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PRECISION MEASUREMENTS OF THE SLC REFERENCE MAGNETS*

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ABSTRACT

Two spectrometers, one on each extraction line of the SLC, have been installed to momentum analyse each SLC beam pulse and determine the electron and positron beam energies. A method of determining and monitoring the absolute magnetic field strength for these dipoles has been developed. A total error on the magnetic field integral of $\delta \int Bdl / \int Bdl = 1 \times 10^{-4}$ has been achieved. The field integral can be monitored continuously during SLC beam operation using radiation hardened equipment. The laboratory field mapping techniques and the field monitoring methods are described.[1]

1. INTRODUCTION

At the Stanford Linear Collider (SLC), a precise, independent measurement of the electron and positron beam energies is essential to determine the mass and width of the Z^0 resonance. Precision spectrometers have been installed in both SLC extraction lines, in order to determine the energy of each beam. The conceptual design of the extraction line spectrometer[2] is as follows: After passing through the interaction point, the beam bunches are transported to the extraction line. Each extraction line consists of a series of magnets which guide the beam through the reference magnet, B32. The energy of the beam is determined from the field integral ($\int Bdl$), and the measured bend angle (α).

To implement this design, two reference magnets (B32N and B32S) with very uniform fields have been designed and built at SLAC. The magnets have very wide gaps to simultaneously accommodate both the electron beam and the magnetic field monitoring devices (Fig. 1). Beam energies are expected to be between 42 and 50 GeV, requiring a field integral of 3.050 T · m.

2. LABORATORY FIELD MAPPING

2.1 *Moving Wire Technique*

In the "moving wire" technique a wire is passed through the magnet gap and returned outside of the magnet to form a closed loop. A ribbon pack of 10, 100-μm diameter wires forms the interior leg of the loop. Transverse motion of the wire pack in the magnetic field induces a voltage in the loop. From a precise measurement of the voltage integral and distance moved, the magnet strength is determined.

$$\int Bdl[T \cdot m] = \frac{-\int V dt[V \cdot s]}{N\,\Delta x} \quad . \tag{1}$$

Here, $\int V dt$ is the time integral of the induced voltage, N is the number of turns, and Δx is the distance moved.

The wires are secured in place at either end by wire holders mounted on precision traveling stages.[3] Both stages are precisely aligned to the magnet to an accuracy of 4 mrad which leads to a measurement error of 8 ppm. Stage positions are monitored by built in optical encoders which count lead screw rotations. The stage position accuracy is better than 30 ppm over the full range of travel as checked by a laser interferometer system.[4] In a measurement, both ends of the wire are moved simultaneously through a ramp up, steady speed and ramp down cycle to smoothly cover the distance desired (typically 10 mm).

The voltage is read by an HP 3457A Digital Voltmeter (DVM) with an accuracy of 25 ppm. The DVM takes a series of readings synchronously to a extemely accurate 50 Hz clock. A set of measurements, five each with the stages moving in the

