MAGNETIC FIELD IMPERFECTIONS IN THE K500 SUPERCONDUCTING CYCLOTRON*

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Abstract

We describe the studies performed to understand the magnetic field harmonic imperfections in the K500 cyclotron. We have analyzed the data obtained with the flip coil measuring system and with the fast harmonic mapper, and interpreted the contributions from different components of the machine (superconducting coils, cryostat, pole tips, etc).

Introduction

The magnetic field measurements in the K500 cyclotron[1] were performed using a 55-channel flip coil gaussmeter built at MSU. The final set of measurements[2] were performed in January 1981 and they constitute the data base used in all our orbit codes (equilibrium orbit, trim coil fitting, etc). During that period, extensive test were performed trying to determine the position of the superconducting coil with respect to the iron mass. The coil bobbin is suspended from 6 vertical links and 3 horizontal ones. The horizontal position was determined looking at the first harmonic measured near the extraction radius and at the forces experimented by the 3 horizontal links. It was then observed that if we tried to minimize the first harmonic component of the field, the forces were too large.The risk of breaking one of the supports made us leave the coil in a compromise position between minimum first harmonic and minimum forces on the links.

Immediately after we had beam in the cyclotron it became clear that the imperfections in the magnet had a significant importance in how we were operating the machine[3]. We then started a detailed study of the imperfections and their origin.

Coil position

We have plotted in Fig. 1 a polar diagram showing the first harmonic measured by the 3 outermost flip coils in our measuring device. They are placed at 25.5, 26.0 and 26.5 inches radius. The different points for each radius correspond to different excitations of the main coils (the superconducting coil is divided into two circuits with separate power supplies).

Looking at the distribution of points for each radius we see that they are pretty much aligned. A least square fit to those points give a common direction for the three fitting straigth lines (65.1 ± 0.3 degrees). If the main coils are producing a first harmonic because of a displacement with respect to the mapping center, the imperfection will have a maximum in the direction of the coil displacement (or 180 degrees away depending on the sign of $\frac{dB}{dr}$).

We can calculate the first harmonic that a given coil displacement would produce. It will depend on the relative excitation of the two sections of the main coil because they have different form factors. As there might be a different first harmonic imperfection for each radius that adds to the one produced by the coils we took an arbitrary origin at each of the three lines and determined the difference along the straight line between that arbitrary origin and the corresponding imperfection for each of the measured fields. We plotted in Fig. 2 that difference versus the first harmonic amplitude produce by a coil displacement of one inch when excited at the same currents. The points can be fitted by a straight line and its slope is the same for all the radii that we analyzed. The value of the slope gives the amount that the coil was displaced, 0.036 inches in our case.

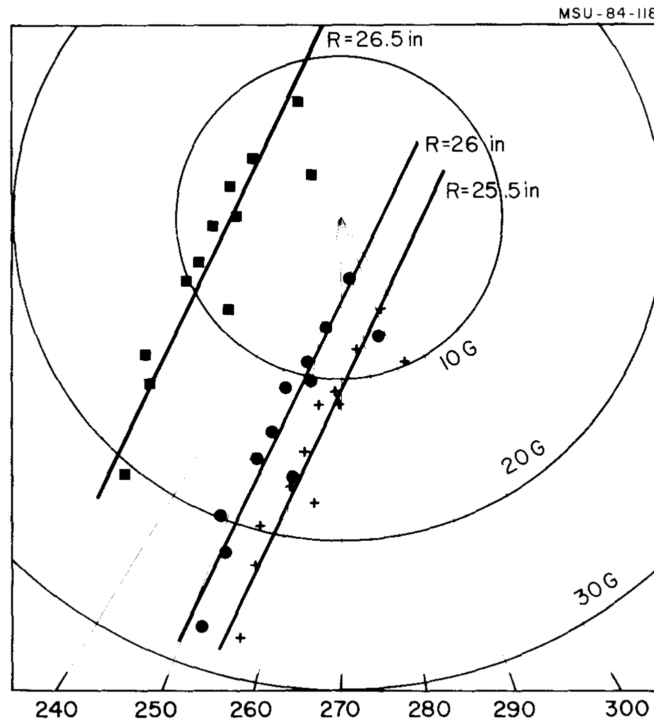

Fig. 1 Polar plot of the first harmonic imperfections for R=25.5 inches (+), R=26.0 in (O) and R=26.5 in (□), for different main magnet currents. The straight lines are least square fits to the measured points. All three lines have a common direction (65.1 ± 0.3 degrees).

