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Magnet Design Considerations for Fusion Nuclear Science Facility

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***Abstract*—The Fusion Nuclear Science Facility (FNSF) is the first strongly fusion nuclear confinement facility to provide an integrated fusion environment with fully integrated components to bridge the technical gaps of fusion plasma and fusion nuclear science between ITER and the demonstration power plant (DEMO). Compared to ITER, the FNSF is smaller in size but generates much higher magnetic field, 30 times higher neutron fluence with 3 orders of magnitude longer plasma operation at higher operating temperatures for structures surrounding the plasma. Input parameters to the magnet design from system code analysis include magnetic field of 7.5 T at the plasma center with plasma major radius of 4.8 m and minor radius of 1.2 m, and a peak field of 15.5 T on the TF coils for FNSF. Both lower temperature superconductor (LTS) and high temperature superconductor (HTS) are considered for the FNSF magnet design based on the state-of-the-art fusion magnet technology. The higher magnetic field can be achieved by using the high performance ternary Restack Rod Process (RRP) Nb_3Sn strands for toroidal field (TF) magnets. The circular cable-in-conduit conductor (CICC) design similar to ITER magnets and a high aspect ratio rectangular CICC design are evaluated for FNSF magnets but low activation jacket materials may need to be selected. The conductor design concept and TF coil winding pack composition and dimension based on the horizontal maintenance schemes are discussed. Neutron radiation limits for the LTS and HTS superconductors and electrical insulation materials are also reviewed based on the available materials previously tested. The material radiation limits for FNSF magnets are defined as part of the conceptual design studies for 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 the first nuclear fusion device to provide both a fully integrated fusion environment with the fully integrated fusion components [1-2]. The FNSF is necessary to bridge the technical gaps between International Thermonuclear Experimental Reactor (ITER), which is currently under construction in south of France, and the demonstration power plant (DEMO) [3]. Both resistive and superconducting magnet systems have been considered in the past for FNSF-type devices. Previous ARIES studies [4-5] 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 the coil winding packs were also assumed. To this end, the ARIES-RS [4] and ARIES-AT [5] studies are based on some ideal situations that may not be practical choices for the FNSF magnets.

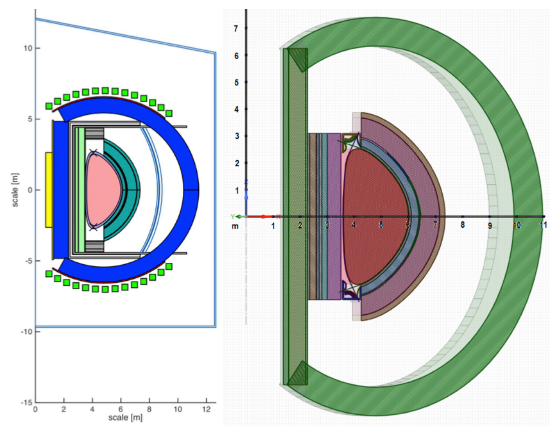

Fig. 1. (a) FNSF Ohmic Heating (yellow), Toroidal Field (blue) and Poloidal Field (light blue) coil and radial built from system code. (b) CAD model for establishing FNSF radial built.

In this paper, we first review the design challenges of large-scale, high-field fusion magnets and summarize the difference between the high-field solenoid or accelerator magnet design and the fusion magnet design. We then present the magnet requirements for the FNSF missions and focus on material radiation limits in the unique radiation environments for FNSF magnets. We also evaluate in details the LTS conductor option and design the winding pack compositions for the FNSF TF magnets. Lastly, we discuss radiation limits for the FNSF magnet materials and define the FNSF design limits. Better understanding of irradiation damage to conductors and insulation materials is needed for both LTS and HTS magnet options. Figure 1 presents the FNSF TF inner and outer leg radial built from the system code output.

In addition, R&D programs to advance LTS and HTS superconducting technology while reducing system cost are essential for the successful development of magnets for FNSF, as well as for DEMO and future power plants. The design is at present focused on the TF magnet system but OH and PF coil design will also be briefly discussed.

