Iron Dominated Resistive Magnets

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1. Amperes Law and Potential Theory (Perfect Iron)

A first start at designing a magnet begins with the idea of infinitely permeable iron formed into a two dimensional (infinitely long in the z direction) configuration in the (x,y) plane with an air gap, in which a path through the iron and air gap link a current I. Induction (B) field lines pass through the iron and air gap, their normal component being continuous. (The coordinate z is chosen to be in the direction the beam takes, the z axis lying in the center of the magnet aperture; x will be chosen to lie in the bend plane and be positive outward, and y will be perpendicular to z and x.) The field (H) is zero in the iron and is given by

$$B = \mu_o H$$

in the air gap. Since the tangential component of H is zero in the iron it and the tangential component of B are zero at the surface of the iron. Since there is no current in the gap, the curl of B and H are zero and the field in the air gap region can be derived from a potential function

$$B = -\nabla\psi$$

If the air gap region is not near the conductor, the field is the same as the electrostatic field due to electrically charged iron surfaces at differing potentials. Because of Ampere's Law

$$\oint H \cdot dl = I = \frac{\delta\psi}{\mu_o}$$

we can take the magnetic potential difference to be the current I.

We may now use standard potential theory such as that of analytic functions $W(\zeta) = \phi(x,y) + i\psi(x,y)$ of the complex variable $\zeta = x + iy = \rho e^{i\theta}$. Both real and imaginary parts ϕ and ψ satisfy Laplace's equation in the two variables and either (usually the imaginary part ψ) can represent the potentials in the air gap. Then ψ is constant on iron surfaces, changing its value as a current is crossed. The other function ϕ is called the "flux function" and represents the flux per unit length linked by the axis (0,0) and (x,y). A very simple class of functions is a power of ζ

$$W_n = \zeta^n = \sum_{r=0}^{r=n} C_r^n (x)^{n-r} (iy)^r = \rho^n e^{in\theta} = \rho^n (\cos n\theta + i \sin n\theta)$$

where C^n_r is the binomial expansion coefficient. The fields of such functions are called "multipoles". Those with fields B_y on y = 0 are called "normal", and those with B_x on y = 0 are called "skew" or "rotated". The simplest is that for n=1, called a dipole field. From $W_1 = -B\zeta$ the potential is $\psi = -By$ so the field is $B_x = 0$, $B_y = B$. If iron surfaces (poles) are located at $y = \pm g/2$, then the required current is

$$I = \frac{Bg}{\mu_o}$$

Similarly we can inspect $W_2 = -B'\zeta^2/2$ to find $\psi = -B'xy$, so $B_x = B'y$ and $B_y = B'x$. The pole surfaces, those of constant ψ are hyperbolae $2xy = a^2$ where a is called the poletip radius and is the radius of the largest circle which can be inscribed inside the poles. Since neighboring poles have potentials $\pm B'a^2/2$, the current which links them is $\pm B'a^2/\mu_o$ This arrangement is called a quadrupole field. The equations for the ideal poles of the general normal and rotated multipole of order n are:

$$\rho^n \sin n\theta = a^n \quad \text{(normal)} \qquad\qquad \rho^n \cos n\theta = a^n \quad \text{(skew)}$$

where a is the poletip radius or half gap. Dipole, quadrupole, and sextupoles, the next multipole, are the most common fields in accelerators. Another useful accelerator magnet is the combined function magnet, incorporating both bending and focusing (field and gradient). In fact, one can describe it as part of a quadrupole, the center of the magnet being at the location in the quadrupole that gives the desired bending field, as in Fig. 1f.

