A Physics Exploratory Experiment on Plasma Liner Formation

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Abstract

Momentum flux for imploding a target plasma in magnetized target fusion (MTF) may be delivered by an array of plasma guns launching plasma jets that would merge to form an imploding plasma shell (liner). In this paper, we examine what would be a worthwhile experiment to do in order to explore the dynamics of merging plasma jets to form a plasma liner as a first step in establishing an experimental database for plasma-jets driven magnetized target fusion (PJETS-MTF). Using past experience in fusion energy research as a model, we envisage a four-phase program to advance the art of PJETS-MTF to fusion breakeven (Q ~ 1). The experiment (PLX) described in this paper serves as Phase 1 of this four-phase program. The logic underlying the selection of the experimental parameters is presented. The experiment consists of using twelve plasma guns arranged in a circle, launching plasma jets towards the center of a vacuum chamber. The velocity of the plasma jets chosen is 200 km/s, and each jet is to carry a mass of 0.2 mg – 0.4 mg. A candidate plasma accelerator for launching these jets consists of a coaxial plasma gun of the Marshall type.
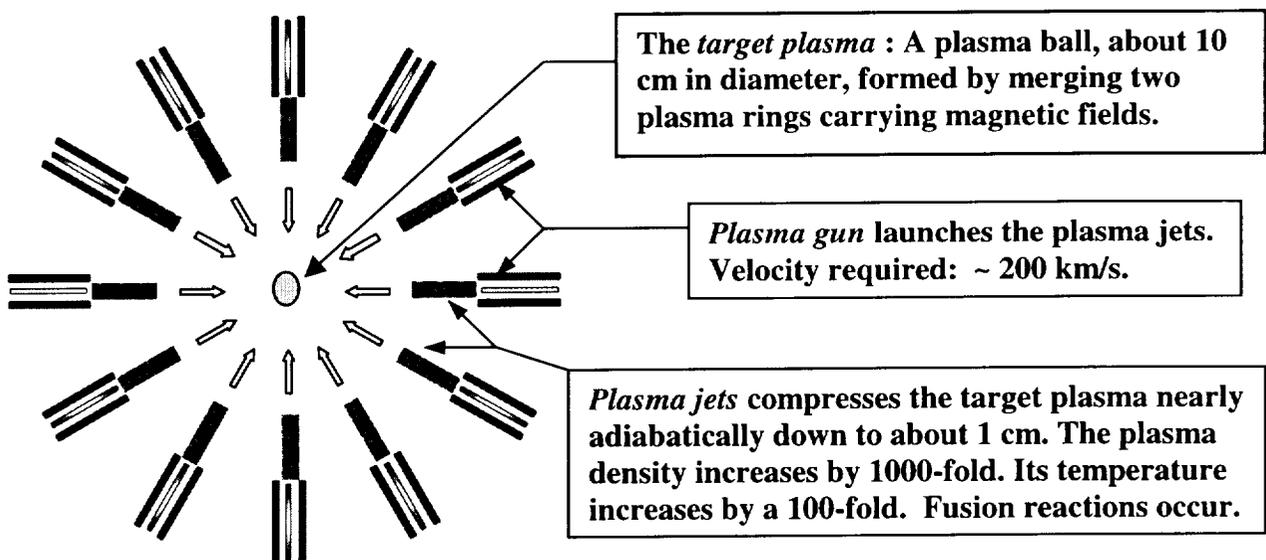
1. Introduction

Magnetized target fusion (MTF) attempts to combine the favorable attributes of both magnetic confinement fusion (MCF) and inertial confinement fusion (ICF), thus providing potentially a low-cost, rapid pathway towards practical fusion[1-5].

In MTF, a magnetized plasma (designated as the target) is compressed inertially by an imploding shell. The imploding shell may be solid, liquid, gaseous, or a combination of these states. The presence of the magnetic field in the target plasma suppresses the thermal transport to the plasma shell, thus lowering the imploding power needed to compress the target to fusion conditions. This allows the required imploding momentum flux to be generated electromagnetically with off-the-shelf pulsed power technology. Practical schemes for standoff delivery of the imploding momentum flux are required and are open topics for research. One approach for accomplishing this consists of using a spherical array of plasma jets to form an imploding spherical plasma shell[6] (Figure 1).

The use of plasma jets to implode a target plasma has its root in impact fusion[7, 8]. Impact fusion would have been a very attractive approach to ICF except for want of a suitable driver (a 0.1-g solid projectile at 200 km/s). The approach is currently being revisited in its modern form in the context of magnetized target fusion[6]. Instead of only two solid projectiles, the required momentum flux is spread over as many as 60 plasma jets traveling at approximately the same velocity. The plasma jets are produced in pulsed electromagnetic plasma accelerators using off-the-shelf electromagnetic pulsed power. Their kinetic energy is accumulated over a spatial extent of about a meter in the plasma gun and over a time interval of several microseconds using the ponderomotive electromagnetic Lorentz force ($j \times B$). Their kinetic energy is deposited in the target abruptly in a 100-nanosecond time scale and in a distance of a few centimeters. As a result, the imploding power flux density is amplified by three to four orders of magnitude.

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We note that, unlike laser driven ICF, the imploding energy is carried directly by the plasma jets. In laser driven ICF, the laser energy needs to be converted into plasma energy at the target either directly or indirectly. Given that the hydrodynamic efficiency of converting the photon energy into directed implosion energy is about 10% and the efficiency of producing the laser beams from electricity is less than 20%, the overall "wall-plug" efficiency of the laser driver is less than 2%. In the case of the plasma jets for MTF, the equivalent driver efficiency, the "wall-plug" efficiency of plasma guns, may be as high as 50%. Thus, laser driven ICF may require a fusion gain at least 25 times greater than MTF just to recover the energy lost in the driver.

With greatly improved target dynamics afforded by the magnetization of the target plasma, taking advantage of the theoretical and experimental advances in spheromak and FRC physics in the last two decades, MTF promises to provide an affordable pathway towards fusion energy on Earth[2] and fusion space propulsion[9].


