Development of Practical Fusion Power
Plasma Jet Driven Magneto-Inertial Fusion

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ABSTRACT

Fusion is the ultimate source of energy for human civilization in all sense of the word. Because fusion transforms mass directly to energy according to Einstein's theory of special relativity ($E=MC^2$,) a very small amount of fusion fuel creates a very large amount of energy. The cost of fusion fuel (Hydrogen-deuterium and Lithium) per mWh of energy is so close to zero that virtually all the cost of electricity generated from fusion arises from the capital cost of the power plant and its amortization of development, operating and maintenance costs. The profit potential of fusion power is immense. Fusion can be used to create synthetic liquid and gas fuels for the transportation industry, thereby replacing petroleum and natural gas, as well as virtually unlimited electricity. Direct fusion propulsion has long been considered by NASA for the next generation of manned spacecraft for long distance space exploration. Fusion power is environmentally clean, emits no greenhouse gases, and produces no appreciable radioactive waste. The planet's fossil fuel reserves are severely limited. Whereas current nuclear fission fuel resources still remain abundant, nuclear power has safety, radioactive waste, and weapon proliferation issues. Fusion power is the only known hope for mankind's survival on this planet in the foreseeable future.

In this paper, we describe an emerging approach to practical fusion power. We first describe fusion power and its ability to provide all the energy the world can consume for eternity. Next we summarize the status, politics, and legacy of the United States government funded fusion research program and provide a historical perspective of the development of alternate fusion approaches. Then we explain how fusion energy can be developed by private entrepreneurial enterprises using the innovative approach of Plasma Jet Magneto-Inertial Fusion (PJMIF.) The scientific and technical description is adapted from the following paper with permission, and is hereby acknowledged:

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1. Background

1.1. What is fusion?

Fusion is the process that powers the Sun and the stars. It is Nature's way of creating energy and is the opposite of nuclear fission, the process by which nuclear power is produced today. In fusion, the atomic nuclei of two light atoms fuse to form heavier nuclei. In the process, a large amount of energy is produced due to the conversion of mass directly to energy according to Einstein's principle of special relativity expressed as $E=MC^2$. For commercial production of fusion energy, the fusion reactions considered usually involve the two isotopes of Hydrogen, namely ^2H or deuterium (D) and ^3H or tritium (T). Deuterium exists naturally in sea water which is a plentiful source of the isotope. It is non-radioactive. Tritium is radioactive, but has a very short half-life of approximately 12 years, and thus is very rare in nature. When deuterium and tritium are chosen as the fuel for a fusion power reactor, tritium is produced as part of a carefully designed fuel cycle involving the very common element Lithium, while deuterium is "mined" from the sea. The nucleus of a deuterium atom contains a proton and a neutron, whereas the nucleus of a tritium contains one proton and two neutrons. When a deuterium nucleus fuses with a tritium nucleus, a Helium nucleus is formed with the release of one neutron. Both the Helium nucleus and the neutron carry the energy produced by the fusion reaction. When one gram of deuterium completely fuses with one and a half grams of tritium, 235,852 kilowatt-hours of energy is produced. At a price of 4 cents per kW-hr, this energy is potentially worth $9,434.00, less reactor costs.

In order to produce fusion reactions, a deuterium-tritium (D-T) mixture is usually heated to a temperature well above 100 million degrees Centigrade in order for the fusion reactions to occur at a significant rate. At such temperatures, the orbiting electrons about the nuclei of the atoms of the D-T mixture are liberated from the electrical attraction of the nuclei which then become positively charged ions, and the mixture of electrons and ions is called a plasma. When a magnetic field is applied to the plasma, the charged particles in the plasma gyrate in circles about the magnetic field lines, preventing their loss from the magnetic field. Thus, in principle, a magnetic field can be used to confine a plasma at very high temperatures keeping them away from any material wall. This is the basic principle of one approach to fusion energy and is called magnetic confinement fusion (MCF). However, in practice, the plasma particles collide and may drift across the field lines and get lost from the magnetic field over a sufficiently long time interval, breaking the magnetic confinement of the plasma.

Another approach to “confining” a hot plasma is to make use of the fact that no matter how hot a gas is, it takes time for the gas to expand and cool because of its own inertia (mass). This is the basic principle of another approach to fusion energy called inertial confinement fusion (ICF). In this approach, a D-T mixture is compressed by some means such as a blast of high power laser beams, which is called the driver, to fusion temperatures and to a very small volume; usually no larger than 0.1 mm in radius, located at some distance from the chamber wall. The fusion reactions occur in this very tiny but very dense ball of plasma for less than a nanosecond. The plasma ball expands and cools and the fusion reactions cease. The process is then repeated like an internal combustion engine in order to produce a continuous stream of energy pulses equivalent to an average continuous power.

The difference between nuclear fusion and conventional nuclear fission is that nuclear fission is accompanied by large amounts of radioactive waste products that have long half-lives (tens of thousands of years), whereas fusion proper produces no radioactive waste products. However, it is anticipated that the very early fusion DT reactors will produce some indirect radioactive products with half-lives of only a few years. Thus, commercial fusion power when realized will not give rise to a nuclear waste problem. Furthermore, in order to maintain the fusion reactions in a reactor, input power is required. In the event of an accident causing malfunction, the input power will be lost and the fusion reactions stop in the reactor. In this sense, a commercial fusion power reactor is fail-safe because it does not have a run-away core melt-down problem as might occur in a commercial fission reactor during an accident or reactor malfunction.

In summary, fusion is safe, clean, the fuel cost is near zero and there is enough of it to last the human civilization for millions of years. It is Nature’s own way of producing energy in the Sun and in the stars. We know absolutely for a fact that it works because it has been produced by humans in thermonuclear weapons. What remains to be done is to engineer a solution to generate fusion energy in a commercial power plant at a sufficiently low operating cost in order to produce electricity, as well as liquid synthetic fuels for aircraft and the like, at a lower cost than what is available today. In this white paper, we propose a path to commercial fusion power based on a proprietary fusion concept with a corollary project plan to develop and commercialize the technology.

1.2 The need for fusion:

If all peoples of the world are to live comfortable lives and have the ability to prosper, we must increase total worldwide annual energy production by a factor greater than ten times current production. That is not possible and if it were it would deplete fossil fuel reserves by the end of this decade. “Alternative green and renewable” energy sources can supply less than 4% of projected 2050 total energy requirements. There is only one way to produce this amount of energy to support mankind. That is the conversion of mass into energy through the process of controlled fusion.

The fundamental ingredient required to support mankind is energy. If other nations are to enjoy a decent standard of living, they will require energy resources in amounts approaching those consumed in the United States and west in ratio to their populations. Today the population of the United States is approximately 304,000,000 or 4.4% of the world population, yet the United States consumes 28% of world energy use. Thus, it can be seen that to support our current world population at a standard of living morally acceptable, we would have to increase world energy production by well over 10 times.

Given the fact that energy production from fossil fuels has by most estimates peeked in terms of capacity, and liquid fossil fuels will be depleted within 50 years, a new much higher flux density source of energy must be found. There is only one known and realistic source. That is the direct conversion of mass into energy based on Albert Einstein's law of special relativity and the equivalency of mass and energy represented by the formula $E=MC^2$. This law teaches us that a very small amount of matter, say one gram, has the energy equivalent of a very large amount of energy when converted.

