CORRECTING COILS OF THE ORSAY 80-INCH ISOCHRONOUS CYCLOTRONS

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The isochronous heavy-ion cyclotron (CEVIL) at Orsay is based on the use of materials of different magnetic permeabilities[1]. This method overcomes the necessity of using circular trimming coils. The coils placed in the valleys are sufficient to assure isochronism for the various heavy ions (e/m = 0.5 to 0.1) accelerated in magnetic fields of between 5 and 14 kG. The number of coils was reduced to a minimum to facilitate the adjustments of the cyclotron. Each coil consists of only one turn so that it can be fastened to the pole piece without insulation on the conductor. It is also worth noting that the power dissipation in the trimming coils is low (10% of the total magnet power).

Principles of the Method used for Correction

Metallic shimming is used for adjusting the topography of the field such that a specified ion describes a theoretical closed orbit[2]. For this ion, described at each point by its intrinsic coordinates, ρ,α, we have

$$B_1(\rho,\alpha) = \frac{\bar{B}_1(R)}{1 + \lambda(R, \alpha)} ,$$

with $\rho = R[1 + \lambda(R, \alpha)]$ and $\bar{B}_1 (R) = B_1^s (R)$,

and where λ is the modulation law, B^s the isochronous field, and $\bar{B}_1$ the average field over an equilibrium orbit. For another particle this equation will become

$$B_2(\rho,\alpha) = \frac{\bar{B}_2(R)}{1 + \lambda(R, \alpha)} .$$

Since there is no correction on the hills, all the correction has to be done in the valleys. To maintain a constant average field at the mean radius of the exit orbit the main field is increased by an amount

$$\Delta B = \bar{B}_2 (o) - \bar{B}_1 (o) .$$

The isochronous law is then adjusted by the correction coils, giving

$$B_2 = \frac{\bar{B}_2(R)}{1 + \lambda_2\ (\rho,\ \alpha)} \quad \text{with } \bar{B}_2(R) = B_2^s(R)\ ,$$

where $\lambda_2(\rho,\alpha)$ is the new modulation law. The only means of determining the difference between the effective average field and the theoretical isochronous field, $\bar{B}_2(R) - B_2^s(R)$, and how the modulation law has been deformed, is by calculating the closed orbits from the corrected field.

Choice of the Correcting Coil System

The first step consisted in determining the minimum number of coils required to give a maximum field error of less than about 10^{-4} and hence in finding an approximate value for the correcting currents.

Determination of the Theoretical Correction: These corrections had to be estimated before the computer programmes for the closed orbits which use the measured fields had been finished. This led to a choice between the two following simplified procedures:

(a) Calculation of the average field due to each turn $H_i(r)$ and the determination of a set of currents such that

$$\sum_{i=1}^{s} I_2\ H_i(r) = B_1^s(r) + \Delta B - B_2^s(r)\ .$$

This assumes, on one hand, a knowledge of the average field along a circle whilst in fact it is given along a theoretical orbit, and, on the other hand, that the average field is independent of the modulation, which is not true.

(b) Calculation of the field on the axis of a valley assuming that the resulting field correction is good for the whole orbit and that the radius for which the correction is calculated is not affected by variation of the modulation. Calculation has shown that an increase of 0.5% in λ results in a corresponding variation of 0.5 mm in r. (Fig. 1).

The second, and simpler, method was adopted.

