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Conceptual magnet design study for fusion nuclear science facility

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ABSTRACT

The Fusion Nuclear Science Facility (FNSF) is a nuclear confinement device to provide the integrated fusion environment with fusion reactor components. The FNSF is the stepping stone to bridge the technical gaps of burning plasma and nuclear science between the International Thermal Nuclear Experimental Reactor (ITER), currently under construction in the south of France, and the demonstration power plant (DEMO). For the next-step fusion reactors, resistive copper magnet cannot be a sustainable solution due to large power consumption in coils of large size needed. Both Low temperature superconductor (LTS) and high temperature superconductor (HTS) are considered for the FNSF magnet design based on the state-of-the-art fusion superconducting magnet technology. Input parameters to FNSF magnet design include magnetic field of 7.5 T at plasma center with a major radius of 4.8 m and minor radius of 1.2 m, and a peak field of over 16 T on the TF coils. The high magnetic field can be achieved by using the high performance ternary Restack Rod Process (RRP) Nb_3Sn strands for toroidal field (TF) magnets and a high aspect ratio rectangular cable-in-conduit conductor (CICC) design. The conductor design concept and TF coil winding pack composition and dimension are discussed based on the horizontal maintenance scheme. Neutron radiation limits for the LTS and HTS conductors and electrical insulation materials are reviewed based on the available materials previously tested. The material radiation limits for FNSF magnets are defined as part of the conceptual design studies. The global structural analysis of FNSF magnets based on the radial build was performed to validate feasibility for the plant layout toward horizontal maintenance and global structural integrity of its magnet system.

1. Introduction

The Fusion Nuclear Science Facility (FNSF) [1–5] is the first nuclear fusion device to provide an integrated fusion environment with fully integrated components to bridge the technical gaps of fusion plasma science and fusion power generation between ITER, currently under construction in France, and the demonstration power plate (DEMO) under worldwide design studies. The FNSF provides the critical database on ultra-long pulse plasma operation, materials, integrated components and the fusion environment, and operating behavior that is needed to pursue a DEMO. This facility advances several missions such as fusion neutron fluence on the blanket, qualification of the plasma facing materials and components, tritium breeding etc. toward ultimately a commercial fusion power plant [1,2]. The FNSF is smaller than ITER and a DEMO to reduce cost and to facilitate a break-in program. Fig. 1 presents the conceptual design of the advanced tokamak FNSF.

Magnet systems are the core empowering technology for the magnetic confinement fusion reactors. Strong magnetic fields are required for the plasma confinement, and fast flux swing of magnetic fields is needed for plasma start-up, shaping, equilibrium and stability control. Both resistive copper magnet and the superconducting magnet systems have been proposed in the past as a favorable choice for FNSF [6,7]. For the next-step large scale fusion magnets designed for long pulse or steady state plasma operation, copper magnets cannot be an efficient long-term option (10 million dollars per pulse electricity cost to run the Fusion Development Facility for two week long steady-state plasma duration [5]). Previous ARIES studies [6,7] assumed full material availability of the most promising Low Temperature superconductor (LTS) and advanced High Temperature superconductor (HTS): the high critical current Nb_3Sn wires and the Yttrium Barium Copper Oxide (YBCO) tapes. More optimistic neutron radiation limits of the LTS and HTS and the organic electrical insulations in coil winding packs were also assumed. The ARIES-RS and ARIES-AT studies were exploring some ideal situations that may not be practical choices for the FNSF magnets.

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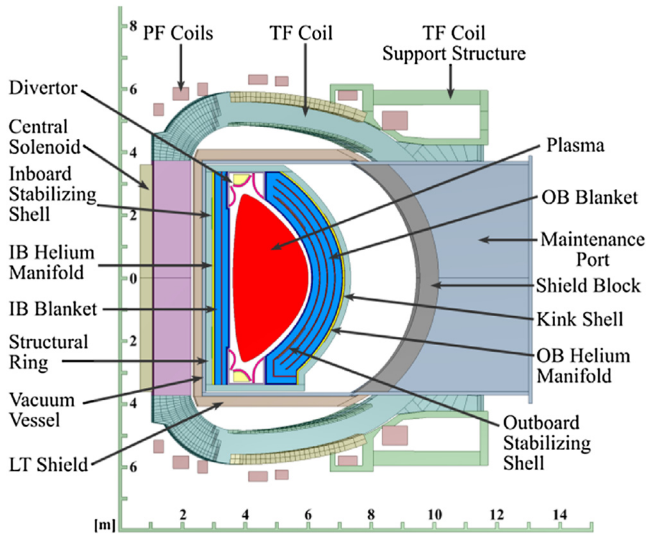

Fig. 1. Conceptual design of Fusion Nuclear Science Facility.

