SINGLE PASS COLLIDER MEMO

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I. Introduction

The evolution of the SLC Final Focus System (FFS) has been discussed in the SLC Red Books¹ and various collider notes. Bulos and Brown² and Murray³ were able to achieve small β^* 's with large l_1 's (the distance between the IP and the effective field boundary of the first quad). However, all current solutions³ which are compatible with the known constraints of total path length, aperture and spot size require high gradient, superconducting quads. Such quads cannot be expected to provide very good inherent field quality (i.e. without correction windings) but can be expected to be comparatively expensive to build and operate simply.

The purpose of this note is to present a more general solution for the FFS telescope which is compatible with the known constraints of detectors, magnet types, available space and the ingoing and outgoing phase space expectations. While a number of different solutions were found, the ones presented provide comparable performance, simpler operation and lower costs. The gradients are sufficiently low to allow the use of conventional electromagnets, intrinsic or cryostable superconducting or rare earth permanent (REP) magnets or any arbitrary combination of all of these magnet types.

II. Discussion

Figure 1 shows the current, superconducting solution (SUPC14) in terms of the constraints mentioned above. While oversimplified, this figure gives a reasonably concise representation of the more important characteristics of the problem. It shows the FFS system from the IP to the soft bend. The incoming, first-order, 10σ beam envelope is given by the solid lines for an emittance of $\epsilon = 3 \times 10^{-10}$ m-rad and momentum spread of $\delta = \pm 0.5\%$. The outgoing, disrupted beam is given by the same curves when the disruption angle is 2.5 mr. The straight dashed lines show some of the corresponding synchrotron radiation envelopes from the quads (QSR) which could produce detector noise when these assumptions are realized. Notice that 2.5 mr beamstrahlung is not the limitation on apertures either here or in the other configurations to be presented. Because the above assumptions are rather conservative, it seems reasonable to fix magnet apertures based on the larger of the two envelopes i.e. either the incoming/outgoing beams or their corresponding QSR. With these magnet apertures one can then ask what magnet types can be used and whether they can be made to fit into the 19-20 cm radius, "detector stay-clear" cylinder. We must also consider the outgoing $e^\pm$ from the IP due to Bhabha scattering¹. The undisrupted, Bhabha scattering at 4 mr is given by the dashed curve which shows that QSR and Bhabha's outside ≈ 4 mr set the limiting aperture for $Q_{2,3}$ at $R \gtrsim 2$ cm. The actual aperture required for acceptable detector noise or to monitor luminosity requires detailed study of the various configurations but we will assume that an aperture of $10 - 16\sigma$ should be acceptable until shown otherwise. This is consistent with the "beam-stay-clear" prescriptions for other rings.

Figure 2 shows the maximum gradient which can be achieved as a function of aperture for various quadrupole types. In this figure I include only reasonably good magnets which are within the capabilities of this laboratory. For instance, the iron-free, superconducting magnets represented by the 3-dashed lines labelled by the superconductor packing fraction $\lambda = 0.1, 0.05$ and 0.033 are for the elliptical coil magnets discussed in ref. 4. St. Loran⁵ has done some coil fabrication studies for this type of magnet. For $\lambda = 1/30$, one approaches cryostable operation and the region below this curve I define as the preferred operating region for superconducting magnets e.g. gradients $G \lesssim 14 \text{ kG/cm}$ for radii $R \gtrsim 1 \text{ cm}$. Although specific numbers depend on the actual design, it should be clear that the FNAL design is not conservative even though it is more efficient than the magnet of ref. 4,5. Most superconducting quads in present operation fall in the vicinity of the $\lambda = 1/20 - 1/30$ curves at radii $R > 3 \text{ cm}$ e.g. the FNAL standard Fe quad has $R = 3.5 \text{ cm}$. For conventional magnets, the results for the PEP standard cell quad ($R=6 \text{ cm}$) have been extrapolated to smaller radii (see short dashed line).

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and are completely consistent with independent simulations done at $R=1.5$ cm by Bill Brunk⁶ which gave $G = 8$ kG/cm. The solid curve for Saturated Cobalt (REP) magnets intersects the conventional magnet curve at $R \approx 2.1$ cm and $G \approx 5.8$ kG/cm. The $SmCo_5$ blocks assumed for the REP curve are commercially available with the required characteristics⁷. Although these REP magnets will be more expensive than conventional magnets, or the REP magnets we are now building, they should be less expensive than the current superconducting design.

