

# CHART Scientific Report (Final Report for Phase 2)

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## High Temperature Superconducting Bulk Undulator (HTSU)

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### 1. Introduction / Original goals of this project

The primary aim of the CHART project was to demonstrate a high-performance short-period high-field undulator constructed from RE-Ba-Cu-O (REBCO, where RE stands for Rare Earth) bulks. Currently, the state-of-the-art undulators in the industry consist of in-vacuum permanent magnet technology, which operates either at room temperature (IVU) or at cryogenic temperatures (CPMU), as well as low-temperature superconductors, specifically those based on NbTi.

Our original target was to achieve a magnetic field strength of 2T with a period length of 10mm in a magnetic gap of 4mm. This target is approximately three times higher than the capabilities of current CPMU technology and twice as high as those of NbTi-based undulators. Achieving these specifications would represent a significant advancement in undulator technology, potentially revolutionizing the field.

During the CHART2 project, we successfully demonstrated this performance and even surpassed it, reaching 2.1T. The following sections present the main milestones achieved in the development of this groundbreaking technology.

### 2. Realisation

The project's activities have been organized along two parallel paths. The first path involves developing a short prototype program to explore REBCO bulk technology and demonstrate its performance. The second path focuses on constructing a cryogenic device to house the meter-long prototype demonstrator, which will be installed in the new storage ring of the Swiss Light Source (SLS2.0) in 2026. The resources for this latter activity have been provided entirely by the SLS2.0 project and its beamline I-TOMCAT via cantonal grant (Argovia).

## 2.1 Short prototype program

The initial focus was on familiarising oneself with the simulation of the field cooling magnetisation process using FEM codes (COMSOL), which solve the H formulation of Maxwell's equations, see Fig.1. To the best of our knowledge, this sophisticated approach was being applied for the first time to study the behaviour of a staggered array undulator composed of REBCO bulks. This allowed for the optimisation of various parameters, such as bulk thickness and diameter, to maximise the on-axis undulator magnetic field amplitude. Additionally, it facilitated the investigation of variants like the hybrid staggered array, which employs ferromagnetic shims to enhance field strength and adjust the phase error of the undulator, as well as helical undulators that are better suited for compact free-electron laser facilities.

