# SUPERCONDUCTING MAGNETS FOR CEBAF

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## ABSTRACT

The Continuous Electron Beam Accelerator Facility (CEBAF) is a new DOE facility presently under construction in Newport News, Virginia. This accelerator will provide a high quality electron beam for nuclear physics research.

CEBAF has elected to build particle spectrometers with superconducting magnets. Two high resolution spectrometers will be built from separated function dipoles and quadrupoles. These magnets will be modular, permitting interchangeability between various spectrometers. A third spectrometer, having a large acceptance detector, will be built using a superconducting toroid. This toroid will have 8 superconducting coils with its axis aligned horizontally.

The superconducting quadrupole will have a 1 m bore, 1.8 m effective length and a 7.2 T/m gradient. The dipoles will be 1.7 T, homogeneous to 1 part in $10^4$, in a field volume 1.2 m x 0.3 m x 3.12 m long. The toroid will be 1 m I.D., 4 m O.D., and 4 m long with a peak field of 1.2 T. The specification, design, cryogenics, and quench protection aspects of these magnets will be discussed.

## INTRODUCTION

The Continuous Electron Beam Accelerator[1] Facility (CEBAF) is a Department of Energy (DOE) funded research facility. CEBAF's purpose is to study nuclear physics using electrons and tagged photons as a probe. The accelerator has been designed to produce a 100% duty factor beam with an energy spread of $10^{-4}$. The excellent beam quality and the desire to perform precision[2] coincidence experiments requires the use of a pair of *high resolution spectrometers*. This paper describes the current status of the design of the magnetic elements used in these spectrometers, which are located in the three end stations (experimental halls) as shown in Figure 1.

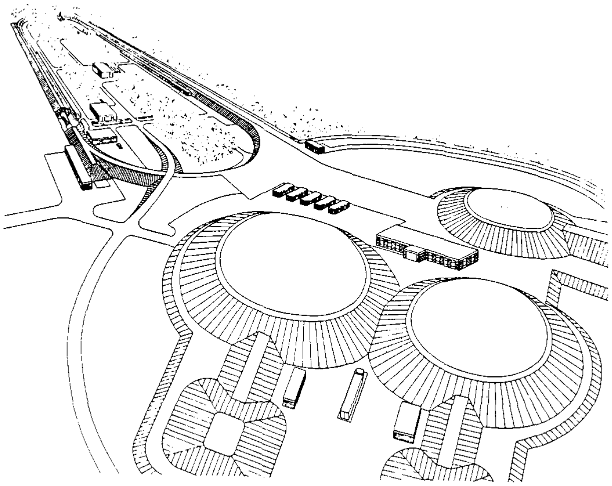


Figure 1 - CEBAF Site Plan.

Present plans are to equip end station "A" and end station "B" with spectrometers. End station "A" requires two high resolution spectrometers, one for hadrons and one for electrons.[3] These spectrometers are constructed from identical modular elements. The hadron spectrometer consists of two quadrupoles and two dipoles. The electron spectrometer has four quadrupoles and two dipoles. The spectrometer optics and magnetostatics were performed by the CEBAF research staff and will be published elsewhere.[4] A different type of spectrometer shall be installed in end station "B", namely a large acceptance spectrometer (LAS).[5] This device is an eight coil torus which will analyze the momentum of particles over nearly 80% of the solid angle surrounding the target.

Spectrometers for hall "C" will be selected in October 1988 and may utilize the modular designs developed here. Superconducting designs were chosen for all of the magnets. The quadrupole is a cosine 2θ design with an inner coil diameter of 1 m and warm iron. The dipole is an "iron dominated" magnet with simple racetrack coils. The toroid is a completely iron-free design.[6]

Procurement is scheduled for FY 88, with installation and operation of both hall "A" and hall "B" apparatus by 1993.

