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核融合原型炉への適用をめざした高温超伝導導体とマグネットの開発
Development of HTS Conductor and Magnet for Fusion DEMO Reactors

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1. Introduction

Due to the significant progress of the wire production technology, the copper-oxide based high-temperature superconductor (HTS) is now being tried for variable electrical applications, such as power cables, transformers, energy storage and motors. It is now considered to be the time to apply HTS also to fusion magnets. One of the advantages of HTS is the high cryogenic stability of coils (low quench probability) due to the increased heat capacity at the operation temperature of >20 K compared to that of metal-based low-temperature superconductors (LTS) relying on the heat capacity of helium at 4 K. Reduction of refrigeration power is also an attractive feature for fusion power plants. Though it is still widely believed that HTS is fragile, one can actually make a stronger coil using the REBCO (YBCO or GdBCO) coated conductor owing to the Ni-alloy substrate. The current status of the HTS conductor development for the helical DEMO reactor and the related technology of applying HTS for plasma experiments are reviewed.

2. HTS option for the FFHR magnet

Based on the progress of steady-state plasma experiments in the Large Helical Device (LHD), the conceptual design studies and related engineering R&D's are being promoted for the helical fusion DEMO reactor. The present design, FFHR-d1, has the major radius of 15.6 m and the toroidal magnetic field of 5.1 T to generate 3 GW fusion power [1]. The stored magnetic energy is 160 GJ and a 100-kA conductor is required to be used at the maximum magnetic field of 13 T. The cable-in-conduit (CIC) conductor with forced flow of supercritical helium is the primary selection for the coils. For the strands of conductors, Nb_3Al should be an attractive choice with better resistance to strains than the presently used Nb_3Sn for the ITER magnet. Though the force-cooled coil with CIC conductors is the established technology and widely applied to the recent fusion magnets, it is not easy to handle considering the proliferation of fusion reactors. In this connection, the counter option is to use indirectly-cooled HTS coils based on the above mentioned attractive features. Figure 1 shows an example of the conductor design. We use YBCO tapes simply stacked in the copper jacket. This is a contrast to the activities in EU and US, where transposed and/or twisted-type conductors are being developed to be applied also to AC coils, such as the central solenoids of tokamaks. Since the helical reactor is DC, we consider that simple stacking, which is much easier for flat HTS tapes, should work. The conductor has a round shape and the orientation of the HTS tapes could be adjusted depending on the orientation of the magnetic field. This mitigates the anisotropy of the critical current on the magnetic field orientation, which is still a remaining issue of the REBCO tape.

Another attractive proposal using HTS is that the segmented fabrication of the huge and continuous helical coils be possible. The original proposal was to have "coil-segments" as illustrated in Fig. 2(a) [2]. Considering the difficulty to join >400 turns of conductors simultaneously, we are proposing a new idea of having "conductor-segments" instead, as shown in Fig. 2(b). A bridge-type joint of conductors is considered as shown in Fig. 3 [3].

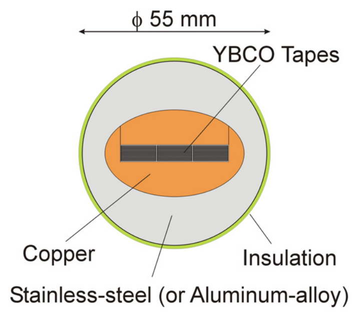

Fig. 1. A 100-kA HTS conductor design for FFHR-d1.

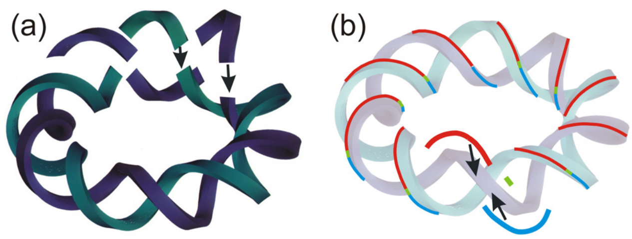

Fig. 2. Comparison between (a) joint of "coil-segments" and (b) "conductor-segments".