The *target plasma* : A plasma ball, about 10 cm in diameter, formed by merging two plasma rings carrying magnetic fields.

Plasma gun launches the plasma jets. Velocity required: ~ 200 km/s.

Plasma jets compresses the target plasma nearly adiabatically down to about 1 cm. The plasma density increases by 1000-fold. Its temperature increases by a 100-fold. Fusion reactions occur.

Figure 1. Kinetic energy is accumulated in the plasma gun slowly (> 5 μs) and over a large distance (~ 1 m), but deposited in a short time (< 0.1 μs) and smaller special extent (< 0.01 m), resulting in 4 orders of amplification in power density.

In this paper, an experiment (PLX) to explore the physics of forming a 2-D plasma liner (shell) by merging plasma jets is described. The experiment complements the experimental investigation being led by Los Alamos National Laboratory for demonstrating and establishing the underlying physics principles of MTF. Successful completion of PLX and LANL MTF Concept Exploration Experiment will provide the necessary scientific data for further evaluation of the physics feasibility and the potential of MTF for practical energy and propulsion applications.

2. Experimental Goals and Parameters

The immediate physics issue concerning plasma-jets driven MTF (PJETS-MTF) is whether a plasma liner can be formed by merging plasma jets. The objective of the Plasma Liner Physics Exploratory Experiment (PLX) is therefore to perform experiments to study the dynamics of merging an array of plasma jets to form a plasma liner, and the implosion of a magnetized target plasma by the plasma liner. We now discuss the considerations leading to the quantitative selection of the experimental parameters for PLX.

To keep the experiment as simple as possible, the physics of the jets merging is studied in two dimensions requiring a far *smaller* number of plasma guns and diagnostics than for producing a 3-D shell. A suite of first-generation computer codes on plasma liner formation can be developed and validated against the experimental results. The codes could then be used to design a follow-on experiment of greater complexity that would demonstrate the 3-D implosion of a magnetized target by a 3-D liner. In PLX, a simpler experiment, using an array of 12 plasma guns arranged in a circle to form a converging cylindrical plasma shell is proposed (Figure 2).
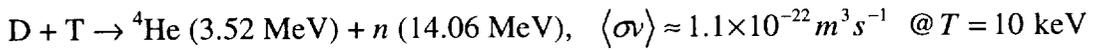
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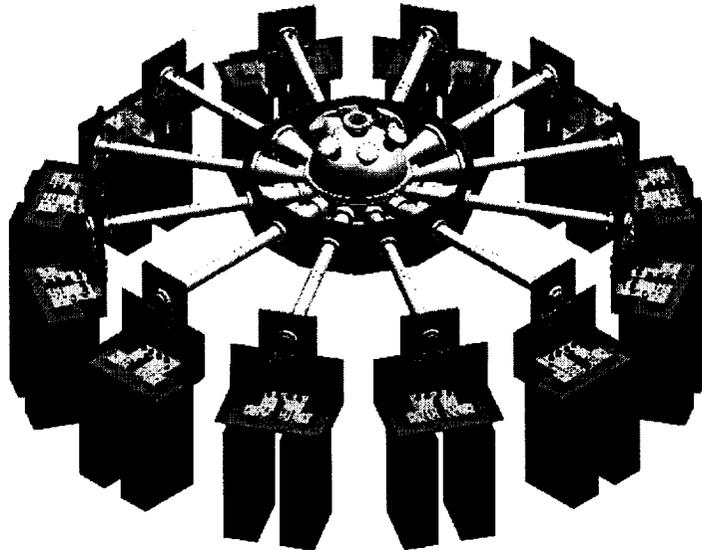
Figure 2. The Plasma Liner Physics Exploratory Experiment (PLX), consisting of merging 12 plasma jets launched by 12 coaxial plasma guns.

The principal objective of the PLX experiment is to pave the way for an experiment to demonstrate the physics feasibility of the plasma-jets driven MTF approach. The parameters for PLX should therefore be carefully chosen so as to enable the Physics Feasibility Experiment (PFX) experiment. Quantitatively, PFX should develop the physics and engineering database to enable the design of yet a Proof-of-Principle (PoP) experiment for the PJETS-MTF concept at a considerably higher energy level. The PoP experiment should at least demonstrate the attainment of a plasma temperature exceeding 5 keV and a Lawson $n\tau$ product within an order of magnitude required for fusion breakeven. In turn, the Physics Feasibility Experiment PFX should demonstrate the attainment of similar plasma temperature but with a Lawson product $n\tau$ two orders of magnitude less than in the PoP experiment, that is, within three orders of magnitude of fusion breakeven.

The Lawson Criteria for Pulsed Fusion. For the fusion reactions to sustain itself, the rate at which the fusion energy is re-deposited in the burning fusing plasma must exceed the rate at which the plasma energy is lost to the surrounding. Thus,

$$\alpha \, n_1 n_2 \langle \sigma v \rangle \, \varepsilon_f > \frac{3nkT}{\tau_E}$$

where n_1, n_2 are the particle densities of the reacting species, $\langle \sigma v \rangle$ is the fusion reactivity, α is the fraction of the fusion energy re-deposited in the burning plasma, ε_f is the energy per fusion reaction, n is the total particle density, T is the plasma temperature, k is the Boltzmann's constant, and τ_f is the energy confinement time. For the D-T reaction,

$$D + T \rightarrow {}^4He \ (3.52 \ MeV) + n \ (14.06 \ MeV), \quad \langle \sigma v \rangle \approx 1.1 \times 10^{-22} m^3 s^{-1} \ @ \ T = 10 \ keV$$

and assuming a 50% re-deposition of the α-particle energy, the above condition reduces to,

$$n \tau_E \geq \frac{12kT}{\alpha \langle \sigma v \rangle \varepsilon_F} = 6 \times 10^{20} \ s.m^{-3}, \quad n_D = n_T = \frac{1}{2} n$$

Thus, the PFX experiment should aim at demonstrating the feasibility of integrating the physics and engineering approach to attain a Lawson product of about 6×10^{17} s.m^{-3}.

