An Electron-Proton Collider in the TeV Range

M. Tigner, Cornell Univ., Ithaca, NY
B. Wiik, F. Willeke, DESY, Hamburg, FRG

Abstract

In ep colliding beam measurements, approximate equality of electron and quark energies is desirable for good detection efficiency. In the TeV CM energy regime, synchrotron radiation makes this requirement very expensive to meet using a storage ring for the electrons. Here we review a scheme.[1] that ameliorates this problem by using a superconducting linac for electron acceleration. Parameter lists show that such an approach may be practical for the next generation ep collider beyond HERA. An example of a 300 GeV electron beam colliding with the HERA p ring is shown in some detail. Examples up to $\sqrt{s} = 12$ TeV are given.

1 INTRODUCTION

Access to ep physics with ep colliders beyond HERA CM energies will require increase of the beam energy product as well as maintenance of a mainimum ratio of e to p energy to maintain reasonable production angles. Its inherent freedom from synchrotron radiation and its geometric flexibility suggest an electron linac on proton storage ring configuration for future, higher energy, ep colliders. The luminosity needed for useful physics together with the accelerator physics and technology limits to stored proton beam densities and interaction region optics work together to demand linac parameters that can be met only with rf superconductivity technology. A schematic layout of such a facility is shown in Figure 1 in which head-on collision of an electron and proton beam are arranged.

2 LUMINOSITY

As shown below, the achievable luminosity is constrained by the electron beam power, the intrabeam scattering limited emittance of the proton beam and the practical limits to focusing strength at the IP.

Assuming round beams and equal transverse beam sizes for e and p at the crossing point then

$$L = \frac{N_e N_p f_b \gamma_p}{4\pi\epsilon_p \beta^*} \quad (1)$$

where ϵ_p is the normalized proton beam emittance or mean square beam size divided by betatron parameter, N_e, N_p the numbers of electrons and protons per bunch and f_b their collision frequency. γ_p is the proton Lorentz factor.

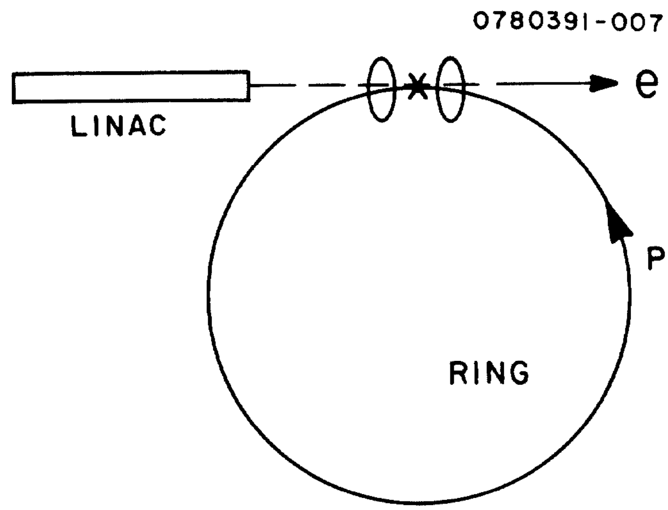

Figure 1: Layout of Linac on Ring e-p Collider

Once the e-beam energy is chosen, then the total electron beam current $I_e = N_e \cdot e \cdot f_b$ is, limited by the allowed electron beam power or $I_e = P_e/E_e$ and from (1), L is independent of N_e and f_b as long as their product is constant. Numerically

$$L = 1.66 \times 10^{31} s^{-1} cm^{-2} N_p/10^{11} \cdot P_e/10^8 \text{watt} \cdot 0.3\text{TeV}/\text{E}_\text{e} \cdot \gamma_\text{p}/1000 \cdot 10^{-6}\text{m}/\epsilon_\text{p} \times 10\text{cm}/\beta^* \quad (2)$$

Table 1 displays some possible examples for future interest.

Table 1

E_p (TeV)	E_e (TeV)	$\sqrt{s}$ (TeV)	L ($10^{32} cm^{-2} s^{-1}$)
1.0	0.10	0.632	1.1
	0.20	0.894	0.56
	0.30	1.200	0.38
8.0	0.30	3.098	3.0
	0.50	4.000	1.75
	1.00	5.657	0.88
20.0	1.00	8.944	2.25
	2.00	12.649	1.13

Luminosities for various proton and electron energies. All have $N_p = 3 \times 10^{11}$, $P_e = 60$MW, $\epsilon_p = 0.8 \times 10^{-6}$m, $\beta^* = 10$cm.

