ISOCHRONOUS FIELDS FOR THE NAC SEPARATED-SECTOR CYCLOTRON

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ABSTRACT

Four 34^0 sector magnets and 41 power supplies are used to generate the isochronous fields required to accelerate variable-energy light and heavy ions in the NAC 200 MeV separated-sector cyclotron (SSC). Use is made of a data base which has been established from the results of extensive field measurements to evaluate the SSC field accurately (10^{-4}) for any given excitation of the magnets. The excitation characteristics are reviewed with particular emphasis on the various factors influencing the field and isochronism.

Procedures developed to obtain isochronous fields are presented. The isochronization method is based on orbit calculations in compiled magnetic fields and computes improved current settings for the 41 power supplies, taking into account the properties of the magnets. Microprocessor-based procedures have been developed to improve the field isochronization, using the results of phase measurements. Observations made during the first two years of machine operation are interpreted in terms of predicted current settings.

1. INTRODUCTION

The NAC separated-sector cyclotron is a variable-energy light-ion and heavy-ion accelerator used for physics research, isotope production and radiotherapy. It is designed to accelerate protons from 25 - 200 MeV at resonator frequencies between 6 and 26 MHz, operating on harmonic numbers h=4 and h=12. A report on the present status of the machine is given elsewhere in these proceedings.[1]

Since the commissioning of the SSC, protons have been accelerated over the full energy range from 27 to 200 MeV. Alpha particles have been accelerated to 140 MeV and singly-charged helium to 50 MeV. Heavier particles will be accelerated as soon as the second injector cyclotron is completed. A 66 MeV proton beam is required for radiotherapy once a week (for three days), so that at least two energy changes are performed every week. It is therefore important that reproducible magnetic fields can be set reliably and furthermore that these fields be as isochronous as possible, in order to reduce the time required to set up the SSC field during energy changes.

Magnetic fields in the SSC are excited by four sector magnets, which produce fields up to 1.27 tesla. Fields are adjusted for isochronism with 29 pairs of trim-coils in each of the sector magnets.[2]

This paper describes the isochronization method based on orbit calculations in compiled fields and the procedure used to obtain improved current settings for the power supplies, taking into account the excitation properties of the magnets.

2. MAGNET EXCITATION CHARACTERISTICS

The four 34^0 sector magnets are conventional C-shaped electromagnets. Pole and yoke coils are provided for the main excitation of the magnets. The pole coils of the four sector magnets are connected in series to one power supply. The yoke coils are powered by four separate power supplies and may also be used to generate first and second field harmonics in the SSC. The radial field gradient required for isochronism of particle orbits is produced by 29 pairs of trim-coils situated above and below the pole gap (outside the vacuum chamber). The current loops of the first fourteen coils are closed around the apex of the pole plates at injection; the remaining

15 coils are closed around the base. Thirty-six power supplies are connected to the trim-coils. Most of these coils are connected in series over the four sectors, one or two radial pairs at a time. However, to provide individual control, especially near injection and extraction, twenty-two of the power supplies make provision for sector-independent field trimming.

The magnets have a relatively strong non-linear excitation characteristic which is usually associated with a considerable relative change of its fringe and stray fields. In the case of the SSC the yoke coil current on each sector is determined in such a way that the relation between the pole coil current and the reference field level in the pole gap is linearized over the whole excitation range. As a direct result, the effective magnetic sector width and the azimuthal field shape in the SSC are nearly independent of the field level and the shape of equilibrium orbits is therefore kept approximately constant for all ions and energies. The effective magnetic sector angle increases radially from 33.53° at injection to 33.82° at extraction and varies only by ±0.02° in different sectors. The slight decrease with respect to the original design value of 34° can be related to the higher steel reluctance. The radial field shape in the pole gap of the magnets changes up to 1% with excitation.

