

Progress in the Development of a 50-period HTS Undulator for SXFEL

Kai Zhang, Dabin Wei, Zhuangwei Chen, Chan Liu, Yimin Tong, Difan Zhou, Chao Li, Marco Calvi, Anthony Dennis, John Durrell, Haixiao Deng and Zhentang Zhao

Abstract—Shorter period undulators typically require a higher on-axis magnetic field in order to achieve a practical deflection parameter, K . Recent simulations and experiments have demonstrated that high-temperature superconducting (HTS) undulators, constructed from staggered-array bulk superconductors, can generate high undulator fields with period length as short as 10 mm. This advanced HTS technology has the potential to significantly enhance the photon energy range of synchrotron radiation light sources and free electron laser facilities. This paper reports on the progress made in developing of a 50-period bulk HTS undulator with period length of 12 mm for Shanghai soft x-ray free electron laser facility. It details the engineering design of the undulator prototype, thermal and mechanical analysis of the HTS variable temperature insert, and the current status of the system.

Index Terms—Superconducting undulator, HTS, ReBCO, short period, insertion device.

I. INTRODUCTION

There has been growing interest in developing advanced superconducting undulators (SCUs) for synchrotron light sources and x-ray free-electron lasers [1-8]. SCUs, particularly high-temperature superconducting undulators (HTSUs), can generate significantly higher undulator fields when compared to permanent magnet undulators of equivalent period length [9-11]. In 2023, following successful experiments with short bulk HTS undulator prototypes [12-16], a 50-period HTSU prototype with period length of 12 mm was proposed for

This work was supported by the National Overseas Young Talent Program, and also by the CAS Project for Young Scientists in Basic Research (YSBR-042), the National Natural Science Foundation of China (12125508, 11935020), Program of Shanghai Academic/Technology Research Leader (21XD1404100), Shanghai Pilot Program for Basic Research – Chinese Academy of Sciences, Shanghai Branch (JCYJ-SHFY-2021-010) (Correspondence: Kai Zhang).

K. Zhang and C. Liu are with Zhangjiang Laboratory, Shanghai, 201210, China (zhangkai@zjlab.ac.cn)

D. Wei, Z. Chen and Y. Tong are all with Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800 China and University of Chinese Academy of Sciences, Beijing 100049, China

D. Zhou is with Shanghai University, Shanghai, 200444, China.

C. Li is with Xi'an Superconducting Magnet Technology Co. Ltd., 710018, China.

M. Calvi is with Paul Scherrer Institute, Villigen 5253, Switzerland.

A. R. Dennis and J. H. Durrell are both with University of Cambridge, Cambridge CB21PZ, United Kingdom.

H. Deng and Z. Zhao are both with Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai 201210, China.

Table 1. HTSU12: main design parameters

Parameter	Value	Unit
Period length, λ_u	12	mm
No. of periods	50	
Magnetic bore	4	mm
Clear beam aperture	3.4	mm
Magnetizing field	7	T
Magnetizing region	$\phi 40 \times 600$	mm ³
Undulator field, B_0	2.0	T

development and testing at the Shanghai Soft X-ray Free Electron Laser (SXFEL) facility [17-18]. The 0.6 meter-long HTSU prototype utilizes a series of staggered-array Gd-Ba-Cu-O (GdBCO) bulk superconductors. The on-axis undulator field is achieved utilizing a 7 T superconducting solenoid magnet for magnetizing these bulks. The process involves initially ramping the background field from zero to 7 T while maintaining the HTS insert above its critical temperature (T_c). After the field ramp, eddy currents are dissipated, and the HTS insert is then cooled to its superconducting state. The background field from the solenoid is then ramped to 0 T and the GdBCO bulks, in their superconducting state remain magnetized, generating permanent eddy currents and the resultant on-axis undulator field.

Details on the electromagnetic design of the 50-period HTSU prototype are discussed in a previous publication [17]. This paper presents the engineering design of the 50-period high-temperature superconducting undulator with 12 mm period, named HTSU12. We first outline the engineering design specifics of HTSU12, followed by a numerical analysis of the innovative support structure for the HTS insert. Finally, we provide an update on the development status of the necessary components and measurement systems for HTSU12.

