Fusion Nuclear Science Facility (FNSF) before Upgrade to Component Test Facility (CTF)

Y.K.M. Peng 1), J.M. Canik 1), S.J. Diem 1), S.L. Milora 1), J.M. Park 1), A.C. Sontag 1), P.J. Fogarty 2), A. Lumsdaine 1), M. Murakami 1), T.W. Burgess 1), M.J. Cole 1), Y. Katoh 1), K. Korsah1), B.D. Patton 1), J.C. Wagner 1), G.L. Yoder 1), R. Stambaugh 3), G. Staebler 3), M. Kotschenreuther 4), P. Valanju 4), S. Mahajan 4), M. Sawan 5)

1) Oak Ridge National Laboratory, Oak Ridge, TN, USA
2) Innovative Design Inc., Oak Ridge, TN, USA
3) General Atomics, La Jolla, CA, USA
4) University of Texas, Austin, TX, USA
5) University of Wisconsin, Madison, WI, USA

e-mail contact of main author: pengym@ornl.gov

Abstract. The compact (R_0~1.2-1.3m) Fusion Nuclear Science Facility (FNSF) is aimed at providing a fully integrated, continuously driven fusion nuclear environment of copious fusion neutrons. This facility would be used to test, discover, understand, and innovate scientific and technical solutions for the challenges facing DEMO, by addressing the multi-scale synergistic interactions involving fusion plasma material interactions, tritium fuel cycle, power extraction, and the nuclear effects on materials. Such a facility properly designed would provide, initially at the JET-level plasma pressure (~30%T^2) and conditions (e.g., Hot-Ion H-Mode), an outboard fusion neutron flux of 0.25 MW/m^2 while requiring a fusion power of 19 MW. If and when this research operation is successful, its performance can be extended to 1 MW/m^2 and 76 MW by reaching for twice the JET plasma pressure and Q. High-safety factor q and moderate-β plasmas would minimize plasma-induced disruptions, helping to deliver reliably a neutron fluence of 1 MW-yr/m^2 and a duty factor of 10% presently anticipated for the FNS research. Success of this research will depend on achieving time-efficient installation and replacement of all components using extensive remote handling (RH). This in turn requires modular designs for all internal components, including the single-turn toroidal field coil center-post with RH-compatible bi-directional sliding joints. Such device goals would further dictate placement of support structures and vacuum seal welds behind the internal and shielding components. If these further goals could be achieved, the FNSF would provide a ready upgrade path to the Component Test Facility (CTF), which would aim to test, at higher neutron fluence and duty cycle, the demanding fusion nuclear engineering and technologies for DEMO. This FNSF-CTF strategy would be complementary to the ITER and the Broader Approach programs, and thereby help mitigate the risks of an aggressive world fusion DEMO R&D Program. The key physics and technology research needed in the next decade to manage the potential risks of this FNSF are identified.

1. Introduction

A U.S. fusion community-based workshop on Research Needs for Magnetic Fusion Energy Sciences (ReNeW) [1] was conducted recently to assess the key scientific and technical foci of magnetic fusion research aimed at bridging the remaining knowledge gaps to practical fusion energy. Complementary to the research topical areas of the burning plasma and boundary to be championed by ITER, and the advanced performance plasmas needed for DEMO, are the areas of *i*) plasma material interactions (PMI); *ii*) plasma facing components (PFC); *iii*) fusion power extraction; *iv*) tritium sustainability; *v*) radiation effects on materials; and *vi*) integrated design and modeling accounting for safety and environment, and reliability, availability, maintainability, inspectability (RAMI).

The needed research identified for these latter areas combined are extensive, encompassing *i*) microstructure properties of material and material combinations under simulated plasma and neutron irradiations; *ii*) macroscopic properties of mock-ups and test loops of increased complexity involving multiple time and size scales; *iii*) interactive properties of partially integrated components using test stands of increased approximation toward the fusion nuclear environment; and *iv*) multiscale synergistic phenomena to be exhibited by prospective internal components in a full fusion nuclear environment.

