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Optimum Integral Design for Maximizing the Field in Short Magnets

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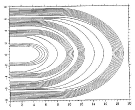
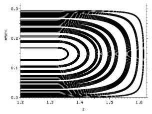
Abstract- An Optimum Integral Design is introduced for cosine(nθ) coils where the entire end-to-end length of the coil generates field with the dilution from ends practically eliminated. The benefits of such a design are particularly significant in short magnets where the overall coil length is comparable to or a few times the coil diameter. The integral field strength is further enhanced as the design allows a larger number of turns than in typical magnet coils. In this concept, the ends and body harmonics are optimized together to create an integral cosine(nθ) azimuthal current distribution. The concept was initially developed for wire/cable wound magnets where the bend radius of turns in the ends can be small. However, the benefit of this general approach can be applied to cable magnets as well. The magnetic design of a corrector dipole for the AGS helical magnet, which was recently built and tested, will be presented as one of several examples. The other examples include a few sub-compact designs: a dipole with coil length less than a coil diameter, a quadrupole with coil length less than a coil radius, etc. Apart from generating a large integral field for the given length, the computed integral field harmonics in these designs are less than one part in 10,000 at 2/3 of the coil radius.

Introduction

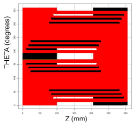
In short-length conductor dominated magnets, where the mechanical length of the coil is comparable to or a few times the coil diameter (aperture), the ends determine the magnetic design and the length of the magnet itself. In conventional conductor-dominated dipole magnets, loss in the effective magnetic length over the end-to-end coil length is generally of the order of a coil diameter in dipoles, a coil radius in quadrupoles, etc. The physical space taken by the turns in the end itself is of the order of a diameter in typical dipoles and of the order of a radius in typical quadrupoles. Thus, in very short dipoles one would have to significantly reduce the number of turns in the cross-section and hence the integral field that can be achieved. This limits how short a magnet can practically be while generating a sufficient integral field and low field harmonics.



Conventional Design. RHIC Dipole (Kahn, Morgan, et al.)



Design with Stream Function. P. Walstrom, LANL.



Serpentine Design. B. Parker, BNL.

All of these design loose integral field due to ends.

The loss becomes significant in short magnets.

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Optimum Integral Design

In a typical conductor dominated design, first the coil cross section is initially optimized for the (2n) multipole to create a *cosine (nθ)* type azimuthal current distribution:

$$I(\theta) = I_o \,.\, \cos(n\theta)$$

The ends are then optimized to minimize the integral end harmonics and to reduce the peak field on the conductor surface. This 2-step optimization creates a magnet with low integral harmonics but, unfortunately, also one that has a magnetic length that is smaller than the coil length, typically by a coil diameter/(*n*).

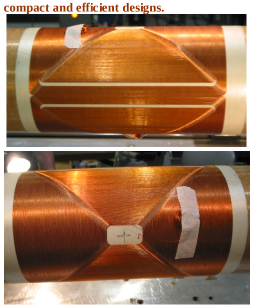
In the proposed *Optimum Integral Design*, the length of the midplane turn is the same as the coil mechanical length (end-to-end) with bend radius of turns in the ends approaching zero. If there are no spacers in the ends or in the straight section, and if all turns are equally spaced, then the length of successive turns decreases linearly in going from midplane to pole. One way to obtain an ideal current distribution (in integral sense) is to modulate the length of each turn so that it is proportion to *cosine (nθ)*. In a more practical approach, the integral modulation will be obtained with the help of a computer program after distributing a total of "*N*" turns in a few end blocks and/or in a few cross-section blocks. The size of spacers between the blocks will be optimized to achieve an integral distribution varying azimuthally as:

$$I(\theta) \,.\, L(\theta) = I_o \,.\, L_i(\theta) \propto I_o \,.\, L_o \,.\, \cos(n\theta)$$

Since the cosine theta modulation is normalized to the current I_o and the length L_o (end-to-end coil length), this equation suggests that the integral field of the magnet may be closer to typical 2-d field times the mechanical length of the coil (L_o). This is a significant improvement from the designs discussed in the previous section where the loss in effective magnetic length from L_o was about a coil diameter/(*n*).

AGS Helical Corrector Dipole

The first example is for the AGS helical corrector dipole, which has been fully optimized, built and tested. Other coil designs are given here for illustration purpose only and are not fully optimized. They are meant to show that the concept can generate very compact and efficient designs.

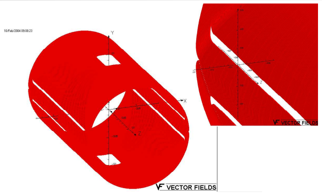


AGS corrector dipole coil built on the Optimum Integral Design. Note that the midplane turns span almost the full end-to-end coil length and the coil has a high fill factor.