Another complication results from requiring solutions to be compatible with two different detector systems — MARK II and SLD. Figure 3 shows these two detectors, as presently proposed, in relation to one of the new hybrid quadruplet solutions (HYBRD2). One solution constraint imposed on all solutions was $l_1 \geq 1$ m so that magnets would basically lie outside the drift chambers. Other constraints included a maximum O.D. of 38-40 cm for the magnets and a total telescope length between the IP and soft bend of $l_{SB} \leq 32.873$ m. MARK II may violate the maximum O.D. constraint for Q_1 but since this could be a REP magnet with a comparatively small O.D. (≤ 20 cm) this is not a problem. In fact, another implicit solution constraint was to seek solutions that reduced the total integrated quadrupole strength required. This generally decreases costs and could do so drastically if it would allow conventional or REP magnets or even superconducting magnets with significantly lower gradients. One way to accomplish this is to increase the number of magnets, realizing that the increase in fringing fields will tend to worsen the high-order contributions to spot size. Because it also becomes more difficult to satisfy the total length constraint, I settled on a quadruplet configuration as the simplest arrangement that could satisfy the first-order telescope constraints in a rather general way. For instance, ignoring possible gradient limitations, the quadruplet could be tunable by either conventional current controls, by longitudinal position (tromboning) or azimuthal angle control or any combination of these. Thus, barring gradient limitations, the solutions should allow any combination of magnet types and control options. The questions are then whether such solutions exist and whether they are practical i.e. satisfy the constraints of Fig. 2.

Figure 4 shows a possible, "low-gradient" triplet solution HYBRD0 ($G=8$ kG/cm) which satisfies the above constraints for an allowable aperture of $R=1.5$ cm (for the conventional magnets) or much larger for superconducting. This may well be a preferable superconducting solution from the standpoint of cost and compatibility with high-field solenoids. Unfortunately, it doesn't easily adapt to a mixed or hybrid system because energy changes result in configuration changes. Although these changes are modest and only slightly degrade spot size they eliminate the nice symmetry of the system and complicate its operation. This was the reason for using quadruplets which don't have these drawbacks. The triplet solution HYBRD0 was used as the base solution to generate the quadruplet solutions.

Figures 5-9 show the various quadruplet solutions (HYBRD1-5) whose characteristics are compared to the current superconducting solution (SUPC14) in Table 1. All calculations were done with TURTLE for the complete North arc with otherwise identical configurations and conditions. The solution using symmetric 8 kG/cm gradients (HYBRD1) compares favorably in all respects. HYBRD1A shows corresponding results for a $\pm 10\%$ energy variation of HYBRD1 when only Q_4 has its strength tuned and $Q_{1,2,3}$ are moved longitudinally. The distances moved are small. HYBRD1B shows similar results when moving all quads to either change energy or β -functions (nominal values of $\beta_x^* = \beta_y^* = 0.5$ cm). Figures 6-9 show the results for HYBRD2-5 which use various combinations of gradient e.g. two 6 and two 10 kG/cm quadrupoles or one 8 and three 6 kG/cm quads. These all allow the use of any combination of SmCo or conventional magnets compatible with the particular detector for quite optimistic phase space and disruption assumptions. The last figure (HYBRD5) shows the results and apertures for one of the configurations whose average gradient is less than half that of SUPC14 and might be implemented with one SmCo magnet and three conventional magnets for MARKII.

III. Conclusions

One virtue of the solutions presented here is that they allow a very significant decrease in initial capital equipment costs. Because the disruption of the beam depends mainly on the transverse emittance

which is achieved, it would appear wise to start with a single REP magnet for Q_1 , similar to what we are now making, together with conventional, current controlled magnets for $Q_{2,3,4}$. Since the configurations are designed as they are, it is then possible to make simple substitutions based on operating experience or when SLD is to be installed. Another reasonable starting point would be to use REP magnets for $Q_{1,2}$ and conventional magnets for $Q_{3,4}$ because this might be carried over for SLD. It should be clear that virtually any combination of magnet types can be used in virtually any control configuration although fewer SmCo magnets allow larger inherent energy ranges. Most of these approaches would cost no more than $\approx 1/4$ of the cost of the superconducting magnets not counting refrigerators, support buildings and supplies etc. An all SmCo system for $Q_{1,2,3,4}$ would still cost only $\approx 1/2$ of the superconducting option but would require some design and prototype studies because of the increase in SmCo block size.