For the physics outcome of the Plasma Liner Exploratory experiment (PLX) to be meaningful, the experiment should exercise all the essential physics and component technologies at a level required for the PFX experiment. In particular, the plasma gun and the plasma jet used in PLX should meet all the requirements of the PFX experiment and should be demonstrated during the PLX phase of the program. A suite of theoretical and computational models are to be developed that can be validated against the experimental results, so that they can be used with a sufficient degree of confidence to extrapolate the experimental results to the parameter space required to design the PFX experiment.

3. The Physics and Technology Requirements

In order to define the experimental parameters for PLX, the technological and physics requirements for PFX need to be identified first. In PFX, an array of plasma guns, as many as 60 guns, arranged symmetrically over a spherical surface is envisaged, that will launch an ensemble of plasma jets converging towards the center of the sphere to form a 3-D imploding spherical plasma shell.

We will now set out to determine the requirements for PFX. To allow for a modest degree of physics excursion and exploration, we will "over-design" the experimental system by a factor of two to four for most of the plasma parameters (temperature, Lawson's number, neutron yield). The starting point is to select the implosion trajectories and profile required for the experiment. For this purpose, we will make use of the 0-D theory developed by Thio[6].

Following Thio, assume a plasma liner in the form of a spherical shell of finite thickness converging on a target plasma, also assumed to be spherical. As the plasma liner and the target plasma are initially relatively cold with relatively low sound speed, when they collide, shock waves are produced in both the target plasma and the liner. The shock in the target plasma converges spherically towards the center and is reflected near the center. In time, the reflected shock meets the radially converging contact surface giving rise to a second radially ingoing shock in the target which is again reflected near the center. The process is repeated until the implosion velocity falls below the speed of sound in the target, after which point the compression proceeds in a shockless fashion. When the radial momentum of the liner is totally dissipated, the target and the liner have reached their peak compression. By design, the first ingoing and reflected shocks in the target are strong. The passage of these two shocks, however, heats the target to a sufficiently high temperature that the subsequent reflected shocks are relatively weak and may be ignored in the consideration of the target compression during this phase. If the magnetic field in the plasma is sufficiently high to provide the

required degree of magneto-thermal insulation, then the compression during this phase is nearly adiabatic.

At peak target compression, further advance by the liner is halted by the immense pressure developed in the target. A stagnating shock propagates outward in the liner with a "piston" speed approximately equal to the local inward flow speed before the arrival of the stagnating shock. When this stagnating shock reaches the outer boundary of the liner, a rarefaction wave propagates backwards towards the center. The confinement time for the target plasma is approximately the transit time of the stagnation shock plus twice the transit time of the rarefaction wave.

Based upon the above scenario, the required jet velocity to obtain a given target temperature is estimated as follows. Firstly, we pick an initial radius (r_1) and final radius (r_2) for the compact toroid. Choosing r_1 to be 8 cm, and r_2 to be 1 cm appears to be a reasonable choice. This gives the overall radial compression (r_1/r_2) of 8. The first spherically converging shock and its first reflected shock from the center lead to a density compression by a factor of $32^{(10)}$, and the corresponding radial compression by a factor of 3.1748. After these two shocks, the compression proceeds by a series of relatively weak shocks multiply reflected between the center of the target and the converging liner. The compression by this series of weak shocks needs to provide a radial compression factor of (r_1/r_2)/ 3.1748. The temperature of the target at peak compression, T_f, is related to its temperature T_{2s} after the first two strong shocks (just before the compression by the series of weak shocks) as,

$$\frac{T_f}{T_{2s}} = [(r_1 / r_2)/3.1748]^2 \tag{3.1}$$

assuming that the compression is completely adiabatic due to the magneto-insulation of the magnetized target. T_{2s} is the temperature of the target after the passage of the first spherically converging shock and its reflected shock through the target, and is given by[6],

$$kT_{2s} = \frac{2.797}{1+Z_i}\left(\frac{m_i u_c^2}{2}\right)$$

(3.2)

where u_c and m_i are the contact surface velocity and the jet ion mass respectively. The contact surface velocity is sufficiently closed to the jet velocity u_l for the purpose of this scoping exercise. Given the temperature T_f of the target at peak compression, the above expressions determine the required jet velocity. Figure 3a graphs the required jet velocity vs the target temperature to be reached.

The liner energy required depends on the degree of compression, the mass of the target plasma and the target containment time desired. Given the target radius at peak compression, the mass of the target plasma is determined by its density at peak compression. Attaining a target plasma density of 10^{25} ions per m^3 at peak compression appears to be a reasonable goal of the experiment. To attain the Lawson product $n\tau$ of 6×10^{17} $s.m^{-3}$, the energy confinement time needs to be at least 60 ns. Assuming that the energy confinement time is of the same order of magnitude as the plasma containment time, this implies that the plasma needs to be contained for at least 60 ns. This determines the amount of liner energy required. Using a 0-D magnetized target plasma compression code (MTFPL0) developed based on the compression dynamics given in Thio[6], the liner energy required vs the confinement time is shown in Figure 3b. It is seen from Figure 3a and 3b that the experimental objectives may be achieved with a jet velocity in the vicinity of 200 km/s, and a total liner energy of about 0.4 MJ. The corresponding mass of the plasma liner is 20 mg. With 60 plasma guns, the mass of each plasma jet is 0.33 mg.

