Compensation of magnetic field imperfections in the NSCL K500 Superconducting Cyclotron

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One of the goals of the refurbishment of the K500 cyclotron during the Coupled Cyclotron Project was the reduction of the magnetic field imperfections present in its original configuration. The purpose of this paper is to describe the work done during the first stage of the K500 mapping, related to the correction of magnetic imperfections.

1 Introduction

1.1 Imperfections in the original configuration

The K500 cyclotron was the first superconducting cyclotron to become operational in 1982. Two independent coils (with currents I_α/I_β) produce a field of approximately 5 T. During the original K500 cyclotron mapping cycle [1] the superconducting coils could not be centered with respect to the steel pole pieces. The forces at high excitation displaced the coil significantly from the centered position. To avoid this motion the coil was left in a location displaced from the steel center. During later studies [2] we found that the coil was displaced approximately 1 mm and that the magnetic imperfections in the K500 beam chamber were explained by a background first harmonic independent of excitation, see figure 1, and a variable term that was produced by the coil being off-centered. The imperfections shown in figure 1 are the result of subtracting the effect of the coil contribution to the first harmonic (due to its off-center position) from the raw data. The raw data before the coil contribution was subtracted showed imperfections that reached values of more than 20 gauss near the extraction region (see fig 2). For magnetic fields above 4.0 T another source of imperfections was detected that we interpreted at that time as being generated in the neighborhood of the outer wall of the coil cryostat. This outer wall had been modified and some sections replaced with non magnetic material while others were magnetic.

In the original configuration the presence of large imperfections forced us to use the extraction harmonic bump (trim coil 13) to compensate for these imperfections and reduce the extent of the ν_r=1 band [3].

1.2 New measurements

The new measurements and corrections described here were performed during the mapping cycle from September to November 1997. Due to a tight schedule for the project completion we decided to perform a single mapping cycle with the copper liner in place. Had we opted for a preliminary mapping cycle with no trim coils and no liner the total project schedule would have been delayed for more than 6 months, due to the extensive cryogenic and assembly work required. Once the liner is in place we do not have an easy way of adding shims to correct local imperfections. So our work was concentrated on the coil position and yoke area modifications.

The mapping system consists of a search coil that moves in a radial track with an optical sensor mounted on the coil cart that produces a trigger signal every 200 μm. The coil voltage is processed through a V/F converter and the pulses accumulated by a counter triggered by the optical sensor. See [4] for more details.

2 Imperfection correction

We studied the imperfections by measuring the magnetic field mainly at four different magnet excitations, with main currents I_α/I_β: 650/2 (B_o=2.7 T), 487.5/350 (B_o=3.4 T), 725/300 (B_o=3.7 T) and 650/720 (B_o=4.8 T). These four points gave us a broad range of I_α/I_β values and return yoke saturation. For some locations of the main coil we could not reach the 650/720 field level due to excesive link forces and the measurements were performed at lower excitations. To study the coil motion we monitored the forces on the three horizontal links L7, L8 and L9 that maintain the radial position of the superconducting coil and correlated them with the signatures obtained from the magnetic field maps.

We see in figure 3 a contour plot of the imperfection field difference for two excitations. The polar grid covers a radius of 26.5 inches with a step size of 0.5 inches and one degree in azimuth. The coil position is centered (within 0.1 mm) with respect to the steel and mapper system, and does not contribute to these imperfections. There is a large dipole field that contributes to the excitation dependent imperfection detected in the old configuration. The reduction of this first harmonic imperfection is specially important near extraction where we cross the ν_r=1 resonance. In our studies of the original