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3 EXAMPLE USING HERA p RING

3.1 Proton Emittance

From (1) it is evident that a small proton emittance is desirable. For the 1 TeV proton beam of our example, the intra beam scattering dilution time of $\epsilon_p = 0.8 \times 10^{-6}$m is 5 hours. In future, this effective luminosity lifetime may be extended by use of bunched beam stochastic cooling.[2] At higher proton energies an even smaller emittance can, in principle, be used. Achievement of bunch intensities in excess of 10^{11} is regularly achieved in high energy proton colliders.[3] Achievement of the low emittances desired may require use of electron cooling in the lower energy stages.[4]Active feedback to damp injection oscillations will also be needed in the higher energy stages.

3.2 Interaction Region Layout

Small β^* are essential for high L. β^* is limited by chromaticity of the proton ring, and by proton bunch length. As chromaticity grows linearly with final focus quadrupole distance from the IP it is necessary to focus e and p simultaneously, thereby minimizing quadrupole distances. At 1 TeV proton energy the bunch length should be 10 cm or longer for adequate intrabeam scattering life time. In addition, avoidance of synchro-betatron excitation of the protons by the electrons requires a head on collision and hence the use of a beam separation technique. The large energy ratio of the beams makes soft magnetic separation a natural choice. Figure 2 shows a component layout and resulting envelope functions that meet the requirements.The e beam is focused by a sc quadrupole triplet and two doublets which give 10 cm β^* and also low β at 25 and 50 m from the IP. At these latter positions strong quadrupoles for the protons are placed which, because of the low electron betas there, have minimal influence on the electrons while effecting a β^* of 10 cm for the protons. A 100 meter long separator magnet acts to merge and separate the beams. This soft, defocusing quadrupole is aligned along the e orbit while the p pass off center and receive a deflection. A small preseparation prevents the first parasitic crossing at 25 m. The separation at the IP is minimized by strong electron focusing there. The average synchrotron power emitted by the e beam due to separation is 180W, half of which passes straight out of the IR through a 30 mm radius beam tube. Quadrupole gradients are 150 T M^{-1}. The exiting electron beam is focused by the beam-beam interaction at the IP as well as the out going lenses. Inclusion of the beam-beam interaction in the linear optics shows that the e beam is still well behaved on its way out. Full separation is achieved at 50 m from the IP.

3.3 Bunch Spacing and Linac Duty Factor

The bunch spacing is constrained by the allowed proton beam-beam tune spread and linac duty factor as long as the beam separation scheme employed permits no parasitic crossings. When the spacing is reduced to twice the separation length it probably cannot be reduced farther without decreasing the per bunch, allowed proton beam-beam parameter ΔQ_p.

