

THREE TESLA MAGNET-IN-MAGNET

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Abstract

A strong field as high as 3 Tesla with little saturation effect is possible in a design of "Magnet-in-Magnet" concept. This concept was introduced originally in a Snowmass2001 with a motivation to increase the field strength of the Pipetron magnet for VLHC but applicable to many situations beside superconducting magnet. Small model magnet was constructed and tested to demonstrate its validity of the concept. Field distribution for different excitation levels are presented.

1 INTRODUCTION

Permanent magnet (PM) has been applied in an accelerator field mostly as undulator/wiggler in a storage ring. There is a myth about PM. They are: The field strength is weak compared to electro-magnet and superconducting magnet. This is because in most cases working point of material is less than half of a residual field B_r where it is 1.2 Tesla for the strongest material of NEOMAX and 0.4 Tesla or so for the ferrite material. PM is only good at small aperture magnet like undulator/wiggler. PM is unstable as magnetization strength depends upon temperature level of a few parts in thousand. Uncontrollable variation of strength of magnetization is a few percent and a high homogeneity required from accelerator performance is difficult.

Recently at Fermilab, large quantity of ferrite magnet was applied to an 8 GeV antiproton storage ring [1]. They made a remarkable progress in PM technology. They have found a solution of the temperature stability problem and homogeneity problem. The field strength of the Recycler PM is only 1.5 kG or so, which is again about 1/3 of a ferrite material's B_r . The strong PM magnet is challenged for Wiggler magnet. 3 Tesla Permanent magnets is so far the strongest [2]. The structure of this PM is the one proposed by K.Halbach where a combination of iron and PM magnet. This configuration can be extended to a circular type dipole magnet. We found out that when the iron pole is driven into a saturated level, the field strength inside the dipole gap is further enhanced [3].

It was found that lowering a temperature of the magnet has a great advantage in increasing the magnetization strength. DC PM can be used for cyclotron or FFAG (Fixed Field Alternating Gradient) accelerator for accelerating charged particle. There is an additional advantage that if a PM magnet can be converted to

variable field magnet. K.Halbach gave an idea of varying field magnet. It is a layered ring magnet where outer ring rotates around the centre of the ring. To avoid the inclination of a magnetic median plane, the iron pole is used. One of the authors made a highest gradient (250T/m) Quadrupole this way in 1985[4]. Another method of varying field is to combine two PM located at axial positions, which was patented by R.F.Holsinger. There is a commercially available varying field dipole magnet on the market called MULTIMAG magnet (Magnetic Solutions Ltd). We have developed our own way of two-layer ring magnet. There is a need in a high gradient Quadrupole magnet in a final focus lens of a linear collider. The final focus magnet system where considerable amount of variation of field gradient is required is placed in a huge detector but an available space for the magnet is limited. Ingenious way of mechanical rotation must be invented. We started a project working on this problem [8]. Beside mechanical methods, we propose that a combination of PM magnet with electro-magnet or superconducting magnet as a promising method [8] when field level is around 3 Tesla. We call this type of magnet as "Magnet-in-Magnet". Small model of "Magnet-in-Magnet" is constructed and its quality is inspected. We think there is a possibility of constructing a 3 Tesla "Magnet-in-Magnet" of 30 mm vertical aperture by a reasonable size. This could be applied to a compact synchrotron for medical application or a compact and economic synchrotron radiation ring.

2 MAGNET-IN-MAGNET CONCEPT

The concept of "Magnet-in-Magnet" is introduced first time at the Snowmass01 workshop [7] as an attempt to increase the field strength of the "super" economic superconducting circular collider of the first phase of "VLHC" by factor 2. The magnet is called a transmission line magnet as it is analogous to a coaxial line. This is composed of a single superconducting line sandwiched by two iron blocks. Two gaps are provided. The maximum magnetic fields of 2 Tesla of both signs are generated at both gaps. Due to a balance of the cancelled magnetic forces between the two magnets, the mechanical structure can be simple compared to a conventional superconducting magnet and a "super" great cost reduction is expected. The maximum field strength can not exceed, however, 2 Tesla due to a saturation effect of the iron. A gap size of the magnet is small as 30 mm or so

as the beam size is small at such high energy. With such a small aperture permanent magnet of 1.5 to 2 Tesla could be compact too. A permeability of a rare earth magnet such as SmCo or NdFeB is about 1.05 and a linear superposition of the magnetic field of the permanent magnet to the superconducting magnet is possible. In this way, the magnetic field of a transmission line magnet could be enhanced by roughly factor two without introducing a saturation effect. In Fig.1, a sketch of a cross section of this concept is shown. We call this type of magnet “Magnet-in-Magnet”.

