Magnet Design and Performance for the CEBAF Beam Transport System*

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Abstract

The CEBAF beam transport system requires approximately 300 dipoles, 700 quadrupoles, 1100 steering dipoles, and 50 special magnets. All operate at fields below 4 kG and, thus, are of conventional iron-copper construction. All are being built by industry. The CW nature of CEBAF permits the magnets to be of solid construction. However, all quadrupoles with pole fields of more than 200 G are laminated in order to achieve the required 0.1% field error requirement at half-aperture. To date, all magnets have performance consistent with modelling and prototyping. Design parameters, field quality data, and comparisons to modelling and prototypes will be presented.

1. INTRODUCTION

CEBAF is a 4 GeV CW electron accelerator being constructed by the US Department of Energy for nuclear physics research. It consists of two parallel 400 MeV CW linacs which utilize 320 superconducting RF cavities. 4 GeV of total acceleration is achieved by recirculating the beam four times through the 800 MeV of acceleration. There are nine 180° recirculation arcs and three end-station beam lines; each is a second-order "achromat" separated-function lattice. 712 quadrupoles, 104 sextupoles, 382 major dipoles, and 1041 steering (corrector) dipoles (2239 magnets total) are required. The specifications, mechanical descriptions, and magnetic field performances of each are described below; it should be noted that the close interaction between lattice and magnet designers was found extremely beneficial to arriving at cost effective designs which would bring the project to a successful operation.

2. MAJOR DIPOLES

The $\int$Bdl requirements for the nine recirculation arcs and three transport lines to the experimental areas span a range of a factor of 18 over the operating range for the accelerator. By judicious combinations of magnets with 1, 2, and 3 m lengths (designated BE, BB, and BA, resp.), the actual range of B for five recirculations is actually about four, thereby permitting the use of a single concept executed in the three lengths. For simplicity of maintenance, a "C" style magnet was chosen. Initial magnetostatics calculations led to a pole of about 11 cm width, with a gap of 2.54 cm, and return leg thickness of 5.5 cm thickness; the backleg thickness was chosen so as to have the field level not exceed 12 kG when the pole was operated at the designed upper pole field limit of 6 kG. CEBAF is a CW accelerator; therefore, the magnets would not be pulsed.

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Laminated magnets were thus not a necessity, and an alternate solution was developed in which the magnets were machined from solid iron blocks utilizing two pieces for each magnet; the block construction eliminates the "twist" that is inherent in laminated constructions. An analysis indicated this option would have more potential vendors and reduced cost relative to a laminated approach. The experience at SPEAR, where a similar approach had been successfully adopted, provided reassurance of the viability of the plan. Each magnet is energized by four double-pancake coils with ten turns in each double pancake for a total of 40 turns on each magnet. The coils are fabricated from hollow-core copper conductor which has received one layer of half-lapped mylar insulation; the mylar wrapped conductor is shielded with a fiberglass sleeve, placed in molds, and VPI potted with epoxy.

The field profile specification called for a region at least 7 cm in width where $\delta B/B < 1 \times 10^{-3}$. For simplicity of construction, a flat pole with square corners was used. 2-d magnetostatics calculations, later confirmed by measurements of a prototype, indicated that the specification could be met with a pole width of 11.8 cm, as is shown in Figure 1. These measurements further validated magnetostatics calculations of an effective-field-edge shift of less than 1 mm over the anticipated field range. An additional specification called for the $\int$Bdl's of each magnet location to match all others within a given recirculation or transport line to within $\Delta(\int Bdl)/\int Bdl < \pm 10^{-3}$. This specification was bettered by a factor of two on a magnet-by-magnet basis and bettered by a factor of five when magnets were paired based on their measured $\int$Bdl. An ancillary concern existed about the stability of the $\int$Bdl during externally induced thermal excursions. Additional

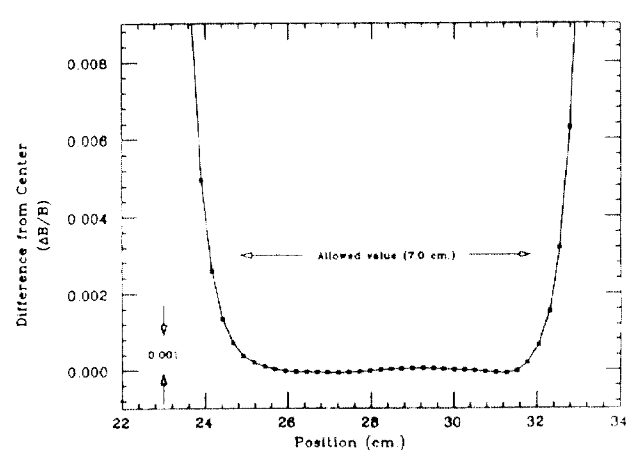

Figure 1. **Comparison of Measured Field Profile to Specification at Center of Dipole.**

testing found no change in the $\int$Bdl at the level of 10 ppm (10^{-5}) of $\int$Bdl when the magnet underwent a 20° C change. Thermally induced changes in $\int$Bdl were therefore judged inconsequential.

