Chapter 7.
CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

The field quality in superconducting magnets has been improved to a level that it does not appear to be a limiting factor on the performance of RHIC. The many methods developed, improved and adopted during the course of this work have contributed significantly to that performance. One can not only design and construct magnets with better field quality than in one made before but can also improve on that quality after construction. The relative field error ($\frac{\Delta B}{B}$) can now be made as low as a few parts in 10^{-5} at 2/3 of the coil radius. This is about an order of magnitude better than what is generally expected for superconducting magnets. This extra high field quality is crucial to the luminosity performance of RHIC.

The research work described here covers a number of areas which all must be addressed to build the production magnets with a high field quality. The work has been limited to the magnetic design of the cross section which in most cases essentially determines the field quality performance of the whole magnet since these magnets are generally long. Though the conclusions to be presented in this chapter have been discussed at the end of each chapter, a summary of them might be useful to present a complete picture. The lessons learned from these experiences may be useful in the design of new magnets. The possibilities of future improvements will also be presented.

In the first chapter, a review of the field is presented. Apart from giving a brief description of the RHIC project a summary of various aspects of a superconducting magnet is presented. The section on magnetic field analysis in accelerator magnets is of particular relevance to the present work. In this section various analytic expressions are given. Most of these expressions have been derived by other authors but more are derived here to give a better foundation to the research and development work to follow in the next five chapters. These expressions are useful to provide a general guidance which is needed to develop a systematic, efficient and logical approach to develop and adopt methods of improving the field quality in superconducting magnets.

In chapter 2, techniques to improve the computational and analysis procedure are presented. It is useful to evaluate mechanical deformations on the coil and yoke cross section under large compressive forces. This has impacts on both magnetic and mechanical design and analysis. A computer aided cross section measurement and analysis method has been developed. The method creates a digital image of the cross section using inexpensive commercial software and hardware. This image can be compared with the original design or expected mechanical deformations. The image can be transferred to the AutoCAD software which facilitates a variety of analyses. However, this method was not used during the R&D phase of the RHIC magnet program because at that time the resolution of the image in the supported software was at the border line of the requirement and alternate methods were already in use. However, the development in computer technology in the past several years makes this method quite attractive now. The major advantage of this method is the availability of a digitized image on the computer which can be used for a variety of interactive analyses.

The POISSON group codes have been used throughout this research work to perform most of the field calculations. These codes have been extensively improved to enhance their capability to make the complicated and reliable computer models required in such applications. The use of these improved techniques allows efficient use of a limited number of mesh points to define the problem. However, there is still a lot of scope for improving both the pre- and post- processors of the POISSON group codes.

Chapter 3 deals with the saturation induced harmonics due to the non-linear properties of iron. It has been demonstrated here that the saturation induced harmonics can be practically eliminated by improving the yoke design. In RHIC-type magnet designs, where the iron contribution enhances the field by 50% over the field produced by superconducting coils, the saturation induced harmonics would be expected to be large. However, the use of holes, cutouts and the choice of material for keys and pins (magnetic low carbon steel or non-magnetic stainless steel) have resulted in reducing the current dependence in the sextupole and decapole harmonics by about an order of magnitude. In a new magnet design one would incorporate such features from the beginning. The improvements in the computer codes and modelling and good agreement with the reliable measurements provides the confidence that one can indeed design a yoke in which the saturation induced harmonics are small.

In SSC dipole magnets the saturation in the sextupole harmonic was reduced by compensating pole saturation with forced midplane saturation. This was done by either using stainless steel keys (BNL design) or a cutout at the midplane (Fermilab design). In some SSC magnets, an appreciable amount of b_2 was generated by coil deformation from Lorentz forces. This should not cause a deterioration in field quality in the magnets since one can minimize the overall change in harmonics from both sources (iron saturation and coil deformation due to Lorentz forces) as both are high field effects. In the BNL-built SSC 50 mm prototype magnets the change in sextupole harmonic was nearly zero (~0.1 unit at 10 mm) in the entire range of operation.

The two-radius method for controlling iron saturation at the yoke inner surface has been used in the design of the 130 mm RHIC insertion quadrupole. This has resulted in reducing b_5 by an order of magnitude as compared to the one-radius method.

