IEEE Transactions on Nuclear Science, Vol.NS-22, No.3, June 1975

ISOCHRONIZATION CALCULATIONS FOR THE INDIANA UNIVERSITY CYCLOTRON*

W. P. Jones
Indiana University Cyclotron Facility
Bloomington, Indiana 47401

Summary

A series of calculations using measured magnetic fields has been performed to determine the optimal gradient coil currents for the wide range of operating conditions to be experienced by the Indiana University main stage cyclotron. Depending on the particle type to be accelerated and final energy desired, the required radial field increase varies from 0.5% to 22%. An iterative least squares fitting technique is used to minimize orbit time variations. For the acceleration of 200 MeV protons (330 revolutions, fourth harmonic) the maximum phase excursion is predicted to be less than two rf degrees. The technique used can be adapted to using measured phase histories to predict corrections to gradient coil currents.

Introduction

The energy spread of a cyclotron beam depends to a large extent on the degree to which the magnetic field has been isochronized. In order to obtain high resolution beams of varying particle types and energy it is necessary to have a technique available for rapid calculation of the appropriate currents for the set of trim coils. If the cyclotron is to be easily tunable when changing energies, these currents should be smoothly varying functions of energy.

The Indiana main stage cyclotron has 21 radial gradient coils. The ratio of r.f. frequency to orbit frequency is 4 for high energy protons and increases for heavier ions. Consequently very stringent requirements are imposed on the field shape necessary for isochronism.

This paper will describe the techniques used to optimize the gradient coil currents and discuss some of the results obtained thus far.

Procedure

The orbit code SYMECN has been used[1] to calculate linear orbit properties as a function of energy including the threshold voltage function

$$f(E) = 2\pi \sum_{i=2}^{NE} \left(\frac{\overline{\omega_T}}{\omega(Ei)} - 1 \right) * \delta E \qquad (1)$$

where $\overline{\omega_T}$ is the desired orbit frequency, $\omega(E_i)$ is the frequency at the i'th energy, and δE is the energy increment used in the calculation. Under the assumption of separation of the longitudinal and transverse motion of the beam the phase of the beam relative to the r.f. is simply related to f(E) by

$$\sin(\phi(E)) = \sin(\phi_o) + \frac{h}{E_g} f(E) \qquad (2)$$

where h is the ratio of r.f. frequency to orbit frequency and E_g is the maximum energy gain per turn. In the present calculations the optimization of $\phi(E)$ has been replaced by the optimization of f(E). The effects on f(E) of an incremental change in the current of each gradient coil has been calculated and stored in tabular form. The effect of an incremental change in the main magnet current has also been stored in the same table. These tables were calculated using median plane magnetic field measurements.[2]

For a given measured magnetic field, f(E) was calculated for a range of energies spanning the injection radius to extraction radius. Optimization of f(E) to the desired function $f_I(E)$ was done by minimizing χ^2 defined as

$$\chi^2 = \sum_{\epsilon=E_i}^{E_f} wt(\epsilon) \left\{ f_I(\epsilon) - f(\epsilon) - \sum_{j=1}^{NC+1} C(J) \frac{\delta f(\epsilon)}{\delta I_j} \right\}^2$$

where the C(j) are the required changes in gradient coil and the main magnet currents and the $\frac{\delta f(\epsilon)}{\delta I_j}$ are the previously tabulated differential effects on f(E). In the present calculations $f_I(\epsilon)$ has been set to zero, $wt(\epsilon) = 1$ and the calculations performed with uniform energy spacing. Typically $f(\epsilon)$ is calculated at 165 energies. The least square fit to $f_I(E)$ has been done using a modified version of a program TRIMFIT[3], written originally to fit a one dimensional field shape with a base field and trim coil contributions.

After calculating C(j) a new field is generated incorporating these changes and f(E) is calculated again and if it is not acceptable a new set of current changes are computed by doing another least square fit. This procedure is repeated until it converges (generally 2 or 3 iterations). The primary reason why a single iteration is not sufficient in the inherent non linear effects of the trim coils on orbit time.

