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RESEARCH ON FIRST HARMONIC SHIMMING METHOD OF CYCLOTRON BASED ON LEAST NORM SQUARE SOLUTION

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Abstract

The magnetic field measurement of cyclotron and the shimming of isochronous magnetic field are one of the important links in cyclotron. Due to the influence of factors such as processing errors, installation errors, and inhomogeneity of the magnetic properties of magnet materials, the main magnetic field of the cyclotron will usually deviate from the required isochronous magnetic field and contain a certain amplitude of the first harmonic magnetic field. The existence of the first harmonic magnetic field will rapidly increase the transverse oscillation amplitude and cyclic emittance of the particles, eventually causing beam loss. In order to improve the beam quality of the cyclotron, the shimming technology of the first harmonic magnetic field is essential. In this paper, through the finite element simulation calculation of the main magnet of the cyclotron, a quantitative algorithm for the first harmonic shimming based on the least norm square solution is proposed. At present, this method is being prepared for apply to the magnetic field shimming of the 10MeV high-current proton cyclotron of the CIAE.

Introduction

Due to the influence of internal defects of iron materials, machining errors and other factors, the magnetic field of the cyclotron usually contains the first harmonic component. During a particle moves in a non-ideal magnetic field, it will be subjected to an additional external force. The lateral oscillation of the particle caused by the external force is a forced oscillation, which will increase the amplitude of the lateral oscillation. When certain conditions are met, it will also cause resonance and cause the particle loss. When constructing a cyclotron, the first harmonic component of the magnetic field must be eliminated, so as to avoid the influence of forced oscillation on the lateral motion of particles and improve the quality of the beam.

The traditional first harmonic shim method is based on the Hard-edge mode method. The hard-edge approximation can be used on transforming the field error to the shape change. However, the accuracy of the calculation results is relatively low. Since a conservative strategy with scaling factor should be adopted to avoid over-shimming and oscillations [1]. For high-current cyclotrons, in order to achieve the physical goal of high-current, the first harmonic component of the magnetic field must be precisely eliminated [2].

In this paper, a magnetic field shimming algorithm based on a multiple linear regression model is proposed to achieve quantitative and accurate shimming of the first harmonic component of the magnetic field.

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Principle of Shimming Algorithm

The research on the shimming algorithm and calculation method proposed in this paper is carried out on the basis of the simulation calculation of the compact cyclotron model shown in Fig. 1, through the software Opera-3d. Compared with the magnetic field distribution calculated by the TOSCA solver in the software and the actual measured magnetic field distribution, the error is within ±0.5% [3].

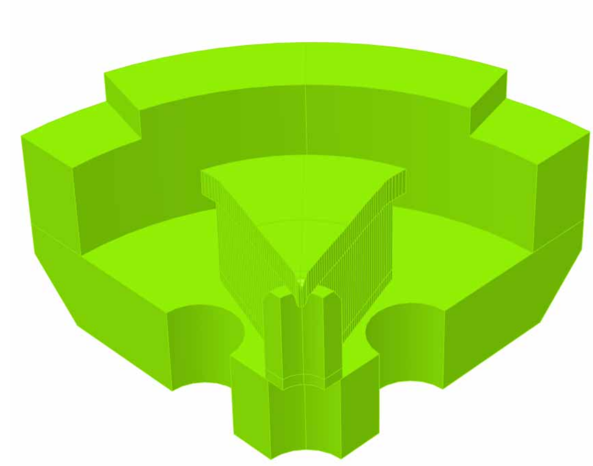

Figure 1: 10MeV cyclotron 1/4 model of CIAE.

