Quasi-steady Fusion Reactor based on the Pulsed High Density FRC

Reactor Embodiment and merits of particular approach

The threshold size of a steady state fusion reactor required to achieve ignition, and offer a safe protective shielding will be quite large. Unlike fission, where the first commercial reactor was 50 MW, a DEMO reactor must start operation at multi-gigawatt powers. A Quasi-Steady Fusion reactor (QSFR) based on the FRC provides for a method to significantly reduce the reactor size and thus the associated risk and development time of fusion as an energy source. Quasi-steady here refers to the repetitive regeneration of the fusion plasma with a suitably chosen duty cycle. For a reciprocating burn with a low duty cycle, wall loading can be varied for optimum power loading, and wall erosion can be minimized while maximizing the reactor power density in the blanket. Most importantly, the need for sustainment and auxiliary heating systems, including current drive, are eliminated, which tremendously simplifies reactor operation. With transient burn, the vacuum boundary is much easier to maintain as recycling, fueling and wall gas issues are much easier to handle. Tritium co-deposition, the dominant retention mechanism, is minimized as the tritium residence time in the reactor is only momentary.

The efficiency of the formation and heating mechanism employed to achieve fusion conditions is critical to a QSFR. In this regard the magneto-kinetic acceleration, translation and compression of the FRC plasmoid provide a unique path to achieve the necessary high efficiency and simplicity. The plasmoid accelerator magnetic field and power requirements are modest. A suitably high duty cycle and accelerator component lifetime can be obtained using existing solid state switch technology. A schematic of the Q~1 QSFR based on this approach is found in Fig. 1.

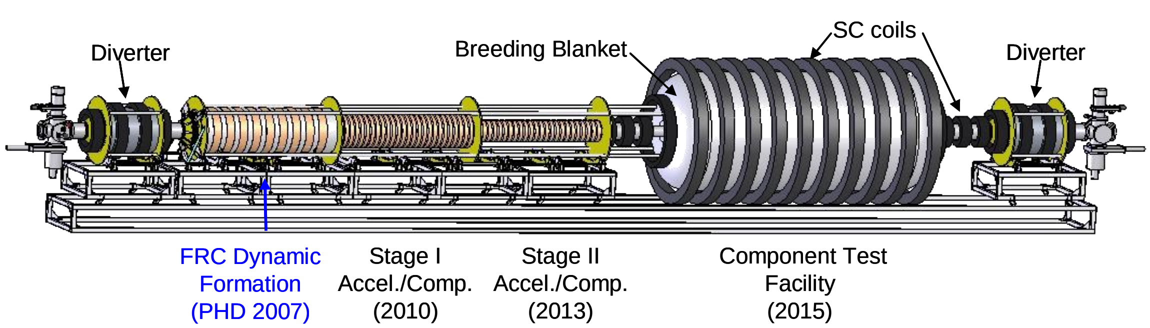

Figure 1. FRC QSFR employing magneto-kinetic heating to fusion temperatures. Kinetic energy is transferred to the FRC from array of axially sequenced low field coils and thermalized by self compression into high field burn chamber

The unique ability of the FRC plasmoid to be translated over distances of several meters allows for the FRC formation and kinetic energy input for fusion burn to be accomplished outside of the burn chamber and breeding blanket. The diverter region can also be well removed from the reactor, eliminating the critical power loading issues faced in tokamaks.

Tritium flow should be significantly improved in this reactor embodiment. The entire high field reactor vacuum flux is external to FRC plasmoid flux and is thus effectively diverter flux. In a transient burn, the tritium particle loss from the FRC will be overwhelmingly directed to the diverter regions as the axial flow time is many orders of magnitude smaller than the perpendicular particle diffusion time in the open flux region. By virtue of the cyclic nature of the burn, virtually all of the tritium can be introduced during the initial formation of the FRC plasmoid with no need for refueling. All tritium introduced can be conveniently recovered in the diverters with each pulse. The ability to access the diverter remotely in an essentially neutron free environment makes prospects for near unity tritium recovery much more feasible.