2. The Government Funded Fusion Program and the perception that Fusion Development is necessarily a multi-billion-dollar and multi-decade R&D effort

Fusion research has been funded by the United States Government for over 40 years at a total cost in excess of $23 billion dollars. The Government funded fusion research has down-selected to two extreme approaches (tokamak-magnetic confinement and laser inertial confinement fusion) very early on, which have proven to have extremely high R&D costs for each incremental step of progress. The official government position today is that it will take another 50 years and approximately $50B more in funding before either of the two approaches could be commercialized.

As a legacy of the government funded fusion research, there is a perception within and without the fusion community that fusion R&D is necessarily a multi-tens-of-billion-dollar and multi-decades R&D program and is thus not suitable for development by the private sector at present. It is a perception that is fostered by the establishment fusion research community (tokamak MCF and laser ICF). It is an argument used by the United States Department of Energy Office of Fusion Energy Sciences (OFES) to justify its long-held policy of early down-select and focusing on the tokamak approach as the path for fusion energy[1]. The argument used by OFES is that there will never be enough Federal resources for developing more than one approach to fusion.

There is also the concern that if the U.S. government is exploring alternative approaches to fusion, it might give rise to a public perception that the scientific foundation for the two mainline approaches of magnetic confinement and inertial confinement, is not sufficiently developed, and thus weaken the argument for continuing the commitment to the multi-billion-dollar investment in the two mainline approaches. Furthermore, since the U.S. has been seen by the rest of the world to be a leader in fusion energy sciences, exploring alternative fusion approaches by the U.S. government might send the "wrong signals" to its international partners in the $20B-plus international ITER project.

Inertial confinement fusion (ICF) research, funded mostly by the National Nuclear Security Administration (NNSA,) has been justified, not for energy application, but for the purpose of scientific nuclear stockpile stewardship in the absence of nuclear weapon testing. Laser ICF is tolerated by the U.S. Department of Energy OFES as a "back-up" (a measure of risk mitigation) to tokamak MCF for fusion energy, because the resources for its development is available from NNSA, and thus the OFES policy of "a focused approach to fusion" (tokamak magnetic confinement) remains whole even though laser ICF is officially pursued by a branch of the U.S. government.

Another result of the long history of fusion research is the perpetuation of another incomplete truth that the government funded research has practically exhausted all possible alternate fusion approaches and has shown that the alternate approaches do not work. In the next section, we will attempt to put the history of the research in alternative fusion approaches in proper perspective and throw some light on the incomplete truth.

3. The Truth about the Cost of Fusion Development and the Fusion Alternates

Recognizing that the facility cost was a large component of the R&D cost which was the principal impediment to the progress of fusion development at the time, around the mid-1990's, Drs. Irv Lindemuth, Richard Siemon and Kurt Schoenberg of Los Alamos National Laboratory began to examine the cost of developing various fusion concepts in a fundamental way. The fusion parameter space is spanned by two basic plasma parameters, namely the plasma density and the magnetic field embedded in the plasma, which govern the physics of attaining fusion burn. The tokamak attempts to burn a plasma at a density of 10^{20} ions per m^3 in a magnetic field of several teslas (T), while laser ICF attempts to burn a plasma at a density of 10^{32} ions per m^3. In conventional ICF, no external magnetic field is applied to the target, but laser-plasma interaction can self-generate magnetic fields up to about 100 T. Essentially, these two mainline approaches sit at two extreme isolated spots in the fusion parameter space.

The results of the Lindemuth, et al, analysis were presented in various papers, workshops and conferences, since the mid-1990's and recently collected and published in their paper of 2009 [3]. The principal results of their analysis are:

(i) The cost of plasma confinement is proportional to the thermal energy or the fuel mass in the confined plasma, whereas the cost of plasma heating is proportional to the required heating power density. The cost of a breakeven fusion facility is the combined cost of confining the burning plasma at breakeven and the cost of heating the plasma up to ignition.

(ii) For magnetically confined plasma, the amount of plasma energy required to produce fusion ignition is approximately inversely proportional to the square root of the plasma density.

(iii) For fusion approaches that use compression to heat the plasma, the power density of the compression required is proportional to the fuel density and the velocity of implosion.

(***iv)*** The net results of the analysis for the cost of a breakeven fusion facility as a function of the fuel ion density and temperature is shown in Figure 3, which correctly explains the costs of ITER and NIF. ITER corresponds to a point in Figure 3 for a density of 10^{14} ions per cc and temperature of 10^4 eV $^($$10^8$ degrees K.) NIF corresponds to a point of 10^{25} ions per cc and the same temperature.

(v) There appears to be a sweet spot where the burning plasma density is in the range 10^{19} to 10^{22} ions per cc. In this sweet spot, the stunning result of their analysis is that fusion approach exists for which breakeven fusion facility might very well cost as low as $51M! (A typical nuclear fission power plant costs in excess of $5.5 billion 2008 USD.)

The tokamak makes use of a fuel density in the range of 10^{14} ions per cc. In order to ignite the plasma in the tokamak at this low density, at least 2 to 3 GJ of thermal energy must be confined in the plasma by the applied magnetic field. This explains why ITER should cost at least $10B.

Laser ICF attempts to create a plasma with a density in the range of 10^{25} ions per cc resulting in a pressure of 10^{17} Pa at ignition. At the same time, because it does not use a magnetic field to suppress heat conduction in the plasma, it is necessary to implode the fusion fuel at a very high velocity of at least 300 km/s for the heating power to outrun the electron thermal conduction losses from the hot spot. The result is that extremely high heating power density in excess of 10^{18} W. cm^{-2} is required. Very advanced, short-pulse, high-energy lasers are required. This explains why the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory costs about $4B. The plasma densities in tokamak and laser ICF differs by as much as eleven orders of magnitude and represent the two extremes in the fusion parameter space.

During the early years of research in controlled thermonuclear fusion, energy confinement and the efficient heating of the plasma are identified as the two main technical challenges for the attainment of controlled thermonuclear fusion energy. The research in alternative fusion approaches during the 50's, 60's and 70's thus sought in an ad hoc manner various "clever" ways of improving the energy confinement, and/or the heating of the plasma, and many concepts were explored. Generally the search for better confinement or more efficient methods of heating were not very successful, and led to the conclusion that it was very difficult to achieve better energy confinement and heating efficiency than the tokamak configuration. The remaining alternates in this old era (pre-1995 approx.) sought to overcome the engineering problems of the tokamak approach (e.g., disruption, heat extraction, steady-state operation, linked magnetic coils and non-inductive heating, etc.). All the alternates in this pre-1995 era generally aim for a similar spot in the large fusion parameter space as the tokamak or the laser ICF. The alternates in this old era includes stellarator, tandem mirrors, the Astron system, z-pinch, impact fusion, theta pinch, reversed field pinch, field reversed configuration (FRC), spheromak, Polywell, IEC, dense plasma focus, etc.

Another important facet of the history of fusion R&D is that there was a general aversion towards any pulsed fusion approach in the early days of fusion energy research in favor of steady-state approaches. This is mainly because of the nascent nature of the electromagnetic pulsed power technologies in those days and the concern for the high cost of the fabrication of the targets for each pulse. Thus fusion concepts that made use of electromagnetic pulsed power as the driver were seldom taken seriously by OFES (or its predecessor) and thus were never funded at any significant level.

By the early 1990's, the state of electromagnetic pulsed power technologies had changed dramatically for the better, thanks to a decade or two of defense and SDI related development of the technology. Low-cost, long-lifetime, repetitive pulsed power storage (capacitors,) switching and transmission technologies became conceivable. A small minority of scientists, mainly from the defense and nuclear weapon establishments, began to see the potential for pulsed power to make a contribution to the quest for practical fusion energy.

