Reinforcement of High T_C Superconducting Bulk Rings for Short-Period Undulators

In most undulators, permanent magnets (PMs) are adopted to generate a strong magnetic field with a periodic length around several centimeters. The magnetic performance of PM materials such as NdFeB has been improved yearly. However, it should be noted that there is a theoretical limit to the remanence of NdFeB, i.e., 1.6 T. To break the limit, undulators based on superconducting magnets exploiting low-T_c superconducting wires have been under development for decades; however, we still have several technical challenges to be overcome for a routine operation of such superconducting undulators (SCUs), especially the thermal budget problem. The operation of SCUs at around liquid helium temperature under the condition where the electron beam and synchrotron radiation are passing nearby can easily lead to quench due to the heat load from them [1].

Instead of low-T_c superconductors, we have proposed the application of high-T_c superconducting (HTS) bulk magnets for the future development of short-period undulators [2], in which ring-shaped HTS bulk magnets (bulk rings) are mounted on the PMs of conventional undulators to enhance the magnetic field. To realize this concept, we have a lot of technical challenges to be overcome as well as the conventional SCUs. What is most important is to improve the mechanical property of the bulk rings, which can be easily damaged due to electromagnetic stress during the magnetization process. In fact, the bulk ring samples used in the proof-of-principle experiments were found to be broken after several trials [3], implying that they should be reinforced by some means. We have tested two procedures to reinforce the HTS bulk ring: resin impregnation and iron ribbing.

The resin impregnation is usually applied to HTS bulk samples to improve the mechanical properties [4]. In this method, the bulk sample is immersed in molten resin and the resin penetrates into the bulk sample through microcracks having openings on the surface. The voids connected to these cracks are also filled with resin, which drastically improves the mechanical properties of the HTS bulk samples. In addition to the resin impregnation, a pole piece made from high-permeability material such as permendur can be inserted and glued to the bulk ring as a rib (iron ribbing). It is worth noting that the pole piece also works as a flux concentrator to achieve stronger magnetic field. It is effective to use the resin impregnation to glue the pole piece and bulk ring. A problem in this scheme is the difference in thermal expansion coefficient. A simple calculation shows that the difference in contraction between the permendur and YBaCuO, a typical HTS material, is around several microns when the temperature is reduced from 300 K to 100 K, which may damage the glue function of the resin impregnation.

To investigate the effects of the reinforcement methods described above, we prepared four bulk ring

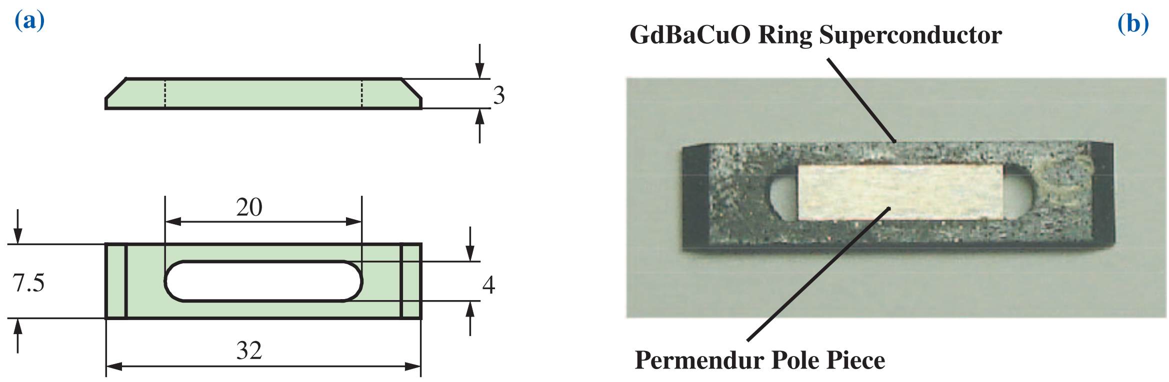

Fig. 1. **(a)** Overall dimensions of the ring HTSC sample prepared for the experiments to check the reinforcement method. **(b)** Photograph of sample C, in which a pole piece made of permendur is inserted.

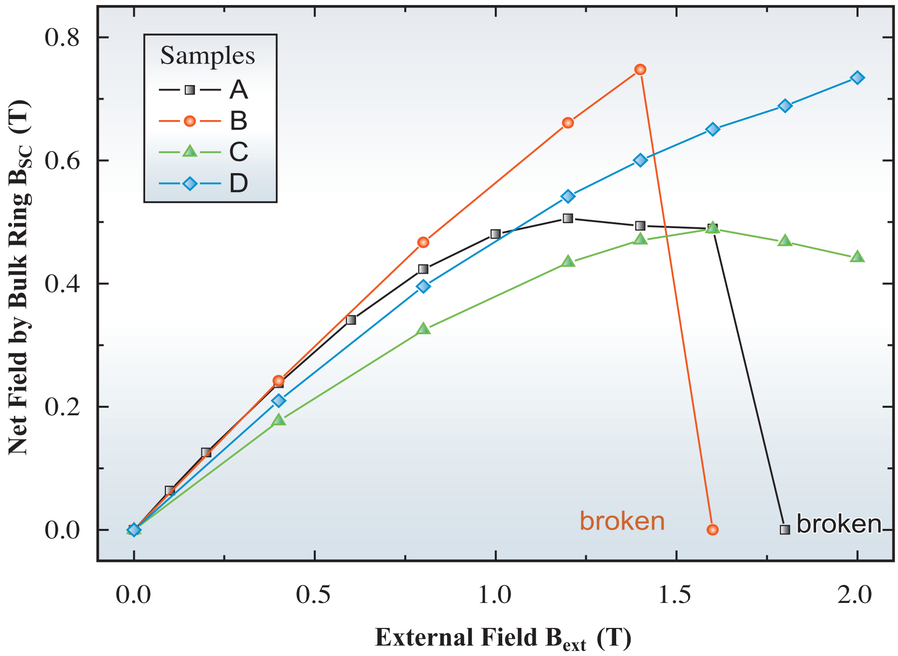

Fig. 2. Summary of the experiments to investigate the reinforcement method. Samples A and B were broken at the external fields of 1.8 T and 1.6 T, respectively, while samples C and D survived even after application of 2.0 T, the strongest field that can be applied by the electromagnet used in the experiment.

samples (A, B, C and D) made of GdBaCuO that were reinforced with several different methods, and carried out experiments to check the mechanical property of these samples. Figure 1(a) shows the overall dimensions of the sample. After machining, three samples (B, C and D) were immersed in epoxy resin for impregnation, where a pole piece made from permendur was inserted into samples C and D. Thus, samples C and D have the same structure. No treatment was made for sample A. Figure 1(b) shows a photograph of the sample C.

To investigate the effect of reinforcement, the samples were cooled to a temperature of 25 K and exposed to an external magnetic field up to 2 T, and the magnetic field at the center of the sample was measured by a Hall probe. Figure 2 shows the results of the experiments, where the net magnetic field B_{sc} generated by the bulk ring is plotted as a function of the external field B_{ext}. Samples A and B were broken after B_{ext} reached 1.8 T and 1.6 T, respectively, which means that resin impregnation alone is not enough to reinforce the bulk ring for undulators. On the other hand, samples C and D survived even after applying 2 T, which is close to the expected peak field of the undulators with HTS bulk rings with a magnetic period around 1 cm. Thus, we can conclude that the iron ribbing combined with resin impregnation significantly reinforces the bulk ring and improves its mechanical properties.

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