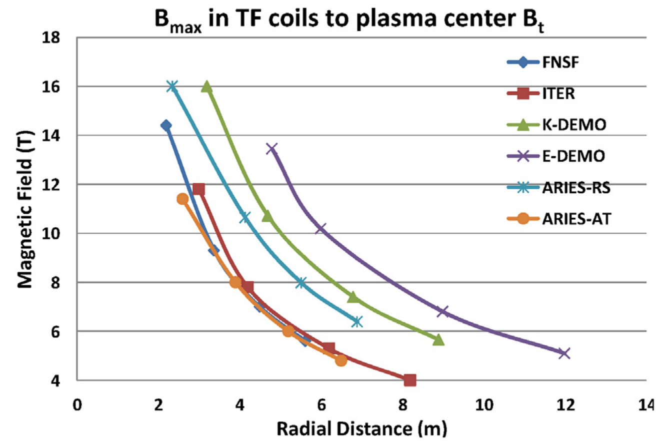

Fig. 2. Toroidal field decay in the mid-plane as function of radial distance (impact from TF outer leg neglected).

We present design parameters for the FNSF missions and focus on utilizing advanced capabilities of the high performance superconducting wires for the toroidal field (TF) coil conductor and TF winding pack design. The magnet design is based on FNSF radial build from the system code analysis [1]. For LTS options, the advanced J_c Nb_3Sn Restack Rod Process (RRP) strand (J_c > 1000 A/mm^2 at 16 T, 4.2 K) manufactured previously by Oxford Superconducting Technology (OST), now part of Bruker Energy and Superconducting Technologies Inc., is under consideration [8–11]. The high strength but low activation jacket materials may also need to be selected.

The FNSF is smaller in size than ITER 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 [1]. The design presented here is focused on the challenging TF magnet system and the TF winding pack details. FNSF will focus on the nuclear and materials science missions to bridge the gap between ITER and the DEMO [1,2].

Better understanding of neutron irradiation damage to superconductors and insulation materials is needed for both LTS and HTS magnet options for the design of next-step fusion magnets [21,22,76,77]. The material radiation limits under unique plasma operating environment for the FNSF magnets are considered in the magnet design. We summarize recent results of LTS and HTS material irradiation tests for the next-generation accelerator magnets and define the material design radiation limits for the FNSF magnets.

The horizontal access of one full sector and one per TF coil offers the easiest, most expedient, reliable and more flexible approach to achieve the required plant availability for FNSF from the view of the device core. Other approaches carry a higher level of technical risk, a longer maintenance period duration and they do not offer flexibility to accommodate access for special systems and the approach for higher levels of availability for future facilities. We also demonstrated in the coil structural analysis that it is feasible to design the inter-coil support structure with sufficient bending stiffness to react the out-of-plane loading. The global structural analysis of proposed FNSF radial build design including the TF, CS and PF coils and the coil support structures was performed to validate feasibility for horizontal full sector maintenance and the global structural integrity of the FNSF magnet system.

2. Fusion magnet design

The fusion power scaling is known to be $P_F \sim \beta^2 B^4$, where β is the plasma pressure to magnetic field pressure ratio and B is the magnetic field at the plasma major radius. The plasma pressure is directly related to fusion power reaction rate based on its density and temperature. An overall dependence of B^2 for the same fusion power implies that for economics of fusion energy, improved plasma performance and/or increased toroidal magnetic field is required [23,24]. The design of a large-scale high field fusion magnet system is unique and different from that of any conventional high field solenoid or accelerator dipole magnet systems where the longitudinal hoop stress and the resultant mid-plane compressive stress of axial clamping force are dominant. Fusion magnet system has more complex geometry as the result of system requirements and the balancing need of plasma pressure and magnetic pressure. The TF coils are designed for plasma confinement; the CS coils as the plasma primary transformer are designed to initiate the plasma current by a fast magnetic flux swing. Although FNSF is intended to adopt largely the non-inductive current drive approach for its operation, relative small CS coils are still needed to facilitate plasma startups [1]. The 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 TF coils are not only subjected to a large longitudinal hoop stress, but also a large centering force due to the 1/R TF field decay shown in Fig. 2, and the large transverse out-of-plane bending stress as a result of the interaction with the poloidal field generated from the PF and CS coils. The magnetic field ripple effect in FNSF is less significant than that in ITER due to the fact that FNSF TF outer legs were pushed radially further away from plasma for the horizontal maintenance shown in Fig. 1. As a result of the out-of-plane loading, a large amount of structural support (virial theorem) is needed [24]. For large-scale fusion magnet design, high current cables (>50–60 kA) are required to limit the coil inductance and thus limit the coil terminal and ground voltages during safety discharges of magnets with the high stored energy [13–15]. The high peak magnetic field on the TF inner leg of ∼16 T requires the use of high performance (advanced J_c) Nb_3Sn wires in the cable-in-conduit conductors (CICCs). The high temperature superconductors are needed for higher field (17–20 T) magnet design options as well as high current density needs (>60 A/mm^2) in the coil winding pack due to the space limit for TF and CS coils.