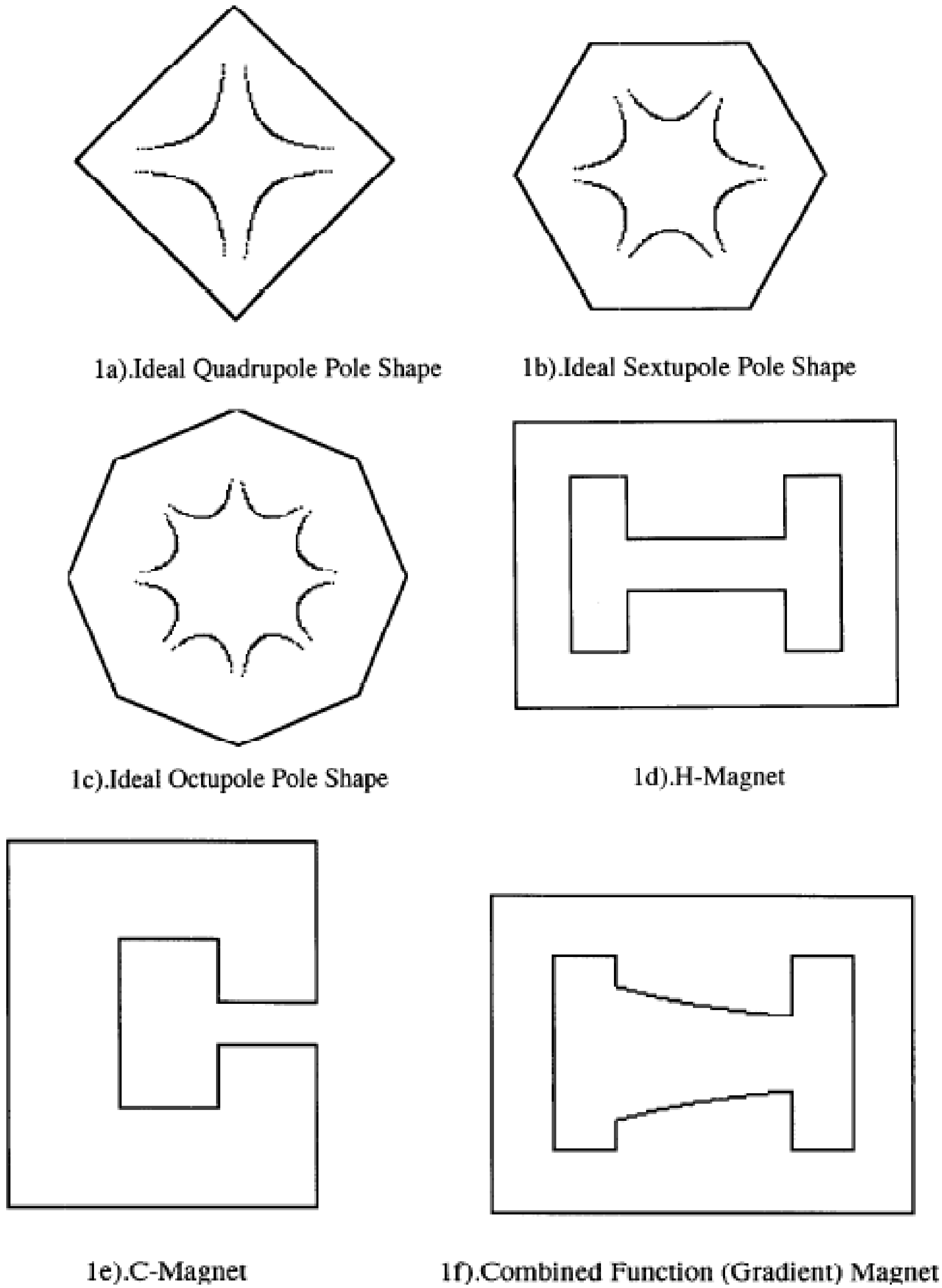

Figure 1. Ideal pole shapes for common magnet types.

To complete the description of a two dimensional magnet, consider first the dipole. We will need only a limited aperture in x to contain the beam so we will truncate the poles. In the first place, we might simply end the pole at x = ±w/2 with a 90˚ corner along the lines x =±w/2. This is satisfactory only if the operating field B is small. The field at the corner is called upon to be infinite, but the iron cannot comply with this need. At the very least, the corner must be rounded with a radius of curvature sufficiently large to limit the iron field below saturation values. Another strategy useful for high field magnets is to shape the pole so that the field in the iron is always in the y direction and therefore is uniform. Then the field shape in the air gap will be the same at all fields and saturation effects will be minimized[1].This will be discussed later in the next section in association with end field problems.

We can estimate the effects of finite permeability by employing Ampere's Law again in a path linking the current and passing through the air gap.

$$\oint \mathbf{H} \bullet \mathbf{dl} = \frac{Bg}{\mu_o} + H_{iron} l_{iron} = I$$

In an H magnet, as one moves from center to edge of pole, the path l_{iron} is reduced, increasing the field B. This gives rise to a symmetric field error (sextupole etc.) while in a C magnet this leads to an asymmetric field error (quadrupole etc.).

