END FIELD TERMINATION FOR BULK HTSC STAGGERED ARRAY UNDULATOR*

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Abstract

Aiming at realizing a short period undulator with strong magnetic field, we have proposed a Bulk HTSC (High Temperature SuperConductor) Staggered Array Undulator which consists of Bulk HTSC magnets with a staggered array configuration [1]. The experiment with the prototype undulator at 77 K shows this configuration can be applicable to real device [2, 3]. We also estimated the magnetic performance of real devices by calculations with a loop current model based on Bean model of type II superconductor [4]. In these experiments, the magnetic field in the ends of the prototype were larger than the field in the center area. End field termination is required for practical use. To suppress the larger magnetic field for end field termination, we performed the calculations and the prototype experiments with the large end gap method. We concluded that the method is effective for Bulk HTSC Staggered Array Undulator.

INTRODUCTION

Short period undulators bring in several advantages, i.e. short lengths FEL with low electron beam energy, and high gain with same undulator length. To achieve short period undulator with the same *K* value, we have to generate strong undulator field. There are two main way to obtain strong undulator field. One is the undulator with low temperature superconductor wires. Another is the In-vacuum undulator. However, the superconducting wires have to be cooled down near liquid helium temperature (4.2 K) with potentially large thermal load from the electron beam or radiation. The permanent magnets have been used for a long time, thus, the drastic improvement was not reported for a long time.

Bulk HTSC magnets are promising for the following reasons. Recent research progress reported that a YBaCuO bulk (26.5 mm dia.) trapped the magnetic field of 17 Tesla at 29 K [5]. Moreover Bulk HTSC magnets can be used at a temperature much above liquid He temperature. Therefore, present compact refrigerator systems make it possible for the Bulk HTSC magnets to be used near the beam line.

We proposed Bulk HTSC Staggred Array Undulator which consists of the Bulk HTSC magnets with staggered array configuration [3]. Figure 1 shows the schematic of the undulator. It has Bulk HTSC magnets with the magnetization direction to *z*. The proof of principle experiment was performed in the 3 periods and 11 periods prototype at 77 K. The undulator field was successfully generated by Bulk HTSC magnets which magnetized by the external solenoid, and the amplitude was controlled by the solenoid current [2]. We also estimated the magnetic performance of real devices by calculations with a loop current model based on Bean model of type II superconductor [3].

For the practical use, we have to consider the RMS error and 1st and 2nd integrals of the magnetic field to avoid the effect of the magnetic field on the radiation and the electron beam trajectory. In the prototype experiment, there were larger magnetic fields in the both ends of the undulator. We have investigated the large end gap method to suppress the larger magnetic field in the end of the undulator.

In this paper, we reported the methodology, the calculation results and the experiment results of the large end gap method for the end field termination.

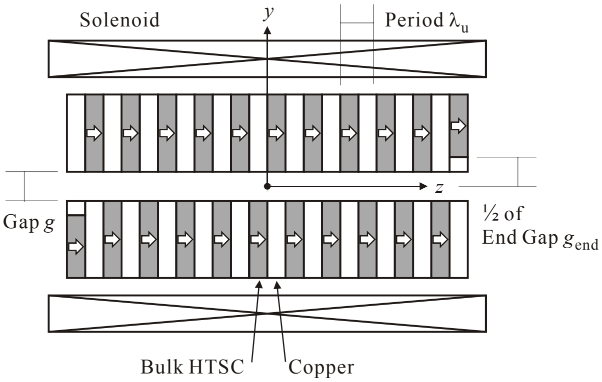

Figure 1: Schematic of the Bulk HTSC Staggered Array Undulator. The Bulk HTSC magnets which have the magnetization of *z* direction generate the undulator field. The Bulk HTSC magnets are magnetized by the external solenoid. The end gap is larger than the gap of the center area.

METHOD

The Bulk HTSC magnet generates the magnetic field by loop current. We are using the Bulk HTSC in unsaturated region. This means: the current flows in a part of the Bulk HTSC magnet; the intensity of the magnetization is not simply decided by the size of magnet, is decided by the current density and the volume of current flowing; the volume is decided by the change of the external field applied to the Bulk HTSC magnet after it changed to superconducting state [3]. Thus, we proposed the large gap method which keeps the currents away from the beam line.

