ISSUES WITH PERMANENT MAGNETS

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Abstract

Various issues of a linear collider final focus system using permanent magnet quadrupole were discussed; temperature stability, radiation damage, incorporation of a vacuum system, variability of field strength, interaction with solenoid and finally an effort of stronger final focus magnet. Some of the issues may be solved and others are still open questions.

Details of variability of the permanent magnet and a new idea of temperature stabilization are presented by coauthors as separate papers.

1 TEMPERATURE STABILITY

Using NdFeB magnet is advantageous over SmCo magnet in strength and cost but disadvantageous in temperature stability and radiation hardness. Typical temperature coefficient of naked NdFeB is 0.11 % /degree Celsius. This stability of a raw material may be acceptable in an application of wiggler or undulator but 0.1 % variation is out of question in an application of the linear collider final focus quadrupole magnets.

Stabilization of the permanent magnet is possible by several methods, namely passive compensation and active compensation of the temperature variation of magnetic material.

Thermal insulation method is one of the passive compensation. Main contribution of a temperature change of a magnet comes from an ambient temperature of a time scale of a period of day. In case of an air conditioned environment, this temperature variation also come into effect. Thermal insulation greatly helps stabilization especially for a magnet of large heat capacity.

Variation of amplitude of the magnet material is considerably reduced by lowering a heat conduction to the material. This insulation technique is essential in Magnet Resonance Imaging(MRI) magnet.

Other clever method is to combine a permanent magnet material with different temperature coefficient. Foster et al. of Fermilab developed a method of using backup material of positive temperature coefficient to a permanent magnet material of negative temperature coefficient in a 8 GeV antiproton storage ring made of Ferrite permanent magnet. They had a successful result in passive temperature compensation.

One of our coauthors, E.A. Antokhin, proposed a passive compensation of different approach. He proposes to combine two permanent magnet of different temperature coefficient of the same sign, namely, SmCo and NdFeB. In this case, direction of magnetization of the compensator is opposite of that of the main magnet. Detail is described in a separate paper by him.

Both compensation above is categorized as a transverse compensation.

Y.Iwashita proposed a pair of magnet with different temperature coefficient of Focusing Quadrupole and Defocusing Quadrupole. In this case, one of the compensation magnet is made very thin. This is the case of a longitudinal compensation.

In either case of a scheme of using backup material, we lose an efficiency of magnet volume which is a tradeoff between stability and field strength.

In active temperature compensation, heaters are inserted in a magnet and feedback circuit is activated. We have installed the active feedback and thermal insulator to a 1/3 model cyclotron magnet made of NdFeB permanent magnet material of Sumitomo Special Metal Co.,Ltd. (SSMC) and monitored its stability in our institute. Fig.1 shows 1/3 scale model of permanent magnet circuit for 3 MeV cyclotron.

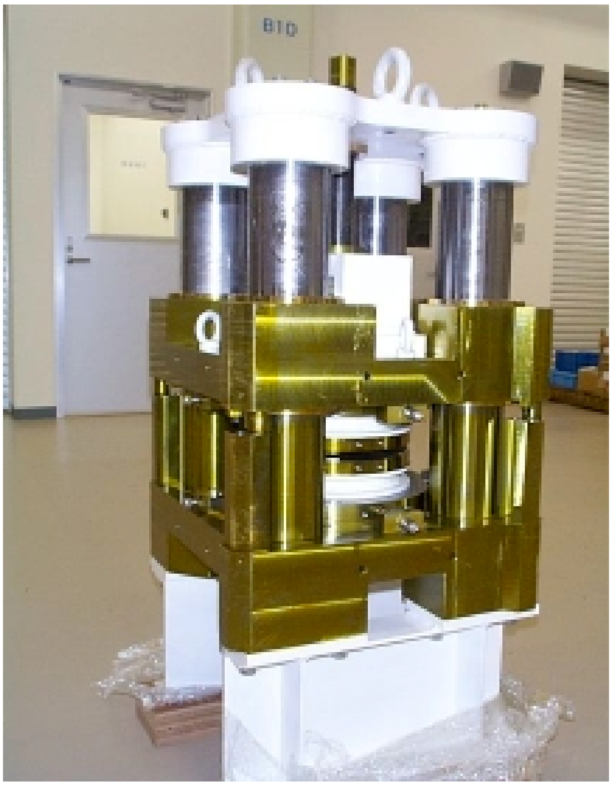

Fig. 1 1/3 scale model of permanent magnet for 3 MeV cyclotron.

