Very High Luminosity Collider at Cornell [*]

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Abstract

A detailed understanding of the B-meson system may require the development of an electron positron collider with luminosity an order of magnitude greater than the present generation B-factories. We are exploring the parameters of such a machine and the possibility of fitting it into the CESR tunnel. Our concept is for a symmetric collider, with beams that intersect with a horizontal crossing half angle of about 6mrad and compatible with bunches placed in every 3 or 4, 500MHz RF buckets. The final focus quadrupoles are common to both beams. The relative simplicity of the interaction region permits the possibility of very small vertical β^*, perhaps as low as two millimeters. We exploit the capability of superconducting cavities and the flexibility of the symmetric energy optics to attain the high accelerating voltage and low momentum compaction required to preserve comparably short bunches. At 3A/beam comprised of 420 bunches, with $\beta_v^* =$ 2mm, beam-beam tune shift parameter $\xi = 0.06$ and beam energy of 5.3GeV, yields a luminosity $> 10^{35}$cm^{-2}s^{-1}.

1 INTRODUCTION

We describe a two ring very high luminosity symmetric energy, electron positron collider that operates in the Υ_{4s} energy range. The machine is designed to fit into the CESR tunnel with minimal disturbance to the operation of the existing storage ring. The machine components are necessarily compact. The equal energy beams share a common wide aperture dipole guide field and are independently focused by superconducting dual aperture quadrupole magnets. Except in the interaction region and the RF cavities the beams are isolated in independent vacuum chambers. The parameters of a machine that are based on a straightforward extrapolation of our operating experience with CESR and its technical components include $\beta_v^* = 7$mm and a peak luminosity of 3×10^{34} cm^{-2}s^{-1}. We observe that the relative simplicity of the interaction region in a machine with equal energy beams permits a very significant reduction of β_v^* and briefly explore the implications of $\beta_v^* = 2$mm optics.

2 GUIDE FIELD

A cross section of the CESR tunnel indicating the existing storage ring, synchrotron injector and dual aperture machine is shown in Fig. 1. The arc dipoles are conventional resistive magnets with good field aperture ($\Delta B/B <$

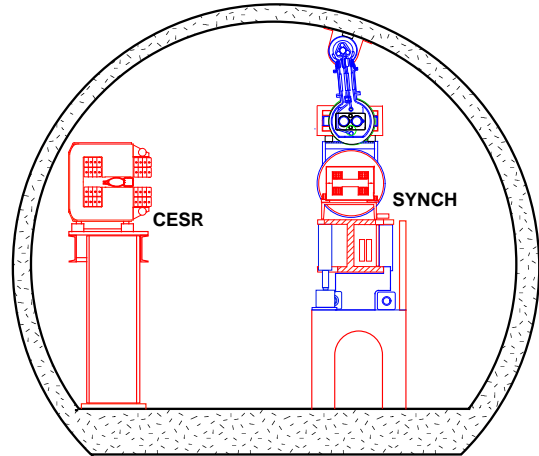0.05%) of 135mm×54mm in order to accomodate the two beams separated by 85mm[1].

Figure 1: Cross section of the CESR tunnel. The CESR storage ring is at the left. The synchrotron is in the same plane as CESR to the right. The dual aperture machine is above the synchrotron.

The minimum separation of the two beams in the arc dipoles is determined by the parameters of the dual aperture quadrupoles. As the separation of the side-by-side quadrupole apertures is reduced, the current density of the windings increases and a superconducting magnet proves more efficient and compact than a resistive design. The superconducting dual aperture quadrupole[2] is shown in Fig. 2. A protoype has been built and the field error measured to be less than 0.05% over the full 54mm aperture. The magnet in its cryostat is shown in Fig. 3. A complication of the cryostat is that the beam tube must be water cooled to carry away 2kW/m of synchrotron radiation power. The superconducting magnet package will include a dual aperture sextupole and dipole corrector in addition to the quadrupole. The tunes, chromaticity, coupling, etc. of the two beams are totally independent.

