SLAC – PUB – 4199
January 1987
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SUPERCONDUCTING QUADRUPOLES FOR THE SLC FINAL FOCUS*

R. ERICKSON, T. FIEGUTH, AND J.J. MURRAY
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

ABSTRACT

The final focus system of the SLC will be upgraded by replacing the final quadrupoles with higher gradient superconducting magnets positioned closer to the interaction point. The parameters of the new system have been chosen to be compatible with the experimental detectors with a minimum of changes to other final focus components. These parameter choices are discussed along with the expected improvement in SLC performance.

1. INTRODUCTION

Achieving the design luminosity at the SLAC Linear Collider depends on focusing the beams to an extremely small spot size ($\sigma \leq 2\ \mu$m) at the interaction point. In general, the stronger the focusing power of the final quadrupoles and the shorter the distance ℓ^* from the interaction point to the face of the nearest quadrupole, the smaller will be the focused beam spot, and the higher will be the luminosity that can be obtained. Two final focus options are being pursued. Conventional iron quadrupoles have been built for the start-up and initial operation because of their simplicity and relatively low cost. In parallel with this effort, a new design, based on superconducting quadrupoles, has been developed. In this paper, we discuss the parameters of this new design and compare it to the conventional design.

There are two reasons for upgrading the final focus with superconducting quadrupoles. The first is that with higher-gradient quadrupoles, a luminosity improvement of roughly a factor of two is possible over the initial machine configuration. The second reason is that superconducting quadrupoles can be operated inside the experimental detector, immersed in a 6 kG solenoid field. This becomes especially important when the SLD, a large second-generation detector, is brought into the SLC.

2. OPTICAL PARAMETERS AND CONSTRAINTS

The final focus system is designed as a series of optical sections which can be thought of as separate modules having distinct functions[1]. These functions include cancellation of linear dispersion, cancellation of second order chromatic aberrations, and demagnification. The demagnification is done in two stages, each consisting of a half-wavelength telescope constructed with quadrupole magnets. The second of these demagnification sections, consisting of two symmetric quadrupole triplets, is the last module before the interaction point. We designate the quadrupoles of the final triplet as QF1, QD2, and QF3, and those of the upstream triplet as QF4, QD5, and QF6, where the numbering sequence starts at the end nearest the interaction point and increases outward. The letters F and D in the quadrupole labels indicate focusing and defocusing, respectively, in the horizontal plane. The conventional version of QD2 is actually two identical magnets mounted closely together. This is done to simplify the fabrication process and to avoid the bending or sagging which would occur with a single quadrupole of the required length at this position. Similarly, QD5 is actually two identical magnets mounted together.

At an early stage in the SLC project, we recognized that the final focus system should be designed to accommodate variations in the last telescope. We anticipated that shorter-focal-length quadrupole lenses would eventually become available, and that the final focus system should be able to exploit any such developments with minimal changes to existing hardware. Ideally, such changes in the final telescope should not require any changes to the other optical modules.

During the design of the final telescope, the first parameter to be frozen was its overall length, the distance between the interaction point and the waist in the beam envelope one-half betatron wavelength upstream. This distance was chosen somewhat arbitrarily to be approximately 126 feet, based on general optical considerations and site boundary constraints. Studies demonstrated that a wide variety of telescope designs were possible using conventional, superconducting[2], or permanent-magnet[3] quadrupoles, all constrained to this total length.

The next step was to select the highest practical magnetic field gradient for the final quadrupole triplet. For a given pole-tip field, the maximum gradient that can be achieved in a quadrupole depends on its aperture. In this triplet, the minimum aperture required is determined primarily by background considerations. Off-axis electrons originating from beam-gas interactions and slit scattering upstream follow trajectories that reach their maximum excursions in the final triplet. It has been estimated that a clear aperture of about 1.5 inches is necessary in this section to avoid an intolerable flux of secondary particles scattering into the experimental detector. Using this aperture as a design constraint, we chose 4.85 kG/cm and 12.0 kG/cm for the conventional and superconducting quadrupoles, respectively, for the 50 GeV operating point. In both cases the fields can be increased for beam energies up to at least 55 GeV.

Choosing the drift distance ℓ^* to the interaction point requires a compromise between the ultimate luminosity and the space requirements of the detector. For the design using conventional quadrupoles, this distance was chosen to be 9.25 feet, the minimum consistent with avoiding any adverse saturation effects of the Mark II solenoid field on the field quality of QF1. At this distance, the stray solenoid field decreases to about 10 Gauss. The use of the conventional triplet at this ℓ^* is not compatible with the SLD detector, however, because of mechanical interference and because of the strong solenoid field extending out to about 12 feet. The design using superconducting final triplets is based on an ℓ^* of 7.25 feet (with either detector). This is the shortest ℓ^* that still allows room for a precision vertex detector, beam position monitors, and other essential beam line components. The superconducting quadrupoles, cryostat, and SLD detector are outlined in Figure 1. The conventional quadrupoles and the Mark II detector are indicated by dashed lines.

