A Community White Paper On

Magnetized High Energy Density Laboratory Plasmas

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Copies of the document may be downloaded from: http://fusionenergy.lanl.gov/mhedlp-wp.pdf

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Magnetized
High Energy Density Laboratory Plasmas

2. Vision:

The behavior of dense plasmas in ultrahigh magnetic fields is a relatively unexplored and intellectually rich regime of plasma physics. By ultrahigh magnetic fields we mean magnetic fields above 5 MG (500 T). The corresponding magnetic pressure is above 1 Mbar. Exceedingly strong magnetic fields are present in astrophysical situations, and present theories suggest that their interactions with plasmas play important role in many astrophysical processes including gamma ray bursts (GRBs), accretion disks, and astrophysical jets. Compression of magnetic flux in plasma is a pathway towards creating ultrahigh magnetic fields in the laboratory. Because intense magnetic fields slow down thermal transport, ultrahigh magnetic fields might facilitate the heating of a dense plasma to thermonuclear temperatures to produce fusion reactions. Research in this field has potential applications to energy as well as astrophysics and materials science.

3. Motivating Intellectual Question:

Can fusion-relevant thermonuclear temperatures be obtained when plasma is compressed with megagauss fields?

We intend to show, with experiments and supported by theory/simulations, that pulsed power can be used to generate high energy density plasmas in ultrahigh magnetic fields in the laboratory by compressing preformed, magnetic plasma structures. Furthermore, the resultant high energy density plasma pressure can be contained by the **inertia** of the liner used to compress the plasma for a duration of time for a significant number of fusion reactions to occur. Hence the term magneto-inertial fusion (MIF).

Megagauss magnetic fields can be created by compressing a seed field using a solid, liquid or plasma (including dusty) liners. This has been demonstrated for many years, starting from vacuum magnetic fields. Seed fields with plasmas, include FRCs, spheromaks, and current drive in dense plasmas using lasers and/or particle beams. Magnetic flux compression allows access to Magnetized High Energy Density Laboratory Plasmas (MHEDLP). The MHEDLP regime has applications to fusion energy, astrophysics, and material science issues.

Magneto-inertial fusion (MIF), offers the possibility of achieving thermonuclear fusion conditions by combining features of both Magnetic fusion Energy (MFE) and Inertial Fusion Energy (IFE). MIF has the potential of operating at higher fuel density and of being more compact than MFE while at the same time alleviating the driver power requirements needed for IFE. As such, MIF will enable the use of slower (and therefore cheaper) pulsed power that has (literally) been around for decades.

4. Research Opportunities, Plans, and Resources

Compression of magnetic flux in the presence of plasmas can be achieved in a variety of ways. Experimentally, going back at least thirty years, a pioneering effort was made by the Russian group of R. K. Kurtmullaev, followed later by teams at NRL and LANL. A variety of experiments and concepts were put forth, even including pulsed fusion reactor studies such as LINUS (NRL) and Fast Liner Reactor (LANL). Today, efforts to achieve MHEDLP conditions follow three main pathways: use of solid liners, use of plasma liners, and use of lasers.

4.1. Solid-Liner Flux Compression

Motivation

The used of low-cost pulsed power to implode a solid metal liner (often aluminum), is a well-developed technique from DOE Defense Programs, and DOD projects. Electromagnetic (JxB) forces are used to crush the liner, on a 10-20 microsecond timescale, with multi-megajoule drivers (either capacitor banks or using high explosive current generators). If the thickness of the liner is chosen correctly, part of the liner remains solid, until very late in the implosion, providing mechanical strength against hydrodynamic instabilities. Experimentally, smooth 10-15 x cylindrical compressions, in liners weighing up to 100 grams, and accelerated to ~ 1cm/μs velocities, with ~ 1 μs stagnation times, have been achieved. In the Magnetized Target Fusion (MTF) concept[Siemon, (a subset in the class of Magneto-Inertial Fusion), we envision compressing a magnetically confined plasma to thermonuclear conditions [Kirkpatrick1995]. Specific initial experiments have the region into which the MTF plasma is injected surrounded by a thin (1-mm thick) solid aluminum cylindrical flux conserving boundary (liner), which is then radially crushed in about 20 microseconds. The compression rapidly increases the magnetic field and the density and temperature of the plasma by a factor of 30 to 100, establishing thermonuclear conditions. As a result, the plasma should fuse and release significant amounts of energy.

Scientific Objectives

Can multi-keV temperatures be obtained by compression of a magnetically confined plasma to megabar pressures using a solid metal liner?

There are corresponding scientific sub-issues associated with this question, such as: *What limits liner compression and dwell time? How do nearby boundaries (walls) driven by intense* *magnetic and radiation fields turn into plasmas? How are hydrodynamic instabilities at boundaries changed in the presence of a thermonuclear (fusing) plasma? How can we minimize impurity influx? Do we have the right material conductivity and transport models (for both walls and plasma)? What effect do velocity shear, initial density profile, finite Larmor radius, and other conditions have on particle and energy transport at MHEDLP conditions? Can we take advantage of ultra high magnetic fields and high density to enable plasma diagnostics that are not possible in more conventional regimes?*

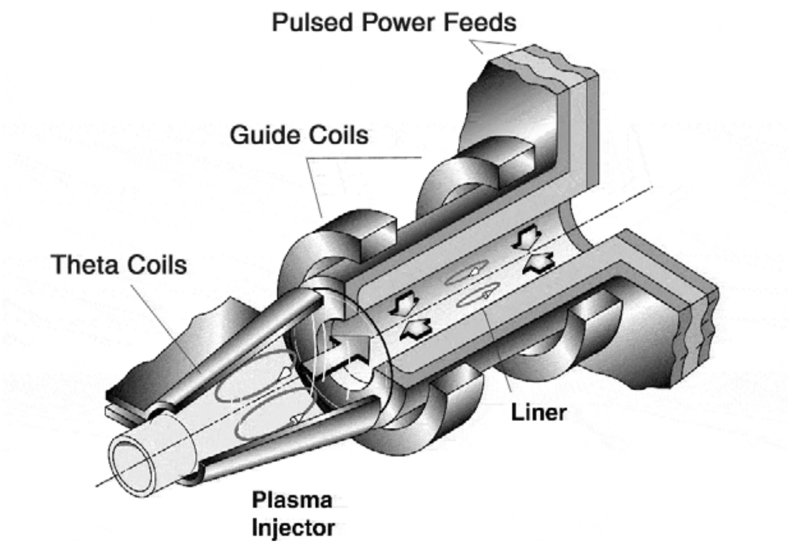

Fig. 1. Schematic of MTF concept using an FRC plasma injector and solid liner.

In our chosen initial example, the magnetized target plasma is a field-reversed plasma configuration (FRC) that is translated over to a solid, cylindrical conductor (liner). The effort combines 30 years of work at LANL to develop a class of plasmas called “compact tori” (CT) . One example CT the “field-reversed configuration” (FRC) takes advantage of 20 years of pulsed-power-driver technology development. A 30 cm tall, 10-cm diameter, 1-mm thick Aluminum wall, shaped deformable liner can be imploded by 12 MA currents on microsecond time scales, using the existing pulsed power facility, Shiva Star at the Air Force Research Laboratory. Simple cylindrical compressions of 10-15x are required to take an initial 3-5 Tesla magnetic field up to the 500 Tesla range. The slow, shockless, adiabatic compression driven by the imploding aluminum liner is expected to remain stable to perturbations, providing some part of the liner remains solid for most of the implosion duration. The external magnetic pressure drives the liner inward, converting the external magnetic-field energy into kinetic energy of the liner. The liner accelerates inward until the compression of the FRC (internal fields and beta ~ 1 plasma) is sufficient to produce a back- pressure that approximately equals the drive pressure, at which time the liner begins to slow down. Stagnation occurs as the inward kinetic energy is converted to magnetic plus thermal energy of the FRC, after taking into account energy loss due to magnetic-field diffusion into the liner and radiation.

