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Development of superconductors for the Large Helical Device

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Abstract

Three types of superconductors have been developed for the Large Helical Device (LHD). A composite-type superconductor with NbTi/Cu compacted strands and an aluminum/copper stabilizer has been developed for the pool-cooled helical coils with nominal currents of 13.0 and 17.3 kA for the Phase I and II operation conditions, respectively. The cryogenic stability of the conductor was improved by adopting a Cu–2% Ni clad around the pure aluminum to reduce Hall current generation. Cable-in-conduit superconductors have been developed for three pairs of force-cooled poloidal coils with nominal currents in Phase II of 20.8–31.3 kA. The strand surface is not coated and a stable DC performance was obtained. Another aluminum stabilized superconductor has been developed for the superconducting bus-lines. An R&D bus-line of 20 m length was successfully tested.

1. Introduction

The Large Helical Device (LHD) is a toroidal fusion experimental device [1,2] which is expected to play a major role in the confinement studies of helical plasmas. One of the main objectives of the LHD project is to demonstrate the production of currentless steady-state high temperature plasmas by taking advantage of heliotron magnetic configuration which requires no toroidal plasma current. In this connection, all the coil systems are superconducting, consisting of a pair of helical coils, three pairs of poloidal coils and nine sets of bus-lines. The coil systems are now in the final stage of assembly, aiming at the first plasma operation scheduled at the end of March, 1998.

An outstanding feature of LHD is that the three superconducting systems require different characteristics and, therefore, three types of superconductors with independent cooling methods have been newly developed. The helical coils will be operated in DC modes with high current density and high magnetic field as well as huge stored energy. Three dimensional winding with high accuracy is also required. In this respect, a composite-type superconductor with a pure aluminum stabilizer is adopted under a pool-cooling condition using liquid helium. On the other hand, the poloidal coils have to be excited also in AC modes for physics experiments and cable-in-conduit conductors force-cooled by supercritical helium were determined to be suitable because of their low AC loss generation characteristics. The superconducting bus-lines need to be more robust than any other coil system and another type of aluminum stabilized composite conductors cooled by two-phase helium have been developed. Each conductor is the product of careful designs and intensive R&D which has taken the first several years in the LHD project [3]. In this paper, the development of these superconductors are reviewed.

2. Superconductor for the helical coils

The two helical coils have a major radius of 3.9 m and an average minor radius of 0.975 m with a poloidal pole number 2 and a toroidal pitch number 10. The coils are pool-cooled by liquid helium at 4.4 K in the Phase I operation condition in which the central toroidal field reaches 3 T. Superfluid helium of 1.8 K will be later

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supplied in Phase II and the central field will be raised up to 4 T with a total coil current of 7.8 MA and a stored magnetic energy of 1.6 GJ. Composite-type superconductors with NbTi/Cu compacted strands and a pure aluminum stabilizer are adopted by incorporating their advantages of high cryogenic stability and mechanical flexibility. Several types of superconductors with various internal structures were proposed and experimentally examined through short sample tests using a 9 T split coil, 100 kA current leads and 75 kA DC power supplies [4].

The final internal configuration of the superconductor is shown in Fig. 1. The conductor size is 12.5×18.0 mm^2 and the nominal current is set at 13.0 kA (with a maximum magnetic field of 6.9 T) and 17.3 kA (9.2 T) for the Phase I and II operation conditions, respectively. The above conductor size was determined by optimizing both mechanical flexibility for facilitating the three dimensional on-site winding process with high accuracy, and cryogenic stability which is partly governed by the surface to volume ratio of the conductor. Fifteen superconducting strands are twisted and formed into a Rutherford-type flat cable. A pure (5N) aluminum stabilizer with a Cu–2% Ni clad is placed next to the strands and these are installed in a half-hard copper sheath. The thickness of the copper sheath was determined to withstand the compressional stress of up to 100 MPa during excitations in 4 T operations. A special technical procedure was introduced for the electron beam welding applied to the grooves of the sheath; this has considerably enhanced the mechanical toughness, especially against the plastic deformation that occurs during the three dimensional helical winding process.

