PROBLEMS ASSOCIATED WITH ATTAINING HIGH FIELD UNIFORMITY AND REPRODUCIBILITY IN MAGNETIC SPECTROGRAPHS*

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Abstract

Precision magnetic spectrographs require a very high degree of reproducibility of the field over relatively large pole areas. For homogeneous field magnets (n = 0), three design principles have long been recognized: (a) The return path should be balanced as well as possible around the magnet; (b) the pole pieces should have Rogowski tapering around the complete periphery; and (c) Purcell filters (homogenizer gaps) should be used. It has been recognized lately that the most nearly perfectly designed magnet still exhibits quite large changes in field distributions, presumably because of hysteresis effects caused by eddy currents in the pole pieces. Efforts to minimize these effects by (1) programing the power supply to follow a prescribed current-versus-time curve and (2) using higher permeability materials are discussed.

I. Introduction

A family of magnetic spectrograph designs with resolving powers exceeding 1 part in 10^4 was discussed at the Third International Magnet Conference.[1] All these spectrographs have large solid angles, meaning that rays that are spread out over a large region of the pole faces must converge to a small spot on the detector. Clearly, this requires very precise control of the field distribution in the pole gaps. The spectrographs referred to all consist of a series of elements; for instance, a quadrupole and three dipoles (Q3D). The requirements of field reproducibility in the quadrupole, because of its location, are not so stringent as are the requirements for the dipoles. We are therefore only discussing the dipoles here. Moreover, the discussion is limited to homogeneous-field magnets (n = 0) with pole pieces, that is, H-frame rather than window-frame magnets, and we are mostly concerned with magnets operating in the range 3 to 15 kG.

In order to obtain routinely a resolving power of 1 part in 10^4, it is not strictly necessary to make magnets with field distributions homogeneous to better than 1 part in 10^4. For instance, a slight n value in the field has little effect other than displacing the image slightly. This, as well as higher order inhomogeneities can at least in principle be corrected for by adjusting the shape of the effective field boundaries. This is accomplished by adjusting the shape of the field clamps[2] which act as verniers on the positions of the effective field boundaries. So, what we really are concerned with here is the reproducibility of the field distribution in a dipole magnet. With "reproducibility," we mean that the field map over the usable region of the pole faces relatively speaking reproduce to an accuracy of 1 part in 10^4 over a large range of the field strength; for instance, over the range 3 to 15 kG. This is a tall order, particularly for a large solid-angle spectrograph, where typically the rays in the middle of the instrument may be spread over a width of 50 cm, or about six airgap distances.

II. DC Effects

We shall here give a brief review of design principles that have long been recognized as important for producing magnets with good homogeneity and reproducibility. The principles are:

1. Balanced Yoke. The return iron must be distributed such that the field from any part of the magnet closes itself with a loop of approximately the same length as that of the field in another part of the magnet. For instance, for a long and slim 90° analyzing magnet, the return iron should be evenly distributed along the length of the magnet.
2. Chamfering of the Poles. It has long been recognized[3] that Rogowski-contoured poles (constant B poles) are far superior to sharp-cornered poles for precision magnets. The effect of chamfering is essentially to produce a uniform field in the poles and therefore magnetic equipotential surfaces inside the poles that are parallel with the front surfaces of the

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*This work has been supported in part by AEC Contract AT(11-1)-3069.

poles. Enge[4] has demonstrated that the effect of the extra flux represented by the fringing field in sharp-cornered magnets is discernible throughout the whole pole gap. Okuma et al.[5] and Skillicorn[6] have shown very dramatically how the homogeneity can be improved by contouring the poles. Kumagai and Motonaga[7] have analyzed the data of Okuma et al. in the terms discussed here.

Figure 1 shows the field distribution measured along the central path in a 90° analyzing magnet built by High Voltage Engineering Corporation.[6] One curve is obtained with sharp-cornered pole pieces, the other with chamfered pole pieces (a single 60° cut along the sides as well as at the ends).

