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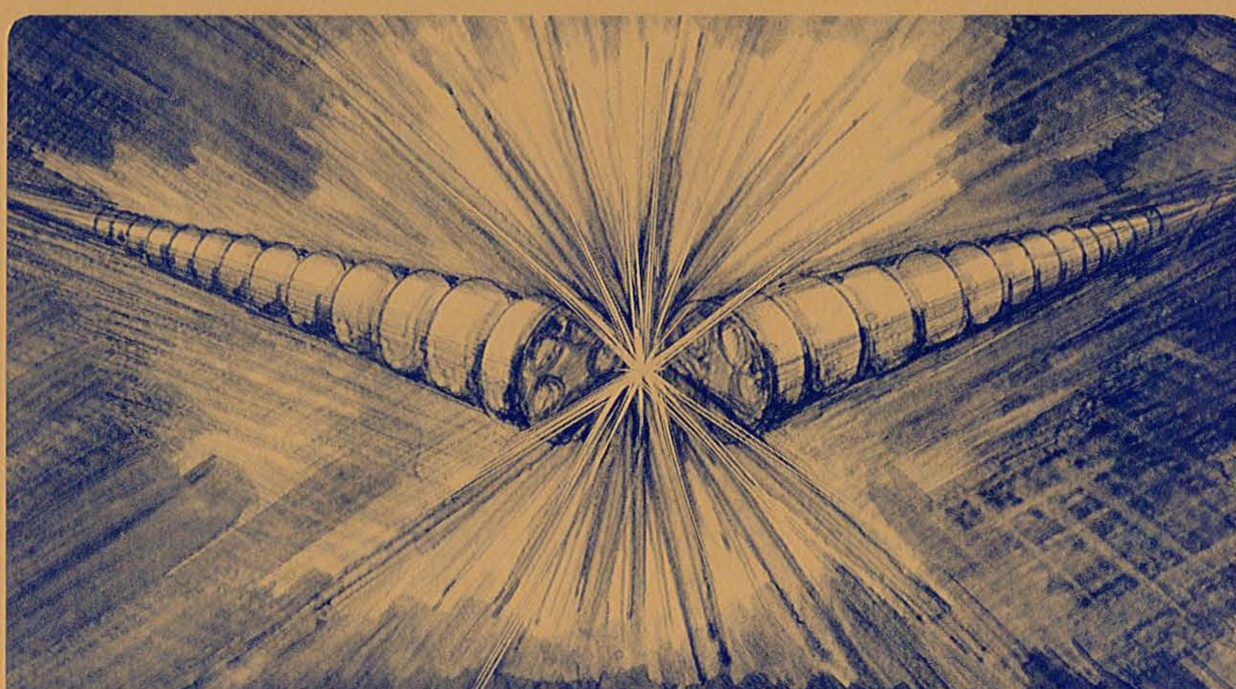
R.B. Meuser

April 1983



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Introduction

A collection of dipole magnet cross sections is presented together with an indication of how they are related geometrically. The relationships indicated do not necessarily imply the actual path of evolutionary development. Brief consideration is given to magnets of higher multipole order i.e., quadrupole magnets, etc.).

The magnets under consideration (Fig. 1) have currents parallel to the axis except at the ends, and are long. The relationship between current distribution and magetic field is essentially two dimensional. The coils are usually surrounded by an iron yoke, but the emphasis is on conductor-dominated configurations capable of producing a rather uniform magnetic field in the aperture; the iron usually has a small effect.

Most of the cross-section sketches show only the first quadrant; the entire cross sections include reflections into the other three quadrants with currents in the senses +, −, −, +, perpendicular to the plane of the cross section in quadrants 1 through 4, respectively. The iron yoke is shown (represented by its inner boundary) only for those configurations where the iron is an essential part of the design or where the optimized coil configuration is independent of the iron. The outer iron boundary can be asymmetrical.

In concentrating our attention on the cross-section we necessarily ignore the practical matter of the design and construction of the ends, which is where many of the problems lie. And too, we carefully sidestep any consideration of iron-saturation effects, important as they are, and of the virtues of one configuration compared with those of another.

Only a few references are presented; the list is far from complete. The cited reference does not necessarily represent the invention or first use of a particular configuration.

