A BULK SUPERCONDUCTOR AND ITS APPLICATION TO INSERTION DEVICES*

T. Kii†, Institute of Advanced Energy, Kyoto University, Uji, Japan

Abstract

High-field short-period undulator will be one of the key technologies for the future light sources. Various approaches have been continued under the limitation of materials for permanent/superconducting magnets. The use of bulk superconductors is attractive because of their high current density in the presence of a high magnetic field. The critical current density for rare-earth barium copper oxide (REBCO) bulk superconductors exceeds 10 kA/mm^2 even at 10 K in a field range below about 3 T, and exceeds 20 kA/mm^2 at 4.2 K.

In order to utilize the relatively high current density in the bulk REBCO and to generate periodic magnetic field we proposed a staggered array bulk superconductor undulator. Recently, we have developed the third undulator prototype consisting of a 6 T solenoid and a 6 period bulk REBCO array, and successfully demonstrated periodic field amplitude of 2.22 T for period length of 10 mm and undulator gap of 4.0 mm at 7 K.

INTRODUCTION

Periodic alternating magnetic fields can be used in magnetic levitation systems, linear motors, undulators/wigglers in accelerators, and low-dimensional electron, spin systems for spin-state control in fundamental physics, etc.

Periodic magnetic fields can be generated relatively easily with strong neodymium permanent magnets. Stronger magnetic fields can be obtained by using commercially available superconducting wires. The critical density of commercially available superconducting wire is on the order of several kA/mm^2 at 4.2 K, and the strength of the periodic magnetic field is limited by this practical critical current density.

In order to generate stronger periodic magnetic field, we have to handle much higher current density than the practical SC wires. Focusing on the core of the superconducting wire, the critical current density is more than an order of magnitude higher than the effective engineering current density. For example, the engineering current density of NbTi and Nb_3Sn superconducting wires is limited to the order of a few kA/mm^2 due to the sheath required for wire fabrication, but the core parts have a critical current density of about 10 kA/mm^2. In the case of rare-earth barium copper oxide (REBCO) coated superconducting tapes, the critical current density of the superconducting thin-film layer can reach a few hundred kA/mm^2, but the thickness of the superconducting material layer is only a few micrometers and constitutes only a few percent of the total volume of the wire, resulting in an effective critical current density of the order of 1 kA/mm^2 as well as NbTi/Nb_3Sn.

On the other hand, the critical current density of bulk superconductors, which are formed from only superconductor materials in a bulk form, is lower than the superconducting part of wires and tapes, but the current density of the material is equal to the engineering current density. Critical current densities exceeding 10 kA/mm^2 at 4 K self-field have been achieved in the best performing rare-earth cuprate superconducting system. Therefore, the use of bulk superconductors potentially makes it possible to control magnetic fields using the superconducting current with current density that is one order of magnitude higher than that of commercial superconducting wires.

Therefore, we proposed [1] and demonstrated [2-4] a staggered array bulk superconducting undulator with periodically arranged bulk superconductors (Bulk HTS SAU), focusing on the high magnetic performance of rare earth cuprate superconductors. Recently, PSI started development for SwissFEL and Swiss Light Source 2.0 (SLS2.0) storage ring [5, 6].

In this study, a 6 T solenoid and a gadolinium barium cuprate (GdBaCuO) superconductor were used to generate and control periodic magnetic fields that significantly exceed the limits of permanent magnets and practical commercial wires.

BULK HTS SAU

The structural schematic drawing of a Bulk HTS SAU and the mechanism of periodic magnetic field generation are shown in Fig. 1.

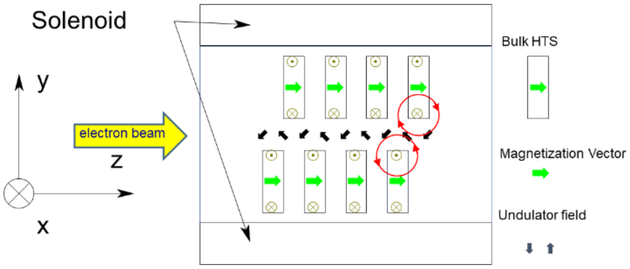

Figure 1: A schematic cross sectional view of a Bulk HTS SAU. When the magnetic field is changed by an external solenoid, a shielding current is induced inside the bulk HTS to cancel out the magnetic field change. The induced current produces a periodic alternating magnetic field along the z-axis.

