

COMPUTER MODELING OF THE ISOCHRONOUS FIELD IN THE VINCY CYCLOTRON

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The nominal operating point of the VINCY Cyclotron is devoted to deuteron acceleration up to 30.2 MeV per nucleon. In this case, the isochronous field should be achieved only by means of iron. Ten circular trim coils per pole are used to enable other regimes. This paper presents the computing methods that are used to determine both the sector profile and the trim coil currents. In the former, the sector thickness is iteratively adjusted according to the local deviation from the isochronous field until a specified accuracy is reached. In the latter, the deviation from isochronous field is minimized by an optimal combination of the trim coil currents. In both cases 2D code POISCR has been largely used. To perform an automatic control of computation two programs have been developed that read the output and prepare the input data for the POISCR run in the next iteration. The final sector design as well as some alternative shapes are presented in this paper.

1. Introduction

The VINCY Cyclotron is a compact isochronous cyclotron with azimuthally varying field. It is designed to accelerate a wide range of ions (73 MeV deuterons, 66 MeV protons, heavy ions of lower energy etc.).¹⁻³ The azimuthal variation of the median plane field is achieved by four straight sectors per pole. Table 1 shows the most relevant sector data.

Table 1: General sector data

Angular span	42°
Spiral angle	0
Minimal radius	45 mm
Maximal radius	980 mm
Maximal thickness	64.5 mm
Minimal gap between the sectors	31 mm
Distance to the pole plate	15 mm
Rogovsky shape	920-980 mm
Material	Armco

The nominal operating point of the VINCY Cyclotron is devoted to deuterium acceleration up to 30.2 MeV per nucleon. In this case the magnetic field in the center is equal to 1.84 T with the main coil current of 650 A. The nominal isochronous field is achieved only by means of iron. Radial shimming of the median plane side of the sectors is used for that purpose. Contrary to the step-wise shimming, that is largely used throughout the cyclotron community, a continuous variation of the sector thickness will be applied to the VINCY Cyclotron. To do that, the sectors will be manufactured on a CNC machine.

There are ten circular trim coils per pole in order to enable other regimes. They are located in the space between the sectors and the pole. The coils are wound from a square

hollow oxygen-free-high-conductivity copper conductor with mineral insulation. The outer dimensions of the conductor cross-section are 8.8x8.8 mm². The details concerning the position of the trim coils are given in Table 2 and Figures 1 and 2.

Table 2: Trim coil parameters

Trim coil	Number of turns	R _{min} (mm)	R _{max} (mm)	I _{max} (A)
1	10	85.0	173.0	200
2	10	183.0	271.0	200
3	10	306.0	394.0	200
4	9	404.8	484.0	200
5	8	519.6	590.0	200
6	8	593.6	664.0	200
7	7	674.4	736.0	200
8	7	739.4	801.0	200
9	6	811.2	864.0	200
10	6	867.2	920.0	200

This paper presents the computing methods that have been used both to compute the sector shape which has to yield the nominal isochronous field, and to optimize the trim coil currents in order to obtain isochronous field in the other working regimes.

2. Computation of isochronous sector profile

A commonly used approach to achieve the isochronous field in a compact cyclotron is to apply sectors with radially varying profile whether in axial, azimuthal, or in both directions. Taking into account the requirements of the beam dynamics, special attention needs to be paid to the high accuracy that is requested both in computations and

