ESTABLISHMENT OF PRECISE MAGNETIC FIELDS IN THE MOMENTUM ANALYZING SYSTEM AT SLAC

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Summary

Precise magnetic fields are necessary to achieve high-quality particle beam-transport in the SLAC beam switchyard. A discussion of the methods of magnetic measurements associated with testing and establishing these fields is presented. These measurements and some of the important results obtained are described. In order to satisfy the criteria placed on the transport systems each magnet was measured and the critical magnets of the transport system were selected for placement in the beam switchyard on the basis of several of their measured characteristics. A description of the selection procedure is presented, and the effects of the individual magnet differences are discussed. Details of measurement techniques and the resulting procedures which are used for setting up the beam switchyard for a particular momentum are given.

Introduction

Present day experiments in high-energy physics require the use of particle transport systems which have high-quality optical properties and which are capable of accurate, reproducible momentum analysis. Measurements associated with testing and establishing of the precise magnetic fields required by these transport systems play an important role in determining the correct operating settings of the magnetic elements and in understanding the operation of the system. As the requirements on accuracy of magnetic field values and characteristics become more stringent, numerous complications develop which must be solved before the requirements can be satisfied. This paper describes the techniques used in establishing the magnetic fields of the numerous three-degree bending magnets which are used in the transport system which momentum analyzes and delivers the beam from the SLAC Linear Accelerator to the experimental areas.

We have found that in order to obtain precise magnetic field settings several parameters must be controlled, e.g., current run-up rate, sequence of run-up, hysteresis, power supply overshoot, etc. Variation in these parameters can cause relatively large, local field variation in the magnet,[1, 2] but long-coil measurements do not show as large a variation with varying conditions. Since long-coil measurements more closely correspond to the magnetic field observed by a particle passing through a magnet than point measurements, most of the results reported here are based on long-coil measurement. When numerous magnets which are identical to high precision are desired, magnet design parameters, and close control of iron composition and heat treatment are very important. Significant differences were found in the magnetic fields of the three-degree bending magnets which can be ascribed to some differences in iron composition and gap-width.

The number and definition of possible parameters which must be controlled for obtaining precise magnetic fields are not well understoood. In an effort to understand the magnetic properties of our transport elements, we have carried out an extensive magnetic measurement program and we have developed a phenomenonological analysis which allows the beam transport system to achieve its design requirements. In the following sections a brief description will be given of the requirements placed on the magnetic elements of the transport system by its design criteria. These system requirements and preliminary magnetic measurements led to a magnetic measurement program designed to give information suitable for (1) insuring that the magnetic fields of the individual magnets satisfy the uniformity requirements of the beam optics, (2) determining the optimum location assignment of the three-degree bending magnets by taking account of the observed magnetic differences, and, (3) defining magnet set-up procedures and current for accurate and reproducible particle momentum determination.

System Description and Requirements

The beam from the SLAC Linear Accelerator is delivered through a beam switchyard to two experimental areas, denoted "A" and "B," located at 24.5° and 12.5° deflection angles from the direction of the incident beam. Various aspects of the beam switchyard and experimental area facilities are discussed in other papers presented at this conference.[3] In particular, these papers contain descriptions of the beam optics of the transport system and also design criteria which are satisfied by the system. Figure 1 is a schematic showing this system. The A-system is similar to the B-system. In the following text, in most cases, the A-system will be described, but similar comments can be made about the B-system. The A-transport system contains eight deflection magnets denoted B-10 through B-17, each of which nominally deflect the beam by three degrees for a total of 24°. These magnets are electrically in series with a precision shunt and with a reference magnet of identical design and construction which are located in the data assembly-control building. Precautions were taken in the design of the system to insure that leakage resistance to ground and shunting the individual magnets is sufficiently large to insure that the current supplied by the single power supply for the system, passes through all the magnets of the system to a few parts in 10^6. The B-transport system has a similar arrangement consisting of four beam transport bending magnets, B-30, B-33, B-34, and B-36, plus a reference magnet. The total of 14 magnets used in these systems were designed and constructed to be magnetically identical and satisfy the requirements placed on the transport system. The absolute momentum calibration of the transport system is based on the geometrical alignment and the results of magnetic measurements of the momentum defining elements of the system. In the A-system these elements consist of the collimator C-0, the quadrupole doublet Q-10-11, the bending magnets B-10 through B-13, and the slit, SL-11. To achieve the requirements for momentum calibration placed on the transport system, it was necessary to make magnetic measurements commensurate to a reproducibility of magnetic field setting of $\pm$ 0.02% and an absolute field determination of $\pm$ 0.1%. Field distribution measurements were required to insure that the magnet design achieved the field uniformity necessary to transport the beam without introducing significant aberration. Using the SLAC TRANSPORT computer program, analysis of beam optics requirements gives the requirement that