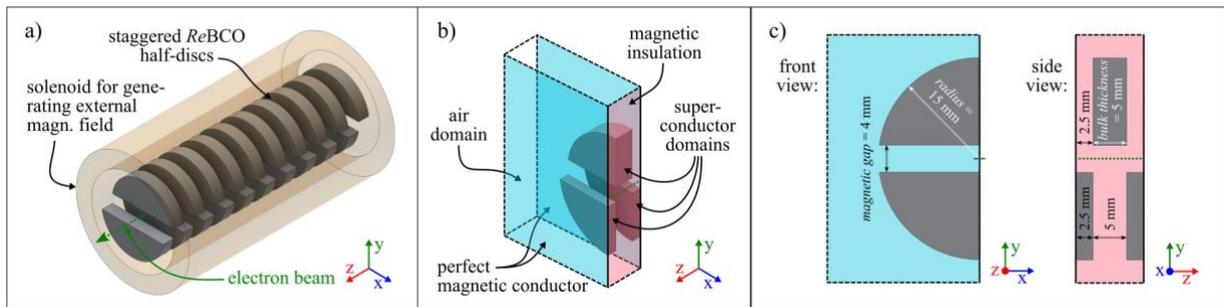


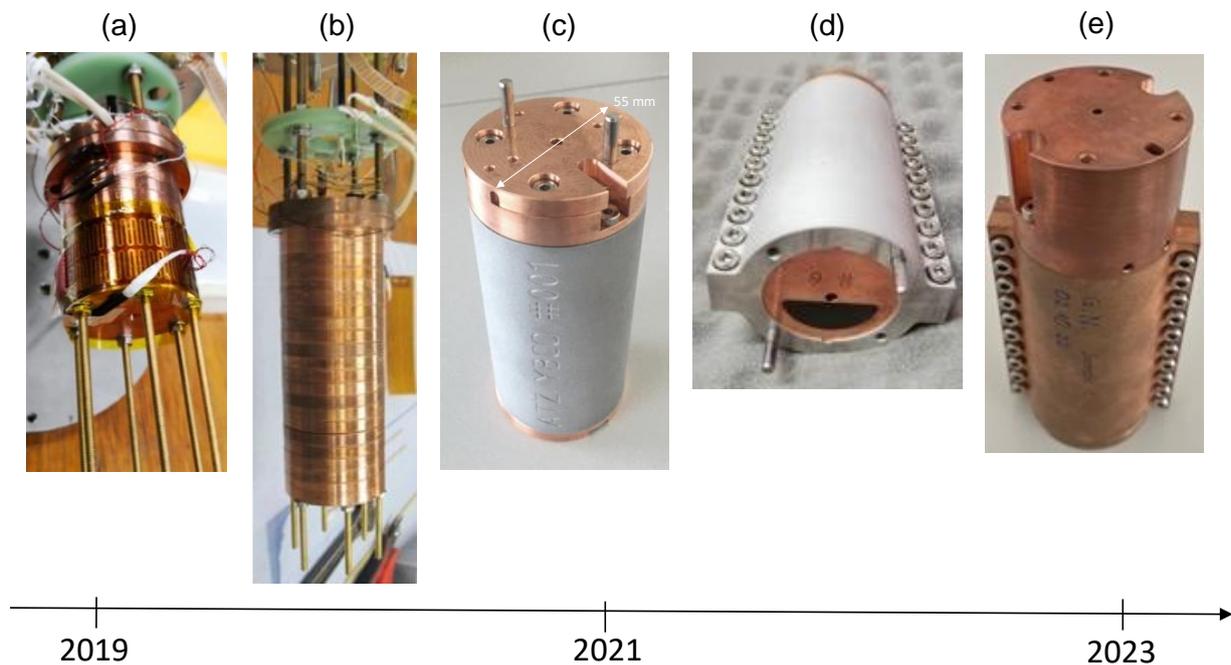
Figure 1 (a) Complete geometry of a ten-period staggered array undulator, composed of 20 ReBCO half-discs. In its application as an undulator within an electron accelerator, the electron beam travels between the upper and lower rows of ReBCO bulks. (b) Simulation model employing two symmetries, implemented via magnetic insulation and perfect magnetic conductor boundary conditions. (c) Dimensions of the reference undulator geometry and optimization parameters, including radius, bulk thickness, and magnetic gap (the depicted sketches are not to scale).

To initiate the experimental activities, a collaboration agreement was signed with the University of Cambridge and its bulk superconductors group, led by Prof J H Durrell. Their 12T solenoid facility was adapted to accommodate the magnetic measuring system, which is crucial for the precise assessment of the short prototype series. A new magnetic probe was developed, and its manufacturing process was transferred to industry to serve a broader community and relieve the group from this task. The first proof of concept for this novel design was conducted using bulks grown at the university and encased in a copper sleeve to hold and stack them together, as well as to provide mechanical reinforcement. This preliminary phase allowed us to improve the instrumentation, identify the limitations of the sample preparation, and demonstrate that the predicted performance was possible, despite being limited by premature quenches and poor field quality.

The second phase was characterised by closer collaboration with the industry, both for procuring the bulks and assembling the short prototypes, see Fig.2. From the outset, it was evident that this new technology required substantial production capabilities to make an impact on the scientific community and enable large-scale procurement of REBCO bulks, thereby competing effectively with permanent magnets. Although developing this technology within the university was feasible, it was not strategically prudent for production readiness. Therefore, a survey of three existing manufacturers of REBCO bulks was conducted, and

samples were produced and tested to assess these companies. Different rare earth elements (Y, Gd, Eu) were used when available to compare their performances, alongside the technique of Ag addition, which is suitable for heavy RE elements.

