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Abstract

The consideration for building an International Engineering Test Reactor emerged from the November 1985 Geneva Summit, in which President Reagan and Secretary Gorbachev called for the "widest practical development of international cooperation" in fusion. In parallel with the OTR design in the USSR, the FER in Japan, and the NET in Europe, the U.S. has pursued the TIBER (Tokamak Ignition/Burn Experimental Reactor). This compact design of 3-m major radius is achievable because of high-current-density, radiation-tolerant magnets with nuclear heating rates up to $10 \text{ MW}\cdot\text{cm}^{-3}$. Full development of cable-in-conduit conductors (CICC) is seen as a credible path to achieve $40 \text{ A}\cdot\text{cm}^{-2}$ at fields of 12 T in the toroidal field (TF) coils and 14 T in the central poloidal field (PF) coils. Since neutron fluences of up to $10^{19} \text{ n}\cdot\text{cm}^{-2}$ are expected in the TF coils, the unalloyed niobium-tin would be superior at 12 T. However, the central PF coil at 14 T is better shielded, so modified niobium tin would be advantageous. Polyimide insulation in the TF coils would withstand the equivalent 10^{10} rads if loads in the winding pack are taken in compression.

Introduction

The TIBER II shown in Fig. 1 is being pursued as the U.S. option for an International Engineering Test Reactor (ETR). This concept evolved from earlier work on a superconducting option for the Tokamak Fusion Core Experiment (TFEX), an effort to develop a small, ignited tokamak. The copper-coil versions of TFEX became the short-pulsed, 1.23-m radius, Compact Ignition Tokamak (CIT), whereas the superconducting TIBER with long pulse or steady state and a 2.6-m radius¹ became a candidate for international collaboration. Recently, the design has been updated to TIBER II,² which can accommodate the conservative Kaye-Goldston confinement scaling, double-poloidal divertors for impurity control, steady-state current drive, and nuclear testing.

Minimum neutron shielding, compact structures, divertor, and high-current-density magnets all contribute to the compact size. However, the thin neutron shield (less than 50 cm in places) not only increases nuclear heating in the TF coil, but requires increased radiation tolerance of the superconductors and insulators. Nominal parameters for TIBER II are given in Table 1.

High-Current-Density, Radiation-Tolerant Magnets

High-current density in the TF coils and the central solenoid are used to limit the dimensions of the center post region. The current density in the TF system must be compatible with the higher neutron fluence resulting from a thin neutron shield. Fortunately, with CICC using Nb_3Sn and force-cooled by supercritical helium, the temperature margin is high and heat removal is large and predictable. In addition, stability against disturbances in the CICC is more dependent on the heat capacity of helium and less limited by heat transfer and copper conductivity as with typical cryostable conductor designs, permitting about twice the typical current density of such large magnets. Because the neutron-damage-induced resistivity rise in the copper is of lesser importance,³ annealing of copper may be unnecessary for stability. Further radiation tolerance of the magnet is achieved by using polyimide insulators that can withstand more than 10^{11} rads of neutron damage while retaining adequate strength against compressive loads.⁴

Figure 2 plots the effects of high-energy neutron fluence on Nb_3Sn conductors, both for pure conductors

and for those modified by adding a third element.⁵ The samples tested were irradiated with 14.1-MeV neutrons at room temperature and then tested for critical current at 4.2 K. The lower horizontal axis in Fig. 2 accounts for the "softer" neutron-energy spectrum calculated for the shielding to be used in TIBER II. The current densities initially increase because the damage increases the normal-state resistivity of the superconductors, which increases the upper critical field. Eventually, at high fluence, the decreases in performance are caused by decreasing critical temperature with increased damage. In the modified materials, the upper critical field has been optimized by adding a third element to increase the normal-state resistivity. Therefore, any further increase due to damage is expected to be small. For unmodified Nb_3Sn , the conductor will retain its initial performance or better beyond the $10^{19} \text{ n}\cdot\text{cm}^{-2}$ fluence in TIBER II. Modified Nb_3Sn will be useful for attaining the high-

1. Model of the TIBER II, the U.S. option for an International ETR.

Table 1. Radiation Environment in the TF Coils

Nuclear heating rate	$10 \text{ MW}\cdot\text{cm}^{-3}$ peak
Superconductor neutron fluence	$10^{19} \text{ n}\cdot\text{cm}^{-2}$
Insulator dose	10^{11} rads
Copper damage	10^{-2} dpa
Lifetime	10^8 s

2. Normalized critical current of Nb_3Sn superconductors vs fluence from a 14.1-MeV neutron source. The lower horizontal axis accounts for the "softer" spectrum expected in TIBER II.

field performance in the central solenoid, where the high-field windings are essentially completely shielded by the TF system and the outer, lower-field turns.

