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ABSTRACT

General requirements for a vertically focusing negative magnetic gradient region near the cyclotron center are stated. Cone shapes were studied with computer program CENREG (IBM 704) and with magnetic measurements in a fifth-scale model magnet. Principal parameters studied were vertical and radial focusing, particle phase slip, and magnetic first harmonic. Shaping of iron to achieve the desired conical field profile in conjunction with circular trim coils is described. A pattern of holes with magnetically saturated iron caps in the 8-in.-diam center plug was needed to get the desired cone shape at all field levels from 8 to 16 kG. Proper placement of holes and modification of the movable ion-source hole in the upper pole tip were necessary to reduce first harmonic at 5 in. radius to less than 2 G at all field levels and at all ion-source positions. Small adjustment of center-region iron were made during full-scale magnet testing. Cyclotron operations to date have shown the choice of center cone to be very satisfactory.

DEVELOPMENT OF THE MAGNETIC CONE FOR THE CENTER OF THE BERKELEY 88-INCH CYCLOTRON†

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1. Introduction

Early in 1960 attention was directed to shaping the magnetic field at the center of the Berkeley 88-inch cyclotron, to provide vertical focusing of the beam during the early turns. Design studies covered two areas: measurements of the magnetic effect of iron changes in the fifth-scale model of the cyclotron magnet, and analytical investigation of the effect of field shapes on particle behavior. To assist in the latter, computer program CENREG^{1}) (IBM 704) was developed to calculate, for a given dee voltage and from simplified magnetic field data, the focusing properties of a field shape and its effect on the phase of a particle of given charge and mass. A second computer program, NORA-2 (IBM 650), was written to make a Fourier analysis of an array of magnetic dipole in the vicinity of the cyclotron center. The NORA-2 program was used in developing first-harmonic compensation for the movable ion-source hole.

Midway through our studies we learned of the beneficial electric focusing resulting from starting ions late with respect to the peak of the rf, as reported by Smith^{2}). Willax^{3}) studied the application of this principle to our cyclotron. He found that with an initial lagging phase of + 30 deg the vertical oscillation frequency ν_z decreased rapidly with radius, becoming less than 0.1, our design-goal minimum, at about 3 in. radius. In our cyclotron, flutter is

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† Work done under the auspices of the U. S. Atomic Energy Commission.

negligible at less than 4 in. radius (see fig. 1), and flutter focusing does not become adequate until about 7-1/2 in. radius. To maintain ν_z greater than 0.1 between 3 in. and 7-1/2 in. required a conical magnetic field to provide a focusing radial gradient.

2. Selection of a Conical Field Shape

For the purpose of discussion the effect of field shape on focusing and phase can be estimated from a knowledge of the radial variation of field flutter (fig. 1), and from an examination of some approximate equations governing particle behavior near the cyclotron center. The approximate equations are:

$$\nu_z^2 = n + F^2,$$

$$\nu_r^2 = 1 - n + F^2,$$

$$\sin\phi = \sin\phi_a + (K/\Delta E) \int_{R_a}^{R} \Delta B(R)\, R\, dR,$$

where

ν_z and ν_r are the vertical and radial oscillation frequencies,

n is the field index $(-R/B)\,\frac{\delta B}{\delta R}$,

F is field flutter, $F^2 = \frac{1}{2\pi} \int_0^{2\pi} \frac{[B(R,\theta) - B(R)]^2}{B^2(R)}\, d\theta$

ϕ is the phase angle between a particle and the peak of the dee voltage (ϕ is positive when the particle lags the dee voltage).

ϕ_a is the phase angle of ions as they leave the ion source.

R_a is the radial location of the ion source

$\Delta B(R) = B(R) - B_{is}$.

$B(R) = \frac{1}{2\pi} \int_0^{2\pi} B(R,\theta)\, d\theta$

B_{is} is the isochronous field

ΔE is the energy gain per turn, and

K is a proportionality constant.

As previously stated, electric vertical focusing is adequate within the first 3 in. If ν_z is to remain constant at about 0.11 beyond 3 in. the approximate equations dictate that n decrease at the same rate that F^2 increases (curve 72, fig. 2). To this extent the shape of the cone is governed by the onset of flutter, and would look like curve 72 in fig. 3a. Curves 72 and 79 in figs 2, 3b, 4, and 5 are results of CENREG analysis of the field profiles of fig 3a, using more refined equations than stated above. Curves LP are data from the first linear programming solution at high field[4]). To maintain ν_z at a higher value (say 0.13) constant with radius would require larger values of n (curve 79, fig. 2) hence a steeper cone (curve 79, fig. 3a). The maximum constant value at which ν_z can be sustained is limited by the particle phase excursion generated by the cone. For cone shapes 72 and 79 in fig. 3a, with 70 kV on the dee, deuterons would undergo the phase shifts shown by curves 72 and 79 in fig. 3b. Note that for cone shape 79 the deuterons undergo a phase oscillation from +20 to -5 deg and then back to +5 deg, because the field profile drops below the isochronous field at the base of the cone. To maintain a larger value of ν_z would require a larger field undershoot at the base of the cone and a phase oscillation greater than ± 5 deg. If the actual field and the isochronous field are plotted as functions of the radius squared, the area between these curves is proportional to the cumulative phase slip. This method is discussed by Stover[5])

We have not yet considered ν_r. Near the center, F^2 is almost zero and μ' is negative, therefore ν_r is less than one. At the base of the cone, F^2 is positive, and as n goes to zero, ν_r becomes greater than one. This transition through one, the well-known 3/3 resonance, results in a strong radial defocusing of the beam. This defocusing is aggravated by the presence of magnetic first harmonic at the resonance radius. To reduce beam loss, first harmonic must be minimized and $\nu_r = 1$ must be crossed quickly; that is, $\frac{\partial \nu_r}{\partial R}$ must be maximized

If we give up the restriction of holding ν_z constant it is possible to reduce the width of the radially unstable region by increasing $\frac{\partial \nu_r}{\partial R}$ at the radius where $\nu_r = 1$. To do this one must increase $\frac{\partial(-n)}{\partial R}$ and/or $\frac{\partial F^2}{\partial R}$ at this radius. The term $\frac{\partial F^2}{\partial R}$ is determined by the geometry of the hills and valleys and cannot be significantly modified in our cyclotron. The term $\frac{\partial(-n)}{\partial R}$ is positive when ν_z is constant with radius (curves 72 and 79, fig. 2) and can be made more positive by allowing ν_z to decrease with radius (curve LP figs. 2 and 4) Curve LP shows the variation of n recommended by the first linear programming solution. At the cost of a decrease in ν_z at 7 in. radius, the width of the unstable region is reduced by a factor of 2 (compare slopes in fig. 5). Increasing $\frac{\partial(-n)}{\partial R}$ at the base of the cone permits a more rapid transition to isochronism, resulting in less total phase shift (curve LP in figs. 3a and b). The best compromise between vertical focusing, width of 3/3 resonance region, and phase slip has yet to be chosen. Beam quality near the center has been very satisfactory at the operating levels, tested to date. Should further optimizing of the cone termination be desired, the circular trim coils provide considerable freedom in shaping the field beyond 5 in. radius (fig 6).

For our variable-energy machine it was necessary to consider the center-region field shape at field levels ranging from 8 to 16-1/2 kG. At all fields the goal is to achieve sufficient vertical focusing without excessive phase excursion, and to cross $\nu_r = 1$ rapidly. It is easier to meet these requirements at low field than at high field. At low field, for the same absolute cone shape, as field level decreases focusing increases, phase slip is less, flutter focusing starts building up at a smaller radius and at a faster rate, and ν_r crosses 1 at a faster rate than at high field. In addition to these factors the profile-correcting trim coils have slightly more control over cone shape at low field than at high Because the cone shape is more critical at high field we concentrated on the high-field case in our optimizing studies. To insure that lower field profiles were suitable, we attempted to make the center profile (with trim coils off) about the same at all field levels.

