Progress report on HTSU Project

Progress on the HTSU project during the 2021 is reported up to the last results obtained in January 2022: new instrumentation, first results with industrially produced HTS samples, following up of contracts and new collaborations are discussed.

1. New measuring system installed in Cambridge

The installation at the university of Cambridge has been upgraded with a new sample holder. The four long rods which held the sample and thermally isolated it from room temperature, have been substituted with a stainless steel tube specially machined to reduce its thermal conductivity while keeping a high position accuracy and rigidity to prevent bending in presence of unbalanced magnetic forces, for instance during the quench of an HTS crystal. The vertical installation outside the cryostat is presented Fig.1, where at the bottom the HTS sample is visible. At the top, a new stage equipped with an incremental encoder is now used to position precisely the Hall probe along the undulator sample and as well to increase the level of automatisation of the whole system. This latter was essential to operate the system remotely during the pandemic where only one person was allowed in the laboratory. In this new approach, there are no longer cold connectors and the wire moves rigidly from the Hall probe up to the warm connector, avoiding any possible collision and damage of the cable with the surrounding cryogenic components. Fig. 2 shows the new Hall probe designed, assembled and calibrated by PSI. Five Hall elements (InAs) are installed, three for the main undulator field (in the picture y-direction): one centred on the axis, the other two respectively one tenth of a millimetre above and below the axis, to permanently monitor the position of the sensor (i.e. the central Hall probe must always measure the lowest field if properly centred). The remaining two Hall elements are for the x- z-component of the field. The x-component shall be

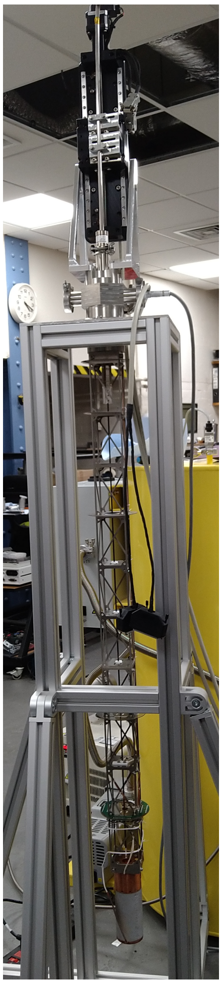

Figure 1 The new sample holder designed by PSI to improve the accuracy and automatisation.

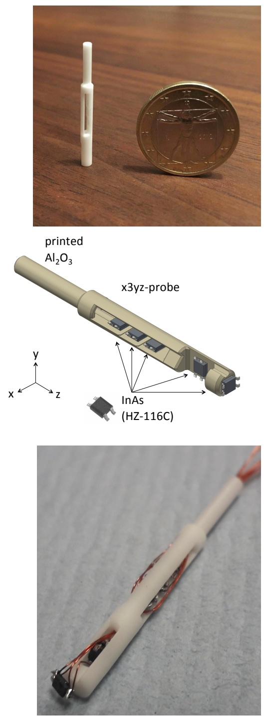

Figure 2 The new probe designed and calibrated at PSI and under technology transfer.

ideally zero and it must be measured and corrected in case of deviation. The z-element monitors the solenoidal components during the magnetisation process and evaluates the residual field present at the extremes of the sample, also when the solenoid is fully discharged. A new version of the above probe is under development with the company SENIS, where the Hall elements will be soldered on a flexible PCB and glued on the ceramic support - slightly modified for this purpose) - for a better control of the position and angles. This approach reduces the complexity of the integration and the manual work required and should allow individual powering of the Hall elements (now connected in series) essential for the implementation of the standard spinning current technique (to minimise the Hall planar effect). Additionally, a thermometer will be integrated in the probe, not essential in the vertical rig at Cambridge where the sample is cooled in a stream of helium, but critical for the long prototype working in conduction cooling where the probe will be in vacuum.

