The Ring Magnets for the SSRL SPEAR Injector*

M.M. Baltay, J. Cerino, R. Hettel, J. Safranek, J. Voss, H. Wiedemann, and K. Zuo
Stanford Synchrotron Radiation Laboratory, P.O. Box 4349, Stanford, California 94309

Abstract

A 3 GeV Injector has been built at SSRL to replace the SLAC linear accelerator as an electron source for the SPEAR storage ring.[1] Described is the 133 meter circumference injector ring AC magnet system, comprised of 32 dipoles, 40 quadrupoles and 24 sextupoles, the support girders, and the power circuit which is not discussed in this paper.[2] Magnet specifications, primary design and fabrication considerations, alignment tolerances, and performance data are presented.

I. INTRODUCTION

Synchrotron radiation users at SPEAR require fill times in of the order of 5 minutes, and a repetition rate of 10 hertz was agreed upon as a compromise between the filling time and the design limitations of higher frequencies. 3 GeV operation around the 133 meter circumference ring allows a conservative dipole field of 0.84 Tesla (Fig.1.), and the peak design energy of 5 GeV the dipole field is 1.39 Tesla. The proposed self-contained inductor-capacitor resonating power circuit set constraints on the magnet design, and furthermore, the decision to drive the quadrupoles in series with the dipoles added limitations on the quadrupole coil design. The technology in this system was fairly well understood at the outset; the primary goals were to minimize costs and to provide a robust system which would provide steady service over the expected lifetime of 20 years. The radiation levels in the magnet area were estimated to be approximately 10^6 rads per year or a total dose of 2×10^7 rads over the system lifetime.

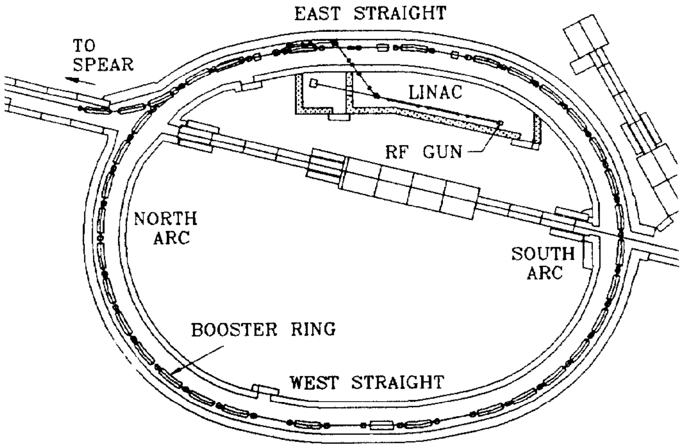

Figure 1
3 GeV Injector General Layout

II. DESIGN AND CONSTRUCTION

At 3 GeV the magnets are designed to run efficiently; the steel is low in saturation and the magnets consume an average of only 147 kW of electrical power. The low conductivity water system was designed for maximum currents, and maintains a very small temperature rise. The ring magnets cost 1.2 million dollars, and required 2 years to design, build, and install. Figure 1 illustrates the general layout.

A. Lamination Steel

After several phases of experimentation, a 16 gauge 1005 low carbon steel lamination was chosen for all ring magnet cores to reduce hysteresis and eddy current effects. This sheet steel has an AISI C0 grade natural oxide surface coating, providing sufficient interlaminar resistance for cycling operation at maximum design levels, and also facilitating epoxy bonding.

Silicon transformer steel with AISI C5 insulation, and one half the thickness of the 1005, was considered for its superior AC performance. However, side by side simultaneous magnet field measurements of 2 separate core blocks of the 2 steels did not indicate any significantly different effects. Core heating is considered to be an accurate indicator of eddy currents,[3] and was found to be tolerably higher in the 1005 material. Temperature Measurements agree with the calculated predictions.[3,4]

Transformer steel is 1.7 times the cost of 1005 and is only available in a maximum thickness of 24 gauge, allowing a 60% reduction in the number of die-stampings when using the thicker 1005 steel. Prior to die-stamping the sheet steel was shuffled at an 8:1 ratio reducing the handling by a factor of 10, and eliminating "de-nesting" of individual laminations.[5] A maximum burr of 0.002 inches was achieved during stamping which was nested with adjacent burrs except at every inch where the stacking direction was reversed to even out the mechanical inconsistencies in the lamination thickness.