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Configurations

The most general configuration, of which all of the other configurations are simply special cases is illustrated in Fig. 2. In principle one can chose almost any shapes for the coil inner and outer boundaries and the iron boundary, and then find a current density distribution which produces a uniform field in the aperture. If one choses circles for these boundaries, for example, then one (not the only one, incidentally) current density distribution that produces a uniform field is $J = J_0 f(r) \cos\Theta$, where J_0 is a constant, and $f(r)$ is any function of r.

The simplest configuration (Fig. 3) consists of a pair of current sheets, with opposite currents, extending to infinity. With uniform lineal current density, a uniform field is produced in the region between the two sheets. The sheets can become finite in thickness by superposition (Fig. 4). To overcome the practical nuisance of coils extending to infinity, the coil can be cut off and iron reflectors added above and below the aperture (Fig. 5). With the further addition of iron at the sides (Fig. 6), the current-sheet pair evolves into the familiar "picture frame" (or is it "window frame"?) configuration (Fig. 7). Addition of pole tips (Fig. 8) increases the field strength; removal part of the coil near the horizontal axis (Fig. 9) permits the use of flat coils. But both of these modifications destroy the uniformity of the field.

If the coil is cut off at some point but iron reflectors are not added, the field uniformity is destroyed. Part of the loss of uniformity can be recaptured by adding current lumps at the extremities of the coil (Fig. 10). By further refinements of the coil shape the configuration could evolve into some of the more complex ones considered later.

The general configuration of Fig. 2 can be specialized somewhat to a thin coil of arbitrary shape (Fig. 11) and further to a thin circular coil (Fig. 12), in which case a uniform field is produced in the aperture if the lineal current density in the coil varies as cosine Θ. The thin shell can be made thick by superposition, with the current density a function of r (Fig. 13).

A continuous azimuthal variation of current density cannot be achieved in practice, and so a number of approximations have been invented.

One such configuration, (Beth Ref. 1), is shown in Fig. 14. The current density within each region is uniform in Θ. If the number of regions is N, then 2N-1 higher-order multipole coefficients can be made exactly zero. If the inner and outer boundaries of the coil are circular, then the only kind of radial variation of current density that can be readily achieved in practice, either by tapering the conductor radially or by inserting wedge-shaped spacers between the turns, is an inverse variation. (For a homogeneous, resistive conductor of keystone-shaped cross section, the current density could be uniform. But for a twisted cable flattened to a keystone cross-section, as used in some superconducting coils, the macroscopic current density varies inversely with radius.)

By making the sides of the current "blocks" parallel (Fig. 15), to accommodate conductor of rectangular cross section, one achieves a current density that varies inversely with radius in an overall sense, while the current density in the region is uniform. The Beth prescription demands that the current density in each region be proportional to the cosine of the angle to the centerline of the region. The average current density in a block can be varied by varying the number of conductors and replacing the missing conductors with spacers. However it is not possible to satisfy Beth's prescription for current density exactly if only one kind of conductor is used throughout. So in practice one makes the current density approximate the Beth prescription, then juggles the angular positions to get the best field quality. The original BNL Isabelle magnets were close approximations to the kind shown in Fig. 15.

To achieve a practical approximation to Beth's prescription in a different way, the current blocks can all have the same current density, but the sizes of the blocks can be varied, by either varying the depth (Fig. 16) or width (Fig. 17) of the block. Again, the angular positions of the blocks are adjusted to produce the best field quality.

In another sort of approximation to a cosine - coil (Fig. 18) (Halbach, Ref. 2, etc.), the current density is uniform in azimuth within each current block, but the azimuthal positions of the block sides are adjusted to produce the best field quality.

If two elliptical regions having uniform current densities in opposing senses are superimposed, leaving a zero-current hole in the region of overlap, the field in the hole is uniform provided the ellipses have the same aspect ratios. But if the net current is zero, then the two ellipses must be equal (Fig. 19. The aperture boundary appears to be circular, but it is really a part of an ellipse). A specialization is the classical overlapping circle configuration (Rabi, 1934, Ref. 3). Various practical approximations have been used or proposed involving horizontal conductor layers (Fig. 20), vertical layers (Fig. 21), flat layers set at an angle (Fig. 22 which is specialized to that in Fig. 23), and cylindrical layers (Fig. 24). The configuration involving cylindrical layers is commonly referred to as an "intersecting ellipse" magnet. But the order of the layers can be inverted or scrambled (Fig. 25) in which case the nomenclature becomes severly strained. Thin coils, at least, of this sort might equally well be called "cosine theta" coils; the conductor density per unit angle indeed varies as a stepwise approximation to cosine Θ .

