CONTROL OF THE MICHIGAN STATE UNIVERSITY CYCLOTRON[*]

R. E. Berg[†], H. G. Blosser, and M. M. Gordon
Michigan State University
East Lansing, Michigan

Abstract. To operate the MSU cyclotron, controls are set to pre-computed values prepared by a computer program known as SETOP; to obtain a complete set of operating instructions the experimenter need only specify the particle of interest and a field identification number roughly proportional to energy. The program uses this information along with measured field data and a pre-computed set of ideal fields to determine the desired "operating point" in a straightforward series of calculations: (1) the fields at the desired excitation are synthesized by interpolation in the measured field data, (2) an average field is obtained using a modified least squares fit of the desired average field by the trim coils, and (3) the rf frequency is determined so as to minimize the energy spread of the beam in a single turn at the extraction energy. This paper describes the procedure used in SETOP to determine such operating points, and discusses the principle features of these computations. A typical SETOP sheet is presented along with instructions for its use. Results of beam measurements are in excellent agreement with computed beam behavior.

Introduction

The Michigan State University sector-focused cyclotron is a multi-particle, variable-energy machine with a low-spiral three-sector magnet designed to minimize saturation effects[1]; the useful range of main magnet excitations covers average fields from roughly 6 to 15 kilogauss. The rf system is designed to operate from 14 to 22 Mc in both push-pull and push-push modes[2]. Maximum energies for typical particles are as follows: 55 MeV protons, 28 MeV dueterons, 75 MeV $^{3}He^{2+}$ ions, and 75 MeV $^{12}C^{4+}$ ions.

In the case of the MSU cyclotron, eight trim coils, the rf frequency and voltage, the main field, and the first harmonic coils must be set with varying degrees of precision in order to obtain a good beam. The computational procedure described herein is designed to produce the best beam possible within the limitations imposed by the accuracy of the measured field data, where best beam is defined as that with minimum energy spread at extraction and good optical properties.

Magnetic Field Preparation

It has been determined from orbit studies that in order to obtain magnetic fields with good beam properties, it is sufficient to specify "ideal" fields possessing good properties and use the trimming coils to obtain a good approximation to this ideal field. Magnetic fields on the full scale magnet have been measured at seven main field excitations, incremental effects of each of the eight trim coils at four of these excitations (alternate excitations of the main field), and the field of the first harmonic valley coils at two excitations. For each measured field excitation ideal average fields were computed for protons, deuterons, $^{3}He^{2+}$ ions, $^{12}C^{4+}$ ions and a non-relativistic "heavy ion"; ideal fields used were isochronous fields with the exception of those for high-energy (above 40 MeV) protons, which deviated from isochronism in order to strengthen the axial focusing. Handling of the field data and computation of ideal fields is discussed elsewhere[3]. All field information is combined into a single field deck containing (1) main magnet Fourier components $\langle B\rangle$, H_1, G_1, H_3, G_3, H_6, G_6, H_9, and G_9, for each radius, where:

$$B(r,\theta) = \langle B(r,\theta)\rangle + H_1\cos\theta + G_1\sin\theta + \sum_{n=1}^{3} H_{3n}\cos 3n\theta + G_{3n}\sin 3n\theta, \qquad (1)$$

(2) ideal average fields for each of the five particles specified above at each excitation, (3) incremental average field of each trim coil at each of four main field excitation values, and (4) radial profile of the first harmonic of the valley coils at each of two main field excitation values.

SETOP Calculations

Calculation of Magnetic Fields

Given an arbitrary excitation, SETOP proceeds to obtain a complete field at that excitation by (1) interpolating in the set of input Fourier component data to obtain the Fourier components at the arbitrary excitation and (2) expansion of the Fourier components to obtain the effective field. The interpolation scheme uses the neighboring four field data points to perform a double three-point Lagrangian interpolation with a weighting factor which forces continuity of the field derivative with respect to excitation, except in the extreme intervals, where straight three-point interpolation is used.