3. Iron Shaping

The high-field cone shape selected as our goal is curve 79 in fig. 3. It has a maximum gradient of about -100 G/in. at 3 in. radius in the field, and a smooth termination at about 8-in. radius. To achieve this profile, iron-shaping studies in the model were undertaken. Figure 7 shows some of the results of these studies. Before discussing the significance of these curves, it is necessary to describe the geometry of the center region. (See fig. 8.)

The dominant feature of the center region is a pair of 8-in.-diam iron plugs 13 in. long, situated at the gap end of a pair of axial holes through the two poles of the magnet. The upper-pole-tip hole contains the ion-source tube and a mechanism to permit moving the ion source radially and azimuthally within 2-1/2 in. of the magnet center[6]) The lower-pole-tip hole has no other purpose than to preserve symmetry in the iron. The requirement for mobility of the ion source ruled out the originally planned extension of the hills over the center plateau (the face of the 8-in. plug) This change had little effect on flutter but had considerable effect on center profile. With the removal of these obstructions to vertical adjustment of the center plugs, the conical field shape could be easily changed by changing the height of the center plateau. In our model studies we found that when the plateau height was adjusted to give an adequate cone at high field, the low-field profile had an undesirable rise at 4 in. radius. In the process of overcoming this difficulty, magnetic measurements were made of the effect of modifications to the center plug, the inner ends of the hills, and the valleys next to the center plug. Figure 9 is a photograph of the removable center region of the fifth-scale model as it appeared at the conclusion of testing. An earlier version, with laminations for adjusting the height of hills and valleys, was used in making the above measurements.

The problem of getting the desired cone at all field levels was finally solved by an iron configuration which also helped reduce the magnetic first harmonic produced by the ion-source hole. In its final form (fig. 8), there are nineteen 3-in.-deep 1-in.-diam holes in the center plateaus, 10 in the bottom plug and 9 in the top. Each hole is capped with an iron cylinder that starts 0.25 in. below, and rises 0.90 in. above, the plateau surface. Each cylinder has an inner diameter of 0.34 in. and an outer diameter of 1.09 in. Magnetically the ion source is very similar to each of the 19 holes and caps, although the details of its construction are quite different. The choice of array pattern and hole and cap dimensions is discussed in sec. 4.

Determination of the plateau and cap heights was made in the model magnet, after installation of holes and caps in the model plateau. Because the hole caps are completely saturated, even at 8 kG, the magnetic effect of the hole caps was found to be nearly the same at all field levels (fig. 7). The variation in profile with field was measured with the plateau set to an estimated optimum height. The change in field with change in plateau height was next measured at several field levels (fig. 7). The plateau height was then adjusted so that the saturation characteristic of the center plug approximately matched the characteristics of the surrounding iron (see the dotted curves in fig. 10). The estimated shape functions of the first three circular trim coils and the shape function of the hole caps were examined to determine what combination of curves would maximize $\frac{\partial B}{\partial r}$ at 3 in. radius and at the same time maximize the second derivative of the field at 5-1/2 in. radius. Figure 7 shows two of these shape functions. (The trim-coil functions are from full-scale magnet measurements.) We found that energizing trim coil No. 2 with reverse current and increasing the height of the hole caps had the desired effect at all field levels. To get the desired cone shape at high field (fig. 6) requires nearly the full negative capacity of trim coil No. 2. The prediction of plateau height from model studies was sufficiently close that final adjustment of the full-scale center plateau gap was less than 1/8 in.

4. Reduction of First Harmonic

Control of oscillation amplitude requires that in the region near 5-1/2 in. radius where $\nu_r = 1$, the magnetic first harmonic must be very small.

Garren[7]) calculated that a 5-G first harmonic would increase the radial amplitude by 1/8 in. When first-harmonic tolerances were tightened during the course of our model testing, the tolerance at $\nu_r = 1$ was set at 1 G. Cyclotron operation to date suggests that this tolerance was unnecessarily stringent.

One of the unique features of our cyclotron is the movable hole in the upper pole tip, which permits radial and azimuthal adjustment of the ion-source position. Magnetic compensation was needed to minimize the effect of this hole at all field levels. In addition to the existence of the moving hole perturbation, the magnetic characteristics of the eccentrically mounted intermediate 5-in.-diam plug might not exactly compensate the 5-in. hole in the 8-in. plug. The plan adopted was to study the effects of holes and hole compensation in the model magnet, select a suitable design, and make final studies and adjustments in the full-scale magnet.

Within the probable range of the center-plateau height, the originally planned 1-3/4-in.-diam ion-source hole produced a maximum perturbation of 75 to 100 G. With the ion source at 2-1/2 in., the first harmonic at 5 in. radius was 16 to 21 G. The higher values in each case are for a plateau height 0.2 in. closer to the midplane. Local compensation, consisting of a ring of iron around the edge of the hole, was unsatisfactory for two reasons: (a) the effect of the hole was much broader than the effect of the ring, and (b) the effect of the hole was much greater at high field than low field, but the ring had about the same effect at all field levels. A more satisfactory solution was to substitute iron for the nonmagnetic parts of the ion source within the pole tip wherever possible.

When the limiting case of two 1/2-in. holes for the arc electrodes was studied in the model, the maximum perturbation was 15 to 19 G, and the maximum first harmonic at 5 in. radius was 3-1/2 to 5 G. These values were for the 16-kG field level (at low field the effect of the holes was negligible). Since local compensation, raising the ion-source iron slightly above the surrounding plateau, had an equal magnetic effect at low and high field, correcting one-half the first harmonic at high field would increase the first harmonic at low field by an equal amount. This plan was superseded by a modification that considered the variation is cone shape with field level in addition to harmonic correction.

The new plan was to cover the center plateau with a magnetically symmetrical array of dummy ion-source holes capped with iron cylinders (fig. 11). This plan simplified ion-source construction, and brought the magnetic compensation of the ion source within tolerance at all field levels.

The principal remaining difficulty was to find an array of capped holes that would retain minimum first-harmonic structure during counter rotation of the eccentrically mounted plugs. Since the 8-in. plug is concentric with the origin, its magnetic effect can only change in azimuth, and the problem can be separated into two parts. First, find an array on the 5-in. plug that has circular symmetry about the center of the 5-in. plug; then find an array on the 8-in. plug that cancels the first-harmonic contribution of the 5-in. plug array. To simplify magnetic measurements, the array was to have a minimum of second harmonic as well. This factor, together with geometry considerations of hole sizes, narrowed the choice of arrays to one. The pattern is based on three equilateral pentagons nested together, with capped holes located at the corners. One of the pentagons is centered on the 5-in. plug and the remaining five holes are in the 8-in. plug (fig. 11). Slight compromises were made with location, so that the holes could be made 1 in. in diameter, the minimum satisfactory size for the ion-source hole. The outer diameter of the caps was limited by interference with the outer shell of the ion source. The holes through the caps are equal in area to the arc-electrode passages in the ion-source cap.

Calculations of the first harmonic due to deviation from symmetry were made with computer program NORA-2, using model data for the effect of capped holes. At 5-in. radius the first-harmonic prediction was less than 1 G.

During full-scale magnet measurements final optimizing of the center to reduce first harmonic was achieved by raising the height of the 5-in. plug 0.005 in. above the 8-in. plug, raising the ion source 0.050 in. above the 5-in. plug, and adding 3/8 in. of subsurface length to the ion-source cap. Measurements of the effect of tilting the 8-in. plug were inconclusive. Figure 12 shows the variation of first harmonic with ion source position at three field levels following the above changes. The remaining first harmonic at 5 and 6 in. radius can be further reduced with the innermost set of harmonic-correcting valley coils.