Intellectually, the exploration of alternate fusion approaches experienced a paradigm shift in the 1990's. The mid-1990's represent the watershed in the research of alternate fusion concepts.

The fundamental feature that distinguishes the alternates in the modern era (post-1995 approx.) from those in the old era (pre-1995 approx.) is that modern alternates seek to find the "sweet spot" in the fusion parameter space, taking advantage wherever possible of the plasma physics we have learned to-date. The modern alternates include the various embodiments of magneto-inertial fusion (MIF) which aim for the intermediate parameter space between magnetic and inertial fusion, mirror-based gas dynamic trap, centrifugal confinement, flow-stabilized z-pinch, various embodiments of helicity injection, levitated dipoles, etc.

It is in this sweet spot of the fusion parameter space that our proposed fusion approach PJMIF sits. Because a lower implosion velocity is planned, a magnetic field is required to suppress the heat loss during the compression. Because it uses a magnetic field as well as plasma implosion, it is essentially a hybrid of MCF and ICF, and is an approach in the class of fusion approaches called magneto-inertial fusion (MIF) or magnetized target fusion (MTF)[4, 5].

Though there were sporadic MIF-related efforts before the 1990's, significant research effort to develop the scientific knowledge base of MIF or MTF did not begin until the mid and late 1990's. An issue central to all plasma implosion schemes is the Rayleigh-Taylor (RT) instability. By the early 1990's, after decades of defense-funded work on the implosion of thin cylindrical metallic shells called solid liners, the science and technology of imploding these thin metallic shells have matured to the point that they are ready for application. The RT instabilities in these liners during the implosion are well characterized and their control is well in hand. Equally mature at the time was the science and technology of producing field reversed configuration (FRC) plasma as the magnetized target plasma to be imploded. The small, fledgling MIF community, led by the Los Alamos National Laboratory group, thus selected the solid-liner technology as the implosion scheme combining with an FRC as the magnetized target to provide the first experimental "existence proof" of MIF[6] (Figure 4). In terms of seeking OFES funding support for the experiment, the choice of FRC has the added political advantage of making connection with the broader magnetic confinement scientific program of OFES. The solid-liner experiment (FRCHX) has been funded by OFES over the last nine years with a cumulative funding total of about $20M.

The implosion of the liner is accomplished by passing megamperes (MA) of current through the liner, which is electrically connected to a set of electrodes and transmission plates. During each shot, a large amount (10s of kg) of electrode and transmission line materials are destroyed as well as the solid liner. Though reactor embodiment of the solid-liner MTF has been suggested in the past, the main criticisms of the approach by critics of the solid-liner MTF are:

a) The relative high-cost of the solid liner to the amount of fusion energy produced;

b) The cost of the recycling of the destroyed hardware after each shot.

c) The clearance of solid material debris from the reactor chamber after each shot.

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4. History and Status of PJMIF R&D

The spherically imploding plasma liner concept for MIF was first proposed by Thio et al. [7], [8] in the late 1990's, inspired by Thio's extensive work in the area of electromagnetic plasma accelerators, and motivated by the desire to further improve on the favorable attributes of MIF by using a standoff driver that would avoid the practical issues of solid-liner MTF as listed above. Analytic calculations [7] and ideal 3D hydrodynamic simulations [9] were performed to provide the first assessments of the plasma jet parameters required to form a plasma liner and compress magnetized target plasma to fusion conditions. It was realized that electromagnetic plasma accelerators at the time could not achieve the required combination of mass, density, and velocity. Consequently, Thio carried out research [10] that led to a theoretical understanding, supported by numerical modeling[11], of how to improve on existing electromagnetic plasma accelerators to achieve the required jet parameters. The key insights were to use a pre-ionized plasma rather than a neutral gas fill in the accelerator stage, and to prevent blowby instability by shaping the accelerator electrodes which allowed most of the plasma fill mass to get accelerated to high velocity. The findings of these research efforts form the basis for NASA to develop a fusion propulsion concept based on the PJMIF approach for human exploration of the outer planets[12].

In 2004, an experimental research program and HyperV Technologies Corp. were initiated to build and optimize electromagnetic plasma accelerators based on the new insights developed over the prior several years. Since then, HyperV has demonstrated steady advances and set records for the combination of jet mass, density, and velocity[13]. Their initial work focused on the larger coaxial guns with shaped electrodes[14], [15] suggested by Thio's research. In the past few years, HyperV's focus has shifted (temporarily) to simpler, more compact parallel plate "mini-railguns" which were originally intended only to ionize and inject the plasma pre-fill into the coaxial guns. However, it was realized that the mini-railguns, much simpler and cheaper than the coaxial guns, could achieve the combination of mass (few mg), density (10^{17} cm^{-3}), and velocity (50 km/s) required for the first spherical plasma liner formation and implosion experiments to be carried out on the Plasma Liner Experiment (PLX)[12] at Los Alamos National Laboratory (LANL). And thus, for reasons of cost and expediency, the mini-railguns are receiving most of the present research attention, although the coaxial guns will likely be needed for fusion-relevant plasma liner implosions, due to their ability to accelerate large masses to high velocities (> 100 km/s) and their better potential for forming composite jets with D-T fuel in front and a heavy high atomic number pusher species in the rear.

In 2008, a workshop[17] was held at LANL to ponder next steps for developing the plasma liner MIF concept. Several studies, summarized in [17], suggested that this concept has promise both for MIF and for reaching HED conditions, but support for the concept was not unanimous among the attendees[18]. The workshop provided an update on the status of plasma gun development, showing that the gun technology was ready for a plasma liner formation demonstration. Also included in the workshop were several presentations related to a unique code development effort to combine the electromagnetic particle-in-cell (PIC) capability of the LSP code[19] with Prism Computational Sciences'[20] advanced equation-of-state (EOS) and opacity models. Such a modeling capability is required to fully assess the plasma liner MIF concept, especially with respect to modeling plasma jet formation and "gun physics," as well the significant portions of the liner evolution where radiative and kinetic effects are important. Furthermore, such a code capability would benefit the entire field of high energy density laboratory plasma research. A large subset of the workshop attendees believed that much more research was warranted and needed to fully assess the potential of the concept. A team was assembled to formulate the present PLX research program aimed at exploring and demonstrating the feasibility of forming spherically imploding plasma liners via merging plasma jets to reach 0.1–1 Mbar of peak pressure upon stagnation. With modest investment, PLX promises near term assessment of the feasibility and quality of plasma liner formation via merging plasma jets, while establishing a unique experimental facility capable of forming cm- and μs-scale high energy density plasmas for scientific studies. PLX is also a natural first step toward a longer term plasma liner MIF research and development program.

As of this writing, phase one construction of the PLX facility at LANL is complete. Experimental physics campaigns on single jet propagation and two jet merging are to begin soon, to be followed by 30 jet experiments to form and study converging plasma liners expected to reach 0.1–1 Mbar of peak pressure. Radiation-hydrodynamic simulations[21] using the 1D Lagrangian RAVEN code[22] have explored both PLX- and MIF-relevant liner parameter space and established a physical picture of liner implosion, stagnation, and post-stagnation dynamics. Ideal 3D smooth particle hydrodynamic[23] simulations using the SPHC code[24] are being used to evaluate important issues of 30 jet implosions and peak pressure scaling with initial jet parameters[25]. The LSP code with EOS/opacity modeling capability is being used to generate detailed predictions of jet propagation[26], merging[27], and also synthetic interferometry and spectroscopy data, all of which will guide initial experiments and be compared directly with forthcoming experimental data. Tech-X Corp.'s Nautilus code[28], an Eulerian two-fluid magnetohydrodynamics (MHD) code with EOS modeling, is also being used as an independent comparison with the LSP results.

