A High Precision Magnetic Field Shimming algorithm for Inclined 45° Continuous Cutting on Spiral Pole of SC Cyclotron

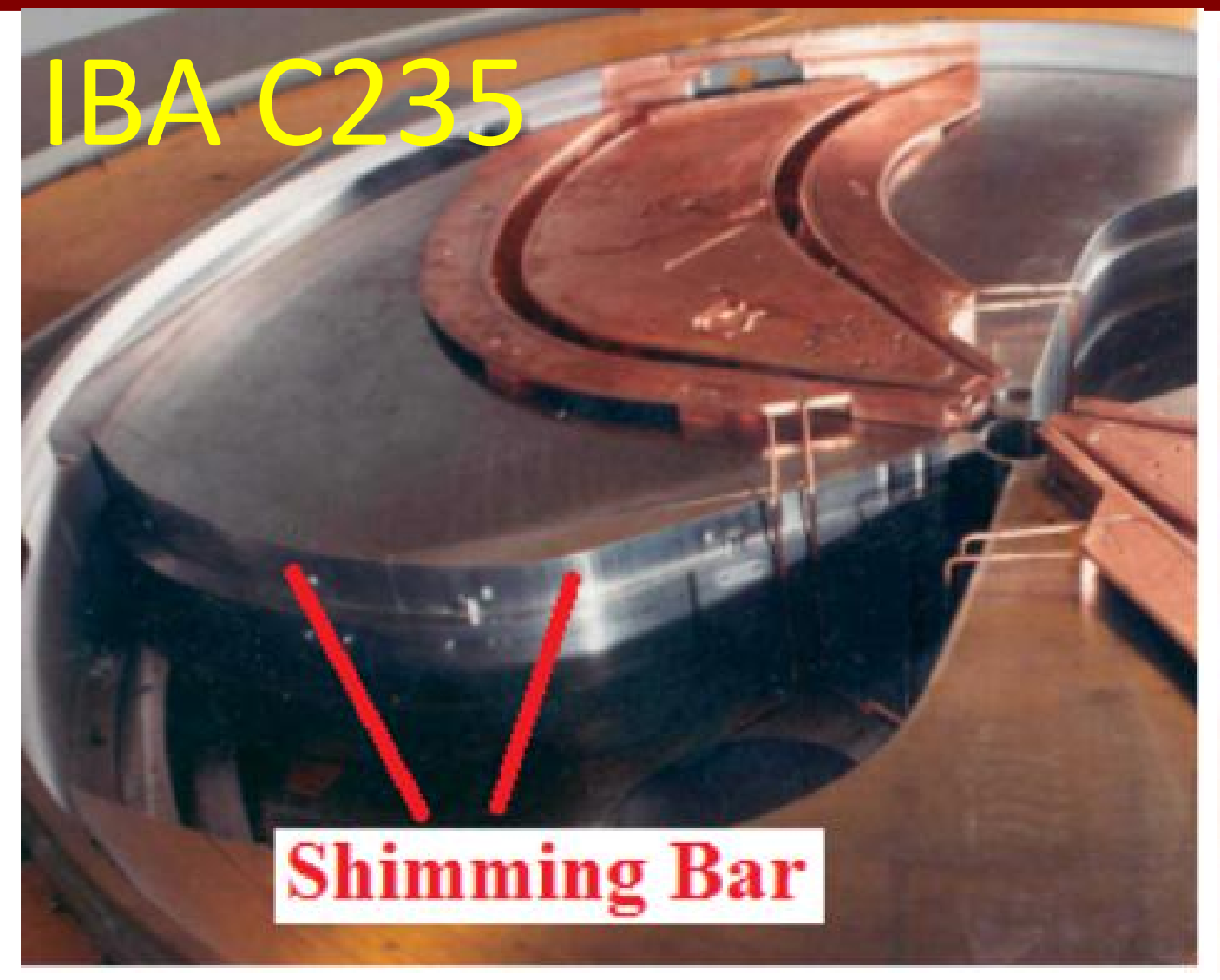
Ming Li, Tianjue Zhang, Chuan Wang, Shenglong Wnag
China Institute of Atomic Energy，Beijing，102413

Mon-Mo-Po1.03-14[33]

