DESIGN STUDY FOR A COMPACT 200 MeV CYCLOTRON*

M.M. Gordon, H.G. Blosser, and D.A. Johnson
Michigan State University, East Lansing, Michigan, USA, 48823

ABSTRACT

A preliminary study has been carried out for a variable energy, 200 MeV cyclotron which is designed for both nuclear physics and medical research. The operational and structural features of this machine are modeled closely on our present 50 MeV cyclotron. The magnet would have the same gap, but twice the diameter (3m) and twice the number of trim coils (17), and it would have four (instead of three) sectors with sufficient additional spiral. The rf system would operate in the 10-20 MHz range, with two 90° dees carrying up to 70 kV. This cyclotron would produce protons at energies up to 200 MeV, and other ions to corresponding energies. By extending our present phase selection and single turn extraction techniques to this cyclotron, the energy resolution of the extracted beam would be: $E/(\Delta E)=7000$. With proton currents of about 2 μA, the beam emittances would be 0.3 mm-mrad radially and 2.5 mm-mrad axially. The estimated cost of the cyclotron itself would be around two million dollars.

INTRODUCTION

The MSU 50 MeV cyclotron has been outstandingly successful in producing extracted beams (particularly of protons) having exceptionally fine energy resolution and unusually small emittance.[1] This success has led us to investigate the design of a 200 MeV cyclotron having comparable performance characteristics. This 200 MeV cyclotron would possess the basic structural and operational features of our present machine including the central region geometry, the phase selection slits, and the single turn (resonance) extraction system.

The 200 MeV magnet would have the same magnet gap and the same maximum field strength as our present magnet, and would therefore have about twice the pole diameter (125 in). However, this magnet would have four sectors with sufficient spiral to compensate the additional relativistic defocusing. The magnet therefore resembles that of the Maryland 100 MeV cyclotron.[2]

The suggested design for the rf system of the 200 MeV cyclotron is closely modeled on the present Maryland and MSU machines. This rf system would operate in the 10-20 MHz range with two dees, about 90° in angular width, allowing for both even and odd harmonic operation. Since these dees would be positioned within the magnet gap, the maximum dee voltage would be restricted to about 70 kV.

*Supported by the U.S. National Science Foundation.

In contrast with the 220 turn operation of our present machine, the 200 MeV protons would require about 1000 turns. For lower energy protons and for other ions, the number of turns would, of course, be smaller. The 200 MeV protons therefore present the greatest operational difficulty, and for this reason, the present study has concentrated on these particular ions.

As will become evident from the discussion below, this compact 200 MeV cyclotron would provide an excellent tool for nuclear research at less than one-half the cost of a comparable separated sector cyclotron. However, the original motivation for the design of this low cost cyclotron arose from its potentially wide application to cancer therapy.

Since 200 MeV protons have a range in tissue of about 10 inches, the variable energy proton beam from this cyclotron could reach nearly any part of the body. Furthermore, the energy loss versus distance (Bragg curve) for protons is very well suited to cancer therapy.[3] Although a high quality beam may be inappropriate for the treatment of large tumors, such a beam could readily be converted to a "spray" by means of sweeping electrodes. Moreover, the high quality property of the beam would be invaluable for producing highly localized irradiations where desired.

BEAM PROPERTIES

The MSU cyclotron is equipped with three carefully located radial slits which reduce the phase width of the transmitted beam down to about 2°.[4] Assuming a corresponding slit geometry for the 200 MeV cyclotron, the energy spread within each turn would continue to have the same proportionate value: $(\Delta E)/E=1.5\times10^{-4}$. This implies a final energy spread of 30 keV for 200 MeV protons, and proportionate values for lower energy protons and for other ions.

Even if the 200 MeV protons require 1000 turns, the 30 keV energy spread would still be only 15% of the 200 keV energy gain per turn, so that single turn extraction should still be feasible. This presumes dee voltage regulation limited to: $(\Delta V)/V\cong\pm10^{-4}$, which is comparable to the control achieved in our present cyclotron.

In addition to performing phase selection, the central region slits confine the beam to a very small and compact area of the radial phase space. The apertures of these slits are usually smaller than 0.4 mm, and since the extraction radius of our present machine is 0.7 m, the radial emittance of our beam should be about 0.2 mm-mrad. Because of practical limitations, measurements of this emittance on the extracted beam have yielded only an upper limit, namely: 0.7 mm-mrad. In either case, this emittance is exceptionally small considering that transmitted proton currents up to 7 μA can be achieved.

Since the emittance varies inversely as the momentum, assuming a similar set of slits for the 200 MeV cyclotron, the radial emittance would become: 0.1 to 0.3 mm-mrad.