The trim-coils are connected in such a way that, with a positive current, the first fourteen trim-coils reduce and the last fifteen trim-coils increase the main field. This arrangement has the advantage that the combined excitation of all trim-coils does not affect the total flux in the magnet much, but merely distributes the flux in a different way. The field level between trim-coils 14 and 15 at radius 3.351m is thus almost unaffected, so that this position on the magnet hill line is selected as a reference radius R_{ref} with associated magnetic field B_{ref}.

Each trim-coil can produce a radial field increment up to 19mT. The excitation characteristics of trim-coil fields are linear in current, but depend on the main excitation of the magnet. Using magnetic circuit analysis, the offset as well as the observed reduction in effectivity can be determined. When isochronous fields are predicted, the trim-coil excitation is essentially determined from the required change in the base field, using the total trim-coil effectivity. Near injection the field in the pole gap must be higher to compensate for the reduced effective magnetic sector angle, with the result that the trim-coil currents reverse direction there. We compensate for the total remaining trim-coil offset with a slight increase in the main excitation of the magnets.

About 800 sector fields have been measured at radial intervals of 20mm and azimuthal intervals of 1/4° or 1/2° at six field levels viz. 0.25T, 0.5T, 0.75T, 1.0T, 1.15T and 1.25T. A data base has been created which contains (for each sector at the six field levels) the base field of the main excitation, the influence of yoke coil current changes on its own and other sectors, the influence of trim-coil excitations and the influence of the injection and extraction bending magnets.

3. PREDICTION OF ISOCHRONOUS MAGNETIC FIELDS

3.1 Isochronization Program

A program has been written to isochronize the magnetic field for a given particle and isochronous frequency. The program integrates the following equations of motion,[3)]

$$\frac{dr}{d\theta} = \frac{r\alpha}{\sqrt{1-\alpha^2}}$$
$$\frac{d\alpha}{d\theta} = \sqrt{1-\alpha^2} - \frac{qr}{p}B(r,\theta) \qquad (1)$$
$$\frac{ds}{d\theta} = \frac{r}{\sqrt{1-\alpha^2}} \quad .$$

with $\alpha = p_r/p$. Orbit integration is started in a valley with zero radial momentum for a certain normalization C_{old} of the magnetic field and continued through the sector which is to be isochronized until the next valley is reached. The final momentum p_r is used to predict a new value of the normalization C_{new} which yields a zero final radial momentum,

$$\frac{C_{new}}{C_{old}} = \left[1 - \frac{\sin^{-1}p_r/p}{\theta_{fi}}\right]^{-1} \quad . \qquad (2)$$

where $\theta_{fi} = 90°$ is the integration angle. An initial value for C is found from the ratio of the values of the hard-edge magnetic field to the magnetic field on the hill of the corresponding hard-edge orbit. The procedure is iterated to convergence at a series of initial valley radii to obtain as result a set of orbits, each with its associated normalization factor C. These data may be used directly with interpolation of the magnetic field to obtain the predicted isochronous magnetic field. Also obtained from the isochronization code are radius and isochronous magnetic field values on the magnet hill, which are used to predict main coil and trim-coil current settings.

The isochronization program was used extensively in calculations required to predict magnet current settings for simulated isochronous magnetic fields measured in the series of field measurements on the sector magnets, and later to obtain the isochronization data for the ensuing measured fields. These simulated fields were measured in each sector magnet for representative charge-to-mass ratios and energies.

3.2 Isochronization of Sector Fields

A program has been written which utilizes the magnetic field master file to predict current settings of the main and trim-coils for a required isochronous magnetic field in a single magnet sector. The predictions are obtained by fitting the field specified by the isochronization code on the magnet hill line only. The point at radius 3.351m is taken as reference as explained previously. Interpolation of the main field between the six base fields yields the main coil current required to produce the field value at the reference radius. Use is then made of a trim-coil effectivity of 19mT per 500A to calculate a current setting for each of the 29 trim-coils. Normally the combined effect of all trim-coils causes a slight reduction (offset) of the total field at the reference radius. We compensate for this offset by increasing the main coil current and by repeating the prediction for the trim-coil settings. The process is iterated to convergence, i.e. until the compiled field value agrees with the required field value at the reference radius.

