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High Performance Superconductors for Fusion Nuclear Science Facility

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***Abstract*—High performance superconducting magnets play an important role in the design of the next step large-scale, high-field fusion reactors such as the Fusion Nuclear Science Facility (FNSF) and the Spherical Tokamak (ST) pilot plant beyond ITER, which is under construction in the South of France. Princeton Plasma Physics Laboratory (PPPL) is currently leading the design study of FNSF and the ST pilot plant study. ITER utilizes present-day state-of-the-art low temperature superconducting (LTS) magnet technology based on the cable-in-conduit conductor design where over a thousand muitl-filament Nb_3Sn superconducting strands are twisted together to form a high current-carrying cable inserted into a steel jacket for coil windings. We present design options of the high performance superconductors in the winding pack for the FNSF toroidal field magnet system based on the toroidal field radial built from the system code. For the low temperature superconductor options, the advanced J_c Nb_3Sn RRP strands (J_c > 1000 A/mm^2 at 16 T, 4 K) from Oxford Superconducting Technology (OST) are under consideration. For the high temperature superconductor options, the rectangular shaped high current HTS cable made of stacked YBCO tapes will be considered to validate feasibility of TF coil winding pack design for the ST-FNSF magnets.**

***Index Terms*—next-step fusion reactors, superconducting fusion magnet design, cable-in-conduit conductors, material radiation limits.**

I. Introduction

THE Fusion Nuclear Science Facility (FNSF) is a nuclear fusion device to provide integrated fusion environment with reactor components [1-4]. The FNSF is the stepping stone to bridge the technical gaps between the International Thermonuclear Experimental Reactor (ITER), currently under construction in the south of France, and the demonstration power plant (DEMO) [5-9]. For the next-step fusion devices designed for long pulse or steady state plasma operation, copper magnets cannot be a long-term option due to cost of electricity. Previous ARIES studies [10-11] assumed the full material availability of the most promising low-temperature superconductor (LTS) and high-temperature superconductor (HTS): the advanced high critical current Nb_3Sn wires and the YBCO tapes. More optimistic radiation limits of the LTS and HTS conductors and the organic electrical insulations in coil winding packs were also assumed. To this end, the ARIES-RS [10] and ARIES-AT [11] studies are based on some ideal situations that are not practical choices for the FNSF magnets.

We present magnet design parameters for the FNSF missions and focus on the capability of high performance superconducting wires for the toroidal field (TF) coil winding pack design. We investigate influence of voids in the ITER-grade Bronze Nb_3Sn wires on local stress intensity and the wire irreversible strain limit. The material radiation limits in the unique plasma operating environment for FNSF magnets are considered in the design. We also present a HTS conductor design option for the FNSF-ST TF magnets.

Figure 1 presents a sector of the FNSF with TF inner and outer leg radial built from the system code. The design presented here is focused on the challenging toroidal field (TF) magnet system and the TF winding pack details. Figure 2 presents the pathway toward the commercial fusion power.

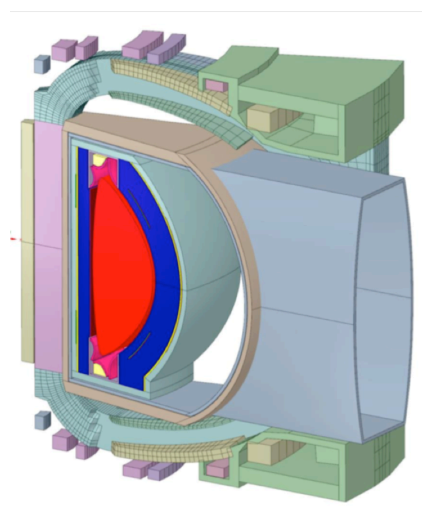

Fig. 1. A sector of the FNSF and its radial built from system code.

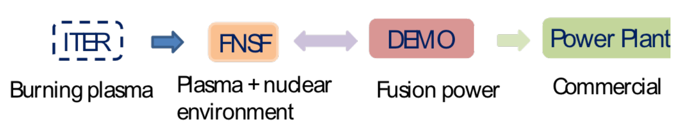

Fig. 2. Pathway toward the commercial fusion power.

