

Feasibility of HTS Magnet Option for Fusion Reactors^{*)}

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Conceptual design studies are being carried out on the application of high-temperature superconducting (HTS) conductors and coils to the magnet systems of fusion reactors. A 100-kA-class HTS conductor is required to be applied at high magnetic fields of > 12 T. A simple stack of YBCO tapes embedded in copper and stainless-steel jackets is found to be a practical approach to producing large-scale conductors that exhibit high cryogenic stability and mechanical rigidity. The feasibility of the segmented fabrication method for large complex HTS coils, such as the helical coils in the LHD-type helical fusion reactor FFHR-d1, is being investigated by developing mechanical bridge-type lap joint technology of HTS conductors.

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1. Introduction

Owing to the significant progress that has been made in wire production technology in recent years, copper-oxide based high-temperature superconducting (HTS) materials are now being applied to a number of prototype electrical devices, such as power cables, transformers, energy storage systems and motors [1]. The production of large-scale HTS magnets for use in fusion reactors has also been considered [2, 3]. Though it is still widely believed that HTS materials are fragile, it is actually possible to fabricate strong coils using rare-earth barium copper oxide (REBCO) tape. In this type of tape, a substrate composed of a Ni alloy such as Hastelloy, with a high yield strength of > 1 GPa, is coated with a REBCO material such as YBCO (where Y represents yttrium) [1].

The application of HTS materials in fusion research began with the floating coil of the Mini-RT device which has been operational since 2003 at the University of Tokyo [4]. In this coil, Ag-sheathed Bi-2223 tape was used, which was the only available HTS at that time. The larger RT-1 device was built in 2006 using improved Bi-2223 tape, and stable levitation for more than 6 hours was achieved [5, 6]. Recently, the floating coil of the Mini-RT was upgraded using the latest GdBCO tape for better per-

formances [7, 8].

As is well known, the biggest advantage of HTS materials is their high critical current density up to high magnetic fields of > 30 T. Another important advantage is their high cryogenic stability (low quench probability) due to the increased heat capacity of the conductor composites at temperatures > 20 K. This is in remarkable contrast to the situation for Nb-based low-temperature superconducting (LTS) materials, which relies on the heat capacity of helium at ~ 4 K. Figure 1 shows the temperature dependence of the volumetric specific heat $C_p\rho$ (C_p is the spe-

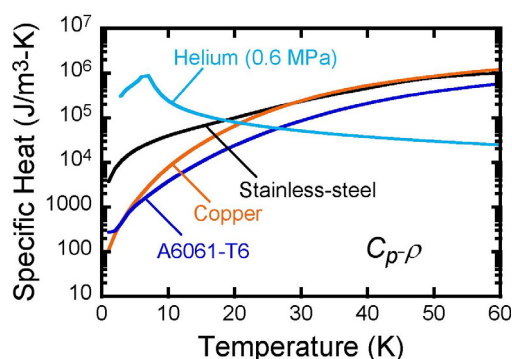


Fig. 1 Volumetric specific heat for metals and helium (pressure: 0.6 MPa) as a function of temperature.

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cific heat and ρ is the density) for several metals and for helium. As can be seen, the $C_p\rho$ for stainless-steel and copper at 30 K are equivalent as that for helium at 4 K. The stability margin (allowable disturbance per unit volume) for a conductor can be estimated using $w = C_p\rho\Delta T$, where ΔT is the temperature margin). Considering that ΔT could be as much as ~ 10 K for HTS conductors (unlike 1–2 K for LTS), w is found to be ~ 2 MJ/m³ (2 J/cc) for a temperature change of 20–30 K under adiabatic conditions. This is even larger than that measured for the presently used cable-in-conduit (CIC) conductors that are internally cooled by forced flow of supercritical helium at ~ 4.5 K [9]. The stability margin allows a heat generation $w' = Bj\delta$ due to the displacement δ of the conductor caused by an electromagnetic force associated with magnetic field B and current density j . For $B = 12$ T and $j = 25$ A/mm², a stability margin of 2 MJ/m³ allows a disturbance (winding motion) of $\delta \sim 6$ mm, which is unlikely to occur in a real magnet.