5. Conclusion

Studies of radial and vertical focusing and particle phase slip, by use of the computer program CENREG, required a minimum of field measurement, and gave results that were in good agreement with the Oak Ridge Code 1482[8]) and with Berkeley code DORO[9]).

Studies of center-region iron geometry necessary to produce the same conical magnetic field at all operating field levels showed that magnetically saturated elements on the center plateau were needed. The uniformity of center field shape with field level was greater in the full-scale magnet than in the model. The degree of uniformity was greater than needed. Trim-coil adjustment of cone termination allows considerable flexibility in choice of focusing and rate of crossing $\nu_r = 1$. Cyclotron operations to date have not tested the full range of this flexibility.

The inclusion of movable iron parts and a movable hole in the upper pole tip presented special problems in control of magnetic first harmonic, and severely limited the choice of saturating elements on the center plateau.

Reduction of first harmonic below 1 G near the radius where $\nu_r = 1$ requires the use of harmonic-correcting coils. Cyclotron operation to date has been with nearly 2 G first harmonic in this region. The increase in radial oscillation has been very small.

Acknowledgment

Of the many people directly and indirectly associated with the center-region development program, the author is especially indebted to Alper Garren for theoretical guidance, Joseph Dorst and Hans Willax for assistance in reduction and interpretation of data, and Robert Anderson for model-magnet measurements.

REFERENCES

1) A. A. Garren, An IBM Code to Investigate the Properties of the Central Region of the 88-Inch Cyclotron (CRP), Lawrence Radiation Laboratory Report UCID-1660, Jan. 1960 (unpublished).

2) W. I. B. Smith, Improved Focusing Near the Cyclotron Source, Nucl. Instr. and Meth. 9, (1960) 49.

3) H. A. Willax and A. A. Garren, Center-Region Geometry of the Berkeley 88-Inch Cyclotron, Lawrence Radiation Laboratory Report UCRL-10071, April 1962, Nucl. Instr. and Meth. (to be published).

4) A. A. Garren, Calculation of Cyclotron Trim-Coil Currents for Field Optimization by Linear Programming Methods, Lawrence Radiation Laboratory Report UCRL-9916, March 1962, Nucl. Instr. and Meth. (to be published).

5) J. E. Stover, Rapid Traversal of 3/3 Radial Resonance near the Center of a Sector Focused Cyclotron, Michigan State University Report MSUCP-3, August 1960 (unpublished).

6) J. M. Haughian and R. J. Burleigh, The Ion-Source Mechanism for the Berkeley 88-Inch Cyclotron, Lawrence Radiation Laboratory Report UCRL-10068, March 1962, Nucl. Instr. and Meth. (to be published).

7) A. A. Garren(Lawrence Radiation Laboratory, Berkeley) private communication.

8) M. M Gordon, T. A Welton, T. I. Arnette, and H C. Owens, An IBM 704 Code for Determining Equilibrium Orbits and Properties of Small-Amplitude Oscillations in Cyclotron Fields, ORNL Report 59-11-2, Nov. 1959 (unpublished)

[9]) D. M. Brainard, A. A. Garren, and A. S. Kenney, DORO, and IBM Code for Making Isochronous Corrections to Cyclotron Magnet Measurements for Use with Oak Ridge Orbit Code 1482, Lawrence Radiation Laboratory Report UCRL-9931.

FIGURE CAPTIONS

Fig. 1. Magnet field flutter, model approximation compared to full scale.

Fig. 2. Radial variation of n from CENREG cases 72 and 79, and from first high-field linear programming solution, compared to flutter at high field.

Fig. 3. Radial variation of average field and deuteron phase shift from CENREG cases 72 and 79, and from first high-field linear programming solution.

Fig. 4. Radial variation of ν_z from CENREG cases 72 and 79 and from first high-field linear programming solution.

Fig. 5. Radial variation of ν_r from CENREG cases 72 and 79, and from the first high-field linear programming solution.

Fig. 6. Range of center profile adjustment with trim coils.

Fig. 7. Magnetic effects of moving the center plugs 0.100 in. closer together (ΔP), increasing the height of 20 hole caps by 0.100 in. (ΔC), and energizing trim coils No. 1 and No. 2 at half capacity.

Fig. 8. Section view of cyclotron center.

Fig. 9. Removable center of fifth-scale model magnet.

Fig. 10. Radial profile of average field, with and without hole caps, compared to a typical operating field profile.

Fig. 11. Center region of upper pole tip; ion source at four locations.

Fig. 12. Sine and cosine components of magnetic first harmonic at three field levels for the ion source positions of fig. 11.