5. The PJMIF Approach to Fusion Energy

A non-proprietary version of the PJMIF approach available in the public domain is illustrated in sequential steps schematically in Fig. 5. A description of each step is given as follows:

Step (a) Two separate sets of plasma jets of the required species, total mass, density, and velocity are formed and launched in sequence with appropriate timing from electromagnetic plasma accelerators mounted at the surface of a large vacuum chamber (with radius measured in meters).

Step (b) Each set of plasma jets merge through a merging radius (R_m), forming a spherical shell converging towards the center of the vessel. The spherical shell formed from the first set of plasma jets, which carry a mixture of deuterium and tritium, stagnates when its inner leading edge reaches the center of vessel. The velocity of the first set of jets is selected to produce a plasma ball with the desired ion stagnation temperature of about 1 million degrees (100 eV). Because the equilibration time between electrons and ions are short compared to the stagnating time, the electrons and ions have nearly the same temperature at stagnation. The resultant plasma ball serves as the initial target plasma to be further compressed.

The second set of plasma jets also merge through its own merging radius forming a second spherical shell which we call the imploding liner. The imploding liner carry a heavy pusher element (such as argon, krypton, or xenon, possibly other) in the rear with a leading D-T layer which is thin and dense. The heavy imploding liner is used to compress the target plasma to the density and temperature required to produce thermonuclear reactions. The leading D-T layer is intended to buffer the high-Z liner from the target plasma to prevent the cooling effects of mixing due to Rayleigh-Taylor instability, as well as to supply an additional afterburner layer that would also burn to amplify the energy gain.

The heavy pusher layer is envisioned to fulfill four separate functions: (1) it provides higher mass (of the order of 10 to 30 g) for a given (gun-limited) number density in order to provide the needed initial jet kinetic energy at more modest velocities, (2) the heavier element with both higher m_i and lower effective g enhances the jet Mach number M ~ $(m_i/\gamma)^{1/2}$ which is a key figure of merit for reaching high liner stagnation pressures $\sim M^{3/2}$ [21], (3) the jet/liner is kept cool and compressible during propagation and convergence due to effective atomic line radiation and cooling associated with having many bound electrons, and (4) upon stagnation and burn, the heavy pusher element helps to trap the radiation from the burning core, thus enhancing the energy confinement time.

Step (c): Standoff magnetization of the target plasma. The distribution of the second set of jets are chosen such that there are pre-arranged channels in the imploding liner in which the plasma is less dense so that laser beams can penetrate to reach the target plasma. A set of intense laser beams are launched through these pre-arranged channels in the liner to drive currents in the target by plasma beat waves. If "hole boring" is required, a preliminary set of ultra-intense lasers can be used to bore holes through the liner to create the required channels.

Step (d): The target is compressed adiabatically to the required density and temperature to produce fusion burn.

Launching the jets: Claims[18], [40] that very high initial jet Mach numbers $M > 60$ are needed were based on the requirement of minimizing density degradation due to jet thermal expansion during jet propagation from the chamber wall to Rm. However, those claims did not take into account that the jet temperature falls and M increases during propagation due to adiabatic expansion and radiative cooling, with the latter expected to be dominant in the case of a high atomic number liner species. Recent research [21], [27], [41] has shown that argon jets with initial temperatures in the 3–10 eV range quickly cool to less than 1 eV well before the jet reaches Rm. This means that it is possible to form and accelerate a highly ionized plasma jet with modest M and then subsequently achieve the desirable situation where M doubles by the time the jet reaches Rm, to a value needed to ultimately reach fusion-relevant liner stagnation pressures.

Radiative cooling is not as effective in the D-T fuel layers, although it still enjoys cooling in transit via adiabatic expansion. Experiments and modeling are needed to arrive at optimized composite jet initial parameters and profiles, and for that matter the ability to form the required composite jets in the laboratory. Another requirement is determining the effects of jet density and temperature profiles on jet propagation, merging, peak liner stagnation pressure, and dwell time.

Jet Merging: At the merging radius Rm, the leading edges of the jets meet to form the leading edge of the imploding spherical plasma liner. Since the jets are supersonic, shocks may form even at oblique merging angles $\theta > 2\arcsin(1/M)$, where θ [radians] is the angle between adjacent jets. Shock heating may defeat the beneficial cooling aspects discussed above, and too much shock heating will reduce the jet M and ultimately degrade the peak stagnation pressure. The shocks may also prove troublesome for maintaining the required liner symmetry and uniformity. The analysis is based on a pure fluid treatment of the jet interaction.

However, the picture is not so straightforward. In reality, the ion collisional mean free path of the merging jets is less than but is not a negligible fraction of the jet radius, and thus some interpenetration of jet ions is expected. Whether a shock would even form is an open question. An accurate treatment of this problem requires two-fluid or hybrid PIC models because, due to the high ion directed velocity (> 50 km/s) and cold electron temperature (< few eV) of the jets, the collisional mean free paths of the jet ions are dominated by the physical mechanism of ions of one jet stopping on electrons of the other jet. 3D two-fluid and/or hybrid PIC codes will be developed and calibrated (validated) against experiments so that they can be used to optimize the jet parameters and the merging process.

Liner Convergence: After the jets merge to form an imploding spherical liner, the liner converges toward the center of the chamber. Both theoretical[18] and numerical modeling[21], [43] have shown that the liner density rises during the quasi-steady-state pre-stagnation phase of convergence as $\rho \sim \rho_0\, r^{-2}$. However, as the liner approaches stagnation, different dynamics take over. A key issue during the convergence phase is the degree of liner non-uniformity (inherited at R_m upon jet merging) and the evolution of this non-uniformity, the reason being that non-uniformity is expected to reduce the achievable peak pressure at stagnation and exacerbate any convergent instabilities that may arise.

The uniformity of the liner during convergence is being examined using 3D SPHC simulations. Initial results are promising in the sense that the relatively substantial non-uniformity present upon jet merging at Rm gets “smeared” by the time the liner reaches stagnation. Fig. 3 of [1] shows 3D SPHC simulation results comparing the evolution of an initially spherically symmetric liner with the evolution of a liner formed by the merging of 30 discrete plasma jets. It is seen that the initial non-uniformity of the discrete jet case gets mostly smeared out during convergence so as to resemble the initially symmetric liner case at stagnation. The peak pressure achieved in both cases is similar. This is a promising initial result suggesting that very stringent requirements on initial liner uniformity may not be required.

Related to the issue of liner non-uniformity is the importance of convergent instabilities (e.g., Rayleigh-Taylor) and associated material mix within an imploding composite liner. Even if the gross liner uniformity is deemed relatively unimportant for achieving a given peak pressure, instabilities and material mix, i.e., trailing colder pusher material mixing and advancing ahead of the leading hotter fuel material, could degrade the peak pressure and temperature of the fuel at liner stagnation and therefore the fusion yield. Ongoing research is addressing these important issues, and definitive answers are not yet available. However, note that unlike ICF or a liner compressing a pre-formed target (as in most MTF schemes) which are both inherently Rayleigh-Taylor unstable during the entire compression phase, the composite plasma liner MIF approach is inherently Rayleigh-Taylor stable for the entire convergence phase because it is imploding on vacuum! There may be a very short duration of Rayleigh-Taylor instability when the central pressure peaks up and the liner has not yet begun to decelerate strongly, and ongoing studies are determining if and how this affects the quality of the implosion.

