§31. Design of 15 T Magnets with Cold Bore of 0.7 m Using Rectangular Conductors

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High field superconducting magnets with large current conductors are needed for future fusion power plants. Degradation of the current sharing temperatures by electromagnetic forces is crucial for brittle superconductors such as Nb_3Sn. It will be more serious in the higher field magnets. Therefore, high field test facility with a large bore is necessary to examine the conductors in real conditions. Coil samples are proposed instead of straight samples to apply electromagnetic hoop forces on the conductors. The outer dimension of the conductors of 100 kA class is around 50 mm. The minimum bend radius of conductors by cold work must be longer than 5 times the outer dimension, and 10 times the dimension is preferable to avoid large deformation of the cross-section. Then, the required bore is longer than 0.6 m. Considering the diameter of the cryostat, the existing 9 T test facility in NIFS is planned to be upgraded to 15 T solenoid coils with the large cold bore of 0.6 m, as shown in Fig. 1.

For the early construction, two rectangular conductors are chosen from commercial lineups of Nb_3Sn and NbTi conductors. Since large current is preferred to reduce the shut-off voltage, the largest conductors in the lineup are selected. The copper ratio of Nb_3Sn conductor is set at 0.9 to attain the temperature margin of more than 2 K at 15 T at the operation current of 750 A. The copper ratio of NbTi conductor is set at 2.4 considering the temperature margin of more than 1 K at 7T and the temperature rise during shut-off. The design criteria are as follows: (1) Two grades of conductors, NbTi and Nb_3Sn are adopted. The highest field in the outer coil is around 7 T for NbTi conductor to attain the high current density. (2) An external resistor is adopted for the quench protection. In order to suppress the hot spot temperature lower than 200 K. (3) The shut-off voltage between layers is lower than 147 V to adopt a thin insulation. (4) The temperature margins of Nb_3Sn and NbTi conductors are larger than 2.0 K and 1.0 K, respectively. (5) Average hoop stress of supporting rings of SUS316 is lower than 600 MPa. The inner and outer coils are divided into four and three blocks, respectively, and each block is supported by each ring made of SUS316. Thicknesses of the rings are determined to withstand the electromagnetic force by themselves only.

The inside case of the inner coil is set at 3 mm thick just for the protection of the coil. In order to reduce the highest field in the outer coil, the length of its innermost block is shorten. The layer numbers of coil blocks are 12, 12, 12, 12, 10, 16, and 16 from the inside. The thicknesses of the supporting rings are 14, 14, 11, 8, 7, 7, and 8 mm from the inside to maintain the largest strain of the conductor within 0.3%. The turn numbers of coil blocks are optimized to reduce the number of joints and loss of conductors. A selected design is shown in Table 1. The total magnetic stored energy is 39.1 MJ, and the total weight of the coils is estimated at 4.9 tons without external supports. The innermost block of the inner coil is designed to be installed individually to enlarge the bore.

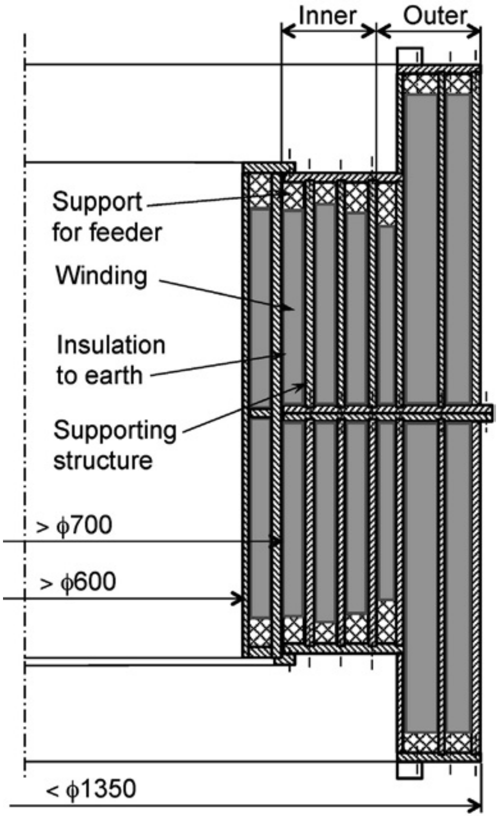

Fig. 1. Layout of 15 T - 0.7 m solenoid coils and a test sample.

Table 1. Specifications of the solenoid coils

	Inner coil	Outer coil
Field at sample position (T)	15.0 at 0.3 m	7.4 at 0.44 m
Maximum field, B_{max} (T)	15.00	6.85
Cold bore diameter (m)	0.60	0.933
Stored energy (MJ)	16.0	23.1
Self inductance (H)	28.8	53.6
Mutual inductance (H)	27.4	
SC material	Nb_3 Sn	NbTi
Temperature (K)	4.4	4.4
Critical current at B_{max}, I_c (A)	1223	3383
I_{op}/I_c on the load line (%)	87.9	73.4
Temperature margin (K)	2.05	1.50
Cu/SC ratio (-)	0.9	2.4
Winding inner diameter (m)	0.612	0.954
Winding outer diameter (m)	0.932	1.176
Outer diameter of coil case (m)	1.029	1.308
Av. winding length (m)	0.55	0.87
Magnetomotive force (MA)	5.58	6.45
Turn number	7392	8544
Operating current, I_{op} (A)	755	755
Conductor width (bare) (mm)	3.2	4.0
Conductor height (bare) (mm)	2.1	2.0
Conductor cross-section (mm^2)	6.51	7.79
Thickness of layer insulation (mm)	0.2	0.1
Cross-section per turn (mm^2)	7.82	8.61
Coil current density (A/mm^2)	96.5	85.9
Thickness of insulation (mm)	0.2	0.2
Conductor length (km)	17.9	29.0
Thickness of side flange (mm)	10	10
Dump resistance (ohm)	7.86	6.38
Highest voltage between layers (V)	136	136
Weight (tons)	1.96	2.88