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LUMINOSITY ENHANCEMENTS AT SLAC*

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Introduction

In this paper we will discuss several ideas that have been proposed to improve the luminosity at the SPEAR and PEP electron-positron storage rings and to insure good luminosity at the SLAC Linear Collider.

There have been two proposals studied recently for SPEAR: a Microbeta insertion using Samarium Cobalt permanent magnets, and a Minibeta insertion using conventional quadrupole magnets. The notations Microbeta and Minibeta used here are somewhat arbitrary since the front faces of the first quadrupole magnets for both insertions are at nearly the same distance from the interaction point.

As motivation for the discussion of the Microbeta and Minibeta proposals, we wish to comment on the physics program at SPEAR. SPEAR now runs fifty percent of the time for High Energy Physics using the MARK III detector in the West Pit Interaction Region, and fifty percent of the time for Synchrotron Radiation Research carried out by the Stanford Synchrotron Radiation Laboratory.

The MARK III detector is shown in Figs. 1(a) and 1(b). The detector is described in Ref. 1 and its main subsystems are described in Refs. 2-6. Briefly, working out from the interaction point, the detector consists of an inner trigger chamber, followed by a large drift chamber, a time-of-flight (TOF) counter system, a gas sampling cylindrical shower counter, a solenoidal coil which generates an axial magnetic field whose value at the interaction point is four kilogauss, the magnet flux-return steel, and finally a muon counter system. Gas sampling endcap shower counters mounted on the removable steel doors complete the detector. The novel feature of the detector is the cylindrical shower counter, which is placed inside the solenoidal coil and has a high detection efficiency for photons with energies as low as 50 MeV.

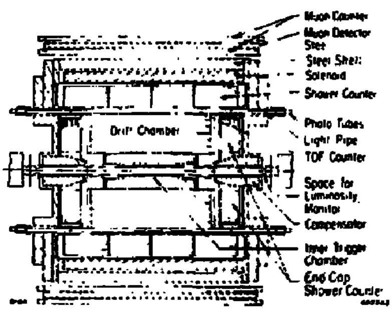

Fig. 1(a). Side view of the MARK III detector.

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Thus far we have taken data at the energies of the ψ and ψ'' resonances (1.548 GeV and 1.884 GeV per beam respectively). At the ψ'' we collide typically 17 mA on 17 mA using wiggler magnets to obtain an average luminosity per run between 1.4×10^{30} and 1.8×10^{30} $cm^{-2}sec^{-1}$. During the next five years we expect to take data at a number of energies between 1.5 GeV and 3 GeV per beam. For example, we have discussed at various times the following objectives: (a) obtain another 10 to 20 million ψ decays; (b) obtain a large sample of ψ' decays; (c) obtain another 10000 nb^{-1} of ψ'' decays; (d) study the production of F and F^* mesons, now that several groups have seen the F meson decay into $\phi\pi$ and $\phi 3\pi$ decay channels and have measured the F meson mass to be about 1970 MeV; (e) study the physics of the τ meson, the charmed baryon, and the charmed-strange baryon; (f) study and understand the energy region between 4.1 and 4.4 GeV in the center-of-mass. Clearly, a significant improvement in the luminosity of SPEAR will allow us to complete this type of program faster or with much better statistics.

Microbeta at SPEAR

The microbeta insertion for SPEAR was proposed first by Dick Helm in April 1982 as an outgrowth of a study that tried to find ways to increase the luminosity at PEP.[7] Helm, Roger Servranckx (a visitor from the University of Saskatoon, Saskatoon, Canada), Karl Brown, and several other SLAC machine physicists, spent large amounts of time and effort studying the details of this proposal.

In order to increase the focusing of the beam and thus make the spot size smaller at the interaction point, Helm proposed placing a quadrupole doublet inside the MARK III detector on each side of the interaction point. He proposed making the quadrupole magnets from samarium cobalt, since the permeability of samarium cobalt is essentially unity and thus one can superpose the quadrupole and solenoid fields without deleterious effects.[8] The one major difficulty with this proposal is that since the pole tip fields of the samarium cobalt quadrupoles are

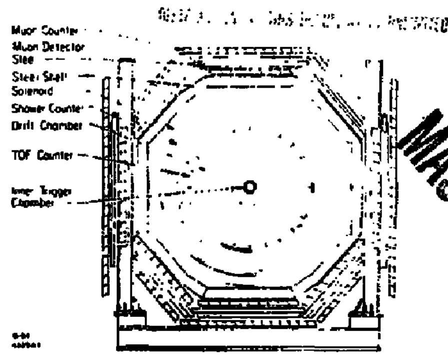

Fig. 1(b). End view of the MARK III detector.