3 RF

The RF system for the dual aperture machine will consist of 10 single cell 500MHz superconducting cavities similar to the four now installed in CESR[3]. In order to provide the maximum possible voltage with the fewest number of cavities, the counterrotating beams share the complement of ten. The beams are separated by 85mm in the machine arcs and maintain that separation through the cavities. Then the beams are displaced by ±42.5mm from the cavity axis. The off-axis beam is weakly coupled to transverse cavity
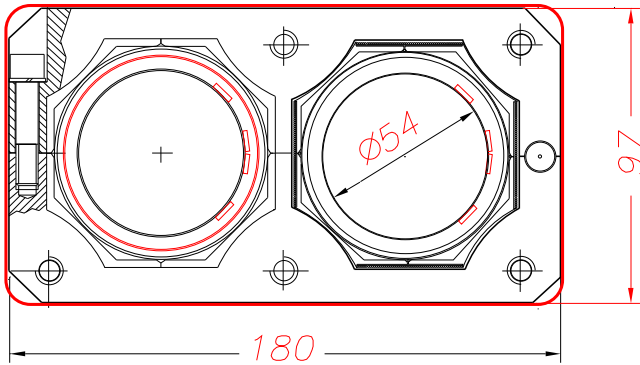
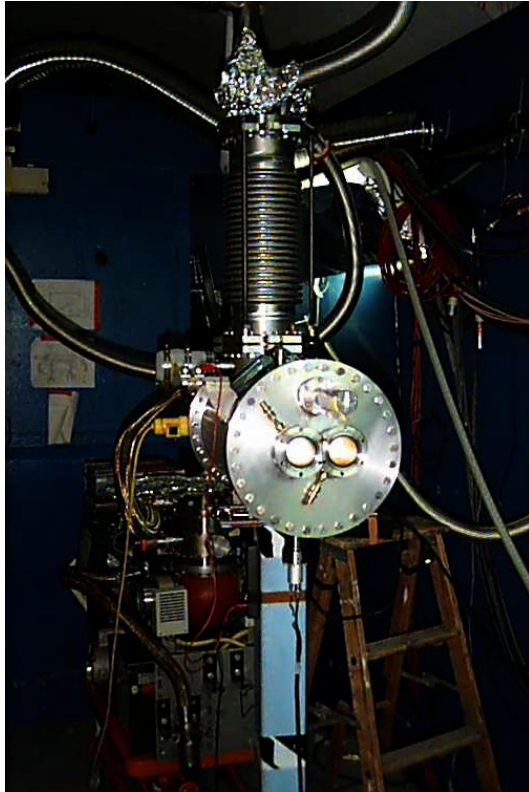Figure 2: Dual aperture superconducting quadrupole magnet.

Figure 3: Dual aperture quadrupole in cryostat in preparation for testing.

modes because of the open cell geometry and large beam tube radius (12cm). The parasitic modes that are excited are effectively damped by the ferrite loads outside the cavity cryostat. Each of the 10 cavities will be required to deliver nearly 800kW to the beams and to operate with a gradient of 10MV/m, (30MV total) in order that the bunch length be no greater than $\beta_v^* = 7$mm. Development of a high power window and coupler are in progress.

4   VACUUM SYSTEM

The vacuum system must be capable of handling a large synchrotron radiation heat load and maintaining low pressure while presenting a minimum impedance to the beam.

