APPLICATION OF A NEW FIELD TRIMMING PROGRAM TO THE MSU CYCLOTRON*

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ABSTRACT

In order to improve the performance of isochronous cyclotrons, a new computer program "Fielder" has been developed which carries out field trimming calculations on a more rational basis. Using an iterated least-square process, this program adjusts the trim coil currents and the rf frequency so as to fit the (central ray) phase-energy curve to a prescribed function, including a given non-zero initial phase value. In addition, the least-square fitting is subjected to constraints which serve to produce "energy stability" as well as "energy focusing" in the extracted beam. This program has been applied to the MSU cyclotron for a wide range of operating conditions, and has invariably produced significant improvements in the resultant phase-energy curves.

INTRODUCTION

Variable energy cyclotrons require an efficient system for determining the multitude of "knob settings" necessary to produce a specific ion beam with a given energy. The MSU cyclotron has operated successfully for a long time with the use of a computer program "Set-op" which provides these knob settings as part of its output.[1]

In order to achieve certain operational improvements, it was decided to rewrite the main part of the Set-op program which calculates the trim coil currents and the rf frequency. As a result, we have developed a completely new field trimming program "Fielder" which systematically determines the values of these parameters on a more rational basis.

In this paper we present a brief description of the Fielder program together with some of the results obtained from its application to our 50 MeV cyclotron. This program was also used in the design study for a compact 200 MeV cyclotron which was described in an earlier paper.[2]

Although the techniques employed in Fielder should be generally useful, this program was specifically designed to fulfill the more demanding requirements of those cyclotrons which operate under a separated turn regime. A copy of this program (Fortran listing), together with a more complete description, can be obtained by writing to the authors.

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FIELDER PROGRAM

For a given rf frequency and dee voltage, the quality of a magnetic field for acceleration purposes can best be assessed from the properties of the resultant phase-energy curve $\phi(E)$ for the central ray trajectory. The Fielder program therefore adjusts the trim coil currents (and the rf frequency) so as to obtain a least-square fit of $\phi(E)$ to a prescribed function between the initial energy (E=0) and the chosen final energy E_f.

The program will accept as input any reasonable prescription for $\phi(E)$. Since $\phi(E)=0$ corresponds to perfect isochronism, we generally employ this prescription at all energies except near E=0. In order to improve vertical focusing (and phase selection) in the central region, we require $\phi(E)$ to start from an initially positive value ϕ_o and then drop quickly to zero.

In the Set-op program, the initial phase has the fixed value $\phi_o=20°$, and for the sake of comparison, the Fielder results presented here are based on the same value.

The least-square fitting routine in the Fielder program contains a provision for imposing a set of linear constraints on the adjusted parameters within the fitting process. These constraints provide the program user with a valuable tool for satisfying certain operational and dynamical requirements. One of the available constraints, for example, prevents the trim coil currents from exceeding pre-assigned limits.

A perfectly isochronous field operating with $\phi=0$ at all energies possesses two properties which are particularly important for a separated turn cyclotron, namely, "energy focusing" and "energy stability". By imposing a pair of appropriate constraints on the fitting process, the Fielder program will obtain a phase-energy curve which possesses the same two important properties, even though the resultant field is not isochronous. These properties will be discussed more fully below.

In order to insure the accuracy of the final results, the Fielder program operates through a self-correcting iteration scheme. In one cycle, the program first obtains the trim coil currents and rf frequency from the fitting process, then calculates equilibrium orbit data (including focusing frequencies) for the resultant field, and finally integrates the longitudinal motion equations to obtain the actual $\phi(E)$ for this field and frequency. The program then uses these data to improve the fitting process in the next cycle. This iteration scheme converges quite rapidly so that one or two cycles will usually suffice to secure satisfactory convergence.

To a certain extent, Fielder resembles the field trimming program developed by Garren using the method of linear programming.[3] However, since these programs differ quite significantly, a direct comparison would be difficult.

PHASE-ENERGY CURVES

Although the MSU cyclotron is equipped with eight trim coils, we have chosen to omit the outermost coil (#8) from our new field trimming calculations, since its effect can be reproduced by a change in rf frequency. Holding the main magnet current fixed, we therefore have eight adjustable parameters available for the fitting process, namely, the first seven trim coil currents and the rf frequency.