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fixed, the only way that one can change the focusing strength of the doublet is to pull the two magnets apart. To see this, consider two lens with focal lengths f_1 and f_2 separated by a distance L. The combined focal length of the doublet, F, is given by

$$\frac{1}{F}=\frac{1}{f_1}+\frac{1}{f_2}-\frac{L}{f_1 f_2} \quad .$$

If $f_1 = -f_2$, which would be the case for equal strength quadrupole magnets in a doublet, then $1/F = L/f_1 f_2$. The samarium cobalt magnets would be placed in both interaction regions to keep the two-fold symmetry of SPEAR.

In Fig. 2 we show the preliminary layout of the microbeta insertion as proposed by Helm, and in Fig. 3 we show the energy dependence of β_y^* (β_y at the interaction point) given by Helm's calculations. Q4 and Q5 are the new samarium cobalt quadrupole magnets, while Q1, Q2, and Q3 are the existing iron-core quadrupole magnets in each interaction region. The "Reference Optics" is the present optics with $\beta_y^* = 10$ cm that has been run at SPEAR through the end of March, 1984, for colliding beam experiments. The two curves marked "Q4 Fixed" and "Q4 Movable" show the effect of pulling Q4 away from Q5 to change the focusing power of the doublet as the beam energy is increased above 1.5 GeV. β_y^* for the "Q4 Movable" case begins to increase when Q4 is pulled away from Q5 so far that it hits Q3 and, of course, can be pulled no further.

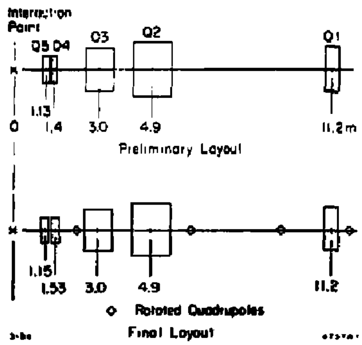

Fig. 2. Preliminary and final layouts of the microbeta insertion for SPEAR.

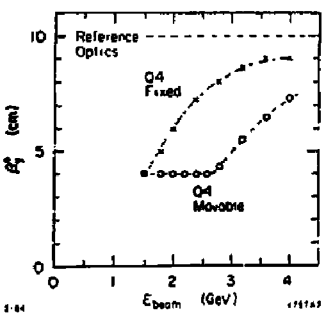

Fig. 3. Energy dependence of β_y^* for the microbeta insertion for SPEAR.

The final parameters for the SPEAR microbeta samarium cobalt quadrupole magnets are given in Table 1. A cross section drawing of quadrupole magnet Q4 is shown in Fig. 4.

SLAC has contracted with a commercial firm, Field Effects, Inc., to build a full sized prototype of Q4. Specifications for this prototype are given in Table 2. We want to have demonstrated that the fabrication techniques exist to build a magnet that meets the positional and magnetic tolerances. The delivery is expected by the end of the summer of 1984.

A solenoid magnet located in an interaction region of a storage ring will mix horizontal and vertical phase space. The MARK III detector presently uses two compensating solenoids connected in series with the main solenoid to insure that the $\int B\,d\ell = 0$ when evaluated along the beamline through the

Table 1. Parameters for SPEAR microbeta samarium cobalt quadrupole magnets.

	Effective Length	Bore Diameter	Pole Tip Field
Q4	37.8 cm	88.9 mm	8.5 kg
Q5	20.6 cm	63.5 mm	9.8 kg

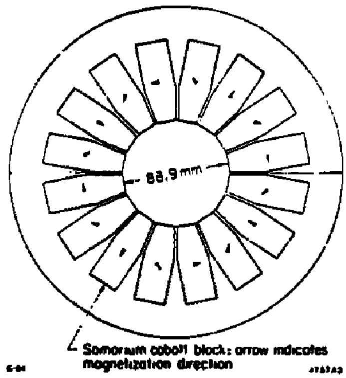

Fig. 4. Cross section drawing of the prototype Q4 samarium cobalt quadrupole magnet.

Table 2. Specifications for prototype quadrupole magnet Q4 for SPEAR microbeta insertion.

Gradient x Length Product	= 7.200 ±0.018 Tesla
Minimum Aperture	= 88.9 mm
Maximum Magnet Overall Diameter	= 266.7 mm
Maximum Magnet Overall Length	= 406.4 mm
Operating Temperature	35° ± 5°C
Maximum Multipole Fields: $\frac{\int (B_{multipole})d\ell}{\int (B_{quadrupole})d\ell}$ at 44.45 mm radius	
6-pole	1.0%
8-pole	0.17%
12-pole	0.57%
16-pole	1.4%
20-pole	3.3%

detector. In order to provide the space for quadrupoles Q4 and Q5, the compensating solenoids must be removed. Compensation can be accomplished also through the use of quadrupole magnets rotated by forty-five degrees about the beam axis. Joe Murray has shown that the use of four such quadrupole magnets on each side of a solenoidal magnet will give exact compensation of the solenoid.[9] The final layout of the microbeta insertion as shown in Fig. 2 shows where rotated quadrupole magnets would be located to provide the compensation for the MARK III solenoid.

