MECHANICAL DESIGN OF A LARGE BORE QUADRUPOLE TRIPLET MAGNET*

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Summary

The mechanical design and construction of a 1 meter bore, low gradient quadrupole triplet is described. The magnet will be used for focussing a proton beam in accelerator studies of neutral particle beams at the Los Alamos National Laboratory. A significant feature of this magnet design is the precision location of the coil conductors within the steel yoke tube. Each of the quadrupole coils have been fabricated from water cooled aluminum conductor, wound in a cosine 2-theta geometry. The conductor bundles have been wound to a positional accuracy within ±0.050 cm which was required to reduce the harmonic content to less than 0.04% of the quadrupole field. Important aspects of the design, construction and assembly are described.

Introduction

Assembly of the triplet has been recently completed, and magnet measurements of the two dimensional line integral and the central field of each of the magnetic elements will begin soon. It is planned that three dimensional measurements of the magnetic elements and their fringe fields will be made later in 1987. The three dimensional measurements will provide the data necessary to understand the three dimensional field distribution in the magnets. The field distribution will be used to compute the theoretical orbits of the beam as it passes through the lens system. Calculated beam trajectories can then be compared with measured trajectories obtained from experiments at Los Alamos.

Mechanical Design

Table 1 shows the design parameters of the triplet. Fig. 2 shows a typical cross section of the magnet, and Fig. 3 provides an elevation view. The yoke tube provides the path for the magnetic return flux of the coils. It is also the structure to which the coils are attached and positioned. Each coil is mounted to the yoke tube with a single coil mounting plug. The coil mounting plugs provide precision azimuthal and longitudinal positioning of the coils while allowing for unconstrained thermal expansion. The brass support feet attached to the coils rest on the precision honed bore of the yoke tube thereby providing accurate radial positioning of each coil. Axial alignment of each coil is achieved by the mounting of a brass pin through the yoke tube wall that fits into a longitudinal slot in each coil. This slot allows for thermal expansion of the coil while maintaining axial alignment. Cut-outs in the yoke tube wall as shown in Fig. 3 allow for penetration of the coil leads to the exterior of the tube where bus bars are attached. Polycarbonate covers fully enclose the bus bars for electrical safety.

Coils

The coils were fabricated of square, hollow, water cooled conductor with two water circuits per coil. A low current density (295 A/cm^2 max.) was chosen in order to minimize the number of cooling circuits required. The conductor is 1060 F aluminum (99.6% pure). This was the material of choice due in part to its short activation life as a high radiation environment is anticipated in the experimental areas. The conductors were wrapped with a single, half lapped layer of 0.003 inch thick mylar tape followed with a single, half lapped layer of 0.005 inch thick dacron tape. Calculation of the coil placement error in the winding of the conductor bundles indicated that the centroid of each bundle would have to be wound with a positional accuracy of ±0.050 cm (0.020 inches). This was necessary to maintain the harmonic content to less than 0.04%.

Precision winding forms for the end coils and center coils of the triplet were machined with faceted surfaces onto which the conductors were wound. The winding form surfaces were machined to within ±0.003 inches of the calculated geometry. Aluminum spacer bars were sequentially bolted in place to the winding forms as winding progressed. Pins were used to accurately locate the spacer bars on the forms thereby providing for the precision spacing required between conductor bundles. After completion of the coil winding, each coil with its integral aluminum spacer bars was removed from its winding form and transferred to a potting form. The surfaces of the potting forms were machined to the same geometry and accuracy as the surfaces on the winding forms. Each coil was pinned and bolted onto its potting form in the same manner as on the winding forms. Potting form covers and seals were than installed over the conductors, and the coils were epoxy encapsulated in a vacuum tank. Aluminum stiffener bars were attached to the top and bottom surfaces of the spacer bars after removal from the vacuum tank. The stiffener bars are individually flexible; however, they provide a rigid exterior coil frame when tightly bolted to the coil spacer bars. The function of this frame on each coil is to reduce the stresses on the epoxy joints.

Table 1
Quadrupole Triplet Design Parameters

	Center Magnet	End Magnet
Aperture radius	0.5 m	0.5 m
Field at aperture	0.1 T	0.1 T
Gradient	0.2 T/m	0.2 T/m
Effective length	2.0 m	1.0 m
Excitation	DC	DC
Conductor size	1.35 cm sq	1.35 cm sq
Number of turns per quadrant	64	64
Current	424 A	435 A
Current density	287 A/cm^2	295 A/cm^2
Total voltage drop per magnet	110 V	67 V
Power required per magnet	47 kW	29 kW
Water flow at 200 psi diff.	8 gpm	11 gpm
Maximum coil temperature rise	22°C	11°C

Overall length of triplet = 6.02 m (237 in.)
Total weight (not including stand) = 23,000 lbs.