In addition to the frequency and its integral harmonic number, the program characterizes the rf system by a single parameter, the peak energy gain per turn E_1. For a given harmonic number, this parameter determines the dee voltage, or vice versa.

The results presented in this paper were obtained for the same E_1 values used by the Set-op program: $E_1=E_f/210$, where E_f is the final energy determined by the program from the relevant equilibrium orbit data. That is, instead of using a fixed dee voltage, our cyclotron now operates with a nearly fixed 210 turn geometry. However, certain improvements in the rf system will soon be implemented which will alter this situation.[4]

The Fielder program has been used to generate revised sets of trim coil currents and rf frequencies for a variety of ions with final energies covering the operating range of our cyclotron. The resultant phase-energy curves are generally excellent, and are quite superior to the old ones produced by the Set-op program in almost all cases.

As representative samples, we present in Fig. 1 the phase-energy curves obtained for 76 MeV helions and for 25 MeV deuterons, with the phase ϕ plotted as a function of E/E_f to facilitate direct comparisons. The solid and broken line curves indicate the new (Fielder) and old (Set-op) results, respectively.

The initial sharp drop in all our phase-energy curves is produced by the central magnet cone which is used for vertical focusing near E=0. For the 76 MeV helion case, the size of this initial drop happens to match almost perfectly the requirements of the Set-op program so that the old $\phi(E)$ curve in Fig. 1 is very good. In this unusual case, the new results are only slightly better.

The $\phi(E)$ curves shown in Fig. 1 for 25 MeV deuterons, which are accelerated on second harmonic, represent a more general situation. Here, the initial sharp phase drop has been handled rather badly by the Set-op program so that the new Fielder results are quite superior. The rms phase deviations are 10.1° and 3.2° for the old and new curves, respectively.

The final steep rise in the $\phi(E)$ curves shown in Fig. 1 is another characteristic of our cyclotron. Since we utilize the $\nu_r=1$ resonance for extraction, the final energy E_f is always chosen beyond this point. The ions must therefore be accelerated into the non-isochronous edge region of the magnetic field where the phase rises with increasing rapidity.

