**Helical Coil Design and Development with 100-kA HTS STARS Conductor for FFHR-d1**

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**Abstract.** The high-temperature superconducting (HTS) option is employed for the conceptual design studies of the LHD-type helical fusion reactor FFHR-d1. The 100-kA-class STARS (Stacked Tapes Assembled in Rigid Structure) conductor is considered to be used for the helical coils and vertical field coils. The joint-winding is considered by connecting segmented conductors to facilitate the on-site fabrication of these coils. Protection of the coils in case of a quench is examined and the hot-spot temperature with an emergency discharge is evaluated using a one-dimensional analysis. Cooling of the HTS magnet is investigated using helium gas circulation with a one-dimensional numerical analysis.

1. Introduction

Conceptual design studies of the helical fusion reactor FFHR-d1 are progressing at National Institute for Fusion Science (NIFS) [1]. The heliotron magnetic configuration of FFHR-d1 is similar to that of LHD [2]; a pair of continuously-wound helical coils has a toroidal pitch number of 10 and two pairs of Outer Vertical (OV) and Inner Vertical (IV) coils are used to adjust the vertical field. The major radius of the helical coils is 15.6 m, which is four times that of LHD. A toroidal magnetic field is 4.7 T at the center of the helical coils. The overall stored magnetic energy reaches 169 GJ. Under these conditions, a self-ignited fusion power of 3 GW is expected to be produced.

We choose the high-temperature superconductor (HTS) in the “challenging” option of the magnet design for FFHR-d1 [3-6] as a counter option of using low-temperature superconductors (LTS) in the “basic” options [7, 8]. For the 100-kA-class conductor, the second generation HTS, the Rare-Earth Barium Copper Oxide (REBCO) coated conductor tape, is selected to be used. In the present design of the helical coils of FFHR-d1, the number of winding turns is 390 and the conductor current is 94 kA at the maximum magnetic field of 11.8 T [6]. The current density is ~25 A/mm² in the winding area. The nominal operation temperature is set at 20 K [6]. In the HTS conductor, REBCO tapes are simply stacked and embedded inside a copper stabilizer and an outer stainless steel jacket for the mechanical reinforcement. Due to this configuration, this conductor is named STARS (Stacked Tapes Assembled in Rigid Structure). The concept of simple stacking of HTS tapes is in contrast to other approaches for making large-current capacity conductors to be used for pulsed magnets of tokamaks, which includes twisting and transposition of tapes to avoid formation of non-
uniform current distribution among tapes and to reduce AC losses. The STARS conductor is expected to be applicable to DC magnets of helical fusion reactors.

The STARS conductor has an internal electrical insulation between the copper stabilizer and stainless steel jacket. This is for the purpose of welding the neighboring turns of conductors on their stainless steel jackets after winding. As a result, the winding package may look similar to that of the ITER TF coils which are equipped with radial plates. By having this configuration, the Vacuum Pressure Impregnation (VPI) process can be skipped. Otherwise, VPI must be applied after the completion of winding by raising the temperature of the whole helical coils up to 150 centigrade. For the internal electrical insulator, Glass-Kapton-Glass tapes filled with epoxy resin is a conventional choice. An advanced ceramic option will be explored in our future studies to ensure good thermal contact and robustness against neutron irradiation.

In our previous study, two prototype STARS conductor samples were fabricated and tested in the superconductor testing facility at NIFS equipped with 9-T split-coils [6, 9-11]. They used 20 and 54 GdBCO tapes (FYSC-SC10 by Fujikura Ltd., tape width: 10 mm, critical current: ~600 A at 77 K, self-field), respectively to ensure the nominal operation current of 30 kA and 100 kA, respectively. Both samples had racetrack shapes and one of the straight sections had a bridge-type mechanical lap joint so that the whole sample formed a short circuit. The sample current was induced by changing the bias magnetic field. For the 100-kA-class sample, the current reached 100 kA at a temperature of 20 K and magnetic field of 5.3 T. At 4.2 K, a 100 kA current was stably sustained for 1 h by controlling the changing rate of the bias magnetic field. The joint resistance was evaluated to be 1.8 nΩ from the measured decay time constant of ~1000 s using the numerically calculated self-inductance of the sample.

Along with the development of the conductor, the HTS magnet design is progressing. The fabrication process is examined based on the joint-winding method by connecting segmented HTS conductors. The quench protection scheme is examined by conducting a hot-spot temperature analysis. The cooling scheme using helium gas circulation is examined by a crude analytical estimation and a numerical calculation.