$\int B(x,y,z)dz$ vary no more than 2 parts in 10^4 for $-2.5 \leq x \leq 2.5$ cm,

where B is the magnetic field in the magnet, x is the traverse direction, y is perpendicular to the pole tip, and z is along the longitudinal direction of the magnet. Another desirable requirement placed on the transport system is that the direction of the beam existing from the system be independent of momentum which is transmitted by the system.

Magnetic Measurements

Magnetic measurements on the magnets were performed in the laboratory and also in the beam switchyard with the magnets in final position and with the power and control systems to be used during beam operation. The measurements were made using standard instruments; most were performed with a long-coil system. Two long-coils were used for measurements in the beam switchyard. One of these is permanently located in the reference magnet and the other was moved from magnet to magnet for comparison measurement.

The instrumentation consisted of a 3.75 meter epoxy-fiberglass coil form wound with copper wire. The coil rested in a cradle with roller supports at many points. The cradle in turn rested on the lower pole of the magnet being tested and positioned the coil in the central plane of the magnet. An electric motor rotated the coil upon command through slightly more than 180 degrees. The coil output was fed into an integrating digital voltmeter which was set to integrate either positive or negative signals only. As the coil began to rotate, no integration began until the coil plane was perpendicular to the direction of B. Integration continued until the coil rotated 180 degrees and the output voltages changed sign. This method required no accurately set limit stops on the coil flipping mechanism and improved the accuracy of the measurement. The long coils were periodically placed in three-degree magnets with field profiles determined by direct measurements to determine and check the coil constant. The readings of magnet excitation current were made with a 0.1 mΩ high accuracy (0.02%) shunt in series with the magnet. The power supply run-up rate and current level was controlled by a stepping motor.

In order to make magnetic measurements reproducible, it is necessary to degauss the magnets before each test. It was found experimentally that the magnets could be consistently degaussed by use of a reverse current held for some definite time and then decreased to zero. This technique of degaussing works very well if the magnet has been excited to at least 400 amps. The reverse current necessary to degauss the magnets is dependent upon rate of change current. A reverse current of 165 amps heldfor 30 seconds degausses all of the magnets to better than 0.5 gauss.

Long-coil measurements of two types were performed: (1) $\int B\,dz$ versus position, at several excitation currents I_{ex} and (2) $\int B\,dz$ versus I_{ex} at the center of the pole transversely and in the center plane. The measurements of $\int B\,dz$ versus I_{ex} were performed in 50 ampere increments and with two modes of current run-up, starting with a degaussed magnet. The modes were (a) "direct" in which the current is run up from zero current to the desired current with no intermediate steps, and (b) "incremental" in which the current is run from zero current to a current I_1 then to current I_2, etc. where a long-coil measurement is made at each current level. "Direct-run-down" and "incremental-run-down" measurements have also been made. In this case the measurements are made by decreasing the magnet current from an initial well defined magnetic state at 800 amp. A 6 amp per-second rate was chosen and unless otherwise indicated, all measurements were made using that rate of excitation.

A typical graph of homogeneity of $\int B\,dz$ versus x is shown in Fig. 2. The dependence of run-up rate on the $\int B\,dz$ achieved, for a given current is shown in Fig. 3 for three different run-up rates. In Fig. 3 the line of zero deviation is the 6 amp per-second rate and it can be seen that the $\int B\,dz$ values for 9 amp per-second are higher than the 6 amp per-second values while the 3 amp per-second rate gives lower values of $\int B\,dz$. This illustrates the need for using a single run-up rate. It has been mentioned before that measurements of induction at a point in the magnet indicate a different dependence on run-up rate than $\int B\,dz$. This is illustrated in Fig. 4. At other points in the magnet different dependences are observed such that the integral effect is that given by the long coil.