Considering these advantages, the conceptual design studies on the use of HTS materials in tokamak reactors were carried out for ARIES-AT [10] and VECTOR [11] more than 10 years ago. Along with the design of VECTOR, a 10-kA-class CIC conductor using round Bi-2212 HTS strands was successfully tested [12]. Although, these studies and conductor development have since been suspended, the HTS option is now being considered for the helical fusion reactor, and conductor development has been underway since 2005.

The present paper considers several aspects of HTS application to the magnet coils of fusion reactors, taking the LHD-type helical reactor FFHR-d1 as an example.

2. Design of a 100-kA-Class HTS Conductor for DC Magnets of Fusion Reactors

As an example of the application of HTS conductors to the magnets of fusion reactors, the conceptual design of the LHD-type helical fusion reactor is considered. The present design, FFHR-d1, is equipped with a pair of continuously wound helical coils, having a major radius of 15.6 m, a minor radius of 3.744 m and a helical pitch number of 10, that produce a 4.7 T toroidal magnetic field to generate 3 GW of fusion power [13]. The stored magnetic energy is 160 GJ and a 100-kA conductor is required to be used at the maximum magnetic field of ~ 12 T. The primary selection for the helical windings is a CIC conductor using Nb₃Al strands [14], which is regarded as an extension of the ITER technology. However, considering the difficulties related to CIC conductors, such as the complicated plumbing required and the degradation of the critical current due to strain, an indirectly-cooled LTS conductor using Nb₃Sn strands and an aluminum-alloy jacket has also been considered [15]. The other option for indirect cooling is to use a HTS conductor.

To fabricate a high-current-capacity HTS conductor,

the general approach has been to employ the same concepts that have been widely applied to LTS conductors. In order to make the conductor resistant to magnetic instabilities (flux jumps), and to achieve high cryogenic stability by avoiding a non-uniform current distribution, round multi-filamentary wires containing thin filaments should be used as strands, and the strands should be twisted and transposed. To achieve this, several methods for producing HTS stranded cable have been developed, such as the “Roebel-assembled” cable [16], “twist-stacked” cable [17] and “Conductor On Round Core (CORC)” cable [18]. However, since these methods are complex and expensive, we propose a simple stacking of HTS tapes. This should be particularly effective for DC magnets by allowing a formation of non-uniform current distribution, since a HTS has a high cryogenic stability. Using this stacking approach, a mechanically strong conductor can be fabricated at low cost.

Figure 2 shows an example of the 100-kA-class conductor design for FFHR-d1. Forty YBCO tapes, each with a width of 15 mm, are simply stacked within a copper jacket. The operation temperature is 20 K. The conductor has a round outer shape produced by a stainless-steel jacket. The major specifications for the conductor are listed in Table 1. We should point out that this is actually an older design and has since been changed [19]. The most recent conductor design has internal insulation, and use a stainless-steel jacket with a square outer shape, which is directly cooled by gas helium. However, it is also worthwhile to evaluate the conductor design shown in Fig. 2, not only with regard to FFHR-d1, but also other applications such as the toroidal field (TF) coils of tokamak reactors.

Simple stacking of HTS tapes may also be applicable to TF coils provided the flux changes by vertical field coils are slow in tokamak reactors. It should be noted that in previous work on the VECTOR design, simple stacking of YBCO tapes was considered. If the field changes are too fast, it is better to reduce both AC losses and the occurrence of non-uniform current distribution, which may be possible by transposing the HTS tapes [20]. This can be

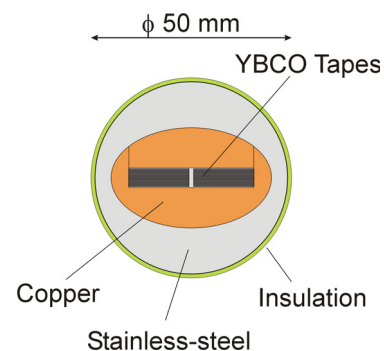


Fig. 2 Cross-sectional illustration of a 100-kA-class HTS conductor design for FFHR-d1 helical coils.

Table 1 Major specifications of a 100-kA-class HTS conductor design for FFHR-d1.

