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New Coil End Design for the RHIC Arc Dipole

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Abstract -- To simplify production, the number of parts in the ends, about 64 in each coil end, was reduced by using thicker spacers between the turns, to about 23. A new computer program was written which gives a description of each turn closely resembling the turn as made. The output of this program is processed by newly written computer programs which change the parts descriptions into forms which are used by a computer-controlled, 5-axis milling machine. The solid spacers replace spacers assembled from laminations and improve the fit as well. The parts will be molded during production. The calculated harmonic content of the ends is compared with measurements on the first magnets built with the new ends.

I. INTRODUCTION

The 80 mm aperture arc dipole magnets in the Relativistic Heavy Ion Collider (RHIC) are currently in production by Grumman Aerospace Corporation. There will be 264 of these magnets in the two rings, and 96 others of the same design but different lengths in the regions near the six beam crossing points. The design maximum field is 3.45 tesla, so a single layer coil of 30 strand superconductor cable is ample. The coil is arranged in four blocks of 4, 8, 11 and 9 turns per quadrant, from pole to midplane, to approximate a cosine theta distribution. "Wedges" separate the blocks; the wedges are terminated in the ends by "wedge tips" which taper to zero thickness at the longitudinal centerline of the coil.

The ends of coils built at BNL are "built-up", that is, the first (polemost) turn is laid around a shaped endpost [1], a "spacer" is put next to it and successive turns are laid on alternately with spacers. The purpose of the spacers is both to reduce the possibility of electrical shorts and to give a distribution of turns which minimizes magnetic field harmonic content. The minimum spacer thickness is 0.25 mm; these thin spacers are made of Dupont "Kapton" polyimide film, typically a ribbon about the same width as the cable and about half the length of the turn, slotted along the bottom edge so that they can conform to the turn.

In the original end design, all spacers thicker than 0.25 mm were built up, or laminated, from a number of Kapton ribbons of varying lengths. These laminated parts are flexible during winding and conform readily to the shape of the previous turn, but tend to fluff out the end during winding, causing a looser coil end. The laminated parts do not take their final shape until the coil is cured, when a thin film of thermoplastic material on the surface glues the laminations together.

The assembly of dozens of these laminated spacers per coil was very laborious. The labor is reduced in the present design both by consolidating groups of spacers into relatively fewer, axially thicker spacers, and by machining or molding the thick spacers from G.E. Ultem 6200. This material can soften and conform to the adjoining parts during curing at elevated temperature; this helps reduce built-in stresses, resulting in a tighter, more consistent coil end. The thinnest wedge tips, located nearest the midplane, are too small to mold or machine, and are still made of laminated Kapton ribbons of various sizes.

Although some alteration of the shape of these parts occurs during curing, the initial design shape must be fairly close to the final shape. In the next section, the procedure for determining the various shapes analytically is described, beginning with the description of a single turn, then the description of a complete but unoptimized end, and finally the computation of harmonics and the optimization of the spacers. Section III describes the translation of design program output into finished drawings and data for the automatic machining of parts, and the final section gives calculated and measured results.

II. TURN SHAPE AND OPTIMIZATION

Initially, the turn is assumed to have zero thickness and, at the junction of the end with the 2-D part of the coil, the plane of the turn coincides with the middle of the turn there. After a turn has been designed as a surface, the surface is extended normally in both directions at each edge half the thickness of the 2-D turn at that edge. A turn is described as having an outer edge which is an ellipse when developed and an inner edge which is an ellipse plus a straight line. By "developed" is meant that the circular cylinder on which the edge lies is unrolled into a plane. A turn at the return (non-lead) end of the coil is anti-symmetric about the pole, but a turn at the lead end is not. The first half of a lead-end turn is the same as the corresponding turn at the return end; the second half has to match up with the next turn of the return end.

As discussed in [1], the mean curvature of the inner edge in the direction perpendicular to the inner edge and in the plane of the turn can be minimized by adjusting the ratio SSF of the straight line length to the semi-major axis of the ellipse. If the inner and outer edge lengths are equal, the turn is said to be "constant perimeter". The ratio of inner edge length to outer edge length is denoted by AKF. If AKF

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differs much from 1.0, the cable is being bent the "hard way", and the wrapped Kapton film on it used for electrical insulation may crinkle or even rupture. A satisfactory end cannot be made without some deviation from the constant perimeter condition ($AKF = 1.0$) in most of the turns, but a well designed end will keep such deviation as small as possible.