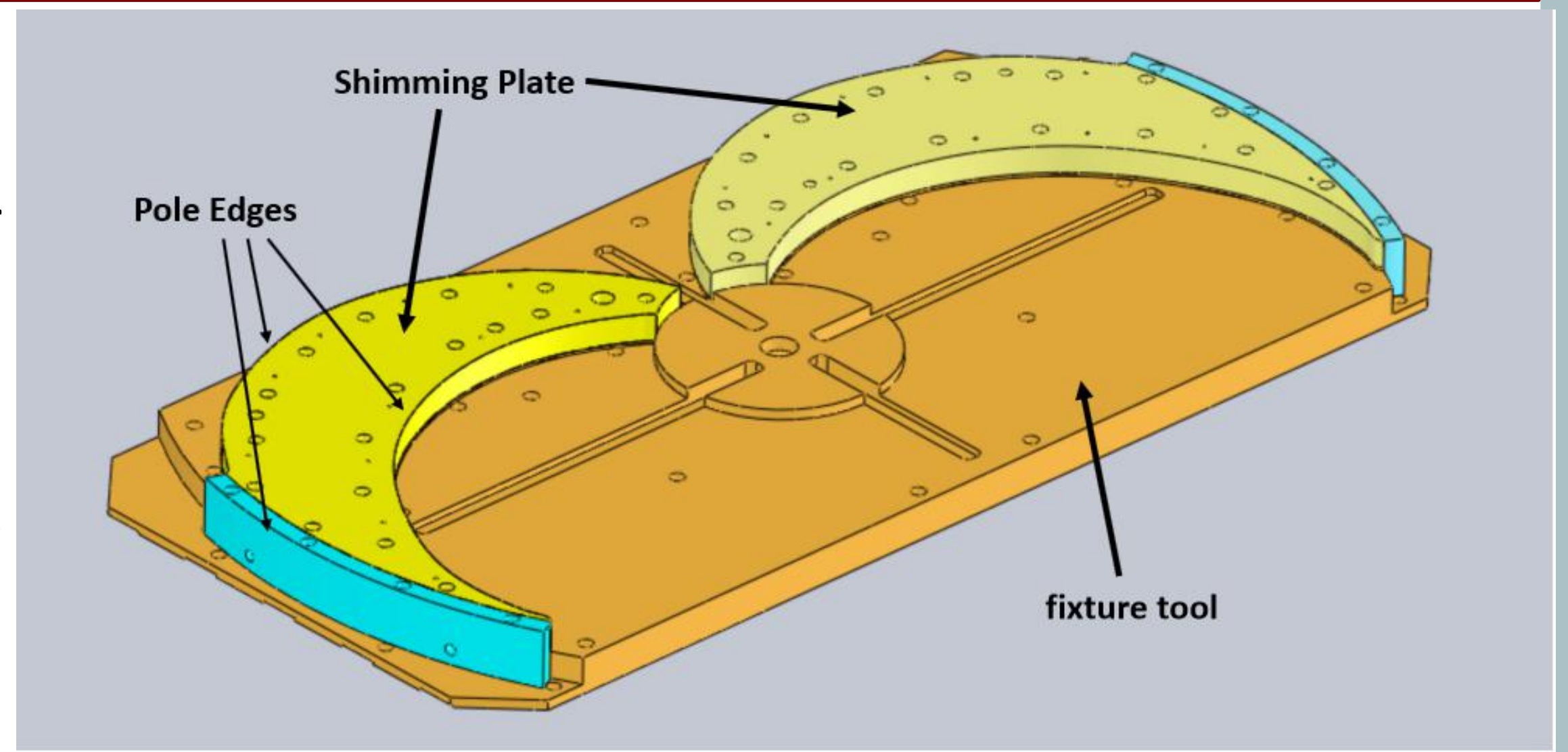
China Institute of Atomic Energy

Introduction

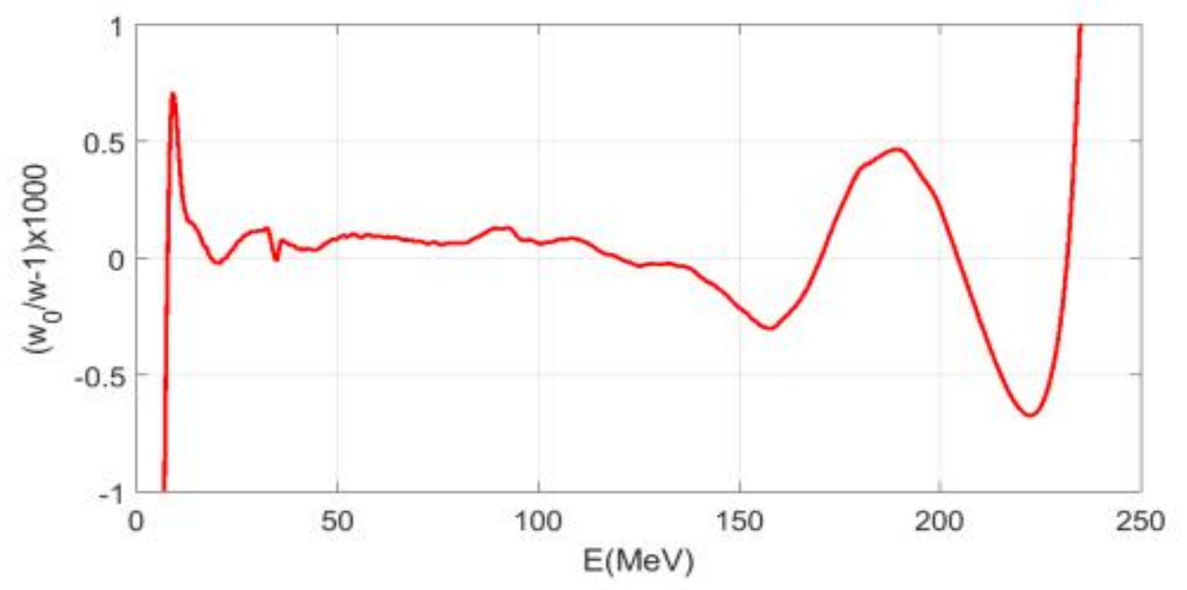
Magnetic field shimming is a critical procedure to achieve isochronous acceleration for cyclotron.The superconducting cyclotron has the characteristics of high field saturation and compact structure.The commonly used shimming bar processing method,such as the IBA C235,in the normal temperature cyclotron is not suitable for the field shimming of the superconducting cyclotron. The trimming coil and the trimming rod are commonly used to adjust the field online for multiple different types of particle acceleration,such as the Kolkata K500, which is operated too complicated for only proton acceleration.



