THE ISOCHRONISM IN THE S.I.N. 590 MeV RING CYCLOTRON

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Abstract

Achieving isochronism on the S.I.N. ring cyclotron was done in several steps including adjustment of sector width, variable gap, side shims and trimcoils.

Actual beam measurements on isochronism are reported and comparisons are made with the calculated predictions. In autumn 1974 an improvement could be achieved by slightly adapting the RF frequency.

With small excitations of the trimcoils we expect to get the magnetic field isochronous to ± 2° giving a good basis for future flattop operation.

Historical Survey

In the initial consideration for the construction of an isochronous cyclotron, isochronism itself is not the primary problem. It just gives one fairly simple boundary condition on the magnetic field integral. Design problems of magnets, RF systems, vacuum, injection, extraction and beam probes, all squeeze together into the task of getting a decent layout of the cyclotron. Tightly coupled with this is the search for a good shape of the magnetic field which is dominated by focusing considerations. Hard-edge approximation of the magnetic field is a good help for finding a layout. Even refined methods, however, tend to give poor results on focusing. In order to investigate focusing properties, the most helpful tool is a computer program performing the function of the "chewing-gum-cyclotron",i.e. numerical simulation of pole geometry changes or of the magnetic field itself.

For the S.I.N. ring cyclotron1), the first layout of the magnets proved to give insufficient vertical focusing at higher energies. While increasing the spiral angle the side contours of the magnets were fixed to be pure circles for simplifying the machining. The radial increase of the average field necessary for isochronism was then produced by adapting the pole gap.

This was the point were the long process of isochronizing through magnetic field shaping actually started. Taking field maps and investigating them thoroughly on the computer became a standard job for many years. First it was done 1 : 5 models then on single sectormagnets and finally on single magnets in their surroundings in the ring. Within this procedure the relative revolution time error was diminished from 5 % to 10^{-3} by proper shaping of the variable pole gap and brought down further to 10^{-4} by shimming.

The fine correction with side shims on the final magnets worked so well that part of the planned trimcoils were not built in. As a matter of fact, in the first beam tests it turned out that the beam could be extracted without any trimcoil being excited. Measurements of **particle phase dependance** on the radius showed the existance of phase excursions up to 50°. With a change of the reference frequency from 50.66 to 50.63 MHz and an appropriate adaptation of the field level, these excursions could be brought down successfully to ± 5° without using trimcoils.

The Magnet Gap Curve

The first steps in shaping the sector magnets brought the relative isochronism errors down from ≃ 8 % to 1 %. In this period, field corrections were simultaneously done through gap changes and sector width adaptations. The next steps, which aimed to achieve isochronism of approximately 10^{-3}, used small changes in the pole gap only.

For the highly saturated magnets, the field change was no longer linear with the gap change. Therefore, the possible effectiveness function for a desired gap change was first empirically determined by measuring the effect of pole-shims which represented a very rough approximation of the desired change. This method helped to speed up the convergence of gap shaping. Especially after the decision to raise the extraction energy from 520 to 590 MeV, the time schedule to establish the new gap curve was very tight. Nevertheless, due to a concentrated effort using parallel work on 1 : 1 and 1 : 5 scale magnets and relying on the methods having been established before, the final machining of the sectormagnets could start in time.

Data Processing

From the first theoretical investigations on,special care has been taken to benefit from the use of computers. Actually, the success of the S.I.N. ring cyclotron would not have been possible without computers. During all the years of planning and construction, a series of programs well matched to each other has steadily been built up: the so-called S.I.N. data mill2).

The field maps have normally been taken in a polar coordinate system with spacings of .25 angular degrees and 2 cm, extending on both sides 24 degrees from the hill center line. The time needed to measure those 30,000 data points, could be diminished from 99 hours

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for the first map to 2.5 hours for the later routine measurements.

The measurement machine providing this speed was a good piece of precision work having 132 flip coils embedded in a 2.6 m long titanium rod. The steering of the process and the recording of the integrated voltages on tape was done with a small computer (first PDP8S, then HP 2145).