In the sector magnet where injection occurs (SM1), trim-coils 1 and 2 are absent and trim-coil 3 is not as wide as those in the other three sector magnets, owing to the presence of the magnetic inflection channel. The predicted current of trim-coil 3 is adjusted to produce the correct average field over this area.

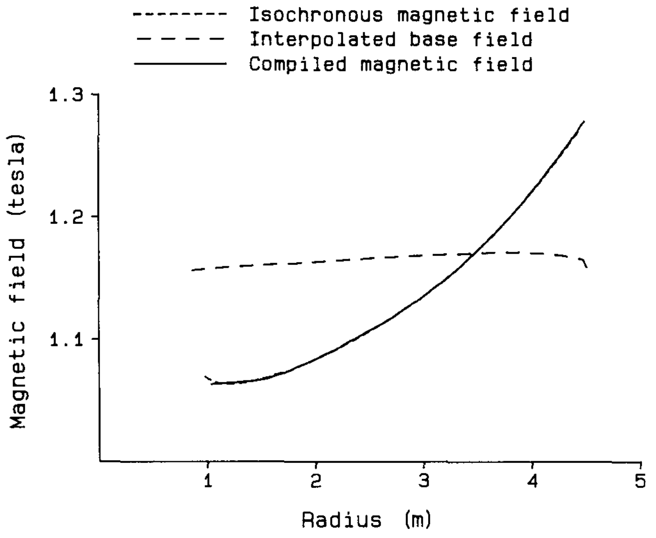

Fig. 1 Magnetic field for 200 MeV protons in sector 1 on the hill line.

3.3 Prediction of Current Settings

The following procedure is followed to predict current settings for the 41 power supplies in a full 360° field, given a particle and an isochronous frequency. Firstly, a base field is compiled by interpolation between base field values in the data base, using the hard edge approximation, to give a first approximation to the field at the reference position. Then isochronization is performed sector by sector in the field, using the programs and procedure described above, to obtain current predictions for each sector from the isochronization data along the hill line. The predictions for all four sectors are used to calculate an average main coil current, corrected additional coil currents and averaged trim-coil currents for those trim-coils which are connected in series. The complete field over four sectors is then compiled from these predictions. The process is repeated using this field instead of the base field. Usually the predicted currents change less than 0.1A after three repetitions and the field is ready to be used in orbit calculations. Figure 1 shows the magnetic field for 200 MeV protons in sector magnet 1 on the hill line. An interpolated base field was used to calculate the isochronous magnetic field given in the figure.

4. ISOCHRONIZATION USING PHASE MEASUREMENTS

Fixed phase probes measuring the beam phase from injection to extraction have not yet been installed in the SSC. So far beam phase measurements have been made with a multi-head probe situated 16° off the centre-line of the injection valley. The measurements are corrected for the probe position and shape of the accelerated orbit to find the rf phase of the beam. The required magnetic field corrections are found from a numerically smoothed derivative of the rf phase using the equation

$$\frac{\Delta B}{B} = \frac{E_G(E)\cos\phi}{2\pi h}\,\frac{d\phi}{dE}\,, \qquad (3)$$

where $E_G(E)$ is the maximum energy gain per turn, ϕ is the rf phase and h is the harmonic number.

A program has been developed for a personal computer to process phase measurements and to predict the current corrections required to isochronize the magnet field. The relative rf phase is entered into the computer from oscilloscope measurements and a plot of rf-phase versus probe radius is produced on the screen (figure 2). The user has the option to correct any input values and to smooth the data with a polynomial fit of degree 1 to 9. The program computes the magnetic field corrections and displays them graphically on the screen (figure 3). From this information the user can interpret the trim-coil current corrections. This interactive user interface is very important, as unwanted fluctuations in the input data can lead to large derivatives and unneccessary trim-coil corrections. The user repeats the smoothing procedure until he is satisfied; only then are the trim-coil current corrections and possibly main coil current increment calculated using the magnetic field data base file on the hill only. Finally, the current corrections are entered into the control system power supply control program to adjust the trim-coil power supplies.

