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ON THE DESIGN OF AVF CYCLOTRONS ABOVE 100 MEV

Robert T. Avery, William M. Brobeck and Philip F. Meads, Jr.
William M. Brobeck & Associates
Berkeley, California

Abstract

Certain problems associated with cyclotrons in the energy range above 200 MeV are discussed and possible solutions suggested. These concern: Producing the flutter and profile changes required for the acceleration of a wide range of particles and energies, the proportion between the RF wave length and the exit radius, phase acceptance, phase slip at extraction, extraction electrical field, turn separation and tolerances on the power supplies. Computer applications in this energy range are also discussed.

Introduction

Much work has been done on the design of AVF cyclotrons below 100 MeV and there are now some thirty machines operating or in the course of design or construction in this energy range. Considerable study including model work has been done by the Oak Ridge and UCLA groups in the region above 500 MeV. Less attention has been given to the region between 100 and 500 MeV.

In this region there appear to be no new problems to be met. However, some techniques practical at lower energies may reach their limit below 500 MeV. Also the machines become more expensive as the energy goes up and their performance should be predicted with more certainty. Fortunately the experience with the lower energy machines provides much background for these predictions.

It is the purpose of this paper to indicate the general effect of the increase of the cyclotron energy above 100 MeV on some of the cyclotron variables. The figures quoted are intended to show trends but not necessarily values to be used in design. Because the variables are so interdependent it is necessary to make reasonably complete designs of individual machines for accurate determination of the effect of a change in the energy. It is hoped that this paper will serve as a guide to designers and will provide some suggestions for design features at energies above 100 MeV.

In the discussion it is assumed that the accelerated particles of highest energy will be protons; that deuterons, helium and other heavier ions will be desired; and that the highest possible energy range is to be obtained for all particles.

Except where otherwise noted it is assumed that the dee voltage and magnet gap remain constant as the energy is changed.

Profile, Flutter and Spiral

For multi-particle, wide-energy-range operation, it is well-known that the magnetic field profile must be varied over the shaded range shown in Figure 1 in order to retain isochronism. Whereas 75 MeV operation requires only 8% change in average azimuthal field, 200 MeV operation requires 21% change and 500 MeV operation requires 53% change.

It is also well-known that the magnetic field requirements for axial focusing of high-energy protons are much different than for low-energy protons or heavy ions. Based on the "smooth approximation" formulae,[1] Figure 2 illustrates the change required in the flutter/spiral term to retain an axial tune of $\nu_z = 0.25$. For a fixed iron arrangement, this indicates that large changes in flutter are required at the higher energies.

Profile, flutter and spiral can be changed by one or a combination of the following:

1. Circular Trim Coils (used on most AVF cyclotrons).
2. Valley Trim Coils (used on many AVF cyclotrons).
3. Hill Trim Coils (e.g. Colorado).[2]
4. Thermal Change in Permeability - Invar (e.g. Manitoba).[3]
5. Radially Removable Iron Shims (e.g. NRDL).
6. Axially Movable Iron Plugs.

Methods 4, 5 and 6 appear capable of achieving large changes in profile, flutter and spiral but introduce complications that would be well to avoid. This paper considers the use of trim coils (Methods 1, 2 and 3).

Profile Coil Power

For circular trim coils, the ampere turns per unit radius to achieve required profile changes vary approximately as

$$\frac{d(NI)}{dR} \propto \frac{G\bar{B}(\gamma^2 - 1)}{R}, \qquad (1)^*$$

where G is effective coil gap, $\bar{B}$ is average

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azimuthal field at radius R, and γ is E/Eo. For coils of conductor area Ac per unit radius, the total profile power can be found by integration;

$$P \propto \frac{G^2 \overline{B}^2_{ext}}{Ac} \cdot \frac{(\gamma_m^2 - 1)^2}{\gamma_m^{\;2}} , \qquad (2)$$

where $\overline{B}_{ext}$ and γ_m are maximum values of $\overline{B}$ and γ at the extraction radius. The curve of Figure 3 shows this relationship as a function of particle kinetic energy E_k for the constant $\overline{B}_{ext}$. This indicates that profile power requirements increase sharply with energy. For example, the profile power at 250 MeV is ten times that at 75 MeV. If valley or hill coils were used to change profile, it is believed the relationships would be of similar magnitude.

