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COMPARISON OF MAGNETIC FIELD CALCULATIONS TO MEASUREMENTS ON A CBA 2-IN-1 MAGNET SYSTEM

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Abstract

The CBA[1] 2-in-1 dipole magnet provides a complex system to test field calculation techniques. In particular the quadrupole term in one half of the magnet induced by the operation of the other half of the magnet is studied. A comparison with field measurement data is made for calculated magnetic field harmonics as a function of current for symmetric and asymmetric operations of the two sides of the magnets. The calculations are made using both differential equation solving programs (PE2D,[2] POISSON[3]) and integration based programs (GFUN).[4] These programs are compared to each other and to the measured data.

Introduction

Finite element field calculating programs can provide valuable information on the expected performance of an accelerator magnet. Three such programs using different solving techniques are available at Brookhaven National Laboratory. In this study we model a CBA 2-in-1 dipole using PE2D, POISSON and GFUN. In the CBA 2-in-1 magnet the field from one dipole is returned through the dipole on the other side with opposite polarity (see Figure 1). The coupling of the fields from the two dipoles through the iron provides a significant test for these non-linear iron finite element programs. This influence of one dipole field on the other (called cross talk) manifests itself most strongly in the quadrupole term of the field harmonic expansion. There are effects, however, in all harmonic terms. As this magnet has been constructed and tested, the calculations can be compared to experimental data.

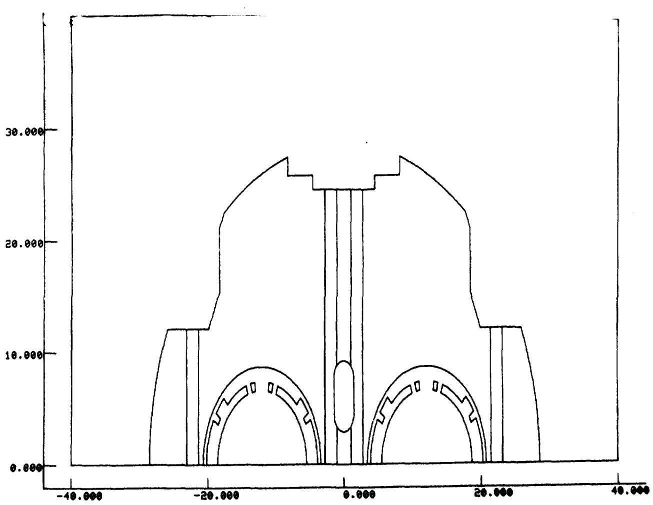

Figure 1. Schematic of CBA 2-in-1 cross section.

The magnet was run with the two sets of coils at the same current (symmetric operation) and with different currents on each side (asymmetric operation). Magnetic measurements were made with both symmetric and asymmetric operation.

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The Programs

The three computer programs all use finite element techniques to solve a non-linear (due to the iron) problem. GFUN solves for the magnetic field at a point by integrating over current source and magnetization (iron) regions. With GFUN one need not "mesh" regions where no iron or current is present. The limit on the number of elements that the iron can be divided into is about 200 on the CDC 7600. This limits the resolution. Both the PE2D and POISSON programs use the differential equation approach solving Poisson's equations in two dimensions. All of space is divided into elements. A practical limit of 10,000 nodes for a problem is set by the required computer time. For example, PE2D requires 24 VAX-780 CPU hours or 40 CRAY XMP minutes for this problem. The PE2D program solves by a direct solution of equations using an Incomplete Cholesky Conjugated Gradient technique. PE2D iterates only because the B vs H relation is nonlinear. POISSON solves by the traditional successive point over-relaxation method which is very efficient if the problem converges rapidly. POISSON required only 6 VAX-780 CPU hours to solve the CBA 2-in-1 model.

The Model

The idea was to model the CBA 2-in-1 magnet system in a similar manner for each of the three programs. In addition the model should be close to the real magnet as constructed so that the comparison with the experiment data would be valid. Figure 1 shows a picture of the model used. The model is drawn in the entire upper plane so that the two sides of the magnet can be operated at different currents. The dimensions of the iron are the room temperature values.[5] The effect of shrinking the dimensions to cryogenic temperatures is expected to cause a small change in B and no change in the field harmonics. This has been verified by calculation. The B vs. H table used to describe the iron contains a small correction ($\sim$1½%) for the gap between iron yoke blocks. The region containing the stainless steel bolts is represented by a special iron B vs. H table that described an average of the iron density. For the differential equation programs (PE2D and POISSON) one must describe the field over all space. The outer boundary should be at a sufficiently large distance so as not to affect the results. We have chosen $\sim$1.5 times the iron outer radius for the outer boundary. Since the flux is small outside the magnet this radius appears adequate. Tests were made by varying this boundary radius to verify this choice.