II. ENGINEERING DESIGN

The primary components of HTSU12, illustrated in Figure 1(a-b), consist of a conduction-cooled superconducting solenoid magnet designed to generate a uniform magnetic field of $B_z = 7$ T, with end-to-end field variation of $\Delta B/B < 2\%$ within a central air region of $\phi 40$ mm \times 600 mm. The undulator system also includes a 1.5 m-long high-temperature superconducting variable temperature insert (HTS-VTI) which consists of 100 pieces of GdBCO disks secured by two-halved clamping copper shells, providing an effective undulator

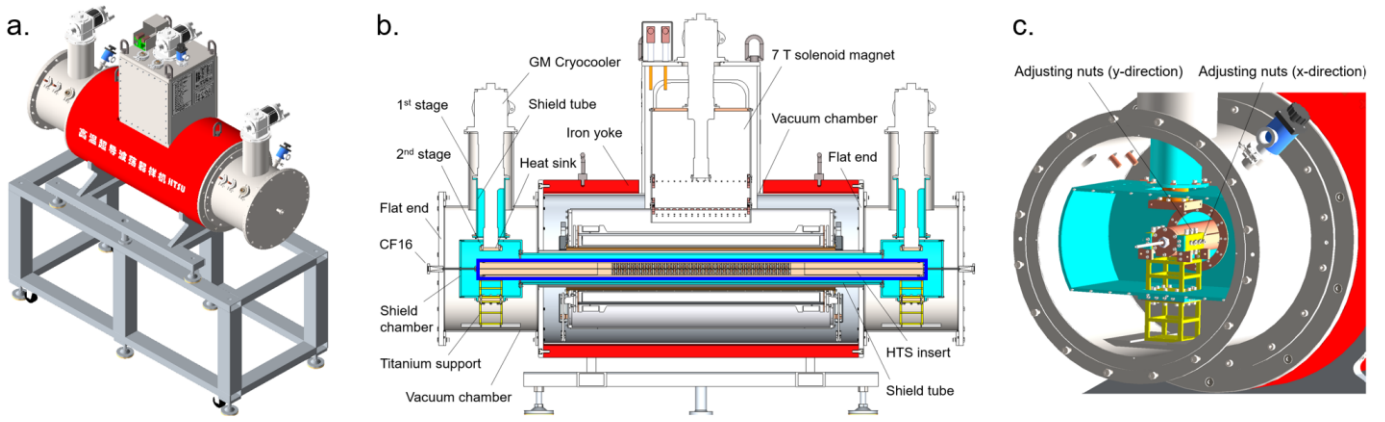


Figure 1. (a) 3D view of HTSU12 mounted on a height-adjustable mechanical support; (b) Mid-section view of HTSU12 including the 7 T superconducting solenoid magnet, the HTS cryostat, and the 1.5 m-long HTS-VTI (highlighted with blue lines); (c) Cut-view of the cold mass support structure with adjusting bolts and nuts for the alignment of the undulator axis.

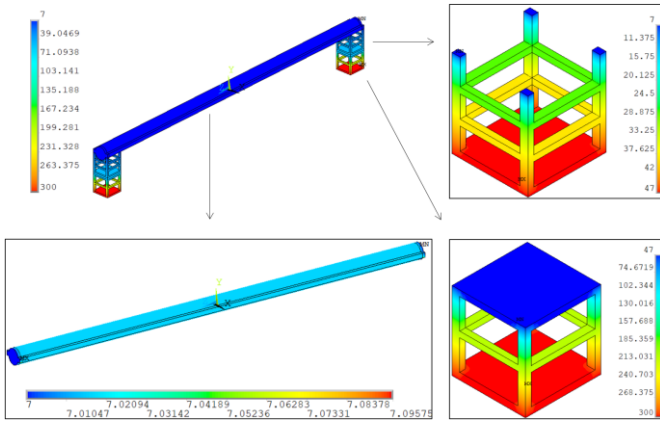


Figure 2. Temperature profile under operational conditions for the cold mass and its support structure, including the 1.5 m-long HTS-VTI, the top-half of TiAl₆V₄ support framework, and the bottom-half of TiAl₆V₄ support framework.