Operation current (12 T, 20 K)	94 kA
Conductor size	$\phi 50$ mm
Current density	40 A/mm ²
Superconducting material	YBCO
Width of YBCO tape	15 mm
Thickness of YBCO tape	0.22 mm
Critical current of a 15 mm width tape (77 K, self-field)	>900 A
Number of HTS tapes	40
Configuration of HTS tapes	Simple-stacking
Jacket material	Stainless-steel
Stabilizer	Oxygen-free copper
Cooling method	Indirect cooling

achieved using a Roebel-assembled conductor. To more easily produce Roebel conductors, the Roebel-MITO (Meandering for Inter-Transposition Optimization) method has been proposed, and this ensures an on-demand realization of transposition using soldered joints [21]. A similar idea was considered for the YBCO conductors of VEC-TOR [22].

3. Design of HTS Coil Winding Pack

Figure 3 shows a schematic cross-section of the winding pack of the FFHR-d1 helical coil using the type of HTS conductor seen in Fig. 2. The total current in the helical coil is 36.66 MA and the current density in the winding region is 24.45 A/mm², which is larger than that for the ITER TF coils (20 A/mm²). The winding pack consists of 390 turns of HTS conductors, each with an operation current of 94 kA, installed in a stainless-steel “internal plate” with circular grooves. This is the same concept employed for the CIC conductor version of the FFHR helical coils [14]. The internal plate is the layer winding version of the “radial plate” used in the ITER TF coils with pancake winding. In Fig. 3, the internal plate is cooled by gas helium flowing through cooling pipes imbedded within it. The conductors are cooled indirectly by the internal plate through thermal conduction. To enhance the cooling capabilities of the internal plate, innovations such as the use of oscillating heat-pipes should be considered [23]. Once again, we note that the winding pack shown in Fig. 3 is our former design, and a different configuration is employed associated with the more recent square-type conductor design having internal insulation cooled directly by gas helium [19].

As shown in Fig. 3, the orientation of YBCO tapes is adjusted so that the plane of each tape is parallel to the magnetic field. This arrangement is used in order to mitigate the dependence of the critical current on the magnetic field orientation, which is still a remaining issue with REBCO tape. This alignment also dramatically reduces AC losses [24]. This is analogous to the reduction in AC

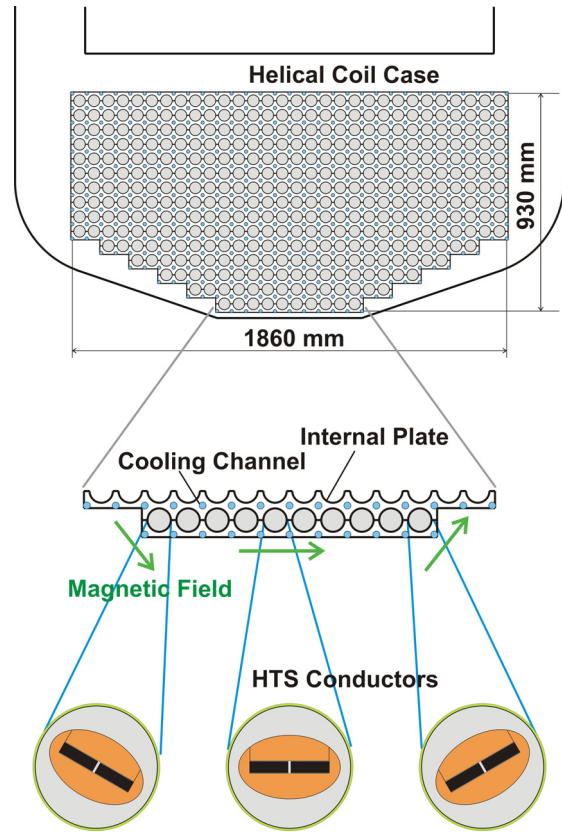


Fig. 3 Schematic cross-section of helical coil windings using indirectly-cooled HTS conductors for FFHR-d1.

losses that occurred when a flat Rutherford-type cable with NbTi/Cu strands was wound by twisting the cable being parallel to the magnetic field [25]. The arrangement shown in Fig. 3 also reduces the production of shielding currents, and therefore the error magnetic field [26].