The recently introduced [2,3] compact (R_0=1.2-1.3m) Fusion Nuclear Science Facility (FNSF) concept with A=1.5-1.6, Q=0.5-3.0, $P_{DT}\leq$152MW, and $W_L\leq$2MW/m^2, was envisioned to provide such a fusion nuclear environment to address the synergistic properties of internal components of interest to DEMO. This FNSF was introduced as Stage-1 for "*fusion break-in & scientific exploration*" in a "*High-Volume Plasma-Based Neutron Source*", which was introduced earlier [4] for fusion blanket development. This volume neutron source (VNS) was subsequently renamed Component Test Facility (CTF) [5,6]. The mission of CTF therefore remained to provide the more demanding fusion environment capabilities of increased fluence and duty factor required to address the Stage 2 "*engineering feasibility and performance verification*" and Stage 3 "*component engineering development and reliability growth*" research already assigned to the VNS.

In this paper we refer in some detail to recent advances in understanding how radiation damages materials [7] to help characterize the nature of synergistic behavior that could occur from otherwise disparate physical phenomena when they are collocated in space and time, and overlap in activation energies (Section 2). A working description of the FNSF research mission is presented that is consistent with the multiscale interacting phenomena [8,9] in a fusion nuclear environment (Section 3). Achieving this research mission during the ITER era, including verifying readiness to upgrade to the CTF, would support and help mitigate the risks of an aggressive DEMO R&D program as defined in the ITER Broader Approach [10]. Initial examples of the FNSF goals in performance, configuration, and operational capabilities can be derived from the mission and will be described at the conceptual level (Section 4). These in turn help identify and clarify the R&D required to achieve these goals and manage the risks of FNSF (Section 5), accounting for the strong commonality of the scientific and technical basis of the the spherical torus and the normal aspect ratio tokamak. A wider range of FNSF research goals of relevance to the realization of fusion energy will be discussed in Section 6. There it will be suggested that the FNSF capabilities in simultaneously handling continuous neutron flux, controlling the plasma dynamics, and recovering operational capabilities with reduced down times, jointly with the associated fusion nuclear science (FNS) R&D programs, will likely pace the progress of research in FNS.

2. Conditions for potential synergistic phenomena involving neutron-material interactions (NMI) and PMI

It is nearly impossible to predict with confidence new physics phenomena that would result from hitherto new coincidence and juxtaposition of otherwise disparate physics mechanisms of similar activation energies. However, experience tells us that new phenomena have been encountered in such situations, which in turn strongly shaped the subsequent R&D. Examples include the discovery of H-mode plasmas when the poloidal divertor configuration was introduced to the tokamak, and the development of radiation resistant ferritic steel following the discovery of severe nuclear damages of carbon steel used in early fission critical assemblies. It is nevertheless appropriate to search for clues for potential synergies involving NMI and PMI in a fusion nuclear environment, and use such prospects to shape and clarify the FNSF mission.

It has been broadly anticipated that fusion neutron dose levels up to 10 dpa, introducing ~100 appm He, can be reached in appropriately designed internal components before substantial deleterious modifications to the ferritic steel properties would occur [9]. Such radiation-induced changes to material microstructure, for temperatures above the ductile to brittle transition (DBTT), include precipitation and solute segregation, permanent deformation under applied stress, volumetric swelling, and high-temperature He-induced embrittlement, etc. However, as can be seen in the following case, it is likely that PMI and NMI can have substantial synergistic interactions, even for damages down to below 1 dpa.

That the conditions are present for strong synergistic interactions is suggested by several recent advances in NMI in such as the bcc iron with regard to the formation and dynamics of microstructure damages by neutrons:

1) A fusion neutron damages material through displacement cascades involving $>10^3$ atoms over a region of $\sim 10^2$ nm in size following a collision of the "primary knock-on atom" [9];
2) In addition to nearly isolated point defects, both interstitial and vacancy clusters of 20 or more point defects are formed during the displacement cascades [11];
3) Such clusters can form planar dislocation loops of sizes up to 20 nm, and undergo 1D motion with fairly low activation energy barriers (~1eV); they were observed via TEM to move at an unexpectedly high rate of 1-5 nm/s at ~300 ^{o}C temperature, likely through interactions with interstitial impurity atoms [7].