LANL and AFRL are combining the required initial plasma target and the liner implosion technology into a scientific & technical effort that will lead to the first MTF physics (multi-keV plasma) demonstration experiments by 2008. Potential higher energy follow-on experiments, using reasonable choices of physical parameters, including magnetic and particle diffusion coefficients, suggest that a 30-MA-current driver, such as the Atlas facility, could achieve 1-cm-radius, 10 cm long plasma at 1 Mbar. This corresponds to a density of 6 x $10^{19}/cm^3$ at 10-keV temperature, a very interesting plasma for producing deuterium-tritium fusion reactions. Even higher field experiments, with larger plasma volumes, could eventually be conducted using 80-MA explosively driven currents, at Ancho Canyon in Los Alamos, or with the (now mothballed) Atlas Facility at the Nevada Test Site.

A unique feature of the liner approach to MHEDLP is that it allows large energies (in the MegaJoule range) to be imparted to a plasma of size much larger than the ion gyroradius, for times much longer than the electron inertial time. This is in contrast to the ultrahigh magnetic fields generated at a laser focal spot, where only the electrons are effectively magnetized.

Finally, here is a list of further scientific issues, some general, and some specific, that can be addressed:

What happens when the liner stagnates on the plasma target pressure? What is the realistic energy partition between liner ablation consequent generated plasma, radiation and ion flux? How does the sheath at the liner- plasma boundary behave? To what extent do the liner and plasma mix?

How can we scale the coexisting high magnetic fields in HED laboratory plasmas to situations of interest? For example atomic physics changes greatly when the ambient magnetic field is much larger than that inside the electron orbitals. White dwarf stars have similar high fields and density.

Are there useful quantities that are approximately conserved? Can we use them to learn about the underlying physics, improve the design, and facilitate simulations? Does the predicted self similar FRC boundary compression hold in the experiments?

Do the FRC scaling laws hold as expected for strong boundary compression? Can strong elongation increase MTF fusion yield? Can an elongated liner remain stable as it is compressed?

What are the details of angular momentum transport? Is angular momentum approximately conserved?How does this impact rotational and n=2 modes?

Is there a CT continuum between FRC and spheromak? Is the embedded helicity the proper criterion to locate a given CT in this range? Which CT is the best for an MTF target?

Experimental/Computational Facilities

- Plasma generators for magnetized plasma target formation to 0.1-1.0 keV, and multi-megampere microsecond pulsed power systems for flux compression to generate megagauss magnetic field.

- Parallel-processor computer arrays and further physics and code development to allow multi-dimensional numerical simulations including radiation, magnetohydrodynamics and boundary plasma interactions, of the integrated plasma and liner compression systems.

A high energy density plasma that is burning with fusion reactions will be highly collisional. Because of the large gyro-radius, kinetic rather than fluid behavior is expected. Plasma transport at such conditions is not understood theoretically, nor has predictive capability been achieved through simulations. Using analytical theory and large scale Particle in Cell (PIC) codes, we need to establish a first principles understanding of impurity radiation loss, and apply it to MTF experiments. We will need to reconcile analytical particle transport to the liner wall with PIC and hybrid code predictions.

Description of LANL FRC Target Plasma Facilities

The FRX-L experiment at LANL is the highest density FRC in the world, n_e up to 1 x 10^{17} cm^{-3}, and has (pre-compression) confined plasma pressures of 20 Atmospheres (higher than any tokamak). This is due to its high plasma beta (~1) at 2-3 Tesla fields. FRX-L will be used to study translating FRC's and their capture in a liner region. Techniques to improve initial flux trapping during FRC formation, (such as using a plasma jet for preionizing the theta-pinch formation region) will also be examined, in parallel with integrated plasma/liner experimental efforts at AFRL

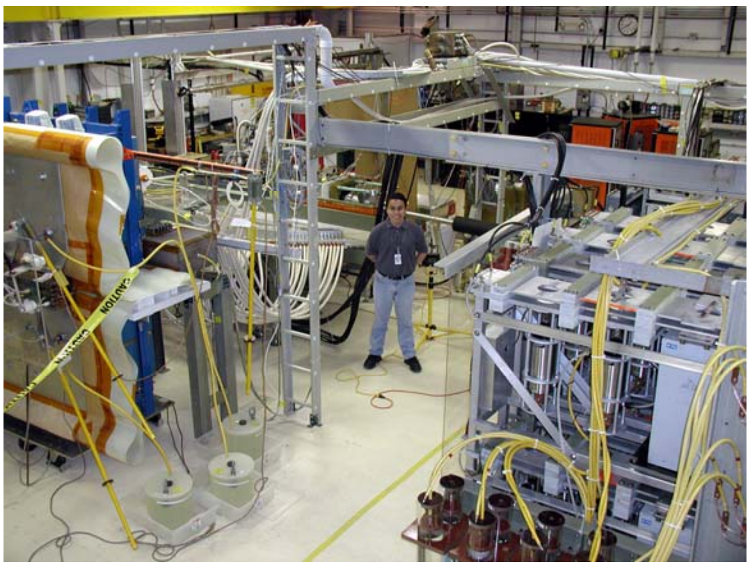

Fig. 2. FRX-L experiment for Field Reversed Configuration plasma formation and translation at LANL.

Description of AFRL Pulsed Power HEDLP Facilities

Experimental facilities at the Air Force Research Laboratory on Kirtland AFB, NM include two laboratory buildings with a variety of capacitor banks ranging from small to large (> 9 megajoules, > 10 megamperes. This includes a recently assembled FRC experiment that is in operation to form the MTF targets for liner on plasma experiments. There is also substantial hardware for data acquisition, vacuum, and power supplies diagnostics for pulsed current, voltage, and magnetic field diagnostics; rotating mirror and gated microchannel plate tube fast photography; optical, RF, 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. There are extensive complementary theoretical and computational abilities and resources in the Division. These include one-, and two -dimensional radiation magnetohydrodynamic, three dimensional magnetohydrodynamic and particle-in-cell codes which have been developed and used to guide and interpret experiments. There is extensive development of parallel versions of these codes, and of parallel processing, high performance computing techniques.

Fig. 3. Photo of Shiva Star 1300 microfarad, 120 KV, 9 Megajoule, 3 microsecond capacitor bank at AFRL, which is available now for implosion-compression experiments.

Description of University of Nevada, Reno HEDLP Facilities

The UNR Nevada Terawatt Facility (NTF) hosts the 2-terawatt Zebra generator and the 10-terawatt Leopard laser. These drivers are being coupled to provide a unique university experimental facility. The NTF complements the large national lab facilities by providing an environment in which students can have a “hands on” learning experience and try new ideas, using tools that access relevant regimes. A recent MIF-related experiment examined plasma formation relevant to liner compression of magnetized plasma, by driving a conductor with a pulsed multi-megagauss magnetic field. Another experiment has been designed to study cross-field heat transport in wall-confined plasma with a stable, closed-magnetic-field-line geometry

[1]. Experiments are designed and analyzed with powerful computer simulations such as the MHRDR radiation-MHD simulation code. The MIF community could perform many MIF-related experiments with this versatile facility.