We have designed a copper chamber with elliptical cross section that is connected to the pump chamber through small holes recessed in slots in order to minimize transmission of TE fields excited by the beam into the pumps.[4]. The width, depth and spacing of the 6 channels is chosen to be $w = 3.5$mm, $d = 2.5$mm and $s = 2$mm respectively. The radius of the holes $a = 1.75$mm and the spacing, $h = 1$mm. The chamber geometry is indicated in Figs. 4 and 5. The loss factor for a 7mm bunch is $K = 4.6 \times 10^{-9} \text{VpC}^{-1}$ for each of the recessed holes and corresponds to a dissipation of 0.68W/m for a 3A beam. The associated impedance is a negligible fraction of the total machine impedance. The conductance from beam chamber to pump chamber is 810 l/s/m.
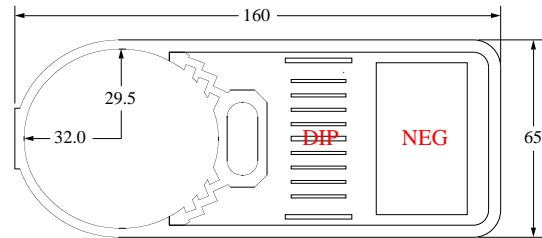

Figure 4: Cross section of copper vacuum chamber. Two such chambers fit into the aperture of the guide field dipole. In the counterpart of the chamber shown, water channel remains at the right and slots and pumping chamber are at the left.
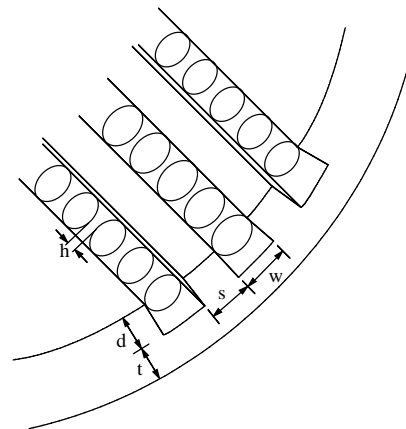

Figure 5: Detail of holes recessed in long slots in vacuum chamber.

Primary pumping will come from nonevaporable getter(NEG) material. Non-getterable gases will be removed by distributed ion pumps. Estimates of the gas load indicate that the NEG will require reactivation weekly. The pressure profile peaks within the quadrupole where pumping is through the beam tube to a lumped pump. The average total pressure is estimated to be 5.6nTorr corresponding to a beam gas lifetime of 4.7 hours.

5 INTERACTION REGION

5.1 Beam Separation

In a two ring symmetric energy machine, the closed orbits of the counterrotating beams can be separated by a crossing angle, electrostatic deflectors, or some combination of the two. If the crossing angle is small, ~ 2.5mrad, then electrostatic separators are required to kick the beams far enough apart to clear a septum. Characteristics of such a machine are summarized by Dugan et.al.[1] If the crossing angle is large ($\sim$ 6mrad) then the optics can be arranged so that the beams clear a septum without the help of separators.

The horizontal separation of the trajectories at a distance s from the interaction point is

$$x = \pm\theta^*\sqrt{\beta_h^*\beta(s)}\sin\phi_h(s) \qquad (1)$$

where θ^* is the crossing half angle. The maximum separation occurs when $\phi_h = \pi/2$, 1/4 wavelength from the IP. Normalized separation, $N_\sigma = \frac{x}{\sigma_x} = \frac{\theta^*}{\sqrt{\frac{\epsilon}{\beta^*}}}$ where ϵ is the horizontal emittance. Typically, $\beta^* \sim$ 1m, and $\epsilon \sim 0.16\times10^{-6}$m-rad. If $\theta^* = 6$mrad, then $N_\sigma = \pm15$. It is at this point of maximum separation, or as close to it as we can manage, that the beams will pass to either side of a magnetic septum and be steered into each of the two rings. If we insist on a 10σ stay clear, then the space between the inner walls of the side-by-side beam tubes is limited to $t = 2\times5\sigma = 10\sqrt{\epsilon\beta(s)}$. Since the coils of the dual aperture quad or dipole and the walls of the vacuum chambers must fit into this space, and since the size of the space scales with $\sqrt{\beta}$, we design the optics so that β is large at the separation point. If $\beta(s) = 40$m, typical of the maximum β in the CESR lattice, then the septum thickness is $t = 2.52cm$, which is consistent with the design of the dual aperture magnet package[2].

