GENERATION OF PERIODIC MAGNETIC FIELD USING BULK HIGH-TC SUPERCONDUCTOR*

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Abstract
We have constructed a prototype of bulk high-Tc superconductor(HTSC) staggered array undulator using 11 pairs of DyBaCuO bulk superconductors and a normal conducting solenoid. Periodic transverse magnetic field on the central axis of the solenoid was successfully produced. The transverse magnetic field was 0.0036 T in peak to peak when the solenoid field of 0.027 T was used to magnetize bulk magnets. Numerical analysis using simple assumption of Bean model was also performed. It was numerically found that simple treatment of superconducting loop current can reproduce the field distribution in the undulator.

INTRODUCTION
A short period undulator with strong magnetic field will play an important role in synchrotron light sources or free electron lasers. Resonant wavelength emitted from the undulator $\lambda_u$ is written by following well-known equations

$$\lambda_u \approx \frac{\lambda_u}{2\gamma^2} \left( 1 + \frac{K^2}{2} \right)$$

$$K = \frac{e \cdot B_0 \cdot \lambda_u}{2\pi \cdot m_0 c} = 93.36B_0 \cdot \lambda_u.$$  (2)

Here, $\lambda_u$ is the undulator period, $\gamma$ is Lorentz factor, $K$ is the undulator parameter, $e$ is the charge of the electron, $B_0$ is the maximum transverse magnetic field strength of the undulator, $m_0$ is the electron mass, and $c$ is the speed of light. In order to obtain shorter wavelength radiation without changing undulator parameter $K$ and electron beam energy, undulator period should be shortened and transverse magnetic field should be increased.

In order to realize strong periodic magnetic field in short period, superconducting undulator[1] and in vacuum permanent-magnet cryogenic undulator[2] have been developed and new idea such as pure type superconducting magnet undulator[3] and hybrid staggered undulator[4] have been proposed. Each undulator aims to realize short period undulator with higher magnetic field than the performance obtained by permanent magnet undulator. Recently, we also proposed a new structure of bulk HTSC stacked array[5, 6]. These proposals which use bulk HTSC magnets are aiming to apply the high performance of bulk HTSC magnet whose maximum trapped field reaches to 17 T[7].

The bulk HTSC staggered array undulator[6] consists of bulk superconductor magnets with same magnetization direction which are magnetized by a single external solenoid. Schematic drawing of the bulk HTSC staggered array undulator is shown in Fig. 1. Merits of this configuration are

- Only single external solenoid magnet is required for magnetization of each bulk HTSC magnets.
- Transverse magnetic field can be controlled by changing solenoid field without any mechanical structure.

EXPERIMENT
In order to prospect properties of a bulk HTSC undulator, we made the 2nd prototype of the bulk HTSC undulator. Period number has been extended from 3 to 11 to reduce the edge effect and estimated the transverse

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*Work supported by the Grant-in-Aid for Scientific Research (B), Japan Society for the Promotion of Science (21340057)
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magnetic field strength. Maximum strength of a normal conducting solenoid magnet has been increased from 0.035 T to 0.3 T.

Experimental setup is shown in Fig. 2. Copper pieces and DyBaCuO bulk superconductor are stacked in a solenoid as shown in Figs. 3 and 4. The DyBaCuO bulk magnets made by QMG method are used[8]. The critical temperature of DyBaCuO is around 91 K and the critical current $J_c$ is about 100 A/mm$^2$ at 77 K, 0 T. Typical trapped field distribution at 77K is shown in Fig 5. Magnetic field was measured by using a Hall generator. Distance between the Hall generator and the bulk superconductor was 0.5 mm,[9] The average and standard deviation of peak field of 22 pieces were 0.11 T and 0.017T respectively. The stacked array is inserted in a liquid nitrogen cooled vacuum duct. A vacuum insulation panel is used for thermal shielding. Temperature on the bulk HTSC array is monitored by Pt100 temperature sensor attached to the copper piece of stacked array. The vacuum duct is inserted in a normal conducting solenoid. Transverse and axial magnetic field is measured using the Tesla meter Model 460, manufactured by Lake Shore Cryotronics, inc. and axial and transverse Hall generators attached to the linear motion drive.

Field measurements of the prototype bulk HTSC undulator were carried out by field cooling method as described below. Solenoid field was applied before cooling down to 77K. In order to avoid saturation effect of each bulk HTSC magnet, solenoid field was set to 0.027 T. The superconductors were cooled down below critical temperature of the bulk DyBaCuO (91K) in the presence of magnetic field generated by the external solenoid. After switching off the external solenoid, transverse and axial magnetic field $B_y$ and $B_z$ were measured. Field distribution along z axis is shown in Fig. 6. The periodic magnetic field was successfully observed. The field strength at $z = 0$ was 0.0036 T in peak to peak.
The periodic magnetic field was successfully generated with a new structure using bulk HTSC magnets and single external solenoid. Field strength at the center of the undulator was 0.0036 T in peak to peak.

In order to investigate the potential of the bulk HTSC staggered array undulator, the numerical calculation using Bean model was also performed. Field distribution along z axis was successfully reproduced. It was expected that the transverse magnetic field of 0.36 T will be obtained by increasing critical current density up to $10^4$ A/mm$^2$.

**REFERENCES**


