Design Improvement of a Staggered YBCO Undulator

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Thu-Af-Po4.03-09

Introduction

➢An undulator is an important light source device in the facilities of accelerator synchrotron radiation and free electron laser. In order to generate a strong transverse periodic field, YBCO Bulks are used to construct a High-Temperature-Superconducting-Undulator (BHTSU).

➢In order to estimate the field strength of sinusoidal transverse field and to optimize the end pole design to minimize the first field integral (i.e. electron angle) and the second field integral (electron position), an energy minimization method (EM-Method) which based on Bean's model theory to simulate the trapped field on the HTS bulks is introduced.

➢This paper is focusing on promoting the reliability of EM-Method simulation work. Aggregating the experiences of measurement of BHTSU under 77K and 7K and the experiences of simulation work based on EM-Method, some issues are tackled to enhance the integrality of BHTSU design work.

Simulation and Jc Setting

➢The EM-Method [1] was adopted to find out the Jc(H), the critical current of a YBCO bulk. First, the M(H) curve of a small rectangular sample of YBCO bulks (with dimension 5.2 x 3.55 x 2.45 mm^3) is measured by SQUID , Fig.1 shows the measurement result.

➢Second, a model comparable to the small sample was constructed by EM-Method, Fig.2, of which the magnetization, M(H), can be calculated by:

$$M_z = \frac{1}{A_{\text{bulk}} L} \sum_{ij}^{nm} I_{ij} A_{ij}$$

, where I_{ij} is current of every single loop, A_{ij} is area, and A_{bulk}*L is the volume of the sample.

➢The sequence of how the current fills into micro loop is decided by comparing the electromagnetic energy change:

$$E_{ij} = I_{ij}\left(\Phi_{ij}^{int} - \Phi_{ij}^{ext}\right) = I_{ij}\left(\sum_{kl}^{filled} L_{ij,\,kl}^{mutual} I_{kl} - \int_{S_{ij}} B_{apply}\, dS\right)$$

➢An iteration process was designed to find out a J(H) curve, hence than a simulated M(H) can match with the measurement result.

➢The behavior of a BHTSU under different magnetizing field is already describe by Ryota Kinjo in 2014 [2], but here a J(H) iteration method is adopted to establish a connection between EM-Method simulation and experimental measurement.

➢It's expecting that the behavior of a BHTSU can be predicted by the simulated J(H). However, further works are necessary. The critical current inside a real single bulk is not uniform.

