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Modification of the CEBAF Transport Dipoles for Energy Upgrade Considerations *

D. Bullard, L. Harwood, T. Hiatt, J. Karn[#], E. Martin, W. Oren, C. Rode, K. Sullivan, R. Wines, M. Wiseman, Thomas Jefferson National Accelerator Facility, Newport News, VA

Abstract

The CEBAF accelerator at the Thomas Jefferson National Accelerator Facility contains 415 resistive dipoles in the recirculation arcs and transport lines. These dipoles were originally designed and magnetically mapped to support the operation of the accelerator at 6 GeV. Recent interests in upgrading the CEBAF energy beyond 6 GeV prompted a study into operating the dipoles beyond their design limits. Finite element modeling was performed to quantify saturation effects at higher currents and to test simple modifications to improve magnetic performance. For confirmation, various setups were prototyped and magnetically measured. Measurement results agreed with finite element models and showed that saturation could be reduced to manageable levels. It was found that the most populous dipole families could be modified to reach twice their design field with minimal cost and effort. At these higher fields, the magnets operate at a reasonable thermal state with minimal saturation losses and little degradation in field quality. Work continues on studying the smaller populations of dipoles to determine their performance at higher fields.

1 INTRODUCTION

CEBAF is a 4 GeV electron accelerator producing CW beams for nuclear physics research. The accelerator consists of a 45 MeV injector and two parallel 400 MeV superconductor linacs. The beam is recirculated through both linacs four additional times to achieve 4 GeV of total acceleration. Multiple beams can be extracted after selected orbits and delivered to any, or each, of the three experimental halls.

The 2,200 magnets in the accelerator were designed and magnetically measured to support an eventual upgrade to 6 GeV. Refinements in SRF cavity performance [1][2] have succesfully increased the linac energies and produced beams for physics as high as 5.5 GeV. A run up to 6 GeV is scheduled for next year.

A proposal is being formulated to increase the energy of the existing five-pass machine to 11 GeV with delivery to the three existing halls. An additional 6th pass through one linac would increase the energy to 12 GeV. The 12 GeV beam would only be delivered to a new, and fourth, experimental hall.

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Email: karn@jlab.org

A study is underway to determine the feasibility of operating the existing magnets at nearly double their design fields. Quadrupoles, sextupoles, and trim correctors, which make up the bulk of the magnet population, have adequate range in most instances. Only a small number of these magnets would need to be replaced. The largest magnet expense, and the most difficult to characterize, are the main bending dipoles. This paper describes simple modifications to a typical CEBAF dipole that significantly improves the magnet's performance at the higher fields.

2 BASELINE DIPOLE

The majority of the bending dipoles (390 out of 415) share a common design. They consist of a solid C-shaped core of modified 1006 steel and pancake coils wound from hollow copper conductor and potted in epoxy. The "*common arc dipole*" typifies these magnets and was chosen as the subject for modeling and prototyping. A cross section of this magnet is shown in Figure 1.

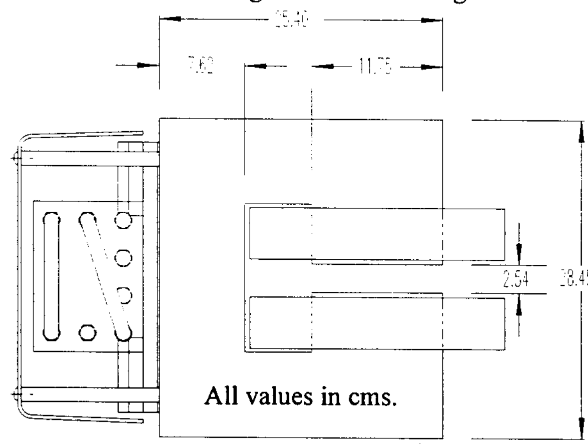

Figure 1: Arc Dipole Cross Section

The dipoles were magnetically mapped up to 300 amps to meet the original 6 GeV design goal. The upgraded dipole would need to run close to 600 amps. Rather than compromising one of the existing spare arc dipoles a new magnet was fabricated. Care was chosen to use steel from the same heat as the production magnets and follow identical annealing conditions. The fabricated magnet was a "BB" style of magnet which has the cross section shown in Figure 1 and a steel pole length of 2 meters.

The BB prototype was powered up to 600 amps and measurements were made of its magnetic and thermal properties.[3] A point-by-point mapping was made inside the pole gap using Hall and NMR probes. Results from measurements showed the field began saturation at 400 amps and was reduced by 18% (from linearity) at 600 amps.

To better understand the saturation effects the BB cross section was modeled using the PC-OPERA 2D finite element package [4]. A plot of the percent saturation is shown in Figure 2 for the measured and PC-OPERA data. As expected, the main area of saturation was the *return leg* of the dipole. A PC-OPERA contour plot of the B field amplitude is shown in Figure 3.