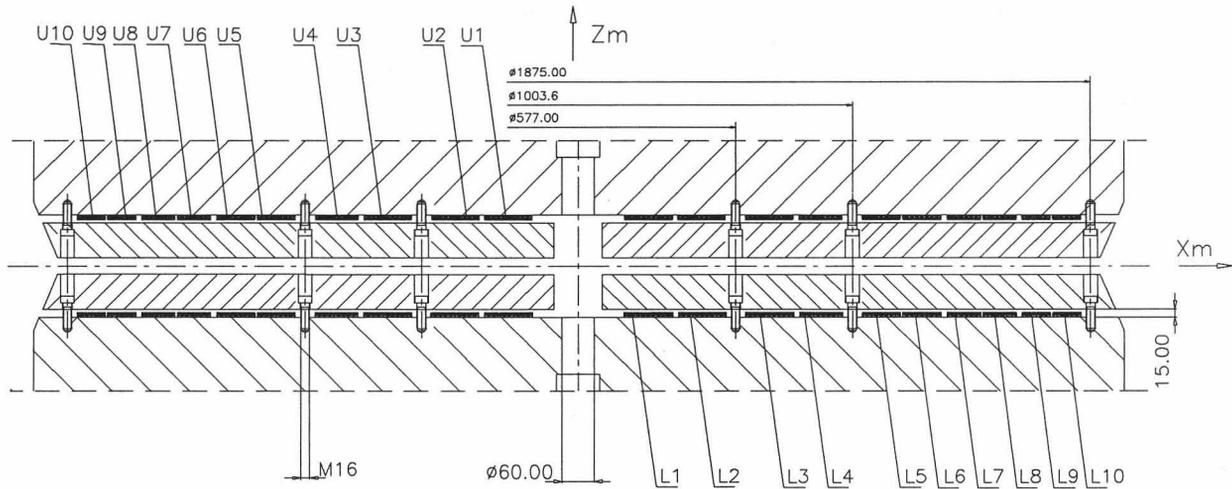


Figure 1: Vertical cross sectional view of the sectors and the trim coils

the manufacturing. The maximum local deviation of the actual field from the isochronous one, must be of the order of magnitude of 0.5 mT. Compared to the average field of 1.8 T, that means a relative deviation less than 0.03%.

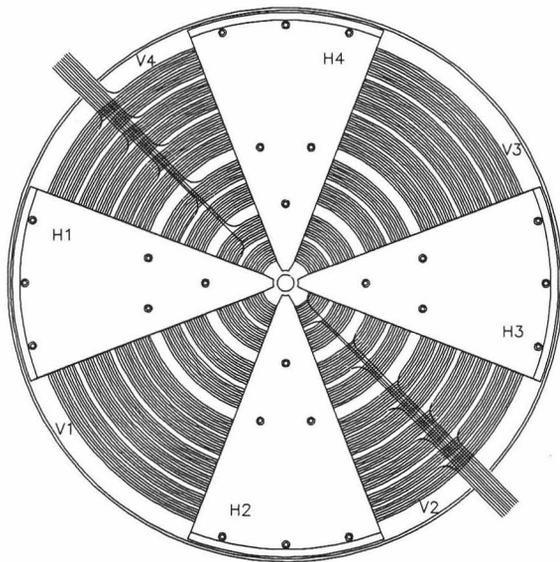


Figure 2: The trim coils view from the median plane

2.1 Computational algorithm

A simple but efficient computational algorithm is developed and presented in this paper. It consists of two steps that are iteratively repeated until the desired accuracy is reached. In the first step the main coil current is adjusted so that the actual field at the extraction radius is equal to the isochronous one. This is done iteratively by the Regula

Falsi method. In each iteration the magnetic field is computed by the 2D program package POISCR.⁴ In the second step the sector profile is changed according to the radial distribution of the deviation from isochronous field. To do this, the magnetic field is computed m times assuming that the half-gap $h(r)$ between the sectors obeys the following equation,

$$h_n^{i+1/2}(r) = h^i(r) - n \cdot c^i \cdot \varepsilon^i(r), \quad n = 1, \dots, m, \quad R_{min} < r < R_{ext} \quad (1)$$

where i is the iteration index, $h^i(r)$ denotes the half-gap from the previous iteration, c^i is a constant in each iteration, $\varepsilon^i(r)$ is the deviation from the previous iteration, R_{min} is the minimal radius from which the actual field should follow the isochronous one, and R_{ext} is the radius of extraction.

For each n the maximum deviation is computed. The case with the minimal value of maximum deviation is chosen as a starting solution for the next iteration, i.e.

$$h^{i+1}(r) = h_n^{i+1/2}(r) \quad \text{such that} \quad \max |\varepsilon_n^{i+1/2}| < \max |\varepsilon_k^{i+1/2}|, \quad k = 1, \dots, m$$

$$\varepsilon^{i+1} = \min \max |\varepsilon_n^{i+1/2}| \quad (2)$$

$$c^{i+1} = \begin{cases} c^i / m, & n < m \\ c^i \cdot m, & n = m \end{cases}$$

A control program is written in order to carry out the above algorithm. Its role is to read the POISCR output and to prepare the input file for the next step. Depending on the starting guess, 4-10 outer iterations are necessary to reach the accuracy of 0.5 mT.

To get a smooth solution for the sector profile, the finite element mesh of the magnetic field computation needs to be sufficiently fine. Hence, an irregular mesh with

$\Delta r = 10$ mm and $\Delta z = 3-6$ mm has been used for the median plane region. The total number of meshes is 240×170 that results in 41624 nodes. It takes approximately 2 min on a 90 Mhz Pentium computer.