A shimming algorithm for inclined 45° continuous cutting on spiral pole of the superconducting cyclotron is proposed to correct the magnetic field with high precision. The magnet pole is divided into the upper and lower two parts. The upper part, named the shimming plate, is fixed on the lower part by many bolts, which can be easily disassembled and used to process the two edges with the help of a fixture tool.The upper and lower magnetic poles can be fixed together on the tooling to ensure the symmetry of the field.This method can effectively shim the isochronous field and first harmonics, reduce the magnetic saturation surround the pole edge, and facilitate the installation of main components such as central region and RF cavity.

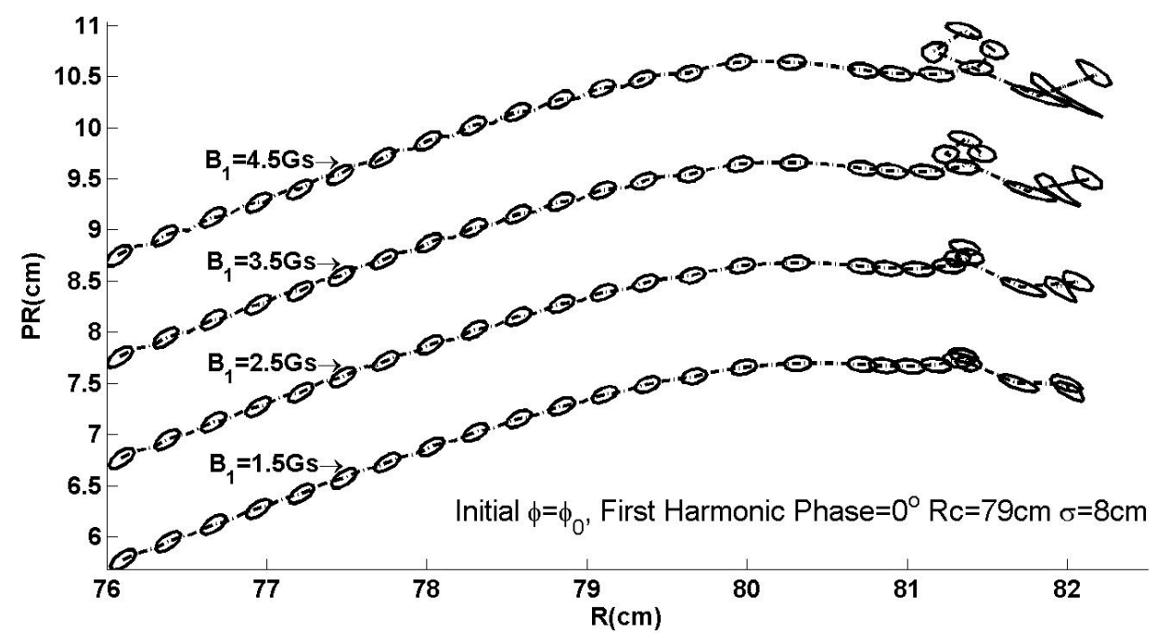


Requirements of Field Shimming



$$\sin\phi = \sin\phi_0 + \frac{2\pi h}{NqV_{rf}}\int \Omega dE, \quad \Omega = \frac{w_{rf}}{hw} - 1 \approx \gamma^2 \frac{\Delta B}{B}$$

$$-40^o \le \phi \le 40^o$$



From the perspective of extractopm design, the first harmonic at extraction position should be less than 2Gs, and other positions are less than 4Gs.