When a magnetic field change is applied to the superconductor array installed in the solenoid, a shielding current is induced in each superconductor to cancel the magnetic field change. As a result, the large supercurrents, whose directions are different and having half a period offset from each other generate a strong periodic alternating magnetic field on the central axis.

---

* Work supported by KAKENHI 17H01127, JP22H03870

† kii@iae.kyoto-u.ac.jp

ISBN: 978-3-95450-224-0 ISSN: 2673-7035 doi:10.18429/JACoW-FLS2023-TH1D2

Here I list the important differences from the case where the circulating current is realized by superconducting wires.

1. The current density of the bulk is one order of magnitude higher than that of the wire
2. The current path follows the bulk boundary, so the current can be bent at a steep angle without being limited by the minimum bend radius of the wire
3. The current flowing in each bulk cannot be controlled by an external power supply.

METHOD AND EXPERIMENT

The prototype undulator consists of a temperature controlled bulk superconductor array, a superconducting solenoid, and a 3D magnetic field scanning system on the beam axis. The bulk superconductor array consists of Nippon Steel QMG™ bulk GdBaCuO bulks and pure copper spacers. Figure 2 schematically shows the single unit of the assembled array.

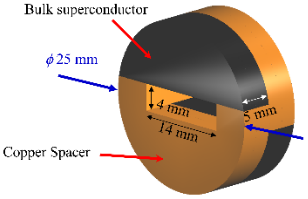

Figure 2: Schematic drawing of a single period of a bulk HTS array. It consists of an almost semicircular disk-shaped bulk superconductor and an almost semicircular pure copper spacer with a rectangular notch.

The undulator period is 10 mm, and the gap between the upper and lower arrays is 4 mm, and pure copper supports are used. The typical magnetic performance of the GdBaCuO superconductor was measured with PPMS using a micro specimen. At a temperature of 4 K, critical current density J_c of 20 kA/mm^2 was recorded [7].

The temperature of the bulk superconductor is monitored using a Cernox™ resistance temperature sensor attached to the end copper block. The bulk superconductor array is mounted in a pure copper sample holder and conductively cooled using a helium continuous flow cryostat. The temperature of the array is controlled by adjusting the helium flow rate and PID control of the heater output attached to the sample holder.

The external solenoid is a custom 6 T superconducting solenoid with a 10 cm diameter room temperature bore from Cryomagnetics. The magnetic field strength is 6.000 T at the center of the solenoid axis and 5.985 T at the edge of the array, 2.5 cm away from the center in the axial direction.

The magnetic field measurements are performed by scanning a Hall sensor array along the solenoid axis (z-direction), which can measure three-directional magnetic field components on the approximate center axis of a 4 mm × 14 mm rectangular cross-sectional space of the array inserted in a vacuum duct. It is estimated that the sensor element measuring the y-component was offset by about 0.2 mm, although no y-directional magnetic field was produced on the perfect central axis.

Figure 3 shows a photograph of the Hall sensor array. The Hall sensor array consists of three custom-made Arepoc model HHP-NU (1.5-300 K up to 5 T) 3 mm × 4 mm × 1 mm and one standard Arepoc model LHP-NU (1.5-300 K up to 30 T) 5 mm × 7 mm × 1 mm. Two elements for measuring the undulator magnetic field B_{und} are installed on the white ceramic plate so that the B_{und} component of the periodic magnetic field section and the B_{und} component of the edge leakage field can be acquired seamlessly in a short time.

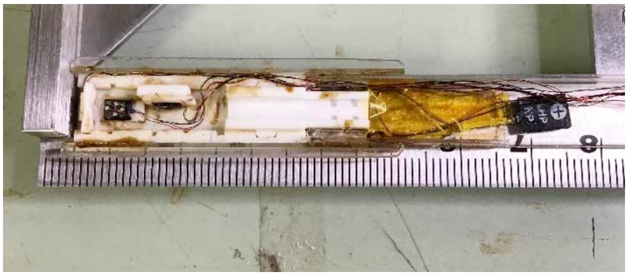

Figure 3: Photograph of a Hall sensor array, which can measure three-component magnetic fields along the z-axis. The second and fourth Hall sensors from the left are used to measure the B_{und} component.

The Hall sensor array was fixed to the end of a 0.5 mm thick plastic rod and driven by a stepper motor with a linear motion actuator. The driving step along the z-axis was 0.2 mm and the total scanning distance was 66 mm.

