Letter

Breakthrough in field amplitude of high-temperature superconductors staggered-array undulators

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The fundamental wavelength of undulator radiation and free-electron lasers depends on the period and magnetic field strength of the undulator. Shortening the undulator period and increasing the magnetic field strength are essential for achieving higher-energy radiation and increased flux. The most promising approach to date has been an undulator utilizing high-temperature superconductors (HTSs), particularly the bulk HTS staggered-array undulator (BHSAU). In this Letter, we demonstrated that adding a ring HTS can increase the magnetic field strength of the BHSAU to two to three times. It was found that the ring HTS not only provides an additional undulator magnetic field but also shields the solenoid magnetic field, allowing for stronger solenoid field variations without affecting the electron beam. This, in turn, enhances the magnetic field generated by the bulk HTS itself, resulting in an exceptionally strong undulator field. The magnetic field of the undulator is more than ten times stronger than that of in-vacuum permanent magnet-based structures of similar design, significantly enhancing the performance of synchrotron radiation and free-electron lasers.

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An undulator utilizing high-temperature superconductors (HTSs) represents a promising technology for achieving short-period and high-field undulators. This advancement extends the fundamental energy range of undulator radiation into a higher-energy photon region, significantly enhancing the photon flux of hard x-ray light in medium-energy storage rings. Compared to conventional undulators made from permanent magnets or low-temperature superconductors, HTS-based undulators offer several distinct advantages. A bulk HTS can trap magnetic fields more than ten times stronger than those produced by permanent magnets. For instance, Tomita *et al.* reported a trapped field of over 17 T in a 26-mm-diameter $YBa_2Cu_3O_{7-\delta}$ (YBCO) bulk at 29 K [1] and Durrel *et al.* reported 17.6 T in a 25-mm-diameter $GdBa_2$ Cu $_3O_{7-\delta}$ (GdBCO) bulk at 26 K [2]. HTSs are better suited than low-temperature superconductors for use in high-current accelerators, where thermal input from the electron beam and radiation is significant.

So far, various approaches to realize HTS undulators have been investigated. The undulator using bulk HTS was first proposed in 2004 by Tanaka *et al.* [3]. Over the next few years, they proposed another type of bulk HTS undulator and performed the demonstrations of those using bulk YBCO [4,5]. In 2007, Tanabe *et al.* demonstrated an undulator using YBCO tape and one using etched MgB_2 film [6]. In 2009, Prestemon *et al.* investigate an undulator using etched YBCO tape [7], Prinkna proposed the application of bulk MgB_2 to an undulator [8], and Majoros *et al.* investigated an undulator using MgB_2 multifilament wire [9]. Weerakonda proposed a method to apply the pulse magnetization technique to the undulator structure [10].

A bulk HTS staggered-array undulator (BHSAU) [11–13] is considered the most practical approach among bulk HTS undulators. In 2013, an undulator field amplitude of over 0.8 T was achieved at 6 and 20 K in a prototype with GdBCO bulks, six periods, a 10 mm period length, and a 4 mm gap, utilizing a 2-T superconducting solenoid and a helium gas cooling system at Kyoto University [14,15]. In 2022, the same prototype demonstrated an undulator field amplitude of 2.2 T using a new 6-T solenoid [16]. In 2023, a collaborative group including PSI in Switzerland and the University of Cambridge in the U.K. achieved 2.1 T with the same period length and gap in a 10-T solenoid [17]. This achievement is also noteworthy as it approaches the theoretically predicted performance [15]. The technology has now entered a practical research phase, with ongoing studies focusing on methods for reverse estimation of the critical current density of bulk HTS from the undulator field and for sorting the bulk HTS to obtain uniform undulator field [18,19].

This research focuses on exploring a way to break the limit of magnetic-field amplitude in BHSAU using ring HTS. We call it a ring HTS staggered-array undulator (RHSAU). The findings of this research could benefit the development of more shorter-period and high-field undulators, which could revolutionize synchrotron radiation and free-electron lasers.

