A Fusion Nuclear Science Facility (FNSF) for a Fast-Track Path to DEMO

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Enabling World-Leading Science

An accelerated fusion energy development program, a "fast-track" approach, requires developing an understanding of fusion nuclear science (FNS) in parallel with research on ITER to study burning plasmas. A Fusion Nuclear Science Facility (FNSF) in parallel with ITER provides the capability to resolve FNS feasibility issues related to power extraction, tritium fuel sustainability, and reliability, and to begin construction of DEMO upon the achievement of $Q \sim 10$ in ITER. Together, these two research programs address the U.S. DOE highest level goals [1] for fusion research in the coming decade: (1) *Advancing our knowledge of plasma dynamics and control in the burning plasma regime*, and (2) *Advancing our knowledge of materials in the fusion environment and harnessing fusion power*.

Fusion nuclear components, including the first wall (FW)/blanket, divertor, heating/fueling systems, etc. are complex *systems* with many inter-related functions and different materials, fluids, and physical interfaces. These in-vessel nuclear components must operate continuously and reliably with: (a) *Plasma exposure*, surface particle & radiation loads, (b) *High energy neutron fluxes* and their interactions in materials (e.g. peaked volumetric heating, tritium production, activation, atomic displacements, gas production, etc.), (c) *Strong magnetic fields* with temporal and spatial variations (electromagnetic coupling to the plasma including off-normal events like disruptions), and (d) a *High temperature*, high vacuum, chemically active environment. While many of these conditions and effects are being studied in separate and multiple effect experimental test stands and modeling, fusion nuclear conditions cannot be completely simulated outside the fusion environment. This means there are many new multi-physics, multi-scale phenomena and synergistic effects yet to be discovered and accounted for in the understanding, design and operation of fusion as a self-sustaining, energy producing system, and significant experimentation and operational experience in a true fusion environment is an essential requirement. Research on FNSF will develop the definitive database essential for both the validation of fusion nuclear science modeling, design and safety codes, and the demonstration of DEMO-ready component operation and reliability, with the following objectives:

- Demonstrate how fusion can *make its own fuel* and possibly produce a tritium supply to start up subsequent machines (e.g. DEMO).
- Develop fusion FW/blanket, and divertor systems that operate effectively in the fusion environment and *extract high grade heat* over an extended lifetime while remaining compatible with plasma operation and tritium production.
- Obtain the essential database on *reliability, availability, maintainability and inspectability* (RAMI) of fusion nuclear components beyond beginning of life.
- Build the knowledge base for *integrated fusion nuclear science phenomena* including but not limited to: mixed material formation and evolution of the near surface; neutron irradiation damage and effects on implanted D, T, and He behavior; evolution of material thermomechanical properties, liquid metal coolant MHD, stability and transport; tritium

solubility, diffusivity and permeation; electromagnetic compatibility, chemical compatibilities.

Facility Description

The technical requirements of a fusion test facility to study and resolve fusion nuclear science questions has been previously specified by international experts [2] as a high-volume, plasma based neutron source for well diagnosed, integrated tests of materials and full-size components under prototypical conditions. In order to accomplish these nuclear science objectives, the FNSF should operate steady-state for periods of up to two weeks, with a significant duty cycle (e.g. 30%) and significant fusion power for a neutron wall loading of ~1-2 MW/m^2 and a neutron fluence of 3-6 $MW\text{-}yr/m^2$ on large sample volume over twenty years (10 to 20 times the fluence in ITER).

