

Pulsed High Density Fusion

John Slough[#]
University of Washington

INTRODUCTION

It is quite possible that nuclear fusion will be the only source that can provide the prodigious power demands that the world will face in the future. Fusion is the only power source where there are large and available quantities of fuel that would satisfy mans needs for centuries if not millennia. The difficulty however for most nuclear fusion concepts is the large complexity and mass associated with the confinement systems. Essentially, the more massive the system required to confine and heat the fusion plasma, the larger the cost to develop and operate. The difficulty that the fusion community is faced with today is consequence of this scaling. The high cost of tokamak research (and thus reactors) is primarily due to the large reactor sizes required for fusion gain with low β steady state reactors (β being the ratio of the plasma to magnetic energy density). At the other end of the spectrum, for most pulsed devices, the mass and complexity of the fast energy delivery systems becomes the problem. In particular, the ability to rapidly and repetitively pulse these lower yield plasmas to achieve reasonable power efficiency is complicated considerably by the drivers (lasers, beams etc.).

It is possible to avoid these difficulties that the current fusion program has evolved to. The path that will be outlined here takes advantage of recent developments in the very compact, high energy density regime of fusion employing a plasma commonly referred to as the Field Reversed Configuration (FRC). Of all fusion reactor embodiments, only the FRC has the linear geometry, low confining field, and high plasma pressure required for magnetic fusion at high energy density. Most importantly, in previous experiments the FRC has demonstrated the scaling with size and density required for fusion at high density². A fusion reactor based on the pulsed formation and high density burn has several advantages over previous high density approaches such as the Z and θ pinches. The FRC is a closed field configuration allowing for much longer energy confinement lifetimes. For this reason, the FRC plasma need not be heated to fusion temperatures on Alfvénic timescales, and it need not burn amidst the high voltage pulse power apparatus required for formation. Translatability, and of course the high β nature of the FRC are significant advantages of over other toroidal magnetic systems such as the tokamak as well. As will be described in more detail, the energy needed to achieve fusion conditions is transferred to the FRC via simple, relatively low field acceleration/compression coils, and it is believed this process can be made very efficient unlike the tokamak, which must rely on inefficient methods such as neutral beams to reach fusion temperatures and sustain fields.

By operating in the small, high density regime, the requirements for the FRC closed poloidal flux is no greater than what can currently be achieved, and orders of magnitude less than required for the low density steady-state regime. The low flux required for PHD has a very important consequence with regard to stability in that the FRC remains in a MHD tilt stable regime from formation through burn³.

[#] slough@aa.washington.edu

BACKGROUND

The critical issue for fusion is not so much one of scientific feasibility as viability. As mentioned, the specific problem is that major fusion technologies currently being pursued involve extremely massive and complex facilities to reach fusion conditions. Satisfying the requisite energy confinement requirement to yield a gain in energy from fusion (e.g. the Lawson criterion) the power produced must be in the several gigawatt range for low β magnetic confinement. To make fusion energy a viable option, a small, lower power fusion system must be found. The conventional regime of Magnetic Fusion Energy (MFE), with plasma densities $\sim 10^{20} \text{ m}^{-3}$ and magnetic fields $\sim 5 \text{ T}$ has been relatively well developed. Another approach to fusion, Inertial Confinement Fusion (ICF), represents the other extreme to low density MFE where the densities are many orders of magnitude higher. Since the fusion cross-section optimizes at $\sim 10 \text{ keV}$, the fusion plasma energy densities are also vastly different. In either case however, the system sizes for producing the fusion conditions have evolved to ones that extremely massive and complex. This has led to reactor designs that have extremely high output powers and gain requirements to produce net power.

There is another regime, which is between MFE and ICF, and where there has been a recent surge of interest. This is the density regime intermediate between MFE and ICF. The region is shown graphically in Fig. 2. The Los Alamos National Laboratory (LANL) and collaborators are in the process of performing a proof of principle experiment at very high density (10^{26} m^{-3}) for magnetic confinement. The fusion system that they have proposed is referred to as Magnetic

(Figure from LANL MTF group)