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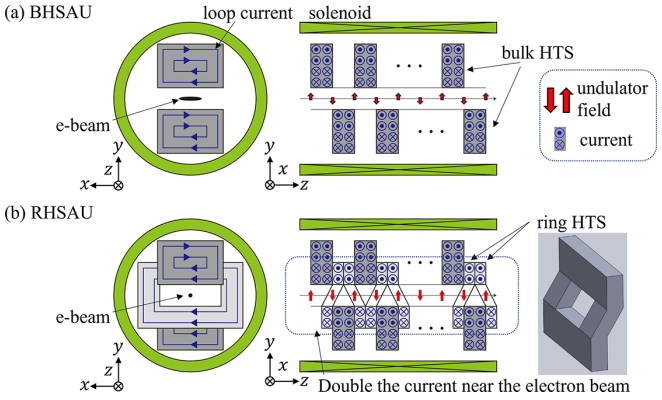


FIG. 1. Principle of (a) the bulk HTS staggered-array undulator (BHSAU) and (b) the bulk and ring HTS staggered-array undulator (RHSAU). In the RHSAU, the superconducting current induced by the solenoid is doubled near the electron beam, resulting in a stronger undulator field compared to the BHSAU.

Figure 1 shows schematic diagrams of BHSAU and RHSAU. In BHSAU, when a solenoid field is applied to the bulk HTS in the negative-z direction, superconducting current loops are established to counteract the change in the magnetic field inside the bulk HTS; therefore, the bulk HTSs are magnetized in the positive-z direction and thus generate a sinusoidal magnetic field in the y direction. In this undulator, because the undulator field is generated by bulk HTS magnetized in the same direction, one external solenoid can magnetize all the bulk HTSs and control the undulator field by controlling the magnetization of the bulk HTS. In RHSAU, loop currents in the same direction as those in bulk HTS are induced within the ring HTS, but the directions of the currents near the electron beam are reversed. As a result, twice the undulator field strength can be expected in the ideal case, where the current distribution in the ring HTS is assumed to be uniform.

The electron beam passes through the ring HTS, but this poses no issue for a single-pass low-emittance linear accelerator used in free-electron lasers or for recently commercialized low-emittance round-beam storage rings, especially employing on-axis injection for the electron beam.

The numerical simulations were made by the finite-element software COMSOL multiphysics [20] and its ac/dc module. The calculations utilized the exponential $E - J$ relationship of superconductivity, known as the n-value model. In the model, the nonlinear resistivity in bulk HTS, ρ_{sc}, is expressed by the following equation:

$$\rho_{sc} = \frac{E_c}{|\boldsymbol{J}|}\left(\frac{|\boldsymbol{J}|}{J_c}\right)^n. \tag{1}$$

Here, the parameters are as follows: n value $n = 21$, critical current density $J_c = 10$–$20\ \mathrm{kA/mm^2}$, and critical electric field $E_c = 100\ \mu\mathrm{V}$. To compare the principles of BHSAU and RHSAU, we assume a constant J_c here. This assumption results in an identical undulator field strength for both field changes from -10 to 0 T and from -5 to $+5$ T; therefore we can compare the experiment and the simulation results within one graph using ΔB_s as the horizontal axis in Fig. 3. In the practical region of the usage, the dependency of J_c on the magnetic field of GdBCO is relatively flat and a constant-J_c assumption gives an accurate undulator field strength with an absolute error of less than 10 % from that considering a real $J_c - B$ relation.

Figure 2 illustrates the one-period simulation geometry of RHSAU [Figs. 2(a) and 2(b)] and its variant RHSAU-II [Figs. 2(c) and 2(d)]. Here, RHSAU-II is a structure formed by combining a ring, positioned vertically (with $\theta = 90^\circ$), and a bulk component, processed together as an integrated unit. Both RHSAU and RHSAU-II can be magnetized in the same way as BHSAU, by simply adjusting the solenoidal field to induce the superconducting current loop. As will be shown later, both RHSAU and RHSAU-II enhance the undulator field, but they exhibit different responses to the solenoid field. The structural parameters for the bulk HTSs are almost identical to the experiments and are as follows: period $\lambda_u = 10$ mm, gap $g = 4$ mm, bulk thickness $D_z = 4, 5$ mm, bulk radius $R = 15$ mm, bulk height $D_y = R - g/2$. The structural parameters for the ring HTSs are as follows: thickness $d_z = D_z$, minor ring height $d_y \approx 0.5$–2.5 mm, ring width $r_x \approx 5$–20 mm, ring vertical gap $g_y = g$, and ring horizontal gap $g_x = 2.5$–10 mm. The undulator field strength B_0 is the peak value of B_y on the z axis. These parameters are briefly adjusted to get the maximum B_0 at $B_z = 0$ in Fig. 4.