A lattice has been designed to match as much as possible the criteria summarized above. The interaction region optics are based on the hybrid of permanent magnet and superconducting final focus quadrupoles[7] that will be installed as part of the CESR upgrade. Vertical focusing begins within 30cm of the IP in a NdFeB permanent magnet and is completed before the beam leaves the CLEO solenoid. In the interest of bringing the beam separation point nearer to the IP and out of the hard bends, two vertically focusing quadrupoles are added in the interaction region, one adjacent to the superconducting Q2, and another on the CLEO end of the soft bend, labelled Q2A and Q2B in Fig. 6 respectively. The quadrupole designated Q3, is horizontally focusing and it is the point where the beams are separated into side by side quadrupole apertures.

A ±6mrad crossing angle corresponds to an orbit displacement of ±36mm at Q3 or $10\sigma + 10.7$mm. A dual aperture quadrupole with beam tube separation of less than 21.4mm is required. We suppose that the beams are steered further apart by the dual aperture horizontal dipole at Q3.

In order that the trajectories are displaced to match the separation of the axis of the standard dual aperture magnets at Q4, ±42.5mm, a kick of ±0.74mrad is required of the dipole correctors at Q3. The separation of the orbits is shown in Fig. 6 and the displacement in Q3, in Fig. 7.
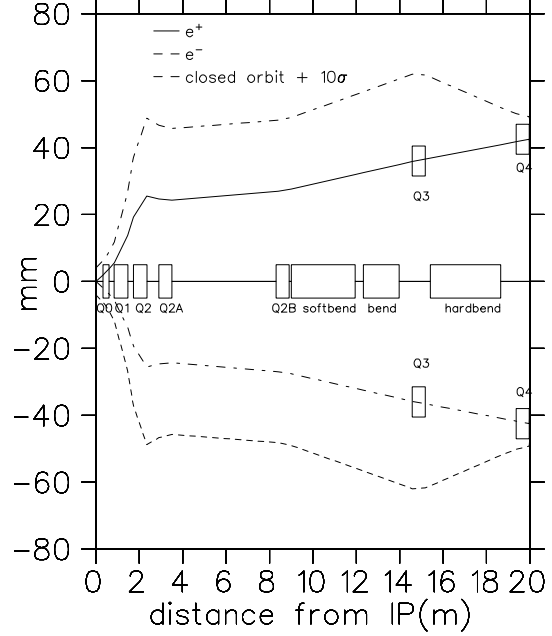

Figure 6: Trajectory of beams and beam envelopes in the interaction region. The quadrupoles labelled Q1-Q2B are common to both beams. Beams are separated into the dual apertures of Q3.
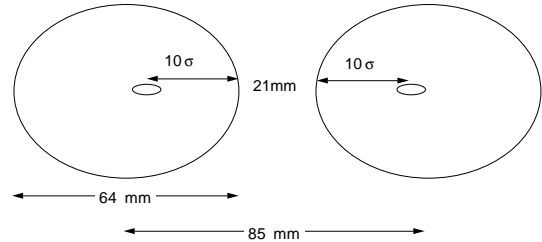

Figure 7: Profile of beams and Q3 dual aperture quadrupole where beams must clear the vacuum chamber walls that are 21mm apart. Magnet coils, iron, cryostat etc are within that 21mm. The full aperture of each beam tube is 64mm. The center to center distance is 85mm.