If $\overline{B}_{ext}$ decreases as E_k increases, the profile power requirements are reduced. For example, consider $\overline{B}_{ext}$ being reduced as a function of E_k so as to obtain constant H^- survival based on Hiskes' curve C as report by Judd.[5] The results are shown in the curve of Figure 3, in which profile-coil power increases slowly as a function of E_k. In this case, the profile power at 250 MeV is only twice that at 75 MeV. The low magnetic fields dictate a large diameter magnet, perhaps similar in configuration to that considered for the UCLA H^- meson factory design.[6]

Hill Trim Coils

Trim coils surrounding the hills, such as shown in Figure 4 and 5A, offer the advantage over coils surrounding the valleys that profile and flutter are increased (or decreased) simultaneously. Figure 5B shows the fundamental azimuthal magnetic profiles that might be obtained as the hill coil current varies, assuming arbitrarily that the average field in the valley remains constant.

An elementary study was performed to determine axial focusing characteristics when hill coil currents are adjusted to maintain isochronism. The radial magnetic profiles of Figure 6A were assumed for 200 MeV protons using 0.275 flutter and 68° spiral at the extraction radius. As shown in Figure 6B for heavy ions, the average valley field was kept constant and the average hill field was reduced to maintain isochronism. To avoid having the flutter drop to zero (dashed line), small supplemental valley coils were assumed at large radii.

Figure 7 shows the vertical tune for these cases. This study indicates that hill coils adjusted for isochronism produce more than enough change in flutter. By shifting a small portion of the ampere-turns from the hill coils to valley or circular coils, it appears that satisfactory vertical tune can be achieved at even higher energies. For hill coils one-half inch thick, the total trim coil power was calculated to be less than 150 KW for $\overline{B}_{ext}$ of 8,200 gauss at 200 MeV.

Thus, it appears practical from the viewpoint of trim coil power to achieve multi-particle, wide-energy operation up to at least 500 MeV by suitably reducing the main magnet field strength and by use of hill trim coils.

It must be recognized that the low fields required to hold down the trim coil power result in large diameter machines for higher energies.

Radio Frequency System

As the energy rises the extraction radius of the magnet approaches a quarter wavelength of the oscillator frequency. The ratio of the extraction radius to the wavelength depends only on the velocity of the particle and is independent of the magnetic field. This ratio, $R/\lambda = \beta/2\pi$, is shown in Figure 8.

The effect of the quarter-wave point moving toward the pole edge is that most frequency-adjusting methods used below 100 MeV become impractical because of the lack of space. It is necessary to fall back to half-wave or three-quarter wave systems which require considerably more power than quarter-wave systems. There may also be a problem in supporting the dee without causing high voltages to appear on insulators at some part of the frequency range.

Many designers desire to preserve the turn separation at the exit radius. To accomplish this it is necessary that the per unit variation in the voltage gained by the ion while crossing the dee gap be less than the reciprocal of the number of turns made. Considering this single effect on phase variation and neglecting transit time effects the permitted phase range, given by $\phi_1 = (2eV)^{\frac{1}{2}} E_k^{-\frac{1}{2}}$ is plotted in Figure 9 where eV is the voltage gain per turn.

The allowable phase range can be increased by "flat-topping" with some third-harmonic added to the dee voltage. In this case the phase range is given by $\phi_3 = (3eV)^{\frac{1}{4}} E_k^{-\frac{1}{4}}$ as shown in Figure 9. The third-harmonic component can be introduced by the use of an auxiliary dee.

Extraction

Extraction problems have been given much attention in the design of present AVF cyclotrons. These problems can be thoroughly studied only by computer calculations and only for particular machine designs. However, some properties of the particle motions may be brought out by analytic solutions under the simplifying assumptions which make such solutions possible. Information of this type is provided here.