The first turn is made with AKF close to one; this was found to be desirable by winding studies [1]. This turn is optimized as described above, and the rest of the turns have the same SSF. Turns described this way constitute a consistent set that will nest inside one another at all points.

As successive turns are added, AKF must decrease to restrain the tilt, which would otherwise become too large. The arc dipole final turn tilt is 25.5 degrees and AKF of that turn is 0.964. Figure 1 gives $\text{tilt}(\theta)$ in the RHIC arc dipole.

Figure 1. Tilt of the turns where they cross the pole.

In the ends, the 2-D cross section blocks are subdivided for computational purposes; the spacer thickness within a block is constant. The subdivision arrived at for the arc dipole return end is $4 \rightarrow 4$, $8 \rightarrow 3+5$, $11 \rightarrow 2+5+4$ and $9 \rightarrow 9$ for a total of 7 blocks. There are 3 spacers of 2.54 mm thickness in the first block for peak field reduction; the two spacers in the second block, the single in the fourth block and the three in the sixth are sized to optimize the harmonics, 13.45, 6.34 and 13.71 mm, resp., using the CERN program MINUIT.

The developed turn and spacer configuration of the lead end outer edges is shown in Fig. 2. Only the first edge of each turn is shown. This end has the same number and approximate positions of the spacers as are used in the optimized return end, but they are typically displaced one turn. Harmonic growth due to shifting the spacer locations in the lead end can be avoided by reoptimizing the spacer thicknesses, but this capability was not developed until after completing the arc dipole design. Fig. 3 shows the outer edge of the lead end wedge tips.

The expression used at BNL for the expansion of the

2-D field at the origin is given by Equation 1.

$$B_y + i B_x = 10^{-4} B(R) \sum_{n=0}^{\infty} (b'_n + i a'_n) (\cos n\theta + i \sin n\theta) \left[\frac{r}{R} \right]^n \quad (1)$$

In Eq. (1), "R" is the reference radius and $B(R)$ is the magnitude of the field due to the *fundamental* at the reference radius. The b'_n and a'_n are dimensionless, and their values are said to be in "units". The harmonic coefficients integrated along the axis are given in "unit-meters". When integrated over the entire end, the fundamental, $\int b'_0 dz$, expressed in unit-meters, is the effective magnetic length of the end in meters. Fig. 4 shows the variation in local b'_0 in the return end [2]. The peaks are much sharper than is the case for ends having distributed spacers.

In the return end, which has left-right anti-symmetry, the b_i , i odd, are zero, and since there is also symmetry about the midplane, all the a_i are zero. The lead end is not midplane symmetric; the remaining pole of the dipole is formed by rotation of the complete first pole through the angle π and changing the sign of the current. Consequently a_i and b_i , i even, are both present and those with odd i are zero.

Figure 2. Outer edges of the lead end turns.

Figure 3. Outer edges of the lead end wedge tips.

Figure 4. Computed variation with z of b_z in the return end.

III. PROCESSING THE COIL DESCRIPTIONS FOR THE 5-AXIS MILLING MACHINE

Besides harmonic coefficients, the program output consists of the x , y and z coordinates of evenly spaced points on all four edges of each turn; each edge is divided into 64 segments of equal length, so that a single turn includes 260 points. Additional outputs are similar tables of coordinates for the wedge tips. Somewhat inconsistently, it is left up to subsequent post-processing to extract the coordinate tables for the thick spacers from the turns tables.

The turns tables are processed to produce three types of output, using the commercial programs "I-DEAS" [3], a solid modeling program, and AutoCAD [4]. The products are 2-D engineering drawings and orthographic projections, IGES (Initial Graphics Exchange Specification) files and parts inspection tables. IGES files are a "lingua franca" means of data transmission between software from varying origins.

Seven programs were written in "Ideal", an I-DEAS programming language; one, DBG, is first used to recreate the turns tables in the form of spline coordinates of the two surfaces of each turn or wedge tip. From these new "spl" tables, the intersection of the two surfaces with coaxial inner and outer circular cylinders of specified radii is computed by program SC; the physical spacers and wedge tips have cylindrical inner and outer surfaces to facilitate assembly. The perspective view of the return end shown in Fig. 5 was produced by this program.

A third Ideal program, AFPC, writes "script" files from the 3-D spl tables; these are used by AutoCAD to draw flat projections of each coil end, used in engineering drawings. Program AOV, creates script files for AutoCAD of orthographic top and front views of a specified coil part.

