STUDY OF PERFORMANCE OF BULK HTSC
STAGGERED ARRAY UNDULATOR AT LOW TEMPERATURE*

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Abstract

The bulk high temperature superconductor staggered array undulator (Bulk HTSC SAU) has several advantages: such as strong magnetic field, potential of short period undulator, K value variability without gap control. In addition to these advantages, compared with the existing superconducting undulator, the Bulk HTSC SAU can be used near the electron beam because the undulator is expected to show good performance at 20 – 30 K. There should be, however, several problems to be solved for realizing the Bulk HTSC SAU. We planned to make new prototype with which we can make experiments under conditions similar to real device: such as high critical current density and strong magnetic field. We discussed the requirements of the prototype, the idea and the equipments to satisfy the requirements. We designed the new prototype and estimated the result expected to be obtained by it. Also, we designed new probe called 3D probe to obtain the current distribution in bulk HTSC.

INTRODUCTION

The bulk high temperature superconductor staggered array undulator (Bulk HTSC SAU) has several advantages of superconducting undulators: such as strong magnetic field, potential of short period undulator, K value variability without gap control. In addition to these advantages, compared with the existing undulators, the Bulk HTSC SAU can be used near the electron beam because the undulator is expected to show good performance at 20 – 30 K.

Figure 1 shows the schematic of the Bulk HTSC SAU. The white arrows indicate magnetization vectors of bulk HTSC magnets. The black arrows indicate undulator fields. All bulk HTSC magnets have the same direction of magnetization, thus, they can be magnetized by one external solenoid and generate undulator field. The amplitude of the undulator field can be varied by the solenoid current.

We have been developping the Bulk HTSC SAU after we proposed the concept at 2006 [1]. We made the proof of principle experiments with 1st prototype at 77 K (3 periods, 0.05 T solenoid, B_y probe) [2]. Then, we developed the undulator field calculation model by the experimental support with 2nd prototype (77K, 11 periods, 0.25 T solenoid, B_y, B_z probe) [3]. The model based on

Bean model [4] of type II superconductor is called "the loop current model". The loop current model can calculate the undulator field by using the critical current density J_c and the change of solenoid field ΔB_s as parameters. We made performance estimations of the undulator field with the high critical current densities at lower temperature [3]. As a consequence, we found that the Bulk HTSC SAU can achieve $K = 1$, for example, with the period of 9 mm, the gap of 3 mm, and J_c of 3.5 kA/mm². This value of J_c can be achieved at 20 - 30 K with bulk HTSC of GdBaCuO. We concluded that the Bulk HTSC SAU is a good candidate for a short period undulator.

We have, however, some problems to be considered (at low temperature and with strong magnetic field). Two problems arise from strong magnetic field. One problem arises from low temperature. A first problem is the large ununiformity of J_c (arises from strong magnetic field). J_c at a point depends strongly on B at the point. B in bulk HTSC is usually not uniform, the large variation of the field produce the large ununiformty of J_c. A second problem is the degradation of J_c arise from clacking of bulk HTSC. A third problem is the ununiformity of J_c arise from temperatrue variation at low temperature. At a low temperature, temperature variation opens up because of smallness of specific heat and thermal conductivity. In a real device of Bulk HTSC SAU, we will have to have been solved these problems.

Therefore, we planned to make the 3rd prototype to make experiments under the conditions similar to real
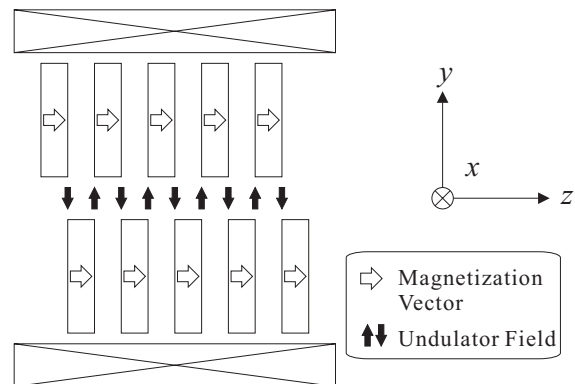