Figure 10 shows the nominal turn spacing for a voltage gain of 200 kilovolts per turn. The relation is $\Delta R = (R/\gamma^2+\gamma)\, eV/E_k$. It is clear that without assistance from orbit precession or resonant growth, the extraction efficiency of the simple electrostatic deflector will decrease considerably with energy. Note, however, at 500 MeV there is still ten mils left which should permit some current to pass a septum of practical thickness.

Figure 11 shows the electric field gradient that produces a separation of one inch from the circulating orbit after 90 degrees in the electric field. It is given by $G = 300B\ \Delta R/R$. As a gradient of around 100 kilovolt per centimeter can be held satisfactorily, it should be possible to produce about two inches clearance which should be adequate for the start of a magnetic channel.

The phase slip occurring from the time the particle leaves the isochronous field until it reaches the point at which the radial field gradient is zero is shown in Figure 12. These calculations are based on departure from the isochronous field corresponding to the field fall-off at the edge of the poles having the stated gap. The relation derived is

$$\Delta \sin \phi = \frac{\pi}{6}\gamma(1-\gamma)\ (\gamma^2-1)\frac{E_k}{eV}\left[\frac{100}{64}(\gamma^2-1)\frac{G^4}{R^4}\right]^{\frac{2}{3}} \tag{3}$$

where G is the gap distance and the factor 100/64 results from fitting the field fall-off at the edge of the gap. It can be seen that as the energy rises the width of the asynchronous region, as expressed by the gap distance, must be reduced. Fortunately the effect of gap distance is very strong. The effect of a small gap can be produced by iron located close to the beam to cause the reduction in field.

Electrical Tolerances

In general as the energy increases the tolerances on variation of the power supply output become tighter. Figure 13 shows the tolerances on magnet current and dee voltage to hold the radial position of the last turn within ten percent of the turn separation. The relations are:

$$\Delta I/I = (3/10)(eV/E_k)(\gamma-1)/\gamma \tag{4}$$

and

$$\Delta V/V = (1/10)(eV/E_k) \tag{5}$$

The factor 3 is an arbitrary allowance for saturation in the magnet and will vary according to the particular case. These tolerances are within the present state-of-the-art of voltage and current regulation.

Regulation of the dee voltage might be accomplished by use of a feedback signal from a wire probe inserted near the exist radius to respond to a single turn of the circulating beam.

Figure 14 shows the relation between tolerances on the magnet current and radio frequency on a profile coil current assuming coil effects extend over one gap width. For one degree phase slip, the relations are:

$$\Delta I/I -- \Delta f/f = 3/360 \quad eV/E_k \tag{6}$$

and

$$\Delta I/I = 2R/360\ (1/\gamma^2+\gamma)(1/\gamma-1)\ eV/E_k\ , \tag{7}$$

where the factor 3 is as explained before. It is usual to regulate the main magnet current and the frequency independently, dividing the tolerance between them. The combined tolerance shown may be difficult to meet in this way. An alternative is to regulate the current or frequency by feedback from the phase of the bunches in the external beam.

It should be noted that the tolerance on the various quantities can be traded against each other to favor the quantities which are most difficult to regulate. The distribution of tolerances presented in the figures is believed to be typical.

Computations

The presently accepted method of building a cyclotron magnet is to first construct a model magnet with a variety of pole face contours and then analyze the suitability of the iron contour using digital computer orbit codes. This process has been extended to the point where digital computers are used to prescribe optimum coil excitations and to identify changes needed in the magnetic field profiles. In this role the computer has proven to be a valuable tool.

The design of the AVF cyclotrons above 100 MeV can take even more advantage of the computer. This is fortunate because the cost of testing model magnets is likely to be greater as larger machines will have greater pole-diameter-to-gap ratios than existing machines and will, therefore, require larger models. In addition, greater accuracy will surely be required as based on present dee voltages, particles will travel further in the proposed machines, nonlinear effects due to larger spiral angles will increase, and a greater premium will be placed upon the efficient use of iron and power.

