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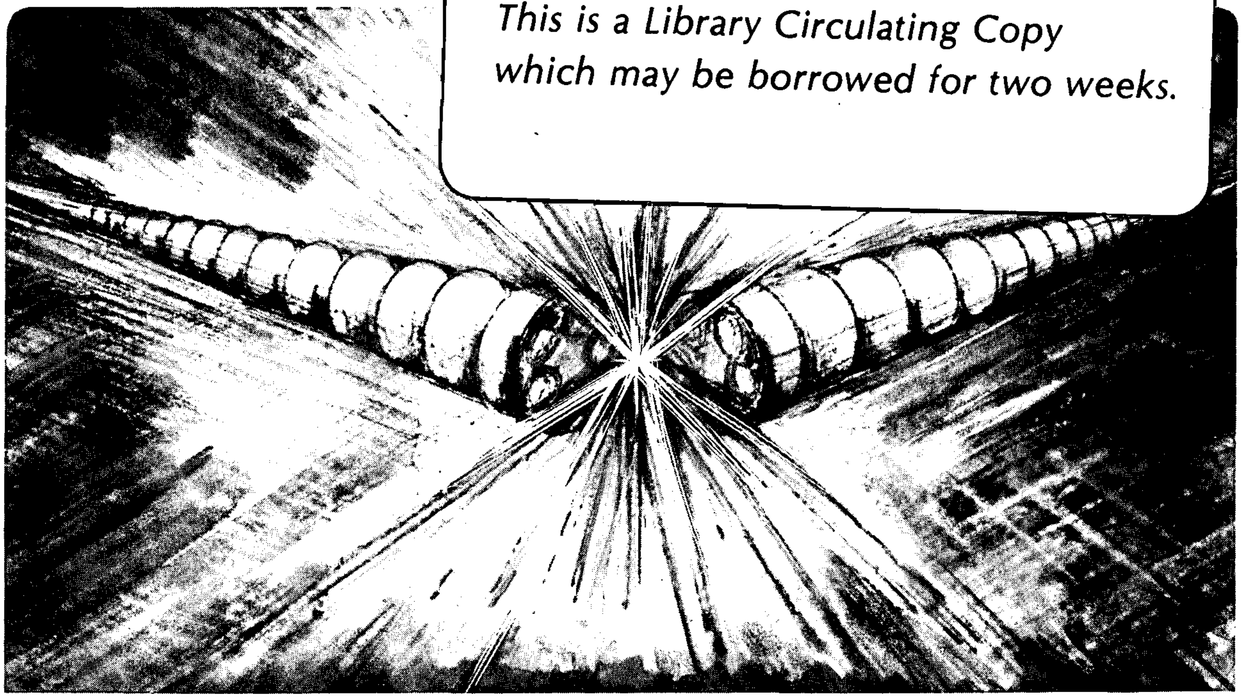

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DESIGN, FABRICATION, AND CALIBRATION OF CURVED INTEGRAL COILS FOR MEASURING TRANSFER FUNCTION, UNIFORMITY AND EFFECTIVE LENGTH OF LBL ALS BOOSTER DIPOLE MAGNETS*

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Abstract

A matched pair of curved integral coils has been designed, fabricated and calibrated at Lawrence Berkeley Laboratory for measuring Advanced Light Source (ALS) Booster Dipole Magnets. Distinctive fabrication and calibration techniques are described. The use of multifilar magnet wire in fabricating integral search coils is described. Procedures used and results of AC and DC measurements of transfer function, effective length, and uniformity of the prototype booster dipole magnet are presented in companion papers.

Introduction

The ALS is a third generation, 1-2 GeV synchrotron radiation facility specifically designed to maximize the brightness of the radiation from wigglers and undulators[1]. Twenty-four dipole magnets will provide the main guide field for the booster synchrotron. The synchrotron is intended to operate at 1 Hz, but the magnets are designed for 10 Hz operation.

The booster synchrotron dipole magnet is of the split H type with flat pancake coils. To minimize the stored energy and power requirements, the core is curved to follow the electron-beam trajectory. Table 1 gives dipole magnet design parameters[2]. An engineering model of this dipole magnet has been designed, fabricated, qualified through magnetic measurements, and twenty four magnets are now in production.

