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Superconducting Final Focus Quadrupoles for a B Factory*

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ABSTRACT

The superconducting final focus triplets now operating at the SLAC Linear Collider (SLC) demonstrate most of the features required for a B Factory in terms of detector interaction and high machine tolerances. These features are discussed, together with reasonable expectations for scaling to a B Factory. The effort and schedule for this project are discussed.

1. INTRODUCTION

Superconducting quadrupole triplets have been operating as the final focusing element of the SLAC Linear Collider (SLC) for the past two years. The challenges were to make a system that did not encumber the detector and that could meet the extreme tolerances in alignment and stability required for focusing beams to micron-sized spots.

The cantilevered design illustrated in figure 1 occludes no more solid angle than the conventional quadrupoles used earlier at the SLC and allow access to the inner detector by rolling out the end cap door within a few hours. Stray field has not been a problem and there has been no detectable interaction between the solenoidal field and the triplets.

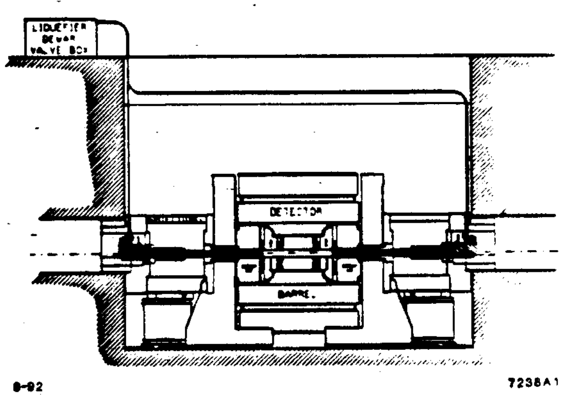

Figure 1. Elevation view of the two triplet barrels inside the SLD detector.

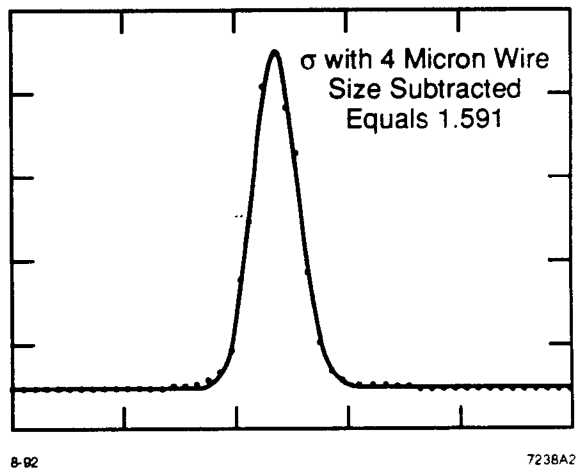

Figure 2. Profile of the electron beam as focused by the triplet onto a 4-micron wire.

The precision mounting, measurement, and alignment of the triplets have resulted in measured spot sizes illustrated in figure 2, which are consistent with the calculated minimum for this machine.

Details of the design and operation of this system have been recently published [1] but the conclusion for this note is that such a system meets the requirements of detector geometry and extremely tight machine tolerances. The question of how this applies to B Factory designs is addressed in Section 2 and the required technical support is considered in Section 3.

2. APPLICATION TO A B FACTORY

This section is reprinted from a study by the author for an earlier conference before the SLD system went online [2]. The conclusions have changed little in the intervening three years apart from the conviction.

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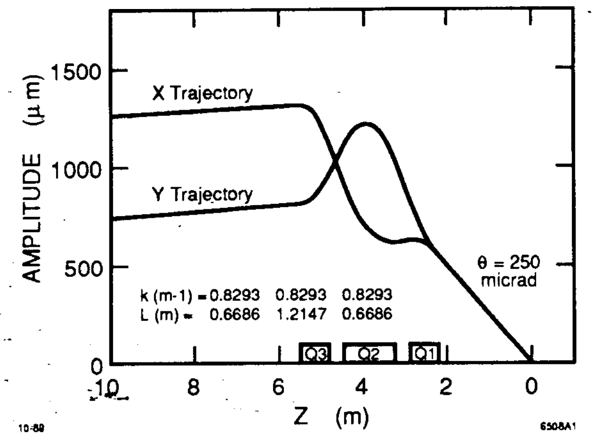

Figure 3. Trajectories and magnet strengths in the SLAC Linear Collider (SLC).