When 3 GW of fusion power is being generated by FFHR-d1, it is required to remove ~ 500 W/m³ of nuclear heating in the winding pack at the inboard side of the torus (~ 100 W/m³ at the outboard side) [13]. A one-dimensional heat conduction analysis using the thermal conductivities of conductor composites such as stainless-steel, copper and epoxy (insulation), shows that a temperature difference of only 1 K develops between the HTS tape and the internal plate.

Over a full 30 years of operation, the neutron fluence and the gamma-ray dose are expected to be $\sim 1 \times 10^{23}$ /m² and ~ 100 MGy, respectively, near the innermost layer of the helical coils at the inboard side of the torus. These values are both marginal for superconductors and insulators [27]. We are also exploring the possibility of using inorganic materials such as ceramics as insulators. Furthermore, optimization of the coil configuration is underway in order to increase the amount of space at the inboard side of the torus, so that the shielding can be increased by ~ 100 mm, leading to a reduction in the neutron and gamma ray flux by about 10 times.

4. Segmented Fabrication of Large Complex Coils using HTS Conductors

To facilitate the winding of large complex coils, such as the helical coils of FFHR-d1, one possibility is segmented fabrication using HTS conductors [26, 28–31] instead of continuous winding using LTS conductors. Segmented fabrication was first proposed for helical reactors in the 1980's with the so-called “demountable” concept [28], which is illustrated in Fig. 4 (a). A similar concept was proposed in 2001 using a HTS approach that took advantage of the reduced refrigeration power required due to the higher temperature operation [29]. However, with present-day technology, it is difficult to find a realistic solution to forming simultaneous connections between hundreds of turns of winding conductors. Thus, we proposed the idea of connecting “conductor segments” as shown in Fig. 4 (b), instead of “coil segments” [26]. For the bridge-type conductor joint shown in Fig. 5 (a), a mechanical joint technique developed at Tohoku University can be applied instead of the formerly considered soldering method [32]. For a mechanical lap joint, the joint resistivity is estimated to be $\sim 10 \text{ p}\Omega\text{m}^2$ [33, 34], giving an overall joint resistance of $\sim 1 \text{ n}\Omega$ for a 100-kA conductor (consisting of 2 connections per joint with 40 HTS tapes, each having a 50-mm joint length). The entire helical coil system has 7,800 joints (390 turns, 10 segments, 2 coils), and requires a $\sim 5 \text{ MW}$ increase in the electrical power to the cryoplant for a coil operation temperature of 20 K. This is acceptable given the power requirements of $\sim 30 \text{ MW}$ for a LTS system operated at 4 K. To further reduce the refrigeration power, we propose the “finger-type” joint shown in Fig. 5 (b), which has a 10 times larger contact area and requires only 500 kW of electricity for the cryoplant.

A rough outline of the in-situ construction procedure for the helical coils is as follows:

1. The helical coil cases are assembled by connecting half-helical-pitch sections along the torus to form the helical coil structure.
2. To prepare the HTS conductors, the stainless-steel and copper jackets of the conductor are pre-bent into a helical shape with each $\sim 16 \text{ m}$ length in a sufficient tolerance. YBCO tapes are then embedded into the copper jacket (applying limited strain) and the stainless-steel jacket is welded along the conductor. The insulator should be attached to the outer surface of the stainless-steel jacket at this stage.
3. One by one, the half-helical-pitch conductors are placed into the circular grooves in the internal plate of the helical coil case.
4. Joints are then formed between two conductors as described above. To ensure the mechanical strength of the joints, welding of the stainless-steel jacket is inevitable.
5. After each joint is formed, an inspection should be

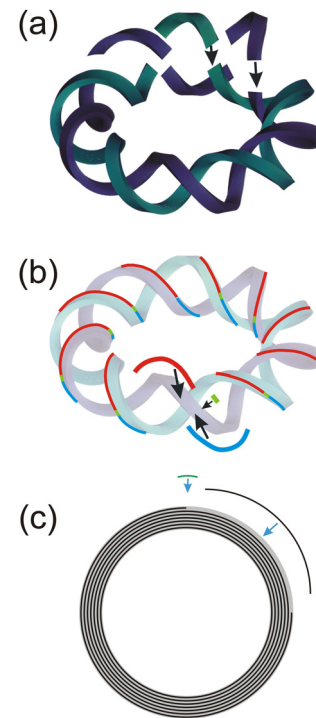


Fig. 4 Conceptual illustrations of the segment-fabrication method for (a) helical coils with coil segments, (b) helical coils with conductor segments and (c) vertical field coils with conductor segments.