Table I. ALS 1.5 GeV Booster Dipole
Magnet Design Parameters

Injection Magnetic Field		.0416T
Design Magnetic Field		1.248 T
Test Magnetic Field		1.6 T
Bend Angle		15 Degrees
Entrance/Exit Edge Angles		7.5 Degrees
Magnet Bend Radius		4.0107 m
Magnetic Length Along Orbit		1.050 m
Magnet Vertical Aperture		4.4 cm
Good Field Aperture Width		+/- 3.0 cm
Good Field Aperture Height		+/- 1.8 cm
Field Quality (excluding fringe field)		$+/- 1.0 \times 10^{-3}$
Excitation Waveform	@ 1 Hz	Modified sawtooth
	@ 10 Hz	DC biased sinusoid

A pair of curved integral coils featuring multifilar wire windings were designed fabricated, calibrated and then used to make AC and, DC magnetic measurements of the Booster Dipole Engineering model magnet.

Magnetic Specification

The primary objective was to make a pair of curved integral coils to measure the magnitude and uniformity of the integral, $\int B_y ds$. A future objective is to use the coils to make accurate comparisons of $\int B_y ds$ between a reference magnet and production magnets. The coils need to follow the electron beam trajectory, requiring that the section within the magnet be curved while the end sections be straight. The coils need to have a sensitivity that will allow measurements of variations of 0.01% at the injection field level of 0.04 T without overloading the instrumentation at the maximum test field of 1.6 T. A single layer coil wound on a square cross section form satisfies the requirement for insensitivity to the even harmonics (i.e. quadrupole and etc), and the sextupole spatial harmonic. In reality, due to the finite number of turns, a slight correction to the square cross section is required.

For making uniformity measurements the noise due to power supply fluctuations can be minimized by placing two identical coils inside a magnet and connecting them in series opposition.

A constraint we had to consider was instrumentation noise level which is approximately 1 microvolt second for measurement durations in the range of one minute.

For ease of construction, we wound the coils from color coded, 12 strand #44 multifilar magnet wire.[3] The twelve strands add up to a width of 0.0635 mm or 0.025 inches. To obtain the required sensitivity, six adjacent windings were used to obtain a total of 72 turns, with a square cross section.

Mechanical Specifications

Fig. 1 shows a plan view of the search coils; Fig. 2 shows a cross-sectional view of one of the coils. Each of the coils consists of 6 windings of 12 strand wire wrapped on a precision ground form. The forms were secured to U-shaped strong backs which provide structural support for the coils. In order to enable positioning the coils adjacent to each other the two strongbacks had cross sections which were 'mirror images' of each other. The convex coil assembly having the winding form attached to the strong back whose outer radius is solid, and the concave coil assembly having the coil form attached to the strong back whose inner radius is solid. The coils conform to the hypothetical beam path through the Booster Dipole, as suggested by Fig. 1; this consists of 0.4 m straight sections at either end, and a curved middle section on a 4.011 m radius of curvature.

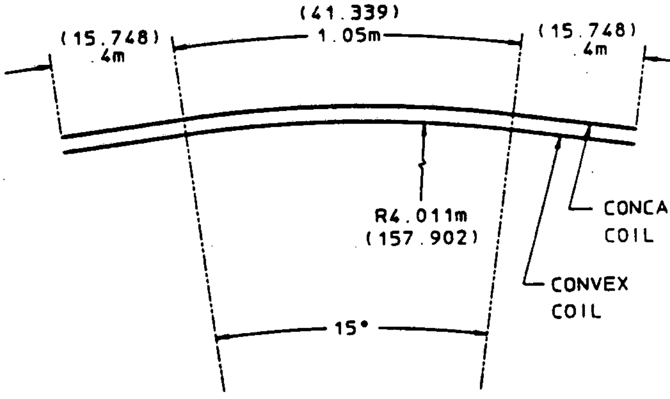

Fig. 1 Plain view of curved integral coils.

The search coil assembly is equivalent to a curved beam with uniform gravitational load acting perpendicular to the plane of curvature. The coil assembly is supported at the extreme ends. Under these load conditions, a curved beam is subject to vertical deflection as well as angular roll. The calculated deflections for the coil assembly with dimensions as shown in Fig. 2 are: maximum vertical deflection = 0.016 in, angular roll = 0.11°.

