THE STRONGEST PERMANENT DIPOLE MAGNET

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Abstract

The authors have been developing very strong permanent magnets. In the past, our magnets could generate a 4.45 Tesla dipole field. We are now in a process of reaching much higher fields by a special magnetic circuit. We will present our latest results of the strongest permanent dipole magnet ever built.

INTRODUCTION

An everlasting desire of magnet builder is to pursue to produce a magnetic field strength as high as possible. The strongest manmade magnetic field must be the one made by Terawatt level of Laser. It is an equivalent magnetic field. Duration of the field is short as the laser pulse. One of the author(Kumada) proposed the magnetic field can be used as a Laser wiggler for a compact X ray Laser FEL but has not been constructed. A very strong magnetic field is generated by flux compression mechanism by theta pinch plasma or metallic cylinder by implosion but they are single shot and destructive. A rather practical strongest field must be the one by hybrid magnet where it is made of a combination of a superconducting magnet and a pulsed magnet. Again the duration of pulse is not very long as the pulsed magnet is made of copper conductor.

The field strength of permanent magnet is rather modest compared with those magnets. Residual field strength of the strongest permanent magnet material is at a level of 1.3 Tesla. And in most cases, the magnetic field strength made by these materials is half of the residual field. But using the permanent magnet is still attractive as it provides us almost eternal field without energy consumption. The permanent magnet is especially attractive to the application of small gap size magnet or magnet having short period. Successful applications to a wiggler or undulator are widely accepted.

Extensive efforts to get higher field with wiggler of undulator with permanent magnet have been made. By using permendur, which is a material of high saturation field, 3 Tesla field was achieved at SPRING 8 by a group of University of Tokyo. The working mechanism of the undulator is due to Halbach. The field strength of this magnet is stronger than the residual field. Halbach had invented a novel magnetic circuit of Rare Earth Cobalt(REC) magnet where the maximum increase can be factor of 2 for the case of his REC quadrupole magnet.

Then a motivation of designing a medical accelerator as compact as possible one of the authors (Kumada) then invented an extended Halbach dipole magnet. A concept of saturated iron and flux compression is developed. Dipole magnet is designed and constructed. A method of increasing the field by cooling the magnet is also shown to work. World record of 4.45 T in 8 mm gap was reached in this way[1,2,3,4]. The increase of the field can also be applied to the permanent multipole magnets. Straight application is to a final focus quadrupole of the linear collider[5,6].

Encouraged by the result of the 4.45 T dipole the authors proposed a project of permanent magnet based cyclotron and got a grant from Japan Science Technology. The magnet consists of hill and valley. The maximum field of the hill is about 2.2 T and the average field is 1.4 T. A new concept of flux compression is invented in it. The details with full of new ideas will be presented in a forthcoming 18-th Magnet technology conference (MT18) in Japan this fall.

Cugart and Block of ESRF of Grenoble broke this record shortly. They recorded a 5 Tesla inside a tiny gap of 0.15mm[7].

Applying similar magnetic compression scheme of the cyclotron magnet, we have designed and manufactured a 6 T dipole magnet. While we broke the new record again, we only reached 5.16 T with a gap height of 2mm where a Grenoble group reached 5 T with a gap height of 0.15mm. In this paper, we will present our data of 5.16 T dipole magnet in more detail.

SIX TESLA PERMANENT MAGNET DIPOLE

To go beyond 5 T, we took a different approach from a previous 4.45 T dipole magnet. In the previous design, we had an extended Halbach type magnetic circuit. To increase the field strength than this, one either need to make the gap small as possible or has to make outer size as large as possible. ESRF group took an approach of a small gap. It has a variable gap length and 5 Tesla was reached with a very small gap of only 0.15 mm. In extended Halbach type magnet, to make a small gap is mechanically difficult. Its assembling accuracy is poor too. This time, we took a small gap approach and chose a magnetic circuit as shown in Fig. 1 and Fig. 2. It is a combination of Halbach type and our flux compression type magnet. Although its effect is not much, we used a permendur as a central pole this time. Permanent magnets surround the pole. Direction of permanent magnet blocks are directing to the centre in order to compress flux[8]. In Table 1, parameters of this magnet are shown.

Three kinds of material are used. The photos of the magnet are shown in Fig. 3. The small radius permendur rod is inserted vertically. As the plots of B vector shows in Fig. 4 and Fig. 5, field direction changes in a middle of the vertical location in the permendur pole as shown in Fig. 6. This shows that the permendur is not used properly. This choice is accepted in the design as its effect is small.

