Fusion Neutron Test Facility

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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 obvious issue of neutron damage is clearly the primary 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, the ideal component test facility would have the capability to address and examine all of these issues in the most accurate manner by employing a D-T fusion plasma. As was pointed out in the recent Research Needs Workshop (ReNeW) on harnessing fusion power, the top level issue for materials development was to understand the basic materials science for fusion breeding blankets, structural components, plasma diagnostics and heating components in high neutron fluence areas. In particular, the material damage incurred by the 14.1 MeV neutron flux from the D-T fusion reaction creates additional materials challenges that would not be as apparent with testing using surrogate lower energy fission neutrons. An intense, high energy neutron source is an essential element for adequate materials assessment. The importance of this task is indicated by the international effort to obtain an intense neutron source at significant cost such as the large beam-target facility known as IFMIF (the International Fusion Materials Irradiation Facility). Even large volume neutron sources based on advanced compact tokamaks have been considered.

The challenge of course is to accomplish this on the smallest appropriate scale and at a price and development time scale far less than the actual fusion reactor itself. A Fusion Neutron Source (FNS) based on the magneto-kinetic compression of the Field Reversed Configuration (FRC)[1] appears to have the necessary properties to provide for a small scale fusion plasma with the necessary radiation intensity (see Fig. 1). The dramatic increase in fusion neutron yield along with a simultaneous reduction in reacting plasma volume is accomplished by a straight forward magnetic flux compression of an FRC plasmoid. The requisite FRC plasma need be no different than those that have been commonly produced in past experiments, and the required magnetic compression field and plasma energy is less than 12 T and 1MJ respectively. Employing the FRC in this way in a repetitive manner yields an intense fusion neutron source where the test reactor size is only a tiny fraction of the tokamak reactor scale plasma (10 liters of reacting volume vs. > 1,000,000 liters for ITER). This reduction in volume is accompanied by drastic reductions in the associated costs, complexity, risk and development time.

The FRC formation methodology that makes such a simple arrangement possible was recently developed at MSNW on the Inductive Plasma Accelerator (IPA) device.[2] In these experiments two FRCs were each simultaneously formed and accelerated to supersonic velocity (Mach 3). The FRCs then collided and merged forming a stable, stationary FRC with essentially all of the kinetic energy input thermalized in the ions due to their much larger mass. The merged

[1]John Slough, *"FRC Based Fusion Neutron Source for Materials Evaluation"*, Fus. Sci. and Techn., **60**, 464 (2011).
[2]J. Slough, G. Votroubek, C. Pihl, "*Creation of a Stationary*, *Hot Plasma through Merging of Supersonic Field Reversed Configuration Plasmoids"*, Nuclear Fusion **51**, 053008 (2011)

FRC was then compressed to high density ($4x10^{21}$ m^{-3}) and temperature (1.3 keV) while exhibiting a configuration lifetime better than that inferred from past FRC scaling.

There are several advantages to employing the FRC as the fusion neutron source. Since fusion power density scales as β^2B^4, a small scale fusion source will optimize in a regime with the highest possible β and at the maximum practical confining field. The FRC is the geometrically simplest, most compact, and highest β ($<\beta>_{FRC}$ ~ 0.9) of all magnetic confinement schemes. It is also desirable that the fusion plasma not be additionally encumbered by a complex confinement geometry. The simply connected nature of the FRC magnetic field with regard to the containment vessel and the linear confinement geometry allow for the translation of the FRC over large distances. The compression to high energy density can then be performed inside a simple, small cylindrical coil set that is specifically constructed for pulsed, high magnetic compression fields. Operation with tritium will necessitate recovery of unused fuel. A very large divertor region can be located at each end of the FRC based Fusion Neutron Source (FNS), well removed from the compression (fusion) region thereby eliminating critical power loading issues while providing easy access for both pump out and divertor materials testing. As a result, tritium recovery is considerably simplified as the divertor is located outside the burn region and can be scaled to any size deemed necessary. The tritium required per pulse is also quite modest at less than a milligram. An illustration of a prototype FRC based FNS device is depicted in Fig. 1.

As can be seen, the entire high field reactor vacuum flux is external to FRC plasmoid flux and is thus essentially divertor flux. In a transient burn, the particle loss from the FRC will be overwhelmingly directed to the divertor regions as the axial flow time is many orders of magnitude smaller than the perpendicular particle diffusion time across the open flux region. The strong axial gradient magnetic field outside the burn chamber assures that the plasma lost from the FRC is swept into the divertor regions essentially eliminating tritium co-deposition and making the tasks of full tritium recovery and divertor maintenance much easier to carry out.

Materials to be examined in the FNS device are placed in an annular cylindrical sample chamber that can be located axially within the compression coils, and placed radially inside the reactor vacuum wall for plasma facing component (PFC) testing or outside the reactor vacuum wall under the compression coils (see Fig. 1) for neutron exposure only. Samples can be formed from refractory insulative materials such as SiC/SiC, alumina, beryllia, etc., or constructed of structural materials such as the ferritic or duplex steels. The reactor vacuum wall could simply be made from the material to be tested as well. It is possible that change-outs to new vacuum walls and compression coils during the sample's exposure duration may be required. The simply connected, linear geometry of the reactor vessel and compression coils are amenable to rapid and frequent replacement when necessary. The simplicity of the FNS provides for easy removal and retesting with minimum downtime and expense. This is not possible with more complex confinement systems.