Target magnetization: Crucial to the plasma liner MIF concept (and all low ρr MIF concepts) is fuel magnetization reducing thermal transport so that the compression of the target plasma ball can be accomplished nearly adiabatically at modest implosion velocities of order 100 km/s or less. The required magnetic field magnitude in the fuel at peak compression is crudely determined by the condition $\omega_{ci} t_i \gg 1$ (where ω_{ci} and t_i are the ion gyro-frequency and collision time respectively) so that particle heat transport is suppressed due to the magnetic field. For a representative compressed D-T fuel density of 10^{21} cm^{-3} and temperature of 10 keV, the condition becomes $B \gg 7.1$ T. MIF concepts generally compress a more modest "seed" field of order 1 T to order 100 T by virtue of field compression that scales as the compression ratio squared, i.e., $B_f = B_i C2 = B_i (r_i / r_f)2$, where for MTF concepts $C \approx 10$. For the plasma liner MIF concept under consideration (no pre-formed magnetized target), the objective is to introduce the required seed magnetic field in the fuel layer of the composite liner prior to peak compression such that the needed field strength is achieved at peak compression. The question of achieving a particular field topology is set aside for now and considered briefly later in this sub-section.

At present, the favored target magnetization scheme is based on the idea of using beat waves [44], [45] generated by lasers to drive electrical current, which has the substantial advantage of also being a standoff system that would avoid destruction with every shot. This technique relies on resonant acceleration of plasma electrons (and therefore current drive and introduction of magnetic field) by a beat wave generated by two electromagnetic waves separated by a correctly tuned frequency. This has been demonstrated in low density plasmas using microwaves[46]. For the case of plasma liner MIF, it is envisioned that the D-T layer of the liner will have a density of order 10^{17}–10^{18} cm^{-3} when it is about 5–10 cm away from the origin. This sets requirements both on the minimum central frequency of the two electromagnetic waves (for penetrating the plasma) and the difference frequency (so that the beat wave is on the same order as the electron plasma frequency).

A recently initiated research program at U.C., Davis to explore the concept has refurbished two CO2 lasers for exploring the laser generated beat wave current drive technique, with estimated expected efficiency $\approx 6 \times 10^{-7}$ A/W and resultant ≈ 60 A driven currents at 100 MW of laser power[47]. There is also a recently initiated, coordinated PIC numerical modeling effort of the beat wave generation and wave-particle interactions at PLX-relevant densities. The primary objectives of the modeling effort are to help optimize experiments on the beat wave generation and wave- particle coupling processes, and to explore the important issue of current drive efficiency and how it scales up to plasma liner MIF relevant regimes. The simulations examined counter-propagating laser beam injection into a plasma with peak density of 3×10^{16} cm^{-3}. Fig. 8 shows initial 2D LSP simulation results confirming the growth of electrical current density and the presence of the beat wave near the expected 1.07 THz envelope frequency for injected beams at 10.4 and 10.8 μm wavelengths and 10^{13} W/cm2 intensities (corresponding to available CO_2 lasers[47]). The electron acceleration proceeds in the direction of the higher frequency beam. In addition, the electron pressure exhibits strong axial modulation at the 5 μm beat wave wavelength. Ongoing simulations are studying varying angles between the injected laser beams and density gradients with the goal of optimizing current drive with minimal heating.

The issue of field topology is an important one for plasma liner MIF. For the typically slower implosion MTF concepts, it is generally believed that closed flux surfaces in the pre-formed target are required to provide sufficient thermal insulation. It would be difficult (but not impossible, with some proprietary ideas being considered) to generate closed, mirror-like, or other flux surfaces via laser generated beat wave current drive. However, a recent interesting work[48] suggests that a random field with sufficient connection length might provide sufficient thermal insulation for MIF, and this would open up the possibilities for fuel magnetization methodologies. Ongoing studies are evaluating different possible magnetic field topologies for plasma liner MIF that might be compatible with laser magnetization.

Another potential liner magnetization scheme, perhaps a natural choice considering the conclusions of [48], would rely on compressing the initial magnetic fields embedded in the plasma jets themselves. However, this would be challenging because the magnitude of the initially embedded magnetic fields are on the order of 0.1–1 Tesla. At jet densities of $\sim 10^{17}$ cm^{-3} and temperatures of $\sim$ 1 eV, that field decays with an exponential time constant on the order of a few μs and thus would decrease to $\ll$ 1 T by the time the jets reached Rm . Understanding how the field would evolve and whether it would get amplified during subsequent convergence, and what field topologies and structures are possible in the initial jet, would require further studies.

<u>Stagnation, burn and disassembly</u>. As the target plasma reaches peak compression, an outgoing stagnating shock is formed and propagates outward into the incoming liner. This shock effectively converts the incoming liner kinetic energy into thermal energy of the post-shocked stagnation region. The post-shock region, after spiking to very high pressure, settles to a lower pressure and maintained (within a factor of a few) until the outward propagating shock meets the back end of the incoming liner (see Fig. 3 of [21}), at which time a rarefaction wave propagates inward quickly leading to the disassembly of the high pressure post-shock region. The latter is qualitatively consistent with an analysis based on a self-similar model [49] and was anticipated in [8]. These dynamics are integral in determining the “dwell time” of the stagnated plasma and ultimately the fuel burn-up fraction which is linearly proportional to the dwell time.

Recent theoretical work[50] based on a family of self-similar analytic solutions (so-called spherical quasi-simple waves)[51] to the spherically symmetric ideal hydrodynamic equations has led to the identification of an interesting potential method for optimizing the dwell time via specially chosen initial liner profiles of density and velocity, i.e., “shaped liners.” Such profiles admit an implosion solution where the post-shock high pressure region is maintained at constant pressure and zero velocity, with the region growing in size at a rate determined by the outgoing shock velocity. Physically, the outgoing shock converts the entire kinetic energy of the incoming liner into the thermal energy of the growing stagnated post-shock region. Radiation-hydrodynamic numerical modeling is now proceeding to test these analytic solutions with finite liner thicknesses (the theory is exact only for infinite thickness liners), and eventually realistic effects such as thermal and radiation transport will be included to see if the solutions remain viable in realistic systems. Shaped liners, if they turn out to be viable, may be particularly well-matched to the use of an afterburner D-T fuel layer because the outward shock could bring the afterburner layer up to the same (fusion-relevant) pressure of the inner compressed fuel layer. More studies are needed to investigate the feasibility of this scenario and whether any amplification of energy gain could be realized over the case without an afterburner layer.

6. Reactor Considerations

The plasma liner MIF concept was originally conceived[8] largely with the motivation of making an attractive fusion reactor by introducing a standoff driver embodiment to the otherwise attractive aspects of MIF. Plasma liner MIF is also potentially amenable to other reactor-friendly technologies such as liquid plasma facing and tritium breeding technologies that would avoid a costly and time-consuming radiation resistant materials development program. Power plant studies for MTF have been performed[52], [53], and an initial reactor study of plasma liner MIF is in process[54]. The intention for plasma liner MIF is to aggressively pursue reactor- friendly technologies with less development time and lower development cost.

