A BULK HIGH-TC SUPERCONDUCTOR STAGGERED ARRAY UNDULATOR

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Abstract

At Institute of Advanced Energy, Kyoto University, we propose new staggered-type undulator with bulk high critical temperature superconductor magnets to achieve short period undulator. The new undulator consists of bulk superconductor magnets with same magnetization direction and then they can be magnetized by an external solenoid field. In this paper, we show the measurement result of transverse field, which are produced by magnetized bulk superconductor magnets in 3-period prototype. We show the dependence of transverse field on reversed solenoid field. We also show that calculation results with simple assumption related to bulk superconductor magnets provide good agreements with experimental results.

INTRODUCTION

Short period undulators bring in several advantages, short lengths FEL with low electron beam energy, high gain with same undulator length. To achieve short period undulator with the same K value, we have to obtain strong undulator field. There are two main way to obtain strong undulator field. One is the undulator with superconducting wires. Another is the In-vacuum undulator. The former can generate 10 times higher magnetic field than the latter. However, the superconducting wires have to be cooled down near liquid Helium boiling point (4.2 K), and large thermal insulation area between beam line and superconducting wires is needed. The undulator field in the former is not stronger than the latter.

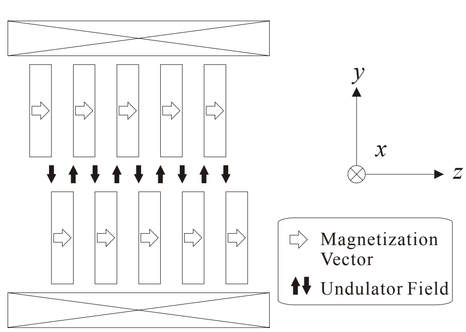

Figure 1: Schematic of new type undulator. White arrows indicate magnetization vectors of HTSC magnets. All magnetization vectors parallel to the direction of +*z*. Black arrows indicate undulator fields.

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Undulator with bulk **HTSC** (high critical temperature superconductor) magnets is promising for short period undulator. Bulk HTSC magnets as represented by YBaCuO bulk can trap magnetic field of several teslas. Recent research progress reports that a YBaCuO bulk trap the magnetic field of 17 teslas [1]. Moreover bulk HTSC magnets can be used at a temperature above liquid Nitrogen boiling point (77 K). Therefore, present refrigerator systems make it possible for the bulk HTSC magnets to be used near the beam line. However, to use bulk HTSC magnets, we have to magnetize them below ***T*c** (critical temperature). Magnetization method is main issue for using HTSC bulk magnets [2], [3].

At our institute, we proposed staggered structure to magnetize HTSC [4]. The conventional Staggered Array Undulator consists of ferromagnetic and nonmagnetic pieces [5]. Bulk HTSC Staggered Array Undulator consists of Bulk HTSC and nonmagnetic pieces. Hybrid Staggered Undulator structure, which consists of ferromagnetic and magnets, is also good candidate for using Bulk HTSC magnets in place of permanent magnets [6]. A schematic of new type undulator is shown in Figure 1.It have bulk HTSC magnets with the magnetization direction to +*z*. In this structure bulk HTSC can be magnetized by an external solenoid field.

The objective of out experiment is to check the conecept of this new undulator.

EXPERIMENTAL SETUP

Figure 2 shows a schematic of experimental setup and a photograph of 3-period prototype of the new undulator. Table 1 shows parameters of experimental setup. HTSC

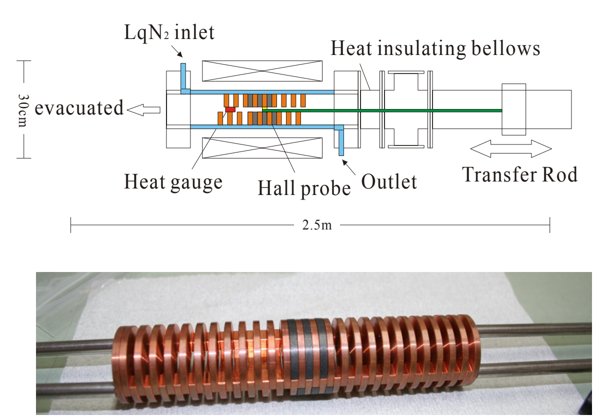

Figure 2: Schematic of experimental setup and photograph of 6 HTSC magnets (3 periods) are retained by copper pieces. B_y in 3 periods prototype is measured by hall probe.

Table 1: Parameters of experimental setup.