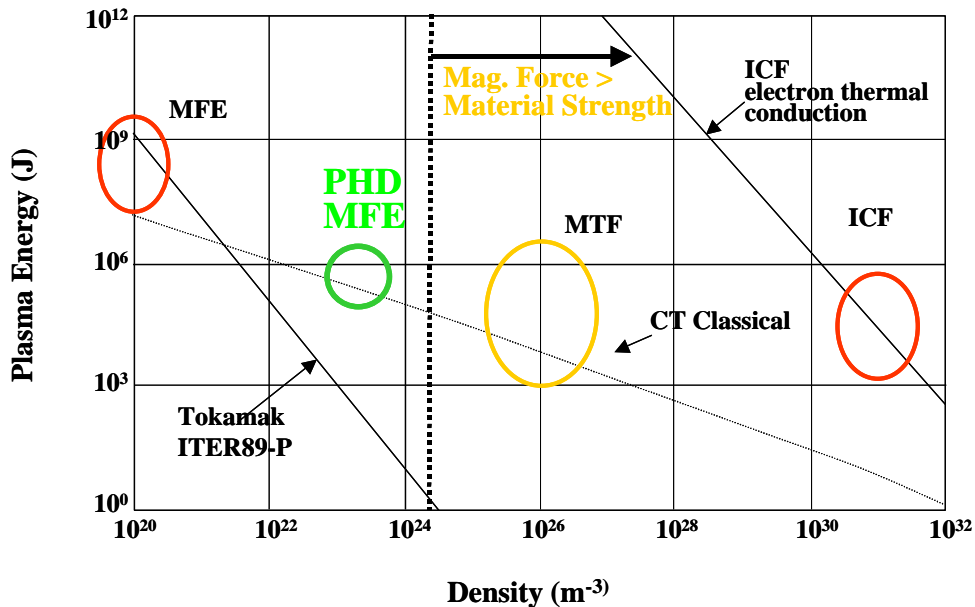


Figure 1. Energy requirements vs. plasma density for various configurations and transport assumptions assuming $n\tau_E = 3 \times 10^{20} \text{ m}^{-3} \text{ sec}$, $T_i = 10 \text{ keV}$, and poloidal $\mathbf{b} \sim 1$.

Target Fusion (MTF). Here, the high-density fusion plasma is produced by imploding a metallic liner on a target plasmoid. The best target plasmoid for compression is the very high β FRC, which would be formed and translated into the liner prior to implosion. While it is likely that fusion gain will be demonstrated with MTF, here are difficulties with this particular approach when it comes to a commercial reactor based upon it. Since the desired density and temperature range for the final plasma requires a confining magnetic field pressure that is well in excess of the yield strength of any material, the local confinement system is destroyed on every pulse. The conversion of this explosive energy into electricity, and at a sufficiently high rep rate will be daunting.

There is however an alternative high density regime that is accessible, and can be reached by a natural extension of past FRC experiments. This regime is the region where PHD FRC fusion is most attractive. The upper boundary of this region remains below the density limit imposed material strength limitations so that repetitive pulsing can be accomplished without the replacement of the magnet and other systems. Historically it is in this region that the first high temperature plasmas were formed in what was called a reverse-field θ pinch (RFTP). It was abandoned due to the difficulty in controlling axial end losses. Later experiments employing the same RFTP formation, but with special end control coils and lower compression power, demonstrated that the end loss could be substantially reduced. This was accomplished by forming a stable, closed field configuration inside the theta pinch coil – the FRC.

Continuing 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. Even though the confinement scaling observed indicated that the FRC may work in a low density, high β reactor regime, it is in the high density pulsed regime that a substantial reduction in power handling and simplicity of operation can be achieved. With a plasma radius on the order of centimeters, and no better confinement scaling than observed for FRCs to date, it would be necessary to raise the density to no higher than $\sim 10^{23} \text{ m}^{-3}$ to achieve significant fusion gain¹.

CHARACTERISTICS OF PULSED FUSION SYSTEMS

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. Assuming for simplicity that the plasma temperature and density are constant during the burn, the fusion yield is also constant and the same as a steady-state device so long as a significant fraction of the plasma fuel is not consumed. As the burn continues, the fusion gain G becomes limited by available reactants. For complete burnup, the gain would be $G_{\text{max}} = 300$ at 10 keV. This is simply the ratio of energy for a 14.1 MeV neutron and 3.5 MeV alpha divided by the 60 keV of thermal energy for a DT ion pair with electrons. Without refueling, the gain G is thus limited in a pulsed reactor, but this limit is far greater than that required for any FRC based fusion reactor.