Various arrangements of single conductors or small bundles of conductors that produce rather uniform fields can be devised. The one shown in Fig. 26 stems directly from the Beth design (Fig. 15), and the same number of higher order multipoles is zero; the magnitudes of the non-zero ones are larger than for the Beth design, however.

The one in Fig. 27 (Rechen, Ref. 4) involves conductors having equal currents. For the configuration shown, three higher-order multipoles are exactly zero. If a different criterion for field uniformity is used, presumably a more cosine-like distribution of conductors could be obtained.

Many of the designs illustrated can be improved, as regards field uniformity, by increasing the number of "layers" or "blocks" of conductors, but often this is not feasible or is costly. Another method that sometimes works is to add spacers, which effectively increases the number of "degrees of freedom" of the design. One illustration is the configuration designed by Palmer (Fig. 28, Ref. 5) as the alternative design for the Isabelle magnets.

A configuration that appears to have come about by the process of spontaneous creation, defying any conceivable path of evolution from simpler forms, is illustrated in Fig. 29 (Ref. 6). (Asymmetrical forms are also considered in the reference, which incidentally is a rather snazzy piece of work.) The sides can be at any angle. The current density in the corner regions is different from that in the flat sides. In particular, if the angle is 45 degrees, then the current density in the top corner is zero, and that in the side pockets is twice that in the sloping sides. The field at the iron surface can be made as small a fraction of the field in the aperture as desired, to avoid saturation effects, by thickening the coil, but that increases the quantity of conductor required, perhaps intolerably. Despite some practical problems, the design stands almost alone, accompanied only by the window frame configuration, among the configurations considered here, that not only creates an absolutely uniform magnetic field but also can be built at all.

Most of the designs illustrated can be transposed into magnets of higher multipole order. For iron-free magnets or some magnets having a circular iron boundary, if the angular position of each infinitesimal element is halved, and the number of quadrants (now "octants") is doubled, then a quadrupole magnet is produced. This is only practical when the configuration is basically cylindrical.

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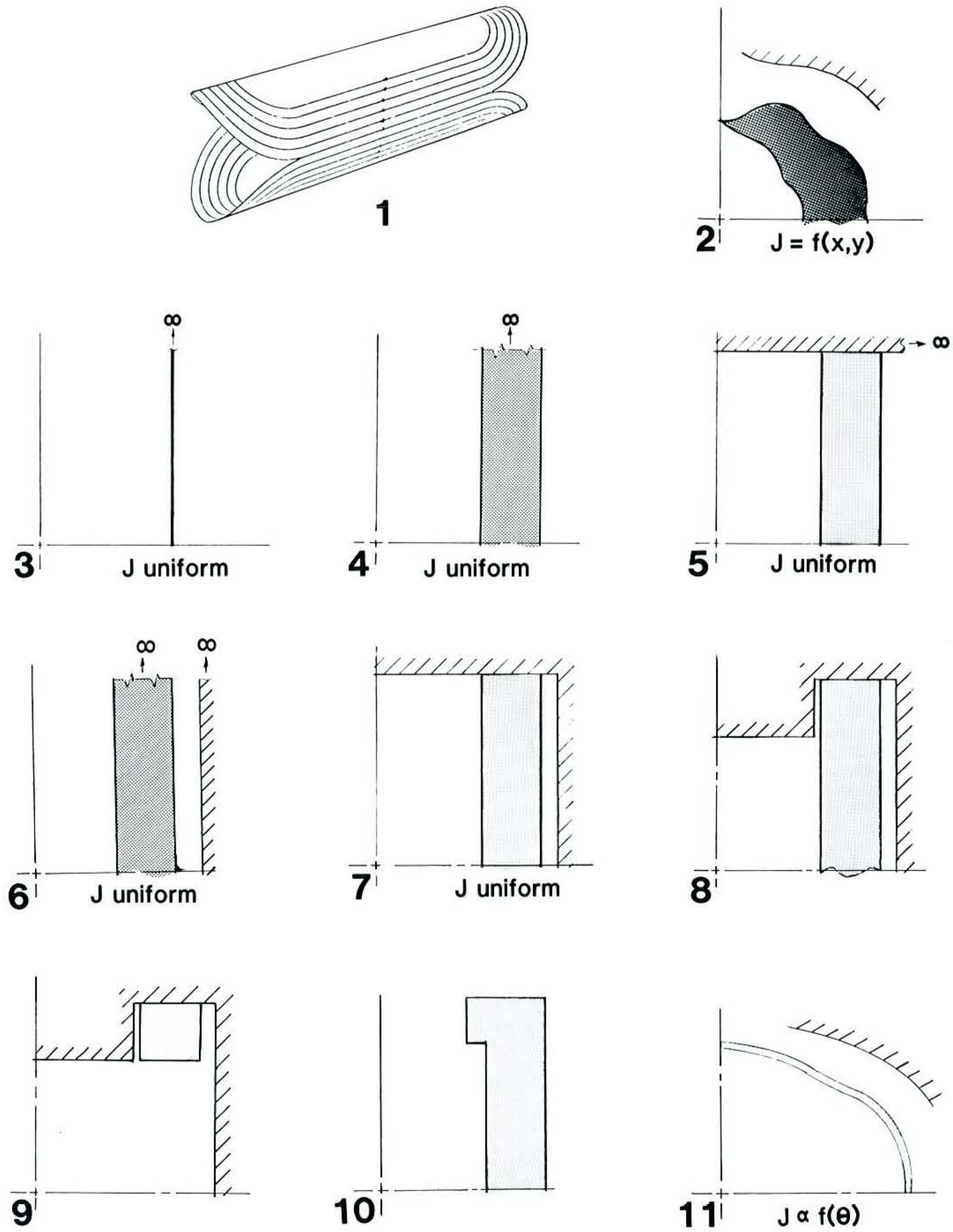
1
2
J = f(x,y)
∞
3
J uniform
∞
4
J uniform
∞
5
J uniform
∞
∞
6
J uniform
7
J uniform
8
9
10
11
J α f(θ)