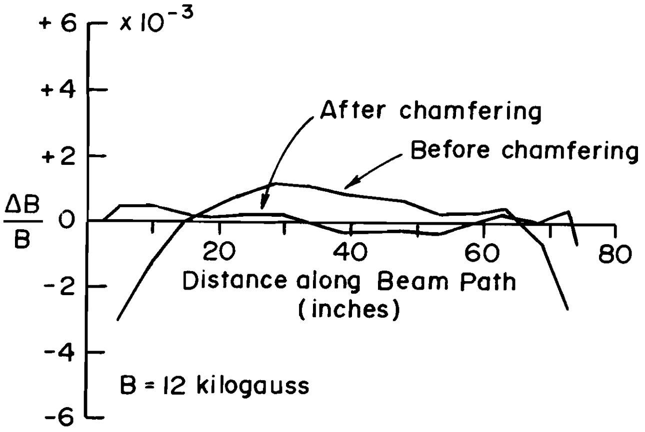

Fig. 1. Variation in the field at B = 12 kG in a 90° analyzing magnet before and after chamfering.

3. <u>Purcell Filters</u>. (<u>Homogenizer Gaps</u>[8]) These small gaps decouple the pole pieces from the yoke in the sense that they reduce the effects of return path differences. Also, they can be used for mechanical decoupling of the pole pieces from the yoke, thereby reducing the distorting effect of magnetic forces.[4]

The extensive investigation of Okuma et al.[5] on a slim analyzing magnet indicates that the beneficiary effect of Purcell filters in a magnet of this kind falls far short of expectations. However, measurements on a split-pole spectrograph,[9] which has a relatively wide pole piece and 3-mm Purcell gaps, give clear indication of inadequate filtering at low field strengths where the permeability is low. Measurements on the largest magnet (D2) of the Heidelberg Q3D spectrograph[10] (6-mm Purcell gaps) show very little or no indication of inhomogeneities that can be ascribed to path-length differences. These results are taken as indirect evidence that Purcell filters do indeed work.

When the poles are inadequately chamfered, the field in the center of the magnet will in general be higher than the field closer to the pole edges. In certain instances, this situation may be reversed if the effective permeability of the iron in the poles is negative, as it may be when the current has been reduced from near saturation to below the remanence field (typically 8-10 kG). In any event, the distribution is different when the current has been decreased before the measurement than when it has been increased. This is illustrated in Fig. 2,

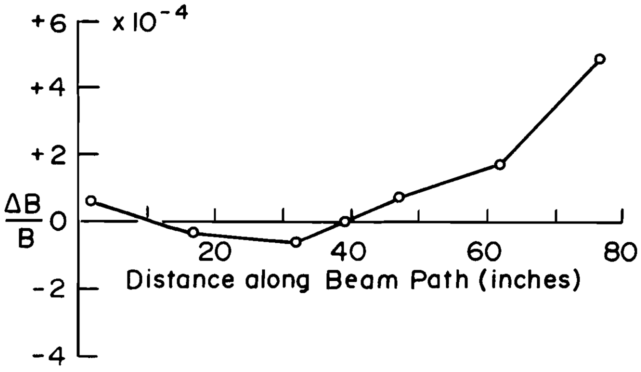

Fig. 2. Differential hysteresis at B = 4.5 kG in 90° analyzing magnet with square edges.

which shows the difference $\Delta B = B_{down} - B_{up}$, divided by the average field $\bar{B}$. The magnet is the sharp-cornered magnet referred to above.[6] Both sets of measurements were performed at B = 4.5 kG, one set after increasing the field from zero (B_{up}) and the other after a subsequent temporary excursion to 5 kG (B_{down}). Figure 3 shows results of a set of simi-

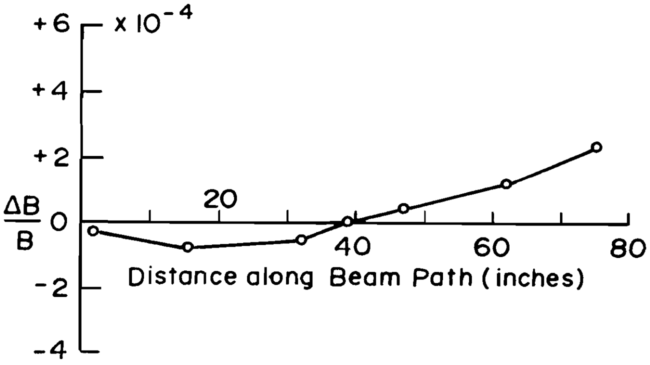

Fig. 3. Differential hysteresis at B = 4.5 kG in 90° analyzing magnet with chamfered edges.

