§2. Feasibility Study of React-and-Wind Method to Helical Coil for LHD-type Reactor

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Main specifications of helical coils for an LHD-type reactor, FFHR2m[1)] are as follows: the magnet-motive force of about 40 MA, the magnetic energy of 120 to 130 GJ, a coil center line of 150 to 175 m, and average coil current density of 25 to 30 A/mm^2. Design criteria for CIC conductors based on the ITER magnets are summarized in Table 1. Since the length of the coil center line of the helical coil is five times as long as the TF coil, some ideas are necessary in addition to adopting a large current of almost 100 kA. Parallel winding is a practical solution to shorten the cooling length within about 500 m.

Two types of mechanical structure are known for CIC conductors. One is a thick conduit type, in which rectangular conductors are simply wound with being wrapped by insulating tapes. Fairly high stress is induced in the insulators by summed up forces on the conductors in line. The other is an internal plate type, in which the conductor is wound in the grooves of the internal plate. The stress in the insulation is reduced. Besides, the force for winding is relatively small because of thin conduits. Its disadvantage is complicated manufacturing process of the internal plates. However, its technology will be improved through the construction of ITER-TF coils. Internal plates with grooves are suited for parallel winding, because CIC conductors are just put in the grooves as shown in Fig.1. In this concept, a react-and-wind method is preferred to use conventional insulator and to prevent huge thermal stress. Nb_3Al is a candidate for the superconducting strands of the conductor because of its good tolerance against mechanical strain. Degradation of the critical current density of Nb_3Al by the axial strain of 0.4% at 12 T is only 5% in comparison with more than 30% of Nb_3Sn. A method of react-and-wind can be adopted by managing strain during winding within about 0.5%.

A winding method is a critical issue for the helical coil. In the case of LHD, a special winding machine was developed. The conductors from a rotating bobbin were plastically formed into the helical shape by the shaping head near the winding guide. This method will not be compatible with the react-and-wind method, because the allowable strain is in the range of 0.5% even for Nb_3Al strands. A candidate of winding method is as follows:

(1) Conductors are heated for reaction of Nb_3Al on a bobbin the circumference of which is same as the length of one pitch of the helical coil.

(2) The conductors are transferred to a reel of a winding machine. The reel revolves through the helical coil as shown in Fig. 2.

(3) The conductors are pulled aside by a set of winding guides and wound in grooves of the inner plate with being wrapped with glass tapes.

(4) After winding the whole turns in a layer, the next inner plates are assembled.

The torsion strain $r\theta$ in winding is given as

$$r\theta = \frac{r \cdot tan^{-1}\eta}{2\pi a_c/4} \qquad (1)$$

where r and η are the radius of the conductor and the lead angle of the helical coil. In the case of FFHR2m2, the strain is estimated at about 0.3%. If the plastic forming of the conduit is needed to be settled into the winding groove, the extra torsion strain is necessary. Since the effect of the torsion strain on the properties of superconducting strands is not known, the feasibility study is needed. Thus, the helical winding with CIC conductors needs the further development of technology for the ITER-TF coil.

Table 1. Design criteria for CIC conductors based on ITER.

Items	Design criteria	ITER-TF
Max. cooling length (m)	< 550	390
Current (kA)	< 100	68
Maximum field (T)	< 13	11.8
Non-Cu current density (A/mm^2)	< 300	273
Coil current density (A/mm^2)	< 30	20.3
SC material for HC	Nb_3Al	Nb_3Sn

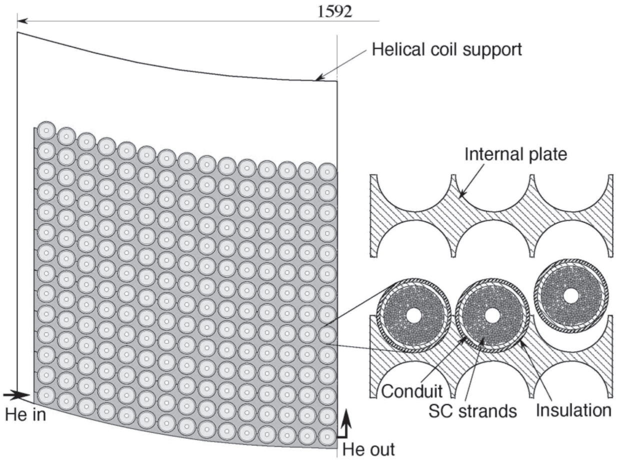

Fig. 1. Concept of helical winding with CIC conductors. The curvature of the bottom of the coil is determined to attain the maximum gap to the plasma. The helical coil support is assembled after winding.

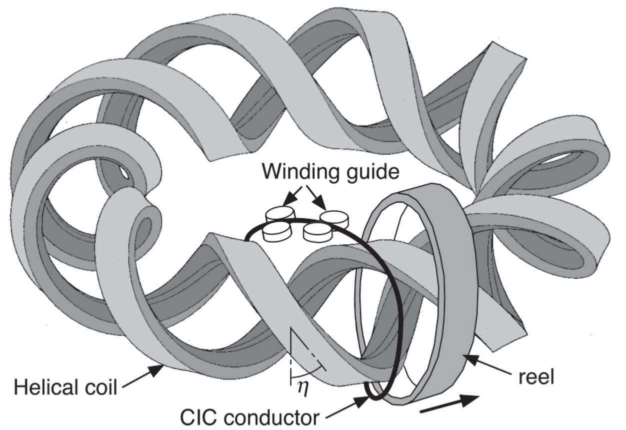

Fig. 2. Concept to wind a helical coil with CIC conductors.

1) A. Sagara, S. Imagawa, O. Mitarai, et al., Nuclear Fusion, 45 (2005) pp.258-263.