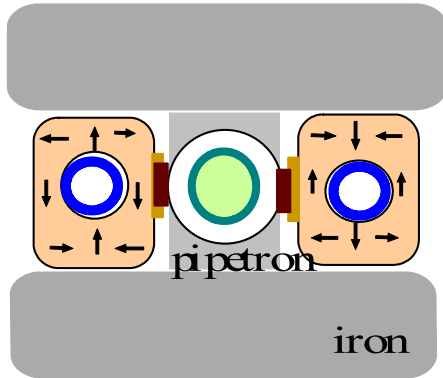


Figure 1. Cross section of conceptual “Magnet-in-Magnet” for VLHC.

3 VARIATION OF MAGNET-IN-MAGNET

There could be variations in “Magnet-in-Magnet”. The simple one is a transverse “Magnet-in-Magnet” with electromagnet. This is shown in Figure 2. The extended Halbach permanent dipole magnet is placed in an electromagnet. The field could be varied from 0 to 3.2 Tesla with bipolar power supply.

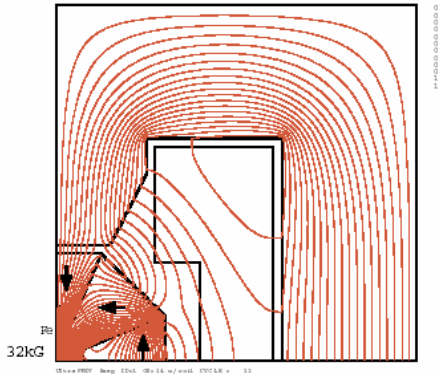


Figure 2. 3.2 Tesla transverse “Magnet-in-Magnet”

Alternative one is a longitudinal “Magnet-in-Magnet”[10]. In this case, permanent magnet and electromagnet are located repeatedly in a longitudinal direction (beam’s direction) as shown in Figure 3.. The average field strength is lower than that of the transverse one but it has an advantage that the gap size of the electromagnet can be smaller.

The permanent magnet is made of blocks of finite dimension. The field of electromagnet is regarded as an

external AC magnet. This external magnet induces the eddy current in the permanent magnet blocks. Preliminary estimation by a computer code Mermaid[11] assures its effect is negligible for a frequency of 20 Hz.

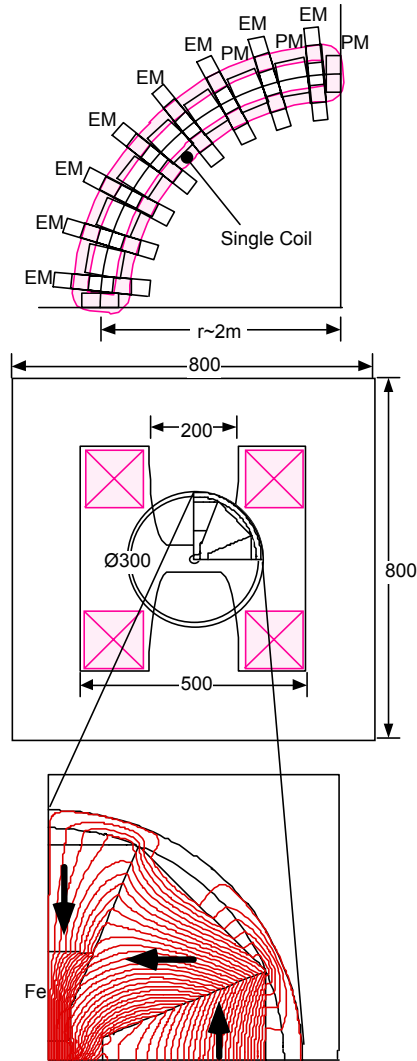


Figure 3. Longitudinal Magnet-in-Magnet (bird view).EM:Electro magnet. PM:permanent magnet.