It is worth mentioning that the use of large samarium cobalt magnets in high energy physics applications has been limited due to the high cost of the samarium cobalt. Recently the discovery of a new magnetic material by several groups in Japan and the United States was announced.[10] The beauty of this discovery is that the compound contains a light rare earth element (usually neodymium), iron, and boron, but no cobalt. Since the price of cobalt is one of the main reasons that samarium cobalt is expensive, the discovery of this new material may allow more widespread use of permanent magnets in high energy physics applications.

Minibeta at SPEAR

The Minibeta insertion for SPEAR was proposed by Klaus Wille, a machine physicist from DESY who is spending a sabbatical year at SLAC.[11] Wille and others had designed and built a similar system for the ARGUS detector at the rebuilt DORIS 5 GeV storage ring. In both the DORIS and SPEAR designs, a strong vertically focusing iron-core quadrupole magnet is placed inside the detector. A bucking coil is placed over the quadrupole magnet to buck out the field from the main solenoid in the quadrupole. In the SPEAR design, the next quadrupole magnet is moved close to the detector to give a strong doublet as close as possible to the interaction point. The DORIS design is similar but incorporates a quadrupole triplet instead of a doublet.

A schematic view of the ARGUS detector is shown in Fig. 5. Highlighted are the two minibeta quadrupoles, the bucking coils, and the compensating coils around the beam pipe between the interaction point and the minibeta quadrupoles. Descriptions of the rebuilt DORIS storage ring and the ARGUS minibeta configuration may be found in Refs. 12 and 13.

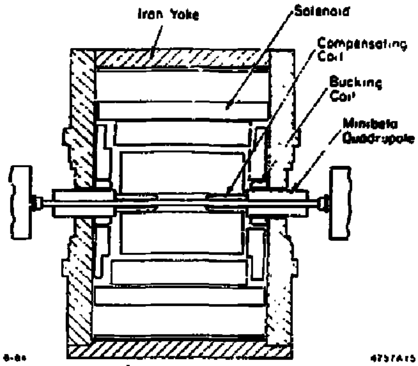

Fig. 5. Schematic side view of the ARGUS detector. Components related to the minibeta insertion for SPEAR are identified. Adapted from M. Danilov *et al.*, Nucl. Instrum. Methods 217, 153 (1983).

The region between the SPEAR arcs and the interaction point in the West Pit is shown in Fig. 6. Quadrupole Q1 is the first magnet next to the end of the arc. Quadrupoles Q2 and Q3 are close to the interaction point and give the focusing that makes β_y^* small at the interaction point. For the minibeta insertion, quadrupole Q3 is replaced by a new "minibeta Q3" (MBQ3) located closer to the interaction region by about one meter. Quadrupole Q2 also is moved closer to the interaction

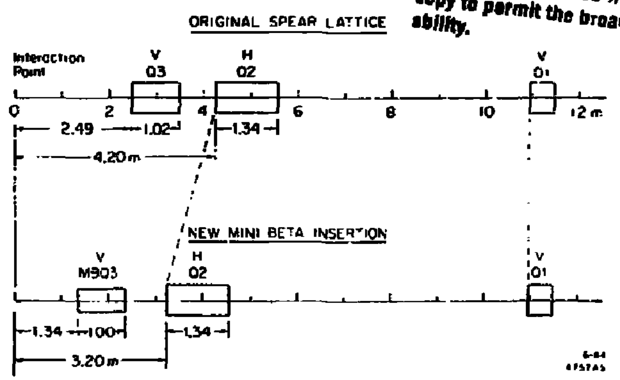

Fig. 6. Region between the SPEAR arcs and the interaction point in the west pit.

region by about one meter, while Q1 is left in its original position.

The parameters for the SPEAR minibeta quadrupoles are given in Table 3. Listed in the table are the values of k^2 for each of the three quadrupole magnets, where $k^2 = (B_o/a)(1/B\rho)$, B_o is the pole-tip field in kilogauss, a is the pole radius in meters, and $B\rho \simeq (\frac{100}{3})p$ is the magnetic rigidity of the particle in kilogauss-meters. The particle momentum, p, is measured in GeV. Also shown in the table are the values of the gradient and pole tip field for each of the three quadrupole magnets for a particle momentum of 4.0 GeV.

