AN e^+e^- COLLIDER IN THE VLHC TUNNEL

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Abstract

We describe the design of an e^+e^- collider that could be installed in the tunnels of the VLHC to run before that machine. We consider the arguments required to maximize the luminosity and indicate what effects would limit the machine performance. We also describe the primary technical issues involved with the construction of the components and consider how costs could be minimized.

1 INTRODUCTION

An e^+e^- collider[1][2] operating in the VLHC tunnels [3] over the energy range 90 < E_{cm} < 400 GeV would be a comparatively conservative extrapolation of the LEP design[4], but would permit high statistics studies of electroweak physics of the Z, studies of light Higgs, production of heavy lepton pairs, search for light SUSY states, and high resolution studies of the $t\bar{t}$ threshold[5]. This paper describes some results of a workshop[6], and an informal study (still incomplete) of the parameters that control the performance and cost of such a machine[7].

2 ACCELERATOR PHYSICS

2.1 Parameters

We describe a collider with the parameters in Table I.

Table I. Basic parameters of the machine

Beam energy, GeV	185
Circumference, km	233
Bending radius, km	25.9
Luminosity, $cm^{-2}sec^{-1}$ (each of 2 IR's)	0.7×10^{34}
Beta functions at IR, β_x^*, β_y^* , m	1, 0.01
Beam-beam parameter, ξ_y	0.14
Dipole field, T	0.0238
Vacuum chamber radii, r_x,r_y, m	0.12, 0.048
Cell length, m	226
Energy loss per turn, GV	4.0
RF voltage, GeV	4.6
Synchrotron power radiated, MW	100

The circumference of this machine is determined by general arguments of cost and power minimization and the requirement of a common tunnel with two stages of the Very Large Hadron Collider (VLHC), which should operate at two magnetic fields, 2 and perhaps 12-14 T.

2.2 Luminosity Limitations

The luminosity of a large circular collider at high energies can be expressed as

$$L = \frac{3}{16\pi r_e (mc^2)} \frac{\xi_y P}{\beta_y^* \gamma^3} \rho,$$

where ξ_y, P, ρ, and β_y^* are the beam-beam tune shift, radiated synchrotron power for two beams, bending radius, and the beta function at the interaction point.

While the beam-beam tune shift, ξ_y, is in the range of 0.03 for most lepton colliders, it was found at LEP that very stable operation was obtained at high energies with values of 0.08-0.09. These values were, however, limited by the bunch current at injection. During the last run of LEP, the goal was to reach the highest energy possible, and the beam-beam limit was not reached. Since ξ_y, scales with the damping decrement, we expect values of 0.14 – 0.17 at 185 GeV with two IR's. With a single IR, the beam-beam parameter could be higher, giving a luminosity close to 10^{34} $cm^{-1}s^{-2}$.

We have assumed that the radiated power, P, for both beams will be 100 MW. In addition to its effect on the luminosity, this number determines the size of the cooling system, the size of the rf system required to replace this power and the majority of the power cost.

The vertical beta function at the interaction point, β_y^*, primarily determines the interaction point optics. In LEP, almost all operation used values of β_y^*= 0.05 m, in part because operation with smaller values lead to undesirable differences in the luminosity between the four experimental groups[7].

We have looked at the constraints on the beam optics and are presently exploring a solution using β_y^* = 0.01 m, using the optics shown in Figure 1.

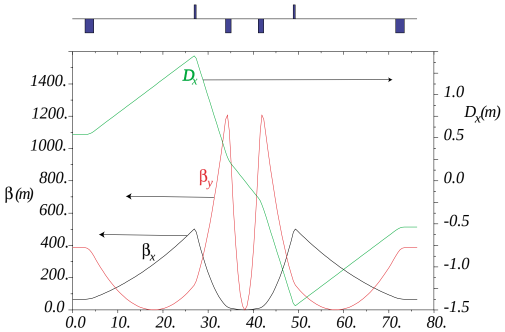

Figure 1, Interaction point optics for β_y^* = 0.01 m.

