Development of a high fluence fusion neutron source and component test facility based on the magneto-kinetic compression of FRCs

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There are several major technological challenges that must be met before fusion can be considered for commercial energy generation. The long term, steady operation of the fusion device is certainly one of the most challenging. Key to achieving reliable operation is a thorough understanding of the behavior of the various reactor components under long term exposure to the fusion process. The patent issue of neutron damage is an obvious one, but equally important questions concern the effects of plasma radiation, particle flux, and tritium deposition. While it may be possible to test the various aspects of the fusion system with substitute sources such as neutron spallation, the ideal component test facility (CTF) would have the capability to address and examine all of these issues by employing a fusion grade plasma, but on a scale and cost far less than the actual fusion reactor itself. It is believed that such a CTF can be developed based on recent experimental results involving the magneto-kinetic compression of the Field Reversed Configuration (FRC). A CTF based on the FRC provides for a method to significantly reduce the test reactor size (4 liter reacting volume vs 450,000 for ITER) and thus the associated risk and development time.

Since fusion power density scales as β^2B^4, a small scale fusion source would ideally operate in a regime with the highest possible β and maximum practical field. It would also be desirable that the fusion plasma not be encumbered by a complex confinement geometry, and where the diverter can be located outside the test chamber blanket providing easy access for materials testing and tritium recovery studies. All of these attributes are found in the FRC-based CTF described here. The FRC is the geometrically simplest, most compact, and highest β of all magnetic confinement schemes. The simply connected nature of the magnetic field with regard to the containment vessel and the linear confinement geometry allow for the translation of the FRC over large distances, and simple compression to high energy density. The maximum plasma

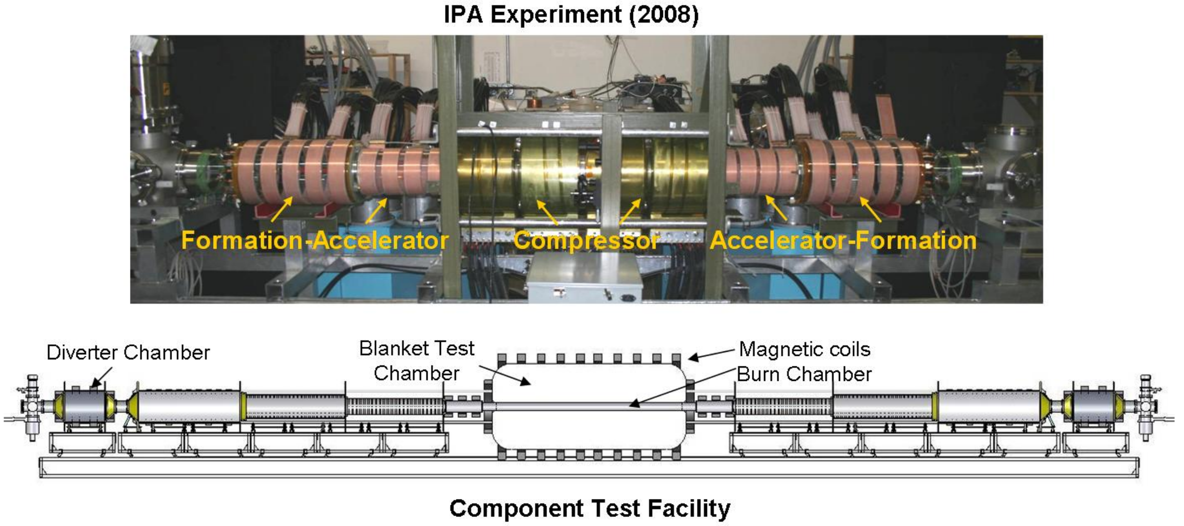

Figure 1. Proof of concept for the generation of fusion energy was demonstrated in the IPA experiments. A picture of the device is shown above. Shown below is a CAD rendering of the application on a scale, and in a manner sufficient to produce energy directly from fusion. (The blanket test chamber is a meter in radius with a length of 5 m).

(magnetic) pressure for the CTF is bounded by an upper limit imposed material strength limitations. The cylindrical coil geometry aids in this regard, and an axial magnetic field that remains below 15 T is employed so that long term repetitive pulsing can be accomplished without damage to the magnet or other systems.

This high energy density regime can be reached through a natural extension of past FRC experiments. The device that was designed and built to demonstrate this capability is referred to as the Inductive Plasmoid Accelerator (IPA) and is illustrated in Fig. 1 along with a schematic of the scale up required for use as a CTF. In experiments on IPA two FRCs were each simultaneously formed and accelerated to Mach 3. They then collided and merged forming a stable, stationary FRC with essentially all of the kinetic energy input thermalized in the ions [1]. The merged FRC was then simultaneously compressed to over 1 keV and exhibited a confinement time considerably better than that inferred from past FRC scaling. The compression field in these initial experiments was very modest ($B \sim 1.3$ T) as it was limited by the available bank energy. 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 demonstrating that the FRC is indeed a robust entity.