The efficiency of a particular saturation control method depends on the details of a particular design. Though not used explicitly in the development of the various yoke designs, towards the end of this research work it has been found that a useful barometer to evaluate the quality of a particular yoke design is to examine the variation in the function $(\frac{\mu-1}{\mu+1})$ with azimuthal angle at the yoke inner surface. In a good design the variation in this function will remain small over the entire operating range. However, in most cases it may be sufficient to examine this function at a high field only.

An asymmetric placement of the dipole coldmass in the cryostat may result in introducing a significant skew quadrupole harmonic at high fields. This can be compensated by deliberately making the lower yoke half heavier than the upper. In RHIC dipoles this technique has resulted in reducing the change in quadrupole harmonic by about a factor of 2 at the design field.

Chapter 4 deals with the methods used and developed to improve the geometric harmonics (the harmonics which are related to magnet geometry and not to yoke or superconductor effects). The coil cross sections for various RHIC magnets have been designed in such a way that they allow for a small adjustment in field harmonics even during the production phase with no change in the copper wedges. In the case of the 80 mm aperture RHIC arc dipole magnets, it provided the iteration which was necessary to remove the measured harmonics due to the change in tooling between the BNL and the industry-built magnets. With an adjustment in the coil pole shim and the midplane gap one can control two harmonics. This adjustment may be needed either to correct for a drift in the manufacturing process or to iterate the initial coil cross section. An adjustment in the midplane gap is more effective in controlling the decapole harmonic. Control of the geometric decapole with this method coupled with a reduction in the saturation-induced decapole harmonic has resulted in reducing this harmonic to a level that use of the decapole correctors installed in RHIC may not be required.

In order to iterate the coil cross section reliably, mechanical changes should be minimized between iterations. This disciplined approach has resulted in obtaining the desired changes in field harmonics in RHIC magnets when a coil cross section iteration is made.

The RHIC quadrupoles are collared like dipoles for cost and simplicity reasons. This has been generally avoided in the past because it breaks the pure quadrupole symmetry and generates a large octupole harmonic. An asymmetric coil midplane gap between the horizontal and vertical planes has been used in the RHIC quadrupoles to remove practically all octupole harmonic. This demonstrates that one can have the simplicity of the dipole-type, 2-fold collaring method while maintaining a good field quality in quadrupoles.

In chapter 5, methods to compensate for construction errors are presented. The field quality performance in well designed magnets (after using some of the techniques described above) will now depend on the actual engineering tolerances. These are generally at the level of 50 μm. These usual mechanical errors produce relative field errors $(\frac{\Delta B}{B})$ which are a few parts in 10^{-4} at 2/3 of the coil radius. A tuning shim method has been developed for the RHIC 130 mm aperture quadrupoles which is expected to reduce the relative field errors to a few parts in 10^{-5}. The eight tuning shims compensate for eight measured field harmonics by adjusting the amount of iron in them. This tuning shim compensation is applied in the body of the magnet. Good agreement has been found between calculations and measurements in the magnets with tuning shims made so far. A second method is to make a lumped correction at the ends by adjusting the amount of iron laminations in the magnet ends.

Similar error compensation schemes may be considered for a large scale magnet production program. This would reduce manufacturing tolerances while assuring good field quality. A plan would have to be developed so that it could be efficiently adopted in an industrial magnet production environment.

The techniques and the methods described above have been implemented in the design and construction of RHIC and SSC magnets. The use of these methods is described in detail in chapter 6 where the magnetic design of the following two selected cases is presented : (a) the SSC 50 mm aperture main collider dipole magnet prototype and (b) the 130 mm aperture RHIC insertion quadrupole magnets. These magnets are designed to have good field quality and a high quench field. Moreover, the design incorporates various features which are expected to make the relevant part of the manufacturing as simple and as error free as possible.

The RHIC 130 mm aperture quadrupole coil cross section has good flexibility in the design. This has allowed a number of iterations to be carried out without changing wedges. This is an efficient way of trying out coil cross section iterations which saves both on the cost and time. Moreover, since the change in the geometry of the coil cross section is either none or small, the magnet ends may not change. In the case when the required iteration can be accomplished by changing only the midplane gaps and the coil pole shims, previously built coils can be used.

Most of the methods described here have been successfully applied to the magnetic design of various RHIC and SSC magnets. The general techniques, improvements and design philosophy presented can however be used in any magnet program.