2.1. The SLC Final Focus System

The Final Focus System (FFS) for the SLAC Linear Collider (SLC) consists of three superconducting quadrupoles run in series. The beam envelope trajectories and the magnet parameters [3] are shown in figure 3. The magnet strength is given in the notation $k(\mathrm{m}^{-1}) = \sqrt{\Gamma(\mathrm{T/m})/B\rho}$ with $B\ \rho\ (\mathrm{Tm}) = p(\mathrm{GeV/c})/0.3$.

The three quadrupoles are aligned as a common triplet supported on the pit wall and the detector end cap, with the final 2.5 meters cantilevering through the end cap of the SLD detector into the central field volume as shown in figure 4. The end cap rolls out for detector maintenance without disturbing the triplet.

Conventional iron quadrupoles have not been ruled out in the above discussion, but in fact the magnets must be superconducting for two reasons. The required gradient and aperture produce a poletip field as $\Gamma = 0.829^2 \times 50$ GeV/0.3 $\approx$ 115 T/m and B(poletip) = 11.5 kG/cm $\times$ 2.5 cm $\approx$ 30 kG, which is beyond soft-iron limits. Second, the magnets protrude into the 0.6-T solenoidal field of the detector which would saturate iron poletips and produce a multiton axial force on the triplet support.

2.2. B Factory Final Focus System

With the above as background, consider an FFS proposed for a B Factory in the CESR tunnel.

One solution using round beams [4] gives the trajectories and quadrupole strengths shown in figure 5. The focusing is a factor of 2 to 3 stronger because of the closer distance to the interaction point

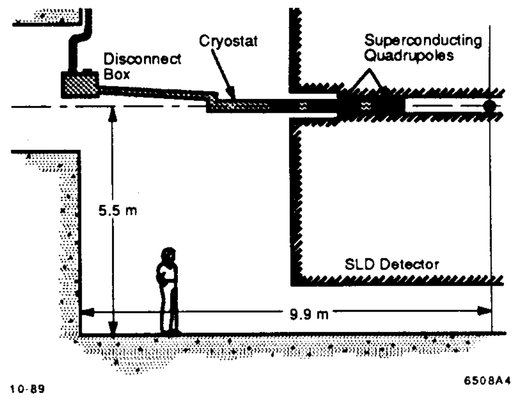

Figure 4. Layout of the superconducting FFS in the SLAC Linear Collider. The quadrupoles extend into the solenoidal field of the SLD detector. The end cap of the detector rolls back to the wall without disturbing the cryostat which is supported from the wall and a rolling point in the end cap.

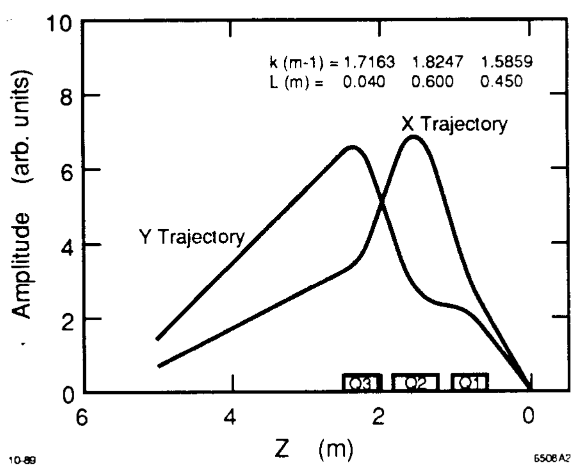

Figure 5. Trajectories and magnet strengths for a typical B Factory lattice for the CESR tunnel.

and the closeness of the upstream focus compared to the SLC.