Figure 3 shows the dependence of the undulator field B_0 on the solenoid field change after the cooling, ΔB_s, in BHSAU (left), RHSAU (middle), and RHSAU-II (right), respectively. Also shown are experimental results of BHSAU, $B_0 = 0.85$ T at Kyoto University (2013) [14,15], $B_0 = 2.2$ T at Kyoto University (2022) [16], and $B_0 = 2.1$ T in PSI (2023) [17]. Note that the experimental result from PSI includes a 0.2-T boost due to the ferromagnetic poles, and the open squares also depict the values without the ferromagnetic contribution for comparison.

The middle graph in Fig. 3 shows that RHSAU having $J_c = 20\ \mathrm{kA/mm^2}$ theoretically reaches $B_0 = 7$ T at $\Delta B_s = 20$ T and it having $J_c = 10\ \mathrm{kA/mm^2}$ reaches 6 T. This value is more than three times higher than the experimental result of BHSAUs, and ten times higher than the widely used in-vacuum permanent magnet undulators having the same period and gap. It can be expected that B_0 will increase without saturation up to a larger solenoid magnetic field in some condition.

The comparison shows that RHSAUs have nearly 1.5 times larger B_0 as BHSAUs at the same ΔB_s. RHSAU-II shows only about 10% higher B_0 than BHSAU at the point $\Delta B_s = 10$ T, but at $\Delta B_s = 20$ T, it shows a 30% higher B_0. To describe qualitatively, B_0 in BHSAU saturates in the latter part of the graph, whereas B_0 in RHSAU and RHSAU-II continues to increase until the latter part. This is because, in ring HTSs, the current starts flowing from the outer side of the ring, which is farther from the center axis, and penetrates into the inner side of the ring, which is closer to the axis.

Comparisons between BHSAUs and RHSAUs considering the zero-axial-field operation are discussed here. The electron beam passing through the undulators is affected by the strong axial magnetic field generated by the solenoid along its trajectory. This field induces effects such as focusing and transverse coupling: Focusing changes the beam size and angular divergence, while transverse coupling causes a rotation of the beam

