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The Pulsed High Density Experiment: Concept, Design, and Initial Results

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An experimental program has been initiated that will explore the very compact, high energy density regime of fusion based on the magneto-kinetic compression of the FRC. Of all fusion reactor embodiments, only the FRC has the simply-connected closed field, linear confinement geometry, and intrinsic high β required for magnetic fusion at high energy density. PHD takes advantage of the linear confining geometry by incorporating a traveling, burning plasmoid, significantly reducing the wall loading as well as keeping the formation well separated from the burn chamber. Being small, compact, and at high β greatly improves the exposed surface to reacting volume ratio. Being pulsed eliminates the need for flux sustainment, and provides for regulation of the average wall loading. A wide range of reactor scenarios are compatible with PHD including liquid metal walls with the prospect of direct energy conversion through cyclical wall compression/expansion.

KEY WORDS: Magnetic confinement; field reversed configuration; accelerator; magneto-kinetic compression.

INTRODUCTION

The difficulty for most nuclear fusion concepts stems from the complexity and large mass associated with the confinement systems. A simpler path to fusion, that avoids these difficulties, can be achieved by creating fusion conditions in a different regime at small scale ($r_p \sim a$ few cm). An experimental program has been initiated that will explore this very compact, high energy density regime of fusion based on the magneto-kinetic compression of the field reversed configuration (FRC) [1] where the energy required to compress the FRC to fusion conditions is transferred to the FRC via low field acceleration/compression coils. The requirement on the FRC closed poloidal flux is reduced to what has already been achieved so that the FRC should remain MHD stable through burn. Most importantly, the FRC has already demonstrated the confinement scaling with size and density required for fusion at high density [2]. The FRC has demonstrated the confinement scaling with size and density required for fusion at a confining pressure well below the yield strength of materials allowing for solenoidal confining magnets. Given the simplicity and small scale, it is ultimately the intent of the PHD experiment to bring the FRC to fusion breakeven conditions.

The initial effort is to construct a source suitable for generating the start-up FRC parameters for a fusion gain > 1. The initial section of the PHD experiment has been constructed with a unique segmented flux conserver that allows for simultaneous formation/acceleration. Several ionization and formation improvements have been initiated to enhance flux retention into the FRC equilibrium. High flux

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retention with operation employing only RF preionization has been achieved for the first time. Several new diagnostics have been constructed and applied to study FRC formation including visible bremstrahlung tomography, ion Doppler spectroscopy, interferometry, bolometry, and magnetic probe arrays.

The energy needed to achieve fusion conditions is transferred to the FRC by the axial propagation of a magnetic compression wave, and it is believed that this process can be made repetitive and very efficient, thus avoiding the need for other methods such as neutral beams to reach fusion temperatures. The initial goal of an initial Pulsed High Density experiment (PHDX) is to form, accelerate and compress an FRC to a density of 1×10^{22} m^{-3} at a temperature greater than 1 keV. With the energy confinement time predicted by previous FRC scaling [3], the FRC should attain a $n\tau$ product of 5×10^{18} m^{-3}s, which would exceed previous FRC results by nearly an order of magnitude. This experiment would essentially be the first step, where progress towards breakeven can be made in incremental steps with additional stages of acceleration and compression based on the successful completion of this first phase.

FRC STABILITY

Given the typically $\tau \sim r^2$ confinement scaling observed in most magnetic fusion experiments, including the FRC, fusion on a smaller scale will require a higher plasma density. With the much higher fusion yield at higher density, small-scale fusion is pulsed. One need not go as far as ICF densities to find a suitably small scale. There is a vast region of density that is between MFE and ICF. A great simplification in reactor design is achieved for a small-scale high density fusion regime that remains below the yield strength of materials. This is the region where Pulsed High Density (PHD) FRC fusion is best suited. Up to now, FRC research moved in the direction of low-density steady-state operation, mainly driven by a mindset instilled by the successful tokamak research in this regime. Significant $n\tau$ products were achieved with the FRC. The continued path to a fusion breakeven by increasing the FRC size has been found to be quite difficult for several reasons. Based on FRC confinement scaling, for fusion at large radius, the poloidal flux of the FRC must be on the order of several Webers which is roughly a fact of a thousand greater than what has been achieved in current FRC experiments. A major concern for the steady-state low density FRC reactor is the stability to tilt, as well as other instabilities, at the high flux required for a reactor. In current and past experiments, the ratio of the separatrix radius to the average ion gyroradius (commonly referred to as s) was 4 or less [2]. This parameter has been used to characterize the kinetic contribution to stability, with significant reduction in mode growth rates for $s < 3$. At Weber levels of flux, $s > 20$, and the highly kinetic behavior of the FRC ions disappears. However, the explanation of the observed stability of the FRC to tilt has been one of the great challenges to theoretical plasma physics.