We can now subtract from the measured fields the contribution of the main coils to the first harmonic. Figure 3a shows the first harmonic amplitude and its phase for two different excitations. Figure 3b shows the same two fields after subtracting the coil contribution. We see that they now agree very well and within the experimental accuracy. The plots shown in Fig. 3b are very much alike in all the measurements we did where the field level was below 4.0 Tesla. Above 4.0 T the imperfections show a new component that increases with radius and with field level but has a slowly changing phase. Figure 4 shows the difference in first harmonic for the four higher field

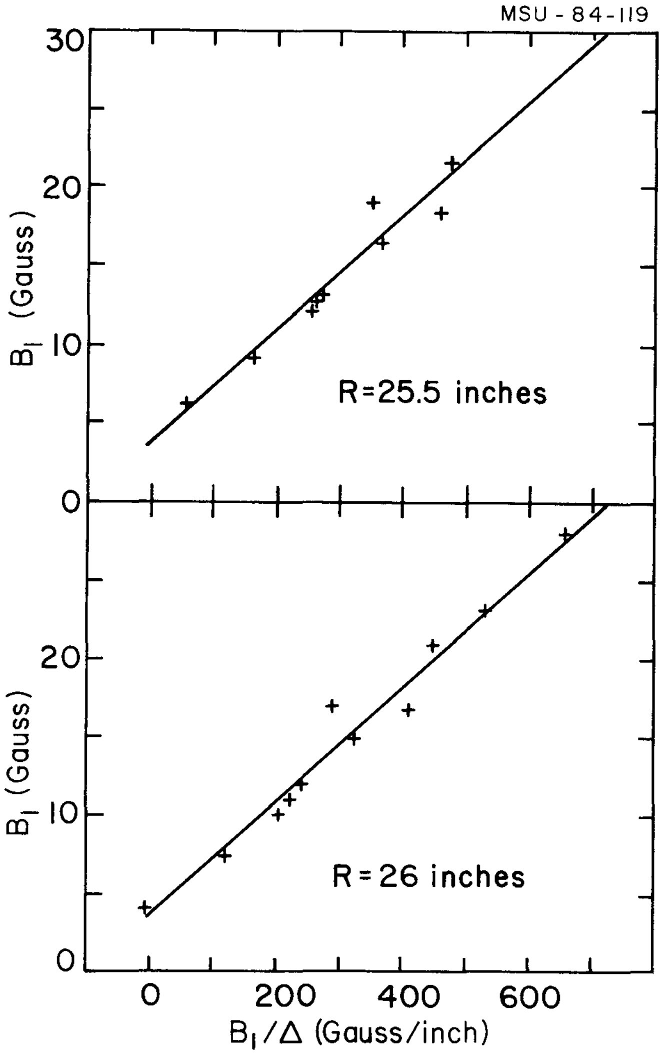

Fig. 2 When the points in Fig. 1 are projected on the straight line that fits their particular radius we can define a difference vector along the line. The magnitude of that vector with an arbitrary constant added to it is plotted here in the ordinates. The first harmonic produced by a displacement of the main coil for the corresponding excitations is plotted in the abcissa. The good correlation implies that a common displacement (0.036 inches) for all measurements explains the different first harmonics imperfections.