The confinement scaling, on which the QSFR is based, was derived from the confinement with size and density observed in past FRC experiments [1] employing pulsed, high density formation techniques. Culminating with the LSX experiment, pulsed high density (PHD) FRC formation has produced by far the highest Lawson triple product for the FRC. The Lawson plot shown in Fig. 2, taken from the 2007 FESAC report, illustrates the significant results obtained with PHD FRCs and the anticipated outcome for the continued development described here.

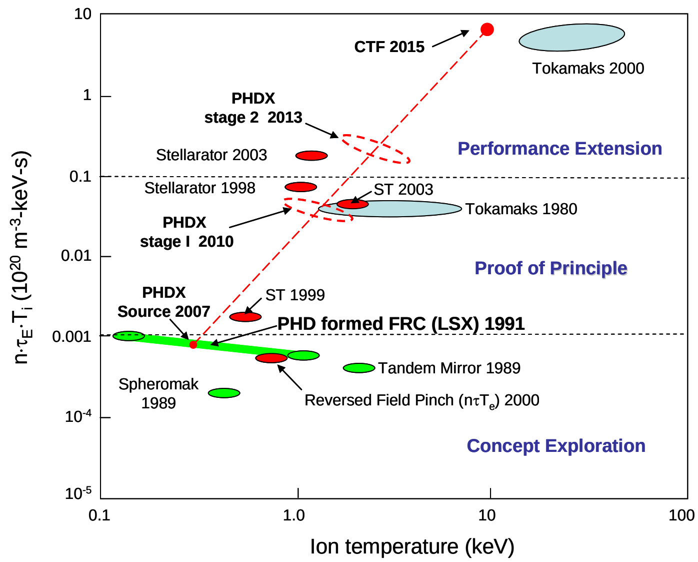

Figure 2. Lawson plot for alternate toroidal systems. Green indicates results obtained prior to the termination of alternate concepts in 1990. Dashed trajectory represents adiabatic compression of an LSX scale FRC assuming the confinement scaling derived on past results from FRCs employing pulsed formation.

To this end an experiment was initiated in 2004 to reestablish a facility capable of achieving the confinement parameters attained in LSX, but in a manner consistent with the subsequent acceleration and adiabatic compression of the FRC plasmoid to fusion burn. It is referred to as the PHDX experiment (see Fig. 3). PHDX is a staged program designed to explore magneto-kinetic compression of the FRC. In 2007 the PHDX experiment produced an FRC plasmoid on the LSX scale and accomplished the first milestone of creating the initial parameters required for a Q ~ 1 fusion burn [2]. It is believed that with the existing large source, combined with dynamic formation and acceleration the necessary flux, density, and temperature for fusion gain in the reactor regime can be achieved. A table with the anticipated parameters at each stage is found in Table I.

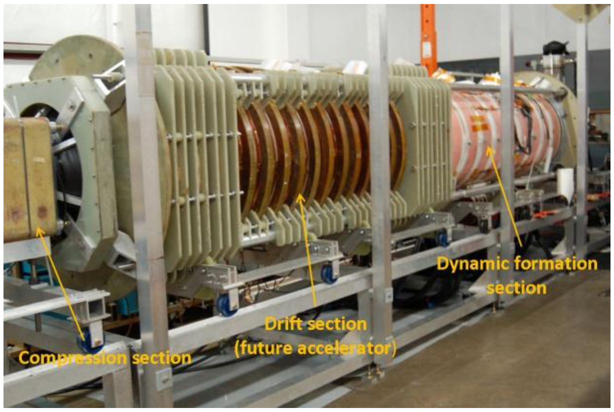

Fig. 3 Current PHDX Experiment constructed with refurbished components from the original LSX device.