Additionally, we improved the overall quality of the short prototype assembly. A new technique was developed to assemble the Cu-REBCO disks, where the Cu shrink-fits into the REBCO to introduce pre-stress at room temperature, which increases further during cooling. This required new techniques to precisely ( $<10\ \mu\text{m}$ ) cut the REBCO bulks and shape them to minimise unwanted stresses (see Fig. 1). Two advanced techniques were identified: EDM wire erosion and Laser MicroJet® (SYNOVA), both yielding satisfactory results. EDM was chosen due to its greater availability in the industry today.



*Figure 2 The evolution of the short prototype assemblies: (a) The initial prototype developed at the university, featuring custom-grown bulks and a 6mm aperture for easier magnetic assessment. (b) A university sample with the standard 4mm aperture and 20 bulks. (c) The first industrial prototype, featuring a closed aluminum shrinking cylinder. (d) An industrial prototype equipped with two aluminum half-shells. (e) Our current baseline design prototype, with copper half-shells, achieving a record undulator field of 2.1T.*

One of the key findings for achieving optimal performance was the presence of micro-cracks in the bulks even before the final machining of the parts. Systematic 2D field mapping of individual bulks in  $\text{LN}_2$  was conducted to identify and reject these components, which could account for as much as half of the production. The finished Cu-REBCO disks were also systematically measured for final screening, indicating that only a minority ( $<5\%$ ) were damaged during the cutting and embedding phase.

As anticipated, magnetic field amplitudes as high as 2.1 T were measured on a prototype short undulator with a 10 mm period length (10 periods, 100 mm long), showing an RMS peak field variation of about 3%, comparable to that of permanent magnets. Subsequently, we investigated various ferromagnetic pole materials, such as FeCo and Ho, different

magnetisation temperatures (8-20 K, range), different flux freezing procedures to reduce creep, and magnetisation ramp rates ranging from 1 T/h to 4 T/h. We identified an optimal variable ramp rate that reduced the magnetisation time to 4 hours, down from the original 10 hours. The reproducibility of the magnetisation process was extensively studied to rule out the presence of induced cracks in the bulks due to Lorentz forces.

Due to the high number of defective bulks produced using the standard Top Seeded Melted Growth (TSMG) process, we decided in 2023 to trial the novel Single Direction Melted Growth (SDMG) process, recently proposed by T. Motoki (2022 *Supercond. Sci. Technol.* **35** 094003) and implemented in the production line at CAN-SUPERCONDUTOR. This new technique better ensures the orientation of the ab plane, reduces the growth time from 2 weeks (TSMG) to 3 days, increases production yield, reduces faulty components, and ultimately lowers the overall manufacturing cost. This is now our baseline material for the meter long prototype demonstrator.

