UNDULATORS WITH HIGH-TEMPERATURE SUPERCONDUCTING PERMANENT MAGNETS

Introduction

Periodic magnetic fields in undulators are usually generated by rare earth permanent magnets (REPMs). The performance of the REPM material is thus important for undulator development and is in fact improved yearly. It should be noted, however, that there is a theoretical limit to the remanent field of REPM materials, which means that the achievable magnetic field in an REPM undulator also has a theoretical upper limit.

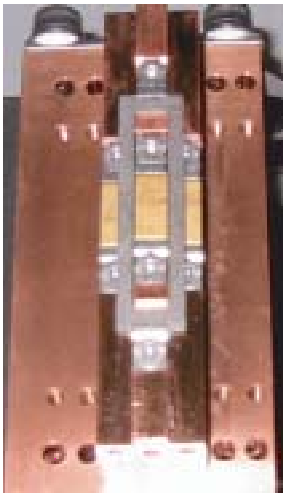
To go beyond the limit, superconductors can be used instead of REPMs. In practice, undulators equipped with superconducting coils (superconducting undulators: SCUs) have been constructed and under development for about 20 years [1]. These SCUs can produce much higher fields than achieved by REPM undulators at the same magnet gap. Note, however, that the construction and operation of SCUs would be more difficult for shorter periodic lengths since they should operate at around liquid helium temperature at narrower gap values.

There is another way of utilizing superconductors as magnets. Because the resistivity of superconductors is exactly zero, a current loop induced by Faraday's electromagnetic induction law is not damped at all and flows forever (persistent current). Thus, such a "magnetized" superconductor works as a permanent magnet with a much stronger field than REPMs and is called a superconducting PM (SCPM). In particular, SCPMs fabricated from bulk-type high temperature superconductors (HTSCs) have better performances than REPMs. We have proposed two schemes for applying such SCPMs to shorter-period undulators. Their principles and results of demonstration experiments are presented in the following sections.

Cryoundulator plus

The cryoundulator plus (CU*plus*) [2] is an extension of the cryoundulator concept [3], in which REPMs are cooled to improve the magnetic performance, i.e., the remanent field and coercivity. Ring-shaped HTSCs are mounted on REPM arrays to enhance the magnetic field. Before operation, the magnet arrays are fully closed at room temperature. By reducing the temperature of the magnet arrays and opening the gap to a certain value, the HTSC rings are magnetized to keep the flux inside, resulting in a field enhancement. To demonstrate the principle, experiments were carried out with magnet modules composed of an HTSC ring made of GdBaCuO and three pieces of REPMs made of NdFeB as shown in Fig. 1(a).

(a)



(b)

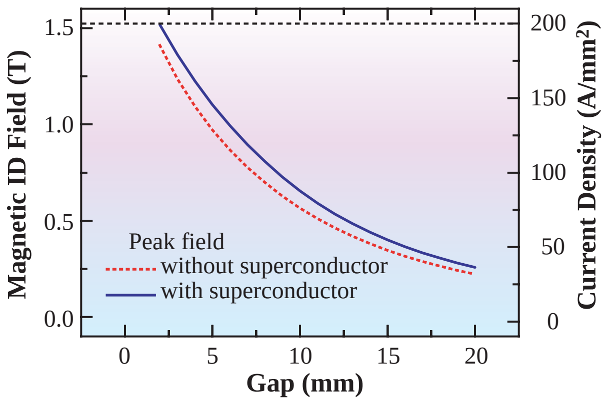


Fig. 1. **(a)** Photograph of magnet module used in experiments to demonstrate the principle of CU*plus*. **(b)** Results of the experiments.

Two of the rings were placed face-to-face and immersed in liquid nitrogen. Then the gap was opened to insert a Hall probe and measure the peak field as a function of the gap value. Figure 1(b) shows the results with and without the HTSC rings, clearly showing field enhancement by HTSC rings. We encountered one problem brought about by a mechanical weakness of the HTSC ring [4] during the experiment: magnetic performance degraded after several trials. R&D to improve the mechanical strength of the HTSC ring is now in progress.

Superconducting Permanent Magnet Undulator

In the CU*plus* scheme, the magnetic field is generated mainly by REPMs and the HTSC plays only a minor role. To take full advantage of the magnetic performance of HTSCs, all the REPMs should be replaced with SCPMs. The most straightforward way of realizing this concept is to place SCPMs with opposite polarities side by side. However, it is easy to understand that this scheme is impractical. Now, let us consider the case when all SCPMs have identical polarities, as shown in Fig. 2(a). Such a situation is realized by magnetizing the HTSC array using an external uniform field. The magnetic field generated by the SCPM array is schematically shown in Fig. 2(b) and is composed of a uniform field (field offset) and a periodic field that reflects the periodic structure of the SCPM array. If the field offset can be eliminated by some measures, the remaining periodic field can work as an undulator field. The undulator period (λu) in this case corresponds to the length of the HTSC piece. We have so far proposed two methods of realizing the concept described above. For details, refer to [5].