The first step in the data mill consisted of format changes, completeness checks and conversion of voltage data into magnetic field values. The next program did checks on smoothness replaced erroneous or missing points and was able to extrapolate the field by fitting on other given field data or analytical functions. Another program in the chain updated the field in order to simulate the neighbouring magnets if necessary. The simple super-position formula $B(R, \Theta) = B(R, \Theta) * (1 - \varepsilon_1) + B(R, \Theta - 45^o) * (1 - \varepsilon_2)$, where ε_1 and ε_2 are small empirical constants, had been developed from measurements on 1 : 5 scale.

Before doing orbit integration, the field data were smoothed by the method of fourier-analysis and Lanczos' weighed re-synthesis3). Each magnet has been measured separately. A 360 degree ring field has then been obtained as a synthesis from an appropriate combination of the individual fourier components.

Two different codes for orbit integration are in use at S.I.N. One performes the task of iteratively searching for equilibrium orbits or for orbits having a prescribed difference between initial and end points. The other one is for direct integration from given initial conditions. This one can add various magnetic field changes like local shims or electric and magnetic channels. A series of general utility programs for data reduction and automatic plotting enhances the efficiency of computer application in general.

Theoretical Considerations

The isochronism error as a function of radius is obtained from a series of orbits. It is a basic problem4) to find the corresponding changes of the magnetic field. A possible first step towards its solution is to present the inverse function in a matrix form5). A given magnetic field is successively modified at one radius after the other. The isochronism changes obtained at different radii form successive columns of the $\Delta T/\Delta B$ matrix. This influence of a field change vector on an isochronism change is a band matrix. For the S.I.N. ring cyclotron its dimensions are 132 x 132 with five non-zero elements on each side of the diagonal. The method described above produced undershoot effects in the off diagonal elements. This originated from the Lagrange method used for radial interpolation. Later on, a procedure was developopped to determine the $\Delta T/\Delta B$ matrix directly from the orbit scalloping and the azimutal field profile (Fig. 1).

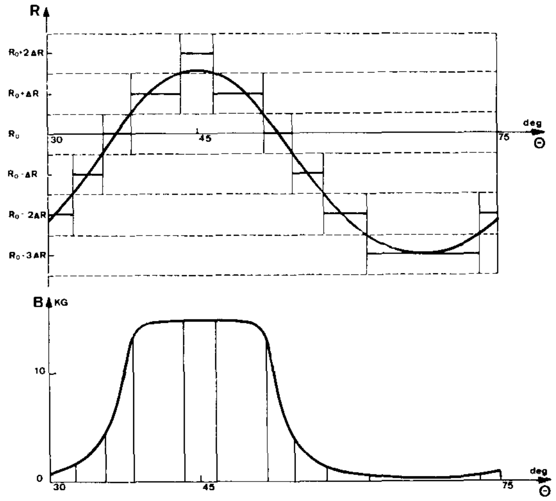

Fig. 1

Method of determining the $\Delta T/\Delta B$-matrix from orbit geometry. Example given at 75 MeV.

Starting on the matrix-diagonal, row-elements correspond to the radial regions around R_o, $Ro \pm \Delta R$, $Ro \pm 2\Delta R$ etc. The relative weight of the elements is given by the azimutal length of the orbit in the corresponding radial region multiplied by the magnetic field averaged over the same azimutal length. The sum of all elements in a row is $-(\gamma^2 * \langle B\rangle)^{-1}$ where $\langle B\rangle$ is the magnetic field averaged over the whole azimutal range.

Having found the matrix, we first tried to invert it and have a general solution to our problem. But this came out as complete nonsense. The following simple reasoning shows that it had to be so. A delta function in $\underline{\Delta B}$ produces a finite size distribution in $\underline{\Delta T}$. So what do you expect to find which is much narrower than a delta function in $\underline{\Delta B}$ to produce a delta function in $\underline{\Delta T}$? Nevertheless, the matrix is very helpful since you can normally solve the implicit problem to find the $\underline{\Delta B}$ for a reasonable a given $\underline{\Delta T}$. Still, when a given $\underline{\Delta T}$ contains too steep edges, one gets bad results characterized by meaningless, strong fluctuations in $\underline{\Delta B}$.

