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High-temperature superconducting coil option for the fusion reactor FFHR and development of indirectly-cooled HTS conductors

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Large current-capacity high-temperature superconducting (HTS) conductors using YBCO wires are being considered as an option for the fusion energy reactor FFHR [1, 2]. Typical required current for such conductors in FFHR is 100 kA at about 13 T magnetic field. The operating temperature for HTS magnets in FFHR is about 20 K with conduction cooling using an indirect cooling method. Since the specific heats of the materials at 20 K are significantly higher as compared with 4.2 K, which is the typical operating temperature of low temperature superconducting (LTS) magnets, the HTS magnets are operated much more stably and reliably against any mechanical or electromagnetic disturbances, which is one of the biggest advantages over LTS magnets. Another advantage is the reduction in required refrigeration power as the HTS magnets are operated at the elevated temperatures. Or, using HTS conductors, it is also considered to be viable to assemble the continuous helical coils in segments with a number of joints for conductors, as we can allow additional heat generation utilizing the surplus refrigeration power [3]. Two options of aluminum-alloy and SUS jacketed HTS conductors have been considered. The maximum strain in the winding has been estimated to be less than 0.3%, which is less than the critical strain of ~0.5% for YBCO conductors. As the first step towards the HTS conductor developments, a 10 kA-class conductor has been fabricated using Bi-2223/Ag tapes, by simply stacking and soldering them inside a copper sheath. The critical currents of the conductor have been measured at 4.2 K and at elevated temperatures up to 30 K. The stability margin experiments have also been done. The HTS conductor was found to be highly stable. In near future, the YBCO coated-conductors are planned to be used for next HTS conductor sample, and the stability and quench characteristics will be compared with those obtained for the present one.

Keywords: LHD, FFHR, fusion reactor, HTS, YBCO, BSCCO, superconductor, stability.

1. Introduction

Force free helical reactor (FFHR) is a LHD-type fusion energy reactor, which is being designed at National Institute for Fusion Science (NIFS) in the framework of inter-university collaborative research. Several designs of FFHR-series reactors have been proposed [4]. Among them, a state-of-the-art design FFHR2m1 has plasma major radius of 14 m, toroidal field of 6.2T, maximum field at the conductor 13 T, and fusion power of 1.9 GW. FFHR2m1 consists of one pair of helical coils and two pairs of poloidal field coils. Already well-developed low temperature superconductors (LTS) are being considered for the helical and poloidal coils of FFHR2m1. However, recently, the high temperature superconductor (HTS) technology has improved significantly and has shown good prospects for future applications. Considering this fact, the HTS has emerged as a competitive candidate for the helical coils of FFHR. The present study is focused on the HTS conductor design for the helical coils of FFHR. High temperature superconductors are being considered for high field magnets in fusion reactors due to their better performances in high magnetic field and elevated temperature operations [5] – [15]. In a fusion reactor, the HTS magnets can be operated at ~20 K or higher and therefore reduces the operational cost compared to conventional LTS magnets, which are used at ~4 K. Secondly, due to the increased specific heat of the HTS conductors at elevated temperatures, they become less prone to quench and therefore more safer operations of a fusion reactor are possible, which is perhaps the most desirable requirement from the magnets. The HTS magnets can be cooled by conduction cooling methods and therefore can avoid the complicated networks of pipings, generally necessary for force flow cooled LTS conductor magnets. The indirect cooling method has been proposed for aluminum-alloy jacketed Nb_3Sn conductor for FFHR helical coils [16]. The same indirect cooling technique can be easily adopted for HTS conductor coils as well. The increased thermal conductivity of the metals at elevated temperatures helps in quickly removing the

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heat generated in the conductor due to the AC losses, mechanical disturbances, nuclear heating and other sources.

