Feasibility and Features of a Staggered Undulator Constructed With HTS YBCO Bulks

S. D. Chen, C. S. Hwang, C. M. Yang, and I. G. Chen

***Abstract*—A staggered undulator with high-temperature superconducting bulks might be a solution to achieve an undulator with an extremely short period for a synchrotron light source. YBCO bulk was thus selected to investigate the feasibility. This bulk (diameter 32 mm, thickness 2.5 mm) was used to build a staggered-magnet array structure and a mock-up staggered undulator of period 5 mm and fixed gap 4 mm was designed for this test. The potential generation of a sinusoidal field was tested in a 3-T magnetization system with field-cooling magnetization (FCM). The practicability of a HTS undulator is discussed in regard to the possibility of correction of the local field, repetition of field trapping and long-term stability. In addition, a field simulation concept was developed for designing the staggered undulator with YBCO bulks.**

***Index Terms*—Magnetization system, staggered undulator, superconducting undulator, YBCO bulk.**

I. Introduction

An UNDULATOR is an important device for radiation from the synchrotron light source; to decrease the period length and to increase the magnetic flux density of an undulator is the primary development. In 3rd generation synchrotron, the development is an efficient way to increase light brightness; in FEL facility, it can shorten the gain length and diminish the trapped-electron instability [1]. A cryogenic permanent magnet was introduced into an undulator and had been developed [2], furthermore researchers in international institutions are using superconducting wire for development [3]–[5]. But it is desired to have improvement with a great step—various approaches have been proposed [6]–[8], and now the HTS bulk arranged as a staggered structure was considered [9].

The use of HTS bulk to produce a sinusoidal magnetic field was first proposed by T. Kii (Kyoto University, Japan) [10], [11]. The mechanism of HTS bulk stagger structure was proved by experiment. The resultant sinusoidal field is, however, only a few ten Gauss, much smaller than expected. To discover the hidden problems and hence to continue that work, two points are the focuses of this paper. First, the field-trapping potential of the staggered HTS undulator was tested under LN_2, which was expected to reveal further characteristics. Second, as a highly precise field and high stability are the first priorities of making an undulator practicable, the possibility of local-field correction, repetition of field trapping and long-term stability are discussed. For field correction, common methods for a permanent-magnet undulator [12], such as sorting, were tried on the HTS bulk undulator; for repetition, the consistency of field trapping under individual field-cooling magnetization (FCM) is discussed. For the long-term stability, the characteristics for YBCO material are discussed elsewhere [13]; the stability within about 2 h was hence measured only to match the requirement of work related to this paper.

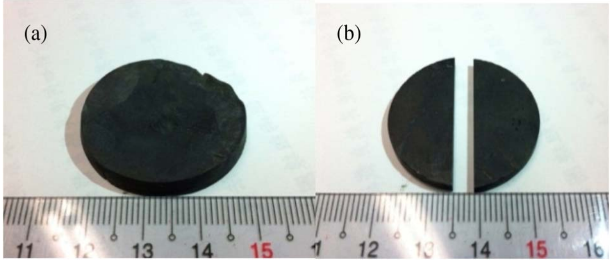

Fig. 1. (a) YBCO bulk manufactured by TSMT process. It has a disk shape but has some defects. (b) YBCO half bulk is made by machining; the surface is smooth.

The material of the YBCO, obtained from NCKU, was manufactured according to a CeO2-doped top-seeded melt- texture (TSMT) process [14]; the fabrication of an YBCO-undulator is described here. The maximum field limitation of an YBCO-undulator in a LN_2 bath has been tested in a 3-T magnetization system [15]. A field measurement system with a cryogenic Hall probe at low temperature was used to measure the magnetic field of the staggered undulator. To understand further the behavior of a staggered undulator with YBCO bulks [16], a model, built with Radia code associated with Mathematica, was developed. The difference between the measured magnetic field and the simulation result is compared and discussed in this paper.