HTSC	DyBaCuO (T_c = 91 K, J_c ~ 1x10^9 A/m^2 at 77 K, 0 T)
HTSC Size	25.2 mm dia. quasi-semicircle Thickness of 2.5 mm
Solenoid Field	0 – 350 gauss (0.035 T)
Gap	4 mm
Number of Periods	3
Period Length	5 mm

bulk magnets are retained by copper pieces. Copper pieces also function as heat conductor between HTSC and cooling duct. HTSC is QMG DyBaCuO of Nippon Steel [5]. The bulk HTSC magnets are critical temperature, T_c, of about 91 K, critical current density, J_c, of about 1x10^9 A/m^2 at 77 K and zero fields, thickness of 2.5mm, easily magnetization axis of *z*. They are not perfect semicircle because of electron beam path. A normal conducting solenoid of 500 gauss (0.05 T) is used with water cooling, used for both magnetization of HTSC and application of reverse field to HTSC.

EXPERIMENT 1: MAGNETIZATION

Magnetization of HTSC bulk magnet is performed by **field cooling** method. This method is commonly used for magnetizing HTSC bulk magnets. We apply external magnetic field to HTSC bulk magnets at temperature above T_c. Then we cool them down to the temperature bellow T_c with keeping external magnetic field on.

Field Cooling

After field cooling with Bs of 250 gauss, we measured transverse fields, B_y, in the prototype. The transverse fields scanned along z-axis were a few gauss. If solenoid field is disturbed by diamagnetism, there are transverse component of the solenoid field. A few gauss of transverse field imply that the solenoid field is not disturbed by diamagnetism, and the solenoid field perfectly penetrates into HTSC.

Switch off solenoid field

Figure 3 shows field trapping concepts based on critical state model [6], what happens when we switch off solenoid field. Because of Faraday's electromagnetic induction law, disappearance of external field induces loop current in HTSC. The magnetic force between loop current and magnetic field is reversed with pinning force. Therefore, the superconducting current flows without losses and magnetic field exists permanently. In other words, HTSC bulk magnets are magnetized. Magnetic field in the undulator has y-component, B_y.

Figure 4 shows a measurement result of transverse field, B_y along to z-axis. Absolute B_y near the centre of the prototype (*z*=0) is weaker than the edge of the prototype (*z*=-7.5, +7.5). B_y has asymmetric property with z-axis.

If hall probe is off to +*x* or –*x* direction, the absolute B_y for whole z will be lower. If hall probe is off to +*y* or –*y* direction, B_y will be ramp with constant absolute value. To analyze causes of this profile, we use magnetostatic field calculation code, "Radia", developed in European Synchrotron Radiation Facility, with a geometry shown in figure 5.

Figure 6 shows the magnetization model. It is hard to

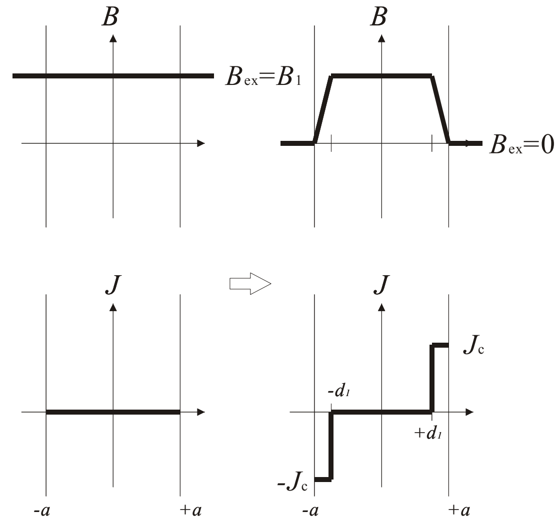

Figure 3: Pinning effect. On field cooling method, magnetic field perfectly penetrates in HTSC (left drawing). Thus, magnetic field in HTSC is equal to an external magnetic field, B_{ex} (=B_1). If B_{ex} reduces to 0, superconducting current is induced near the wall of HTSC (|*x*|=*a*.) Magnetic force between superconducting current and magnetic field is reversed with pinning force. Superconducting current can flow without losses. Therefore, HTSC has magnetization of B_1 permanently (right drawing).

