IMPROVEMENTS IN THE NUMERICAL MODEL OF THE NSCL K800 SUPERCONDUCTING CYCLOTRON MAGNET*

L.H. Harwood
NSCL, Michigan State Univ.
East Lansing, MI 48824-1321
U.S.A.

Abstract

The results of a recent recalculation of the magnetic field properties of the NSCL K800 cyclotron magnet showed improved agreement with the measured fields. The size of the remaining errors were larger than desired. The errors in the model's field have been investigated and their dominant features understood as arising from the azimuthal components of the magnetization of the iron. Further improvements to the model are also discussed.

Introduction

Historically cyclotron magnets have been constructed after two or more laborious cycles of building and mapping successive model magnets. While this has by and large been successful, the cost becomes prohibitive with large magnets; secondly the construction of a model magnet for a 30-50 kG superconducting magnet can be more of an engineering challenge than a full scale magnet due to the limits of current density for present superconductors.

Computer modelling was the basis for the designs of the NSCL K500 and K800 cyclotron magnets and no small-scale model was built for either. The successful operation of the K500 cyclotron has proved that the procedure works with some shimming of the actual magnet. Nevertheless, discrepancies between the calculations and the measurements in the azimuthal average of the median plane field were as large as 0.4 kG[1]. The K800 cyclotron magnet proved a more formidable task. The radius of the magnet is increased by 40%, thereby straining the computer codes used for the original modelling and putting the new calculations' accuracy at risk; the larger size would also increase the forces on various parts of the magnet. We have therefore moved to enhancements in the codes used for the calculations and enhancements in the details in the numerical model. Accurate measurements of the field of the magnet have allowed reliable testing for the calculations. We will discuss here the enhanced calculations, comparisons with the data, and proposed future enhancements.

Numerical model

The orbit dynamics in cyclotrons are dominated by the azimuthally averaged magnetic field, hereafter refered to as B_{avg}. Next comes the azimuthal modulation in the field, hereafter refered to as $B_{flutter}$. Software to do the B_{avg} calculation with some detail exists, eg. POISSON, TRIM, PANDIRA, GFUN. However, $B_{flutter}$ requires some type of three-dimensional calculation. It was decided, therefore, to break the calculations into two stages, first B_{avg} and then $B_{flutter}$.

A) Azimuthal average of field

The basis for the new B_{avg} calculations is the NSCL version of the code POISSON.[2,3,4] The axial symmetry option is used. Regions which do not have axial symmetry are modelled with an effective permeability curve which reflects the mixed occupation by air and iron. 22000 points, with 12000 in the iron, are used with the "universe" boundary at R = 3000 in and z = 3000 in. Table 1 lists the errors in the calculated B_{avg} for several magnet excitations. Eventhough the agreement is better with the new calculations, there is room for improvement. It is this improvement that is addressed here.

Table 1

Error in B_{avg} at R = 0.5 m

B(r=0)	$B_{meas} - B_{calc}$ (kG) old	new	after offset
2.75	-.08	.47	.02
3.0	.19	.51	.06
3.2	.12	.40	-.05
3.4	.09	.64	.19
3.8	-.01	.52	.07
3.9	-.11	.32	-.13
4.1	-.25	.23	-.22
4.4	-.28	.33	-.12
4.6	-.47	.24	-.2[illegible]
4.7	-.70	.11	-.34

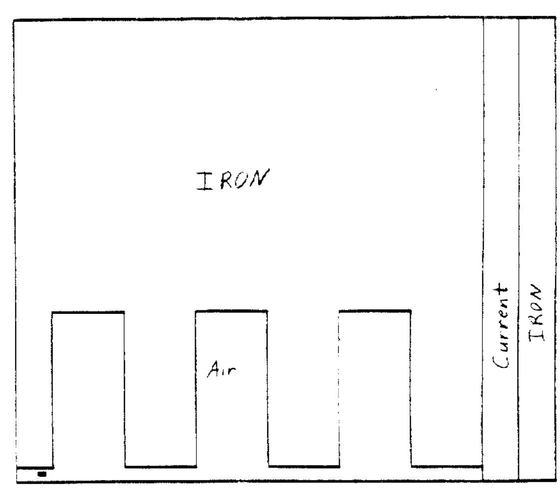

Figure 1. "End" view used for tests of accuracy of stacking factor. For "side" view, the pole-valley region was replaced with a "stacked" material.

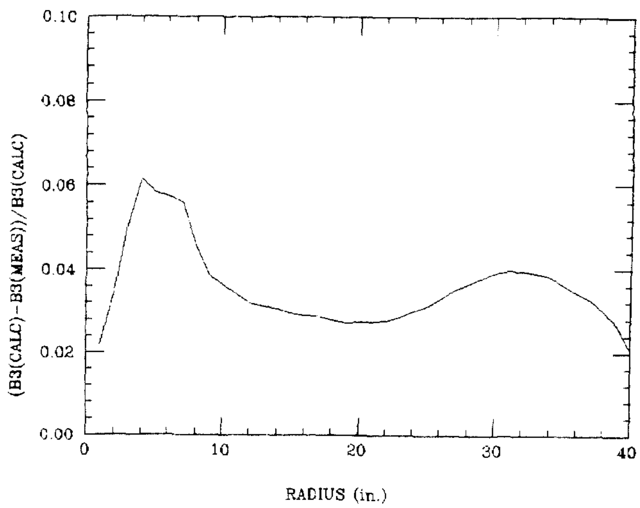

Figure 2. Percentage error in the leading harmonic term in a Fourier analysis of the field.