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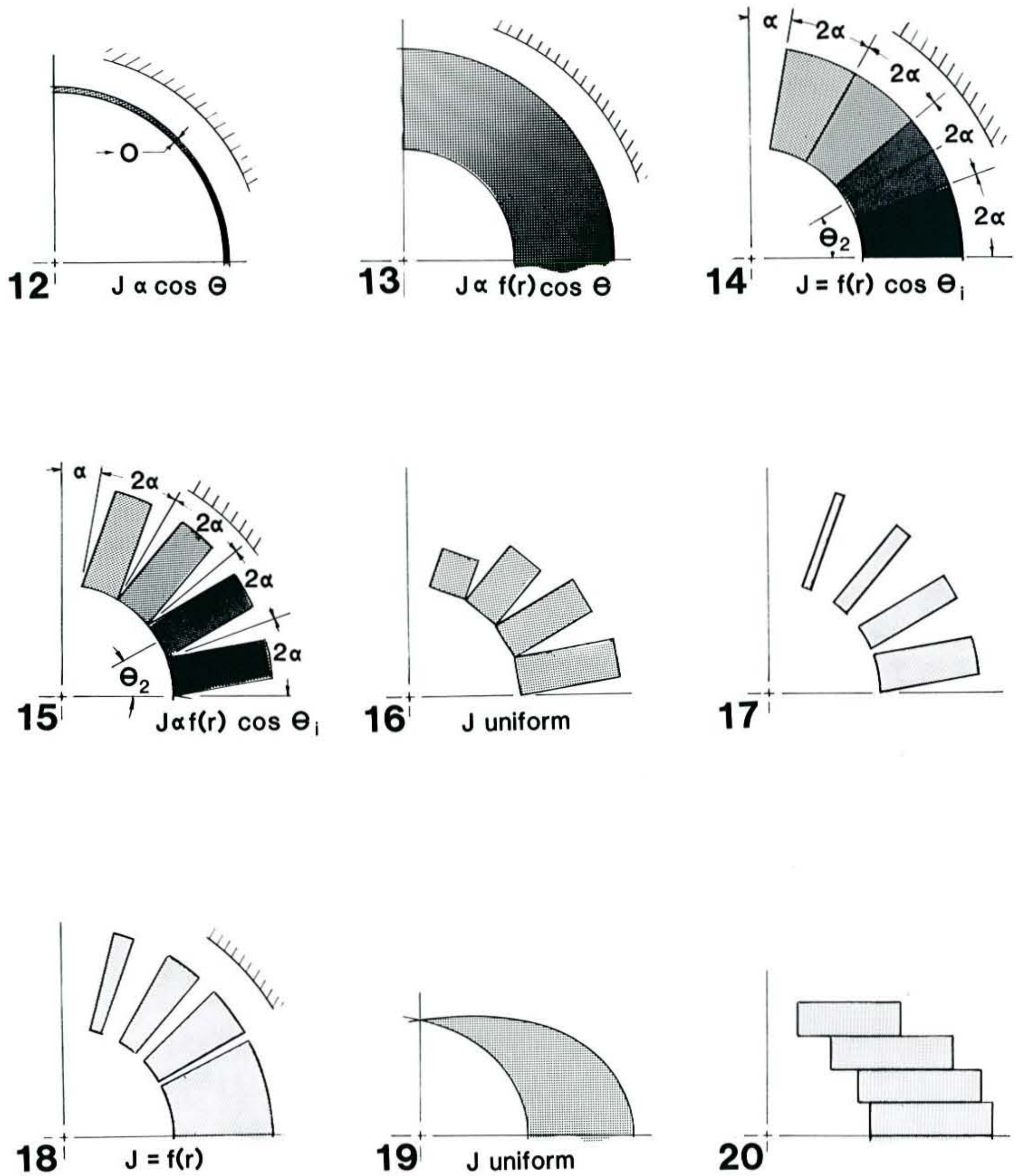
12 J α cos Θ
O
13 J α f(r) cos Θ
14 J = f(r) cos Θ_i
α
2α
2α
2α
2α
Θ2
15 J α f(r) cos Θ_i
α
2α
2α
2α
2α
Θ2
16 J uniform
17
18 J = f(r)
19 J uniform
20