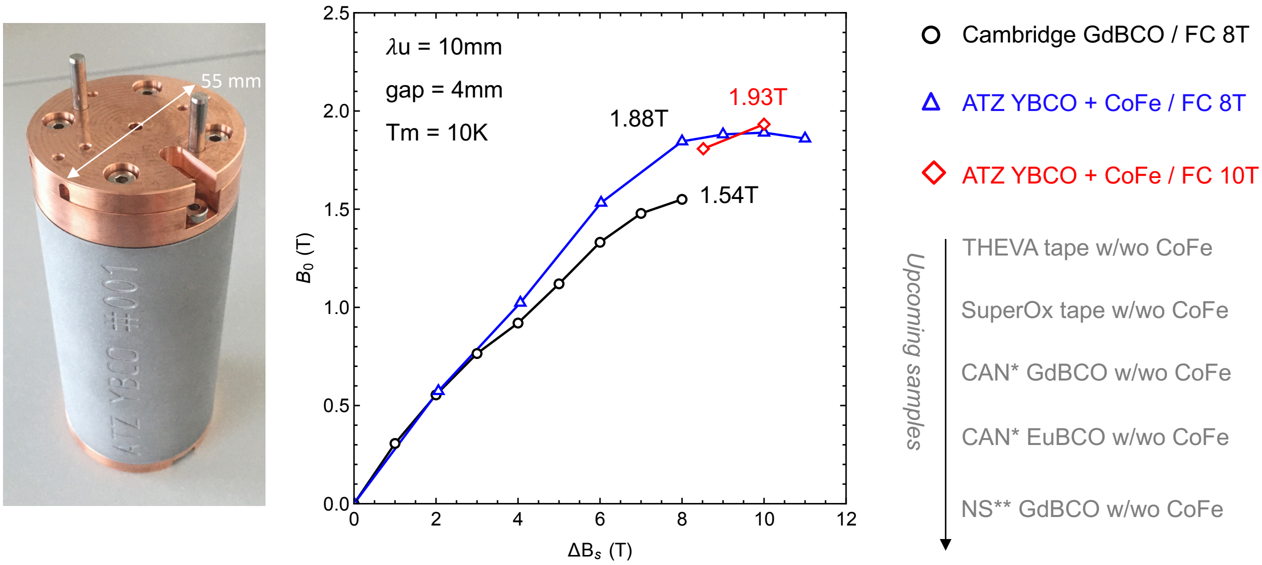

Figure 3 In the above plot the summary of the results of the first industrially prepared sample (blue & red) are compared to the performance of the previously tested sample assembled at the university. The crystal quality of the two samples are not directly comparable because the industrial sample was equipped with CoFe to increase the undulator field.

2. Results of the first industrially prepared sample

The first industrially prepared sample was tested making use of the new measuring system described above. The results are summarised in Fig.3 and compared to the best results obtained with the previous sample produced at the university. Two runs were carried out, the first (in blue) starting with field cooling level of 8T and the second one (in red) with 10T. A record undulator field of 1.93T (average value among 18 poles) was achieved for the first time, increasing of 0.39T the previous record. This sample, see Fig. 4, was assembled with YBCO crystals from the German