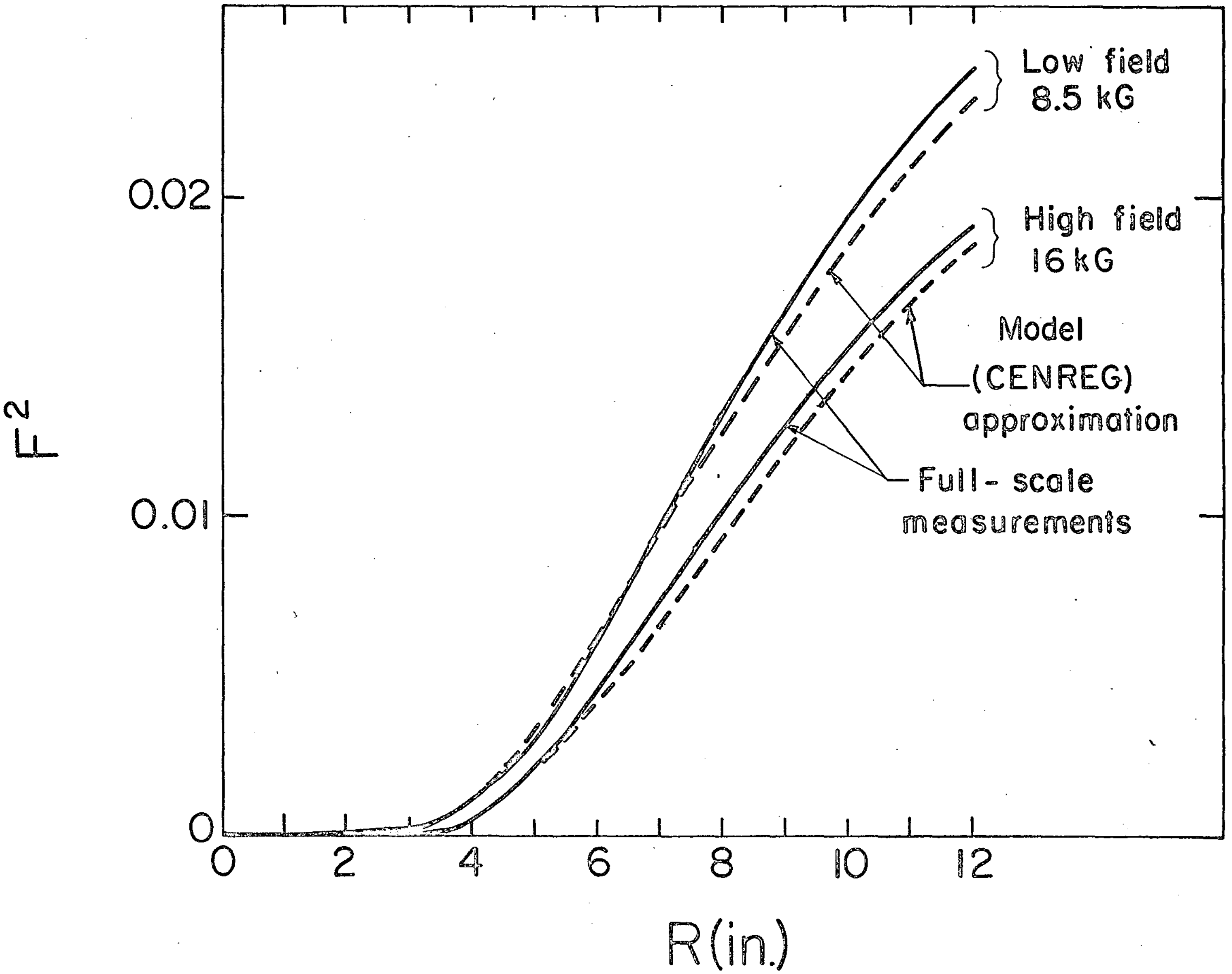

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Fig. 1

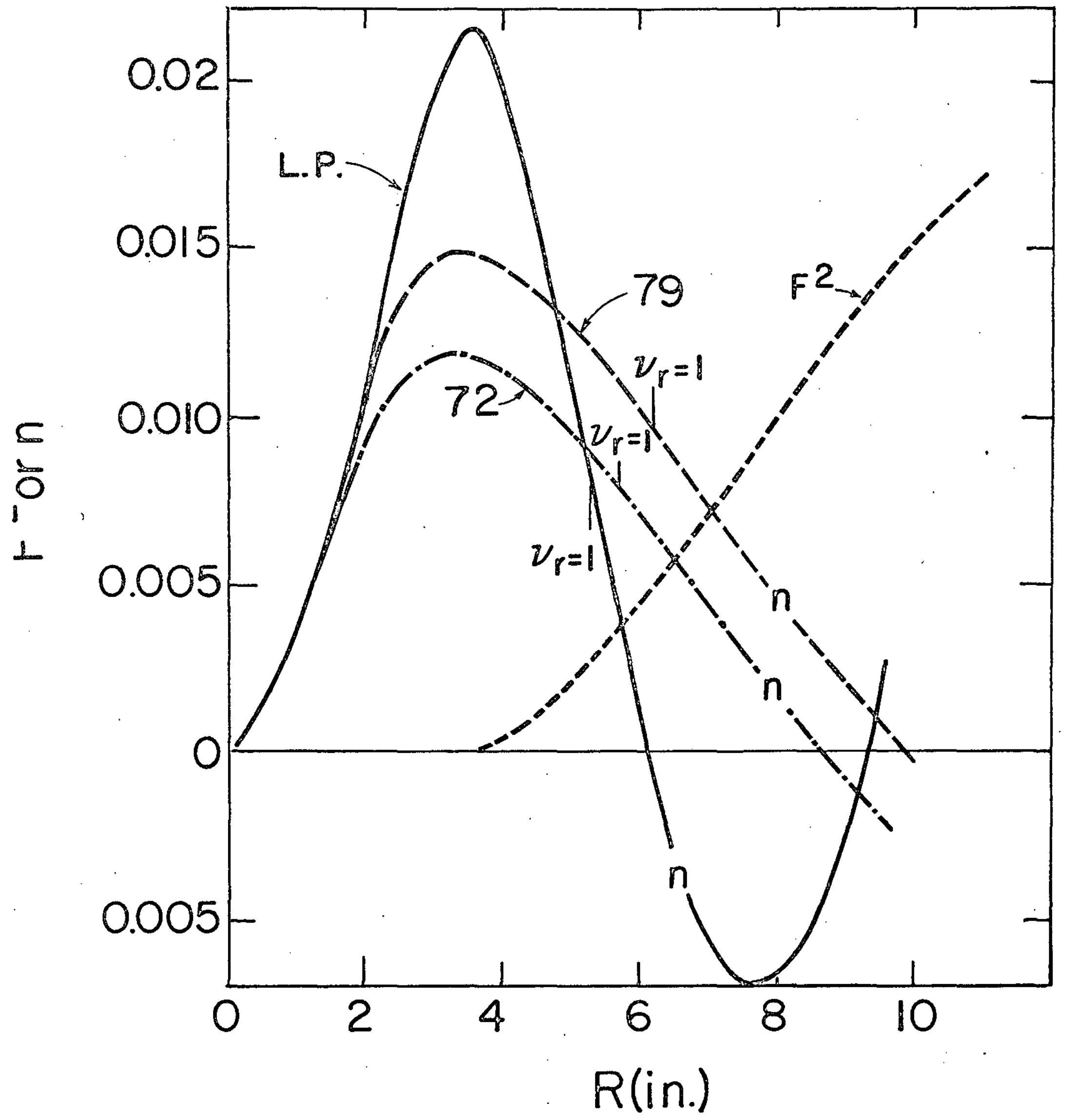

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Fig.2

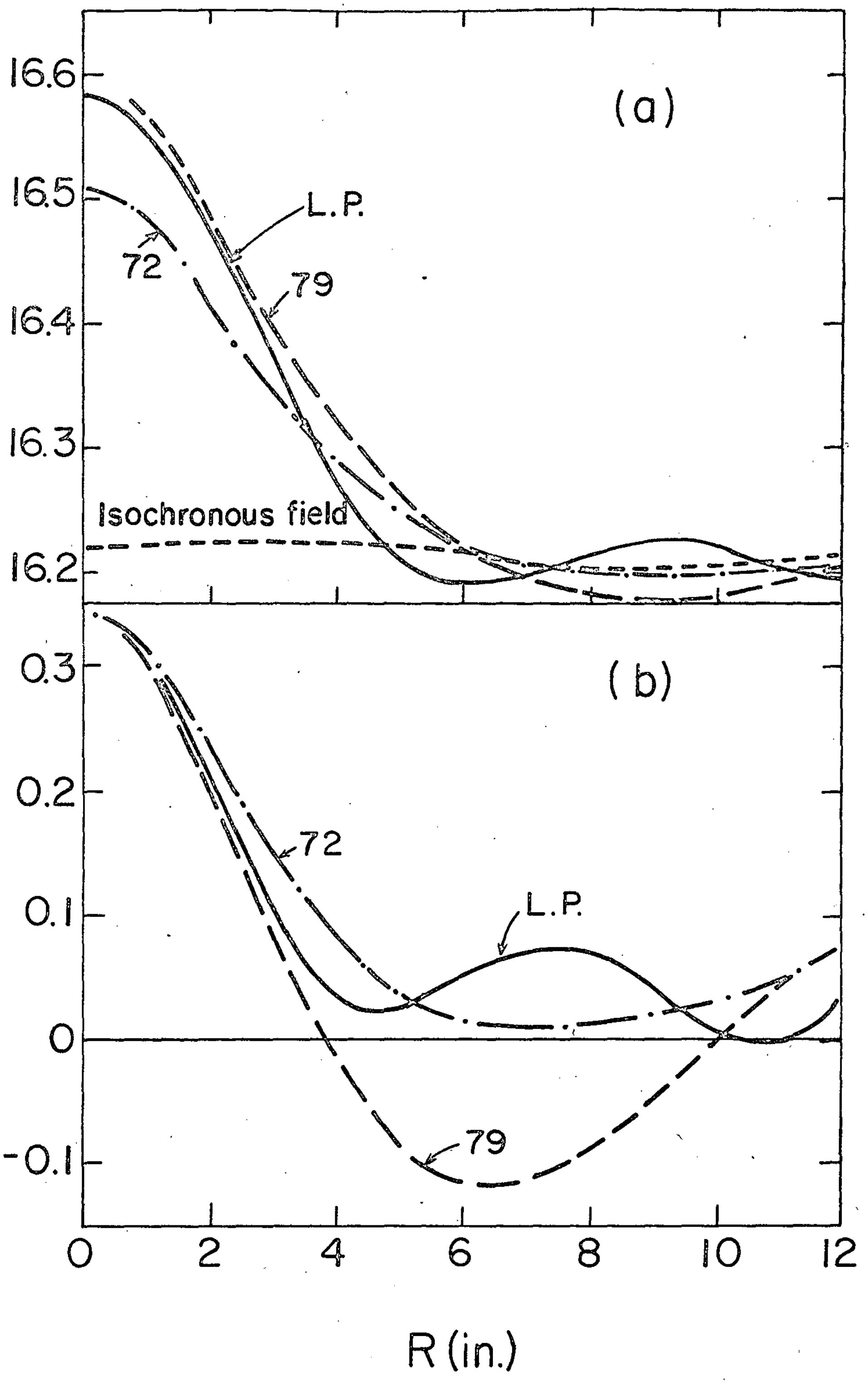