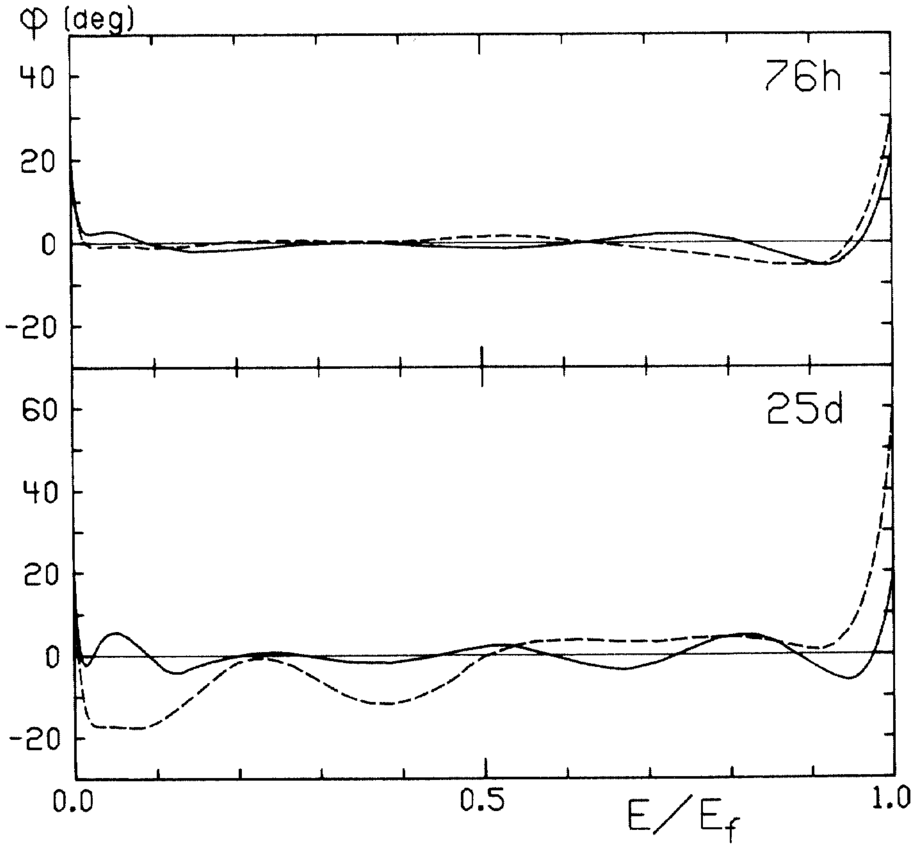

Figure 1 Phase ϕ (in degrees) versus E/E_f for E_f=76 MeV helions (top) and E_f=25 MeV deuterons (bottom).

Figure 2 displays the phase-energy curves obtained for 30, 40, and 50 MeV protons. As in Fig. 1, the solid and broken line curves indicate the new (Fielder) and old (Set-op) results. The new curves are evidently superior except near the final energy, $E=E_f$. The rms phase deviations for the old and new $\phi(E)$ curves are, respectively, 6.6° and 2.1° at 30 MeV, 4.7° and 2.9° at 40 MeV, 12.3° and 6.9° at 50 MeV.

Protons present a very special field trimming problem since our cyclotron magnet has insufficient spiral to provide vertical focusing for these ions above about 40 MeV. A new solution of this problem has been obtained by fixing the currents in trim coil #6 and #7 according to an empirically determined formula. This formula was devised so that the lowest ν_z value in the troublesome region would not fall below one-half of its previous maximum value.

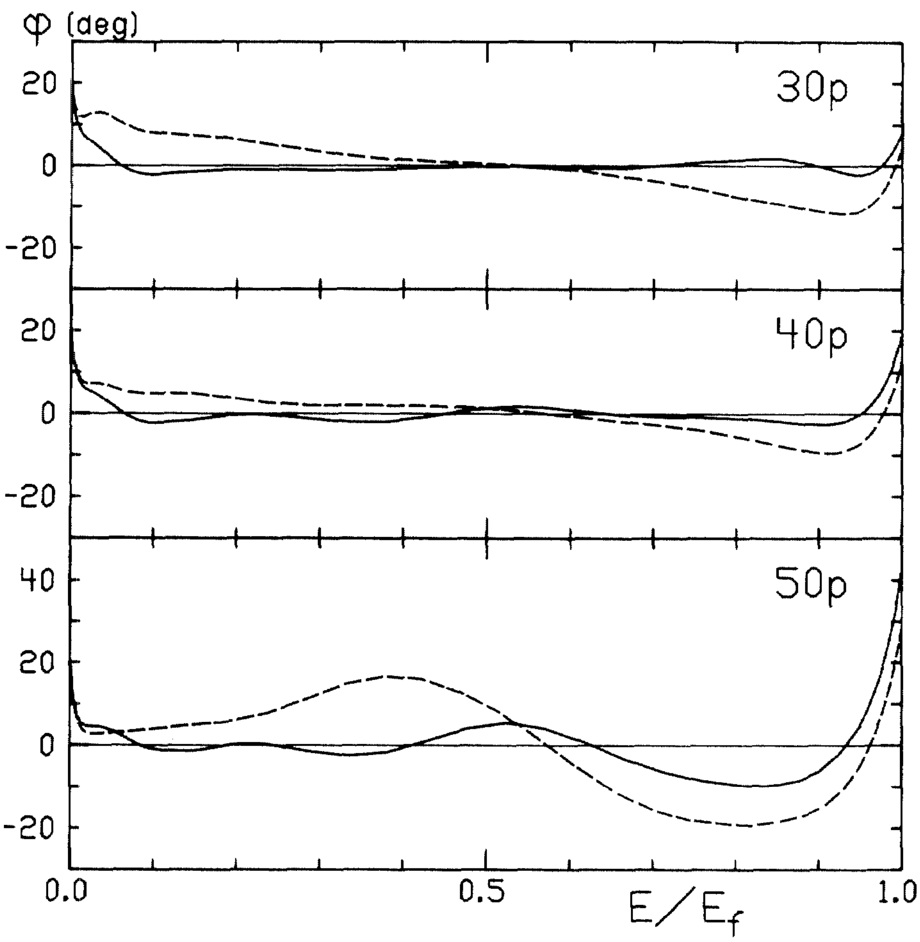

Figure 2 Phase ϕ (in degrees) versus E/E_f for E_f=30 (top), 40 (middle), and 50 (bottom) MeV protons.