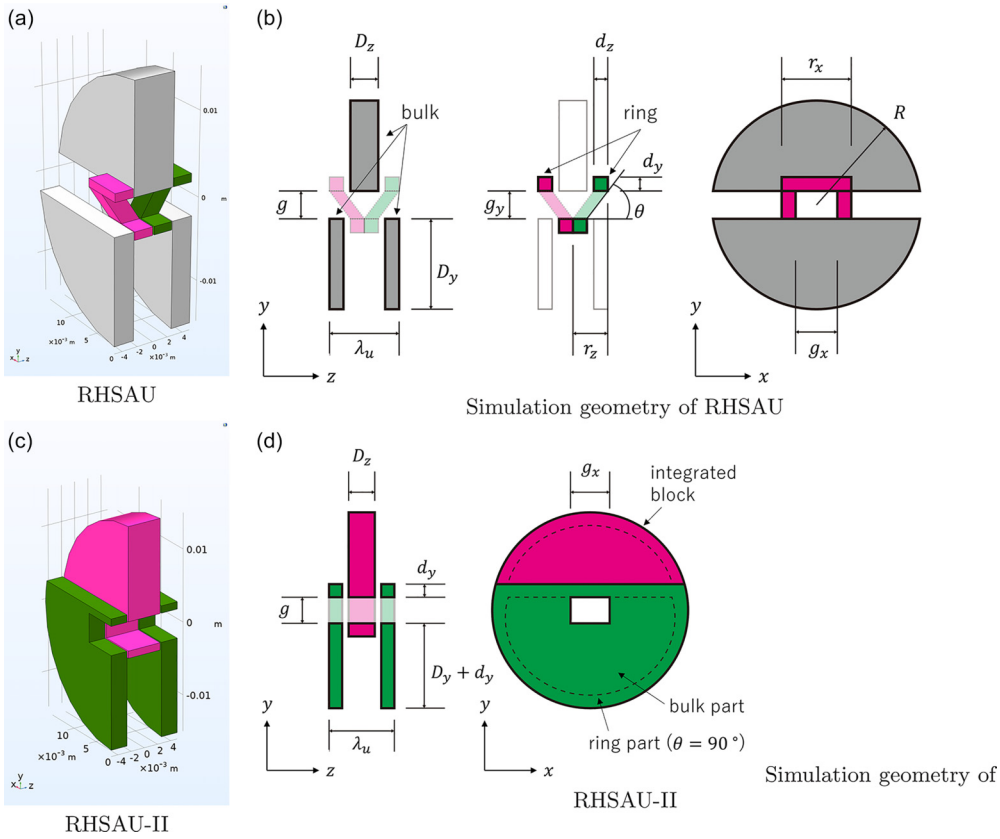


FIG. 2. One-period half-cut three-dimensional (3D) models and simulation geometries of RHSAUs. (a), (b) RHSAU consisting of bulks (gray) and rings (pink and green). (c), (d) RHSAU-II consisting of integrated blocks of bulk and upright rings ($\theta = 90°$).

ellipse in the xy plane due to the interdependence between horizontal and vertical motions. Indeed, the PSI group uses a 10-T solenoid instead of an economical ±5-T solenoid to get the condition $\Delta B_s = 10$ T. The group cools BHSAU down under a 10 T magnetic field (i.e., field cooling at 10 T) and then turns off the solenoid.

Figure 4(a) shows the dependence of the maximum z-direction magnetic field on the z axis B_z on the solenoid field B_s in each method. Because the ring HTSs counteract with the solenoid field, zero-axial-field points in RHSAUs are at $B_s > 0$.

Figure 4(b) shows the dependence of the undulator field B_0 on the maximum rated solenoid field $B_{\rm spec}$, under the condition where the axial magnetic field is zero, i.e., $B_z = 0$. A comparison shows that RHSAUs can generate 2.5–3 times the B_0 of BHSAUs when using the same solenoid, and RHSAU-II