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Fig. 3

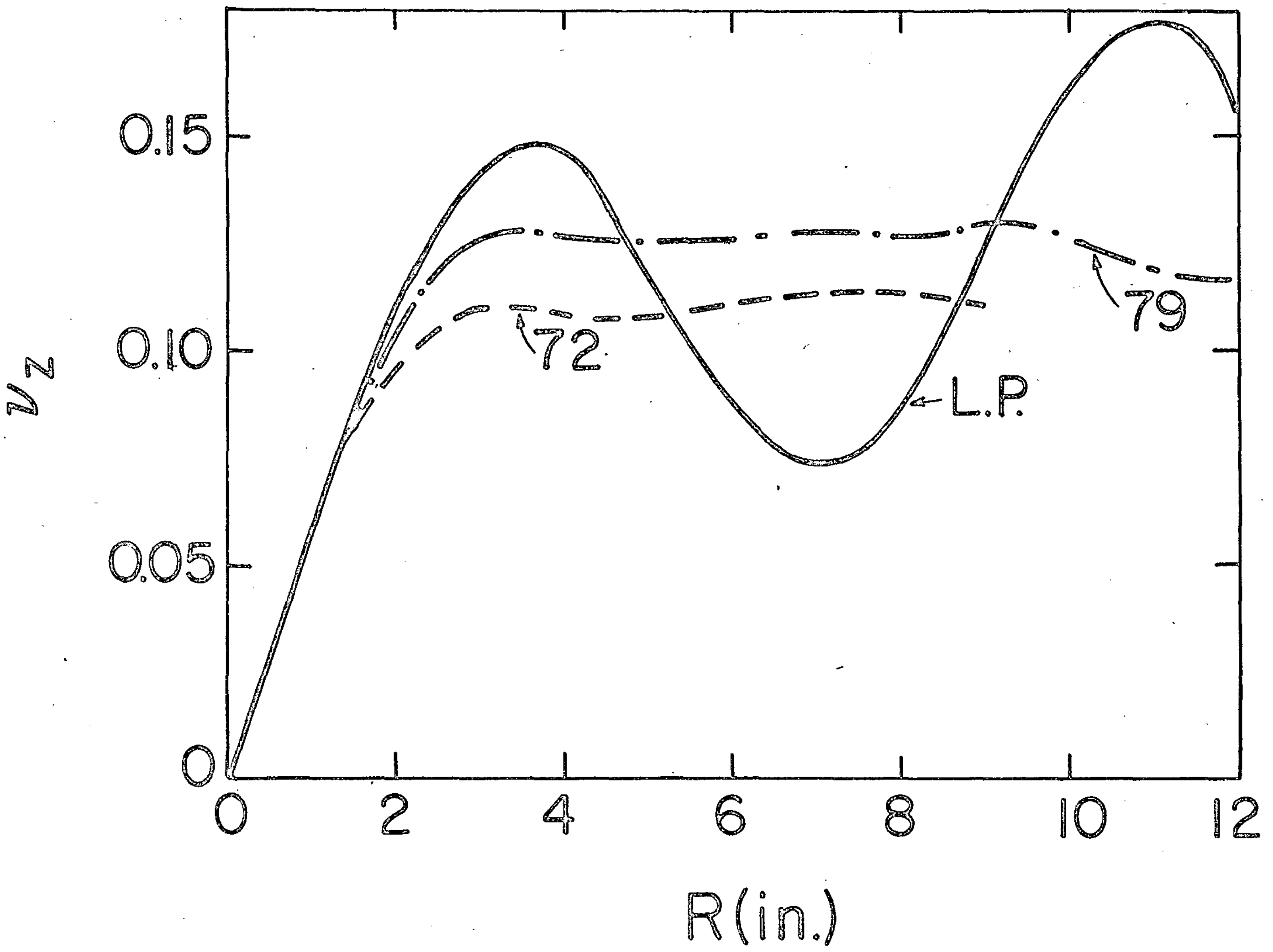

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Fig. 4

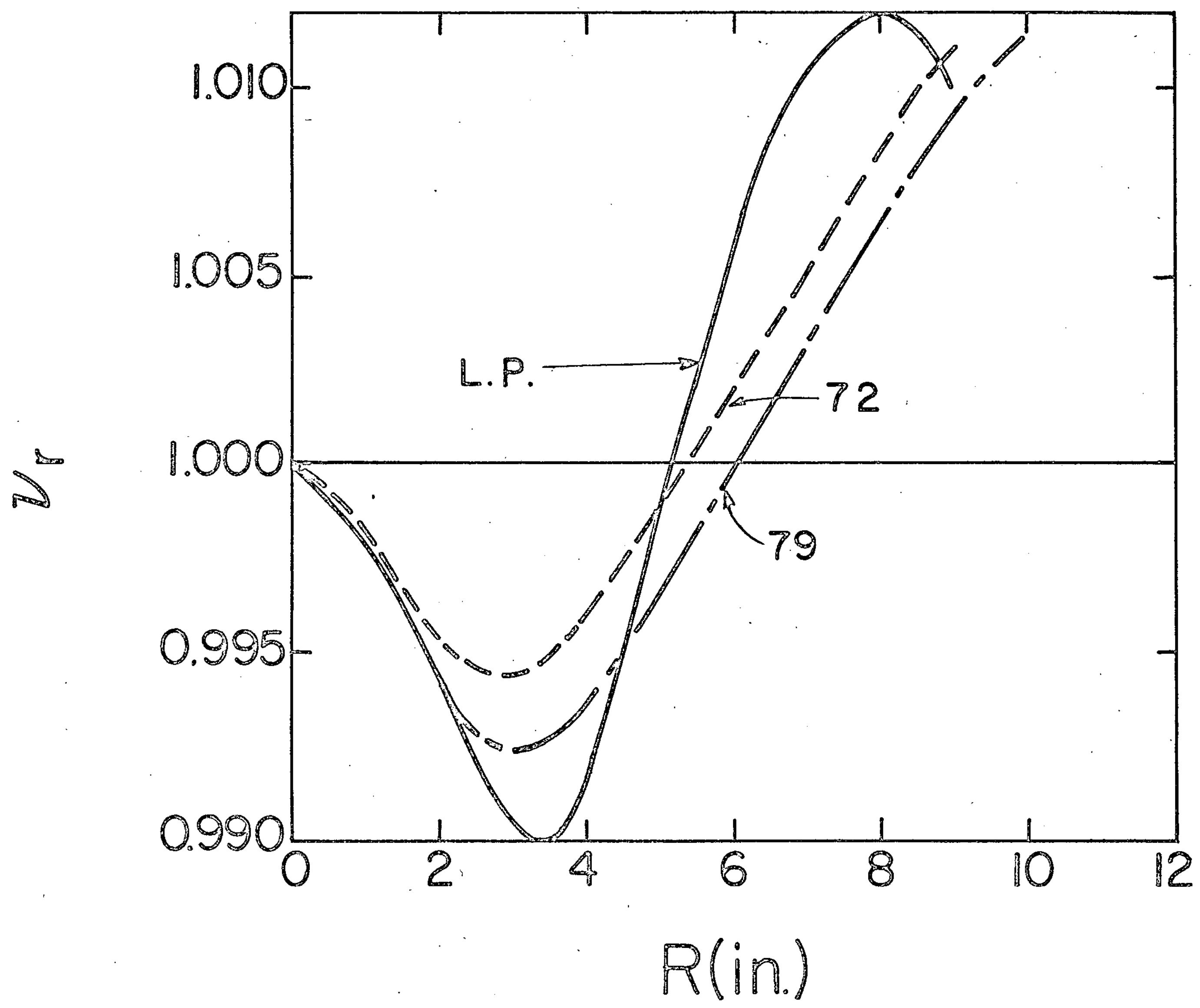