A key difference between plasma liner MIF and other MTF concepts is that the former, with its standoff driver, can in principle fire at higher repetition rates, e.g., ≈1 Hz rather than ≈0.1 Hz. This would allow for lower energy yield per shot for the same average power, i.e., ≈100 MJ rather than ≈1 GJ per shot for 1 GW average fusion power, which reduces thermal and radiative loading stresses on reactor components. On the other hand, the higher repetition rate places greater demands on pulsed power technology including capacitor, plasma gun, and switch performance. Clearly, much pulsed power research and development is needed to make pulsed power based fusion concepts, including plasma liner MIF, a reality. The plasma guns are deliberately chosen to be “low technology” and low cost in the sense that they can be made of radiation resistant materials that are available today, and that a plasma liner MIF reactor could be configured such that changing out all the guns (even if they number into the hundreds) periodically would require minimal plant down time and keep cost of electricity low. Because the fusion reactor core for plasma liner MIF (i.e., spherical chamber with plasma guns, standoff magnetization lasers, and liquid first wall) is envisioned to be relatively low-cost and low-complexity, plant down time (and repetition rate) could be reduced by operating several imploding plasma liner fusion reactor cores in parallel, sharing the same (more expensive) central tritium processing and electricity generation “balance of plant” systems.

The hydrodynamic efficiency of a plasma liner is expected to be lower than that of a solid liner, and depending on how high of an energy gain is ultimately realizable, it may be necessary to implement technologies to recover part of the energy in the outgoing, post-stagnation liner to keep the engineering gain as high as possible. Examples of potential liner energy recovery techniques were briefly discussed in [49] and would need further assessment for any plasma liner MIF reactor design. Furthermore, additional studies are needed to determine how much energy remains in the outgoing, post-stagnation liner and how much is lost due to radiation.

Many of the reactor technologies envisioned for plasma liner MIF share commonalities with ICF reactors, especially with heavy ion beam driven fusion, which has a substantial body of research, e.g., [55], from which to draw. In particular, flowing molten salts such as a mixture of Lithium Fluoride (LiF) and Beryllium Fluoride (BeF_2) as a plasma facing component and tritium breeding medium has been considered extensively for heavy ion fusion. The interesting technique of localized vortex liquid flows[56] on the inside surface of the vacuum chamber appears especially well-suited for plasma liner MIF which requires gun penetrations distributed around the entire spherical chamber. Thus, the guns themselves would be “sacrificial” to neutron and hard x-ray damage, and need periodic replacement, but the spaces between guns would have localized vortex flows of a thick liquid molten salt that would protect the structure from neutrons and x-rays, as well as breed tritium and serve as the coolant for driving the steam cycle to generate electricity. Adapting the vortex surface liquid flow method to plasma liner MIF, and determining required flow rates and re-circulating power will be developed on the program.

The important question of achievable energy gain of plasma liner MIF has been studied using a 1D Lagrangian hydrodynamic code[38]. These initial studies are idealized in that magnetic field effects are not treated self-consistently but are rather approximated by reducing or turning off thermal transport in the code, and α-particle deposition fraction is a specified parameter. In addition, these studies thus far have used only an ideal gas EOS with specifiable adiabatic exponents and have neglected radiation losses. With these caveats in mind, preliminary (and unoptimized) results[38] show energy gains up to 20 with a 30 MJ composite plasma liner, with slightly less than half of the yield coming from the main D-T fuel layer and slightly more than half from a denser D-T “afterburner” layer. Physics and engineering optimizations using proprietary schemes could further improve the gain values, whereas inclusion of more physics in the simulations such as radiation transport and 3D effects could reduce the gain. Therefore more work is needed with a state-of-the-art 3D radiation-magnetohydrodynamics code such as HYDRA [39] to obtain a more realistic, self-consistent, and accurate gain estimate, and to optimize the composite plasma liner initial conditions at Rm .

7. Concluding Remarks

PJMIF is an attractive approach to practical, economic fusion energy for the following reasons:

(a) Plasma guns, made of metallic alloys, are robust.
(b) The plasma guns are energy efficient and theoretically can have efficiency exceeding 50%. They are driven directly by pulsed power, which has lower cost than lasers per unit energy.
(c) Plasma guns and pulsed power supplies, being 'low-tech', are inexpensive making the capital cost of the fusion reactor very inexpensive.
(d) The physics of the implosion scheme is robust with respect to practical engineering variability in the fabrication of the targets, etc. The size of the implosion is relatively large. The initial target and liners are about 10 cm in diameter.
(e) The targets and liners are ordinary gases and require no special fabrication. The recycling cost is low. There is no solid debris to be removed from the chamber after each shot.
(f) PJMIF is ‘reactor friendly’. It is compatible with the use of liquid or disposable first-wall to protect the critical components of the system from neutron damage.

Note also that, unlike some MIF approaches, no material debris is generated by the implosion in the PJMIF approach, because it uses plasma jets as drivers launched from standoff distances. And unlike laser ICF, the evacuation of the reactor chamber does not present as challenging an engineering problem as laser ICF, because firstly it is sufficiently economical to operate the reactor at a much lower repetition rate of 1 to 5 Hz, and secondly PJMIF does not requires as high a vacuum as laser ICF in the chamber, as the propagation of dense plasma jets is much more tolerant of residual gases in the chamber as laser light.

The above description of PJMIF is based on PJMIF embodiments and configurations that have been released to the public domain. Proprietary embodiments of PJMIF known to the authors of this paper exist that considerably improve on the overall reactor performance and address the key issues. This forms the basis of proprietary intellectual property (IP; patents and the like) which in combination with scientific expertise and know how, form the competitive “unfair business advantages” enjoyed by a private venture based on the participation of the various authors of this paper.

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9. Figures

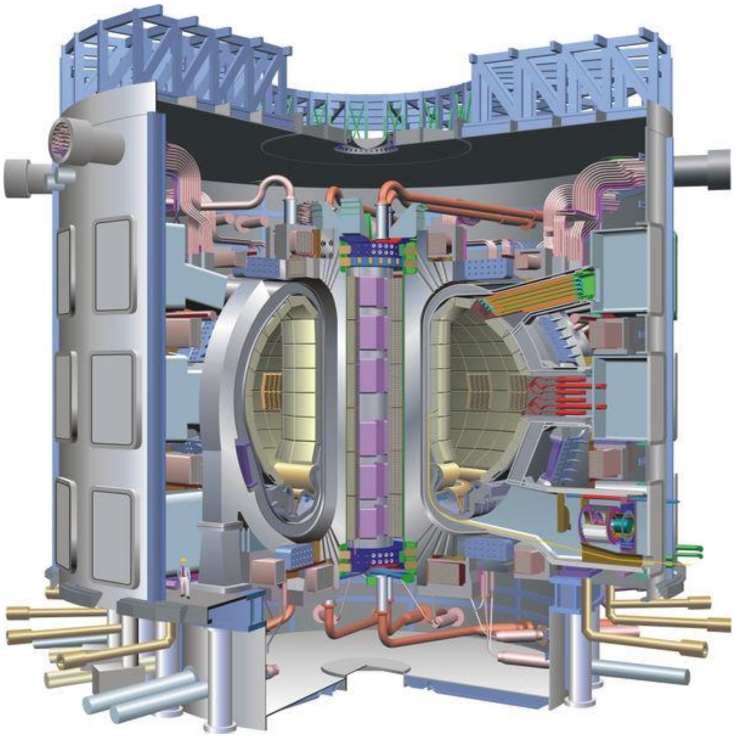

Figure 1 ITER - a $20B project scheduled to have first plasma in 2020, with the first DT experiment scheduled for 2027.