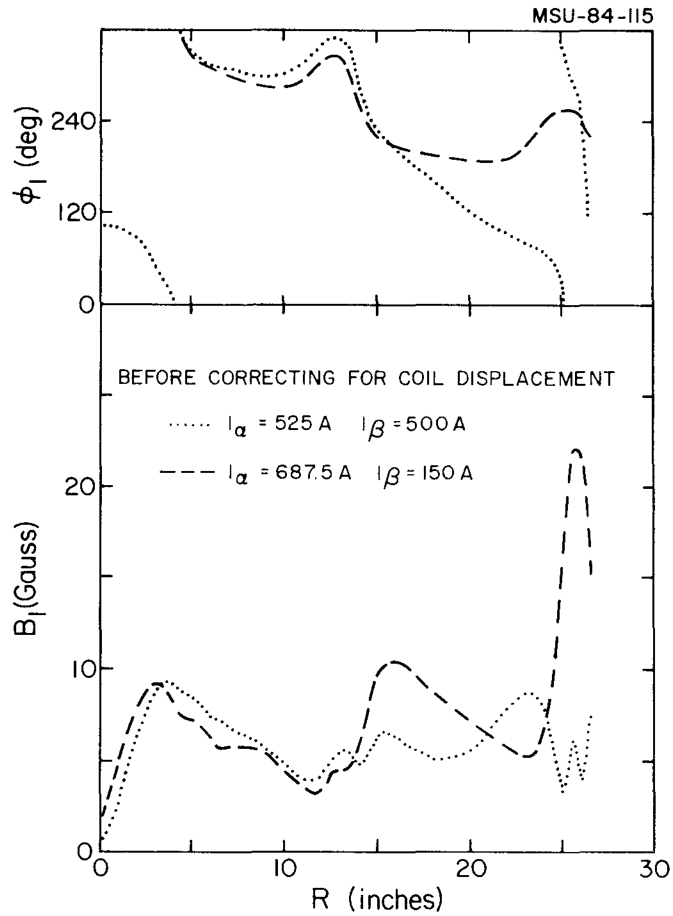

Fig. 3a First harmonic and its phase as a function of radius as they were measured for two different excitations.

measurements we made where we have subtracted a medium level field (3.22 T). The phase differences are very small and we just plotted a typical one.

The median plane of the coil cryostat is perforated to allow for the extraction elements (electrostatic deflectors and focusing bars) and their drives. The inside ring of the cryostat is made out of stainless steel, but the outer one is soft iron. These holes have not been compensated, i.e. no extra holes were perforated to keep a pure 3N harmonic in the distribution of iron. We have computed the first harmonic produced by the existing holes assuming a uniform magnetization equal to the saturation field. Circular holes have been replaced by square holes of equal area. The dots in Fig. 4 show the results of this calculation. The radial profile is very much like the high field case (B_o=4.8 T, curve d) "excess" with respect to the low field cases. The analysis of the field measured through those holes[4] indicates that they are not saturated at low excitations.

The first harmonic imperfections common to all field levels probably come from construction and assembly errors. The pole tips are split in two parts at a radius of 14 inches. Fig. 3b shows a sharp change on the imperfections at precisely that radius. The other sharp change occurs near the extraction radius 26.0 inches where the pole tip ends and continues as an independent iron piece attached to the cryostat.

The Chalk River Nuclear Laboratory group[5] observed the same discrepancy that we found between both methods of centering the superconducting coil (forces on the bobbin versus first harmonic measurements). They concluded that a residual first harmonic of just 6 Gauss was enough to create the equilibrium force that would require a displacement like the one observed in their case. The origin of this residual field can probably been found in the asymmetries in the iron (mostly the holes in the yoke). This conclusions are probably valid in our case too. The holes in the yoke have been compensated assuming uniform magnetization, but we know that that is not a very good approximation, especially when there are different shapes and sizes of the holes.