lar measurements for the chamfered magnet. The cause of the nonreproducibility displayed in Figs. 2 and 3 is clearly associated with hysteresis, as explained above. We call it differential hysteresis. It is puzzling that, whereas the distribution displayed in Fig. 1 showed a dramatic improvement by tapering, the differential hysteresis curve did not improve nearly so much. The effects discussed below may throw some light on this.

III. Effect of Eddy Currents in the Pole Pieces

Many large magnets have been designed in accordance with the three design principles discussed above, and measurements have indicated that the magnets have substantial differential hysteresis effects. It was then discovered that eddy currents in the pole pieces may produce very substantial residual and nonuniform polarization in the iron during an increase or decrease of the field.

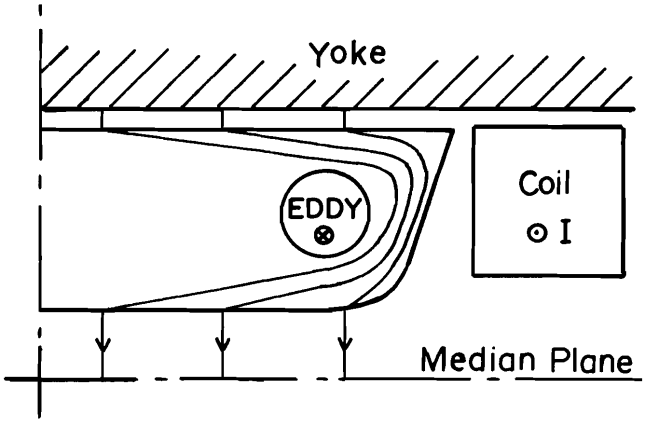

Fig. 4. Field distribution in a pole piece shortly after the current in the coil has been turned on abruptly.

Figure 4 shows schematically the current and field distribution in a pole piece immediately after the current in the coil has been turned on abruptly. The eddy current forces the field initially to follow the skin of the pole piece as shown, but because of the higher reluctance of air, the field will distribute itself more or less uniformly over the pole gap. Depending upon details, it may spread out more or less uniformly also over the Purcell gap. The result of this is that the skin of the pole piece will initially go into saturation, even if the final field is relatively low.

What happens if the magnetizing current is increased slowly? How slow is slowly? If the magnet were laminated so that a time constant could be defined, it might be typically of the order of a few seconds. However, the time constant for the eddy currents in the solid pole pieces of a large magnet is of the order of minutes.

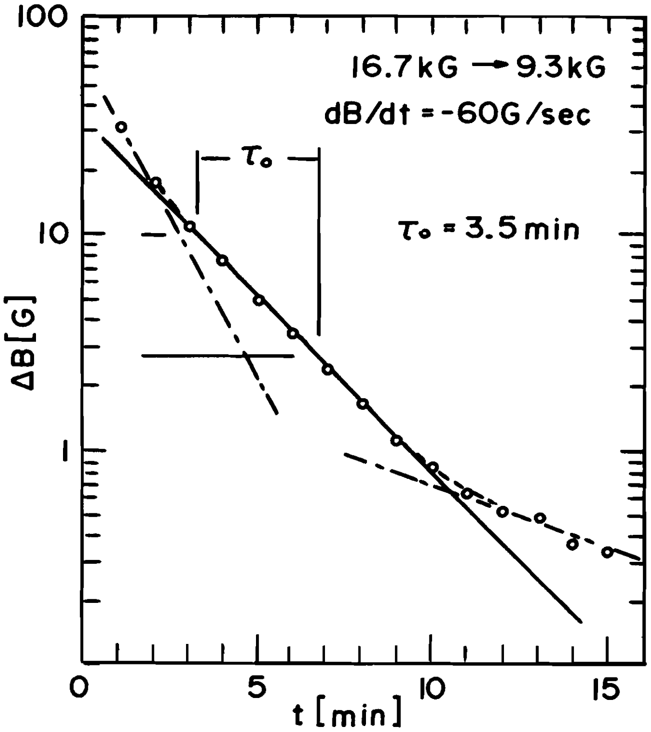

Fig. 5. Slow after-decay of the field in a large magnet measured from the time a large current decrease has been completed.