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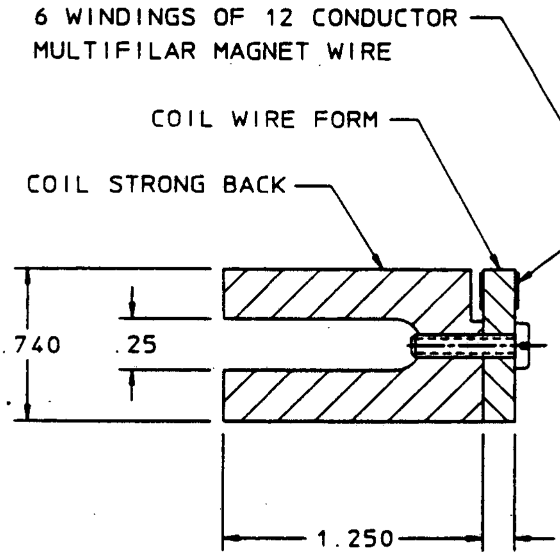

Fig. 2 Cross section of a coil assembly. The convex coil for example, having the center of radius of curvature to the left.

Mechanical Fabrication

The coils were fabricated in two separate pieces: the coil strong back, and the coil wire form. Both components were fabricated from NEMA G-10. The components were first Blanchard ground to the specified thickness. The coil strong back was then shaped on an NC mill to the required final shape. The coil form was initially straight; the coil was wound onto it in this configuration. After winding, the coil and coil form were bent and secured to the coil strong back to conform to the required final geometry.

The coil winding was done in a fixture consisting of two flat steel bars clamped to sandwich the coil form. The upper surfaces of the steel bars had been previously ground flat with a sharp corner, placed adjacent to the coil form. The upper surface of the steel bars provided a register for the first turn of the multiple filament wire cable. This arrangement is shown in Fig. 3.

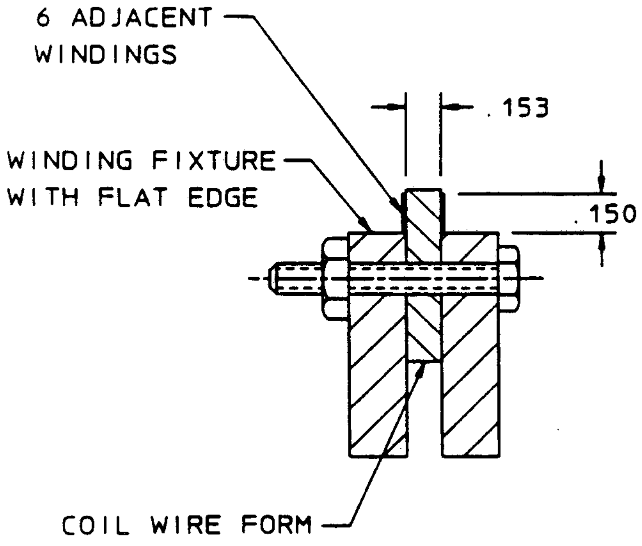

Fig. 3 Cross section of winding fixture wtih coil form.

The multiple filament wire cable consisted of 12 strands of #44 gauge insulated copper wire. The cable is coated with a polyvinyl butyral bonding agent that is activated by the application of isopropyl alcohol. The same material was used to bond the individual strands together.

The original plan was to bond to the coil form by clamping the wire in place and activate the bonding agent with alcohol and allow it to cure. This technique proved unsuccessful, since the application of the alcohol also released the inter-strand bond, resulting in delamination of the cable. After considerable experimentation a procedure was developed where an acrylic bonding agent was activated by ethylene dichloride, which does not activate polyvinyl butyral.

