BROOKHAVEN NATIONAL LABORATORY

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MEMORANDUM

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Task Force: Coil Geometry Analysis

Title: Common Coil Design for High Field Magnets

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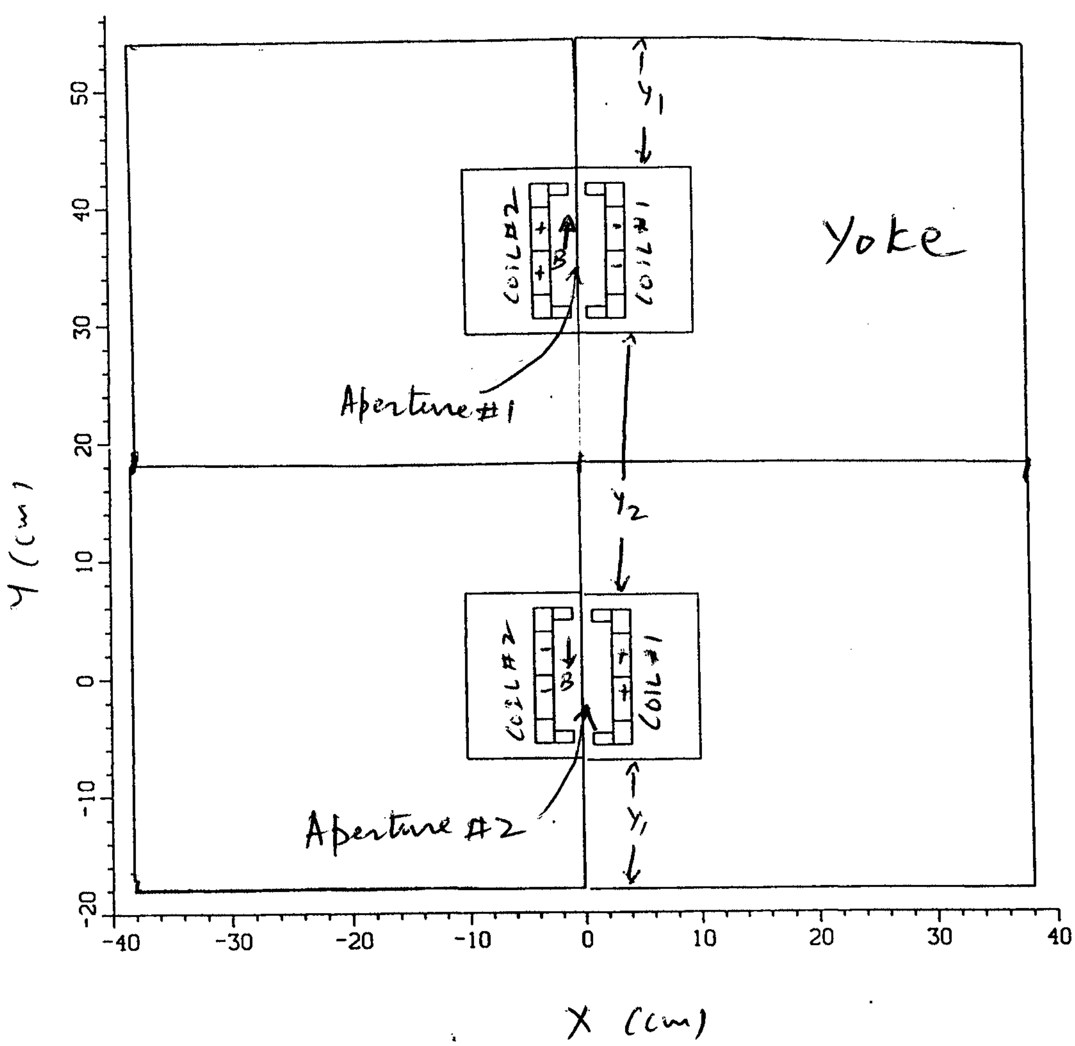
Common Coil Design for High Field Magnets

A common coil design for high field magnets is investigated here. The design concept is suitable for magnets with two or more apertures. The two aperture would be in the same vertical plane. The coil would consists of rectangular blocks stacked-up vertically with one half of the coil going from one aperture to another aperture. In this method the coils would be coplanar (truly pancake) and the ends would be simpler to wind. The cable would experience practically no strain in the concerned direction which is an important consideration. A possible scenario of supporting coil structure and magnet assembly is given. This geometry is also preferred from Lorentz forces reasons which is another important consideration in the design of high field magnets. The magnet geometry has inherent top-bottom asymmetry. It is shown how the saturation induced skew harmonics in the body and how the geometric skew harmonics in the ends can be minimized.

