A Very Preliminary Look at LUMPED SEXTUPOLE CORRECTORS FOR RING DIPOLES

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BASIC CONSIDERATIONS

In order to keep the current small, single strand conductor (as opposed to cable) is appropriate. For an effective length of 120 mm, and conservatively designed conductor, a coil thickness of about 5 mm is required.

WINDING TECHNIQUES

There are several winding techniques to choose from:

1 Random wound.

2 Layer wound, layers lie on essentially radial surfaces.

3 Layer wound, layers lie on cylindrical or tangent surfaces.

Random-winding is a job for high-speed semi-automatic machines; layer winding is a job for skilled craftsmen.Over the past 35 years, perhaps 100 million random-wound dipole magnets (TV deflection yokes) have been made. They are of about the size of the sextupoles, and the production cost can't be more than a buck or two. So from the cost point-of-view, random-winding seems like the way to go. But there are other factors:

Field quality of random-wound coils might not be good enough. That could be determined by making a few coils and testing them, or testing available commercially made coils. I doubt if the field quality could be bad enough to tip the scale toward the layer-wound method. The field quality could be improved by simply increasing the inside radius; cost would be greater, of course.

Space factor for random-wound coils is not as high as for layer-wound coils, so the coils would have to be thicker. But the coil thickness is not a problem.

Superconducting random-wound dipole magnets were made at LBL in the early seventies and by John Purcell at ANL a few years later. (Purcell might have made quads also.) I am told that there are some random-wound magnets at FNAL too.

CROSS-SECTION CONFIGURATIONS

There are several cross-section configurations that could conceivably be used:

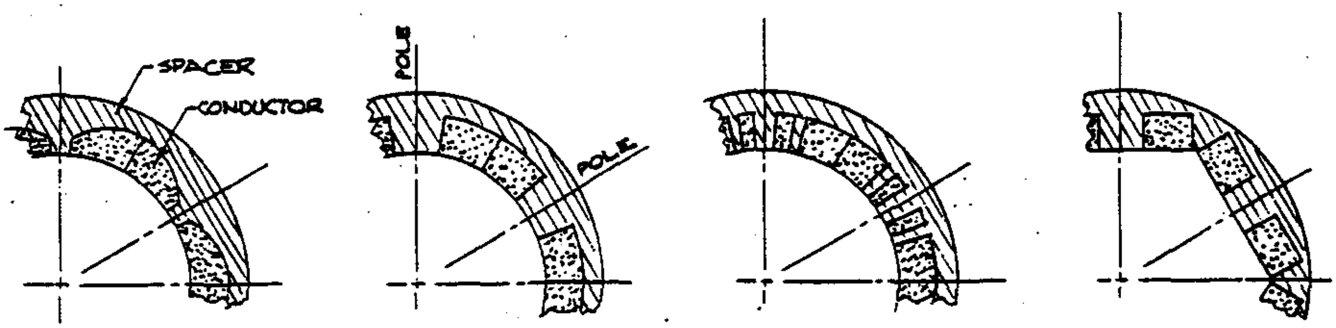
1 Cylindrical inside surface, thickness approximately proportional to cosine 3 theta.

2 20-deg. cylindrical sector.

3 Cosine 3-theta current distribution.

4 Flat coils.

These are illustrated below.



THICKNESS ≈ COS 3θ   20° SECTOR   CURRENT ≈ COS 3θ   FLAT COIL

The choice of cross section depends on manufacturing cost and field quality. The present distributed sextupole coils use the 20-degree sector configurations. The field quality of all the above configurations is at least as good as that. Furthermore, the inside radius of the lumped corrector is greater than that of the distributed corrector, which further increases the field quality in the aperture.

The "cos 3 theta current distribution" configuration is simply the "20-degree sector" configuration with a spacer added. Adding the spacer would certainly increase the cost. The field quality would be better, but who needs it?