Shimming Algorithm

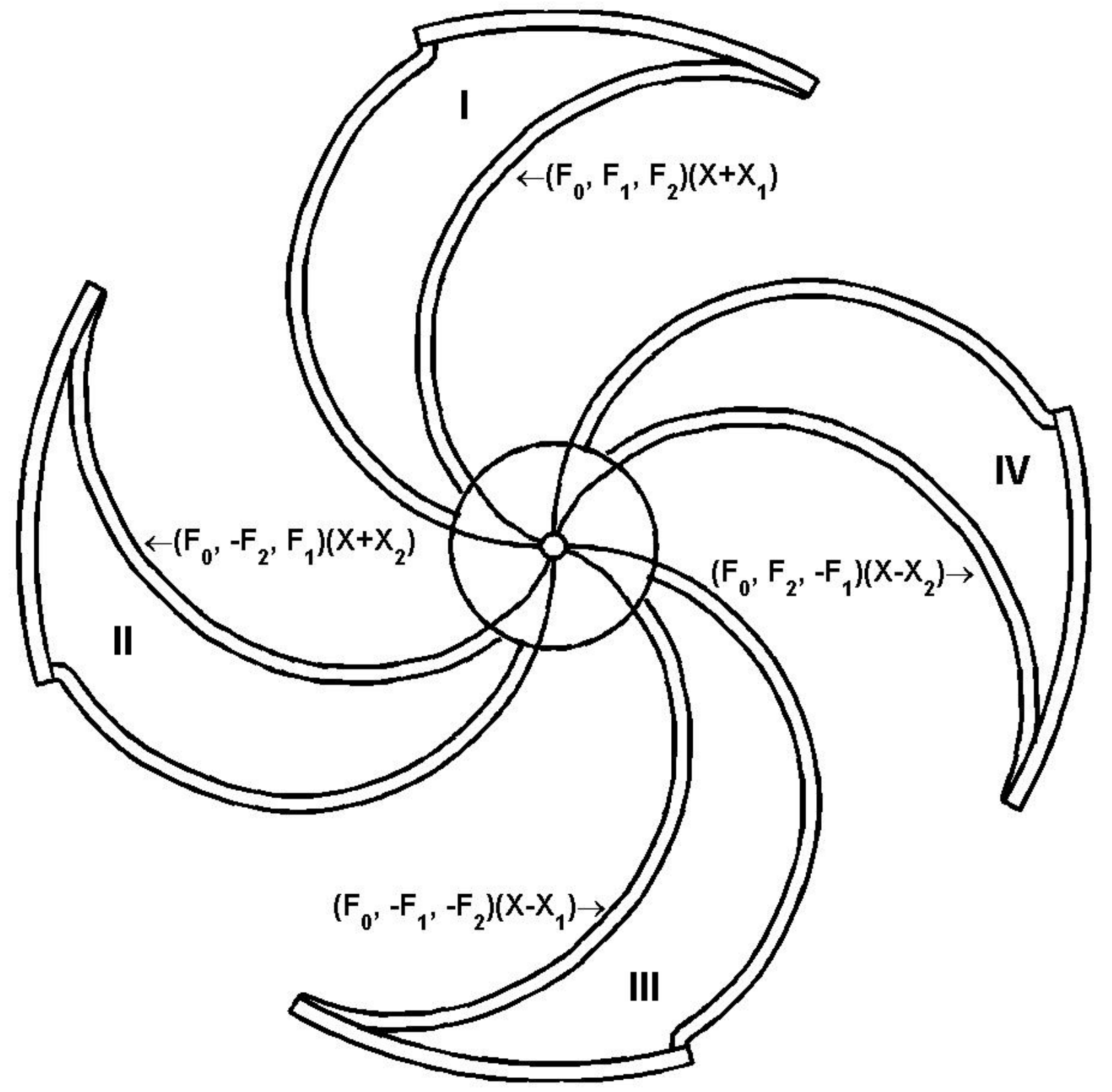
ΔB to be shimmed for a cyclotron: $\Delta B = B_0 + C_1\cos\theta + S_1\sin\theta$

Assuming:

- The change of the magnetic field generated by the processing amount at one position is independent of the processing amount at other positions, so that the total field change can be superimposed by all the effect at every position.
- The magnetic field change is proportional to the processing amount, based on which the problem could be transformed into a linear equation, rather than a nonlinear equation.

Shape Function

$$\Delta B(r) = \int_{r_0}^{r_N} F(r, r^*)x(r^*)dr^* \Rightarrow \Delta B(r_i) = \sum_j F(r_i, r_j^*)\Delta r_j^* x(r_j^*) = \sum_j F_{ij}x_j$$



Equation for average field shimming: $4F_0X = B_0$

Equation for first harmonic shimming:

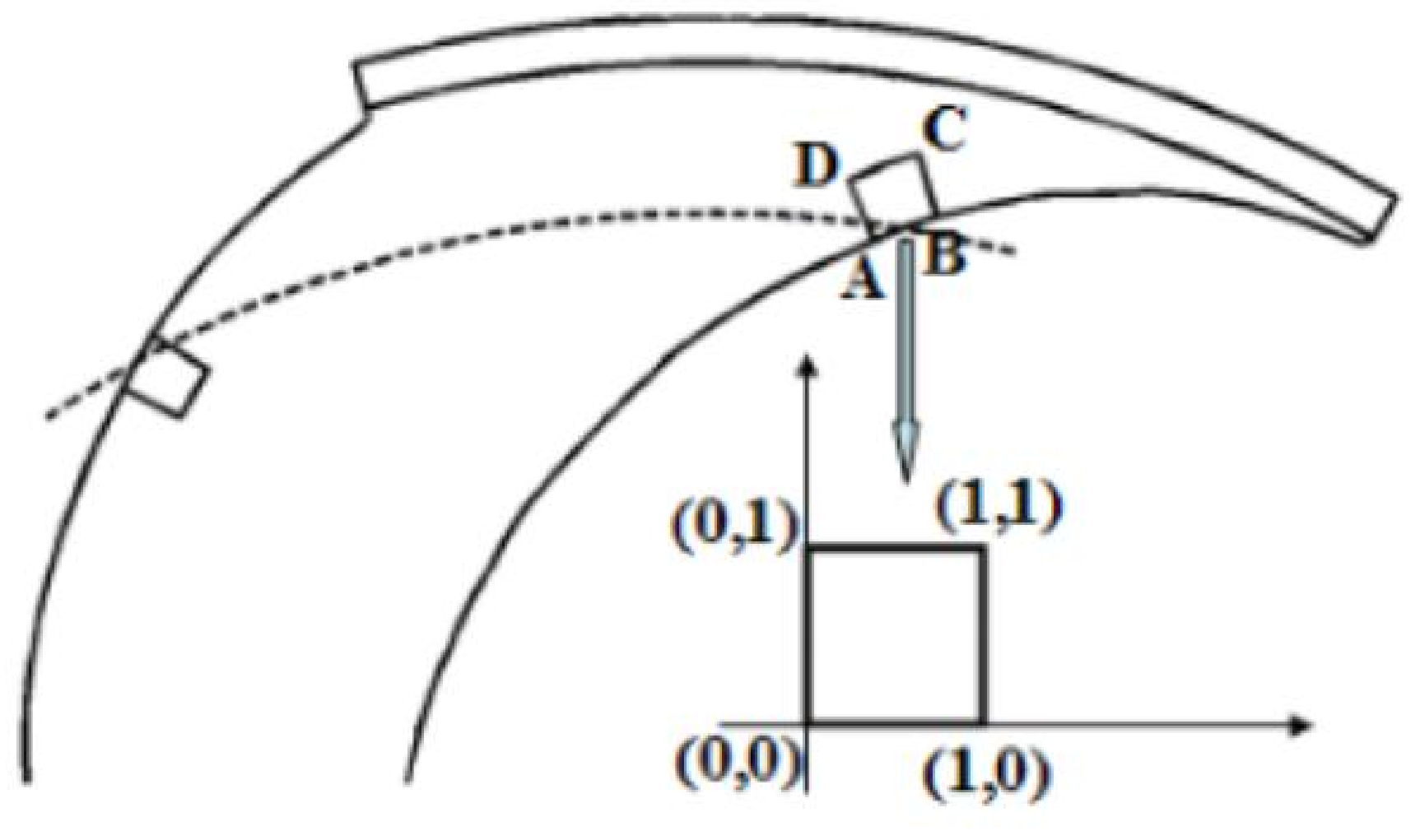
$$2(F_1X_1 - F_2X_2) = C_1$$
$$2(F_2X_1 + F_1X_2) = S_1$$