Because of the idiosyncrasies of the particular programs, certain small compromises have to be made. The GFUN program cannot handle curved surfaces. Polygons of equal area are used to approximate circular holes. This applies both to the iron aperture and the holes in the iron used for helium flow and to reduce the effects of cross talk (see Figure 1). PE2D puts restrictions on what is an acceptable mesh. The mesh must be continuous with nodes on element boundaries shared with adjacent elements. An element should not be too oblong nor drastically different in size from its neighbors. This means that gaps at the midplane and gaps between the inner and outer coils cannot be modelled. It is possible with small compromises to adequately describe the CBA 2-in-1 magnet system by all three programs.

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Results - The Symmetric Case

The magnet was operated with symmetric current loading of the coils for most of the testing program. A complete current sweep up to 3700 amps was made. Figure 2 shows the test data and the results of the various computer programs. The results are shown for B_o/I and for the harmonics b_1, b_2, b_3, b_4 defined for B on the midplane as follows:

$$B = B_o \left(1 + b_1(\frac{x}{r_o}) + b_2(\frac{x}{r_o})^2 + \ldots\right)$$

The b_i harmonics are normalized to $r_o = 4.4$ cm, the effective size of the useful aperture. The measured data is indicated by a dashed line on the graphs. Calculations were made with each of the three computer programs at 8 current settings. The results are plotted on Figure 2 with a different symbol for each program. Figure 2a gives B_o/I vs. I. All of the programs agree well with each other and with the measured data for B_o/I. The cross talk between the two sets of coils manifests itself most strongly in the odd harmonics breaking left-right symmetry. The measured b_1 data in Figure 2b shows the cross talk contribution for I > 2500 amps reaching about 20 b_1 units at 3700 amps. All three programs show this cross talk b_1 term in the high current region. They all have a tendency, however, to over estimate b_1 by about 30%. GFUN predicts a large positive b_1 between 2000 and 3000 amps that is not seen either in the measured data or in the results of the other programs. This is not understood. The b_3 distribution (Figure 2d) shows features that are similar to the b_1 distribution. Above about I = 1800 amps effects of cross talk become apparent. At 3700 amps there are 7 octupole units present. The three programs reproduce the basic trend of the curve but over estimate the effort by about 25%. The sextupole and decapole distributions probably best illustrate the effect of the iron geometry in the magnet. In these distributions the different programs do exhibit different trends. The POISSON program results for the b_2 distribution fall off faster at high current than the data. The PE2D results are systematically higher than the data for the entire b_2 distribution. This may, however, only reflect the fact that any discrepancy of the construction of the magnet coils from the design parameters will raise or lower the entire b_2 distribution by a constant value. The experimental b_2 distribution shows the effects of superconducting magnetization at low current. This effect is not included in the calculations. Table I gives the difference of the sextupole at low field from the peak value and the position of the peak for the three programs and the measured data.

Table I

	Δb_2	Current at b_2 peak
data	31.0	3100 amps
PE2D	25.7	3200 amps
POISSON	25.6	3000 amps
GFUN	34.1	3450 amps

Figure 2e shows the decapole distribution. The experimental results show a characteristic dip at 2200 amps. PE2D and POISSON also indicate this behavior in the b_4 distribution, however, GFUN does not. GFUN does not do well in the low current, high permeability region. The POISSON results are low in the high current region - this effect may be related to a similar effect seen for the sextupole.