2.2 Results

In order to test the method, as well as to study the effects of the sector shape in the end region, four series of computations have been carried out. The computed profiles are shown in Figure 3. The shape No 4 is adopted as the most convenient one. However, it has to be mentioned here that the magnetic computations have been carried out with constant stacking factors for the sector region. This assumption may lead to very unrealistic results. Therefore, an additional computation was performed with variable stacking factors as suggested in Ref. 5. The results for the sector shape No 4 are given in Figure 4. To get the final justification of the validity of magnetic computation, the computed profile will be checked with the 3D program TOSCA.⁶

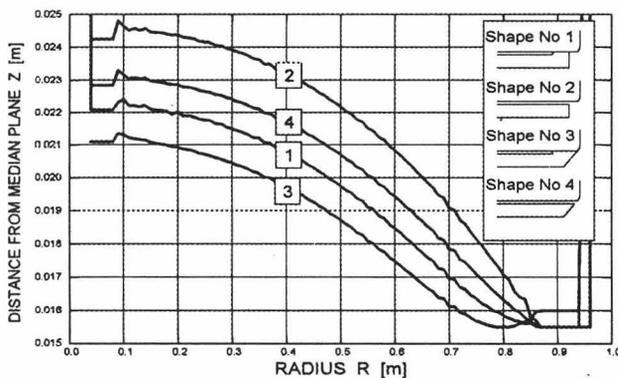


Figure 3: Isochronous profiles for various shapes of the sector end

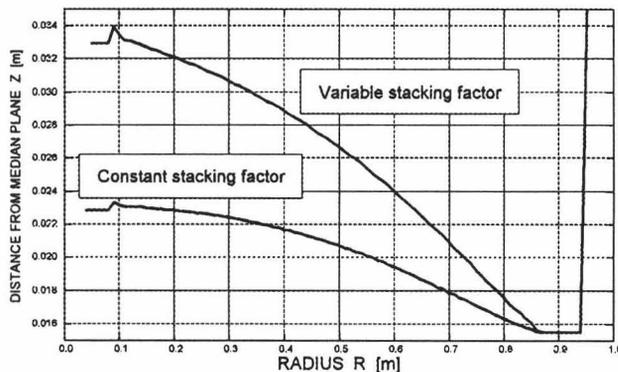


Figure 4: Isochronous sector profile computed by two different 2D models; constant and variable stacking factors

The sharp jump at the radius of 10 cm is due to the assumption that the sector thickness is constant for $r < R_{min}$.

3. Optimization of the trim coil currents

To get an impression of the accelerating possibilities of the VINCY Cyclotron the operating range is computed in terms of maximum deviation and presented in Figure 5. The role of trim coils is to correct the actual field for a given working regime. Figure 6 shows the necessary correction for various values of $\eta = z/A$ when the main coil current is equal to 1000 A. It is evident that the most inconvenient case is $\eta = 0.5$ due to the high gradient in the end region.

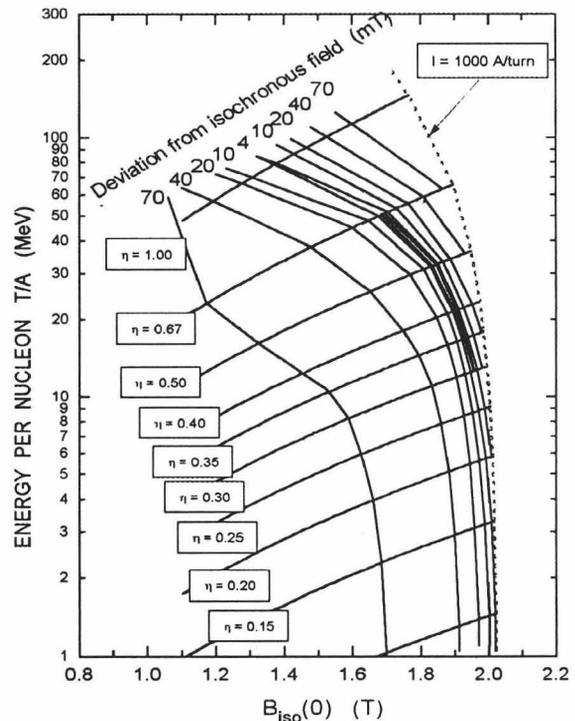


Figure 5: Operating range of the VINCY Cyclotron expressed in terms of deviation from isochronous field