II. FNSF Magnet System

A. Fusion power and magnet system

The fusion power scaling law, known to be $P_F \sim \beta^2 B^4$, where β is the plasma pressure to magnetic pressure ratio and B is the magnetic field at the plasma major radius, implies that for any economic fusion power, either improved plasma performance or increased toroidal magnetic field is required. For large-scale fusion magnet design, high current cables are

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necessary to limit large coil inductance and control terminal and ground voltages during safety discharges of magnets with high stored energy. The high peak magnetic field and tighter space for the coil winding pack requires high performance (advanced J_c) Nb_3Sn wires in the high current carrying cable-in-conduit conductor (CICC) or the high temperature superconductors (HTS) as the magnet design options.

B. *FNSF Design Parameters*

The FNSF magnet design parameters are listed in Table 1 together with ITER and DEMO design parameters. FNSF is smaller than ITER as it is not focused on the fusion energy or power generated but more on the fusion nuclear environment needed for DEMO or pilot plant. Higher magnetic fields using high performance Nb_3Sn strands are used for the long-pulse near steady state operating requirements. In comparison, both the K-DEMO – more aggressive in high field (B) [5-6], and E-DEMO - more expensive in size [7-9] is larger than ITER.

C. *Magnet Design Consideration*

Large outboard TF legs are required for the horizontal maintenance of the FNSF. Compare to high field accelerator magnets in high energy physics, fusion magnet is inefficient in utilizing its winding pack space as a significant amount of structure support is required to ensure structural integrity of the TF coil [12]. The ratio between the maximum magnetic field on the TF inner leg and the plasma center field is factors of 2-3 higher than that in high field solenoids or dipole magnet of a few centimeters bore size. As a result, current density in state-of-the-art fusion TF coils such as that in ITER TF coil cross-section is only 15-17 A/mm^2 as compared to ~50 A/mm^2 winding pack current density in the series-connected hybrid solenoid magnet using cable-in-conduit conductors (CICCs). Improving winding pack current density via better conductor design and more optimized structural support will be a significant part of the magnet design for the next step fusion devices.

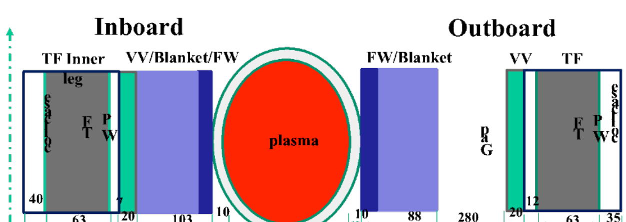

Fig. 3. Inboard TF leg radial built and the available TF winding pack space.

Magnet radiation shielding requirements were developed to minimize material radiation damage to the inboard TF magnet for its radial built to achieve protection by minimizing the peak dose to insulators and the peak fast neutron fluence to superconductors [13]. Figure 3 presents the inboard and outboard radial built for FNSF. As shown in Table II, a total inboard sector toroidal width of ~1.35 m is needed for shielding the TF inner leg in long pulse, high neutron fluence operation.

TABLE I
COMPARISON OF BASIC DESIGN PARAMETERS

Symbol	FNSF	ITER	K-DEMO	E-DEMO
major radius (m)	4.8	6.2	6.8	9
minor radius (m)	1.2	2	2.1	2.25
plasma current (MA)	8	15	12	14
plasma center B_0 (T)	7.5	5.3	7.4	6.8
TF operating current (kA)	70	68	65.5	80-85
TF max field (T)	15.5	11.8	16	13.45
TF current density (A/mm^2)	27	17	25	15
TF Ampere-turns (MA)	12.5	9.11	15.72	19.8
No. of turns	179	134	240	232
No. of TF coils	16	18	16	16
Half of vertical force (MN)	355	206		
Centering force (MN)	920	403		1220
TF coil inductance (H)		18		51
TF discharge time constant		11-14		23
Fusion power (MW)	450	500	3,000	500