Figure 5 shows some results obtained with dipole 2 of the Heidelberg Q3D spectrograph.[10] The field was decreased from 16.7 kG to 9.3 kG at the rate of 60G per second. The figure shows the field in the middle of the magnet, as measured with a proton-resonance fluxmeter as a function of the time after the final current was reached. The part of the decay curve between 3 and 10 minutes is approximately exponential with a time constant of 3.5 minutes. Note that the field is within 1% of the final value already at the start of the measurements. What we are seeing here is a perturbation on the field in the airgap resulting from the slow redistribution of the field in the pole pieces.

Halbach[11] has developed an approximate formula for the decay of the eddy current in the pole pieces. Applied to this case for which the pole piece is approximately 70 cm wide, the formula gives a time constant of 3.5 minutes, in good agreement with the measured value.

After the eddy currents have died out, the field penetrates the rest of the pole piece but the prehistories of the various parts are very different, in particular,the skin has been magnetized to saturation and therefore the iron is here polarized (as a permanent magnet) with a polarization roughly corresponding to the coercive force.

In order to study the effect of this polarization, we have used the computer program TRIM[12] to calculate the field in a magnet with a skin polarization simulated by current conductors, as shown in Fig. 6a. The currents increase linearly from the center line at left along the horizontal pole face to simulate the increasing flux carried along the surface. The currents along the chamfered parts are equal. The resulting field distribution, as calculated for the median plane is shown in Fig. 6b. This field, produced by the iron polarization is superimposed (roughly speaking) on the otherwise homogeneous field produced by the current in the main coils. For the example calculated, the perturbation is approximately 3G, which is of the order of magnitude of the observed effect in magnets of this size. In these calculations, the saturated skin thickness was rather arbitrarily taken as being 1 cm. Also, it may have been more realistic to simulate skin saturation also along the back face of the pole pieces against the Purcell gap, as hinted in Fig. 4. However, these calculations are meant as an illustration only, and the absolute value of the field calculated is certainly not reliable. We believe, however, that we have demonstrated that eddy currents in the pole pieces can produce sizable inhomogeneities that persist after these currents have decayed.

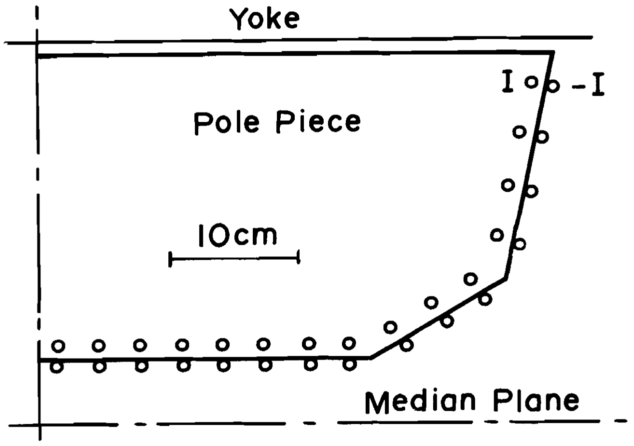

Fig. 6a. A model used for computing the effects of magnetization of the skin of a pole piece. I = 3A in the 7 outermost conductor pairs and increasing from 0.2A to 3A in the 8 conductor pairs along the horizontal surface.