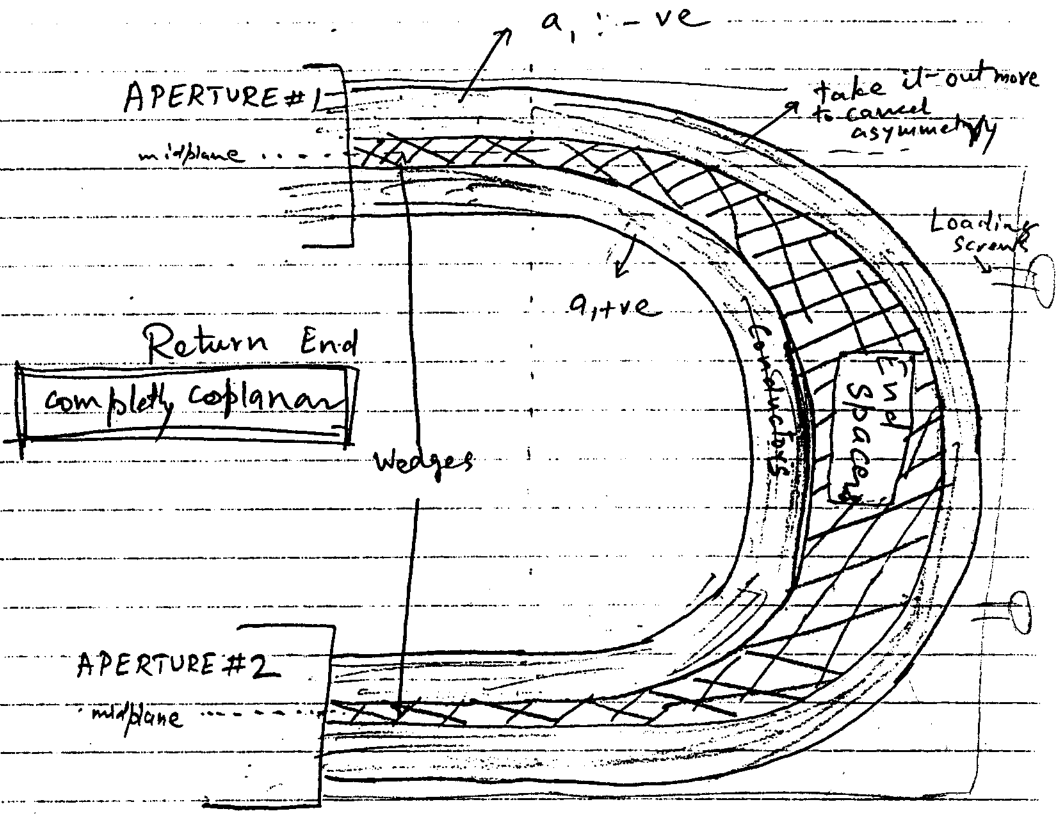
The conceptual design is shown below in Fig. 1.