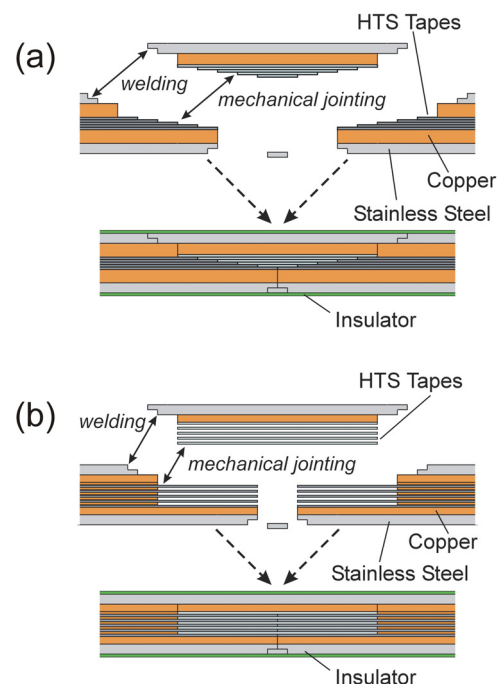


Fig. 5 Schematic illustrations of HTS conductor joints: (a) “bridge-type” lap joint and (b) “finger-type” lap joint.

carried out using a technique such as ultrasound or X-rays. Mechanical testing can also be performed. For quality assurance, the joint formation and inspection

should be done automatically using industrial robots (not by hand). In the inspection stage, the electrical resistance of the joint can be measured while cooling a joint section with liquid nitrogen, should it be required.

6. Insulation should be separately attached around a joint after the mechanical jointing process is finished.
7. Using the above procedure, one layer of windings is formed, and the internal plate for the next layer (fabricated in pieces and welded together along the torus on site) is then placed onto the lower layer. In this way, all the layers (fifteen in the example of Fig. 3) are fabricated using 7,800 half-helical-pitch conductors connected one by one to form the continuously wound helical coils.
8. After the winding process is completed, the top lids of the helical coil cases are attached and welded.
9. In order to fill the gaps within the winding area, vacuum pressure impregnation (VPI) should ideally be carried out at a temperature of ~ 150 centigrade.

Regarding the final procedure, since performing VPI for such a large coil is expected to be difficult, we have proposed an alternative to the VPI process [19]. Nevertheless, the use of VPI is worth exploring further.

Segment fabrication could also be applied to the vertical field coils, as shown in Fig. 4 (c). On the other hand, demountable coils could be a future option for the manufacture of commercial helical-type reactors, and also for producing medium-scale TF coils for tokamak reactors that allow blanket maintenance [35].

5. Development of 100-kA-Class HTS Conductor and Joint for FFHR-d1

Large-scale HTS conductor development for FFHR began with a 10-kA-class conductor in 2005 [36, 37]. In 2012, a 30-kA-class conductor sample was fabricated using the latest GdBCO tape produced by Fujikura Ltd. Twenty tapes were simply stacked in 10 layers and 2 rows [19]. In the sample, a bridge-type mechanical lap joint developed at Tohoku University [33, 34, 38] was used so that the racetrack shaped sample formed a short circuit. A sample current was induced by changing the bias magnetic field, and a critical current of 45 kA was measured at 20 K and 6 T [39]. Stable operation at a current of > 30 kA was sustained for more than 20 min at 30 K. The maximum current was 70 kA at 4 K and 1 T with a fast ramping rate of 1 kA/s. No premature quench was observed, which confirms the high cryogenic stability of the HTS conductor. Details concerning this conductor test are described elsewhere [19, 38, 39].

6. Summary

The application of HTS conductors to fusion reactor magnets seems feasible owing both to the rapid progress

in wire production technology and development of high-current capacity conductors at National Institute for Fusion Science. Simple stacking of REBCO coated-conductor tapes is a promising method for producing cryogenically stable and mechanically rigid conductors for DC magnets at a reasonable cost. Segmented fabrication of large complex coils, such as the helical coils for the LHD-type helical reactor FFHR-d1, is expected to be possible using mechanical bridge-type lap joints.

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