II. YBCO Bulk Fabrication and Magnetization System

The material of the YBCO, as obtained from NCKU, had dimensions diameter 32.5 mm and thickness 4 mm, cf. Fig. 1(a). The bulk was first ground into a perfect disk shape of diameter 32 mm and thickness 2.5 mm, then cut into two half disks, between which the gap was designed to be 4 mm, cf. Fig. 1(b).

Manuscript received July 16, 2013; accepted January 16, 2014. Date of publication January 30, 2014; date of current version February 14, 2014. This work was supported in part by the National Science Council of Taiwan under Contract NSC 101-2627-E-006-001.

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Digital Object Identifier 10.1109/TASC.2014.2302914

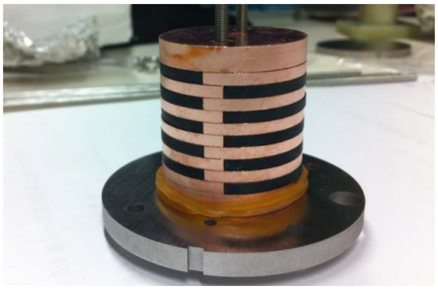

Fig. 2. A staggered undulator is assembled with an YBCO half-bulk and a copper mold.

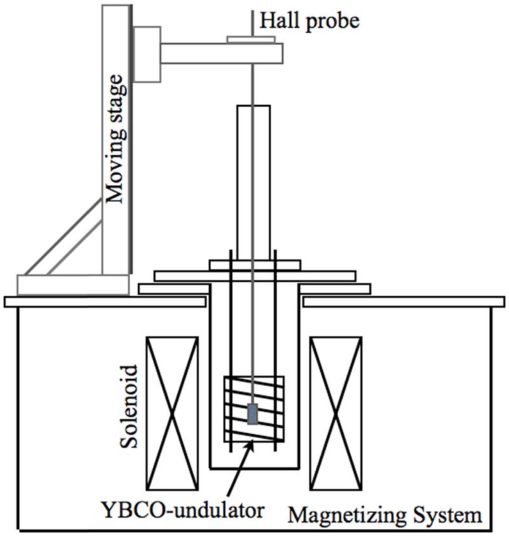

Fig. 3. Diagram of the measurement system; the YBCO undulator is in the bore of the magnetization system.

Fourteen full disk bulks were manufactured and were subjected to machining. Some bulks were crazed after machining, and a few of them broke into pieces. The un-crazed half bulks were selected, in total 17 half bulks, and were assembled as a staggered-magnet array structure. Fig. 2 reveals a staggered undulator with period 5 mm, gap 4 mm, and number of periods 5.

The YBCO bulk was under the FCM process with a 3-T superconducting solenoid system, which has a room temperature bore of diameter 60 mm. The field uniformity is 0.15% over 25 mm. Fig. 3 is a diagram of the measurement system assembled on the top of the solenoid system.

III. Field Trapping of the YBCO Staggered Undulator

An YBCO staggered array, comprising 10 bulks, was assembled and insert into a LN_2 vessel for a field trapping experiment. It was initially magnetized with a field 1 T and increased step by step. The YBCO bulk undulator was expected to trap a large field with increasing magnetizing field, but the peak field strength was shown not to increase with an increased magnetization field: the field trapping of YBCO bulk was already saturated from the 1-T magnetizing field. The result also shows significant differences between the peaks, which means that the saturation field of each bulk has a significant variation.

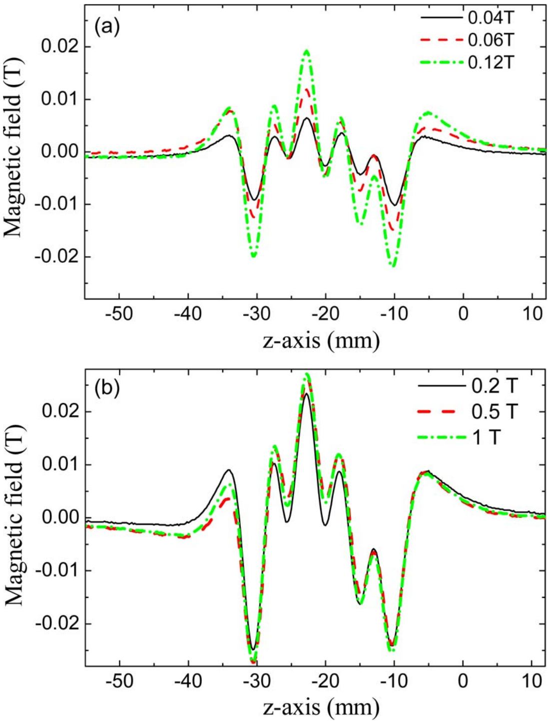

Fig. 4. Field trapping of an YBCO staggered undulator was magnetized in (a) low field and (b) high field range.