Scientific Issues

As mentioned, the values reflected in Table I are based on previous PHD FRC formation results assuming particle confinement was the most significant determinant of FRC lifetime in a pulsed burn. This past scaling exhibited the following dependence: $\tau_N = 3.2\text{x}10^{-15}\, \varepsilon^{0.5}\, x_s^{0.8}\, r_s^{2.1}\, n^{0.6}$

stated in terms of externally measured parameters: FRC elongation - $\varepsilon = l_s/2r_s$, separatrix to coil ratio – $x_s = r_s/r_c$, FRC separatrix – r_s , and density – n. This scaling is empirical but closely follows the edge driven transport scaling predicted for lower hybrid drift turbulence ($\tau_N \sim r_s^2/\rho_i$) for a β ~1 plasma. There is no reason to believe that the scaling will change as the FRC plasmoid is heated and compressed, yet it is clearly something that needs to be established. This would be accomplished experimentally by decelerating and compressing the FRC after each stage. In fact, current experiments on PHDX are aimed at evaluation of the FRC confinement parameters following dynamic formation (see Fig. 3).

Table I

PHDX Source	Stage I	Stage II	CTF
R_{wall} = 0.4 m	0.28	0.2	0.15 – 0.1
n ~ 10^{21} m^{-3}	4×10^{21}	10^{22}	1.1×10^{23}
T_i ~ 0.3-0.4 keV	1 keV	2 keV	8 keV
T_e ~ 100 eV	150 eV	250 eV	1 keV
B_{vac} ~ 0.3 T	0.9	2	15
V_{FRC} > 200km/s	400	800	~ 4

FRC parameters at various stages of development.

One must also consider the issue of the rapid acceleration and subsequent compression of the FRC plasmoid. These processes must not destroy the configuration or negatively affect transport. There is encouraging evidence from current experiments that this should not be an issue. A device similar to that envisioned in Fig. 1 but at one quarter the scale was constructed and operated, and is referred to as the Inductive Plasma Accelerator (IPA). A picture of the IPA device is shown in Fig. 4. As can be seen, two accelerators were employed. Two FRCs were each simultaneously formed and accelerated to

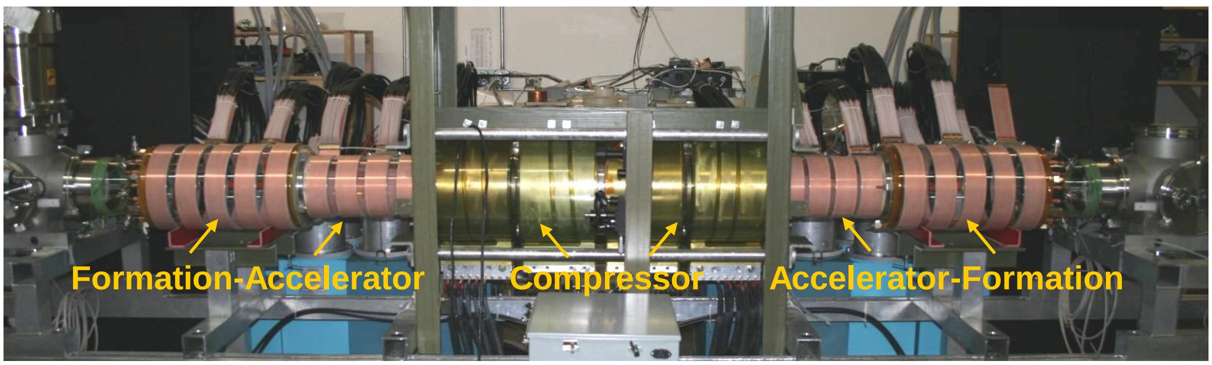

Figure 4. Current Inductive Plasma Accelerator (IPA) Experiment with compression

Mach 3. They then merged forming a stable, hot (500 eV) FRC with essentially all of the kinetic energy input thermalized in the ions [3]. The merged FRC was then simultaneously compressed to over 1 keV and exhibited a lifetime consistent with past FRC scaling. This compression was very modest (B ~ 1 T) limited by the available bank energy. The current effort is aimed at increasing this compression several fold, but the key finding was that FRCs can be accelerated at a rate of 4.6×10^{10} m/s^2 without loss of stability or confinement. The deceleration in merging was several times higher so the PHD FRC is indeed a robust entity.