The total power loss per unit volume during burn is normally given by $3nT/\tau_E$, where τ_E is the global energy confinement time. To obtain the minimum possible system size one desires $\tau_E \sim \tau_{\text{burn}}$. That is, if τ_E were much less than τ_{burn} the plasma would dissipate before it burned. On the other hand if τ_E were much larger than τ_{burn} , the plasma should be made smaller to equalize the two, which requires less energy. Thus one sets $n\tau_E \sim n\tau_{\text{burn}} \sim 1 \times 10^{20} \text{ m}^{-3} \text{ sec}$. This criterion, similar to the Lawson criterion, can be used to determine the plasma confinement time required

for a plasma at a given density. Clearly one would desire a higher $n\tau$ for larger gain ($G \sim 3$ for $10^{20} \text{ m}^{-3} \text{ sec}$) for a commercial reactor, but this represents a good target for evaluation of feasibility.

HIGH ENERGY DENSITY FRC FUSION

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 pictorially in Fig. 2. The reactor can be broken up into four distinct sections. The conditions required in the burn chamber, to a large degree, determine the parameters of the other sections and the requirements for this section will be addressed first.

Assuming a plasma density of $n_0 = 2 \times 10^{23} \text{ m}^{-3}$, well away from material structural limitation on the confining coil (see Fig. 1), one has. $\tau_E = 5 \times 10^{-4} \text{ s}$. For a high β plasma such as the FRC, the confining field need be no greater than the maximum radial plasma pressure i.e. $B_e^2/2\mu_0 =$

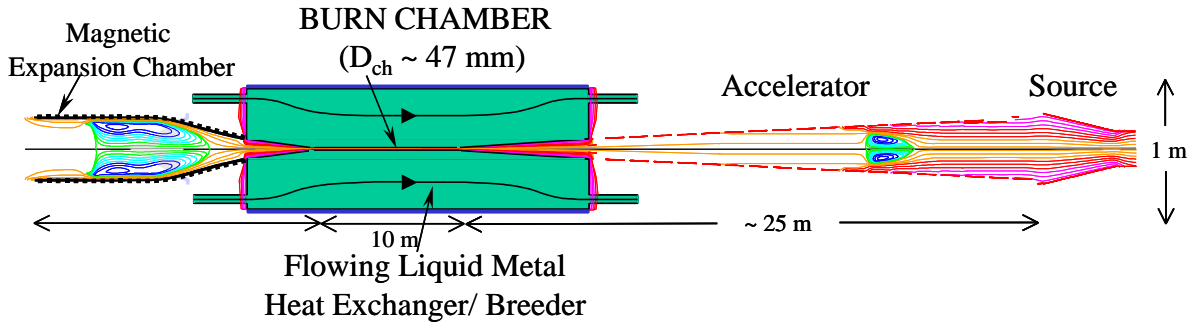


Figure 2. FRC fusion reactor. Horizontal scale has been expanded by a factor of 5.

$n_0 kT$. With $T = 10 \text{ keV}$, one has that $B_e = 28 \text{ T}$. While this is a substantial field, the vacuum field of 18 T is within the range of superconducting magnets. With a flux conserving vacuum boundary wall, the increase in the external field from the vacuum field comes from the flux compression as the FRC enters the burn chamber. The axial field strength confining the FRC is in this way enhanced by a factor of $1/(1 - x_s^2)$ from flux conservation (where the ratio of the FRC plasma separatrix radius to wall radius, x_s is assumed to be 0.6). In this way, the vacuum wall experiences only the pressure difference between the compressed and vacuum fields, and only for the duration of the FRC transit. The burn chamber field can thus be maintained at a substantially lower field than that required for fusion. The field is only higher during the brief time that the FRC passes through, and only over a region locally near the FRC.

With the above criteria for burn, the FRC size and energy can be determined given the confinement scaling for FRCs. 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 observed particle confinement from all experiments yields the following scaling²:

$$\tau_N = 3.2 \times 10^{-15} \epsilon^{0.5} x_s^{0.8} r_s^{2.1} n^{0.6}, \quad (1)$$

where ϵ is the ratio of FRC length to radius. It is believed that the only significant energy loss from the FRC is particle loss as the FRC in translation is vacuum insulated from the chamber boundary resulting in negligible thermal conduction losses. The particle confinement scaling is thus the relevant scaling. It will be shown that the adiabatic scaling from the source FRC plasma results in an elongation ratio $\epsilon \sim 20$ in the reactor. Evaluating eq. (1) with this plus the other

parameters specified above, the separatrix radius, r_s can be determined with the result that $r_s = 2.8$ cm. For the ellipsoidally shaped FRC, the plasma energy, E_p is given by

$$E_p = 3/2 \langle \beta \rangle n_{\max} kT (4/3\epsilon r_s^3) = 720 \text{ kJ.} \quad (2)$$