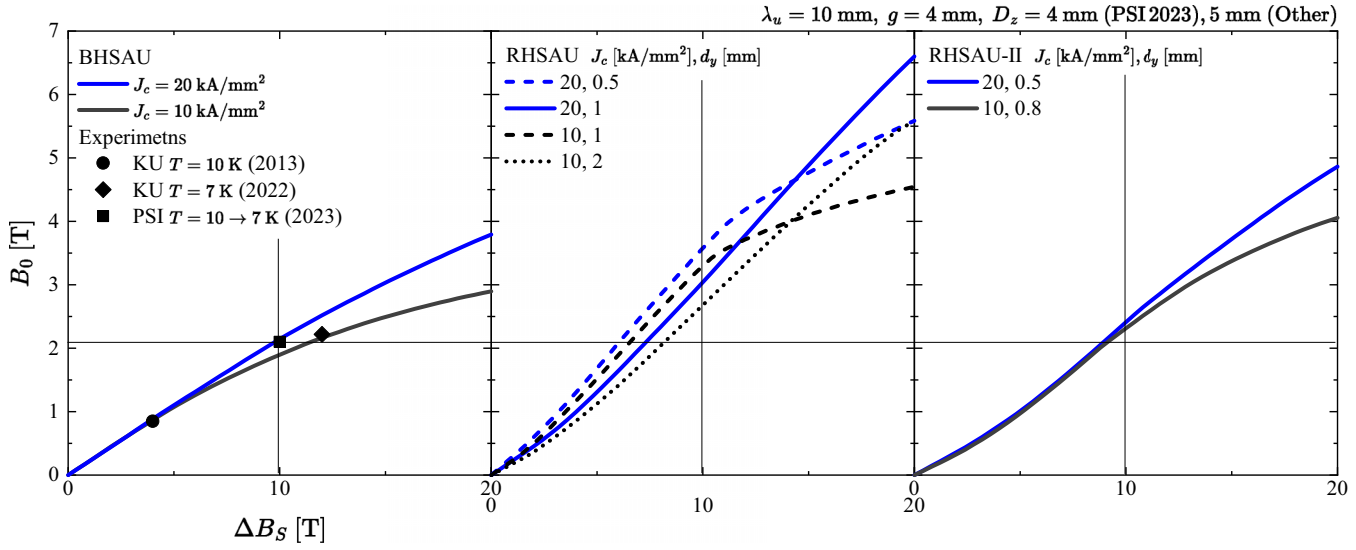


FIG. 3. Comparison of the undulator field amplitude B_0 of BHSAU (left), RHSAU (middle), and RHSAU-II (right).

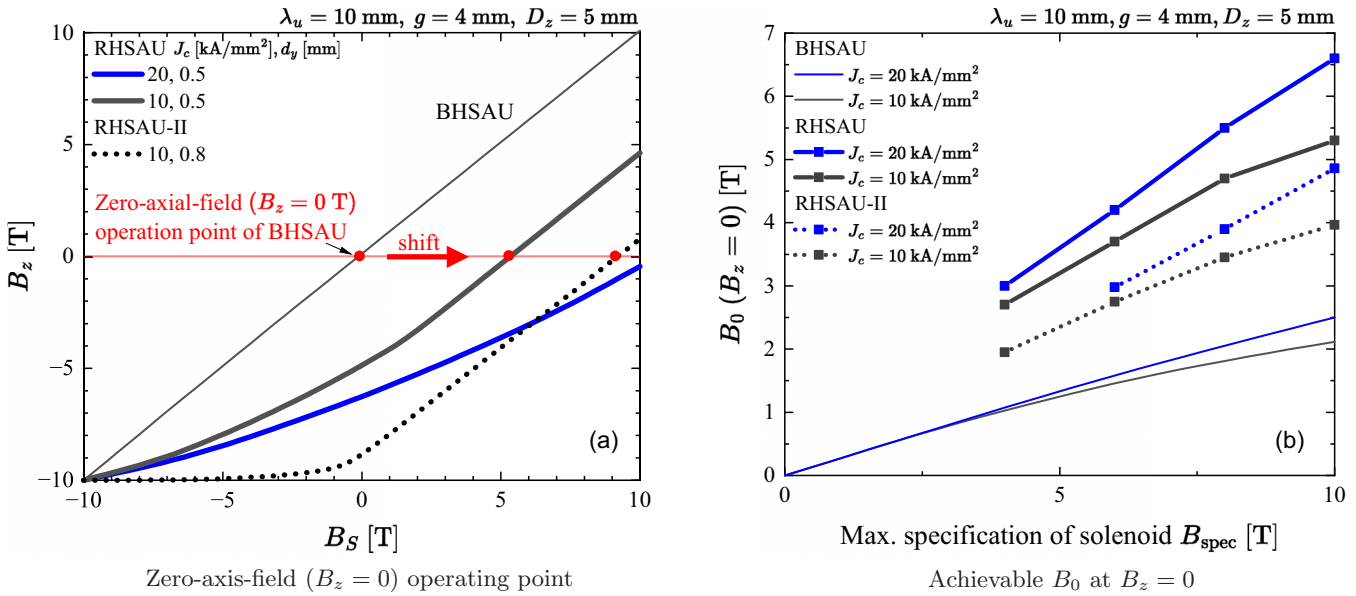


FIG. 4. Comparison of BHSAU and RHSAUs considering the zero-axis-field operation. The ring HTSs counteract the solenoidal field, causing the zero-axial-field operating point to shift to a larger B_s. As a result, the advantage of RHSAU having a larger B_0 when using solenoids with the same specifications is further enhanced.

can generate approximately twice the B_0 of BHSAUs. The zero-axis-field operation further highlights the advantage of RHSAUs.

