A Study on a High Performance Dipole Magnet for an Accelerator

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Abstract

A new theoretical method by using three dimensional Laplace's equation for determination of the pole shape of a dipole magnet was proposed. The calculation shows some distinctive features, one of which is a shim structure.

A new magnetic field measurement apparatus using moving search coils was also developed. A preliminary experimental result shows that the apparatus is useful for the H-type magnet.

1 Introduction

In resent years, high energy beam generated by a synchrotron-type accelerator have been required not only for pure physics but also for technology and medical care. Under this condition, a smaller synchrotron-type accelerator have been favored mainly for cost performance and, therefore, accelerator elements, such as a dipole magnet, a quadrupole magnet and an rf cavity should be smaller.

In the case of a small dipole magnet, the edge effect of the magnet to an expectable dipole field comes not to ignore. Therefore, two demensional Laplace's equation and two deminsional numerical computation are not enough to determine the pole shape of the small magnet wholly. In fact, the edge structure of the magnet pole was generally determined by an empirical way mainly through the magnetic field measurements, which comes that no guiding principle for the small dipole magnet was found out. Three dimensional numerical computation is seen to be not so useful by now. One idea to determine more theoretically the pole structure of the small dipole magnet is using analytical solution of three dimensional Laplace's equation, which was proposed by Langenbeck in a quadrupole magnet case[1].

2 Three dimensional Laplace's equation

The pole shape of a dipole magnet is regarded as a surface with constant scalar potential, when the permeability of the matter of which the magnet pole consists is high enough. Though this condition is not satisfied for a real magnet, the surface with constant scalar potential may be useful at the start point of the determination of the pole shape. After calculation, successional magnetic field measurements with changing a part of pole shape may make us find a rather good pole shape.

The scalar potential, ψ, is assumed as

$$\psi(x,y,z) = \sum_{m=0}^{\infty} y^m f_m(x,z). \qquad (1)$$

where y-direction is a direction of the dipole field and z-direction is that of the beam. Since a magnetic field to the y-direction, B_y, should be symmetrical with respect to the medium plain of the magnet, therefore,

$$B_y(x,y,z) = -\frac{\partial\psi}{\partial y} = -\sum_{\mu=0}^{\infty}(2\mu+1)y^{2\mu} f_{2\mu+1}(x,z). \qquad (2)$$

The scalar potential ψ should be solution of three dimensional Laplace's equation, i.e., $\triangle\psi = 0$, and then we can obtain

$$\psi(x,y,z) = \lim_{N\to\infty}\sum_{\mu=0}^{N}\frac{(-1)^\mu y^{2\mu+1}}{(2\mu+1)!}\left[\sum_{i=0}^{\mu} {}_\mu C_i \times\left(\frac{\partial^2}{\partial x^2}\right)^{\mu-i}\left(\frac{\partial^2}{\partial z^2}\right)^{i} f_1(x,z)\right]. \qquad (3)$$

We assumed $f_1(x,z)$ as

$$f_1(x,z) = -B_0 g(x) G(z), \qquad (4)$$

where B_0 is a constant. In order to realize almost constant B_y within certain regions, the functions $g(x)$ and $G(z)$ are adopted as

$$g(x) = \frac{1}{2erf\left(\frac{x_0}{\sigma_x}\right)}\left[erf\left(\frac{x+x_0}{\sigma_x}\right) - erf\left(\frac{x-x_0}{\sigma_x}\right)\right], \qquad (5)$$

and

$$G(z) = \frac{1}{2erf\left(\frac{z_0}{\sigma_z}\right)}\left[erf\left(\frac{z+z_0}{\sigma_z}\right) - erf\left(\frac{z-z_0}{\sigma_z}\right)\right], \qquad (6)$$

where x_0 and z_0 are measures of the pole width and the pole length, respectively, σ_x and σ_z are mesures of the stray magnetic field extension and error function, $erf(x)$, is represented as

$$erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt. \qquad (7)$$

Figure 1 shows a typical shape of the function $g(x)$ or $G(z)$. Roughly speaking, the magnetic field B_y related to $g(x)$ and $G(z)$ through eq. (2) is almost constant at $|x| < x_0$ and $|z| < z_0$, decreases smoothly at $|x| \sim x_0$ and $|z| \sim z_0$ and almost zero at $|x| > x_0$ and $|z| > z_0$.

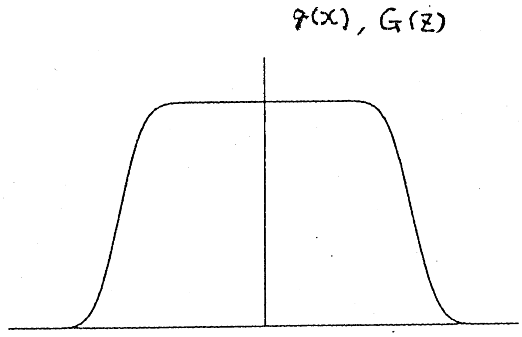

Figure 1: A typical shape of the functions $g(x)$ or $G(z)$.

