Chapter 4.
FIELD QUALITY IMPROVEMENTS THROUGH COIL DESIGN

The research work described in this chapter is partly based on the following papers :

- R.C. Gupta, S.A. Kahn and G.H. Morgan, *Coil and Iron Design for SSC 50 mm Magnet*, Proceedings of the 1990 American Society of Mechanical Engineers (ASME) Winter Annual Meeting in Dallas (1990).
- R.C. Gupta, S.A. Kahn and G.H. Morgan, *A Comparison of Calculations and Measurements of the Field Harmonics as a Function of Current in the SSC Dipole Magnets*, Proceedings of the 1991 IEEE Particle Accelerator Conference, San Francisco, pp. 42-44 (1991).
- R.C. Gupta, S.A. Kahn and G.H. Morgan, *SSC 50 mm Dipole Cross section*, Proceedings of the International Industrial Symposium on Super Collider (IISSC), Atlanta, pp. 587-600 (1991).
- R.C. Gupta, *Correcting Field Harmonics after Design in Superconducting Magnets*, Proceedings of the 4^{th} International Industrial Symposium on Super Collider (IISSC), New Orleans, pp. 773-800 (1992).
- R. Gupta, et al., *Large Aperture Quadrupoles for RHIC Interaction Regions*, Proceedings of the 1993 Particle Accelerator Conference, Washington, D.C., pp. 2745-2747 (1993).
- R. Gupta, et al., *Field Quality Improvements in Superconducting Magnets for RHIC*, Proceedings of the 1994 European Particle Accelerator Conference, London, UK, pp. 2928-2930 (1994).
- R. Gupta, et al., *Field Quality Control Through the Production Phase of RHIC Arc Dipoles*, Proceedings of the 1995 International Particle Accelerator Conference, Dallas, Texas (1995).
- R. Gupta, *Field Quality in the Superconducting Magnets for Large Particle Accelerators*, Proceedings of the 1996 European Particle Accelerator Conference at Sitges, Spain (1996).

4.1. Introduction

An iteration in coil cross section is usually carried out to change the allowed harmonics by a constant amount at all currents. To help understand the following discussion, a coil cross section is shown in Fig. 4.1.1. This coil cross section is used in the optimized design for the 100 mm aperture RHIC insertion dipole *D0*.

The details of the coil cross section design and optimization process are described in Chapter 6, *"OPTIMIZED CROSS SECTION DESIGNS"*. In the present chapter only iterations of a previously optimized design will be discussed. These iterations are required to remove the differences between the design and measured harmonics in the initial magnets. These differences are present because of (a) a difference between the parts used in the design and in the actual magnet (b) a deformation in the mechanical shape of the coil and iron cross section as a result of the large compressive forces applied on the coils during the magnet assembly (c) deviations in the tooling and manufacturing (assembly) process from the initial ones used, etc. The cross section of the coil is iterated in an attempt to remove systematic values of field harmonics due to such sources. This is usually accomplished by changing the copper wedges in the coil, an approach which is discussed later in this chapter. This method, however, requires a long time to implement since a new magnet must be built. Moreover, in addition to a wedge itself, several other associated components (particularly in the coil ends) may also require a change. In RHIC magnets, an alternate approach to coil cross section iteration is used which does not require changes in the wedges (and associated components). A symmetric gap at the coil midplane has been used to effectively reduce the crucial decapole harmonic in RHIC arc dipoles. Moreover, the coil pole shims can be used as additional parameters to adjust a number of field harmonics. A large octupole harmonic in RHIC quadrupoles (which like dipoles are collared in a 2-fold symmetric way) is removed by using unequal coil to midplane gaps between horizontal and vertical planes. These methods are discussed in separate sections. The calculations presented in this chapter are mostly performed with the computer code PAR2DOPT [130] which computes field harmonics analytically based on coils made of constant current density, trapezoidal conductors in an infinite permeability circular iron cylinder.

