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Interaction Region and Luminosity Limitations for the TESLA/HERA e/p Collider

R. BRINKMANN
DESY, Notkestr.85, D-22603 Hamburg - GERMANY

1. Introduction

The concept of combining a proton storage ring with an electron linac to achieve e/p collisions becomes particularly attractive when a future Linear Collider is constructed close to a laboratory site where a high energy proton ring already exists. In this case, the e/p collider can be realized with comparatively low additional investment. By comparing the linac pulse structure and the available beam power for different Linear Collider approaches [1], it is rather obvious that the superconducting TESLA linac would be by far the best one suited for a linac/ring e/p machine. An additional argument results from the fact that the TESLA cavities are of the standing-wave type so that both linacs of the e^+e^- collider could be used to accelerate an electron beam in the same direction, whereas in conventional accelerating structures (travelling-wave) reversal of the beam direction is impossible. In order to be specific, I will also consider only the HERA-p ring as a possible candidate for the linac/ring collider. The considerations of the tunnel geometry for the planned TESLA Linear Collider at the DESY site [2] take this option into account and foresee the linac starting tangential to the existing HERA ring. It would, of course, be possible to construct the machine in a very similar fashion at Fermilab (using the TEVATRON) or at CERN (using the future LHC ring).

Linac/ring e/p colliders have been discussed by several authors (see e.g. [3, 4, 5]). In the following a somewhat more detailed discussion of the limitations concerning the interaction parameters and luminosity for the TESLA/HERA case will be given.

2. Basic Parameters

The problem of achieving a high luminosity in this type of machine results from the fact that the average bunch collision rate is orders of magnitude smaller than in the HERA ring, because the e-linac has to be operated in a low duty cycle pulsed mode: Whereas the collision frequency at HERA is about 10 MHz, the bunch frequency foreseen for TESLA is only about 5.6 kHz [2]. Going to CW-operation in the TESLA linac would lead to excessive requirements for the cryogenic plant and for the RF- system average power.

With limited electron beam power P_e, a sufficiently high luminosity can only be obtained by improvements in the proton beam phase space density, as can be seen from the general luminosity scaling:

$$L = 0.43 \times 10^{31} cm^{-2} s^{-1} \times \frac{P_e}{E_e} \frac{N_p}{(\epsilon_x \beta_x^\star)^{1/2} (\epsilon_y \beta_y^\star)^{1/2}} \tag{1}$$

where P_e is in MW, E_e in GeV, N_p in 10^{11}, ϵ in 10^{-6} m (normalized one-sigma p-beam emittance) and $\beta^\star$ in m. Furthermore, E_p=820 GeV and matched e- and p-beam sizes are assumed. The p-beam beta-function at the IP is limited by the bunch length σ_z, unless the method of dynamic focus is applied (see below). Assuming $\beta_x^\star = \beta_y^\star = \sigma_z$, and taking the HERA design values $N_p/(\epsilon_x \epsilon_y)^{1/2} = 10^{11}/5 \times 10^{-6}$m, $\sigma_z = 0.3$m we find for E_e=250GeV[1]

$$L = 1.15 \times 10^{28} cm^{-2} s^{-1} \times P_e[MW], \tag{2}$$

so that reaching a luminosity comparable to the present performance of HERA ($L \approx 10^{31} cm^{-2} s^{-1}$) would require an unrealistically high average e-beam power of 1000MW.

The TESLA superconducting linac is designed to operate at an accelerating gradient of 25MV/m. Each of the two linacs of the e^+e^- collider provide a beam energy of 250GeV, so that for operating the machine in the e/p collider mode with E_e=250GeV the gradient can be reduced to 12.5MV/m. Making full use of the installed RF-system power then allows to increase the beam pulse current. At the same time, due to much smaller Lorentz-force detuning and lower external quality factor, very little extra power is required for RF-regulation. Thus an increase of the beam pulse current by a factor of 2.5 compared to e^+e^- operation seems feasible. A summary of the linac parameters in comparison with the TESLA design values is given in Table 1.

Table 1. TESLA linac parameters for the e/p collider in comparison with e^+e^- operation (from ref. [2]).

	TESLA e^+e^-	TESLA e/p
Acc. gradient g [MV/m]	25	12.5
Beam energy E_e [GeV]	2×250	250
Pulse length T_{pulse} [ms]	0.8	1.2
Pulse current I_{pulse} [mA]	8	20
Klystron peak power [MW]	8	8.5
External Q [10^6]	3	0.6
Rep. Rate f_{rep} [Hz]	5	5
Av. Beam power P_e [MW]	2×8	30

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[1] In principle the e-beam energy can be 500 GeV. The lower value is chosen here because according to eq. (2) the luminosity would be higher and the separation of the e- and p-beams in the interaction region is facilitated. With this choice for E_e, the cms-energy of e-p collisions is still increased threefold compared to HERA.

