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# MAGNETIC FIELD MEASUREMENTS OF THE NSCL K800 CYCLOTRON MAGNET

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## Abstract

The median plane magnetic field of the NSCL K800 magnet has been measured over its entire operating range and out to r=55 in. The results indicate that the magnet assembly and measurements were both quite good as deviations from symmetry are typically less than 5 G. Likewise, the first harmonic in the field is less than 10 G at all magnet excitations. Measured effects of calculated shims are presented.

## Introduction

Accurate understanding of the orbit dynamics of a cyclotron depend critically on knowledge of its magnetic field. This paper presents the results of measurements of the magnetic field of the K800 cyclotron at NSCL. A short description of the measurement device will precede the presentation of the data results.

## Mapping Procedure

The measurement hardware has been described in detail previously[1,2]. The procedure is to measure the field at the center of the magnet with a NMR probe and then measure the difference in field at other points in the magnet relative to the center. This is done with a search coil whose output goes to a precision bipolar voltage-to-frequency (v/f) convertor. The number of pulses output by this unit between two coil positions is directly proportional to the field difference between the two positions. The constant of proportionality was found by measuring the field at a local maximum in the magnet's field with the NMR unit and at the center; the difference in the two fields served as the calibration. The coil moved radially on a G-10 cart from r=-6.4 cm to r=105.5 cm. The cart moved on a graphite composite support bar; "droop" in the bar was compensated to about 0.05 mm. After the ~1.1m radial scan, which took about 3 sec, the bar was rotated to the next angle and the coil returned to its starting position. Radial increments between data points was 2.54 mm. The increments between datapoints were set by photosensors viewing a glass bar with alternating reflecting and non-reflecting stipes, each 2.54 mm long. The output of the photosensor was discriminated and whenever the output crossed a threshold, a logic signal was generated which signalled the computer to read the CAMAC scalers which were recording the pulses from the v/f. The angular position of each scan was determined by an incremental angle encoder accurate to 0.001°; the value of the encoder was recorded with each data point. A map in 0.5° steps (with radial steps always 2.54 mm) over the 1.1 m radial range took about 1.5 hours.

A variety of mechanical and electronic sources of error had to be dealt with in the data processing. The coil didn't pass directly over the axis of rotation of the bar, the axis of the bar was not coincident with the "center" of the magnet, there was no datum at exactly r=0, and sometimes the cart would stick slightly. The last problem manifested itself when some of the electronic errors were being corrected. These errors consisted of spurious stobes to the "read data" line, failure of the flip-flop circuit to act, unequal spacing between sequential data due to the finite width of the photosensor, and a radial offset between scans with the cart moving out and those with the cart moving in. The first two electronic errors were detected by examining the number of pulses from a fixed rate pulser that was part of the data stream and by examining the "state", ie "on" or "off" for the photosensors at each data point. The unequal spacing was handled by a four-point LaGrange interpolation to the center of the intervals defined by the fixed rate pulser values; this to made[2] the data radially good to about ±1 G. The first two mechanical "errors" were fixed by requiring that the field at $(r,\theta)$ equal the field at negative radius and 180° away, ie $B(r,\theta)=B(-r,\theta+180°)$. The results of this adjustment is summarized in Table 1. The "center" of the machine was found by assuming the poles were symmetrically placed, which is supported by the template comparisons, and minimizing the deviation from three-fold symmetry at r=25 cm. A plot of the deviation from three-fold symmetry at two radii is shown in Fig. 1. Note that the largest values occur at the pole edges where the gradient is as much as 1.57 kG/cm. The measurements thus appear to be quite good in the face of high fields and high gradients.

