SLAC-PUB-6116
April 1993
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PRECISION MEASUREMENT OF TRANSPORT COMPONENTS*

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Abstract

We report on the methods and results of magnetic measurements of the centers and moments of magnetic focusing elements for the Final Focus Test Beam at SLAC. The magnetic center is located by observing an electromotive force (EMF) generated on a vibrating wire within the magnetic aperture. It is found that the center can be located with a precision of a few microns. The multipole coefficients can also be measured by using a grid of stretched-wire sweeps, and mapping the time-integrated voltage throughout the aperture. By fitting directly to this map, the dipole, quadrupole, and sextupole terms of the magnetic field are extracted. The design fields of quadrupoles and sextupoles can be measured with a precision better than 0.1%, and the resolution of sextupole aberrations of quadrupole magnets is well below design tolerances. This method has been used to process twenty-five quadrupoles and four sextupoles. Results of these measurements are presented.

I. INTRODUCTION

The Final Focus Test Beam (FFTB) is a transport line designed to test both concepts and advanced technologies for application to future linear colliders. It is currently near completion at SLAC in the straight-ahead tunnel at the end of the linac. The primary optical elements of the FFTB are a family of quadrupole magnets and a family of sextupole magnets used for chromaticity correction. In order to achieve the desired spot sizes at the focal point ($\sigma_x = 1\ \mu m$, $\sigma_y = 60$ nm), tolerances on alignment, design field strength, and aberration field strength must be met [1]. We describe below our use of a stretched-wire technique for measuring each magnet's compliance with its tolerances, and discuss our experiences with the apparatus to date.

II. CONCEPT OF THE METHOD

Figure 1 below depicts a schematic of our apparatus. A computer-controlled Coordinate Measuring Machine (CMM) is used to establish a coordinate system parallel to the mechanical axis of the magnet, with $x = y = 0$ on the axis and $z = 0$ at the longitudinal midpoint of the magnet. A thin wire which has been stretched lengthwise down the magnet aperture is then made parallel to the longitudinal axis to within a few tens of microradians.

The technique for measuring the magnetic center of the magnet relative to the mechanical center has been described in detail elsewhere [2]. In brief, the wire is set to vibrate at its resonant frequency ω, and the resulting EMF is monitored on a spectrum analyzer. By nulling the EMF at the driving frequency in horizontal and vertical planes, the magnetic center can be located and measured relative to the mechanical coordinate system, via the CMM.

In order to measure the magnetic moments of the magnet, the wire is swept by a known horizontal or vertical distance (δ_x or δ_y, respectively) about a point (x,y). The expansion to second (sextupole) order of an arbitrary beamline component's magnetic field is:

$$B_x = B_{ox} + G_n y + G_s x + 2S_n xy + S_s(x^2-y^2)\ ,$$
$$B_y = B_{oy} + G_n x - G_s y + S_n(x^2-y^2) - 2S_s xy\ , \qquad (1)$$

where B_{ox} and B_{oy} are the horizontal and vertical field components at the origin, respectively; G_n is the normal quadrupole (preserving midplane symmetry); G_s is the skew quadrupole (violating midplane symmetry); and S_n and S_s are the normal and skew sextupole components, respectively [3]. When the wire is swept through the magnetic field, the time-integrated EMF across the wire is a function of the center point of the motion and of the total distance traveled in each direction:

$$\int v dt = L\{\delta_x\,[B_{oy}+G_n x-G_s y+S_n(x^2-y^2)-2S_s xy+S_n d_x{}^2/12]$$
$$-\,dy\,[B_{ox}+G_n y+G_s x+2S_n xy+S_s(x^2-y^2)-S_s d_y{}^2/12]\}\ ,\ (2)$$

where L is the effective length of the magnet. The wire is moved to locations throughout the aperture of the magnet, and swept by known amounts, vertically and horizontally. The potential difference across the wire is monitored by an integrating voltmeter, which allows direct measurement of the time-integrated voltage as a function of position and sweep vector. By fitting the mapped measurements directly to the equation above, it is possible to extract the coefficients of the magnetic expansion directly. Note that Eq. (2) is only correct up to an overall sign, which is influenced by the connection between the voltmeter and the wire, among other variables.

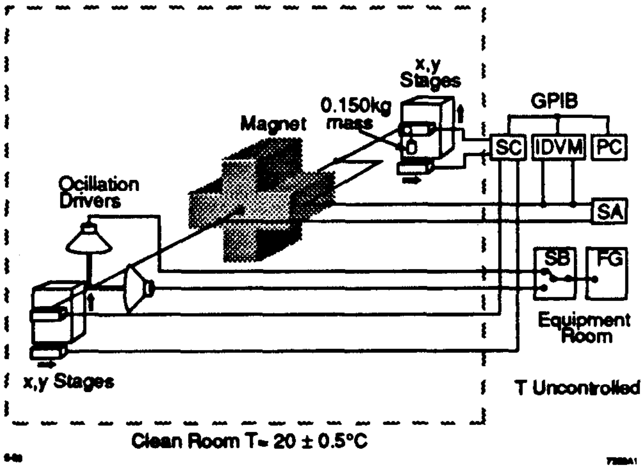

Figure 1. Schematic diagram of apparatus, including Stage Controller (SC), Integrating Digital Voltmeter (IDVM), Spectrum Analyzer (SA), frequency generator (FG) and switch box (SB). Not shown: mounting table and CMM.