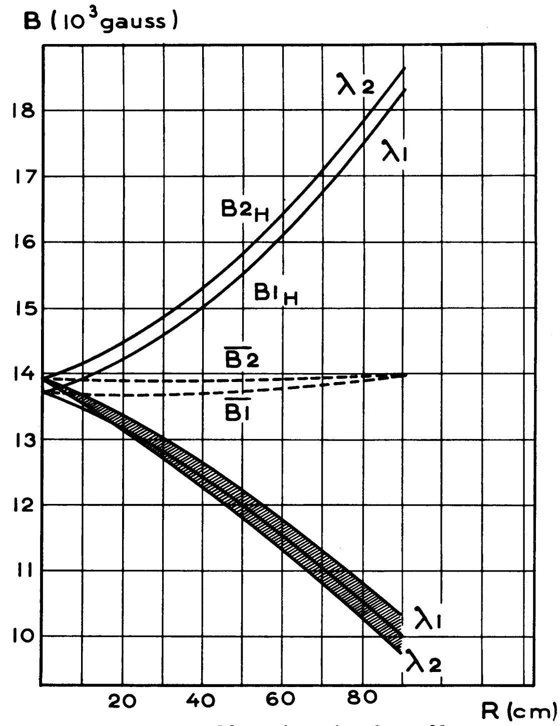

Fig. 1 Correcting field on the axis of a valley.

Let $\Delta B = B_2^s(0) - B_1^s(0)$ be the increase in the main field, then, supposing that small variations in the current in the magnet have a linear effect on the whole pole face, the field along the axis of the hill becomes

$$B_{2h} = \frac{\bar{B}_2(R)}{1 - \lambda_1(R)} + \Delta B \ ,$$

to which corresponds a new modulation,

$$\lambda_2 = 1 - \frac{B_2^s(R)}{B_{2h}} \ .$$

The next step is to estimate the correction field required for an average field $\bar{B}_M$ on the exit orbit of average radius R_M, where $\bar{B}_M$ and R_M are constant.

Put $B = \frac{1}{\pi\rho}$ with $\pi^2 = \frac{1}{R^2 \bar{B}_h^2} + \frac{q^2}{M_o C^2}\left[\frac{R_h^2}{R^2} - 1\right]$,

where π is some parameter, then the field in a valley will be equal to

$$B_{2\nu} = \frac{B_2^s}{1 + \lambda_2} = \frac{1}{\pi_2 R\left[2 - \frac{1}{\pi_2 R\left[\frac{1}{\pi_1 R(1-\lambda_1)} + \Delta B\right]}\right]} \ ,$$

and hence the correction B(r) required along this axis is

$$B(r) = \frac{1}{\pi_1 R(1+\lambda_1)} + \Delta B - \frac{1}{\pi_2 R\left[2 - \frac{1}{\pi_2 R\left[\frac{1}{\pi_1 R(1-\lambda_1)} + \Delta B\right]}\right]} \ .$$

Determination of the Minimum Number of Coils and Calculation of the Currents

Preliminary tests on a 1/7 scale model showed that 5 coils were sufficient to produce a correction B(r) with an error of 1%. The tests were made again on the 2 meter magnet with a turn every 2 cm. The 5 coils giving the optimum correction were chosen on the basis of the results from a computer calculation (Fig. 2). The classical least-squares method leads to alternatively positive and negative currents of more than 7,000 A for a maximum correction field of 300 gauss. It is impossible to divide

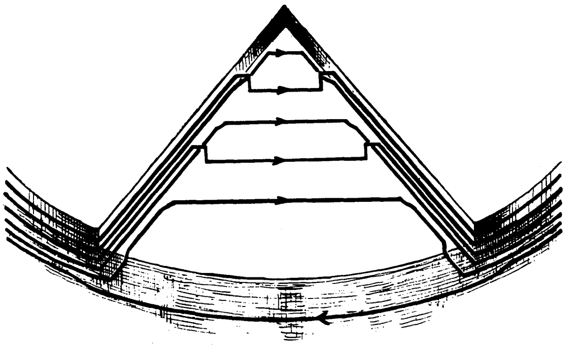

Fig. 2 Trimming coil valley.

5 coils into two groups to be used consecutively in the least-squares method[3]. Thus, an empirical method had to be adopted; it consisted in choosing 5 points for which the difference between the theoretical and the experimental fields was zero

$$\sum_{i=1}^{5} I_i H_i (r_j) - B (r_j) = 0 .$$

The r_j were chosen by successive permutations in such a way that the error was evenly distributed and that the currents were of the same sign and suitable intensity.