## Coil Centering

The first use of the measured fields was to center the coil and coil bobbin on the main body of the magnet iron. This was done by minimizing the net first harmonic in the field. The magnet was ramped to a low excitation and a map taken. Using a first order expansion in displacement, the contribution of displacements of the coil and bobbin depend on the radial derivatives of the average field of these components. A fitting procedure was written which made use of this and a prediction of the motion necessary to center the coil on the magnet was made; the indications were that the bobbin was centered within 0.12 mm. The predictions were averaged from two magnet excitations. Two iterations of the procedure brought the coil to a location which yielded little de-centering force, independent of magnet excitation. This was doubly pleasing because it showed to be working the compensation scheme that had been used for the many

Table 1

| Radius | Ampl. of 3rd harm | Phase of 3rd harm. |
|---|---|---|
| -2.0 | 738.536 | -20.417 |
| -1.5 | 341.082 | -19.600 |
| -1.0 | 105.681 | -19.105 |
| -0.5 | 13.517 | -18.887 |
| 0.0 | 0.0 | |
| 0.5 | 13.444 | -18.955 |
| 1.0 | 105.488 | -19.117 |
| 1.5 | 340.849 | -19.582 |
| 2.0 | 739.409 | -20.425 |

penetrations in the median plane of the return yoke. The hope had been that it would be largely excitation insensitive, and it apparently was.

## Magnet Assembly Quality

The critical part of the assembly of this magnet was in making it three-fold symmetric. Many opportunities existed for breaking the symmetry ranging from fabrication errors to using bolts of the wrong material. Assembly accuracy can be tested in several ways. One can examine the first harmonic or second harmonic in the field, or, alternately, the absolute deviation from three-fold symmetry. Figure 1 gives a plot of the latter; Fig. 2 shows the former two. We see that the first harmonic in the field is less the 10 G, which is within the range of the trim coils to correct. We also see a small peak in the second harmonic near the center. This could be an indication that the center plug and pole tip inner extensions may not be aligned with the rest of the machine. The deviations from three-fold symmetry shown in Fig. 1 indicate that the poles are symmetrically machined and installed to an accuracy of approximately 0.05 mm. The large derivative in the first harmonic outside 35 in. could be indicative of several possibilities. First, we could be seeing some effect from an off-center bobbin; second, one or two poles could be shifted radially relative to some chosen "reference" pole; third, the bobbin may not have an azimuthally constant gap. Calculations showed that 0.76 mm thick shims placed on two of the pole edges would greatly reduce this derivative. These shims were installed with the result shown in Fig. 3 where the original first harmonic is compared to the first harmonic after shimming. The agreement between measured and calculated shimmed fields was heartening.

## Scope of Measurements

a) Measurement domain - Figure 4 shows the operating range of the K800 cyclotron magnet in the space of its main coil excitations (Note: The two Boils combine to make a field which is nearly isochronous for a given particle, thereby greatly reducing the required trim coil power.) Superimposed on that operating is a regular grid of points; these were the excitations that served as the basis for the mapping array. Note that the two orthogonal axes of the grid are: 1) $I_\alpha + I_\beta/4$ (roughly proportional to the flux level in the yoke and to total energy), and 2) $I_\alpha/4 - I_\beta$. The ramping scheme for the magnet is to ramp only along the axes of this grid and thereby minimize hysteresis effects.

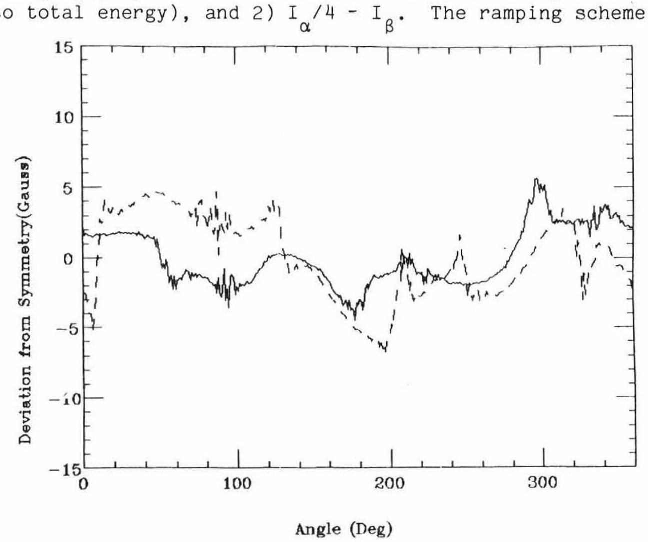


Fig. 1--Plot of deviation from 3-fold symmetry at r=10 in. (solid) and r=30 in. (dashed). This is for map full field.