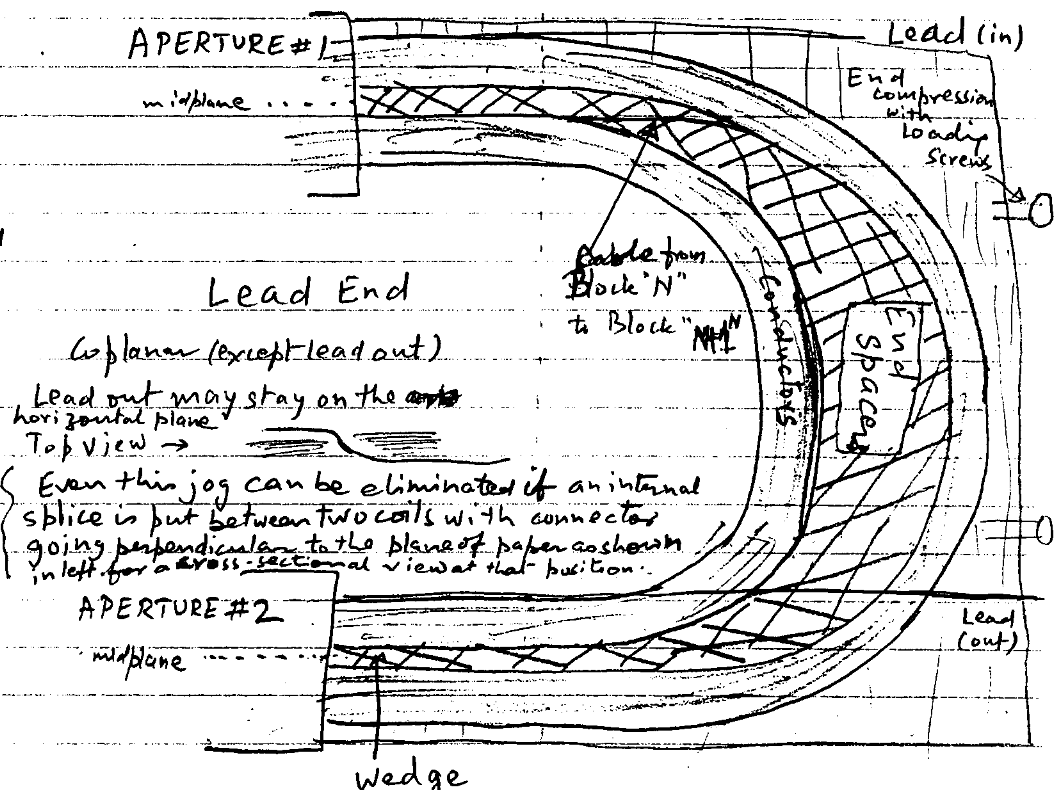
Ends

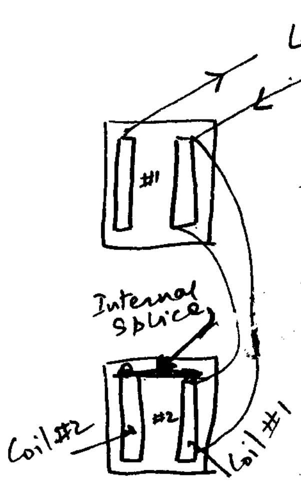
The major advantage of this approach is in the ends which are one of the most critical items in the design.

- These ends are simpler to wind. In cosine theta and in most pancake coil dipole geometry, the conductor at the midplane must come up and bend. This puts strain on the cable which could causes problems.
- In contrast to the above, practically no strain would be put on the conductor when they are stacked up since they are not bent in the critical direction. The coils in the ends (and as well as in the body of the magnet) are coplanar. The only exception where the conductor must be bent in the difficult direction is one of the two lead. But that could be done gradually and even there the conductor can be kept in the same horizontal plane. Even this jog can be eliminated if an internal splice is put between the two coils with connector going perpendicular to the plane of paper as shown in Fig. 2 (see figure on left side for the cross-section view of the internal splice area).
- To align the conductors parallel to the field, one may like to stack them sideways. Even in that case, only a small strain is put in the ends because the bend radius in going from one aperture to another aperture could be much larger than bending conductors within the same aperture.
- The conductor in the ends is fully supported/constrained by a simple geometry. Beyond simplicity, it may also assure a good performance.
- As usual, the end spacers would minimize the peak fields in the ends. These spacers could be extensions of the wedges in the magnet cross section (though the thickness in general would change). In additional to those originating from the wedges there could be additional end spacers, as done in the most present designs. The peak field can be further reduced by using reverse field coils (as suggested by McIntire), but that may not be necessary.
- The end spacers would also minimize the field harmonics. In addition to minimizing the normal harmonics they would also be used to remove the skew harmonics generated by the inherent top-bottom asymmetry with respect to the midplane of the aperture in the end region of the design. As shown, in Fig 2, the conductors at the top of the top aperture (or bottom of the bottom aperture) can be carried further out to perform this optimization. The reverse field coils, if used, can further aid in this process. Moreover, the top-bottom asymmetry in the ends can easily be compensated by an opposite top-bottom asymmetry in the body of the magnet.