$$M = 4F_0,\quad M_1 = 2\begin{pmatrix} F_1 & -F_2 \\ F_2 & F_1 \end{pmatrix},\quad Y = \begin{pmatrix} X_1 \\ X_2 \end{pmatrix},\quad B_1 = \begin{pmatrix} C_1 \\ S_1 \end{pmatrix} \Rightarrow \begin{matrix} MX = B_0 \\ M_1Y = B_1 \end{matrix}$$

Least square equation with Ridge regression:

$$Minimum:\ T = X^TM^TWMX - 2B_0^TWMX + \kappa X^TX$$

Shape Function



$$A \leftrightarrow (0,0), B \leftrightarrow (1,0), C \leftrightarrow (1,1), D \leftrightarrow (0,1)$$

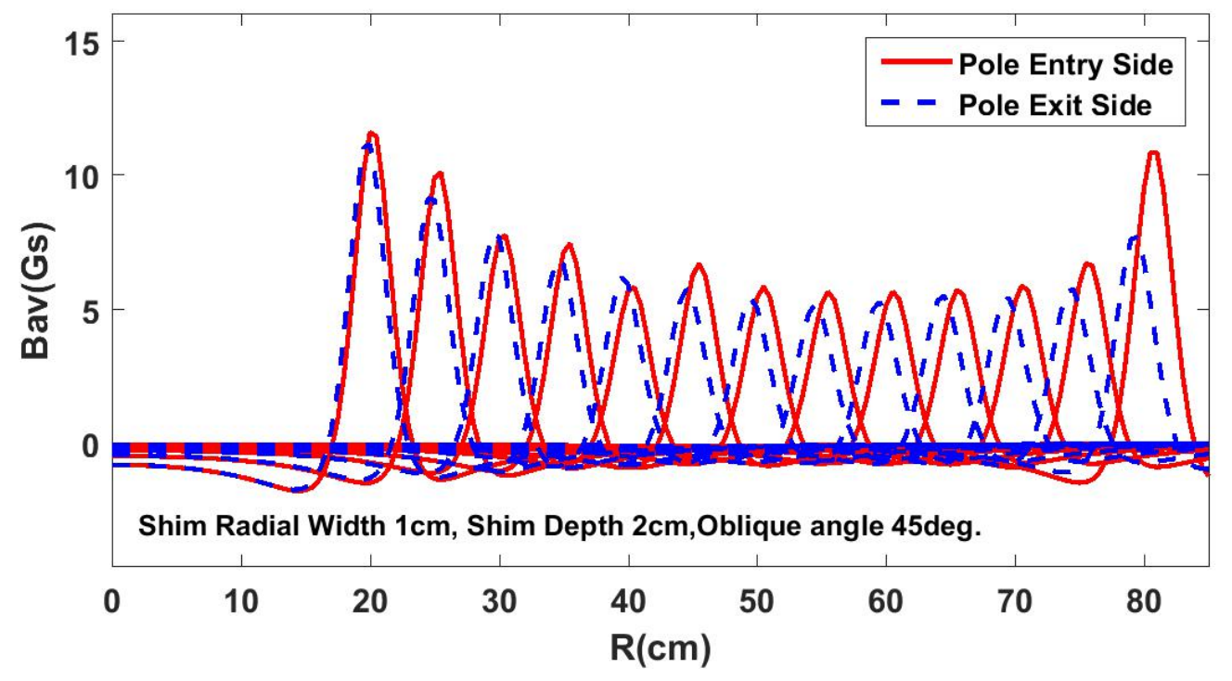
$$x = (1-x^*)(1-y^*)x_A + x^*(1-y^*)x_B + x^*y^*x_C + (1-x^*)y^*x_D$$
$$y = (1-x^*)(1-y^*)y_A + x^*(1-y^*)y_B + x^*y^*y_C + (1-x^*)y^*y_D$$