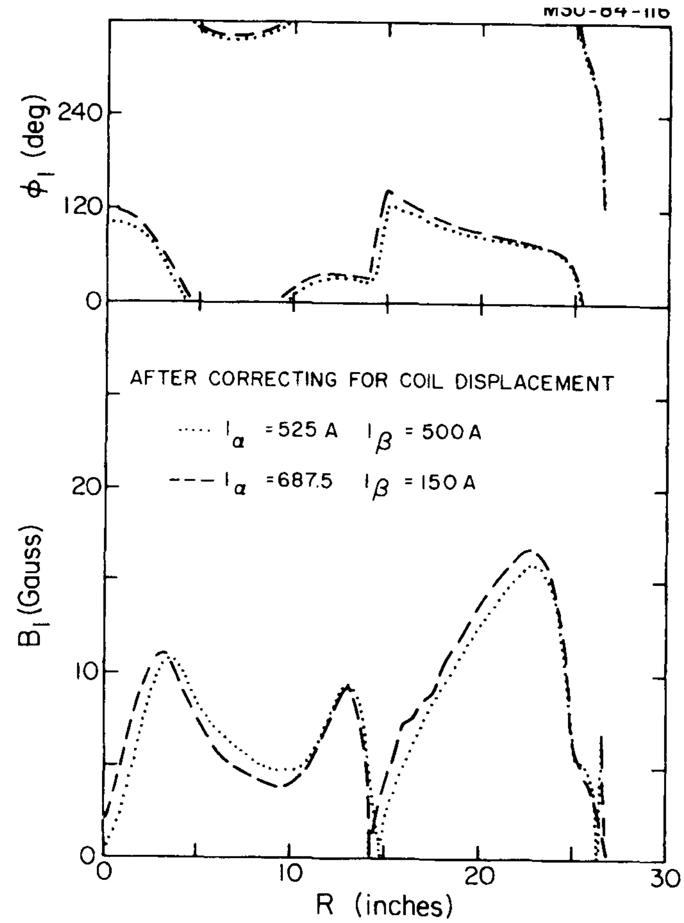

Figure 1: Comparison of first harmonic residual imperfections for two different excitations (525/500 3.9 T and 687.5/150 3.2 T) for the original configuration. These are the residual imperfections after subtracting numerically the effect of the coil being off-centered 1 mm.

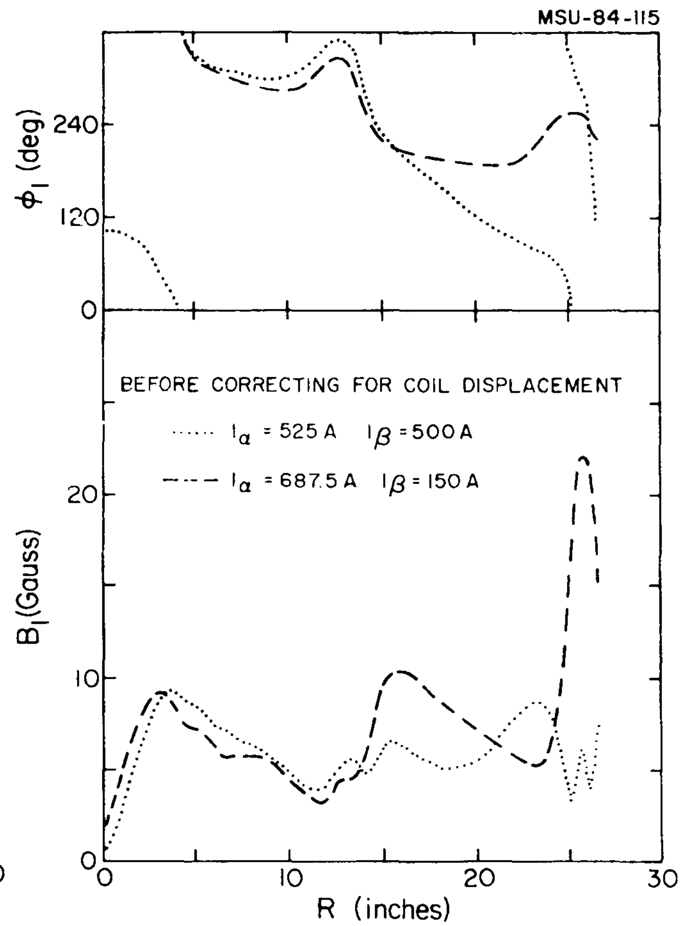

Figure 2: Similar to figure 1 (original configuration) but before subtracting the effect of the coil being off-centered.