Table 3. Parameters for SPEAR minibeta quadrupoles

	$k^2 = \left(\frac{B_o}{a}\right)\left(\frac{1}{B\rho}\right)$	
Q3	0.9205 m^{-2}	
Q2	−0.3712 m^{-2}	
Q1	0.1766 m^{-2}	
	For $E = 4.0$ GeV	
	Gradient (kg/cm)	Pole Tip Field
Q3	1.23	6.14 kg at 5.0 cm
Q2	−0.495	6.29 kg at 12.7 cm
Q1	0.236	1.79 kg at 7.6 cm

Two comments should be made at this time. The enhancement of the luminosity is set by how close to the interaction point the front face of the first quadrupole magnet can be placed. In the case of the MARK III we are limited by interferences with parts of a working detector. The second point is that the minibeta design as presented here has changed only the straight section areas around the two interaction regions. With the exception of a change in the sextupole power supplies that will be explained below, the rest of SPEAR will remain unchanged. The minibeta modification will be placed in both interaction regions in order to keep the two-fold symmetry of SPEAR.

In Fig. 7 we show the SPEAR luminosity versus the energy of each beam. We show several luminosity values measured in 1978 and 1983 with the wiggler magnets turned off, and a curve of the calculated luminosity for the new minibeta optics, again without wigglers. The curves have been calculated assuming the values shown on the figure for the beta functions at the interaction point and the horizontal to vertical emittance coupling (ϵ_y/ϵ_x), and a beam-beam tune shift of 0.026. If we believe that the beam-beam tune shift will be the same for the minibeta optics, then we can expect an increase of a factor of five in luminosity. In Fig. 8 we show the β_x and β_y functions for the new minibeta optics as well as the dispersion function η_x. These functions are plotted from the interaction point to about half way around one arc of SPEAR.

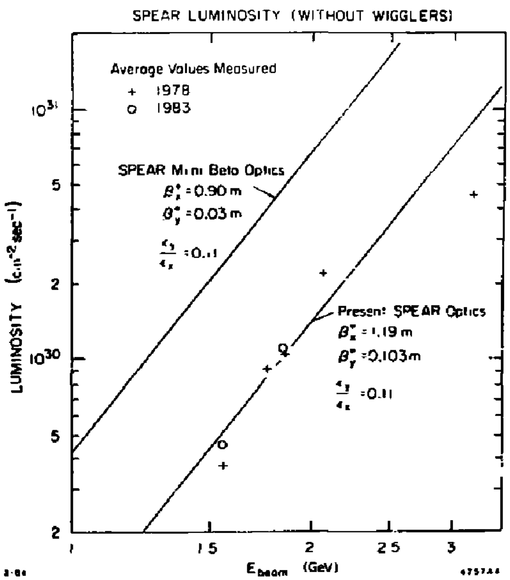

Fig. 7. SPEAR luminosity versus beam energy with the wiggler magnets turned off. The curves are calculated according to assumptions mentioned in the text.

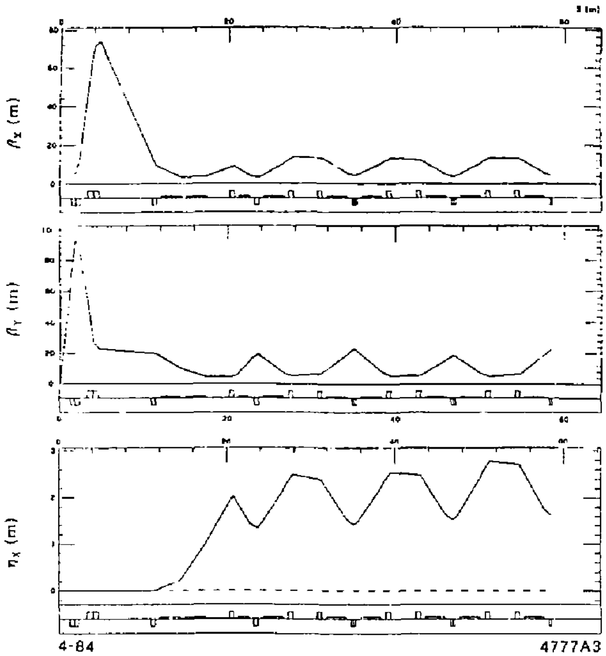

Fig. 8. The beta functions, β_x and β_y, and the dispersion function, η_x, for the minibeta optics ($\beta_y^* = 3$ cm) plotted as a function of the distance from the interaction point (in meters) along the central trajectory of the SPEAR ring.