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*Work Supported by the Department of Energy Contract DE-AC03-76SF00515

Presented at the Particle Accelerator Conference (PAC 93), Washington, DC, May 17–20, 1993

III. DETAILS OF THE APPARATUS

As shown in Figure 1, the principal elements of the measurement apparatus are the wire, the oscillation drivers, the stages which move the wire, the integrating voltmeter, the mounting table upon which the apparatus rests, and the magnets themselves. Many of these components have been described in detail in Reference [2], so for these only supplementary information is given.

A. The Wire

The wire employed is a 35 μm gold-plated tungsten wire, of the type often used in drift-chamber applications. Under the conditions of the experiment, the overall sag of the wire is 12 μm. If the height of the wire is measured close to the entrance and exit of a half-meter long magnet, the effective sag correction is about 1 μm. The sag causes no alteration to the fitted field gradients, and an alteration to the sextupole terms that is unmeasurably small.

B. The Wire Stages

The wire is moved within the magnet by a set of precision stages made by the Newport Corporation. Four stages were used, one for x-motion and one for y-motion at each end of the wire. The stages were moved independently to align the wire parallel to the magnet, and then in pairs (x or y) to sweep the wire parallel to the magnetic axis for field measurements. The stages are controlled from a PC via a GPIB interface. The stage system has internal monitoring and feedbacks, and in principle each mover is capable of 0.1 μm precision. In practice, this requires that the wires repeatedly iterate their motions, and for our purposes a tolerance of approximately 0.3 μm was chosen. In experimental tests with the wire and CMM, it was found that the x and y motions have a difference in scale of approximately 0.3%, which varies slightly between magnets. This scale factor was determined for each magnet by fitting, and is believed to be due to non-orthogonality between the x-movers and the magnet z-axis. The absolute accuracy of the stages over millimeter-sized motions was highly variable, but always on the order of microns.

C. The Integrating Voltmeter

The time-integrated voltage on the wire was measured by a Solartron-Schlumberger Model 7061 Systems Voltmeter. The voltmeter was controlled and read out by a PC via a GPIB interface. The voltmeter has a built-in time-integration function which returns values in volt-seconds. By integrating the voltage in DC mode, the voltmeter rejected high-frequency transients, such as 60 Hz line noise. The integration time was set to 5 seconds, which was found experimentally to be long enough to allow the wire to stop oscillating after being swept.

D. The Mounting Table

The magnet, Newport stages, the wire, and the Coordinate Measuring Machine are mounted on a polished flat, 3.2-ton granite block that is seismically isolated from the ground by soft rubber pads in a temperature-controlled clean room. As part of the premeasurement procedure, the magnet is made flat with respect to the table through CMM measurements of the table and the magnet split-planes (see below).

E. The Magnets

The outer surfaces of the four quadrupole quadrants were machined with "split-plane" slots to allow access to the mating planes. In all, 30 standard quads were made, of which 28 were destined for installation in the FFTB beamline. After an initial acceptance test using a rotating coil to measure excitation curves [4], each quad was disassembled for installation of a precision Beam Position Monitor (BPM), and reassembled on a remote-controlled mover apparatus for beam-based alignment [5]. At this point, 25 quads were retested using the present technique, both for tolerance-checking and as a final quality control checkout before installation. Two of the quads were not retested because of time constraints, and one was not retested because it had not been split and was downstream of the focal point; therefore, its aberration content was not critical. All measurements were made at a current of 165 amperes on the rising leg of the hysteresis curve.

The standard FFTB sextupoles have a bore diameter of 2.065 cm and an effective length of 25.0 cm. The sextupoles were constructed in a fashion similar to the quadrupoles, and are each capable of producing sextupole coefficients of 7,100 T/m^2. Each sextupole was subjected to an initial acceptance test similar to that of the quadrupole, and was then mated to a remote-controlled mover. Although the sextupoles were not disassembled after delivery, it was necessary for alignment purposes to mount each sextupole on the apparatus described above, and subsequently each one was measured using a swept wire in the same fashion as the quads. Sextupole measurements were all made at a current of 215 amperes on the rising leg of the hysteresis curve.

IV. RESULTS

A. Vibrating-Wire Measurements

Magnetic center location was accomplished by placing the wire at six different small angles (<1 mr) with respect to the magnet axis, and zeroing the first harmonic EMF signal each time. The resultant six lines were used to find the point at which the average distance from the point to each of the lines was minimized. This fitting would produce a magnetic center point unconstrained by any mechanical reference to the magnet. In all, 28 magnets were measured using this procedure.