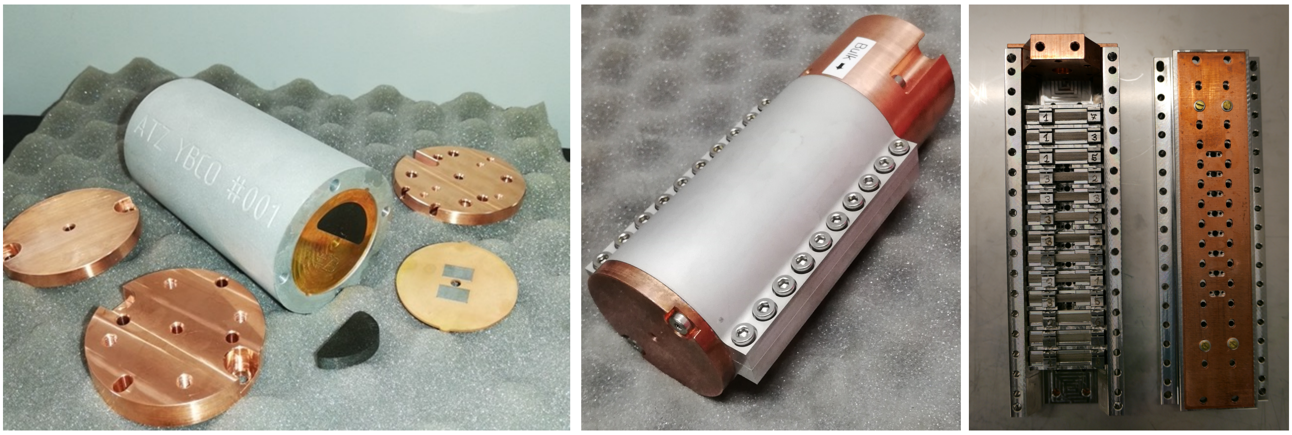

Figure 4 (a) On the left the sample as it was recently tested in Cambridge, where you can see the details of the crystal shape and the CoFe poles. The disks are finally assembled inside of a very tight Aluminium tube designed to add additional pre-stress to the crystals during the cooling down. (b) In the middle an alternative sample assembly to be tested, where the disks are hold by two half Al cylinder screwed together. This approach is more practical when it comes to disassemble and re-assemble the sample to test different optimisation schemas. (c) On the right, the sample made with HTS tape stack technology.

company ATZ[1] and precisely ground to the nominal thickness of 4+/-0.01mm, wire eroded (EDM) to their final shape (5um accuracy) and shrank fit into copper disks. A test without ferromagnetic poles was originally planned but had to be postponed, thus the results presented are with CoFe poles. This was the first time that this geometry was tested and it is mandatory to compare soon the same sample without iron poles in order to have a quantitative experimental estimation of the impact of this novel approach. If the undulator field level achieved was very satisfactory, the spread among poles was still exceeding the specifications. Having an accurate geometry (required as well for the shrink-fit technique) better than 10um, allows to conclude that the main problem of this technology is the quality of the crystal itself. A spread around 10% in the peak to peak variation does not allow to start the optimisation of the field (sorting, swapping, pole height adjustment, etc.) and further efforts are required to reduce this parameter well below 5% (2% is the typical value for permanent magnets). Better performance are expected with GdBCO and EuBCO from CAN[2] and GdBCO from NS[3] which will be tested in the coming months. In parallel, new quality control processes are under negotiation with the manufactures, in general imported from the experience with permanent magnets. NS partially does it, implementing a magnetic campaign at LN2 and providing the field map of individual crystals and delivering only products which satisfy a certain quality level. On top of this, additional measurements shall be established

[1] Adelwitz Technologiezentrum GmbH.

[2] CAN SUPERCONDUCTORS, s.r.o.

[3] Nippon Steel Corporation.

after embedding the crystals in the copper sleeves to evaluate the integrity of the parts and to make an assessment of the current density over the flat part of the half disk which is the closest