As mentioned earlier, a solenoid magnet located in an interaction region of a storage ring will mix horizontal and vertical phase space. In the minibeta design for SPEAR, the bucking coils will require about thirty percent of the ampere-turns of the solenoid. This means that only about seventy percent of the main MARK III solenoid remains uncompensated. The remaining compensation will be provided by two rotated quadrupole magnets in the West Pit (one on each side of the detector just outside the detector) and two rotated quadrupole magnets in the East Pit. The locations of the rotated quadrupole magnets are shown in Fig. 9. Since β_x^* is so large compared to β_y^*, any mixing of the vertical phase space into the horizontal will not change β_x^* appreciably. However, the mixing of the horizontal phase space into the vertical will have a large effect due to the small size of β_y^*. This may not be as bad as one might think because our experience at SPEAR with the present optics (including, of course, the proper solenoid compensation) has been that the beam-beam blowup during collisions is equivalent to operating with a horizontal to vertical coupling of eleven percent. The compensation system described here[14] will reduce the horizontal to vertical coupling to approximately one percent. Thus we believe that four rotated quadrupole magnets, two in each interaction region, will be sufficient to minimize the effects of the four coefficients that couple the position and angle of the horizontal phase space into the position and angle of the vertical phase space.

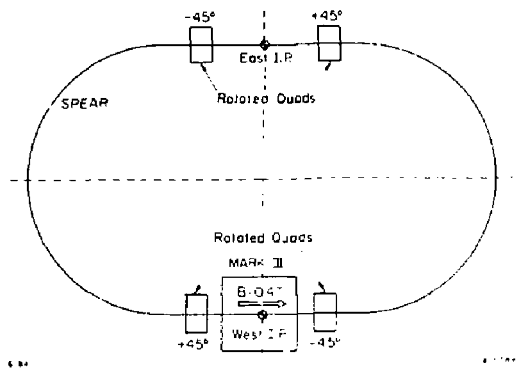

Fig. 9. Locations of the rotated quadrupole magnets that will compensate the effects of the MARK III solenoid.

When the MARK III detector was being assembled, the magnetic field was mapped both with and without the two compensating solenoids connected. Thus the field distribution formed by the main solenoid and bucking coils will be bounded by these two magnetic field maps, since the current will flow in the bucking coils in the same direction as in the compensating coils. We expect that field calculations using the computer program POISSON,[15] particle tracking using Bhabha scattering ($e^+ + e^- \rightarrow e^+ + e^-$), and the field distributions measured previously, will allow us to determine the field distribution for the MARK III detector with minibeta without having to dismantle the detector and remap the entire field volume.

The major parameters for the present optics with $\beta_y^* = 10$ cm and the minibeta optics with $\beta_y^* = 3$ cm are shown in Table 4. The momentum acceptance of the SPEAR ring, when set to the minibeta optics, can be improved greatly by splitting the vertical sextupoles into two separate families with each family running on its own power supply. This modification also allows much better control of the large vertical chromaticity. In Fig. 10 we show the beta functions of SPEAR with the horizontal sextupole family and the two vertical sextupole families highlighted. Ideally in each family of sextupoles, the betatron functions should be equal at the sextupoles and the betatron phase between the sextupoles should be 180 degrees. Figure 10 shows that the sextupoles in each of the vertical families are at nearly the ideal locations.

Because the MARK III detector already exists, the minibeta quadrupole and bucking coil must occupy essentially the same space as the original compensating coil. As mentioned earlier, this then sets the scale of the improvement in luminosity that we can expect to achieve. In Fig. 11 we show the SPEAR-MARK III interface when SPEAR is configured for the present optics and for the minibeta optics.

There are still several questions whose answers are not quite complete. For the same beam-beam tune shift, we will have to store a factor of 1.6 times more current per beam. Can we, or will some other beam effect become important? Will the use of the wiggler magnets increase the minibeta luminosity by the same factor as was obtained with the present optics? Are there deleterious effects due to the finite bunch length that will be seen? Will the rotated quadrupole scheme described earlier give sufficiently small horizontal to vertical coupling?

Table 4. Major parameters for SPEAR optics.

Parameters		3 cm Optics	10 cm Optics
Beta Functions at the	β_x^*	0.900 m	1.100 m
Interaction Point:	β_y^*	0.030 m	0.103 m
Tune:	ν_x	5.2957	5.273
	ν_y	5.1633	5.161
Chromaticity:	ξ_x	−12.102	− 8.05
	ξ_y	−26.485	−13.36
Momentum Compaction:	α	0.04115	0.0418
Emittance	ϵ_x	4.872×10^{-8}	4.94×10^{-8}
(at 1 GeV):		mrad	mrad

SLAC has chosen to proceed with the minibeta design. Components are being fabricated and the minibeta insertion will be installed during the summer of 1984. There are several reasons why the minibeta design was chosen over the microbeta design. The minibeta design gives a higher luminosity than the microbeta design, and works over a larger beam energy region. At this time, the required samarium cobalt magnets would cost more money and take longer to fabricate than the conventional iron-core quadrupole magnets for the minibeta design. Finally, the microbeta design is more complex mechanically than the minibeta design, and that complexity does not give any large advantage in improved operational performance.