The flat-coil configuration appears to be the simplest of the bunch, but the difference might be small or non-existent. On the negative side, the overall diameter is greater for a given thickness, and the field quality is not as great (still sufficient, probably -- I can look into that but haven't).

The "cos 3-theta thickness" configuration has a little better field quality than the "20-degree sector" configuration, has a thinner, hence more fragile, pole island, and may or may not be more expensive to manufacture. Winding the conductor into a tapered slot might be easier than winding into a slot of uniform width.

END CONFIGURATIONS

The ends could be either racetrack-type (lying on the cylindrical surface) or the turned-type (bedstead or saddle). The field aberrations produced by the turned-up ends are smaller, and the turned-up ends are also shorter.

For the sextupole correctors, the end-field aberrations are unimportant; all that counts is the integral field. The proposed effective length of 120 mm is great enough for the end field aberrations to be canceled by a small change in the parameters of the straight section.

For the racetrack ends, the length of the two ends is only about 15 mm; about half of that could be saved by turning up the ends; the same length decrease could be affected by increasing the coil thickness about 6%, or 0.4 mm.

So neither the length-saving nor the field-quality arguments seem sufficient to justify the more elaborate turned-up end shape. However since the industry is used to making TV deflection yokes and motor field windings with such ends, perhaps they would cost no more than racetrack ends.

SPACERS

I suggest closed-die compression-molded fiber-reinforced plastic pieces that are integral with the windings. Billions of parts are made by injection molding reinforced thermoplastics. I'm not sure that the required high glass content for strength and low expansion can be obtained in an injection-molded part, therefore I suggest compression molding. We (LBL) tried molding chopped glass in epoxy some time back, with a high glass/resin ratio; it doesn't flow like hot nylon, and the cure-time is a pain, but something like that might be necessary to get the required properties. I think we could lean on industry for a lot of help on such practical matters.

YOKE

The yoke increases the sextupole field (by 40% for the case illustrated), and increases the higher-order multipoles by a smaller amount, so it decreases the relative systematic errors, all of which are higher order than sextupole, and the higher-order random errors. However it increases the subharmonic multipoles, which can be generated by random errors.

If the yoke can be used as the structural clamp, and doesn't impair the field quality too much, then the use of the yoke makes sense. If not, it adds to the cost, and it would probably be cheaper to simply make the coil thicker.

I have suggested that the yoke be an iron-wire wrapping. I built a magnet that way once.

WHERE DO WE GO FROM HERE?

I think it would be dumb to make a firm selection of a configuration at this time; there are too many open questions. I suggest we make a tentative selection, and build and test a few coils in order to answer some of those questions. Since the field is low, some testing could be done using a monopole coil with iron reflectors. (I don't think one can measure field aberrations that way, however.) We should, of course, talk to manufacturers early on.

There are many important engineering details to be worked out: assembling the magnet, mounting it firmly and aligning it, getting the leads out, etc. None seems overwhelming. The biggest problem I see is getting all of the windings to have the same azimuthal dimension, so that when they are clamped up the poles come out at the right places.

CONCLUSIONS

There is nothing about the development of the lumped sextupole corrector that seems so esoteric or difficult as to prevent it from being accomplished in short order.

LUMPED SEXTUPOLE CORRECTOR

Magnetic Field Requirement:

± 2 units of $\int B\,dz$ at 10 mm radius

Mag. length of dipole magnet = 16.6 m
Mag. field " " " 6.6 T
Required sextupole
$\pm 2 \times 10^{-4} \times 16.6 \times 6.6 = 0.0219$ T-m at 10 mm rad.