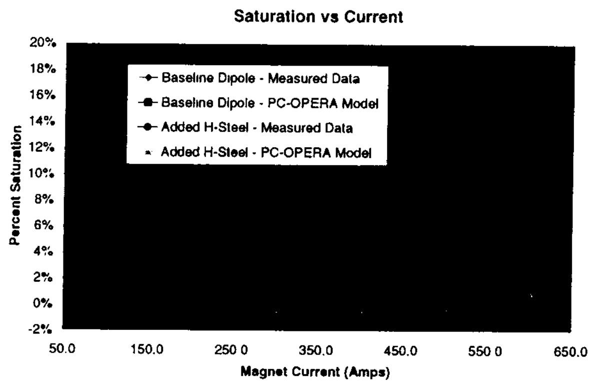

Figure 2: Saturation Plot

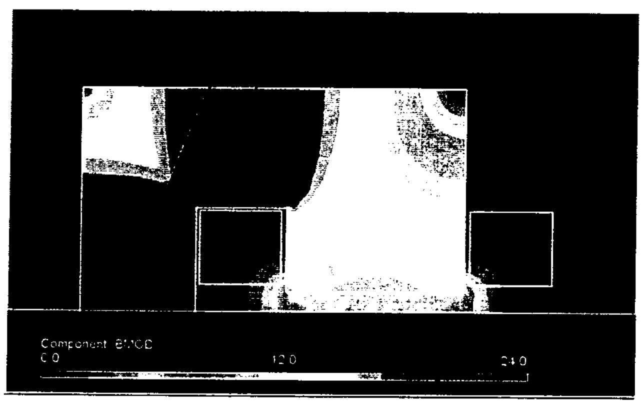

Figure 3: PC-OPERA Model of Baseline BB

3 MODIFIED DIPOLE

The excessive saturation needed to be eliminated in order to reduce power supply requirements. Adding steel to the return leg could reduce saturation effects in the magnet. However, this is the side of the magnet containing the coil terminations and the side that faces the support stands in the accelerator enclosure. A more simplistic fix would involve adding a second return leg to the *outside* of the magnet. That is, convert the C-shaped core to a modified H-shaped core. This solution has several rewarding mechanical features. It faces the aisle of the accelerator enclosure that permits installing the extra steel without having to remove the magnets from their mounts. Further, the existing coil supports can be removed and the same bolt pattern used to hold the added steel, and in turn, support the coils.

Modeling was made in PC-OPERA of the BB cross section with the added *H-Steel*. The design goal is to find the minimal amount of steel required that brings the saturation to an acceptable level. Figure 4 shows that in the optimized model a 3.8 cm. thick side leg and 5.1 cm. thick top/bottom legs would reduce saturation to the one percent level. The required H-steel pieces were prototyped from commercial 1006 steel, annealed, and mounted to the magnet. The steel pieces were deliberately mounted over the existing paint on the magnet to test the effect of the small paint gap. Having to not scrape paint from the mating surfaces would significantly ease future installation efforts. A photograph of the BB with H-steel is shown in Figure 5.

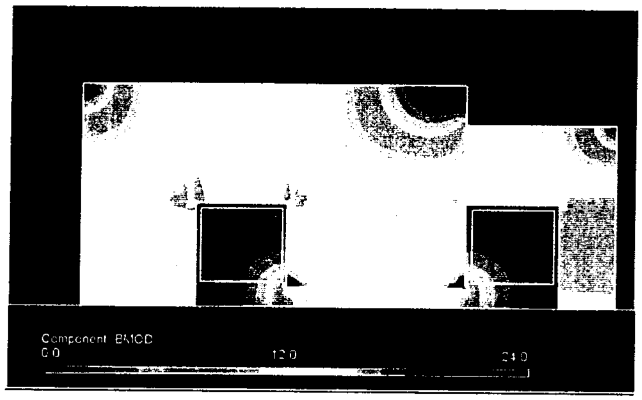

Figure 4: PC-OPERA Model of BB with Added H-Steel

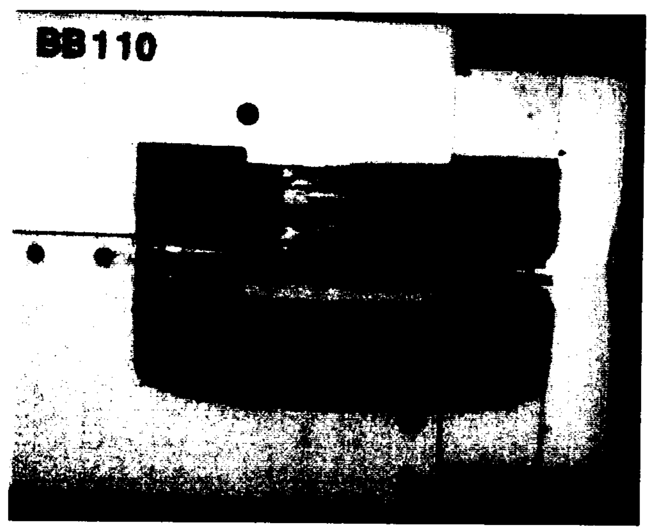

Figure 5: BB with Added H-Steel

Magnetic measurements were performed on the BB with the added H-Steel. The measured data agreed with PC-OPERA modeling to within 0.6% and showed that the saturation was reduced to below one percent (Figure 2.)