where the plasma average beta, $\langle \beta \rangle = (1 - 0.5x_s^2)$. It should be noted that the particle inventory and plasma confinement time are in the range of those obtained in past FRC experiments². The significant difference of course is that the plasma radius was larger (~ 0.20 m), and with a much lower density (10^{21} m^{-3}) and magnetic field (0.5 T). Given the FRC scaling in eq. (1), the $n\tau$ scaling for fusion scales like $n^{3/2}$. Since $n \sim r^{-3}$, the density scaling more than compensates for the size scaling as the plasma size is reduced. It is for this reason that a small, high density reactor becomes the best route to fusion.

In D-T fusion a significant amount of fusion energy is released as energetic neutrons. Again, the open, linear nature of the confinement system is ideal for the application of a liquid metal wall for neutron capture. In Fig. 2 the flowing liquid metal blanket (LiPb) functions as both a neutron absorber and flux conserver. With a flowing liquid metal for the burn chamber, density limitations due to wall loading and damage are removed. The target density assumed here ($2 \times 10^{23} \text{ m}^{-3}$) was chosen to stay well within the limit for a solid wall. With higher fields, higher fusion gain can be achieved. Although superconducting magnets cannot operate at fields much higher than 20 T, one must again take into account the flux compression that occurs when the FRC enters the burn chamber. By translating the same FRC into a smaller radius core with less flux (same field), the FRC will attain a larger x_s . Recalling that the axial field strength confining the FRC is enhanced by a factor of $1/(1 - x_s^2)$, for $x_s = 0.8$, a vacuum field of 20 T would be increased by nearly a factor of 3. If the duration of this compression is long enough, the impulse conveyed to the liquid wall can be translated directly into work on a compressible gas. This was the principle behind the LINUS reactor concept⁴, where demonstration of the basic operation with a rotating liquid metal was actually demonstrated.⁵

The fusion power is determined not by the requirements for steady state, but by the pulse rep rate f_p . Since the reactor volume is relatively small, the average power must be kept low to allow for regeneration of conditions for subsequent pulses. The higher the f_p , the greater the output power. Another advantage of pulsed fusion is that the power can thus be modulated to fit demand. Since the output power during the burn is the same regardless of pulse rate, there is no problem operating at a lower fusion power output as there is with steady-state approaches. Since the reactor lifetime is determined by the total accumulated burn time, there is no significant penalty from a low rep rate, since the lower the pulse rate, the longer the reactor lifetime. The linear pulsed system described here is geometrically and topologically simple, so that replacement costs of reactor facing materials will be much lower as well. A small radius device has a much better absorbing surface to fusion volume ratio as well. The FRC allows for a moving fusion burn that can also 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 only 10 Hz would produce 70 MW of fusion power. With the burn time of 0.5 msec, the “duty cycle” for this reactor is only a small fraction of the time between pulses ($\sim 0.5\%$).

Accelerator

The energy necessary for burn is transferred to the FRC in the form of translational energy, which is produced by a propagating magnetic wave accelerator⁶. The simplicity of this approach

to fusion heating lies in the fact that the directed energy of the FRC mass, E_d is much greater than the FRC internal energy, E_i . Since E_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 ($\sim 0.5 - 1$ T). This leads to a large simplification in acceleration coil construction as well as stored energy requirements for the accelerator. The conversion of the FRC directed energy into thermal energy occurs only after the FRC has reached the burn chamber where the FRC is slowed and compressed to fusion conditions in the steady field of the superconducting magnets (see Fig. 2). With 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:

$$v_{\text{FRC}} = (5kT / m_{\text{DT}})^{1/2} \sim 1 \times 10^6 \text{ m/s} \quad (3)$$

where the factor 5 represents the additional energy needed for compressing the burn chamber flux. For an acceleration a of $2 \times 10^{10} \text{ m/s}^2$ (in the range of that achieved in current experiments) the accelerator length, $L_{\text{acc}} = v_{\text{FRC}}^2 / 2a \sim 25 \text{ m}$ with the time for acceleration $\tau_a \sim 50 \mu\text{sec}$. The FRC emerges from the burn chamber into an expansion chamber, which has a much weaker magnetic guide field to maintain the magnetic plasma-vacuum insulation.