In order to start the chromaticity correction with sextupoles close to the IR, the dispersion is zero at the IR, however its slope is not. Although a complete tracking study has not been done, the chromaticity correction allows a momentum acceptance of about $\delta p/p \sim \pm 0.9\%$[7].

In addition to these direct limitations on the luminosity, the Transverse Mode Coupling Instability, TMCI, limited the bunch current and thus the luminosity at LEP and would be expected to play a dominant role in the operation of this machine. The single bunch threshold associated with this instability is given by

$$I_{th} = 8 f_s E \,/\, e \sum_i \beta_i k_{\perp,i}(\sigma_s),$$

where f_s, E, β_i, k and e are the synchrotron frequency, injection energy, beta function, loss factor and electron charge. We plan to raise the threshold by injecting at a comparatively high energy, minimizing the loss factors by minimizing the number and complexity of bellows, and using a comparatively large vacuum chamber. We use a chamber with internal dimensions 0.12 m and 0.048 cm to minimize the broadband impedance which should give a threshold for the TMCI instability of 0.2 mA or $9.7 \cdot 10^{11}$ particles/bunch. The injection energy, in part determined by the TMCI threshold, is a comparatively high 45 GeV. It is useful to point out that the injector for this machine could be the basis for a very high luminosity Z factory[7].

The polarization of the beam in this ring would be dominated by a number of processes. The Solokov-Ternov process will polarize the beam and depolarizing resonance will remove this polarization. Except at the highest energies, the self polarization time would be very long, t[h] ~ 6 (185 GeV / E)^3. At high energies, however the energy spread of the beam seems to become comparable with the separation between depolarizing resonances, so the polarization may be quickly lost. This has been calculated[7]. We are continuing to explore these issues.

3 TECHNICAL CHALLENGES

We assume the ring would be a standard racetrack shape with one straight section used for an interaction point and the other used for injection, beam absorbers, rf systems and collimation. The large number of bunches in the ring could produce excessive emittance growth due to parasitic collisions so we assume two rings in the arcs, one above the other, for e^+ and e^-. The beams would be separated by electrostatic separators and septum magnets at the ends[7].

Since particles gain energy in the cavities and lose it in the arcs, the horizontal closed orbit is a function of the position around the ring. The distribution of rf cavities is chosen to smooth out this energy sawtooth.

3.1 Vacuum system

The limitations imposed by the TMCI process require that the wall impedance must be minimized and since a large component of the loss factors are due to the expansion joints, we are considering a “no bake, no bellows” system which would utilize prebaking and welding in-situ, allowing the use of only minimal number of bellows. Since the beam lifetime due to vacuum is τ[h] = $3 \cdot 10^{-8}$ / p_{N2}[torr], a one hour lifetime imposes a pressure requirement on the average pressure in the ring before the first beam is injected and the walls are scrubbed.

The spectrum of synchrotron radiation produced by the beams changes dramatically over the design energy range of the collider ring. At 45 GeV, the critical energy of the photons is 6.5 keV, but at 185 GeV, the critical energy of the photons is 453 keV. At low energies the photons are almost entirely absorbed by the aluminum chamber, but at higher beam energies, the photons penetrate the aluminum chamber. Synchrotron radiation power is absorbed at ~50m intervals, in copper blocks outside the vacuum chamber, after the radiation passes through 1 mm Al windows. This minimizes outgassing in the vacuum region. The majority of the vacuum chamber pumping is done very close to the lumped absorber.

Pumping will be done primarily using ion pumps and NEG located near the lumped absorbers. These will pump the vacuum chamber slowly through the conductance offered by the vacuum chamber and the antichamber. Turbo pumps will be used for rough pumping. A substantial cost saving could be possible by providing common pumps and pumping manifolds for the two rings.

3.2 Magnet system

The dipole gap height of 12 cm requires 2300 A to reach full field. This excitation current is carried by conductors on the inside and outside of the iron lamination. These conductors and the laminations are supported by spacers made of die cast or stamped aluminum as shown in Figure 2.