ONLY for Schematic (In reality several wedges and endspacers & No wedge at the midplane. Wedges to optimize body harmonics. ~~and~~ End spacers for peak field and normal & skew harmonics)





Schematic only

Fig. 2. Ends showing how coil goes from one aperture to another.

Magnet Cross-section

(a) Mechanical Design Considerations:

Fig. 3(a) and Fig. 3(b) show the field lines in (a) case of cosine theta design and (b) in case of block design. Since the Lorentz forces are perpendicular to the field lines, Fig 3(a) reflects a large accumulation of the azimuthal component of the Lorentz forces towards the conductors on the midplane in the conventional cosine theta design. However, in the case of block design (see Fig. 3(b)), the vertical component (equivalent to the azimuthal component in cosine theta magnets) of the Lorentz force is relatively small. This is the reason why several magnet designers have preferred block design over cosine theta designs for high field magnets. The built-up of the vertical/azimuthal component of the Lorentz force can be further reduced following the approach discussed by Willen where the azimuthal forces are transferred to the collar. As shown in Fig. 4, that could be simply adopted here by having wedges larger than the conductor and then resting in the cutouts in the collar. A smaller vertical/azimuthal component means that a large pre-compression on the coil is not necessary to counter the Lorentz forces.

The horizontal component (equivalent to radial component in cosine theta magnets) must be transferred outward to the structure of the magnet. It may not be necessary that the full amount of the Lorentz force is to be taken by the collar only. One may allow a part to be transferred to the yoke structure and to the shell of the magnet. A vertical gap between the collar and yoke present at low field due to cool down and normal mechanical clearances would close as the Lorentz force deflect the collars to the yoke. From then on, the complete coldmass at the midplane could be considered as a single composite entity. In a vertically split yoke design, this gap could be further minimized by pushing the two yoke halves horizontally until they make contact to the coil. In the later case a small vertical gap could be left on the vertical axis of the two apertures.

In any case a larger thickness of the collar in horizontal plane does not offer a penalty on transfer function as the transfer function is primarily determined by the vertical yoke gap.

In the design shown here, the yoke inner and outer surface are shown to have rectangular surface. As a variations to this design, one could consider circular or elliptical surfaces. Though the basic principle remains the same, the efficiency of the design and the overall magnet optimization would be considered in determining the preferred shape. For a crude comparison purpose, the block designs use of the order of 30-60% more conductor than the cosine theta magnets.