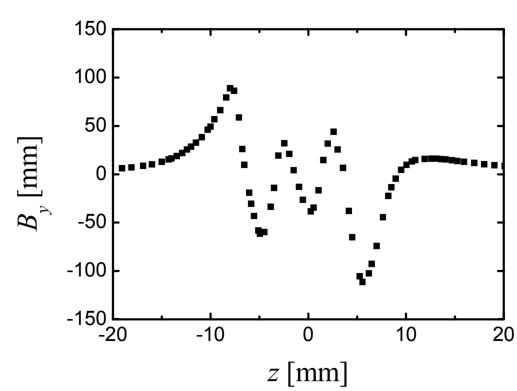

Figure 4: Measurement result of B_y. After field cooling with solenoid field of 250 G, solenoid field is set to be 0.

measure how magnetic flux lines are pinned in HTSC. Thus, we assume one magnetization vector of each magnet as representation of magnetization vectors in HTSC bulk magnets. The white arrows in figure 6 indicate the representative magnetization vectors. θ indicates the angle between the average magnetization vectors and z-axis. The amplitude of average magnetization vector is 250 gauss.

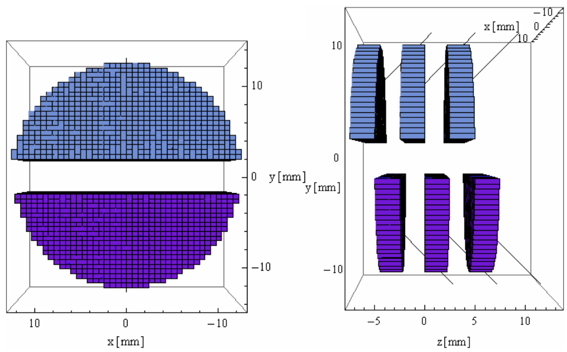

Figure 5: Calculation geometry. Magnetic field calculation is performed by Radia.

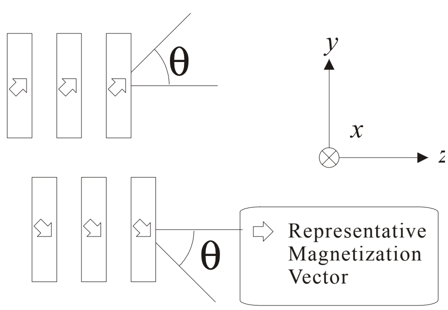

Figure 6: Magnetization model. White arrows indicate average magnetization vectors of each magnet. θ indicates the angle between the vector and *z*-axis. The magnitude of the vector is 250 gauss.

It is obvious from figure 3 that surface magnetic field of HTSC is not uniform. However, length of supercurrent region in HTSC, d is

$$d = a - d_1 = \frac{B_1}{\mu_0 J_c} \tag{1}$$

and d=0.2mm with B_1 = 0.025 T, $J_c = 1\text{x}10^8$ A/m^2. Thus, we assume that the surface magnetic field is flat and the strength is 250 gauss (low-d approximation).

Figure 7 shows the comparison of calculation and experimental result of B_y. It can be seen that this rough approximation makes similar result. The magnetization of each HTSC is not parallel to *z*-axis in this staggered undulator structure, although their easily magnetization axis (*c*-axis) is parallel to z-axis.

EXPERIMENT 2: REVERSE SOLENOID FIELD

After magnetization of HTSC bulk magnets, we apply reverse solenoid field, B_s, (B_s < 0). In case of staggered-type undulator consists of permanent magnets, B_y may not be changed when reverse magnetic field is applied. If B_y changed, magnetization of the permanent magnet must have degaussed by strong reverse field.

Reverse Solenoid Field

Figure 8 shows experimental results of B_y. Upper figure shows B_y with several reverse solenoid field, B_s (B_s < 0) and lower figure shows B_y when reverse solenoid field is removed It is obvious that B_y changes in proportion to Bs and B_y return almost initial value when Bs disappear. Hence, this is not degaussing but special phenomenon based on intrinsic property of HTSC bulk magnets.