J(H)=25/(H+0.8) A/mm3 ;
R.M.S. residual difference is 0.0037 T

J(H)=4940/(H+5.03) A/mm3 ;
R.M.S. residual difference is 0.0118 T

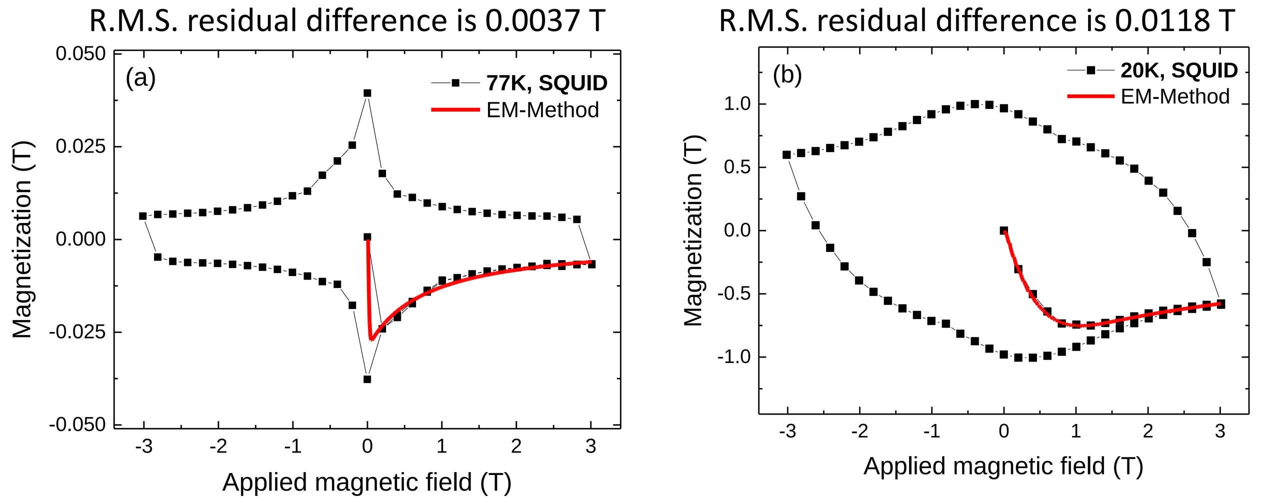

Fig. 1. The magnetization of sample was measured by SQUID under 77K and 20K. The black dots mark the measurement result, and the red line shows the calculations by EM-Method.

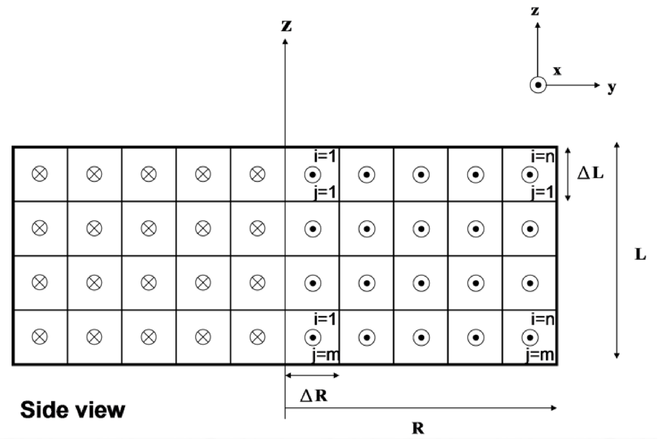

Fig.2. The bulk is divided into concentric micro loops. Each loop can have a current flow obeying critical current density Jc. EM-Method tells how the loops should be filled one by one. Generally, physical property consists with Bean Model.

Tolerance of Jc variation between bulks

➢In order to realize an undulator, Fig.3(a), lot of efforts are aim to achieve high magnetic field uniformity. An quality inspection device based on 2D-scanning Hall probe system associated with a filed-cooling process under liquid nitrogen was establish to measure relative filed trapping strength of bulks, Fig. 3(b).

➢Fig.4 shows three different cases of measurement result of half disks machining from disk shape YBCO bulks of 32mm in diameter. Case (a) shows a good performance. Case (b) tells the crystallized region is a triangle, which means as preparing bulks array for a BHTSU the direction of cutting line, dividing a disk shape bulk into two half circles, which dominates the crystallized region should be noticed. Case (c) discovers the invisible crack might exist even the defects not observed on exterior. The quality inspection device is going to help quality control of bulks.

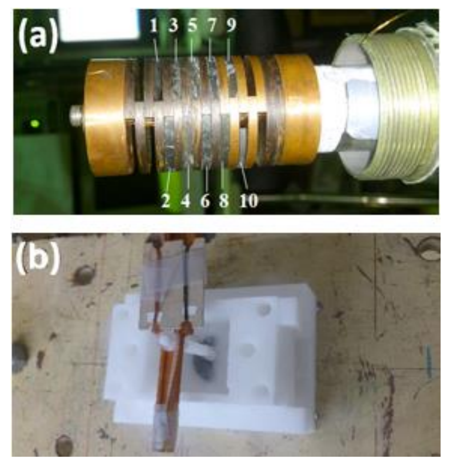

Fig. 3. (a) A BHTSU with 10 half bulks, conducting to a cryocooler, can be cooled down to 7K. (b) A half bulk, magnetized and immersed in LN2, is under 2D scanning by Hall probe.