The resolution of the linear systems and the calculation of the errors was done on the CAB 500 computer. These calculations gave the following currents

65 A, 860 A, 1,040 A, 1,160 A, and 3,800 A

for the maximum corrections (e/m = 0.1) at 14 kG. The error on the axis is less than 4 G up to

$$R/R_{max} = 0.7$$

For the other ions, the first-order field correction is proportional to

$$\frac{\Delta B_i}{\Delta B_k} = \frac{(\frac{e}{m})_1 - (\frac{e}{m})_i}{(\frac{e}{m})_1 - (\frac{e}{m})_k}$$

Measuring Apparatus. This includes a Hall-effect probe (Siemens FA 23) temperature stabilized to $1/10^{o}$C the current of which is regulated to $\pm 3 \times 10^{-5}$, and a counter-voltage stabilized to $\pm 1 \times 10^{-5}$. The Hall potential due to the main field is compared with the reference potential, then a current of 2,000 A is sent successively through each coil and the resulting field, $H_i(r)$ is measured.

Field Optimization

The effective influence of the coils on the modulation in all the sectors has to be taken into account. A series of measurements of the field distributions with and without correction will be made after the chosen coils have been mounted.

The isochronous condition requires

$$\oint [B_1(r_j) + \Delta B(r_j) - B_2(r_j)] d\theta = \sum_{i=1}^{5} I_i \oint H_i(r_j, \theta) d\theta$$

$$\bar{B}_1(r_j) + \Delta B(r_j) - \bar{B}_2(r_j) = \sum_{i=1}^{5} I_i \bar{H}_i(r_j),$$

where the r_j are chosen as before.

A computer programme on the IBM 704, of which a simplified diagram is given in Fig. 3, permits a comparison of the corrected and theoretical fields. The deformation $\Delta\lambda$, the error $\Delta\mu$ on the normal to the orbit, and the velocity law can be obtained from the error $\Delta B/B$ calculated from the intrinsic coordinates of the closed orbits. This can be used to give the new distribution of the correcte field. The currents are recalculated in the same manner to take into account the successive modification of the average field.

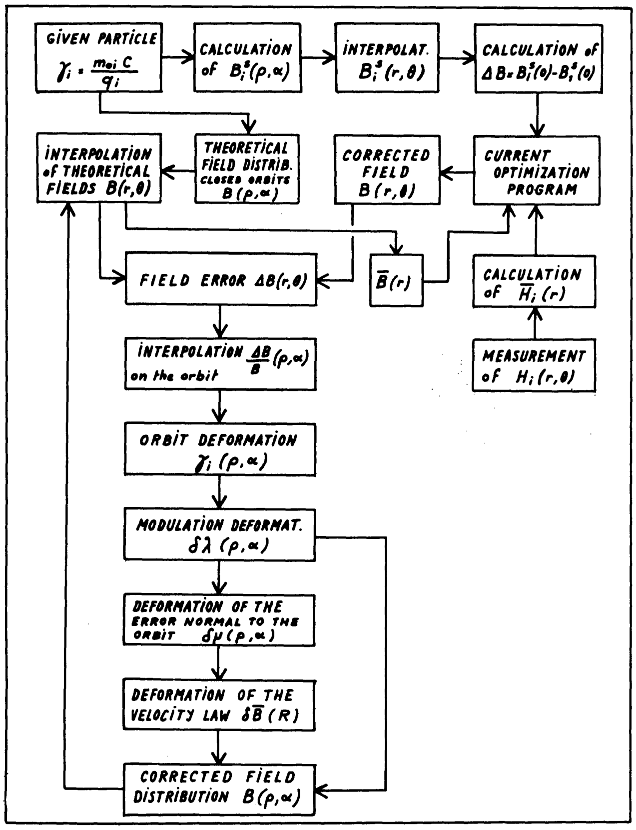

Fig. 3 Computer programme diagram.

References

1. A. Cabrespine and M.P. Bourgarel, Nucl. Instr. and Meth., 18-19, 81 (1962).
2. F. Fer, Nucl. Instr. and Meth., 18-19, 229 (1962).
3. H.G. Blosser, Nuclear Science Series, Report No. 26, 121 (1959).

DISCUSSION

BERKES : What is the maximum field difference to be corrected by the coils?

BIETH : It is about 300 gauss.