The dynamic formation of a plasma liner from the merging of the jets has never been attempted before in the manner and of the scale envisaged here where the plasma jets are transported over a large distance (> 1 m), detached from the electrodes of the plasma guns, and in particular, for

producing plasma liner having the momentum flux density envisaged here. Encouraging results, however, were observed in an experiment conducted in the US Air Force Research Laboratory at Kirtland AFB in the late 1980's, in which a circular array of 12 and 24 radial electrodes were used to produce a hypercycloidal discharge[11]. The 12 and 24 discharges formed a cylindrical plasma that was seen to implode towards the center. The experiment was a follow-up on an earlier experiment at Sandia National Laboratory in which a cylindrical array of eight plasma gun discharges were operated[12]. The objectives of these experiments were somewhat different from the experiment we are proposing here. They were designed to investigate the feasibility of achieving dense plasma focus (DPF) using multiple plasma guns to form a hypercycloidal discharge instead of a single coaxial plasma gun[13]. The objective was to get around the limitation of a single plasma gun of conventional dense plasma focus. The experiment proposed here is unique in terms of forming a plasma liner using detached plasma jets produced by pulsed plasma accelerators or Marshall guns.
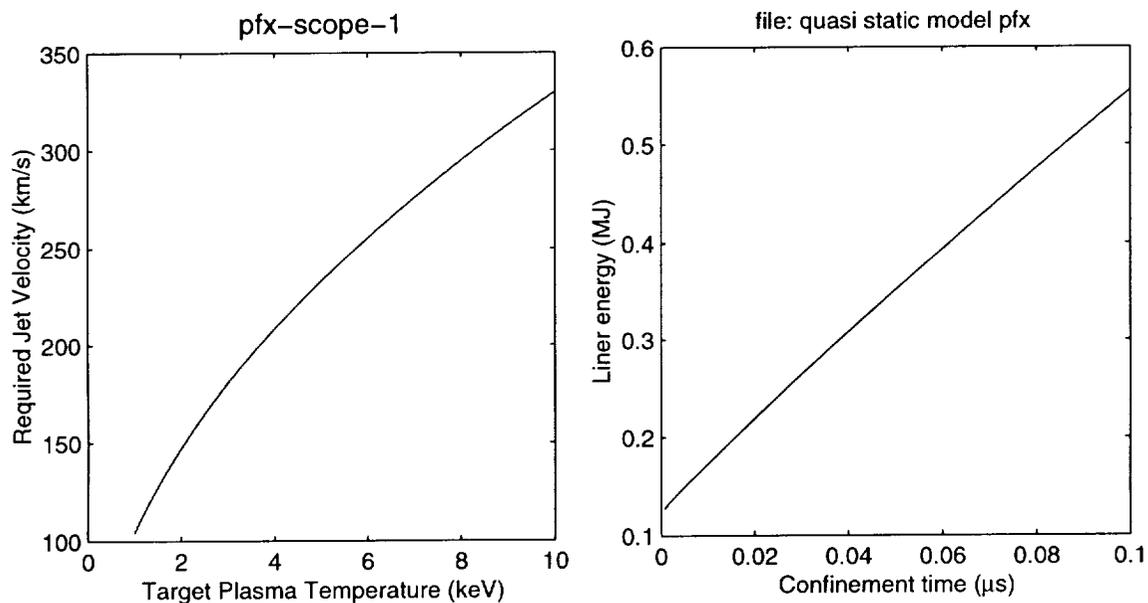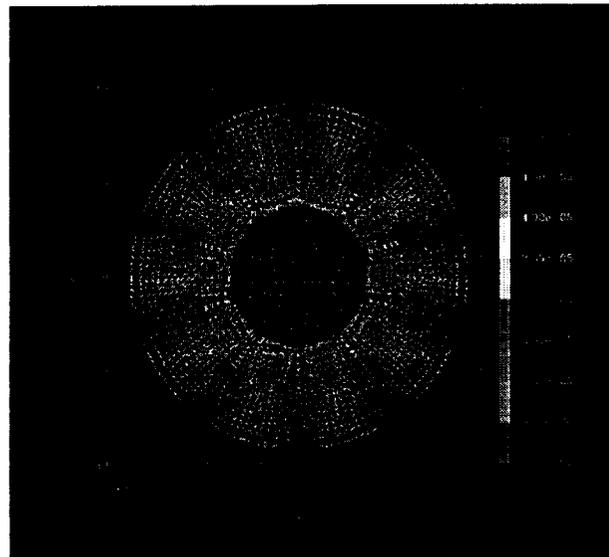

Figure 3. (a) Liner velocity vs. target temperature, assuming a radial convergence ratio of 8. (b) Liner energy vs. target confinement time.

Some theoretical modeling and analysis on the merging of these jets to produce a plasma liner have been done. 3-D fluid dynamics modeling of the merging of the jets have been performed by Thio, Knapp and Kirkpatrick[14] (Figure 3c). The modeling was done with the Los Alamos National Laboratory's code, SPHINX. The code uses a modern fluid modeling technique called Smooth Particle Hydrodynamics (SPH). The results of the 3-D modeling are encouraging, showing that the jets do merge to form cylindrical and spherical shells as the case may be, and the resulting plasma shells can be used to compress a target plasma to thermonuclear conditions. Using the 0-D model, Thio, et al[6] have also conducted analysis to indicate how these plasma liners may be used in MTF schemes to produce fusion gains exceeding 70, and confinement time of the order of several hundreds of nanoseconds.

4. The Plasma Accelerator

Over the last 40 years, pulsed plasma acceleration has been studied and developed for various applications involving a wide range of plasma density from below 10^{20} m^{-3} to over 10^{25} m^{-3}. Towards the low density end of the spectrum (~ 10^{21} m^{-3}), pulsed plasma thrusters used for space propulsion have accelerated small plasma mass typically less than 100 µg to velocity up to 50 km/s[15]. Towards the high density regime, plasmas with density ~10^{25} m^{-3}

Figure 3(c). 3-D SPHINX modeling results of plasma liner formation from the merging of 60 plasma jets arranged in a spherical array.

and masses of 10's mg have been accelerated in devices such as railguns for launching solid

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projectiles. The highest projectile velocity attained in railguns reproducibly in the laboratory is 8.2 km/s obtained by Thio in 1986[8], and plasma densities used in these guns are estimated at 10^{25} to 10^{26} m^{-3}. Plasma of intermediate densities have been accelerated in Marshall guns to velocities in excess of 10 km/s for application in plasma focus. Spheromaks[16, 17] and field reversed configurations have been accelerated to velocities more than 200 km/s, but the plasma densities are low[18, 19]. The acceleration of plasmas with the mass in the range 0.1 to 0.5 mg and with the density in the range 10^{23-24} ions m^{-3} required here has not been done before. More importantly, the plasma jets need to be launched with extremely high timing and velocity precision for MTF application. The research issue here is: how compact can the plasma accelerator be, how high can the plasma jet densities be, how precise can the plasma jet be launched, while attaining the high velocities required?

