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An ep Collider with E_{cm} = 1 TeV in a VLHC Booster Tunnel

M. Derrick, H. Friedsam, A. Gorski, S. Hanuska, J. Jagger, D. Krakauer,
J. Norem, E. Rotela, S. Sharma, L. Teng, K. Thompson, ANL;
T. Sen, FNAL; E. Chojnacki, Cornell; D. P. Barber, DESY

Abstract

The low field option for the VLHC includes a 3 TeV proton booster with a circumference of 34 km. We are studying the option of an electon ring to fit in this tunnel which can produce ep collisions with a luminosity of 1 fb^{-1}/yr with a center of mass energy of 1 TeV. The machine would utilize superconducting rf and small low field magnets for the ~80 GeV electron beam. We describe the vacuum chamber / magnet system, rf power supply requirements, vacuum chamber cooling, interaction regions and installation of the facility in the tunnel, as well as provide preliminary estimates of beam stability and lifetimes.

1 INTRODUCTION

The present studies for the Very Large Hadron Collider (VLHC) [1] consider both high (10-14 T) and low field (2 T) options for reaching 100 TeV in the center of mass. The low field option includes a 34 km circumference tunnel for a 3 TeV booster. We are considering an 80 GeV electron ring in this tunnel to produce an ep collider which could extend the operating range for ep collisions to $\sqrt{s}$ = 1 TeV. If this machine utilized existing detectors and some of the superconducting cavities available after LEP was decomissioned, the cost could be considerably reduced. This machine could produce physics during the construction of the large VLHC collider ring.

We have assumed that the minimum requirements of such a machine would have: 1) sufficient luminosity to produce 1 fb^{-1}/y, 2) the ability to collide e^+ and e^-, 3) useful polarization, 4) adaquate beam lifetime, 5) detector access to the maximum range of momentum transfer Q^2, and, 6) $\sqrt{s} \sim 1$ TeV. In addition, the priorities of this machine seem to imply operation with or before, rather than after, the LHC.

We have looked at issues which would affect the cost and performance of the machine with the aim of determining its feasibility.

2 BASIC PARAMETERS

The parameters of the machine determined by fixing synchrotron radiation loss, and the β^*'s for the proton beam at the interaction point and limiting the beam beam tune shifts, ξ, for the proton and electron beams, are given in the following table. We have assumed that the proton ring would be the low field VLHC injector described in [2] and the injector chain would be located at Fermilab. In addition we have imposed the condition that the total synchrotron power would be 50 MW, to limit cooling and power requirements.

PARAMETERS

Circumference	33962.13	m
ep Luminosity	$2.6 \cdot 10^{32}$	$cm^{-2}s^{-1}$
Center of Mass energy	1	TeV
Electron energy, E_e	~80	GeV
Proton energy, E_p	3	TeV
Synchrotron radiation Power	50	MW
Electron dipole field	0.009 - 0.6	T
Bunch Spacing	100	ns
Arc Cell length	100	m
Bend Radius	4451	m
β_{max}/β_{min} in cell	171/29	m
$\beta^*_{p,x}/\beta^*_{p,y}$, $\beta^*_{e,x}/\beta^*_{e,y}$	2/0.5, 0.115/0.115	m
$\xi_{e,x}/\xi_{e,y}$, $\xi_{p,x}/\xi_{p,y}$	0.011/0.021, 0.0013/0.0065	
Equilibrium emittance	28	nm-rad
Electron Beam current	55.3	mA
Proton beam current	1	A
electrons/bunch	$3.26 \cdot 10^{10}$	
Energy loss per turn	0.814	GeV
electon rf Voltage	1.09	GV
electron energy spread, σ_E/E	$1.03 \cdot 10^{-3}$	
Proton emittance, $\varepsilon_{RMS,N}$	$3.6 \cdot 10^{-6}$	mm-mr
Expected luminosity lifetime	20	hrs
Sokolov-Ternov polarization time	0.9	hrs

The electron ring contains two 180° arcs connected by 1.8 km long straights. The arc lattice is made of 90° FODO cells with each half-cell consisting of a 46-m long dipole, a 1.5-m long quadrupole and a 2.5-m cell straight section.

The Sokolev-Ternov polarization time for electrons is sufficiently short to produce polarization

The electron ring would be located in the tunnel above the proton ring, and would be installed at the same time.

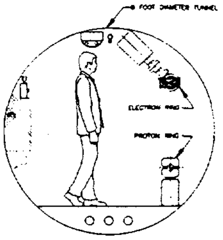

Figure 1, The collider rings in the tunnel.