It is therefore of interest to determine whether such clusters of defects, when and if born within $\sim 10^2$ nm of the plasma facing surface, would migrate to within ~20 nm of the surface and affect those PMI properties that have activation energies of up to ~eV. A fusion environment is required to test and understand the roles of this synergistic interaction, and determine whether a similar process occurs in such materials as the reduced activation ferritic steels at ~500 ^{o}C and tungsten at temperatures of $\sim 10^3$ ^{o}C, which are of interest to DEMO.

Additional examples of potential synergistic interactions of internal components include: degradation of thermal conductivity and changes in surface morphology and plasma erosion rates in C and ceramics at ~0.1 dpa [12]; changes in tritium retention and permeation as neutron induced defects accumulate through ~1 dpa [13]; and property changes of tritium permeation barrier in nuclear environment [14]. In the latter example, substantial reductions of the permeation reduction factor (PRF) were measured at low irradiation doses in a research fission reactor. Tested in this case was the ceramic coating of Cr_2O_3–SiO_2 including $CrPO_4$ on the inner surface of a ferritic steel F82H container of liquid lithium lead eutectics, $Pb_{17}Li$.

Solutions for internal components therefore need to be tested in a fusion environment to investigate synergistic phenomena before confidence can be established for use in DEMO.

3. Preliminary mission and required capabilities of FNSF

The FNSF mission is to provide an integrated, continuously driven fusion nuclear environment of copious neutrons that can be used to test, discover, and understand the multiscale interacting phenomena involving fusion plasma material interactions, tritium fuel cycle, and power extraction, while accounting for the nuclear effects on materials. The interactions range in scale from picoseconds to years, from nm to meters, and involve up to four states of matter. Improvements to the internal components based on the new understanding so obtained would be developed and further tested, until adequate scientific and technical basis for DEMO-capable components are established.

The FNSF mission therefore complements the ITER mission [15], which is to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes. Its inductive operation is expected to produce significant fusion power (~500MW) through the D–T reaction with high fusion gain *Q* ~ 10 for 300–500 s. Figure 1 shows this complementarity; the FNSF could utilize low Q conditions to achieve its mission for a fluence of 1 MW-yr/m^2, pulse lengths of up to 2 weeks, and a duty factor up to 10%.

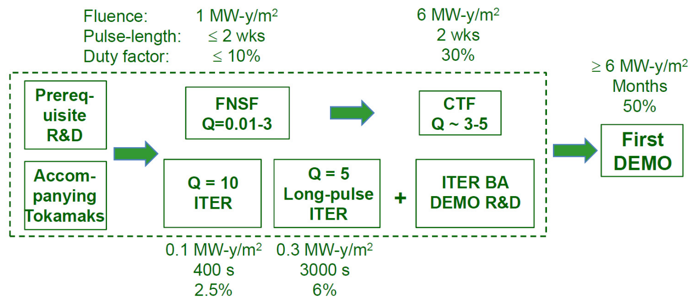


FIG. 1. Mission complementarity between FNSF-CTF and ITER & ITER-BA to develop basis for DEMO.