Each iteration takes approximately four minutes on our Datacraft 6024/1 data acquisition computer. It has been found to be sufficient to use the same table of differential current effects for all calculations with a particular charge to mass ratio.

Results

This procedure was followed for each of 32 main field settings corresponding to operation with charge to mass ratios of 1, 2/3, 1/2 and 1/4, with magnet excitations ranging from below saturation to the maximum useable by an ion with a given Q/M. For all ions orther than protons the maximum field used was essentially at the limit of the power supply.

Figure 1 shows the predicted phase history for protons with a final energy of 195 MeV. This phase history is typical of those obtained for all modes of operation. The maximum phase excursion is less than 2 r.f. degrees and there is one oscillation about 0° per gradient coil.

* Work supported by the National Science Foundation

The variation of gradient coil current with final energy is shown for typical coils in figure 2 for protons and in figure 3 for singly ionized Helium-4. The smooth variation of these currents with energy (the remaining currents exhibit similar behavior) give us confidence that the settings for intermediate cases can be obtained by straightforward interpolation techniques. For final energies below the lowest measured for a given ion the settings will be obtained by scaling those at the lowest energy and correcting for the change in relativistic corrections needed. As a check on the interpolation procedure, the field for 178 MeV protons was mapped using current settings obtained by a 4 point interpolation formula using two points on each side of that energy. The phase history for the measured map was as isochronous as for the two adjacent maps.

Due to temporary constraints on the gradient coil currents, the final measured maps were not perfectly isochronous having maximum phase excursions of 30 r.f. degrees. Relatively small (less than 15 amps) corrections will be sufficient to minimize these excursions.

The procedure described in this paper can be easily modified to use a measured phase history rather than a calculated f(E) as the object of optimization. During operation of the cyclotron corrections to the precalculated settings, for example, those arising from sector to sector field differences may be determined and the precalculated table can be updated if required.

References

1. M. M. Gordon, Private Communication.
2. D. L. Friesel, et. al., "Field Mapping Results of the IUCF 200 MeV Cyclotrons", IEEE Trans. Nucl. Sci., preceding paper this conference.
3. J. Rivers Moore, Private Communications (TRIUMF Design Note, TRI-DN-69-31).