1. V. Makhin, R.E. Siemon, B.S. Bauer, A. Esaulov, I.R. Lindemuth, D.D. Ryutov, P.T. Sheehey, and V.I. Sotnikov, 'Self-organization observed in numerical simulations of a hard-core diffuse z-pinch,' Phys. Plasmas 12, 042312-1-9 (2005).

Research Plans/Milestones, 2-year and 5-year horizons

We plan to capitalize on FRC generation methods developed by LANL and liner implosion methods developed by AFRL to do a series of integrated liner-on-plasma experiments at the AFRL using the Shiva Star facility for liner compression. We can investigate what determines plasma temperature – available heating power, stability, heat transport, radiation, or other? Megajoule level implosions are expected to cost ~$150k per shot, and so a program to take advantage of the Shiva Star facility would need of order $1M per year (an increase over existing $2.2 M/year LANL/AFRL effort). Theory/simulation support needs to be increased as well, to 20% of the experimental efforts.

- Integrate a significant theory and simulation effort and budget into the existing magnetized HEDLP programs.
- Model the hydrodynamic, kinetic, collisional, and radiation effects in an integrated manner.
- Characterize the sheath and edge transport problem for magnetized HEDLP
- Predict sputtered impurity flux from wall using sheath physics
- Predict impurity ion transport and radiation losses

During the 5-10 year period, we would increase experimentally accessible magnetic fields to 10 Tesla prior to compression, and increase compression ratio during implosions. Additionally, investigation of other plasma configurations such as the Russian MAGO wall-confined plasma or spheromaks may be warranted. We don't know how much helicity is optimal for a compact torus (CT) plasma Magneto Inertial Fusion (MIF) target. For example there is a continuum between FRC's which are robust but short lived and spheromaks whose ability to survive massive boundary forces is not known, but have longer lifetimes. Double-sided merging of CT's may simplfy equipment in the liner compression region (at the expense of other complexity).

If 5-10 keV temperatures are obtained with deuterium, we would introduce tritium to investigate the thermonuclear regime in which the plasma is a significant energy source of its own. A DT Q ~ 1 series of experiments in Nevada could cost $10 M, not including the operations of a facility such as Atlas.

4.2. Plasma-Liner Flux Compression

Motivation

A potential improvement and extension on solid liner for flux compression of magnetized plasma to create ultra-high magnetic fields and burning plasmas is the use of plasma liner. Plasma liner provides an avenue for addressing three major issues relating to the practical implementation of magneto-inertial fusion for energy application and for HEDLP research: (1) standoff delivery of the imploding momentum, (2) repetitive operation, (3) liner fabrication and cost. It can achieve faster compression and higher density for the compressed plasma than solid or liquid liners. For applications to HEDLP research, potential opportunities exist for forming strongly coupled and Fermi degenerate plasmas. 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. Opportunities exist for forming very high seed magnetic field with the use of laser current drive, leading to very high fields in the target at peak compression. The higher field capability might facilitate either astrophysical research or the trapping of charged fusion products to enhance bootstrapping of the fusion burn in the compressed target. 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 dynamics processes found in astrophysical plasmas as well.

Scientific Objectives

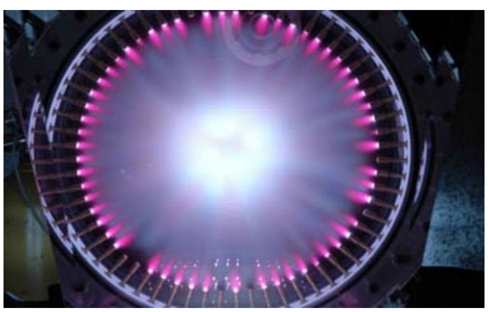

Fig. 4 Picture shows on-going preliminary experiments on the convergence of a cylindrical array of plasma jets to produce a plasma liner, by an array of electrothermal capillary discharges at HyperV.

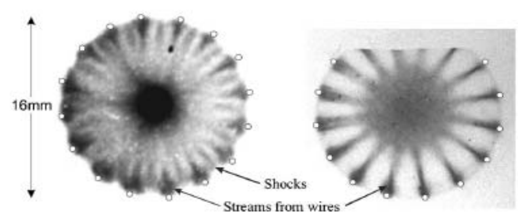

FIG. 3. End-on XUV emission from 16 mm diameter arrays of (left) 16×20 μm Al at 134 ns, and (right) 16×13 μm W at 134 ns. (White circles indicate positions of wires)

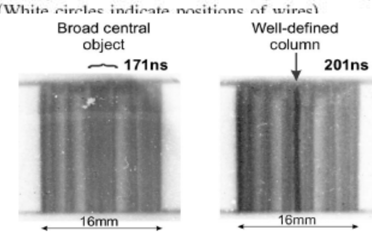

FIG. 2. Side on XUV emission image of a 16 wire tungsten array showing formation of the compact precursor column.

Fig. 5. Cylindrically converging precursor plasma flow stagnating to form a compact HED plasma seen in wire-array Z-pinch. S. C. Bolt, et. al. Phys Rev E, 74, 2006.

One method of creating plasma liner is by merging an array of supersonic dense plasma jets [A5.1]. Experiments using plasma jets produced by capillary discharges and in wire-array Z-pinch suggested that plasma jets can be merged to form an imploding plasma liner [A5.4]. Experiments to form plasma jets by magnetic reconnection and other processes are on-going and overlap with research in astrophysical jets [A5.5]. Staged Z-pinch and theta pinch can also be used to produce cylindrical (2D) plasma liners [A5.7]. Slow, deeply subsonic plasma liners can also be created by electrothermal heating of a plasma shell [A5.2]. Experiments are on-going to use a 2D cylindrical liner to compress a field reversed configuration to keV temperatures [A5.6]. The main motivating intellectual question in this area of research for the next five years is:

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

Considerable theoretical analysis and computational modeling exist that indicate the promise of compressing a magnetized plasma and the limitations imposed by the effects of known instabilities (Rayleigh-Taylor). Analytical models, 3D meshless Smooth Particle Hydrodynamics (LANL SPHINX code), extended MHD code (Mach2), 3D hybrid PIC code (LSP) and 1D Lagrangian radiation-hydrodynamics code (BUCKY) have been and being used to model the concepts to provide preliminary results in this regard [A5.1, A5.3]. Compression of a magnetized plasma to thermonuclear temperatures hinges on the suppression of cross-field thermal diffusivity of the plasma by sufficient flux compression during liner implosion. However, experimental data on the transport characteristics of a magnetized plasma undergoing dynamic compression, as a function of the key plasma parameters (n_e, n_i, T, B) and its magnetic topology, to validate the theoretical and computational models are few and far between.

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

> *What are the transport properties of magnetized plasma during compression? Could magnetic fluctuations or other instabilities be excited by the compression? How do the magnetic flux and field lines behave during the compression?*

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

Experimental/Computational Facilities

Experimental facilities to study the acceleration of plasmas to form plasma jets are available at HyperV Technologies Corporation, UC-Davis and Caltech.

