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MAGNETIC RINGS: CATALOGUE OF FIELD PROFILES

A. Tilak, H. A. Leupold and E. Potenziani

ELECTRONICS TECHNOLOGY AND DEVICES LABORATORY

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13. ABSTRACT *(Maximum 200 words)*

Magnetized toroidal rings are much used in permanent magnet beam-focusing structures in electron tubes. In the design of such structures it would be useful to know the axial field profiles of many rings of different aspect ratio. This study describes computer compilation of such profiles for rings that are magnetized in either the radial or axial directions. Graphs depicting both types of profiles are shown together with the mathematical procedures used in their generation.

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MAGNETIC RINGS: A CATALOGUE OF FIELD PROFILES

INTRODUCTION

Modern electron tubes often require permanent magnet beam focusing structures that are composed of stacks of axially and/or radially magnetized toroidal permanent magnets. Some more complex magnetic arrays can effect field modulations such as the production or elimination of field gradients, the sharpening of transitions in field strength or the smoothing of aberrations incurred in manufacture or from peculiarities of design. Both types of toroidal magnets have proven useful as components of such arrays.

Choice of dimensions and magnetic parameters of permanent magnet toroids is straight-forward for traveling wave tubes and for the structures of permanent magnet solenoids, but the choice is not so obvious when structural peculiarities demand a custom ring.

Accordingly, it was decided to generate a catalogue of both radially and axially magnetized rings of rectangular cross section. Axial fields for different aspect ratios and bore diameters were generated by computer and plotted as a function of distance from the center of one of the flat faces of the ring. From these curves peak fields, peak widths and, in the case of the radially oriented magnets, peak separations are obtained. These are then plotted as a function of axial ring width for rings of different outer radius.

AXIALLY MAGNETIZED RING

Figure 1 shows the cross section of an axially magnetized ring, where a and b are the inner and outer radii of the ring, and L is its width (width is the axial component and length is the radial component). The pole charge density σ is equal to the magnetization M and is given by

$$\sigma = M = B_R / 4\pi \qquad (1)$$

where B_R is the remanence of the magnetic material used.

The magnetic field H at any point along the axis of the ring is given by

$$H = H_1 + H_2 \qquad (2)$$

where H_1 is the magnetic field from the positive poles and H_2 is the magnetic field from an equivalent negative pole distribution. According to Coulomb's Law, the magnetic field at any point along the axis of the ring is given by

$$H_1 = \int_a^b \frac{2\pi M \cos\theta \, d\rho}{r^2} \qquad (3)$$

where $d\rho$ is the thickness of a circular charge element a distance ρ away from it its axis and r is the distance of the pole element from the point on the axis at which the field is calculated. The cosine term reflects the contribution from the longitudinal component alone. The transverse components cancel. a and b are the maximum and minimum values of ρ respectively.

By analogy, a similar expression can be written for H_2, the contribution from the negatively poled plate, with M replaced by $-M$.

Summation of H_1 and H_2, subsequent to integration, yields

$$H = B_R/2\left[x\left(x^2+a^2\right)^{-1/2} - x\left(x^2+b^2\right)^{-1/2} + (x+c)\left\{(x+c)^2+b^2\right\}^{-1/2} - (x+c)\left\{(x+c)^2+a^2\right\}^{-1/2}\right] \quad (4)$$

where x is the distance from a face of the ring to the point at which the field is being determined.

RADIALLY MAGNETIZED RING

Figure 2 shows the cross section of a radially magnetized ring where a, b, and c are the same dimensions stated earlier for the axially magnetized ring. The magnetic field H at any point along the axis of the ring is a combination of three contributions,

$$H = H_1 + H_2 + H_3 \quad (5)$$

where H_1 and H_2 are the respective contributions from the positive and negative surface poles. As before, the surface pole density is calculated with Equation 1, and H_1 and H_2 are obtained through Equation 3 with M being positive and negative for H_1 and H_2 respectively. H_3 is the contribution from a net volume pole distribution and is given by

$$\tau = -\vec{\nabla}\cdot\vec{M} = -\frac{1}{\rho}\frac{\partial}{\partial\rho}(-\rho M) = \frac{M}{\rho} \quad (6)$$

where τ is the volume pole density.

Again, Coulomb's Law yields the field from a positive pole element of width dy, a distance x away from the ring along its axis. The contribution H_3 from the volume pole is determined by the insertion of the volume pole density in Coulomb's Law. Integration yields

$$H_3 = (B_R/2)\ln\left[\frac{\left\{b+\left(b^2+(x-c)^2\right)^{1/2}\right\}\left\{a+\left(a^2+x^2\right)^{1/2}\right\}}{\left\{a+\left(a^2+(x-c)^2\right)^{1/2}\right\}\left\{b+\left(b^2+x^2\right)^{1/2}\right\}}\right] \quad (7)$$

where x is measured from one face of the ring.

The total magnetic field H results when the fields due to the surface and volume poles are added viz.

$$H = (B_R/2)\left[a\left(a^2+(x-c)^2\right)^{-1/2} - a\left(a^2+x^2\right)^{-1/2} - b\left(b^2+(x-c)^2\right)^{-1/2} + b\left(b^2+x^2\right)^{-1/2} + \ln\left[\frac{\left\{b+\left(b^2+(x-c)^2\right)^{1/2}\right\}\left\{a+\left(a^2+x^2\right)^{1/2}\right\}}{\left\{a+\left(a^2+(x-c)^2\right)^{1/2}\right\}\left\{b+\left(b^2+x^2\right)^{1/2}\right\}}\right]\right] \tag{8}$$

CATALOGUE COMPILATION PROCEDURE

RPL routines called AX_RING and RAD_RING, Figures 3 and 4, were written to generate tables of magnetic fields at regularly spaced intervals along the axis of the rings. The inner radius of the ring was held at 1.0 cm and remanence of the magnetic material used was 10 kG. The outer radius of the ring was increased from 1.2 cm to 2.0 cm in steps of 0.2 cm while the ring width was held constant. The magnetic field profiles for axially magnetized rings of width 0.1 cm, 0.5 cm, 1.0 cm, 2.0 cm, 4.0 cm and 10.0 cm are shown in Figures 5 through 10. The field profiles of radially magnetized rings of the same remanence and the same sequence of physical dimensions were calculated and the results are shown in Figures 11 through 16.

SUMMARY

A. AXIALLY MAGNETIZED RINGS:

A summary of the catalogue for axially magnetized rings is presented in Figures 17 and 18.

1. As expected, the field is maximum at the center of the ring and for a given ring thickness, the peak field is greater for larger outer radii.

2. Maximum peak fields were obtained when the ring thickness was equal to the inner diameter of the ring.

3. For thin rings, i.e. where the width of the ring is less than the inner diameter, the width of the magnetic field profile is an order of magnitude wider than the width of the ring itself.

4. For rings of width equal to or greater than the inner diameter of the ring, the peak width, to zero field, is the same as the ring width.

5. For rings of width considerably larger than the inner dimeter, the magnetic field is maximum close to but within the edges of the ring; the field in the interior of the ring is somewhat less than the peak field.

b. RADIALLY MAGNETIZED RINGS:

A summary of the catalogue for radially magnetized rings is presented in Figures 19 and 20.