4 MODEL MAGNET TEST

For a proof of principle test, a small model “ Magnet-in-Magnet” were made. The permanent magnet is shown in Figure 4. The flux is squeezed from four horizontal directions. The permanent magnet is placed in an electrical magnet of the gap size of 2 mm x 9mm x 9mm. The horizontal distribution of the excitation dependence was shown in Figure 5 where the field was varied from 0 to 3 Tesla. Figure 6 shows positive sextupole exist at low field. It was found that initial hysteresis exists and demagnetization of about 2 kG was found as seen in Figure 7. Computer simulation by Mermaid shows this is because the permeability of the permanent magnet differs by 0.05 from the air.

A stability of the magnetic field of the permanent magnet was tested independently by a model permanent cyclotron magnet we are developing.

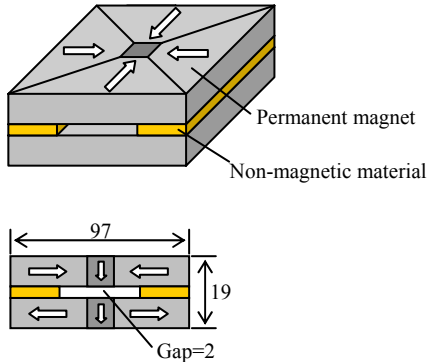


Figure 4. Model permanent magnet
Magnetic pole size is 9x9 and Gap size is 2(in mm).

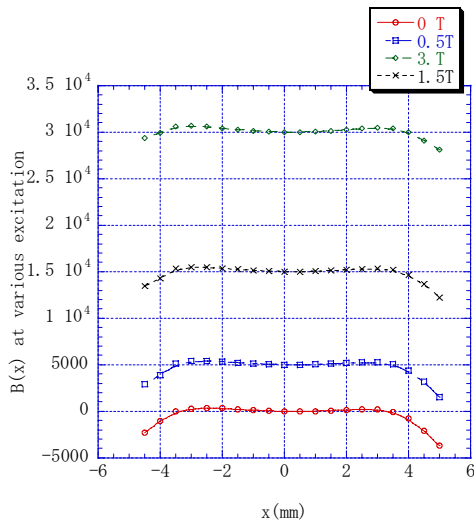


Figure 5. Field distribution from 0 to 3 Tesla.

We found out that passive temperature control by thermal insulation of the magnet from the air environment works quite well. A field stability of better than 0.01 % is possible by this method. With a temperature control further stability of an order of + - several ppm was confirmed for a couple of days. At this level of stability, we need to improve a NMR measurement system.

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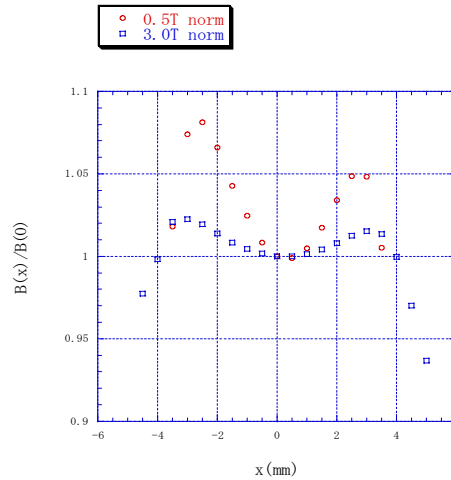


Figure 6. Field distribution at 0.5 Tesla and 3 Tesla.

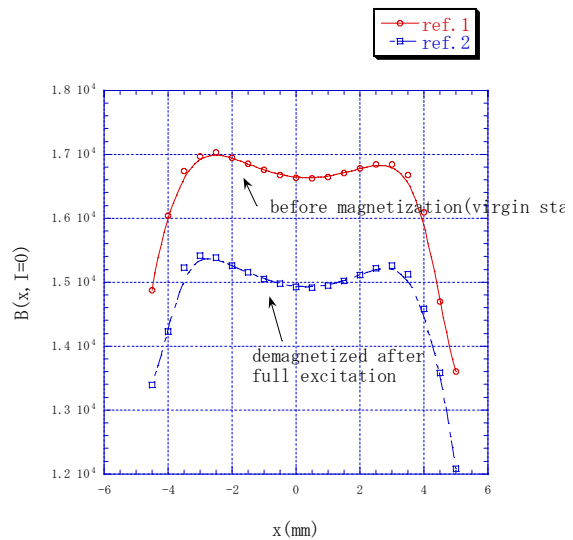


Figure 7. Demagnetization effect