Creation and injection of initial plasma mass into a coaxial accelerator, in a suitable form to shape the high-density plasma slug, is one of the key technologies for achieving hypervelocity high-density, high Mach-number plasma jets for MIF and fuelling of magnetic fusion devices. The scientific knowledge base for the development of this technology is being developed at HyperV Technologies Corporation. Experimental facilities at HyperV Technologies Corp. consists of 4400 sq. ft. of laboratory space, a large rf shielded screen room, 68 channels of 1 Gs per second digitizers for data acquisition, a small machine shop, numerous vacuum pumps, HV power supplies, HV sparkgap switches, and the usual array of supporting equipment. A prototype half-scale plasma gun (shown in Figure) is currently undergoing testing and has achieved velocities in its design range of 60-100 km/s. Present efforts are focused on obtaining definitive density measurements of this jet. Recent pressure probe measurements show a plasma slug arrival which correlates well with fast imaging. Mini-injector development takes place on several test fixtures, the most important of which is the 2pi test fixture incorporating 64 capillary discharges mounted in a 24-inch diameter circular array, all firing radially towards the axis. Jet merging, interaction, and implosion studies are underway on this facility (see picture previous page). The facility is being upgraded to include additional diagnostics (high resolution spectroscopy, visible light imaging using a fast gated PI-MAX camera, pressure probes, and a laser interferometer). On the simulation side, HyperV has an operational 34 processor Linux cluster (which will be upgraded later this year to 64-100 processors) on which it runs LSP and Mach2.

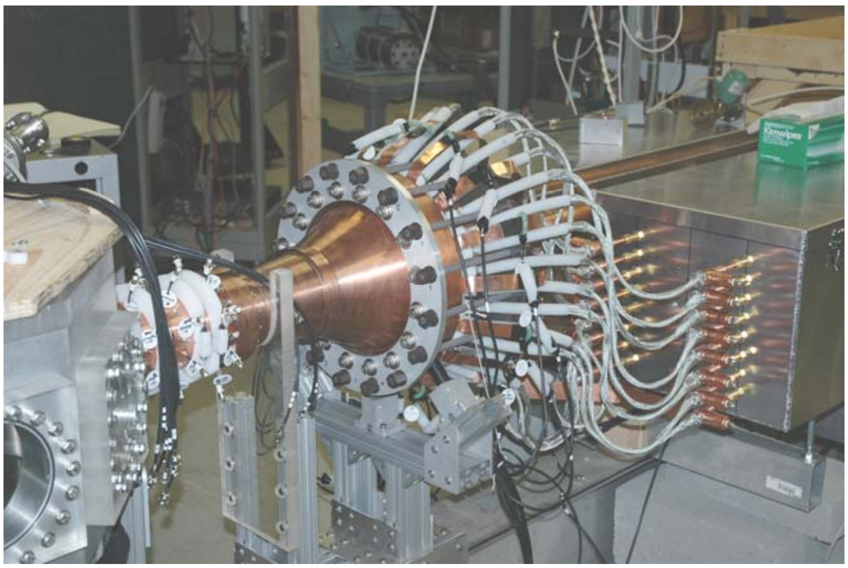

Fig. 6. HyperV's plasma jet accelerator with 32 capillary discharge plasma mass injectors.

At UC-Davis, the acceleration of plasmas in the form of compact toroids is being studied in the the CTIX facility. CTIX is a reliable experimental facility with a proven control and diagnostic system and good 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. The CTIX group also collaborates with the UC Davis program of plasma microwave diagnostics, which offers a wide range of sources and detectors over a range of frequencies suitable to the CTIX plasma. An academic environment, high repetition rate, and small-scale experimental facility with plasma conditions relevant to large scale machine makes the facility attractive as a research facility and for diagnostic development.

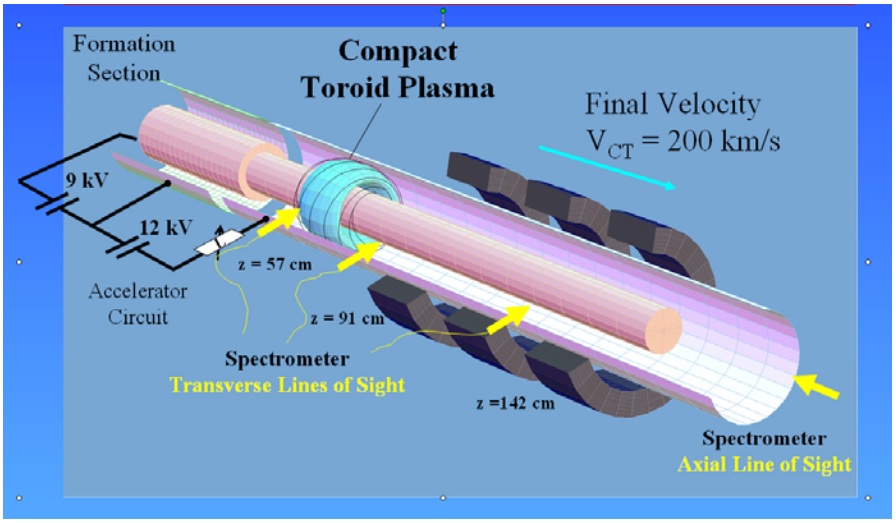

Fig. 7. UC Davis CTIX accelerator, which may be used for the study of multiple-ion acceleration processes for plasma liner compression.

At Caltech, an experimental facility is available for addressing the fundamental science issues governing MHD-driven jets and spheromak formation. The emphasis is on experimental reproducibility, achieving very clear results, comprehensive diagnostics, and achieving agreement between observations and first-principles theoretical models. The inter-shot time is 2 minutes, high-speed photography is used, and no damage occurs to hardware as a result of shots.

An experimental facility to begin developing the database for the compression of a magnetized plasma by a plasma liner in the immediate future is being developed at MSNW/University of Washington. Two inductive plasma accelerators (IPA) have been constructed and tested forming a stable, hot (500 eV) target FRC for compression. In the Inductive Plasma accelerator (IPA) the formation and acceleration of the FRC plasmoid is through the electromagnetic interaction of the radial magnetic field of the sequentially activated accelerator coils (see Figure), and the large FRC toroidal plasma current (i.e. the Lorentz force). The magneto-kinetic compression heating of the FRC plasma has the potential to be much more efficient than other methods. Not only is the energy coupling mechanism low-loss, virtually all of the kinetic energy is thermalized in the plasma in the form of ion energy. 2D imploding plasma shell will be available in the near future for experimental campaigns to obtain data of the interaction of an imploding plasma liner with the FRC as the magnetized target plasma.

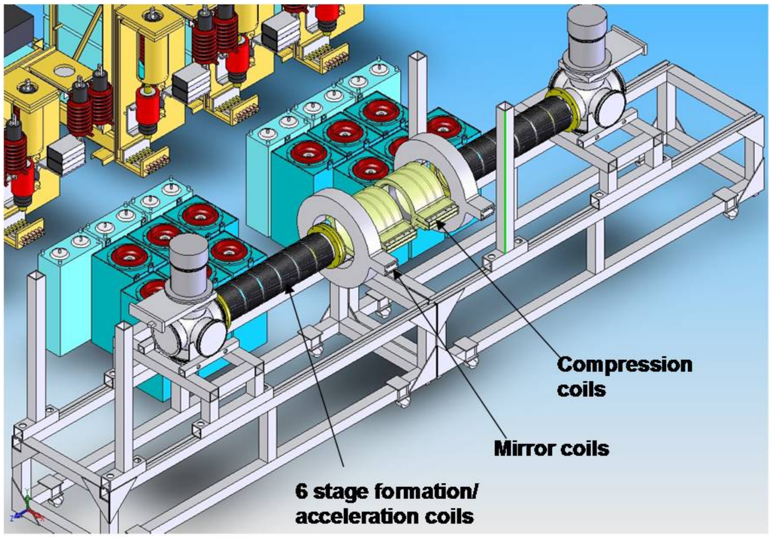

Fig.8. The IPA experiment on the compression of an FRC by a 2D cylindrical liner at MSNW.