B. Dipole Magnet (Table 1)

The dipole core is excited by a single coil pair, yet is made of 5 straight individual laminated blocks, each 44.7 cm long, and offset by 2.25 degrees. This approach eliminates many of the mechanical distortion problems that would be associated with welding one 2.3 m long single curved core of 11.25 degrees. As opposed to welding the blocks together with a plate to create the core assembly, we chose to bolt the blocks directly onto the machined support girder, allowing greater serviceability. Although inconsequential, there exists a small quadrupole gradient due to the tapered air gap

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between blocks, and the overall length of the magnet was increased slightly to compensate for the lower magnetic field at the inter-block regions.

Table 1
Dipole Magnet Specifications

Beam Energy	3.0 GeV
Field Strength	8.4 kG
Excitation	10 Hertz Biased Sinewave
Gap Height	36 mm
Bending Angle/Radius	11.25°/11.9 m
Magnetic Length/Steel Length	2.322/2.286 m
Ampere Turns/Magnet	24,064
Peak Current	633 Amps
Turns per Magnet	38 (19 x 2)
Induced Voltage @ 10 Hertz	417 volts
Trim Coil Field	5% of Main
Magnet Efficiency	99%
Magnet Resistance @ 37°C	23 mOhms
Total Average Power Loss at 10 Hertz	4.1 kW
Cooling	LCW 1gpm @ 130 psid
Temperature rise	12°C
Aluminum Conductor	18.2 X 18.2, 6.35 mm D Hole
Core Lamination Steel	1005 1.52 mm Thick
Magnet Weight	3137 kG

To reduce the local eddy current heating and to reduce the lamination separation force by 36 percent, the last 12 laminations at the pole ends were clipped at different heights and were epoxied together, approximating the magnetic end-field geometry. The glued laminations serve as solid end plates which sandwich the interior laminations together and keep them from moving under excitation.

Each dipole coil has 19 turns of vacuum impregnated hollow aluminum conductor and its design is governed primarily by the power circuit and the pole geometry. The solenoid coil design allowed cost savings in the fabrication, but required the omission of the 20th turn due to space constraints. Aluminum was selected for its for its lower initial cost, its reasonable power consumption over the expected machine lifetime, and its winding ease. An analysis of the eddy currents generated by the changing magnetic fields in both the dipole and quadrupole coils was performed.[6] These eddy currents were found to increase the power losses in the dipole and quadrupole coils by 12% and 5% respectively, and field distortions from eddy currents were shown to have no significant effects on electron beam dynamics. Eddy currents in the coils would have increased if copper conductor had been used. Each dipole coil also has a pair of 10 turn trim windings, one for horizontal orbit correction and the other to compensate for the induced voltages from the main coils.[2]

C. Quadrupole Magnet (Table 2)

The QF and QD quadrupole families, of 20 magnets each, are driven in series with the dipole magnets, which required the adjustment of the core lengths to provide the proper integrated focussing fields when excited with the same current. A computer-controlled wave form generator is used to match the AC quadrupole field to that of the dipole.[2]

Table 2
Quadrupole Magnet Specifications

	<u>QD/QF</u>
Beam Energy	3.0 GeV
Field Gradient	1.4 kG/cm
Excitation	10 Hertz Biased Sinewave
Bore Diameter	60 mm
Ampere Turns/Pole	5,064
Peak Current	633 Amps
Trim Coil Field	10% of Main
Magnet Efficiency	95%
Average Total Power Loss at 10 Hertz	0.6/0.7 kW
Cooling	LCW, 10°C Temperature Rise
Aluminum Conductor	11.7 X 21, 0.46 X 0.83 mm Hole
Lamination Steel	US 1005, 1.52 mm Thick
Core Magnetic Length	29/35.5 cm

A dipole-quadrupole series configuration requires the quadrupole coils to conduct 633 amperes of peak current, which is necessary for the bending magnet field. Packaging 8 turns of relatively large cross-section conductor in the available area between the poles and staying within the overall length requirements was difficult, and in the end, the insulation thickness between the windings and the magnet pole was compromised. Hollow aluminum conductor was selected to facilitate winding the tight compound cross-overs. Again, each coil has 2 individual trim windings; one for correction and one for compensation. Some quadrupole trims are used for vertical steering, and others for quadrupole correction.

The cores are divided into 4 quadrants to allow the installation of the coil over the pole. Each stacked quadrant of laminations was bolted together, eliminating the need for welding. Excellent reproducibility and accuracy of mechanical dimensions was achieved by bolting the quadrants, enhancing the final pole to pole dimensional consistency. The pole ends on the quadrupoles were not tapered because harmonic measurements showed the 6th harmonic to be an acceptable 0.2% of the quadrupole field, only 3 times higher than any other un-allowed harmonic fields.