Thermal Loading and Cooling

The calculated maximum conductor temperature rise is 22°C for the center coils and 11°C for the end coils. These calculations are based on measured water flow rates through the coils at a 200 psi differential. De-ionized water is distributed through lines to each of the coils as shown in Fig. 3. High pressure

*Work performed under U.S. DOE Contract Nos. W-7405-ENG-48 and DE-AC03-76SF00098 and supported by the U.S. Army Strategic Defense Command.

fittings with o-ring seals are used for all water connections. All metal parts of the manifolding including the fittings are made of passivated stainless steel to minimize galvanic corrosion. Special hose was selected for the cooling lines. The hose, which is commerically manufactured is designed specifically for pure water applications. A seamless core tube formulated from a high quality polymer, free of plasticizers prevents the extraction of contaminants into the water. The outer sheath of the hose is non-conductive to prevent electrical tracking from the coils to ground.

Yoke Tube

The 46 inch I.D. x 2 inch wall yoke tube was centrifugally cast from low carbon steel (ASTM A-27-70 grade N-1). Two separate lengths were cast and welded together. The circumferential welding of the two lengths of tube was performed with a submerged arc utilizing a back-up ring on the inside surface of the tube. The submerged arc produced a high quality, full penetration joint, and the back-up ring together with the root of the weld were removed during finish machining. The inside of the tube was precision bored and honed to provide an accurate surface for the radial mounting of the coils. A numerically controlled mill with a 240 inch long bed was used to machine all the coil mounting holes in the tube. The mounting holes which determine the azimuthal and longitudinal positioning of the coils were machined to a locational accuracy of ± 0.005 inches. The centrifugal casting process produced a tube having a homogeneous, isotropic structure. The non-directional grain orientation and consequently non-directional physical properties of the yoke tube allow for a uniform magnetic flux distribution thus aiding the field quality of the magnet. The cast tube also proved to have outstanding dimensional stability. The bore of the tube was machined to within ± 0.002 inches circularity and was straight to within 0.010 inches over its full length.

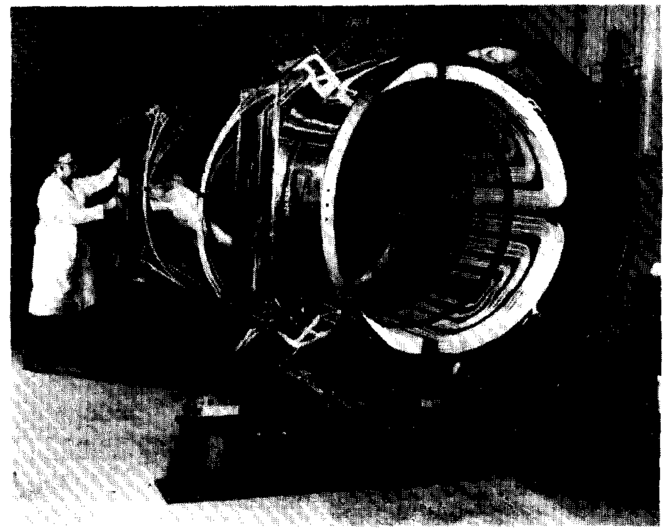

Figure 1: Magnet fully assembled

Assembly

The magnet was assembled on a special stand which had roller supports at each end providing for 360^{o} rotation of the yoke tube about its longitudinal axis. This rotational capability allowed each coil to be