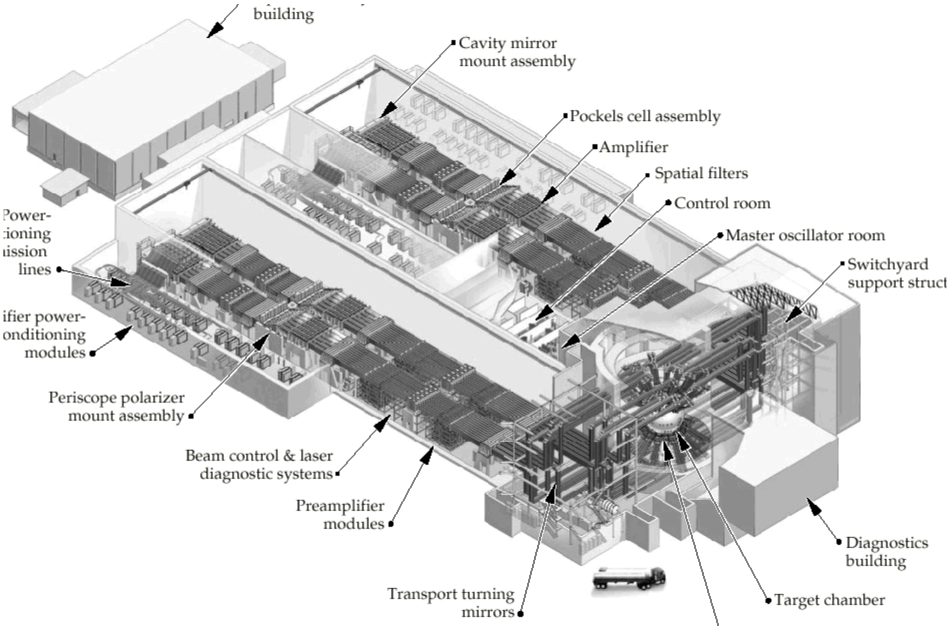

Figure 2. National Ignition Facility at the Lawrence Livermore National Laboratory.

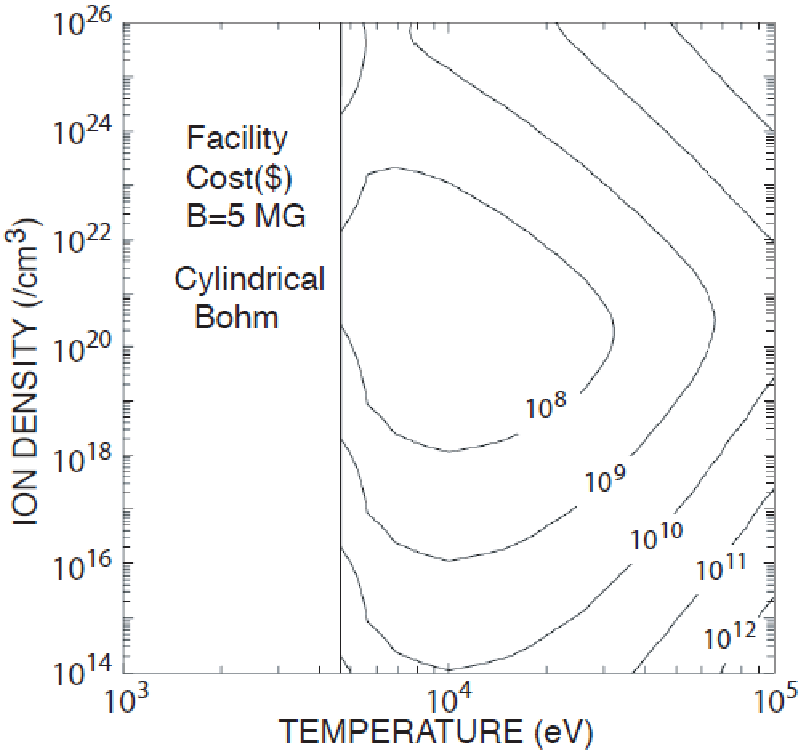

Figure 3. Cost of a fusion break-even facility as a function of ion density and temperature of the burning plasma. Cost model consistent with known Tokamak and Laser system costs. Shows that minimum cost occurs between conventional regimes. Assumption of Bohm diffusion is pessimistic.

B= magnetic flux density B=5MG or 500 Teslas Contours 10^8 - 10^{12} in US Dollars

