a conducting shell up to temperatures of a few keVs and densities up to 10^{19} per cm^3. Experiment at the U. Rochester is ready to demonstrate compression of magnetic flux in ICF plasmas to create field up to 1000 T. Testing of a new plasma gun concept has begun at HyperV Technologies Corp., successfully launching a plasma jet of 157 mg to 70 km/s. The experiment is ready to study the merging of plasma jets to form plasma liner.

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