Research Plans/Milestones, 2-year and 5-year Horizons:

Over the next 2 years, 2D plasma liners formed by theta pinch can be used to compress an FRC to obtain data on the interaction of dense plasma liners with magnetized plasma [A5.4, A5.5, A5.6]. If successful, research will continue in the next five years to create high-density (> 10^{20} per cm^3) and keV plasmas for research. Concurrent diagnostic development and/or application to measure the magnetic field, plasma density, composition, velocity and temperatures are required the research and the research described below.

Further development of advanced plasma guns to overcome the blow-by instability is required for accelerating compact plasma slugs in coaxial plasma guns to high velocity and high Mach number. The plan for the next 2 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 [A5.6]. If successful, the plan in 5 years is 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 [A5.4, A5.5, A5.6, A5.7, A5.8].

Extended MHD codes will continue to serve as the workhorse in support of the research in determining the global characteristics to guide experimental design and development. Adaptation and extension of state-of-the-art 3D hybrid PIC codes (LSP or equivalent) to include ionization and radiative transport are required to help resolve the detailed physics with some degree of precision. This is needed in order to develop eventually a predictive capability in this area of research. Strong gradients and potentially strong asymmetries are present, associated with using discrete jets to implode compact toroids or other magnetized targets. 3D meshless Smoothed

Particle Hydrodynamics (SPH) extended MHD codes will be valuable for this research. The BUCKY ICF code can be used to model the implosion and burn dynamics. Analytical models are required to guide the detailed computer modeling [A5.1, A5.2, A5.3, A5.7]. Modest expansion of existing computational facilities or access to national supercomputing network or both are required.

4.3. Generation of Ultrahigh Magnetic Fields by Current Drive with Lasers

Scientific Objective:

- *What is the highest magnetic field that we can produce terrestrially?*
- *What new multi-body, atomic, and quantum effects can be understood in the regime which combines HEDP with ultra-high magnetic fields?*

Motivation:

The short space and time scales notwithstanding, experiments are already approaching Giga-gauss through laser-surface interactions. Fields of at least 350 Megagauss have been inferred by observing the polarization of harmonic emission from the laser interaction region. Yet that still remains about 5 or 6 orders of magnitude less than the fields in magnetars. The physics associated with such large fields is not well understood and represents a new frontier in physics. Those astrophysical fields are likely produced by dynamo mechanisms that magnify the already huge magnetic fields of neutron stars. But the question remains: what is the technology that we need in place to produce the highest magnetic field on Earth?

Our first thinking on this is that the technology involves impressing a very high magnetic flux in a plasma and then compressing that plasma. That will utilize the extreme compression technology that is being developed in NNSA facilities like Z or NIF. To get to the highest fields one also imagines pushing a lot of electrons (dense plasma) with very intense power source (laser). If the plasma is dense but still realizable and compressible, then it will be cold, which suggests Fermi degenerate plasma. Now we did investigate last year current drive in a Fermi degenerate plasma, where due to suppression of electron-electron collisions, the laser wave-driven currents could happen more efficiently. That would facilitate in principle the generation of the very large seed fields that could then be compressed for further intensity yet.

In any event, although the concepts that will generate the highest magnetic fields still need to be advanced, the technology will likely involve compression of a magnetized target plasma by one means or another. Thus, if we accept the generation of the highest magnetic field possible as a worthy scientific long-term goal for this nation, then the science of compression of magnetized plasma is exactly what we need to be exploring today.

5. Appendices

In this Appendix the detail inputs provided by the various individuals and institutions are collected, and form the basis for writing the Summary. All authors for a given section have been listed alphabetical.

5.1. Theoretical analyses and computational modeling

To solve the “standoff” problem it was proposed to use a focused array plasma jets launched from the periphery of the blast chamber to form a spherical plasma “piston” liner for compressing a centrally placed magnetized plasmoid to fusion ignition conditions [Thio, 1999]. The imbedded magnetic field inside the target is compressed along with the target plasma to achieve magnetic insulation, and the heavy plasma liner holds the pressure for an inertial time scale over which the fusion reactions take place. Plasmoid targets envisaged are compact toroids (CTs) having nested magnetic flux surfaces, such as spheromaks and FRCs; or linear targets, such as a z-pinch. Current drive in a dense plasma sphere (formed by the merging of plasma jets) using lasers or electron beams may also be used to create seed fields in the target plasma.

Broadly speaking, the problem divides into three parts. First there is the propagation of the discrete supersonic plasma jets in the quasi-vacuum space and in the external magnetic field of the central target plasma. Next there is the merging of the jets to form a contiguous plasma liner that collapses and implodes on the target. Finally, there is the ignition of the target and the thermonuclear firing up of the surrounding liner fuel necessary for high gain.

The initial analysis of the concept by Thio (1999) assumes the jets to merge and form a liner at a radius of 20 cm and compresses a magnetized DT plasma with an initial radius of 2.5 cm and density of 10^{18} per cm^3 down to a radius of 2.5 mm when the density of the target plasma reaches 10^{21} per cm^3. Using the model of alpha deposition in magnetic field provided by Kirkpatrick, the analysis show that target B field of 1000 T (10 MG) is required for significant re-deposition of the energy of the alpha particles in the target to occur and to achieve significant fusion burn of the target. The stagnation of the liner against the target creates a very dense inner layer for the liner, and presents an opportunity to burn a thin inner layer of the liner (<u>not</u> propagating burn) by the passage of the alpha particles produced by the burning target and thus amplifying the fusion gain. For this to occur, the analysis show that inner surface layer of the liner needs to have a density exceeding 10^{23} per cm^3, that is, close to or exceeds solid density. 1-D Lagrangian modeling produce results consistent with the analytical model [Thio, et. al. 2002]. 3-D Smoothed Particle Hydrodynamics simulations were made to show that plasma jets can merge to form a plasma liner and compress targets to fusion temperatures and reasonable confinement time [Thio, Knapp, Kirkpatrick, et al. 2000, 2001, 2002]. Similar results were shown by 2-D MHD modeling using the MACH2 code [Cassibry, 2002]. In particular, the MACH2 simulations show that the rate of thermal conduction is significant compared with the rate of implosion, so that adiabatic assumptions are likely to be inappropriate. Thermal conduction smooths out shocks and helps to keep the Mach number of the liner low during compression. Stability analysis was also made estimate the growth rates of interfacial instability when the jets merge with differential velocity between the jets [Cassibry, Thio, Wu, 2000, 2001]. The 1-D BUCKY radiation hydrodynamics burn code is being used to model the fusion burn [Santarius, 2007].

Using a simple quasi-steady state flow model, Parks [2007] show that, assuming a fully ionized DT liner with a constant gas γ of 5/3 and formed at a radius of 60 cm, in order to obtain the high stagnation pressure required for ignition, Mach number as high as 60 might be required. Furthermore, the oblique shocks produced in the jet merging process can degrade Mach number, even if jets at high M could be realized [Parks and Thio ICC 2006; Parks, 2007]. A composite liner consisting of multiple layers with the use of high-Z (e.g. Argon) outer layers may relax the jet parameters [Thio et al 1999]. Using a similar semi analytical quasi-steady state implosion model used for the DT liner problem, it is shown that for a high-Z liner ionization acts as thermal sink and helps to keep the temperature of the liner low and the Mach number of the liner high during the implosion. This effect allows the use of a lower initial jet Mach number [Thio, 2007]. For example, a two-component liner with a heavy (eg. argon, xenon, or possibly a "macro-particle") outer shell and an inner DT shell allows one to achieve the necessary ignitions at much reduced M number, and possible sufficient energy gain. We shall explore further the implosion and energy gain physics of multi-layered concentric plasma liners, including the burning of an inner DT fuel layer using a combination of analytical models and numerical simulations.