One of the largest obstacles we met during the development of this superconductor was the discovery of cryogenic stability degradation due to the deterioration of magnetoresistivity in the copper-clad aluminum stabilizers [4]. This observation could be explained by the Hall current generation model [5,6] for metal–metal composites which consist of different conductive materials. By taking into account the details of this model, we concluded that the clad material around the pure aluminum stabilizer should be sufficiently resistive to reduce the Hall current and to hence prevent the increase of magnetoresistivity. In this connection, Cu–2% Ni (resistivity: $\sim 2.5 \times 10^{-8}$ Ωm at 7 T) was finally selected. A clear improvement of the recovery current was demonstrated with this type of clad as shown in Fig. 2 [7]. Two short sample conductors were prepared with the same internal configuration as in Fig. 1 but with different clad materials; Cu–2% Ni and oxygen-free-copper. Stability tests were performed using resistive heaters attached on the conductor surface. As is seen in Fig. 2, the measured recovery currents for a Cu–2% Ni clad sample are about twice the values obtained for an OFC clad sample.

The superconductor has been fabricated for the helical windings with a total length of 36 km. The inspection tests were carried out not only for component materials during fabrication but also for 38 lots of the

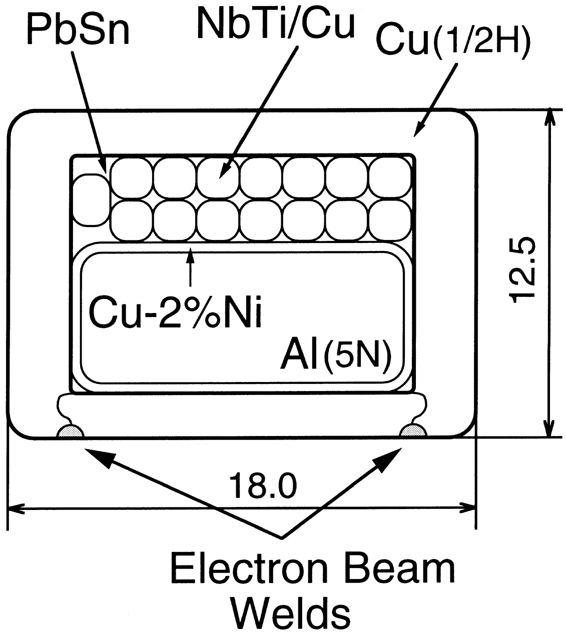

Fig. 1. Cross-sectional view of the superconductor for the helical coils.

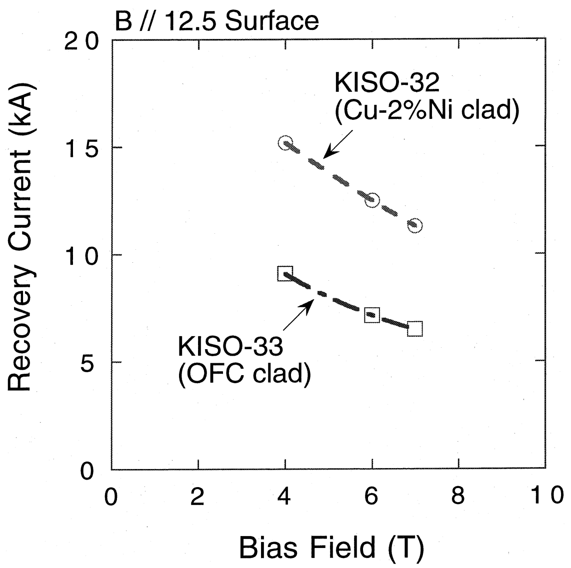

Fig. 2. Measured recovery currents for an OFC clad sample and a Cu–2% Ni clad sample. The external magnetic field was applied in the direction parallel to the 12.5 mm surface in this experiment.

final products by conducting short sample tests [8]. The measured critical currents were in good agreement with predicted values based on the measured critical currents for single strands. The self-field effect due to the large transport current as well as the three dimensional bias magnetic field distribution should be taken into account. All the recovery currents exceeded the specified value of 13.0 kA at 7.0 T (magnetic field parallel to the 18.0 mm surface) with an exposure rate of 50%, although the scattering of the measured values are rather large due to the Hall current generation.