length of 0.6 meters, a novel cold mass support structure comprising two TiAl₆V₄ support frameworks, and an HTS cryostat to house the HTS-VTI and its mechanical support. Table 1 summarizes the key design parameters of HTSU12. Utilizing a 7 T solenoid magnet for field-cooled (FC) magnetization, we anticipate achieving an undulator field of $B_0 = 2.0$ T within a beam aperture of 3.4 mm and a magnetic bore of 4.0 mm.

The electromagnetic design details of the 7 T solenoid magnet were previously described in [17]. Here we present the updated design parameters. Specifically, the diameter of the room-temperature bore of the 7 T solenoid magnet has been increased from 110 mm to 120 mm to facilitate the installation of the 1.5 m-long HTS-VTI. Additionally, the updated operation current and inductance for the 7 T solenoid magnet are now 240 A and 16.3 H, respectively.

As depicted in Figure 1(b), the 1.5 m-long HTS-VTI is thermally shielded by two aluminum shield chambers and a lengthy aluminum shield tube. To achieve a temperature

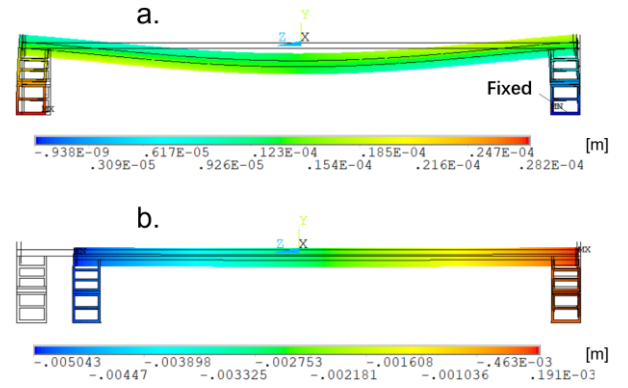


Figure 3. Longitudinal displacement, UZ of the 1.5 m-long HTS-VTI and the TiAl₆V₄ support frameworks (a) under gravity and (b) after further cooling to operational conditions, not to scale.

difference ΔT_c below 0.1 K and minimize variation in magnetization currents within the staggered-array of GdBCO bulks, two GM cryocoolers from CryoPride are employed to conductively cool both ends of the HTS-VTI. To support FC magnetizations, the temperature regulation across a broad range from 4 to 120 K is realized by a Lakeshore model 336 temperature controller, combined with a heater and a Cernox sensor. Additionally, the HTS cryostat features two stainless steel (SS) vacuum chambers, each equipped with CF16 flanges welded to the flat ends. To reduce beam loss during the transport of high-energy electron bunches, the bore size of the CF16 flanges tapers gradually from 16 mm to 3.4 mm.

Figure 1(c) depicts the cut-view of the cold mass support structure, which includes adjusting bolts for precise alignment of the undulator axis. The innovative support structure, consisting of two titanium alloy support frameworks (TiAl₆V₄) with low thermal conductivity, is designed to secure the ends of the HTS-VTI. Both TiAl₆V₄ support frameworks are thermally intercepted by ~ 40 K aluminum shield chambers to reduce the conduction heat leak to the HTS-VTI. One framework is fixed to a room-temperature SS plate, the other

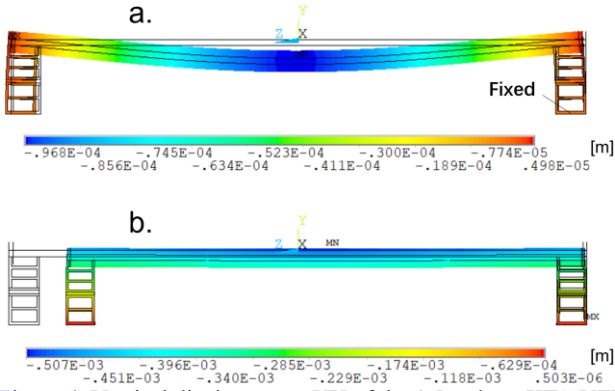


Figure 4. Vertical displacement, UY of the 1.5 m-long HTS-VTI insert and the TiAl₆V₄ support frameworks (a) under gravity and (b) after further cooling to operational conditions, not to scale.