There is another pressing problem at the pole corner. That is that the potential can no longer be uniform in y since the equipotentials must bend 90˚ at the corner and the field in the pole must have an x component to provide the x component of field on the side of the pole. The errors in field so defined will propagate into the gap region and give a distorted field. Solutions of the Laplace equation which have the correct boundary conditions and symmetry are

$$\psi = \sum_n A_n \cosh k_n x \sin k_n y$$

where $k_n = 2n\pi/g$ and A_n is a constant. We can see that if we Fourier analyze the error potential at the pole corner we will have a picture of individual terms lapsing toward the center at different rates. If we can null the first harmonic, then we will have gotten rid of the worst error. Higher terms will lapse so rapidly as to be minuscule. This can be done by putting a step or Rose shim[2 3] at the pole corner. The width and height of the shim are adjusted to achieve the maximum "good field" aperture. There is no reason to use an

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[1]S. C. Snowdon, Magnet End Termination, FN-184, April, 1969 (Fermilab Physics Note). In this note he gives a reference to unpublished work by Werner Hardt. Hardt used this method on combined function magnets of the DESY-1 Accelerator in 1959, but apparently did not publish his work.
[2]M. E. Rose, Magnetic Field Corrections in the Cyclotron, Phys. Rev. 53, p 715 (1938)
[3]S. C. Snowdon, On the Calculation of Rose Shims, TM-710, January, 1977 (Fermilab Technical Memo)

abrupt step, so the shim can be incorporated into the smooth profile described in the previous paragraph. These calculations are best done with the aid of digital computer programs such as Trim, Poisson, etc.[4]developed in the past 40 years by S. C. Snowdon, K. Halbach, Bill Trowbridge and others.

The above considerations apply equally to magnets of multipolarities greater than 1.

2. Magnet Ends

For a non-curved magnet, we can define a two dimensional potential Ψ(x,y) such that the negative of its gradient is the integral of its field through the magnet . The potential is given by

$$\Psi(\mathbf{r}_2) = \frac{1}{4\pi} \iint d\mathbf{S}_1 \cdot \mathbf{B}(\mathbf{r}_1) \ln(|\mathbf{r}_2 - \mathbf{r}_1|)$$

where the surface integration is taken over the magnet iron surface and $\mathbf{r}_2$ is a two dimensional vector. In practice, it is difficult to know the fields and the source fluxes sufficiently well to find this potential. But we can make small changes to the iron surface in which we can predict the fields on the new surfaces, and so use the difference in potentials to estimate the changes in integrated fields.

Consider the integration of the potential at the end of the magnet. We can see in a general way that as we move from magnet center to pole edge the amount of flux contributing to Ψ is reduced so the potential will be weaker. The integral dipole field will have symmetric higher multipoles, sextupole, decupole, etc. In order to correct them, we can effectively make the magnet pole longer as a function of x. Although in principal one can find the required correction pattern by evaluating the potential, in practice it is easier to find the required shims empirically in conjunction with a magnet measuring program. This same potential can be employed to find the step shims described above in section 1. It also can be employed to calculate the effect of errors in pole positions, shapes etc. Only recently have 3-D field calculations using Opera 3-D (successor to Tosca)[5] been sufficiently precise to devise corrections to predict accurately the necessary corrections to dipole end fields.

The second end effect of importance in high (>1.5 T) field magnets is similar to the saturation problem discussed above because of the finite pole width. The source of the problem is the flux emanating from the end of the magnet. For infinite permeability iron, flux lines, normal at the exit from the iron, can approach the surface at grazing

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[4]These programs, and many other Accelerator Physics and Design programs are available from the Los Alamos National Laboratory Accelerator Code Group. See "Computer Codes for Particle Accelerator Design and Analysis: A Compendium", LA-UR-90-1766, LANL, Los Alamos, NM 87545

[5]These and other programs are available commercially from Vector Fields Inc., 1700 N. Farnsworth Av., Aurora, IL 60505

angle, so there needs be essentially no B_z in the iron. As the permeability μ decreases, the required B_z increases. Considering solutions to the Laplace equation in either the iron region or the gap region of the form

$$e^{i\mathbf{k} \bullet \mathbf{r}} = e^{i\left(k_x x + k_y y + k_z z\right)}$$

We find $$k_x^2 + k_y^2 + k_z^2 = 0$$

Fields from the potential $\psi = A \sin ky \cosh kz$ in the gap give fields

$$B_z = Ak \sin ky \sinh kz \qquad B_y = -Ak \cos ky \cosh kz \text{, or}$$

$$\Delta B_z\big|_{y = g/2} = kA \sin\frac{kg}{2} \sinh kz \qquad \Delta B_y\big|_{y = 0} = -kA \cosh kz$$