The FNSF mission aimed at reducing the risks for DEMO R&D with efficient upgradability to the CTF will require that the following conditions and capabilities be provided [2,3]:

1) For an adequate fusion environment – fusion neutron flux $W_L \leq 1$ MW/m^2 at the outboard mid-plane.
2) To address long time-constant interactive phenomena – plasma duration ~10^6 s (~2 weeks).
3) For reliable plasma operation – limiting plasma induced disruptions and transients via large margins to MHD stability limits: $\beta_N \leq 0.75\ \beta_N^{\text{no-wall}}$; $q_{cyl} \geq 4$.
4) For continuous plasma operation – I_p must be maintained non-inductively, likely using co-NBI and RF heating and current drive.
5) To maintain plasma T and n profiles and purity for ~10^6 s – divertors capable of handling peak heat flux ≤ 10 MW/m^2 and control the plasma density using fueling, heating, current drive, and active particle removal.
6) To enable time-efficient cycles in which to test, discover, understand and innovate solutions for internal components – modular components in configurations that allow RH, and extensive RH capabilities to install and replace these components.
7) To prepare, maintain, and repair activated internal components – extensive hot-cell capabilities based on RH.
8) To carry out post-mortem investigations of failed components to discover and understand unexpected phenomena – extensive diagnostic, research, and component manipulation capabilities in a hot-cell laboratory to examine physical properties and changed conditions of critical locations in the components.

To deliver these FNSF mission capabilities, accompanying FNS R&D programs will be required to develop the basis for the plasma operation, design the appropriate modules for all the internal components, and manage the risks inherent in such a new fusion research facility. These will include R&D to develop, including optional approaches when appropriate:

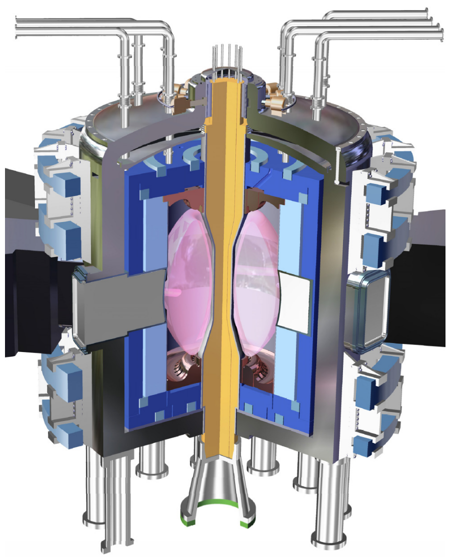
1) Adequate database, predictability, and modularized components to control the plasma dynamics, including measurements, heating, fueling, current drive, and stability control.
2) Divertor modules, mid-plane test blanket modules, and off-mid-plane tritium breeding blanket modules, including optional designs for these modules.
3) RH and hot cell systems and tools, including post-mortem research capabilities.

These mission capabilities are compatible with component design options as determined by the accompanying R&D programs, and apply equally to the low aspect ratio and the normal aspect ratio configurations. In the case of the low aspect ratio spherical torus [2,3] for an

FNSF-ST, which requires the use of a single-turn normal conducting, water-cooled toroidal field coil center post with limited nuclear shielding and no central solenoid, as an additional internal component. Solenoid-less startup and ramp up of the plasma current will also be required in this case. These may influence the choices of the internal component designs. The aspect ratio choices for FNSF will therefore require comparative assessments of performance, cost and risks, accounting for such a center post and the associated operations.

4. Preliminary FNSF performance, configuration, and operational goals

In the case of low A, the systems code used in [2,3] was applied to update working examples of the FNSF goals in performance, configuration and operational capabilities, which are driven by the FNSF mission and mission components described in Section 3. The results are summarized in Figure 2.



Stage-Fuel	I-DD	II-DT	III-DT	IV-DT
Current, I_p (MA)	4.2	4.2	6.7	8.4
Plasma pressure (MPa)	0.16	0.16	0.43	0.70
W_L (MW/m^2)	0.005	0.25	1.0	2.0
Fusion gain Q	0.01	0.86	1.7	2.5
Fusion power (MW)	0.2	19	76	152
Tritium burn rate (g/yr)	0	≤105	≤420	≤840
Field, B_T (T)	2.7	2.7	2.9	3.6
Safety factor, q_{cyl}	6.0	6.0	4.1	4.1
Toroidal beta, β_T (%)	4.4	4.4	10.1	10.8
Normal beta, β_N	2.1	2.1	3.3	3.5
Avg density, n_e (10^{20}/m^3)	0.54	0.54	1.1	1.5
Avg ion T_i (keV)	7.7	7.6	10.2	11.8
Avg electron T_e (keV)	4.2	4.3	5.7	7.2
BS current fraction	0.45	0.47	0.50	0.53
NBI H&CD power (MW)	26	22	44	61
NBI energy to core (kV)	120	120	235	330