The data of Fig. 2-4 is taken for about 6 days in summer in SSMC. Ambient temperature varied from 21.5 degree to 25 degree Celsius. Large variation of a temperature is due to an absence of thermal insulator on the first day. Then magnet is placed inside a simple thermal insulator box. Two separate curves in Fig. 3 are due to this setup change. The second curve shows a powerful effect of thermal insulation. The resolution of a temperature measurement is set to 0.01degree Celsius. Finally, with more careful thermal insulation and active feedback ON, we could achieve a field stability of as much as ± 10 ppm level as shown in Fig. 5

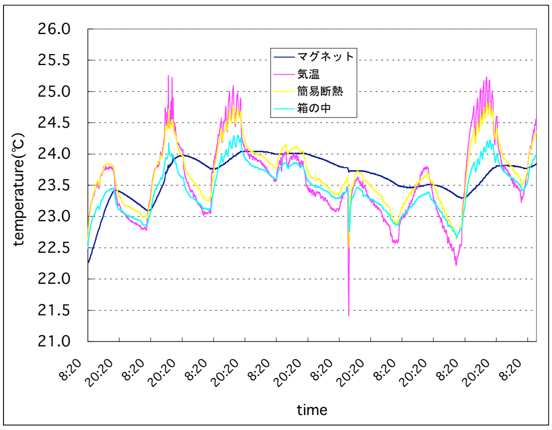

Fig. 2 Temperature variation of magnet, ambient temperature, insulated box A, insulated box B. Insulator was not installed on the first day.

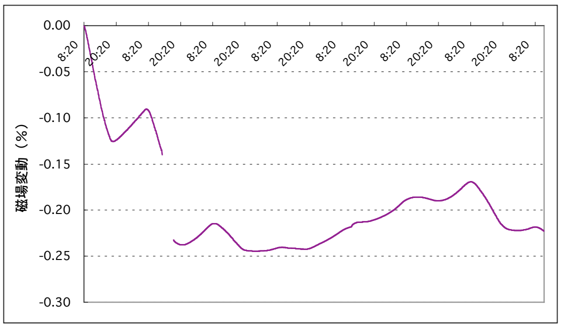

Fig. 3 Magnetic field variation of magnet.

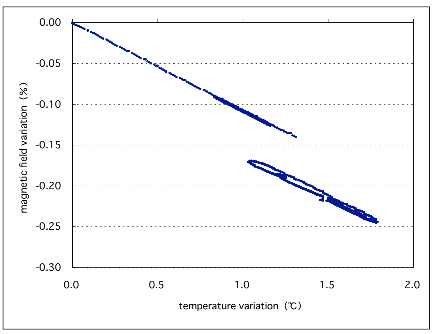

Fig. 4 Magnetic field vs. magnet temperature.

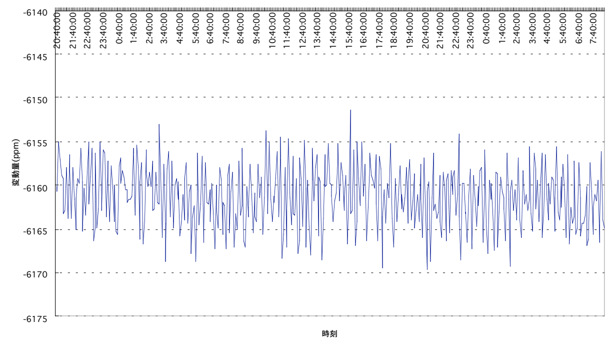

Fig. 5 Magnetic field variation vs. time. Vertical axis denotes field variation and horizontal axis denotes elapsed time. One division in vertical axis corresponds to 5 ppm.

2. RADIATION DAMAGE

Permanent magnet could be affected by a slight asymmetric heating up or degraded by an intense radiation. Asymmetric heating up of permanent Quadrupole from a radiation at the interaction point is a cause of magnetic axis offset. This issue is related to a thermal stabilization. As a requirement of a temperature regulation seems so severe, correction magnet of the magnetic axis may be a possible solution.

Regarding radiation damage, several experiments were performed. Y.Itoh of W-MAST reported a 20 % of degradation of NdFeB magnet (N32Z of Shin-Etsu Chemical Co., Ltd.) is caused by 23 kGy to 290 kGy by 200 MeV proton depending upon conditions[1]. Typical SmCo material of R26H of Shin-Etsu Chemical Co., Ltd. is much radiation resistant than N32Z.