Differences of $\int B\,dz$ between magnets at a given I_{ex} can be attributed to differences in gap width, core length and core impurities. Measurements of $\int B\,dz$ versus I_{ex} were made on each magnet and it was found that the differences between magnets could be separated into two types, current dependent and non-current dependent. The non-current dependent differences were characterized by a nearly constant percentage offset of $\int B\,dz$ over the whole range of excitation current. The percentage offsets compared to magnet No. 4 are listed for each magnet in Table I. Superposed on these differences are current dependent differences which group themselves according to the heat number of the steel from which the cores were fabricated. These differences, which are shown in Figs. 5 and 6, are seen to be quite large in the case of some heats. Figure 5 shows the relative differences attributable to steel impurities based on measurements of $\int B\,dz$ using incremental run-up of current. Figure 6 is similar data for direct run-up of current. In these figures heat 86 is taken as the standard of comparison and is plotted as zero deviation. Table II gives a chemical ladle analysis of the various heats of steel from which the magnet cores were made.

Magnet Location Selection

Initial TRANSPORT calculations made to design the beam switchyard transport system assumed identical magnets each bending the beam by three degrees. However, in practice, the magnets are required to have identical current, and measurements show that small but significant differences exist in the $\int B\,dz$ magnetiziation versus current data for the individual magnets.

See Figs. 5 and 6 and Table I. The result is that each bending point in the system is not exactly three degrees and, furthermore, the ratio of the various actual deflections produced by the magnets varies with current and, therefore, the momentum setting of the system. Since the current through the system must be set to define the momentum, the exit angle from the system will vary slightly with the momentum.

Since fourteen magnets were to be located into fourteen positions there are 14! ($\sim 8.7 \times 10^{10}$) possible permutations from which the optimum arrangement was selected A number of magnetic features such as degaussing characteristics, transverse magnetic homogeniety, magnetization characteristics, etc., need to be considered in determination of the optimum permutation. However, our measurements and calculations indicated that magnets were sufficiently identical that consideration of magnetic features other than magnetization was not necessary. The number of permutations was reduced significantly by imposing the requirements that momentum defining magnets (the first four in A-Beam and the first two in B-Beam) and the respective reference magnets in each system have similar magnetization curves. This choice gives more confidence that future measurements on the reference magnets will indicate the behavior of the nearly inaccessible momentum-defining magnets in the system. Also, since the requirements for optical quality are more stringent for high-energy experiments planned using the A-Beam, this beam was given priority in the selection of the remaining magnets. Based on these requirements, the four magnets from heat 60, the magnets from the magnetically similar heat 86, and the magnet from heat 25 were assigned to A-Beam. The magnetization data for these magnets and the heat 73 magnets was supplied to a computer program designed to select the permutation of magnet assignment which resulted in a minimum deviation of the deflection of the exit beam from the ideal beam as the beam momentum is changed from one value to another. The program was required to select three magnets from heat 60 plus one magnet from heat 86 for the first four momentum-defining magnets. The remaining heat 60 magnet was assigned as the A-Beam reference magnet. The last four magnets in A-Beam were selected by the program from heats 86, 73, and 25, with the requirement that three heat 73 magnets remain un-used. This completed the assignment of magnets to the A-Beam. The program was then used in a similar manner to assign the remaining magnets to location in the B-Beam. Heat 73 magnets were used in the first two momentum-defining positions and as the B-reference magnet.

As a result of the magnet differences the beam exit angle from the installed A-transport system will vary from the design figure of 24.5° depending on the momentum setting of the system. If not compensated by the steering magnets provided at the end of the transport system, the extremes of angular variation for momentum settings between 3 BeV and 20 BeV is sufficient to cause a motion of about one centimeter in the location of the beam spot in the end station. The corresponding displacement in the B end station is about four centimeters.