Of course, with two less trim coils to work with, the fitting process in the Fielder program is considerably handicapped. The new $\phi(E)$ curve shown in Fig. 2 for 50 MeV is consequently quite inferior to the one for 30 MeV, or to the new curves shown in Fig. 1. Nevertheless, the new proton results will provide highly satisfactory operating conditions up to at least 52 MeV.

As shown by the samples in Fig. 1 and Fig. 2, the old phase-energy curves produced by the Set-op program appear to represent quite acceptable operating conditions for the cyclotron. The operational advantages of the new Fielder results really become apparent only when we consider energy focusing and energy stability.

ENERGY FOCUSING

For a cyclotron such as ours, which operates with phase selection slits in the central region and consequently achieves single turn extraction, the initial phase spread $\Delta\phi_o$ within each ion pulse will ultimately produce a corresponding spread ΔE_f in the final beam energy. Optimum performance will be achieved only when ΔE_f is properly minimized, that is, when "energy focusing" is attained. Under this condition, ΔE_f is proportional to $(\Delta\phi_o)^2$.

In the Set-op program, energy focusing is obtained by "frequency optimization" following the field fitting process.[5] This procedure has the disadvantage of producing an overall slope in the phase-energy curves, as can be observed in Figs. 1 and 2.

The Fielder program obtains energy focusing simply by imposing a suitable constraint within the fitting process, and the resultant $\phi(E)$ curves consequently oscillate about zero. Because of this difference, the Fielder program generally produces energy focusing at several different energies including E_f, while the Set-op results exhibit energy focusing only at the final energy. The extra focusing produced by Fielder has obvious advantages when, as in our cyclotron, differential probe turn patterns are routinely obtained for diagnostic purposes.

Both Set-op and Fielder integrate the longitudinal motion equations to obtain the energy E and the phase ϕ as a function of turn number, not only for the central ray with its initial phase ϕ_o, but also for two displaced rays with initial phases: $\phi_o \pm \delta\phi_o$. For a given initial phase width: $\Delta\phi_o = 2(\delta\phi_o)$, these data will then yield the resultant energy spread ΔE as a function of turn number, as well as the final spread ΔE_f. The data presented here were obtained by assuming $\Delta\phi_o = 2°$, which is consistent with the measured value for our cyclotron.[6]

Figure 3 shows the calculated values of ΔE obtained for the 30 MeV and 50 MeV proton cases depicted in Fig. 2. To facilitate comparisons, ΔE is plotted as a function of E/E_f, where E is the central ray energy. Here again, the solid and broken line curves indicate the new (Fielder) and old (Set-op) results.

The curves in Fig. 3 show that energy focusing is indeed obtained in all cases at the final energy E_f. For the E_f=30 MeV situation, ΔE_f equals 4.1 keV and 4.4 keV for the new and old results, respectively. For the E_f=50 MeV case, the corresponding values are: 6.4 keV and 8.0 keV.

The 30 MeV curves shown in Fig. 3 are quite typical of those obtained for protons below about 40 MeV, and for other ions at all energies. The old curves for ΔE invariably exhibit a broad peak