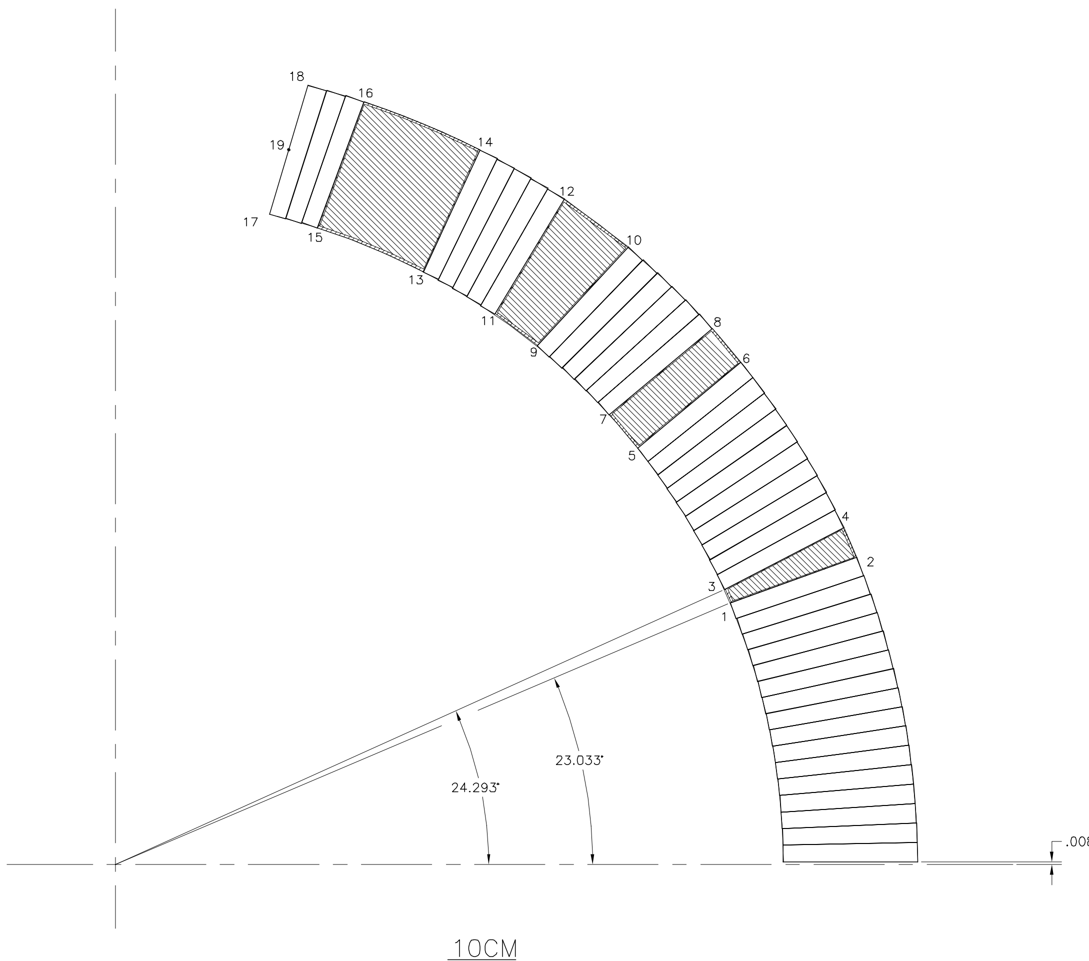

Figure 4.1.1: The coil cross section used in the design of the 100 mm aperture RHIC insertion dipole *D0*. This shows only one half of the upper coil, the other half is symmetric with respect to the vertical plane. The shaded parts represent copper wedges and the non-shaded part, the insulated superconducting cable. The first wedge is between the points marked 1, 2, 3 and 4 and angles 23.033 and 24.293 degrees. ".008" represents the coil midplane gap of $0.008''$ ($\sim$ 0.2 mm) as measured from the horizontal axis of the magnet. Point 19 represents the location where the coil pole angle is defined.