FIG. 2. Updated FNSF configuration with $A=1.6$, $R_0 = 1.3$ m, H-mode H factor ≤ 1.25, $J_{TF\text{-}avg} \leq 4$ kA/cm^2, ≥ 10m^2 area for mid-plane modules, and parameters for Stage-I) D-only operation at $I_p = 4.2$ MA, II) D-T at the same current ($W_L = 0.25$ MW/m^2), III) D-T at 6.7 MA (1 MW/m^2), and IV) at 8.4 MA (2 MW/m^2).

Note that, relative to [2,3], a reduced average current density $J_{TF\text{-}avg}$ to ≤4 kA/cm^2 over the narrow part of the center post, an decreased β_N / $\beta_N^{\text{no-wall}}$ to ≤0.75, an increased q_{cyl} to ≥4, and a reduced HH-factor to ≤1.25 (in Hot Ion H-Mode [16]) increased A to 1.6 and R_0 to 1.3m.

Ready upgradability of all internal components would enable effective staging of research foci, as indicated in Figure 2 for example,

1) Stage-I (DD): to commission PFC-divertor capabilities, continuous control of plasma dynamics in steady state, neutron transport, shielding and safety integrity, RH operation, etc., at low levels of activation that is equivalent to JET DD plasma operation.
2) Stage-II (DT): JET DT conditions for W_L=0.25MW/m^2 to test and achieve predictability of tritium breeding, power extraction, full RH operations, etc. Note that, at a duty cycle of 10%, the tritium burn rate would be ~100 g/yr, easing tritium supply while basis for tritium breeding and recovery are tested toward a TBR goal of ~100%
3) Stage-III (DT): Two time the JET conditions for W_L=1.0MW/m^2 to test and achieve the full fusion nuclear science research capabilities, following upgrade of NBI to negative ion source systems, etc.

4) Stage-IV (DT): Three times the JET conditions for W_L=2.0MW/m^2 to advance the FNSF research toward CTF.

The goal of ready upgradability to enable staging will also require effective approaches to place the vacuum seal welds behind the internal and shielding components to allow repeated application and removal of these seals. Concepts of such seal configurations and the associated vacuum boundaries are depicted in Figures 3a, 3b, and 3c. It is seen that hands-on access to these well shielded seal welds are conceptually feasible, if the goal of radiation cool down in the FNSF test hall could be achieved in two days after plasma shutdown.