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2.1 Lattice Design

Our primary design criteria are a low beam energy spread, a low emittance beam to get a small spot size at the IP and a large bending radius to reduce the synchrotron radiation power. The chosen lengths of the FODO cell magnets are shown in Table I. A phase advance of 90^0 is chosen in the horizontal plane to get an equilibrium emittance of 28 nm-rad. The phase advance in the vertical plane will be chosen to minimize the chromaticity burden and ensure sufficient dynamic aperture. We have assumed an emittance coupling ratio of 25 % to equalize the beam sizes of the protons and electrons at the IP.

A preliminary design of the triplets used to focus the electrons to the required spot sizes at the IP suggests that superconducting quadrupoles will be required for the interaction region. The smallest β^* achievable is determined by the available gradients, the distance to the first quadrupole and the maximum value of β in these quadrupoles. In order to ensure a good quantum lifetime, the magnet aperture must be greater than 10σ. With the value of β^* shown in Table I, the first quadrupole may have to be placed as close as 1m and no further than 3m from the IP. The focusing of the protons will start after the two beams are sufficiently separated so that the electrons will not be subject to the fields of the proton magnets. The design could be similar to that of the interaction region in HERA.

2.2 Lifetime

The electron beam lifetime has been calculated with the inclusion of the following effects: i) residual gas scattering with an initial pressure of 10^{-9} Torr together with synchrotron radiation induced desorption assuming a desorption coefficient of $2\text{x}10^{-9}$, ii) e-p bremsstrahlung at the single IP, iii) quantum lifetime assuming a physical acceptance of 10σ in the transverse planes and an RF acceptance of $10\sigma_E$, iv) Touschek scattering. These four effects lead to an electron lifetime of 26hours. Other effects not included such as ion trapping, effects of orbit distortion, larger emittances and energy spread on the quantum lifetime, scattering off thermal photons etc. will reduce the lifetime somewhat from this value.

3 MAGNET / VACUUM CHAMBER

3.1 Vacuum Chamber

The vacuum chamber aperture is determined by requiring 10σ plus 0.2 cm for closed orbit distortion in both horizontal and vertical. We have used an antechamber to increase the pumping conductance along the length of the chamber. The vacuum chamber is made of 6063-T5 aluminum extrusions with the profile shown in Fig. 2 There are 2 channels included to heat the chamber during bake-out with pressurized, hot water. The length of the chamber sections between bellows is limited by the thermal expansion and other effects to about 9 m is used. With a chamber section anchored at the center of a dipole section, both ends of the chamber expand about 2 cm during bake-out. The ends of the chamber sections are connected to 20-cm diameter, stainless steel vacuum flanges with bimetallic transition pieces. The transition pieces on the down stream ends also contain simple water cooled absorbers in the aluminum parts to intercept the synchrotron radiation that would strike the walls and bellows that are located in the sections just beyond the dipole sections.

The vacuum pumps for the ring are 30 l/s ion pumps located at the ends of each dipole section. The conductance of the chamber is sufficient to give pressures $<10^{-9}$ torr at the centers of the chamber sections including the effects of both thermal and photo desorbtion. Provisions are included in the chamber profile to permit the use of NEG strips. This may allow the use of smaller and fewer numbers of ion pumps.

3.2 Dipoles

The electron ring must operate in close proximity to the proton ring, which produces peak fringe fields that are large compared to the field strength in the dipole at injection (90 G). The electron ring, therefore, is located inside at least a single layer, magnetic shield as shown in Fig. 2. The shield also provides the support structure for the ring. The choice of thickness and the number of layers in the shield depend on the separation between the two rings. A single layer of 6-mm thick low carbon steel has been calculated to reduce the fringe field strength to less than about 1 G near the center of the electron dipole when located at a distance of about 2 m from the center of the proton dipole. The core of the electron dipole is stacked from 1.5-mm thick low carbon steel laminations. Each dipole has a water cooled, copper coil consisting of one turn per pole. Cost optimization of the magnet system at a later date may lead to a choice of aluminum conductors. The water cooling is not only required during excitation but also during the bake-out of the vacuum chamber.

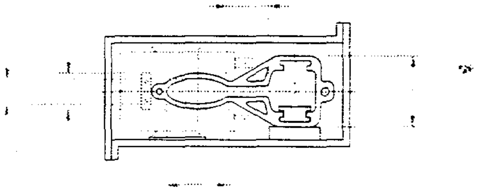

Figure 2. The magnet, vacuum chamber and support.