As the stacking factor option in POISSON is a critical part of the calculations, the accuracy of this option was tested. Earlier tests[3] were for a different geometry and lower fields; however, the method used for the test was similar to that in ref. 2. In the tests, a model magnet was calculated with POISSON in two-dimensions as viewed from two orthogonal perspectives. In the first view, termed "end", the magnet has repetitive structure, as shown in fig. 1. The "poles" of the model are analogous to the poles of the cyclotron. In order to reduce edge effects, the fields of only the central pole, valley, and first pole are used. The "side" view replaces the "poles" and intervening spaces with a region of uniform material that has a stacking factor representative of the pole geometry, ie. if the poles and spaces are equal in size then the factor is 0.5. The same current is used for both views. For a factor of 0.4, comparable to the 0.38 which is valid for the cyclotron's pole region, the error in B_{avg} is 0.45 kG. This value varies little with field level above 30 kG; it does, however, depend fairly linearly on the stacking factor with the error going to 0. as the factor approaches 1. If this "offset" in B_{avg} is added to all fields, then the range of the range of errors changes from +110 - +640 G to -350 - +190; this is not a big improvement in the maximum error but the average error is much closer to 0, ie. 0.4 kG is reduced to -0.1 kG which is a four-fold improvement.

B) Azimuthal modulations in the field

Flutter calculation utilize a model in which the non-axisymmetric portions of the magnet are given a uniform, vertical magnetization[5] distributed over the exact geometry of the magnet's parts. The field is then calculated as a surface integral of the effective currents on the pieces. This process obviously neglects the radial and azimuthal magnetization components. The rounded edges of the poles tips (which facilitate wrapping the trim coils around the pole tips) are modelled by square notches in the pole edges which remove the same volume of iron from the calculation as is removed on the real pole tip. These calculations yield $B_{flutter}$ values in error by as much as 0.3 kG or, typically, 3% of the amplitude of the third harmonic term in a Fourier series representation of the field as shown in fig. 2; it is this term which dominates the flutter of our 120 degree symmetric field. If the amplitude of this harmonic term is receives an ad hoc correction, the remaining errors occur at the pole edges, as shown in fig. 3.

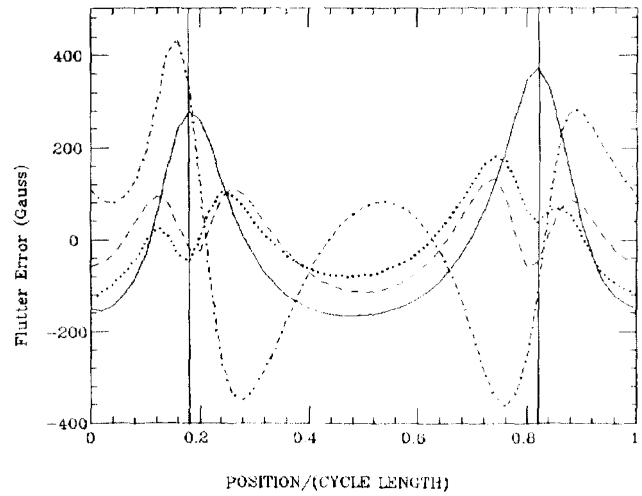

Figure 3. Comparisons of flutter field after scaling to make the leading harmonic terms equal. Pole edges are marked with vertical lines. Solid curve is the difference between the real data and the original flutter calculation. Dots: same as solid curve except the calculated pole has no notch (see text). Dashed curve: two dimensional test. Dot-dash: Data minus two-dimentional POISSON (without any scaling).

The flutter error decreases with increasing field level. Table 2 lists the flutter error at three fields. Over this field range, the error changes from 3.5% to 2.4%. One would expect the effects of azimuthal components of the poles' magnetization to have a similar behavior.[1] To test this hypothesis POISSON was again used to model the geometry. Fig. 4 shows the problem in POISSON form. This geometry was used as it closely matches the pole-valley geometry of the K800 magnet near r=0.5 m; the amount of iron removed with the bevel on the pole edge has the same area as that removed by the rounded pole edge described earlier. It is one cell out of an infinite lattice of identical cells. The vector potential is set constant along each vertical boundary, a Neumann boundary condition is required for the top and bottom surfaces, and a Dirichlet condition at the left and right boundaries. The field level is varied by changing the potentials along the sides. The average field was subtracted from the result. The POISSON results were compared to a calculation of the same iron geometry (but without the edge bevel) in a uniform, vertical

Table 2

Flutter Error (%)