b) Types of maps - Three basic type of maps were taken. 360° maps were taken at 27 points in the grid in 0.5° steps. These provide the basis of the data set for calculating all field parameters and serve as the base to compare the subsequent maps to. The trim coil fields were measured by exciting each coil individually, at each of four points in the main coil grid, and subtracting the field at the same radius and angle of the map with no trim coil but the same main coils. This was done over 135° in 3° steps for all coils except 1 and 20 which were measured over 360° as each hill must be known separately for these two in order to set the bump fields correctly. The average fields show some excitation dependence; for example, the field at r=0 of trim coil 1 with the main coils turned on to grid point 1 (833A,884A) is 128.1 G while it is 121.2 G with the main coils at grid point 25 (904A,-394A). The flutter field was quite independent of main coil excitation. It should be noted that processing the trim coil fields provide a test of the reproducibility of maps; for example, the r=0 field obtained from the trim coil map and from the base field differed by an amount that agreed with the difference in NMR readings within 2 G.

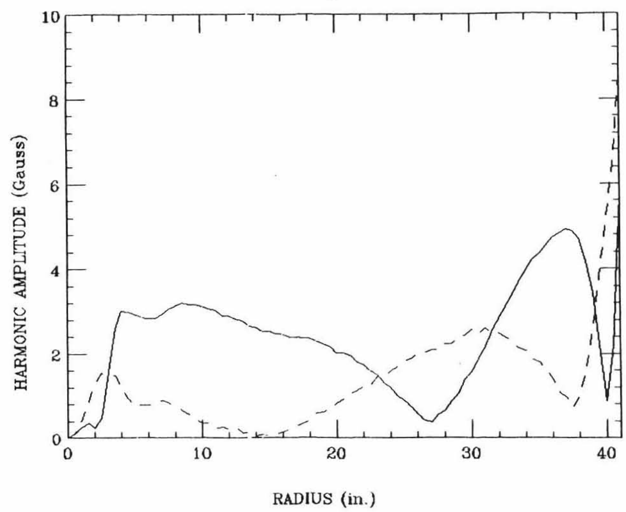


Fig. 2--Plot of the amplitudes of the first harmonic (solid) and second harmonic (dashed) in the field.

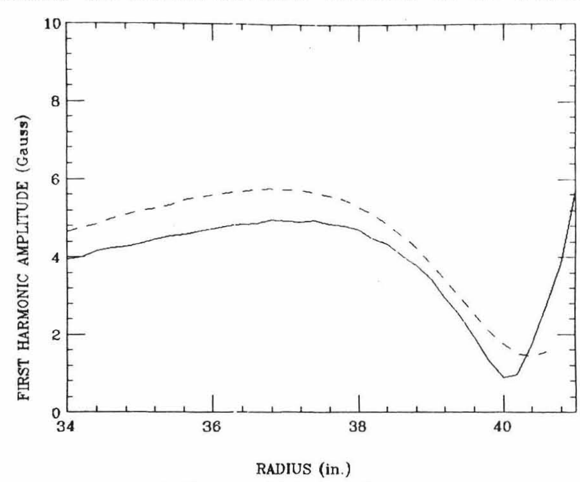


Fig. 3--Plot of the amplitude of the first harmonic in the field before shimming to remove the large derivative (solid) and after insertion of the calculated shim (dashed).