Magnetic Field Set-Up for Momentum Analyses

There are three methods for setting up the deflection magnets in the beam switchyard transport system, the first two of which methods are presently in use and are being tested to determine their relative advantages. The first and operationally preferable method is to adjust the current in the deflecting magnets until the desired $\int B\,dz$ is achieved in the reference magnet. For this measurement, the long-coil permanently installed in the reference magnet is used and its integrating digital voltmeter measures the volt-second integrator resulting from a flip of the coil. In this method the $\int B\,dz$ of the reference magnet is related to the $\int B\,dz$ (and hence the momentum setting of the transport system) through previous magnetic measurement on the individual magnets of the system. Obviously, this method requires that the $\int B\,dz$ in the transport system tract with the $\int B\,dz$ of the reference magnet. As has been discussed, we assigned magnets to the momentum analyses locations of the transport system which have nearly identical $\int B\,dz$ magnetization variation with current and tests have been performed to study the tracking characteristics of the magnets. We find that over the measured range of parameters these magnets track each other to within 0.02% independent of run-up rate and the mode of operation (direct or incremental, up or down). Although the evidence is incomplete and further tests are planned, it seems that this method makes it possible to set up to a desired momentum setting in a precise, quick, and flexible way.

The second method for setting the transport system to a specified momentum uses current reading from the precision shunt in series with the transport magnets. The accuracy of this method depends upon the stability and accuracy of the current monitoring shunt and associated voltmeter. This method requires that the magnet be degaussed and then set via direct run-up to the current corresponding to the desired momentum setting. This current setting is determined from analysis of the direct-run-up magnetic measurements. To allow step increases in the momentum setting, tables giving the required current change have been prepared from the incremental-run-up measurement. These should give good results providing that only a few steps increase in momentum are made and that the steps are not too large. All the tables were prepared by fitting eight degree polynominals to the magnetic data. A similar scheme has been worked out using the run-down data. In using this method we have only sufficient data to allow changes in only one direction, but not both in a single run. In principle this method for setting up the beam switchyard momentum analysis system should be as accurate as the $\int B\,dz$ measurements outlined above. In particular, the direct-run-up technique, although it is long and tedious, is based on a well-defined sequence on the hysteresis loop of the magnets. It should yield reliable results when a check on other methods is necessary.

A third method for establishing fields in the transport system magnets is based on readings from nuclear magnetic resonance (NMR) probes which are installed in the cavity of each of the momentum defining magnets. These probes give the induction at that point in the magnet. These can be used to set up the required magnetic fields for the deflection systems; however, the accuracy is not as good as the long flip-coil measurements because the induction is sensitive to local variations in field and to gap changes caused by temperature variation. The installed NMR's however, serve as a basic check against shunt changes or electrical shorts in the magnets and may detect anomalous behavior of a magnet which would not be reflected in the reference magnet readings.

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References

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Table I

Summary of Differences in $\int B\,dz$ of Magnets

Core Number	BSY Position	$<\int B\,dz$ Magnet N $>$ / $<\int B\,dz$ Magnet 4 $>$
1	B-33	± 0.347%
2	A-Ref.	± 0.193
3	B-10	- 0.050
4	B-16	0
5	B-13	- 0.020
6	B-12	± 0.131
7	B-32	± 0.015
8	B-11	± 0.110
9	B-17	± 0.120
10	B-Ref.	- 0.017
11	B-14	- 0.049
12	B-15	- 0.031
13	B-30	± 0.084
14	B-35	± 0.304

Table II

Chemical Ladle Analysis

Percent Impurities in Steel for 3° Bending Magnet Cores

Heat # / Impurity	56	60	86	0	73	25
C	.06	.06	.06	.05	.08	.07
Mn	.29	.26	.30	.15	.28	.30
P	.009	.009	.008	<.03	.008	.008
S	.029	.025	.017	.025	.025	.022
Si	.004	.18	.18	.08	.13	.16
Ni	.02	.01	.04	.06	.04	.01
Cr	.03	.05	.04	.01	.04	.03
Mo		.01	.01	.01	.02	.01
Cu	.05	.04	.04	.04	.04	.03
Al	.005	.008	.012	<.005	.009	.004
Magnet Cores	1	2, 3, 6, 8	4, 5 11	14	7, 9, 10, 13	12