The lattice functions for half of the east west symmetric ring are summarized in Fig. 8 and Table 1. Tune, emittance, momentum compaction and chromaticity are similar to CESR optics except of course without constraints related to pretzeled orbits. The value of $\beta_v^* = 7$mm is limited by the bunch length that obtains with an accelerating voltage of 30MV and momentum compaction typical of CESR optics of 0.01.
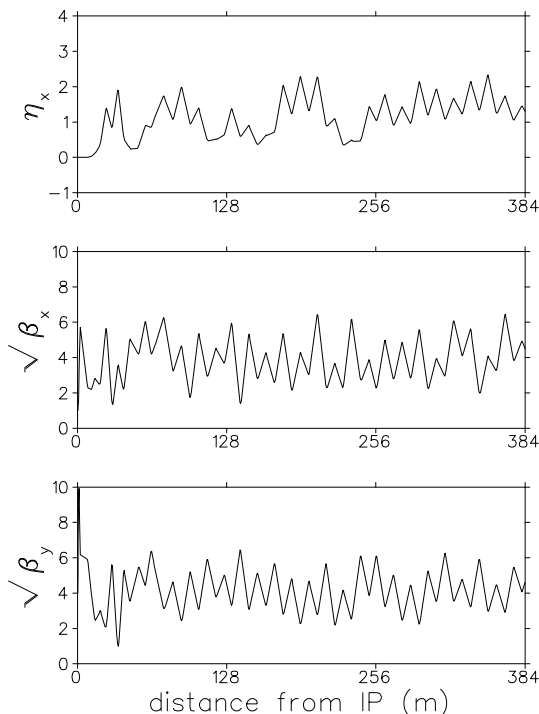
Figure 8: Optical functions for half of the east west symmetric lattice.

Table 1: Global lattice parameters.

Parameter	baseline
Q_h	11.52
Q_v	9.59
β_v^*	7mm
β_h^*	0.9m
η^*	0
θ_h^*	± 6mrad
ϵ_h	0.16×10^{-6}m-rad
α_p	0.01
$\beta_h(Q3)$	40.2m
$\phi_h(Q3)$	$0.21(2\pi)$
$\sigma_x(Q3)$	2.54mm

5.2 Crossing Angle

CESR operates with a crossing angle of ± 2.3mrad, $\epsilon_x = 0.21 \times 10^{-6}$ m-rad, $\beta_h^* = 1$m and $\sigma_l = 19$mm [5]. The crossing angle badness parameter $\kappa = \frac{\theta^*}{(\sigma_x/\sigma_l)} = 0.095$. In CESR we typically measure a beam beam tune shift parameter near $\xi_v \sim 0.05$. We conclude that $\kappa \sim 0.1$ is not inconsistent with good beam-beam performance.

In the dual aperture machine, bunch length is reduced to 7mm. Then with a 6mrad crossing angle and the parameters in Table 1, $\kappa = 0.105$, insignificantly greater than the typical CESR value and unlikely to degrade beam-beam performance. Indeed we are speculating that freed of the complications related to pretzeled orbits and the large number of parasitic crossings in the bunch train configuration,

that we will be able to increase the beam-beam tune shift parameter somewhat above the value achieved in CESR.

5.3 Parasitic Beam-Beam Interaction

The large crossing angle allows for a decrease in bunch spacing and an increase in the number of bunches in each beam. If the bunch spacing is 6ns, the first parasitic crossing point is 0.9m from the IP. In the optics described above, $\beta_v = 90$ m and $\beta_h = 6$m at the crossing point. The orbit displacement at the crossing point is ± 6mm. We assume that the bunch current limit will be imposed by vertical long range beam beam tune shift. That limit can be estimated by comparison with our observations. We have operated CESR with a 14ns spacing, 8mA/bunch and $\theta^* = 2.3$mrad in a configuration in which the maximum parasitic vertical tune shift also occurs at the first parasitic crossing [6]. For 8ma/bunch its value is $\Delta Q_v = 0.002$. We conclude that the maximum tolerable is at least $\Delta Q_v = 0.002$, and that corresponds to 4.7mA/bunch in the dual aperture machine with 6ns spacing, and 6mrad crossing angle. Our parameter list calls for 7.3mA/bunch in 420 bunches. The long range tune shift at the parasitic crossing scales with the square of the crossing angle. If the crossing angle is increased to 7.5mrad, $\Delta Q_v = 0.002$ with 7.3mA/bunch. The optimum choice of crossing angle is a compromise between aperture requirement, crossing angle badness parameter and long range beam-beam interaction.