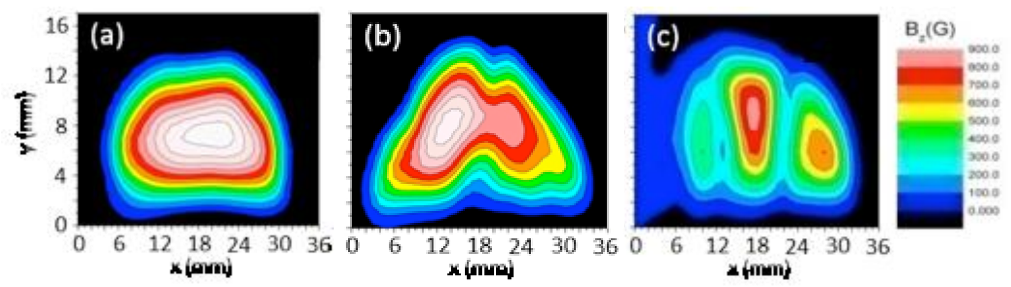

Fig.4. Three different half bulks magnetized by Field-Cooling process under 77K were measured by Hall probe system. The magnetic field normal to the surface is shown.

➢The EM-Method is adopted to analyze the tolerance: how the sinusoidal field is affected by the quality variation between bulks.

➢Here is to discover how peak field difference be affected by tuning magnetizing field.

➢A -10% difference of critical current, simply called *"defect" in the following, is placed into a bulk inside a BHTSU array. The effect of existing defect is simulated by EM-Method under different magnetization field, and the results are in Table I.*

➢*For a bulk with 10% critical current density lower, the current penetration is deeper; hence than the peak field difference is predicted less than 10%, however, for saturate case, the difference between bulks will completely emerge.*

➢*The simulation results reveal that as the percentage of current penetration goes larger, the peak field difference become larger.*

➢*According to Table I, the fraction of current penetration should be no much larger than 20%.*

➢*As far as an undulator is concerned, if a precision of 1% variation between field peaks is requested, a bulk uniformity of around 2% is required. That is a major challenge in present stage.*

➢The field error simulation under Jc difference smaller than 5% is not available by our presented simulation code. The micro-current-loop number in a bulk, *n x m in fig.2, should be increased if asking for higher field precision. Numerous loop number heavily increases computing time. To shorten the computing time is in our future plan.The Fraction of current penetration:*

$$\Gamma_{all} = \frac{\text{Number of filled loops}}{\sum_i^{all\ bulks} n_i \times m_i}$$

TABLE I. A J(H)=4940/(5.03+H) A/mm^2, referring to Fig.1(b), obtained by iteration method mentioned in previous section with a sample measured by SQUID under 20K, was used for following simulation.

External field strength of field-cooled (Tesla)	0.25	0.5	0.75
Sinusoidal peak field (Gauss)	143.0	280.1	373.9
Peak field difference by 10% *defect*; at sixth bulk (%)	4.8 ±0.7	4.4±0.36	8.4±0.27
Γ_{all} without 10% *defect* (%)	9.68	19.93	30.18
Γ_{all} with 10% *defect* (%)	9.80	20.15	30.52

Method of Integral field correction

➢Integral field correction is to keep the transverse position and propagation direction of electron beam unchanged as beam passing through the insertion device; BHTSU also needs to obey this role.

➢Normally, the first and second field peak is weakened to match the requirement, and experimentally, the peak field strength of first one is roughly one fourth of central peaks. Decrease the thickness and increase the gap of first and second bulks, called end-poles, are generally accepted as an effective method, however, it will lead to a disadvantage.

➢If the end-poles are shrinking to one fourth in thickness, it will close to saturate, Fig.5(a), as the array magnetized, and penetrated, to around 25%, which is a nice operation point suggested by previous section. And it is gradually losing efficacy while it is close to saturate.

➢This disadvantage can be improved by adopting Side-Pair, diagramed in Fig.5(b).

➢Side-Pair can transfer the extra current induction originally on the thinning end-poles, which makes the thinning pole saturates before center poles.