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We performed the magnetic field calculations of the large end gap configuration (see Fig. 1). We used our original magnetic field calculation code of the loop current model based on Bean model. In the calculation, we assumed following. The solenoid field was changed from 0 mT to -27.4 mT to magnetize the Bulk HTSC magnets. The critical current densities of all the Bulk HTSC are the same and 200 A/mm^2. This value is from the measured data of GdBaCuO superconductor which is used in the prototype.

We also performed the experiment with the 11 periods prototype with the gap g of 4 mm and period λ_u of 5 mm and the magnet size of 10.6 mm in y direction. It has the cooling system of liquid nitrogen temperature (77 K), the solenoid of 0.25 T, and the magnetic field measurement system. The magnetic field measurement system consists of the two hall probes of y and z direction mounted on the linear transfer rod. The solenoid field was changed from 0 mT to -27.4 mT.

RESULT AND DISCUSSION

Calculation result

Figure 2 shows the calculated magnetic field B_y in the 11 periods prototype. The black solid line indicates the field with the end gap g_y of 4 mm (same with the gap g). The blue dotted line and the red dashed line indicate the field with the end gap g_y of 8 mm and 12 mm. The 1st and 2nd peak of the left end were successfully suppressed. The 3rd peak became larger than other peaks near the center area. The 4th peak became smaller than the other peaks. To compensate the effects on the 3rd and 4th peak, combinations of the various large gap magnets is needed.

Table 1 shows each peak's height in units of central peak's height with each value of end gap g_{end}. The end gap g_{end} of 8 mm was preferable. Because it let the 2nd peak be reduced by one-thirds and kept the 3rd peak smaller than 2nd peak.

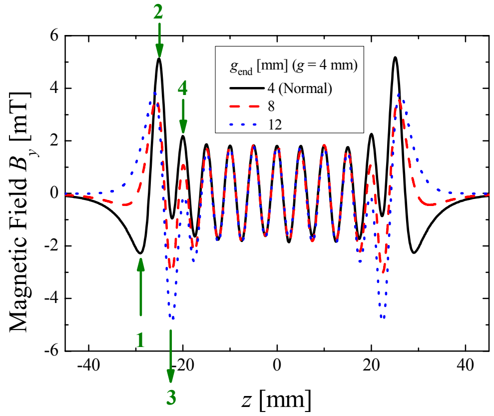

Figure 2: Calculated magnetic field B_y along z axis in the 11 periods prototype with the g_{end} of 4, 8 and 12 mm. The 1st and 2nd peak were successfully suppressed. The 3rd peak became larger than other peaks in the center. The 4th peak became smaller than the other peaks.

Table 1: Peak's heights in units of central peak's height

g_{end} [mm]	1st	2nd	3rd
4	1.3	2.9	0.54
6	0.85	2.2	1.2
8	0.25	2.0	1.7
10	0.082	2.0	2.3
12	0.0036	2.2	2.8

From these calculations, we found that the large end gap method is the promising way to suppress the larger field in the ends. It is needed for the end field termination of Bulk HTSC Staggered Array Undulator.

Experimental result

From the calculation result, the end gap g_{end} of 8 mm was preferred to suppress the larger field in the end of the undulator. We installed two small Bulk HTSC magnets in the both ends of our prototype instead of normal size ones.

Figure 3 shows the measured magnetic field B_y along z axis in the 11 periods prototype with the end gap g_{end} of 4 and 8 mm. The 1st, 2nd and 4th peak display similar behaviour with that in the calculation. The 3rd peak became larger than anticipated. Left-right asymmetry to z = 0 is due to the individual difference of current density of each Bulk HTSC magnet.

From this result, it was proved that the large end gap method is the effective way to suppress the larger field in the end. Moreover, for the accurate measuring to advance the large end gap method and achieve the end field termination, we need to introduce shims or some ordering methods and need to consider the RMS error and 1st and 2nd integrals of the magnetic field.