A number of excellent two dimensional magnetostatic codes have been developed in recent years. Given the distribution of iron and current they will calculate the magnetic fields to within 1% accuracy, taking full account of the saturation properties of iron. At least one of these codes has been successfully "inverted" to prescribe the optimum pole contour of a synchrotron magnet. A two-dimensional code might be adapted to an AVF cyclotron by introducing a curvilinear coordinate system based on the spiral of the cyclotron field.

However, the magnetic field of an AVF cyclotron is basically a three-dimensional field, requiring a three-dimensional magnetostatic code to accurately represent it. Fortunately the cost of computing has gone down by a factor of several hundred in the last decade so a three-dimensional code, requiring approximately 100 times as much computing as a two-dimensional code, should now cost no more to run than a two-dimensional code did when the existing AVF cyclotrons were designed. Available memory capacities have also increased so the requirement of 100,000 mesh points to be stored for a three-dimensional calculation is now available. A problem with a 30x50x50 mesh would require approximately one hour on a CDC 6600 computer, assuming optimum programming, and costs about $400. Such a code could be intimately coupled with an orbit code to yield a "one shot" specification of optimum pole profiles and coil configurations. Inasmuch as detailed magnetic-flux densities in the iron return path would be calculated, the code could eliminate unnecessary iron mass from the cyclotron.

Conclusions

As far as this study has indicated, no serious difficulties appear in the design of machines as the energy rises from 100 to 500 MeV. Production of the necessary flutter changes will be practical if magnetic fields are kept low. Wide range radio-frequency systems will become more difficult and third harmonic dees will become more attractive. Resonant extraction will be preferred with perturbing elements close to the median plane. Electrostatic channels will still be practical. Tolerances will grow gradually tighter but are still not too severe. Feedback schemes exist for avoiding high absolute accuracy requirements in any case. Machine computations can be expected to play an even greater part than in the past in the design of machines over 100 MeV.

References

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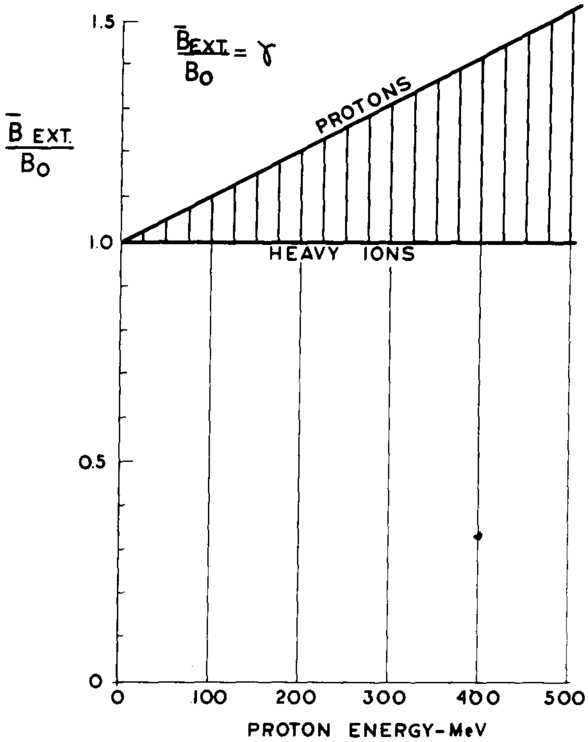

Fig. 1. Required change in average field.