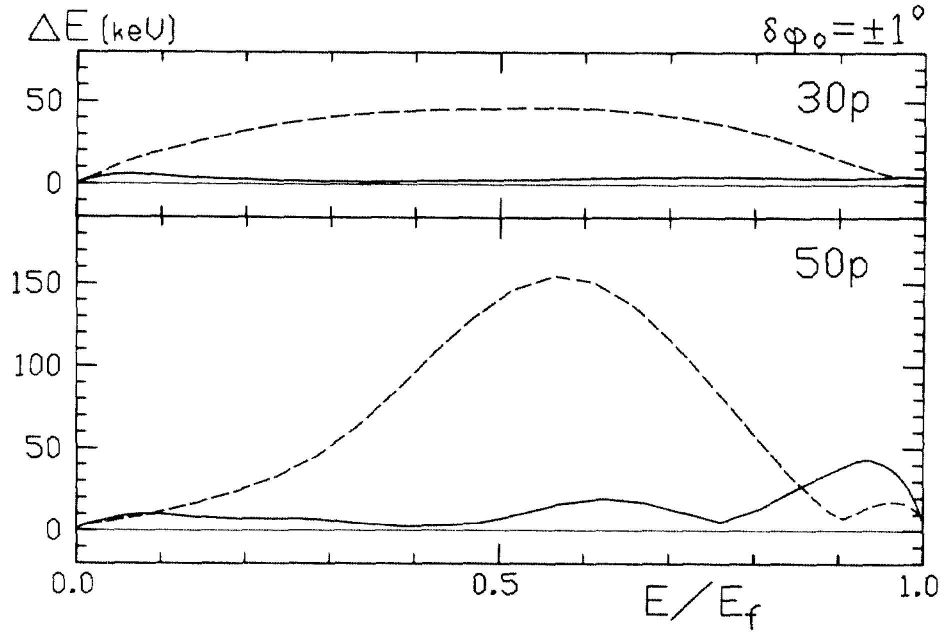

Figure 3 Energy spread ΔE (in keV), produced by 2° initial phase width, versus E/E_f for E_f=30 (top) and 50 (bottom) MeV protons.

near $E=E_f/2$, and in general, the height of this peak varies linearly with $\Delta\phi_o$. By contrast, the new ΔE values remain quite small at all energies because of the oscillatory Δ(E) curves produced by Fielder.

The values of ΔE shown in Fig. 3 for 50 MeV protons are unusually large because of the above-mentioned difficulty in obtaining high quality φ(E) curves at this energy. However, even in this case, the new results are generally quite good, with the largest ΔE=45 keV found at E=47 MeV. Here again, the old results exhibit a broad peak with a maximum ΔE=154 keV at 28 MeV. These data should be compared with a peak energy gain per turn: E_1=238 keV for this case. As usual, the new results are evidently superior.

ENERGY STABILITY

A slight change in the magnetic field level (or rf frequency) will produce a nearly linear shift in the phase-energy curve, and hence, a small change δE_f in the final energy of the central ray. If ε is the fractional change in the field level (or frequency), then δE_f will usually vary linearly with ε. However, for a perfectly isochronous field with φ(E)=0, the value of δE_f is proportional to ε^2, and we therefore refer to this condition as "energy stability".