A reasonable milestone to set for the PLX experiment is to accelerate 0.2 mg – 0.4 mg of plasma to 200 km/s in a plasma gun with a length of no more than 1 m and with a muzzle diameter of less than 0.2 m, and a timing precision of better than 100 ns.

A shaped pulsed plasma accelerator of the Marshall type, as illustrated in Figure 4, is a candidate concept for producing the plasma jet. The gun consists of a coaxial pair of electrodes. A pulse of current enters one of the electrodes and returns by the other. Current conducts through the plasma between the electrodes. The magnetic field generated by the current produces a magnetic force (the Lorentz force) on the current flowing in the plasma, accelerating the plasma to high velocity. Collimation and focusing of the plasma jet is provided by the mechanical tapering (shaping) and electromagnetic (z-pinch type) focusing at the muzzle of the gun. The plasma gun can be driven by a pulse forming network (PFN). A π-type PFN is considered. Each PFN section consists of a capacitor and an inductor, as shown in Figure 5 where a four-section PFN is shown as an example.

Initially 4 PFN sections per gun were considered. But discussions with the potential capacitor vendor (General Atomics Energy Products) reveals certain economics and fabrication trade-offs. The outcome of these discussion is that we decided to consider exploring design with only two PFN sections per gun. In particular, the current per capacitor is limited to about 500 kA.
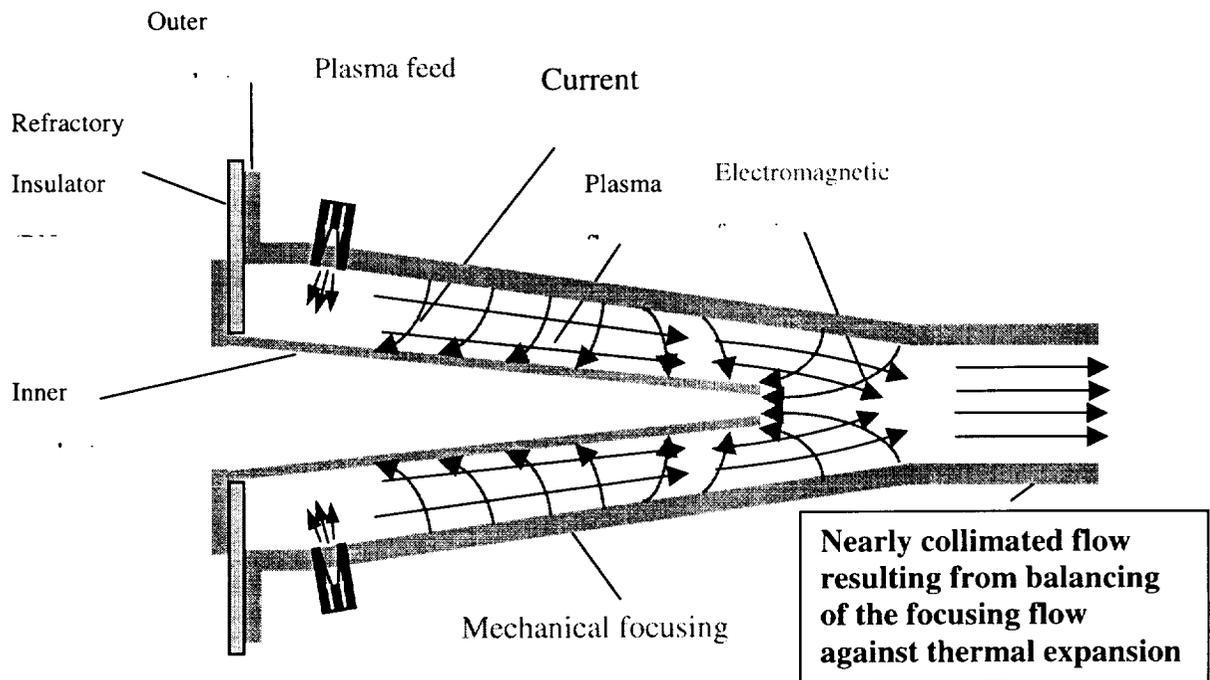

Figure 4. A coaxial plasma gun of the Marshall type for electromagnetic acceleration of plasma.
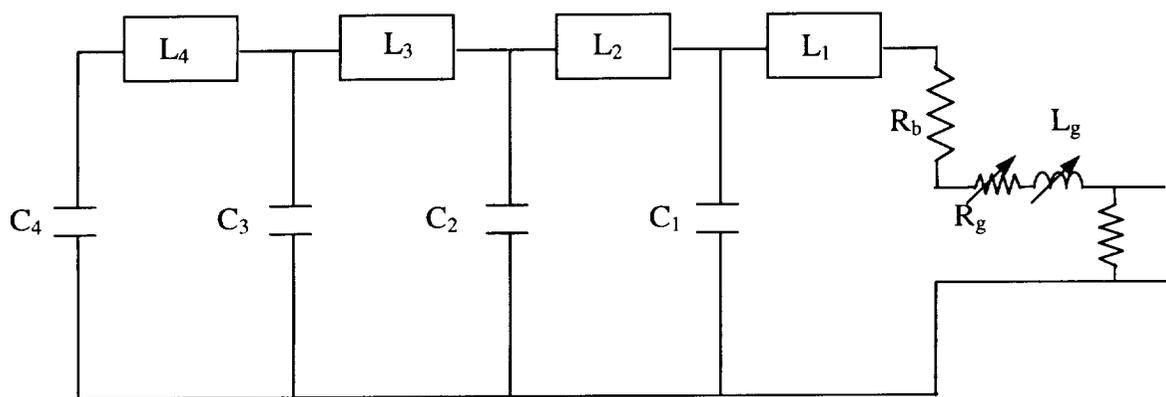

Figure 5. A Marshall-type plasma gun driven by a pulsed forming network, each section of which consists of a capacitor connected in series with some inductance.