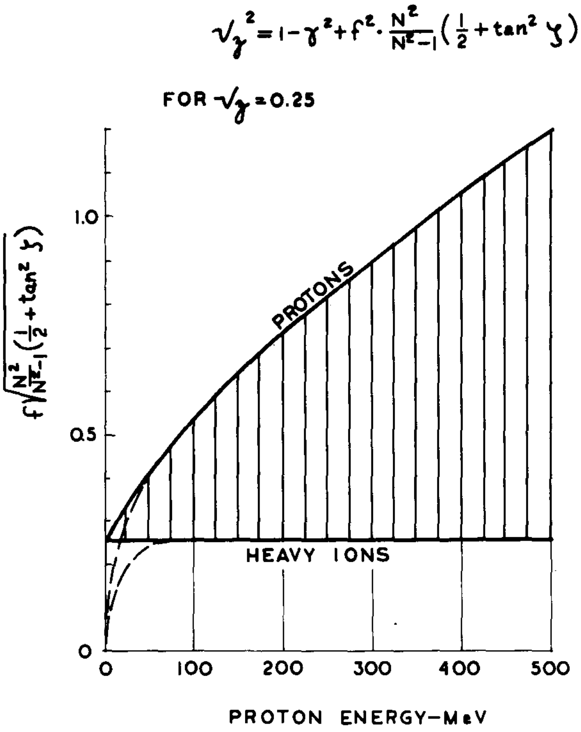

Fig. 2. Required change in flutter/spiral.

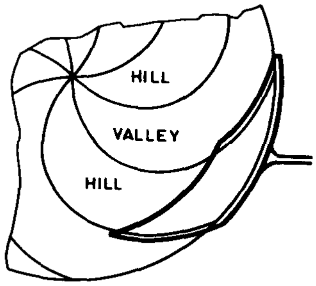

Fig. 4. Plan view of one hill coil at a single radius. Hill coils at other radii and on other hills are not shown.

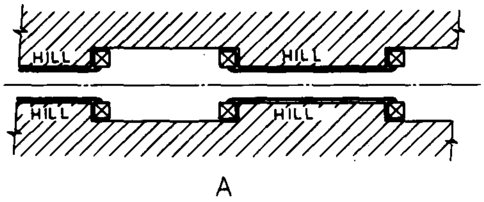

Fig. 5A. Azimuthal section looking radially inward showing hill coils running alongside of hills.

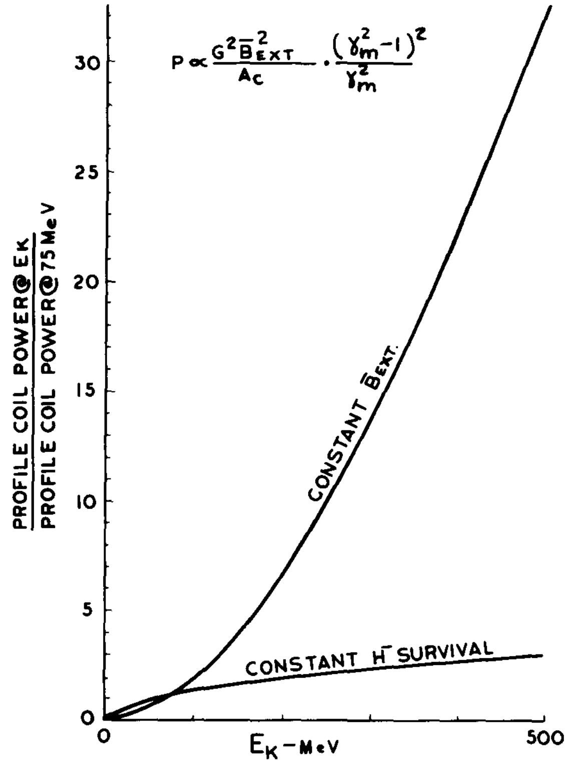

Fig. 3. Profile coil power as a function of maximum proton energy.

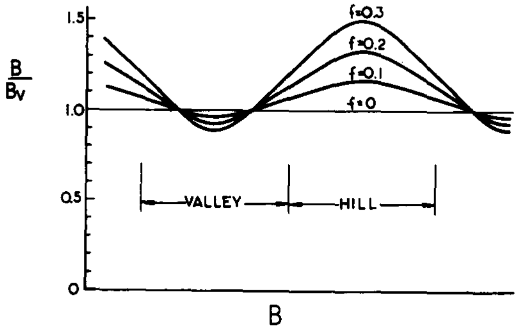

Fig. 5B. Assumed sinusoidal flutter change produced by hill coils with average field in valley assumed to remain constant.

