Topic: FT

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

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In recent discussions on Research Needs for Magnetic Fusion Energy Sciences [1], a broad range of research activities, outside of the ITER burning plasma and supporting technology scopes, were identified as required to establish the remaining scientific basis for technologies to harness fusion power in a steady-state fusion Demo. All components in the Demo fusion chamber will simultaneously involve up to four phases of matter (solid, liquid, gas, and plasma) and encounter physical phenomena with sizes across the nuclear, atomic, nano, meso, and macroscopic scales, for continuous durations up to 1-2 weeks. In such a fusion nuclear environment, synergistic effects of multiple interacting physical mechanisms related to plasma, materials, and power extraction are unavoidable and should be expected. We developed the Fusion Nuclear Science Facility (FNSF) concept to enable research toward the discovery and understanding of such synergistic effects for the first time.

The need for "scientific exploration" before "engineering and technology testing and development" was already articulated when the concept of Component Test Facility (CTF) was introduced and studied [2,3]. The FNSF research capabilities are therefore a subset of those of CTF, as determined by this work and listed below:

1) The total fusion neutron fluence and facility operation duty factor are 1 MW-yr/m^2 (~10 dpa) and 10%, respectively, with a fusion neutron wall loading W_L up to 1.0 MW/m^2, for scientific research on the synergistic effects [4].
2) Full modularization of all chamber components, including the toroidal field (TF) coil center-post, to allow time-efficient replacements via remote handling to and from hot-cell laboratories, to enable effective cycles of research testing, discovery, understanding, leading to component design improvements for retesting.
3) Device support structures shielded by the chamber components to reduce the accumulated radiation dose by two orders of magnitude. This would also ensure upgradability to the CTF stages of operation, when and if the test components are adequately developed for this purpose.
4) Strongly conservative plasma operating conditions to avoid plasma instability-induced disruptions and allow continuous operations up to 1-2 weeks, which is required by fusion nuclear science (FNS) research.

An improved FNSF device concept is shown in Fig. 1, with example parameters shown in Table 1 for the multiple stages of FNS research, leading up to the conditions for later possible, upgraded conditions for CTF testing. Key features for FNSF include:

1) Plasma Facing Component (PFC) testing and commissioning in deuterium and minimal neutron dose with plasma conditions already operated in JET (I_p = 4.2 MA).
2) Initial FNS research with JET-level D-T plasma conditions (Q = 0.86) producing W_L ~ 0.25 MW/m^2 at the outboard mid-plane.

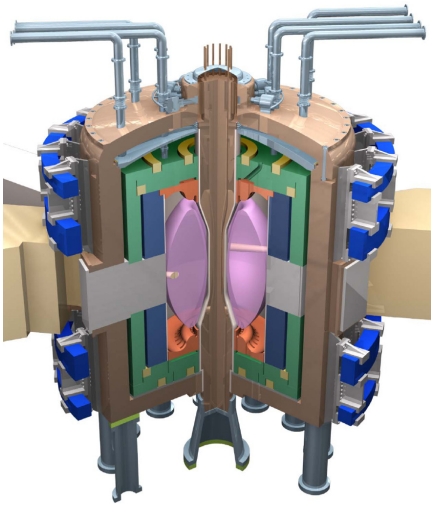

Fig. 1. FNSF concept with full modularization and remote handling

Plasma pressure level	JET-DD	JET-DT	2xJET	4xJET
$B_T^2\beta_T$ (T^2-%)	32	32	85	140
Tests enabled	PFC	FNS	FNS-CTF	CTF
W_L (MW/m^2)	0.005	0.25	1.0	2.0
Current, I_p (MA)	4.2	4.2	6.7	8.4
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
Fusion power (MW)	0.2	19	76	152
NBI energy (kV)	120	120	235	330

Table 1. Example FNSF parameters with A=1.7, R_0 = 1.3m, $J_{TFavg} \leq$ 4kA/cm^2, small inboard gap, HIHM plasmas with strong stability.

3) Full FNS research with twice JET level plasma pressure producing $W_L \sim 1.0$ MW/m^2 at the outboard mid-plane, before possible upgrade to CTF operations.
4) Single-turn, single-pass water-cooled TF center-post with conservative average peak current density $J_{TFavg} \leq 4$kA/cm^2 and bi-directional sliding joints to ease replacement and installation via remote handling.
5) A 10-cm thick inner wall of tungsten, cooled by single-pass high-pressure helium.
6) Toroidally complete divertor modules with extended divertor channels to limit peak heat fluxes to below 10 MW/m^2.
7) Conservative hot-ion H-mode (HIHM) plasma confinement (HH-factor $\leq$ 1.25) and stability conditions (q_{cyl} = 4–6 and $q_0 > 2$; β_N = 3.3–2.1 below the so-called no-wall limit) to minimize plasma-induced disruptions, and allow NBI-driven (aided by RF if necessary) current and bootstrap current fractions of ~0.5.

While such a design for FNSF can be shown to instill high confidence in continuous plasma operation conditions needed for FNS research, key plasma physics issues [5] still remain in

1) Solenoid-free plasma initiation, ramp-up, and sustainment, which is a unique requirement for the ST version of FNSF.
2) Solutions to continuous divertor operations with HIHM plasma and divertor heat flux up to 10 MW/m^2.

Detail of the plasma and engineering design analysis for this FNSF concept will be presented.

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