In our present 50 MeV cyclotron, the axial phase space area occupied by the beam is determined entirely by the ion source since with adequate vertical focusing, the beam height always remains smaller than any of the vertical apertures along its entire path. Measurements on the extracted beam indicate an axial emittance of 5 mm-mrad. Again assuming comparable conditions, this implies an axial emittance of 2.5 mm-mrad for the 200 MeV beam.

An extensive analysis of the longitudinal space charge effect on energy resolution was presented at the last conference.[5] Applying this analysis, we find that this effect will be the same for both machines if the 200 MeV proton current is 30% of the current in our present cyclotron. Since the longitudinal space charge effect can be nearly canceled, in our present machine for proton currents up to 7 μA, we expect the same result at 200 MeV provided the current does not exceed about 2 μA.

For the same BR value, the energy of an ion having charge q and mass number A is q^2/A times the proton energy (with a relativistic correction factor). Corresponding to 200 MeV protons, other maximum ion energies would be, for example, 280 MeV for helions, 210 MeV alphas, and 290 MeV for $^{12}C^{4+}$ ions.

The proton (and deuteron) ion source has exceptionally high luminosity so that the high quality beam characteristics given above can be achieved with reasonable beam currents. Since Helium and heavy ion sources generally have much lower outputs, some sacrifice could be made in energy resolution and emittance in order to improve the final beam current for these ions.

MAGNETIC FIELD

In order to obtain magnetic field data appropriate for 200 MeV protons, we extrapolated the available data from our present 52 MeV field. Since the magnet gap (6.750 in) and the pole tip thickness (6.865 in) would be the same, the results should be fairly realistic. Moreover, these results provide a very good basis for a model magnet design which could then furnish more precise field data.

The magnetic field in our present cyclotron is well represented by the abbreviated fourier series:

$$B(r,\theta) = \Sigma\, B_n(r) \cos nN[\theta-\zeta_n(r)], \qquad (1)$$

where N=3 is the sector number, and where the sum extends over n=0,1,2, and 3. We assumed that the 200 MeV field had the same form with the same B_n values, but with the radius (at the final energy) increased from 28 to 56 inches.

Because of the 6.75 in magnet gap, this radius change was accomplished as follows. The values of B_n for $0 \leq r \leq 7$ in were left unaltered. The values for $r \geq 21$ in were transcribed intact to the new edge region: $r \geq 49$ in. The remaining B_n values were then smoothly stretched (by means of interpolation) to cover the new range:

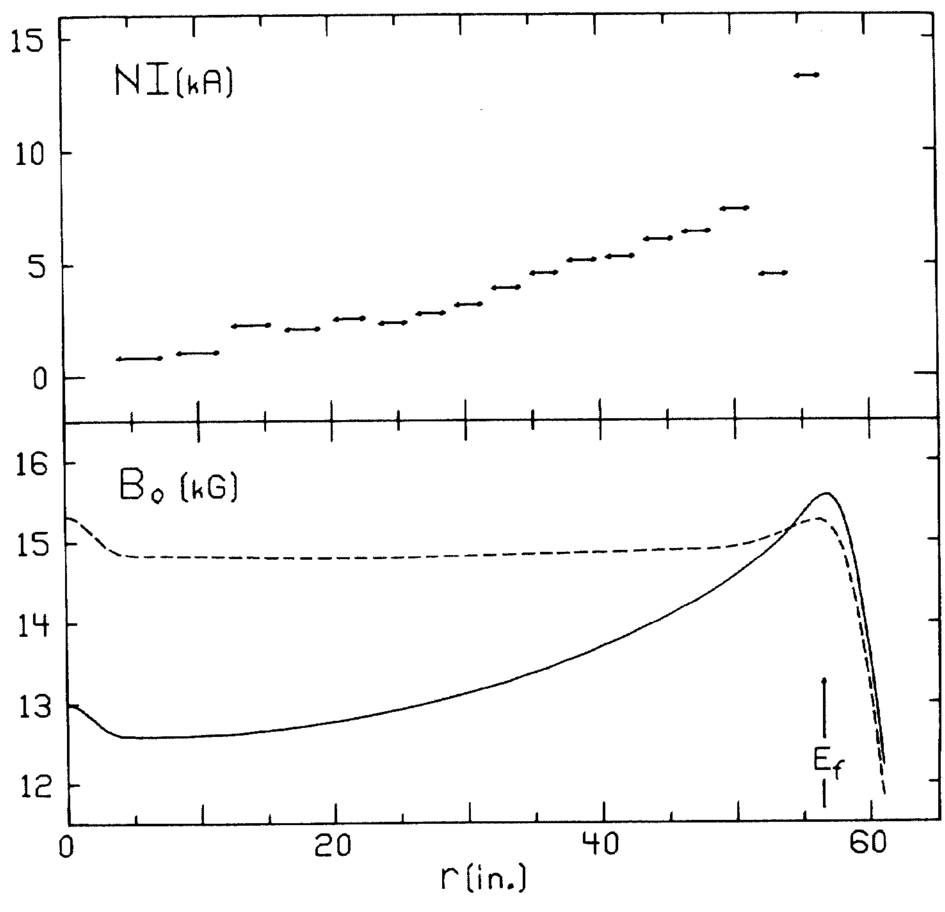

Figure 1 Ampere-turns of the 17 trim coils (top), and resultant average magnetic field (bottom) as a function of radius. Final radius is 56.4 inches at 209 MeV.

$7 \leq r \leq 49$ in. The same set of transformations was also applied to the spiral functions $\zeta_n(r)$.

Next, the value of N was changed from N=3 to N=4. This change makes the flutter field somewhat dubious near r=0, but much of the focusing in this region is provided by the magnet cone, so that the flutter error here is not so significant.

Finally, in order to produce additional vertical focusing, the revised sprial functions were uniformly incremented by a linear term: $\zeta_n(r) \rightarrow \zeta_n(r)+kr$, where k is a constant. Using the well known smooth approximation formula for ν_z, the value k=0.025 rad/in was

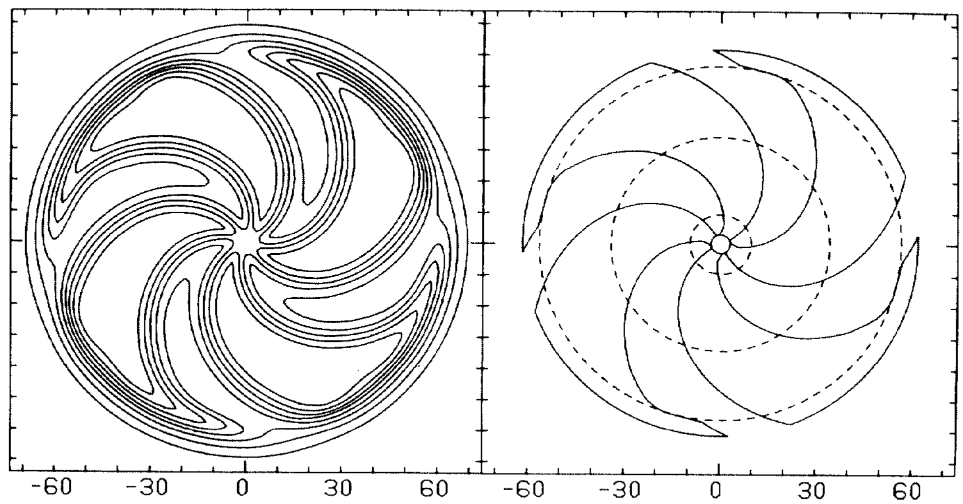

Figure 2 Isogauss contour map (left), and four sector pole tip geometry (right). Scale is in inches.

determined, and this parameter then completed the specification of the main magnetic field for 200 MeV protons. Subsequent accurate calculations of ν_z (see below) proved this value to be satisfactory.

Realistic field trimming calculations were carried out with our new computer program "Fielder", which is described elsewhere.[6] The trim coil field data required as input to this program was obtained by judiciously extrapolating the data available for our present cyclotron.

Although different numbers of trim coils were investigated, we found that excellent results could be achieved with the use of only 17 coils. Figure 1 shows the ampere-turns in these coils as a function of their radial position, with their radial width indicated by arrows. The average fields $B_o(r)$ with (solid line) and without (broken line) the trim coil fields are also shown in the figure. The total power consumed by the trim coils in this case would be only about 90 kW.

Figure 2 displays an isogauss contour map of the resultant 200 MeV proton field. Going up in steps of 2 kG, these contours range from 4 kG at the outer edge up to 18 kG near the center of each hill. The field contributed by the 17 trim coils is also included here.

A tentative design for a set of magnet pole tips was obtained from our present pole tips by applying the same set of geometric transformations used to generate the 200 MeV field. The resultant four sector pole tip geometry is also shown in Fig. 2. The broken circles in this figure indicate the locations of trim coil nos. 1, 9, and 17; the remaining trim coils, which are not shown, are almost uniformly spaced between those shown in the figure.

