DIPOLE MAGNETS FOR THE SLAC 50 GeV A-LINE UPGRADE*

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The SLAC A-Line is a transport system originally designed to deliver electron beams of up to 25 GeV to fixed target experiments in End Station A. To raise the beam energy capability of the A-Line to 52 GeV, the eight original bending magnets, plus four more of the same type, have been modified by reducing their gaps and adding trim windings to compensate for energy loss due to synchrotron radiation. In this paper we describe the modifications that have been completed, and we compare test and measurement results with predicted performance.

I. HISTORY AND MOTIVATION

The A-Line is one of SLAC's two original beam transport systems and has been in use since 1966. The function of the A-Line is to guide and focus the electron beam from the linac through the Beam Switch Yard (BSY) to the experimental facilities in End Station A. From there, the beam drifts to a high-power beam dump in a heavily shielded chamber in the hillside east of End Station A. The A-Line consists of a series of magnets, collimators, diagnostic devices, vacuum chambers, and associated instrumentation. The original magnets were conservatively engineered and have run without failure to support a large number of high energy physics experiments over this long period of service.

Over the last decade, the linac has been upgraded as part of the SLC project, so that long-pulse beams can now be accelerated up to about 33 GeV, and short-pulse beams can be accelerated up to about 50 GeV. The purpose of the present project is to upgrade the A-Line so that these higher energy beams can be transported to End Station A for use in fixed target experiments.

II. MAGNET REQUIREMENTS

As originally designed, the A-Line used eight large dipole magnets to deflect the beam through a total bend angle of 24 degrees. These are conventional magnets, each nominally three meters long, consisting of water-cooled copper coils on solid iron cores. The design, fabrication, and measurement results for the original magnets are described in detail in Reference 1. To transport a beam with energy greater than 25 GeV requires that the total

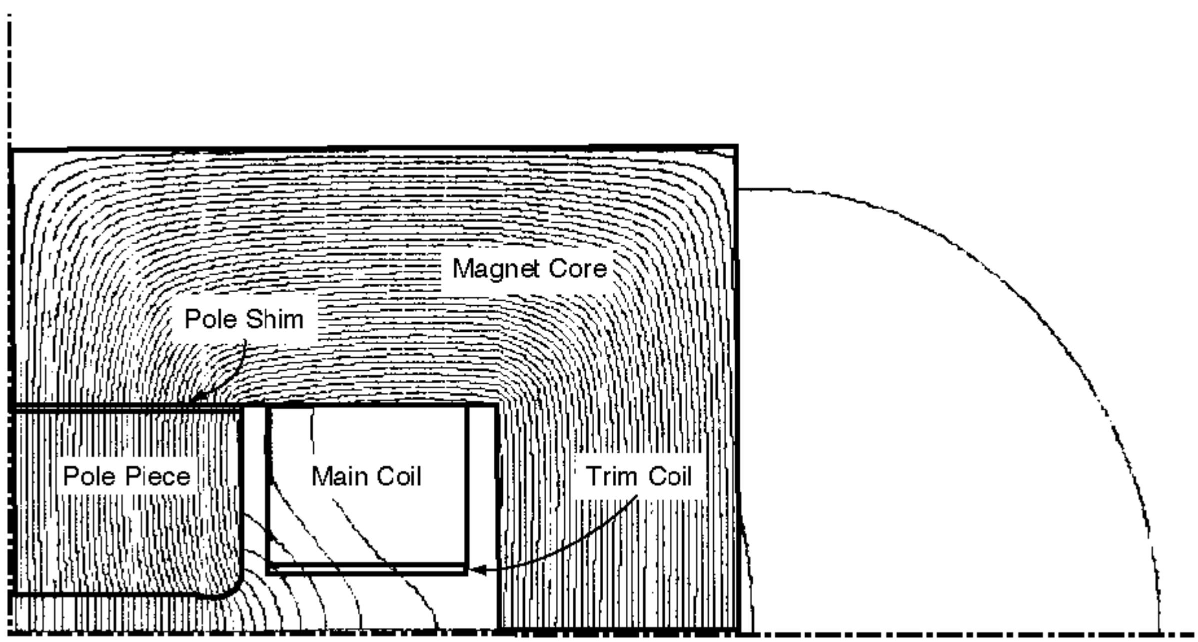

Figure 1. POISSON model of one quadrant of a modified dipole showing magnetic flux lines.

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bending strength be increased. This will be done by installing four additional magnets, identical to the original eight, which will be powered in series with the original eight. All twelve magnets have been modified to increase their strengths by reducing their pole-to-pole gaps. This has been done by installing steel shim plates under each pole piece of each magnet. In addition, the LCW plumbing is being modified to increase the flow of cooling water to the magnets.