configuration we had attributed this effect to the uncompensated outer wall of the cryostat, but in the new configuration we had made an effort to fix this oversight [5]. The source of this error was traced to the saturation effects of the cyclotron assymetric yoke. During the refurbishment of the K500 we tried to make the yoke perforations more symmetric by analyzing the volume of steel missing at several radial and vertical regions [6]. We tried to improve over the original yoke compensation design that had just looked at saturated steel (charge sheet) fields in the beam chamber region. It became obvious during the first maps that our attempts had not improved adequately the overall imperfection produced by the yoke. We then decided to insert iron pieces in the yoke holes where available. Five different steel pieces were inserted by a trial and error method that converged very quickly. These steel pieces not only modified the imperfection field, but also changed the equilibrium position of the main coil, allowing us to move the stable position to match the center of the hill steel configuration. When adding a steel piece in the yoke we create a high field bump at the same azimuth. The coil is attracted to the new piece and the stable configuration for the coil moves away from the new added steel. The approximate sizes of steel pieces are given in Table 1 .

The hole configuration available in the yoke allowed us to reduce significantly the first harmonic. The error in the field difference between a high and a low field is shown in Figure 4. This figure shows that after adding the correcting steel shims in the yoke, the excitation dependent imperfections generate mostly a second harmonic imperfection. The effect on the beam of this residual second harmonic is less important than the original first harmonic.

Cyc Angle	Map Angle	height(in)	depth(in)	width(in)	weight(kg)
90	201	8.5	22	6	145
125	236	8.5	19	2.5	52
140	251	3	20	6	47
210	321	8.5	11	2	24
0	111	54	0.75	4	21

Table 1: Yoke shims added to reduce excitation dependent first harmonic.

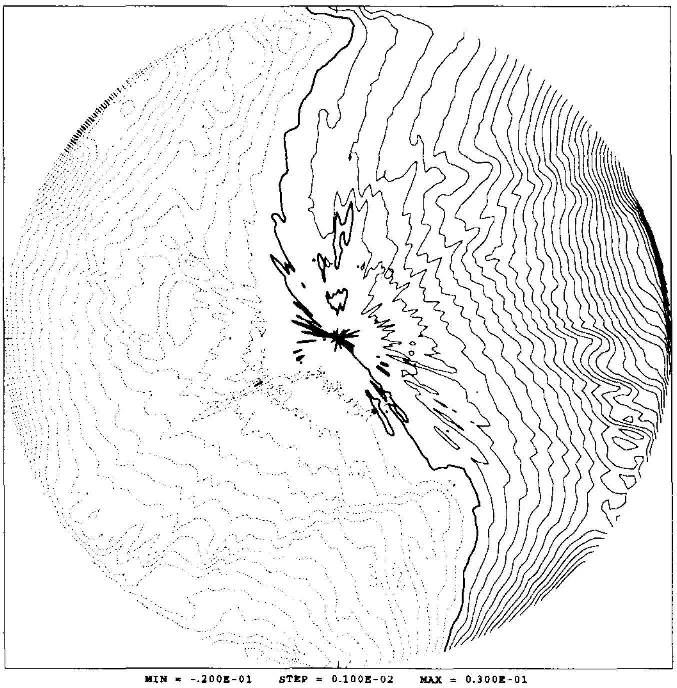

Figure 3: Contour plot showing the difference of two fields with excitations I_α/I_β=650/2 (2.7 T) and I_α/I_β= 550/605 (4.26 T). Only the imperfection fields (harmonics different from 3N) are shown. The contour step is 1 gauss, with a maximum positive contour of 30 gauss on the right and a minimum of 20 gauss negative on the left of the figure.

