EDDY CURRENT EFFECT OF VERY LONG TIME CONSTANT OF BLOCK MAGNETS

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Abstract

We have observed a transient effect of a magnetic field in a gap of block magnet with very long time constant, which extends to an e-folding time of an hour. It was confirmed that not only a response of the magnetic field strength but also the field gradient changes. This phenomena could be accounted for the eddy current field induced in iron core and yoke of the magnet. An attempt was made to explain by analytical expressions and by a numerical computation. Details of the data and analysis are presented.

1 INTRODUCTION

In a cyclotron, it is known that during a start-up a sophisticated initialization of magnets is necessary. The way of initialization seems to vary from institute to institute. In spite of extensive efforts, it is common that operators have to wait for more than a couple of hours until a beam stabilizes. The reason is not clearly understood but is usually ascribed to a magnetic after-effect, a warm-up effect of magnet iron, or a temperature change of the cooling water. Recently it was found at RCNP that the effect of the temperature of cooling water of trim coil is of vital importance [1] to stabilize the beam. In the cyclotron of JAERI Takasaki, it was found that the beam stability is related with long time constant [2] of two distinct components. One of the time constant of an order of day seems to indicate the effect of the temperature change. Another time constant of several hours seems to indicate the presence of the effect of eddy current. Its effect in a spectrometer magnet was first mentioned by K.Halbach [3]. He pointed out that a block magnet has a long time constant and could give an effect to an accuracy of the energy resolution. It has been known that the spectrometer magnet had a puzzlingly unstable long drift. Knowing this work, a large DC magnet of Mainz Microtron (MAMI) was divided into several parts so that the effect of the eddy current is weakened [4]. In spite of an extensive field mapping in MAMI, the experimental confirmation of the eddy current effect has not been done [5]. Looking for the examination of the experimental observation, the effect of the ramp rate of the excitation current to the magnitude of the residual field of the DC magnet at KEK Photon Factory was found [6]. The evidence of the eddy current in cyclotron block magnet was dug out from the old data as an effect of trim coil at ring cyclotron magnet [7] at RIKEN. The size of the sector is about 3.1m × 3.9m in roughly triangular shape.

It may be surprising that the eddy current effect can not be negligible even in laminated magnets of synchrotron. The field delay from the excitation current has been observed in GSI [8] and KEK [9] and also at HIMAC [10] beam line pulse magnet. More measurements and numerical calculation are under progress and will be reported elsewhere [11].

2 EVALUATION OF EDDY CURRENT EFFECT

In a DC block magnet, a transient phenomena appears as an eddy current effect at start-up of the power supply or also at a change of current settings. The time constant of the field change is proportional to a square of the width of magnet and to the conductivity of the iron.

The analytical expression was given by K.Halbach, P.J.Bryant [12] and K.Sato. Here we use the formulation by Bryant for a rectangular magnet. The governing equation for the dipole magnet of the gap length g and the path length l in the iron is,

$$\frac{\partial B^2}{\partial x^2}+\frac{\partial B^2}{\partial z^2}=\frac{l}{g+{l}/{\mu_r}}\sigma\mu_0\frac{\partial B}{\partial t}. \qquad (1)$$

This equation is a diffusion equation in the magnet. For simplicity, we consider the case when the excitation current is abruptly turned off. The equation (1) has a solution of,

$$B=\sum_m\sum_n B_{mn}\cos[\alpha_m x]\cos[\beta_n z]e^{-\frac{t}{\tau_{m,n}}} \qquad (2)$$

where the time constant $\tau_{m,n}$ of the mode m and n for coordinate x and z is written as

$$\frac{1}{\tau_{mn}}=\frac{g+{l}/{\mu_r}}{l}\sigma\mu_0\left[\left(\frac{m\pi}{a}\right)^2+\left(\frac{n\pi}{b}\right)^2\right]. \qquad (3)$$

It is instructive to relate the time constant to the skin depth δ as

$$\frac{1}{\tau_{mn}}=\frac{\omega}{2}\delta^2\left[\left(\frac{m\pi}{a}\right)^2+\left(\frac{n\pi}{b}\right)^2\right] \qquad (4)$$

where in δ the path length factor of the first term in eq.(3) is taken account. As we see, the effect of the eddy current causes a cosine distribution. This distribution is like a "hat" and is called "a hat effect" as Halbach first coined it. In the case of turning-on the excitation current, the distribution has "a dish" shape. These distributions are caused as the magnetic field near the coil responds faster and that of at the center responds slower. This changes of

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field gradient is the cause of the change of focussing force and effects the beam stability. For the evaluation of the time constant for lower mode number, that of the size up to 5 m was plotted in Fig.1. In the calculation we have assumed that the $l/g \approx 200$ and the conductivity of the iron is 10^{-7} ohm. Note the amplification factor l/g in the time constant. It is shown that for the principal mode (m=1), the time constant exceeds 1752 sec (30 minutes) above 4 m size magnet. This means to reach a field level below 10-4 accuracy one need 2 hours for this size of magnet.