B_{avg} (T)	2-d	3-d
3	3.6	3.5
3.4		3.4
4	2.4	
4.7		2.3
5	1.6	

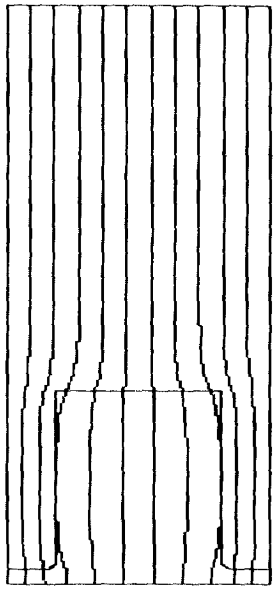

Figure 4. Geometry used for POISSON study of flutter.

magnetization model; to form the lattice, the pole is repeated for 300 cycles of the lattice and the fields of the central cycle was used. Table 2 shows the results. As the POISSON results simulate the "real" field and the uniform magnetization calculation represents the original model for the cyclotron's poles, we see that our hypothesis as to the source of the flutter error appears to be correct: including the azimuthal components in the magnetization of the pole, the test model results give a field level dependence to the flutter error which is close to that of the error in calculating the field of the cyclotron. A new technique for calculating the flutter could therefore include a step which the flutter calculated with the quasi- three dimensional uniform magnetization model is reduced by the fraction predicted by the comparison of the two dimensional POISSON and uniform magnetization calculations.

After performing the scaling just described, the remaining flutter error is at the pole edges. It was noted that the agreement between the 2-d calculations was distinctly better than that between the 3-d calculation and the data as shown in fig. 3. This was surprising in that while the 3-d calculation attempts to include the effect of the pole edge chamfer, the 2-d calculations have a bevel in the POISSON calculation but none in the uniform magnetization calculation. The 3-d uniform magnetization calculations were modified to remove the square notch and the resulting field compared to the data (again, after scaling the overall calculated flutter as described earlier). Fig. 3 compares the results to the earlier ones. The square edge worked equally well at all radii. The square edge does, however, increase the discrepancies in the overall flutter. The errors do not surpass 3.5% (after applying the correction deduced from the 2-d calculations) and occur at the inner end of the poles where the flutter is markedly reduced from the 0.2 m< r < 1.0 m region. The net result is an improvement in the flutter calculation at all radii. With these results, one might expect that the 2-d POISSON calculations would be sufficient for an accurate representation of the flutter; fig. 3 shows this to not be the case. The 3-d aspects of the problem remain strong.

The accuracy of the flutter field calculation depends critically on the saturation field value used for the magnetization. While the value of the saturation field of the iron in our magnet is not precisely known, some sources give a value of 21.2 kG for low carbon steel while others give 20.8 kG. The calculations presented here used 21.4 kG as the saturation value of the magnetization. Reducing this value would accomplish the scaling suggested by the 2-d POISSON results. It is, nevertheless, intriguing that the inclusion of the azimuthal components of the poles' magnetizations accounts for the shortcomings of the original model without having to resort to changes in the 21.4 kG value. In particular, the peak-valley field difference of the POISSON calculation matches the real magnet quite well as seen in fig. 5. Using the default permeability table in POISSON which has a saturation value of 21.2 kG changed the 2-d flutter results by less than 0.5%, ie. less than half the change in M. The effects of the detail of the permeability curve are still under investigation.

Future Improvements

Several avenues of investigation are open. An intriguing step would be to utilize the magnetizations found by POISSON in the r-z and θ-z calculations in a 3-d integration of the $B_{flutter}$ and B_{avg} field of the poles. Inclusion of the flutter produced by sections of the magnet which are not presently included would also improve the model; for example, eventhough the cryostat inner wall is cylindrically symmetric, its radial magnetization would have azimuthal variations due to the field of the poles. Plans exist to further upgrade our POISSON to permit each triangle of the lattice to have a different stacking factor; thus the major discontinuities in the stacking factor would be eliminated. As mentioned previously, modification of the permeability curve used in the POISSON calculations is under study. The ultimate approach is a 3-d calculation; software design and mathematical models testing are presently underway as no existing code, eg TOSCA or GFUN3D, can address the problem in sufficient detail.

Conclusions

The field calculations for 30-50 kG cyclotron magnets are presently good enough to permit construction of full scale magnets without small-scale modelling. With the modifications in the model outlined here, the B_{avg} calculations can be brought to an accuracy of 0.35 kG or 1 % at low fields and the flutter to better than 0.2 kG or 3% at the end of the poles.

References

1) G.Bellomo, et al, NIM 180 (1981) 285.
2) R. Holzinger, private comm.
3) L.H.Harwood and D.A.Johnson, Proc. of 10th Int. Cycl. Conf., (1984) 99.
4) L.H. Harwood and B.F. Milton, Proc. of 11th Int. Cycl. Conf, Tokyo 1986, in press.
5) M.M.Gordon and D.A.Johnson, Part. Accel. 10, (1980) 217.
6) J. Verster, private comm.

* This material is based upon work supported by the National Science Foundation under Grant No. HY83-12245.

** During this study a similar approach for the flutter was proposed independently by Verster.[6] However, no results were presented.