The inspection table for a spacer, produced by program CPIP, consists of tables of points (x , y and z) on the first and second surfaces, slightly inboard of the edges, and

Figure 5. Perspective view of the return end.

the normal unit vector at that point to the surface. This latter is needed to ensure that the computer-controlled measuring machine stylus is normal to the surface. Twenty points near each edge are used.

Finally, the edges of each part are converted to 3-D curves and written in the form of IGES files. The machine shop reads these files using the CAMAX program [5] which generates tool paths and related data for the computer-controlled, 5-axis milling machine.

VI. RESULTS

To date, four magnets have been made using this end design, two short (1.8 m DRS009 and DRS010) and two full length (9.7 m DRE011 and DRE012). All four used spacers and wedge tips machined from the program-produced data. The coils were easier to wind than previous coils using laminated parts, and when cured showed no gaps between spacers or wedge tips and adjacent turns. The end lengths tend to come out a few mm smaller than design, because of flowing of the Ultem 6200 during curing. The quench properties are about the same as in previous magnets using distributed, laminated spacers in the ends [6].

Measurements of the ends have been made in the first two of these using a short coil which integrates over the entire end, including part of the 2-D part of the magnet; the latter is subtracted in the Tables below. Measurements on the two long magnets were not available in time for this report.

Table 1 gives the harmonics in the return end as computed by the design program, by a more detailed procedure [7], and measured. The detailed procedure includes a correction for the presence of small notches in the iron at the poles used for rotationally positioning the coils. Accompanying the measured numbers is an estimate of their uncertainty. Not shown in Table 1 is a measured $\int a_z$ in the amount of -0.7 ± 0.3 unit-meters; this is not allowed by both up-down and left-right symmetries. The differences between calculation and measurement are probably due to shortening

of the ends during curing, to centering errors of the coil in the iron and to displacement of the midplane of the coils during collaring.

TABLE I
Return End

	$\int b'_1$	$\int b'_2$	$\int b'_3$	$\int b'_4$	$\int b'_5$	$\int b'_6$	
design program	1249.	0.0	-0.78	0.0	-0.23	0.0	-0.07
detailed calc. [7]	1271.	0.0	-0.58	0.0	-0.24	0.0	-0.06
measured	--	1.4 ± 1.0	-2.3 $\pm 1.$	-0.07 ± 0.04	0.5 ± 0.2	-0.05 ± 0.05	0.1 ± 0.05

Table 2 gives the harmonics in the lead end, as computed by the design program, by the detailed procedure and as measured. The design program includes a simple description of the leads through the end of the coil. In addition to the notch correction described above, the corrections in the detailed procedure include a larger notch in the iron for the pole leads, a careful description of the ramp between the turn and the lead, and that part of the leads outside the end proper. The large $\int b'_1$ and $\int a'_1$ are due to the leads, but the sources of the $\int b'_1$ and $\int a'_1$ are unknown.

TABLE II
Lead End

	i	0	1	2	3	4	5	6
design program	$\int b'_i$	1282.	0.0	6.42	0.0	0.10	0.0	0.18
	$\int a'_i$	16.17	0.0	-6.59	0.0	1.32	0.0	-0.37
detailed calc. [7]	$\int b'_i$	1293.	-0.36	17.7	0.05	-1.26	0.0	1.08
	$\int a'_i$	22.8	-0.50	-9.01	0.03	2.59	0.0	-0.97
measured	$\int b'_i$	--	-2.0 ± 1.0	15.0 ± 2.0	0.3 ± 0.2	-0.7 ± 0.2	0.0 ± 0.2	0.5 ± 0.1
	$\int a'_i$	--	3.7 ± 1.0	-7.8 ± 1.0	-0.6 ± 1.0	1.5 ± 0.3	0.3 ± 0.1	-0.7 ± 0.2

V. CONCLUSIONS

The new programs and procedures outlined here enable one to construct an end without iteration, and have resulted in ends which are easier to make and have better harmonic content than did previous end designs. The unwanted harmonics appear large when expressed in unit-meters; the sum of both ends should be divided by about 9.2 m for comparison with the harmonics in the body of the magnet. Doing so, only a'_1 , b'_2 and a'_2 are sizable: 0.3, 1.4, and -0.8 units, respectively, compared with measured body harmonics in the amount of 1.24, 0.24 and 0.39 at a current

of 1450 A. The b'_2 is due to the lead end not being reoptimized, a procedure recently inaugurated. The origin of the a'_1 is not known; the a'_2 is due to the inherent asymmetry of the lead end.

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