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Fig.5

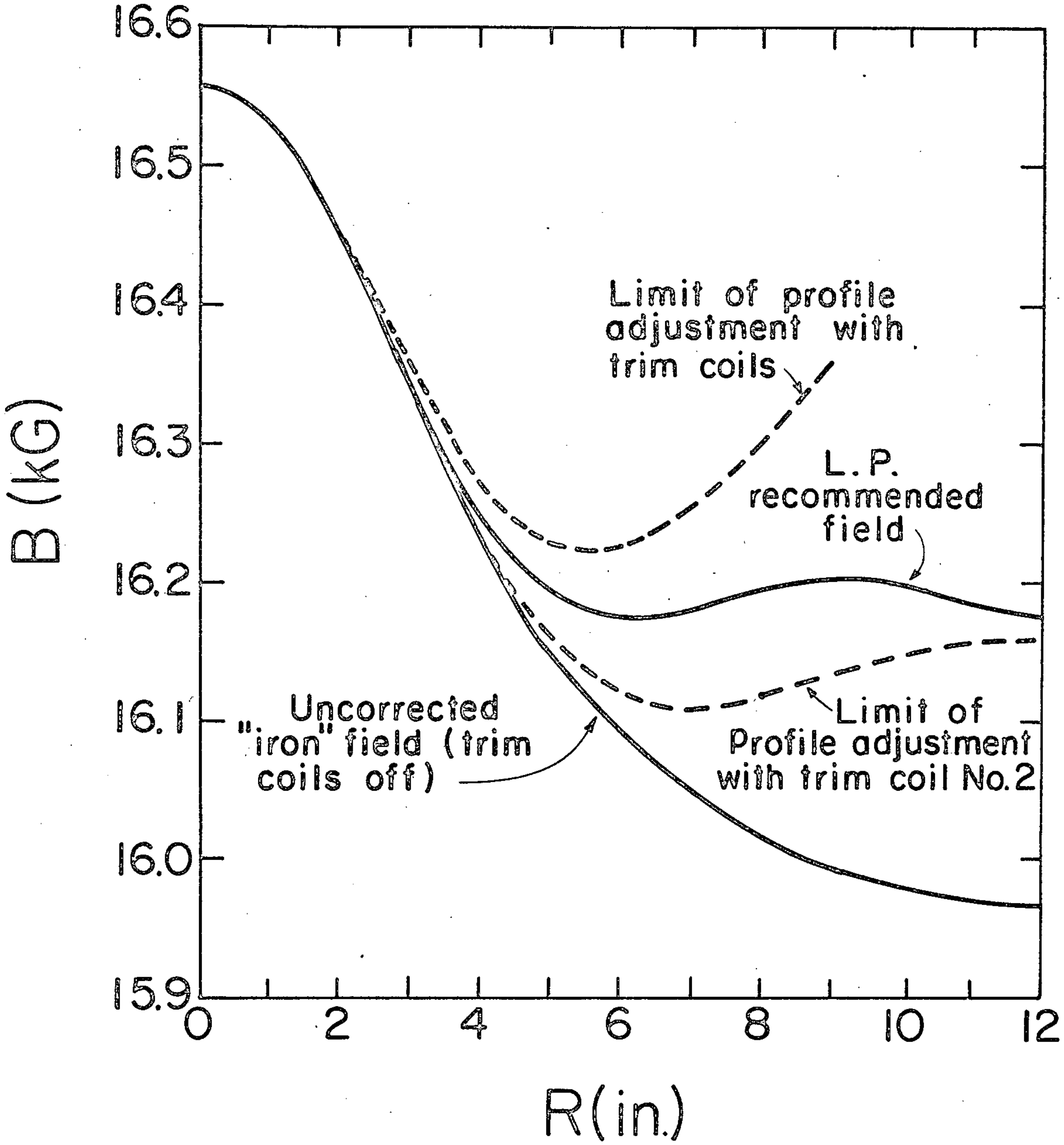

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Fig. 6

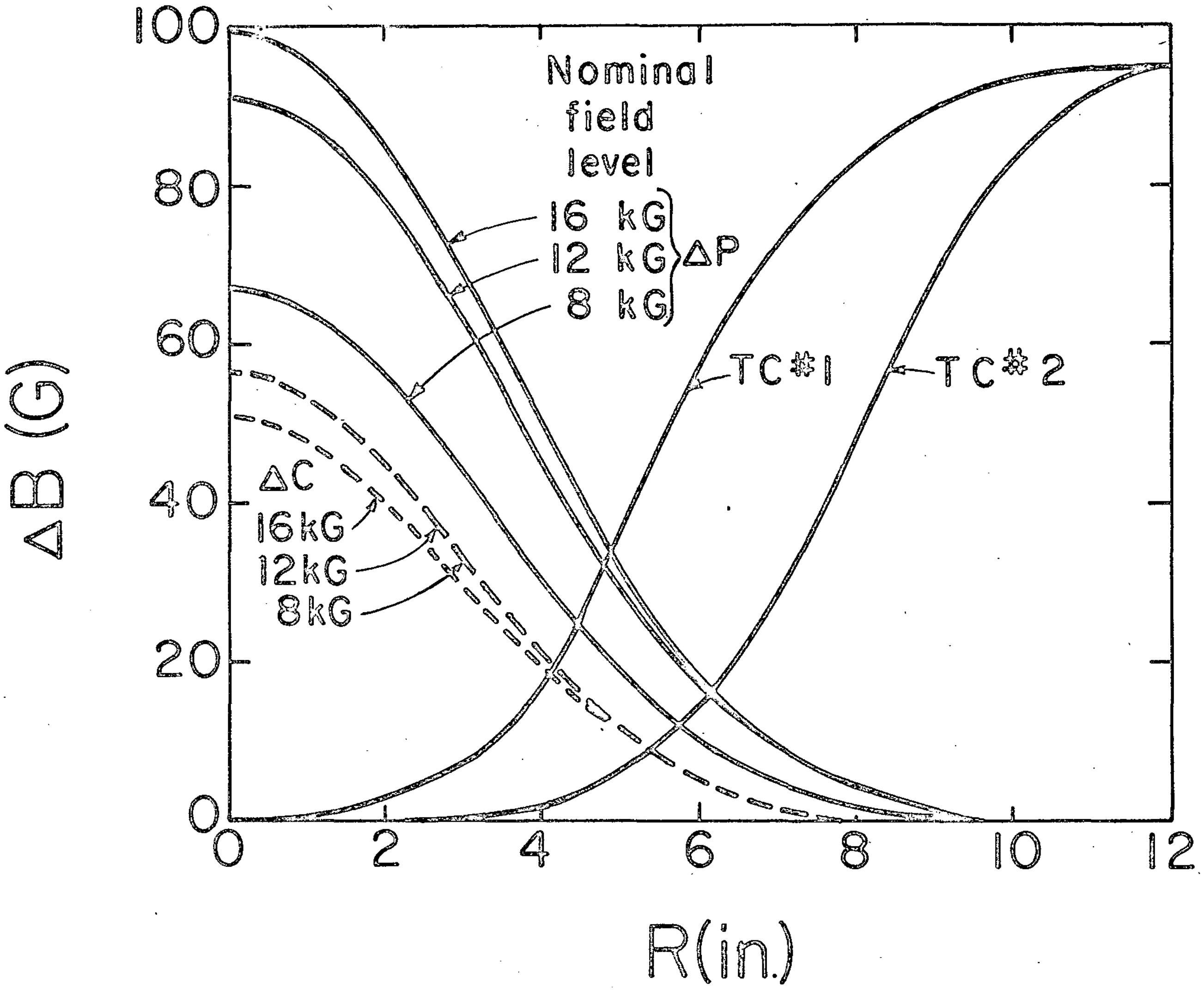