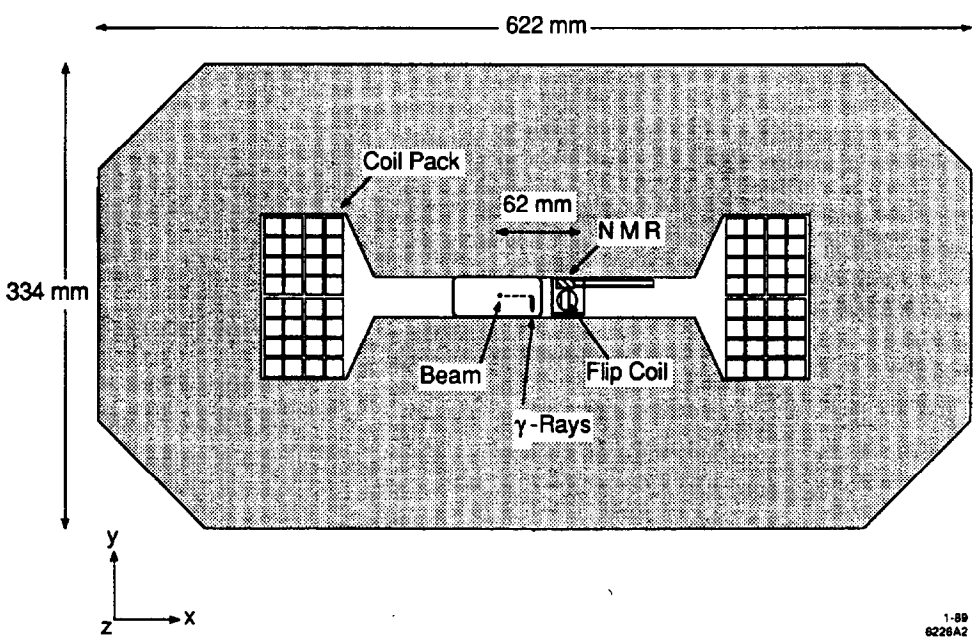

Fig. 1. Cross-sectional view of magnet B32.

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positive or negative x direction, allow for detection and cancellation of any DC offset level and estimation of the repeatability of the technique (28 ppm). Estimated systematic errors for the "moving wire" method are summarized in Table 1.

Table 1
Systematic errors for "moving wire" method

Error Source	Error (ppm)
Distance determination (stage)	30
Misalignment of travel	8
DVM accuracy	25
Time base	2
Combined systematic error	40

The field uniformity across the gap is important because the beam and monitors are at different positions. Measurements are made at currents corresponding $E_{beam} = (42, \ldots, 55$ GeV). Field integral maps are shown in Fig. 2 with the measurements normalized to 1.0 over the central region. The field shape is uniform to 54 ppm in the region occupied by the beam.

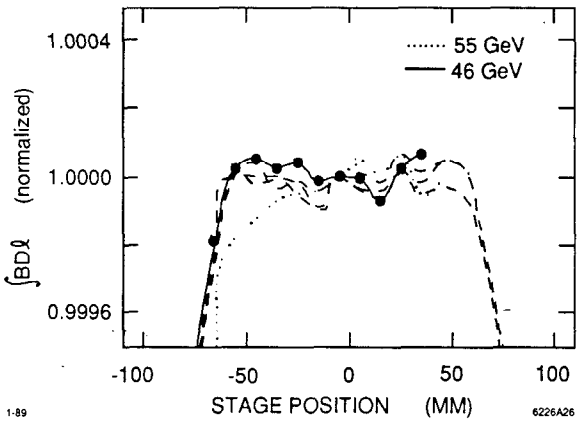

Fig. 2. Map in x of normalized field integral of B32N.

2.2 Moving Probe Technique

The "moving probe" technique measures the field integral by driving NMR[5] and Hall probes[6] along the length of the magnet in small steps. A laser interferometer determines the probe position at each step. The magnet strength is determined by summing the measurements of the magnet — $\int Bdl = \sum[(B_i + B_{i-1})/2]dl_i$. The B_i are the field measurements at each point and dl_i is the step size. The probes are mounted with a laser retroreflector on a rail assembly which runs the length of the magnet. The NMR probes are custom, radiation hard, miniature probes with an accuracy of 10 ppm. A Hall probe with a precision of 300 ppm is used in the fringe field of the magnet (6% of total $\int Bdl$). The Hall probe is sensitive to rotations and the maximum possible tilt would result in a total error of 48 ppm.

The field map in z is initiated at a location 28 cm beyond the end of the magnet. A schematic diagram of the mapping system is shown in Fig. 3. A stepping motor drives the probes on a lead screw in steps ranging from 100 μm to 1 cm. Smaller steps are taken where necessary to reduce the error in the field integral due to linear interpolation to less than 10 ppm. The short-term repeatability of this method is quite good (15 ppm). Table 2 summarizes the estimated systematic errors.

2.3 Measurement Consistency

As part of the calibration procedure, measurements of $\int Bdl$ are made at the beam and monitor locations at several excitations, with both techniques. The mean difference between these techniques is 72 ppm with a point-to-point variation of 53 ppm. The agreement between the two absolute techniques is within the level expected due to the known systematic errors.