At this writing, 144 of the 256 dipoles had been installed after passing mechanical and magnetic testing. A further 20 have passed mechanical inspection and magnetic field testing as deliveries continue from industrial firms. Costs for the magnets averaged $12K/magnet.

3. QUADRUPOLES

The range of $\int$B'dl for the quadrupoles is largely due to the large range of energies that are focussed, *i.e.*, 2.5 MeV in the injector to 4 GeV in the beam transport lines. It was therefore decided to have two fundamentally different regimes, lower field and higher field. The two will be addressed separately below. One limitation on the design of all "small" magnets was the management choice to have a single size of power supply, *i.e.*, 10A/20V which requires a minimum load impedance of 1.8 Ω.

3.1 Low field Quadrupoles

The very low energy (2.5 MeV) beams in the injector call for exceedingly small fields. When combined with the relatively tight specifications on multipole content, the solution called for a "nonstandard" approach. A particular concern was the effects of remnant field if iron dominated magnets were used. The alternative selected was "Panofsky" [1] style quadrupoles. These magnets greatly reduce the effects of remnant fields in the iron and can give high quality fields without complex machining. The historical engineering problems with "Panofsky's" are two-fold: the necessity for high current densities for a given pole field and the difficulty of getting the conductor from quadrant to quadrant without occluding the aperture. The former is reduced in importance by the low fields involved, *i.e.*, 200 G at a radius of 2.06 cm. The latter was solved by making each quadrant an independent coil by looping the coil around that quadrant's iron, *i.e.*, each quadrant consists of a rectangular iron plate with a racetrack coil around it. Water-cooled plates are attached to to the external "return" leg of each coil. Two different "Panofsky" designs were developed, one for very low fields (QS) and the other for moderately low fields (QD). The two differ by a factor of 15 in $\int$B'dl by having a larger aperture shorter length, and fewer turns for the weaker magnet.

Magnetostatics calculations set allowable tolerances for the dimensions and positions of the coils and iron. Prototypes passed thermal and magnetic field testing; testing was critical in defining the dodecapole content of the design as the magnetostatics were 2-d studies which did not address the fringe field contributions to the field integrals. The designs bettered the dodecapole content specification without modification. All magnets were built by industrial firms to CEBAF prepared drawings. A summary of the magnetic field performance is given in Table 1. Magnets of both types are presently installed in the machine and are performing within specifications.

3.2 High Field Quadrupoles

For higher fields, a more conventional "modified hyperbola" pole, iron-dominated approach was used. As the multipole content specification was similar to that of the ALS booster ring, the pole tip shape was adopted directly from those magnets. Construction from stacked, stamped laminations was judged the only cost effective method of holding the required construction tolerances with the desired pole shape. Analysis at CEBAF indicated that alignment tolerances (± 0.2 mm) could be met without the costly step of characterizing each magnet on a coordinate measurement machine; the repeatability of the construction has subsequently been verified by measurement of assembled magnets. Water-cooled plates are attached to each coil. Three sizes of these laminated magnets were required: $\phi\times$ length = 5.4 cm × 15 cm (QB), 5.4 cm × 30 cm (QC), and 2.7 cm × 30 cm (QA). The performance specifications are summarized in Table 1. The laminations are identical for the two 5.4 cm ϕ designs. The pole tip shape of the 2.7 cm ϕ design is a direct scaling of the larger magnet. All exterior features of both laminations are identical.

Prototypes were constructed and subjected to mechanical, thermal and magnetic field testing. The dodecapole component was found unacceptably high. Subsequent field testing in 1 cm longitudinal increments localized the problem to the ends; this was not unexpected as the prototypes had no special provisions for control of dodecapole or icosapole content of the fringe fields. A brief empirical study found that a 45° bevel of each pole end which removed 4.75 mm (2.4 mm) of material for the 5.4 cm ϕ (2.7 cm ϕ) magnets brought the designs within specification, as shown in Table 1. The icosapole content was slightly degraded but still within specification. The symmetry breaking multipoles were gratifyingly small, indicating tolerances were being accurately held in the assembly.

Deliveries to CEBAF by industrial firms of all three sizes began in January, 1992. Costs range from $2800/magnet for the QB's to $3800/magnet for the QC's.

4. SEXTUPOLES

The sextupoles for CEBAF have quite simple requirements. The fields are not high. Furthermore, the multipole content specification is modest as shown in Table 1; this is due to the specification being derived from a desire to keep the integrated field error from the beam being off-axis in the sextupoles less than than from being off-axis an equivalent in the quadrupoles. The latter argued against the necessity of complex pole shapes which would require laminated construction. Magnetostatics studies found that rectangular poles with longitudinal, 45° bevels could achieve acceptable field performance. Further, it was felt that the symmetry produced by utilising six coils (one per pole) was not necessary. Therefore, a very simple design was developed which bolts six flat, longitudinally bevelled iron plates to the machined I.D. of commercial thick-wall iron tube. A coil is placed around each of three symmetrically located poles; the three coils are powered in the same "sense." The two models (SA and SB) differ only in the length of the plates which constitute the poles, the longer plates giving a smaller aperture and a higher field since the same coils are used on both models.