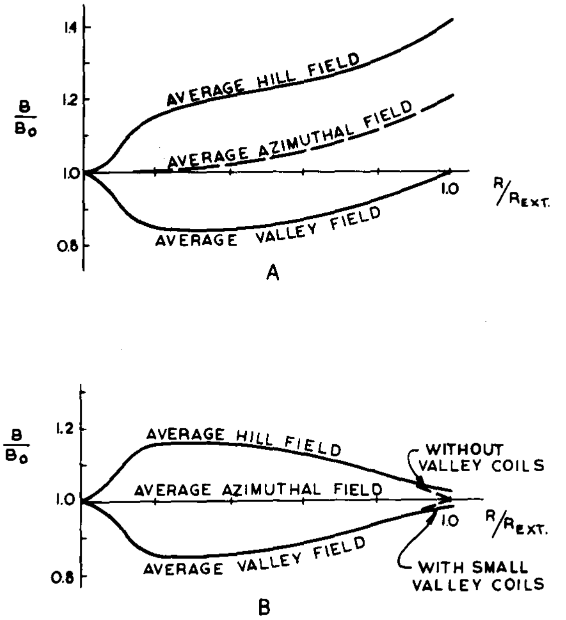

Fig. 6. Assumed field profiles; A) for 200 MeV protons, B) for heavy ions.

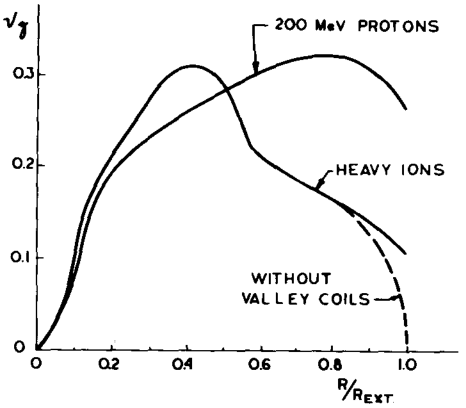

Fig. 7. Calculated vertical tune for 200 MeV protons and heavy ions based on smooth approximation. It is indicated that hill coils which provide required profile change also provide more than enough flutter change.

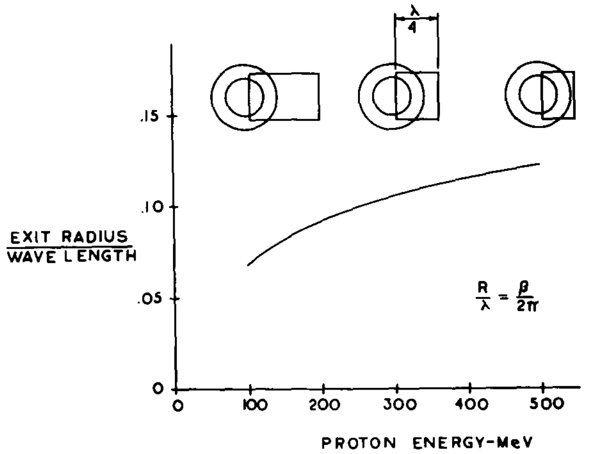

Fig. 8. Relative proportions of pole radius and wavelength.

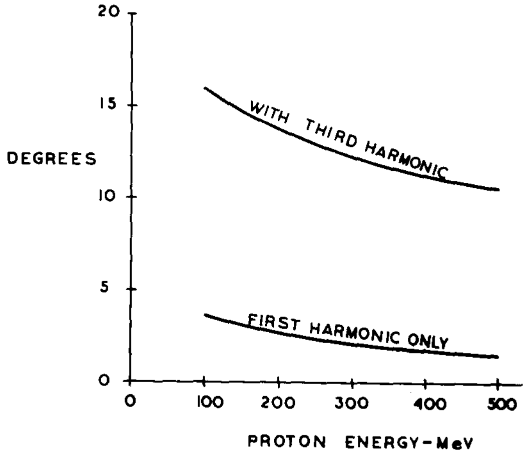

Fig. 9. Half-angle of phase acceptance at 200 KeV energy gain per turn.