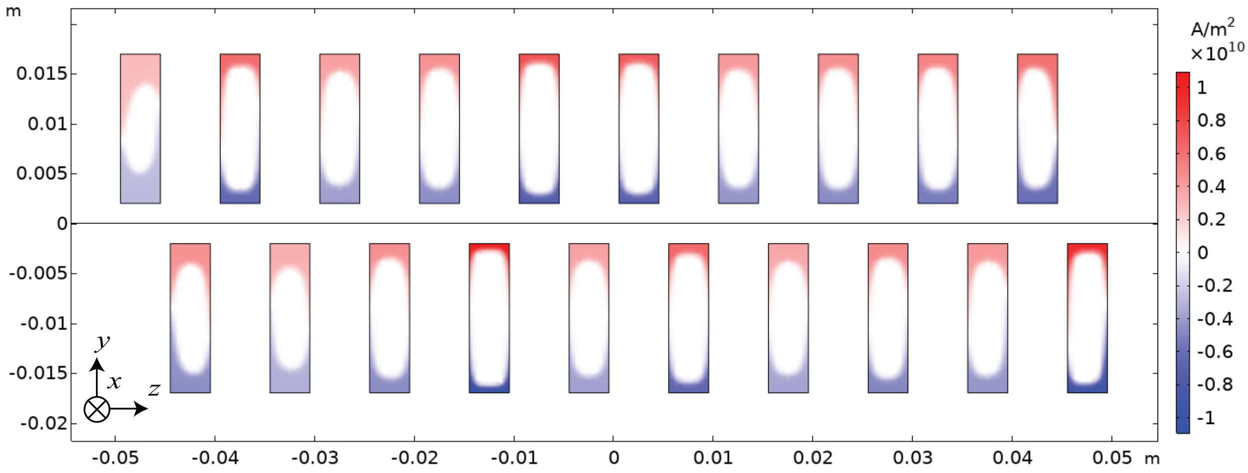

Figure 5 Example of inverse analysis, where the current density distribution is reconstructed starting from a magnetic field profile measurement along a short sample tested at 10K.

to the beam axis. In parallel, the evaluation of the alternative design based on HTS tapes progresses steadily and the first sample will be tested at the end of February 2022.

3. Enhanced data analysis of sample measurements

Novel algorithms have been developed to extract more information out of the magnetic profile measurements. The most important to be mentioned is the evaluation of the average Jc in each crystals, see Fig. 5. This information allows to sort the disks and reassemble the sample in a configuration where the peak to peak pole variation is minimised. Moreover, this technique is more effective the higher the number of disks to be sorted is (assuming that the spread remains constant in the production), allowing an optimistic scaling from 20 disks of the standard short sample to the 200 disks of the first full scale prototype. More details will be shorty available in the manuscript[4] accepted on January 31 (2022) in PHYS. REV. ACCEL. BEAMS.

4. Procurement contract for the 12T Sc solenoid signed with Fermilab

The collaboration agreement between Fermilab and PSI (CRADA FRA-2020-0032 PSI SC Technologies) for the procurement of the 12T superconducting solenoid was signed in September 2021. The kick-off meeting (via Zoom) was held few days later (09.09.21) where the specifications were discussed in details once again. The coil designed is based on the last generation Nb_3Sn wire (the one developed and implemented for the High luminosity upgrade of the LHC, CERN) and

[4] RYOTA KINJO et al. Inverse analysis of critical current density in a bulk high-temperature superconducting undulator PHYS. REV. ACCEL. BEAMS XX, 000000 (2022)

any step back to more conventional conductors would require a substantial redesign and would increase the complexity of the cooling system. The choice of conduction cooling is appreciated for the absence of LHe in the accelerator tunnel, but requires a coil size (coil thickness) compatible with the largest acceptable temperature gradient, easily guaranteed only with high performance conductor. For the above mentioned reasons, the procurement of the wire received the highest priority and the negotiation with Bruker OST (Carteret, NJ 07008, USA) was critical, since only their Rod-Restack Process (RRP®) meets the specifications. Finally the contract was placed and the wire is expected for September 2022, in line with the time plan. With this link the authorised people can follow the regular exchange meetings, https://indico.psi.ch/category/542/. In Fig. 6 the final design of the vacuum vessel is presented: details of the mechanical supports, cryocoolers, current leads, pumps are finalised and all components are under procurements (some, like cryocoolers, are already in-house). Overall the contract is moving on at a good pace.