To simulate the performance of the plasma gun driven by the PFN, a computer simulation code was developed. The resistance of the bus bars and the conductors making up the coaxial plasma gun are modeled taking into account time-dependent skin effect. For rapid scanning of the parameter space to select the circuit parameters, the plasma mass is modeled as a lumped mass element (a "slug") accelerated by the Lorentz force,

$$F_L = \frac{1}{2} L' I^2$$

where I is the current through the plasma and L' is the inductance gradient of the plasma gun.

Applying Kirchoff's Law to the circuit and Newton's law of motion to the plasma slug, we obtain the following equations:

$$\left(L_1 + L_g\right)\frac{dI}{dt} = V_1 - \left(R_b + R_g + R_p + L'v\right)I, \quad L' = \left(\frac{\mu}{2\pi}\right)\ln\left(\frac{b}{a}\right), \quad L_g = L'z, \quad R_g = R'z\left(\frac{1}{A_{in}} + \frac{1}{A_{out}}\right)$$

$$L_{i+1}\frac{dI_{i+1}}{dt} = V_{i+1} - V_i, \quad C_i\frac{dV_i}{dt} = -\left(I_i - I_{i+1}\right), \quad i \geq 1,$$

$$\frac{dv_p}{dt} = \frac{\frac{1}{2}L'I^2}{m_p}, \quad \frac{dz}{dt} = v_p$$

where L_1, L_g are the transmission inductance (bus-bar and the internal inductance of the capacitor) and the time-dependent inductance of the plasma gun, C_1 is the capacitance of the capacitor connected to the plasma gun, R_b, R_g, R_p are the resistances of the transmission (bus-bars), the conductors of the gun, and the plasma sheet respectively, R' is the resistivity of the gun conductors, A_{in}, A_{out} are time-dependent cross-sectional areas of current conduction of the inner and outer conductors (electrodes) of the coaxial plasma gun, taking into account the skin depth due to the pulsed nature of the current, b and a are the outer and inner radii of the electrodes respectively. The

PFN sections are numbered as section $i = 1, 2, 3, ...$ counting from the section nearest to the gun. C_i and L_i are the capacitance and the inductance of the i-th PFN section. I_i is the current through L_i and and V_i the voltage on C_i.

Before integrating the above set of equations numerically, some initial estimate of the circuit parameters would be useful in bounding the region of the parametric space for further exploration. This is obtained as follows. The kinetic energy of the jet (0.4 mg, 200 km/s) required is $E_{jet} = 8$ kJ. Limiting the acceleration length in the plasma gun to $\ell = 0.5$ m, the mean Lorentz force F_L required to accelerate the plasma is $E_{jet} / \ell = 16$ kN. Assuming the diameters of the outer and inner electrode to be about 6 inches and 2 inches respective, the inductance gradient L' is approximately 0.2 μH/m for the plasma gun. The r.m.s. value of the current I_{ave} to produce the required Lorentz force is 447 kA. The mean velocity is 100 km/s. The gun impedance due to plasma motion is $Z_L = L'v = 20$ mΩ. The back emf generated by the gun at this instant $= I_{peak} Z_L \sim 10$ kV. The initial voltage in the PFN needs to be approximately twice this voltage, i.e. approximately 20 kV. The total capacitance C of the PFN is chosen to produce the desired pulse width, Δt, which is determined by $\Delta t = 2 C Z_L$. The required pulse width $\Delta t \sim 2\ell/v_{max} \sim 5$ μs where v_{max} is the maximum velocity. Thus the total capacitance required is 125 μF. At 20 kV, this capacitance stores about 25 kJ of energy. The net electric-to-kinetic efficiency is approximately 32%, which is consistent with past experimental experience with pulsed plasma thrusters.

Provided with these initial estimates, extensive parametric exploration was made by integrating the complete set of equations governing the circuit and the motion of the plasma sheet. A code (PFNX) was developed for this purpose using a 4 (1/2) – order Runge-Kutta-Fehlberg differential equation solver. Although the effect of tapering the electrodes with the attendant variation in L' as a function of the plasma current in the gun can be simulated, in order to keep the parametric exploration

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tractable, a nominal ratio of the radii of the outer and inner electrodes is assumed. We began the

parameteric exploration with the values of the capacitances and voltages as determined analytically

above for the 2-stage PFN. A large number of cases were run. The circuit parameters were varied but

the total stored energy in the capacitor is kept more or less constant. Table 1 provides a summary of

15 of these cases. From this series of runs, it is concluded that the experimental goal of launching a

plasma jet of 200 μg – 400 μg to approximately 200 km/s could be attained with 2-section PFN, each

with a capacitor of 17.5 μF charged to 40 kV. The inductance of the output stage (connected to the

gun) should be held to less than 60 nH, while the inductance of Section #2 of the PFN should not

exceed 50 nH. Theoretically, the impedance of the PFN matches that of the gun better for the low

voltages ~ 20 kV. However, it was found that the margin of comfort in velocity is larger with higher

charging voltages. This is because at the higher voltages, the capacitance is smaller for the same

stored energy. With realistic values for the bus-bar inductance, the smaller capacitance results in

faster current rise and better use of the fixed acceleration length. The higher voltage of 40 kV was

chosen, despite the larger impedance mismatch, to provide a greater degree of experimental

flexibility. A trade-off is the greater degree of voltage reversal on the capacitor. Figure 6 shows the

plasma velocity versus the length of acceleration, Figure 7 the current pulse shape versus time, Figure

8 the current flowing out of capacitor #1, Figure 9 the current flowing out of capacitor #2. It is seen

that the capacitor currents are near the current limit of 500 kA.