The equation to represent the pole shape of a dipole magnet is

$$\frac{d}{2} = \lim_{N\to\infty} \sum_{\mu=0}^{N} \frac{(-1)^{\mu} y^{2\mu+1}}{(2\mu+1)!} \left[\sum_{i=0}^{\mu} {}_{\mu}C_i \right.$$
$$\left. \times \left[\left(\frac{\partial^2}{\partial x^2}\right)^{\mu-i} g(x) \right] \left[\left(\frac{\partial^2}{\partial z^2}\right)^{i} G(z) \right] \right], \quad (8)$$

where d is a gap length at the center of the dipole magnet, which corresponds to a minimum gap.

Since eq.(8) has infinite terms at the right hand, it is very difficult to calculate strictly. Therefore, we ignored the sign "lim" at the right hand of the eq.(8) and calculated it for N=1 and 2.

Figure 3 shows a typical calculation of the pole shape for N=2 represented by using normalized variable, i.e.,

$$X = \frac{x}{G}, \quad Y = \frac{y}{G}, \quad Z = \frac{z}{G},$$
$$\sigma_x' = \frac{\sigma_x}{G}, \quad \sigma_z' = \frac{\sigma_z}{G}$$

where $G = d/2$. Even though the evaluation of the calculations up to larger N value should be needed for detailed discussions, qualitative features of the pole shape was found out from the limited calculations. Near the center of the magnet, i.e., for smaller $|Z|$, $Y \sim 1$, i.e., minimum gap, within certain range of $|X|$ in this case $|X| \leq 6$, which corresponds to $|x_0|$. The value of Y increases rather sharply without the range of $|X|$. For larger $|Z|$, Y is also constant but is bigger than that for smaller $|Z|$ with small $|X|$. Near the $|X|$ corresponding to $|x_0|$, as $|X|$ increases $|Y|$ firstly decreases slightly and then increases sharply. In other words, cross-sectional view of the pole has two projections at the pole end, which may coresspond to the presence of the shim structure, which is well known to be one of the effective methods for a wider good magnetic field region. For N=1, qualitative tendency is very similar with that for N=2.

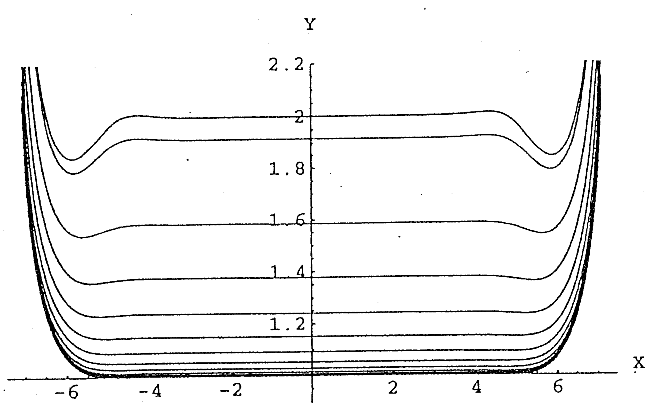

Figure 2: A calculated pole structure of the dipole magnet for N = 2, $\Delta Z = 0.5$, $\sigma_x' = 1.316$ and $\sigma_z' = 2.8$.

3 A magnetic field measurement apparatus

We prepared an H-type dipole magnet with widely adjustable edge pieces and constructed a new magnetic field measurement apparatus for the magnet. In order to ensure conceptual adequency of eq. (8), we need to measure so-called BL product with a very wide range of x. We selected a moving search coil method, which is generally used for magnetic field measurements of a large amount of magnets at once. Using the rectangular search coil, the BL product is obtained by

$$(BL) = \frac{1}{N_c w} \int V dt \quad (9)$$

where N_c is the turn number of the search coil, w is a width of the coil and V is a voltage appearing between both ends of the coil wire, respectively.

Schematic drawing of the magnetic field measurement apparatus is shown in figure 3. Four search coils(750mm $\times$ 20mm), which are put on the medium plain of the magnet, are separated into two pieces at the center. Each piece is drawn out straightly toward each edge of the magnet along the beam orbit by using a long guide($\sim$3.5m) and a wire and finally it is completely shifted to the free space without any magnetic field. Separation of the moving search coils is a rather adequate method to measure the magnetic field of the H-type dipole magnet with relatively small radius of curvature. The coil guide was designed to move along the x-axis by $\pm$110mm. Since the apparatus is prepared for a conceptual test, it was carried out by hand to move the search coils and the coil guide. Cost performance of this measurement apparatus is, then, rather good due to its simple structure. In order to measure the magnetic field of a large amount of the magnet, automatical moving of the search coils and the coil guide will be easily carried out without changing the main part of the apparatus design.

The turn number of the coils was firstly set to be $\sim$ 700. Since the square measure of each coil was a little bit different, we adjusted to add the correction coil empilically. Finally the difference comes to less than 2×10^{-4}.