5.4 IR Quad Aperture

The orbit displacement in the superconducting IR quad Q2 is 4.2mm/mrad of crossing angle. The crossing angle in the proposed separation scheme is just about double the crossing angle in the CESR Phase III design, and the orbit displacement in Q2 increases by nearly ± 15mm. The Phase III IR is designed so that the displacement of the incoming beam from the axis of the horizontally focusing quadrupole is no more than 2mm to reduce synchrotron radiation generated in that quad to a tolerable level. If we suppose that the same restriction applies in Phase IV, then the half aperture of Q2 must be increased by as much as 2×15mm.

5.5 β^*

The value of β^* that can be practically achieved in a collider is limited by the chromatic effects of the final focus quadrupoles and the aperture required to accomodate the counterrotating beams, and of course bunch length. Both chromaticity and aperture are minimized by placing short and strong quadrupoles very close to the interaction point. In a symmetric energy machine, both beams share a common set of magnets, and very low β^* optics become practical. It is of interest to explore the capability of the interaction region quadrupoles that will be installed as part of the CESR upgrade in 2000. We set aside for a moment the issue of bunch length.

An example with vertical and horizontal β^* equal to 2mm and 90cm respectively is indicated in Fig. 9. Note that vertical β reaches a peak of 400m in the 62cm long superconducting magnet about 120cm from the IP. The gradient of the superconducing magnet is about 2.4m^{-2}. Horizontal β is never greater than values typical of the arc lattice. Vertical chromaticity is double the value of the baseline design described above. Strong sextupoles will be required to correct the chromaticity with a consequent decrease in dynamic aperture. Whether or not a sextupole distribution exists that is consistent with good dynamic aperture is not clear. We have observed in CESR that beam-beam performance is quite sensitive to the details of the sextupole distribution. At least part of that sensitivity is presumably due to the feeddown associated with the pretzeled orbits in CESR. In the dual aperture machine, the beam trajectory will be everywhere on the axis of the chromaticity correcting sextupoles and the greater flexibility will certainly enhance tolerance of chromaticity. Investigation of sextupole distributions for the 2mm optics is in progress.

The beam stay clear is indicated in Fig. 10. A modest increase in the aperture of the permanent magnet front end would be required to accomodate the beam due to the rapid growth in vertical beam size. And as noted above, the aperture of the horizontally focusing quad must increase so that it is possible to keep the incoming beam near the quad axis.
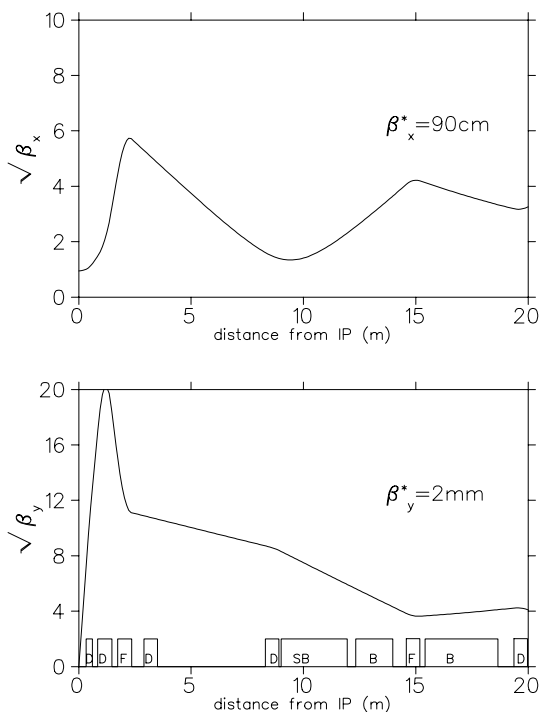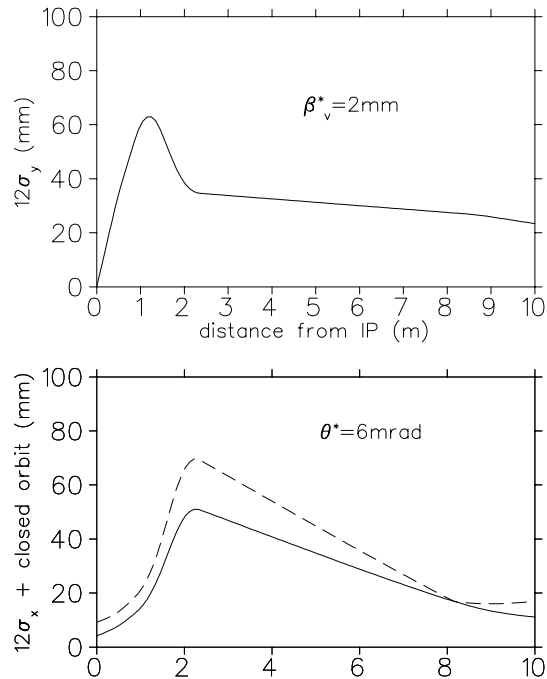