We are developing techniques to utilize state-of-the-art meshless 3-D Smoothed Particle Hydrodynamics (SPH) to model plasma jets for MIF applications and for research in high energy density matter. Among the numerous challenges facing theoretical modeling of PJMIF are the presence of strong gradients and potentially strong asymmetries associated with using discrete jets to implode compact toroids or other magnetized targets. Because of its meshless nature, SPH has the advantage of tracking particle (fluid element) trajectories and interfaces while avoiding the pitfalls of mesh entanglement of Lagrangian codes requiring a grid. Recent advances in shock capturing techniques enable modern SPH codes to accurately model strong gradients in the flow field, expected at plasma jet and liner interfaces. Since particle neighbor search procedures are common to all dimensions of flow, the adaptation from 1D to 2D and 3D is almost a trivial exercise. Thus, 3D simulations, necessary to capture PJMIF asymmetries, are easily accommodated in SPH simulations. Furthermore, unlike the true particle codes, SPH solves the fluid equations, and thus potentially has the advantage of computational efficiency.

5.2. Subsonic Plasma Liner and Other Standoff Concepts

An outgrowth of the concept of a plasma liner is an idea to use plasma streams to solve the stand-off problem, without necessarily using them to directly implode the target plasma. This approach was pursued by D.D. Ryutov and Y.C.F. Thio [1, 2]. One version of this approach would use a subsonic hydrogen plasma (T~10 eV) to drive a 3D implosion of a shell made of high-Z gas, whose temperature remains low due to the radiative cooling. The low temperature then leads to a small thickness of a dense shell and allows for it significant convergence, thereby leading to a large power-density amplification. The shell can then be used to either adiabatically implode a pre-formed magnetized target, or to drive a magneto-compressional generator that would constitute a part of a target assembly dropped into the chamber [3]. An advantage of this approach is that it allows a considerable reduction of requirements to the performance of plasma guns. Its disadvantage is that it loses elegant simplicity of the “direct” drive by converging, high Mach number jets.

In the version where a magneto-compressive generator is used, a converging heavy shell can be used in combination with a local spherical blanket [4] surrounding the magnetized plasma. This would allow one to provide an efficient protection to the reaction chamber and plasma guns from the neutron damage, and simultaneously breed tritium. A vaporized blanket could be used as a driver for gas turbines.

Another possible way of using plasma jets for solving a stand-off problem would be formation disc-like plasma electrodes by merging a number of a relatively cold (T ~ a few eV) plasma jets with a moderate Mach number (M~3-4) [2]. These disc electrodes would connect the external power source with an imploding liner situated inside the local spherical blanket. An analysis presented in Ref. [2] shows that this system would allow one to deliver to the liner (situated inside he blanket) multi-MA currents within a few microseconds.

All in all, approach described in this section allows one to use the ideas of a plasma liner to solve a stand-off problem for an MTF approach based on the current-driven liner for plasma compression.

A converging thin high-Z shell [1] is of a significant interest for the studies of high-energy-density physics in the system that would deliver multi-megajoule energy to the volume of ~ 100 cm^3.

Interesting science questions are related to the stability of the imploding heavy shell and the possibility of suppressing possible instabilities by a feedback technique [1]. In the concept [2], an interesting science question is, again, stability of the disc electrodes, as well as the processes occurring at the interface of the disc plasma electrodes and solid (disposable) electrodes attached to the local blanket.

1. D.D. Ryutov, Y.C.F. Thio. "Plasma liner with an intermediate heavy shell and thermal pressure drive", Fusion Sci. Technol., **49,** 39, 2006.

2. D.D. Ryutov, Y.C.F. Thio. “Solving the stand-off problem for Magnetized Target Fusion: plasma streams as disposable electrodes, together with a local spherical blanket.” Journal of Fusion Energy, **26**, 173, 2007.

3. R.P. Drake, J. Hammer, C. Hartman, J. Perkins, D.D. Ryutov. ”Submegajoule liner implosion of a closed field line configuration”. Fusion Technology, **30**, 310, 1996.

4. B.G. Logan. “Inertial fusion reactors using Compact Fusion Advanced Rankine (CFARII) MHD conversion.” Fusion Engineering and Design, **22**, 1953, 19

5.3. LSP simulation for plasma jet merging

The merging of plasma jets to form converging cylindrical/spherical plasma shells is potentially an attractive method of creating a voluminous amount of Warm/Hot Dense Matter (WDM/HDM) or Dense Plasma, which may be magnetized. The concept consists of several important areas: high speed plasma jets, plasma liner formation by merging jets, and inter-penetration of liner with a magnetized plasma.

FAR-TECH, Inc. is tooling up and adapting the LSP code, to bring the capability of state-of-the-art 3D hybrid particle-in-cell simulation to meet the needs of modeling required to support the development of plasma jets and its applications, including MIF and creation of high energy density matter. We began by characterizing the capabilities and deficiencies of the LSP code with plasma open switch experimental data and modeling. We then identified and are performing the necessary upgrades to the code to perform plasma jet merging simulations. A few Matlab/FEMLAB based codes have also been developed to support the simulations.

We have begun to apply the LSP code to explore and identify the challenges and issues of applying 3-D hybrid PIC to model the interaction of high Mach-number, high density, and high velocity jets. So far, we have applied the code using the Child-Langmuir emission model for charged particle emission from walls, single ionization by electron impact, and charge exchange. Thermal and radiative transport model or cooling effects are not yet included. Friction and mass loading from electrode erosion are also not yet included. Within the validity of the model, using hydrogen plasma, the following preliminary results were learned. The merging of plasma jets and neutral gas jets were studied and compared for a wide range of parameters (density 10^{12} - 10^{17} /cm^3) temperature 1-10 eV, jet velocity 10-1000 km/s, merging angle 30 degrees-120 degrees. Different regimes of plasma jets merging were found. Merging angle and density of jets are crucial parameters for plasma jets interaction. The smaller the angle the better focused the beam is. The lower the jets density the better they merge in a well focused beam. Well focused merged plasma jets are observed for relatively low density and velocity of jets. High turbulent plasma flows without a preferential direction and are observed for higher plasma jet densities. Higher plasma jet velocity leads to non-symmetrical twisting flow structure. Neutral gas jets merging simulations show much different behavior than that of plasma jets. Neutral gas jets tend to scatter easily as they merge and even show a stronger scattering with a higher jet density.

In addition, we obtained, using simple models, the conditions of the plasma liner formation and dynamics of the liner including instabilities. We determined the required density and velocity to form a liner, and the required spatial and temporal precision for uniform implosion to the target plasma.

We expect that these results will be significantly modified by the use of high-Z liner materials. We plan to test LSP for multiple ionization effects with Ar for which FAR-TECH has complete data base. For high –Z liner materials, the multiple ionization cross sections will have to rely on code simulations based on a theoretical model, as there is no experimental data available at present. Inclusion of radiative transport and cooling is also expected to modify the dynamics of jet merging in high density regimes. Use of LSP to simulate the very dense strongly coupled regime is challenging, and yet to be investigated.