The experiment was performed using the following so-called field cooling method: after applying an initial magnetic field of 6 T, the superconducting array was cooled to operating temperature. The magnetic field of the solenoid was then varied to induce a shielding current in each superconductor to generate a periodic magnetic field.

RESULTS AND DISCUSSION

The initial applied magnetic field was set to 6 T, and magnetic field changes of 3, 6, 9, and 12 T were applied at temperatures of 20 K, 10 K, and 7 K. The magnetic field in three directions along the z axis was measured. Figure 4 shows the measurement results when the magnetic field was changed from 6 to -6 T at 7 K.

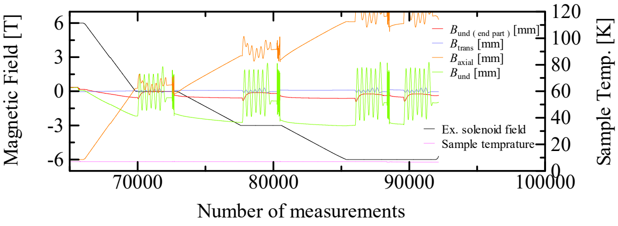

Figure 4: Results of undulator field measurements.

The relationship between the given magnetic field change and the undulator magnetic field B_{und} for each measurement is shown in Fig. 5; the B_{und} is the average of the magnetic field peak values of the 10 central peaks is adopted. For the peak field strength, a discrepancy was observed, with a variance of approximately 10%. This is due to the non-uniformity of the critical current properties of the superconductor used in the array assembly. The bulk superconductor used in this experiment exhibited a variation of about 15%, according to the estimated magnetic field strength at a temperature of 77 K. The cause of the variation is thought to be due to the difference in critical current properties depending on the distance and angle from the seed crystal during the recrystallization process with the seed crystal during the synthesis of pseudo-single crystallized REBCO superconductors.

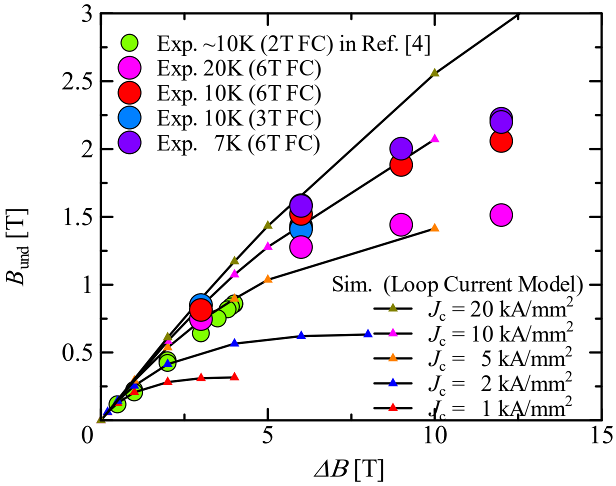

Figure 5: Relationship between undulator field and solenoid field change. As the field change is increased, the undulator field increases, but it gradually leaves the linear increase and tends to saturate.

The curves in Fig. 5 are the predicted results of the numerical model based on the loop current model developed by us [8]. Undulator magnetic fields of 2.22 T at 7 K, 2.06 T at 10 K, and 1.51 T at 20 K are observed. The undulator field strength tends to deviate from a linear trend at all temperatures, indicating that as the total amount of induced current in the superconductor increases, the induced current becomes more located closer to the center of the bulk, and when the entire bulk is filled with the shielding current, the undulator field saturates.

The experimental saturation characteristics are close to those predicted for about 5 k/mm^2 at a temperature of 20 K, and about 10 kA/mm^2 at 10 and 7 K. These critical current densities are consistent with the results of critical current characteristic measurements performed by PPMS for a small specimen [7].

For comparison with undulators using permanent magnets and superconducting wires, the magnetic field strength of various undulators with the horizontal axis as gap/period is shown in Fig. 6. The 2.22 T obtained at 7 K is approximately 3.1 times higher than the 0.71 T that can be generated by a cooled hybrid-type permanent magnet undulator, indicating that the Bulk HTS SAU can generate a much stronger period alternating magnetic field than conventional technologies. It also has an advantage of more than 25% over the superconducting wire type [9, 10]. Considering the advantages of small cold mass and significantly higher operating temperature than 4.2 K, the Bulk HTS SAUs are expected to have high potential as insertion devices for future light sources.