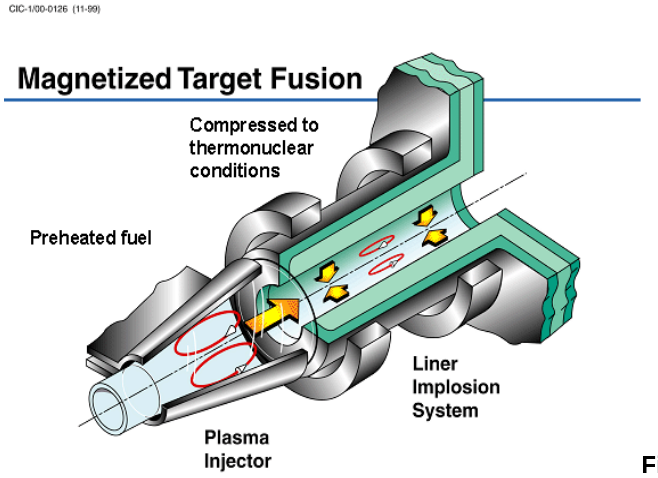

Figure 4. Solid-Liner MTF

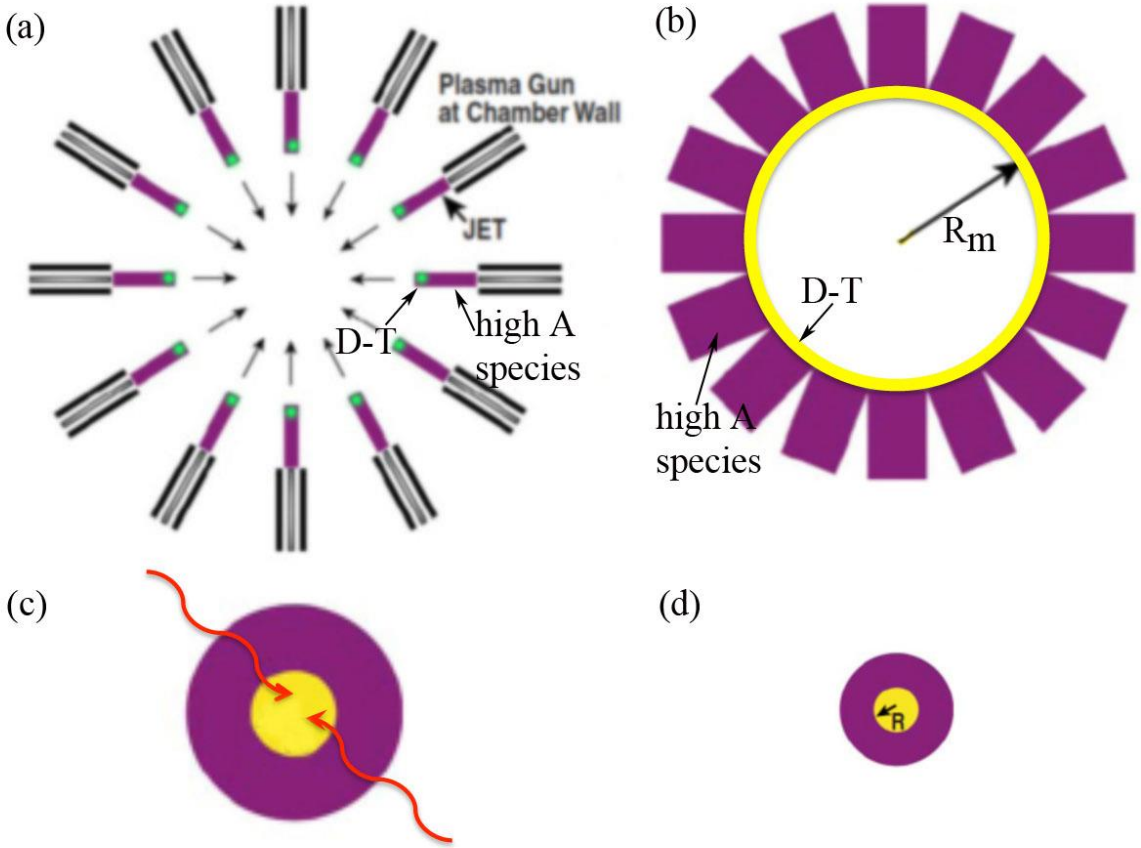

Figure 5. A Schematic of the PJMIF Concept. (a) Two sets of jets are launched from the periphery of the chamber. The first set of jets are shown already merged forming the target shell converging towards the center. (b) The second set of jets have just arrived at the merging radius (R_m) and are merging through the merging radius forming the imploding liner. The jets are arranged in such a way that "channels" are provided to allow insertion of laser light in step (c) below. At the leading edge of these jets is a thin, dense layer of DT, serving to buffer the high-Z liner from the target plasma, as well as serving as an afterburner to boost the fusion gain. (c) A set of intense laser beams shine through pre-arranged "channels" in the liner to drive currents in the target by plasma beat waves. (d) The target is compressed adiabatically to the required density and temperature to produce fusion burn.

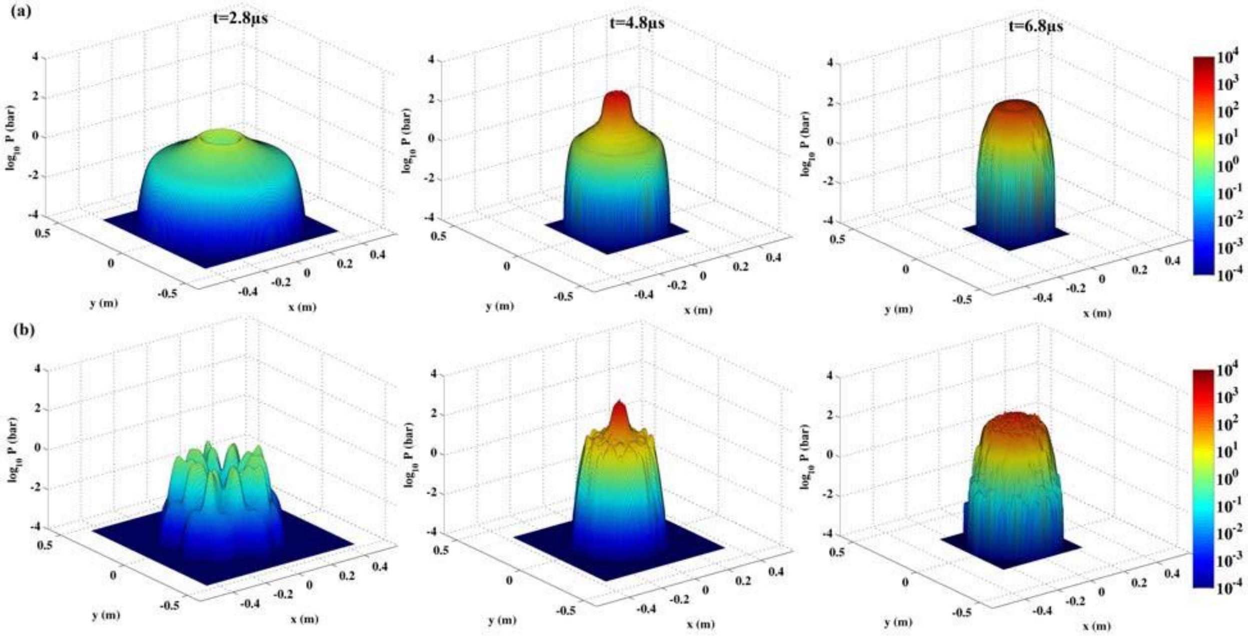

Fig. 6. Surface plots in the *x*-*y* plane of plasma liner pressure (logarithmic) from 3D ideal hydrodynamic simulations. The top row shows the evolution of an initially spherically symmetric liner, and the bottom row shows the evolution of a liner formed from 30 discrete plasma jets.

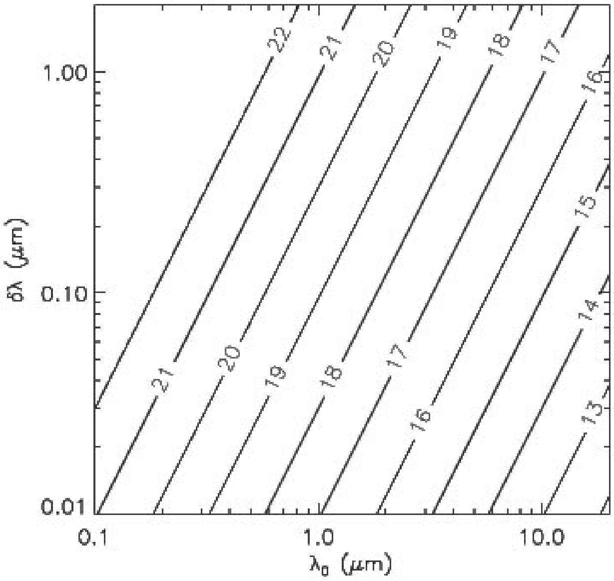

Fig. 7. Contours of the logarithm of the electron density (in cm^{-3}) as a function of the difference ($\delta\lambda$) and central (λ_0) wavelengths of the injected electromagnetic waves of frequency ω_1 and ω_2, satisfying the beat-wave resonance condition $|\omega_1 - \omega_2| = \omega_{pe}$.

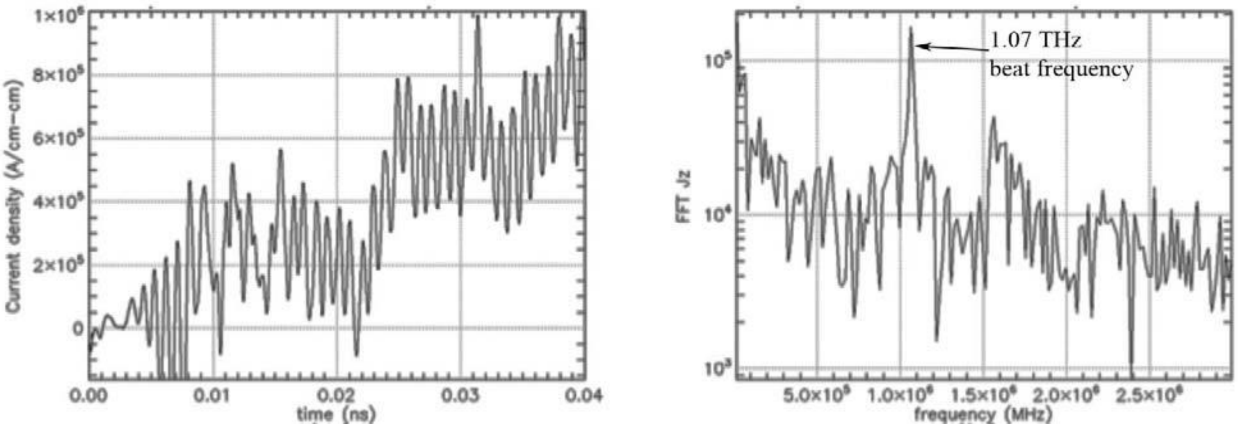

Fig. 8. LSP simulation result for counter-propagating laser beams of (left) growing current density versus time and (right) FFT of the current density with a peak at the beat frequency.