3. Superconductor for the poloidal coils

The three pairs of poloidal coils; Inner Vertical (IV) (average radius 1.80 m), Inner Shaping (IS) (2.82 m) and Outer Vertical (OV) (5.55 m) coils have a maximum coil current of 5, −4.5 and −4.5 MA, respectively. The poloidal coils have force-cooled cable-in-conduit conductors. Each coil consists of eight double-pancakes, and supercritical helium of 4.5 K, 1 MPa, is supplied in parallel circuits from the inner (high field side) turns to the outer (low field side) turns with a mass flow rate of 80 g/s. The conductor consists of a cable with 486 NbTi/Cu superconducting strands and a conduit of rectangular cross-section of 3 mm thick (for IV and IS) and/or 3.5 mm thick (for OV). A cross-sectional view of the IV coil conductor is shown in Fig. 3. The nominal currents for the Phase II operation conditions are set at 20.8, 21.6 and 31.3 kA, for the IV, IS and OV coils, respectively.

The conductor tests of the poloidal coils have been carried out using both short samples and R&D coils. The critical current is designed to be three times higher than the operating current to obtain a sufficiently high stability margin [9]. The critical current of the conductor was measured with short samples in liquid helium using the superconductor test facilities. The measured critical currents showed good agreement with predicted values which were obtained from the measured critical currents for single strands by taking account of self-field effects. The cryogenic stability of the conductor was investigated by fabricating R&D coils and testing them with supercritical helium. Inductive heaters were used for initiating a normal conducting zone. One of the features of the LHD cable-in-conduit conductors is that the surface of strands is not coated, which is effective in increasing the cryogenic stability in DC operations due to the uniform current distribution among strands and the high heat transfer characteristics from strands to supercritical helium. This is clearly seen in Fig. 4, in which the stability margins measured for two R&D coils having similar size and configuration of cables are plotted as a function of the transport current [10]. TOKI-PF is the first R&D coil fabricated through the R&D programs of the LHD poloidal coils and its strands were coated with formvar. As shown in Fig. 4, the stability margins showed sharp drops before reaching the nominal operation point of 20 kA. On the other hand, the strand surface was not coated for the next IV–S coil and sufficient stability margins were seen to be kept over the nominal operation point. For the poloidal coil conductors, the void fraction in the cable area is designed to be 0.38, which is determined to be optimum from the viewpoint of strand movements and inter-strand coupling losses.

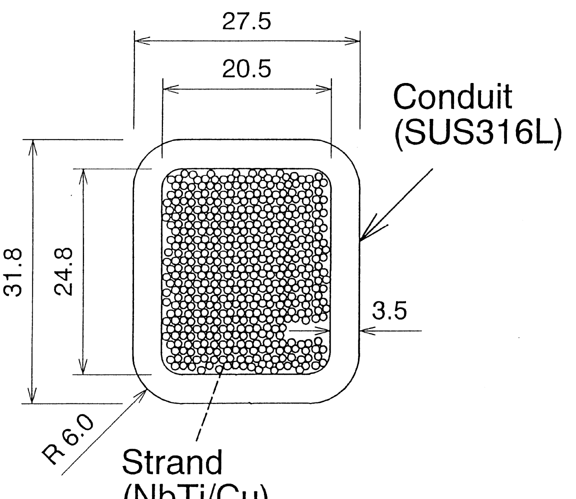

Fig. 3. Cross-sectional view of the superconductor for the IV poloidal coils.

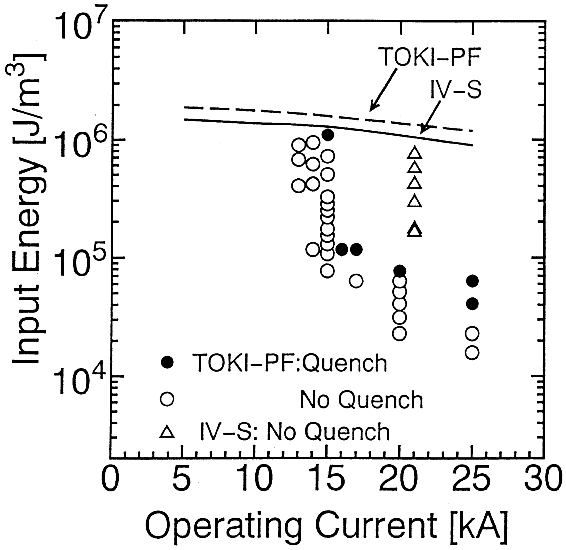

Fig. 4. Stability margins measured for TOKI-PF (with formvar coated strands) and IV-S (with bare strands).