Figure 10: Horizontal aperture required to accomodate beam with orbit displaced by 6mrad crossing angle plus 12σ. The solid line is if ingoing and outgoing beams are symmetric about the quad centerline. The dashed line corresponds to the outgoing beam if the crossing point is displaced by 5mm so that the incoming beam is nearer the axis. The upper plot indicates required vertical aperture.

5.6 Bunch length

If indeed we can manage the nonlinearities generated in the interaction region in the $\beta^* = $2mm optics, the luminosity benefit acrues only if we can reduce the bunch length as well. In order to reduce the bunch length from 7mm to 2mm we either increase $\frac{dV}{dt}$ of the accelerating voltage by $3.5^2 = 12.25$ or reduce the momentum compaction by the same factor, or some combination of the two. An increase in the accelerating voltage by more than a factor of two to $> 20MV/m$ is unlikely. With some rearrangement of the machine layout we might find space to add harmonic cavities. Such cavities will necessarily have smaller aperture than the 500MHz cavities and that will result in increased impedance and higher order mode dissipation. Independently of how the short bunch length is achieved, the resultant high peak currents and associated wakes will strongly interact with vacuum system discontinuities.

Alternatively we can design low momentum compaction optics and attempt to unravel the dynamics that complicate the operation of such a machine [8]. The payoff of $\beta^* \sim 2$mm is substantial and we propose to explore the possibilities in detail.

Parameters of the $\beta^* = $ 7mm machine and a possible $\beta^* = $ 2mm machine are summarized in Table 2. For the 2mm machine we assume bunch shortening is accomplished by 10MV of harmonic RF(1500MHz) and a factor

Figure 9: β functions in the interaction region for the $\beta^* = $ 2mm machine.

of 5 reduction in momentum compaction.

Table 2: Parameters of High Luminosity Collider

Parameter	7mm	2mm
Q_h	11.52	?
Q_v	9.59	?
β_v^*	7mm	2mm
β_h^*	0.9m	0.9m
α_p	0.01	0.002
$V_{peak}@500MHz$	30MV	30MV
$V_{peak}@1500MHz$	0	10MV
Beam current	3.06A	3.06A
Bunch current	7.3mA	7.3mA
Tune shift parameter	0.06	0.06
Luminosity[$10^{34}cm^{-2}s^{-1}$]	3	10

6 CONCLUSION

The very low values of β^* that are accessible at a symmetric energy collider in the Υ_{4s} energy range provide a possibility of significantly extending the luminosity reach of e^+e^- factories to $10^{35}cm^{-2}s^{-1}$. Limitations arise as a result of shrinking dynamic aperture and the requirement for very short bunches. We are exploring low momentum compaction optics and high gradient harmonic superconducting cavities as tools for reducing bunch length. Meanwhile optics with β^*=7mm yield luminosity in excess of $10^{34}cm^{-2}s^{-1}$ by straightforward extrapolation of CESR parameters.

7 REFERENCES

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