Even with the much lower momentum beam, this leads to quads with a gradient more than half that of the SLC. With the larger aperture discussed later, the poletip fields are comparable in the two cases. Since these quads would also be well inside the central field volume for any detector for a B Factory, the requirements on an FFS are the same as for the SLC.

Conceptual design parameters for a B Factory system are listed in Table 1 and discussed in the following sections.

Table I. Characteristics of SLC and B Factory triplet designs. The interquad spacing of (1) is probably too small. The aperture of 10 cm of (2) was assumed to permit a warm bore for the B Factory case, required in view of heating from RF, I^2R, and synchrotron radiation. The outer diameter in (3) comes by adding the aperture increase. The range of helium use of (4) depends on options discussed in the article. The fringe field outside the cryostat is given in (5) where r is the mean coil radius and R is the distance to a point outside the cryostat. This may be important for some detector components.

Item	SLC	B Factory
$L*$	2.20 m	0.60 m
L_{quad}	0.67 m	0.45 m
	1.21 m	0.60 m
ΔL_{quad}	0.36 m	0.20 m$^{(1)}$
Γ	11.5 kG/cm	$\leq$ 6 kG/cm
Aperture (ID)	5 cm	10 cm$^{(2)}$
B_{poletip}	30 kG	30 kG
	4250 A	1600, 2200 A
Cryostat diameter	37 cm	42 cm$^{(3)}$
Alignment	$\pm$ 100 μm	acceptable
	$\pm$ 1 mrad	marginal
Support	cantilever	same
	through end cap	
Helium plant	2 × 50	2 × (5–40)$^{(4)}$
	liquid liters/hr	liquid liters/hr
Fringe field	$\sim \Gamma r(r/R)^3$	same$^{(5)}$
	$\sim$ 500 G at OD	

Table 2. Characteristics of several existing superconducting quadrupoles. The comparisons are meant for illustrative purposes only. The outer diameter in (1) was obtained by adding to the actual cold diameter a radial clearance of 11 cm to account for cryogenic insulation, following SLC designs. For those with (2), the diameter was scaled from drawings. The very low current in (3) results from using *five-in-one* conductor discussed later in this article.

Machine	Coil Inner Diameter (cm)	Outer Diameter (cm)	Gradient (kG/cm)	I_{op} (A)	I_{op}/I_{max}
SLD	5	34	12	4300	60%
D0 low β	7.6	$\sim 50^{(1)}$	14	4800	—
D0 correctors	7.6	$\sim 40^{(1)}$	6.3	1100$^{(3)}$	—
LEP low β	18	$\sim 55^{(2)}$	3.6	1625	$\leq$80%
SSC arc	4	$\sim 50^{(1)}$	23	6500	74%
HERA arc	7.5	$\sim 90^{(2)}$	9	5000	71%
Tristan	—	40	—	$\leq$4000	—

2.3. Magnets

The SLC superconducting quadrupoles themselves were designed and built at Fermilab in a very productive collaboration [5]. The magnets required for the B Factory study are similar to those for the collider. They would have a larger bore, which is generally easier to use provided the peak field stays within range. Their somewhat shorter length also is an advantage.

The features of these magnets are listed in Table 2, together with those used in, or proposed for, other machines [6,7]. The message is that the parameters required for the B Factory are well within present technology.

2.4. Beampipe

The essence of the SLC is very small beam size at the collision point, meaning very low average currents for equivalent luminosity. This eliminates the problems of beampipe heating encountered in storage rings. As a result, the SLC cryostats run with a cold beampipe, resulting in smaller magnets, a simpler design, and a smaller outside diameter.

The large currents considered for the B Factory produced RF heating of tens of kilowatts in common structures and I^2R heating of 20 W/m in stainless tubing [8]. The RF losses in a completely smooth pipe inside the cryostat would in principle be zero. Plating the beampipe with a good conductor (even better at very low temperatures) would bring these losses to near zero. Nevertheless, the presence of such large amounts of power so close to the cryostats almost certainly require the use of a warm beampipe insulated from the coldbore of the cryostat.