Having obtained a complete set of fields, the difference between measured and ideal average field is fitted with the trim coil fields using a least-squares procedure between 5 inches (outside of the field cone) and 28 inches, where the ideal field is joined smoothly to the edge field. If after such a fit any of the trim coil currents lies above the power supply limit, the largest is set at this limit, and the fitting is repeated using only the remaining trim coils. If no maximum current limits are obtained, a check is made for currents below the minimum allowed for adequate regulation by the supply, the smallest of which is set to zero, and the fitting repeated

Reprinted from IEEE Transactions on Nuclear Science NS-13 (4), Aug 1966 © IEEE 1966

using the remaining trim coils. This process is repeated until no current limit violations appear. The complete fitted field is then synthesized, where the average field component is obtained by adding trim coil average fields to the average field of the main magnet and the flutter components are taken to be those of the main magnet.

It has been found sufficient to truncate the main magnetic field Fourier series to include only the 3rd, 6th, and 9th harmonics and to neglect the flutter field of the trim coils.

Precise determination of the amplitude and azimuth of an "ideal" first harmonic is a difficult problem, and has not been solved in its entirety. A numerical method has been derived which enables cancellation by the valley coils of precessional radial motion induced by the natural first harmonic, but this method has not as yet been introduced into SETOP. An approximate value of the first harmonic necessary to produce a desired precession for resonant extraction can be obtained, but due to the additional complexity introduced by the gap-crossing resonance, the precise effect of this harmonic can only be ascertained by actual orbit computation in the complete magnetic field.

Given a desired first harmonic amplitude SETOP computes valley coil currents such that the total first harmonic (the vector sum of the effect of the valley coils and the natural first harmonic) has the desired value. The valley coil power supply is constructed to produce a first harmonic of a desired amplitude and azimuth while contributing no net average field[4] by demanding that the algebraic sum of the coil currents be zero.

Equilibrium Orbits

After the fitted field is assembled a set of equilibrium orbits covering the complete acceleration range is computed using the MSU equilibrium orbit code as a subroutine[5]. Tabulated results from these computations include the radial and axial betatron oscillation frequencies and the phase slip per revolution, which is used in the rf section. The extraction energy is defined to be the energy at which $\nu_r = 0.8$, and the dee voltage is chosen as a constant fraction of the extraction energy to preserve constant orbit geometry (approximately 220 turns).

Energy-spread Minimization

Using the calculated phase slip per revolution from the equilibrium-orbit data and a given value for the nominal starting phase of a central ray, a correction to the isochronous rf frequency is calculated which minimizes the energy spread in a single turn at the extraction energy[6,7]. The program also computes energy spread, the first and second derivatives of energy with respect to starting phase at the desired extraction energy, and also the ratio of the second derivative to the cosine of the phase (which is a figure of merit for the field fitting.)

E-ϕ Ray Tracing

Using values of phase slip per revolution corrected to the frequency which minimizes energy spread in the extracted beam, the program integrates the phase-slip equation to obtain energy and phase as a function of turn number for a beam of particles grouped in phase about the given central ray[8]. This data is useful in diagnosing certain problems in beam behavior as well as calculations for the method used to set up the main magnet excitation.

Determination of Main Field Excitation

Fine adjustment of the main field excitation is accomplished through use of the trim coils. By increasing or reducing the current in an outer trim coil a small amount, the beam can be swung out of phase with the rf. Using trim coil currents pre-computed to produce 50% attenuation of the beam (the central ray phase goes to ± 90°) at a given radius, small adjustments can be made in the main field until the appropriate behavior is obtained, thus fixing the main field excitation. (The central-region slits in the MSU cyclotron make it necessary to use a pair of coils in this procedure, the inner coil canceling the perturbation of the outer coil in the central region so as to maintain an identical orbit pattern through the slits.)