1. The field at the center of the ring is zero and increases as the edges are approached. Again, for a given ring width, the larger the outer radius, the higher the peak field.

2. Peak fields are maximum when the width of the ring is twice the inner diameter; increasing the ring width beyond this ratio yields diminishing return as far as field strengths are concerned.

3. For narrow rings where the width of the ring is less than the inner diameter, the peak separation is up to an order of magnitude higher than the ring width.

4. For ring widths equal to or greater than the inner diameter of the ring, the peak separation is of the order of the ring width, with the peak close to but outside of the ring itself.

5. As the rings get much wider than the inner diameter, the fields remain zero in the interior of the ring along its axis with significant magnetic fields close to the two surfaces.

EXAMPLE OF MAGNETIC RING MODULATION

An application of magnetic field modulation through the use of radially, as well as axially, magnetized rings is illustrated in the following example 1. A permanent magnet field source was designed to provide a constant axial field of 2.0 kOe in the larger of two chambers and 0.5 kOe in the smaller of the two tandem permanent magnet solenoids as shown in Figure 21. Figure 22 shows the original bichambered model and its on-axis field profile whereas Figure 23 displays the equivalent ring modified model and the resulting field along its axis. Comparison of Figures 22 and 23 shows how the presence of a radially magnetized ring internal to the junction of the two solenoids affects the transition in field values: in the absence of the above mentioned ring, the transition is narrowed by approximately 50%.

Also, as Figures 22 and 23 indicate, the field gradient in the circuit chamber arising from flux leakage due to imperfect cladding at the ends is reduced by the strategic placement of axially magnetized rings, one outside and another inside the circuit chamber. Figure 24 illustrates the details of transition narrowing by placement of the radially oriented ring at the junction of the chambers.

List of Figures

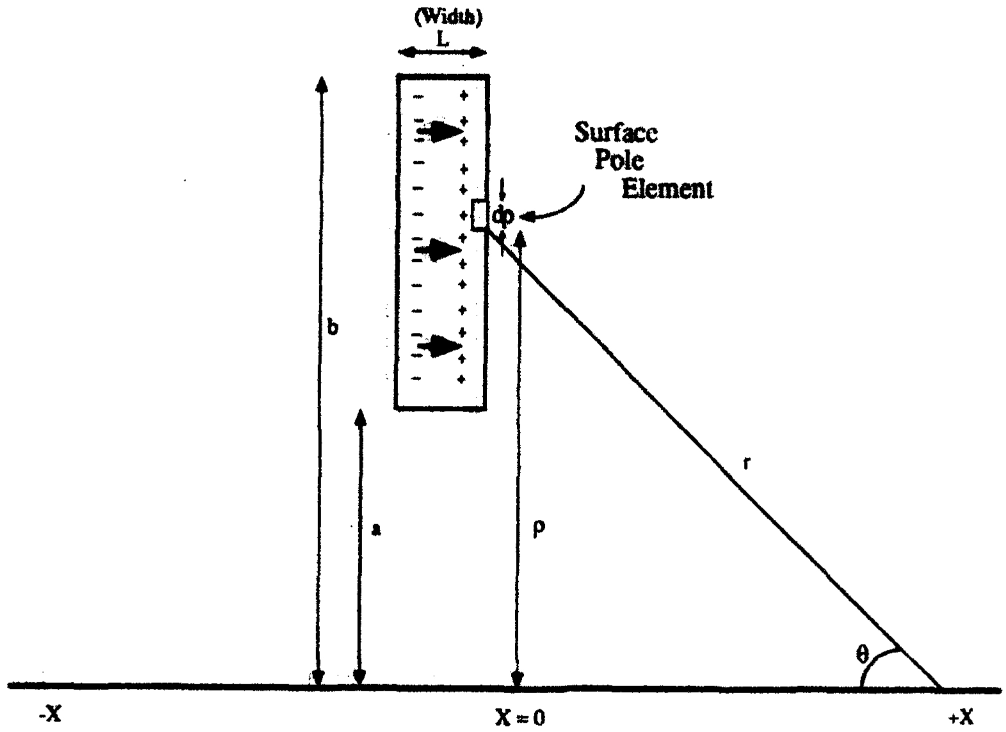

Figure 1. Parameters for axially magnetized ring

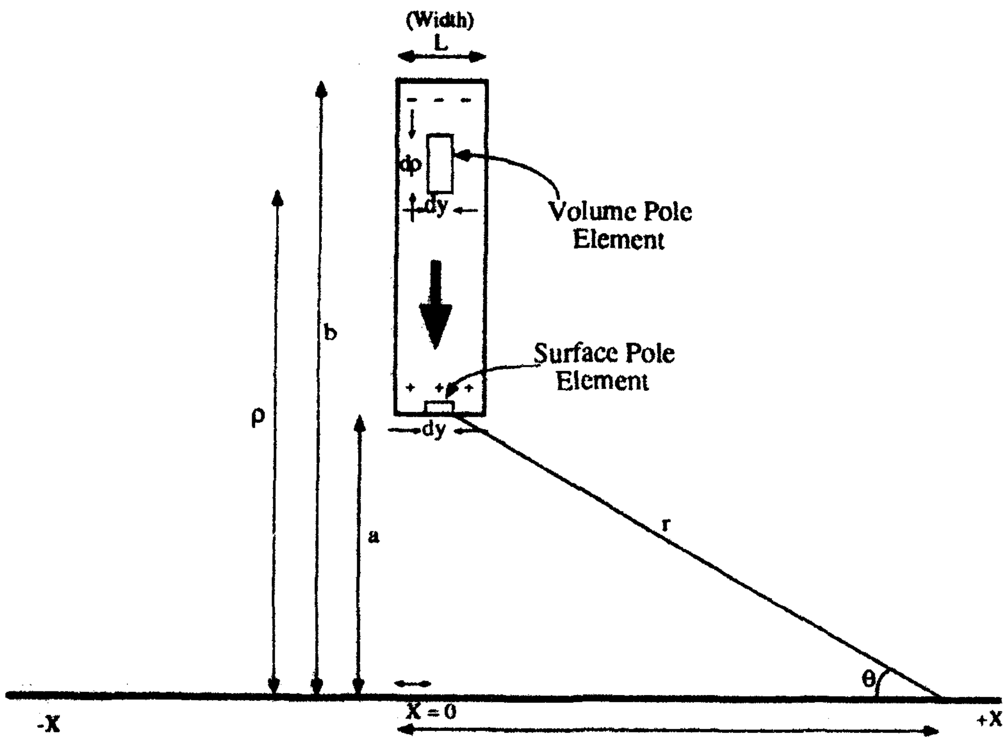

Figure 2. Parameters for radially magnetized ring

```
PROCEDURE; /* This procedure, AX_RING, asks for the name for a table it will
          generate, upon being told the number of rows 'R' and the number
          of columns 'C' it should have. The table cell values are
          determined by a function that calculates the magnetic field at
          0.1 cm intervals along the axis of an axially magnetized ring;
          where: M = remanence of the magnetic material
               L = axial width of the ring
               D = is the outer radius of the ring
          The inner radius of the ring is 1 cm and the calculated function
          is symmetrical about one edge of the ring. */

        TNAM=GETTABLE("Name of new table:",TRUE);
        A=GETNUMBER("Number of rows,any odd number:");
        M=GETNUMBER("Remanence of magnetic material in kG:");
        L=GETNUMBER("Width of axially magnetized ring in cm:");
          C=1;
          DO D=1.1 TO 2 BY .1;
            R=1;
            DO X=-(A-1)/20 TO (A-1)/20 BY 0.1;
            VALUE= M*1000*(X/SQRT(X**2 + 1)
                -X/SQRT(X**2 + D**2)
                +(X+L)/SQRT((X+L)**2 + D**2)
                -(X+L)/SQRT((X+L)**2 + 1))/2;
            SET ROW R COL C OF TABLE(TNAM) TO VALUE;
            SET ROW R COL 0 OF TABLE(TNAM) TO X;
            R=R+1;
            END;
          C=C+1;
          END;
         DISPLAY TABLE(TNAM);
END;
```