TABLE II
TOROIDAL FIELD RADIAL BUILT

Fusion Device	Radial built (Δ_{int}) (m)
ITER	0.91
FNSF	1.35
K-DEMO	1.48
E-DEMO	1.6

III. TF WINDING PACK

Similar to ITER, the FNSF TF coil composition includes 65% cross-sectional area of the case support structure with a thickness of 7-8 cm in plasma side, and 35% cross-sectional area of coil winding pack, including 2% superconductor in 750 Nb_3Sn strands, 15% copper, 10% steel jacket, 3% insulator and 5% helium. The low activation jacket steel materials similar to JK2LB shall be selected. Jacket and liquid helium cooling is 29% and 14% of the winding pack area respectively. The TF winding pack design has roughly similar space allocated but more compact and efficient in using wire current carrying capacity by utilizing the high performance of advanced J_c strands. Table III presents Nb_3Sn and copper strand distribution and cabling pattern for the TF conductor. TF conductor is design at 37.5% of the wire J_c, where ITER uses 33% of the wire J_c. Tables IV-V listed the composition of TF cross section and TF winding pack composition. Compared to ITER, lower fraction of Nb_3Sn is used as result of higher performance of the advanced J_c wires. Figures 4-5 present the winding pack composition of a slice through the inboard and outboard TF legs.

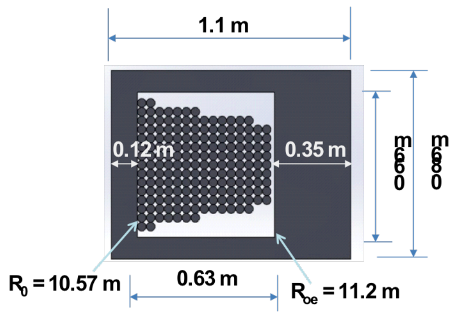

Fig. 4. Dimension of FNSF TF outer leg and the coil support structure.

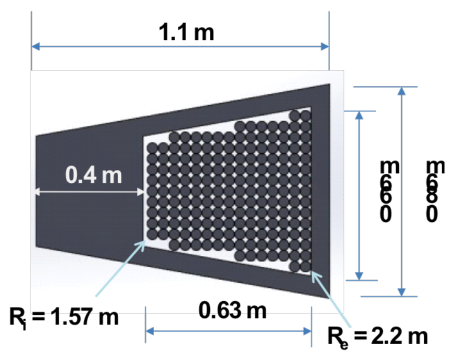

Fig. 5. Dimension of TF inner leg winding pack and coil structure.

TABLE III
TF COIL WINDING PACK AND CABLING PARAMETER

	FNSF	ITER
Op. current (kA)	70	68
No. of s/c strands	750	900
No. of Cu strands	405	522
Cabling pattern	((2+1cu)x3x5x5+3cux2)x5	((2+1cu)x3x5x5+3cux4)x6
Current/std (A)	93.3 (37.5% I_c)	75.5 (33% I_c)
Op. field (T)	16.5	12

TABLE IV
WINDING PACK COMPOSITION

WP composition	FNSF (%)	ITER (%)
s/c (Nb_3Sn)	6	17
copper	43	37
steel jacket	29	20
insulator	8	6
helium	14	20

TABLE V
COMPOSITION OF TF CROSS SECTION

TF composition	FNSF (%)	ITER (%)
s/c (Nb_3Sn)	2	6
copper	15	13
steel jacket	10	7
insulator	3	2
helium	5	7
Case support	65	65

A. *Wire Selection*

Steady improvement in J_c and mechanical performance has been achieved in past decades in Nb_3Sn wire development for accelerator magnet design in high energy physics [14-15]. It is thus advantageous to use high performance Nb_3Sn wires such as the Restack Rod Process (RRP) wires developed at Oxford Superconducting Technology (OST). Figure 6 presents the RRP wire cross section and 40 mm diameter CICC with jacket thickness of 3-5 mm for TF coils where Table VI listed wire functional specification for the conductor design.

B. *Cable Design Consideration*

For TF operation, high current cables are used to lower inductance for coil protection during fast discharges. The 70 kA CICC with 179 turns will provide Ampere-turns of 12.5 MA needed for TF fields. Significantly larger centering force compared to ITER TF coils, is mainly due to a higher field and closer to central axis of the TF inner leg.