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II. FNSF Magnet System

A. Fusion power and magnet system

Fusion power scaling law is 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. The scaling law implies that for any economic fusion power, either improved plasma performance or increased toroidal magnetic field is needed. The design of a large-scale high field fusion magnet system is unique and very different from that of conventional high field solenoid or dipole magnet systems where the longitudinal hoop stress and mid-plane compressive stress (axial clamping force) are the dominant design stress factor. The fusion magnet system has complex geometry (largely as the result of system requirements) and the balancing need of the plasma pressure and magnetic pressure. The toroidal field (TF) coils are designed for plasma confinement, and the central solenoid (CS) coils as the plasma primary transformer are the Ohmic heating (OH) coils to initiate plasma current by the OH current and magnetic flux sweeping. The poloidal field (PF) coils are the equilibrium field coils to generate radially inward force to equilibrate a radially outward force for the plasma pressure equilibrium, and to control plasma shape during operation. Once energized, the D-shaped toroidal field (TF) coils are not only subjected to a large longitudinal hoop stress, but also to a large centering force due to the 1/R TF field decay as shown in Figure 2, and large transverse out-of-plane bending stress as a result of poloidal field interaction from PF and CS coils that requires a large amount of structural support (virial theorem). For large-scale fusion magnets, high current cables (>50-60 kA) are also needed for better protection of the TF coils during the fast discharges. In addition, auxiliary in-vessel coils for vertical stability and plasma ELM mode control and correction coils for refining error field harmonics are needed. The > 15 T peak magnetic field on the TF inner leg is likely to require the use of high performance advanced Nb_3Sn wires (advanced J_c wires) in the cable-in-conduit conductor (CICC) or even high temperature superconductors as the magnet design options.

B. FNSF Design Parameters

As the first nuclear fusion device to provide both a fully integrated fusion environment with the fully integrated fusion components, the FNSF magnet design parameters from the system code analysis are listed in Table 1 as compared to ITER and the DEMO design parameters. The FNSF is smaller than ITER machine while generating higher magnetic field (utilizing high performance Nb_3Sn strands). In comparison, both the K-DEMO – more aggressive in high field (B), and E-DEMO – more aggressive and thus expensive in size (R) are larger machines than ITER.

C. Magnet Design Consideration

For the horizontal maintenance of FNSF, large outer board TF legs are required. Straight assembly gaps shall be avoided to alleviate neutron streaming problems. Steady state or long pulsed operations for FNSF are considered for the magnet design.

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)	62.5	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 Amper-turns (MA)	11.25	9.11	15.72	19.8
No. of turns	180	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 cons		11-14		23
Fusion power (MW)	450	500	500	500

The next-step fusion reactors require magnet system with a sufficiently large aperture size for plasma fusion reaction. This makes fusion TF magnet highly in-efficient in utilizing the winding pack space because a significant amount of structure support is required to ensure structural integrity of the magnet system for a large sized high field TF magnet system. It is

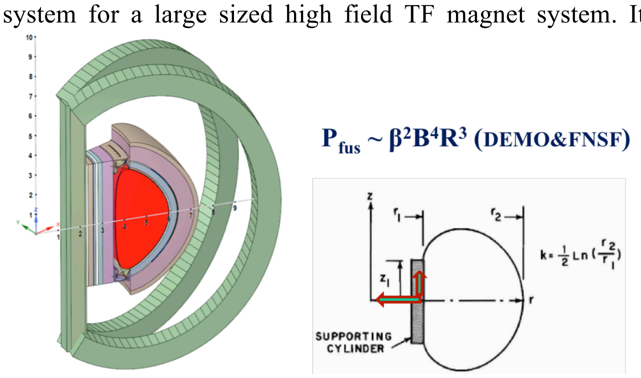

Fig. 2. CAD model generated based on FNSF radial built

common to have a 2-3 or even higher ratio between the maximum magnetic field on the TF inner leg and the plasma center field as compared to the close to 1-1.1 ratio between maximum field and the central field in typical high field solenoid or dipole magnets with a few cm's bore size. As a result, current density in state-of-the-art fusion TF coils such

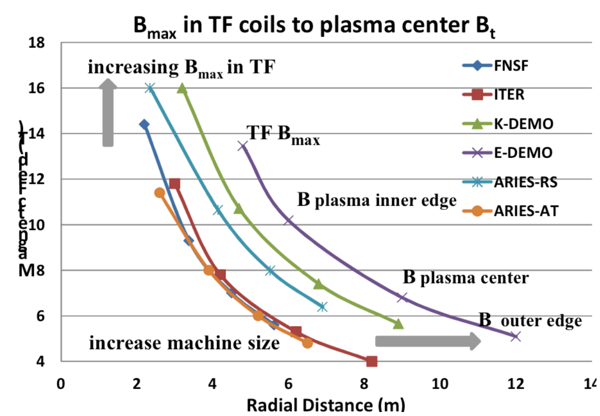

Fig. 3. (a) Toroidal magnetic field as function of radial distance for TF coil winding pack design

as in ITER 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 also CICC conductors

High field solenoid or accelerator magnets are generally designed to have a high pack factor and so to be highly efficient in using the high field winding pack space with high current density.

