§24. Configuration Optimization of 15 T Magnets with Cold Bore of 0.7 m

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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 dimensiont 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 0.7 m, as shown in Fig. 1.

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 by shut-off with the time constant of 16 s, the copper current density is set at 112.3 A/mm^2. (3) The shut-off voltage is lower than 800 V to adopt a thin insulation. Therefore, conductor current is set at 6 kA, and a Rutherford type conductor is selected. The packing factor of wires is assumed to be 92%. (4) Average hoop stress of supporting rings of SUS316 is lower than 600 MPa. The thicknesses of outside cases of the inner and outer coils are set at 40 and 20 mm, respectively, to withstand the electromagnetic force by themselves only. The inside case of the inner coil is set at 10 mm thick in considering the role to fix samples, and that of the outer coil is 7 mm thick.

From the study on a single solenoid with Nb_3Sn wires, the current density of the inner coil is set at 65 A/mm^2 to maintain the load factor less than 90%, which seems marginal even for firmly fixed magnets. Its length is set at 1.2 m to shorten the outer diameter of the single solenoid within 1.3 m. After that the turn number of the inner coil is determined to make the highest field in the outer coil less than 7.5 T. The length of the outer coil is optimized for the same inner coil as shown in Fig. 2. Its current density is fixed at 81.5 A/mm^2 to attain the temperature margin of 1.0 K at the length of 1.0 m. By shortening the outer coil from 1.2 m, the highest voltage and weight decrease, and the load factor is the lowest around 0.9 m. The optimal range of length is 0.8 to 1.0 m, and 0.8 m is selected because the lighter weight is preferable for the test facility to shorten the cool-down and warm-up time. A selected design is shown in Table 1. The total magnetic stored energy is 64.8 MJ, and the total weight of the coils is estimated at 8.1 tons. It will take one week to cool-down with the existing helium refrigerator, the liquefying power of which is 200 liter/hour. New wires with the higher critical current are effective to lower the load factors.

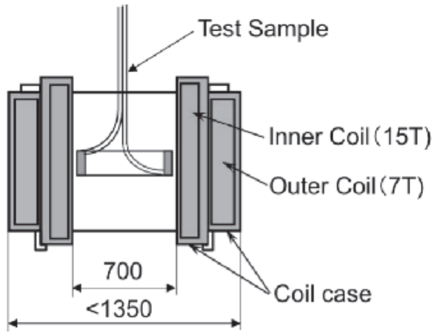

Fig. 1. Layout of 15 T - 0.7 m solenoid coils and a test sample.

Table 1. Specifications of the solenoid coils

	Inner	Outer
Field at sample position (T)	15.0 at 0.3 m	7.4 at 0.44 m
Maximum field, B_{max} (T)	15.37	7.20
Cold bore diameter (m)	0.70	1.035
Stored energy (MJ)	15.6	23.6
Self inductance (H)	0.867	1.309
SC material	Nb_3 Sn (or Al)	NbTi
Temperature (K)	4.4	4.4
Operating current, I_{op} (A)	6000	6000
Critical current at B_{max}, I_c (A)	10980	13140
I_{op}/I_c on the load line (%)	90.4	82.6
Temperature margin (K)	1.41	1.00
Cu/SC ratio (-)	1.573	3.71
Winding inner diameter (m)	0.720	1.049
Winding outer diameter (m)	0.949	1.268
Outer diameter of coil case (m)	1.029	1.308
Winding length (m)	1.2	0.8
Magnetomotive force (MA)	9.00	7.13
Coil current density (A/mm^2)	65.5	81.5
Strand cross-section (mm^2)	2.5	2.61
Number of strads (-)	16	20
Thickness of insulation (mm)	0.2	0.2
Conductor length (km)	3.93	4.32
Thickness of side flange (mm)	15	15
Highest voltage (V)	592	758
Weight (tons)	4.56	3.54

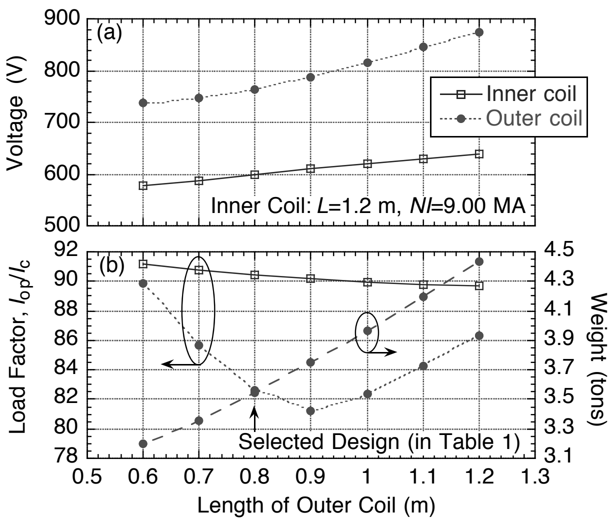

Fig. 2. The voltage during shut-off (a), load factor and weight (b) versus the length of the outer coil.