2. HTS Conductor Design

Second generation coated conductors, such as YBCO and GdBCO, are the promising candidates for future demo fusion reactors as they sustain high critical currents at high magnetic fields. A cross-section of the proposed 100 kA-class HTS conductor for FFHR2m1 helical coils is shown in Fig. 1. This conductor uses YBCO or GdBCO tapes along with copper tapes inside a thick jacket of aluminum-alloy or SUS. The dimensions of the conductor have been chosen the same with its LTS counterpart proposed in [16]. The critical current of the HTS tape is considered as 100 A/mm-width at 13 T and 25 K, which is expected to be developed soon. The copper to superconductor ratio in HTS conductor is 7.0 and the critical current of the conductor is 128 kA at 13 T, 25 K.

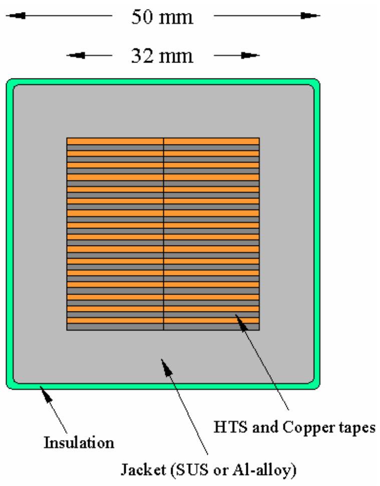

Fig.1 Cross-section of proposed HTS conductor for the helical coils of FFHR2m1.

Fig. 2 shows the rectangular cross-section of the helical coil (1.8 m wide and 0.9 m high). The helical coil consists of 12 layers with 36 turns in each layer. Inside the winding, four 75 mm thick cooling panels with embedded cooling channels are installed. The winding is cooled by conduction due to the flowing coolant through the cooling channels of the panels. The expected steady state nuclear heat load on the superconducting coil in FFHR is 100 W/m^3 [16,17], which should be removed by the coolant effectively. The temperature increase of the conductor, ΔT_{max}, can be estimated by one dimensional heat conduction equation.

$$\Delta T_{\max} = \frac{Ql^2}{2\lambda_e} \tag{1}$$

where Q is the heat load, l is the distance, λ_e is the effective thermal conductivity. In Fig. 2, the maximum distance between heated zone and coolant, l, is 0.1 m. If the conductor temperature is allowed to be increased by 1 K due to the nuclear heating of 100 W/m^3, the required effective thermal conductivity is 0.5 W/m-K.

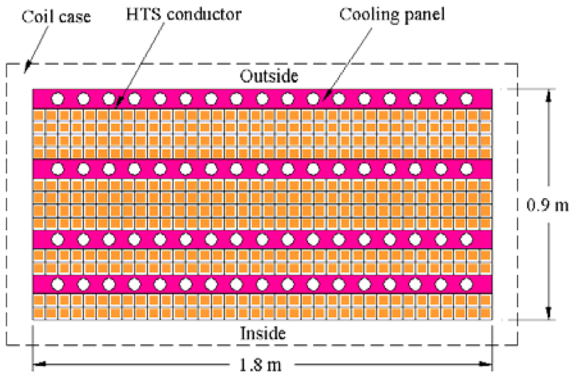

Fig.2 Cross-section of helical coil of FFHR2m1.

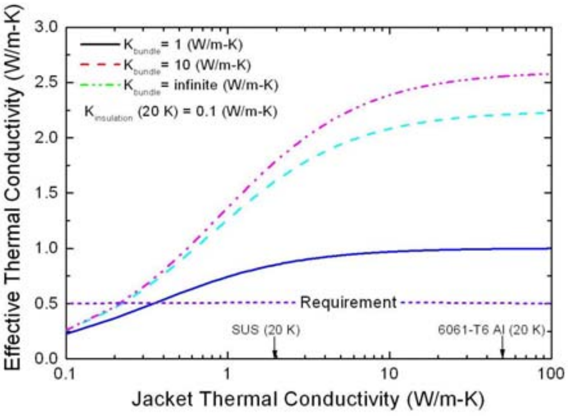

Fig.3 Effective thermal conductivity in the cross-sectional direction of the winding as a function of the jacket and HTS bundle thermal conductivities.