Table 2
Systematic errors for "moving probe" method

Error Source	Error (ppm)
Position determination (laser)	1
Misalignment of laser to beam path	0
NMR system	10
Hall probe precision (300 ppm ×6%)	18
Hall probe tilt (800 ppm ×6%)	48
Linear interpolation	10
Combined systematic error	53

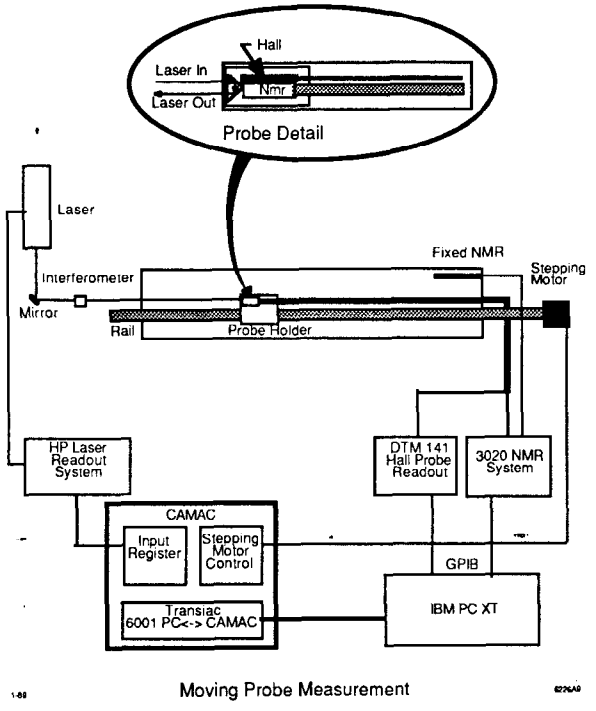

Fig. 3. System block diagram for "moving probe" technique.

3. FIELD MONITORING TECHNIQUES

The absolute measurements are used to simultaneously calibrate three independent, transferable standards for monitoring the field strength: a rotating "flip coil" and three NMR probes installed in the magnet and a current transductor.

3.1 Flip Coil

The flip coil consists of a rod of fused silica quartz 2.80 m long and 15 mm in diameter, with a ten-wire coil pack wrapped around it lengthwise and epoxied in place. An AC motor rotates the coil at 3 rpm. A DVM measures the voltage induced by the changing flux. The time integral of the voltage ($\int Vdt$) over a half-wave-form is proportional to the magnet strength.

The field monitors are calibrated by correlating the monitor measurements with the absolute measurements done simultaneously at each magnet excitation. The data is then fit to the lowest order polynomial function which yields fit residuals less than 100 ppm.

$$B(x) = (a_0 + a_1 x + a_2 x^2 + \cdots) \times (1 + C_T \cdot \Delta T) \quad . \qquad (2)$$

Here, $B(x)$ is the magnet strength as function of the monitor value (x) and the difference from nominal temperature (ΔT). Comparison of the monitors with the absolute standards at low (27°C) and high (35 − 40°C) temperatures determines C_T. The average fit residual for the flip coil is 20 ppm. In Table 3, the estimated systematic errors with the flip coils are shown. Errors for this method include: the DVM accuracy (35 ppm), flip coil

misalignment (1 ppm), and the uncertainty on C_T (9 ppm). Short-term repeatability is measured to be 28 ppm.

Table 3
Systematic errors for flip coil

Error Source	Error (ppm)
DVM accuracy	35
Time base	2
Misalignment of flip coil	1
Average fit error	20
Thermal effects	9
Combined systematic error	42

3.2 NMR Probes and Current Monitors

The second monitoring method uses the readings from a set of three NMR probes installed in the flip coil support structure. Changes in the field shape due to saturation or thermal effects are expected to affect this technique. Calibration of the NMR probes is performed with "moving wire" data with a mean fit residual of 42 ppm. Systematic errors for the NMR probes include the NMR system accuracy (10 ppm), a typical 1-mm uncertainty in probe position (20 ppm), and the error on C_T (30 ppm). These errors are summarized in Table 4. Short-term repeatability with this method is measured to be 5 ppm.