Each quadrupole triplet is powered as a series string by a single power supply. Thus, the field gradient is the same in each member of each triplet. The desired quarter-wave focusing property of each triplet is obtained by adjusting the length and spacing of the magnets and the length of the middle magnet relative to the first and third (which are constrained to be identical to preserve the symmetric triplet properties).

With ℓ^*, the total length, and the gradients of the final triplet quadrupoles fixed, and with the additional constraint that the system as a whole must preserve half-wave telescopic properties in both dimensions, the lengths and spacings of QF1 (and 3), QD2, QF4 (and 6), and QD5 and the overall strength of the upstream triplet are varied to obtain the desired demagnification.

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*Work supported by the Department of Energy, contract DE–AC03–76SF00515.

Presented at the Particle Accelerator Conference, Washington, D.C., March 16–19, 1987

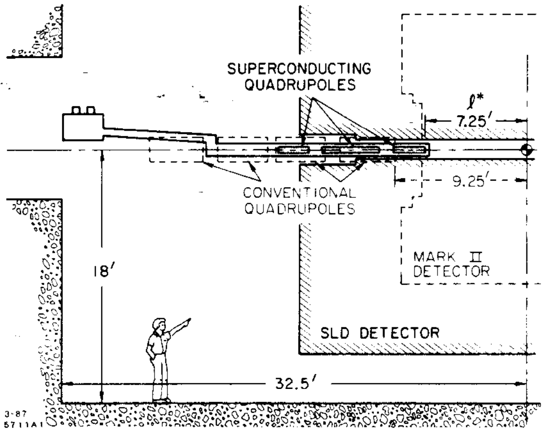

Fig. 1. Elevation view of the SLC interaction region showing the existing facilities (dashed lines) with the superconducting configuration superimposed.

For a fixed total demagnification, the magnitudes of the sextupole fields in the chromatic correction section, and by implication the severity of the uncorrected aberrations, grow as the final triplet strength is reduced. Demagnification factors of 4 and 5 have been chosen for the conventional and superconducting configurations, respectively. These magnifications are "diminishing returns" points in each case. Attempts to reduce the spot sizes by choosing stronger demagnifications are offset by increasing third-order aberrations.

The optimum configurations using conventional and superconducting final triplets do not have identical upstream triplets. However, a pair of solutions was found in which the location of QF6 is the same, and changes to other components are minimal. This is discussed in Section 4 below.

3. THE SUPERCONDUCTING QUADRUPOLES

Collared superconducting coils for this application are being designed and tested at Fermilab. The design for the SLC quadrupoles is an extrapolation of the design used at the Fermilab Tevatron. They differ in having a smaller aperture, improved conductor, and they contain no ferromagnetic materials.

The diameter of the innermost surface of the conductor is 2 inches. This diameter is a practical lower limit imposed by the geometry of the keystone-shaped superconducting cable. Allowing space for an inner helium passage and for the beam pipe, the clear aperture is 41.28 mm. This leaves about 2 mm of radial clearance at the upstream end of QF3 if a disruption angle of 2.2 mrad is achieved. A prototype tested recently at Fermilab reached a maximum gradient of 18.3 kG/cm at 6550 amps and 4.2°K. This gradient is substantially higher than any used previously in a high-energy accelerator application. The design features and early prototype test results were reported previously [4].

The SLC quadrupoles must be operable when immersed in the 6 kG solenoid field of the SLD detector. This requirement precludes the use of iron in these quadrupoles, because of the large magnetic forces and the uneven saturation effects. The magnetic environment due to an external field of this magnitude is expected to lower the quench current by about 6%.

A gradient of 12 kG/cm has been chosen for the optical design at 50 GeV. This scales to 13.2 kG/cm at 55 GeV, (the maximum beam energy that can be transported and focused by the other parts of the final focus system), and corresponds to approximately 75% of the quench limit when operated at 4.6°K in the SLD solenoid.

4. FINAL FOCUS CONVERSION PLANS

The three quadrupoles of each superconducting triplet will be mounted in a single cryostat with an outer diameter of 13 inches, small enough to pass through the SLD end cap hole. When used with the Mark II detector, the cryostats will be supported on the same structures now used for the conventional triplets. When used with SLD, the cryostats will be supported directly by the detector end-caps.