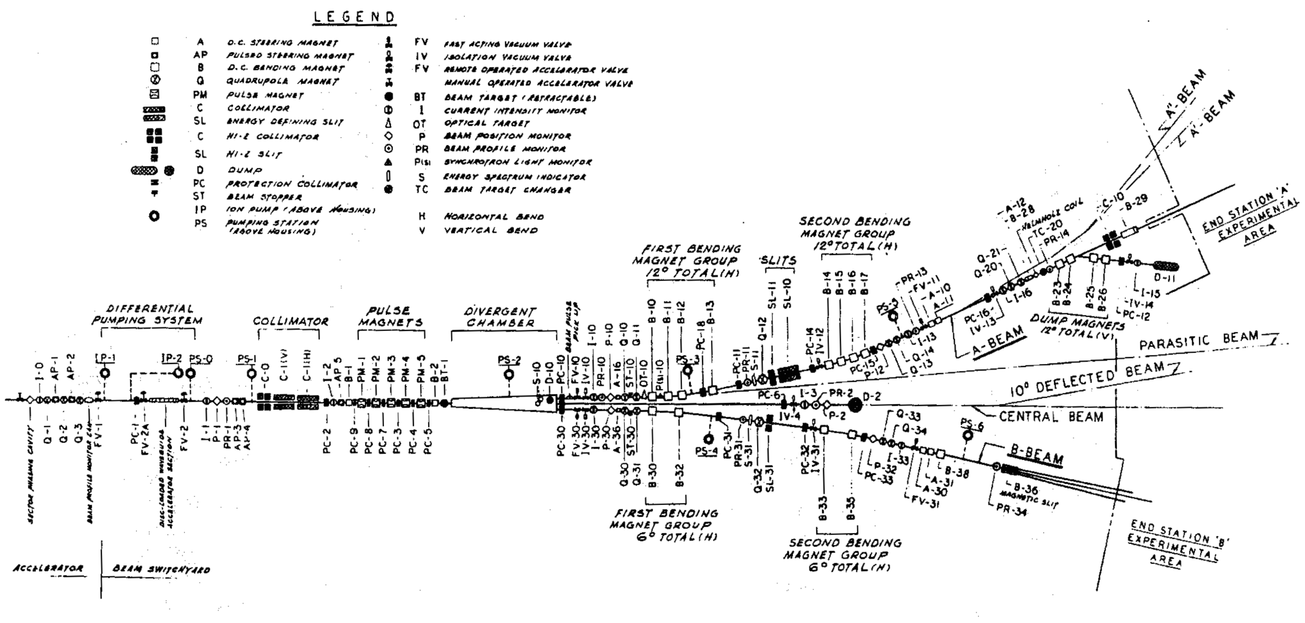

Fig. 1. Beam Switchyard Transport System.

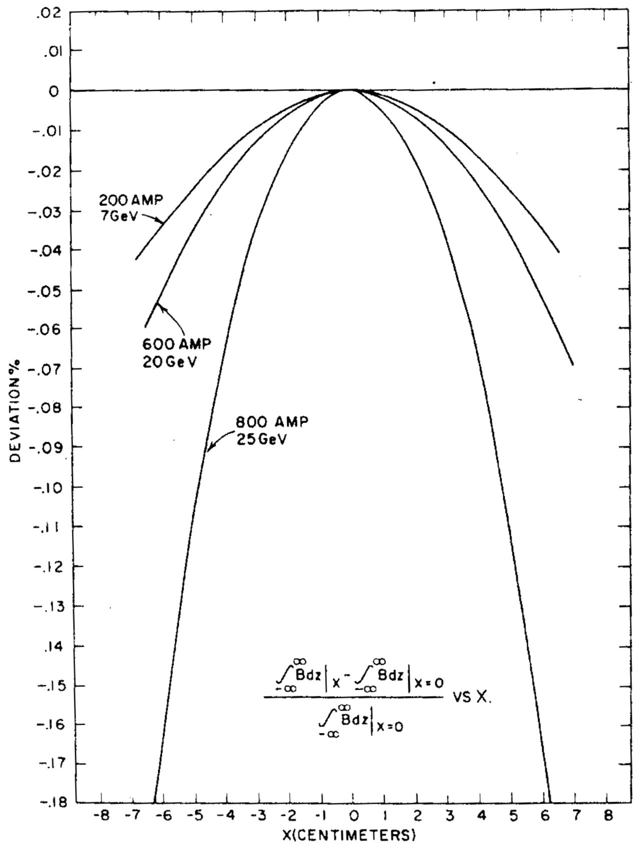

Fig. 2. Homogeneity of 3° Bending Magnets.

