§11. Magnet Design with 100-kA HTS STARS Conductors for the Helical Fusion Reactor

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There is considerable progress in the conceptual design studies of the helical fusion reactor FFHR-d1 [1]. The major radius of the continuously wound helical coils (Fig. 1) is 15.6 m. This is four times larger than that of the currently working Large Helical Device (LHD). The HTS (high-temperature superconducting) magnet is a plausible candidate as a “challenging option” in the design studies. The 100-kA-class STARS (Stacked Tapes Assembled in Rigid Structure) conductor is being developed using a simple-stacking technique of HTS YBCO tapes [2]. A prototype STARS conductor of 3-m in length reached 100 kA at a magnetic field and temperature of 5.3 T and 20 K, respectively. A bridge-type mechanical lap joint is also developed to realize the “joint-winding” [3] to connect and wind segmented conductors. It was confirmed by 3D printing that the unit length of a segmented conductor can be a helical pitch in maximum. In the prototype conductor sample, the joint resistivity was ~15 pΩm^2, which assures that an additional electricity of <3 MW is required in the cryoplant for cooling 3,900 joints. If a joint fabrication is completed in a day using an industrial robot that also performs inspection, then it is expected that the entire onsite winding can be completed in <3 years, assuming that the work will be performed simultaneously in 4 locations. The vacuum pressure impregnation (by increasing the entire coil temperature to ~150 centigrade after winding) is not required in the HTS option [2].

The high cryogenic stability of HTS intrinsically reduces the quench risk. The massive copper stabilizer (current density: 77 A/mm^2) further enhances the stability. It was observed in the 30-kA-class conductor sample [2] that a quench did not occur when the current density in the copper stabilizer was <85 A/mm^2 even after reaching the critical current. Numerical analysis is conducted to verify the stability dependence on current density. In the rare event of a quench occurrence, a numerical simulation shows that the hot-spot temperature is restricted to <200 K with a discharge time constant of 30 s. The quench detection is considered at a threshold voltage of 100 mV. This requires ~20 s for a normal-zone to expand because of the slow propagation speed [4]. However, this is acceptable, as the hot-spot temperature does not increase rapidly because of the efficient heat conduction through the copper stabilizer. When an emergency discharge is activated, the voltage generation is restricted to <3 kV if the two helical coils are divided into 30 blocks. A good organic or inorganic insulation should be developed and installed between the stainless steel jacket and copper stabilizer to withstand the helical deformation during the prefabrication processes of conductor segments.

Helium gas flow through the four corners of the conductors is considered for the cooling scheme of the HTS helical coils as depicted in Fig. 1. Transverse cooling channels are provided by grooves on the conductor surfaces. The inlet and outlet of the helium gas supply are placed at the bottom and top of the helical coils, respectively. The primary heat input occurs from the nuclear heating caused by fusion neutrons. It is more intense on the inboard side of the torus because of the thinner blanket space than on the outboard side. In the latest design, a pair of sub-helical coils, named “NITA coils” (see Fig. 1) with opposite-directed currents, are used to enlarge the blanket space to 1.08 m [5]. In this condition, the maximum nuclear heating is reduced to ~1/5 compared to the former design. This corresponds to ~3 W along a longitudinal cooling path of ~18 m. The joule heating at a joint is ~9 W and this should be cooled by outboard channels. The necessary mass flow rate of helium gas for cooling 9 W is ~0.34 g/s by setting the inlet and outlet temperatures at 15 K and 20 K, respectively. The total mass flow rate in the two helical coils is ~2 kg/s. Numerical simulation is conducted to examine the flow distribution in multi-path channels with non-uniform heat generation.

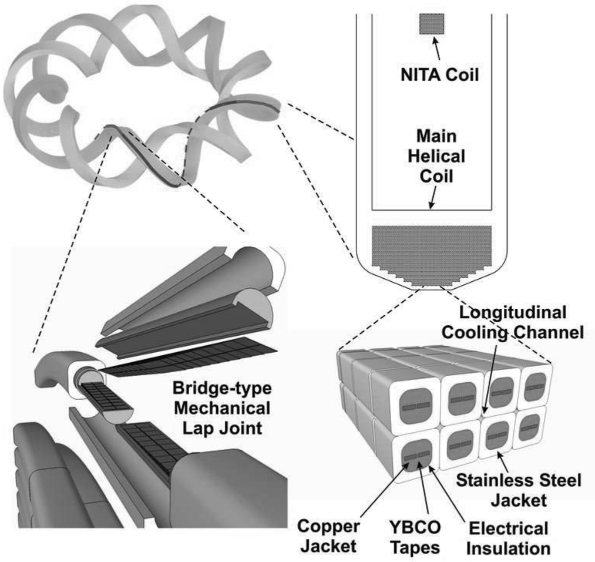

Fig. 1. Schematic illustration of the FFHR-d1 helical coils with the HTS STARS conductors. The NITA coils are located at the outer region of the main helical coils. The cooling channels for helium gas are indicated in the winding cross-section.

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2) Yanagi, N. et al.: Nucl. Fusion **55** (2015) 053021.
3) Ito, S. et al.: IEEE Trans. Appl. Supercond. **25** (2015) 4201205.
4) Hemmi, T. et al.: NIFS Annual Report (2008) 278.
5) Yanagi, N. et al.: Plasma Fusion Res. **11** (2016) 2405034.