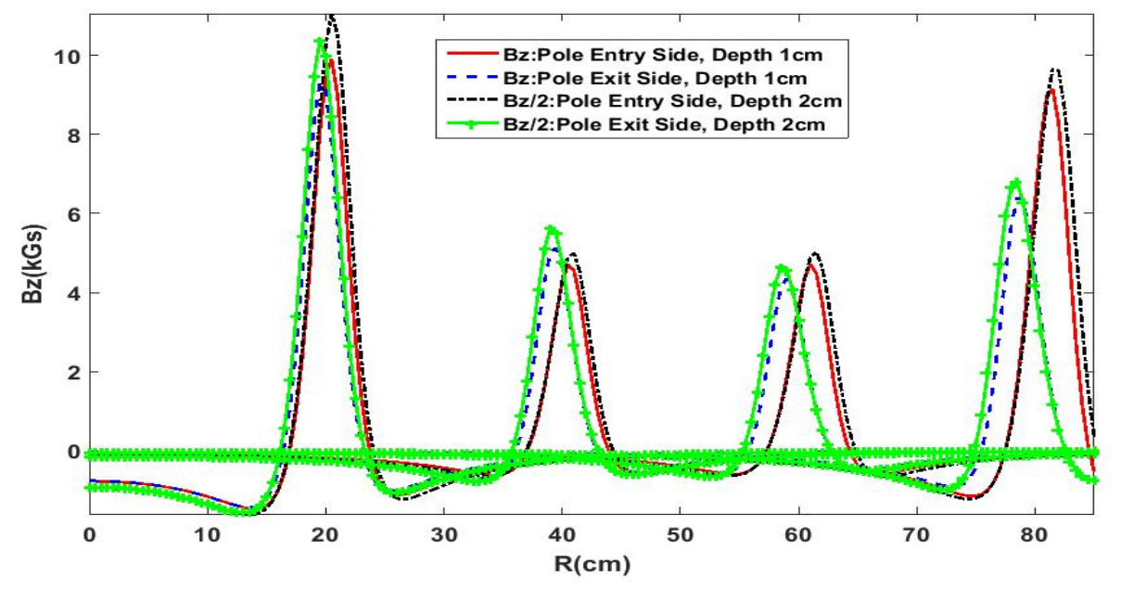
The area fraction on an arbitrary quadrilateral is converted into an area on a square by mathematical transformation.

$$dS = |J|dS^* = \left|\begin{pmatrix} \frac{\partial x}{\partial x^*} & \frac{\partial x}{\partial y^*} \\ \frac{\partial y}{\partial x^*} & \frac{\partial y}{\partial y^*} \end{pmatrix}\right| dS^*$$

Magnetic saturation approximation:

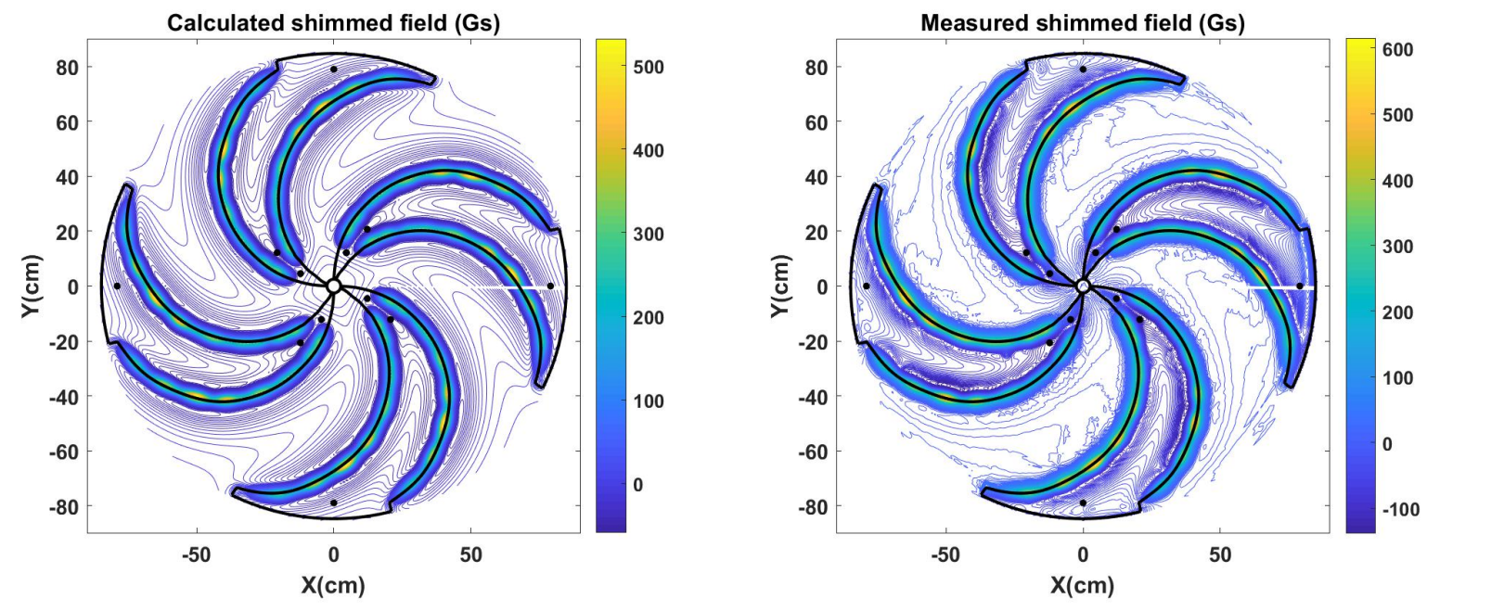
$$d^2B_z = \frac{B_s}{4\pi}\frac{z\cos\alpha}{|\vec{r}-\vec{r}_0|^3}dS$$