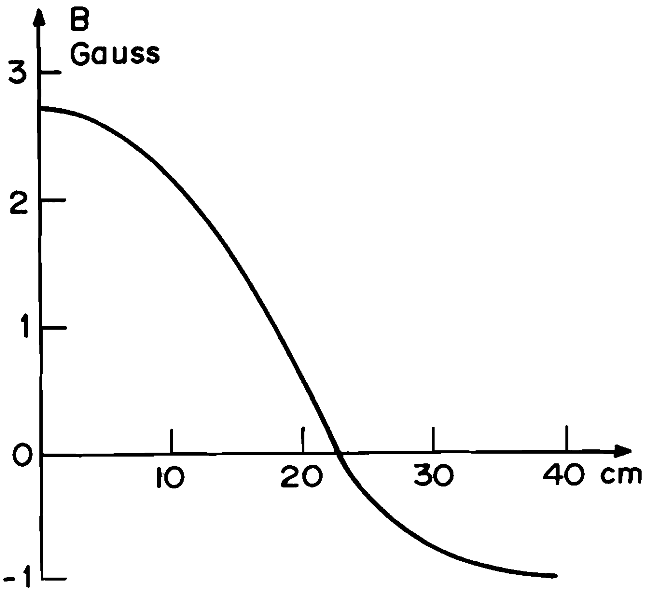

Fig. 6b. Computed field distribution in the median plane.

IV. Remedies

Because the magnetic properties of iron are so nonlinear, it is clear that reproducibility, as we have defined it, can only be obtained by making the pole faces coincide with magnetic equipotential surfaces. This will assure that both the DC effect and the lasting effect of the eddy currents are eliminated.

1. Cycling. The reluctance of the iron is lowest on the upper branch of the hysteresis loop which is traversed when the current is decreasing. Therefore, the DC effects of hysteresis are minimized when a procedure is used by which the iron is brought up to a high magnetization and then decreased towards the value that is desired. A modification of this procedure is used to minimize also the effects of the eddy currents. It was discovered experimentally by Pollock[13] that a more uniform distribution can be obtained if the current is reduced somewhat below the final value (undershoot). Alternatively, Pollock discovered that one could obtain good uniformity by starting from zero current, increasing it to slightly above the final value (overshoot). Halbach discusses the theory of these effects in detail in the work referred to earlier.[11] Experimentally, the effects have been studied on the largest dipole of the Heidelberg Q3D spectrograph.

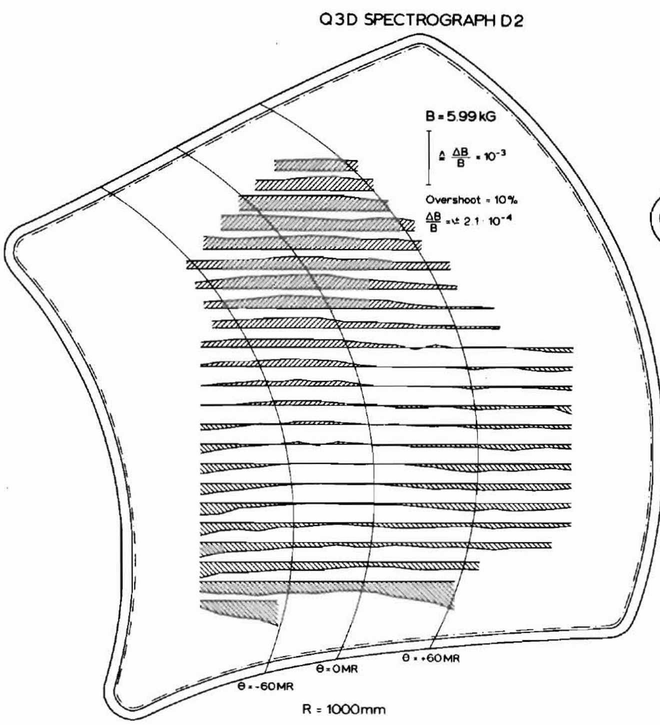

Fig. 7a. Field map of a large magnet at 6 kG with uprate 32 G/sec, overshoot 10%, and downrate 11.7 G/sec.