The intense synchrotron radiation from the quadrupoles may also require a larger-aperture, bakeable warmbore.

The design assumed for the B Factory assumes a 10-cm aperture, allowing 2.5 cm in radius for insulation. In the SLC case, 1 cm is enough for a static insulating shield when a warmbore is used during magnetic measurements. If a vapor-cooled shield is required, more space may be needed.

2.5. Mechanical Issues

The SLC cryostat extends through the end cap of the detector with supports from the wall and in the end cap itself. This partial cantilevering minimizes the interference with the detector solid angle. A similar system should meet the criteria for a B Factory detector as well, with a few caveats.

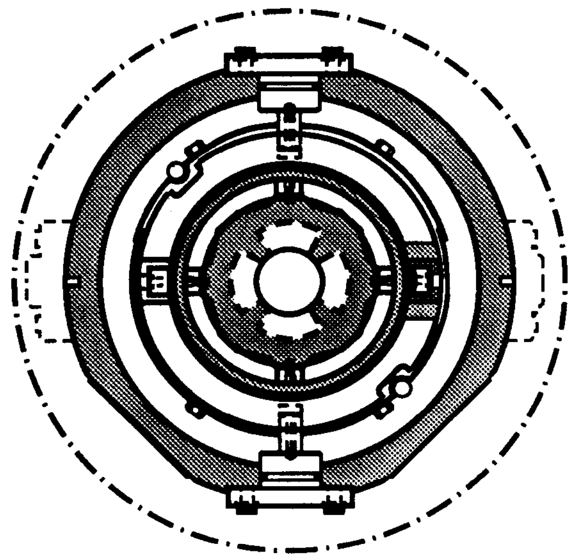

Figure 6. Cross section through the SLC triplet cryostat. The outer circle is a 40-cm stayclear through the end cap of the SLD detector. The outer diameter of the 2.5-cm-thick cryostat vacuum vessel is 33 cm, with some additional space required for support structures. Next inside is a thin copper vapor shield, cooled by helium gas boiloff. Next in is the ~ 7-mm-thick helium jacket containing the magnet and its 4.4-cm-diameter coldbore.

The separation between quads is 20 cm in the B Factory case. A separation of 36 cm was required for the SLC system to account for the internal buss connections inside the physical quadrupole and enough room to make external splices. Increasing this would require some compromises in the optics.

In the proposed B Factory optics, the magnetic field of the first quadrupole begins 60 cm from the interaction point. About 20 cm of this must be used for cryogenic insulation and the end connections of the magnet itself. Thus the cryostat barrel comes to within 40 cm of the interaction point. This estimated 43-cm-diameter structure would obscure too much of the detector solid angle. Although some reduction in outer diameter may be possible, there is not much to be gained. (The cross section of the SLC cryostat is shown in figure 6.) A compromise in the optics design to increase this distance is probably required.

2.6. Fringe Field

Most of the magnets listed in Table 2 use a soft-iron flux return. This slightly reduces the current required for a given gradient, provides a necessary stiffening member for the weak lamination structure that supports the coils, and reduces external stray field. This is not permitted with the SLC or B Factory designs due to the detector magnet field.

The fringe field just outside the SLD cryostat is about 500 G, falling off cubically. This cryostat is far enough from the SLD's tracking and Čerenkov detectors that the stray field is not an issue. The magnets in the B Factory case, however, are much closer to the central region and the effects of the fringe field must be looked at.

2.7. Alignment

The first problem in aligning magnets is to ensure that they are individually straight and untwisted. The magnet laminations and shims assure precise location of the coils in the transverse plane, but they must be locked into an external, stiff jacket or they will warp by almost a millimeter and twist by tens of milliradians. The method used in the SLC case consists of rails keyed to the laminations and pinned into the 7-mm-thick helium jacket. This results in magnets straight to 100 μm and true to better than 1 mrad.