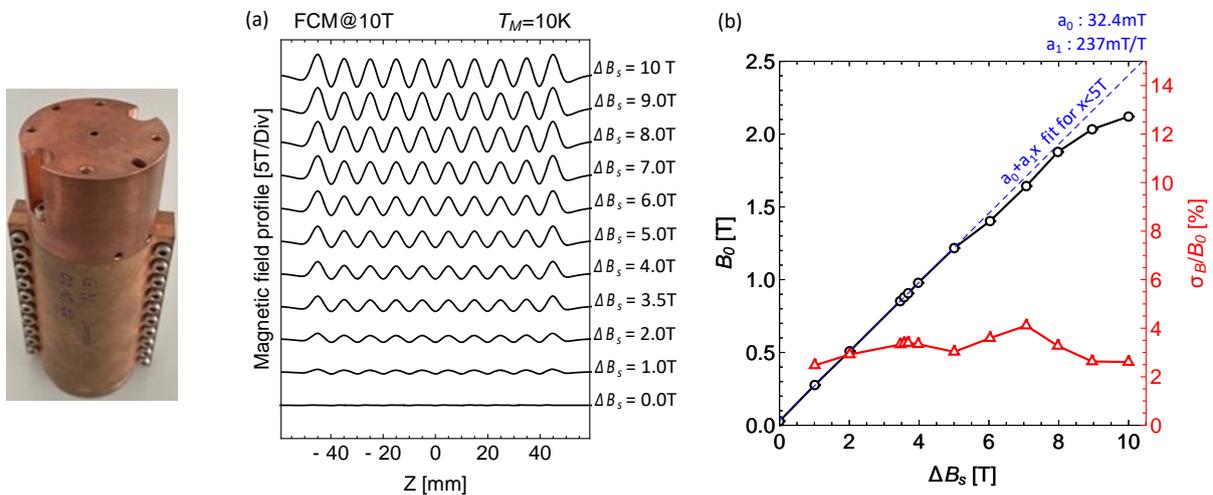


Figure 3 (a) measured on-axis magnetic field during the FC magnetization.  $\Delta B_s$  refers to the change in the background solenoid field. (b) Relation between the mean undulator field  $B_0$ ,  $\sigma_B/B_0$  and  $\Delta B_s$ . A record field of 2.1 T is obtained for a 10 mm-period undulator.

## 2.2 The meter long prototype demonstrator

Following the initial proof of principle, in 2021, a Cooperative Research and Development Agreement (CRADA) was signed with Fermilab for the procurement of a 12T solenoid equipped with the necessary features to host a meter-long staggered array made of REBCO bulks (hereafter referred to as the HTS insert). Concurrently, PSI began designing this latter part and procuring the 200 (+50 spares) Cu-REBCO disks and 400 (+100 spares) Cu-Ho disks to serve as ferromagnetic pole shims, along with all components required for the assembly of the HTS insert.

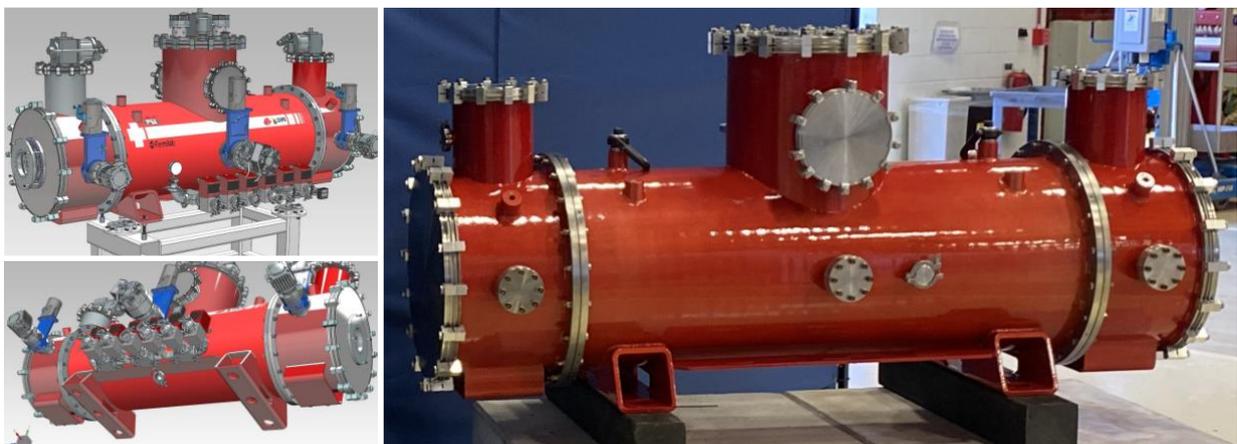
The 12 T solenoid was co-designed with Fermilab engineers, utilising an innovative conduction cooling technique that eliminates the need for cryogenic fluids within the vessel, see Fig.4. This approach reduces the requirements for overpressure and safety measures in the accelerator tunnel. For the coil, high-performance Nb<sub>3</sub>Sn (RRP®) insulated with glass fibres single wire from

Bruker OST was selected to ensure a sufficient temperature margin ( $>5$  K), thereby reasonably avoiding any training during operation at 4 K. The solenoid comprises four identical coils, each 300 mm in length, mechanically and electrically connected in series. This configuration was chosen to minimise production risks and to enable optimal positioning of the electrical joints in a quasi-zero background magnetic field.