## TOROIDAL MAGNET

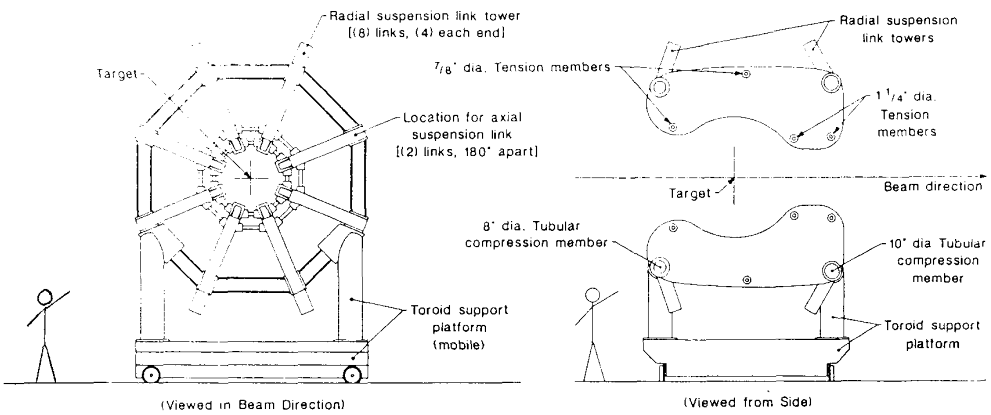
The requirement for a multi-particle spectrometer with large acceptance has led to a toroidal field configuration. Momentum analysis of particles arising from collisions will be done with drift chambers occupying the free volume between the eight coils. It is necessary to provide an $\int B dl$ of at least one Tesla meter to achieve acceptable momentum resolution. Some experiments using polarized targets require a field-free region in the target area, and thus the toroid is the optimal choice.

An eight coil configuration for the torus has been fully analyzed and that design is presented here. Examination of a six-coil torus for comparison purposes is also underway.

Particle focusing considerations require a field configuration, such that the inner leg of the coils be wound on a 1 m radius. This negative curvature makes it difficult to pretension the conductor by traditional coil winding techniques. Therefore, a

*This work was supported by the Department of Energy under contract DE-AC05-84ER4015.

0018-9464/88/0300-1264$01.00



(Viewed in Beam Direction)

(Viewed from Side)

Figure 2 - LAS Toroid.

decision against potted coils in favor of a fully cryostable coil, in order to avoid the possibility of excessive training, has been reached.

The coil experiences large electromagnetic forces. These forces are of three types: the normal operating forces, forces arising from coil misalignment, and those arising from an "upset condition".

The net "centering" force on each coil is approximately 50 tons. These forces will be taken directly, from coil-to-coil, by a support structure at the operating temperature (4.4 K). The coil experiences forces that attempt to enlarge the coil. Such forces are carried internally by the bobbin.

The coils, if not installed in perfect symmetry, experience a large force which tends to increase the displacement. Without sufficient rigidity in the support structure a run-away condition is encountered. This force has a maximum value of 100#/in per inch displacement.

All coils operate in series. Therefore, the possibility of a short circuit that would permit a current imbalance in one coil must be anticipated. A worst case, with one coil off, was chosen to model the upset condition. This condition results in forces as high as 550 lb./linear inch of coil circumference. The structures required to cope with these forces are more than sufficient to provide the rigidity requirements for the slight misalignments described above.

The magnet will be cooled by helium pressurized to 2 atm and subcooled by a 1.2 atm bath, thus operating at 4.4 K. The coils shall be cooled in series and inter-coil re-coolers will be employed to maintain the 4.4 K temperature. Temperature differentials not exceeding 50 K will be maintained during cooldown to avoid thermally induced stresses in the support structure. Calculations indicating a flow rate of 20 gm/sec will provide a safe cooldown of the entire torus in two weeks. The parameters for the toroid magnet are listed in Table 1, and the magnet is shown in Figure 2.

## QUADRUPOLE MAGNET

The spectrometers have been designed for a large acceptance and require quadrupoles with a useful aperture of 80 cm. The inner diameter of the winding is one meter. The maximum operating gradient is 7.5 T/m with an operating current of 3000 Amperes. The coil is a three current block

TOROIDAL MAGNET PARAMETERS

TABLE 1

| | | |
|---|---|---|
| Total Stored Energy | $10.8 \times 10^6$ | J |
| Number of Ampere-Turns (8 Coils) | $5 \times 10^6$ | A-Turns |
| Maximum Current | $3 \times 10^3$ | A |
| Inductance | 2.4 | H |
| Dump Resistor | .25 | Ω |
| Time Constant | 9.6 | Sec. |
| Maximum voltage During Quench | 750 | V |
| CONDUCTOR: | | |
| Maximum Field at the Conductor | 2 | Tesla |
| Maximum Temperature at the Conductor | 4.5 | K |
| Current Density (Superconductor Only) | $2.2 \times 10^3$ | $A/mm^2$ |
| Cross Section (Superconductor Only) | 1.36 | $mm^2$ |
| Critical Current Density at 4.2K and 2T | $4.4 \times 10^3$ | $A/mm^2$ |
| Hot Spot Temperature | 50 | K |
| Current Density (Cu and SC) | 66 | $A/mm^2$ |
| CU:SC Ratio | 31:1 | |
| Dimensions Overall | 3.5 mm x 13 mm | |