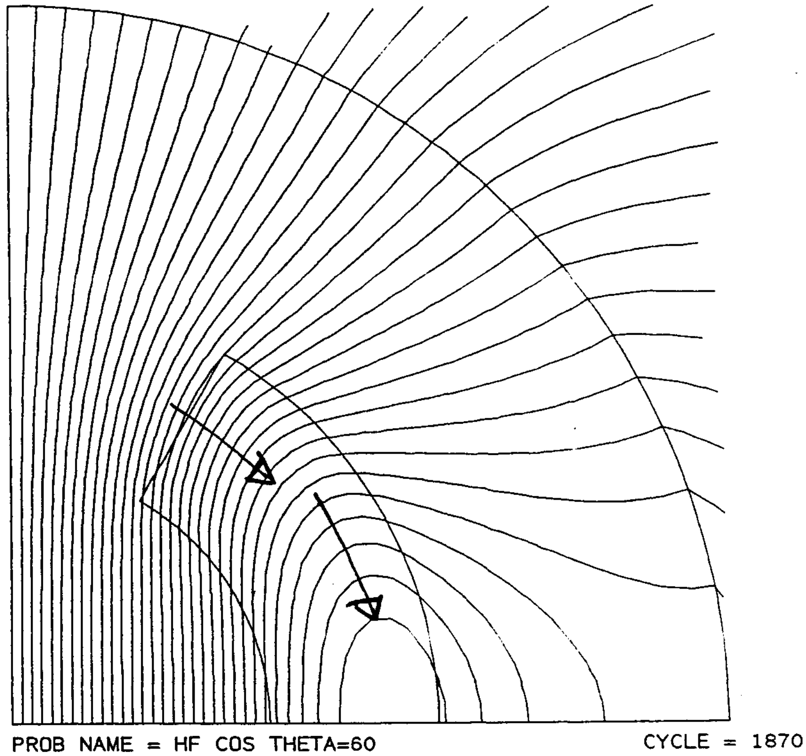


Fig 3(a) Field lines and Lorentz forces in conventional Cosine theta magnets. A large azimuthal component of the Lorentz force can be seen.

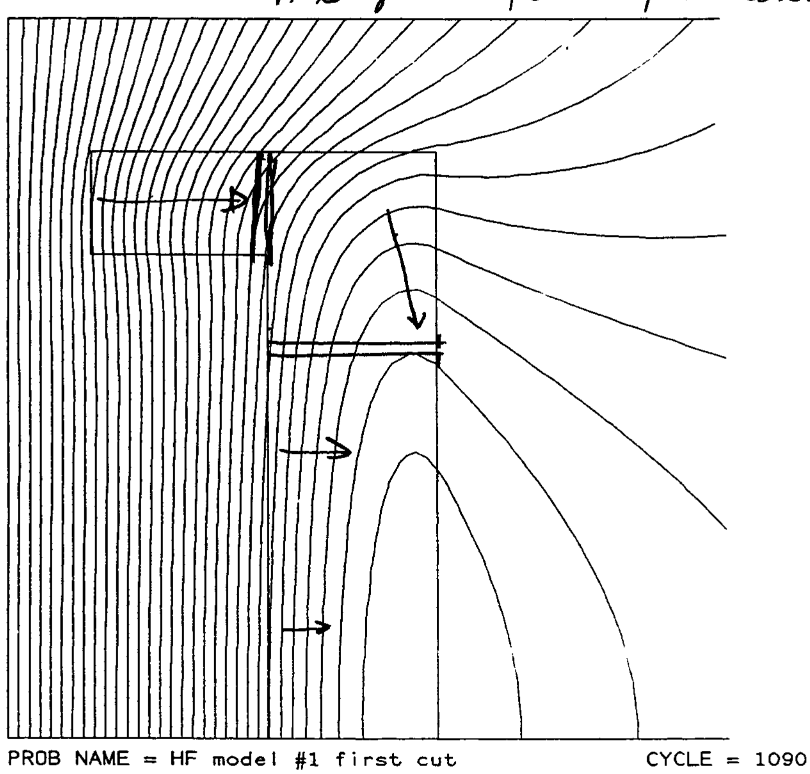


Fig 3(b) Field lines and Lorentz forces in block design. The Azimuthal / vertical component of the Lorentz force is smaller than in Fig 3(a).