2. Joint-Winding of the FFHR-d1 Helical Coils with HTS Conductors

Using the HTS conductor, the “joint-winding” has been proposed for the helical coils, which facilitates the fabrication by connecting conductor segments onsite [4]. This is a practical extension of the original ideas regarding demountable coils [12, 13]. A one-helical-pitch conductor of ~30 m length could be the basic unit, as was confirmed by a 3D printing [14] (see Fig. 1). A bridge-type mechanical lap joint with a staircase-like structure has been developed at Tohoku University [10, 11]. The joint process can be performed by lifting the conductor at 500-1000 mm above the final position in the windings, as the close-up view is shown in Fig. 2. If a joint fabrication (including inspection) is completed in one day using an industrial robot, the entire onsite winding is expected to be completed in <3 years, assuming that four joints (two helical coils in two directions along a conductor) will be done in parallel. If one joint is made in half a day, the entire process will be completed in <1.5 years.

According to the joint resistance of 1.8 nΩ measured in the 100-kA-class prototype STARS conductor sample, the joint resistivity is evaluated to be ~15 pΩm. This expects a joint resistance in the FFHR-d1 helical coils to be ~1 nΩ at each joint [11]. Having a 94 kA current, the Joule heating occurs at ~34 kW for the entire helical coils with 3,900 joints. Recently, a new technique for drastically decreasing the joint resistance has been developed [15]. By increasing the temperature to ~100 centigrade during the joint fabrication using
single tapes, the joint resistivity was evaluated to be $\sim 3.5 \ \text{p} \Omega \text{m}^2$. If this technique can be applied to the 100-kA-class conductor with multi-layers of REBCO tapes, it gives only $\sim 8 \ \text{kW}$ of joule heating in the entire helical coils, which is $\sim 1/10$ of the previous value.

One of the difficult problems associated with the present magnetic configuration is that the blanket space between the helical coil and plasma on the inboard side of the torus is very tight [16]. Thus, the nuclear heating becomes intense in this region. It was recently discovered that this distance can be considerably enlarged by using a pair of sub-helical coils, named NITA (Newly Installed Twist Adjustment) coils, outside the main helical coils [17] (see Fig. 3) with an opposite-directed current. It was found that the nuclear heating could be lowered to be $\sim 1/5$ by having a thicker blanket in this case [17]. The NITA coils can also be fabricated using the joint-winding method.

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**FIG. 1.** Schematic illustration of the FFHR-d1 helical coils with HTS STARS conductors. The “joint-winding” method is indicated with one-helical-pitch conductor segments. The cross-sectional view of the main helical coil (winding package) and a sub-helical coil (NITA coil) is also shown. A photo of a mockup of the STARS conductor is also shown.

**FIG. 2.** A close-up view of the joint section in the FFHR-d1 helical coils. The joint section is lifted at 500-1000 mm above the final position.
3. Cryogenic Stability of the STARS Conductor and Protection of the Helical Coils

The cryogenic stability of the STARS conductor is considered to be sufficiently high due to the intrinsic nature of HTS having high critical temperature [5, 18]. The massive copper stabilizer and thick stainless steel jacket enhances this feature by setting the current density relatively low. A feature of the high stability characteristics was observed in the 30-kA-class short-sample STARS conductor experiment. Figure 3(a) shows two cases when a normal-transition (or a quench) occurred or did not occur when the sample current was raised up to the critical current (~50 kA). It is understood that the critical current is very close to the limiting current that causes a normal-transition above it. This feature is summarized in Fig. 3(b) for various conditions of the bias magnetic field and current. It is seen that there is no quench when the current density assumed in the copper stabilizer is <85 A/mm². These features will be examined by numerical calculations in our future studies.

(a) Waveforms of the sample current, bias magnetic field, and temperature (at two locations on the stainless steel jacket) observed in the critical current measurement of the 30-kA-class HTS STARS conductor sample. (b) Quench or no quench points on the bias magnetic field and current plane observed in this experiment.