D. Sextupole Magnet

The sextupole is 9 cm long with a field gradient of 0.23 $\mathrm{kG/cm^2}$, has a bore diameter of 7 cm, and the coils are air cooled. This magnet also has a bolted core, however the field is fairly low in its pole, allowing the laminations to be secured with a welded tension rod without significant eddy current heating. This core is split in 2 halves and the coils can be installed over the poles, and each coil has 32 turns of vacuum casted copper conductor. The sextupole is the only magnet which was designed to permit installation without the removal of the vacuum chamber, allowing greater flexibility of the system installation schedule.

III. SUPPORT

The ring has a racetrack configuration (Fig. 1); it is divided into the north and south arcs, each containing 14 dipole girders, and the east and west straight sections, each containing 2 additional dipole girders as well as 4 straight girders. The 8 straight girders support kicker and septum magnets, beam transport components, the ring RF cavity, beam diagnostic instrumentation, and one vacuum drift section.

In all cases the components were pre-assembled onto the girders and then installed as a single part, and all girders share a common set of pedestals. The only exceptions are the 8 quadrupoles located in the east and west straight sections of the ring, which are mounted directly on modified pedestals. Figure 2 depicts a full arc magnet girder loaded with the quadrupole, sextupole, 5 block dipole and vacuum chamber. Each girder section is supported on 3 points by pedestals, and its position can be adjusted by 3 mover assemblies. A single pedestal supports the downstream end of one girder and the upstream end of the following. All of the individual magnets are bolted to a single support girder, including the beam position monitor support cradle, and the 8600 pound girder assembly can be installed as one unit.

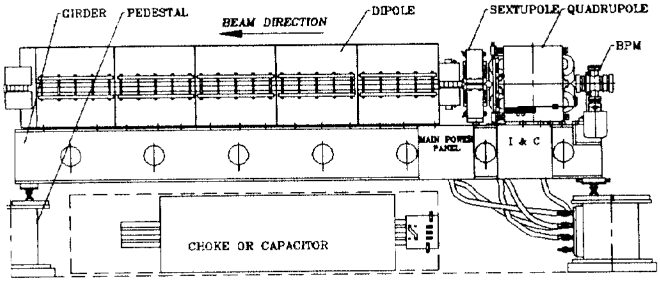

Figure 2
Arc Dipole Girder

Aside from being held by the BPM support cradle, the vacuum chamber is completely captivated at the upstream end of the quadrupole, and is just restrained at the downstream end of the quadrupole, and in 5 locations inside the dipole magnet.

IV. ALIGNMENT

The alignment system architecture attempted to minimize the amount of field surveying by eliminating unnecessary adjustments, by using mechanical tooling where possible, by accomplishing magnet to magnet alignment using the support girder itself, and by pre-adjusting the movers prior to installation.

A non-adjustable, brass plug, monument network was established[7] with respect to known monuments at the SPEAR storage ring. Using an electronic distance meter and theodolite angular measurement equipment, the monuments were surveyed on 3 individual occasions to ascertain the most accurate "as-built" monument positions. The SLAC alignment group computed a least squares fit of the survey data, dividing the measurement error into each of the 40 plug positions, and generated the working monument coordinate network. Elevation rivets were installed and also measured with respect to the same SPEAR reference monuments. Using AutoCad software the magnet lattice[8] was superimposed over the working monument network and we were able to determine the offsets from the monument plugs to the components.

Through precision machining of the support girder and steel cores, the magnets on a given girder were automatically aligned upon assembly, with respect to each other and with respect to several machined reference surfaces on the ends and bottom of the girder. The 3 girder adjusters were put in their nominal positions and were attached to a precision reference plate. Upon installation, the girder plate was aligned directly to the pre-aligned pedestals with pins. The pedestal positions were within +/-0.75 mm of their nominal position and the girder mating holes within 0.5 mm, and the dipole end of the girder was allowed to give, in order to accomplish the fit. Later, after the downstream quadrupole was installed, the dipole magnet was adjusted to be coincident with the quadrupole axis. Only the quadrupoles in the east and west straight sections and the 3 quadrupoles at the beginning, middle, and end of each arc were optically aligned. In this fashion the quadrupoles were installed to within +/-1 mm, and a beam path, perhaps not exactly true to position, but continuous, was formed.

V. PERFORMANCE

In July of 1990 80 MeV of unaccelerated beam was passed through the magnetic orbit for 100 revolutions before decaying. This was accomplished on the first attempt. The system was commissioned in the summer of 1990 to 3 GeV and has successfully operated with beam at 2.4 GeV since then.

VI. ACKNOWLEDGEMENTS

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