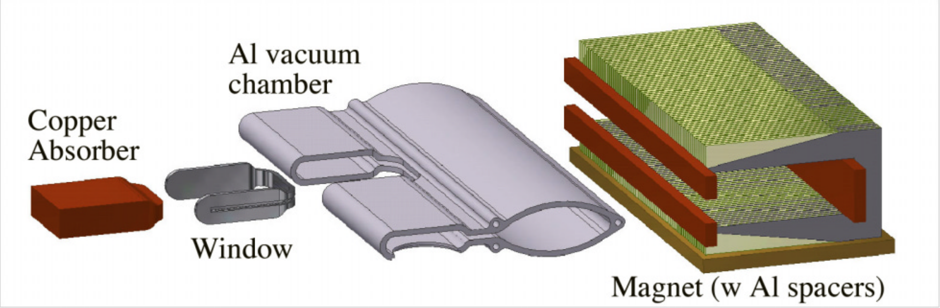

Figure 2, The magnet and vacuum chamber assembly.

The bending magnets required for the arcs will operate at low fields, from 0.0057 T at injection, to 0.0238 T at full field. These low fields make the optics particularly susceptible to external error fields, either due to the earth's 0.00005 T field or the fringe fields from the low field VLHC magnets. Ideally the error fields in accelerator magnets should be on the order of $10^{-3} – 10^{-4}$ times the dipole field. The external fields will be naturally attenuated by two mechanisms: 1) the external structure required to support the comparatively fragile magnet and vacuum chamber assembly can be made from iron, which will shield the magnets inside from external fields, and 2) the yokes of the magnets are a low reluctance path to guide external magnetic fields around rather than through the vacuum chamber.

The most useful material for these magnets is steel with very low carbon content. As the carbon is removed, the hysteresis losses decrease in a nonlinear way, but drop by approximately an order of magnitude from commercial 1010 steel, with 0.10% carbon. The low carbon steel is produced by vacuum annealing, a process which is fairly commonly available and adds only about 10% to the cost of the steel. While the steel becomes somewhat softer, it can be fairly easily worked and stamped.

The magnets, vacuum system and magnet supports would be combined into a single package which could be taken into the tunnel and assembled as a unit.

3.3 RF system

The total voltage of 4.66 GV required to support the electron beams is 33% higher than that of LEP-II. The only way to keep the size of the accelerating structure reasonable is to use superconducting RF technology as was done at LEP. Although sheet metal niobium cavities are capable of delivering very good performance, we propose to use niobium sputtered on copper, developed at CERN. There are several advantages: 1) higher thermal conductivity gives better quench stability, 2) a higher Q factor than bulk Nb, 3) insensitivity to small magnetic fields, and 4) cheaper raw materials.

Cost optimization determines the choice of accelerating gradient, and the frequency choice is determined by the operating temperature and availability of klystrons, which leads to a system like that used in LEP. The parameters of the system are shown in Table II.

Table II rf System Parameters

f_{rf}, MHz	352
V_{rf} total, GV	4.66
E_{acc}, MV/m	8
Cells/cavity	4
Cavities/module	4
k(s), V/pC	4.1(at σ=7.5 mm)
ε_{rf} total, %	58

The effects of beam loading and higher order modes have been studied and have been found to be small. The low synchrotron frequency, 175 Hz, complicates the mechanical design of the cavities, since this begins to be in the range of mechanical cavity resonances.

4 R & D ISSUES

There are a number of open issues which require more effort. It is not clear what the lower limit on β_y or the upper limit on ξ_y or the number of bunches in the ring is. There may be ways of overcoming the TMCI limitations by coalescing bunches at high energies, but this has never been done. Is feedback useful against TMCI? What does an optimized 45 GeV Z^0 factory look like? How can polarization at high energies be optimized? What is the optimum method of pumping the long vacuum chamber sections? How much cost and power minimization is possible in the complete design? These questions will require some continuing study and perhaps experimental work.

5 CONCLUSIONS

We have outlined the primary constraints on the design of a large e^+e^- collider operating in the tunnel of the VLHC. This machine, while a fairly conservative extrapolation of LEP, should be able to operate at higher luminosity if more aggressive values of the beam-beam tune shift and beta functions can be used. We have tried to identify beam physics and technical issues which would be critical in optimizing the performance and cost of this machine.

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