Recent theoretical analysis [4] and numerical calculations [5] have shown that there is near stability when Hall and finite ion gyroradius effects are properly accounted for. The stability in this limit is characterized by the ratio of the FRC radius to the ion collisionless skin depth, $S^* = r_s/(c/\omega_{pi})$. MHD stability is found when $S^* < 2\varepsilon$ where ε is the separatrix elongation. Past FRC experiments have shown good confinement for $S^*/\varepsilon \leq 5$ [6], implying that there is still a significant kinetic effect yet unaccounted for at small values of S^*/ε. Confinement was observed however, to significantly degrade for FRCs with $S^*/\varepsilon > 5$. For the PHD regime, with the small radial size and high elongation, $S^*/\varepsilon \sim 4$, even for the fusion plasma. The kinetic contribution to stability will still be present, since the poloidal flux is of the same order as that obtained in past experiments. In fact, once the FRC is formed in the source region, both stability criteria, s and S^*/ε, should improve as the FRC is accelerated and compressed to reactor conditions.

FRC SCALING

Although previous FRC experiments were aimed in the direction of achieving a relatively low density steady-state reactor embodiment, there were several reactor studies that took advantage of the translatability and compressibility of the FRC [7, 8]. A limitation for these studies was the lack of sufficient data regarding the scaling of FRC confinement. Since these studies, many experiments over a wide range of conditions have been performed, and considerable data has been accumulated from various FRC experiments that span over two orders of magnitude in density and an order of magnitude in radius. The scaling has been stated previously in terms of inferred quantities that are not directly measured (ϕ_p, ρ_i, etc). For the purposes here, it is better to state confinement in terms of the basic external parameters that can be easily and accurately measured from all experiments. The observed particle confinement, cast in these terms, yields the following scaling [3]:

$$\tau_N = 3.2 \times 10^{-15} \varepsilon^{0.5} x^{0.8} r_s^{2.1} n^{0.6}, \qquad (1)$$

where ε is the FRC separatrix elongation, and x_s is the ratio of the FRC separatrix radius, r_s to coil radius, r_c. It was found that the only significant energy loss channel for the FRC was particle loss [6], so that the particle confinement scaling of equation (1) will be assumed for the energy confinement scaling in determining reactor parameters.

From this empirical scaling it can be seen that the improved confinement with density more than compensates for the size scaling as one reduces the size of the FRC. It is noteworthy that the confinement scaling observed for tokamaks has a very similar dependence on radius and density. The need for a very large toroidal field and complex tokamak coil geometry however, limit the amount of size reduction possible for the tokamak.

In a pulsed system, as opposed to steady state, the time the plasma is sustained at fusion temperatures, τ_{burn}, is an important variable. The pulse duration determines the amount of fuel that reacts or "burns," leading to an $n\tau_{\text{burn}}$ requirement in a similar way that $n\tau_E$ is determined from power balance in a steady-state system. To obtain the minimum possible system size one desires $\tau_E \sim \tau_{\text{burn}}$. Thus for fusion gain, one has $n\tau_E \sim n\tau_{\text{burn}} \sim 1 \times 10^{20}$ m^{-3} s similar to the Lawson criterion. Clearly one desires a higher $n\tau$ and thus larger gain ($G \sim 3$ for 10^{20} m^{-3} s) for a commercial reactor, but this represents a good target for evaluation of parameters.