4 FIELD PROFILE

Also of concern was that the transverse good field was not compromised from pole tip saturation. Transverse profile measurements were made inside the core using a hall probe at 300 and 600 amps. Figure 6 shows a decrease in the 0.1% good field region from 7.0 to 6.5 cms. This measurement was repeated when the H-steel was added to the core and a minimal change in the profiles was observed.

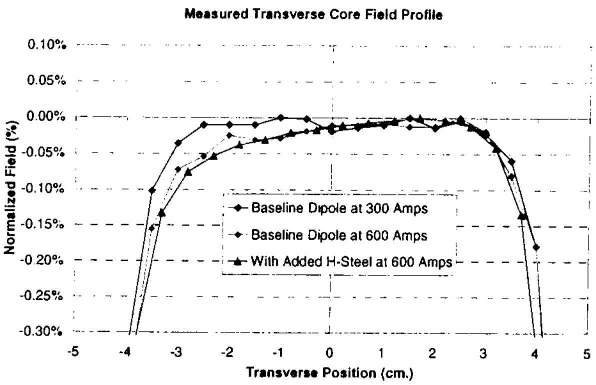

Figure 6: Core Profile

The core field measurements show a small loss in good field but the accelerator specification is based on the longitudinal field integral. Existing magnet measurement probes capable of this measurement were based on the open C-shaped cores and integrated along a straight line. The closed off cores created by the added H-steel and the request for integrals along a beam-following curved trajectory have complicated measurement efforts. Until measurement data is available OPERA-3D [4] can be used to model these profiles. Figure 7 shows an OPERA-3D profile of the gradient integral at 300 and 600 amps. Even at the high currents these magnets still meet the accelerator specification.

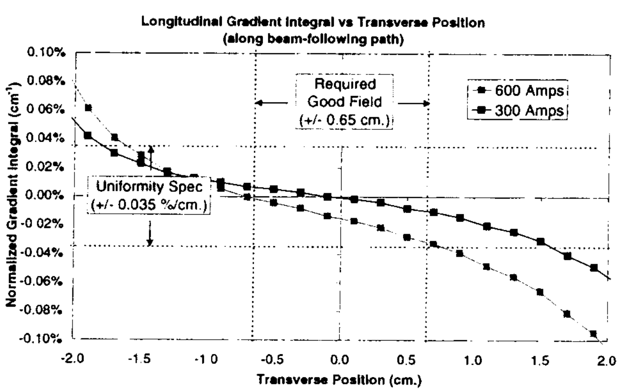

Figure 7: Gradient Integral Profile

5 THERMAL MEASUREMENTS

In addition to magnetic measurements, the thermal properties at the higher current were studied. The magnet was outfitted with thermocouples to measure the steel core and cooling water temperatures. To represent the *highest power* magnet in the accelerator the water flow was set to 2.12 GPM and the dipole powered to 550 amps. The cooling water temperature increased from 29.4°C to 66.6°C and the steel core reached an equilibrium temperature of 39.1°C. The total input power to the magnet was 16.9 kW and the output power matched within two percent. These are acceptable operating temperatures and calculations are underway to determine the need for additional plant cooling.

6 OTHER DIPOLES

As mentioned earlier, the BB was chosen to be prototyped since its cross section represents the largest population of bending dipoles. The remaining dipoles consist of twenty families differing in cross section and coil turns. Design efforts for these magnets will rely heavily on finite element analysis routines and less prototyping. This is justified from the excellent agreement between finite element models and measured data. To characterize the limitations of these magnets a considerable amount of PC-OPERA and OPERA-3D modeling is underway. Those families that experience the return leg saturation can be improved by the addition of H-steel. In some cases, coil turns can be added into the pole gap to reduce pole tip saturation and maximize the transverse good field.

7 CONCLUSIONS

An effort is underway to study the feasibility of pushing the existing CEBAF magnets beyond their design capabilities. Simple and cost effective modifications can be made to the majority of the bending dipoles to achieve the required field strengths. Finite element modeling and magnetic measurements were performed to support this study. Measurements also verified the thermal integrity of the magnets and that field quality was not compromised. Work continues on characterizing the smaller populations of bending dipole families.

8 REFERENCES

[1] J. Preble, *Cryomodule Development for the CEBAF Upgrade*, these proceedings.

[2] J. Delayen, *Upgrade of the CEBAF Acceleration System*, these proceedings.

[3] J. Karn, A. Guerra, L. Harwood, and E. Martin, *Magnetic Measurement of a Common Arc Dipole for Energy Upgrade Considerations*, Jefferson Lab Tech Note 98-032, 1998.

[4] PC-OPERA and OPERA-3D are products of Vector Fields Inc., 1700 N. Farnsworth Ave., Aurora, IL 60505