It is conceivable to increase the p-bunch charge with constant or even lower emittance by upgrading the injector complex. The ultimate limitation on the phase space density in the HERA proton ring will then be due to intrabeam scattering (IBS), as discussed in the following.

3. IBS Growth Times

Using the approximation given in ref. [6] the IBS growth rates for different scenarios of increased p-bunch density are estimated. The emittance growth caused by IBS affects mainly the longitudinal and the horizontal plane, whereas in the vertical plane the IBS effect is expected to be much lower and essentially determined by beam optics imperfections (spurious dispersion, betatron-coupling). In this context, using a flat proton beam ($\epsilon_y < \epsilon_x$) seems to be advantageous. This is demonstrated in Figure 1, where the estimated growth time for the horizontal emittance is shown as a function of $(\epsilon_x \epsilon_y)^{-1/2}$, the latter quantity being proportional to the luminosity. A bunch charge of $N_p = 2 \times 10^{11}$ and a bunch length of $\sigma_z = 0.2$m are assumed here. The case with a round beam ($\epsilon_y = \epsilon_x$) has IBS growth times below one hour for a phase space density an order of magnitude or more larger than the present HERA-p value. The flat beam case with $\epsilon_y = 0.1 \times \epsilon_x$ shows much slower IBS-growth (note that the longitudinal IBS growth time, not shown in Figure 1, is roughly comparable to the horizontal one for an energy spread of $\sigma_p/p \approx 2 \times 10^{-4}$). In case a cooling system counteracting IBS in all three planes of phase space is available, a flat beam will naturally evolve (even if the beam is “round” initially). The assumed emittance ratio of 10:1 is a guess at this point, but the preference of a flat beam scenario in general is rather obvious. From the results obtained here one may conclude that with a cooling scheme capable of about 1h cooling time an improvement of the 1^{st} term on the r.h.s. of eq. (2) (essentially determining the achievable luminosity) by a factor of 60 would be possible.

4. Proton Beam Cooling

So far, emittance cooling of proton beams at very high energies has not been achieved. Conventional stochastic cooling of a bunched high-intensity beam is practically ruled out with a bandwidth of the cooling device of the order of 10GHz. In principle a scheme where the beam is de-bunched, cooled and then re-bunched is possible, but that is likely to cause serious problems with preservation of the longitudinal emittance and also leads to a reduction of operation efficiency. The method of optical stochastic cooling [7] allows for orders of magnitude higher bandwidth and could be a very interesting option. Up to now, also this method has not been demonstrated yet in practice. Electron cooling by using a low-emittance storage ring [8, 9] (with $E_e \approx 450$MeV for the case considered here) is another possibility. At this point in time, it is difficult to judge whether the development of sufficiently fast cooling techniques will be possible in the near future. Finally, one could also consider the possibility to re-fill the proton ring at a rate much higher than common practice at HERA (say, once every half hour). The filling and energy ramping times would have to be drastically reduced to make such an operation mode efficient.

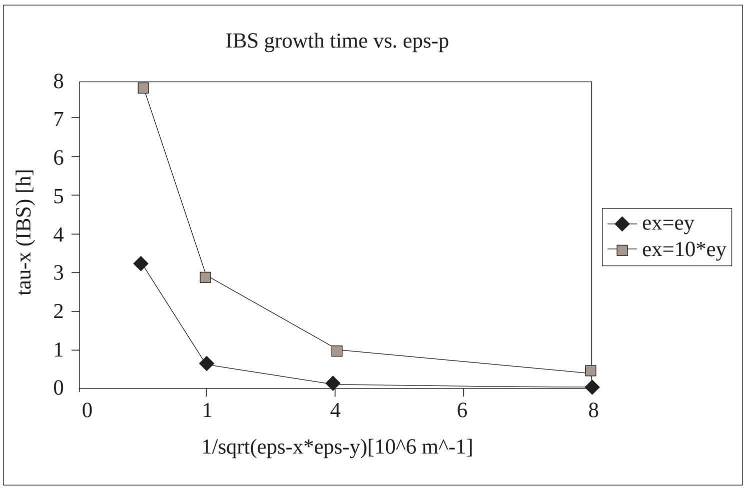

Figure 1. Estimated horizontal IBS growth time as a function of one over the geometric mean of the p-beam transverse emittances.