5. RESULTS

We have reached the stage where we can set isochronous fields, especially for particles and energies which are used frequently, with a high degree of reproducibility. As an example, the 66 MeV proton field, which is set once a week, do not exhibit phase excursions of more than ±10 rf degrees for 80 turns. Recently we have also obtained excellent results with the 200 MeV proton beam, when phase excursions of less than ±10 rf degrees were observed for 250 turns in the isochronous field obtained from predicted settings (see figure 2). A factor contributing to the improved reproducibility, is the new system of magnet cooling regulation which keeps the average steel temperature within 0.2^0 C at 25.4^0 C for all magnet excitations. Previously the temperature of the inlet water was regulated. Observations on the 200 MeV beam showed that the overall phase drift in 4 days was less than 10 rf degrees, i.e. 2 parts in 10^{-5} of the magnetic field.

6. DISCUSSION

Excellent results have been obtained with fields that are set regularly. We continuously improve the isochronous magnetic fields obtained from predetermined power supply settings. Each time an isochronous field is set with the aid of phase measurements, the trim-coil current increments are updated in the control system data base. Also, if an adjustment must be made to the main coil current which could affect the yoke coil current, undershoot current and wait times for the magnetic field stabilization, these corrections must then also be included in the updates.[4] This information will be used in future to make corrections to the data base file, thus allowing better predictions.

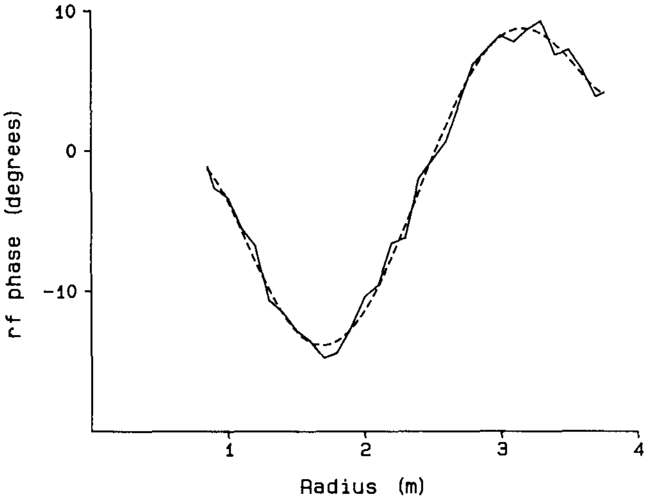

Fig. 2 Measured phase of 200 MeV proton beam

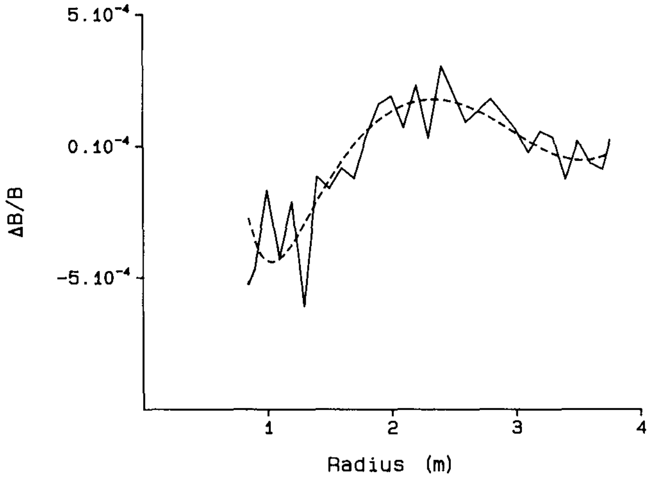

Fig. 3 Field corrections calculated from phase measurement for 200 MeV proton beam

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