Figure 3. RPL routine for obtaining field profiles for axially magnetized rings.

```
PROCEDURE; /* This procedure, radring, asks for the name of a table it will
        generate, upon being told the number of rows 'R' and the number
        of columns 'C' it should have. The table cell values are
        determined by a function that calculates the magnetic field at
        0.1 cm intervals along the axis of a radially magnetized ring;
        where: B = remanence of the magnetic material
            L = axial width of the ring
            D = outer radius of the ring
        The inner radius of the ring is 1.0 cm and the zero of the
        x-axis sits on the left edge of the ring. */


        TNAM=GETTABLE("Name of new table:",TRUE);
        A=GETNUMBER("Number of rows:");
        B=GETNUMBER("Remanence of magnetic material in kG:");
        L=GETNUMBER("Width of radially magnetized ring in cm:");
        C=1;
         DO D=1.1 TO 2.0 BY 0.1;
           R=1;
           DO X=-(A-1)/20 TO (A-1)/20 BY 0.1;
           VALUE= B*500*(1/SQRT(1+(X-L)**2)
               -1/SQRT(1+X**2)
               -D/SQRT(D**2+(X-L)**2)
               +D/SQRT(D**2+X**2)
               +LOG(D+SQRT((X-L)**2+D**2))
               -LOG(1+SQRT(1+(X-L)**2))
               -LOG(D+SQRT(D**2+X**2))
               +LOG(1+SQRT(1+X**2)));
           SET ROW R COL C OF TABLE(TNAM) TO VALUE;
           SET ROW R COL 0 OF TABLE(TNAM) TO X;
           R=R+1;
           END;
         C=C+1;
         END;
     DISPLAY TABLE(TNAM);
END;
```

Figure 4. RPL routine for obtaining fiueld profiles for radially magnetized rings.

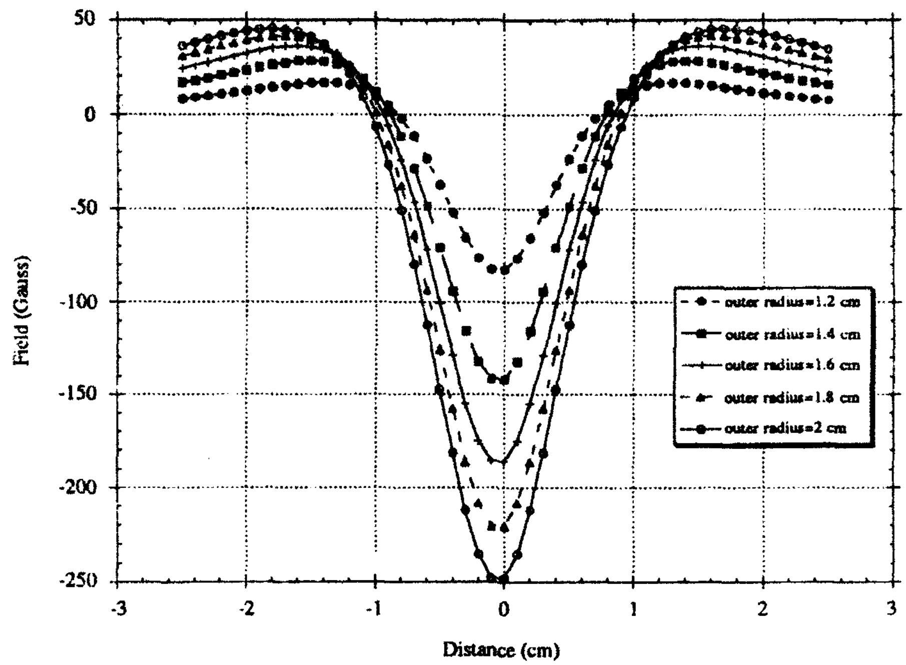

Figure 5. Magnetic field along the axis of a 0.1 cm wide axially magnetized ring.

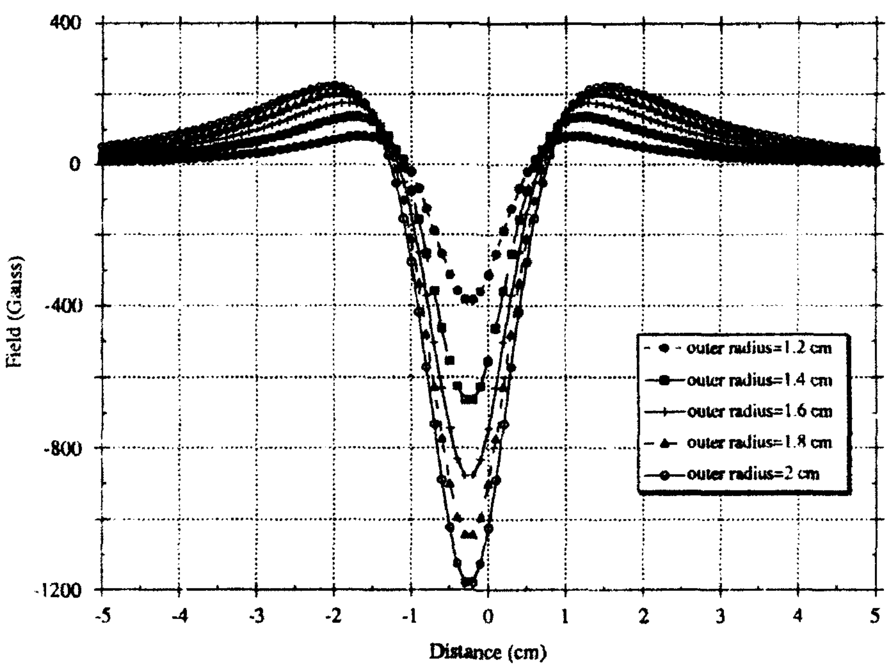

Figure 6. Magnetic field along the axis of a 0.5 cm wide axially magnetized ring.