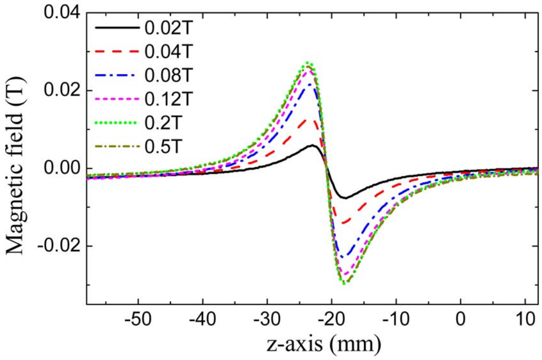

Fig. 5. Field trapping of a single bulk was excited in different magnetization field.

The field trapping under an unsaturated magnetization field is also interested. The YBCO array was magnetized with low fields 0.04, 0.06, 0.12, 0.2, 0.5, and 1 T. Fig. 4 reveals the whole filed profile. The first observation is that the field-trapping ability of an array is limited. This caution should be clarified; it might be limited by the field-trapping ability of every single bulk or by the cross-talk effect between the nearby bulks in the staggered structure. The single fifth bulk inside the array was tested alone; the result is shown in Fig. 5. Saturation of a single bulk at 77 K was discovered to occur at magnetization field $0.2 \sim 0.5$ T, similar to the saturation magnetization field of an array. Under 77 K, the field intensity of an YBCO undulator is hence limited by the field-trapping ability of a single bulk. Three ways to improve the trapped field strength are to decrease the working temperature of a magnetized YBCO, to use a bulk with larger diameter, and to improve the YBCO bulk quality.

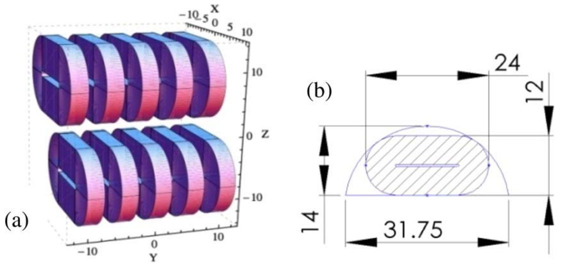

Fig. 6. (a) 3D model from Radia associated with Mathematica in a racetrack coil structure. (b) Diagram of the size of a half bulk and racetrack coil (slash line).

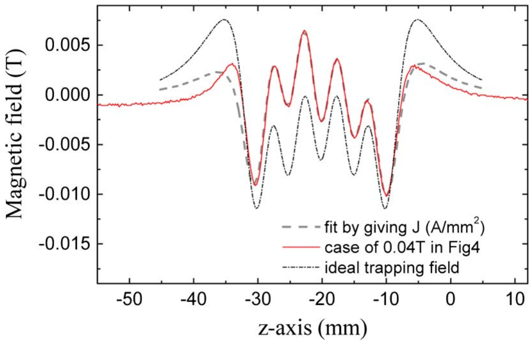

Fig. 7. A measured field was fitted on giving an appropriate current density. The data of a magnetization field 0.04 T in Fig. 4(a) is shown with their fitted result. One result of ideal simulation of the trapping field is also seen here. The current density (A/mm^2) of the fitted curve from the first to the tenth bulk is 42, 68, 61, 68, 74, 67, 66, 57, 63, 46; the current density of an ideal field is 66 A/mm^2 for all ten bulks.