SETOP Operating Instructions

The principle result of such a series of computations is a SETOP instruction sheet, which is shown in Fig. 1. Using this sheet the operator makes a trial setting of the main magnet with the monitor gaussmeter (accurate to about 1 part in 10^4) and sets the dee voltage to within a few percent using calibrated meters; the rf frequency and trim-coil currents can be set exactly using the given data. With the valley coils set to cancel the natural first harmonic, the beam is turned on and main field accurately adjusted using the "Set Main Field by Trim Coils" data, and the rf voltage readjusted, if necessary, to give the correct number of turns. The first harmonic can then be tuned to obtain the desired turn separation pattern in the extraction region using the computed value as a first approximation.

SETOP instructions have been used to tune up the cyclotron over a wide range of particles and energies. In every case best operation has been obtained with all controls set at the calculated values[9].

Field Fitting Results

Figure 2 shows the results of the modified least-squares fitting procedure for two widely varied cases. Fitting only radii greater than 5 inches allows the field to be fit more accurately in the region where the turn density is greatest and at the same time conveniently preserves the focusing effect of the central "cone" of the untrimmed field. Joining the ideal field smoothly to the main magnet field at the peak field value of 28 inches reduces the load on the trim coils while at the same time allowing a very accurate fit. Errors in the field fitting are typically of the order of a few gauss, occasionally becoming greater than 10 gauss near the outer radii.

The trim coil currents for proton fields over the entire energy range are shown in Fig. 3. The general smoothness of trim coil currents with excitation is one of the pleasant features of the procedure. It is clearly possible to obtain a continuum of energies by interpolation in points of roughly this energy spacing, and an on-line computer system capable of controlling such a procedure is now being developed[10].

Figure 4 shows the computed energy as a function of turn number for a band of starting phases. (Phase widths of order 6° are attainable with the central region configuration of the MSU cyclotron, as has been discussed in another paper[11]. The final energy for which the energy spread was minimized occurs between turn 220 and 221. Although an absolute minimum energy spread occurs two turns later, extraction at the higher energy is incompatible with mechanical features of the deflector.

Beam Measurements

Figure 5 shows a series of five radial probe scans with a differential beam probe varying frequency in 5 kc steps, where the central scan is that obtained with the computed frequency. The loss of turn structure as the frequency is varied from the computed value results from an expanded energy spread in the turns. The sharp turn structure at the computed frequency similarly indicates that the phase excursion must be approximately as predicted by SETOP; similarly the energy spread per turn must be approximately minimized.

Using a differential beam probe radial scans of current versus radius have been obtained with sharp turn structure over the complete range[11]; such radial scans can be used to obtain accurate values of the radial focusing frequency.

A z probe with a 1/8 inch square sensitive area which can be moved vertically over a 3/2 inch distance has been used to obtain data on motion. For these measurements a large coherent axial oscillation was induced in the beam using a thin slit 0.15 inches above the median plane at the position of the first quarter turn. Making successive radial scans with the probe at various z values, an effective 9 finger axial probe was obtained. Through such data it is possible to follow the coherent axial oscillation out to the edge region of the magnetic field, and obtain accurate measurement of the axial focusing frequency.

Figures 6 and 7 show computed radial and axial focusing frequencies in the fitted fields obtained from SETOP, and the results of the measurements described above. Field 280, it should be noted, is obtained entirely by interpolation.