Figure 1: Schematic of the Bulk HTSC Staggered Array Undulator. The white arrows indicate magnetization vectors of bulk HTSC magnets. The black arrows indicate undulator fields. All bulk HTSC magnets can be magnetized by external solenoid and generate undulator field. The amplitude of the undulator field can be varied by the solenoid current.
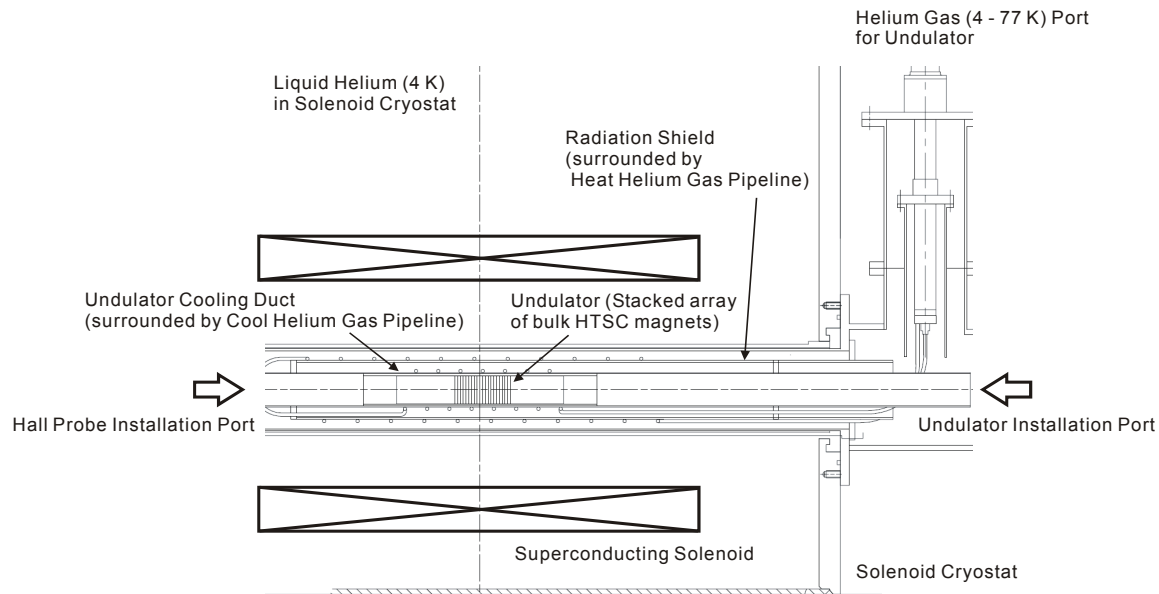
Figure 2: Schematic of the third prototype. The bulk HTSC magnets are located in the undulator cooling duct. The helium gas in pipeline is used to cool the undulator cooling duct firstly, and the heated gas is also used to cool the radiation shield in the vacuum chamber. The temperature of the solenoid cryostat and it of the undulator cooling duct are controlled independently. For the flexibility of the experiment, the undulator installation port and the hall probe installation port is located at each side of the vacuum chamber. The specification is in Table 1.

device ($K = 1$ and low temperature). Moreover, we need new calculation model include the ununiformity of J_c. Therefore, we planned to make the 3D probe to measure the field distribution in 3D space near the surface of a few bulk HTSCs to know the current distribution in them.

In this paper, we will clarify the requirements for the 3rd prototype, kick around the ideas to satisfy the requirements, and show the design of the 3rd prototype. Also, we will show the design of the 3D probe. The performance estimation to decide the specifications of 3rd prototype is showed at the end of this paper.

DESIGN OF NEW PROTOTYPE

We set the requirements for the 3rd prototype:

- The temperature of bulk HTSC magnets can be controlled from 4.2 K to 77 K.
- The K value should be close to 1.
- The undulator can be easily installed in and removed from the vacuum chamber.
- The magnetic field on the surface of the single or a few bulk HTSC magnets can be measured in 3D space.

