<u>**The Prometheus Magneto-Inertial Fusion Research Facility**</u> LA-UR-13-20790

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Summary: A next generation pulsed power magnetized high energy density laboratory plasma (MHEDLP) research facility, named Prometheus, which will enable demonstration of Q=1 (DT equivalent) low-convergence ratio pulsed-power magneto-inertial fusion (MIF) plasmas. The USA presently leads the world in pulsed power MHED research, with efforts primarily at AFRL's Shiva Star Facility (FRCHX) and Sandia (Z-Machine MagLIF). Magneto-inertial fusion combines features of both magnetic and inertial fusion approaches, creating an intrinsically pulsed hybrid approach to fusion in the laboratory which solves some of the pressing problems that the two conventional (MCF and ICF) approaches face individually. Physics demonstrations of kilovolt MHED plasmas are expected in the next few years on these present facilities.

HEDLP Report Recommendation on facilities [1]: The current excitement surrounding HEDLP is based upon existing and near term large- and intermediate- scale experimental facilities in the U.S. that are capable of generating high energy density conditions. Taking full advantage of these opportunities over the next decade requires continuing and assured access for the broader scientific community to these facilities. **Modest facility upgrades will enable even more exciting and challenging experiments of high intellectual value.** Finding: Alternative inertial fusion energy (IFE) concepts are required for a viable path to high energy gains and economically attractive fusion energy systems. Alternative IFE concepts funded by OFES & NNSA have the potential to generate gains needed for inertial fusion energy.

Prometheus - a new MIF Research Facility

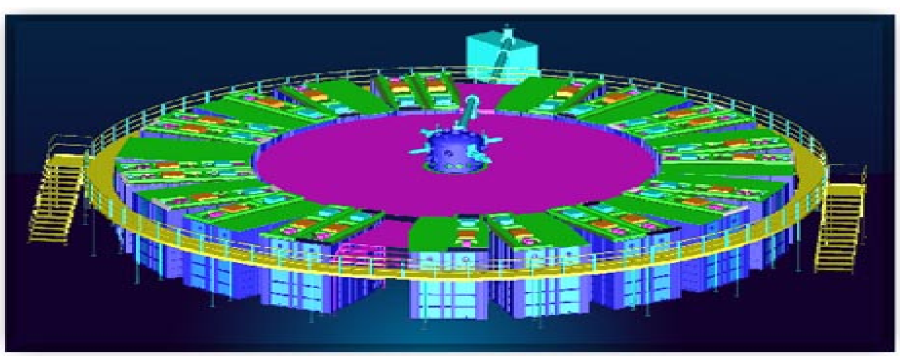

Figure 1. CAD drawing of the previous ATLAS pulsed power experiment.

The Prometheus Facility will be a 60-MA pulsed power machine, based on proven ATLAS technologies with the purpose of demonstrating breakeven (DT-equivalent) MIF implosions. ATLAS construction cost was $49M in 2000 (without a building), and was a 30-MA, 24-MJ, 240-kV machine[2], presently mothballed in the desert in Nevada. The Prometheus machine would be capable of delivering ~ 15 MJ of energy to a liner, with ~ 5 microsecond current rise-time, resulting in shock-less implosion velocities of 7.7 km/second for a 0.5 kg liner. This would allow larger (longer-lived) targets than possible today. Operating costs for a robust MHEDLP research program are estimated at $20M per year. A key, exciting, capability of this MHED facility, is to allow access to multi-megabar hot magnetized plasmas with macroscopic (cm-scale) features, using low-convergence ratio MTF designs, yielding > 0.1 MJ DD neutron yields. Low-convergence (10-15x, cylindrical) ratio, heavily tamped, "slow" implosions coupled with solid liner material strength, can mitigate Rayleigh Taylor mix issues, compared to shorter timescale, higher-power experiments (such as NIF and Z). Prometheus represents an upgrade of a factor 5-10x in energy over existing experiments. Extrapolating from known ATLAS costs and inflation, and adding in a reasonable building, one estimates a cost range of $110-130M. As a side note, when ATLAS was moved to the Nevada Test Site from LANL, it took 2 years (completion July 2005), and cost $20M for the relocation (which included a modest building).

Magneto-Inertial Fusion (aka. Magnetized Target Fusion (MTF))

All fusion systems must maintain a high temperature for long enough to allow the fuel to ignite and burn. Magnetic fields can reduce the thermal conductivity perpendicular to the field. This is the fundamental basis for any concept in the magnetic-fusion-energy program. Theoretically, magnetic fields in an inertial fusion approach would allow significant advantages, such as reduced implosion velocity and operating with lower energy density (than conventional ICF).[3–6] The potential reduction of the required energy density and total required energy assuming a magnetic field embedded in the fuel is shown in Fig. 2.