Sextupole $\int B dz$ at r = 10 mm	0.0219 T-m	
Effective length	120 mm	(4.72 in.)
Field at r = 10 mm		
= .0219/.120	0.1825 T	
Coil mean radius	25 mm	(0.984 in.)
Field corresponding to coil mean rad		
$(25/10)^2 \times .1825$	1.141 T	
Max. field at conductor (est)	1.2 T	

Wire diam., bare	0.254 mm	(0.010 in.)
Insulation thickness	0.038 mm	(0.0015 in.)
Wire diam., insulated	0.330 mm	(0.013 in.)
Coil cross section per turn		
$.33^2$	0.1089 mm^2	
Copper-to-superconductor ratio	3.0	
S.C. cross section		
$\frac{1}{3.0+1} \times \frac{\pi}{4} \times .254^2$	0.01267 mm^2	
Specified j_c at 5T, 4.2K	2750 A/mm^2	
Expected j_c at 1.2T, 4.5K		
(Per Morgan's formula)	6285 A/mm^2	
Short-sample current		
6285 × .01267	79.6 A	
Design factor of safety ≈ 2		
Design current	40 A	
Design current density, overall		
40 / .1089	367.3 A/mm^2	

For thin true-cos 3θ coil w/o iron, current per pole is

$$I_{POLE} = \frac{2}{\mu_0} \frac{Ba}{3}$$

where B is field at coil radius a

$$I_{POLE} = \frac{2}{4\pi 10^{-7}} \cdot \frac{1.141 \times .025}{3} = 15130 \text{ A-turns}$$

Lineal current density at midplane

$$J_\ell = \frac{3 \times I_{POLE}}{a} = \frac{3 \times 15130}{25} = 1816 \text{ A/mm}$$

Coil thickness

$$h = \frac{1816 \text{ A/mm}}{367.3 \text{ A/mm}^2} = 4.944 \text{ mm}$$

Turns per pole = 15130 A / 40 A/turn = 378

Check:

Coil area per semi-pole

$$= \frac{1}{12} \times 2\pi r \times h \times \frac{2}{\pi}$$

← for cos θ winding

$$= \frac{1}{12} \times 2\pi 25 \times 4.944 \times \frac{2}{\pi} = 41.2$$

$$\text{Turns per pole} = \frac{41.2}{.1089} = 378$$

Iron considerations

Iron inside radius, say 29 mm

Iron enhancement factor

$$= 1 + \left(\frac{25}{29}\right)^6 = 1.41$$

Field at iron

$$1.141 \frac{\left(\frac{25}{29}\right)^4}{1 + \left(\frac{25}{29}\right)^6} = 0.447 \text{ T}$$

Flux in iron = $.447 \times 29 \times \frac{1}{3}$ = 4.32 T-mm

Iron thickness for B = 2T at midplane

= 4.32/2.0 = 2.16 mm

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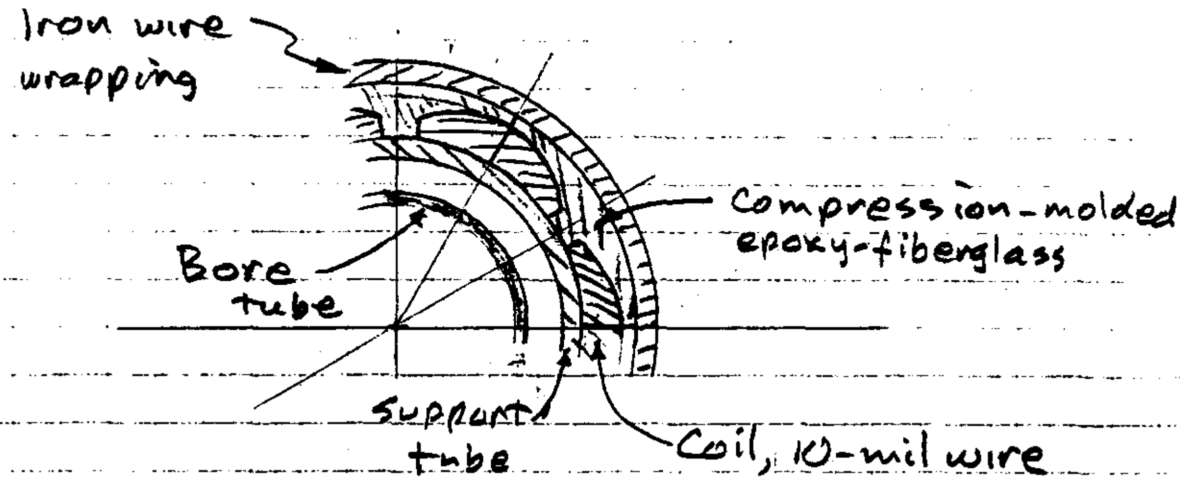
SUGGESTED DESIGN
LUMPED SEXTUPOLE CORRECTOR
FOR RING DIPOLE