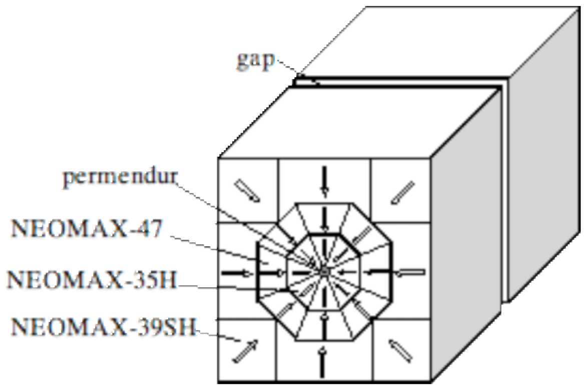

Fig. 1 6 T magnet cut out view.

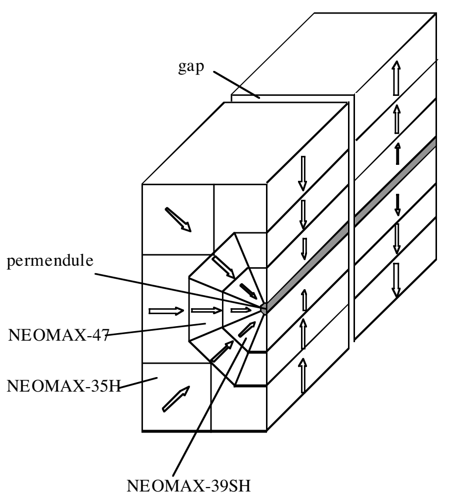

Fig. 2 Cut-out view of the 6 Tesla magnet showing magnetization directions inside.

Fig. 3 Photos of the 6 Tesla magnets

Table 1 Specification of the 6 Tesla magnets

Central field strength (T)	
Calculated	6.29 (g=2mm)
Measured	5.16 (g=2mm)
Variable gap size g (mm)	2,5,10
Outer dimension (magnetic part (mm^3))	340x340x390
Weight of the magnet material (kg)	340
Outer dimension (with supporting structure (mm^3)	570x570x490
Total weight(with supporting structure (mm^3))	900

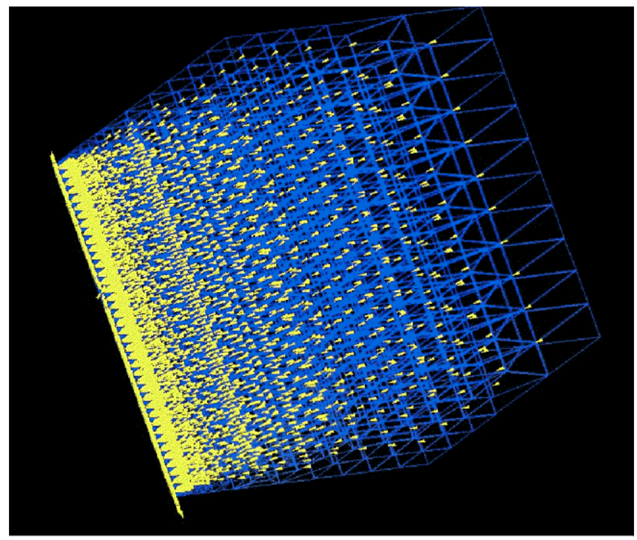

Fig. 4 Plot of B vector inside magnet.

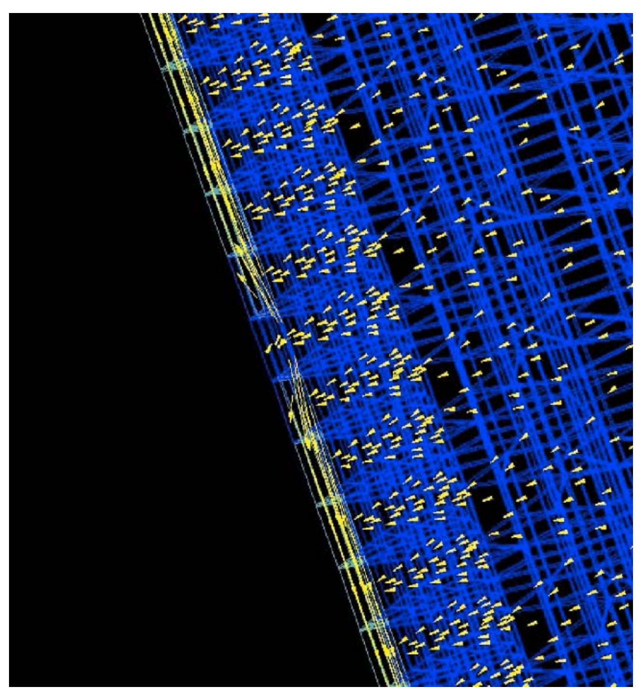

Fig. 5 Enlarged view of the centre of a permendur pole.