Fig. 3 shows the calculated effective thermal conductivity considering different materials over a length of 0.1 m in winding cross-section. The insulation thickness is taken as 1 mm and its thermal conductivity is 0.1 W/m-K at 20 K. The effective thermal conductivity is calculated by varying the jacket and HTS and copper tapes bundle thermal conductivities. In the worst case, when HTS and copper tapes bundle thermal conductivity is considered to be 1 W/m-K and HTS conductor jacket is SUS, the effective thermal conductivity comes out to be ~0.85 W/m-K at 20 K. This value is still higher than required effective thermal conductivity of 0.5 W/m-K, which suggests that SUS can also be used in HTS conductors, which was not possible for LTS counterpart proposed in [16]. Aluminum-alloy jacket provides higher effective thermal conductivity of ~1 W/m-K at 20 K and therefore is a better option as far as the heat removal is considered.

3. Stress and strain in the coil

The helical coils of FFHR will experience large electromagnetic forces and therefore the stresses and strain will be developed in the coil. Stresses and strain in the coil have been estimated by considering the coil as an infinite solenoid and only the radial forces are taken in account [16,18]. The average radius of curvature of helical coil is 5.5 m and therefore the same radius of curvature is considered for infinite solenoid model. The cross-section of the solenoid model is also the same as that of helical coil shown in Fig. 2. The calculated stresses and strain are shown in Fig. 4 for both the options of aluminum-alloy jacketed and SUS jacketed HTS conductors. The radial stress at inner radius and outer radius of the winding are taken to be zero as the boundary conditions. The maximum hoop stress in the SUS cooling panel and aluminum-alloy jacket are 510 MPa and 210 MPa respectively. The maximum hoop stress in SUS structure is 370 MPa when HTS conductor jacket is SUS. The stresses are always less than the yield strengths of the materials at 20 K and therefore safe under large electromagnetic forces in helical coils of FFHR. The strain is always less than 0.3%, which is less than the critical strain of ~0.5% for YBCO. Fig. 4 suggests that SUS jacketed HTS conductor is a better choice from stress and strain point of view.

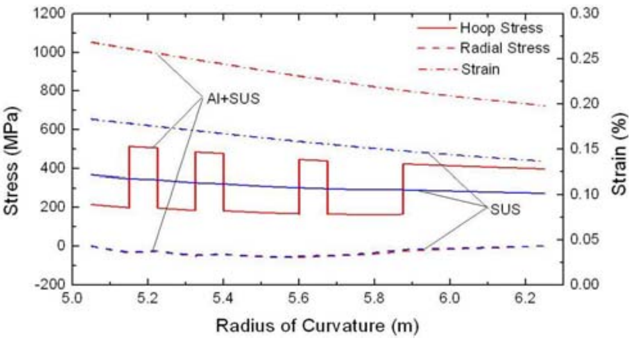

Fig.4 Hoop stress, radial stress, and strain in the helical coil of FFHR2m1. Both options of aluminum-alloy jacketed and SUS jacketed HTS conductor are shown.

4. Quench detection and protection

Due to the increased specific heat of the materials at elevated temperatures, the thermal diffusivity becomes smaller and therefore the quench propagation also becomes slower. Hence, the voltage development in HTS conductors at elevated temperatures is very slow and therefore the quench detection becomes difficult. This is one of the biggest problems in HTS conductors. Fig. 5 shows the voltage across the conductor as a function of conductor length at different temperatures and 100 kA current. At 45K, the conductor length is about 6 m to observe a voltage of 100 mV whereas it is about 2.5 m at 50 K. The required length further reduces with increased temperature. Fig. 6 shows the final hot-spot temperature with different jacket materials in adiabatic condition. The coil current is 100 kA at 25 K and the stored magnetic energy is dumped into an external resistor with a time constant of 20 s after the quench detection.