The first harmonic magnetic field component of the compact cyclotron can be calculated by Fourier analysis, and the amplitude and phase of the first harmonic along the radial direction can be obtained by Eq. (1):

$$B(r,\theta) = B_0(r,\theta) + \sum_{0}^{\infty} b_{rk} \cos(k\theta + \beta_{rk}) \qquad (1)$$

where $B_0(r,\theta)$ is the perfect magnetic field, b_{rk} is the harmonic amplitude, k is the harmonic coefficient, β_{rk} is the initial phase. The principle of shimming the first harmonic is: without changing the average magnetic field of the cyclotron, artificially introduce a reverse first harmonic to offset the first harmonic component of the original magnetic field. As shown in Fig. 2, in order not to change the average magnetic field, cutting at one pole must be supplemented at the other pole, but in the actual shimming process, the magnetic pole shimming can only be done by cutting. Fortunately, compared to the isochronous error of the magnetic field, the first harmonic magnetic field is a small amount, so the shimming of the first harmonic magnetic field can be included in the shimming process of the isochronous magnetic field, so as to solve the problem of the first harmonic shimming.

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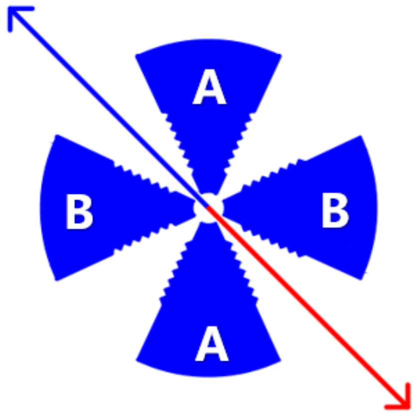

Figure 2: The blue arrow indicates the original first harmonic component of the magnetic field, and the red arrow indicates the artificially introduced reverse first harmonic through magnetic pole shimming, thereby eliminating magnetic field errors.

The shimming method proposed in this paper adopts the asymmetrical cutting method of the magnetic poles to shimming the first harmonic magnetic field. If the cyclotron has m shimming points in the radial direction, the four magnetic poles correspond to $4 \times m$ shimming amounts. The shimming amount at any shimming point can be expressed by X_k^p (P: The Pth pole, k: The kth shimming point). Then the total shimming amount of the cyclotron can be expressed by column matrix: $X = [X_1^1, X_2^1, \ldots, X_m^1, \ldots, X_m^4]^T$. If there are n magnetic field measurement points in the radial direction, the phase decomposition of the first harmonic magnetic field is performed to obtain two components $\beta \sin\phi$ and $\beta \cos\phi$, then the first harmonic component of the magnetic field can be further expressed as: $\beta = [\beta_1 \sin\phi_1, \ldots, \beta_n \sin\phi_n,\ \beta_1 \cos\phi_1, \ldots, \beta_n \cos\phi_n]^T$. Among them, β_1 represents the amplitude of the first harmonic at the first magnetic field measurement point r_1, and $\sin\phi_1$ and $\cos\phi_1$ represent the phase of the first harmonic at r_1.

The shimming equation of the first harmonic magnetic field can be expressed as:

$$\beta = A \cdot X + \varepsilon \tag{2}$$

where, A represents the shimming matrix, which is a correlation regression matrix of order $2n \times 4m$, ε is a random disturbance vector, and its mathematical expectation value is zero. The magnetic field error matrix b is obtained by Fourier analysis of the measured magnetic field, and the magnetic pole shimming amount matrix X is the shimming amount required at each shimming point in order to eliminate the magnetic field error, which is the unknown quantity to be solved. Equation (2) can be solved only by obtaining the shimming matrix A.

Shimming matrix A can be pre-calculated with Eq. (3) by comparing the field difference using an array of unit cutting patches. For example, when cutting an unit triangular patch at R_1 on a pole, as shown in Fig. 3. We have: $X = [1, 0, 0, \ldots, 0]^T$, The first harmonic magnetic field introduced after cutting: $\beta = [\beta_1, \beta_2, \cdots, \beta_{2n}]$, the calculation results are shown in Fig. 3, $A_1 = [A_{11}, A_{21}, \cdots, A_{2n \cdot 1}]^T$ is calculated by $A_{k1} = \beta_k$. Repeat the above process to find all the elements of the padding matrix.

$$\beta_i = A_{i1} \cdot X_1 + A_{i2} \cdot X_2 + \cdots + A_{i \cdot 4m} \cdot X_{4m} \tag{3}$$