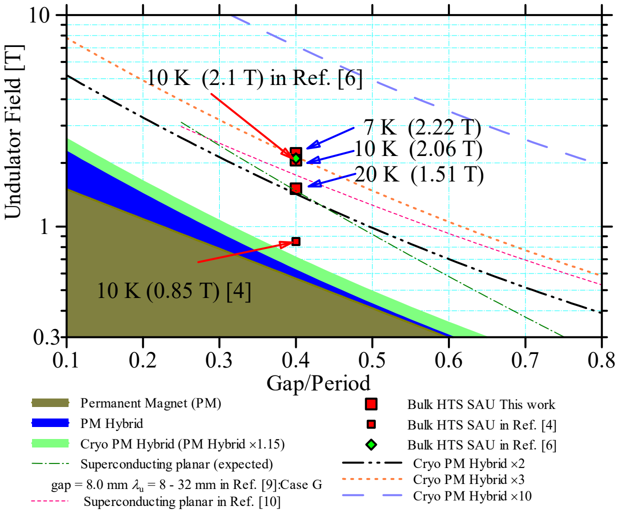

Figure 6: Comparison of undulator magnetic field strength of different types of undulators scaled by gap/period. Performance prediction curves for superconducting wire-wound planar undulators [9, 10], and characteristic curves for ×2, ×3, and ×10 based on the cryo hybrid permanent magnet type are also shown for comparison.

CONCLUSION

A new method for generating short-period, strong periodic magnetic fields using bulk superconductors has been presented. Bulk superconductors, which are composed entirely of superconducting materials, can handle current densities approximately 10 times higher than those of superconducting wires, which are expected to have high undulator fields. In this report, I attempted to generate a magnetic field using an array of bulk REBCO superconductors and a 6 T solenoid. The periodic magnetic field generation of 2.22 T is confirmed at a temperature of 7 K with a period of 10 mm and a gap of 4 mm. The results of the experiment show that the bulk superconductor has high potential as an insertion device for future light sources.

ACKNOWLEDGEMENTS

This work was supported by KAKENHI 17H01127, JP22H03870 and Research Center for Low Temperature and Materials Sciences, Kyoto University.

REFERENCES

[1] T. Kii *et al.*, “Design study on high-TC superconducting micro-undulator”, *in Proc. 28th Int. Free Electron Laser Conf. (FEL’06)*, pp. 653-655, 2006.

[2] R. Kinjo *et al.*, “A bulk high-TC superconductor staggered array undulator”, *in Proc. 30th Int. Free Electron Laser Conf. (FEL’08)*, pp.473-476, 2008.

[3] T. Kii *et al.*, “Proposal of a bulk HTSC staggered array undulator”, *AIP Conf. Proc. (SRI’09)*, vol. 1234, pp. 539-542, 2010. `doi:10.1063/1.3463261`

[4] R. Kinjo *et al.*, “Demonstration of a high-field short-period undulator using bulk high-temperature superconductor”, *Appl. Phys. Express*, vol. 6, no. 4, p 042701, 2013. `doi:10.7567/APEX.6.042701`

[5] M. Calvi *et al.*, “A GdBCO bulk staggered array undulator”, *Supercond. Sci. Technol.,* vol. 33, p. 014004, 2020. `doi:10.1088/1361-6668/ab5b37`

[6] K. Zhang *et al.,* “Record field in a 10 mm period bulk high-temperature superconducting undulator”, *Supercond. Sci. Technol.,* vol. 36, p. 05LT01, 2023. `doi:10.1088/1361-6668/acc1a8`

[7] T. Kii *et al.*, “Low-temperature operation of a bulk HTSC staggered array undulator”, *IEEE Trans. Appl. Superconduct.*, vol. 22, no.3, p 4100904, 2012. `doi:10.1109/TASC.2011.2180498`

[8] R. Kinjo *et al.*, “Numerical evaluation of bulk htsc staggered array undulator by Bean model”, *in Proc. 31st Int. Free Electron Laser Conf. (FEL’09)*, pp. 746-749, 2009.

[9] P. Elleaume, J. Chavanne, and B. Faatz, “Design considerations for a 1 Å SASE undulator”, *Nucl. Instrum. Methods,* vol. 455, no. 3, pp. 503-523, Dec. 2000. `doi:10.1016/S0168-9002(00)00544-1`

[10] J.A. Clarke *et al.*, “Superconducting planar undulator development in the UK”, *in Proc. 2nd Int. Particle Accelerator Conf. (IPAC’11),* San Sebastián, Spain, pp. 3320-3322, 2011.