The cool-down and excitation test of one of the IV coils (IV–L) was a highlight of the poloidal coil R&D. The hydraulic characteristics of the conductor were investigated during cool-down [11] and the coil was successfully excited up to the specified current of 20.8 kA without a coil quench [12].

4. Superconductor for the bus-lines

Another type of aluminum stabilized NbTi/Cu compacted strand cable has been developed for the flexible superconducting bus-lines which connect the LHD coil system with DC power supplies located about 60 m away from LHD. This is one of the innovative components newly applied to a fusion device through the LHD project.

A cut-away view of the bus-line is shown in Fig. 5. A pair of superconducting cables are installed in a cryogenic transfer line consisting of five-layered flexible corrugated tubes. The cables are cooled by two-phase helium at 4.2 K with a mass flow rate of 12 g/s for each line. Nine sets of bus-lines (six of them for the helical coils, three for the poloidal coils) with lengths 45.7–58.0 m have been installed in the basement of the LHD experimental hall by allowing a minimum bending radius of 1.5 m.

As shown in Fig. 5, each of the nine superconducting strands consists of NbTi/Cu and a pure aluminum stabilizer drawn together. The characteristics of a single strand were first examined by conducting a short sample test [13]. The critical current was confirmed to satisfy the required specification which should give the critical current of a whole conductor of >180 kA at 1 T.

The characteristics of a whole conductor was examined by constructing an R&D bus-line of 20 m length [14]. The critical current was hard to measure because of its large current carrying capacity and stability tests were only conducted. Fig. 6 shows a result in which the heater energy required for initiating a normal zone is plotted as a function of the transport current. It should be noted

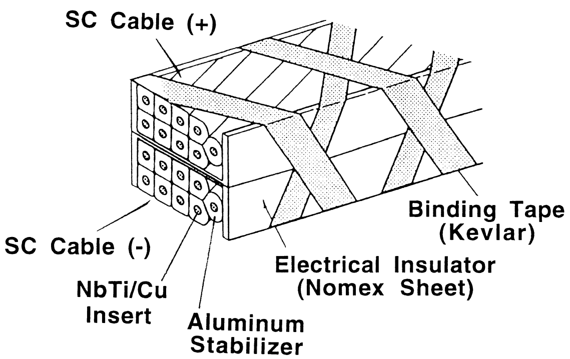

Fig. 5. A cut-away view of the superconducting cables for the bus-line.

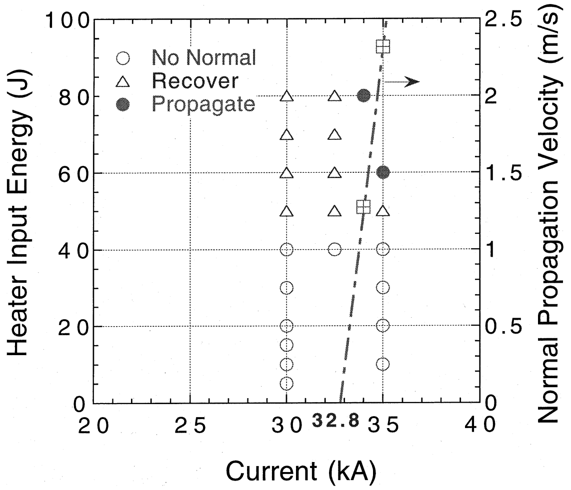

Fig. 6. Heater input energy required for initiating a normal zone in the R&D bus-line. The propagation velocity of the normal zone is also plotted.

that a transition to the normal state was never observed up to the nominal current of 32 kA. Moreover, according to the propagating velocity of the normal zones measured in the higher current region, the minimum propagating current was evaluated to be 32.8 kA. In the excitation tests of the R&D bus-line, the uniformity of the transport current among strands was examined using Rogowski coils wound around each strand at a terminal region. The result showed that the deviation of each current from the average value is less than 3%.

5. Conclusions

Three types of superconductors have been developed for the superconducting coil systems of LHD. These are the pool-cooled composite-type aluminum stabilized superconductors for the helical coils, force-cooled cable-in-conduit superconductors for the poloidal coils, and another type of aluminum stabilized superconductors cooled by two-phase helium for the bus-lines. All the conductors show sufficient characteristics to be used in LHD operations.

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