A fusion neutron source based on the pulsed formation, acceleration and compression of the FRC in a high density burn has several advantages. The FRC plasma need not be heated to fusion temperatures on Alfvenic timescales, and it need not burn amidst the pulse power apparatus employed for formation and acceleration. Translatability proves to be a key advantage as it provides for a simple way to introduce the FRC plasmoid into the test blanket chamber and bring the FRC to fusion conditions. The energy needed to achieve fusion conditions is transferred to the FRC plasmoid via simple, relatively low field acceleration/compression coils. By operating in a compact, high density regime, the requirement on the FRC closed poloidal flux is no greater than what has already been achieved. Most importantly, the FRC remains in a stable regime with regard to MHD modes such as the tilt from formation through burn

The efficiency of the plasma formation and heating mechanism employed to achieve fusion conditions is critical when employing a pulsed device as a CTF. In this regard the magneto-kinetic acceleration and compression of the FRC plasmoid should provide a simple path to achieve the necessary high efficiency and repeatability. The FRC plasmoid accelerator magnetic field and power requirements are modest. It is believed that a suitably high duty cycle as well as accelerator component lifetime can be obtained using existing solid state switch technology. Most importantly, the need for sustainment and auxiliary heating systems, including current drive, are eliminated, which tremendously simplifies CTF operation. With transient burn, the vacuum boundary is much easier to maintain as recycling, fueling and wall gas issues are greatly simplified. The entire high field reactor vacuum flux is external to FRC plasmoid flux making it 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. Tritium co-deposition is thus be minimized if not eliminated. The diverter region is well removed from the burn chamber and outside the blanket making tritium recovery, diverter material change-out and maintenance much less challenging.

The confinement (burn) time on which the CTF fusion neutron yield is based, was derived from the confinement with size and density observed in past FRC experiments [2]. The FRC decays on a resistive time scale that is anomalous. The observed particle confinement, stated in terms of directly measured quantities that can be accurately measured across all experiments yields the following scaling: $\tau_N = 3.2\text{x}10^{-15}\ \varepsilon^{0.5}\ x_S^{0.8}\ r_S^{2.1}\ n^{0.6}$, where x_s is the ratio of the FRC separatrix radius, r_s to flux conserver radius, r_c, and ε is the FRC separatrix elongation, $l_s/2r_s$. 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 $\beta \sim 1$ plasma. From this expression the neutron yield scaling can be stated in terms of parameters more relevant to the IPA concept, that being the FRC plasma energy E_p acquired from acceleration, and compression and the burn chamber magnetic field B:

$$N_{neut} \cong 2.6\text{x}10^{31} \frac{B^{7/4} E_p^{3/2} \sqrt{\varphi_p}}{r_c^{1/3}} \frac{\langle \sigma v \rangle_{DT}}{T_i^{2.6}} \qquad (1)$$

where the ion temperature is measured in keV, and φ_p is FRC poloidal flux. The $T^{-2.6}$ weighting moves the optimum plasma ion temperature to a temperature somewhat lower (~ 7 keV) than that found for an optimization like the Lawson criterion which is constrained by radiation losses alone. The strong scaling of neutron production with both the plasma energy and magnetic field make a fusion driven system based on the FRC plasmoid far more advantageous than other approaches of neutron generation such as neutron spallation where the neutron yield scales only with the energy of the proton beam at best.

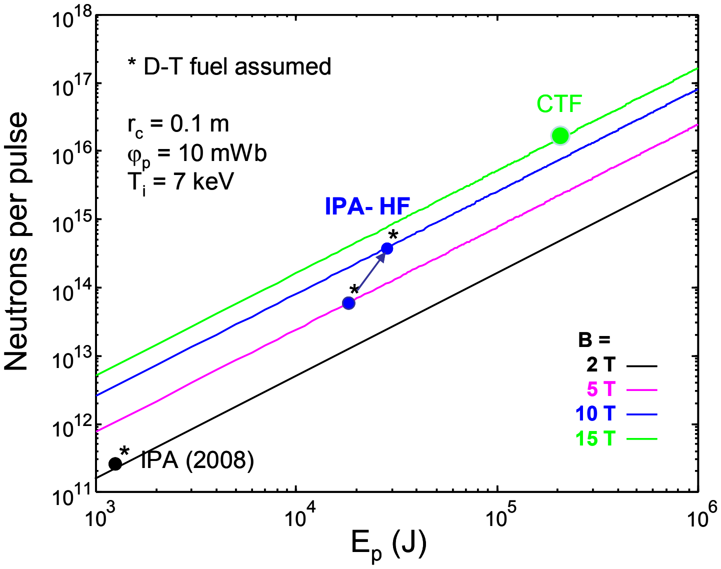

Figure 2. Neutron Yield based on Eq. (1).

A plot of the neutron yield per pulse as a function of the two key variables can be found in Fig. 2. The IPA (2008) result was actually obtained at T_i ~ 1 keV and φ_p = 1 mWb in deuterium. The data point represents the yield expected if a DT fuel was used. Improvements planned for the current IPA device are to increase the energy of the FRC by an additional stage of acceleration and increase the compression field substantially. With these upgrades, the neutron yield will be increased by over two orders of magnitude. The target yield for the CTF would be obtained by employing a larger source, an additional stage of acceleration, and a somewhat higher magnetic field. This facility can be constructed in less than 2 years. With a parallel development aimed at validating the envisioned repetitive pulse power technology, a prototype CTF could be completed within three years. Given a 20 Hz rep rate, this device would produce an average neutron output of ~ $4\text{x}10^{17}\text{s}^{-1}$, spread over an axial extent of ~ 1 meter depending on the FRC post merging length. This would represent a wall loading of 1.6 MW/m^2 at the burn chamber wall. Higher loading can be obtained by increasing E_p, B, or φ_p.

[1]. 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)
[2] A. L. Hoffman and J. T. Slough, Nucl. Fusion **33**, 27 (1993).