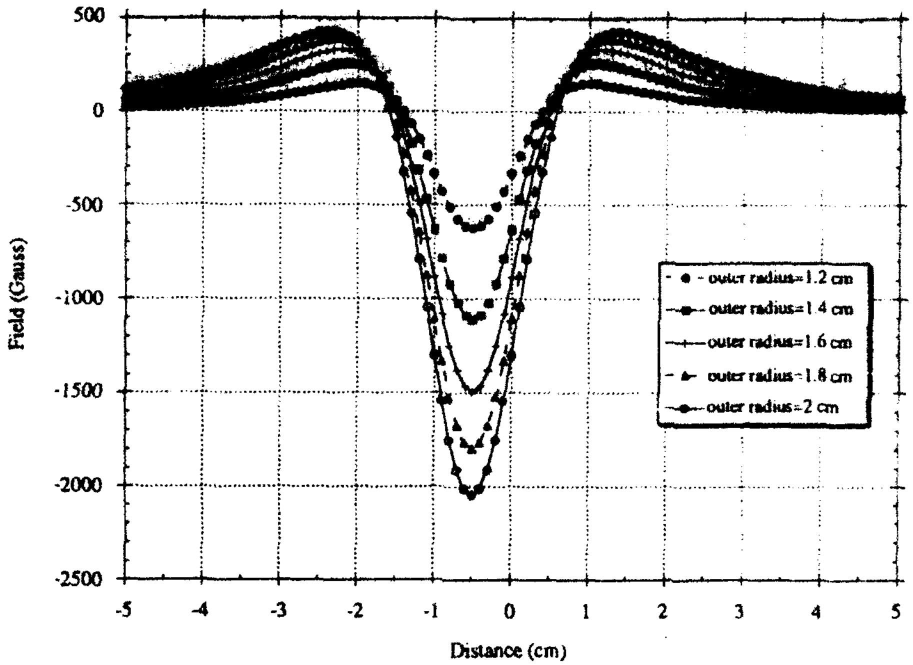

Figure 7. Magnetic field along the axis of a 1.0 cm wide axially magnetized ring

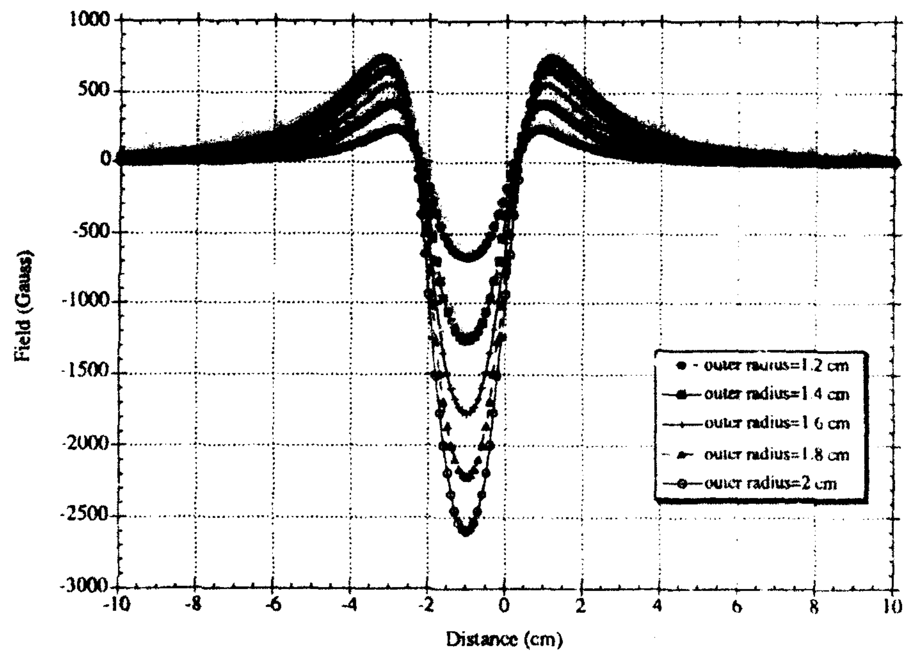

Figure 8. Magnetic field along the axis of a 2.0 cm wide axially magnetized ring

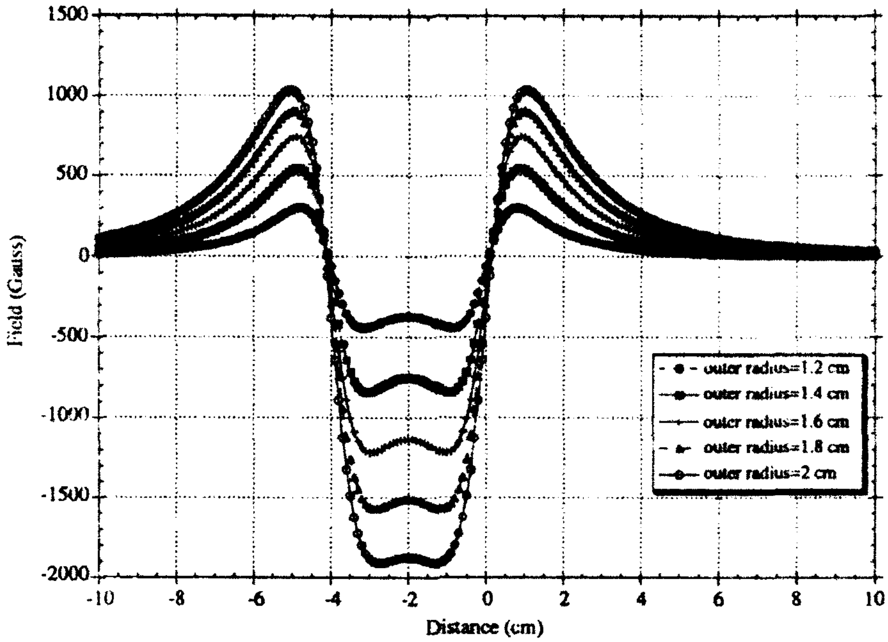

Figure 9. Magnetic field along the axis of a 4.0 cm wide axially magnetized ring

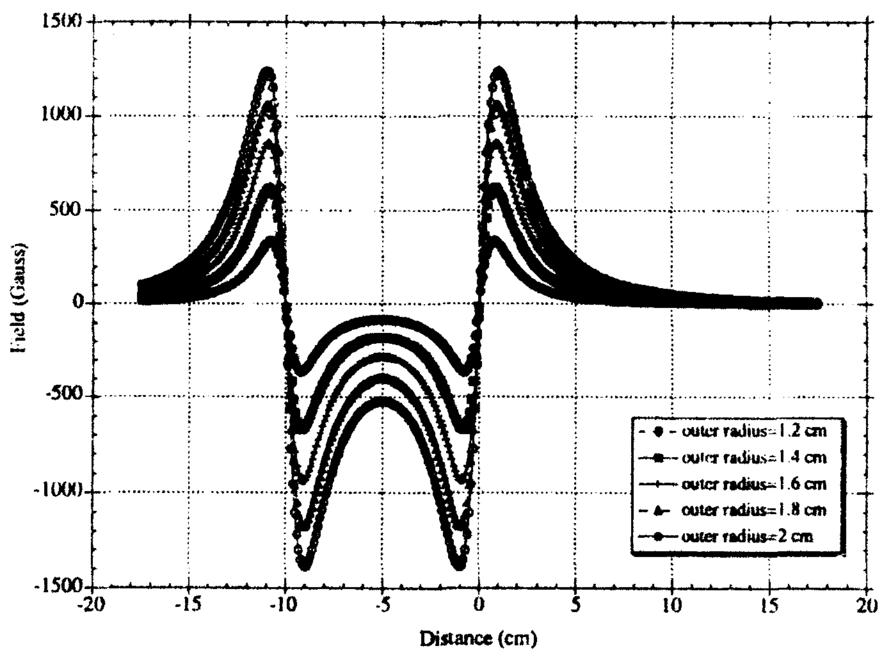

Figure 10. Magnetic field along the axis of a 10.0 cm wide axially magnetized ring