References

1. H. G. Blosser, Proc. Int. Conf. on Sector-Focused Cyclotrons & Meson Factories, CERN, 1963, p. 270.

2. W. P. Johnson, Proc. Int. Conf. on Sector-Focused Cyclotrons & Meson Factories, CERN, 1963, p. 279.

3. R. E. Berg, Mich. State Univ. Cyclotron Project Report #22 (1966).

4. C. Dols, UCLRL Engineering Note UCID-1106 (1959).

5. T. I. Arnette, Mich. State Univ. Cyclotron Project Report #10 (1961).

6. M. M. Gordon, "Single Turn Extraction", (paper at this conference).

7. M. M. Gordon and W. Joho, Mich. State Univ. Cyclotron Laboratory internal report.

8. M. M. Gordon and W. Joho, Mich. State Univ. Cyclotron Laboratory internal report.

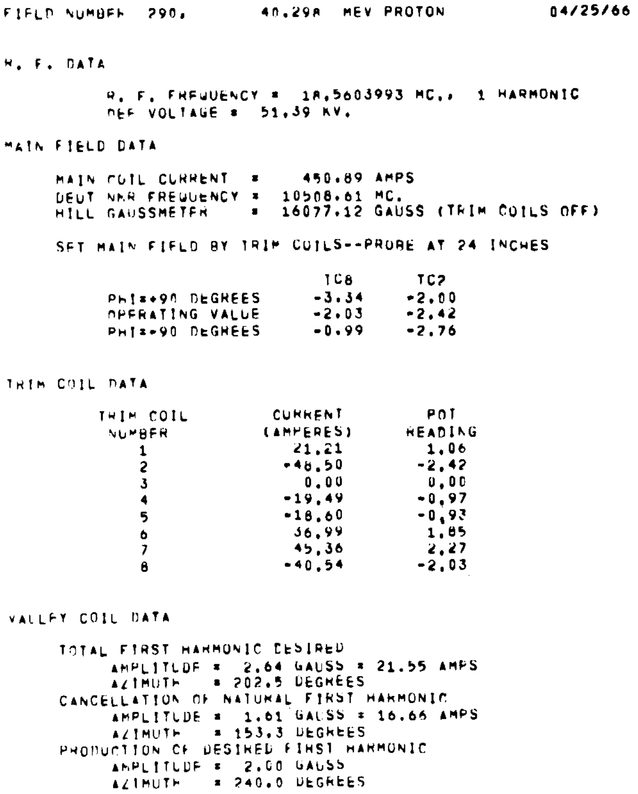
9. H. G. Blosser and A. I. Galonsky, "MSU 55 MeV Cyclotron: Progress and Status," Feb., 1966 (paper at this conference).

10. A Scientific Data Systems Sigma 7 computer system has been ordered for delivery in late 1966.

11. H. G. Blosser, "Problems and Performance in the Cyclotron Central Region," (paper at this conference).

*Work supported by National Science Foundation.

†National Science Foundation Cooperative Graduate Fellow.



```
FIELD NUMBER  290.        40.298  MEV PROTON          04/25/66

R. F. DATA

          R. F. FREQUENCY =  18.5603993 MC.,  1 HARMONIC
          DEE VOLTAGE =  51.39 KV.

MAIN FIELD DATA

      MAIN COIL CURRENT  =    450.89 AMPS
      DEUT NMR FREQUENCY =  10508.61 MC.
      HILL GAUSSMETER    =  16077.12 GAUSS (TRIM COILS OFF)

      SET MAIN FIELD BY TRIM COILS--PROBE AT 24 INCHES

                                 TC8       TC7
          PHI=+90 DEGREES       -3.34     -2.00
          OPERATING VALUE       -2.03     -2.42
          PHI=-90 DEGREES       -0.99     -2.76


TRIM COIL DATA

         TRIM COIL           CURRENT        POT
          NUMBER            (AMPERES)      READING
            1                 21.21          1.06
            2                -48.50         -2.42
            3                  0.00          0.00
            4                -19.49         -0.97
            5                -18.60         -0.93
            6                 36.99          1.85
            7                 45.36          2.27
            8                -40.54         -2.03


VALLEY COIL DATA

      TOTAL FIRST HARMONIC DESIRED
           AMPLITUDE =  2.64 GAUSS = 21.55 AMPS
           AZIMUTH   = 202.5 DEGREES
      CANCELLATION OF NATURAL FIRST HARMONIC
           AMPLITUDE =  1.61 GAUSS = 16.66 AMPS
           AZIMUTH   = 153.3 DEGREES
      PRODUCTION OF DESIRED FIRST HARMONIC
           AMPLITUDE =  2.00 GAUSS
           AZIMUTH   = 240.0 DEGREES
```

Fig. 1. SETOP data sheet, showing information necessary to tune up the cyclotron at the given energy.