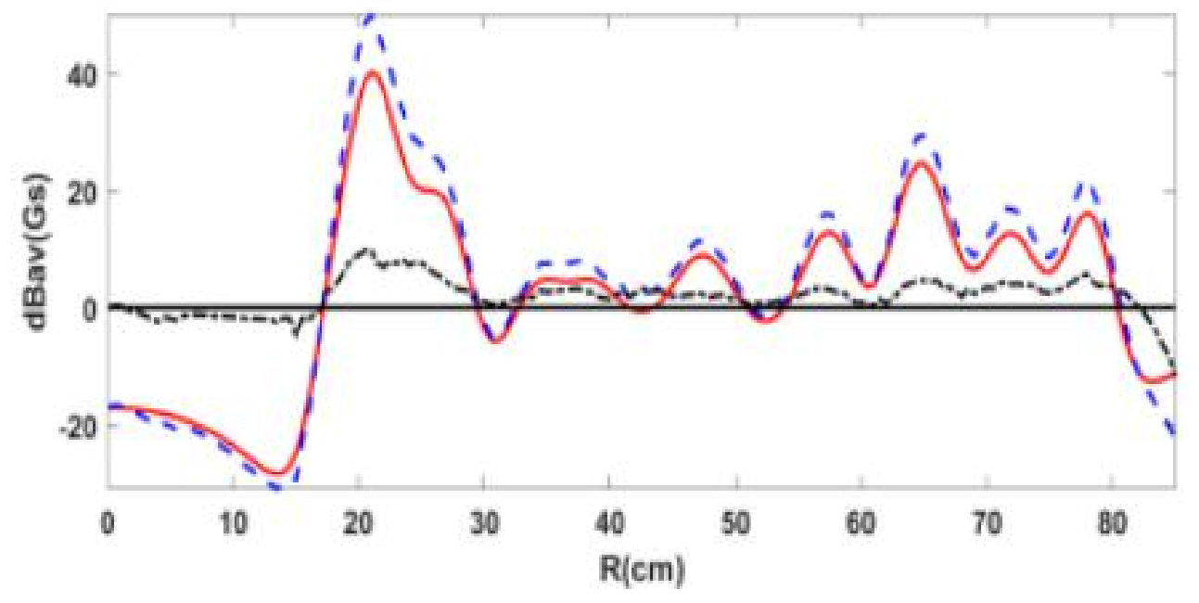




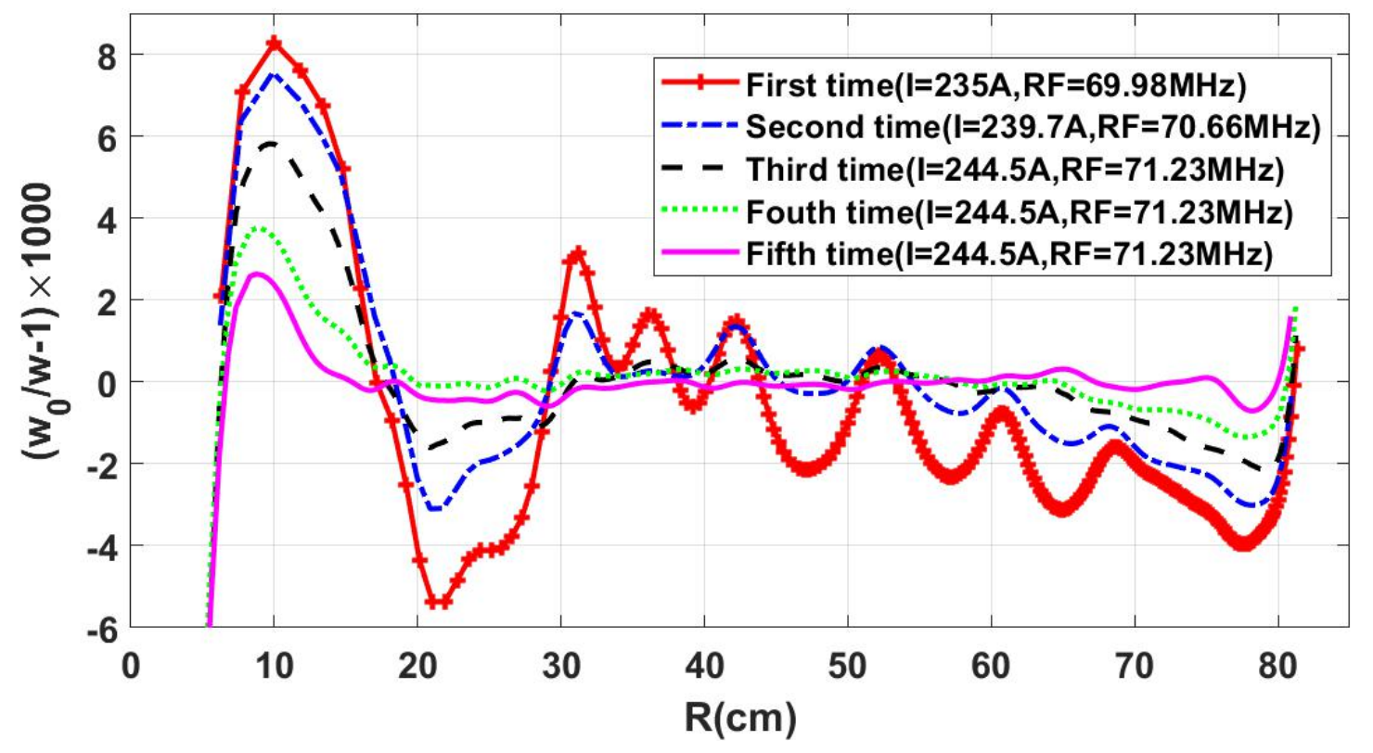
Shimming Results for CYCIAE-230

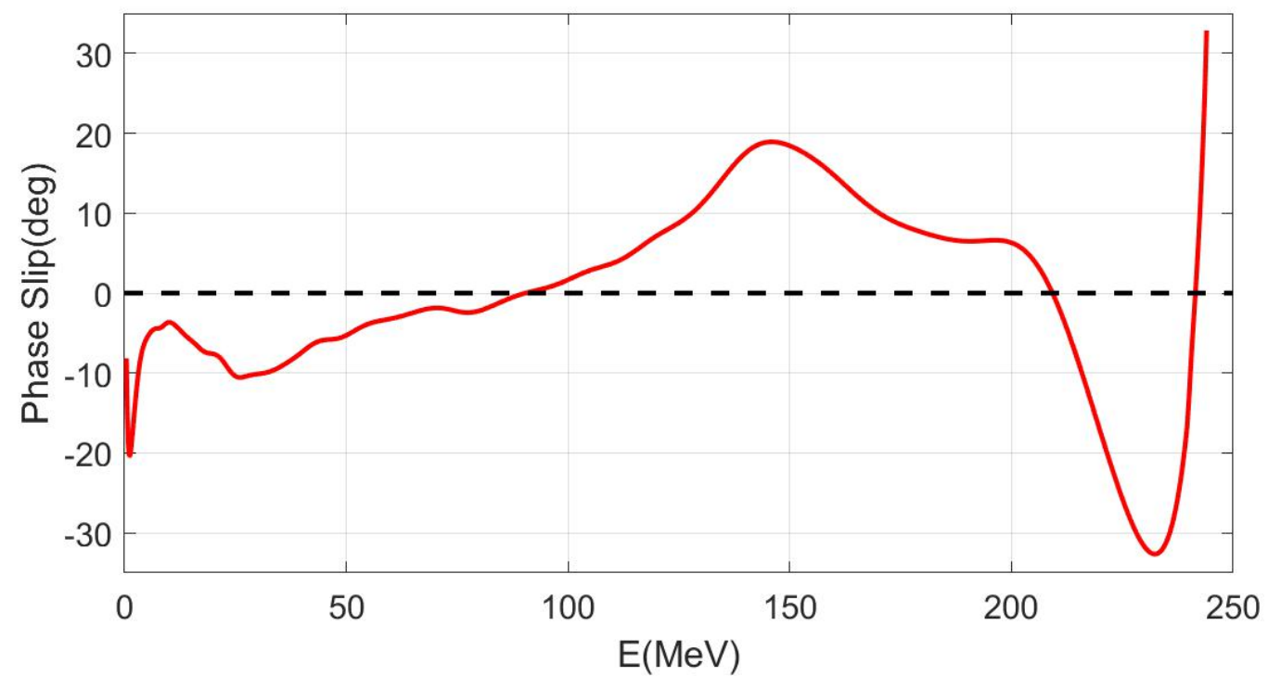
The results show that the magnetic field change solved by the algorithm is basically consistent with the actual measured magnetic field change, the average magnetic field error is less than 15%.





The isochronous error gradually decreases with every shimming. After the fourth shimming, the phase slip is kept within 35 degrees, which satisfies the requirement of isochronous acceleration.





Conclusion

A general analytical model is established to shim the average and first harmonic field Simultaneously for cyclotron. Based on the least square method and magnetic saturation approximation, a processing method of inclined 45° continuous cutting on the two pole sides is at the first time proposed to shim the field in compact superconducting cyclotron.The results of the shimming algorithm applied to the CYCIAE-230 show that, after four times of shimming, the isochronous error converges quickly, greatly reducing the cyclotron construction time. In the next step, the effects of the shimming algorithm on first harmonic compensation will be investigated by means of coil shift and cutting the pole edges.

MT 26th International Conference on Magnet Technology, September 22-27, 2019