5. Interaction Region

The above considerations on the luminosity limitations do not involve the specification of parameters such as the bunch spacing in the ring and in the linac, or the electron beam bunch charge. An important aspect in this context is the beam-beam interaction. For proton rings the tune-shift parameter ΔQ is limited to values typically below 0.01 in order to limit the strengths of high-order non-linear resonances which can cause emittance growth. Since the duty cycle of the electron linac is small, so will be the average bunch collision frequency f_{coll} and high-order resonances are unlikely to be a limiting problem for the linac-ring type machine. A more serious problem is related to the fact that the proton bunches interact with "new" electron bunches for each collision and so random fluctuations of the electron bunch parameters (charge, size, orbit) can occur. The p-beam emittance growth caused by these fluctuations can be roughly estimated as

$$\frac{\Delta\epsilon}{\epsilon}/\Delta t \approx f_{coll}(4\pi\Delta Q)^2 \times C \quad \text{with} \quad f_{coll} = f_{rep} \times \frac{T_{pulse}}{T_{rev}} \tag{3}$$

where f_{rep} is the linac repetition frequency, T_{pulse} the e-beam pulse length and T_{rev} the p- ring revolution time. The quantity C scales the relative fluctuation strength (e.g. $C = (\Delta y/\sigma_y)^2$ for orbit fluctuations, $C = 0.5(\Delta N_e/N_e)^2$ for bunch charge fluctuations).

With the TESLA linac parameters given above, $f_{coll} \approx 250$Hz and with typical bunch-to-bunch fluctuations $C \approx (1\%)^2$ (a relatively tight tolerance!) the tune shift parameter must be limited to $\Delta Q \approx 4 \times 10^{-3}$ in order to get an emittance doubling time not smaller than 5h. For flat beams and with $\beta_x^\star = \beta_y^\star$ the tune shift is approximately given by:

$$\Delta Q \approx 2 \times 10^3 \times \frac{N_e[10^{10}]}{\sqrt{\epsilon_x \epsilon_y}[10^{-6}m]} \tag{4}$$

This imposes an upper limit on the electron bunch charge of $N_e < 2 \times 10^{10}$ if we assume a geometric mean proton emittance of 10^{-6} m. The maximum beam pulse current which can be accelerated in the TESLA linac is about 20mA (see above). Thus the bunch spacing should be about $\Delta t_b = 160$ns for $N_e = 2 \times 10^{10}$. In order to match the present RF- system of HERA-p and of the pre-accelerators, we choose $\Delta t_b = 192$ns.

First studies of the beam optics in the interaction region are presented in refs. [4, 10]. The basic concept consists in common focussing elements for both the proton and the electron beam and in separating the beams outside of the low-beta insertion. Whereas this concept provides the minimum possible chromaticity for the p-ring (an important point given the small value of $\beta^\star$ at the IP), it also has to be ensured that beam separation starts before the first parasitic collision point (about 30m from the IP). Further work on the detailed layout of the IR optics, including the latter boundary condition and also aspects concerning the requirements of the detector, is necessary.

So far it has been assumed that the lower limit on $\beta^\star$ is given by the p-beam bunch length. This limitation can be overcome by applying a "dynamic" focusing scheme, where the p-beam waist travels with the e-bunch during collision [10]. This scheme requires a pair of pulsed RF-quadrupoles to be installed on either side of the IR. In principle, the limitation on $\beta^\star$ is then given by the electron bunch length, which can be more than two orders of magnitude smaller than the p-bunch length. However, it is unlikely that such small beta-functions are realistic from the point of view of beam optics. More conservatively, an upgrade of the luminosity by a factor 2 - 4 may be possible.

6. Conclusion

Based on the above discussions, a parameter set for the TESLA/HERA e/p collider is proposed. These parameters can be considered to be realistically achievable under the condition that a cooling system with 2h cooling time becomes available. The luminosity is comparable with the present performance of HERA, at a cms-energy threefold higher. The "dynamic" focussing scheme could provide a further upgrade of the luminosity by about a factor of three. If this scheme is applied to reduce the vertical β-function, it would also help to bring down the vertical tune shift, which is somewhat high in the parameter set considered here.

Table 2. Proposed parameters of the TESLA/HERA e/p collider.

Center-of-mass energy [GeV]	905
p-bunch charge $N_p[10^{11}]$	2
# p-bunches in HERA	110
bunch spacing Δt_b [ns]	192
p-beam norm. emittance $\epsilon_{x,y}[10^{-6}$ m]	2, 0.2
IBS growth time [h]	≈2
p-beam $\beta_{x,y}(=\sigma_z)$ at IP [m]	0.2, 0.2
p-beam energy spread σ_p/p	2×10^{-4}
e-bunch charge $N_e[10^{10}]$	2.5
beam size at IP $\sigma_{x,y}[\mu m]$	21, 6.8
p-beam tune shift ΔQ	0.002, 0.007
Luminosity $[10^{31} cm^{-2} s^{-1}]$	1.3

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