The conversion of translational to thermal energy upon deceleration and compression of the FRC into the burn chamber is based on what has been routinely observed in FRC translation experiments, where the FRC was translated out of the source, and brought to rest in an external magnetic mirror⁷. In these experiments, as the FRC came to rest, the ion thermal energy ($3/2 nkT_i$) was observed to increase in the same amount as the translational energy was decreased.

Expansion Chamber

Significant improvements in power conversion mass and efficiency can be realized with the FRC fusion system over other toroidal devices like the tokamak, again due to the unique nature of the compact toroidal geometry of the FRC. With the translatable FRC, after fusion burn, the fusion heated plasma can be ejected into a much larger chamber filled with smaller vacuum magnetic field. This field is then driven radially outward by the expanding FRC. With the appropriate circuit, this flux compression/expansion can produce a large voltage across a conductor (and capacitor) surrounding the expansion chamber. This emf driven by the plasma expansion allows for a direct conversion of the plasma thermal energy into electrically stored energy. There is little if any loss in this conversion process as the plasma has only an electromagnetic interaction with the circuit. This type of conversion can potentially yield much high power conversion efficiencies than can be obtained from a thermal cycle conversion ($\sim 35\%$). Thermal conversion is the only option for virtually all other fusion devices (magnetic, inertial), where the plasmas must remain where they were generated, deep within the confinement system.

Source plasma

The FRC plasma required in the source can be obtained from the adiabatic scaling laws found in Fig. 4. All basic parameters can be determined from the ratio of the reactor field to the source field which was set to 28. It can be seen that the FRC parameters are in the range of those

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

Burn Chamber		\Rightarrow	Accelerator-Source	
B_e	28 T	\Rightarrow	1 T (0.64 T vac)	
T	10 keV	\Rightarrow	700 eV	
n_0	$2 \times 10^{23} \text{ m}^{-3}$	\Rightarrow	$3.7 \times 10^{21} \text{ m}^{-3}$	
r_s	0.028 m	\Rightarrow	0.15 m	
ε	20	\Rightarrow	7	
l_s	1.1 m	\Rightarrow	1.1 m	
τ_N	500 μsec	\Rightarrow	850 μsec	

Figure 4. Source parameters determined by adiabatic scaling from reactor parameters.

obtainable in a conventional FRC. The size of the formation coil would be similar to the FRX-C experiment that was operated at the Los Alamos National Laboratory. The 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.

SUMMARY

The high density plasma fusion reactor outlined here provides for a technologically appealing method for extracting energy from the fusion products, as well as possible direct energy conversion of the fusion heated plasma. The formation regime required for source FRC is in a range that is achievable with conventional field-reversed θ -pinch technology. Efficient acceleration of FRC has been demonstrated ($a > 10^{10} \text{ m/s}^2$), and thermal conversion of translational energy without loss of confinement has been realized as well. The FRC parameters needed for PHD at no time exceed the empirical or theoretical regime where stability and good confinement have already been observed.

Another advantage of small scale pulsed fusion as outlined here is that the development should not require significant time or cost. The technologies involved in all aspects of the concept have been developed to the point that rapid testing and development are possible. A proof of principle experiment that would establish plasma confinement and temperatures near fusion level conditions, would be the next step and could be accomplished in a few years. If successful, a breakeven fusion experiment could be performed in a similar time frame.

REFERENCES

- [1]. J. T. Slough, “*Propulsion based on a pulsed high density fusion plasmoid*”, AIAA 2000-3364, July 2000.
- [2]. A.L. Hoffman, J.T. Slough, "*FRC Lifetime Scaling Based on Measurements from the Large s Experiment (LSX)*", Nuclear Fusion **33**, 23 (1993).
- [3]. D.C. Barnes, “*Stability of long field-reversed configurations*”, Phys. Plasmas **9**, 560 (2002).
- [4]. A.E. Robson, “*A conceptual LINUS fusion reactor*”, Transactions of the American Nuclear Society, **27**, 45 (1977).
- [5] P.J. Turchi, A.L. Cooper, R. Ford, and D.J. Jenkins, “*Rotational Stabilization of an Imploding Liquid Cylinder*”, Phys. Rev. Lett., **36**, 1546 (1976).
- [6]. J.T. Slough, “*Rapid Manned Mars Mission With a Propagating Magnetic Wave Plasma Accelerator*”, NASA Institute for Advanced Concepts, Final Report (2000), www.niac.usra.edu
- [7]. H. Himura, S. Okada, S. Sugimoto, and S. Goto, “*Rethermalization of a Field-Reversed Configuration Plasma in Translation Experiments*”, Physics of Plasmas **2**, 191, (1995).