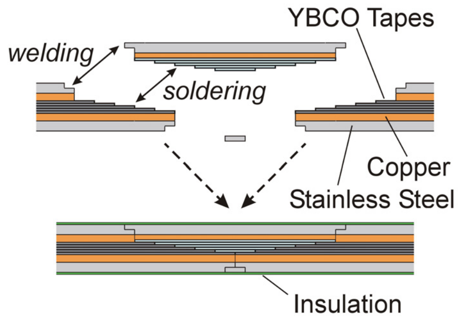

Fig. 3. Bridge-type joint of the REBCO conductor.

2. Development of 100-kA conductor and joint

We started the HTS conductor development from the 10-kA class in 2005 [4]. In 2012, we fabricated a 30-kA conductor sample (Fig. 4) using the latest GdBCO tape supplied by Fujikura Ltd. (critical current: >600 A at 77 K, self-field with 10 mm by 0.22 mm cross-section including a laminated copper stabilizer) stacked in 10 layers and 2 rows. A bridge-type mechanical lap joint developed at Tohoku Univ. was used [5] and the sample formed a short-circuit with a race-track shape.

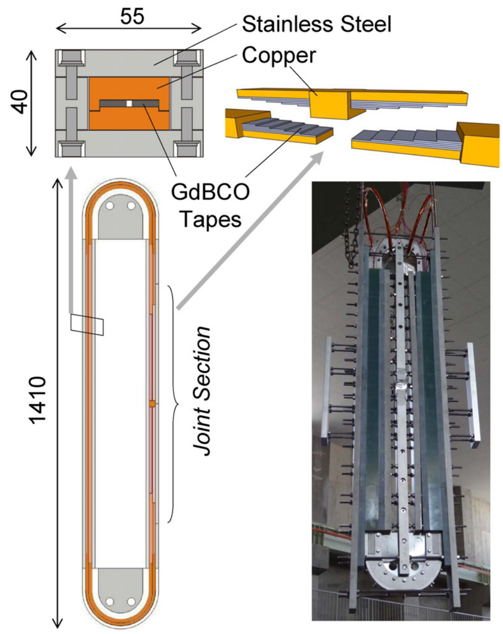

Fig. 4. The 30-kA class GdBCO conductor sample.

The sample current was induced by changing the bias magnetic field, and the critical current of 40 kA was measured at 20 K and 6 T. We also tried to achieve higher currents at 4 K, however, the sample quenched due to the unexpectedly large joint resistance in one of the two joints. We are now planning to improve the joint to achieve 100 kA at 4 K and <2 T in the early 2013. Then, the number of HTS tapes will be increased so that 100 kA will be reached at 20 K and >6 T, which may surpass the performance of the ITER conductor.

3. Application of HTS for plasma experiments

Along with the development of large-current capacity conductors for fusion DEMO magnets, it is also important to develop the basic technology for handling HTS tapes to wind small-scale coils. We here note that the application of HTS for fusion research has started with the floating coil of the Mini-RT device which has been operational since 2003 at Univ. of Tokyo [6]. The Ag-sheathed Bi-2223 tape was used, which was available at that time, and the time constant of the persistent current was unexpectedly short due to a probable mechanical damage of the still fragile tape. The larger RT-1 device was later built in 2006 using the upgraded Bi-2223 and the stable levitation of >6 hours has been available. Presently, the floating coil of Mini-RT is being upgraded using the same type of GdBCO tape as mentioned above. It is expected that the time constant will be prolonged and the magnetic field will be increased.

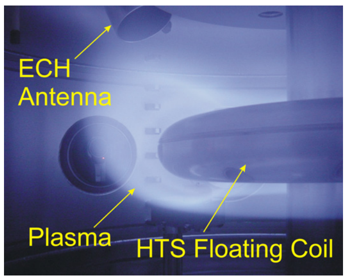

Fig. 5. The levitated Mini-RT HTS coil (present).

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