Figure 4 presents the inboard and outboard radial built for

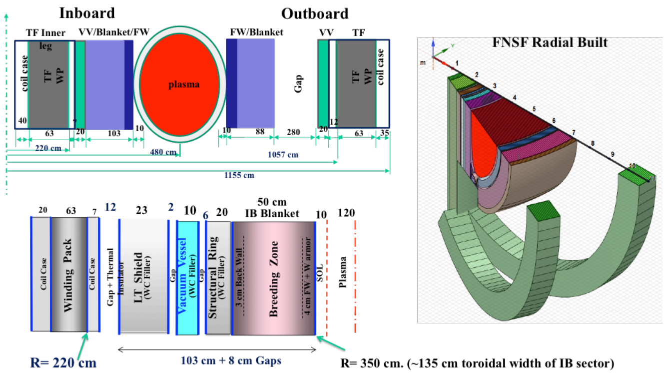

Fig. 4. Inboard and outboard radial built of FNSF (upper left) and details of inboard TF leg radial built (lower left). The plot on the right shows 3-D CAD model of inboard and outboard TF legs in the FNSF radial built.

the FNSF. A total inboard sector toroidal width of ~1.35 m is needed for the FNSF TF inner leg due to long pulse and high

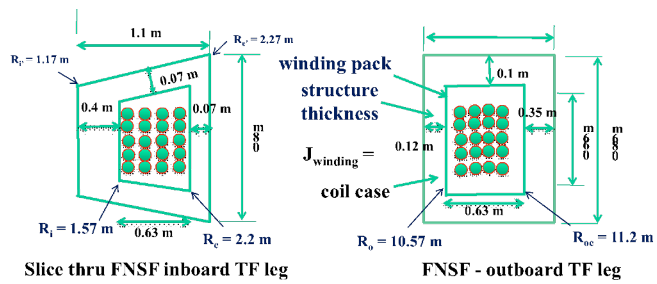

Fig. 5. (a) Dimensional details of TF inner leg winding pack (b) Dimensional details of FNSF TF outer leg and coil structure.

fluence operation.

III. TF Winding Pack

Figure 5 presents the TF coil winding pack composition. The TF coil design includes 65% cross-sectional area of the case structure with a thickness of 7-8 cm in facing plasma side, and 35% cross-sectional area of the coil winding pack, which includes 10% superconductor (about 600 Nb_3Sn superconducting strands), about 15-20% copper and 10% insulator. The low activation jacket structural material similar to JK2LB may be selected. Jacket and liquid helium cooling take about 30% of the winding pack area respectively.

A. *Wire Selection*

High performance Nb_3Sn wires such as the OST RRP wires for FNSF TF coil conductors will be selected for the winding pack design. Figure 6 presents the RRP wire cross section and a jacket thickness of 3-5 mm is needed.

B. *Cable Design Consideration*

For TF operation, high current cable is needed for coil protection during fast discharges. The 62.5 kA cable-in-conduit conductor with 180 turns will provide the needed Ampere-turns of 11.25 MA for the TF field at plasma center. There is a significantly larger coil centering force as compare to ITER TF coils.

C. *PF and CS coils*

Fields on PF coils are relatively small and NbTi can be a good LTS option. As the next step fusion machine, the plan for FNSF is steady state non-inductive startup operation. However, a very small OH coil is needed for small inductive current drive of the plasma operation. The size of the small OH coil makes the HTS coil design with no-insulation, no cable (direct winding of the HTS tapes) and no liquid helium and combined with conductor grading for improving coil wind efficiency a potential attractive option for the small size, high field FNSF OH coils.

D. *Conductor radiation limits*

Recent radiation test in LTS and HTS conductors [8-9] indicates that YBCO is no better than binary Nb3Sn but can be better (bellow 40 K operation) than the ternary Nb3Sn. REBCO at $3x10^{22}$ n/m2 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 II
Material Radiation Limits

materials	Fast neutron fluence	unit
Nb_3Sn	$5x10^{22}$	n/m^3
YBCO	$3x10^{22}$	n/m^3
Gd-123 (40 K)		
copper	$2x10^{21}$	n/m^3
epoxy	10^6	Gy
Polyimide/Kapton	10^7	Gy
CE/epoxy	$2x10^8$	Gy
hybrid	$5x10^8$	Gy
Mgo	10^{11}	Gy

YBCO is no better than binary Nb_3Sn but can be better (below 40 K) than ternary Nb_3Sn. Recent test indicates that REBCO at $3x10^{22}$ n/m^2 radiation has > 50% I_c degradation for 64 K operation and at $2x10^{22}$ n/m2 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 radiation.