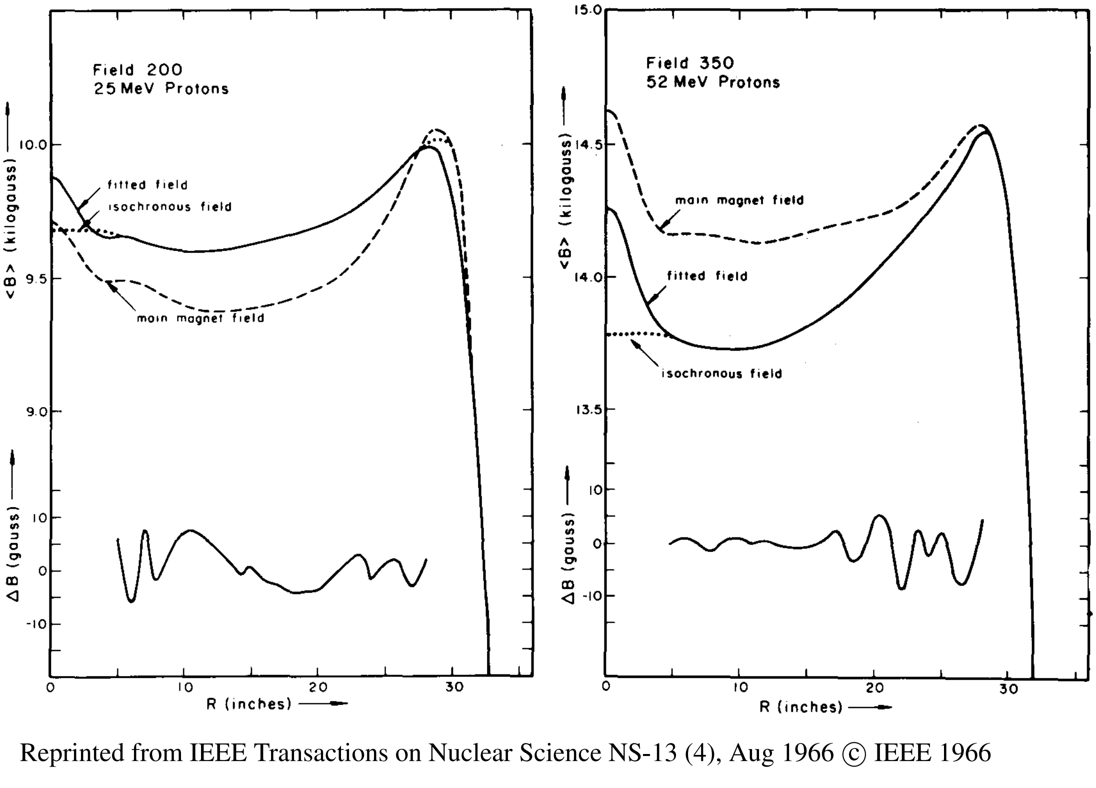


Fig. 2. Average fields obtained by the modified least squares procedure for 25 and 52 MeV protons. Ideal average fields, main magnet average fields and fitted average fields are shown, along with the resulting error fields in the interval over which the fit was performed.