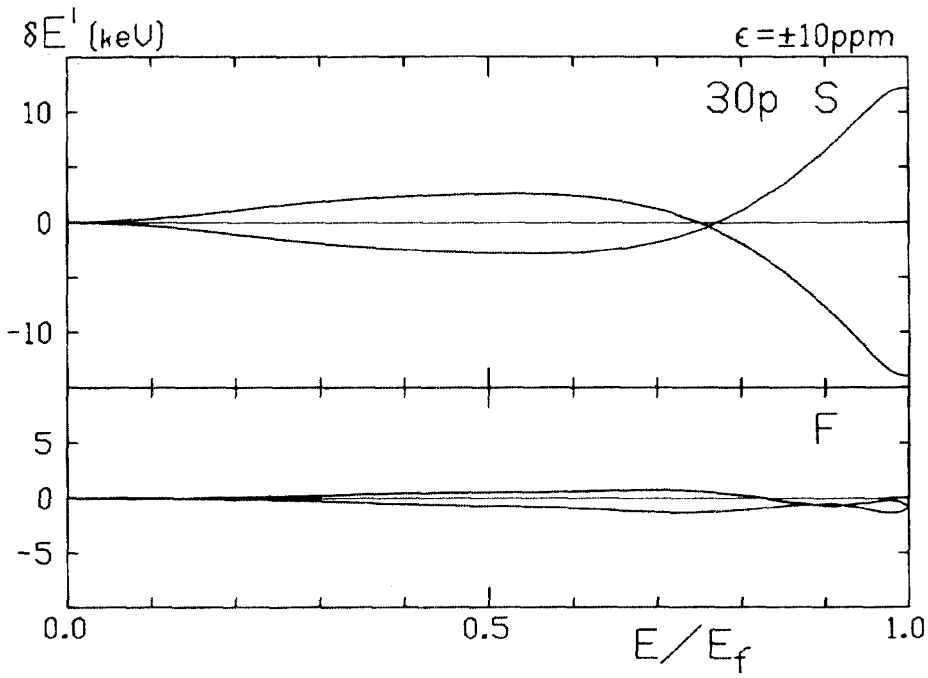

Figure 4 Energy shift δE'(in keV), produced by ±10 ppm field change, versus E/E_f for E_f=30 MeV protons. Top: Set-op; Bottom: Fielder.

By imposing a special constraint within the fitting process, the Fielder program can produce a nonzero phase-energy curve which nevertheless fulfills the energy stability condition. That is, for central ray ions entering the electrostatic deflector after executing a fixed number of turns, the energy shift δE_f will be proportional to ε^2. For those cyclotrons (such as ours) which operate with single turn extraction, this condition must be fulfilled for optimum performance.

In order to check energy stability, the Fielder program integrates the longitudinal motion equations to obtain, as a function of turn number, the shift δE' in the central ray energy produced by a fractional change $\pm\varepsilon$ in the rf frequency. Figure 4 shows the results obtained for the 30 MeV proton case which was discussed above. Here, values of δE' are plotted as a function of the undisturbed central ray energy E, with the three superimposed curves corresponding to: $\varepsilon=\pm 10^{-5}$ and $\varepsilon=0$ ($\delta E'=0$). The set of curves at the top were derived from the old Set-op results, while those at the bottom were obtained from the new Fielder results.

The Set-op curves in Fig. 4 exhibit energy stability only at E=23 MeV, but at the final 30 MeV energy, they display a δE_f variation from -14 to +12 keV. By contrast, the Fielder curves show a maximum $\delta E'$ swing from -1.4 to +0.7 keV at E=21 MeV, and exhibit energy stability at the final energy with δE_f=-0.9 keV. These results are fairly typical of those obtained for protons below about 40 MeV, and for other ions over their complete energy range.

The poorest results were obtained for the difficult 50 MeV proton case with the phase-energy curve shown in Fig. 2. The Set-op results indicate a δE_f variation from -26 to +22 keV for $\varepsilon=\pm 10^{-5}$. Despite the relatively poor $\phi(E)$ curve, the Fielder results nevertheless exhibit energy stability at the final energy with δE_f=-1.3 keV for the same two ε values. The superiority of the new results is clearly evident.

CONCLUSION

For a wide variety of operating conditions, the Fielder program has enabled us to obtain improved phase-energy curves which fulfill both the energy focusing and energy stability conditions. Although these results look very promising, they are still tentative. Systematic measurements are being carried out in order to fix certain input parameters, such as the initial phase ϕ_o. In addition, measurements of phase-energy curves and of external beam properties will be used to verify the Fielder results and to provide the necessary feedback for systematically improving these results.

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DISCUSSION

WEGNER: Presumably you compared the original calculations with the experimental performance of the machine. Could you comment a little bit more on the comparison of the real world with your curves?

GORDON: I think I should refer your question to Dr. Blosser.

BLOSSER: With respect to how the old calculations compare with the observed energy spreads--these calculations, of course, only show the contribution of the magnetic field to the energy spread, and the RF system is another important contributor. Nevertheless, there is an approximate agreement to within a factor of two between the observed energy spread and the calculations, say, for the field. Our record best energy spread out of the machine is 4 parts in 10^4 and a normal value is 7-8 parts in 10^4. We have taken reaction spectra at energies of 30 MeV where you are summing energy spreads from many processes--target thickness, kinematics and so on. We have seen actual nuclear lines with 3 kV from 30 MeV beam, so you know the cyclotron can't be doing much worse than the numbers say.

POLLOCK: Could you tell us how large are the changes in the trim coil currents between the outputs of the two programs?

GORDON: They are small although I don't recall exact values.