## QUAD SPECIFICATION

### TABLE 2

| | |
|---|---|
| Useful Bore | 80 cm |
| Field Gradient | 7.5 T/m |
| Total Stored Energy | $7.9 \times 10^6$ J |
| Number of Ampere-Turns | $6.0 \times 10^6$ A |
| Inductance | 1.75 |
| Dump Resistor | .27 Ω |
| Maximum Voltage During Quench | 800 V |
| Maximum Current | 3000 A |

### CONDUCTOR

| | |
|---|---|
| Maximum Field at the Conductor | 4.5 T |
| Maximum Temperature at the Conductor | 4.5 K |
| Current Density (Superconductor Only) | 2300 A/mm$^2$ |
| Cross Section Area (Superconductor Only) | 1.9 mm$^2$ |
| Conductor Size (Includes 2 Wraps Half Lapped 1 mil Kapton) | 3 x 7 mm |
| Critical Temperature | 5.2K |
| Hot Spot Temperature (Worst Case) | 100K |
| Current Density (Cu + Sc) | 160 A/mm$^2$ |
| Current Density Overall | 143 A/mm$^2$ |

Cos 2θ design chosen to provide adequate uniformity of $10^{-3}$ at 80 cm diameter. The parameters for the quadrupole are listed in Table 2 and illustrated in Figure 3.

Provision has been made to incorporate correction windings in the quadrupole. These windings will allow higher order corrections of the spectometer optics. The correction coils are capable of providing a sextupole field of .05 T/m$^2$ and an octupole field of .09 T/m$^3$. The corrections will be wet-wound on the inner wall of the helium vessel and will be separately powered.

Each coil quadrant has three current blocks which are epoxy impregnated. The four quadrants are joined together by banding with fiberglass/epoxy tape. Stainless steel clamp rings are applied over this banding. Aluminum-2027 rings are then shrunk fit over these stainless steel clamp rings. The combination of the interference fit at room temperature, plus the differential thermal contraction during cooldown provides high clamping at operating temperature. This clamping is sufficient to keep the coils in compression in both the radial and tangential directions at full field.

The suspension system has been designed to support the projected 2g vertical and 1g lateral shipping loads. If the coil is not installed concentric with the " warm iron" steel, decentering forces are present. The rigidity of the support system is sufficient to handle these forces. The suppression rods are made from Nitronic 50 steel, the radial members being 1" diameter, and the lateral members being 1/2" diameter.

## THE DIPOLE MAGNET

The pair of high resolution spectrometers requires four modular dipole magnets having identical performance. The requirements are a maximum field of 1.7 T over a field length of 3.12 m having a homogeneity of one part in $10^4$ over the useful aperture. The iron and coil placement has been designed by use of the program POISSON.

The large size of the useful aperture of 30 cm high by 100 cm wide by 312 cm long in conjunction with high homogeneity implies a magnet of large physical size, 2.08 m high by 3.5 m wide by 3.7 m long weighing over 200 tons. Economic considerations and the absolute need for superconducting quadrupoles lead to an early decision to use a superconducting coil.

The modular design was chosen by CEBAF to make most efficient use of the considerable design, engineering and tooling required for fabrication of superconducting magnets. The practical consideration of limiting the number of large outside contracts to be administered to the minimum necessary, will permit better use of CEBAF resources. The technical features of this dipole were chosen on the basis of the best available technology. The magnet is the traditional H geometry and the superconducting coil is a cryostable design using niobium-titanium. The detailed magnet specifications are in Table 3 and illustrated in Figure 4. The cryostable conductor is a soldered composite spread apart by G10CR with 2 mm between turns and 3 mm between layers. The coil is restrained by brass bolts, springwashers, and G10 clamps to the stainless steel bobbin. The bobbin is the winding fixture and becomes part of the coil support within the cryostat. The 80 K shield will be cooled by LN$_2$ through integral flow passages in the commercial heat transfer plates that make up the shield assembly. The upper and lower coils are spread apart by column supports at 4.2 K and will be in tension due to the coil position within the iron yoke.