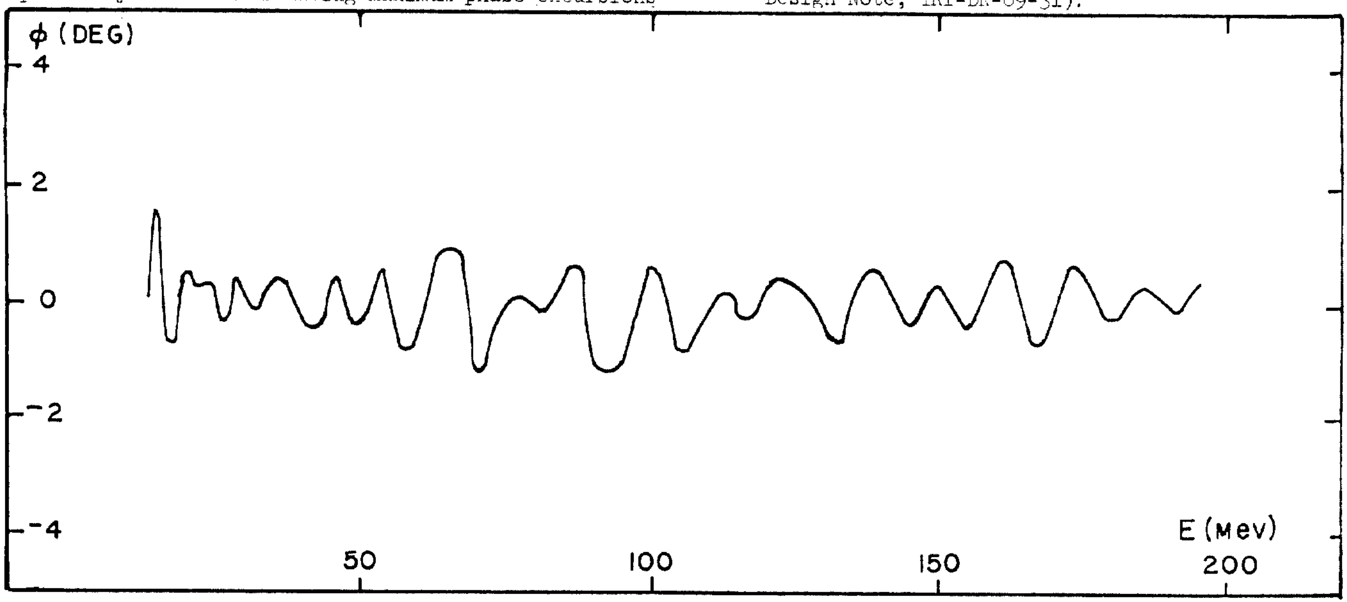

Figure 1. Phase history for 195 MeV protons (330 turns, fourth harmonic).

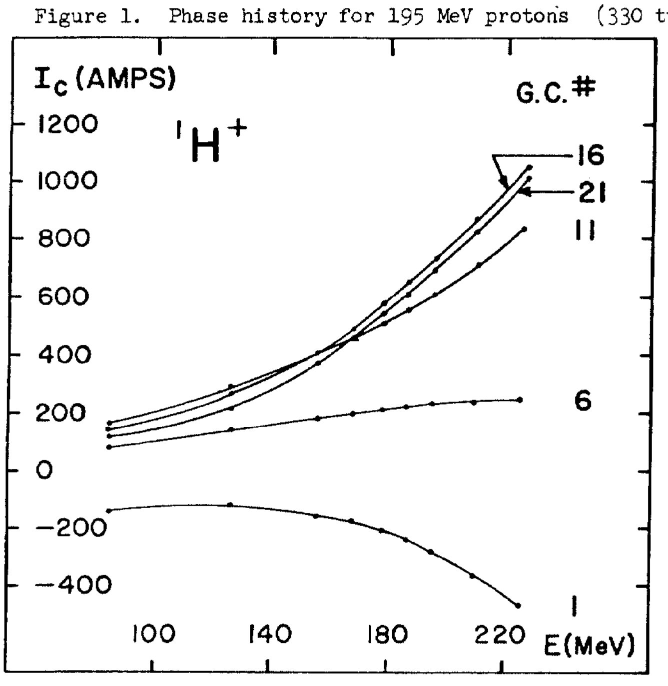

Figure 2. Selected gradient coil currents for protons.

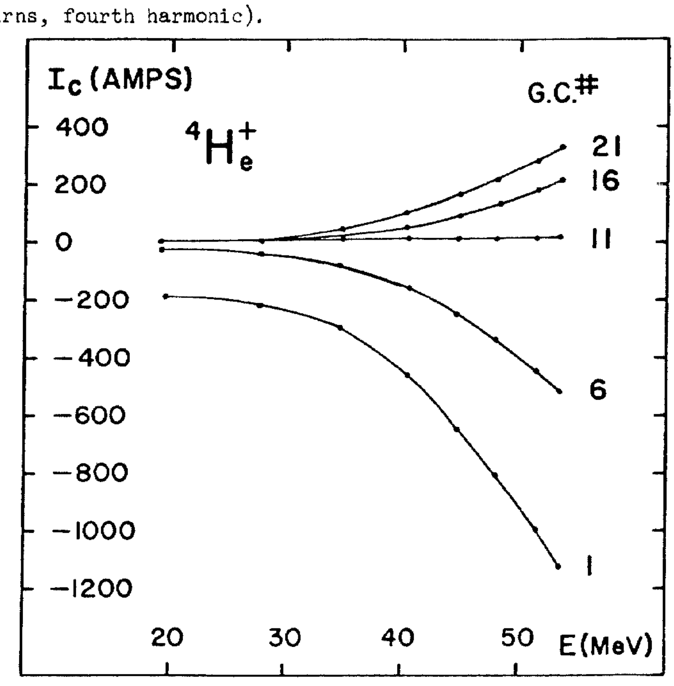

Figure 3. Selected gradient coil currents for singly ionized helium.