These fields must be matched to those in the iron. Some relevant considerations are that the value of k_x, here taken to be zero, might be finite if there are substantial field variations across the pole. Second, since the field lines in the iron region must be bent to pass through the back leg, the value of k_y must be approximately

$$k_y = \frac{\pi}{2d}$$

since the field must be in the x direction at the magnet top or bottomsurface, a distance d above or below the pole surface. Then the main effect is the curvature of the field lines and the value of k is determined by that, its value depending somewhat on the ratio of pole width to back leg height and by the actual sextupole in the gap field. Note that the B_z in the iron is μ times that in the above equation.

The strength A will be large enough to carry the required flux to the end of the magnet to produce the end field. Even with some attempt to terminate the pole with, for example, a compound bevel, these errors can reduce magnet strength by of order 1% for fields of 1.7 T. If all magnets are the same length, this is not important, but if there are several magnet lengths in a lattice, problems can ensue.

As remarked above, this problem can be avoided if the magnet end profile is shaped so as to maintain the field in the iron in the y direction so no horizontal end flux is needed. For AC magnets (frequencies greater than a few Hertz) this solution has another benefit. That is that the end flux passes perpendicular to the laminations and so has high eddy current heating, leading to thermal and mechanical trouble. In passing we might note that while the pole shape is easy to accomplish because it can be stamped on every lamination, the end shape requires many different kinds of lamination.

The expression for the pole end shape is:

$$z = \frac{g}{\pi}(1 + t) \qquad\qquad y = \frac{g}{\pi}\left(\frac{\pi}{2} + e^{t}\right)$$

where g is the total magnet gap and t is a parameter (flux function) which varies between $-\infty$ and ∞. Such pole ends have the appearance of those in Figure 2 below.

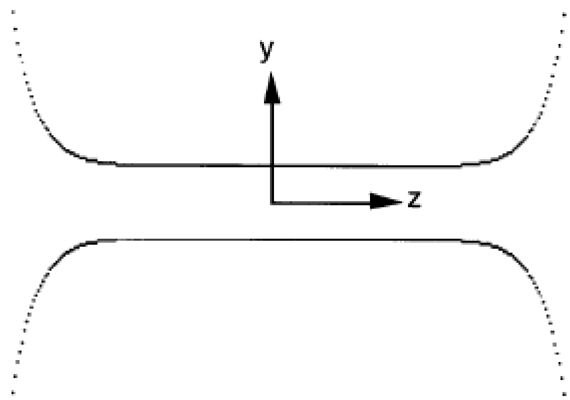

Figure 2. Ideal Finite Dipole Pole Longitudinal Profile

3. Curved Magnets

Several complications arise in the construction of laminated curved dipole magnets. The first is simple. Since the laminations are stacked parallel, there is a reduction of available radial aperture as the bend angle gets large. This can be accommodated by making the pole and coil window wider on the lamination.

In building such magnets, it is less expensive to fabricate the core with parallel ends. The core can then be stacked against a curved rail and the laminations can be compressed periodically to assure efficient and precise stacking. The edge angle created can be compensated easily in the lattice design by the quadrupoles. The effective edge angle, however, does not turn out to be half the bend angle, but slightly smaller. This can be understood with the aid of the two dimensional potential described above. There is simply more pole area and flux to act as a source for the potential on the outside (obtuse angle) than on the inside (acute angle). Depending on the ratio of pole width to gap, and the side treatment of the pole, there may be both a linear and a cubic departure of the field integral from that naively assumed. The reduction in edge angle at each end turns out to be about 3 mrad for each 10˚ of bend.

4. Coil Construction

a. DC and Slowly Pulsed Magnets

Water cooled hollow copper conductor is usually employed to excite magnets with repetition rates below about 5 Hz. Normally the coil water configuration is chosen so that the water flow is turbulent to promote good heat transfer. Flow velocities should remain low to avoid erosion of copper. The water temperature rise is normally less than about 20˚C. At a flow of 1 gal/min and a temperature rise of 3.8˚C, 1 kW of heat is removed by the water. For flow in a tube of length L (in) and diameter D (in) with a pressure drop of P (psi), the approximate[6] estimates for turbulent and laminar flows in Gal/min are

$$F_{turb} = \sqrt{\frac{19{,}600PD^5}{L}} \qquad\qquad F_{lam} = \frac{31{,}900PD^4}{L}$$

Analysis of construction costs and operating costs show that there is a broad minimum in overall cost for magnets with rms. current densities in the region of 1.5-2.5 A/mm^2.