In the following section, we circumstantially will discuss these requirements, the method and the equipment to satisfy the requirements. Figure 2 shows the schematic of the 3rd prototype.

The critical current density of the bulk HTSC magnet is strongly depends on the temperature of it. To realize temperature controlling, we employed two methods. First, we separated the helium pipeline for the cooling duct from that for the superconducting solenoid coil. Second,

we used not liquid helium but helium gas in the pipeline for bulk HTSC magnets. The temperature of the cooling duct is measured by thermometer. The flow rate of the helium gas is controlled to keep the temperature constant.

To achieve $K = 1$, we roughly estimated the undulator field in the new prototype by our calculation code. The estimated result will be discussed later. From the result, we found that the temperature of 4.2 K and the solenoid

Table 1: Specification of 3rd prototype

Undulator	
Period, λ_u	5 – 10 mm
Periodic number, N	16 (λ_u = 5 mm),
	8 (λ_u = 10 mm),
Gap, g	4 mm
Expected field, B_y	1 T (λ_u = 10 mm, J_c = 10 kA)
Superconducting solenoid	
Solenoid field, B_z	- 2 ~ +2 T
B_z flatness	< 2% (-40 ≤ z [mm] ≤ 40,
	-30 ≤ r [mm] ≤ 30)
Bore	70 mm
Cooling duct & Vacuum chamber	
ID / OD of cooling duct	29.2 / 33.2 mm
Temperature	4 – 77 K

field from -2T to 2T is enough to achieve $K = 1$
the smaller bulk HTSC magnets than that we e⟨
be used in real device.

Accessibility to the undulator is important
efficient experiment. High accessibility enab
make experiments in various conditions and to ⟨
order of bulk HTSC magnets in a short time
correction. To achieve high accessibility we l⟨
undulator installation port and the hall probe i⟨
port at each side of the vacuum chamber.

The magnetic field in 3D space near the surf⟨
bulk HTSC magnet is crucial information to
current density distribution in the bulk HTSC
Detailed current density distribution can im⟨
calculation model of the undulator field. In the
prototype, we could observe the magnetic field ⟨
the beam line of the prototype. We have been d
the 3D probe and sample holder. The detail of
probe is described in the following section.

From these discussions, we designed the 3rd
Table 1 shows the specification of the 3rd prototy⟨

DESIGN OF 3D PROBE

The field distribution on the surface of the bulk HTSC
magnets is helpful information to know the distribution of
current density in bulk HTSC magnets. With the current
distribution, we can develop the more precise numerical
model for undulator field calculation.

Figure 3 shows a concept of the 3D field distribution
measurement by the 3D probe. With this system, we can
make a measurement of B_z field distribution in 3D space,
in addition to the normal B_y, B_z measurement along z axis.
The 3D probe and the copper sample holder are in the
undulator cooling duct. One or two bulk HTSC magnets
are cooled down through the copper holder and
magnetized by the superconducting solenoid. The probe
consists of the two substrates: the substrate for Hall IC
and the substrate for AD converter IC. On the former
substrate, there are 24 Hall ICs located concentrically
with different radii. The outputted Hall voltages are
proportional to the magnetic field Bz at each IC's place (r,
q, z), and they are converted to digital data in each
channel of AD converter and transmitted to PC by serial
cable. The probe can be rotated in xy plane and moved
along z-axis, thus, we can measure the field in 3D space.
By changing the sample holder of bulk HTSC magnets,
we can measure the field of various configurations, such
as a single bulk HTSC magnet, hybrid structure with
ferromagnetic pieces, and so on.