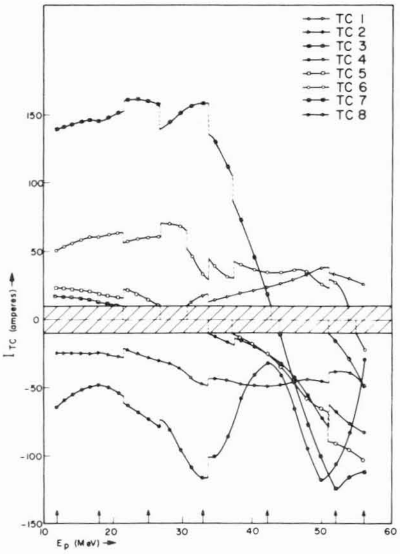


Fig. 3. Trim coil currents as a function of proton energy over the entire range of magnetic field of the MSU cyclotron. Discontinuities occur at points at which one of the trim coil currents drops below the minimum (10 amperes) imposed by the power supply regulator. Arrows indicate measured field excitations.

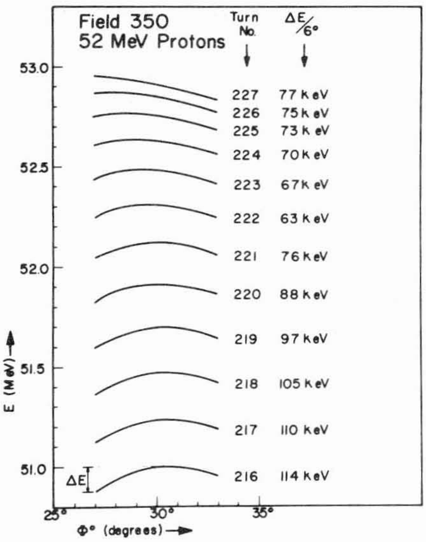


Fig. 4. Energy vs. starting phase for turns near the extraction energy for a beam of 6 phase width about a central ray of nominal +30 starting phase. The energy spread has been minimized for 51.97 MeV protons, turn 220.4.

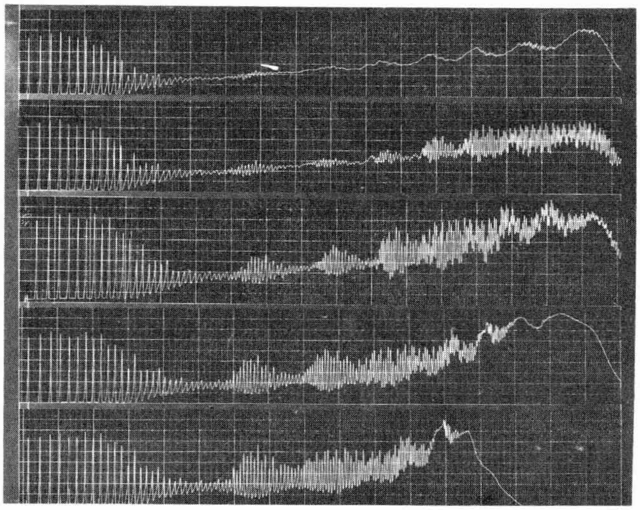


Fig. 5. Differential radial beam probe scans for Field 200 as a function of frequency, taken in 5 kc. steps, where the central scan corresponds to the computed frequency of 14.75238 Mc..