4 Preliminary results

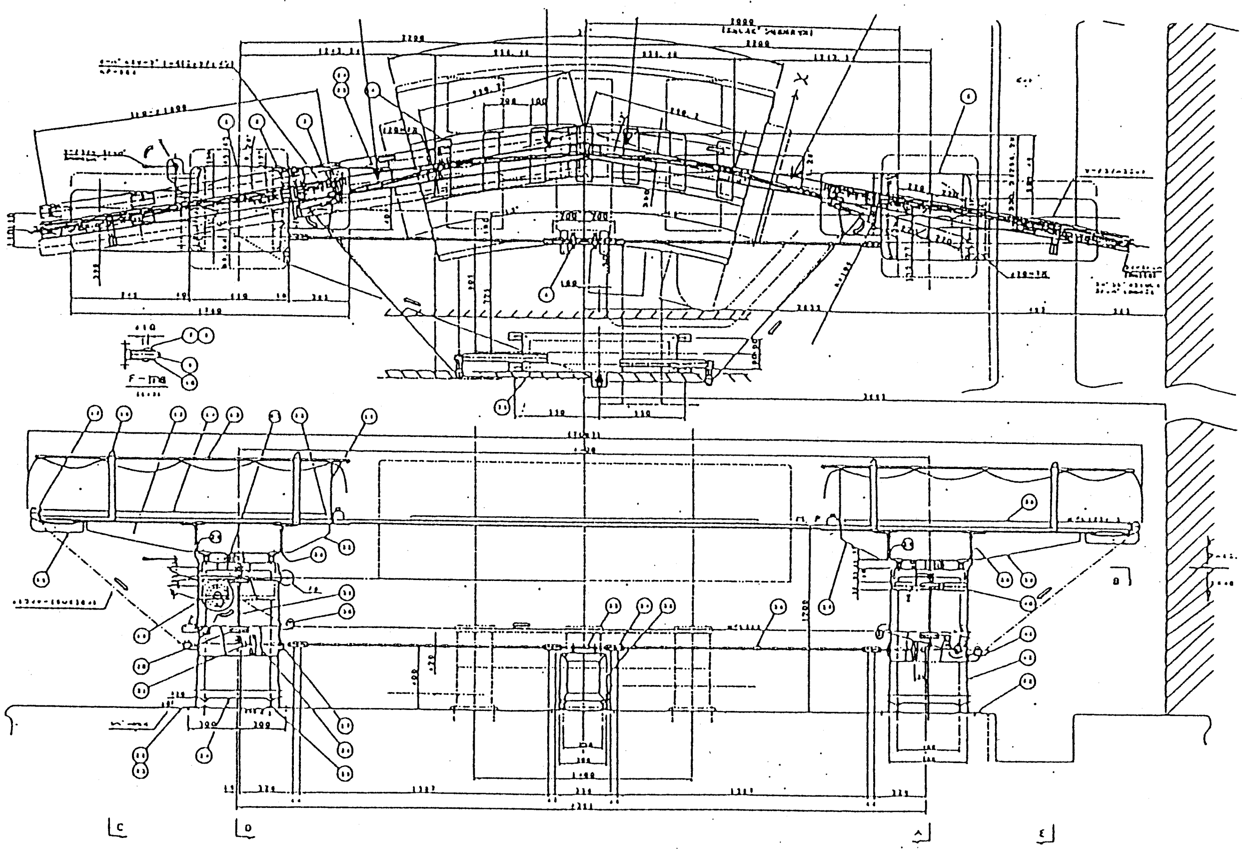

Figure 3: A schematic drawing of the magnetic field measurement apparatus.

Some preliminary tests were carried out. Figure 4 shows an example of an observed V signal as a function of time. After 2.5 seconds from the rising point of V, the value of V come to zero, which ensure that all of the search coils are drawn out to no magnetic field space. Observed four peaks come from the change of the drawing

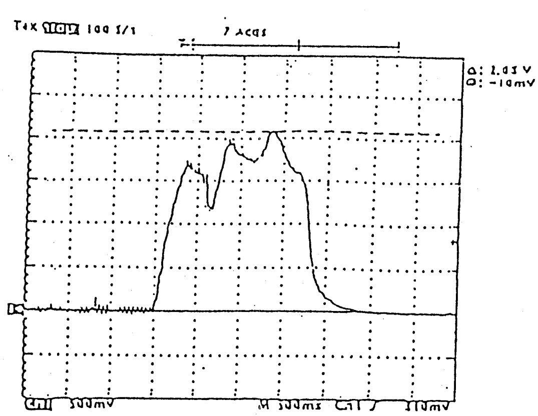

Figure 4: An example of an obserbed voltage signal as a function of time.

speed of the search coils because we move it by hand. Nevertheless, the reappearance of the measured magnetic field was found out to be within 10^{-4}, which is good enough to judge the justification of the concept discussed above.

Magnetic field measurements of the dipole magnet without any changes of the pole edge was carried out. It was found that new magnetic field measurement apparatus works as designed except for some trivial experimental problems, all of which are easily solved in principle. Detailed analyses of the obtained data are under way.

The edge piece of the magnet with the shape based on the analytical solution of the three dimensional Laplace's equation have been made and the magnetic field measurements are now under way.

References

[1] B. Langenbeck, IEEE Transcation on Magnet **24** (1988) 1369.