For the FRC scaling above, one can solve for the minimum plasma radius that satisfies the Lawson criteria ($n\tau = 10^{20}$ m^{-3} s) by making some reasonable assumptions for the FRC reactor plasma, i.e. $\varepsilon \sim 20$ and $x_s = r_s/r_c = 0.6$. One then has:

$$r_s \cong 1.0 \times 10^{17} n^{-4/5} \qquad (2)$$

For a fusion plasma temperature $T \sim 1 \times 10^4$ eV, the confining magnetic field for a high β plasma such as the FRC need be no greater than the maximum radial plasma pressure at the magnetic null:

$$B_e = (2\mu_0 n_0 kT)^{1/2} = 6.4 \times 10^{-11} n^{1/2} \qquad (3)$$

The internal FRC flux is related to the plasma size by:

$$\phi = \pi r_c^2 B \left(\frac{x}{\sqrt{2}}\right)^{3+\alpha} \approx 0.43 B r_s^2 \qquad (4)$$

where α is a profile dependent parameter between 0 and 1 [1]. For lack of any direct measurement of the equilibrium FRC profile, α is taken to be 0.5 in equation (4). FRC stability and confinement put a limit on the maximum plasma size for a given density. Assuming a somewhat conservative value of S^*/ε for the domain of good FRC confinement and stability, one has:

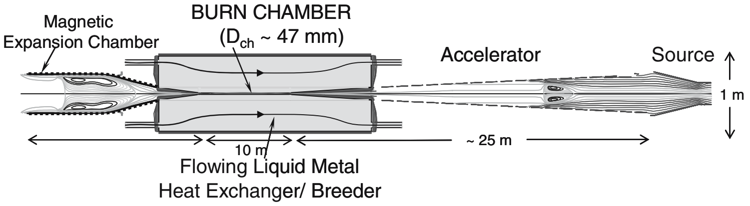
$$S^* \le 3.5\varepsilon \Rightarrow r_s \le \frac{2.2 \times 10^{10}}{n^{1/2}} \qquad (5)$$

The minimum reactor density can be determined from this relation together with equation (2) with the result that $n \ge 1.5 \times 10^22$ m^{-3}, or equivalently $r_s \le 0.18$ m. The reactor operating point is most influenced by the FRC flux required. Taking the reactor target flux to be no more what has already been achieved experimentally (~10 m Wb), equation (4) together with (2), and (3) determine the target plasma radius to be $r_s = 2.8$ cm. As small as this radius may seem, there are over 30 fusion ion gyroradii in the vacuum region between the FRC separatrix and the vacuum wall. Higher fusion gain can be obtained with a larger flux plasma since the plasma size could be increased considerably without exceeding the stability limit.

A claimed disadvantage of a pulsed system is the need to reheat the plasma to fusion temperature with each pulse, where an ignited, steady state reactor is heated by the fusion alphas. Since the poloidal flux accounts for the entire confining field in the FRC, and the fusion burn does not sustain the toroidal currents, the power required for current maintenance could easily exceed the plasma thermal losses. There will most likely always be a high recirculating power for the steady state FRC, providing no real advantage to steady state operation.

PULSED HIGH DENSITY FUSION CONCEPT

The process by which a "garden variety" FRC, such as those that can be formed with the current state of FRC development, can be brought to fusion conditions with greater than unity gain is shown in Figure 1. The reactor can be broken up into four distinct sections. The conditions required in the burn chamber determine to a large degree the parameters



1 - FRC formed at low energy (~30 kJ) and relatively low density (~10^{21} m^{-3})

2 - FRC accelerated by low energy propagating magnetic field (~ 0.5 T) to

3 - FRC is wall compressed and heated as it decelerates into burn chamber

4 - FRC travels several meters during burn time minimizing wall loading

6 - FRC expands and cools converting thermal and magnetic energy back into stored electrical energy

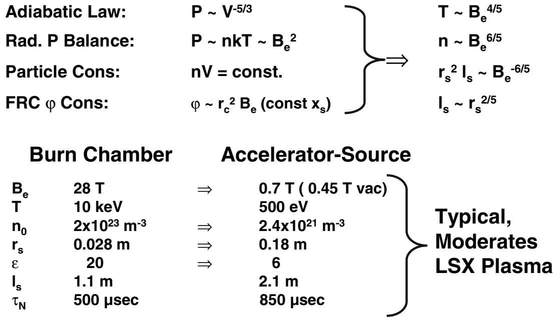
Fig. 1. Outline of Pulsed High Density Fusion reactor concept.

of the other sections and the parameters for this section will be addressed first.