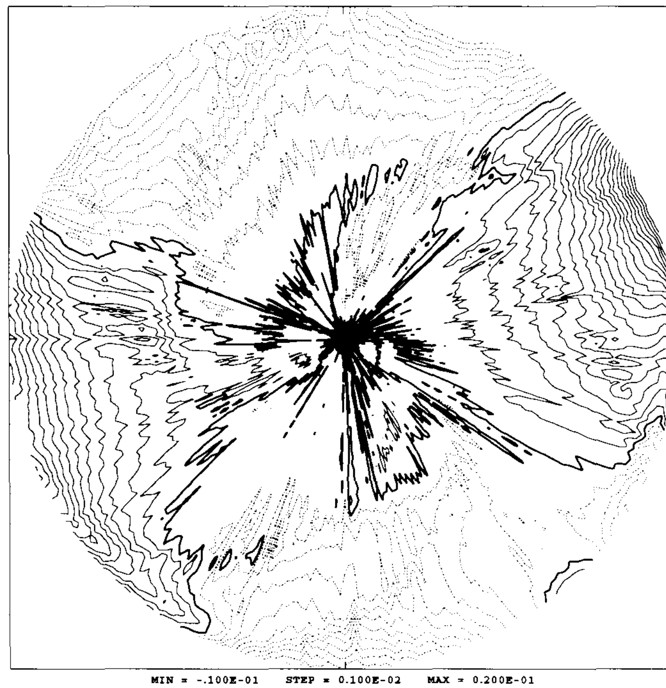

Figure 4: Contour plot of the difference of two fields after the yoke compensation was performed I_α/I_β= 593.75/618.75 (4.4 T) and I_α/I_β= 375/275 (3.0 T). The minimum contour is -10 gauss and the maximum is 20 gauss, with 1 gauss steps.

The ν_r=1 resonance occurs at R_{ave}=24-24.5 inches. The first harmonic shown in figure 5 at the resonance radius can be decreased by using the focusing bar compensators, but their locations will be different for different points in the operating diagram depending on the position of the focusing bars for the specific operating point.

We show in figure 6 the error field for the high field in the pair used to generate figure 4. This is a 3-sector difference plot where we have subtracted from the field at each point the average of its own value and the other two points 120 degrees away in the other two sectors. This essentially removes the 3N harmonics that are the dominant contribution and let us examine the error field. An excess field of one unit at some point appears then as a 2/3 excess here and in the other two points 120 degrees away we generate a -1/3 decrease field. The dominant features near the maximum radius are the focusing bars appearing as reduced field (dashed lines) and their "ghosts" at 120 degrees away. The positive field near the center of the figure and above it at approximately 80 degrees and a similar structure 120 degrees later marked as lower field can be interpreted as pole tip gap errors and they generate the 7 gauss first harmonic bump seen in figure 5 at a radius of 5 inches.

3 Conclusions

During the process of mapping the refurbished K500 cyclotron we have introduced steel shims in the cyclotron yoke that have reduced the large first harmonic that was