➢Fig.5: The YBCO Bulks with diameter of 32 mm and thickness of 2.5 mm was constructed and assembled as a staggered array undulator. The period length and magnet gap is 5 mm and 4 mm, respectively.

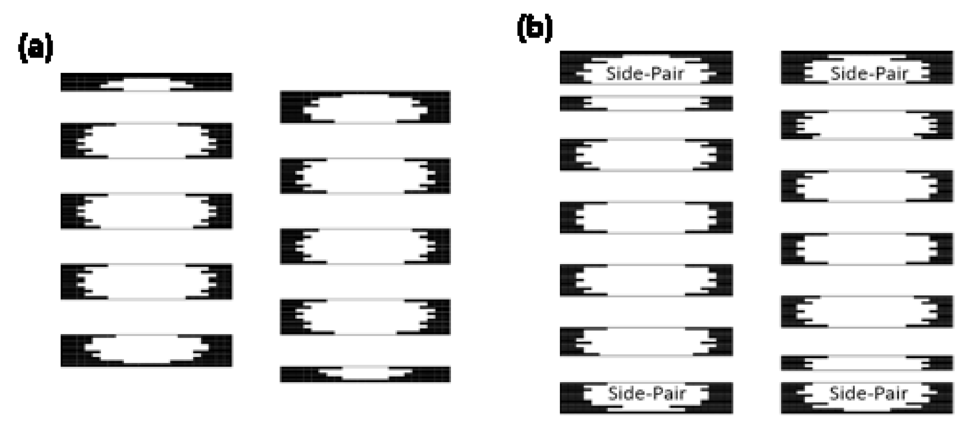

Fig.5. (a) Diagram of current penetration of a BHTSU with 10 bulks magnetizing by Field-Cooling with 1 Tesla and with J(H) curve in Fig.1(b) adopted. (b) Side-Pair added.

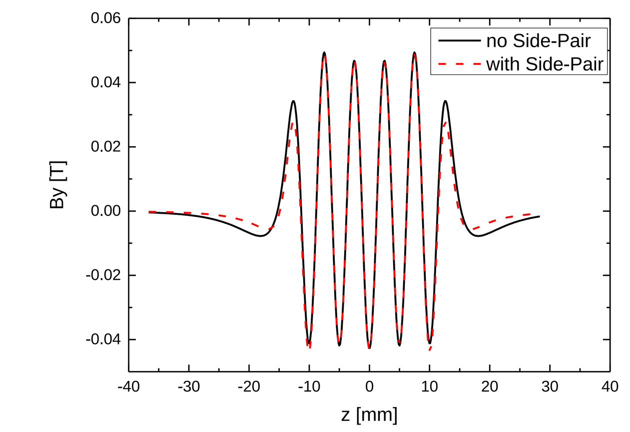

Fig.6. The magnetic field of Fig.5. The black solid line refers to Fig.5(a); the red dashed line refers to Fig.5(b).

Summary

➢Focusing on promoting the simulation model, EM-Method, being more particle, some relative works are described in this paper.

➢To establish a connection between simulation and real model, an iteration method based on SQUID measurement and EM-Method is constructed.

➢Its reliability should be improved by further analyzing of the property of YBCO bulks and better quality control of manufacturing.

➢The variation between bulks affects the quality of a stagger array. Even though the mechanism of field trapping of BHTSU can suppress the peak field error, it's not effective enough, requiring further improved high precision selection process or manufacturing process.

➢The Side-Pair was expect to shrink the variation of second integral as magnetization field adjusted. Further optimization works are needed to quantify the effect.

[1] A. Sanchez and C. Navau, "Magnetic properties of finite superconducting cylinders. I. Uniform applied field," *Physical Review B, vol. 64, no. 21, p. 214506, Nov. 2001.*

[2] *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, vol. 17, no. 2, p. 022401, Feb. 2014.*

Presented at MT-25, 2017 Aug. 27 – Sep. 1, Amsterdam, Netherlands; Session: Wigglers and Undulators; Program I.D. number: Thu-Af-Po4.03-09