Each coil is wound, followed by additional glass fibre tape wrapped around it. A copper hollow cylinder for cooling is then installed, along with a stainless-steel shrinking cylinder that, together with the flanges, serves also as a mould for impregnation. The coil is then heat-treated at  $650^{\circ}\text{C}$  for approximately three weeks to form the  $\text{Nb}_3\text{Sn}$  phase via a slow diffusion process of Sn into Nb. It is finally vacuum impregnated with epoxy and the flanges are cut using EDM wire erosion. This summary outlines the process; however, it is not the appropriate place to provide all technical details.

After assembling the four coils, they are placed in the vessel inside the thermal screen and connected to the main cryocooler and the current leads. The vessel is equipped with two auxiliary chambers at both ends to integrate the cooling system and the supports for the HTS insert. This integrated design is crucial for operation in the accelerator, where the space allocated to this photon source is limited to 2 metres.

The HTS insert is currently in the procurement phase, with a contract awarded to CAN Superconductor for the procurement of the Cu-REBCO bulks made using the innovative SDMG technique. Assembly of the insert is scheduled to commence later this year, with completion expected within the same timeframe.



*Figure 4 On the left is the cryostat design for the metre-long prototype, developed in collaboration with Fermilab. Cooling is achieved via conduction, utilising three cryocoolers: the central one for the superconducting solenoid and two side ones for the HTS insert, the undulator's core. On the right is a photograph of the vacuum vessel.*

### **3. Results / Conclusions / Deliverables**

We successfully demonstrated that REBCO bulks operated at 10 K can produce an undulator magnetic field amplitude of approximately 2 T for a 10 mm period length and a 4 mm magnetic gap. This achievement surpasses the state-of-the-art NbTi superconducting undulators by a factor of more than two. Our findings, which include detailed analyses of field optimisation, the

impact of ferromagnetic poles, and novel magnetic configurations such as the helical undulator based on REBCO bulks, have been documented in esteemed international scientific journals including JSR, PRAB, PRR and IEEE<sup>1</sup>.

These advancements have garnered significant attention from the scientific community, as evidenced by the numerous seminars listed in the subsequent section. The implications of our work are profound for both the light source scientific community, which can dramatically enhance the throughput of their instruments and explore new photonic techniques, and the materials science community, which anticipates positive feedback from new applications of REBCO bulks. This success is expected to attract additional funding for further improvement and understanding of these materials.

#### 4. Publications and Outreach

Below is a list of publications in order from the most recent, including the latest submission which is not yet published:

1. Calvi, M., Arsenault, A., Gafa, C., Sammut, N., Sammut, A., Zhang, K., Hellmann, S., Liang, X., Kinjo, R., Schmidt, T., Ainslie, M. D., Dennis, A. R. & Durrell, J. H. Experimental results of a YBCO bulk superconducting undulator magnetic optimisation. Submitted to *Physical Review Accelerators and Beams* (19 July 2024).
2. Weerakonda, D., Dennis, A., Calvi, M. & Durrell, J. Pulse magnetized superconducting bulk array undulator concept. *Phys. Rev. Res.* 6, L022060 (2 June 2024).  
<https://link.aps.org/doi/10.1103/PhysRevResearch.6.L022060>
3. Wei, D., Calvi, M., Zhang, K. & Deng, H. Electromagnetic Design Study of a 12-mm-Period Bulk High-Temperature Superconducting Undulator. *IEEE Transactions on Applied Superconductivity* 34, 1–5 (2024).
4. Calvi, M., Hellmann, S., Prat, E., Schmidt, T., Zhang, K., Dennis, A. R., Durrell, J. H. & Ainslie, M. D. GdBCO bulk superconducting helical undulator for x-ray free-electron lasers. *Phys. Rev. Res.* 5, L032020 (3 Aug. 2023).  
<https://link.aps.org/doi/10.1103/PhysRevResearch.5.L032020>
5. Zhang, K., Pirodda, A., Liang, X., Hellmann, S., Bartkowiak, M., Schmidt, T., Dennis, A., Ainslie, M., Durrell, J. & Calvi, M. Record field in a 10 mm-period bulk high-temperature superconducting undulator. *Superconductor Science and Technology* 36, 05LT01 (Mar. 2023). <https://doi.org/10.1088/1361-6668/acc1a8>
6. Zhang, K. & Calvi, M. Review and prospects of world-wide superconducting undulator development for synchrotrons and FELs. *Superconductor Science and Technology* 35, 093001 (July 2022). <https://doi.org/10.1088/1361-6668/ac782a>
7. Kinjo, R., Calvi, M., Zhang, K., Hellmann, S., Liang, X., Schmidt, T., Ainslie, M. D., Dennis, A. R. & Durrell, J. H. Inverse analysis of critical current density in a bulk high-temperature superconducting undulator. *Physical Review Accelerators and Beams* 25 (Apr. 2022).  
<https://doi.org/10.1103/physrevaccelbeams.25.043502>