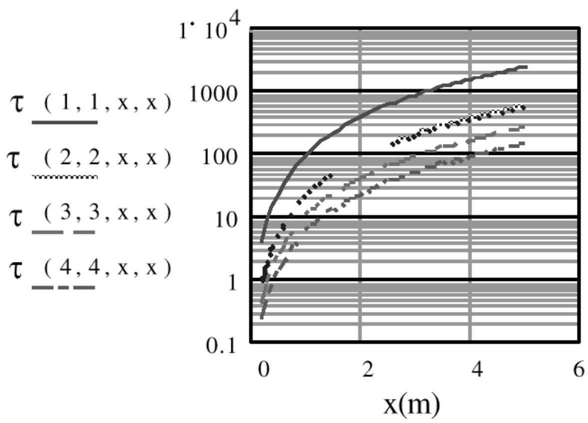

Fig.1 Size dependence of the time constant up to m=n=4 for the size of up to 5m. τ in sec and x in meter.

The numerical calculation was performed using Opera2D(Vector Field) for cylindrical pole of 1 m radius and shown in Fig.2. The time constant of a principal mode at r=624 mm is 500 sec. Figure 2 clearly shows the hat and dish effects. Fig.3 shows a residual current density 700 sec after the turn-off of the excitation current. It is interesting to see opposite direction of the current co-exists, which is due to the trapezoidal excitation having opposite dB/dt.

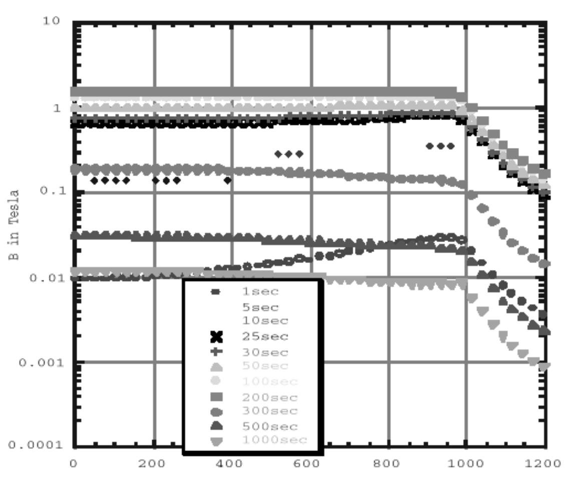

Fig.2 Transient response of field distribution for trapezoidal current excitation (100sec rise, flat top and fall).

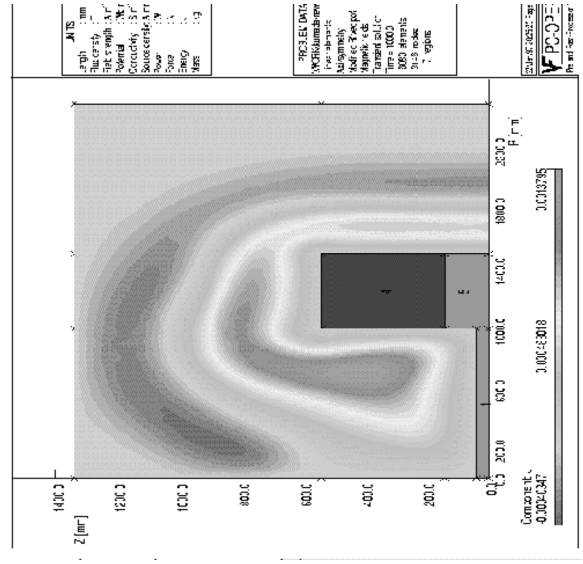

Fig.3 Distribution of current density at t=1000 sec. Excitation current is turned off at t=300 sec. The figure is rotated by 90 degree.

3 OBSERVATION OF EDDY CURRENT EFFECT

Transient response of the magnetic field at three points in the gap of various size of magnet from steering magnet to ring cyclotron magnet were measured using FW Bell hall probe and NMR probe where excitation current was always simultaneously monitored. Due to an insufficient measuring apparatus capability, the ratio of the magnetic field at three locations were measured instead of monitoring the whole distribution. Fig.4 shows the transient response of the magnetic field and its ratio. The ratio indicates the change of field distribution. It should be noted that eddy current effect is responsible for a huge hysteresis effect. They are shown as a field strength and as a ratio of the field as in Figs.5 and 6.