FNSF should be a device that is complementary to ITER. ITER will explore high fusion gain Q~10 and superconducting technology and reactor scale maintenance schemes. FNSF is conceived as a small fusion power, externally driven device (low Q~3) with copper coils enabling the flexibility and maintainability required to advance our knowledge of fusion components and interaction between materials in the fusion environment, and harnessing fusion power. The facility would also have the capability to develop advanced steady-state operating modes toward an attractive power plant. Such a FNSF together with ITER will fulfill all the development gaps from present machines to a tokamak DEMO, identified in recent U.S. MFE community initiatives [3]. There are two candidate machine types aimed at the same FNSF mission: FNSF-AT (Fusion Nuclear Science Facility - Advanced Tokamak) [4] and FNSF-ST (Fusion Nuclear Science Facility - Spherical Torus) [5], though other variants could still be envisioned. The FNSF-AT is a strong candidate for an FNSF as a consequence of its mature physics base, capability to address the key issues, and the direct relevance to an attractive target power plant. The finite aspect ratio provides space for a solenoid, assuring robust plasma current initiation, and for an inboard blanket, assuring robust tritium breeding ratio (TBR) >1 for FNSF tritium self-sufficiency and build of inventory to start up DEMO. An example design point gives a Cu-coil device with $R/a =$ 2.7 m/0.77 m, k = 2.3, $B_T = 5.4\,T$, $I_p = 6.6$ MA, $\beta_N = 3.7$, $f_{BS} \sim 0.75$, $P_{FUS} \sim 230\,MW$, and $P_{COILS} \sim 400\,MW$ [6]. The FNSF-ST can be significantly smaller (roughly half the major radius) than the FNSF-AT. However, with very limited space for an inner blanket and large sections of the outboard wall area devoted to external current drive, the FNSF-ST may not be able to demonstrate tritium self-sufficiency or build the tritium supply to start up DEMO.

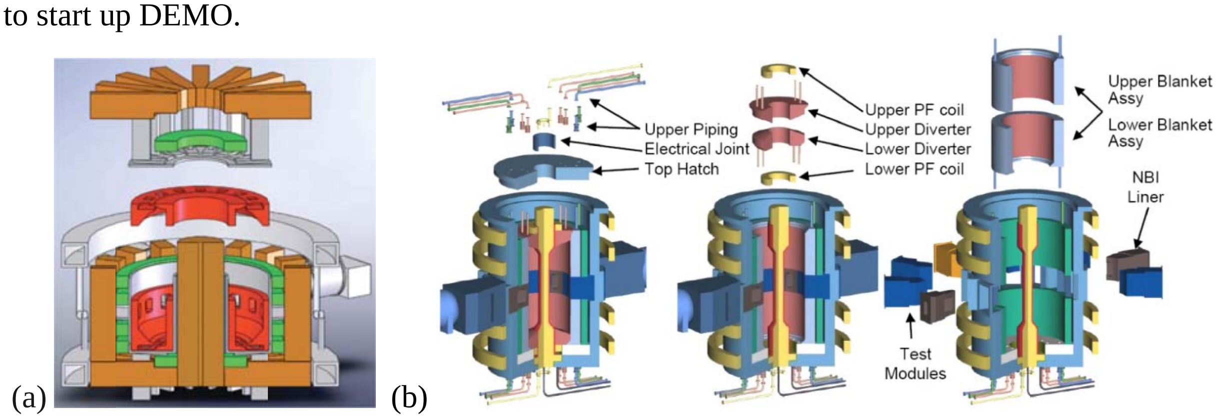

Fig. 1. Baseline maintenance scheme for (a) FNSF-AT and (b) FNSF-ST allows crane lift of toroidally continuous ring structures.

A design feature common to both the FNSF-AT and the FNSF-ST, meant to allow them to be effective research machines by enabling frequent planned changeouts and maintenance of the in-vessel components, is their jointed copper TF coil, as in DIII-D, Alcator C-Mod, and NSTX. The choice of copper coils minimizes shielding requirements significantly reducing the size and cost of the facility. The TF coil joint allows a vertical maintenance scheme in which the divertor and FW/blanket structures inside the TF coil can be built as axisymmetric ring structures and maintained and changed out quickly as large units. The construction as axisymmetric rings also enables precision toroidal alignment of plasma-facing surfaces for handling of the plasma exhaust. This vertical maintenance approach is shown in Fig. 1.