TABLE III
CONDUCTOR AND COIL INSULATION

	Conductor	Conductor Insulation	TF Coil Impregnation
ITER	Nb_3Sn	Glass/Polyimide (Kapton)	Blended CE/DGEBF 40/60
ARIES-AT	YBCO	Inorganic MgO	High performance epoxy
FNSF LTS	Ternary Nb_3Sn	Glass/Kapton	Hybrid epoxy
FNSF HTS	REBCO	Ceramic MgO	Epoxy/MgO

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IV. CONCLUSION

For next step large scale fusion magnets designed for long pulse plasma or steady state operation after ITER, copper magnets cannot be a long-term option (~10 million dollars per pulse cost of electricity to run Fusion Development Facility for two week long steady state plasma duration). Low temperature superconducting magnets are the present-day state-of-the-art technology option. Initial construction cost can be reduced by conductor grading. Magnet materials with high radiation limits should be selected and tested. ITER experience of CICC performance degradation over significant load cycles is not a critical issue for steady state plasma operation.

High temperature superconducting magnet is costly but may offer better long term options for small Ohmic heating CS 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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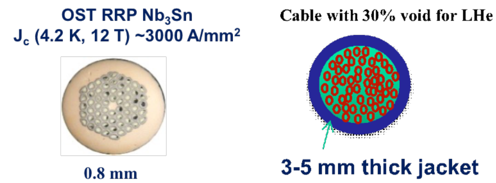

Fig. 6. State-of-the-art cable-in-conduit-conductors for ITER and next step fusion magnets.

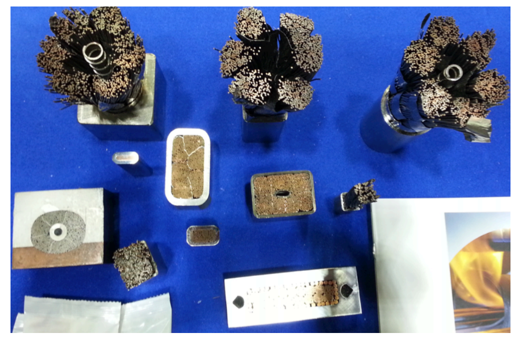

Fig. 7. State-of-the-art cable-in-conduit-conductors for ITER and next step fusion magnets.

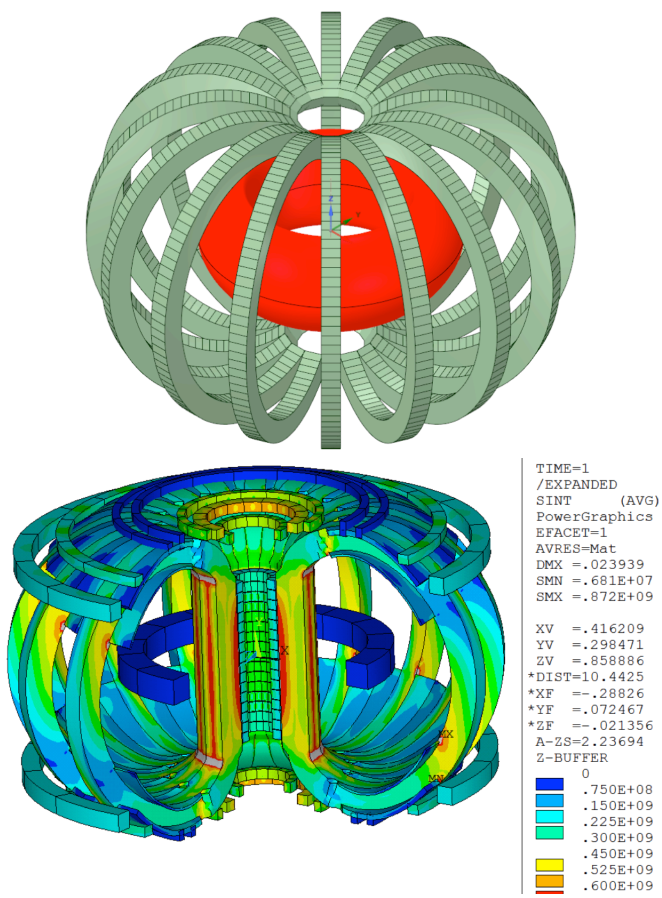

Fig. 8. Stress analysis under EM loads indicate that 1) the top and bottom caps for out-of-plane loads are needed 2) Outer board TF coil superstructure is required which enlarges the structural footprint mostly radially to accommodate horizontal maintenance and toroidal expansion of TF coil structural footprint also helps and should be taken advantage of 3) top and bottom OB structures are required to meet force and stress allowable.

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