Here, in the region where $B_{\mathrm{spec}} < 5$ T, the ring HTSs overcompensate for changes in the solenoid field, requiring d_y to be reduced to an impractically small value, and thus no plot is shown. Using materials such asMgB_2, which have a critical current density lower than that of REBCO, for creating rings could potentially ease manufacturing requirements. Additionally, the use of ring-shaped HTS tapes [21] also be applicable to RHSAUs.

To tune the radiation wavelength by adjusting the undulator field strength, the solenoidal field must be slightly varied around zero. This problem is common to both BHSAU and RHSAU configurations. While compensation schemes for solenoidal fields below a few tesla are well established [22], their practical implementation may be limited in medium-energy storage rings due to space constraints. Nonetheless, these schemes can still support field tuning under such conditions.

Here, a point of caution should be noted. If RHSAU operates under a nonzero solenoidal field, leakage of the solenoidal field can occur at both ends of the undulator. However, this issue can be resolved by installing long rings at both ends, made of the same material as bulk or ring HTSs, such as REBCO, MgB_2, or stacked HTS tapes.

In conclusion, this Letter has introduced a ring HTS staggered-array undulator (RHSAU) as a groundbreaking advancement in undulator technology, demonstrating its potential to significantly enhance performance over the conventional bulk HTS staggered-array undulator (BHSAU). By incorporating ring-shaped HTSs, the RHSAU achieves a substantial increase in the undulator field strength (B_0), with simulations showing values as high as 6 T—approximately 2.5–3 times greater than BHSAU under zero-axial-field conditions. The RHSAU-II variant also showed improved performance.

The RHSAU design holds the promise of enabling shorter-period and higher-field undulators, which could dramatically enhance photon flux and expand the energy range of undulator radiation. This research represents an important step toward realizing next-generation undulator technology, providing an innovative approach that simultaneously improves performance and reduces costs.

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The data that support the findings of this article are not publicly available because they contain commercially sensitive information. The data are available from the authors upon reasonable request.

[1] M. Tomita and M. Murakami, High-temperature superconductor bulk magnets that can trap magnetic fields of over 17 Tesla at 29 K, Nature (London) **421**, 517 (2003).

[2] J. H. Durrell, A. R. Dennis, J. Jaroszynski, M. D. Ainslie, K. G. B. Palmer, Y.-H. Shi, A. M. Campbell, J. Hull, M. Strasik, E. E. Hellstrom, and D. A. Cardwell, A trapped field of 17.6 T in melt-processed, bulk Gd-Ba-Cu-O reinforced with Shrink-fit steel, Supercond. Sci. Technol. **27**, 082001 (2014).

[3] T. Tanaka, T. Hara, H. Kitamura, R. Tsuru, T. Bizen, X. Maréchal, and T. Seike, Application of high-temperature superconducting permanent magnets to synchrotron radiation sources, Phys. Rev. ST Accel. Beams **7**, 090704 (2004).

[4] T. Tanaka, R. Tsuru, and H. Kitamura, Pure-type superconducting permanent-magnet undulator, J. Synchrotron Radiat. **12**, 442 (2005).

[5] T. Tanaka, T. Hara, R. Tsuru, D. Iwaki, T. Bizen, X. Marechal, T. Seike, and H. Kitamura, Utilization of bulk high-temperature superconductors for shorter-period synchrotron radiation sources, Supercond. Sci. Technol. **19**, S438 (2006).

[6] T. Tanabe, D. A. Harder, G. Rakowsky, T. Shaftan, and J. Skaritka, Insertion device R&D for NSLS-II, in *Proceedings of PAC07, Albuquerque, New Mexico, USA* (IEEE, New York, 2007).

[7] S. Prestemon, D. Dietderich, A. Madur, S. Marks, and R. Schlueter, High performance short-period undulators using high temperature superconductor tapes, in *Proceedings of PAC09, Vancouver, BC, Canada* (2009).

[8] T. Prikhna, Properties of MgB_{222} bulk, arXiv:0912.4906.