In order to determine the optimal current distribution the following functional is considered:

$$F(I_k) = \int_{R_{min}}^{R_{max}} \left[\Delta B(r) - \sum_{k=1}^K I_k \cdot b_k(r) \right]^2 dr. \quad (3)$$

where $\Delta B(r) = B_{is}(r) - B(r)$, K is the total number of trim coils, I_k is the current, and $b_k(r)$ the response of each trim coil. The response is computed as a difference between the field with and without the related trim coil. Similarly, the necessary correction is obtained as a difference between the actual and the isochronous field. To do this a number of POISCR calculations are performed. The isochronous field is computed by the following formula that takes into account the azimuthal variation of the field,

$$B_{ia}(r) = \frac{B_0 \sigma}{\sqrt{1 - (C \eta \sigma B_0 r)^2}}, \quad \sigma = 1 - \frac{(B_N / B)^2}{2(N^2 - 1)}, \quad N = 4, \quad (4)$$

where B_0 is the field in the center and B_N denotes the N -th Fourier harmonic.

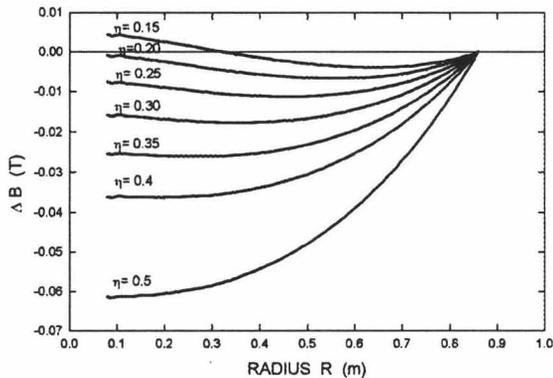


Figure 6: The necessary field correction for the main coil current of 1000 A

The downhill simplex method as used in the subroutine AMOEBA⁷ is applied to minimize the functional (3), where the current constraints are introduced by the following transformation,

$$I_k = I_{k,max} \sin(\alpha_k) \quad (5)$$

Figures 7 and 8 show the error distribution for several possible trim coil corrections. An additional degree of freedom of the trim coil correction is due to the fact that the actual field can be corrected with respect to some reference points other than the extraction radius. Then, the magnetic field at the radius of extraction is equal to a shifted value of the isochronous field. Figure 7 shows three such solutions when the maximum coil current is limited to 200 A.

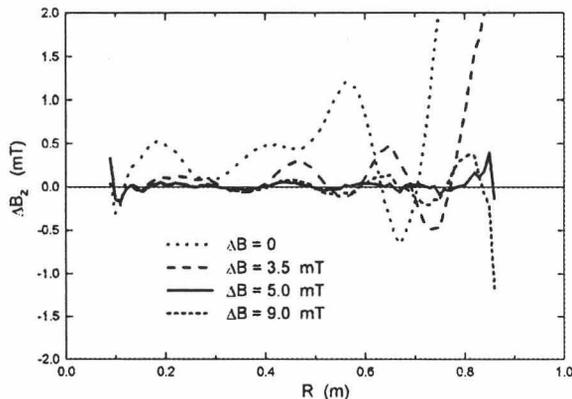


Figure 7: Error distribution of the corrected field for various values of the reference correction

Another possibility to achieve the necessary field correction is to increase the maximum trim coil current. Figure 8 compares three such solutions. It is evident that by increasing the maximum current the error is substantially decreased. However, in this case the cost of power supply is remarkably increased as well. Thus, to reduce the cost the maximum current is fixed to 200 A.

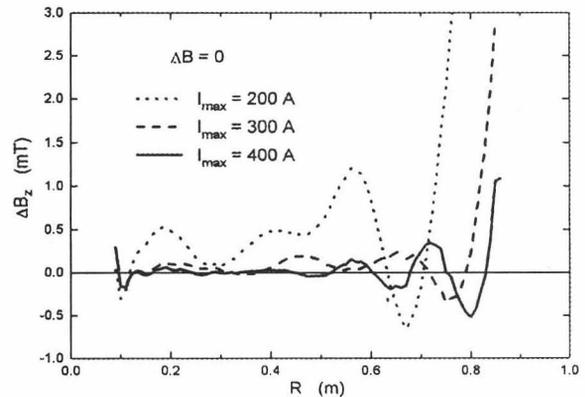


Figure 8: Error distribution of the corrected field for three values of maximum current

4. Conclusions

In order to model the isochronous field of the VINCY Cyclotron, two computing methods have been developed and presented in this paper. They were extensively used to study various effects. As a result, the final design both of the sector and the trim coils is obtained according to the multipurpose character of the machine.

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