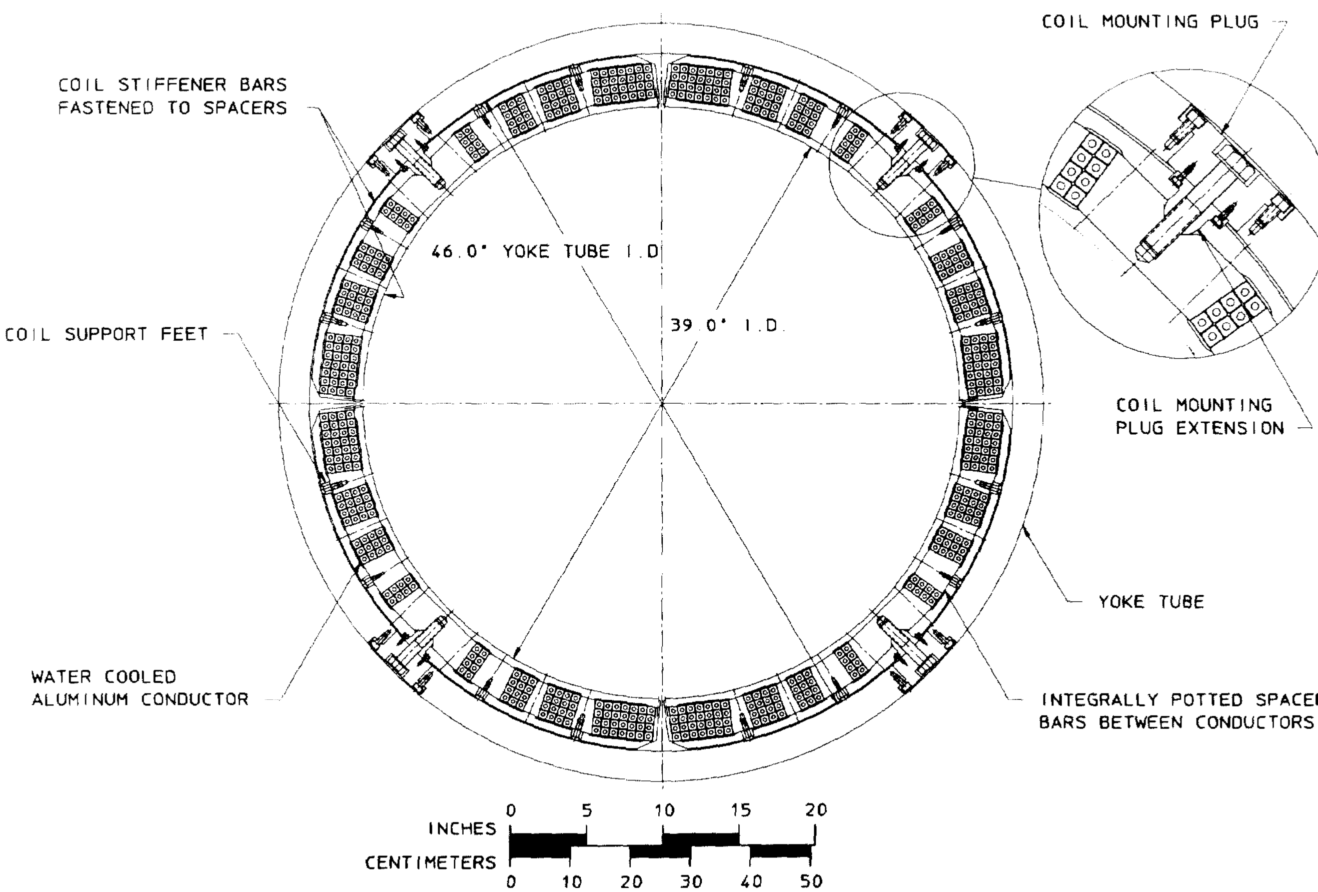

Figure 2: Typical cross section of magnet

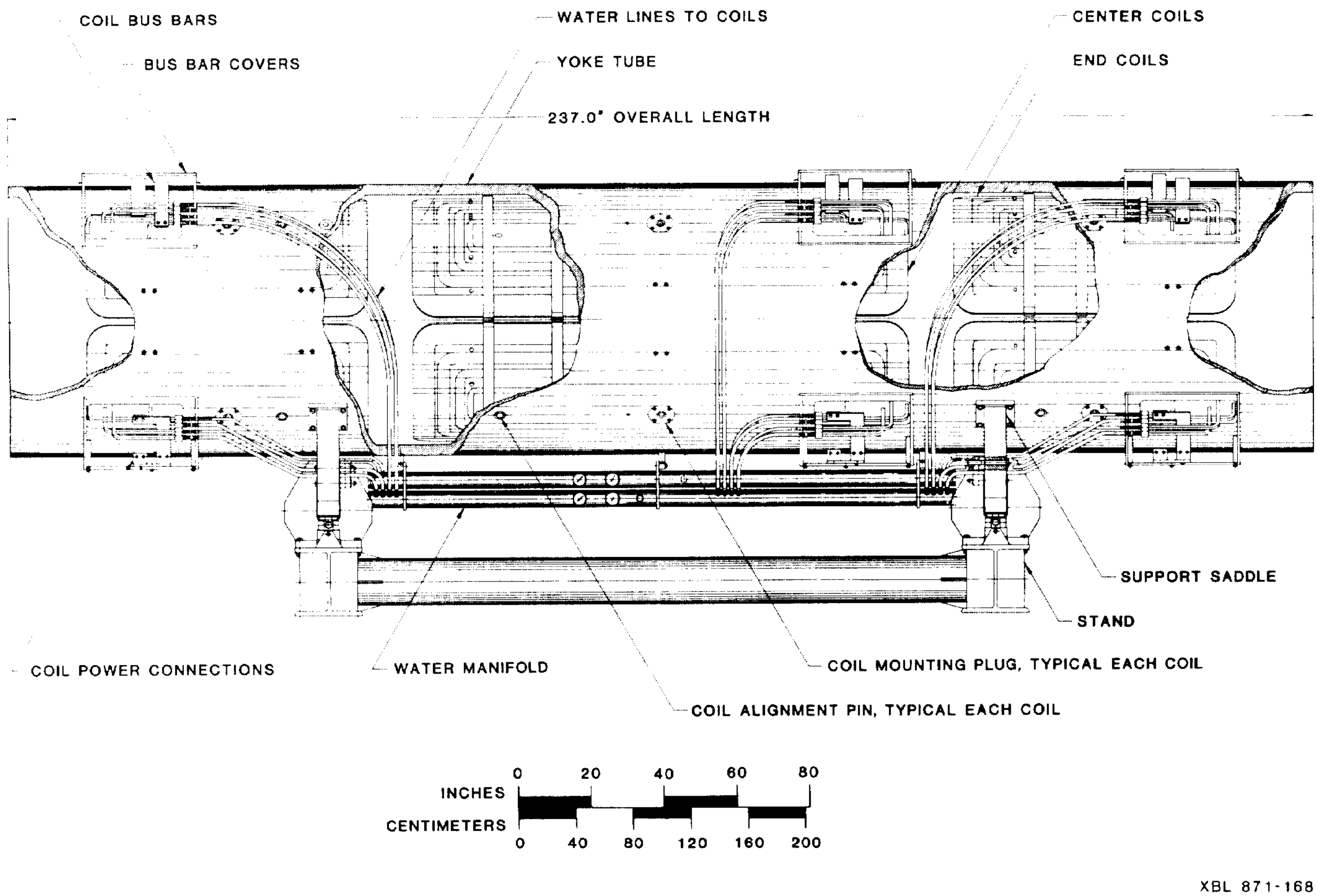

Figure 3: Elevation view of magnet

mounted to the bottom of the yoke tube bore. The installation procedure for each coil was as follows. Coil support feet were attached to a coil, and the coil was placed on the inside, bottom surface of the yoke tube directly over its mounting plug hole in the tube. Placement of each coil inside the tube was accomplished by hanging the coil at the end of a beam which was cantilevered from the tines of a forklift. After the coil was in place an axial alignment pin was mounted through the yoke tube wall and into a slot along the longitudinal centerline of the coil. The coil mounting plug was then put in place through the tube as shown in Fig. 3. The exact length of the brass extension on the mounting plug was determined and machined at assembly. The yoke tube was then rotated 90^{o}, and this assembly procedure was repeated for the next coil. As can be seen from Fig. 2 there is very little space between adjacent coils. It was therefore necessary to temporarily crowd together the first three coils installed for each quadrupole to allow room to install the last coil for each set. Special coil mounting plugs were used to crowd the coils. After installation of the last coil for each quadrupole the special assembly plugs were removed, and the permanent coil mounting plugs were installed with the coils in their proper position. After all the coils were assembled to the yoke tube the magnet was removed from its special assembly stand and set on its permanent support stand.

Support and Alignment

The support stand has been designed to provide for axial, vertical and lateral positioning of the magnet to facilitate its beamline alignment. The magnet is supported by two aluminum saddles as shown in Fig. 3. Ground stainless steel pads bolted to the outside of the yoke tube in four places provide smooth, flat surfaces which rest on top of the saddles. The saddles are mounted to a steel support stand. Self aligning leveling jacks between the stand and saddles provide for vertical adjustment, and jacking screws at each corner of the stand provide lateral adjustment capability. An axial bolt provides for longitudinal positioning of the magnet. Brackets are used to fasten the yoke tube to the saddles after the axial adjustments are completed. Low friction bearing pads are used on all sliding surfaces where adjustment has been provided. The support stand and magnet assembly have been designed to withstand earthquake loads resulting from vertical or horizontal accelerations as high as 1g.

Alignment of the magnet can be accomplished by either bore sighting or by the use of external targets. Pin holes are located at each end of the yoke tube for precision mounting of the external targets.

Acknowledgements

The authors gratefully acknowledge the efforts and support of Otto Draeger, Dennis Greenway, Paul Wong, Vic Wray, Bill Gath and Al Harcourt of the LBL shops for the construction and assembly of the magnet.

References

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