Burn chamber

For a given FRC size, the higher the density, the higher the fusion gain. The highest density, consistent with material wall structural limitations, has $n \sim 10^{24}\ \mathrm{m}^{-3}$. The target plasma radius $r_s = 2.8$ cm was determined to fall within the range of current experimentally achievable FRC flux. For this radius equation (2) above requires a plasma density of $n_0 = 2 \times 10^{23}\ \mathrm{m}^{-3}$ for the reactor, which is well away from material structural limitation on the confining coil (see Fig. 1), and leaves considerable room for increased fusion gain. For the assumed density, one has for the external field (equation (3)) $B_e = 28$ T. While this is a substantial field, the vacuum field can be significantly less than this. This is due to the conservation of the vacuum flux on the short timescale that the FRC resides within the burn chamber (the required $\tau_{\mathrm{burn}} \sim 0.5$ ms for the target reactor). With a conducting vacuum boundary wall, the vacuum field is conserved and compressed by the FRC as it enters the burn chamber. From flux conservation, the axial field external to the FRC is enhanced by a factor of $1/(1-x_s^2)$ over the vacuum field. With $x_s = 0.6$, the vacuum field need be $B_{vac} = 18$ T, which is within the range of superconducting magnets.

The fusion power is determined by the pulse rep rate. Since the reactor volume is relatively small, the average power can be kept low allowing for regeneration of conditions for subsequent pulses. With pulsed fusion, the power can be modulated to fit demand. Since the output power during the burn is the same regardless of pulse rate, there is no inherent disadvantage to a lower fusion power output. Since the reactor lifetime is determined by the total accumulated burn time, there is no real penalty from a low rep rate. Since the linear reactor vessel envisaged here is significantly smaller and simpler (essentially a steel pipe), replacement costs of reactor facing materials will be much lower as well. A smaller device has a much better absorbing surface to fusion volume ratio as well. The drifting FRC provides for a moving fusion burn that can substantially increase this ratio. For the FRC parameters determined above for fusion burn, a 700 kJ FRC with a fusion gain of 10 pulsed at 10 Hz would produce 70 MW of fusion power. With the burn time of 1 ms, the "duty cycle" for this reactor is a small fraction of the time between pulses (~1%).



$$\left.\begin{array}{ll}\textbf{Adiabatic Law:} & P \sim V^{-5/3} \\ \textbf{Rad. P Balance:} & P \sim nkT \sim B_e^2 \\ \textbf{Particle Cons:} & nV = \text{const.} \\ \textbf{FRC } \varphi \textbf{ Cons:} & \varphi \sim r_c^2\, B_e\ (\text{const } x_s)\end{array}\right\} \Rightarrow \begin{array}{l} T \sim B_e^{4/5} \\ n \sim B_e^{6/5} \\ r_s^2\, l_s \sim B_e^{-6/5} \\ l_s \sim r_s^{2/5}\end{array}$$

	Burn Chamber		Accelerator-Source	
B_e	28 T	⇒	0.7 T (0.45 T vac)	Typical, Moderates LSX Plasma
T	10 keV		500 eV	
n_0	$2 \times 10^{23}\ \mathrm{m}^{-3}$	⇒	$2.4 \times 10^{21}\ \mathrm{m}^{-3}$	
r_s	0.028 m	⇒	0.18 m	
ε	20	⇒	6	
l_s	1.1 m		2.1 m	
τ_N	500 μsec		850 μsec	

Fig. 2. Source parameters determined by adiabatic scaling from reactor parameters for prolate FRC.

Accelerator

The energy necessary for burn is transferred to the FRC in the form of translational energy produced by a series of axially sequenced coils. The simplicity of this approach to fusion lies in the fact that the directed energy of the FRC mass, $E_{\rm d}$ can be much greater than the FRC internal energy, $E_{\rm i}$. Since $E_{\rm d}$ is in the form of a coherent translational motion, the confining magnetic fields, as well as accelerating fields, need to be no greater than required to contain the low-pressure FRC generated in the source coil (~0.5 T). This leads to a large simplification in acceleration coil construction as well as stored energy requirements for the accelerator.

By matching the timing and risetime of the coils, one can create, in the frame of the FRC, a quasi-steady field configuration where the magnetic field (and pressure) gradient is maintained across the FRC. The FRC then "surfs" on a magnetic pulse that propagates axially along the accelerator. In this manner, FRCs have been accelerated to velocities $v_{\rm FRC} \sim 4 \times 10^5$ m/s. When there is no compression as the FRC is accelerated, all of the thermal energy for fusion must be stored in the kinetic energy of the plasma. This worst-case condition represents the highest velocity requirement:

$$v_{\rm FRC} = (5kT_{\rm fus}/m)^{1/2} \sim 1.4 \times 10^6\,{\rm ms}, \qquad (7)$$