Staged Testing Approach

A staged research and development schedule is a defining characteristic of FNSF, essential in order to be able to learn and improve over time the operating scenarios, diagnostics, nuclear components, and structural and plasma facing materials. This enables an early start for FNSF that maximizes synergy with the parallel ITER burning plasma program. An initial commissioning period is envisioned in which the working fuel will progress from H to D to D-T. The basic operating modes of the machine can be developed in this phase without dependence on the fusion power with sufficient auxiliary power. This stage would also allow the study of plasma surface interactions, enabling improved understanding of materials under simultaneous exposure to high plasma heat and ion fluxes, and testing FW and divertor components together at sufficient engineering size and prototypic integrated environment with all conditions except neutrons. In the following D-T operation period, three types of main blanket systems could be tested, while the plasma performance, the blanket system design and operation, the closed loop tritium system design and operation, are gradually improved. It is envisioned that teams of universities, laboratories, and industry will propose to field and study test blanket modules (TBMs) on the FNSF as a user facility. Planned shutdowns will enable each main blanket change-out. The third main blanket will be built from the best result of the TBM tests, using more advanced materials if available, and operated to higher fluence. The price paid for this necessary flexibility in the FNSF-AT or FNSF-ST is the high power consumption in the copper coils. A detailed construction and operation costing has not been performed. A rough estimate projects the construction cost to a few billion dollars, depending on design choices.

Readiness to Construct

To make possible a fusion DEMO as the next step triggered by the achievement of Q=10 in ITER, an aggressive fusion nuclear science research program is essential to advance understanding and simulation of FW/blanket, divertor and tritium system materials. The current generation reduced activation ferritic steel (e.g. F82H, EUROFER) has a sufficient irradiation database to serve as the main structural material for first phases of FNSF. Required functional materials (insulators, tritium barriers, armors, breeders, etc.) are less developed and need more focus in the near term research program, as well as research on power extraction and tritium control in LM breeder/coolants, ceramic breeder and multiplier packed beds, and helium cooled structural response to prototypic heat flux and thermomechanical conditions.

Key physics features of FNSF-AT are fully noninductive current drive, strong plasma cross section shaping, internal profiles consistent with high bootstrap fraction, and operation at moderate to high beta. The FNSF-AT vision is largely based on the advanced physics performance and key features demonstrated on DIII-D, JT-60U, JET, and ASDEX-U, but that would be carried out at a new nuclear capable site. Using moderate AT physics, the baseline scenario achieves neutron flux at the outboard wall of 2 MW/m^2, sufficient for nuclear science objectives with ample margin over the minimum requirement (~1 MW/m^2). This provides risk mitigation against shortfalls in physics and/or engineering performance. Recent experiments have shown that full noninductive scenarios with the levels of normalized fusion performance required by FNSF-AT are obtained and sustained for many energy confinement times. Key remaining challenges are to sustain these AT scenarios for several current redistribution times, and develop high heat and particle fluence boundary solutions consistent with high plasma performance. The FNSF-ST also aims at steady-state operation, but intends to achieve this with more conventional physics operating modes with the majority of the plasma current driven by auxiliary power. The ST class of machines has some special challenges for auxiliary heating, particularly for ECH/ECCD, and has two feasibility issues: startup without an OH transformer and quite high peak divertor heat flux (from its small size). The physics basis for the choice of the best FNSF machine concept can be attained in the next few years with proper focus in the U.S. research program including international collaborations.

Finally, FSNF enabling technology issues must also be addressed, such as cooling of the TF-coil joints, fusion power core components maintenance, continuous operation of heating and current drive systems, and diagnostics for the harsh neutron environment.

The near term research focus should be on those tasks that are deemed to have direct impact on machine engineering design. During this time, pre-conceptual design studies should provide physics and plasma operation objectives for the baseline cases, and for a few alternative operating modes possible in the reference machines, physics and plasma science assessments, and definition of physics and other design requirements.

By immediately initiating the FNSF activities, the U.S. Fusion Program has the opportunity to be a world leader in the understanding of fusion nuclear science and burning plasma dynamics and control toward an attractive DEMO. The mission need has been clearly identified through the community processes [3]. It is now time to move forward with a clear and definitive mission need and scope, design concept, and readiness, with a target of completing the definition phase and CD-1 approval under DOE Order 413.3B in next 3 – 4 years. These activities, together with focused research in the base program to fill remaining physics and engineering gaps to FNSF can enable construction (CD-3) of FNSF to begin in approximately 7 years.

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