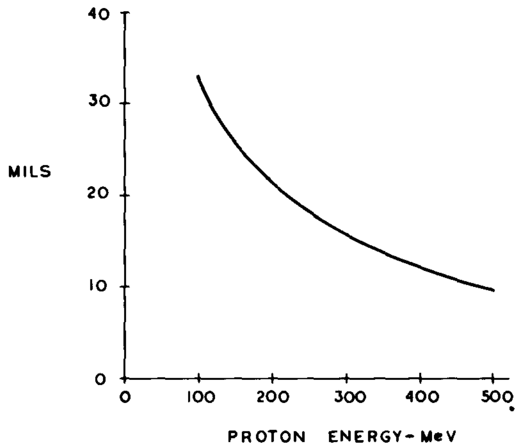

Fig. 10. Average turn spacing at exit radius in 15 kilogauss field for 200 KeV energy gain per turn.

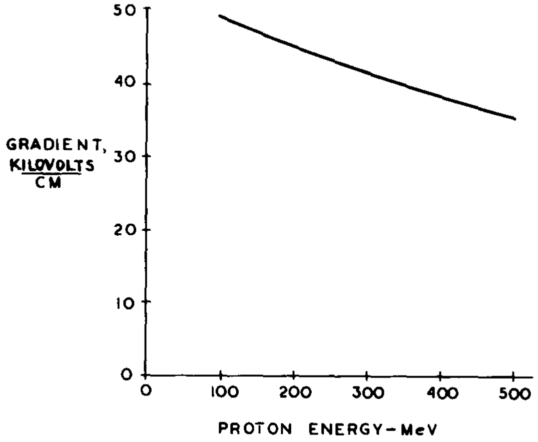

Fig. 11. Electric field gradient for one inch radial separation after 90 degrees in 15 kilogauss field.

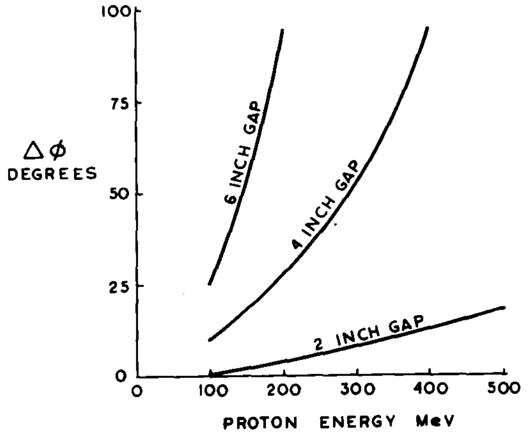

Fig. 12. Phase slip through asynchronous region at extraction. Based on 15 kilogauss field, 200 KeV per turn, and unstaturated iron with square edge.

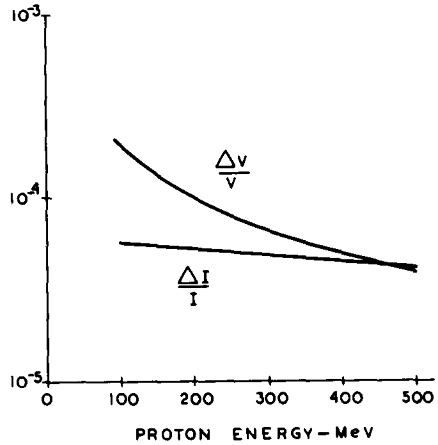

Fig. 13. Tolerances on dee voltage and main magnet current for radius shift of 10% of turn spacing at exit radius.

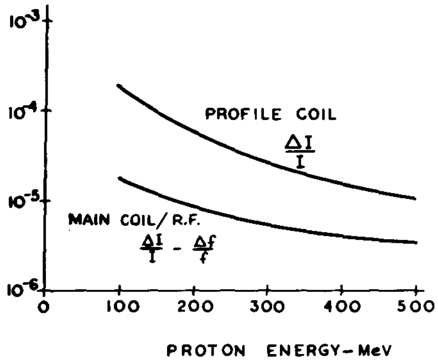

Fig. 14. Tolerances on main magnet current/frequency deviation and on profile coil current for phase slip of one degree. Fifteen kilogauss field, 200 KeV per turn; 10 inch gap.