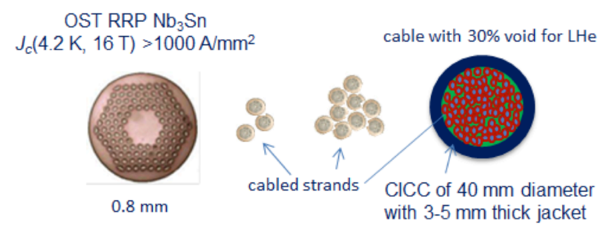

Fig. 6. High performance advanced J_c wires and CICC for FNSF TF coils.

TABLE VI
FUNCTION SPECIFICATION FOR TF STRANDS

Process	Ti-Ternary RRP	Specification
Strand diam. (mm)	0.85	0.8-1
I_c (16 T, 4.2 K), A	>250	J_c (16T, 4.2K) > 1000 A/mm^2
N-value	>30	
Ds, um (sub-element diam.	<50	108/127 sub-elem.
Cu: non-cu ratio	1.2 +/-0.1	
RRR	>150	Residual resistivity ratio
Twist pitch, mm	19	

IV. CONDUCTOR RADIATION LIMITS

FNSF generates a high radiation environment identifying necessary steps to advance fusion nuclear science for DEMO or pilot power plants. Therefore, nuclear assessment including radiation limits of magnet materials is a critical aspect to ensure FNSF mission success. Recent radiation test in LTS and HTS conductors [18-22] indicates that YBCO is no better than binary Nb_3Sn but can be better (<40 K operation) than the ternary Nb_3Sn conductor. REBCO at $3x10^{22}$ n/m^2 radiation has over 50% I_c degradation for 64 K operation and at $2x10^{22}$ n/m^2 radiation, it has ~30% I_c degradation for 40 K operation and below 40 K operation is possible at $3x10^{22}$ n/m^2 level of neutron radiation. Table VII listed radiation limits for magnet materials for the winding pack design. The organic/inorganic hybrid insulation has the potential for higher neutron radiations.

TABLE VII
MATERIAL RADIATION LIMITS

materials	Fast neutron fluence	unit
Nb_3Sn	$5x10^{22}$	n/m^3
YBCO	$3x10^{22}$	n/m^3
copper	$2x10^{21}$	n/m^3
epoxy	10^6	Gy
Polyimide/Kapton	10^7	Gy
CE/epoxy	$2x10^8$	Gy
org/inorganic hybrid	$5x10^8$	Gy
Mgo	10^{11}	Gy

V. FINITE ELEMENT WIRE MODELING

Finite element (FE) modeling of Nb_3Sn wires were developed to understand correlation of stress intension factor as the result of initial voids after wire heat treatment and its measured mechanical property. Bronze wire FE model (with randomly distributed voids) under an axial loading is developed to quantify impact of the void shape and size to wire irreversible strain limit. Local stress concentration around the initial void tip as result of cool down is expected as shown in Fig. 8-9. The first principal stress shows the local tensile stress concentration around the void tips. The stress intensity factor is 0.5 MPa $m^{0.5}$ for 45 degree angle voids. Existing Nb_3Sn fracture toughness measurement [16] indicates this brittle material has a fracture toughness of 1.1 MPa $m^{0.5}$.The level of stress intensity factors at void tips suggests that cracks