Reprinted from IEEE Transactions on Nuclear Science NS-13 (4), Aug 1966

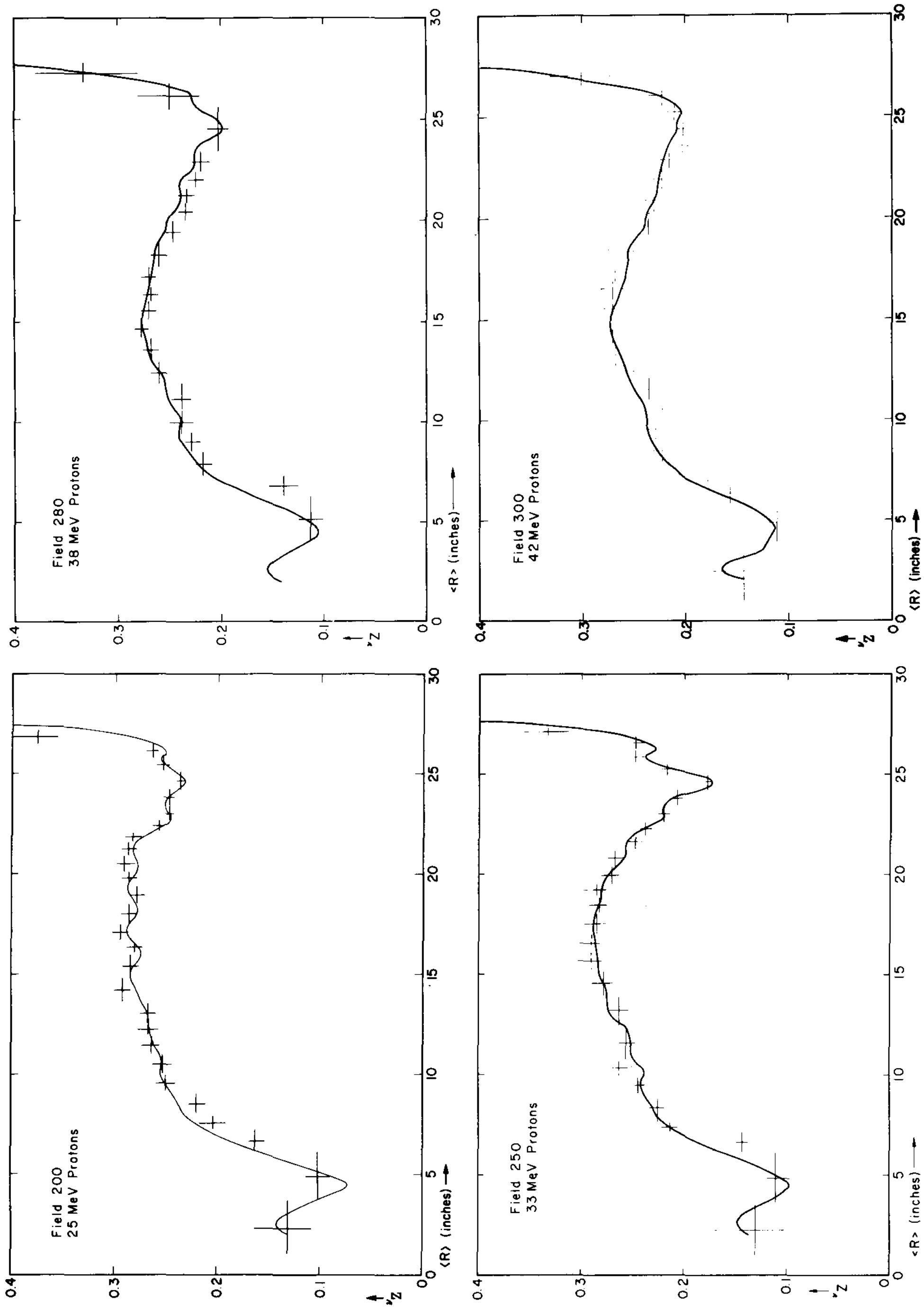


Fig. 6. Axial focusing frequency as a function of average radius for four proton fields; computer values obtained from SETOP fitted fields are shown along with measured data. Field 280 is obtained entirely by interpolation and field 250 trim coil fields are obtained by interpolation.