Table 2 shows the specification of 3D probe at room
temperature (25°C). The Hall IC is used in constant current
mode. Because the low temperature of the cooling duct
affects the characteristics of the probe, we will make tests
at low temperature and investigate the temperature
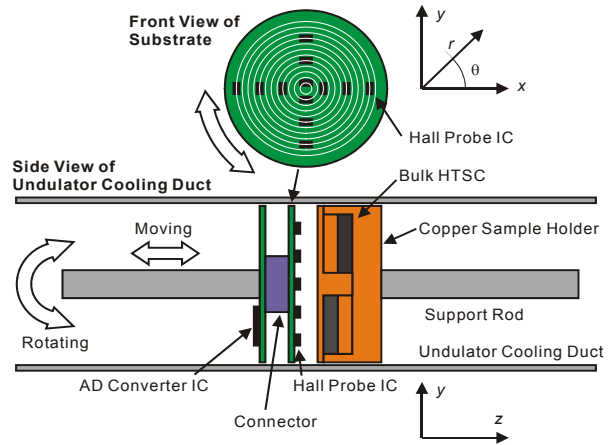dependency of the probe by thermal diode.

Figure 3: Concept of 3D probe. The probe is consists of
many Hall ICs located concentrically with different radii.
The z-component of magnetic field B_z generated by one
or two bulk HTSCs is measured by the movable and
rotatable probe in 3D space (r, θ, z).

Table 2: Specification of 3D probe at RT (25°C)

Measureable range	$1 \leq r$ [mm] ≤ 12.5,
	$0 \leq \theta$ [°] ≤ 360
Resolution	r: 0.5 mm,
	θ: < 0.5°
Distance from surface of bulk HTSC (z-direction)	≥ 2 mm
Resolution (z-direction)	12 μm
Hall probe IC	Asahi Kasei Microdevices HG-0111
	8 ICs in series x 3 (24 ICs)
AD converter	Analog Devices AD7708
	16 bit 10 Channel x 3
Field range	1 – 18 T with 0.3 mT step
	0 – 1 T with 0.06 mT step
Temperature sensor	Thermal diode

PERFORMANCE ESTIMATION OF 3RD PROTOTYPE

To estimate the undulator field expected in the 3rd
prototype, we made undulator field calculation by the
loop current model. Figure 4 shows the calculated
magnetic field B_y along z axis in the prototype. In the
calculation, the period is 10 mm, the gap is 4 mm, the
number of period is 8, and the critical current densities are
3.5 and 10 kA/mm^2. These values of the critical current

densities are expected to be obtained at 20 – 30 K and 4.2 K, respectively. At 10 kA/mm^2, we can achieve $K = 1$. Even at 3.5 kA/mm^2, we can accomplish a purpose, making experiments under conditions similar to real device.
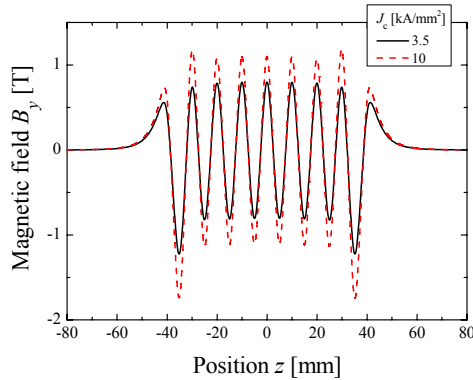

Figure 4: Expected undulator field in the 3rd prototype. In the calculation, the period is 10 mm, the gap is 4 mm, the number of period is 8, and the critical current densities are 3.5 and 10 kA/mm^2 for the black solid line and for red dashed line, respectively.

CONCLUSION

We had performed the experiment with the 1st and the 2nd prototype for the proof of principle experiment and the data taking for the numerical model development. In this paper, we designed the 3rd prototype to solve the problems to realize the Bulk HTSC SAU. We discussed the requirements for the 3rd prototype, the methods and the equipments to satisfy the requirements. We found:

- The temperature of bulk HTSC magnets can be controlled from 4.2 K to 77 K by the helium gas pipeline which independent from the liquid helium pipeline for the superconducting solenoid. Therefore, we can make experiments with various critical current densities of bulk HTSC magnets.

- The K value of the prototype can be reached to 1 with small bulk HTSC magnets, thus, we can make experiments under conditions similar to real device.

- The magnetic field on the surface of the single or a few bulk HTSC magnets can be measured in 3D space by using 3D probe. The result should be helpful information to develop precise numerical model to calculate the undulator field.

Therefore, we concluded that we have successfully designed the 3rd prototype.

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