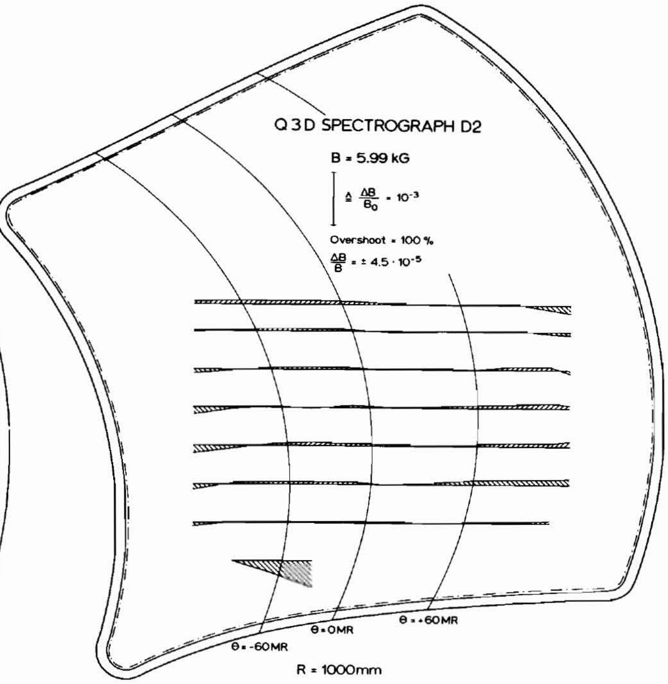

Fig. 7b. Field map of a large magnet at 6 kG with uprate 11.7 G/sec, overshoot 100%, and downrate 11.7 G/sec.

Figure 7 shows two field maps of D2 (dipole 2) taken with two different current cycles, as indicated. The distribution in Fig. 7b is substantially better than Fig. 7a, resulting from a different value of the overshoot.

It was found that the amount of overshoot or undershoot was generally more important than the current increase or decrease rates. This may suggest that a part, maybe the major part, of the inhomogeneities is caused by residual DC effects which will also be reduced by over- and undershoots. However, some differences were found also when only the rates were changed. Table 1 shows some results of field measurements in D1 of the Heidelberg Q3D. The field was measured at three different points, near the edge (B_1) in the middle (B_2), and again near the edge on the opposite side (B_3). Tabulated is a measure of the second-order variation of the field across the pole piece defined in the following way:

$$\frac{\Delta B}{B} = \frac{B_2 - 0.5(B_1 + B_3)}{B_2}$$

The field was quite low for these measurements ($B \approx 1.5$ kG). The current was started from zero and the overshoot and rates were as specified in the table:

Table 1

Measure-Ment	Uprate G/sec	Down-rate G/sec	Over shoot kG	$\Delta B/B \times 10^{-4}$
1	60	40	1.1	2.2
2	60	120	1.1	3.0
3	60	120	2.2	1.7

The measurements have not been corrected for airgap variations. Hence, only the differences between the three measured values of ΔB/B are really meaningful.

Figure 8 gives another example, also from the Q3D spectrograph. It shows the field distribution across dipole 2 in the radial direction. The five curves are for the different overshoots and downrates as indicated

2. High Permeability Materials. For magnets operating in the range 1 to 14,000 G, it is possible to use more exotic materials in the pole pieces. An alloy with approximately 50% nickel and 50% iron (Hiperm 49 or 47-50 material) has a coercive force of approximately a tenth of an oersted, which is only 10% of the value for high-quality magnet steel. Two magnetic spectrographs are presently being made at MIT with pole pieces of Hiperm 49. Because of the high cost of this material, the pole

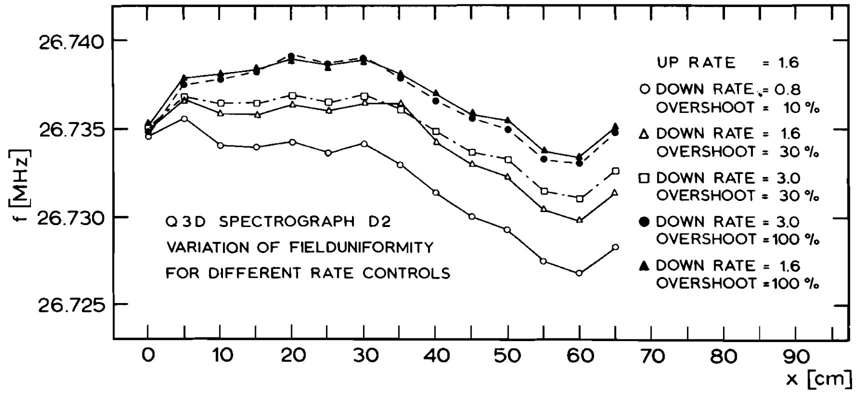

Fig. 8. Effects of varying the current rates and overshoots on dipole 2 in the Heidelberg Q3D