After the coil is wound, the copper is wrapped with epoxy impregrated insulation (conductor wrap) and if there are many layers, the layers, or "pancakes" may be wrapped, and finally the coil receives a "ground wrap" to provide insulation from the iron core. This may also be augmented with insulation attached to the core itself. The coil is placed in a potting or curing fixture which determines the shape of the coil, and is cured or impregnated and cured at about 350˚F. The curing fixture is the main aid to precision in coil fabrication.

A complication which occurs during coil winding comes when bends of small radius of curvature are made in the coil[7]. The outside of the bend is stretched while the inside is compressed, so that the conductor acquires a trapezoidal shape. Winding under tension reduces this "keystoning", but does not remove it, and too much tension will tend to close the hole. Good practice is to bend with normal winding tension, and to limit the radius of curvature to no less than two conductor thicknesses. Under these conditions, the increase in conductor axial width and the reduction in conductor radial width can be kept less than about 5%. One must deal with even this amount. The keystoning will cause abrasion in the coil ends during insulating and curing, leading to turn-to-turn shorts later. The offending material can be ground away or the coil can be designed to include inter turn spacers to separate the conductors by more than the keystoning. If space for the coil is not at a premium, the second choice is usually less expensive.

Because the potential of a multipole of order n varies as the poletip radius to the n th power, higher order multipoles and miniature magnets require higher current density. Also, specialty magnets, such as extraction septum magnets, require high current density in the septum region. If the application will not tolerate low duty short pulsed magnets,

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[6]More careful estimates would use the von Kármán correlation for turbulent flow.
[7]J. Gunn, Distortion of Square Hollow Copper Conductor at Bends, UCRL Design Note, 5/5/73

the above advice cannot be taken. At the Princeton-Penn Accelerator[8], a septum magnet operated with more than 400 A/mm^2. using 1000 psi water pressure to cool each 40" of conductor. More recently, such problems have been avoided by using Lambertson septum magnets which have a steel septum and a horizontal field.

b. AC Magnets

The skin depth in copper is about 8 mm at 60 Hz. For conductors of about this size, the AC magnetic fields and currents will not penetrate the conductor completely, raising the current density, and increasing resistive losses. If the magnet configuration calls for the conductor to be in a region of strong field, then the losses can be enhanced by the need for the flux lines to cross the conductor. By avoiding such designs, i.e. locating the conductor in a low field region, and using small conductors, hollow conductor coils can be used up to 15-30 Hz. Eventually the current carried by the coil is too small, complicating the coil and power supply. At this point one attempts to employ a fully transposed cable of small conductors. The coil can be cooled by imbedding a water carrying tube in the cable. Alternately one can simply operate at lower current density and lower field. There has been no "standard" cable for this application, but AC magnets have historically operated at lower field (0.5-0.9 T) than DC or slowly pulsed magnets.

5. Core Construction

a. DC and Slowly Pulsed Magnets

The field quality, and therefore the performance of the magnet is determined by the location, and to a lesser degree by the composition, of the iron core and its surface. On the other hand the cost of the magnet is dominated by the coil and the power supply. Low carbon steel, 1006-1008, in 0.06" thick coils, costs about $0.50/lb. The properties of several types of low carbon steel are shown in Figure 3 and 4[9]. The Main injector steel has been specially heat treated to grow its grain size, yielding a lower coercive force, visible in Figure 3.

[8]Private communication from Joe Kirchgessner.
[9]This data was made available to me by Bruce Brown.

