A Study on High Performance Dipole Magnet for an Accelerator

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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 should be smaller. In a dipole magnet, the edge effect of the magnet to an expectable dipole field comes not to ignore. However, generally speaking, since the edge structure of the magnet pole was determined by an empirical way, no guiding principle was found out. One idea to determine the magnet pole structure is using analytical solution of three dimensional Laplace's equation, which was proposed in a quadrupole magnet case[1].

The pole shape of a dipole magnet may be regarded as a surface with constant scalar potential, ψ, which is assumed as

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

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

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

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

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

Assuming that $f_1(x,z) = -B_0 g(x) G(z)$, 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

$$g(x) = \frac{1}{2erf\left(\frac{x_0}{\sigma_x}\right)}\left[erf\left(\frac{x+x_0}{\sigma_x}\right) - erf\left(\frac{x-x_0}{\sigma_x}\right)\right], \tag{4}$$

and

$$G(z) = \frac{1}{2erf\left(\frac{z_0}{\sigma_z}\right)}\left[erf\left(\frac{z+z_0}{\sigma_z}\right) - erf\left(\frac{z-z_0}{\sigma_z}\right)\right], \tag{5}$$

where x_0 and z_0 are mesures of the pole width and the pole length, respectively, and σ_x and σ_z are mesures of the stray magnetic field extension. Roughly speaking, the magnetic field B_y is almost constant at $|x| \le x_0$ and $|z| \le z_0$. Therefore, the equation to represent the pole shape of a dipole magnet is

$$\frac{d}{2} = \sum_{\mu=0}^{\infty} y^{2\mu+1}\frac{(-1)^\mu}{(2\mu+1)!}\left[\sum_{i=0}^{\mu}{}_\mu C_i \left[\left(\frac{\partial^2}{\partial x^2}\right)^{\mu-i} g(x)\right]\left[\left(\frac{\partial^2}{\partial z^2}\right)^{i} G(z)\right]\right], \tag{6}$$

where d is a gap length at the center of the dipole magnet.

Test calculations of eq. (6) were carried out for $\mu = 0$, 1 and 2. The results show us that distinctive shape of the pole. At the center of the magnet, the cross-sectional view of the pole shape is similar to parallel straight line within a certain range. On the other hand, the outward shape of the cross-sectional view of the pole has two projections at the both sides. The evaluation of these limited calculations, however, is under way.

We prepared an H-type dipole magnet with widely adjustable edge piece and constructed a new magnetic field measurement apparatus for the magnet. In order to ensure conceptual adequacy of eq. (6), we need to measure so-called BL product with very wide range of x. We selected a moving search coil method.

Four search coils(750mm x 20mm), which are put on the medium plain, are separated into two pieces at the center. Each piece is drawn out straightly along the beam orbit toward each edge of the magnet by a wire and finally it is completely shifted to the free space without any magnetic field. In this method, the BL product is proportional to the time integral of the induced voltage. This measurement apparatus has a simple structure and cost performance is rather good.

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 empirically. Finally the difference comes to less than $2\text{x}10^{-4}$.

Some preliminary tests were carried out. The reappearance of the measured magnetic field was checked and found out to be within 10^{-4}, which is good enough to judge the justification of the concept discussed above. The edge pieces of the magnet with the shape based on the analytical solution of the three dimenstional Laplace's equation have been made and the magnetic field measurements are now under way.

References

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