The other major scientific question concerns the stability of the FRC as one scales to larger size. The configuration is unstable in the MHD regime where the ion gyroradius ρ_i is small compared to the plasma radius. It is believed that the FRC remained stable in past studies due to kinetic effects from the hot ions generated with PHD formation. The parameter "s" has been used to characterize this regime and is defined as

$$s = \frac{1}{r_s}\int_{null}^{r_s} \frac{r}{\rho_i}\,dr \;=\; \frac{\varphi_p}{2\pi r_s B_e \rho_{ie}} \;\sim\; 6.7\,\frac{\varphi_p}{r_s} \quad (\text{for } T_T \sim 9 \text{ keV})$$

Since the FRC closed poloidal flux, φ_p scales as r_s^2, it can be seen that small s requires small size even at fusion temperatures. Also in past experiments it was found that the more prolate the FRC, the larger the s value before a marked deterioration in confinement was observed. FRCs formed with s/ε values less than 0.5 displayed good confinement. Compression will increase the FRC elongation to ~ 20, but the observed threshold based on confinement effectively limits the FRC flux to 75 mWb or less. A flux of 25 mWb is sufficient for a Q ~ 1 fusion burn for the PHD QSFR, and well within the stability and good confinement regime. For higher Q fusion burn, more flux would be required to extend the burn time. For Q > 3 either better confinement scaling must be obtained, or a means for achieving stability at higher flux must be found. It is thought that the kinetic contribution from the helium ash may enhance FRC stability, and allow for higher flux operation. There is reason to believe that the dynamically formed translated FRC has enhanced confinement over the in situ formed FRCs used in the scaling [4]. Significant toroidal flux generation is thought to occur during dynamic formation which has been shown to stabilize rotational modes [5]. Future experiments will tell. However the true value of the FRC based QSFR may not necessarily come from the production of heat from fusion neutrons. Operation as a component test facility for a fusion DEMO, or more notably as a fissile/fusile fuel breeder, a low Q device will be sufficient and possibly even desirable.

Technical Issues

As mentioned, the key to a QSFR is the ability to efficiently heat the FRC plasmoid to fusion conditions. The heating mechanism relies on the acceleration and self compression of the FRC. The technologies for the acceleration have been developed and tested in both the IPA and PHDX experiments. The accelerator interaction with the plasmoid is principally through the Lorentz body force acting on the induced currents in the FRC as it passes through each accelerator coil. During acceleration and compression, the only important losses are ohmic losses in the coils and external circuit elements. There is good news here due to the revolution that is occurring in the field of pulse power electronics. With the introduction of high power solid state devices one no longer needs to resort to old spark gap and ignitron technologies for energy transfer. The technology now exists to operate the accelerator at the voltages and currents desired in a repetitive mode at rate up to 60 Hz with devices capable of operating for decades at high efficiency [6]. With recuperative techniques it is believed that the accelerator electrical to plasma kinetic energy efficiency can be 80 to 90% [7].

The superconducting magnet technology appears to be at hand with the demonstration of a large bore cylindrical, superconducting coil at high field (1.4 m diam., 13 T) [8]. For the FRC based QSFR, with the smallest reactor+blanket cross section and simple linear geometry, extending these results to achieve the target field (15 T) and bore (~ 2 m) should not be difficult. An even higher field would be desirable as the fusion gain Q ~ $B^{2.15}$ with the PHD FRC scaling. In any case, it should be possible to perform all experiments leading up to the final QSFR with conventional resistive coils so that the SC magnet technology is only required at the end.