where the factor 5 represents the additional energy needed for compressing the burn chamber flux. For an acceleration a of 2×10^{10} m/s^2 (in the range of that achieved in current experiments, and the target a for PHD) the accelerator length, $L_{\rm acc} = v_{\rm FRC}^2/2a \sim 50$ m with the time for acceleration $\tau_{\rm a} \sim 50\,\mu$s. There should be little need to accelerate to this high velocity since the combination of acceleration and compression prior to the final deceleration and conversion can be incorporated in the acceleration coils. The conversion of translational to thermal energy upon deceleration and compression of the FRC process is routinely observed in FRC translation experiments, where the FRC is translated out of the source, and brought to rest in an external magnetic mirror. As the FRC is rapidly decelerated, the ion thermal energy increases in the same amount as the translational energy is decreased [9].

Source plasma – PHDX

The FRC plasma required in the source can be obtained from the adiabatic scaling laws found in Figure 2. All basic parameters can be determined from the ratio of the reactor field to the source field where it was assumed to be a typical field for most FRC experiments. It can be seen that the other FRC parameters are also in the range of those obtainable in a conventional FRC. The size of the formation coil required here would be similar to the LSX experiment that was operated at Spectra Technology Inc., as well as the RMF experiments at the UW. For the scaling

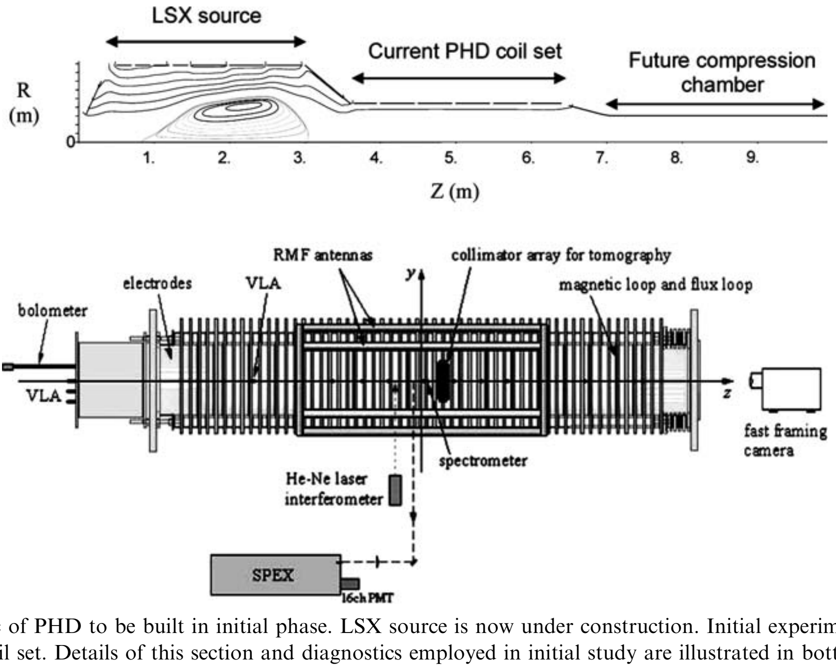


Fig. 3. Top: Schematic of PHD to be built in initial phase. LSX source is now under construction. Initial experiments were conducted in accelerator coil set. Details of this section and diagnostics employed in initial study are illustrated in bottom schematic.

in Figure 2, conservation of flux and particles is assumed since the confinement time predicted for the source plasma is much longer than the time to accelerate into the burn chamber.

To date the accelerator section has been built and constructed so that 12 individually controlled axial field coils can be sequenced to produce a uniform acceleration of a high flux FRC. For the initial experiments it was possible, by reversing the bias field, to actually form FRCs in the acceleration section and test most of the diagnostics that will be employed in the initial experiments. A schematic of the full formation/acceleration/compression experiment, and the section constructed for initial testing is shown in Figure 3. In these initial experiments, a new formation technique provided for the formation of FRCs at very high flux. These FRC were thus formed well beyond the stability range observed in previous experiments (here $S^*/\varepsilon \sim 10$). These experiments acted as a check on the stability criterion, and for the first time provided detail as to the mechanism for the lack of equilibrium observed in prior experiments in this MHD-like regime. Both end-on imaging, and midplane tomography were used along with the diamagnetic loop array to provide a picture of the development of the FRC during formation. The tomographic diagnostic consisted of a midplane array of 64 chords of visible light filtered through a narrow band pass filter (1–10 nm) at 523 nm. This wavelength was chosen as it was known to be line free on other fusion devices as well as this device. A large scale "inner tube" instability was observed to grow on a radial Alfven time that precluded a long lived FRC equilibrium. The growth of this sausage-like mode had been predicted to be unstable in 3D MHD calculations and had been inferred in previous FRC experiments. It was only from this data that it became clear that this mode could destroy the FRC prior to the advent of even the tilt mode. The implication for future experiments is that sufficiently hot ions are required very early in formation to provide the stability required to stabilize this mode. The larger source planned for PHD (LSX source in Figure 3) will provide for much hotter ions as the fill pressure can be much lower for the same flux in a larger radius formation chamber (Fig. 4).