5.4. Developing the enabling technology for the concept.

Creation and injection of initial plasma mass into a coaxial accelerator, in a suitable form to shape the high-density plasma slug, is one of the key technologies for achieving hypervelocity high-density plasma jets for MIF and disruption mitigation.

High velocity dense plasma jets are under development at HyperV Technologies for a number of applications, with the initial primary motivation being Magneto-Inertial Fusion using high density, high velocity plasma jets as standoff drivers. The technical approach utilizes symmetrical pulsed injection of very high density plasma into the breech of a coaxial EM accelerator having a tailored cross-section geometry to prevent formation of the blow-by instability, and is an outgrowth of papers by Thio et al, and computational and experimental work performed by Cassibry and Thio. Key to this approach is an array of mini-injectors used to produce the initial working plasma. HyperV is following two parallel development paths to accomplish this initial injection. The first uses a large number (ultimately up to 64) of ablative electrothermal capillary discharges, while the second will concentrate on injection of pure or mixed gases, including microns (dust), using non-ablative means. The experimental effort is conducted in collaboration with the University of Maryland and UC-Davis (especially in diagnostics). Computational support for the experimental development is provided by Numerex, FAR-TECH, Voss Scientific, Prism Computational Sciences, as well as HyperV in-house resources. We also anticipate the participation of University of Alabama in Huntsville in the near future. State-of-the-art extended MHD code (Mach2), 3-D hybrid PIC code (LSP) and 3-D Smoothed Particle Hydrodynamics code (SPH) are being used or planned to be used in this research.

A prototype half-scale plasma gun is currently undergoing testing and has achieved velocities in its design range of 60-100 km/s. Present efforts are focused on obtaining definitive density measurements of this jet. Recent pressure probe measurements show a plasma slug arrival which correlates well with fast imaging. This plasma gun will be installed on MCX to test injection of momentum to drive rotations in the central cell. An important additional benefit of these tests will be to study the propagation of the plasma slug across the B field, both in vacuum and with warm plasma present.

Mini-injector development has taken place on several test fixtures, the most important of which is the 2pi test fixture which incorporates 64 capillary discharges mounted in a 24-inch diameter circular array, all firing radially towards the axis. Jet merging and interaction studies are underway on this facility with some recent good observations of jet merging and implosion on axis. The facility is being upgraded to include faster pumping to substantially lower the background pressure from its present 1 mTorr, and also to include additional diagnostics (high resolution spectroscopy, visible light imaging using a fast gated PI-MAX camera, pressure probes, and a laser interferometer). These diagnostics are also used on the other experiments.

Experiments to date have concentrated on the ablative approach using several test fixtures. Development of pure H2/D2 (or any gas) injectors is underway and will be an important focus over the next two years of the preparatory phase, during which time HyperV will also build a full scale gun capable of reaching 200 km/s.

FAR-TECH has found that TiH2 grains pulsed sources [as demonstrated on Globus-M] may be the best candidate not only for fueling, but also for MIF and disruption mitigation. The TiH2 pulsed source provides bursts of high-density molecular hydrogen at high velocity for fast injection. Their new idea is to use these sources as a pulsed "oven" to sublimate the very heavy C60 fullerene molecules (which can have noble gases inside, if needed) homogeneously mixed with the TiH2 grains. That way a compact dense plasma slug can be created and further accelerated. Due to the large mass difference between C60 and D2/T2 molecules, which can easily replace H2 in TiH2 grains since they have identical chemical properties, a suitable liner-fuel structure of the plasma slug is naturally created from the beginning of the acceleration. FAR-TECH is investigating this scheme, which may have a good potential for (merging) plasma jets driven MIF. In addition, FAR-TECH estimates that the C60/TiH2 source is able to provide the hypervelocity high-density plasma jet with the large impurity mass required for disruption mitigation in a tokamak fusion reactor.

HyperV's experimental facility consists of 4400 sq. ft. of laboratory space, a large rf shielded screen room, 68 channels of 1 Gs per second digitizers for data acquisition, a small machine shop, numerous vacuum pumps, HV power supplies, HV sparkgap switches, and the usual array of supporting equipment. On the simulation side, HyperV has an operational 34 processor Linux cluster (which will be upgraded later this year to at least 64 processors and possibly more) on which it runs LSP and Mach2. Numerical modeling efforts have focused on gaining an understanding of the dynamics of initiating, accelerating and transporting the plasma slug in a plasma jet in order to support the engineering design of plasma jet experiments and to optimize plasma jet performance. Studies to date have included modeling the physics of capillary injectors (in collaboration with NumerEx,) parametric studies of optimal electrode shape for the acceleration phase of the plasma jets in order to avoid or slow the blow-by instability, and characterization of the plasma detachment from the accelerator.

5.5. Plasma Jets Research at Caltech

Facilities, activities, goals, and intellectual/scientific issues being addressed.

The Caltech research group is investigating the physics of MHD-driven jets and the closely related topic of how spheromaks form. We have an experimental facility designed to address the fundamental science issues governing MHD-driven jets and spheromak formation. The emphasis is on experimental reproducibility, achieving very clear results, comprehensive diagnostics, and achieving agreement between observations and first-principles theoretical models. The inter-shot time is 2 minutes, high-speed photography is used, and no damage occurs to hardware as a result of shots.

We are investigating the jet acceleration mechanism, the convection of magnetic flux frozen into the jet, dependence on particle mass, topological evolution of the magnetic field, shocks when jets collide with each other or with a gas target, and single-particle orbit physics. We have identified several previously unknown mechanisms that are important in jet physics and spheromak formation. Our most important results to date are the observation and developing a first-principles understanding of:

(i) conversion of toroidal flux into poloidal flux,
(ii) collimation of a stagnating jet because of the axial compression of frozen-in magnetic flux, and
(iii) a single-particle orbit instability whereby heavy ions are ejected sideways from a magnetized jet emanating from the cathode.

We plan to continue this scientific investigation of jet behavior and spheromak formation physics. Our goal is to develop scaling laws so that the properties of higher energy density jets and spheromaks can be predicted with good confidence. We are planning to upgrade the capabilities of our existing facility so that longer jets can be produced.

5.6. MSNW/University of Washington contribution to plasma liner fusion

The fusion concept and initial experimental program to be described here takes advantage of developments in the very compact, high energy density regime of fusion employing a compact toroidal plasmoid commonly referred to as a Field Reversed Configuration (FRC). To make fusion practical at this smaller scale, an efficient method for repetitively compressing the FRC to fusion gain conditions is required. A promising approach to the compressional heating of the FRC, and the one is being explored at the MSNW facility will employ a plasma shell to radially compress and heat the FRC plasmoid to fusion conditions. The closed magnetic field in the target plasmoid suppresses the thermal transport to the confining shell, thus lowering the imploding power needed to compress the target. With the momentum flux being delivered by a low mass, but high velocity imploding plasma shell, many of the difficulties encountered with the implosion power technology are eliminated or minimized.

The energy that is required for the implosion compression and heating of the FRC plasmoid is derived from both the radial kinetic energy of the plasma used to compress it, and the axial kinetic energy of the FRC’s motion prior to compression. Both the formation of the FRC and the plasma liner can be well separated. The inward acceleration of the plasma liner and the axial acceleration of the FRC can then be performed in staged manner to provide for a very rapid evolution of the FRC into a state fusion burn. The timescale for forming and accelerating both the FRC and liner (τ_{form} >> 1μs) can be much longer than the time that the energy is thermalized in the implosion (τ_{heat} < 1 μs). The consequence is a greatly reduced demand on the power delivery systems as the energy can be accumulated over a time interval of several microseconds far from the interaction region. The need for local high-voltage, multi-megajoule energy storage and delivery systems is removed. The feasibility for achieving fusion gain will be evaluated near term with an experimental demonstration of the plasma liner compression of the FRC plasmoid to fusion conditions.