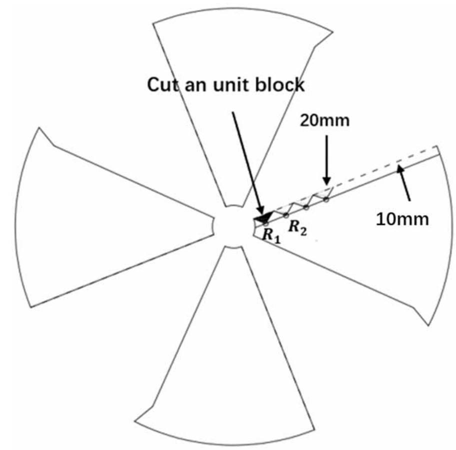

Figure 3: Schematic diagram of cutting to calculate shimming matrix.

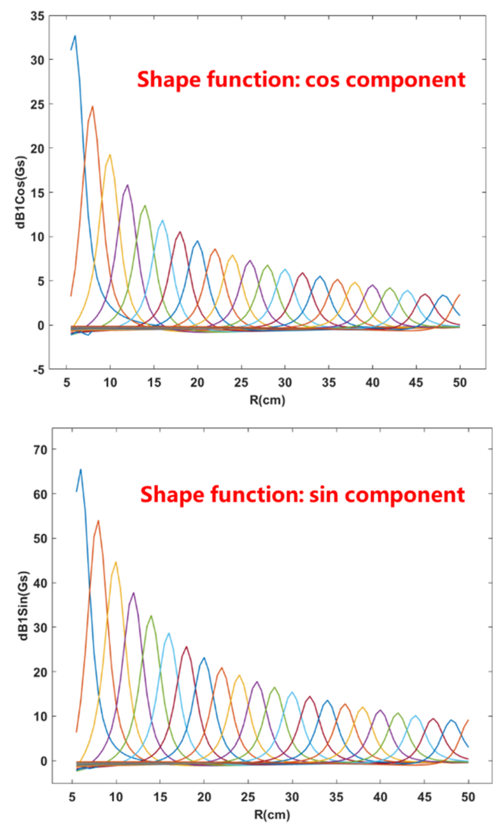

Figure 4: The first harmonic shape function calculated by TOSCA simulation.

We only need to perform finite element simulation calculations on the first magnetic pole to obtain the first harmonic magnetic field introduced by cutting unit shimming blocks at each shimming point. Figure 4 shows the shape function of the first harmonic magnetic field of a single pole obtained by finite element calculation. The magnitude of the first harmonic magnetic field introduced by cutting unit shimming blocks on different magnetic

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poles is the same. The phase of the first harmonic is related to the azimuth angle, and the phase difference of the first harmonic magnetic field caused by the cutting of adjacent magnetic poles is 90°. Therefore, as long as the first harmonic magnetic field shape function of one magnetic pole is obtained, the first harmonic magnetic field shape functions of the other three magnetic poles can be obtained.

After obtaining the shimming matrix A, the shimming Eq. (2) can be written in the following form to solve:

$$X = (A^T A)^{-1} A^T \beta \tag{4}$$

In general, the spacing of the shimming points in the radial direction is twice the spacing of the magnetic field measurement points, and the number of elements of the magnetic field error vector b is greater than the number of elements of the shimming amount vector X. Equation (4) is an underdetermined system of equations, and the shimming vector X can be obtained by solving the method of least norm square solution.

CONCLUSION

In our study, using the first harmonic magnetic field shimming method based on the multiple linear regression model can realize quantitative and accurate shimming of the first harmonic error of the magnetic field, and the shimming magnetic field error can be on the order of 10^{-3}. The method is based on a multiple linear regression model of independent magnetic pole shimming effects, which provides a good basis for magnet shimming. The premise is that the area of the shimming block to be cut is much smaller than the area of the magnetic pole, and then the multiple linear regression model can be used. Before integrating the shimming procedure, an appropriate radial cut step size should be chosen to avoid oscillations in the least squares fit.

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