Main Injector and Pbar Source Steel-Low Field

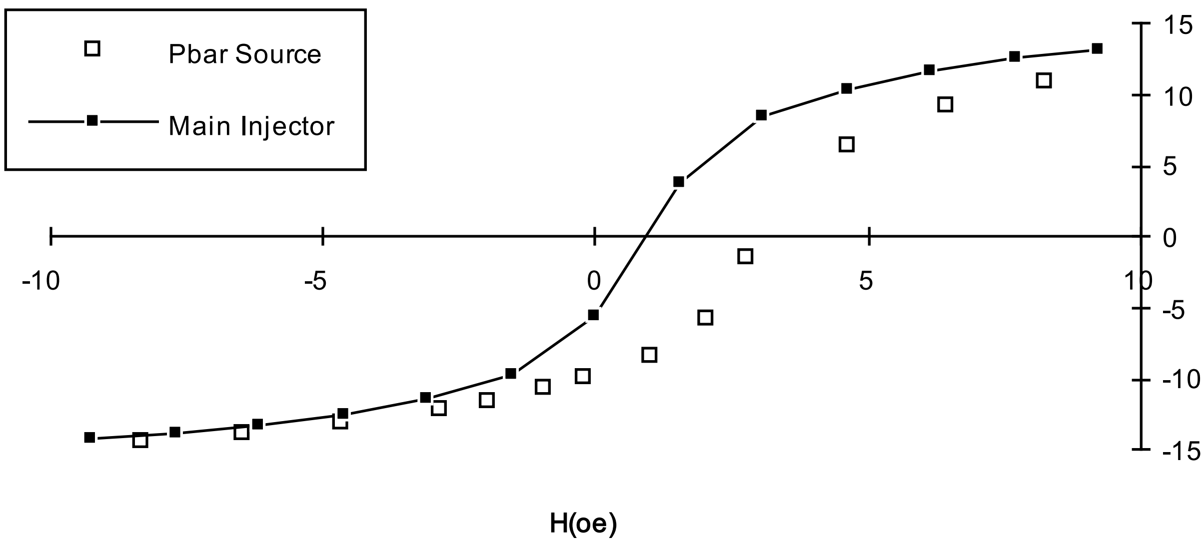

Figure 3.

At high fields, there is little difference, the Pbar source steel having slightly higher permeability as seen in Figure 4. Since the rings operate DC, there is little need for low coercive force, and a substantial sum was saved.

Main Injector and Pbar Source Steel

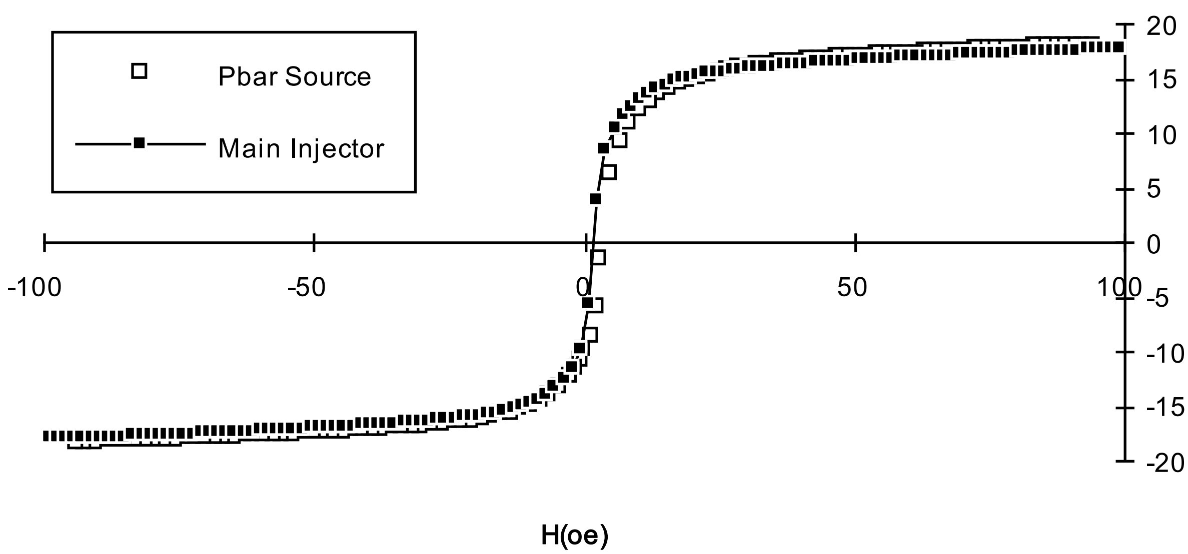

Figure 4

To punch large quantities into laminations costs about $50/in of magnet. It is impossible to obtain the same precision for this cost by machining forged steel pieces. For this reason many dc magnets are built of laminations, as are all pulsed magnets, whereas single magnets, or those too large to employ laminations are usually machined from solid steel blocks and assembled. Steel used for magnets is usually produced in wide sheets, about 4 m or more in width. The steel is slit as it is rolled and wound into coils of the width one specifies (usually 5-10 mm extra is left around the final lamination shape to minimize the effects of stress induced during the subsequent punching.) The steel is not perfectly flat, thicker in the middle than the edges, with a crown in the center of up to 1% of its nominal thickness. Depending on the location in the roll, the lamination may be relatively flat, or have a taper. As such laminations are stacked, the magnet end surface becomes deformed unless one alternates the orientation of the taper to avoid the wrong taper at the end.