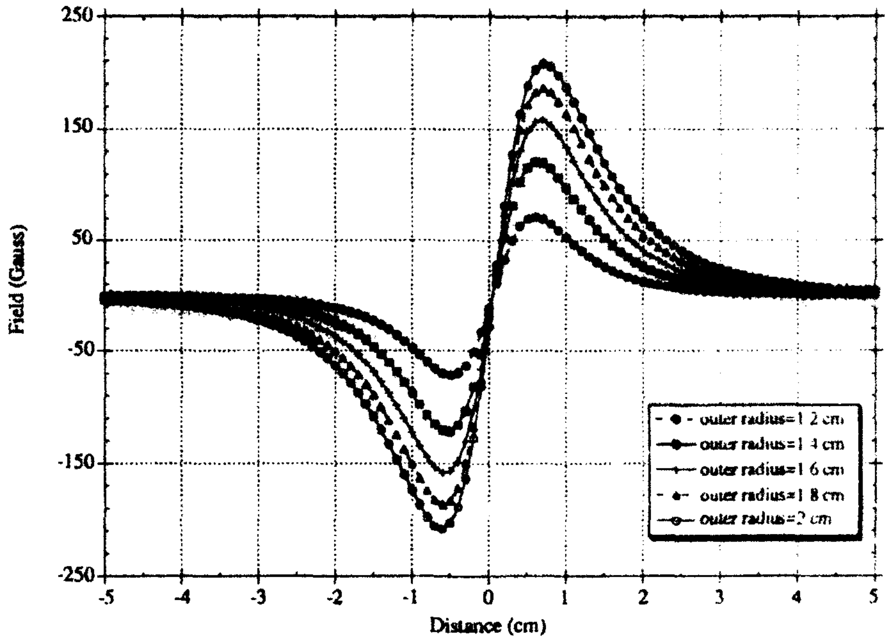

Figure 11. Magnetic field aong the axis of a 0.1 cm wide radially magnetized ring.

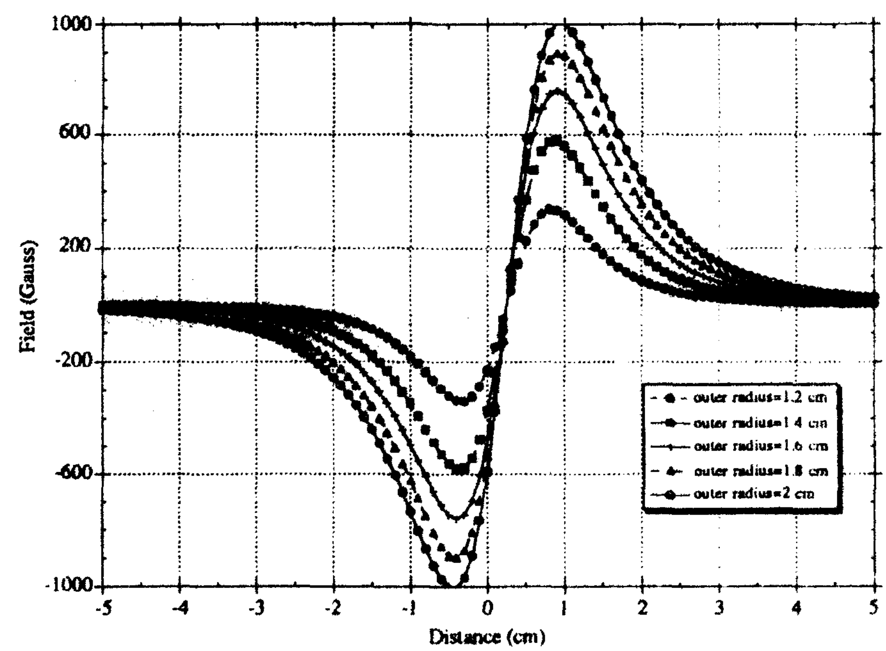

Figure 12. Magnetic field aong the axis of a 0.5 cm wide radially magnetized ring.

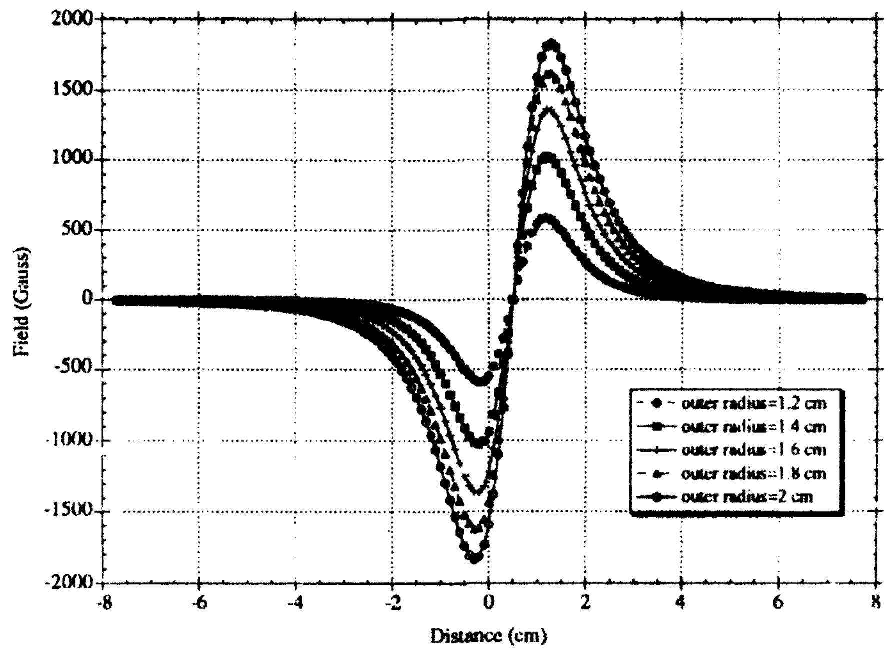

Figure 13. Magnetic field along the axis of a 1.0 cm wide radially magnetized ring

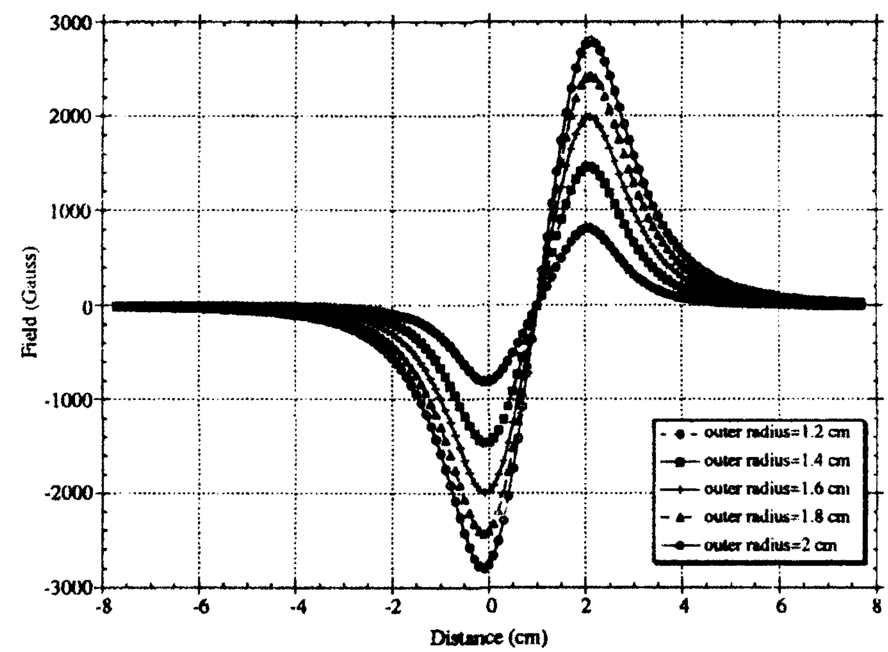

Figure 14. Magnetic field along the axis of a 2.0 cm wide radially magnetized ring