Since the fusion power density scales as $\beta^2 B^4$, an FRC based QSFR will operate at the highest optimal level. The anticipated FRC plasmoid energy is 1-2 MJ in the burn chamber. It is expected that the FRC will drift axially along ~ 5 m of reactor blanket during the millisecond burn time for Q ~ 1. Maintaining an average power of 20 MW (10-20 Hz) the average wall neutron loading would be ~ 3-6 MW/m^2, depending on the reactor inner wall radius. The loading can be reduced (increased) by more (less) drift or lower (higher) duty cycle. The same would be true at higher Q. It can be seen that the FRC QSFR offers the possibility of entirely different reactor power regime and range of application for fusion power. This level of power is particularly well suited for applications such as fissile fuel breeding, as well as space-based applications.

In addition to much lower reactor costs, the quasi-steady approach greatly reduces the cost of research as single pulses will suffice for exploring the physics, transport, dynamic behavior and scaling of the PHD FRC.

Several reactor issues will be the same as other toroidal devices, i.e. self sufficiency in tritium breeding, plasma facing components, remote handling, etc. As described earlier, all of these issues become much more tractable due to reduced scale, low duty cycle, and geometric simplicity.

Complementary Applications

There are other non-fusion electric applications for which the FRC based QSFR is well suited. Several relate to the themes and issues presented in the 2007 FESAC report, and will be so indicated.

Deep fueling, momentum source and profile modification

(Theme A: 6. Plasma Modification by Auxiliary Systems)

Current conventional fueling methods have not demonstrated successful fueling of advanced tokamaks, and may not be able to adequately deep fuel ITER. In present experiments neutral beams are used for fueling, which provides a source of toroidal momentum input in high performance discharges. By fueling with tangentially injected beams momentum is transferred to the plasma, which heats the plasma and also provides for plasma rotation. In a reactor there will no longer be a mechanism for rotational velocity shear as a neutral beam based core fueling system is not practical or economical. Without new methods, present fueling systems may be incapable of satisfying the fueling requirements of steady-state discharges that rely on high fractions of bootstrap current. Fueling with PHD FRC plasmoids has the potential to meet these needs, while simultaneously providing a source of toroidal momentum input. The PHD FRC plasmoid has several aspects that make it superior for fueling. The FRC has the maximum plasma content for a given magnetic energy (highest β), and the plasma radius can be maintained far from the injector (accelerator) wall. This improves acceleration efficiency, enhances the plasma purity, and minimizes excess neutral gas hindrance in rep rated operation. Repetitive operation of the power delivery system for an FRC based IPA at high frequency (10 kHz) has been demonstrated [7].

Development of the PHD FRC as a Component Test Facility (CTF)

The QSFR burn chamber would offer a unique opportunity to provide a volumetric neutron source of 14.1 MeV neutrons. The simple linear geometry and easy access would prove an ideal test bed for various wall materials, tritium breeding blankets, and magnets. It could likely become an integral component of several initiatives as a Component Test Facility (CTF) and would contribute to - Theme B: 8. Plasma-Wall Interactions, and 9. Plasma Facing Components, and Theme C: 11. Fusion Fuel Cycle 12. Power Extraction and 13. Materials Science in the Fusion Environment. It could also be effectively employed in the following initiatives:

I-4. Integrated experiment for plasma wall interactions and plasma facing components

I-5. Advanced experiment in disruption-free concepts

I-7. Materials qualification facility

I-8. Component development and testing program

I-9. Component qualification facility

Neutron source for fissile and fusile fuel breeding

FRC plasmoid fusion, as presented here, has the unique attribute of maintaining critical formation, heating and diverter systems physically far from high neutron fluence and blanket energetics. This key feature greatly mitigates many of the difficult design issues associated with a fusion/fission hybrid system, and is critical to the applications considered here. In addition, the capability of generating a small, intense source of high energy neutrons makes it well suited for use as a nuclear fuel breeder. With projected production costs of over $100M/kg, the need for an alternate source of tritium is obvious. For there to be any growth in fusion energy production, tritium self sufficiency is not enough. Tritium breeding will be essential. Having no need for large structural elements in the cylindrical blanket, parasitic neutron absorption will be minimal. The small source size and the relatively large extended blanket geometry make for near unity blanket coverage so that a TBR significantly greater than one is feasible.