Let us consider the fabrication of a laminated H magnet core made in two halves with mating surfaces. This will require a stacking fixture with a "pusher" to compress the laminations: typical clamping pressure is 150-300 psi. The laminations are not perfectly flat because of the locked-in stress due to the punching. Further the laminations are usually "flipped" every few inches to average out asymmetries due to die errors. Thus the laminations appear to be like springs. The stack is usually compressed until its effective Young's Modulus exceeds 1,000,000 psi[10]. (The Young's Modulus of steel is about 30,000,000 psi.) The laminations are stacked on rails on their mating surfaces and pushed sideways against a rail. The orientation of the laminations is alternated periodically ("flipped") to average out asymmetrical die errors. If the magnet is curved, the laminations must be alternately pushed and compressed in order to position them properly. Usually, end packs of solid steel or glued laminations are placed at each end to keep the stack from bowing out when the clamping pressure is released. Corrections for the end fields are included on these end packs. The laminations and end packs are clamped to the table. This can be done with hydraulic systems, but a cheaper and more powerful method is to excite a magnetic field through the rails and the lamination back leg. Since the air gap in this loop can be small, a modest current can get a 1.5 Tesla field, yielding a 6 atm stress between the lamination and the rail. Steel bands, plates, or angle iron are welded to the laminations and end packs. It is critical that the first weld on each side be continuous. Otherwise the mating surface becomes wavy due to "weld pull". To assemble the magnet, the half cores are turned over, ground insulation and the coils are installed and fixed in place. The top half is rolled over, placed on the bottom half, the two are clamped together and either bolted or welded together using "weld patches". The welded magnet is superior to the bolted magnet, achieving much higher clamping stress than the bolted magnet, which usually is not clamped sufficiently to close the mating surfaces, adding reluctance to the magnetic circuit. If problems occur pulling the mating surface together, it can be closed by magnetizing the core in the same flux pattern used on the stacking table.

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[10]C. Theisen, Modulus of Elasticity of Steel Laminations, February 1978, Brookhaven Report

C magnet construction poses somewhat different problems than H magnet construction. Since the laminations tend to be larger, the problems of punching induced stress and die errors are more serious, since the laminations can only be flipped top for bottom. It is important to make the single back leg thick enough so that neither does the gap open up due to punching induced stress nor does the gap close due to magnet excitation. Attention must be paid to the crown effects as well. The magnets can be stacked with the gap straddling a vertical rail to position the laminations. They can be supported on curved rails to produce a curved magnet, if desired. Since there is no problem of mating surfaces, the laminations need only be clamped longitudinally during welding. Straps or plates should be welded on top and bottom to keep the laminations clamped during assembly and operation.

Quadrupole construction offers interesting choices. The magnet can be assembled from either two or four cores. The two core magnet has no mating surface problem, since each core has a complete flux plot, like the C magnet (as well as the possibility of a mechanically weak back leg). On the other hand, the coil fabrication becomes more expensive than the coil for the simpler four core quad. At least for magnets with modest fields, four core quads are built which perform successfully. Some of these have protrusions on one side which, because of the flipping, can be used to clamp the cores together with bolts for assembly. In other cases, the cores are stacked and clamped magnetically against rails while being pressed longitudinally during welding. The coils are installed, and the cores are welded together inside and out to make half magnets. The use of a slotted weld strap on the outside allows post facto adjustment of the pole positions.

b. AC Magnets

Most of the problems of AC magnets have been treated above. In addition to these, eddy current losses in the core material call for thinner laminations and lower loss iron. Silicon steel, with silicon content between 1% and 5% is usually employed, in thicknesses of 0.35 mm (0.014") for 60 Hz. The steel is non grain oriented[11] In order to avoid the problems of the mating surface, it is preferable to build one piece cores, either in H magnet form, or in C magnet form. A small penalty of about 0.1 T is paid in saturation field by the use of silicon steel. Because of the tendency to lower fields noted above, this is more than offset by the lower coercive force of silicon steel (0.5 Oe instead of 1-3 Oe for low carbon steel).