Although we have reached the world strongest field strength of 5.16 Tesla in the aperture of 2 mm by a permanent magnet, the design field of 6 Tesla could not be reached. The reason is under investigation. The higher field could be reached by reducing the gap when thinner magnetic sensor is available. Fig. 7 shows the comparison of the calculation and the measurement. The discrepancy between them become larger as the field increases. To see the reason of discrepancy between the calculation and the measurement, Fig. 8 was plotted at a relatively low field level of 3.7 Tesla. The field distribution of the measurement shows a broader distribution than that of the calculation. This indicates an important feature is missing in the calculation model. Understanding the mechanism of the discrepancy may lead us to go one step beyond.

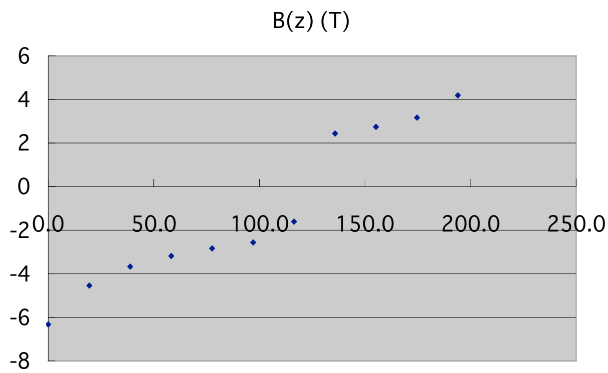

Fig. 6 Field distribution inside the permendur pole on a vertical direction

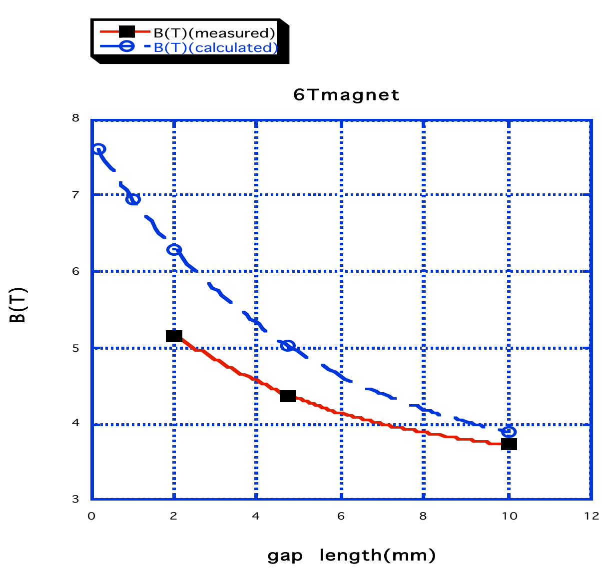

Fig. 7 Comparison of field strength between those of computation and measurement.

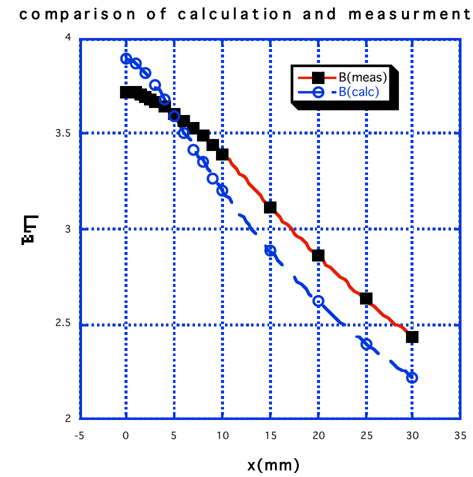

Fig. 8 Comparison of a field distribution between that of calculation and measurement.

CONCLUSION

We have achieved the world strongest magnetic field of 5.16 Tesla in a 2 mm gap in a permanent dipole magnet at a room temperature. The designed field value of 6.29 Tesla could not be reached. There is still an indication that an important feature is missing in a design of the magnet.

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