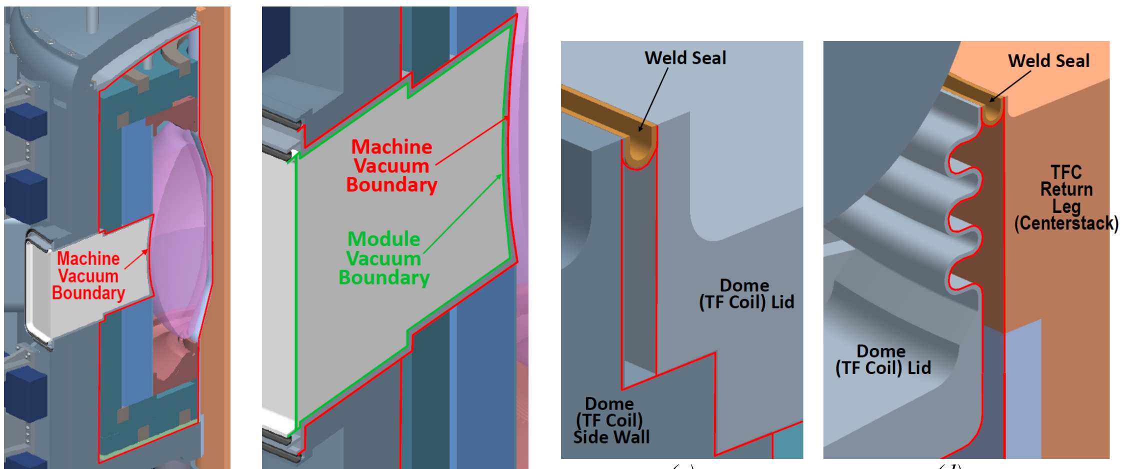


FIG. 3. Vacuum boundary and seal welds concepts for (a) FNSF chamber (red line), (b) mid-plane test module (green line), (c) for the top dome / TF coil (red line), and (d) top of the TFC center post (red line).

Assuming that such seal welds are feasible, the assembly and disassembly procedures for the FNSF internal components via RH become feasible. The procedures for the center post with a bi-directional sliding joint and the top vacuum dome are depicted in Figures 4a and 4b. More detailed conceptual development of this type of seal welds and center post will be needed before the prerequisite research for them can be defined. The configuration concepts for the rest of the modular components and RH approaches remain similar to references [2,3].

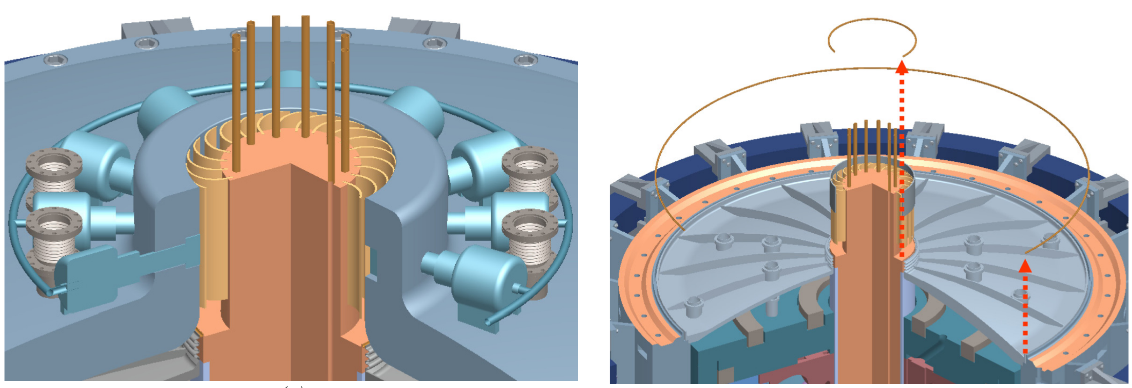


FIG. 4. Configurational concepts for (a) bi-directional (vertical and toroidal twist) sliding joint at the top of the TF coil center post, and (b) removable vacuum seal welds before vertical removal of the top vacuum dome and then the TF coil center post.

5. Prerequisite R&D

The preliminary FNSF mission and its goals in performance, configuration, and operation also serve to help identify the prerequisite R&D to establish the basis for FNSF design, and manage the risks in achieving these goals. It is assumed that the accompanying R&D programs would be in place to determine the designs and options of the internal component modules, including the material choices. The FNSF R&D needs are focused on those goals described in Section 4, including the low A features, which are driven by the FNSF mission described in Section 3.