4.2. Sources of Harmonics Allowed by the Magnet Geometry

A cross section iteration is generally carried out to remove only allowed harmonics. The allowed harmonics are those which are allowed by the symmetry of the magnet cross section, for example, b_2, b_4, b_6, ... in dipoles. Dipole coils have a reflection symmetry with respect to both the horizontal and vertical plane which effectively generates a four fold symmetry. Because of this basic symmetry all harmonics except b_2, b_4, b_6, ... will be zero. The presence of harmonics other then these means that the ideal dipole symmetry is broken. Similarly quadrupoles have eight fold symmetry and b_5, b_9, b_{13}, etc. are the only allowed harmonics.

The allowed harmonics are primarily caused by (a) systematic errors in components used in the magnet (b) an imperfect design which is limited by the number of parameters used in cross section optimization and (c) the difference between the design and the realized cross section due to mechanical and thermal deformations discussed below. The value of the allowed harmonics is primarily controlled with copper wedges. These wedges are placed between the blocks of superconducting cables and they primarily determine where an individual turn will go. To obtain a high field quality, as desired in high energy accelerator magnets, the conductors must be placed at an appropriate location to an accuracy of 50 μm. However, after the coils are wound, they go through a significant deformation during the curing, collaring and cool down processes and there is no direct control on where an individual turn will actually end up (although, the overall coil dimensions are constrained by the cavity in which the coil must fit). In principle, one could compute these mechanical changes and incorporate them in the original design. In practice this is not done since the reliability of mechanical model calculations is generally less than the required accuracy of 25-50μm in geometric deformation. The mechanical errors due to these effects do not alter the basic magnet symmetry and therefore only the allowed harmonics are generated in the process. These harmonics are removed by coil cross section iterations.

In order to simplify the magnet construction and to save the cost of tooling used in the collaring process, all RHIC quadrupoles are collared like dipoles. This collaring process creates an elliptical deformation in the coil and iron shape (which creates the allowed harmonics b_2, b_4, b_6, ... in dipoles). However, the elliptical shape does not have a reflection symmetry at the quadrupole poles, which are at 45°, 135°, 225° and 315°. As a result, in addition to the quadrupole allowed harmonics b_5, b_9, b_{13}, ..., the normally non-allowed harmonics b_3, b_7, b_9, ... are also generated.

4.3. Reduction in the Allowed Harmonics through Wedges

The most common method of removing the systematic values of allowed harmonics measured in the magnet is to change the size of the wedges used in the initial design. The possible sources of them and limitations in predicting these harmonics accurately in the initial design have been discussed in the last two sections. To overcome those limitations, the measured systematic values of allowed harmonics are empirically removed by making a new cross section such that the design harmonics have the same magnitude but opposite sign to the measured harmonics. Care is taken so that the change in wedge thickness and other mechanical component is small. A small change assures that the mechanics of the cross section will not change significantly and the iterated cross section will go through a mechanical deformation similar to the original one. This approach has been found quite successful in RHIC magnets [71,72].

In this paragraph the SSC 50 mm aperture dipole magnet cross section (Fig. 3.2.2) is examined. This cross section is described in detail in chapter *"OPTIMIZED CROSS SECTION DESIGNS"*. The basic coil cross section consists of two layers of coils with three wedges in the inner layer and one in the outer. In the first four rows of Table 4.3.1, the computed change in the transfer function and field harmonics are given at a reference radius of 10 mm for a change in the wedge thickness of $+25\mu m$. The changes in the values of harmonics higher than b_6 is small and they are not given here. In these calculations the pole width is held constant while the wedge thickness is changed. This means that the effective cable thickness is reduced by an appropriate amount. The wedge number counting starts in the inner layer and in each layer in the wedge which is closest to the midplane. The pole width, which was kept constant in these calculations, however, need not be constant in general; the effect of increasing the pole width by $+25\mu m$ in the inner or outer layer is given in the final two rows.

In Table 4.3.2, the change in transfer function and in field harmonics is given at the 25 mm reference radius for a $+25\mu m$ change in wedge thickness, pole width and coil midplane gap in the 80 mm aperture RHIC arc dipoles [72] whose model is shown in Fig. 3.2.1.

When an iteration in the coil design is performed following the guidelines given earlier (that the mechanical changes are small during iteration), the differences in field harmonics between calculation and measurement are within the errors expected from the mechanical tolerances [71].