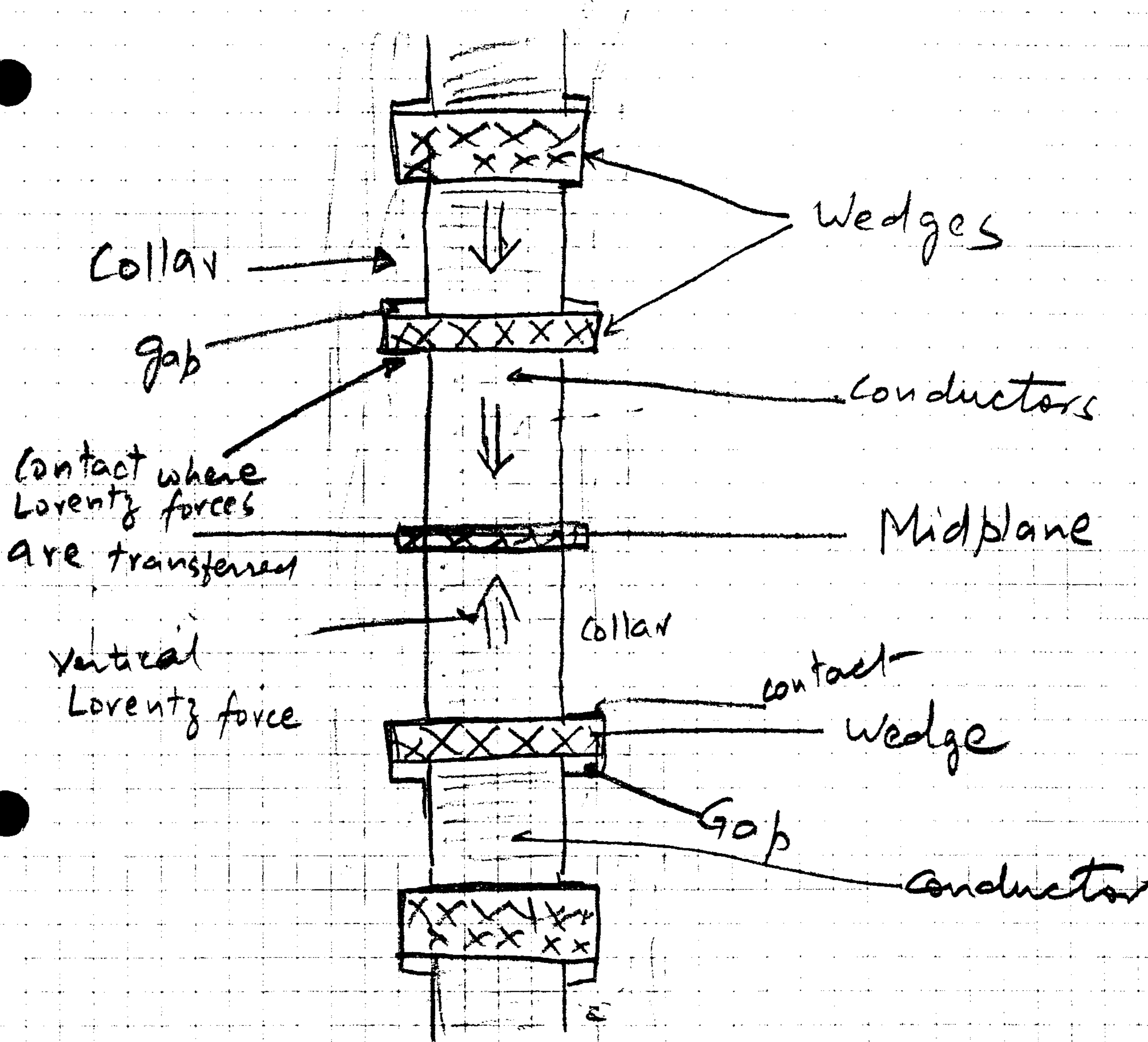


Fig 4 A schematic representation of how a vertical component of the Lorentz force is transferred from coil to collar at intermediate places. This, as suggested by Wilken, would avoid built-up of Lorentz forces on the conductors.

(b) Magnetic Design Considerations:

The coil cross section is optimized by the layout of the layers and by the size of wedges in each layer. The wedges do not necessarily have to be rectangular as chosen here. The present coil optimization program PAR2DOPT, which optimizes a circular coil in circular iron aperture, is being modified to deal with rectangular coil and iron geometry. The preliminary coil optimization performed for this study has been carried out with the code POISSON. From this limited experience it is concluded that it is possible to design a coil cross section with an acceptable field quality. A number of previous publications by several other authors have presented a number of such coil cross sections where the field harmonics are low.

The yoke optimization requires not only minimizing the saturation induced normal allowed harmonics but also a minimization of skew harmonics generated due to a cross-talk between two vertical apertures. No cross-talk induced harmonics will be observed if a sufficient amount of iron is present between the two apertures. It may be pointed out that the iron requirement to contain the flux lines in the vertical dimension are much smaller than that in the horizontal dimension. The separation between the two apertures and hence the weight/volume of the coldmass can be further reduced by optimizing the height y1 and y2 (see Fig. 1) and by controlling the flux lines and iron saturation by introducing the holes and cutouts at the strategic places. The POISSON calculations based on this optimization strategy show that the current dependence in the skew harmonics can be kept under control.