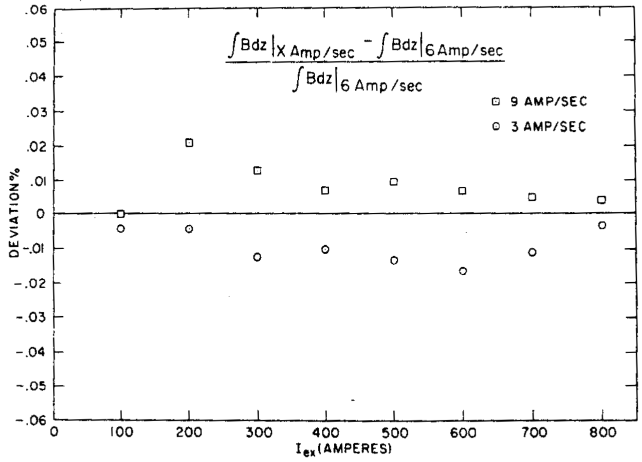

Fig. 3. Differences in ∫ B dz caused by rate of excitation.

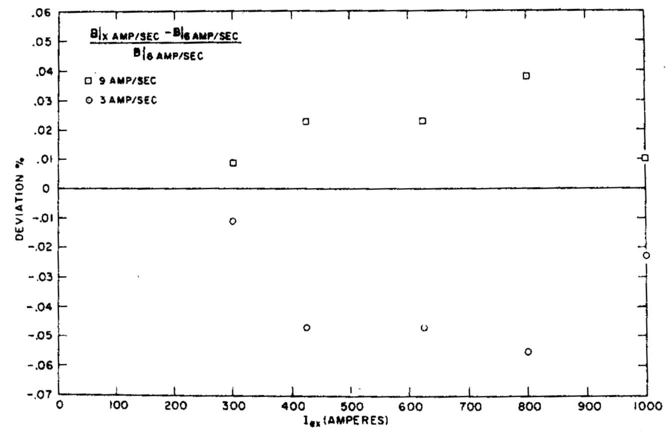

Fig. 4. Differences in ∫ B caused by rate of excitation.

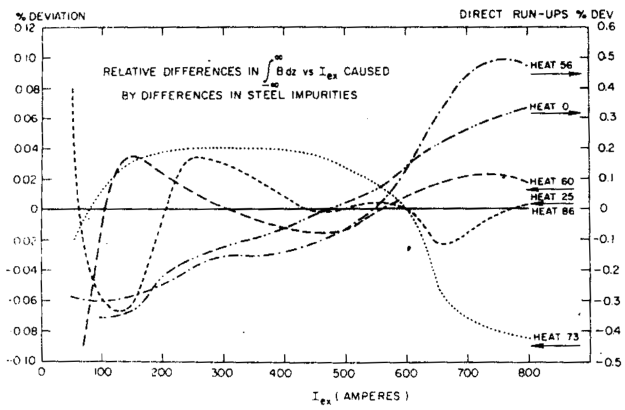

Fig. 5. Relative difference in ∫ B dz versus I_{ex} Incremental.

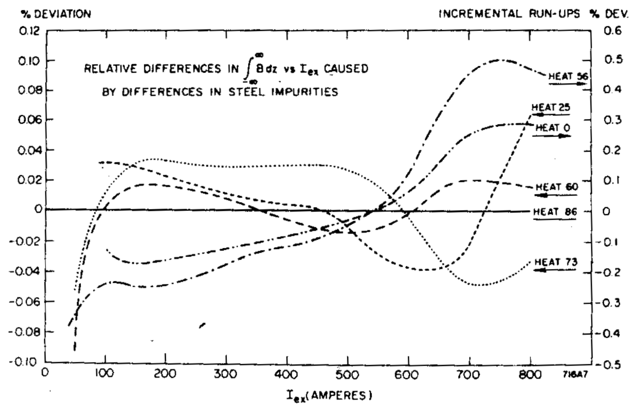

Fig. 6. Relative difference in ∫ B dz versus I_{ex} Direct.