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Fig. 7

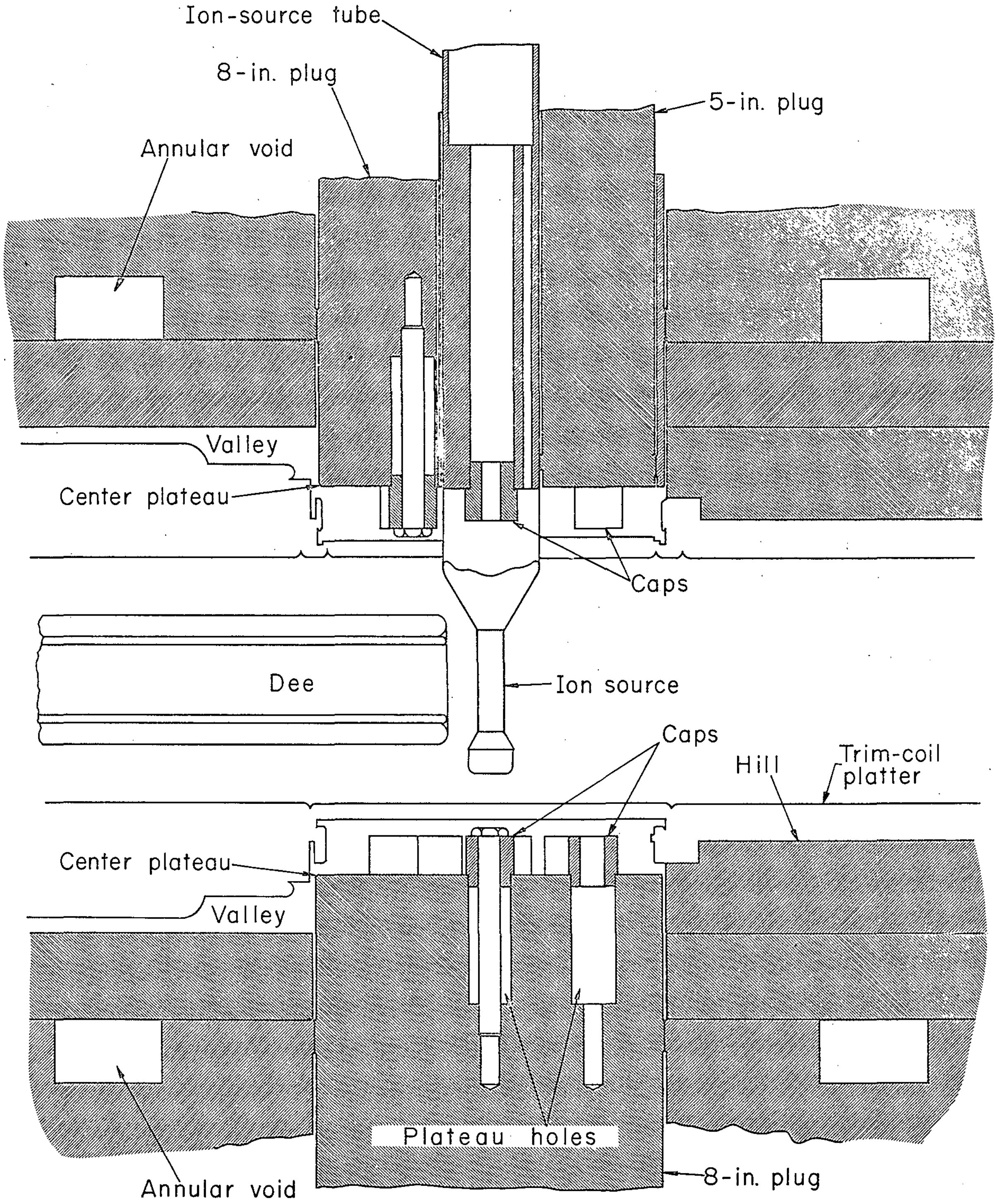

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Fig.8

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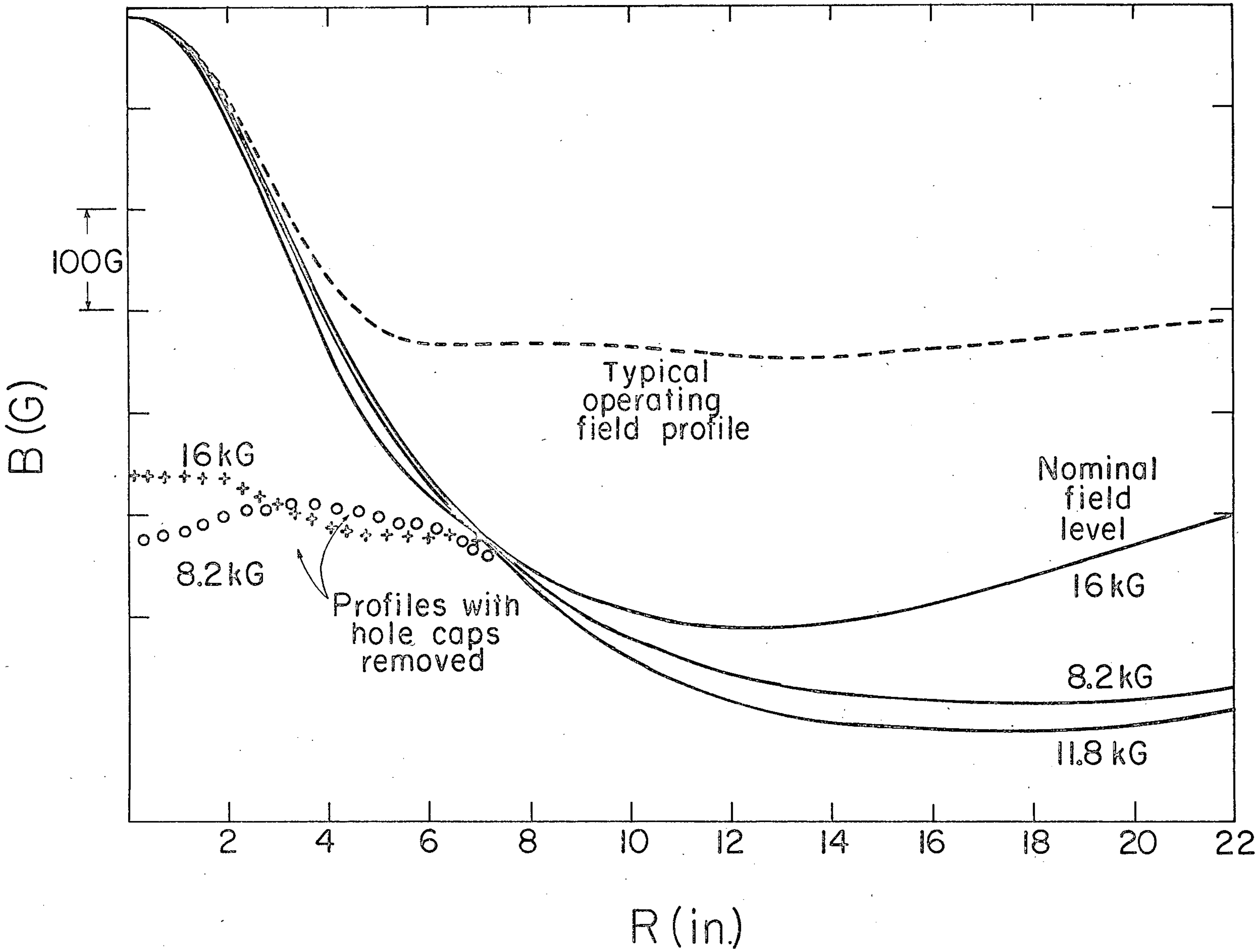