These advantages also apply to fissile fuel breeding, in particular the enabling of an alternate fuel cycle based on thorium. Unlike uranium, thorium is not fissile and can not be used for weapons manufacture. When enabled by an external source of neutrons, thorium can be burned without generating the long-lived high level waste characteristic of the uranium cycle. While all conventional PWR reactors can burn the activated thorium, a symbiotic linking with a molten salt breeder provides for an even more attractive nuclear option. By co-locating a molten salt reactor with FRC QSFRs, a waste mitigating closed nuclear cycle is achieved that is highly proliferation resistant. Only non-fissile material enters the plant in the form of thorium. All fuel for the reactor is produced on-site by the FRC QSFR. Only a relatively small fusion power source is required (~ 7% of the fission reactor output) as it is leveraged by the much larger energy yield from the fissile fuel enriched thorium reactor. The fissile fuel doubling time can be as short as 5 years, and essentially all the thorium can be consumed in fission reactions, thus extending the energy reserves from thorium to several thousand years, limited only by the lithium reserves required for DT fusion [9]. Waste from the thorium cycle is orders of magnitude smaller than that of a current PWR, and decays to background levels in less than 500 years – only slightly longer than that from fusion neutron activation. By using the FRC QSFR to enable a thorium based energy cycle, nuclear power can finally deliver what the current uranium based fission can not: abundant, safe, and clean energy. Most importantly, it can be done in a timeframe to allow fusion to play a role in the effort to move from a carbon based energy economy.

References;

[1] A. L. Hoffman and J. T. Slough, Nucl. Fusion **33**, 27 (1993).
[2]. John Slough, Samuel Andreason, Hiroshi Gota Chris Pihl, "Dynamic Formation of FRCs on the PHD Experiment", Bull Am. Phys. Soc., 49th Annual Meeting of the Division of Plasma Physics, November 12–16, 2007; Orlando, Florida.
[3]. G. Votroubek, J. Slough, S. Andreason and C. Pihl, "Formation of a Stable Field Reversed Configuration through Merging", Journal of Fusion Energy, **27**, 123 (2008)
[4] H.Y. Guo, A. L. Hoffman, L. C. Steinhauer, and K. E. Miller, "Observations of Improved Stability and Confinement in a High-β Self-Organized Spherical-Torus-Like Field-Reversed Configuration", Phys. Rev. Lett. **95,** 175001 (2005)
[5] R. D. Milroy and L. C. Steinhauer, "Toroidal field stabilization of the rotational instability in field-reversed configurations", Physics of Plasmas, **15**, 022508 (2008).
[6] H. Sanders and S. Glidden, "High Power Solid State Switch Module", 2004 IEEE Power Modulator Conference, San Francisco, CA, May 23-26, 2004.
[7] John Slough, Arthur Blair, Chris Pihl, and George Votroubek, "Magnetically Accelerated Plasmoid (MAP) Thruster – Initial Results and Future Plans", IEPC-2007-16, 30th International Electric Propulsion Conference, Florence, Italy, September 17-20, 2007
[8] Norikiyo Koizumi, Takao Takeuchi and Kiyoshi Okuno, "Development of advanced Nb3Al superconductors for a fusion demo plant", Nuclear Fusion **45**, 431 (2005).
[9] Wallace Manheimer, "Can Fusion and Fission Breeding Help Civilization Survive?", Journal of Fusion Energy **25**, 121 (2006).