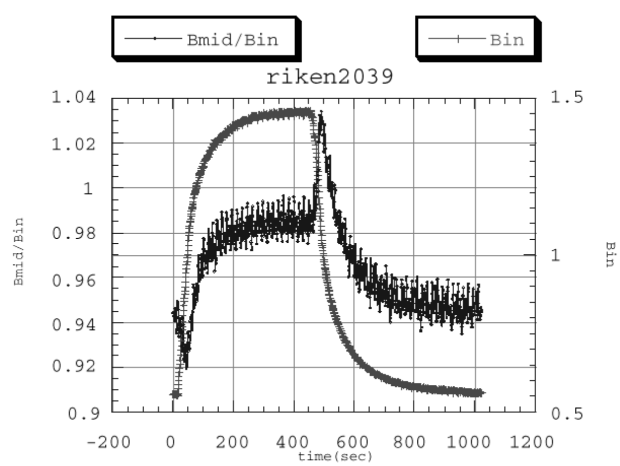

Fig.4 Response of magnetic field and the ratio at two locations, at a middle and inside each 10 cm apart.

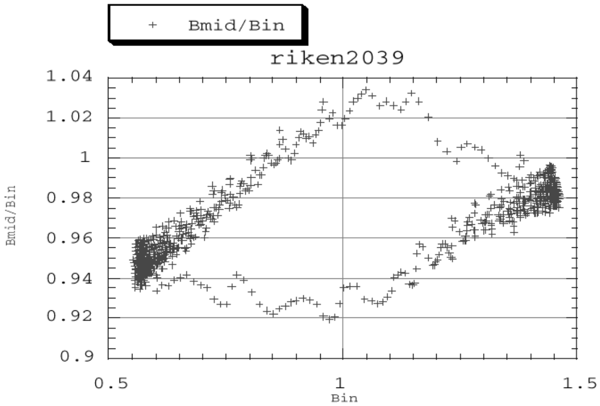

Fig.5 Hysteresis effect of the field ratio as in Fig.4.

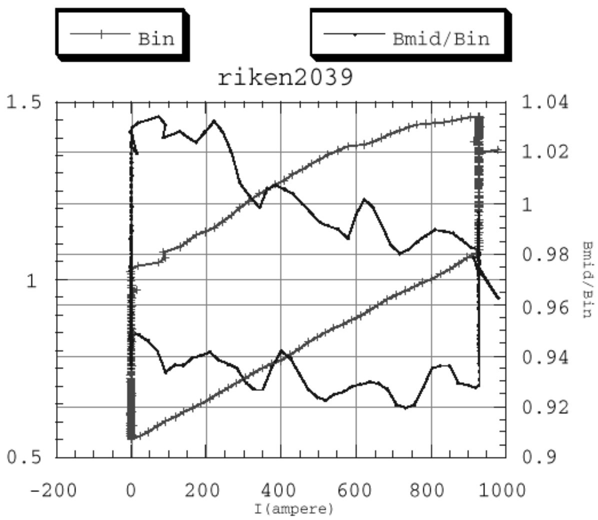

Fig.6 Hysteresis effect of the field strength and the field ratio as in Fig.4.

The measured time constant of the principal mode of ramp-down current is 4900 sec for ring cyclotron magnet shown in Fig.7. The scaling factor of 3 in size could account for this time constant from the calculation of Opera2D.

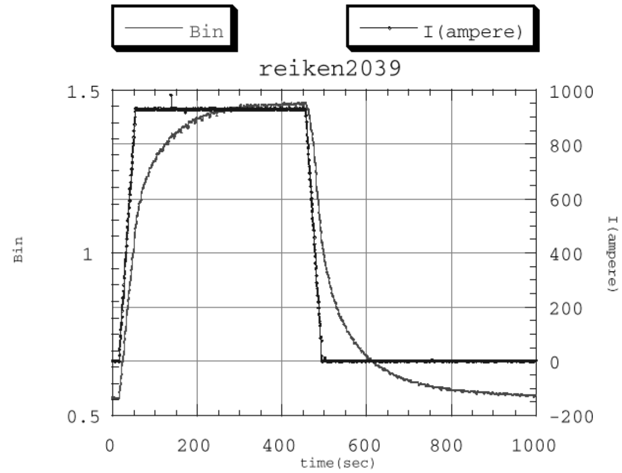

Fig.7 Excitation current and its response of the field strength in RIKEN ring cyclotron magnet.

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