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<sup>1</sup> Journal of Synchrotron Radiation (JSR), Physical Review Accelerator and Beams (PRAB), Physical Review Research (PRR) and IEEE Transaction in Applied Superconductivity.

8. Zhang, K., Ainslie, M., Calvi, M., Kinjo, R. & Schmidt, T. Fully-staggered-array bulk Re-Ba-Cu-O short-period undulator: large-scale 3D electromagnetic modelling and design optimization using A-V and H-formulation methods. *Superconductor Science and Technology* 34, 094002, (Aug. 2021). <https://doi.org/10.1088/1361-6668/ac1c14>
9. Zhang, K., Hellmann, S., Calvi, M., Schmidt, T. & Brouwer, L. Magnetization Current Simulation of High-Temperature Bulk Superconductors Using the ANSYS Iterative Algorithm Method. *IEEE Transactions on Applied Superconductivity* 31, 1–6 (2021).
10. Zhang, K., Ainslie, M., Calvi, M., Hellmann, S., Kinjo, R. & Schmidt, T. Fast and efficient critical state modelling of field-cooled bulk high-temperature superconductors using a backward computation method. *Superconductor Science and Technology* 33, 114007 (Oct. 2020). <https://doi.org/10.1088/1361-6668/abb78a>
11. Hellmann, S., Calvi, M., Schmidt, T. & Zhang, K. Numerical Design Optimization of Short-Period HTS Staggered Array Undulators. *IEEE Transactions on Applied Superconductivity* 30 (June 2020). 1–5. <https://doi.org/10.1109/tasc.2020.2965873>
12. Calvi, M., Ainslie, M. D., Dennis, A., Durrell, J. H., Hellmann, S., Kittel, C., Moseley, D. A., Schmidt, T., Shi, Y. & Zhang, K. A GdBCO bulk staggered array undulator. *Superconductor Science and Technology* 33, 014004 (Dec. 2019). <https://doi.org/10.1088/1361-6668/ab5b37>

These activities have been presented in seminars with videos available for some of them:

1. A GdBCO Undulator. CONECTUS Summer school, Prague, June 24th, 2024. <https://www.conectus.org/summer-school/>
2. A GdBCO Undulator for Tomographic Microscopy at the new Swiss Light Source, SLS2.0. TE-MS Seminar, CERN, Geneva, February 1st 2024. <https://indico.cern.ch/event/1325657/>
3. Superconducting Undulators for Future Light Sources, IPAC23, Invited talk, Venice, Italy, May 9th, 2023.
4. A REBCO Superconducting Permanent Magnet Undulator. Applied Superconductivity Seminar Series organised by Prof. Susie Speller of the University of Oxford and Dr John Durrell of the University of Cambridge, April 1st, 2021. <https://www.youtube.com/watch?v=RtcsCgOcT1U>
5. HTS Magnets for Light Sources. 105th Plenary ECFA meeting, CERN, Geneva. November 14th, 2019. <https://cds.cern.ch/record/2701795>