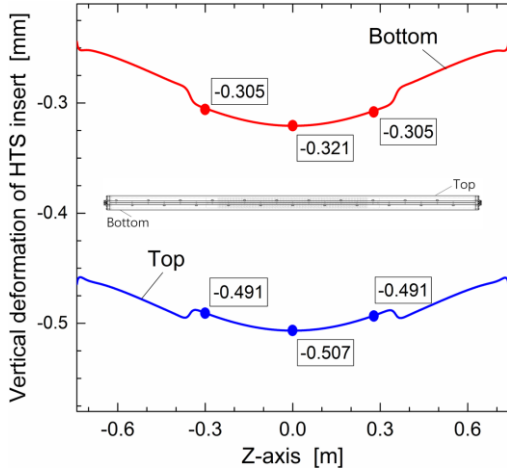


Figure 5. Vertical displacement, UY of the top and bottom lines of the HTS-VTI under operational conditions. The difference between UY at the center and UY at the ends is $\sim 16 \mu\text{m}$ within the effective undulator length of 0.6 meter.

is free to move positioned within a groove on the plate. This design allows the TiAl₆V₄ support framework and the HTS-VTI to contract inward without experiencing significant thermal stress or deformation. The alignment of the 1.5 m-long HTS-VTI can be precisely adjusted in the x - y plane.

Figure 2 illustrates the temperature distribution of the HTS-VTI and its support structure under operational conditions. The temperature difference ΔT_z within the HTS-VTI is calculated to be 0.096 K, and the total conduction heat leak from the TiAl₆V₄ support frameworks to the HTS-VTI at 7 K is approximately 0.25 W. Figure 3 shows the longitudinal displacement (UZ) of the HTS-VTI and its support structure under gravity and after cooling to 7 K. The impact of gravity is minimal, whereas cold shrinkage of the HTS-VTI may induce a longitudinal displacement of ~ 5 mm at the end supported by a floating TiAl₆V₄ framework. Figure 4 shows the vertical displacement (UY) of the HTS-VTI and its support structure under gravity and after cooling to 7 K. Gravity causes a deflection of approximately 97 μm , while the cold



Figure 6. Superconducting solenoid magnet system. After undergoing training quenches, it achieved the design current of 240 A, offering a uniform magnetic field of 7 Tesla within a central air region of $\phi 40 \text{ mm} \times 600 \text{ mm}$.

shrinkage of the TiAl₆V₄ support frameworks results a global downward shift of the HTS-VTI. Figure 5 presents the vertical deformation of the top and bottom lines of the HTS-VTI at 7 K. The non-linear behavior of these deformations is attributed to the composite structure of the HTS-VTI. Within the effective undulator length of $-0.3 \leq z \leq 0.3$ m, the vertical deformation (UY) is around 0.5 mm for the top line and 0.3 mm for the bottom line. The difference between the centers and ends is approximately 16 μm , which is within the tolerance for obtaining anticipated undulator field. For both centers and ends, there is a difference of approximately 16 μm , which is acceptable to the undulator design. To assess the mechanical properties of the TiAl₆V₄ support frameworks, transportation simulations were conducted, revealing a safe Von-Mises stress of around 220 MPa under a 4g axial acceleration.

The key steps for integrating the 7 T solenoid magnet with the HTS-VTI and the HTS cryostat are as follows: a) Attach two SS vacuum chambers to both ends of the 7 T solenoid magnet; b) Secure one TiAl₆V₄ support framework to the SS plate while allowing the other to move within the groove of the plate; c) Assemble the aluminum shield chambers onto the TiAl₆V₄ support frameworks; d) Install the HTS-VTI into the HTS cryostat, securing its ends with adjusting bolts/nuts in the x - and y -directions and aluminum blocks in the z -direction; e) Mount two GM Cryocoolers onto the SS vacuum chambers and connect their 1st stages to the aluminum shields and their 2nd stages to the HTS-VTI using copper braids.