Each magnet originally had a 60 mm pole-tip gap and was designed for a maximum integrated strength of approximately 44 kG·m. To achieve the desired strength of about 61 kG·m, the gap has been reduced to 46 mm. This choice was based on a requirement that the beam stay-clear be at least 3 sigma for a 5 GeV beam. This was also a convenient choice because it was small enough to accommodate the required trim windings sandwiched between the existing main coils and the new vacuum chamber, yet was just large enough to stay clear of the beam aperture as defined by existing collimators. Figure 1 illustrates the cross section of one quadrant of a modified magnet. Superimposed on the magnet are magnetic flux lines as calculated with the POISSON program assuming a current of 1382 amps, which corresponds approximately to the field needed for a 52 GeV beam. At this current, the pole tip field was calculated to be 20.11 kG. The flux leakage outside the iron return yoke indicates substantial saturation at this field strength.

The original magnet coils were cooled with low conductivity water (LCW) from a system capable of supplying approximately 12 gallons/minute to each magnet. Calculations indicated that this would be inadequate for the higher beam energies, even with the reduced gap. To avoid coil damage due to high temperatures, the plumbing system is being modified to provide LCW from the pumping system used for the research area, which was designed to support numerous large spectrometer magnets. It has been estimated that the pressure drop across each magnet will be approximately 200 psi with this system, corresponding to a flow of about 20 gallons/minute in each magnet.

At energies above about 30 GeV, the emission of synchrotron radiation by the beam is significant as it passes through the bend magnets in the A-Line. The next two fixed target experiments planned at SLAC require a longitudinally polarized electron beam with an energy of about 48.6 GeV. This energy corresponds to a total spin precession of 15π rotations as the beam traverses the beam transport system from the linac to the experimental target. At this energy, the total loss due to synchrotron radiation is about 0.8 percent. To keep the beam properly steered through the A-Line, it will therefore be necessary to adjust the magnet strengths according to a "synchrotron taper" scheme. Although there are several ways to accomplish this, the most conceptually straight forward is to provide individual trim windings on each dipole. The main bend power supply can then be set to a value appropriate for the beam energy as it exits the last of the twelve bend magnets and the trims can then be used to boost the strength of each of the other magnets to a level corresponding to the beam energy at each point. Computer simulations have shown that grouping the magnets in pairs for this purpose gives a smooth enough taper; i.e., the trim windings of pairs of consecutive magnets may be powered in series. Therefore, a total of six trim supplies will be sufficient if each supply powers the trims on two adjacent magnets.

The strength required of the trim windings is based on the calculated beam energy loss. The energies corresponding to 15π and 16π electron spin precessions in the A-Line are approximately 48.6 GeV and 51.8 GeV, respectively, in the absence of synchrotron radiation. With synchrotron radiation, the energy corresponding to 15π precession is achieved with 48.75 GeV at the end of the linac and 48.36 GeV in End Station A. For 16π rotations, the corresponding numbers are approximately 52.04 GeV and 51.54 GeV, respectively. The most demanding requirement for the trim windings is in boosting the first pair of magnets to 52.04 GeV when their main windings are powered to 51.54 GeV. This requires raising the strength of each magnet from 60.067 kG·m to 60.65 kG·m, an increase of about 1 percent.

III. DESIGN AND FABRICATION

The magnets, which are constructed of solid pieces of iron, were completely disassembled to permit the removal of the pole pieces from the rest of the magnet core. It was interesting to note that, after some 28 years of service, the magnet components were still in excellent condition. There was very little evidence of radiation damage to the epoxy insulation of the main coils. The ceramic insulators which carry LCW to the main coils were generally free of deposits and exhibited no defects.

The steel shims were fabricated out of AISI 1006 steel and precision ground to 7 mm (0.276 inch) thickness. Prior to release for fabrication, special attention was paid to the metallurgical certification of the shim material in an effort to obtain the optimum magnetic permeability. In an additional attempt to enhance permeability, the steel was heat treated by firing in air for a 9.5 hour cycle of controlled heating and cooling, with a peak temperature of 760°C (1400°F).

The trim coils were wound from 6.5 mm (0.255 inch) square copper with a 3.2 mm (0.125 inch) round internal passage. Prior to winding, the conductor was insulated using double dacron glass. Each nineteen turn coil was wound in a single layer and installed in the magnet with a layer of 0.23 mm (0.009 inch) dacron-mylar-dacron between the main and the trim coils. The position of the trim coil is indicated in Figure 1.