6. Quality Control Methods

[11]In most magnets, for example C magnets or H magnets, the flux lines turn through at least 180˚ in the iron, negating any advantage of the orientation. "Feathering" or interlacing laminations in corner regions is used in transformers, where there is no serious requirement on dimensional precision, but is considered to be too expensive to use in accelerator magnets.

Particularly in systems with large number of magnets, a variety of means are available to minimize the effect of errors in fabrication of parts of magnets and magnets themselves.

In the first place measurements can be made of a few sample laminations from individual heats or coils of steel. These can include the B-H curve for high field permeability and coercive force, as well as critical dimensions such as gap. Magnets can then be created from the appropriate mix of laminations to average out the effects of fluctuations in these properties.

In the second place, the laminations can be designed to accommodate flipping, or alternation as noted above, to average out asymmetries. The design should incorporate a "witness mark" so that the pattern of alternation is evident. The lamination can also include built in fiducial surfaces for surveying the magnet in its final location.

Finally, the location of individual magnets in the lattice can be assigned on the basis of measurements of the fields of the magnets. The general approach is to attempt to cancel contributions to the appropriate Fourier- Floquet harmonic coefficients of the error fields responsible for the excitation of resonances by individual multipoles. For example the closed orbit error is driven by dipole errors, half integral resonance and amplitude variation by quadrupole errors, etc. Improvements in the performance can easily attain values of 5-10. Several multipoles can be corrected at the same time, but this usually leads to less improvement for each.

7. Examples of Recent Magnets Built

In the three tables below there are descriptions of the major magnets for three recent projects, the Antiproton Source Magnets for the Tevatron Collider at Fermilab, the Advanced Photon Source at Argonne, and the Main Injector at Fermilab. Typical lengths, operating fields, and currents are given, as well as the strength variations. It is typical, as in the second and third examples, to give the rms field error (usually for many multipoles, but here as a maximum) at some offset (usually 25 mm) as input for tracking codes for beams on the axis of the magnets. In the first example the system was required to store beam at widely different locations (note that the quadrupoles had a good field region of about 1.5 poletip diameters) so the maximum strength variation is shown as a tolerance, which was met.[12]

Table 1
Antiproton Source

Type	Large Dipole	Large Quadrupole	Small Dipole	Small Quadrupole
Strength	1.7 T	8.9 T/m	1.7 T	10 T/m

[12]The author is indebted to Bruce Brown and David Harding of Fermilab, and Suk Kim of Argonne for helping assemble the data in these tables.

Magnetic Length m		.439,.643,.772,.874,.830	1.65,1.52,3.05,4.57	.46,.604,.665,.792,1.277
Gap or PT Diameter mm	60.3	168.3	60.3	88.9
Good Field Region (GFR) mm	254	254	120	120
Operating Current	1178	1206 A	1178	235 A
Number Built	13	38	99	251
10^4 •Strength rms	5	10	5	15
10^4•max strength error in GFR	3	25	3	25

Table 2.
Advanced Photon Source

Storage Ring				Booster	
Type	Dipole	Quad	Sextupole	Dipole	Quadrupole
Strength	0.6 T	18.9 T/m	415 T/m^2	0.7 T	16.6T/m
Magnetic Length	3.06 m	0.8,0.6,0.5 m	0.253 m	3.08 m	0.5 m
Gap or PT Diameter	60 mm	80 mm	98 mm	80 mm	56.56
Pole width	140 mm	57 mm	45 mm	114 mm	42 mm
Operating Current	450 A	386 A	160 A	930 A	600 A
Number in Ring	80	400	280	68	80
10^4 •Strength rms	4.4	1.1	3.2	3.4	5.1
error @ 25 mm, rms	0.4	2	2.5	0.4	1.5

Table 3.
Main Injector

Type	Dipole	Quadrupole
Strength	1.73	16.15 T/m
Magnetic Length m	6.1,4.1	2.118,2.522,2.930
Gap or PT Diameter mm	50.8	83.4
Good Field width mm	88	75
Operating Current A	9420	2830
Number in Ring	344	208
10^4 •Strength rms	4	4
10^4 •error @ 25 mm, rms	0.2	1