roots are made of high-quality magnetic steel and only a 2" liner separated from the pole root with a 1/8" Purcell gap is made of the high permeability material.

Figure 9 shows schematically the cross section of such a pole piece. The philosophy of this design, in short, is that the second Purcell filter will remove both AC and DC effects existing in the pole roots, and secondly that the coercive force in the pole piece is so low that magnetization of this to saturation will produce much smaller inhomogeneities than if it had been made of iron. There are also extra benefits from the second Purcell gap with regards to the effects of the eddy currents in that it reduces the thickness of the pole piece and therefore the length of the fully magnetized skin. Neither of the two spectrographs has been tested, thus far.

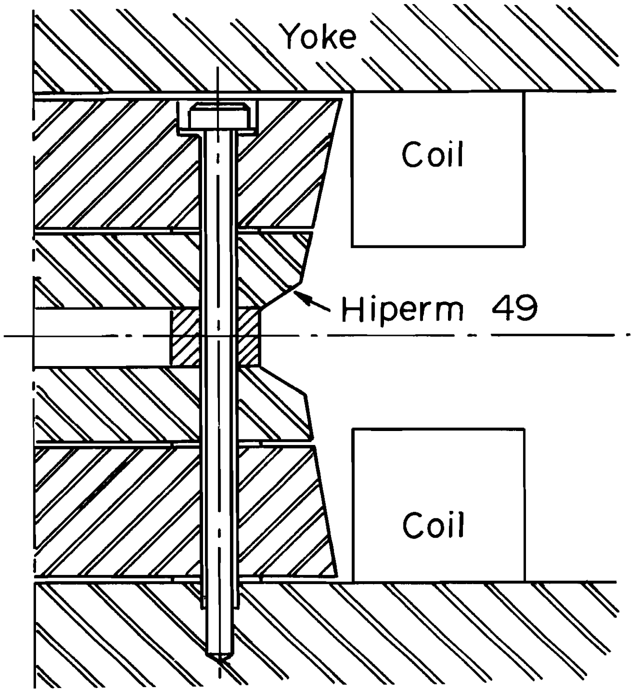

Fig. 9. Cross section of a set of pole pieces utilizing the alloy Hiperm 49 as a pole liner.

3. Surface Windings. It is clearly possible to improve substantially the distribution of the field over the pole area by using a set of strategically placed pole-face windings. This is, of course, a well-known technique in cyclotron work. For the LAMPF high-resolution spectrograph, Halbach^{14} has suggested, instead, windings running parallel with the direction of the particles inside the poles slightly behind the pole surfaces. These windings are called H_T windings, because the product is a tangential component of H on the surface of the pole pieces. One only needs to adjust the weighted field integrals through the magnet along the paths of the particle, and this can be accomplished with these windings if one always follows the same magnetization procedure and once and for all decides by careful mapping of the field what the currents in the various conductors should be at a given excitation.

4. Laminations. Laminations parallel to the direction of the field have been considered but deemed impractical or too expensive, in particular for magnets that have entrance and exit boundaries with higher order curvatures. It is anticipated that the nonuniformity of the insulation between the laminations may cause problems. To our knowledge, no dipole magnet has been laminated for the purpose of eliminating the lasting effects of eddy currents in the poles.

Laminations perpendicular to the direction of the field could be considered. A step in this direction has been taken on the MIT magnets, discussed under Section 2 above. Even with multiple laminations, the eddy currents are not reduced, but Purcell-type filtering by the small airgaps between the various segments of the pole pieces will prevent the polarization in the back part of the pole piece to affect appreciably the field in the main gap.

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