For pulsed systems such as the FNS the relevant quantity is the total neutron yield per pulse. The pulse length is determined by the FRC particle confinement. Past FRC experiments indicate a scaling that 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 with further dependences on the FRC elongation $\varepsilon = L_s/2r_s$, and the FRC separatrix to coil radius ratio $x_s = r_s/r_c$, yielding an empirical scaling:

$$\tau_N = 3.2x10^{-15}\ \varepsilon^{0.5}\ x_s^{\ 0.8}\ n^{0.6}\ r_s^{\ 2.1}. \qquad (1)$$

The neutron power per unit wall area in terms of experimentally controllable variables is:

$$\hat{P}_{neu}\left(W/m^2\right) = 1.7x10^4\ B^{15/4} L_s^{1/2}\ \varphi_p^{3/2}\ r_c^{-1/3}\ R_p\ \ , \qquad (2)$$

where R_p is the pulse rate. It is clear that the experimental parameters to maximize are the compression magnetic field magnitude and the FRC poloidal flux. Flux is maximized by forming the FRC in a large chamber. The FNS will employ the same chamber size used in the LSX FRC experiments. The compression field energy is minimized by compressing at the smallest burn chamber volume, which is exactly what is accomplished with the process depicted in Fig. 1. The expected D-T neutron energy per pulse for the parameters of the FNS is 1.4 MJ/m^2. A pulse rate of 1-3 Hz would be sufficient to study neutron wall loading at the reactor level.

The prototype device operating in deuterium at a low pulse rate (R_p ~ 0.01 Hz) is ready for construction with no significant science or engineering challenges. A detailed costing of this facility has been carried out. The proto-FNS device with material diagnostics has a cost of $10 M with a construction time of 1.5 years with full operation by the end of the second year. Roughly $3 M of the necessary equipment is available at the U. of Washington and MSNW. A yearly operating budget of $2 M is sufficient to maintain both the operation of the FNS and staff the material diagnostics. The design and engineering of a rep-rated facility employing tritium would require roughly 2 years and would be performed in parallel with the prototype construction and initial operation. The construction of the full FNS facility would commence once the prototype has been validated for the expected yields and the proper pulse power system has been designed and demonstrated. The total cost of this engineering task is estimated to be $5 M. The full FNS facility is estimated to cost $50-100 M and would likely be constructed at a national laboratory capable of both the tritium handling and activated materials handling such as PNNL.

Proto-FNS Facility - University of Washington and MSNW

This staged approach to the FNS has several advantages. It minimizes risk and provides for a very low cost facility for initial materials testing with a fusion plasma. For example, it is clear that plasma surface interactions during transient events in ITER remain among the most important issues that will determine both the tokamak performance and the lifetime of PFCs. With the operation of ITER, particularly in H-mode at high gain (Q_{DT} = 10), the PFCs will be exposed to intense plasma heat loads from Type I edge localized modes (ELMs) and disruptions. The expected transient energy fluxes on the ITER divertor during the Type I ELMs will be in the range of 0.5–4 MJ/m^2 on timescales of 0.3–0.6 msec. There is scant experimental data concerning materials erosion under transient loads from plasmas similar to those expected in ITER. The FRC divertor plasmas that would be produced in the prototype FNS span virtually all pedestal edge conditions anticipated for ITER during Type I ELMs. These plasma conditions are achieved in the edge region of the FRC plasmoid during the normal decay of the FRC. The FRC plasma exhaust along the axis of symmetry is well suited as a source plasma for divertor studies. The closed field of the FRC is separated from the "open" divertor flux by a separatrix. The plasma lost from the FRC can be guided over several meters axially to a divertor chamber where it is terminated on test surfaces. The energy content of the FRCs to be formed in the proto-FNS can be varied from 40 kJ to 1 MJ, and will be lost primarily in the form of particle flow onto divertor flux as in past large FRC experiments. Based on previous FRC results, the particle confinement time, varies between 0.4 to 1 msec thus providing for a range of power densities from 1.6 to 20 GW/m^2. The power density experienced at the divertor plate can of course be readily adjusted to the range of interest (1.5 GW/m^2 for an ELM with τ = 0.5 ms) by the degree of flux expansion employed in the divertor section. The proto-FNS can also be used to create conditions in the divertor similar to a disruption in ITER. For a disruption, the heat load to the ITER divertor components is anticipated to be about 10–100 MJ/m^2 with a load duration of 1–10 ms. With high flux operation, the FRC lifetime is expected to be greater than 2 ms. With the initial FRC energy of 1 MJ, delivered by particle convection to the diverter plate without significant flux expansion of the plasma jet, a heat load of 170 MJ/m^2 will be deposited over a cross sectional area of 30 cm^2. It should thus be possible to study divertor behavior even under the most extreme conditions anticipated for ITER. The smaller scale of the plasma source and the larger physical separation of the divertor are amenable to both frequent vacuum openings and sample replacements.