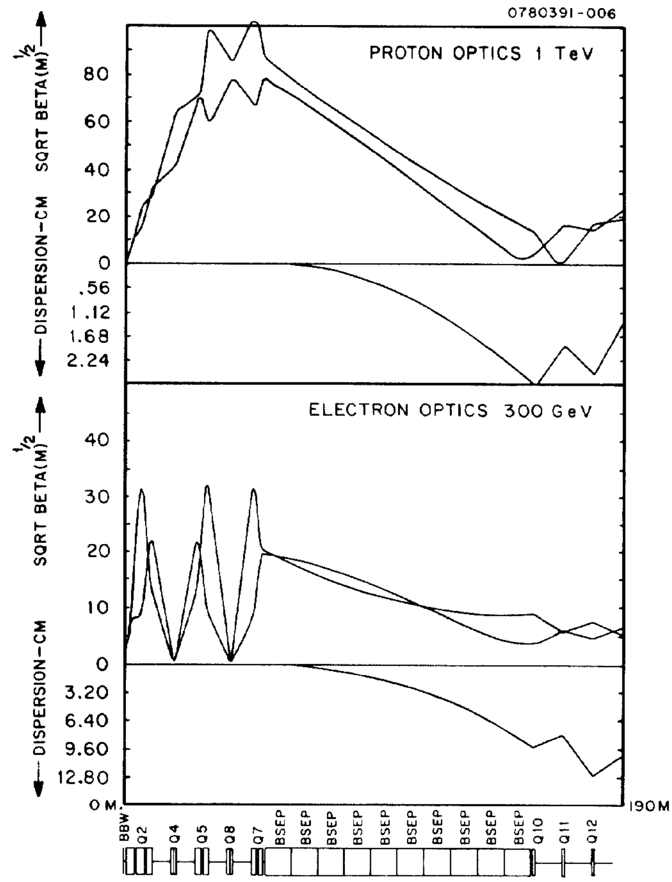

Figure 2: Component Layout and Envelope Functions - 1 TeV p, 0.3 TeV e.

$$\Delta Q_p = \frac{r_p N_e}{2\pi\epsilon_p(1+\kappa)} \quad (3)$$

where r_p is the proton classical radius and κ is the beam aspect ratio at the crossing point which we have taken as 1. Introducing this relation into the electron beam power and current relation, including the linac duty factor, d, we can find the needed bunch spacing, expressed in time units, as

$$t_s = 118ns \cdot \frac{E_e}{0.3\mathrm{TeV}} \cdot \frac{\Delta Q_p}{0.003} \cdot \frac{\epsilon_p}{10^{-6}m} \cdot \frac{d}{0.01} \cdot \frac{10^8 W}{P_e} \quad (4)$$

d is to be selected as the result of an economic optimization balancing refrigerator operating and capital cost against the need for stronger higher mode damping as the bunches are closer together. About 1% appears reasonable.[2]

3.4 The Electron Linac

The requirement for high current subdivided into many bunches spaced relatively far apart with high duty factor in addition can be met only with a superconducting linac. The emittance and current requirements can be met with existing injectors.[5] High current polarized electron guns are also in development for the SLC and should be available in time for this application. Mass produced, multicell accelerating structures now being produced achieve 9 MeV per meter or more with standard chemical processing. Recent improvements in processing by vacuum heating have doubled this figure.[6] It is not unreasonable to expect that (at the present rate of improvement) 25 MeV/m will be available[7] at Q's of 5×10^9 though improved niobium purity and processing techniques. The choice of rf frequency is somewhat arbitrary at this stage. We have chosen 1.5 GHz for our example as a compromize between the beam stability, number of rf feeds and HOM couplers per unit length and low BCS wall losses all of which favor low frequencies, and fabrication lost, small surface area, short filling times and low stored energy which favor high frequency. Table 2 displays the principal parameters of such a linac.

Table 2-Electron Beam Parameters

Electron Energy	$E_e = 300$ GeV
Number of Electrons per bunch	$N_e = 2 \times 10^{10}$
Bunch length	$\sigma_L = 1$ mm
Invariant emmitance	$\epsilon_e = 2.2 \times 10^{-4}$ m
Beta function at IP	$\beta_{x/y} = 0.2$ m
Electron tune shift	$\Delta\nu = 0.3$
Disruption	$D = 0.02$
Bunch spacing	$t_{be} = t_{bp} = 156$ ns
RF frequency	$f = 1500$ MHz
Accelerating gradient	$g = 25$ MV/m
R/Q	R/Q = 10^3 Ohm/m
Unloaded quality factor	$Q_o = 5 \times 10^9$
Loaded quality factor	$Q_L = 1.25 \times 10^6$
Pulse length	$\tau = 1$ ms
Duty cycle	$d = 10^{-2}$
Repetition rate	prr = 10 Hz
Beam Power	$P_b = 60$ MW
Peak RF power	P_{rf} =6GW
Peak klystron power	$P_{klys} = 4$ MW
Static heat leak	$P_s = 17.2$ kW
Resistive wall loss	$P_w = 15$ kW
Higher order mode loss	$P_{HOM} = 17$ kW
Operating temperature	$T = 2$K
Refrigeration efficiency	$\eta = 1000$ W/W

4 Conclusion

As the era of e-p colliders begins we need to begin a search for practical schemes for increasing the available center of mass energies. The use of an SC linac on SC proton ring approach may offer a practical possibility while maintaining a favorable electron to proton beam energy ratio.

References

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