Work to be carried out to define details of the R&D that is needed to ensure the operational capabilities of the FNSF-ST and manage risks, include:

1) Electron Bernstein Wave [17] and plasma gun helicity injection [18] start up research to establish the needed database and predictive modeling capabilities.
2) Predictive modeling capability, using such as the SWIM [19] and the GLF23 [20] codes, to estimate steady-state operation conditions, assuming the Hot-Ion H-Mode [16] operational scenario based on dominating NBI heating and current drive.
3) Predictive modeling capability, using such as the SOLPS-EIRENE codes [21], to estimate appropriate divertor designs and operational scenarios, using such options as the extended divertor channels, to mitigate the risk of uncertainties in heat flux foot print and limit the peak divertor heat fluxes to below 10 MW/m^2, for W_L up to 1 MW/m^2.
4) Assess the engineering requirements for the RH systems capabilities to reduce the mean-time to replace (MTTR) all internal component modules adequately to achieve a duty factor of 10%.
5) Assess the engineering requirements [22] for the TF coil center post to achieve reliable operation, and determine the R&D needed for fabrication.
6) Assess the engineering requirements for the low voltage, high current dc TF power supply with relatively stiff control of current, and determine the R&D needed for fabrication.
7) Assess the hot-cell and RH capabilities required to support the fusion nuclear science research onsite in concert with the accompanying FNS research programs offsite, jointly to manage the risks of the overall program.

6. FNSF-AT, FNSF-Stretch, and pacing

The FNSF mission and the performance, configuration, and operation goals can be implemented similarly with normal A. For normal A, an FNSF-AT concept has been identified [23,24] with increased H-factor, bootstrap current fraction, and β_N (to just beyond the no-wall limit), providing W_L =1-2 MW/m^2 at moderate Q. These cases are therefore equivalent to the Stages III-DT and IV-DT cases shown in Figure 2. These FNSF stages are placed in Figure 5 relative to DD superconducting tokamaks, JET DT [16], ITER [15], and DEMO, also showing the FNSF mission complementarity with ITER.

Substantial margins to plasma and engineering limits are included in these FNSF device concepts. Their hardware capabilities could be more fully utilized to support research at even more advanced physics performance and higher neutron fluxes [25], such as $Q > 7$ and $W_L \sim$ 4 MW/m^2. This case is included in Figure 5 as "FNSF-Stretch", which is realizable only if the FNSF mission is already accomplished through the preceding stages of FNS research.

Each of the devices or operating conditions included in Figure 5 will require simultaneous success of internal components to handle the fusion neutron and plasma fluxes and to control the plasma dynamics to deliver the required fusion performance. This would imply that the AT-level fusion plasma dynamics and fusion nuclear sciences properties should be further pursued together in FNSF. But the fusion nuclear science studies can begin at the JET level conditions (Stage II-DT) and do not require advances in tokamak physics much beyond the no-wall beta limit.

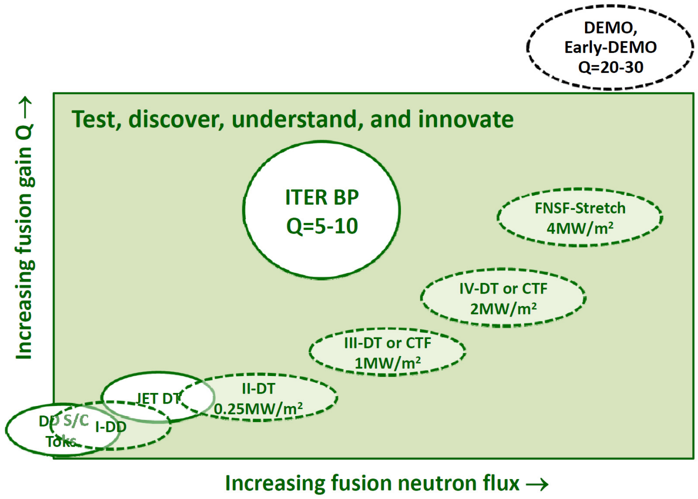


FIG. 5. FNSF performance goals from Figure 2 in comparison with superconducting tokamaks, JET-DT, ITER, and DEMO in the parameter space of neutron flux and fusion gain.

These considerations suggest that the FNSF capabilities in handling continuous plasma and neutron fluxes, controlling the plasma dynamics to produce these fluxes, and recovering operational capabilities with a minimized down time, jointly with the associated FNS R&D programs, will likely pace the progress of research in fusion nuclear science.

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