III. DEVELOPMENT STATUS

The superconducting magnet system, designed to provide the magnetizing field, was received in August 2024, as illustrated in Figure 6. After undergoing two training quenches, the magnet system achieved the design current of 240 A and produced a uniform magnetic field B_z of 7 T, with a measured

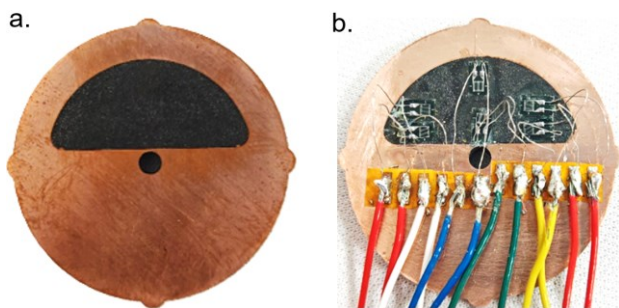


Figure 7. (a) Shrink-fit assembly of the “HTS-Copper” unit; (b) Strain gauges mounted on the surface of the half-moon shaped GdBCO disk for mechanical stress measurement.

end-to-end field inhomogeneity of approximately 1.3% within the central air region of $\phi 40 \text{ mm} \times 600 \text{ mm}$. The superconducting solenoid magnet has been mounted on a SS support framework, with its central height adjustable within the range of $1300 \pm 25 \text{ mm}$, fulfilling the installation requirements for the SXFEL facility.

GdBCO bulk superconductors from both CAN Superconductor and from Shanghai University are being evaluated for the production of the “HTS-Copper” disks that will form the staggered array for the HTS-VTI assembly. To machine the GdBCO bulks into half-moon shapes, we have tested laser cutting, Computer Numerical Control (CNC) machining and electric discharge machining (EDM). Based on our comparisons, EDM has been determined to be the most effective method for achieving precise machining accuracy while minimizing the risk of cracking in the GdBCO bulks. Figure 7(a) illustrates the shrink-fit assembly of the “HTS-Copper” disks, and Figure 7(b) shows strain gauges mounted on the surface of the half-moon shaped GdBCO disk for mechanical stress measurement. Details on the fabrication and characterization of the “HTS-Copper” disks are provided in an accompanying article [19]. Figure 8 depicts a large bore, 0.3 T DC electromagnet system developed for magnetization testing of “HTS-Copper” disks and short undulator models at 77 K. Four linear stage motors were equipped with degrees of freedom for linear movement along the x , y and z axes, as well as rotation in the xy plane. Despite tests at 77 K, additional testing of short undulator models at 7 K is demanded before the assembly of the 1.5 m-long HTS-VTI. These tests are planned at the University of Cambridge, utilizing the existing 12 T superconducting solenoid magnet from the Bulk Superconductivity Group and the magnetic field measurement equipment offered by the Paul Scherrer Institute (PSI).

For the HTS cryostat that will house the HTS-VTI, we have received the machined components, including SS vacuum chambers, AL thermal shields, and TiAl_6V_4 support frameworks. Additionally, we have procured two GM Cryocoolers from CryoPride, a Lakeshore model 336 temperature controller and Cernox sensors for controlling the HTS-VTI temperature in the range of 4 to 120 K during FC