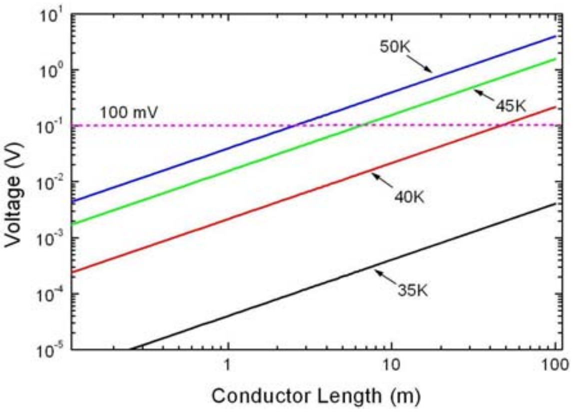

Fig.5 Voltage development as a function of conductor length at different temperatures and 100 kA current.

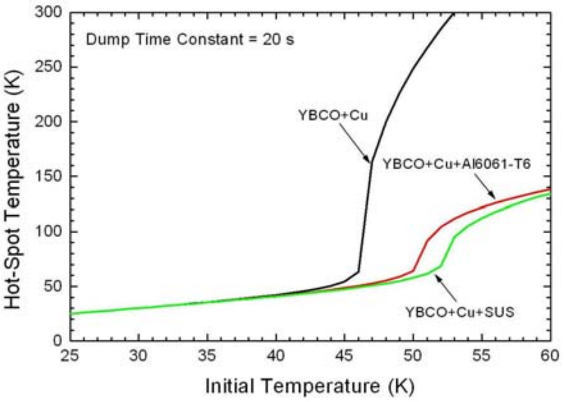

Fig.6 Final hot-spot temperature as a function of initial hot-spot temperature (just before the dumping) and jacket materials.

Fig. 6 suggests that SUS jacket for HTS conductor allows higher initial hot-spot temperature (for a condition of final hot-spot temperature less than 150 K) before dumping. This means that less conductor length is required to develop larger voltage as shown in Fig. 5, and therefore quench can be detected rather quickly and easily with SUS jacketed HTS conductor.

5. Proposal of segmented helical coils

It may not be easy to realize a continuous winding of the huge helical coils in FFHR, therefore, the segmented helical coils might be a viable choice to wind the helical coils with a number of joints between the segments. This idea was first proposed by Hashijume et al. [3]. Due to the elevated temperature operation of HTS coils, the surplus refrigeration power can be used to take away the heat generated by the joints between the helical coil segments. Since, the HTS conductor has large temperature margin, the temperature rise of few Kelvin due to the joints may not be a big concern for the stability of the coils. Fig. 7 shows the maximum temperature rise of the conductor as a function of heating density calculated by equation 1. Both the options of SUS jacketed and aluminum-alloy jacketed conductor have been considered. If a temperature rise of 5K of the conductor is acceptable, the heat density of about 990 W/m^3 on the winding can be allowed. This means a joint resistance of about 3 nΩ is acceptable as the number of joints between the conductors in one helical coil, made by 10 segments, is 4320.

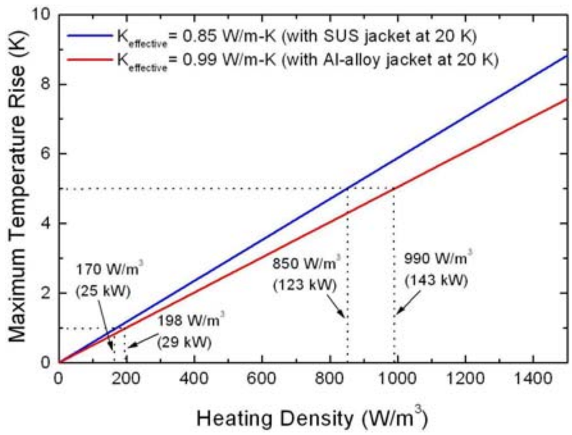

Fig.7 Maximum temperature rise of the conductor as a function of continuous heating density on the helical coil winding.