Table 4.3.1: The effect of a $+25\mu m$ change in a wedge thickness or pole width on the transfer function and the field harmonics in the SSC 50 mm aperture dipole magnet. The field harmonics are calculated with a 10 mm reference radius. The numbering of the wedges is counter-clockwise from the midplane. The pole width is measured from the vertical axis.

Parameter changed	δTF $10^{-4}\frac{T}{kA}$	δb_2 10^{-4}	δb_4 10^{-4}	δb_6 10^{-4}
Wedge No. 1	-0.78	-0.24	0.01	0.005
Wedge No. 2	0.42	0.30	0.03	-0.005
Wedge No. 3	1.16	0.36	-0.02	0.00
Wedge No. 4	-0.29	-0.06	0.00	0.00
Pole Width (inner)	2.0	0.23	-0.03	0.005
Pole Width (outer)	1.13	0.21	0.00	0.000

Table 4.3.2: The computed change in the transfer function and field harmonics produced by a $+25\mu m$ $(0.001'')$ change in the wedge thickness, pole width or midplane gap in the RHIC 80 mm aperture arc dipoles. The field harmonics are calculated with a 25 mm reference radius. The numbering of the wedges starts at the midplane. The pole width and midplane gap are measured from the vertical and horizontal axis, respectively.

Parameter changed	δTF $10^{-4}\frac{T}{kA}$	δb_2 10^{-4}	δb_4 10^{-4}	δb_6 10^{-4}	δb_8 10^{-4}
Wedge 1	-0.6	-0.98	-0.122	0.061	0.043
Wedge 2	0.1	0.69	0.423	0.022	-0.050
Wedge 3	1.1	1.42	-0.090	-0.068	0.041
Pole Width	1.7	1.11	-0.154	0.039	-0.014
Midplane Gap	-0.9	-1.68	-0.557	-0.156	-0.050

4.4. Reduction in the Allowed Harmonics in RHIC Arc Dipoles by Changing the Midplane Gap

The Northrop Grumman Corporation (NGC) started building the 80 mm aperture RHIC arc dipoles based on a design previously tested in prototype magnets built at BNL. Due to differences in tooling and in the details of the manufacturing process between the magnets built at BNL and NGC, a small change in the harmonics (particularly the first few allowed ones) was expected. Such differences are normally removed by changing the wedges in the coil cross section in an iterated design as discussed in the last section. The most critical allowed harmonic in 80 mm RHIC arc dipoles is b_4, since the sextupole correctors incorporated in the machine have a more than adequate capacity for changes in b_2. Moreover, b_6 and higher harmonics were not expected to deviate much from the value measured in prototype magnets.

To adjust only the b_4 harmonic by a small amount, a more efficient scheme than the wedge-based iteration was incorporated in the production RHIC arc dipole design. In these magnets, the measured b_4 is removed through an adjustment in the gap between the coil and the midplane. In the original BNL-built prototype magnets, $\sim$0.10 mm Kapton "caps" were placed on the top and bottom coils at the midplane. These Kapton caps are used to provide electric insulation between the two coils. In the production dipole design, this gap was increased to $\sim$0.15 mm [71]. The purpose of this increase was to permit an adjustment, if needed, of $\pm$0.05 mm ($\sim$0.10 mm to $\sim$0.20 mm) which would change b_4 by $\sim \mp 1$ unit at 25 mm reference radius (see Table 4.4.1). In principle, a similar adjustment can be obtained by a change in the coil pole shims, an adjustment which has been routinely used in the past for other purposes. However, as shown in Table 4.3.2, the change required in the pole shim to produce a similar adjustment in b_4 is over three times the change required in the midplane gap and it also creates a larger change in the b_2 harmonic. Such a large change in pole width would also cause a bigger change in the compression on the coils, which could affect the quench performance of the magnets.