At MSNW two inductive plasma accelerators (IPA) have been constructed and tested forming a stable, hot (500 eV) target FRC for compression. In the Inductive Plasma accelerator (IPA) the formation and acceleration of the FRC plasmoid is through the electromagnetic interaction of the radial magnetic field of the sequentially activated accelerator coils (see Fig. 1), and the large FRC toroidal plasma current (i.e. the Lorentz force). The magneto-kinetic compression heating of the FRC plasma has the potential to be much more efficient than other methods. Not only is the energy coupling mechanism low-loss, virtually all of the kinetic energy is thermalized in the plasma in the form of ion energy.

Based on these initial FRC merging/compression results, the design and methodology can now be implemented in an experimental demonstration of the PLC. The next step would have the colliding/merging FRCs simultaneously compressed by the plasma liner to fusion temperatures.

5.7. Enhanced Energy Accumulation in a Staged Z-Pinch

Traditional methods for energy accumulation in a plasma are limited in their maximum-attainable parameters by the Rayleigh-Taylor instability. Techniques exist to mitigate this instability, using plasma-dynamic processes to adjust the transfer timescales. Such studies have general relevance and broad intellectual merit for: the stabilization of high-energy-density plasmas, generation of ultra-high magnetic fields, development of advanced measurement-science technologies, continued advance of numerical simulation capability, and the production of plasmas at previously unattainable parameters.

Over the past decades the principal focus of the UCI Z-pinch Group has been on the production of laboratory-scale, ultra-high-energy-density plasmas (or more precisely, the conditions needed to produce high-fusion-energy-gain). Our university-scale programs have resulted in approximately a dozen PhD dissertations and numerous journal publications. Facilities and resources that have been developed, or currently exist, include: impulse-power systems up to 0.1 TW output, sophisticated laser-based plasma diagnostics, basic theory describing high-energy density plasmas, and sophisticated modeling using advanced radiation-MHD codes. Early results, obtained with gas-mixture Z-pinch implosions, indicated, via nano-second laser interferometry and filtered x-ray spectroscopy, the formation of a double-shell implosion that was more stable and higher accumulated energy density, than was possible for an implosion of either gas species separately. The present "Staged Z-pinch" evolved from these concepts, which consists of a cylindrical, high-atomic-number plasma liner used to compresses a low-atomic-number target plasma; for example, a krypton shell imploding onto deuterium-tritium target fill.

Further analysis of the Staged Z-pinch, clarifies the precise initial conditions, driver requirements, and physical dynamics needed for optimal energy transfer into the target plasma. The optimal compression dynamics leading to high-energy density involve tradeoffs in the actual physical parameters: the time-scale for diffusion of the azimuthal-magnetic field, the formation time of compression shock waves, current amplification in the target, and the generation of ultra-high magnetic fields to confine fusion alpha particles. Our predictions for a national-laboratory-scale impulse-generator facility are based on extensive analysis using the MACH2 code. For realistic experimental conditions, our results suggest that an inertially-confined plasma may be compressed to high-density ($10^{23}cm^{-3}$) and high-temperature (tens of KeV), with a fusion-energy gain far in excess of a factor of ten.

Further development of these concepts should involve refinements in computational capability, with code runs specifically benchmarked against well-diagnosed, sub-nanosecond impulse generator experiments. Short-term studies should be performed first on 10-100 kJ class facilities; longer-term, studies should be scaled to the multi-mega Joule level. A small-scale facility could be assembled to produce a well-characterized plasma, or an existing impulse-generator facility might be used, for example, such as those found at the University of Nevada in Reno, the Los Alamos National Laboratories, the Sandia National Laboratories, and elsewhere. In the three-year timeframe financial support at the level of $1.5 M/year would be required to provide understanding at the 10-100 kJ stored energy levels. Thereafter, in the three - six year timeframe, support at the level of $6 M/year would be required to provide scaled understanding at the higher, stored-energy levels.

5.8. HEDLP-Relevant Plasma Diagnostics on CTIX

Several major differences exist between the conventional and MIF approaches to HEDLP. First, compared to IFE, magnetic fields in MIF experiments play a larger role, with field strengths in the mega-gauss range. Second, peak plasma densities are lower, making the plasma transparent to longer wavelengths. Finally, plasma lifetimes are comparatively long, relaxing the difficulty of diagnostic measurement. To have powerful diagnostic techniques for full-scale MIF experiments, it is important to develop these techniques beforehand, and to verify their accuracy, practicality, and agreement with theoretical and computational models. It will be cost-effective to develop such diagnostics in a smaller-scale experimental facility with plasma conditions relevant to large-scale experiments. Reduced machine size, absence of ionizing radiation or machine activation, high repetition rate, and an academic environment are all advantages of a smaller facility. We propose to use the CTIX facility as a test bed for development of MIF-relevant diagnostic techniques. CTIX is a reliable experimental facility with a proven control and diagnostic system and good 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. The CTIX group also collaborates with the UC Davis program of plasma microwave diagnostics, which offers a wide range of sources and detectors over a range of frequencies suitable to the CTIX plasma.

Some of the possible diagnostic approaches suitable to CTIX, and relevant to HEDLP MIF experiments, include:

I. Measurements of internal magnetic fields via propagation of electromagnetic waves. This category is subdivided into spectroscopic methods (e.g., Zeeman splitting), and microwave methods (e.g., terahertz beams). On CTIX facility is new, noninvasive techniques may be directly compared to direct magnetic measurements. Systematic study of (gyro-radius)/(mean free path) effects could be performed.

II. Measurement of plasma density and plasma density gradients. In addition to conventional interferometers, CTIX has developed the plasma deflectometer, a direct diagnostic of plasma density gradient, which does not require complex phase-quadrature measurement. Deflectometry becomes increasingly accurate in high-density plasma, an advantage for large-scale MIF.

III. Testing of multi-species plasma acceleration, accretion, and axial-separation mechanisms. CTIX can produce plasma with a varying mix of ion species on a shot-by-shot basis, accompanied by single-wavelength optical diagnostics with sub-microsecond time resolution. By isolating individual ion species, turbulent plasma transport or differential acceleration may be studied.

IV. Plasmas exiting the CTIX accelerator are accessible, permitting direct measurement of impurity content via Auger target analysis, gridded energy analyzers, finite gyroradius diagnostics, etc.

2Year Plan:

- Multiple ion species acceleration study. Quantify species separation during acceleration, using narrowband optical filters
- 2-D sub-microsecond imaging
- Deflectometry measurements at high density gradient plasma
- Microwave (terahertz) diagnostics of magnetic field
- Improved application of formation voltage for increased timing accuracy
- Improved diagnostic access to formation and acceleration sections

5 year Plan:

- Compression electrodes for high plasma density and energy density
- High density buildup via gas, liquid, or capillary-plasma injection
- High-resolution spectroscopy for Zeeman or Doppler measurement
- Multiple CT merging at small angles for liner formation

6. REFERENCES

A list of Magnetized Target Fusion (MTF) articles can be found at:
http://wsx.lanl.gov/MTF/mtf_bib.html

A list of Field Reversed Configuration (FRC) articles can be found at:
http://wsx.lanl.gov/Publications/FRC.html