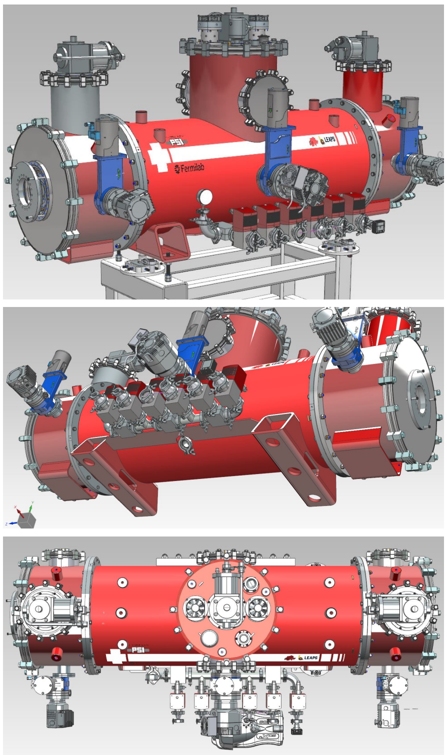

Figure 6 views of the final design of the vacuum vessel. All components are out for procurement.

5. Collaboration agreement with university of Kyoto

A new collaboration agreement is going to be signed with the Institute of Advanced Energy at the University of Kyoto to increase the speed of the short test program, now only supported by the University of Cambridge. The experience of the Japanese team with HTS bulks and undulators and their new +/-6T facility makes their support very valuable for the success of the project in the time frame of the SLS2.0. Their facility will be dedicated to our research for not less than 20 weeks per year, under the support of both their technical and scientific staff. During the time of the collaboration, Prof. Ryota Kinjo will be permanently at PSI to help with design work and data analysis.

6. Strain measurements

To minimise the peak tensile stress (1st principle stress) in the ReBCO bulk superconductor and prevent a premature quench during FC magnetisation, we have proposed a novel shrink-fit assembly technique and first adopted it in one single YBCO-Cu-Al piece. To characterise the mechanical strains in the YBCO bulk and evaluate the pre-stress contribution from the copper sleeve and the aluminium shell, an inverse measurement method is proposed as shown in Figure 7. It can be concluded that the majority of the compressive mechanical strain comes from the shrinking force provide by the copper sleeve at 77 K while the two shrink-fit assembly steps and the shrinking force provided by the aluminium shell at 77 K contribute little. The most affective structure element is the copper sleeve, while the Aluminium cylinder is not strictly required, relaxing constrains on the final design, where different criteria can be used, like for instance the heat conductivity to improve the cooling of the insert. Figure 7 also shows the simulated peak tensile stress in the pre-stressed YBCO bulk which drops from 82 MPa to 39 MPa, a safety value. Two 10 cm long industrial HTS samples were then fabricated by assembling twenty

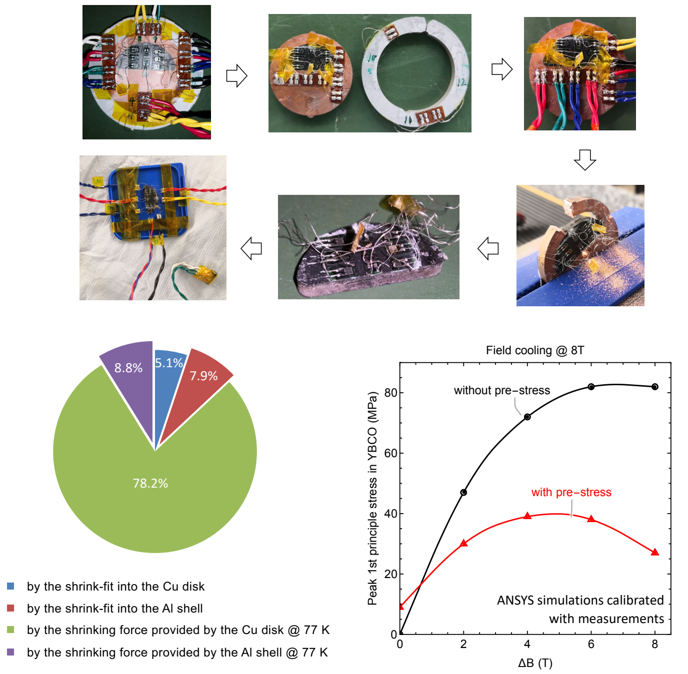

Figure 7 On the top the sample used for the strain measurements during the different steps of the assessment, on the bottom the summary results.