Fast Mapper

When the coil is warmed up the tension on the supporting links is released because their length increases. Due to an operator error during a warm up

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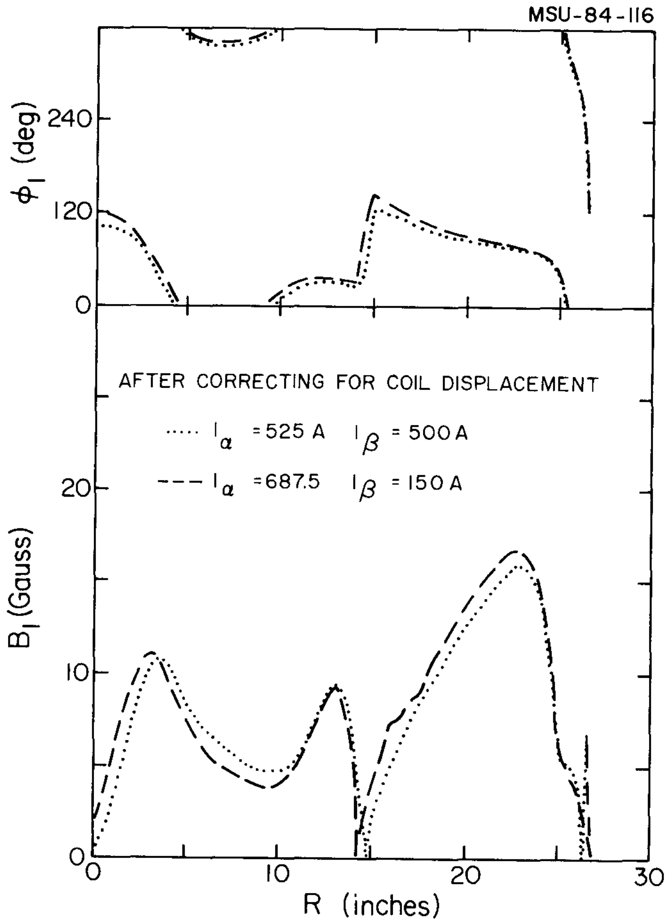

Fig. 3b Similar to Fig. 3a but after subtracting the calculated effect of moving the main coil in the direction and amount described in Figs. 1 and 2.

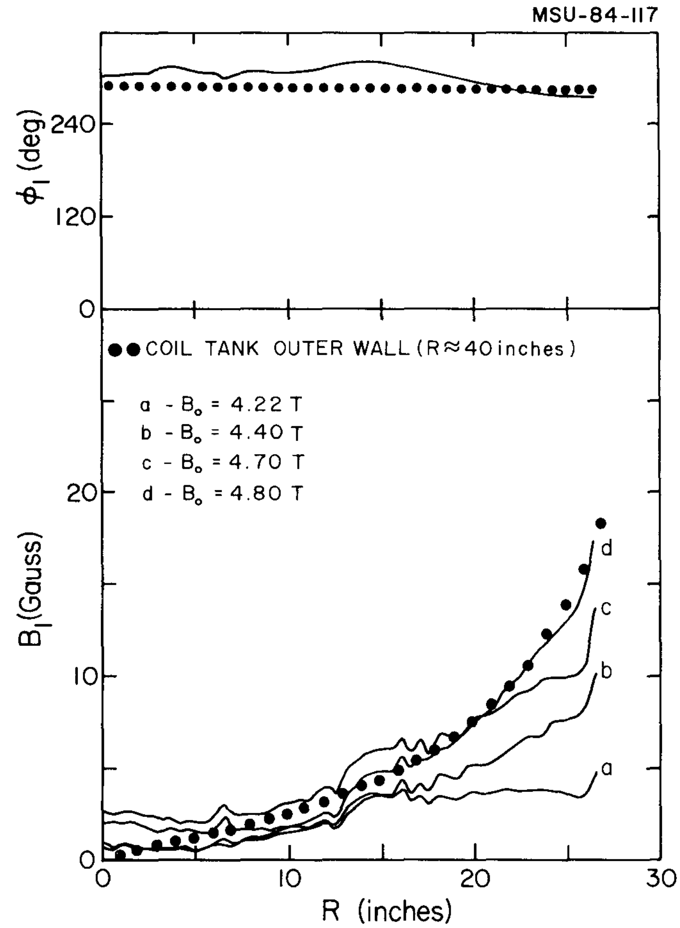

Fig. 4 First harmonic difference of the high excitation fields (4.22 to 4.8 T) minus a typical medium excitation field (3.22 T). The dotted curves correspond to the calculated first harmonic produced by the perforations on the outer wall of the cryostat tank assuming uniform magnetization (saturation field).

in the months following the mapping, the places of the adjusting nuts were not recorded, and consequently we lost the exact position of the coil bobbin. It was then decided to build a system to repeat the centering of the coil and verify the results of the previous flip coil arrangement. The old system required several hours to complete a full 360 degrees map. The new system is described in another paper in this conference[6].