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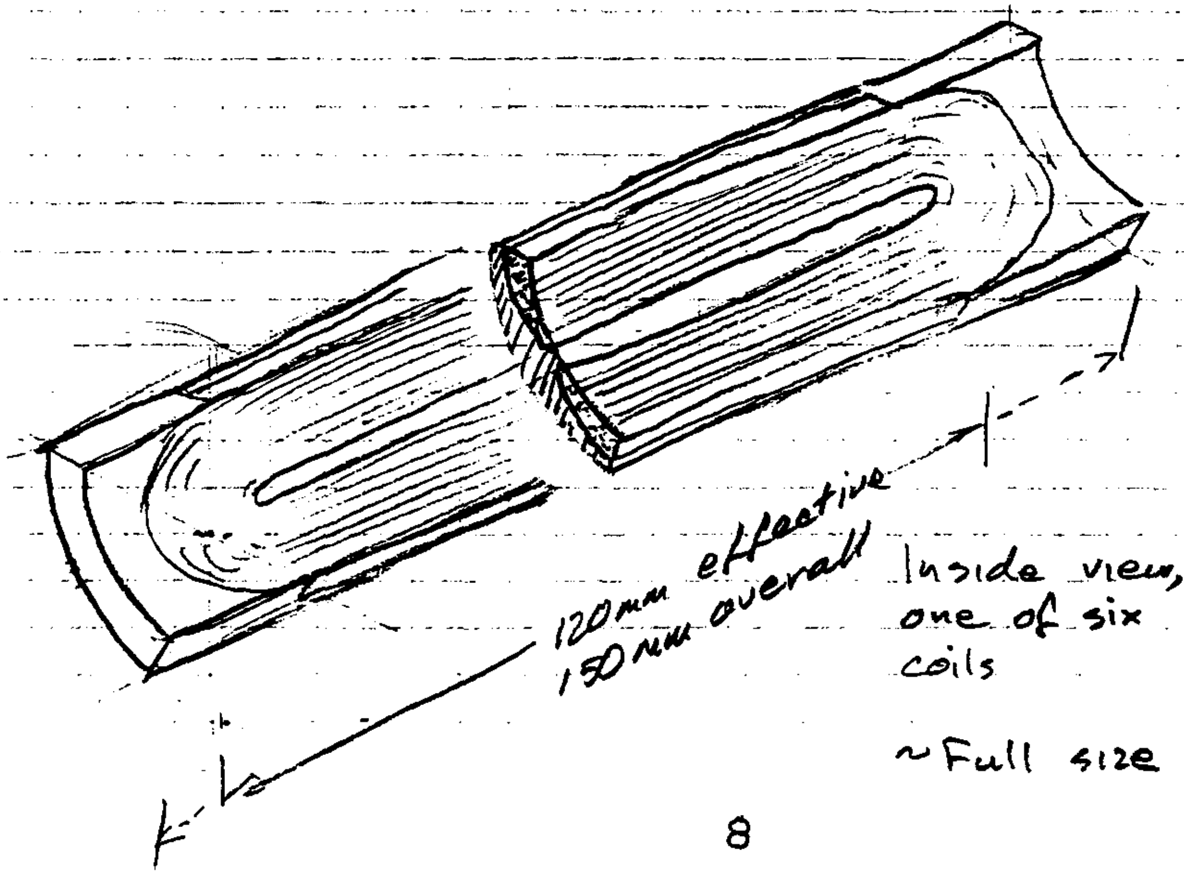
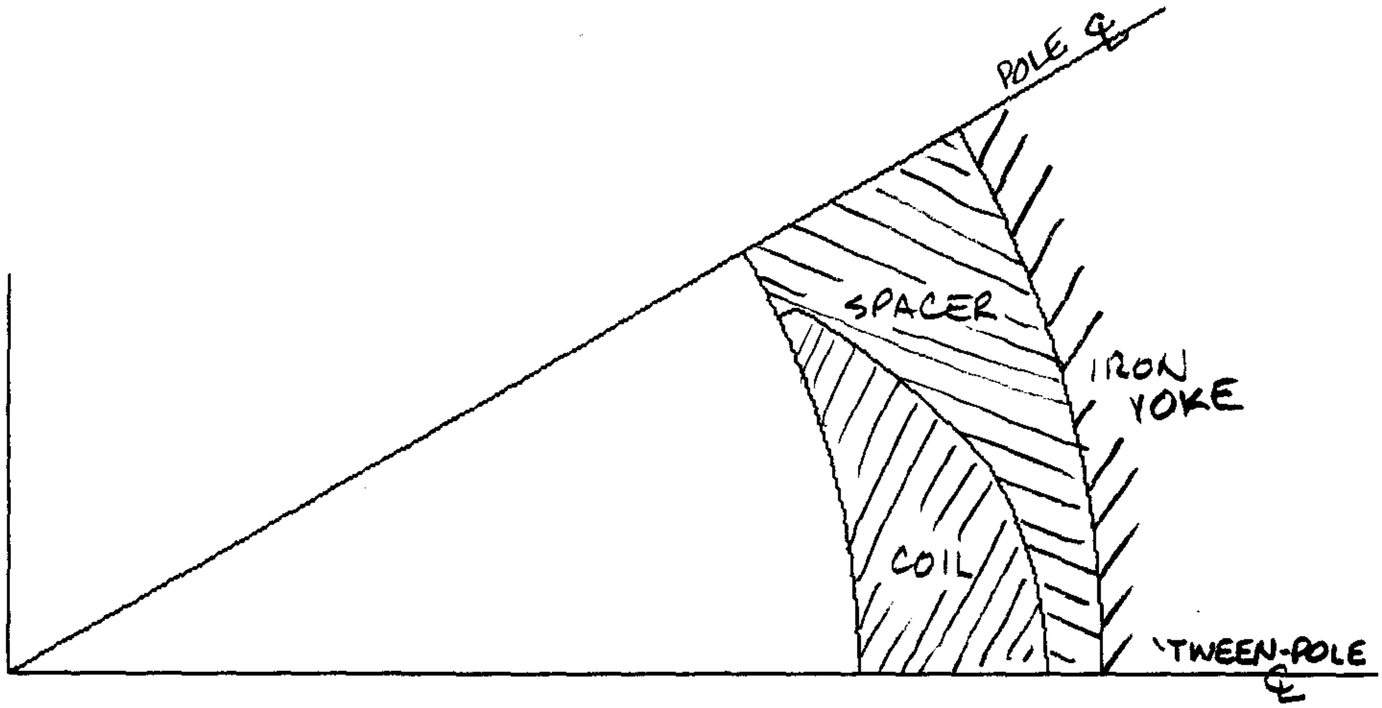


Inside view, one of six coils

~ Full size



5 × FULL SIZE

	Above[2] design	20°[2] sector
Current density	367 A/mm^2	
Sextupole field at 10 mm	0.252 T	0.201 T
18-pole / 6-pole (3)	9.5×10^{-6} (1)	0
30-pole / 6-pole (3)	9.6×10^{-7}	3.3×10^{-6}

(1) could be optimized to zero

(2)... for same O.D., I.D. and current density

(3)... at r = 10 mm