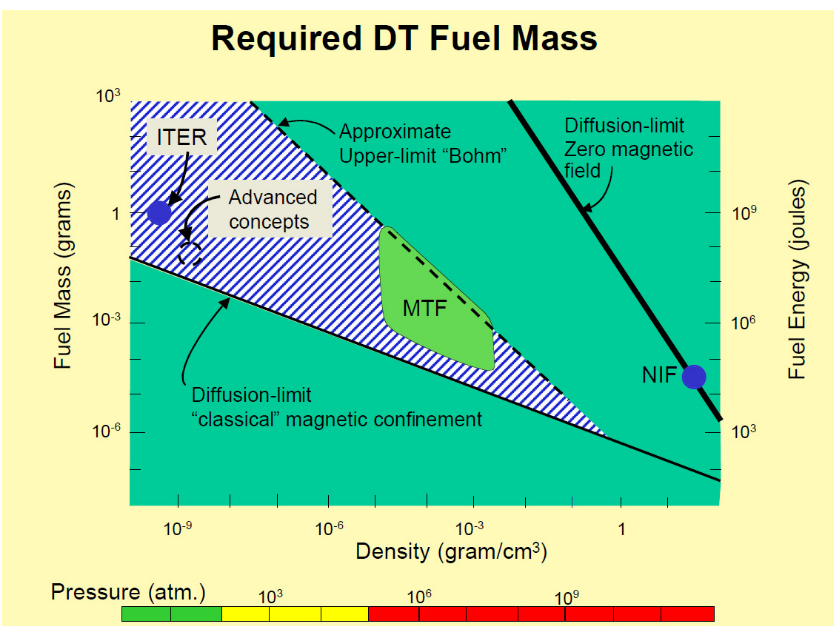

Figure 2. Required mass for fusion gain of unity (or required energy assuming kT= 10 keV) as a function of fuel density (or pressure).

Assuming a temperature of 10 keV, then fuel density (or pressure) determines the characteristic scale length needed to achieve breakeven in the presence of diffusive energy loss. (Color-coded pressure scale is red in the region where materials strength fails). The scale length, assuming a spherical or quasi-spherical geometry, then implies a minimum volume, or mass given the density, or thermal energy given the 10-keV temperature, which leads to the plot in Fig. 2 (mass on the left, and energy on the right)[7]. It is shown that working with density considerably higher than in typical magnetic systems leads to much reduced system size and energy, but requires working at pressures that exceed normal material strength, which implies the use of a pulsed system. Magneto-inertial fusion (MIF) systems allow ignition-relevant fusion parameters to be achieved with reduced power input, or implosion velocity[4].

For some parts of this parameter space the requirement for “high gain” might be relaxed if more electrically efficient drivers than lasers were used for compressing and heating the fuel[7,8]. In some versions of MIF an additional benefit comes from the better confinement of alpha particles in the burning fusion plasma. Preliminary analyses have shown that HEDP-magnetized plasmas will still be susceptible to a variety of small-scale instabilities leading to enhanced transport[9]. However, because of much shorter confinement times (compared to MFE systems), the margin on the acceptable transport enhancement is much wider. As research progresses from basic scientific studies to practical and economic considerations, the potential improvements made possible by magnetic fields are likely to attract even more interest (in light of recent NIF difficulties at achieving ignition).

One way magnetic fields are presently used is by imploding and shocking material into high energy density conditions. High-power Z-pinches, like the ones developed at Sandia National Laboratories, allow efficient conversion of pulsed electricity into several MJ of x-ray energy or to act as a magnetic liner driver. MagLIF is a new magnetically driven liner MIF approach using the Z Machine[10]. A lower voltage type of implosion system, such as the Shiva Star facility at the Air Force Research Laboratory (AFRL) in Albuquerque, uses liners (conducting metal shells) in cylindrical or quasi-spherical geometries to achieve slower but highly precise implosions to Mbar conditions of compressed magnetic flux, compressed plasma, or a combination of the two. Exploratory experiments at the AFRL and Los Alamos National Laboratory, working in collaboration with the University of Nevada at Reno and the University of New Mexico[11], are ongoing to study liner-compression of preheated plasmas. Using plasma jets for standoff, instead of solid liners, has also been explored[12]. Cylindrical implosions driven with laser ablation have also been used at the U of Rochester to study compression of magnetic flux trapped by a shock-heated deuterium plasma [13]. Compressed magnetic fields of up to 30 megagauss (MG) were inferred for implosions with ~0.1 MG initial (seed) field. The Rochester work is the first experimental proof of the utility of adding magnetic fields to ICF targets.

Potential for stimulating interest in graduate students and scientists from other fields.

The challenges associated with using state-of-the-art pulsed power machines to produce magnetized HED plasmas, and to determine the properties of those plasmas is already known to be attractive to some of the best graduate students at universities around the country. The opportunity to carry out experiments in totally new regions of plasma parameter space and to discover totally unexpected phenomena is very attractive to graduate students. Some astrophysicists are excited about some of the data they are able to collect on magnetized jets, opacities, etc., using magnetically driven HED plasmas in the laboratory.

Ability to Conduct World-Leading Science: Grade (a)

There is no question that this facility would enable the USA to extend its lead in the world in this research area, while enabling a lower-cost approach to studying burning plasmas.

Readiness to Proceed: Grade (b)

A demonstration of the utility of pulsed power MIF implosions (beyond the already successful Rochester demonstration of the utility of combining magnetic fields with inertial implosions) needs to be completed. These demonstrations (either at SHIVA or Z) are projected to occur within the next three years, so now is the time to plan for a new facility. A high current machine design[14,15], and an MTF Q=1 point design, are required prior to proceeding to construction.

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