PEP

A committee of PEP users concluded in July 1983 that an upgrade in luminosity of at least a factor of four would be much preferable than an increase in PEP energy.[16] Most, if not all, of the detectors at PEP would have to be modified to take advantage of this increase in luminosity. In making these modifications, it would be very difficult not to compromise small angle tagging (i.e. two-photon physics). Hence we have a conflict! Two-photon physics yields scale as

$$\left[\ell n\left(\frac{\theta_{max}}{\theta_{min}}\right)\right]^2 \quad .$$

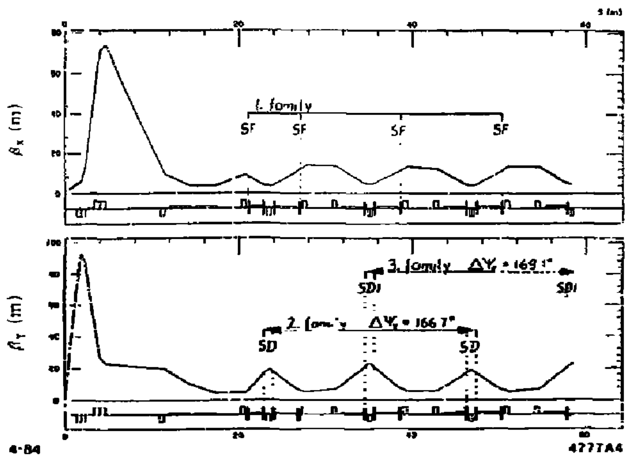

Fig. 10. Locations of the horizontal and vertical sextupole families compared with the beta functions of the SPEAR minibeta optics ($\beta_y^* = 3$ cm).

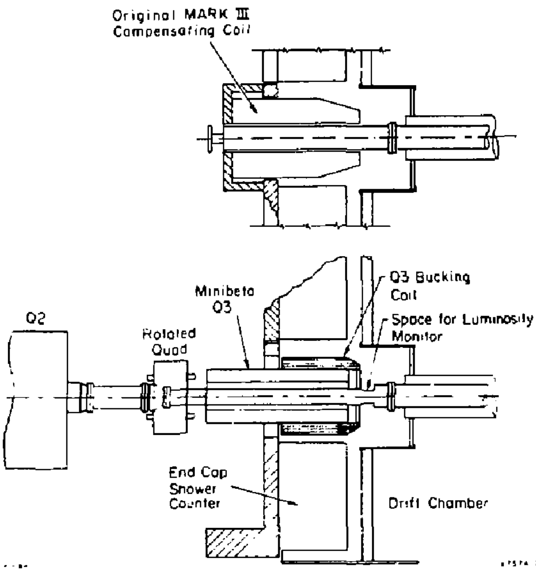

Fig. 11. The SPEAR-MARK III interface. The lower figure shows the new minibeta configuration in the region of the minibeta Q3 and the MARK III drift chamber. The upper figure shows the original compensating solenoid in place. The space occupied by the original compensating coil is essentially the same as the space that will be occupied by minibeta Q3 and the bucking coil.

Present PEP two-photon detectors record data down to tagging angles slightly less than thirty milliradians and angles down to ten milliradians or less are likely to be in use within two years.[17] If one increases θ_{min} from thirty milliradians to 150 milliradians and keeps θ_{max} at its maximum value of 90°, then the $\gamma\gamma$ luminosity is decreased by a factor of four! Two potential upgrades were considered by the aforementioned committee. In the first, a samarium cobalt quadrupole magnet would start one meter from the interaction point, followed by two superconducting quadrupoles starting about 2.4 meters from the interaction point. The specifics are given in Table 5. This upgrade would give a luminosity increase of about a factor of four. In the second scheme, two superconducting quadrupole magnets would be used, starting 2.4 meters from the interaction point. This design does much less violence to the detectors, but with less improvement in luminosity. The specifics for this second upgrade are given in Table 6. Although the first scheme gives a larger luminosity increase, it has a much more restricted region of useable energy because of the fixed field of the samarium cobalt magnet.

Table 5. Preliminary parameters of first upgrade to improve the luminosity of PEP.

	Length	Bore Radius	Field at Bore Radius
Q1	1.3 m	3.3 cm	10 kg (fixed)
Q2	0.5 m	4.5 cm*	22.5 kg } at 18 GeV
Q3	0.9 m	5.7 cm*	21.9 kg } at 18 GeV

* Assumes Warm Bore Design.

Expect to Get:	$\beta_y^* \sim 0.03$ m
	$\beta_x^* \sim 0.75$ m
Existing Lattice:	$\beta_y^* \sim 0.11$ m
	$\beta_x^* \sim 3.0$ m
Luminosity Increase:	~ 4

Table 6. Preliminary parameters of second upgrade to improve the luminosity of PEP.