The cryostat is supported within the vacuum vessel and iron by a set of triaxial tension rods that are externally adjustable. The supports will be

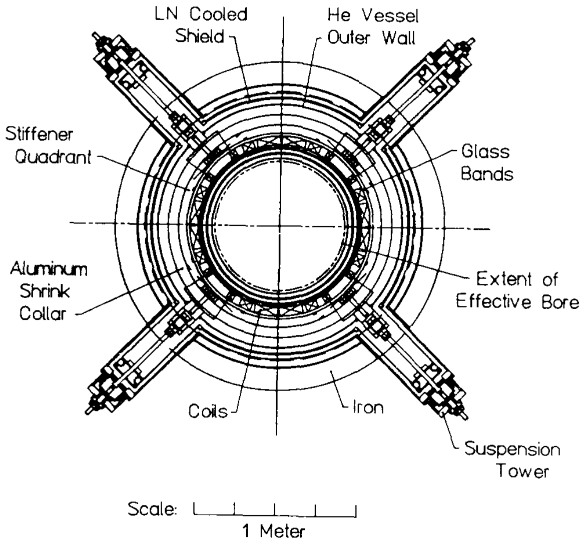


Figure 3 - Modular 1 Meter Superconducting Quadrupole.

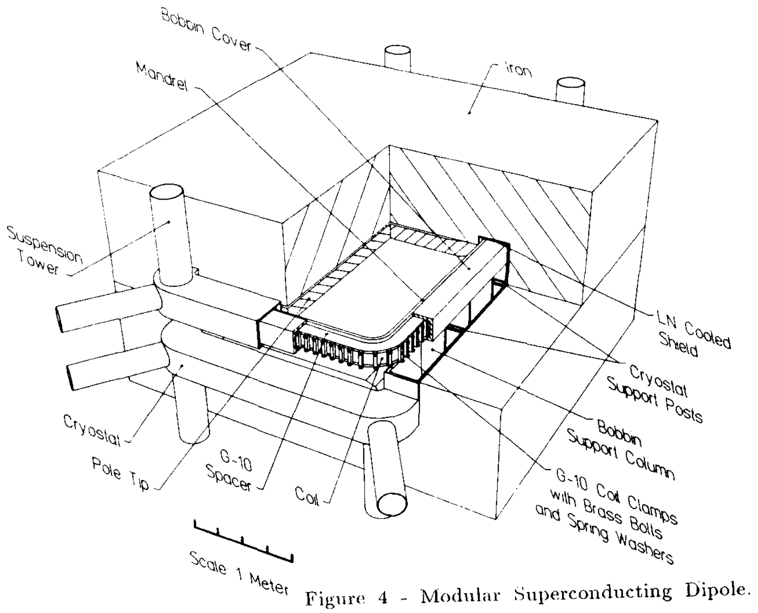


Figure 4 - Modular Superconducting Dipole.

## DIPOLE SPECIFICATIONS

TABLE 3

| | |
|---|---|
| Field | 1.7 T |
| Field Length | 3.12 m |
| Homogeneity | $10^{-4}$ |
| Useful Aperture | 100 cm x 30 cm x 312 cm |
| Overall Size | 3.5 m x 2.08 m x 3.7 m long |
| Current | 1000 A |
| Turns | 500 |
| Length or Conductor | 4000 m |
| Energy | $3 \times 10^6$ J |
| Inductance | 6 H |
| Weight | 425,000# |
| Steel | 1006 |
| Conductor | NbTi |
| $I_{crit}$ at 3.8T | 1,500 A |
| Cu:Sc (Insert) | 1.5:1 |
| $A_{Sc}$ | 0.5 mm$^2$ |
| $A_{Cu}$ | 20.5 mm$^2$ |
| Cu:Sc Overall | 41:1 |
| Cooling | 1 atm LHe |
| Heatload Budget | 20W + 3 l/hr |

equipped with strain gauges to permit precise trimming of the coil position within the iron. Cryogenics for the experimental halls has been described[7] and uses a bath-cooled cryostat for the dipole directly coupled to a satellite refrigerator for cold vapor return. The helium from vapor cooled leads will also be returned and the LN$_2$ shield gas will simply be vented.

## CONCLUSION

CEBAF has chosen to use superconducting magnets to perform high precision studies of electronuclear physics. It is our intention to fabricate these magnets in industry with the contractor providing a substantial contribution to the mechanical design. The magnetostatic design will be as specified by CEBAF along with the overall conceptual design. A conservative path was deliberately chosen with the belief that an engineering and industrial base exists that can provide these magnets for the research community and avoid magnetic designs that are themselves research projects. These considerations are believed to best serve the CEBAF users community and the Department of Energy.

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