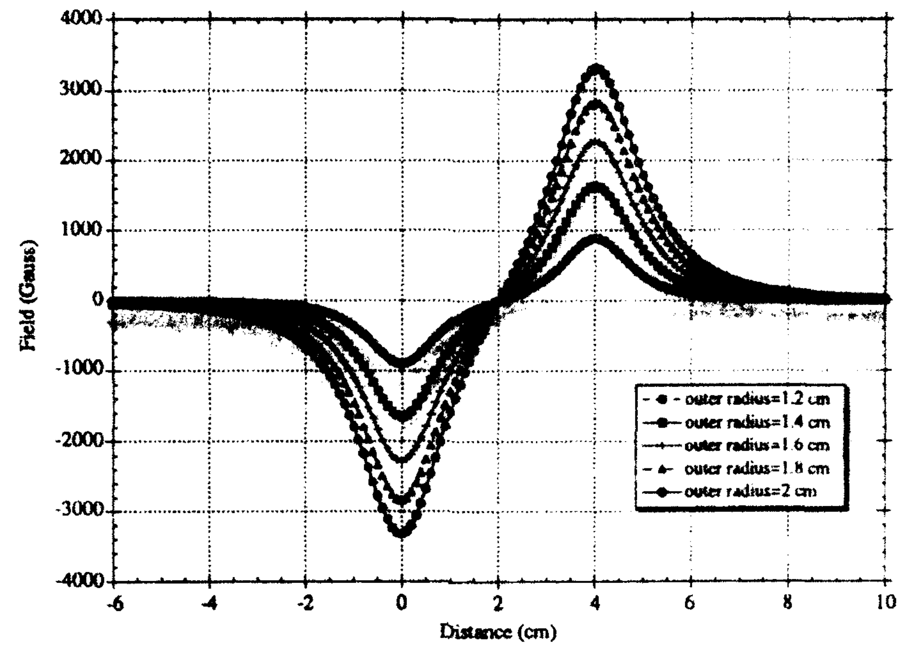

Figure 15. Magnetic field along the axis of a 4.0 cm wide radially magnetized ring

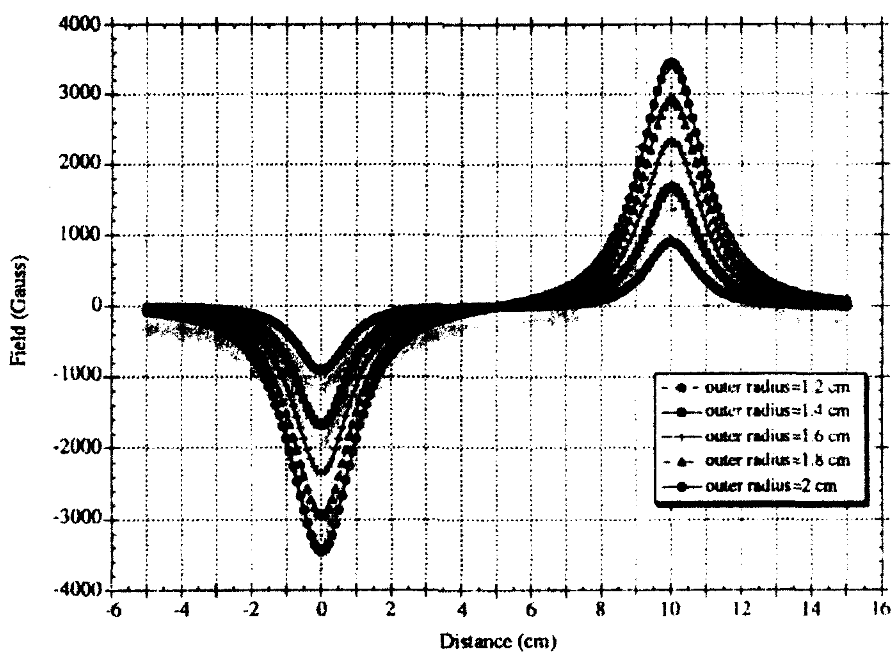

Figure 16. Magnetic field along the axis of a 10.0 cm wide radially magnetized ring