Finally, it should be pointed out that because the REP magnets are being assembled in layers, even a pure REP system operated like HYBRD1B could operate at any energy (e.g. to carry out searches for the top quark) by either rotating every other layer to cancel the adjacent one or simply removing them to give better energy tuning range. Techniques for remotely positioning them and/or rotating or removing layers without requiring significant realignment would have to be considered, however. Such configurations are presently being studied for their detector noise implications³ since this is the constraint that must ultimately determine the actual make-up of the configuration by determining the required apertures for each magnet. The quadruplet approach in conjunction with Fig. 2 should simplify this selection process. A subsequent report will look at exact ray-tracing results for some of these configurations (and others being studied) as well as the effects of higher-order multipole components in the various magnets and other questions such as positional and rotational tolerances.

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3. J. J. Murray, SLC-CN-239, July 1983.
4. H. Shoenne and J. E. Spencer, SLAC/AP-3, April 1983.
5. S. St. Laurent and E. Tillman, SLC-CN-224, May 1983.
6. B. Brunk, private communication.
7. E. Marik, Private communication from Product Manager of Vacuumschmelze, Inc.
8. H. DeStaebler, private communication.

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Table I: Comparison of various final focus configurations based on TURTLE runs for the complete North arc. Results are given for 200 rays both with and without radiation broadening due to all dipole fields.

Configuration Name	Energy (GeV)	l_1^* (m)	l_2^* (m)	l_3^* (m)	l_4^* (m)	G_{max}/G_{min} (kG/cm)	σ_x^*/σ_y^* (μm)	Radiation Broadened σ_x^*/σ_y^* (μm)	Comments
SUPC(20)	50	2.21	2.97	4.19		20	1.58/1.38	1.70/1.54	Murray - CN-239
SUPC(14)	50	2.21	3.11	4.51		14	1.64/1.39	1.78/1.55	
SUPC(10)	50	2.21	3.27	4.96		10	1.73/1.41	1.52/1.59	
HYBRD0	50	1.37	2.51	4.47		8	1.66/1.40	1.80/1.58	Reduces soft bend length
HYBRD1	50	1.13	2.26	3.48	4.55	8	1.64/1.47	1.70/1.61	Vary $Q_{1,2,3,4}$ Strengths
	45					7.2		1.64/1.58	
	55					8.8		1.78/1.60	
HYBRD1A	45	1.16	2.14	3.59	4.55	8/7.4	1.64/1.48	1.63/1.59	Vary Q_4 & $Q_{1,2,3}$ positions
	55	1.05	2.40	3.35	4.55	8.6/8	1.64/1.45	1.79/1.65	
HYBRD1B	45	1.10	2.14	3.58	4.50	8	1.64/1.47	1.63/1.58	Vary $Q_{1,2,3,4}$ positions $\beta_x^* = \beta_y^* = 0.45cm$ $\beta_x^* = \beta_y^* = 0.60cm$
	55	1.18	2.41	3.35	4.62		1.64/1.47	1.80/1.67	
	50	1.17	2.27	3.23	4.34		1.60/1.40	1.67/1.55	
	50	1.06	2.22	3.94	4.94		1.74/1.59	1.77/1.74	
HYBRD2	50	1.08	2.52	3.53	4.39	10/6	1.65/1.44	1.75/1.60	
HYBRD3	50	0.99	2.13	3.61	4.93	10/6/6/6	1.67/1.41	1.79/1.58	
HYBRD4	50	0.70	2.12	3.58	4.89	8/6/6/6	1.66/1.42	1.77/1.59	
HYBRD5	50	0.99	2.08	3.54	4.84	11/6/6/4	1.66/1.40	1.80/1.56	
HYBRD6	50	0.90	2.02	3.62	5.07	11/5/5/4	1.68/1.40	1.83/1.55