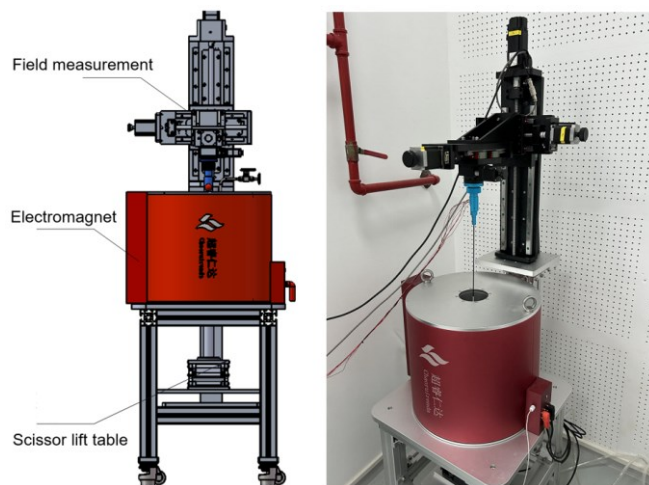


Figure 8. 0.3 Tesla DC electromagnet with integrated magnetic field measurement system for magnetization tests at 77 K. Four linear stage motors were equipped with degrees of freedom for linear movement along the x , y and z axes, as well as rotation in the xy plane.

magnetization. We anticipate completing the assembly of the 50-period HTSU12 prototype by the end of 2024. Meanwhile, we are developing a horizontal magnetic field measurement system designed to characterize the local undulator field via Hall probe scanning and to obtain the first and second field integrals via the moving wire method. A specialized xy^3z Hall probe, leveraging technology and expertise from PSI [13], will be employed for these measurements. The process of measuring and correcting the undulator field through sorting GdBCO disks and adjusting the heights of ferromagnetic poles is expected to take several months [14][20-21]. Optimistically, we hope to install the 50-period HTSU12 prototype in the SXFEL tunnel during its summer maintenance period in 2025.

IV. CONCLUSIONS

The engineering design of a 50-period HTS undulator prototype with a period length of 12 mm, named HTSU12, has been completed for the SXFEL facility. Thermal-mechanical coupled simulations have confirmed the feasibility of utilizing TiAl_6V_4 framework to support the HTS variable temperature insert. The mechanical design of the HTS cryostat and the assembly process for integrating the HTS variable temperature insert with the HTS cryostat and the 7 T superconducting solenoid magnet are outlined. The development of key components and measurement setups is progressing well. We anticipate assembling the HTSU12 prototype within the next few months.

Acknowledgement

We would like to thank Yiyong Liu, Chao Feng, Wei Zhang, Shuhua Wang from Shanghai Advanced Research Institute (SARI), Chinese Academy of Sciences (CAS) and Zhengrong Ouyang from ShanghaiTech University for helpful discussions

and suggestions on the engineering design of HTSU12 and its installation at SXFEL tunnel. We gratefully acknowledge Bo Liu from SARI, CAS, for his invaluable support in fostering international collaborations on the HTS undulator project. We would also like to thank Wentao Zhang and Huading Zhang from Xi'an Juneng superconducting magnet technology Co., Ltd. for their contributions to the development of the superconducting solenoid magnet.