Stability in a CICC is obtained primarily from the enthalpy available in the internal helium over the temperature margin provided by operating the conductor at less than its critical current. As a result, there is no large penalty on stability as the conductivity of the copper is reduced by accumulated damage. However, to protect the TIBER-II magnets in the event of a quench, knowledge of copper resistivity vs damage is essential. We assume the residual resistivity of copper is increased by radiation damage according to

$$\Delta\rho_0 = s[1 - \exp(-\dot{D}/S)] ,$$

where $s = 3.0 \text{ n}\Omega\cdot\text{m}$ is the saturation level, D is the damage, and $\dot{D} = 720 \text{ n}\Omega\cdot\text{m}\cdot\text{dpa}^{-1}$ is the saturation rate.⁶ Magnetoresistivity is a function of field B per the relation

$$\rho(B) = \rho_0(1 + 0.0339 (B/\rho_0)^{1.07}) ,$$

where ρ_0 includes the effects of radiation damage.⁷

In a CICC system, the strain in the Nb_3Sn filaments determines critical current at operating conditions. Differential strains in the sheath and the cable result from formation at about 1000 K, cooldown to the operating temperature at about 4 K, and electromagnetic forces due to charging to full field and current. An experimental program at LLNL is examining the conductor/sheath interaction through a series of electromechanical tests; some results are already available.

In the first series of tests, the critical currents of model CICC were measured while the axial load applied to the sheath was increased by small

increments until the measured critical current was observed to pass through a maximum.⁸ The ratio I_c/I_{cm} of initial or "no-load" critical current to maximum critical current varied with the fraction of the internal space available for helium in the otherwise identical specimens. These data are plotted in Fig. 3; other values for similar conductors are inferred from data in the literature.⁸ In more recent tests, the variation of strain in the superconductor has been measured under electromagnetically generated loads typical of the situation in a magnet (cf. Fig. 4).⁹ We expect continued testing to give the predictive capability we need to determine the strain state of the superconductor in a CICC at the conditions of operation, which is essential for reliable design with Nb_3Sn at high-fields. The coils for the TIBER-II TF system and central solenoid of the PF system will be wound before reaction for performance and strain predictability.

Polooidal Field Coils

The PF system was designed with the aid of the FEDC equilibrium code, which performs fixed- and free-boundary toroidal equilibria analyses.¹⁰ In fact, two separate systems have been designed. In the baseline configuration where we want to drive the current by other than inductive means, a minimum number of coils was designed to achieve the desired plasma shape. We used a pair of equilibrium coils on the outboard, two elongation coils at the top and bottom, puller coils near the tips of the plasma, and a pusher coil at the midplane.² Only about 12 V/s of usable flux swing is available in an "OH flat-top" mode in this configuration. Alternative configurations have been investigated in which all available space in the core of the machine was filled with coils to increase the flux swing to 58 V/s while maintaining the plasma shape.¹¹ (Fig. 1).

In the baseline configuration, the peak field in the pusher coil is 14 T and an average winding pack current density of $40 \text{ A}\cdot\text{mm}^{-2}$ is required. A layer wound design with current-density grading at 14, 11, and 8.5 T was chosen to attain that performance. For the alternate design, both the field and the current

3. Variation with helium fraction of the ratio of initial or unloaded critical current to maximum critical current in a group of similar cable-in-conduit conductors. Applied field was 12 T.

4. Variation of critical current in a test conductor with sheath strains resulting from electromagnetically generated loads.

density requirements are slightly lower, but ramped fields are an added complication, especially because of the cyclic loads and the implications regarding limited life due to fatigue. We ameliorate the fatigue problem for the coils of the central solenoid by designing them to support and be supported by the inward force at the TF system.

The coils are designed to be layer wound with a 60-mm-thick case at the outer diameter. Current leads enter the modules through the high-field region at the center so that the interface between the outer layer of a coil and its thick outer case is solid. The coil is vacuum impregnated in its case after winding. There are 16 coil modules in the central solenoid. The stack is tied together vertically by a tension member with a + shaped cross section. The open quadrants of the + allow space for the current leads and helium connections to reach the coil modules.

An analysis has been made of the stresses in the PF modules loaded on the outside by the TF system using the codes STANSOL¹² and EFFI.¹³ Figure 5 shows the hoop strain vs radius in a particular module if: (a) the central solenoid is charged to full current without loading from the TF system; (b) the central solenoid is loaded by the TF system, but not charged; and (c) the central solenoid is both loaded by the TF system and charged to full current. Operation (a) would be limited by fatigue to about 10,000 cycles; however, if the TF system always loaded the central solenoid as in (b) and (c), a module would always remain in compression, as indicated in Fig. 5, and thus has a greatly extended fatigue life.

Toroidal Field Coils

The TF system produces 6 T at the plasma radius of 3 m. The space requirements for the plasma, blanket shield, etc., dictate that the TF coils have an opening of about 6 m on the vertical and about 4 m on the

5. Calculated hoop strain vs radius in the windings of a central solenoid module under three load conditions: (a) full current in the central solenoid, not loaded on the outside by the TF system; (b) loaded on the outside, but no current; and (c) full current and loaded by the TF. In the present design, central solenoid modules would cycle between the states represented by (b) and (c).

horizontal. Coil protection and forces on the conductor within the winding pack are determining factors in the design. The requirements can be met with a 16-coil set, a winding-pack current density of $40 \text{ A}\cdot\text{mm}^{-2}$, and a maximum field of 12 T. The CICC design for the TF system has a structural channel outside the conduit as shown in Fig. 6. Coil and winding-pack parameters are summarized in Table 2.