T.Kawakubo made a study[2] using 12 GeV proton. Four different kind of NEOMAX, namely NEOMAX 47, NEOMAX 44H, NEOMAX 35EH, were irradiated. He concluded that no appreciable effect was detected for the material of NEOMAX 35EH of Sumitomo Special Metal (SSMC) up to 3 kGy where degradation is about 5%. 3kGy corresponds an extracted 12 GeV beam of 1.4 10^{18} protons per pulse at a possible location.

Choice of high H_{CJ} , intrinsic coercive force, is important for radiation resistance. This value measured in Oersted corresponds to zero intrinsic induction in the material after saturation. Note that H_{CJ} differs from H_C. Permanent magnets with high intrinsic coercive force are referred as "Hard" permanent magnets, which usually associated with high temperature stability too. In Fig. 6, H_{CJ} is plotted with H_C and B_r for different grade of NdFeB magnet (source data quoted from http://www.stanfordmagnets.com/magnet.html and edited by the author). It can be seen intrinsic coercive H_{ci} varies in a wide range for each material of the same energy product. The same property is plotted in Fig. 7. Intrinsic coercive force of N30EH and N28EH is the strongest in the table.

In Table 1, we show an interesting and attractive characteristic of NEOMAX of SSMC. Here B_r,H_c and H_{ci}

are shown in the table. Drastic increase, by factor 5, of the intrinsic coercive force H_{ci} is observed at Liquid Nitrogen(LqN) temperature. This feature indicates a possibility of higher radiation resistivity of a final focus quadrupole with a lower temperature operation by LqN.

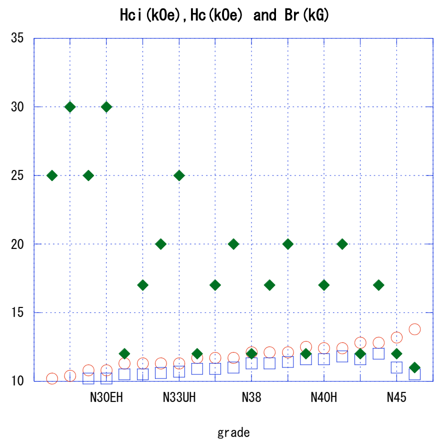

Fig. 6 Intrinsic coercive Hci (green diamond), coercive force Hc(red circle) and residual field Br (blue rectangle). Intrinsic coercive Hci varies in a wide range for each material of the same energy product.

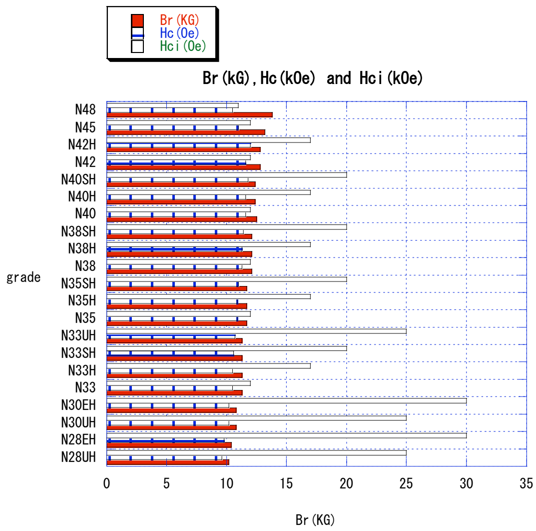

Fig. 7 Intrinsic coercive H_{ci} (green diamond), coercive force H_c(red circle) and residual field B_r.(blue rectangle).

3. VACUUM SYSTEM

Permanent magnet material is easy to be oxidized. To avoid it, various coating methods were developed in the past. Permanent magnet undulator were also installed in vacuum in various electron beam storage ring under a condition of ultra vacuum as good as 10^{-9} Torr[3]. Coating materials of Cu (10 μm), Ni (50 μm), Ti and Al (5 μm) are available on a market.

4. FIELD VARIABILITY

The first attempt of varying magnetic field was proposed by Holsinger. His idea was to install Halbach type magnet in a beam direction and combine magnets by transverse rotation. By that way, it is possible to change the magnetic field on a beam axis introducing skew component. Then, Halbach proposed a magnet combining iron pole and permanent magnet which is capable of azimuthal rotation in a transverse plane.