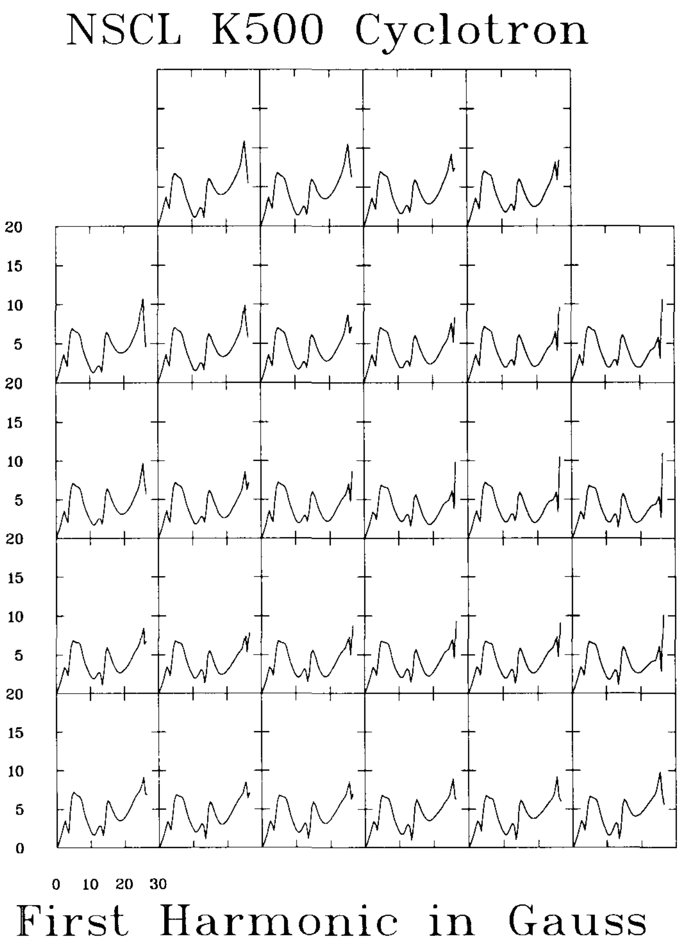

Figure 5: First harmonic imperfections over the complete mapped grid. Maps in a horizontal row have approximately the same central field and increase vertically from approximately 3.0 T to 5.0 T in 0.5 T steps. We see that no large variations are present.

present in the $\nu_r=1$ resonance crossing region near extraction. This new configuration allows us to run the superconducting coils centered over the whole operating region. This smaller imperfection should let us run the cyclotron with smaller magnetic bumps for extraction and improve the extracted beam quality.

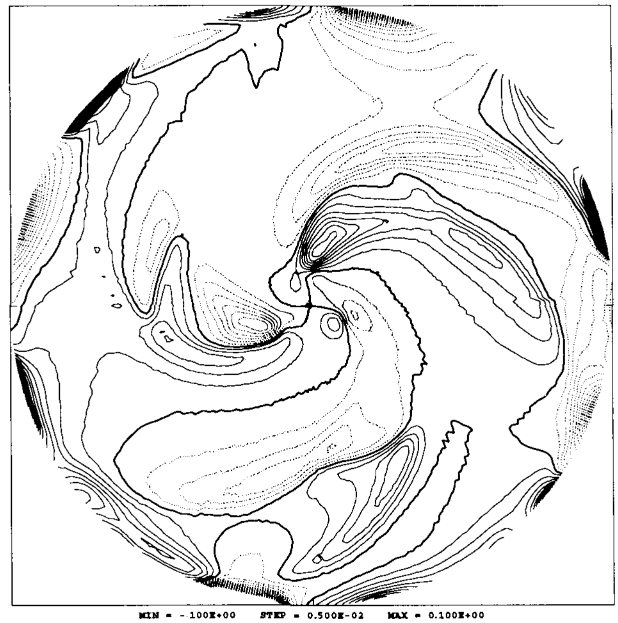

Figure 6: Contour plot of the imperfection field for I_α/I_β= 593.75/618.75 (4.4 T). The step size is 5 gauss. Maximum radius shown is 26.5 inches. Positive countours are shown in continuous lines and negative as dashed lines. The thick line corresponds to zero.

References

[1] P. Miller, D. Johnson and H. Blosser, Proc. of the 9th Intl. Conf. on Cyclotrons and Their Appl., Caen, 1981, 387.

[2] F. Marti and P. Miller, Proc. of the 10th Intl. Conf. on Cyclotrons and Their Appl., East Lansing, 1984, 107.

[3] F. Marti, H.G. Blosser and M.M. Gordon, Proc. of the 10th Intl. Conf. on Cyclotrons and Their Appl., East Lansing, 1984, 44.

[4] F. Marti, A Labview based cyclotron magnetic field mapping system,this conference.

[5] F. Marti and D. A. Johnson, NSCL-CCP11-1996.

[6] D. A. Johnson, NSCL-CCP12-1996.