The trapped field of each bulk evidently varies, and the variation increases with increasing magnetizing field. This phenomenon is deleterious for making an undulator. The homogeneity of all bulks should hence be improved to overcome this problem; the HTS-undulator should otherwise be operated under a magnetizing field far from the saturation field of a single bulk. With the use of a magnetizing field less than 0.04 T, the peak field of the sinusoidal field surly is not strong enough. A lower temperature of operation of an YBCO array is thus necessary, and a method of correcting the field under the near-saturation region should be developed.

IV. A SIMPLE COIL MODEL

A model was developed in a simple way, by racetrack coils to estimate the field strength and the sinusoidal field distribution, but not using pinning effect of superconductor, because we wish to realize the field distribution in an unsophisticated way. A racetrack coil were used to simulate the behavior of an YBCO half-bulk, cf. Fig. 6(a). The size of the racetrack coil was set intuitively and with reference to the size of the YBCO half-bulk, cf. Fig. 6(b). According to this model, all ten bulks trap the same field that will be similar to the same current density was excited on all ten racetrack coils. If current density is given to each racetrack coil individually, a field that matches the measurement result of YBCO bulk can be produced; some interesting topics then arise to be discussed. For example, Fig. 7 reveals the field trapping of individual bulks under 0.04-T magnetization is quite consistent (in the central poles) to the racetrack coil simulation with giving current density; however, Fig. 8 reveals the variation is a little big difference under 0.5-T magnetization. The difference between bulks is hence decreased when the magnetization field is less than the bulk saturation field. Therefore, the simple coil mode need to be improved. (Any result based on the simple model is, however, significant for only qualitative analysis currently.)

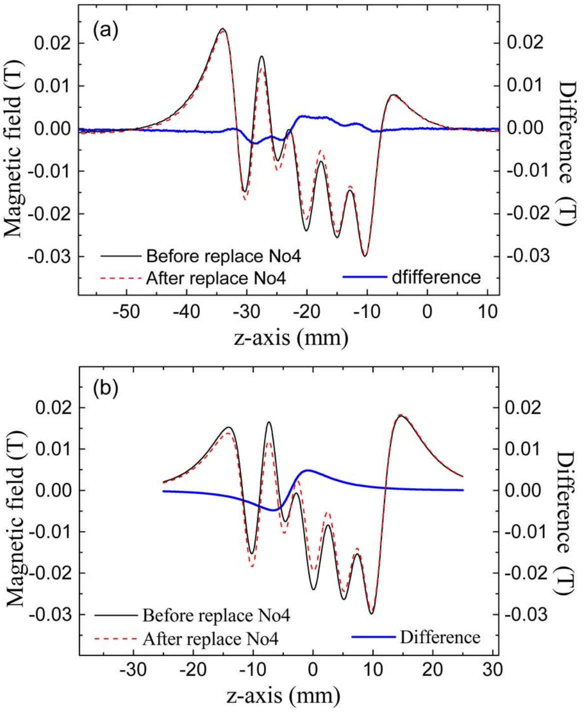

Fig. 8. (a) Measurement under magnetization field 0.5 T. (b) The simulated field was generated on fitting with the measurement result through adjusting the current density of the racetrack coil. The current density/A mm^{-2} of the initial array from the first to the tenth bulk is 91, 118, 108, 57, 93, 80, 80, 75, 73, 117; only the fourth bulk was modified from 57 to 77 A/mm^2 for comparing the field difference in the magnet array.

V. CONCEPT OF FIELD CORRECTING

Field correction has the purpose of making the produced undulator field a nearly perfect sinusoidal field. Sorting or replacing the unsatisfied magnet bulk is one of the field correction methods. A bulk with different field strength might make the field a more nearly perfect sinusoidal field. The action, bulk replacement, was executed on a HTS bulk undulator: two arrays, between which the difference was a single bulk, No. 4, replaced, were measured and compared, cf. Fig. 8(a). The same action was done on simulation with a simple coil model: the simulated result appears in Fig. 8(b). For the simulation result, only the replaced bulk has a field strength difference obviously, but, for the measurement result, Fig. 8(a) shows that the field trapping of the nearby bulks had a slightly unexpected result. This result seems a complex cross-talk effect between bulks, which makes field correction difficult. For the purpose of the development of field correction for a HTS-undulator, the complex cross-talk effect between bulks must be clarified to enhance the precision of field correction.