| Filename pfnx-	L (nH)	C (μF)	m_{plasma} (μg)	V_o (kV)	u_p @0.5 m (km/s)	I_{peak} (kA)	$I_{p,C1}$ (kA)	$I_{p,C2}$ (kA)	$V_{p\text{-}p}$ (kV)
22kV-400ug-01	60 20	44.4 44.4	400	22 (10.7 kJ, 10.7 kJ)	230	540	360	460	35
22kV-200ug-01	40 20	44.4 44.4	200	22 (10.7 kJ 10.7 kJ)	300	540	410	485	34
20kV-400ug-02	80 100	100 100	400	20 (20 kJ, 20 kJ)	220	500	430	420	30
20kV-200ug-01	80 100	100 100	200	20	280	450	400	360	25
30kV-400ug-01	40 50	44.4 44.4	400	28 (17.4 kJ, 17.4 kJ)	260	700	580	600	47
30kV-400ug-02	60 80	44.4 44.4	400	28	235	610	500	520	51
30kV-200ug-01	35.6 44.4	44.4 44.4	200	30 (20 kJ, 20 kJ)	350	675	600	540	48
40kV-400ug-01	30 10	25 25	400	40 (20 kJ, 20 kJ)	335	920	650	750	60
40kV-400ug-02	30 30	25 25	400	40 (20 kJ, 20 kJ)	310	900	700	800	68
40kV-200ug-01	30 20	25 25	200	40	420	800	700	600	60
30kV-200ug-03	30 30	25 25	200	30	330	650	580	500	50
28kV-400ug-01	40 30	25 25	400	28 (9.8 kJ)	225	620	450	560	52
40kV-200ug-02	40 40	12 12	200	40 (9.6 kJ, 9.6 kJ)	302	620			
40kV-200ug-07	60	17.5	200	40 (14 kJ)	277	550			65
40kV-400ug-07	60 50	17.5 17.5	400	40 (14 kJ) 40 (14 kJ)	250	630	450	570	73

Table 1. Parametric scan to select the circuit parameters of the plasma accelerator.

A variety of real plasma effects are not taken into account in the above system study in order to make the parametric exploration tractable. These effects include features such as plasma injection, electrode erosion associated with charge-transfer, radiative ablation, mass entrainment by snow-plowing of the pre-filled gas, mass ejection rearward due to plasma instabilities, shock formation ahead of the plasma, skin friction, etc. These plasma effects potentially could degrade the performance of the plasma gun. For this reason, a generous performance margin is allowed for in the parametric scan to accommodate these plasma losses. The parametric exploration evaluates relative gun performance as a function of the capacitances, the inductances and the charging voltage. The potential degradation of performance due to plasma dynamical effects is assessed later during the
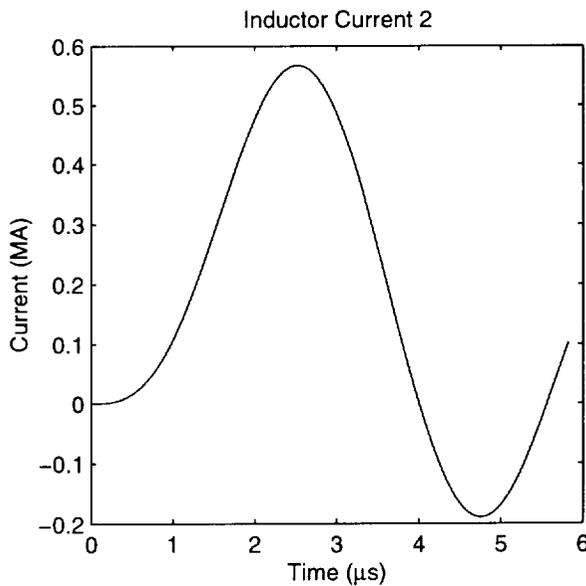
detailed design of the plasma accelerator. The plasma mass may be introduced by the use of pulsed

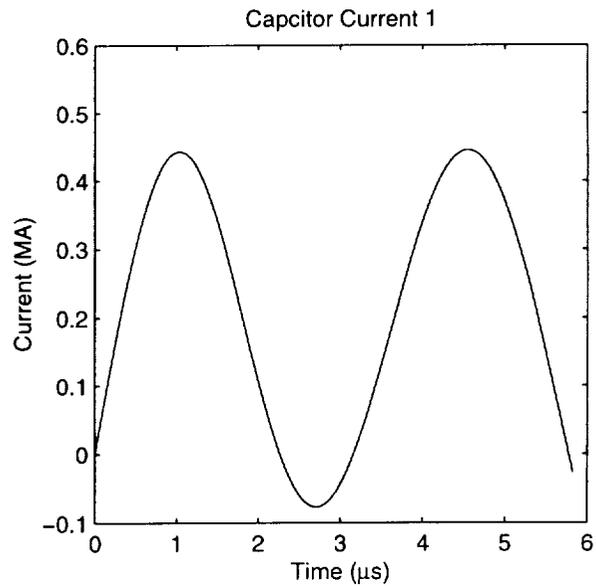plasma injector[20] or by puffing in gas and initiating the plasma behind the puffed gas.
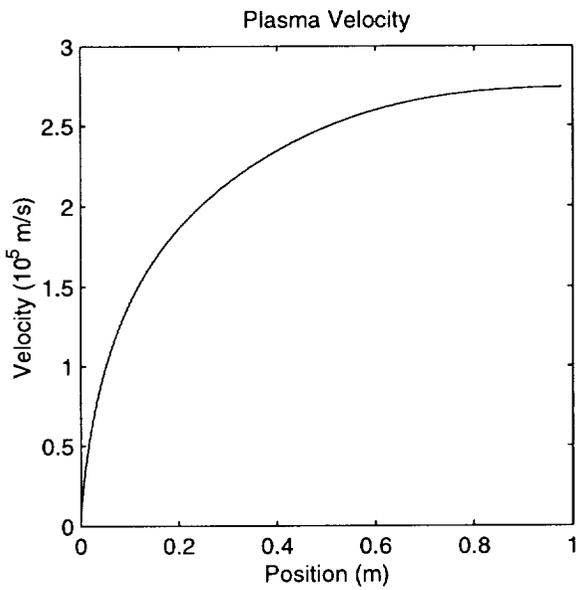
Figure 6. Plasma jet velocity