Converting the final focus from the conventional to the superconducting configuration will require modifications to the upstream triplets, in addition to replacing the final triplets. QD5 must be shortened by 10.9% to reduce its strength relative to QF4 and QF6 (or be bypassed by an adjustable precision shunt), and QF4 and QD5 must be moved upstream 7.81 feet and 3.91 feet, respectively. QF6 will remain fixed. The locations of bulky items, in particular the concrete support girders and the water-cooled tune-up dumps, have been chosen to be compatible with either the conventional or superconducting designs, and will not have to be changed. Several small devices, including steering correctors, vacuum components, and collimators, will be relocated along the beam line to accommodate the movements of QF4 and QD5. The power supplies now connected to the upstream triplets on the north and south sides of the interaction point are capable of supplying the increased current when the conversion is made.

The quadrupoles of the conventional final triplet have separate trim windings with individual power supplies. These trims correct for fabrication errors and allow separate adjustment of the focal lengths in the horizontal and vertical planes. The superconducting quadrupoles do not have separate trim windings. Instead, the trim functions will be performed by bucking or boosting the triplet current with small supplies connected across each individual quadrupole.

5. EXPECTED PERFORMANCE

Figure 2 shows horizontal and vertical betatron functions (βx and βy) for the final telescope. The solid lines show these functions for the superconducting quadrupoles. The dashed lines show these functions for the conventional triplet configuration.

The main differences between the conventional and superconducting configurations are summarized in Table 1. The spot size listed is the rms radius (σ) of the beam at the interaction point, including residual aberrations. For low beam currents, the luminosity is inversely proportional to σ^2; thus, the superconducting configuration is expected to yield at least 1.6 times greater luminosity than the conventional. As the number of particles per beam pulse is increased, this relative luminosity gain is expected to increase, multiplied by a "pinch factor" due to the beam-beam disruption effect. This would enhance the luminosity by an additional factor of 2 for the full design current[5].

ACKNOWLEDGEMENTS

We are indebted to the Fermilab Magnet Group, which designed and is constructing the superconducting magnets, and especially to H.E. Fisk for his advice in the establishment of practical design parameters. It is a pleasure to acknowledge F. Bulos, who first suggested the use of superconducting quadrupoles in the SLC, and also G. Bowden, K.L. Brown, J. Ferrie, D. Leith, G. Putallaz, J. Voss, and D. Walz for their assistance in the early stages of this project.

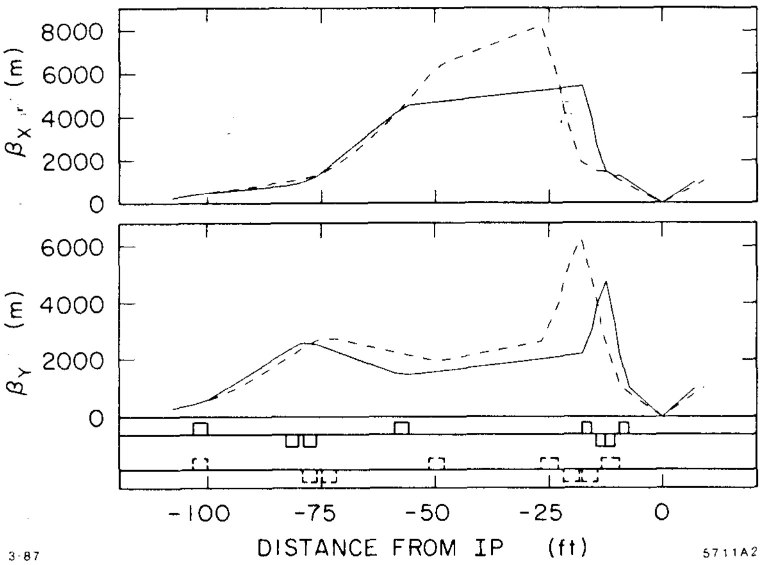

Fig. 2. Horizontal and vertical beta functions in the final telescope. The solid lines indicate the superconducting configuration; the dashed lines indicate the conventional configuration. The positions of the quadrupoles are shown along the bottom of the figure.

Table 1
Parameters for the two final focus configurations at 50 GeV

	Initial	Upgraded	
Quadrupoles	Conventional	Superconducting	
Clear Aperture	3.95	4.13	cm
Gradient	4.85	12.0	kG/cm
Drift Length (ℓ^*)	9.25	7.25	ft.
Demagnification	x4	x5	
β^*	0.75	0.50	cm
First Order Focus	1.5	1.2	μm
Spot Size (σ^*)	2.07	1.65	μm

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