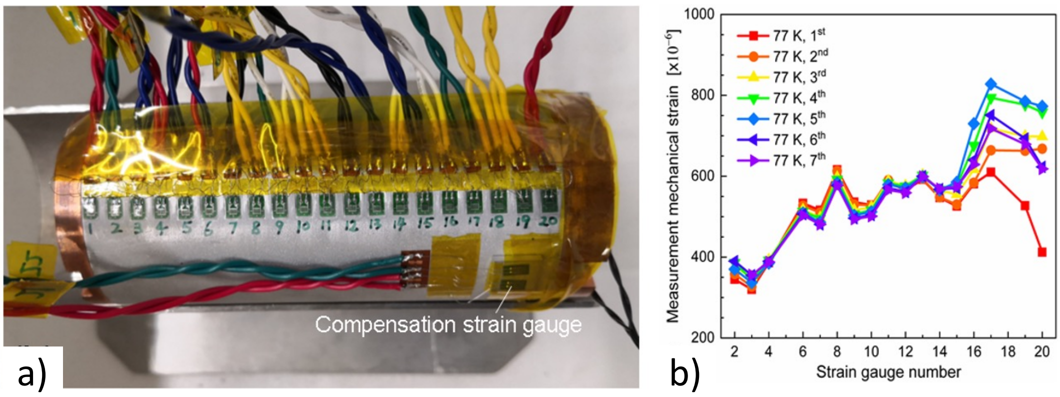

Figure 8 (a) 10-cm long HTS sample with mounted strain gauges; (b) measurement mechanical strains after thermal cycle trainings.

4.0 mm thick shrink-fitted YBCO-Cu pieces and twenty 1.0 mm thick copper pieces into a 10 cm long aluminium shell with transition fits. To validate the aluminium shell is in close contact with YBCO-Cu pieces in cryogenic environment, twenty strain gauges are mounted on the outer surface of the aluminium shell and two compensation strain gauges are mounted on a small stress-free aluminium block as shown in Figure 8a; after cool down to 77 K, the thermal strains of the aluminium shell are compensated and the recorded values are net mechanical strains. Figure 8b plots the measurement mechanical strains after each thermal cycle at 77 K. It can be found that all strain values are positive which means the aluminium shell experiences tensile hoop stress along the axial length and the copper sleeves are compressed by the aluminium shell at 77 K. This proves well that the transition fit between the 10 cm long aluminium shell and forty copper sleeves is a feasible solution.

Additional experiments were carried with neutron beam at the ZEBRA beamline of PSI. Measuring the intensity of a diffracted neutron beam on a crystal as a function of the out-coming beam angle (2θ), gives information on the atomic spacing and consequently to the strain if stress is applied. A this beamline it is possible to control as well the temperature and the magnetic field, which allows to reproduce (on a small sample) the same operating conditions of the crystal in the undulator and to measure the strain and calculate the stresses. An example of raw data is presented in Fig. 9 where the counts on the detector are recorded as a function of the angle. This technique is very promising but additional tests need to be carried out to evaluate the accuracy of this approach, which at the time being looks not enough for the practical purpose of our investigation. A straight forward improvement to this technique would be a change of particle, from neutrons to photons, not sensitive to the nuclear forces. Unfortunately, there is not a beamline available at PSI with sufficiently short photon wavelength to cope with our thick sample. Discussions of ESRF beamline scientists are ongoing to establish a collaboration.