REFERENCES

- [1] S. Casalbuoni, T. Baumbach, S. Gerstl, A. Grau, M. Hagelstein, D. S. Jauregui, C. Boffo, J. Steinmann and W. Walter, "Training and magnetic field measurements of the ANKA superconducting undulator," *IEEE Trans. Appl. Supercond.*, vol. 21, 1760-3, 2011.
- [2] S. Casalbuoni, E. Blomley, N. Glamann, A. Grau, T. Holubek, E. Huttel, D. S. Jauregui, S. Bauer, C. Boffo, Th. Gerhard, M. Turenne and W. Walter, "Commissioning of a full scale superconducting undulator with 20 mm period length at the storage ring KARA," *AIP Conf. Proc.* 2054, 030025, 2019.
- [3] M. Kasa, S. Bettenhausen, J. Fuerst, Q. Hasse, Y. Ivanyushenkov, I. Kesgin, Y. Shiroyanagi, E. Trakhtenberg and E. Gluskin, "Design, construction, and magnetic field measurements of a helical superconducting undulator for the Advanced Photon Source," *Proc. IPAC2018 Conf. Vancouver, Canada*, 1263-5, 2018.
- [4] Y. Ivanyushenkov, C. Doose, J. Fuerst, K. Harkay, Q. Hasse, M. Kasa, D. Skiadopoulos, E. M. Trakhtenberg, Y. Shiroyanagi and E. Gluskin, "Development and performance of 1.1-m long superconducting undulator at the Advanced Photon Source," *Proc. IPAC2015 Conf. Richmond, USA*, 1794-6, 2015.
- [5] I. Kesgin, S. MacDonald, M. Kasa, J. Fuerst, Y. Ivanyushenkov, E. Barzi, D. Turrioni, A. V. Zlobin and E. Gluskin, "Quench behavior of 18-mm-period, 1.1-m-long Nb₃Sn undulator magnets," *IEEE Trans. Appl. Supercond.*, vol. 34, 4100905, 2024.
- [6] S. Casalbuoni, J. E. Baader, G. Geloni, V. Grattoni, D. L. Civita, C. Lechner, B. Marchetti, S. Serkez, H. Sinn, W. Decking, L. Lilje, S. Liu, T. Wohlenberg and I. Zagorodnov, "Towards a superconducting undulator afterburner for the European XFEL," *Proc. IPAC202021 Conf. Campinas, SP, Brazil*, 2921-4, 2021.
- [7] J. E. Baader, S. Casalbuoni, V. Grattoni, M. Yakopov, A. Grau and P. Ziolkowski, "Magnetic performance assessment of the S-PRESSO superconducting undulator mock-up," *IEEE Trans. Appl. Supercond.*, vol. 34, 9002009, 2024.
- [8] Q. Tang, Q. Zhou, J. Zhang, Y. Ding, Y. Wen, M. Qian and J. Zhang, "Cooling design for the magnetic structure of SHINE superconducting undulator," *IEEE Trans. Appl. Supercond.*, vol. 30, 4100104, 2020.
- [9] J. Bahrtdt and E. Gluskin, "Cryogenic permanent magnet and superconducting undulators," *Nuclear Inst. and Methods in Physics Research, A*, vol. 907, 149-168, 2018.
- [10] K. Zhang, M. Ainslie, M. Calvi, S. Hellmann, R. Kinjo and T. Schmidt, "Fast and efficient critical state modelling of field-cooled bulk high-temperature superconductors using a backward computation method," *Supercond. Sci. Technol.*, vol. 33, 114007, 2023.
- [11] K. Zhang and M. Calvi, "Review and prospects of world-wide superconducting undulator development for synchrotrons and FELs," *Supercond. Sci. Technol.*, vol. 35, 093001, 2022.
- [12] 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*, vol. 6, 042701, 2013.
- [13] M. Calvi, M. D. Ainslie, A. Dennis, J. H. Durrell, S. Hellmann, C. Kittel, A. D. Moseley, T. Schmidt, Y. Shi and K. Zhang, "A GdBCO bulk staggered array undulator," *Supercond. Sci. Technol.* vol. 33, 014004, 2020.
- [14] 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*, vol. 25, 043502, 2022.
- [15] 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.* vol. 36, 05LT01, 2023.
- [16] M. Calvi, S. Hellmann, E. Prat, T. Schmidt, K. Zhang, A. R. Dennis, J. H. Durrell and M. D. Ainslie, "GdBCO bulk superconducting helical undulator for x-ray free-electron lasers," *Phys. Rev. Research*, vol. 5, L032020, 2023.
- [17] D. Wei, M. Calvi, K. Zhang and H. Deng, "Electromagnetic design study of a 12-mm-period bulk high-temperature superconducting undulator," *IEEE Trans. Appl. Supercond.*, vol. 34, 4100705, 2024.
- [18] B. Liu et al., "The SXFEL upgrade: from test facility to user facility," *Appl. Sci.* vol. 12, 176, 2022.
- [19] D. Wei, Z. Chen, X. Wang, D. Zhou, K. Zhang and H. Deng, "Mechanical stress analysis of Re-Ba-Cu-O bulk superconductors for the HTS undulator during assembly, cool down and field-cooled magnetization," *IEEE Trans. Appl. Supercond.*, submitted to this conference, 2024.
- [20] 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*, vol. 27, 100702, 2024.
- [21] Z. Chen, M. Calvi, J. Durrell, C. Boffo, D. Wei, K. Zhang and Z. Zhao, "Recent progress in high-temperature superconducting undulators," *Superconductivity*, vol. 12, 100134, 2024.