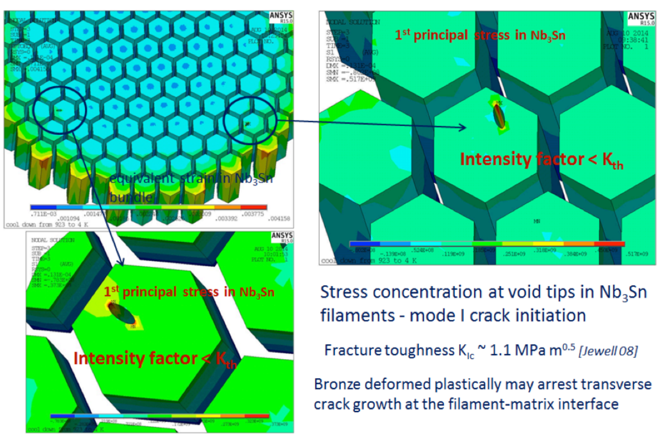

Fig. 8. Stress concertation around the voids inside filament bundles

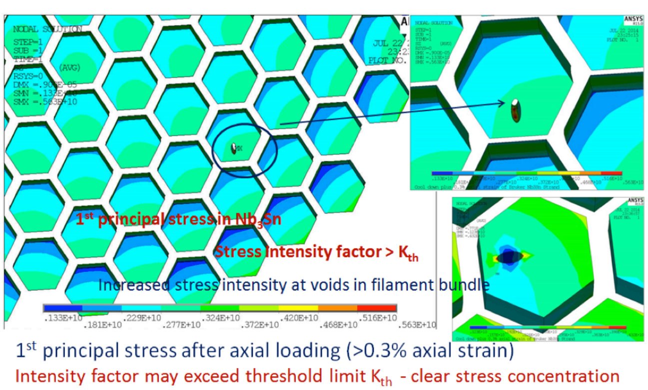

Fig. 9. Stress concertation around the voids inside filament bundles

may initiate at a relatively low level if wire in the coils is under an applied axial mechanical strain. Voids parallel to the longitudinal axis have a significantly less impact on stress intensity since they are less likely to activate cracks. Table VI presents the likelihood correlation between the void tip stress concentration and the wire irreversible strain limit for the two types of ITER-type Bronze wires studied.

TABLE VI
POTENTIAL CORRELATION - VOID TIP STRESS AND IRREVERSIBLE LIMIT

	Irreversible limit (%)	Average size (mm)	% of voids with high stress intensity
Bruker EAS	0.86	2	low
Bochvar & ChMP	0.8	3	low
PIT (EAS #29992)	0.4	10000	high

VI. HTS CONSIDERATION

Although FNSF is targeting a non-inductive plasma startup operation, a relatively small CS coil is still needed [1-3]. In addition to the Advanced Tokamak (AT) FNSF, an extension study of the Spherical Tokamak (ST) version of the FNSF has also been ongoing. Space for the TF coil winding pack is very much limited and improving winding pack current density is necessary. A concept of high current square shape HTS conductors of 25 layer YBCO tapes as shown in Figure 10 is proposed for design evaluation.

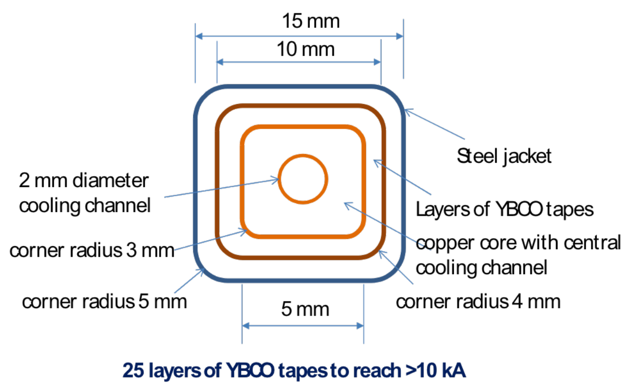

Fig. 10. High current HTS conductor of 25 layer YBCO tapes for FNSF

VII. CONCLUSION

FNSF is the stepping stone on the pathway to the next step fusion reactor such as DEMO and the pilot plant. It integrates fusion plasma environment with reactor components. Design of FNSF magnet system has unique challenge of high field in high nuclear radiation environment. TF magnet winding pack compositions, material radiation limits and global structural analysis based on a radial built for horizontal maintenance of FNSF are presented.

High temperature superconducting magnet is costly but offer higher field options for the need of small OH coils for FNSF. Research and development needs for FNSF magnets include wire and cable design option, joint for TF coils and better structural materials. The YBCO irradiation resistance is better than the high J_c ternary Nb_3Sn but less tolerant than the binary Nb_3Sn.

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