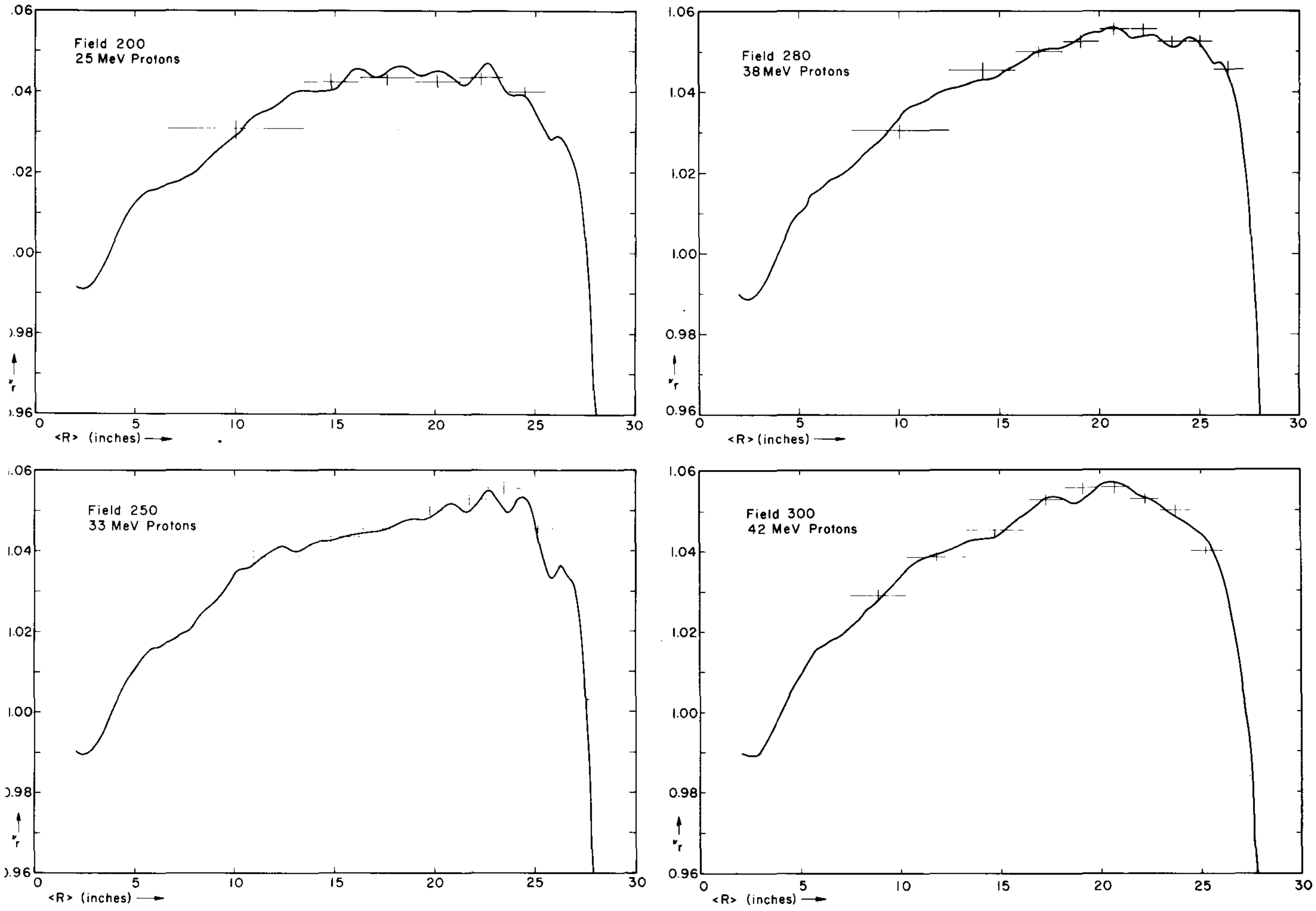


Fig. 7. Radial focusing frequency as a function of average radius for four proton fields; computed values obtained from SETOP fitted fields are shown along with measured data. Field 280 is obtained entirely by interpolation and field 250 trim coil fields are obtained by interpolation.

DISCUSSION

ALEKSEEV: At what intervals did you measure the magnetic field, so that you could then set the trim coils?

BERG: The average minimum field measured was 6 kG, the top field about 15.5 kG. Seven different main field excitations were measured at roughly equal intervals.