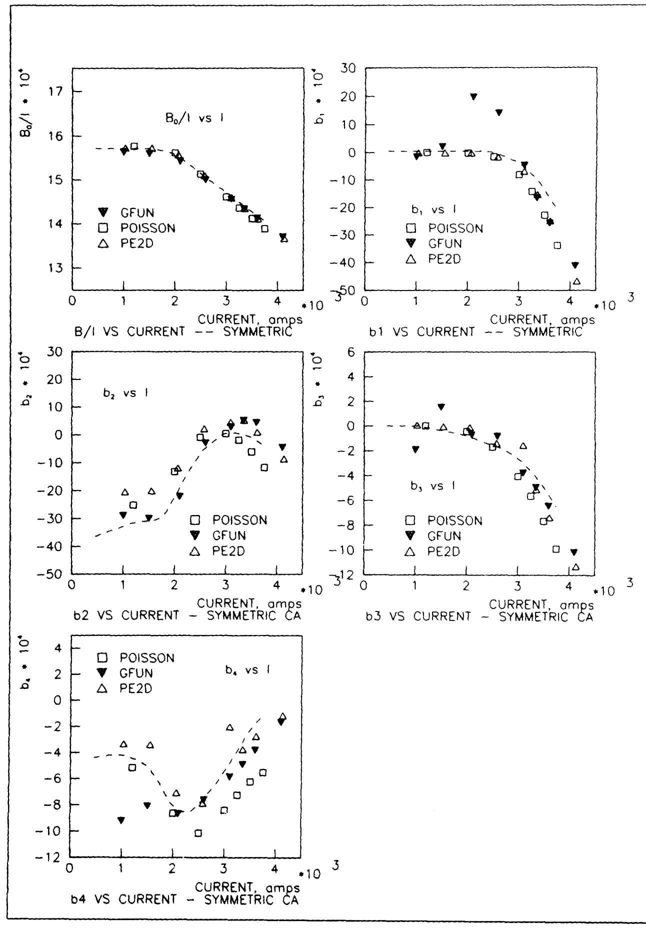

Figure 2. B_o/I and field harmonics b_1, b_2, b_3, b_4 for symmetric operation. Dashed curve represents experimental measurements.

Results - The Asymmetric Cases

The 2-in-1 magnet was tested with asymmetric loading of the current to gain insight on the effect of "cross talk". The two sides of the magnet were run with the following current ratios: 1.1:1, 1.5:1, 2.5:1. For each current ratio four current positions were measured. The actual field measurements were made on the low current side since one would expect the coupled field effects to be the largest there. Figures 3, 4, and 5 show the results for each harmonic for the three current ratios listed above. In particular, Figure 5 shows the most asymmetric situation with the current ratio of 2.5:1. The differential equation programs, PE2D and POISSON, agree with each other and with the relatively sparse experimental data. GFUN does not describe the trends of the data very well. There are large discrepancies in the GFUN calculation of the higher harmonics b_3 and b_4, and to a lesser extent in b_1, but b_2 agrees well with measurement.

Conclusions

The CBA 2-in-1 magnet system provides a rigorous testing ground for magnetic field calculating programs. The magnet was modelled for the GFUN, PE2D, and POISSON programs. The GFUN program, although simpler to use, did not agree with the data as well as the other programs. This may, in part, be due to the limited segmentation available because of computer memory restrictions. PE2D and POISSON did adequately well in describing the magnetic properties of the CBA magnet systems. PE2D and POISSON each have different properties that might be favorable in

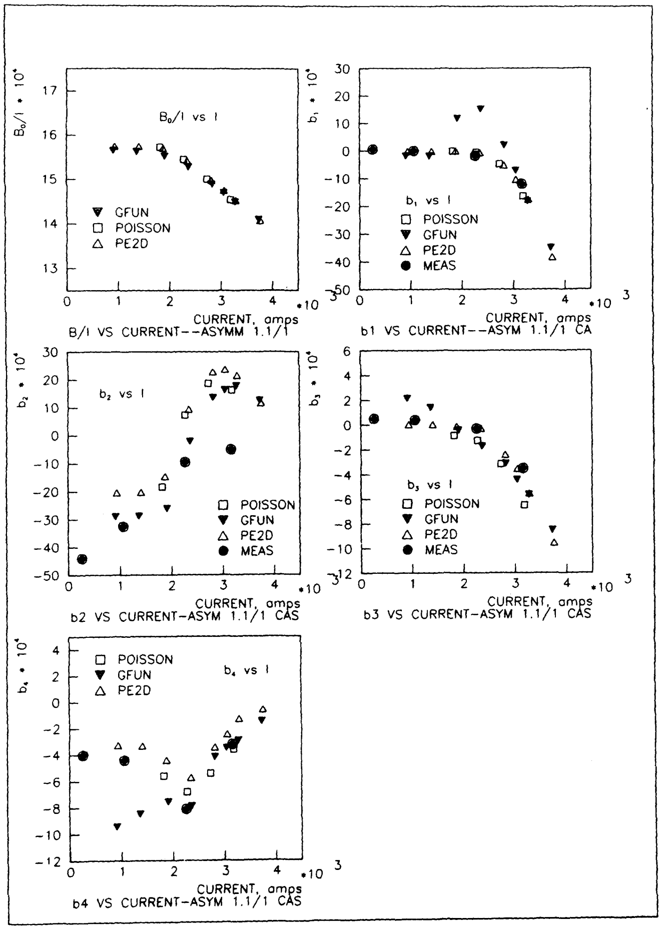

Figure 3. Field calculations and measurements for asymmetric operation with 1.1:1 current ratio. Low current side is displayed.