FOCUSING FREQUENCIES

The focusing properties of the 200 MeV magnetic field were determined with the aid of our Equilibrium Orbit computer program. The resultant values of the radial and axial focusing frequencies, ν_r and ν_z, are shown plotted in Fig. 3 as a function of energy. The focusing effect of the central magnet cone is evident in these plots near E=0.

The ν_r values rise almost linearly with energy and reach a maximum $\nu_r=1.26$ at E=190 MeV, so that the $\nu_r=4/3$ resonance is not encountered in this cyclotron. Beyond about 190 MeV, the ions enter the non-isochronous edge region of the field and the values of ν_r drop sharply, passing through the resonance $\nu_r=1$ at E=207.8 MeV.

With the aid of a field bump to drive the orbits off center at the $\nu_r=1$ resonance, the ions would then enter the electrostatic deflector at the selected final energy $E_f=209$ MeV. At this energy, $\nu_r=0.94$ and the average orbit radius is R=56.4 inches.

After an initial rise, the values of ν_z remain between 0.27 and 0.34 out to 190 MeV, except for a temporary drop to 0.2 at 150 MeV. The small variations observed in the ν_z curve in Fig. 3 result either from the small irregularities in the field data or from the field ripple produced by the trim coils. (The small arrows in Fig. 3 indicate the locations of the 17 trim coils.)

The ν_z curve in Fig. 3 appears very satisfactory in all respects. In particular, the $\nu_r=2\nu_z$ resonance occurs at 201 MeV, and would be safely crossed well before the $\nu_r=1$ resonance extraction.

For lower energy protons or for other ions, the maximum ν_r value will be smaller. The ν_z curve for these ions will rise nearly linearly with energy, but will not exceed $\nu_z=0.8$ in the isochronous part of the field, so that the dangerous $\nu_z=1$ resonance will not be encountered. With minor precautions, crossing the $\nu_z=1/2$ and $\nu_r=2\nu_z$ resonances should not be a problem.

PHASE-ENERGY CURVE

At the bottom of Fig. 3 is a plot of the central ray phase-energy curve $\phi(E)$ which was derived from the output of our field trimming program mentioned above. For this field, the chosen rf frequency is 19.2 MHz, and acceleration is on the first harmonic with an assumed peak energy gain per turn: $E_f/999=208.8$ keV.