IV. MEASUREMENT RESULTS

Each completed magnet is being processed through an extensive series of measurements before installation in the BSY. The measurements are done using a long flip coil which has been calibrated against an NMR system. Measurements of the first complete magnet were used to develop a standardization procedure to be used whenever high accuracy is desired. The standardization procedure adopted involves ramping the magnet current from 25 amps to 1400 amps at a rate of 11 amps/sec for 90 percent of the way to the end point, followed by a ramp of 5.5 amps/sec for the remaining 10 percent. The magnet is then allowed to settle at 1400 amps for 60 seconds before ramping down in the same way to 25 amps. Again the magnet is allowed to settle for 60 seconds before proceeding. If this cycle is repeated three times before ramping up to the final desired set point, then the field accuracy is reproducible to a level of 5.3×10^{-4}. With the main coils powered to 1400 amps and the trim windings powered to 130 amps, the temperature rise in the main coil, as measured at the LCW outlet, is 35˚C, and the rise in the trim winding is 32˚C. These values are consistent with the expected temperature rise, and are acceptable for reliable long-term operation. The finished magnet properties are summarized in Table 1.

Pole to pole gap	46.0 mm
Effective length	3.0277 m @ 1400 A
Weight	30,000 lb. approx.
Main coil	2x (48 turns/pole)
I (main)	1400 amps max.
Terminal voltage	133 volts @1400 A
Trim coil	2x (19 turns/pole)
I (trim)	120 amps max.
LCW flow (main)	20 gal/min. @ 200 psi
Temp. rise	35˚C @1400 A
∫Bdl	62.008 kG·m @1400A

Table 1. Summary of bend magnet specifications.

Figure 2 shows the integrated magnetic strength vs. current for the first completed magnet. The round data points are measurements made with a 60 mm pole tip gap before the magnet was modified. The square data points are measurements of the finished magnet with a 46 mm gap. The smaller dots show design values calculated using the POISSON modeling program. Note that the measured performance matches the calculated field strength closely for currents up to about 600 amps, and is somewhat stronger than anticipated for higher excitation. This can be attributed to better magnetic properties of the steel yoke material and shims than was assumed in POISSON.

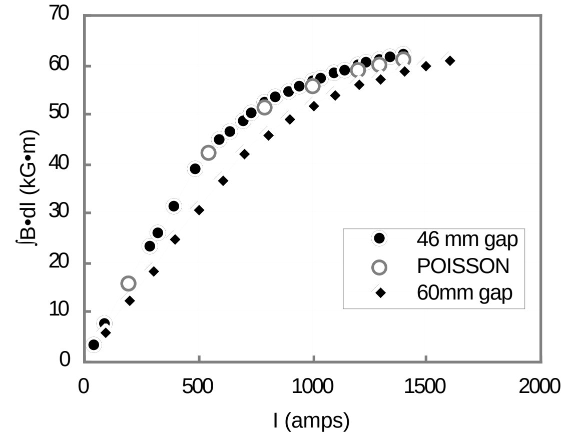

Figure 2. Integrated magnetic strength vs. current.

Figure 3 shows the measured properties of the trim windings on the first complete magnet. The increase in integrated magnet strength due to the trim coils is plotted against trim coil current for two values of the main coil current: 550 amps, where the magnet response is very linear, and again at 1000 amps, where the iron is significantly saturated. The hysteresis effect, which is clearly evident when the main coil is set to 550 amps, becomes negligible as the iron becomes saturated.

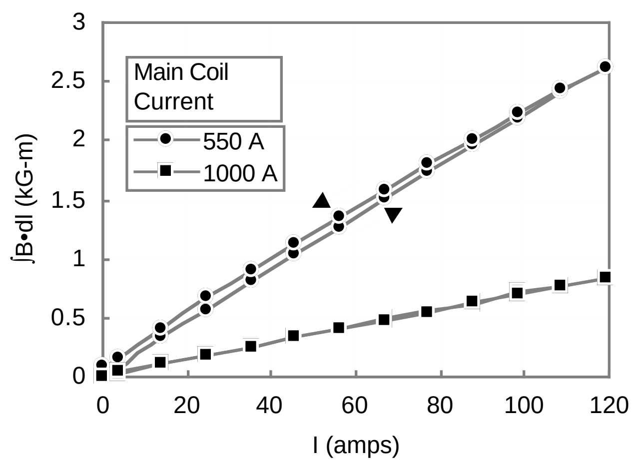

Figure 3. Trim coil strength vs. trim current for two values of the main coil current.

VI. REFERENCES

[1] *The Stanford Two-Mile Accelerator*, R. B. Neal, Editor, 1968.