An additional problem in comparing the old measurements to the new ones was an error we had in the center of the measuring devices. The second harmonic imperfection does not depend on the position of the coil with respect to the measuring center, but the iron field produces a second harmonic when displaced. We then used the difference in second harmonics to find the relative position of both measuring systems. Fig. 5 shows the measured difference and the calculated effect of shifting the measuring center by 0.0115 inches with a phase of 190 degrees.

The coil was then positioned back where the old measurements were performed, being very close to where it had been positioned trying to reproduce the readings for the forces on the links.

We are in the process of analyzing the influence of temperature changes in the magnet. The saturation magnetization of iron depends on the temperature, decreasing approximately 4 G/°C. We have found that when we change the cooling water entrance temperature we have to retune the RF frequency by several kHz.This low conductivity water is used to cool the dees as well as the trim coils that are wraped around the pole tips. To produce a first harmonic bump at extraction we excite the three branches of trim coil 13 with different currents. They might be reaching different equilibrium temperatures and consequently changing the local iron temperature, thus inducing a first harmonic of the opposite sign that we want to create forcing us to increase the current on the hill with higher temperature. We have observed in the machine a similar drift of the amplitude of the first harmonic bump that we have to create to extract the beam.

Acknowledgements

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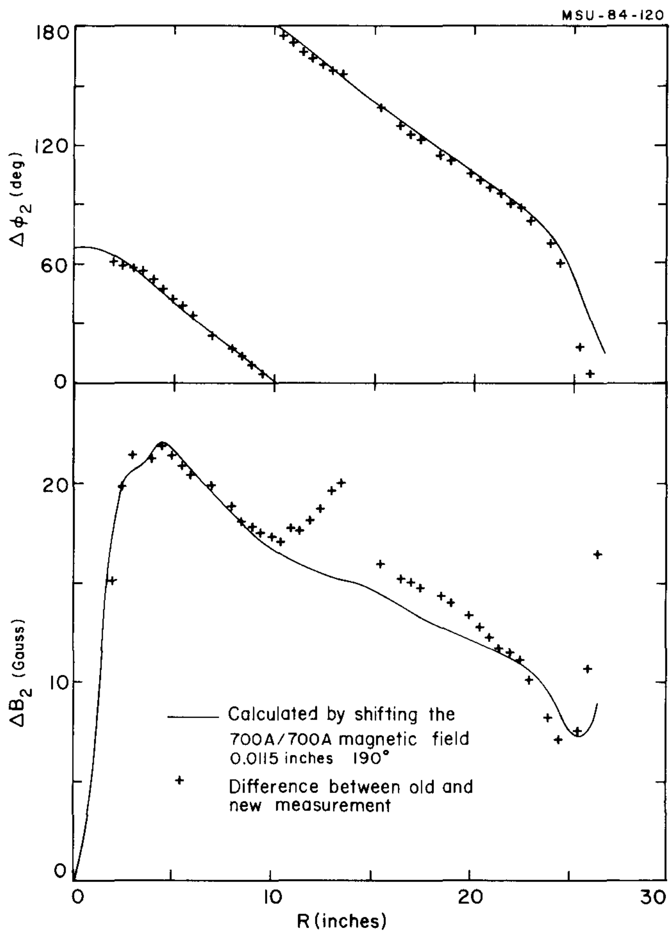

Fig. 5 The differences in second harmonics between old and new measurements for a 700 A/ 700 A excitation field are given as crosses. The solid line shows the calculated effect of displacing the mapping apparatus by 0.0115 inches.

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