The second problem is to ensure that the magnets are aligned to these tolerances to one another. In the SLC case, the magnets are azimuthally locked on final assembly but are individually adjustable in the horizontal and vertical planes. The adjustment turrets add up to 3 cm in radius.

2.8. Helium Plant

The cryogenics for the SLC triplets was designed with the large existing SLAC helium plant in mind. This includes choosing simple large-current (but thermally lossy) leads, separately powering the two triplets, and cooling the vapor shield with helium boiloff instead of liquid nitrogen.

The resulting system should run at about 50 liquid liters per hour for each triplet, based on results from a two-magnet prototype. This is well above the scale of small liquefiers that can be run by a small, unspecialized crew.

The main load (gas-cooled current leads) can be reduced first by going to a new Fermilab scheme of breaking each magnet cable into five parallel pieces, connected in series. Magnets have recently been built and tested with this technique [6]. This allows gas-cooled leads to be a factor of 5 smaller, and with proportionally smaller losses. The Tristan system connects the two triplets by a superconducting cable, eliminating one pair of leads. Cooling the shield with liquid nitrogen reduces the second biggest load on the helium system.

The result could in principle be a helium load as low as 10 liquid liters per hour, a much more manageable scale.

2.9. Electrical

The B Factory design calls for three different gradients in the magnets. Assuming the same current-to-gradient ratio as the SLC quadrupoles, the currents are 1640, 1930, and 2170 A. These magnets are normally wound as four-terminal devices by having one of the conductors in one coil treated as an individual turn. This allows the magnets to be connected directly in series without a separate, uncompensated return buss. Trim currents are directed to the input side of two of the three quads. With this arrangement the main current would be 1930 A; the first trim would be +240 A, to give 2170; the second trim would be −240 A to buck the first trim and −290 A to provide the actual trim.

This is not a trivial complication, requiring two pair more of large-current gas-cooled leads and precision high-current supplies. A compromise in the optics design to allow equal-gradient magnets would reduce the trim currents to trivial values.

2.10. Summary

The proposal for a B Factory in the CESR tunnel requires high-gradient, large aperture, close-in quadrupoles that can operate in the presence of a large solenoidal magnetic field. A system similar to that built for the SLAC Linear Collider with quadrupoles built at Fermilab could meet these requirements.

Problems that must be addressed include minimizing the cryostat diameter near the interaction point, increasing interquad spacing, developing a thin warmbore beampipe, and understanding the effects of the quadrupole fringe field on the detector. Modifying the optics to allow equal gradient magnets would simplify the power system.

The large helium supply system required could be dramatically reduced by going to the new

Fermilab five-in-one coils, joining the triplets by a superconducting cable, and using a liquid nitrogen shield.

3. TECHNICAL SUPPORT

The support for building and then operating a superconducting device should be considered along with the strictly design issues.

3.1. Construction

The SLC triplet project at SLAC was launched in early 1986 and installed in early 1991. Moreover, significant work on the coil design had already begun at Fermilab a year or so earlier. Much of this time went into R&D on new winding techniques and materials at Fermilab and into new helium transfer systems, support, alignment and measuring techniques at SLAC—including two prototypes. Development of a new system for a B Factory could be accelerated based on this experience, but one should not underestimate the time to resolve new features, such as a warm bore.

3.2. Operation

The infrastructure for operating a system such as this does not scale with size. The helium requirements for these triplets are virtually the same as those for a large superconducting detector solenoid as they are dominated by losses in the inevitable high-current leads.

For the SLC case, the operations infrastructure, which included some 20 staff, backup compressors, and purifiers, was already in place due to a history of other projects at the lab. The current organization, moreover, can be amortized over the three SLC superconducting spin rotator solenoids and the SLC Large Detector (SLD) liquid argon systems. Creating such support solely for a superconducting final focus would be a significant factor in the overall project planning.

Acknowledgement

I thank Paul Mantsch who supplied me with the latest information on tests of the five-in-one coils at Fermilab.

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