An European manufacture also developed a variable field PM magnet, although details are not published and seems to be protected by a patent.

Eventually, the author (Kumada) developed and submitted various patents of variable field permanent magnets. They are Magnet-in-Magnet(MiM) presented at snowmass 2001. In MiM permanent magnet and electromagnet are combined. In the original idea, they are combined in a transverse plane. Then longitudinal combination was proposed by the authors(Iwashita and Kumada). This concept will be used in a development of a compact synchrotron of medical use. The project of development of this MiM is funded and is started in October 2002 at NIRS/JST (Japan Science Technology).

Variable filed without resorting to MiM is also possible. We developed an idea of two layers Halbach type magnet. This is shown in Fig. 8 and Fig. 9. By having two independent knobs, it was shown to remove skew components while varying normal field component.

In a linear collider final beam delivery system, length of final quadrupole is quite long. Thus a longitudinal field variation is possible. For simplicity, a rotation angle of individual quadrupole magnet may be set to 90 degrees. Length of magnet could be varied as multiples of binary length. The rotation mechanism of 90 degrees is now under study by one of the author(Iwashita). This project,

Temperature (K)	B_r (T)	H_c (MAm^{-1})	$(BH)_{max}$ (kJm^{-3})	H_{cJ} (MAm^{-1})
5	1.52	1.17	429	6.18
77	1.45	1.08	396	5.43
296	12.5	0.91	295	1.13

Table 1. Temperature dependence of Intrinsic coercive H_{ci} coercive force H_c and residual field B_r. of Neomax-50CR.

“a development of super strong final quadrupole for linear collider” is funded and started in June 2002 as a 4 years project. Details is presented by Iwashita in a separate presentation.

5. INTERACTION WITH SOLENOID

This is an open question. The issues to be clarified are demagnetization of PM material and its possible decrease of the maximum attainable field gradient, availability of non-magnetic position controller of the final focus quadrupole magnet, threshold magnetic force strength between solenoid and PM quadrupole.

As for demagnetization effect, we have limited data except for the cases from our high field 4.45 Tesla extended dipole PM magnet (see Fig. 10). We are now developing 6 Tesla level magnet and more data will be accumulated.

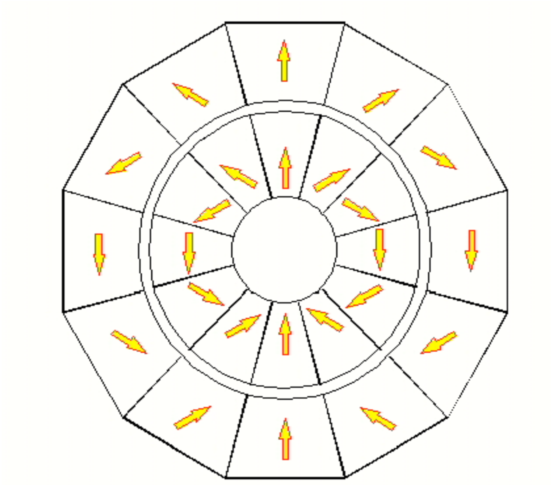

Fig. 8 Cross section of Two layer Halbach type dipole magnet.

Fig. 9 Photos of Two layer variable field Halbach type dipole magnet. The normal field strength could be changed without introducing skew component.

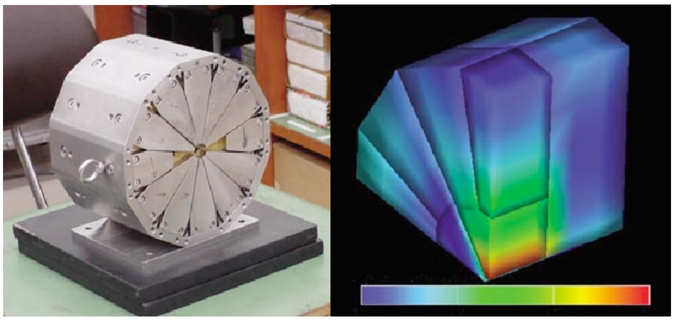

Fig. 10 4.45T magnet (at –29°C). The magnetic field at room temperature is 3.9T.

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[2] KEK-ASN-458, June 7, 2002, in Japanese

[3] T.Hara, “In-vacuum undulators of SPring-8”, J. Synchrotron Rad. (1995,403-405)