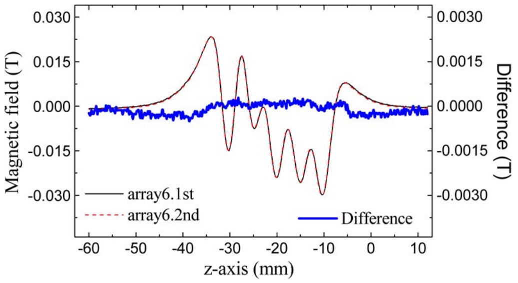

Fig. 9. The two measurement results were from the same magnet staggered array but distinct filed cooling process.

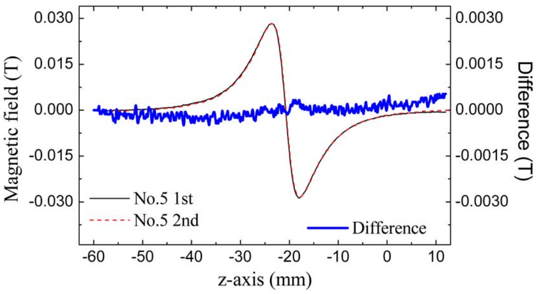

Fig. 10. The two measurement results were from the same bulk but distinct filed cooling process.

VI. REPETITION AND STABILITY OF A TRAPPED FIELD

The repetition and the stability of the trapped field in YBCO bulk is very important for the application on stagger undulator. Three related topics follow.

A. Field-Trapped Repetition for a Magnetic Array

One YBCO bulk array was experienced twice of the process of "field cooling magnetization under 0.5 T, field measurement and worming up to room temperature." Two results were compared. Fig. 9 shows the maximum difference of field strength is under 5 Gauss.

B. Field-Trapped Repetition for a Single Bulk

One YBCO single bulk was experienced twice of the process of "field cooling magnetization under 0.2 T, field measurement and worming up to room temperature." Fig. 10 reveals the difference of the field profile. The maximum difference is under 5 Gauss.

C. Long Term Stability

Trapped field decay as time escape. An YBCO bulks array was magnetized under 0.12 T, and the stability of trapped field was measured. The first measurement is marked as $t = 0$. The following measurements follow that first one at $t = 20, 40, 60, 105$ min. The measurements show that the maximum difference is less than 6 G.

Section VI-A and B show the difference to be less than 5 G; the repetition is satisfactory but inadequate for an undulator application. It should still be improved; the objective is a difference within 0.5% for two independent FC processes. This topic is important in the future. Reference [13] shows that the long-term stability is excellent for a single YBCO bulk; the stability of a YBCO array, tested in Section VI-C, is satisfactory within 2 h in the present case. This duration, 2 h, is appropriate only for work in this paper; a much longer period, such as a week, is necessary for an undulator application. A highly precise experiment is planned for the next stage.

VII. CONCLUSION

YBCO bulk was introduced to make a staggered undulator of extremely short period, and was expected to advance on field intensity. With a liquid-nitrogen bath at 77 K, the field trapping was, however, limited; the produced undulator field was also far from expectation. In the future, the first step to improve the undulator field is to undertake the field-cooling magnetization at a lower temperature; as the saturation field of YBCO becomes increased, a stronger undulator field can be produced. In the meantime, the homogeneity of bulks should be improved appreciably. The next step to improve the undulator field is to promote the field quality when magnetizing with a field nearer the YBCO saturation field; YBCO bulk sorting and field correction are, hence, important issues. The reason for the cross-talk effect must be clarified in the sorting mechanism in the first step. About the repetition of trapping field and the long-term stability in this staggered magnet array, a highly precise experiment is necessary for the next stage. An optimized end-pole design of the YBCO bulk is necessary to meet the ideal sinusoidal field requirement of the accelerator beam dynamics, and a simulation model must be improved to predict the trapped field and the sinusoidal field distribution in the staggered undulator structure.

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