Figure 2 shows the distribution of z positions, and the average distance from the fitted center point to the six lines, d. Note that the longitudinal center points are clustered around −2 mm from the mechanical longitudinal centers. The RMS deviation of any line from the point of closest approach was less than 4 μm relative to the external fiducials of the magnet.

B. Swept-Wire Measurements

For the swept-wire measurements, the area of the magnet aperture mapped was limited by interference of the apparatus. The total length of each sweep was chosen to be 2 mm, and the centers of each sweep were separated by 2 mm. A square grid was used, containing a total of 25 center points, and each point centered a vertical and a horizontal sweep, for a total of

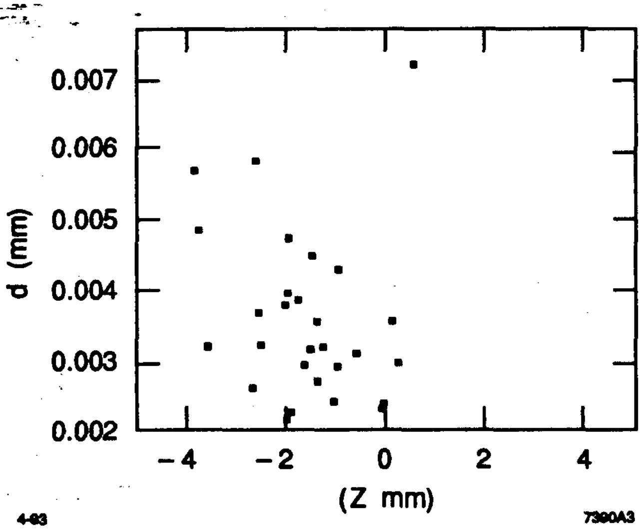

Figure 2. Z and d distributions of magnetic centers relative to mechanical center

50 measurements. This pattern was repeated ten times, and an average and rms deviation was computed for each of the 50 measurements. For most magnetic measurements, the rms was found to be consistent with the measured intrinsic noise of the system, about 80 nV sec, but in some cases it was up to an order of magnitude larger. In the latter cases it was also found that the absolute accuracy suffered, as did the resolution of the measurements. It is believed that high temperatures in the equipment room, which was outside the climate-control area, affected the performance of the Newport stage controller unit. Six out of the 25 quads were so affected; their results are included in the quad strength analysis, but not in the sextupole aberration.

It was also shown that the rms of the measurements did not describe well the deviations of the measurements from fitted values. It was speculated that although the movers have a precision of 0.3 μm, their absolute accuracy might be somewhat lower. We found that an absolute accuracy of approximately 3 μm described the deviations quite well. As the temperature in the equipment room came down, we found that this number also came down, to approximately 1 μm.

Fitting of the magnetic field expansion was done by a special-purpose FORTRAN program utilizing the CERNLIB fitting engine MINUIT, which returned fitted values for the parameters, errors on the fitted values, and a final chi-squared for the fit [6]. In fitting the magnetic field expansions, it proved useful to add three parameters, x_0, y_0, and θ, corresponding to origin offsets and roll angle, respectively. By introducing these, it was possible to eliminate three magnet parameters from Eq. (1).

The fitted quadrupole coefficients, G_n, of the normal quads were found to have a resolution of 0.015 T/m at an excitation of approximately 62 T/m, corresponding to a precision of 2.5×10^{-4}. This was dominated by the 3 μm wire mover accuracy. For measurements with better accuracy, the precision was as good as 8×10^{-5}. With the exception of measurements that were clearly anomalous, there was a systematic deviation of 0.11±0.011 T/m between our results and those obtained with a rotating coil, which has intrinsic resolution similar to our own. This deviation is believed to be due to slightly different absolute calibrations of the two systems.

The construction tolerance on sextupole content of the quadrupole magnets is a sextupole contribution to the magnetic field not to exceed 1×10^{-3} of the quadrupole contribution at 70% of the aperture [7]. This translates to a limit of 7.7 T/m^2 at a quad strength of 62 T/m for our magnets. Out of the 25 magnets tested on our apparatus, we found that 14 met the construction tolerances, five exceeded the tolerances by small amounts, and six gave anomalous readings due to apparatus difficulties. Typical resolutions were 1.0 to 2.0 T/m^2. Because this was the first sextupole measurement made of these magnets, no comparison figures are available.

The sextupole components of the sextupole magnets were found to have a poorer resolution than those in the quadrupole magnets, typically 4 /m^2 at a sextupole strength of 6500 T/m^2, for a precision of 6×10^{-4}. Because the currents were not recorded during these measurements, no comparison with the rotating coil tests is possible.

ACKNOWLEDGMENTS

We wish to acknowledge the contributions of many members of the SLAC staff, in particular H. Maxson and O. Dorsey for their help with the apparatus, W. Lockman for his help with MINUIT, and G. E. Fischer for technical and conceptual assistance.

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