Owing to the high cryogenic stability, the probability of experiencing a normal-transition and a subsequent quench is supposed to be very low. Even with this situation, protection of the magnet should be well prepared. A conventional protection scheme using a resistive circuit is considered to dump the stored magnetic energy quickly. In this scheme, the time constant of the emergency discharging process should be decided by evaluating the hot-spot temperature. For this purpose, a one-dimensional numerical simulation is supposed to give good predictions [19, 20]. In the present analysis, the thermal conduction equation is solved by the Finite Element Method (FEM) [21]. For making a normal-transition in the HTS tapes, a disturbance energy is assumed at the conductor center. For giving the subsequent heat generation, the effective resistance of the superconductor is evaluated by including the critical
current characteristics of a single tape dependent on the temperature, current density and magnetic field and its orientation into the percolation model [22]. The resistances of the copper stabilizer and stainless steel jacket are considered in a parallel circuit. In our previous calculation, the threshold voltage was set at 100 mV, which was actually lower than that used in the present LHD. There is, thus, a concern of having a false initiation of an emergency discharging process in a noisy environment. Then, in the present analysis, the threshold voltage is set at 200 mV. Two cases of calculation results are shown in Fig. 4: the stainless steel jacket is included or excluded on the assumptions that the internal electrical insulation does not work and does work as a thermal resistance between the copper stabilizer and stainless steel jacket, respectively. In the former case, the hot-spot temperature is evaluated at \(\sim 170\) K with a discharge time constant of 30 s as shown in Fig. 4(a). A long duration (~90 s) is waited for a normal-zone to expand, due to the slow propagation speed in the HTS conductor, before the discharge starts at the threshold voltage of 200 mV. If the stainless steel jacket is not included, the hot-spot temperature becomes too high with the same discharge time constant of 30 s, and then it is shortened to be 15 s. The result is shown in Fig. 4(b), in which the hot-spot temperature is observed at \(\sim 230\) K. Though this is significantly higher than the usual criterion of 150 K, it is considered to be still acceptable. In our future studies, more precise analysis will be performed by incorporating two-dimensional calculations.

![Fig. 4](image_url)

**FIG. 4.** One-dimensional FEM calculation results for temporal evolutions of the temperature, current, and voltage of the HTS STARS conductor. Both the copper stabilizer and stainless steel jacket are included in (a) on the assumption that the electrical insulation between them does not work as thermal insulation. The discharge time constant is 30 s. In (b), it is assumed that the electrical insulation gives perfect thermal insulation and the stainless steel jacket is not included. The discharge time constant is 15 s. A disturbance energy of 1.8 kJ is assumed to be injected for both cases.

### 4. Feasibility of Helium Gas Cooling of HTS Helical Coils

For cooling the FFHR-d1 magnet with the HTS conductor option, we consider helium gas circulation. A crude feasibility study has been done in Ref. [21]. Here, it was assumed that longitudinal cooling channels are formed in the winding package by utilizing the four corners of conductors. Transverse cooling channels are also supplied by grooves on the conductor jacket. As a severer condition, the maximum nuclear heating on the inboard side of the torus and at the innermost layer of the helical coil package is given as \(\sim 500\) W/m\(^3\) in the analysis. A numerical calculation is done for a longitudinal cooling channel having a an equivalent diameter of \(\sim 4.4\) mm and a path length of 17.6 m. The inlet temperature of 10 K, inlet
pressure of 200 kPa, and mass flow rate of 0.47 g/s are assumed. The calculation result is shown in Fig. 5 for the variations of temperature and pressure. The outlet temperature is found at ~20 K and the pressure drop is 0.8 kPa. This result is not so different from the previous crude analysis based on the analytical expressions. The numerical analysis will be further extended in our future studies to deal with multi-paths of cooling channels with non-uniform heat generations.

![Graph showing temperature and pressure variations along a cooling channel](image)

**FIG. 5.** Example of the 1D numerical analysis of the temperature and pressure variations along a cooling channel formed by conductors in the helical coil package. The inlet temperature is 10 K and the inlet pressure is 200 kPa. The equivalent diameter is 4.4 mm and the path length is 17.6 m. A nuclear heating of 500 W/m³ is assumed all along the cooling path.

### 5. Conclusions

The magnet design of the helical fusion reactor FFHR-d1 is progressing by employing the 100-kA-class HTS STARS conductor having simple stacking of REBCO tapes and an internal electrical insulation. The joint-winding of segmented conductors is expected to be completed in <3 years if one joint fabrication is done in one day. To prepare for a rare chance of a normal-transition and a subsequent quench, a one-dimensional numerical analysis is conducted to evaluate the hot-spot temperature. When the stainless steel jacket is included in the analysis by assuming a good thermal conduction through the internal insulation, a fairly long time constant of 30 s for an emergency discharging process still limits the hot-spot temperature to be ~170 K. The threshold voltage for the quench detection is set at 200 mV in the present analysis. If the stainless steel jacket is not included on the assumption that the electrical insulation also works as thermal insulation, the discharging time constant should be 15 s and the hot-spot temperature is ~230 K, which is considered to be still acceptable. Further calculation will be performed by two-dimensional analysis. The cooling scheme of the helical coils, using helium gas, is examined with a one-dimensional numerical analysis. The required mass flow rate gives a sufficiently small pressure drop. Further analysis is necessary to examine the flow distribution in multi-paths of helium gas circulation with non-uniform nuclear heating.

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References