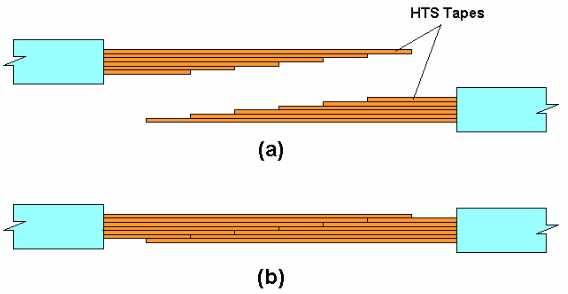

Fig.8 (a) HTS tapes cut in step like structure (b) overlap joint between two HTS conductors.

The joint between the conductors might be the mechanical joint proposed by Hashijume et al. in [3] or simple soldered lap joint. A soldered joint configuration with few numbers of HTS tapes is shown in Fig. 8. The HTS tapes are cut in step like structure and then overlapped and joined YBCO side with YBCO side.

6. Development of 10 kA-class HTS conductor

As the first step towards the development of large current capacity HTS conductor, we have developed a 10 kA-class HTS conductor using Bi2223/Ag HTS tapes. The critical current of one Bi2223/Ag tape is 140 A at 77K and self field. The HTS tapes were soldered inside a copper sheath of outer dimension of 12 mm × 7.5 mm. The HTS tapes were simply stacked and soldered. One HTS conductor consists of 34 HTS tapes and no copper tape. Thin stainless steel heaters were attached on the surface of the conductor to elevate the conductor temperature up to 30 K for the critical current and stability measurements at elevated temperatures. Then the conductor was insulated using epoxy and GFRP sheets to isolate it with liquid helium in the cryostat. During the experiments, the conductor was cooled by conduction through the ends. A cross-section of the HTS conductor is shown in Fig. 9. The

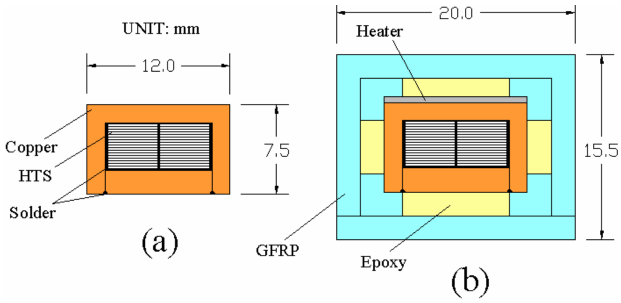

Fig.9 (a) Cross-section of 10 kA-class HTS conductor, (b) GFRP insulated HTS conductor configuration (to realize conduction cooling) in experiments.

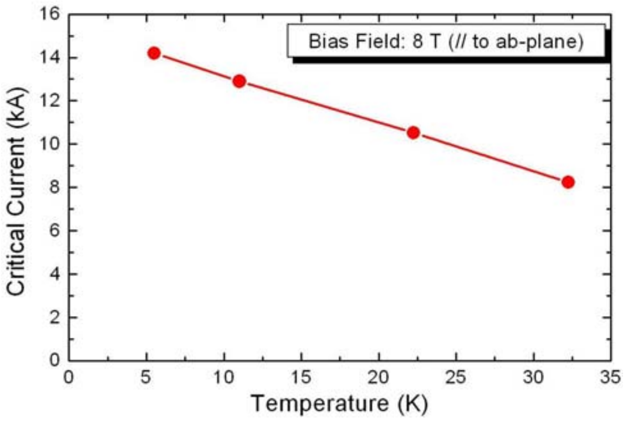

Fig.10 Measured critical currents of HTS conductor at different temperatures.

epoxy and GFRP insulated conductor configuration (to realized conduction cooling in the experiments) is also shown.