To demonstrate the principle described above, experiments were carried out using three pieces of HTSC made of GdBaCuO and a normal conducting electromagnet to magnetize the HTSCs and eliminate field offset. The results are shown in Fig. 3, in which the magnetic field distributions generated by the three HTSCs pieces magnetized by the electromagnet are plotted. We can find periodic fields with three periods, i.e., the number of HTSC piece.

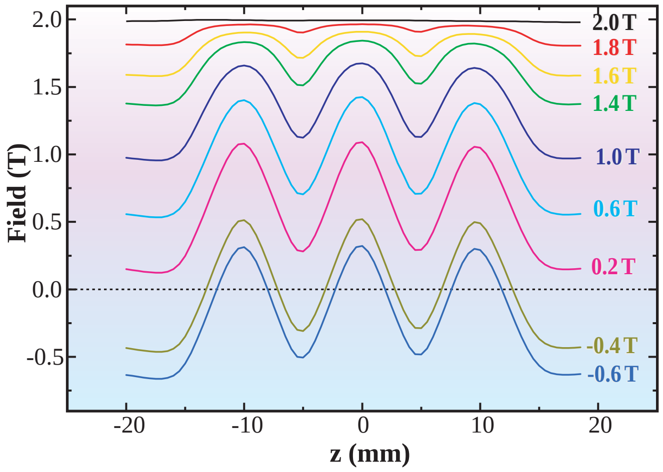


Fig. 3. Results of experiments for demonstrating the principle of SCPMU.

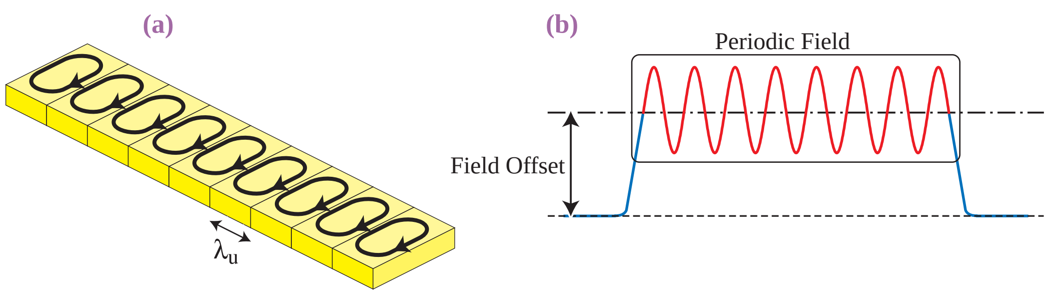


Fig. 2. **(a)** SCPM array with identical polarity and **(b)** its typical field profile.

Expected Performance

Now let us compare the expected performance of the proposed undulator schemes with those fo conventional ones. As an example, a periodic length of 14 mm and a gap value of 5 mm are taken for undulator parameters. Figure 4 shows the calculated peak fields achievable in the proposed undulator schemes as functions of the critical current density of the HTSC material (*jc*).

In the same figure, peak fields in the other undulators, i.e., SCU, cryoundulator and conventional PM undulator, are indicated. We can find a criterion for *jc* whether or not the undulators with SCPMs are practical. The performance of the proposed undulators, i.e., the CU*plus* and SCPMU, can exceed that of the existing SCU, if *jc* is higher than 1 kA/mm^2, which is not difficult to achieve with the state-of-the-art technology in HTSC materials science.

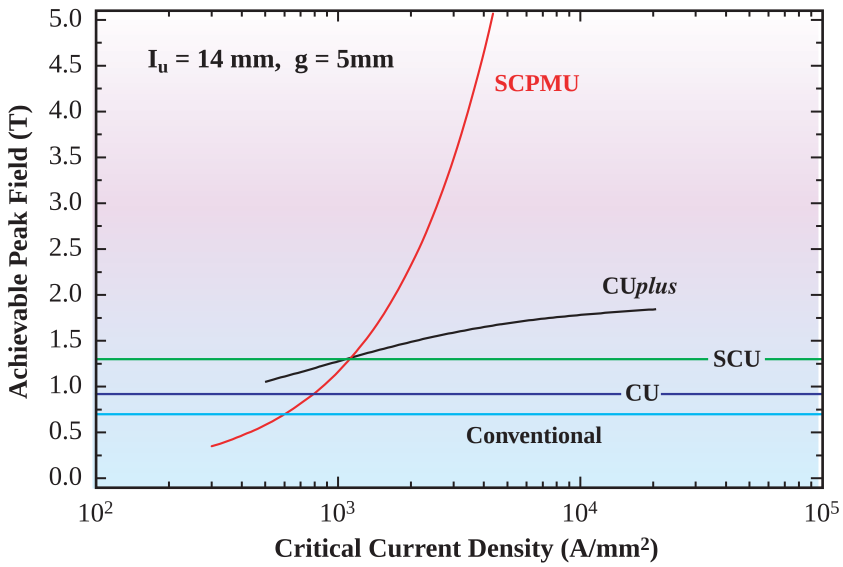


Fig. 4. Expected performance of proposed undulator and comparison with that of existing undulators.

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