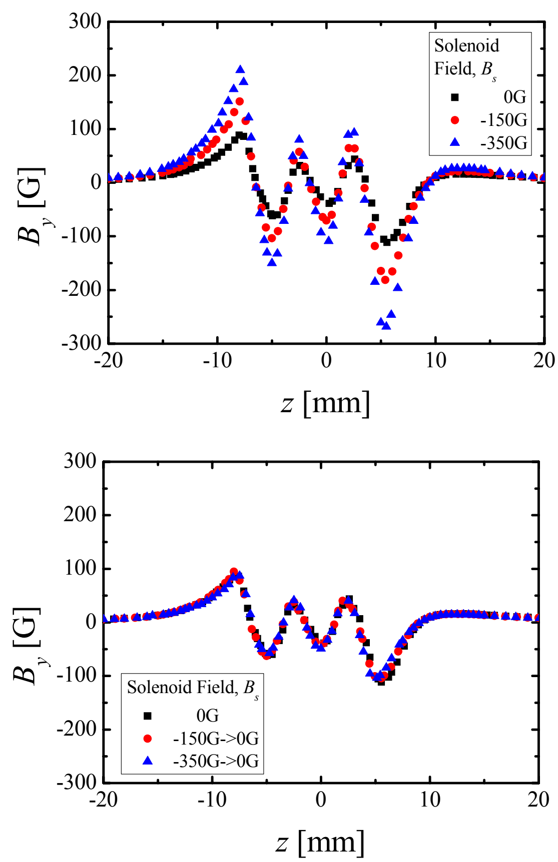

Figure 8: Measurement result of B_y. Upper drawing is B_y with reverse solenoid field. Lower drawing is B_y after removing of reverse solenoid field. B_y changes when B_s changes though no degaussing cannot be found after removing of reverse field. This phenomenon is perfectly different in case of permanent magnet.

Figure 9 shows what happened in HTSC bulk magnets when reverse field is applied. If external field $B_{ex} = B_2$ (B_2 < 0) is applied to HTSC, from Faraday's

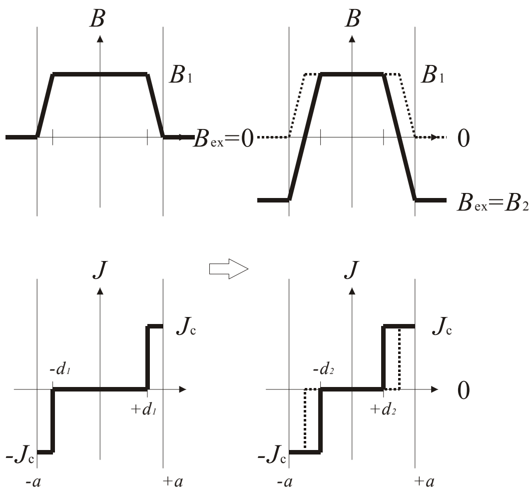

Figure 9: If you apply reverse magnetic field, B_{ex}, to HTSC, current-flowing region in HTSC enlarge. Total loop current in HTSC increase. Thus, HTSC work as a stronger magnet.

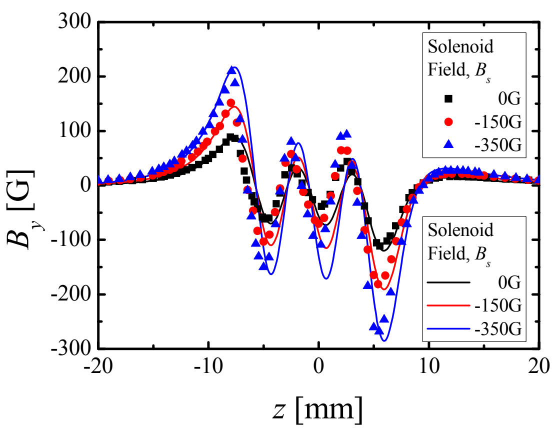

Figure 10: Comparison between measurement and calculation results of B_y with reverse solenoid field. This approximation provides good agreement with experimental result.

electromagnetic induction law, loop current flow in a direction for inhibit of magnetic field's change. In case of reverse field for HTSC, new loop current flow in a parallel direction with original current. In critical state model, superconducting current is always equal to J_c, therefore, current-flowing region in HTSC enlarge.

We calculate B_y by Radia with calculation geometry and model mentioned in EXPERIMENT1 section. At the same time, we use one more model that external field applied to the magnets is regarded as additional magnetization of the magnets. For instance, in case of solenoid field, B_s, is -150 G, we calculate B_y with 400 G (250 G + 150 G) magnets and zero solenoid field. This assumption is based on features of HTSC mentioned above, which total loop current increase in reverse external field.

Figure 10 shows calculation and experimental result of B_y with external reverse field, B_s ($B_s < 0$). The calculated B_y is in good agreement with measured B_y on absolute values and profile.

DISCUSSION

The periodic transverse magnetic field was successfully generated in 3-period prototype. Transverse magnetic field can be controlled by reverse solenoid field.

Moreover, the amplitude of the transverse field, B_y, is about 1/5 times B_m - B_s. However, for use of HTSC bulk magnets with magnetic field of several teslas, low-d approximation is not realistic. We have to take into account non-uniform magnetic field on surface of HTSC bulk magnets and hysteresis. Therefore, stronger solenoid is required and more detailed magnetic field profile in prototype is to be measured.

CONCLUSION

The periodic transverse magnetic field was successfully generated in 3-period prototype. Transverse magnetic field can be controlled by reverse solenoid field. We get the experimental proof of the concept of Bulk HTSC Staggered Array Undulator. The calculation with model based on superconductor feature has a good agreement with the experimental result.

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