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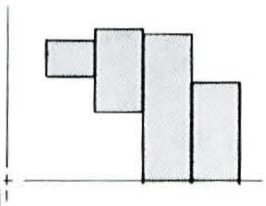

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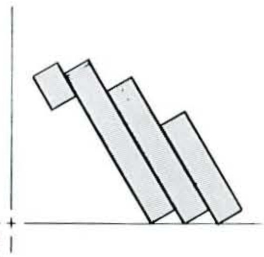

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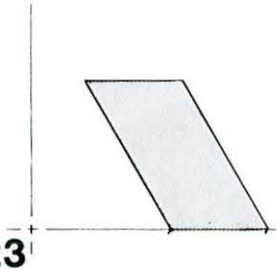

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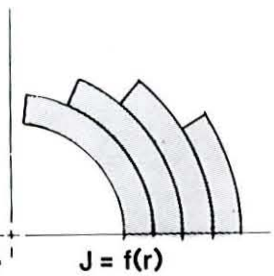

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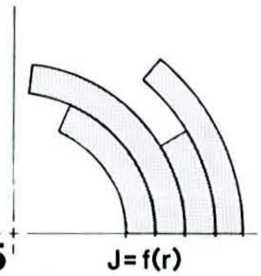

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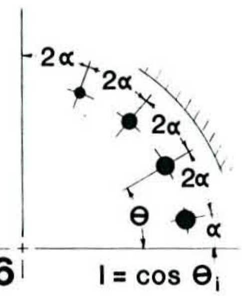

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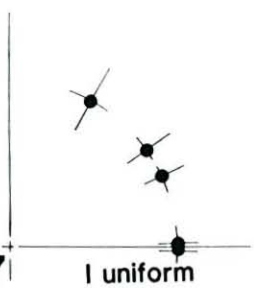

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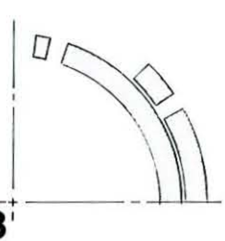

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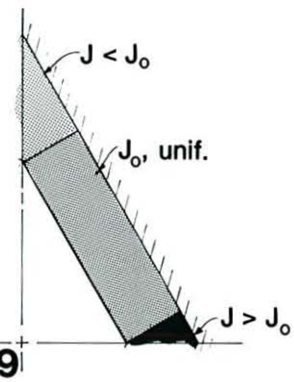

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