Table 4
Systematic errors for NMR probes

Error Source	Error (ppm)
NMR system	10
Probe position	20
Average fit error	42
Thermal effects	30
Combined systematic error	57

The final method of determining the field integral is to monitor the current in the magnet with a transductor with an estimated error of 190 ppm. However, the transductor is sensitive to the installation environment and is therefore only a relative measure of the field strength.

4. OPERATION AND CONCLUSION

4.1 Operation of Magnets and Monitors

With the magnets in operation in the extraction lines, the performance of the magnets and the monitors are investigated. Over periods of many hours, the current measured by the transductor is stable to 50 ppm. Data from the flip coils and the NMR probes show that the short-term relative precision is very good, but there can be changes ($\approx$ 100 ppm) in the magnet strength due to thermal effects. Over several months of operation, the mean difference between the flip coils and the NMR probes is 40 ppm, while for the transductor it is 483 ppm. An excitation curve of the north and south spectrometer magnets is taken over the range of $3.40\ [T \cdot m] > \int Bdl > 2.40\ [T \cdot m]$. A plot of the difference between the flip coil measurement and the other two magnet monitors is shown in Fig. 4. The NMR and flip coil track with a 25 ppm average difference.

4.2 Conclusion

Table 5 summarizes the known contributions to errors in the measurement of the field integral for each monitoring method. The absolute error is from the uncertainty in the absolute measurements. Uniformity is the error due to changes in the field strength at different transverse locations, while survey errors are from misalignments of the magnet relative to the beam. The monitor error is the systematic error for each monitoring technique. Adding all these errors in quadrature yields the combined error.

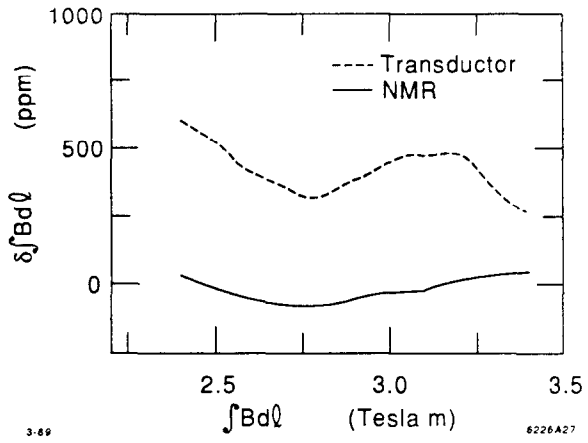

Fig. 4. Difference between the flip coil and the other monitors.

Table 5
Summary of errors in monitors of $\int Bdl$

Error Source	Flip Coil (ppm)	NMR (ppm)	Transductor (ppm)
Absolute	72	72	72
Uniformity	54	54	54
Survey	4	4	4
Relative	42	57	190
Combined	100	110	210
Precision (short-term)	28	5	16

In summary, several absolute and relative measurement techniques for determining the $\int Bdl$ of a dipole magnet have been developed. Measurements with these methods have determined the field quality and strength of the SLC reference magnets with an extremely high accuracy under a wide variety of operating conditions. The accuracy of these techniques has been determined and the relative monitoring methods have been calibrated with the absolute standards. Combining all sources of errors results in a total error on the measurement of the field integral, by the best monitor, of 100 ppm.

ACKNOWLEDGMENTS

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2. Mark II Collaboration and SLC Final Focus Group, SLAC–SLC–PROP–2 (1986).
3. The Klinger MT–160 is a precision translation stage.
4. Hewlett Packard HP 5526 Laser Interferometer system.
5. The NMR system is a MetroLab 3020 Teslameter with associated amplifier/multiplexer (Model 2031) and probes (Model 1065).
6. The Hall probe is a Group 3 Model DTM–141 system.