The midplane gap adjustment method was experimentally tested earlier in the RHIC short dipole DRS009. The magnet was originally built with $0.0045''$ (0.114 mm) thick midplane caps. This magnet was later rebuilt with $0.0063''$ (0.160 mm) thick midplane caps. The total change was $0.0018''$ (0.046 mm). The computed and measured change in harmonics is given in Table 4.4.1. Good agreement between the calculations and measurements can be seen.

Table 4.4.1: The computed and measured change in field harmonics at 25 mm reference radius due to a change in the coil midplane gap. The midplane gap was increased from 0.114 mm to 0.16 mm in the rebuilt 80 mm aperture RHIC model dipole magnet DRS009. In the production magnets, the midplane gap was changed back to 0.114 mm from 0.16 mm to adjust the b_4 harmonic.

	Δb_2	Δb_4	Δb_6	Δb_8
Computed	-3.0	-1.0	-0.28	-0.09
Measured	-3.0	-1.0	-0.29	-0.12

Magnetic measurements in the first few industry-built magnets showed that this adjustment in b_4 harmonic was indeed needed. After building 19 dipoles with a 0.16 mm midplane gap, a change to a 0.114 mm midplane gap [72] was decided on for the next 86 magnets. This adjustment could be quickly implemented in the production as it did not require any change in the wedges or in the coil-ends and already-built coils could be used in the new series.

4.5. Reduction in b_3 in RHIC Quadrupoles with Midplane Gaps

As mentioned earlier, in order to simplify construction and to save the cost of tooling, the RHIC arc quadrupoles [160] and RHIC insertions quadrupoles [69] are collared like dipoles. This creates an elliptical deformation of the yoke aperture which breaks the quadrupole symmetry and therefore generates the non-allowed octupole harmonic b_3 (also b_7, b_{11}, etc.). In early prototype production of RHIC quadrupoles (both 80 mm aperture and 130 mm aperture) $\sim$7 units of b_3 was observed.

The ideal way to correct this problem would be to start width a pre-ovalized non-circular yoke aperture which would become circular after the deformation during collaring. This would require a new yoke die, an option that is both expensive and time consuming. The amount of pre-ovalization would be based on mechanical calculations. Given that the reliability of those calculations is generally 25-50 μm an additional design iteration may be required to remove the residual b_3 harmonic.

An alternate method to the above is outlined here. Recall that b_3 is caused when the quadrupole is not symmetric between the horizontal and vertical planes. The proposed method consists of introducing another asymmetry which is used to compensate for the above asymmetry caused by an elliptical yoke (and hence coil) deformation. This new asymmetry is a difference in the gaps between the horizontal (0° and 180°) and vertical (90° and 270°) planes and the coils when the four coils are assembled in the magnet. There are a total of eight such gaps in the quadrupole magnets as, for example, there are two gaps at 0° – one from horizontal plane to upper coil and another from horizontal plane to lower coil. In the earlier designs these eight coil-to-midplane gaps had an identical value of 0.1 mm. In the present designs to remove b_3, the four horizontal midplane gaps at 0° and 180° are increased from 0.1 mm to 0.2 mm but the four vertical gaps 90° and 270° are left unchanged at 0.1 mm. This asymmetry of 0.1 mm between the horizontal and vertical planes generates the right amount of change in b_3, but with an undesired change in b_7. This change in midplane gap also increases the average value of the midplane gap by 0.05 mm which generates the allowed harmonics b_5 and b_9. The change in the allowed harmonics b_5 and b_9 is corrected in the regular coil cross section iteration. However, a b_7 would remain remain if nothing additional were done to remove it. In the 80 mm aperture arc quadrupoles, this b_7 can be tolerated but in the 130 mm aperture insertion quadrupoles, it is unacceptable and is corrected with the help of "tuning shims" (to be described in the next chapter).

An experiment was done to test the validity of this method before incorporating it in to the large scale production. In Table 4.5.1 calculations and measurements are compared in a rebuild of the 130 mm aperture RHIC insertion quadrupole QRI002. Good agreement between the calculations and measurements can be seen.

The same method has been used in the 80 mm aperture arc quadrupole design. A similar experiment was done to verify the validity of this scheme in those magnets.