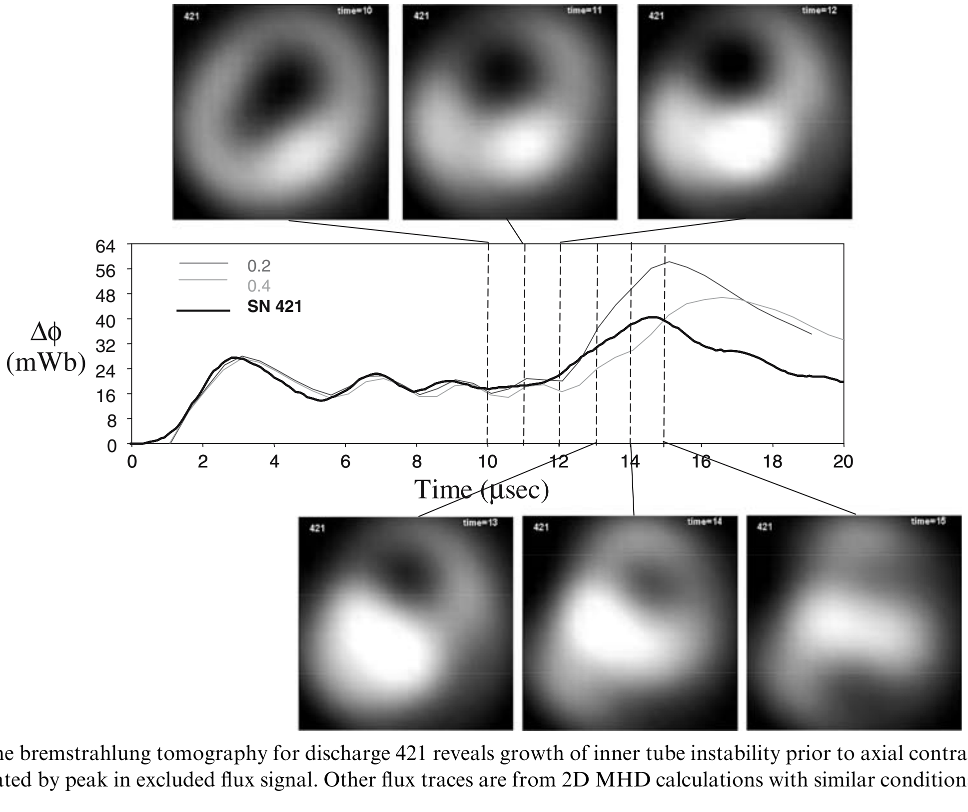


Fig. 4. Midplane bremstrahlung tomography for discharge 421 reveals growth of inner tube instability prior to axial contraction to equilibrium FRC indicated by peak in excluded flux signal. Other flux traces are from 2D MHD calculations with similar conditions to experiments.

DISCUSSION

Small scale fusion in the form outlined is an approach that does not require significant time or resources. The technologies involved in all aspects of the concept have been established and rapid testing development of the concept is underway. The source FRC parameters have been achieved already in past FRC experiments. In previous experiments, rapid acceleration of the FRC has been demonstrated ($a > 10^{10}$ m/s^2). A simpler and a more efficient accelerator/compressor has been tested. The thermal conversion of translational energy without loss of confinement has also been demonstrated. In the reactor scenario outlined for PHD, the FRC at no time exceeds the empirical regime where stability and good confinement has been observed throughout the entire formation process through burn. The PHDX experiment finally completes the stability and confinement study begun with LSX with improvements that provide for a test of the stability limits and confinement for the FRC. The PHDX experiment, if successful, would serve as a proof of principle experiment that could be rapidly developed toward a breakeven FRC fusion experiment.

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