Magnet Construction and Assembly

As mentioned earlier, the coil geometry of this design is rather simple both in the body of the magnet and in the ends of the magnet. This should translate in to a simplified and relatively less expensive tooling for winding and curing the coils. For the straight section part, one could probably stack up conductors under tension on a flat surface. In the end regions the conductors would follow an elliptical-type surface with no tilt in it. The ends will be automatically constant perimeter ends with no strain on the conductors if they are stacked vertically and the deviation would be rather small if they are stacked horizontally. In both cases each block of conductors could follow some kind of channel to define the shape during winding and curing of the coils.

The collars on the two sides of the coil will not be directly connected to each other. The advantages and disadvantages of the two coils in the same aperture having a common collar or two collars separated/connected by a well defined structure can be examined.

The collars may be made of either stainless steel or aluminum. As mentioned earlier, the amount of required vertical compression in this design is smaller than that is required in conventional cosine theta design.

The yoke could either be horizontally split or vertically split. In the vertically split case the coldmass would have only two yoke halves. In the horizontally split case one would need yoke consisting of three parts, however, the top and bottom parts may have a similar geometry.

The end support/structure is schematically shown in Fig 2. As mentioned earlier, the coil ends will be well defined and well supported by a simple geometry. Because of this reason the mechanical design and behavior of the ends under high Lorentz forces can probably be made as good as that of the straight section by utilizing the similar design concepts.

For testing purpose, one could imagine a much simpler setup in which a flat coil is wound with only some end spacers. In this case the pre-compression may alternatively be provided by a series of bolts.

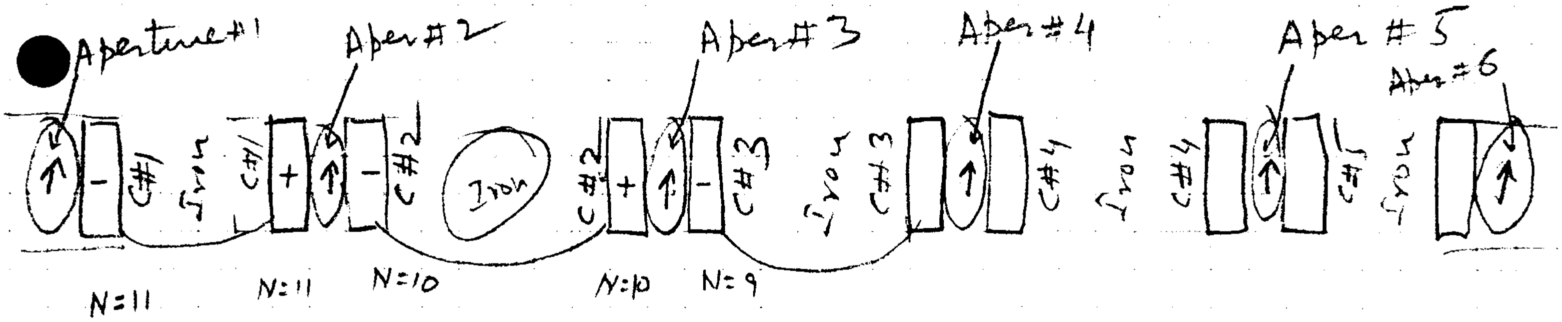
Multi-aperture Magnets

In multi-aperture magnets, such as those required in muon accelerator system, the coil structure described earlier can not be directly used. The magnet system requires (a) the field to be in the same direction in each aperture and (b) the magnitude of the field to be different in different aperture of the magnets. However, in principle, the above concept can be used by laying the coils in the horizontal plane instead of vertical plane as shown in Fig. 5(a) and Fig. 5(b). This assures that the direction of field is the same in each aperture and also the bend radius of the coils in the ends is large as compared to that in the conventional cosine theta magnets. The magnet system in the most simplest case leaves the two extreme ends of the coils unmatched (i.e. left side of extreme left end aperture and right side of the extreme right end aperture) which must be shielded inside the extended yoke. The unmatched halves of the coils can, however, be used to generate field which is about half in magnitude (since the effective number of ampere-turn is half) as that of the aperture containing the other half of the coil. In this case the aperture would contain coil only on one side and in the low field case where the iron pole surface determines the field quality, the design could be easily optimized. The two schemes shown in the figures 5(a) and 5(b) differ in the way the change in field intensities in different aperture is handled. The two options are briefly described below.