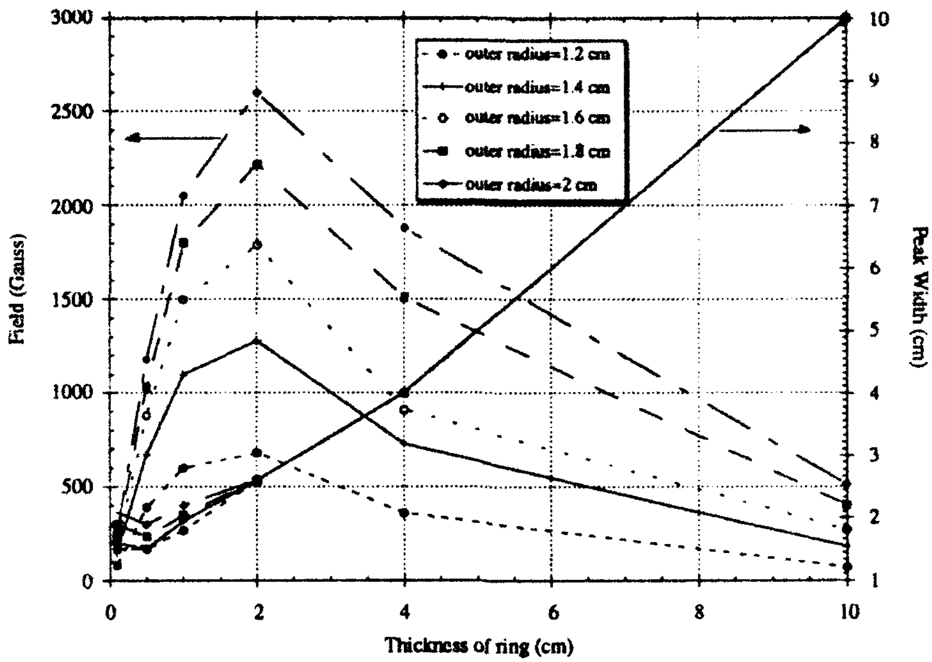

Figure 17. Summary of field profiles generated by axially magnetized rings

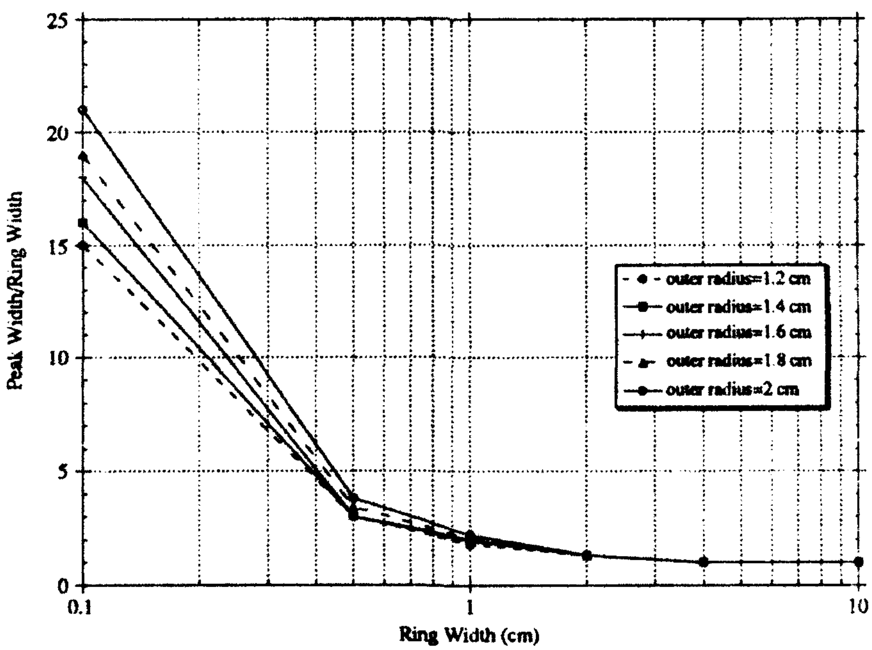

Figure 18. Peak width/ring width for axially magnetized rings

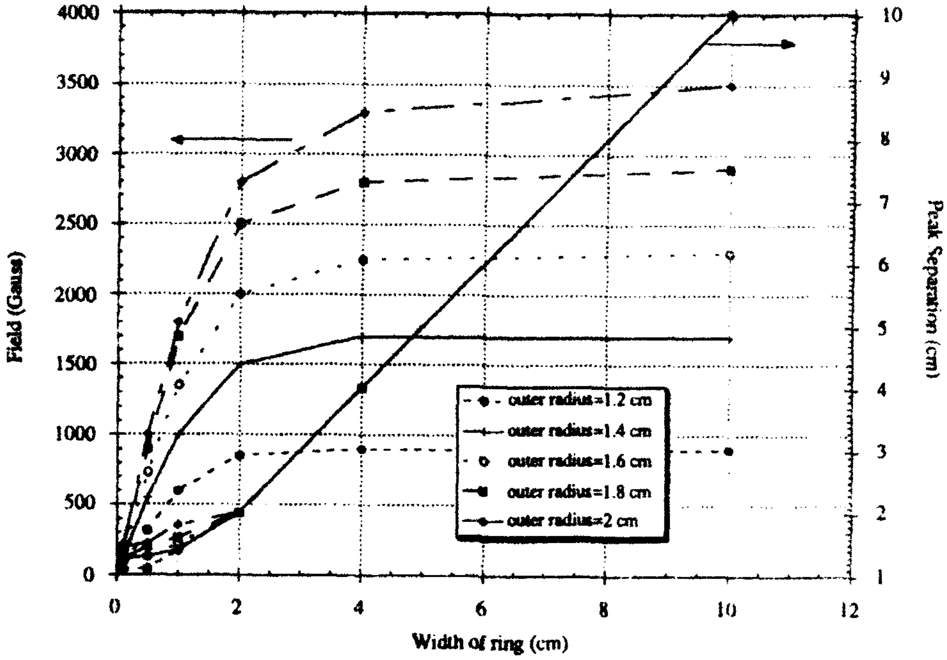

Figure 19. Summary of field profiles generated by radially magnetized rings

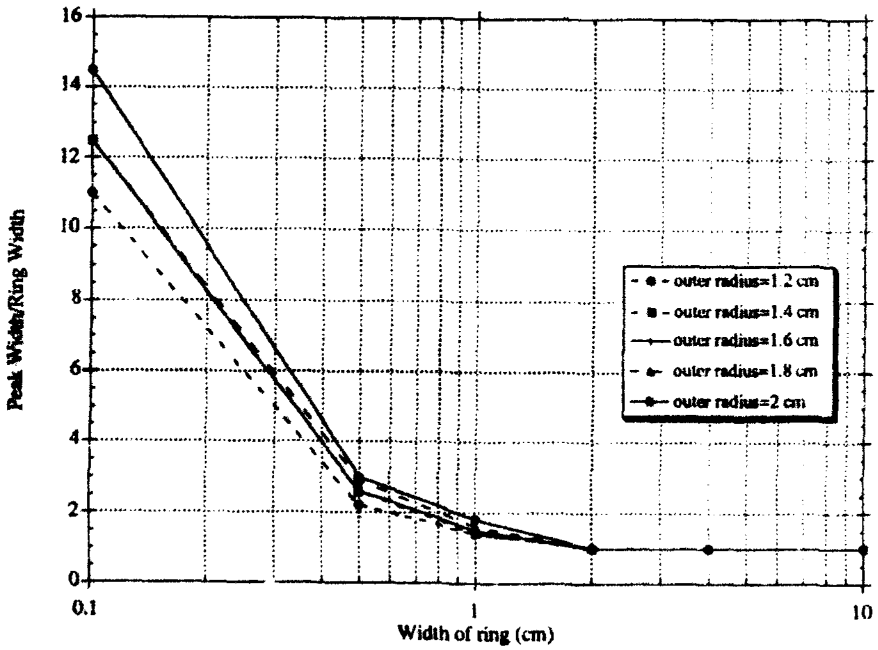

Figure 20. Peak width/ring width for radially magnetized rings

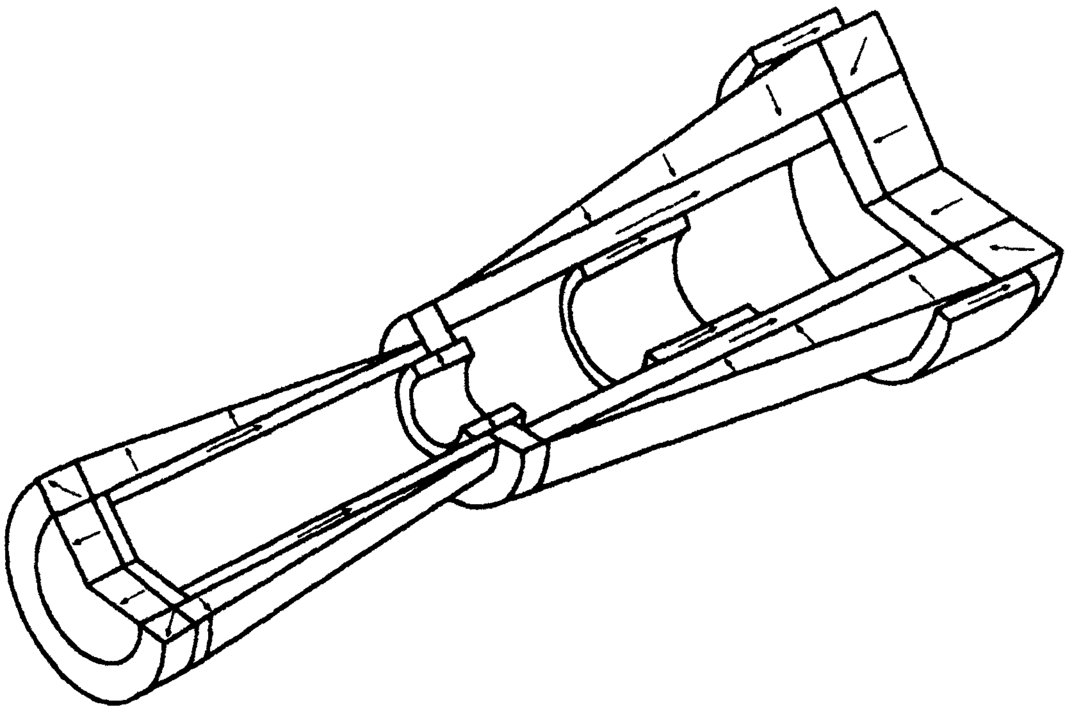