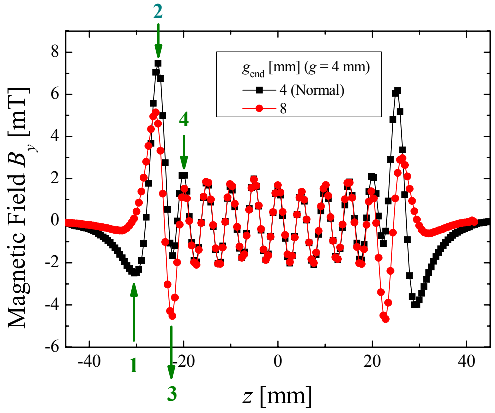

Figure 3: Measured magnetic field B_y along z axis in the 11 periods prototype with the g_{end} of 4 and 8 mm. The 1st, 2nd and 4th peak display similar behaviour with that in the calculation. The 3rd peak became larger than anticipated. Left-right asymmetry to z = 0 is due to the individual difference of current density of each Bulk HTSC.

Comparison between calculation result and experiment result

Figure 4 shows the comparison between the calculation result and the experiment result with the end gap g_{end} of 8 mm. There was a big difference between the calculated result and the measured result. The calculation with the loop current model did not reproduce the magnetic field in the both ends of the prototype.

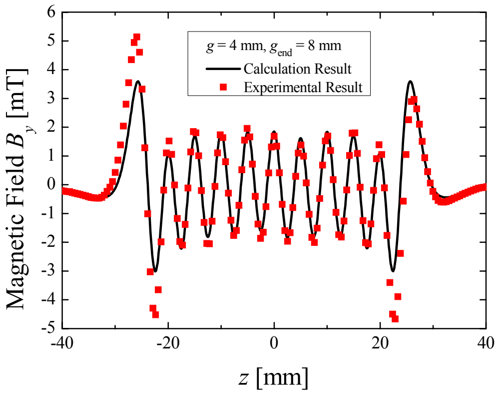

Figure 4: Comparison between the calculation result and the experiment result with g_{end} of 8 mm. There was a big difference between the calculated result and the measured result. The loop current model did not reproduce the magnetic field in the both ends of the prototype.

There are two main reasons of this difference between experiment result and calculation result with the loop current model. First, the model assumed that the magnetization vectors of all Bulk HTSC magnets have only z component. Figure 1 shows that the distances between the z axis and the centers of the Bulk HTSC magnets are different by associating with size. It is obvious that the small magnets of both ends and the magnets near them have not only z components but also y components. Second, the model assumed the same critical current densities of all Bulk HTSC magnets. Actually Bulk HTSCs have individual difference in their critical current densities. This is not a big problem to calculate the magnetic field in the center area. The difference of the critical current density of the each magnet is compensated by a field penetration depth of each magnet [3]. Since the all magnets have close strengths of magnetizations. However, this is a big problem in the end areas. Not only the strengths of the magnetizations but also the field penetration depths affect the magnetic field on the z axis. The small capacities of the field penetration depths of the small magnets affect additionally.

To advance the large gap method for end field termination, the more accurate numerical model than the loop current model is required. The model is needs to include the magnetization vector with y component and the critical current density of each Bulk HTSC magnet.

CONCLUSION

To investigate the methods for the end field termination of Bulk HTSC Staggered Array Undulator, we performed the calculations and the experiments. The calculation was performed by the loop current model based on Bean model. We investigated the large end gap method for Bulk HTSC Staggered Array Undulator. As a result, we found that the method is promising to suppress the larger magnetic fields in the ends of the undulator than the field in the center area. We also performed the experiment with the 11 periods prototype. As a result, we proved that the large end gap method is effective to suppress the big fields in the ends of the undulator. The calculation with the loop current model reproduced behaviour of the magnetic field well, though there still were big differences in the amplitude of the field in the ends of the undulator. To investigate the large gap method more precisely for end field termination, the more accurate numerical model than the loop current model is required.

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