Finally, maps were made where the coil was mounted on a rod which allowed access to the interior of penetrations of the cryostat into the coil region, ie. out to 56 in. These penetrations allowed measurements at 15 angles with varying spacing; the spacing was chosen to enhance the density at angles where the azimuthal gradients are large. Measurements were made at 19 main coil excitations. These data can be used after they have been matched to the interior 360° data; interpolation between the data is based on scaling the calculated flutter to closely match the measured flutter.

During the acquisition of all maps, the quality of the data were checked with a plot of the field at r=20" vs angle. Whenever irregularities were noted, that portion of the map was redone for inclusion in later processing.

## Summary of Results

The body of data acquired of the K800 magnet is far too great to present in detail in this paper, so a brief summary will be presented instead.

a) Coil centering - The success of the coil centering indicates that we should be able to accurately center the coil on the magnet at the time of final assembly. Further, we may be able to improve the positioning of the cryostat over that during the last mapping.

b) Average fields - The average fields measured vary smoothly with coil excitation and follow the basic trend of the calculated fields[3].

c) Field errors - The important first harmonic in the field is less than 10 G in the accelerated beam region at all excitations. It varies smoothly with radius and has no well localized source until r=40 in. is reached, where it undergoes a rapid change. The source of this rapid change is yet to be found; however, small shims were able to greatly reduce the change. The remaining excitation dependence of the first harmonic could be due to one or more of several sources; these include pole motion, incomplete compensation of the yoke median plane penetrations, and coil motion. An analysis which examined the differences between various excitations and one reference excitation found the largest difference to be concentrated at large "beta" coil excitation; the ramifications of this on the analysis is still under study.

d) Shimming - After a first mapping cycle, shimming is often found necessary to achieve the desired orbital characteristics. The success achieved in pre-calculating the shims necessary to reduce the gradient in the first harmonics near 40 in. indicates that we will be able to do that operation quite reliably should it be necessary.

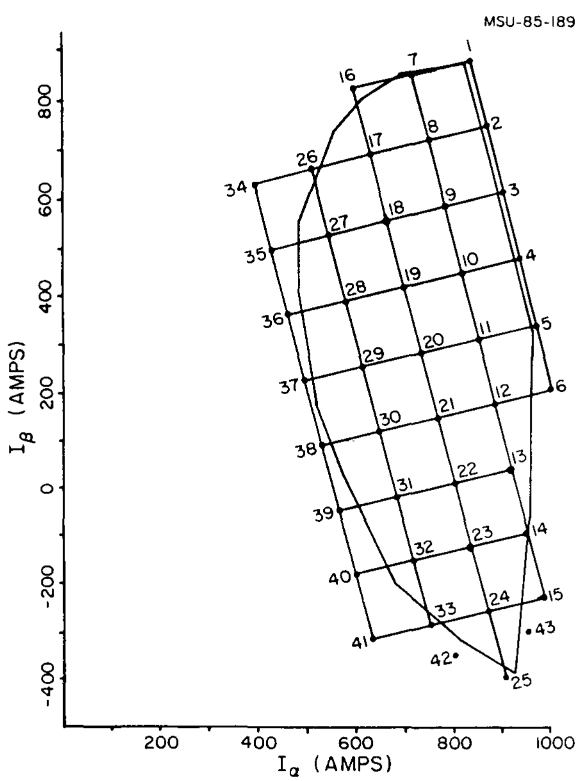


Fig. 4--Grid of points used as basis for mapping. Operating region of the magnet for real beams is shown with the full line.

## Conclusions

We have developed a system which can produce highly reliable, highly accurate maps of a high field magnet with large gradients. This system has been used to measure the field characteristics of the NSCL K800 cyclotron magnet. The results show that the magnet was machined and assembled quite well with very good adherance to tolerances. Further, all observables in the field vary smoothly with radius, angle and coil excitation. Our ability to accurately place the coil based on analysis of the fields agrees with force analyses. Finally, shimming, if necessary, can be done reliably based on calculated shims.

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