Figure 21. Fully adjusted permanent-magnet solenoid

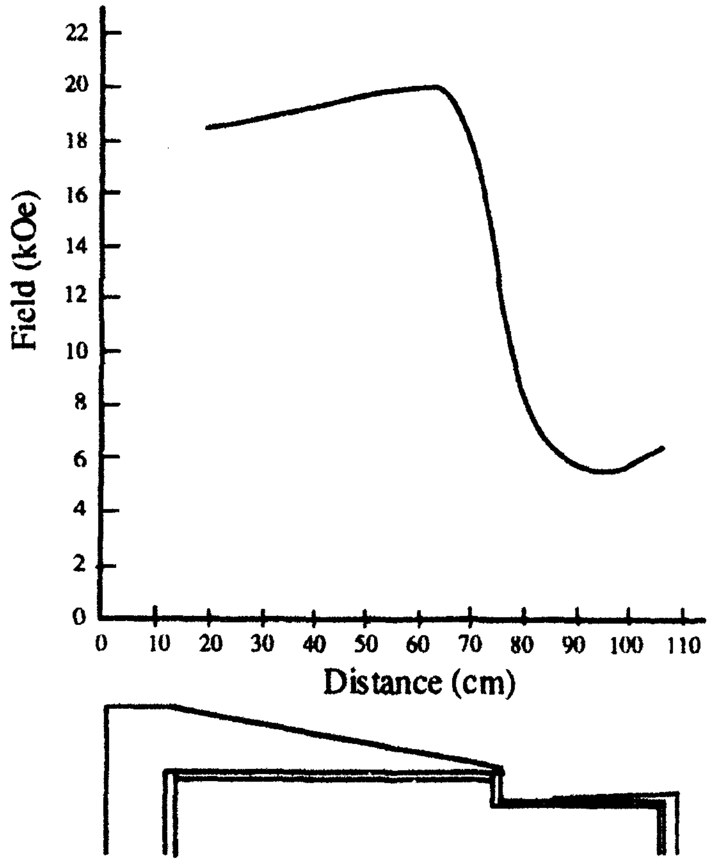

Figure 22. On-axis field plot of bi-chambered permanent-magnet solenoid

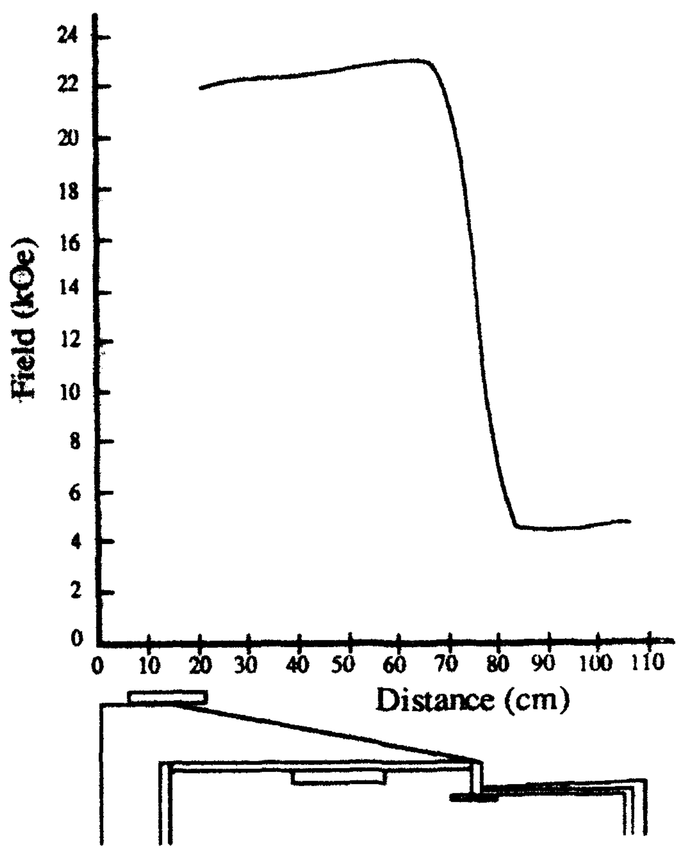

Figure 23. On-axis field plot of fully adjusted permanent magnet solenoid

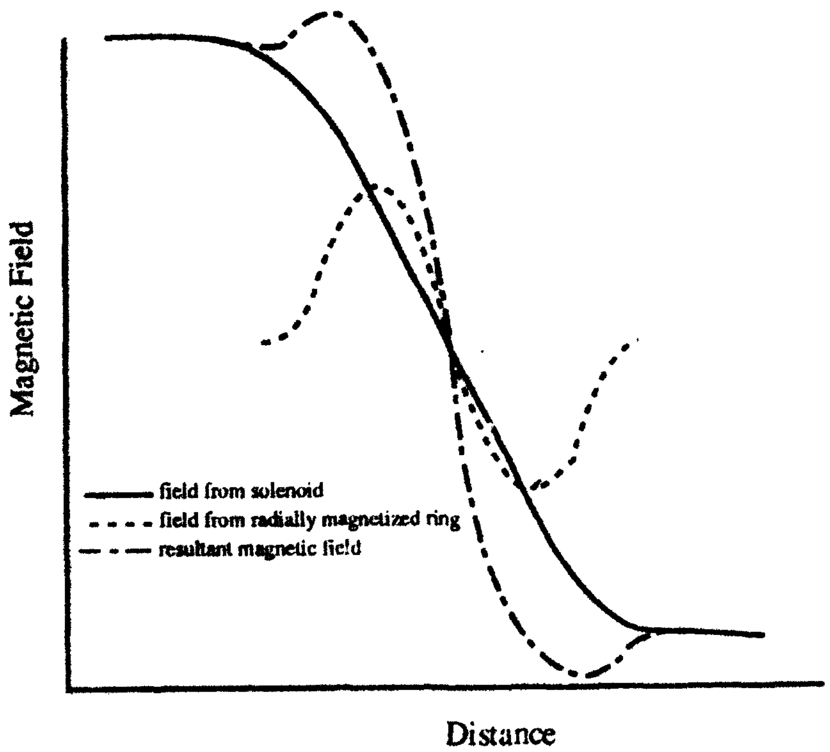

Figure 24. Transition width narrowing by placement of radially magnetized ring

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