[9] M. Majoros, M. Sumption, M. Susner, S. Bhartiya, S. Bohnenstiehl, E. W. Collings, M. Tomsic, M. Rindfleisch, J. Phillips, D. Lyons, and J. Yue, A model superconducting helical undulator wound using a wind and react MgB_2 multifilamentary wire, IEEE Trans. Appl. Supercond. **19**, 1376 (2009).

[10] D. Weerakonda, A. Dennis, M. Calvi, and J. Durrell, Pulse magnetized superconducting bulk array undulator concept, Phys. Rev. Res. **6**, L022060 (2024).

[11] R. Kinjo, T. Kii, H. Zen, K. Higashimura, K. Masuda, K. Nagasaki, and H. Ohgaki, A bulk high-T_c superconductor staggered array undulator, in *Proceedings of FEL08, Gyeongju, Korea* (2008).

[12] R. Kinjo, T. Kii, M. A. Bakr, K. Higashimura, K. Yoshida, S. Ueda, K. Masuda, K. Nagasaki, H. Ohgaki, T. Sonobe, and H. Zen, Numerical evaluation of bulk HTSC staggered array undulator by bean model, in *Proceedings of FEL09, Liverpool, U.K.* (2009).

[13] T. Kii, R. Kinjo, M. A. Bakr, T. Sonobe, K. Higashimura, K. Masuda, H. Ohgaki, K. Yoshida, and H. Zen, Proposal of a bulk htsc staggered array undulator, in AIP Conf. Proc. **1234**, 539 (2010).

[14] R. Kinjo, M. Shibata, T. Kii, H. Zen, K. Masuda, K. Nagasaki, and H. Ohgaki, Demonstration of a high-field short-period undulator using bulk high-temperature superconductor, Appl. Phys. Express **6**, 042701 (2013).

[15] R. Kinjo, K. Mishima, Y.-W. Choi, M. Omer, K. Yoshida, H. Negm, K. Torgasin, M. Shibata, K. Shimahashi, H. Imon, K. Okumura, M. Inukai, H. Zen, T. Kii, K. Masuda, K. Nagasaki, and H. Ohgaki, Magnetic property of a staggered-array undulator using a bulk high-temperature superconductor, Phys. Rev. ST Accel. Beams **17**, 022401 (2014).

[16] T. Kii, Progress report of JSPS KAKENHI 17H01127 (in Japansese), https://kaken.nii.ac.jp/ja/file/KAKENHI-PROJECT-17H01127/17H01127seika.pdf (2022), accessed on 1 December 2024.

[17] K. Zhang, A. Pirotta, X. Liang, S. Hellmann, M. Bartkowiak, T. Schmidt, A. Dennis, M. Ainslie, J. Durrell, and M. Calvi, Record field in a 10 mm-period bulk high-temperature superconducting undulator, Supercond. Sci. Technol. **36**, 05LT01 (2023).

[18] R. Kinjo, M. Calvi, K. Zhang, S. Hellmann, X. Liang, T. Schmidt, M. D. Ainslie, A. R. Dennis, and J. H. Durrell, Inverse analysis of critical current density in a bulk high-temperature superconducting undulator, Phys. Rev. Accel. Beams **25**, 043502 (2022).

[19] M. Calvi, A. Arsenault, X. Liang, T. Schmidt, A. R. Dennis, J. H. Durrell, C. Gafa, A. Sammut, N. Sammut, M. D. Ainslie, R. Kinjo, K. Zhang, and S. Hellmann, Experimental results of a YBCO bulk superconducting undulator magnetic optimization, Phys. Rev. Accel. Beams **27**, 100702 (2024).

[20] COMSOL Multiphysics, v. 6.3. http://www.comsol.com. COMSOL AB, Stockholm, Sweden (2020).

[21] J. Sheng, M. Zhang, Y. Wang, X. Li, J. Patel, and W. Yuan, A new ring-shape high-temperature superconducting trapped-field magnet, Supercond. Sci. Technol. **30**, 094002 (2017).

[22] I. Asparuhov, Staggered undulator x-ray source for low emittance electron storage ring, Ph.D. thesis, Université Grenoble Alpes, 2023.