Table 4.5.1: The measured and computed change in field harmonics caused by an asymmetric increase in the coil-to-midplane gap in the prototype 130 mm aperture RHIC interaction quadrupole QRI002. The gap was increased by 0.1 mm in the horizontal plane only. The harmonics are given at a reference radius of 40 mm.

	Δb_3	Δb_5	Δb_7	Δb_9
Computed	-6.8	-1.3	-0.45	-0.16
Measured	-6.5	-1.2	-0.30	-0.17

4.6. Coil Cross-section Iterations without Changing Wedges

In the previous two sections, an adjustment in one critical harmonic with the help of an adjustment in midplane gaps has been discussed. However, the initial design iteration generally requires (a) an adjustment in two harmonics (sometime even more) and (b) an adjustment for a deviation in coil size from the design value either due to a change in the size of the insulated cable, or conversely, a coil size change to obtain a desired compression of the coil. In the past such adjustments have been incorporated by an iteration in the coil cross section through a change in the wedges and associated components in the ends. As mentioned earlier, this is a major design iteration and therefore it can have a significant impact on the cost and schedule.

A simpler alternative to the above approach to cross section iteration has been used in several RHIC magnet designs. In this approach, instead of changing wedges (and hence the coil cross section) both the coil midplane gap and the coil pole shims are adjusted. In a multi-layer coil magnet (all RHIC magnet designs use only a single layer of coil), the number of parameters would be twice the number of layers. In RHIC magnets these two variables (which determine the starting and the end point of the coil) are used to minimize the first two allowed harmonics (b_2 and b_4 in dipoles and b_5 and b_9 in quadrupoles). In dipoles, an increase in the midplane gap produces a negative change in all of the allowed harmonics (b_2, b_4, etc.) and an increase in the pole shim produces a positive change in b_2 and a negative change in b_4. Similarly in quadrupoles, an increase in the midplane gap gives a negative change in all of the allowed harmonics (b_5, b_9, etc.) and an increase in the pole shim gives a positive change in b_5 and a negative change in b_9. In order for these two parameters to optimize the two harmonics independently, the azimuthal coil size must be allowed to change. A method was developed during the SSC and RHIC magnet *R&D* program [5] which permits a modest change in the coil azimuthal size during the coil curing cycle by adjusting the curing pressures and hence effective cable insulation thickness.

Since the third allowed harmonic is b_6 in dipoles and b_{13} in quadrupoles, the success of this approach means that the allowed harmonics below it can be removed with this method. In the cases where this adjustment in the first two harmonics is sufficient, this is a very efficient approach. Moreover, an asymmetric adjustment in the coil-to-midplane gap and/or coil pole shim can be used to remove additional non-allowed harmonics also, as discussed in the previous section.

The application of this approach is demonstrated in Table 4.6.1 where the desired adjustment in harmonics in the RHIC 130 mm insertion quadrupoles is obtained with the help of coil pole shims and midplane shims. As mentioned in the previous section, the midplane shims are made to have different values at the horizontal midplane (0° and 180°) and at the vertical midplane (90° and 270°) to eliminate the measured b_3 in the prototype magnets. In the design used in magnets QRI103-QRI110, the values of coil-to-midplane gap was 0.25 mm and 0.15 mm respectively at the horizontal and vertical midplanes which removed practically all b_3. However, this intial 0.1 mm asymmetry between the two planes in design 1 generated a relatively large b_7 (-0.32 unit). To reduce this large b_7, the asymmetry was reduced from 0.1 mm to 0.075 mm for the rest of the Q1 program (magnets QRI111-QRI128), which reduced b_7 from -0.32 to -0.26 but left a b_3 of $\sim$2 unit. This b_3 is removed by the tuning shims (which are iron shims attached to the yoke inner radius, see the next chapter). The sign of the change in b_3 and b_7 due to the asymmetric coil midplane shims and the asymmetric tuning shims is opposite and therefore when the two are used in the proper combination they can make both b_3 and b_7 small. Design 2, which is used in magnets QRI111-QRI119 and QRI122-QRI125, has on the average a larger midplane gap (0.27 mm instead of 0.2 mm) and a decreased pole shim of 0.03 mm. This was done to obtain a desired change in b_5. In design 3, which is used in the last three magnets QRI126-QRI128, the pole shims were adjusted by 0.05 mm to correct for an undesired change in b_5 caused by errors in other components in the magnet. Design 4 compensated for a reduction in the cable thickness of 0.009 mm (9 μm). Since there are 27 turns in the cross section, this changed the coil size by 0.24 mm. This would have created unacceptable changes in the harmonics and pre-compression of the coils in the magnet. However, in this method, the decrease in cable thickness was accommodated using an increase in the coil midplane gap of 0.09 mm and an increase in the coil pole shim of 0.15 mm. This proportion of coil midplane gap and coil pole shim adjustment also reduced b_9 without changing b_5. This cross section is used in two magnets QRI120 and QRI121. These two magnets were actually used to test the cross section for the longer 130 mm aperture quadrupoles, where a reduction in b_9 is much more beneficial because of a larger beam size.