We used a pancake-wound coil design and a single grade of conductor, which eased the problem of nuclear heat removal. Detailed analyses of the heat removal issue show that respectable operating margins are retained even with 72-kW nuclear heating in the TF system (cf. Fig. 7), which represents an upper bound on estimates with the TIBER shield system.¹¹

6. A cable-in-conduit conductor design for the TF system showing a structural channel added outside the helium containment sheath.

Table 2. TF Coil Parameters

Total current	5.2 MA
Stored energy	380 MJ/coil
Coil dump voltage	10 kV
Conductor current	36 kA
Critical current at 12 T, 4.5 K, and operating strain level	60 kA
Winding-pack cross section	0.130 m ²
Average winding-pack current	40 A/mm ²
Density	144
Number of turns	Pancake
Winding type	904 mm ²
Effective area of a turn (Conductor + insulation)	(26.9 mm x 33.6 mm)
Cable space current density	71 A/mm ²
Fraction of conductor in the cable space	0.60
Fraction of copper in the conductor	0.60
Cable pattern	5 x 5 x 5 x 3 x 1.02 mm dia.
Overall winding-pack materials fractions:	
f' steel	0.37
f' insulation	0.05
f' cond	0.34
f' He	0.23
Est. maximum hot-spot temperature	130 K
Est. maximum quench pressure	40 MPa

Summary

TIBER-II is designed to achieve compactness and lower costs by using performance characteristics of superconducting magnet systems that exceed traditional levels on several counts, e.g., higher fields, higher current densities, and higher levels of radiation exposure on the windings. Although untraditional, the fundamental design is sound, and the benefits to be achieved from the smaller size are great.

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References

1. C. D. Henning et al., "TIBER--Tokamak Ignition/Burn Experimental Research," *Proc. of the 11th Symp. on Fusion Eng.*, Nov. 1985, IEEE Cat. No. CH2251-7, p. 331.
2. C. D. Henning et al., "TIBER-II--an Upgraded Tokamak Ignition/Burn Experimental Reactor," *Fusion Technology* 10, 1079 (1986).
3. J. R. Miller, "Empirical Investigation of Factors Affecting the Stability of Cable-In-Conduit Superconductors," *Cryogenics* 25, 552 (1985).
4. C. D. Henning et al., "Superconducting (Radiation-Hardened) Magnets for Mirror Fusion Devices," *Proc. of the 10th Symp. on Fusion Eng.*, December 1983, IEEE Cat. No. B3CWI916-6.
5. F. Weiss, R. Flukiger, W. Maurer, P. A. Hahn, and M. W. Guinan, "Changes in Superconducting Properties by Room-Temperature Irradiation for Binary and Alloyed Nb₃Sn Multifilamentary Wires," presented at the Applied Superconductivity Conference, Baltimore, MD, September 1986.

7. Calculated available stability margin vs distance along a conductor in a TF winding with 72-kW total nuclear heat load to the TF system. TF coils are pancake wound with supercritical He at 4.5 K injected into the inner, crossover turn and removed at the outer joints. For this case, $\dot{m} = 21 \text{ g s}^{-1}$ in the channel, obtained with $p_{in} = 2.5 \text{ MPa}$ and $p_{out} = 1.2 \text{ MPa}$.
6. M. Sawan, "Charts for Specifying Limits on Copper Stabilizer Damage Rate," *J. Nucl. Mat.*, 122-123, 1376 (1984).
7. M. W. Guinan, *Radiation Effects Limits on Copper in Superconducting Magnets*, Lawrence Livermore National Laboratory, Livermore, CA, UCID-19800 (1983).
8. J. R. Miller et al., "The Initial Filament Strain State of Cable-In-Conduit Superconductors and Its Relation to the Design of Large-Bore, High-Field Magnets," accepted for publication in the *Proceedings of the 1986 Applied Superconductivity Conference, Baltimore, MD*.
9. J. R. Miller et al., "Investigations of Cable-Sheath Interactions in Cable-In-Conduit Superconductors," presented at the International Cryogenic Materials Conference, St. Charles, IL, June 14-18, 1987.
10. D. J. Strickler et al., *Equilibrium Modeling of the TFCC Poloidal Field Coil System*, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL/FEDC-83/10 (1984).
11. TIBER II/ETR final Design Report, Lawrence Livermore National Laboratory, Livermore, CA, UCID-21150 (in press).
12. The version of STANSOL used is a modification described in W. H. Gray, "Stress Analysis of Solenoids That Develop Gaps," *IEEE Trans. on Magnetics*, MAG-18, 679 (1982).
13. S. J. Sackett, *EFFI--A Code for Calculating the Electromagnetic Field, Force, and Inductance in Coil Systems of Arbitrary Geometry*, Lawrence Livermore National Laboratory, Livermore, CA, UCID-17621 (1977).