Two such corrector magnets have been built and tested for quench and field harmonics. The quench current test was limited by the power supply (45 A) and was 80% over the design current of 25 A. The measured harmonics agreed with the computed harmonics within measurement errors.

TABLE I
COMPUTED INTEGRAL FIELD HARMONICS IN THE AGS CORRECTOR DIPOLE DESIGN AT A REFERENCE RADIUS OF 60 MM. THE COIL RADIUS IS 90.8 MM. NOTE b_2 IS SEXTUPOLE MUTLIPLIED BY 10^4 (US CONVENTIONS).

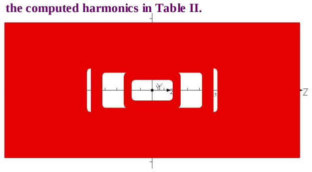
Integral Field (T.m)	b_2	b_4	b_6	b_8	b_{10}	b_{12}
0.0082 @ 25 A	0.4	0.8	-4.7	4.1	5.3	2.4



OPERA3d model of the AGS corrector dipole based on the Optimum Integral Design.

A Dipole Optimized with End Spacers Only

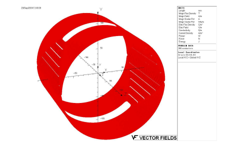
We present a 2-layer dipole whose integral harmonics are optimized with end spacers only, i.e. the cross-section does not have any spacers (or wedges). The dipole has an aperture of ~224 mm and a length of 500 mm (about twice the average coil diameter). The design has 250 turns in the inner layer (with end turn configuration of 200, 30 and 20) and 220 turns in the outer layer. There is no spacer in the outer layer. The pole angle is 80.9 degree for the inner layer and 70.7 degree for the outer layer. The configuration is chosen for its lower peak field. An OPERA-3d model of the design is shown in Fig. 5 and the computed harmonics in Table II.



OPERA-3d model of a 2-layer coil (seen from the top/pole) based on the Optimum Integral Design. It has no spacers (wedges) in the cross-section and has only two each in the either end of the inner layer.

Dipole with Coil Length Less Than Coil Dia

When the coil length is less than half the circumference of a dipole coil, the coil length limits the fill factor in the cross-section. In addition, a space must be left a splice. This gives a maximum fill factor of ~61%. We used empty space in the cross-section to demonstrate that six small spacers (wedges) in the cross-section can make the first six allowed harmonics nearly zero.



OPERA3d model of a short length dipole based on the Optimum Integral Design. Coil length is ~175 mm and coil diameter is 200 mm.

TABLE III
COMPUTED INTEGRAL FIELD HARMONICS FOR A SHORT DIPOLE (COIL LENGTH < DIAMETER) AT A RADIUS OF 66.6 MM. THE COIL RADIUS IS 100 MM. NOTE b_2 IS SEXTUPOLE MUTLIPLIED BY 10^4 (US CONVENTIONS).

Integral Field (T.m)	b_2	b_4	b_6	b_8	b_{10}	b_{12}
0.00273 @ 25 A	0.0	0.0	0.0	0.0	0.0	0.0

Quad with Coil Length Less Than Coil Radius

In a quadrupole, the coil length limits the fill factor in the cross-section when it becomes less than one-fourth of the circumference. We used six spacers (wedges) in the cross-section to make the first six allowed harmonics nearly zero. Once again, a large integral transfer function is obtained since the midplane turns span the entire end-to-end coil length. The design has a coil diameter of 200 mm and coil length of 90 mm (less than half the radius).

Sextupole with Coil Length 2/3 Coil Radius

We carried out a similar exercise for a 200 mm aperture sextupole having an end-to-end coil length of 66 mm. This is ~1/3 of diameter. We were again able to get a design with low harmonics and a good integral transfer function.

Approach in Long Magnets
Built with Rutherford Cable

In long accelerator magnets, the *Optimum Magnet Design* approach cannot be applied in a manner used in previous sections. However, the general approach and philosophy of *Optimum Integral Design* will reduce the loss in integral field due to ends. In the conventional ends, the bend radius is smallest for the pole turns and largest for the midplane turns. In an approach based on the *Optimum Integral Design*, the turns near the midplane will have as small a bend radius as the turns near the pole and the midplane turns will be longer.

Conclusions

The proposed *Optimum Integral Design* concept offers a solution that allows magnets with large integral field and low integral harmonics to be built in a short length. This practically eliminates the loss in integral field due to ends. The design opens a new window for building very short magnets. Proof of principle examples of a dipole with length shorter than coil diameter, a quadrupole with length shorter than coil radius and sextupole with length shorter than one third of coil diameter have been presented.

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