	Length	Bore Radius	Field at Bore Radius
Q1	1.7 m	6.5 cm*	21.4 kg } at 18 GeV
Q2	1.0 m	6.5 cm*	17.2 kg } at 18 GeV

* Assumes Warm Bore Design.

Expect to Get:	$\beta_y^* \sim 0.05$ m
	$\beta_x^* \sim 1.25$ m

A more radical idea is now being studied.[18] The PEP ring can be reconfigured to give high luminosity in three interaction regions (and thus for three detectors) instead of the present six. As part of this reconfiguration, three of the six interaction regions will be equipped with minibeta insertions, while the other three interaction regions will become high beta regions. In these new PEP insertions, the front faces of the closest quadrupole magnets will be at 3.5 meters from the interaction point. Assuming, as was done in the minibeta design for SPEAR, that one operates at a constant beam-beam tune shift, then β_y^* will be reduced from 12 cms to 4 cms, and the luminosity will be increased by a factor of five. The new insertion quadrupoles will be iron-core magnets (pole-tip fields around 10 kilogauss) since they all will be outside the detectors. Hence the cost should be much less than the cost for either of the two schemes mentioned earlier.

Since SPEAR is smaller than PEP and has less complicated optics, SPEAR becomes a good testing arena for many of these ideas.

SLC

The first detector for the SLAC Linear Collider (SLC) will be the upgraded version of the MARK II Detector. The final focus design for SLC[19] is very complicated because it involves many quadrupole and bending magnets to focus the electron and positron beams to the required micron-sized beam spots and then transport the scattered beams to their beam dumps. Only the final triplet of the final focus affects the detector design (and vice versa). There are two schemes for the final triplet that have been studied. One involves saramium cobalt quadrupole magnets starting one half to one meter from the interaction point, and the other involves superconducting quadrupole magnets starting 2.25 meters from the interaction point. A working decision has been made to use the superconducting quadrupole magnet scheme. A transverse view of the MARK II detector at SLC is shown in Fig. 12. Enlargements of the area near the interaction point are shown in Fig. 13 for the two final triplet arrangements that have been studied.[20] Considerations that led to the working decision to use superconducting quadrupoles are: (a) the need to be able to have access to the cables and electronics of the vertex drift chamber, (b) the desire to minimize the minimum angle reached by the Small Angle Detector in order to better measure the background effects in $e^+ + e^- \to \gamma + \nu + \bar{\nu}$, and in order to better determine the Bhabha cross section, and (c) the desire to be able to minimize the effects of synchrotron radiation hitting the beam pipe, final focus elements, and parts of the detector. Beam and synchrotron radiation envelopes for the samarium cobalt scheme[20] are shown in Fig. 14. Three remarks are in order. SLC is not a storage ring. Thus one wants very small spots but to first approximation the angular spread of the beam particles is not important. The superconducting quadrupole magnets must be kept small in diameter so that the detector doors and endcap calorimeters will clear the quadrupole magnets when they are removed from the detector. In principle, this is merely an engineering detail. Finally, it must remain possible to align very accurately both final foci with respect to each other so that the two micron-size beams can be collided and then transported to their respective beam dumps with a minimum amount of background generated. This probably means that alignment holes will have to be provided that traverse the entire detector.

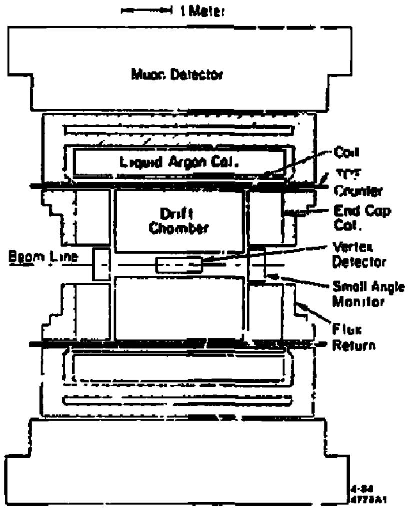

Fig. 12. Side view of the MARK II detector at the SLC.