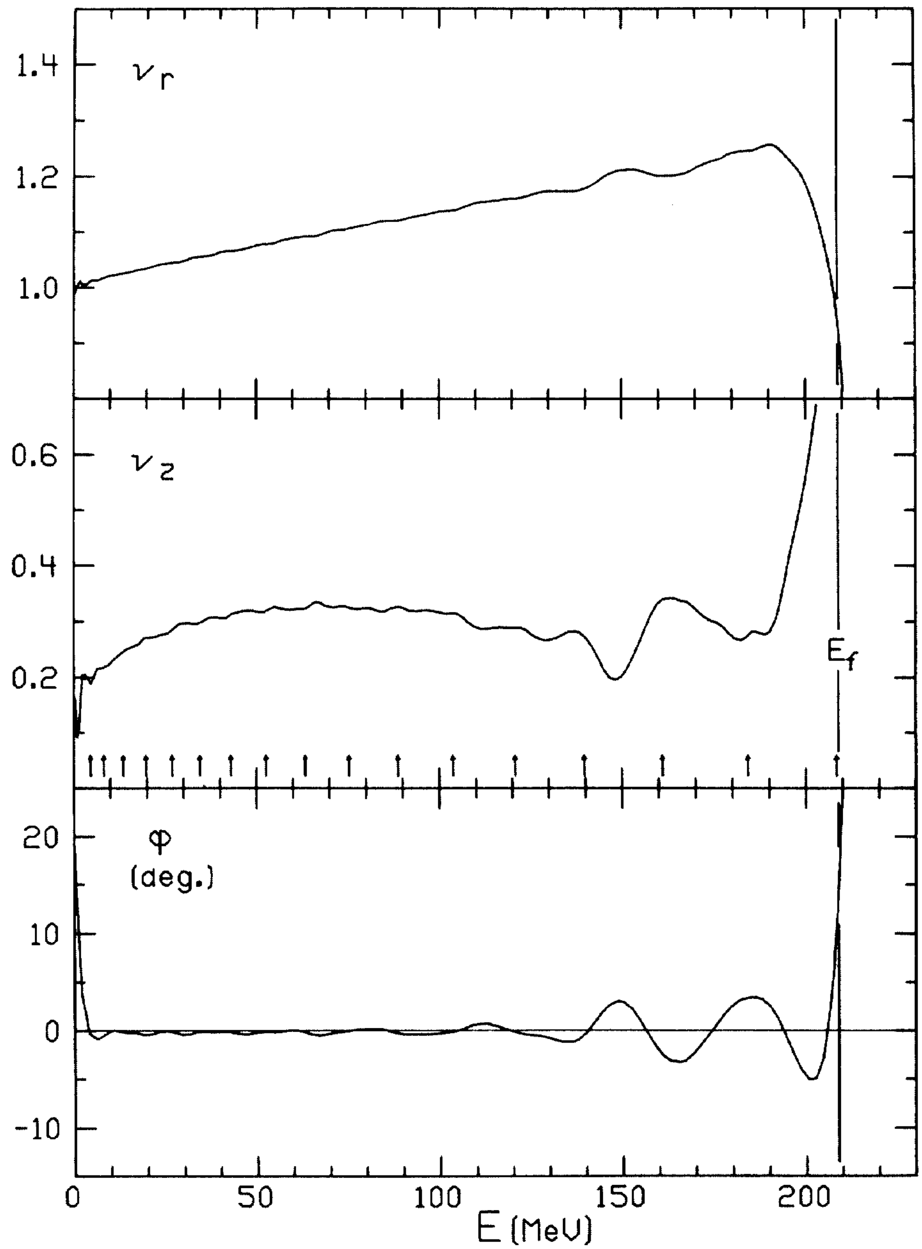

Figure 3 Focusing frequencies ν_r(top) and ν_z(middle), along with phase ϕ(bottom) as a function of energy. Final energy: E_f=209 MeV.

The initial drop in the phase curve from ϕ_o=20° down to zero at 2.1 MeV was purposely aimed for in order to improve vertical focusing and to aid the phase selection mechanism. This same type of initial phase curve has proved quite successful in our present cyclotron.

Beyond the initial portion, the $\phi(E)$ curve shown in Fig. 3 hovers around zero until close to the end where it rises rapidly and reaches a final phase value of about 20° at the extraction energy, 209 MeV. To reach this energy with this central ray phase curve, would require 999.6 turns, which is only 0.6 turns greater than the absolute minimum possible.

As a result of our new trim coil fitting process, the resultant field and phase-energy curve possess two important characteristics of a perfectly isochronous field with $\phi(E)=0$, namely, energy focusing and energy stability. Thus, if the beam has the 2° phase width described above, then our results show that the final energy spread will be 27 keV at 209 MeV. In addition, the final central ray energy will have minimum sensitivity to small variations in the magnetic field level.

EXTRACTION

The equilibrium orbit data for this field also reveals that the average radius gain per turn would decrease to a minimum of 22 mils (0.55 mm) near 190 MeV, and then increase to 32 mils (0.8 mm) at the final energy, 209 MeV. After passing through the central region defining slits, the (incoherent) radial width of the beam would be about 15 mils, and this width will damp down to about 13 mils at the final energy. Evidently, if the orbits remain centered, the clear turn separation will be less than 20 mils, which is rather tight.

Orbit computation studies have shown that the turn separation at the final energy can easily be increased to 150 mils by driving the beam off center with a 3 G field bump as it passes the ν_r=1 resonance. These results are very similar to those obtained for our present cyclotron, and which were discussed in detail some time ago.[7] We are therefore reasonably confident that single turn extraction could be achieved in the 200 MeV cyclotron.

For lower energy protons or for other ions, the orbit dynamics should be equally good, if not better, since these ions are less relativistic and require fewer turns than the 200 MeV protons.

CONCLUSION

We believe that the results of this study have provided a very promising design for a variable energy, compact 200 MeV cyclotron. All of the important parameters have been established, and only minor details remain to be worked out.

Based on an extrapolation from smaller machines of this type, the estimated cost of the cyclotron itself should be in the neighborhood of two million dollars. Although a design of this type might be extended to perhaps 250 MeV, we have not investigated this possibility.

REFERENCES

1. H.G. Blosser, et al., Nucl. Instr. and Methods 91, 61(1971).
2. T.H. Johnson, et al., IEEE Trans. Nucl. Sci. NS-16, 438(1969).
3. P.H. Fowler, Proc. Phys. Soc. 85, 1051(1965).
4. H.G. Blosser, Proc. Fifth Intl. Cyclotron Conference (Butterworths, London, 1971), p. 257.
5. M.M. Gordon, Proc. Fifth Intl. Cyclotron Conference (Butterworths, London, 1971), p. 305.
6. M.M. Gordon and D.A. Johnson, Proceedings of this Conference.
7. M.M. Gordon, IEEE Trans. Nucl. Sci. NS-13, 48(1966).