Each of the 304 lattice dipoles is made up of 5 sections. The sections have effective lengths of 8.96 m with 30-cm spacings. Each dipole section has a 3.5-cm gap height and produces central fields ranging between 0.009 T and 0.0616 T. The conductor size is 1.55 cm by 1.0 cm with a 0.66-cm diameter hole. The peak current through the dipole is 876 A resulting in peak power losses of 4.3 kW per section for a total of 6.6 MW for all the dipoles. Using a single cooling circuit in a section, a water flow of 0.1 l/s is required. This gives a temperature rise of 10°C in the water and a total flow of 160 l/s for the dipoles in the ring.

3.3 Quadrupoles

Each of the 304 lattice quadrupoles has an integrated strength of 1.545 T, a bore radius of 2.5 cm, and cores stacked from 1.5-mm thick low carbon steel laminations.

3.4 Vacuum Chamber Cooling

Most of the radiated synchrotron power is absorbed on the outside radius wall (right inside face in Fig. 2) of the chamber with an imbedded water channel used for cooling. The average power distribution of 1.64 kW/m through the 180° arcs gives 14.7 kW over the length of a chamber section. A water flow of 0.18 l/s gives a 20°C water temperature rise across a cooling channel and a total flow of 552 l/s(8750 gal/min). The heated water would be collected in pipes which would be located underneath the floor and these pipes would discharge into the two injector tunnels and then into the cooling ponds.

4 RF SYSTEM

Superconducting rf is required to obtain high luminosities at high energies, since the losses in normal rf cavities would require reduction in the electron beam current. The available luminosity at high energies is shown in Fig. 3.

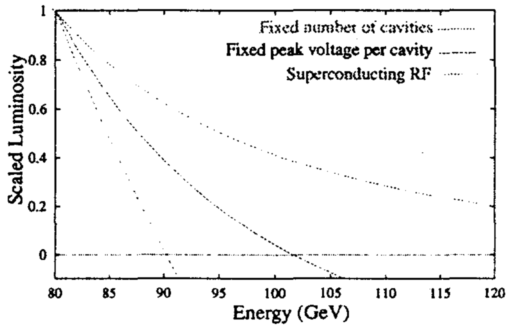

Figure 3, Luminosity for different rf options.

Minimization of number of SRF cryostats is obtained by maximizing RF power per coupler, or the number of cells per cavity. Among promising long-term cures are: 1) geometry chanages to spoil multipactor resonances, 2) high temperature in situ bakable vacuum seals on RF components for high temperature bakes, and 3) in situ RF processing utilizing a variable standing-wave apparatus to scan peak electric field over the coupler region. These improvements should allow delivery of beam power per coupler to levels limited by RF sources and vacuum windows, about 1 MW at 352 MHz.

The use of the LEP rf would require rebunching the protons at injection into the 3 TeV ring. We assume the electrons occupy one bucket in 35 at the LEP frequency (1140 bunches), and proton rf operates at 1/7 of the lepton rf, i.e. ~50.3 Mhz. Proton rebunching should be done adiabatically, initially at 10 Mhz. Rebunching and acceleration would be done at 50.3 MHz, after further bunching this frequency.

6 INJECTOR CHAIN

In addition to the present Fermilab injector, a new e^+ / e^- linac would be required, which would include an accumulator ring for positrons. The present Booster and Main Injector could be used up to energies of 4.5 and 10.5 GeV, respectively, with existing rf. The Booster would require a lattice correction package to adapt the combined function lattice to electrons. Present positron sources produce ~$9 \cdot 10^{10}$ e^+/sec, and the collider requires $3.26 \cdot 10^{13}$ e^+, so e^+ production would take 6 min. An electron injector could look like Figure 4.

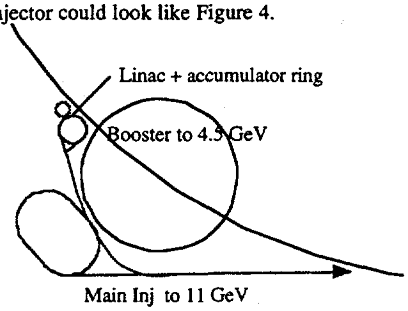

Figure 4. An electron injector chain.

7 DETECTOR

We assume it would be possible to move either the ZEUS or H1 detector from HERA after this machine was decomissioned.

8 CONCLUSIONS

We have done a preliminary study of an ep collider that could be installed in the low field booster of the VLHC. This machine could be operational before the LEP/LHC and would have a higher luminosity than HERA/TESLA.

REFERENCES

1 VLHC
2 L.E.BOOSTER