Prototypes passed mechanical, thermal and magnetic field testing. Results for production units are given in Table 1. Construction has been completed by industrial firms for all units at a total cost of $160K.

5. STEERING DIPOLES

The role of the steering dipoles (correctors) in the machine design was to correct for mis-steering of the beam due to going through quadrupoles off-axis. Corrector strengths were defined by calculating the $\int Bdl$ that an electron would experience if it were 1mm off-axis of the nearest quadrupole. Like the quadrupoles, there are five models, whose parameters are summarised in Table 1. The multipole specifications for the very low energy region were rather stringent, so "window-frame" designs were used. To simplify construction, as in the "Panofsky" quadrupoles described above, the coil was of simple racetrack configuration and looped around the flux return legs. Water-cooled plates are attached to the exposed coil. The two designs (BD and BS) differ only in number of turns and the addition of a ballast resistor for the low turn-count BS magnet in order to bring it up to the requisite 1.8 Ω.

The other three models (BC, BM, and BT) are "C" magnets constructed from three iron plates with a racetrack coil around the backleg. The gain is a substantial reduction in cost relative to the BD and BS; the penalty is increased multipole content particularly coming from the "fringe" of the open side. Cost was of major consideration because of the large number of units required. The penalty is not a problem as the multipole specification was not as stringent for the locations where these models are used as where the BD and BS models are used. In absolute terms, the allowed multipole strengths are the same as for the neighboring quadrupole. However, the correctors' multipole specification in fractional terms is modified by their intended use, *i.e.*, to correct for 1mm beam displacements in the neighboring quadrupoles. Therefore, the $\int Bdl$ of the corrector is 1/15 or 1/27 (depending upon the aperture of the neighboring quadrupole) of the $\int Bdl$ of that quad at full aperture. Thus, the allowed multipole content of the correctors is 15 or 27 times larger than for the quadrupoles when taken as a ratio to the dipole strength at the same radius as the specifications for the quadrupoles' specifications. The specifications are summarised in Table 1 along with the performance of the magnets.

BS and BD magnets have been installed in the machine and are performing within specifications. The BC, BM, and BT magnets are being delivered from industrial firms at an average cost of $500/magnet.

6. SUMMARY

Dipole, quadrupole, and sextupole designs are complete for the CEBAF beam transport system. While required levels and field qualities have not pushed the "state of the art," all requirements have been met with costs within budget. This has been accomplished by close interaction between the accelerator physics team and the magnet design team. Performance of the units which have been installed and operated has also been within specifications. At this time, we are on schedule for completion of magnet deliveries in mid-FY93 and completion of installation of the entire accelerator in early FY94.

7. REFERENCES

[1] L. N. Hand and W. K. H. Panofsky, "Magnetic Quadruple with Rectangular Aperture", The Review of Scientific Instruments, vol. 30, no. 10, pp. 927-930.

Table 1. Focussing and Steering Magnet Characteristics

Type	Number	Style	Effective length (cm)	Aperture diameter (cm)	Field pole (G)	Allowed multipole content (Spec/achieved) (@ 1/2 aperture unless otherwise noted; 0.1% of fundamental harmonic)		
Quadrupoles						Dodecapole (@ full aperture)	Icosapole (@ full aperture)	Sum of symmetry breaking multipoles
QA	472	laminated, iron dominated	30	2.9	4200	1.0/0.25	2.0/1.2	1.0/0.25
QB	137	"	15	5.4	2450	1.0/0.5	2.0/1.2	1.0/0.25
QC	75	"	30	5.4	1930	1.0/0.25	2.0/1.2	1.0/0.25
QD	18	solid, "Panofsky"	15	4.1	200	4.0/3.0	2.0/0.8	1.0/0.4
QJ	5	"	7.5	11.6	25	4.0/2.0	2.0/0.6	1.0/1.0
Sextupoles							Sum of octupole and higher	
SA	56	solid, 3 coils	15	2.9	551		5.0/1.8	
SB	48	"	15	5.4	292		5.0/1.2	
Correctors						Quadrupole (@ full aperture)	Sum of octupole and higher	
BD	32	solid, "window", backleg coil	15	4.1	933	0.5/0.5	1.0/0.8	
BS	10	"	15	4.1	230	5.0/3.0	5.0/4.0	
BC	642	solid, "C", backleg coil	15	2.9	630	15.0/6.0	15.0/6.0	
BM	48	"	15	5.4	550	27.0/0.6	27.0/0.7	
BT	276	"	15	5.4	110	27.0/6.0	27.0/6.0	