For isochronous cyclotrons, a small change in magnet excitation is usually equivalent to a small frequency change. Above proton-energies of 90 MeV ($\gamma > 1.1$), however, this rule is violated (Fig. 2). The difference is explained by the formulas $\Delta T/T = - \Delta fRF/fRF$ and $T/T = -(1/\gamma^2) * \Delta B/B$, where the factor $1/\gamma^2$ has little effect at lower energies.

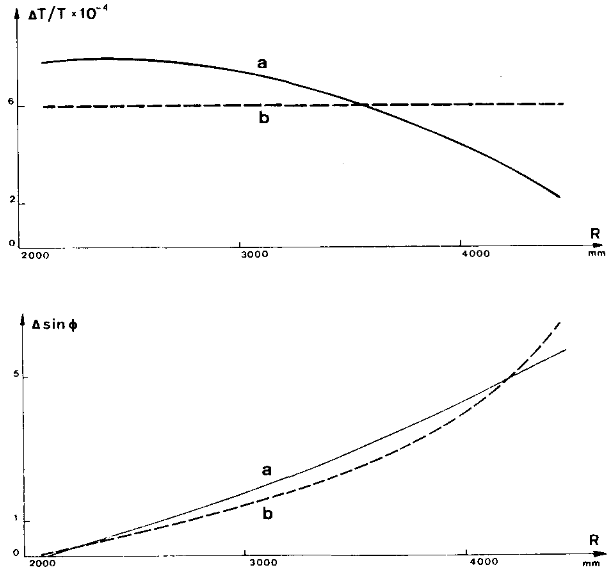

Fig. 2

Changes in relative revolution time and phaseslip produced by:

a) lowering the magnetic field excitation by 3.5 Amp.

b) increasing the RF-frequency by 30 KHz.

The choice is left open between RF frequency and magnetic field to use for the fine-adjustment of isochronism. By adjusting both, an additional possibility arises to correct for small triangularly shaped timing errors extending over the full radial range. The typical form of phase error vs. radius correctable in this manner is given in Fig. 3.

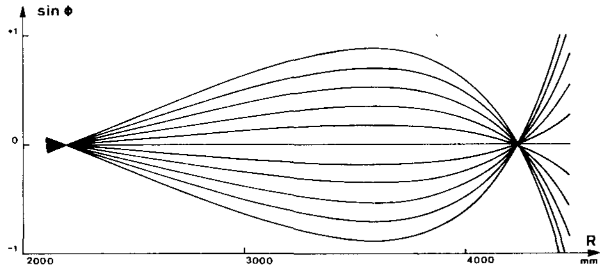

Fig. 3

Changes in the particle phase as a function of radius obtained from a combined shift of RF-frequency and magnetic field. The step between two lines is 10 KHz and 1.17 Amps.

Shimming

The shims used to isochronize the S.I.N. ring cyclotron are small pieces of iron, 1 to 12 mm thick, 30 mm high and between 30 and 200 mm long. They are clamped to the side-surface of the magnet-pole along the pole edge.

The isochronism error of each magnet was obtained by computer-evaluation of a field map. A series of fundamental measurements and the results of previously corrected magnets provided the basic knowledge about shim-effects. Then the appropriate shim-configuration was determined and refined in three to five iterations The minimum time needed for one iteration was 48 hours. To make life easier, the shims have been quantized to 0.5 mm in thickness. The lengths, however, were adjusted to an accuracy of 2 mm to achieve the best correction.

An attempt was made to determine the shims with the computer. We found a satisfactory mathematical representation of the shim effects (Fig. 4), but the problem of finding the proper length of each shim is so highly non-linear that, with the restricted manpower we could invest in it, we never brought the program so far as to converge reasonably.

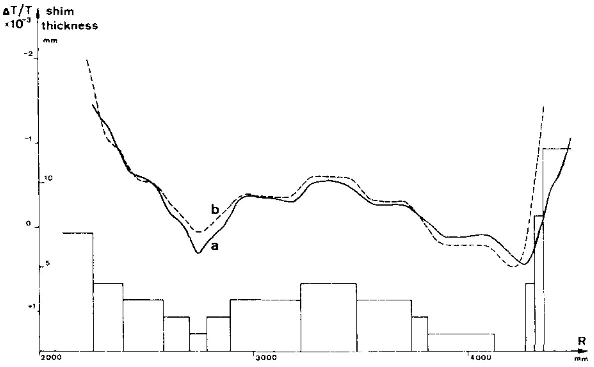

Fig. 4

Relative change in particle revolution time produced by the shim-configuration used for the 1st iteration on magnet D6.

a) from field data processing,
b) prediction from a mathematical model.