Table 4.6.1: A summary of designs used in various 130 mm aperture 1.44 meter long Q1 (QRI) quadrupoles for RHIC insertion regions. All designs used the same wedges and only the coil midplane gap and coil pole shims were changed. The cable used in all but design 4 had the same thickness. The thickness in the cable of design 4 was smaller by 0.009 mm. Since there are 27 turns in the cross section, this would have meant a 0.24 mm change in the coil size. The calculated field harmonics are given at 40 mm reference radius. Generally good agreement has been found between the calculated and measured changes in field harmonics during these iterations. b_3 and b_7 are further reduced by tuning shims which were not included in these calculations.

Parameter	Design 1	Design 2	Design 3	Design 4
Magnets QRI...	103-110	111-119 122-125	126-128	120-121
Coil pole shim	0.46[a]mm	0.43 mm	0.48 mm	0.63 mm
Midplane gap (0°,180°)	0.25 mm	0.30 mm	0.30 mm	0.39 mm
Midplane gap (90°,270°)	0.15 mm	0.225 mil	0.225 mm	0.315 mm
Midplane gap (asymmetry)	0.1 mm	0.075 mm	0.075 mm	0.075 mm
Midplane gap (average)	0.2 mm	0.27 mm	0.27 mm	0.36 mm
Body b_3	0.5	2.2	2.2	2.2
Body b_5	3.2	1.0	1.0[b]	1.0
Body b_7	-0.32	-0.2	-0.2	-0.2
Body b_9	0.7	0.5	0.5	-0.05

[a] The actual thickness of the pole shim used in these magnets was 0.53 mm but the thickness of the pole piece was smaller by 0.07 mm. The value 0.46 mm used in the table accounts for this difference in the pole thickness between these and the subsequent magnets.

[b] The calculated value of b_5 was 2.5 unit; the value given above includes corrections for errors in the size of other components.

4.7. Conclusions on the Field Quality Improvements through Coil Design

It has been demonstrated that the coil cross section can be reliably iterated to obtain field harmonics which are quite close to the desired values. Mechanical changes in the coil cross section should be minimized during such iterations to minimize the change in mechanical deformations between the two designs. This disciplined approach has resulted in producing desired changes in field harmonics during cross section iteration whether a change in a wedge is required or not. This is an improvement over past experience where a good field quality was not always obtained in a single coil cross section iteration.

A change in coil midplane gap has been found to be an efficient method to reduce the crucial decapole (b_4) harmonic during the production run of the RHIC arc dipoles. An asymmetric coil midplane gap has been used to reduce the octupole harmonic which is generated in RHIC quadrupoles due to dipole-like collaring. Instead of iterating the coil cross section by changing wedges, a limited adjustment in harmonics and mechanical parameters has been obtained by adjusting the coil midplane gap and the coil pole shims. This has been used in a number of design iterations in the 130 mm aperture RHIC interaction region quadrupoles where changes in the b_3, b_5, b_7 and b_9 harmonics and/or a change in cable size is corrected. Since the wedges and the associated components in the ends are not changed, this is an efficient alternative method. In addition this method allows for using coils which have already been built.