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Fig. 10

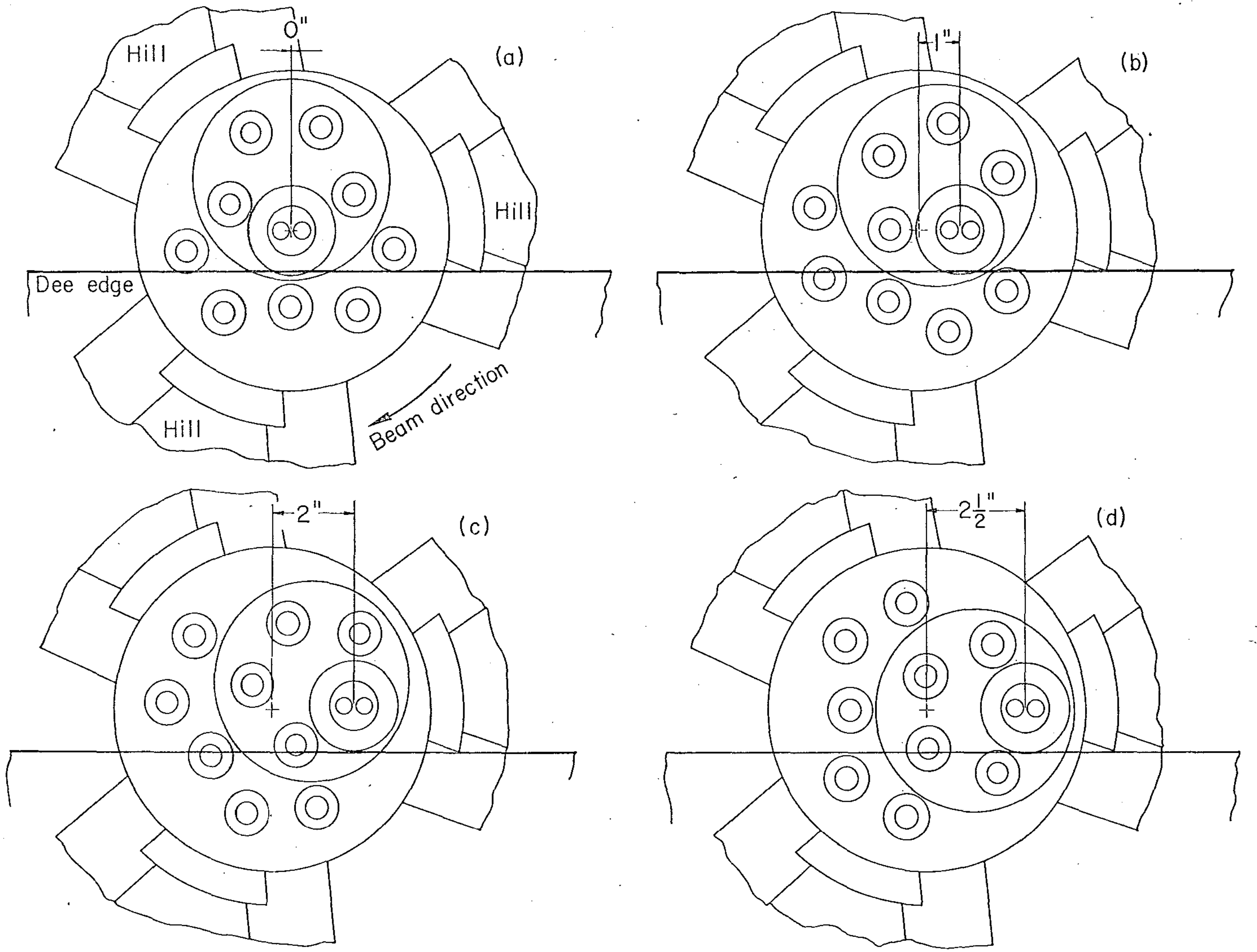

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Fig. 11

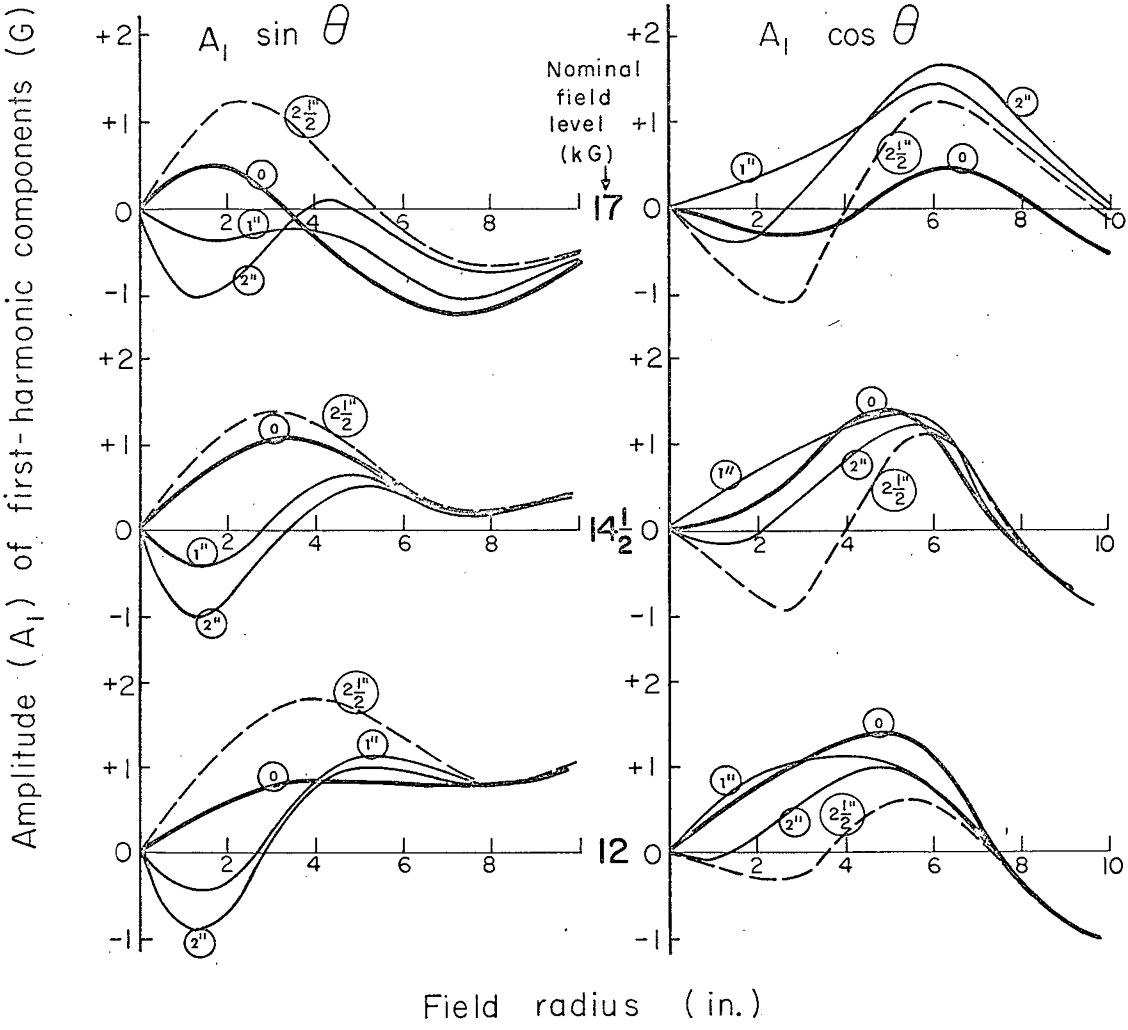

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Fig. 12