versus acceleration length.
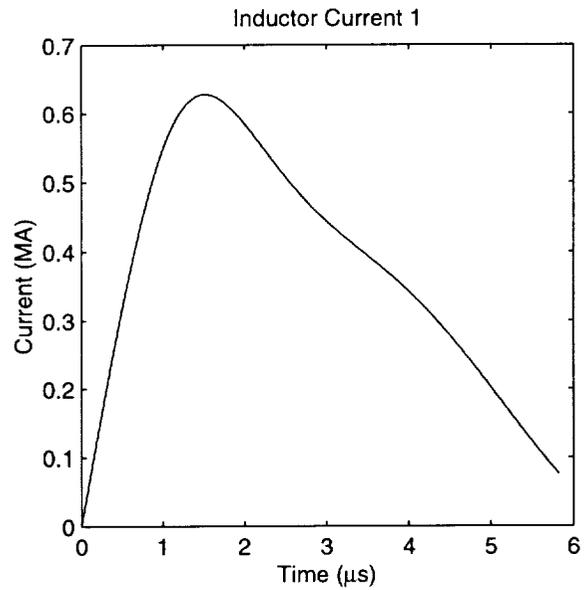
Figure 7. Current fed into the gun

versus time.

Figure 8. Current in inductor of PFN

section #2 versus time.

Figure 9. Capacitor current of PFN

section #2 versus time.

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Experimental Procedure

The baseline approach is to arrange 12 coaxial plasma guns in a circular array as illustrated in Figure 2. Each gun will launch a plasma jet towards the center of a vacuum chamber. The dynamics of the interactions of the jets to form a plasma liner will then be studied by a range of diagnostics. High-speed, multi-frame, spectrally filtered photographs of the plasma jets and the resulting plasma liner can be taken. These photographs will provide global information of the plasma jets (velocity, shapes, integrity, plasma species) and the plasma liner (symmetry, stability). Multi-channel light pipes can be used to monitor the velocity of the plasma jets and the liner. They can also be used to diagnose the time-of-flight, the spread and the composition of the plasma inside the gun. Laser interferometry can be used to measure electron density of the plasma jets inside and outside the gun. Magnetic probes can be deployed to detect the presence of magnetic flux trapped in the plasmas. They can also be used to diagnose the current distribution in the plasma gun. EUV and X-ray spectroscopy can be used for temperature measurement of the imploded liner. Thompson scattering will be a powerful diagnostic for profiling the high densities and temperature reached in the compressed liner. Langmuir probes can provide additional information on the electron density, velocity and temperature of the plasma.

5. Potential Spin-offs

It is remarkable that a project as described in this paper, if pursued, would have several spin-offs in the near term, each of which has valuable application in its own right:

- A new, high power, pulsed plasma thruster

- High-current electrode materials development

- High-current, high-voltage, compact, low-inductance, low-jitter, ultra-fast switches

- Plasma processing (surface treatment) of materials

- High-energy, low-jitter, high-precision, ultra-fast trigger generator and plasma initiator

- High energy plasma radiation source for environmental testings and for weapon effects simulation.

6. Summary

In this paper, we examine what would be a worthwhile experiment to do in order to explore the dynamics of merging plasma jets to form a plasma shell (liner) as a first step in establishing an experimental database for plasma-jets driven magnetized target fusion (PJETS-MTF, Figure 1). Using past experience in fusion energy research as a model, we envisage a four-phase program to advance the art of PJETS-MTF to beyond fusion breakeven (Q ~ 1). The experiment, PLX, described in this paper, serves as Phase 1 of this four-phase program. PLX is designed to establish the physics and the component technologies required to enable Phase 2 of the program. The objective of Phase 2 of the program, identified by the acronym PFX, is to establish the physics feasibility of PJETS-MTF. Quantitatively, PFX may be defined as an experiment that will exercise all aspects of the plasma physics of the PJETS-MTF concept at the level of 6×10^{17} s.m^{-3} $\times 2$ keV for the Lawson triple product $n\tau(kT)$. Phase 3 of the program, a proof-of-principle (PoP) experiment, will be the major R&D phase, and will take the Lawson triple product for the concept to the level of 6×10^{17} s.m^{-3} $\times 5$ keV, within one order of magnitude required for breakeven.

In order to meet the requirement for enabling the physics feasibility experiment PFX, the experiment PLX must develop a plasma accelerator capable of launching a plasma jet carrying a mass of 0.4 mg to 200 km/s with a diameter no larger than about 20 cm, with a jitter no larger than 100 ns. The simplest experiment in which the merging of the jets can be studied is one in which a 2-D cylindrical plasma liner is formed. This may be formed by using 12 plasma guns arranged in a circle (Figure 2).

A candidate plasma accelerator meeting the project objective is based upon a Marshall plasma gun with a coaxial geometry (Figure 4). A first-cut at designing the required Marshall gun is conducted. Working within the approximate limit of pulling no more than 0.5 MA from a capacitor can, we find that the performance objective can be met by powering a Marshall gun with a two-stage π-type PFN (Figure 5) with capacitances, $C_1 = C_2 = 17.5$ μF charged to voltage of 40 kV, and inductances, $L_1 = 60$ nH, $L_2 = 50$ nH.

There are a number of potential spin-offs from pursuing the project PLX. These include the use of the plasma accelerator as a high-power pulsed plasma thruster (rocket); the development of high-current electrode and insulator material; the use of the plasma accelerator as a low-jitter, fast current rise, high-current switch; the development of a high-dosage (high-energy), low-jitter, plasma injector; and as a potential source of high repetition-rate radiation source.

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