In the case of Fig. 5(a), it is assumed that the magnets are designed so that they have a quadrupole component. Thus the focusing in one plane is entirely provided by these combined function lattice dipole. The focusing in other plane can be obtained by the usual quadrupoles in the lattice. The coil optimization may require that the two sides of these coils have two different geometry. This should not be a problem since the two sides can be wound in an independent configurations as long as they are properly matched in the ends. Since the ends are long, the blending of the two sides could be carried out smoothly.

In the case of Fig. 5(b), all apertures would primarily have a dipole field component only. Two sides of the coils would have a different number of ampere-turns in the aperture, with a part returned through the yoke between the two magnet aperture. The design of the magnet would include the field generated by this section of the conductor.

The above description is given here only to demonstrate that the basic principle can be adopted to these type of requirements. However, it is not clear if the concept offers any advantage over the conventional designs based on a single coil in each magnet aperture.



Note: N is number of turns in the coil (for illustration purpose)

Fig 5 (a): A possible combination of coils for producing field in the same direction with a decreasing strength in consecutive aperture. In addition to the dipole field each aperture will have a quadrupole field.

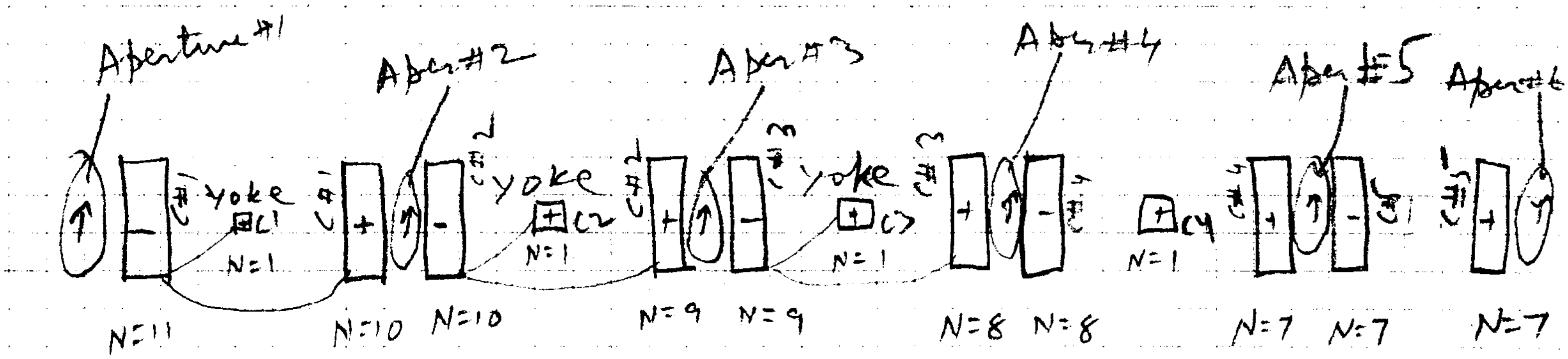


Fig 5 (b) Another possible combination of coils for producing field in the same direction with a decreasing strength in consecutive aperture. It would produce only dipole field since two coils in the aperture have a same number of turns. In this case part of the conductors must be returned elsewhere.

Conclusions

A conceptual design for high field magnets has been presented here. The common coil design concept offers several advantage over the conventional cosine theta designs. The ends are simpler to wind and put practically no strain on the conductors. However, even in the case when the conductors (or a part of them) are aligned in the direction parallel to the field, only a small amount of strain is put on the conductors because of the larger bend radius between two apertures. The block cross section design has a lower built up of vertical Lorentz forces as compared to the azimuthal Lorentz forces in the conventional cosine theta designs. The inherent up-down geometrical asymmetry in the ends and saturation in the body may be minimized by the methods presented.

The design concept, though discussed here mainly for high field magnets, may be considered as an alternate to normal cosine theta designs for medium field magnets in some special applications.