Magnetic Calibration and Wiring

Wiring

The A.L.S. Booster Dipole Integral Coil was wound with 12 conductor ribbon wire. In order to make the coil a single conductor coil the ends (terminations) were soldered with low thermal emf solder in an offset configuration, i.e., eleven wires from the start of the cable were soldered to eleven wires at the end of the winding. The required connections were made in a manner that minimized changes in the coil's sensitivity (turns area). A printed circuit board with narrow, close traces was attached near to one end of the coil form to terminate/join the individual conductor ends of the ribbon wire. A service loop (doubled back) was put into the ribbon before it was terminated to facilitate repair. The ribbon ends were prepared before they were soldered to the circuit board by separating the conductors (no small task) and fanning them, then sticking them to some kapton tape so that they would align with the traces of the circuit board. This made it easier to solder the almost invisible wire to the trace with minimum effort. One end of the ribbon was terminated at one "level" on the circuit board and then at a different "level" the other end of the ribbon was terminated. The leads were attached to a stick-on cable mount to relieve the strain from the circuit board connection. Resistance was measured for each individual turn and for the coil as a whole. The individual turns measured ~210 Ohms and the coil as a whole measured ~ 2500 Ohms. The the terminations were covered with a thin, flexible plastic material to protect them.

Magnetic Calibration

The coils were calibrated absolutely against a Nuclear Magnetic Resonance (NMR) Magnetometer and relatively against each other, using a long bending magnet as a transfer device.

For calibration the two coils were mounted on a fixture that preserved their angular integrity, and provided a number of precision holes for positioning the NMR probe to measure magnetic induction $B_y(S_i)$ (S_i is the position of the i-th hole on the imaginary line that bisected the two coil center lines and determined the hole pattern.) After measuring B_y at each S_i, we used numerical integration to determine $\int B_y ds$ over the coil's length;. Before and after the NMR measurements we measured changes in flux-linkage of each coil separately due to $\int B_y ds$ by extracting the fixture from the magnet and placing it in a "field free" location. The sensitivity (nw) of each coil was determined from eq. 1

$$nw = n\O / \int B_y ds \text{ [turn meters]} \qquad (1)$$

where:

$n\O$ = the flux linkage in the magnet
$\int B_y ds$ = the integral determined from the NMR measurements

The flux linkage was determined by flux-standard calibrations immediately before each measurement. Variations in $\int B_y ds$ over the fixture's width were determined to be negligible through separate measurements of the variations in flux linkage of one coil as the fixture was translated so that the coil covered the positions both of the hole pattern and the other coil. The "field free" location outside the magnet and normal to the earth's magnetic field and stray field from the bending magnet was established by another measurement The net field integral at the chosen location was verified to be negligible by flipping the fixture 180 degrees.

In order to demonstrate that the sensitivities of the two coils could be matched to 1:10000, by adjusting a signal divider installed between the most sensitive coil and the integrator, we connected the two coils in series opposition and measured the change in flux-linkage when the fixture was extracted. We recorded the divider setting that nulled the resultant signal. This setting was used in making DC measurements. During AC measurements, we found that a slightly different divider adjustment was necessary to minimize the time dependant peak to peak signal from the two coils connected in series opposition.

Magnetic Measurements

Measurements were made with the coils connected to analog integrators. DC BLeff was determined with the following procedure. With an integral coil in a zero field chamber, the analog integrator was zeroed; the time and integrator voltage were computer recorded. The coil was then inserted into the magnet, the magnet ramped to the desired fields, simultaneously recording both the time and the integrator output. After recording data for all specified fields, the coil was resinserted into the zero field chamber in order to measure the integrator drift. All coil signals were corrected assuming linear drift of the integrator.

A signal representing the magnet's effective length was created by dividing the integral signal by the magnetic induction signal from a point coil and/or Hall probe. The transfer functions were produced by dividing both the integral signal and the magnetic induction signal by the current signal.

DC uniformity data was acquired using null techniques. The moving integral coil was connected in series opposition to the stationary integral coil in order to cancel out power supply noise and drift. The magnet was ramped to the desired field, integrator zeroed, and then the moving coil was positioned at the various horizontal and/or vertical positions by computer controlled stepping motors. All data, position, time, integrator voltage, power supply shunt voltage were recorded and processed by the computer.

Quadrupole and sextupole coefficients were extracted from the uniformity data.

The results of some of these measurements are reported at this conference and elsewhere.[4,5,6,7,8]

Magnet parameters were also measured at 2 and 10 Hz frequencies. Together with measurements at selected DC levels, the AC measurements demonstrated that the magnet design met specifications and qualified it for production.

Acknowledgements

We gratefully thank Dave Van Dyke and Chinh Vu for their careful soldering of the multifilar cable under a stereo microscope.

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