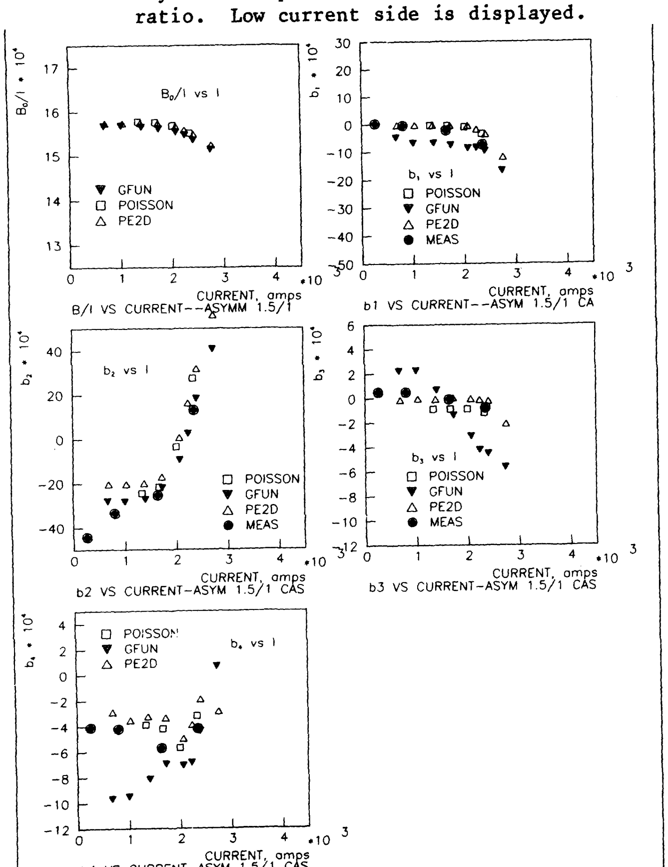

Figure 4. Field calculations and measurements for asymmetric operation with 1.5:1 current ratio. Low current side is displayed.

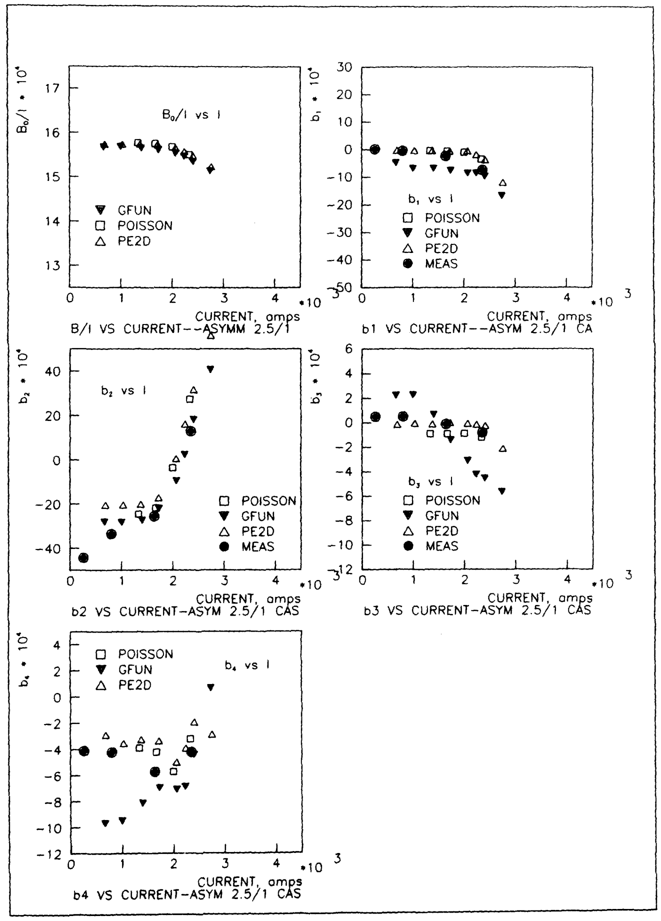

Figure 5. Field calculations and measurements for asymmetric operation with 2.5:1 current ratio. Low current side is displayed.

different situations. For example PE2D had higher order elements (quadratic elements) whereas POISSON only has linear elements available but converges much faster allowing more nodes to be used practically. (The limitation on the number nodes is essentially the computer time needed to run the problem.) Both of these programs provided reliable results for the case modelled, to an accuracy of a few parts in 10^4.

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5. The temperature should have been at 4.5K corresponding to the magnet test temperature.