The proto-FNS represents the core of an integrated engineering facility that will test and develop materials suitable for fusion devices. Materials samples will be exposed to neutron irradiation and high heat fluxes, and then analyzed using sophisticated in-situ and ex-situ methods. Results will be used to design or modify the material to be used for further testing. This closed-loop approach provides a path to rapidly engineer materials for reactor components that can survive long-term exposure to the fusion process. The facility would provide a cost-effective means for testing and developing materials on the timescale needed, and provide a unique opportunity to contribute to critical ITER issues both with regard to both neutron and transient plasma interactions.

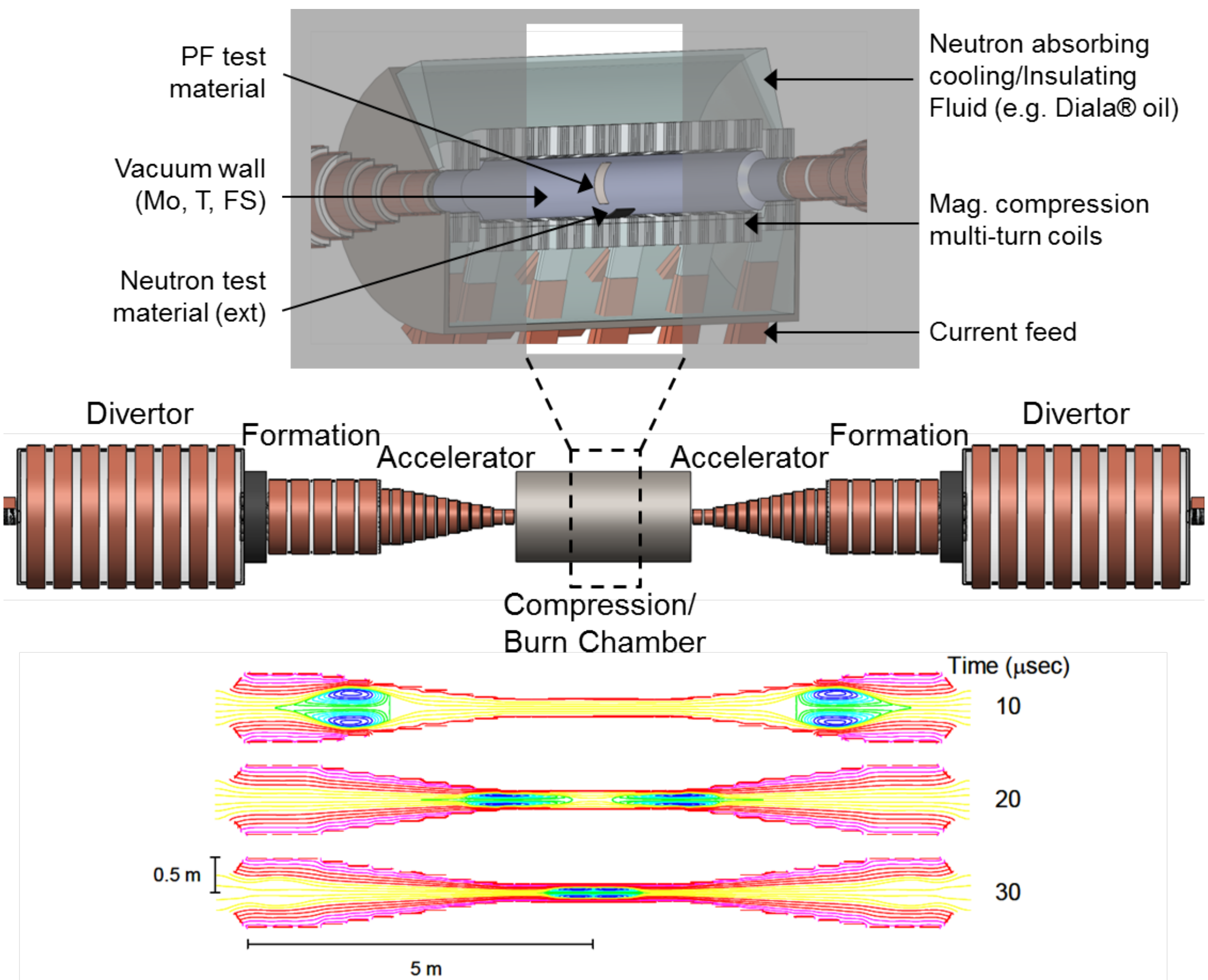

Figure 1. Shown at top is a CAD rendering of the Fusion Neutron Source designed for a compression field and scale sufficient to produce E_{neut} = 1.4 MJ/m^2 at the vacuum wall of the central compression region. The central section is shown in cutaway to illustrate possible sample test locations. Below are flux contours from MHD calculation at various times in the formation, acceleration, merging and compression of the FRC to fusion conditions. Yellow contours indicate SOL to be used in materials studies in the divertor regions.