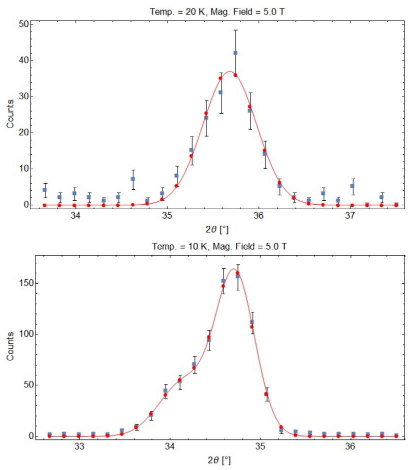

Figure 9 An example of 2theta neutron diffraction measurements on a YBCO sample

7. Large-scale 3D electromagnetic modelling and design optimisation

The development of a new hard x-ray beamline I-TOMCAT equipped with a 1 m long HTS undulator has been scheduled for SLS2.0. One of the key challenges for designing such long undulator is the large-scale simulation of the magnetisation currents inside 200 staggered-array ReBCO bulk superconductors. A feasible approach to simplify the electromagnetic model is to retain five periods from both ends of the 1 m long HTS undulator, reducing the number of DOFs to the scale of millions. The theory of previously proposed 2D backward computation method is

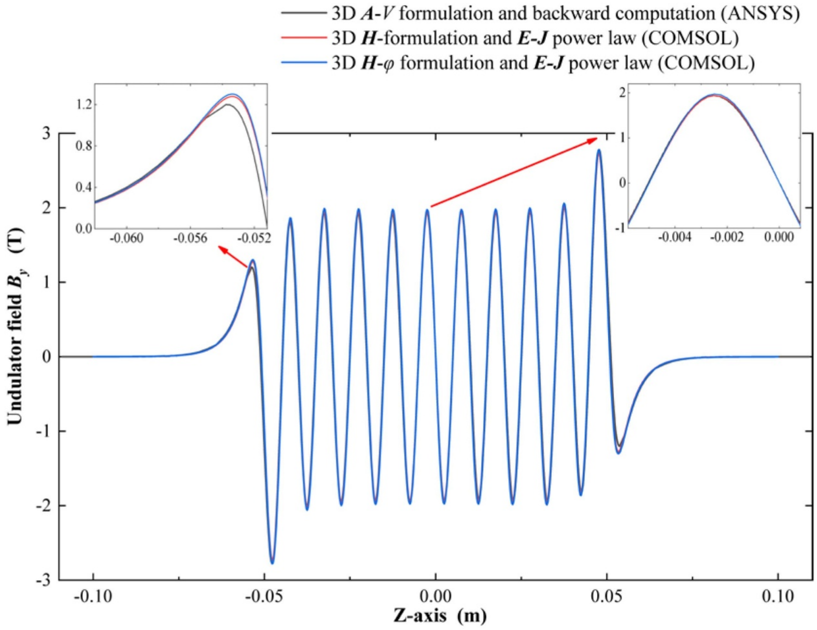

Figure 10. Comparison of the calculated undulator field By along the z-axis (x = y = 0) obtained using the A-V, H and H-ϕ formulation models.

extended to calculate the critical state magnetisation currents in the ten-period staggered-array bulk HTS undulator in 3D. The simulation results of the magnetisation currents and the associated undulator field along the electron beam axis are compared with the well-known 3D H-formulation and the highly efficient 3D H-ϕ formulation method as shown in Figure 10, all methods showing excellent agreement with each other as well as with experimental results. The mixed H-ϕ formulation avoids computing the eddy currents in the air subdomain and is significantly faster than the full H-formulation method, but is slower in comparison to the A-V formulation-based backward computation. Finally, the fastest and the most efficient A-V formulation in ANSYS 2020R1 Academic is adopted to optimise the integrals of the undulator field along the electron beam axis by optimising the sizes of the end bulks. The associated paper has been published in SUST [1].

8. Review on Sc undulators for SUST journal

The Superconductor Science and Technology journal asked our group for a review paper on superconducting undulators. We have recently submitted this work which has been preliminary evaluated, for its extension and details, the most complete and updated review presently in the literature. We hope that the manuscript will be available soon to the public in open access on the SUST site.

[1] Kai Zhang et al 2021 Supercond. Sci. Technol. 34 094002).