Fig. 10 shows the measured critical current of the conductor at 4.2 K and elevated temperatures up to 30 K under a bias field of 8 T parallel to ab-plane of the HTS tapes. The critical currents are measured with 1μV/cm criterion. During the critical current measurements at 4.2K, it was not possible to maintain the conductor temperature exactly at 4.2 K due to the heating by flux flow resistance in the HTS conductor. At 1 μV/cm (criterion for critical current), the conductor temperature was about 5.5 K, which is reported in Fig. 10. The similar temperature rise was observed at elevated temperature measurements at 10K, 20K, and 30K as well. Fig. 10 suggests that the critical current of HTS conductor shows a linear dependence on temperature.

The stability of the HTS conductor was also measured using thin film heaters attached on the surface of the conductor. The conductor was found to be very stable and could not be quenched even with very high energy input of 30 J/cm^3 at 20 K and 10 kA conductor current (~90% of the critical current) under a bias field of 8 T. With 30 J/cm^3 energy input, the temperature of the conductor increased up to 34 K, which was more than the current sharing temperature of 31 K. But the conductor temperature goes down quickly due to the thermal conduction towards the ends of the sample and therefore no thermal runaway was observed. The typical stability margin for a LTS cable-in-conduit conductor (CICC) is 300 – 500 mJ/cm^3 at ~4 K and 30% – 50% of the critical current in the conductor. Hence, one can say that HTS conductors are highly stable compared to their LTS counterparts and therefore can provide much safer operation of the fusion machines. The details of the experimental set-up and results of the 10 kA-class HTS conductor can be found elsewhere [19].

7. Summary

The feasibility study of HTS conductor option for LHD-type helical fusion energy reactor FFHR has started. The preliminary design of the HTS conductor has been proposed, which seems to be suitable for FFHR helical coils. Quench detection and stress calculations suggest that SUS should be adopted as a jacket material for the conductor. On the other hand, aluminum-alloy might be a better choice from winding point of view being a softer material compared to SUS. Segmented helical coil with mechanical or soldered joints might be a viable choice due to the large temperature margin of the HTS conductor and available surplus refrigeration power, which is a big advantage in HTS conductors over their LTS counterparts. A 10 kA-class HTS conductor with Bi2223/Ag HTS tapes has been successfully fabricated and tested at 4.2 K and elevated temperatures up to 30 K. More studies e.g. error fields due to the shielding currents, current distribution in the conductor, and AC losses are planned to be done on the HTS conductors. The development and testing of a 10 kA-class conductor using YBCO tapes is also planned in near future.

References

[1] A. Sagara et al., Fusion Eng. Design **81, 2703** (2006).

[2] T. Hemmi et al., to be published in NIFS Annual Report (2007).

[3] H. Hashizume et al., J. Plasma Fusion Res. SERIES **5, 532** (2001).

[4] A. Sagara et al., Nucl. Fusion **45, 258** (2005).

[5] J. R. Hull, Jour. Nucl. Materials **191-194, 520** (1992).

[6] T. Ando et al., presented at SOFE 2005.

[7] F. Dahlgren et al., Fus. Eng. Design **80, 139** (2006).

[8] T. Isono et al., Fus. Eng. Design **81, 1257** (2006).

[9] G. Janeschitz et al., Fus. Eng. Design **81, 2661** (2006).

[10] P. Komarek, Fus. Eng. Design **81, 2287** (2006).

[11] W.H. Fietz et al., Fus. Eng. Design **75-79, 105** (2005).

[12] L. Bromberg et al., Fus. Eng. Design **54, 167** (2001).

[13] T. Ando et al., IEEE Trans. Appl. Supercond. **14, 1481** (2004).

[14] T. Isono et al., IEEE Trans. Appl. Supercond. **13, 1512** (2003).

[15] W Goldacker et al., J. Phys. Conf. Ser. **43, 901** (2006).

[16] K. Takahata et al., to be published in Fus. Eng. Design (2007), doi: 10.1016/j.fusengdes.2007.04.050.

[17] A. Sagara et al., Fus. Eng. Design **81, 1299** (2006).

[18] M. N. Wilson, Superconducting Magents, (Clarendon Press, Oxford, 1983) p. 41.

[19] G. Bansal et al., submitted to IEEE Trans. Appl. Supercond., August (2007).