The original aim to reduce the error in relative revolution time to 10^{-4} could not be reached completely since some error-curves contained higher gradients than the shims could correct. Still the calculation predicted the phase slip in the ring to be within ± 5°.

The simulation of neighbouring magnets for fields having been measured alone worked reasonably well but not quite to our standard. Therefore, one to two additional shim-iterations were done on the fields measured with both neighbouring magnets in place and excited.

Each magnet has been isochronized for his own, but, naturally, all to the same frequency. Since this condition completely freezes the field integral at all radii, dangerous harmonic bumps could only occur if the pole contours or the iron quality of different magnets would be different by an unrealistic amount.

Phase Measurement with the Beam

The accelerated particles are the real test of isochronism. In order to measure the phase as a function of radius, the main field was detuned and the corresponding maximum radii of the beam were determined. For the evaluation, we use the knowledge about the effect of a magnetic field change upon the phase, obtained from field measurements. All the phase values at the different maximum radii are then transformed back from ± 90° to the value they had at the field level where the beam was extracted. This method gave an accuracy of about 5°. Other methods like γ-detection and capacitive probes are still in development for more precise measurements in the future.

The first measurement showed phase excursions up to 50° (Fig. 5). The form of the error was very similar to the one correctable with a frequency shift of -30 KHz with adapting the magnetic field as described before. After the frequency shift the next measurement showed even a bigger error in the other direction. Later,we found out that in this case the magnet has not been turned on with the proper ramp. The final measurement showed then the phase being mainly within ± 5°, near to the precalculated values.

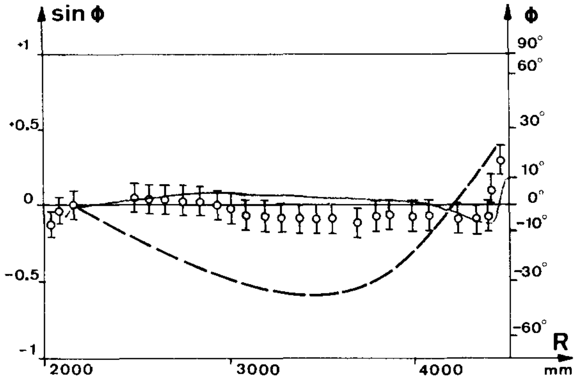

Fig. 5

Particle phase vs. Radius

______ calculated prediction fRF = 50.65 MHz

------ first measurement fRF = 50.66 MHz

final measurement, properly turned on magnet fRF = 50.63 MHz

Trimcoils

The S.I.N. Ring Cyclotron has two types of trimcoils. Number 1 - 3 and 15 - 18 have one winding with up to 200 Amps., closing itself outside the magnet pole surface. The others have nine windings with up to 25 Amps. (= 225 Amp. * turns) and form individually closed loops on the pole surface. Coils 6 - 14 are mounted only on 4 of the 8 magnets. The change of the hill field obtainable is 40 - 60 Gauss compared to the field level of 15 - 21 kGauss. The small pole gap allowed only a total construction height of 11 mm for the trimcoils including insulation and water cooling, which had posed enormous technical problems.

Around injection and extraction many trimcoils are excited asymmetrically to do vertical steering of the beam. For the small isochronism corrections still necessary, only 25 % of the trimcoils are used. They are excited not more than 30 % of their maximum current. This leaves a reasonable reserve for fine adjustment of the phase, based on more precise measurements, as it will become important for flattop acceleration planned to be installed in 1977.

Acknowledgement

The reader should consider the author much more as the reporter than as the originator of the work described. Out of the long list of people involved I should like to mention especially H.A. Willax, B. Berkes, H. Braun, W. Joho, G. Rudolf.

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