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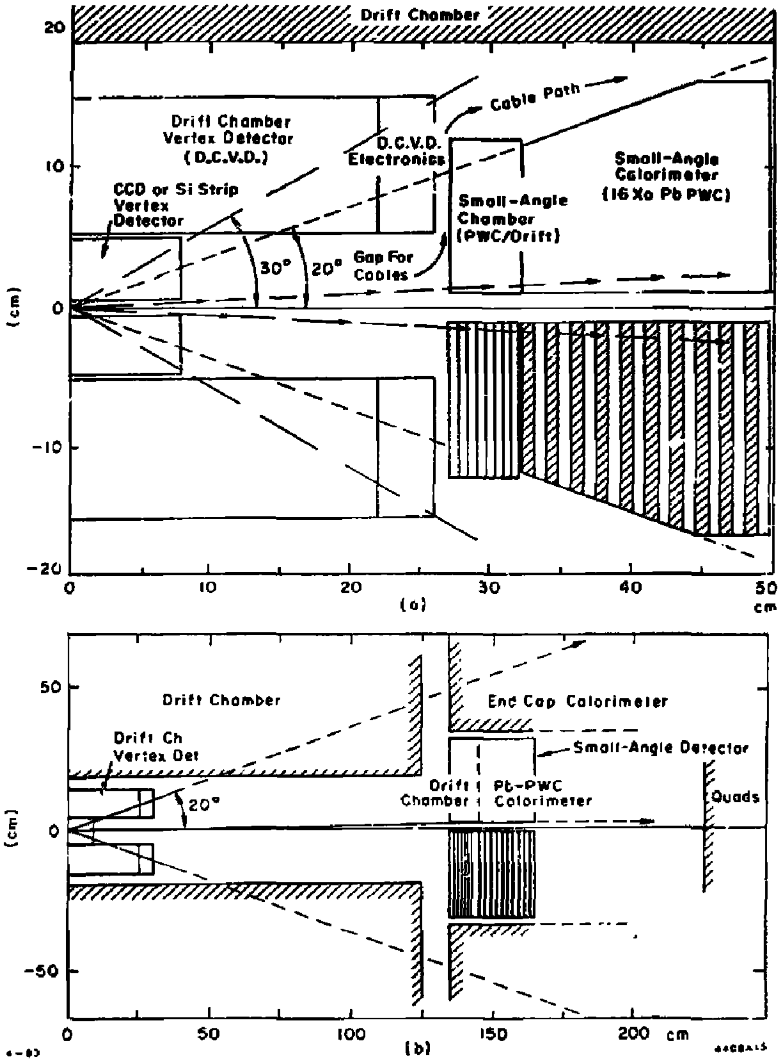

Fig. 13. Two geometries of the portion of the MARK II detector near the SLC in· ·raction point that are compatible with the two final triplet schemes that have been studied. For the reasons given in the text, the detector will be designed to be similar to the geometry given in (b).

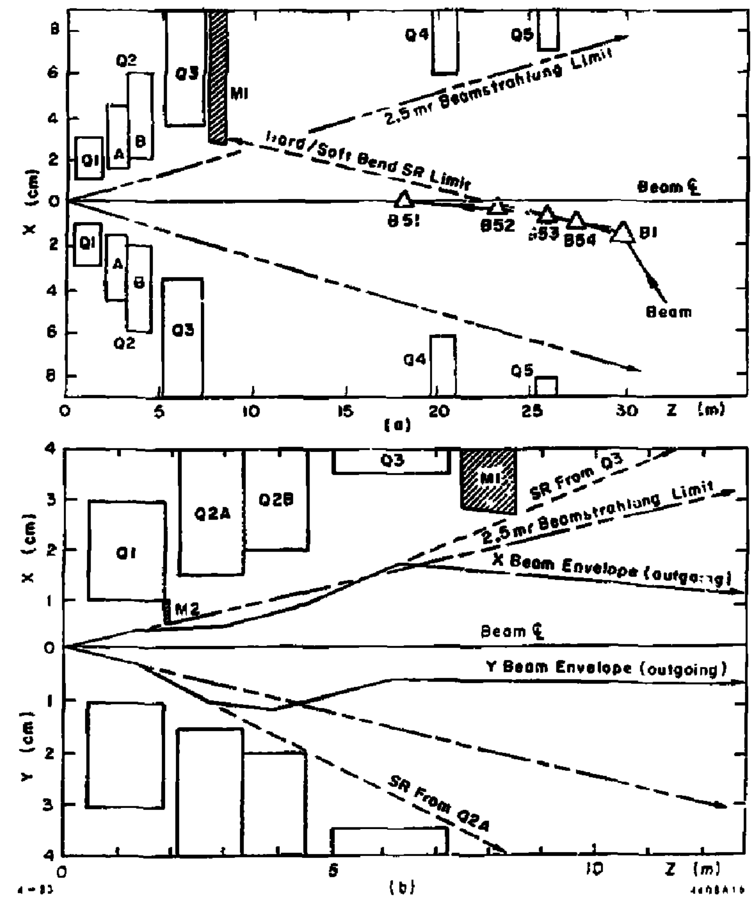

Fig. 14. Beam and synchrotron radiation envelopes for the MARK II detector at the SLC. The magnets that make up the samarium cobalt final triplet scheme are shown, along with the next seven quadrupole and bending magnets of the final focus system, and masks to intercept synchrotron radiation.

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