Achievable Luminosities at the THERA and Linac⊗LHC Based ep Colliders: 1. Round Beams

A.K. Çiftçi, E. Recepoglu
Dept. of Physics, Faculty of Sciences, Ankara University, 06100
Tandogan, Ankara, TURKEY

S. Sultansoy
Physics Dept., Faculty of Arts and Sciences, Gazi University, 06500,
Teknikokullar, Ankara, TURKEY
Institute of Physics, Academy of Sciences, H. Cavid Ave. 33, Baku,
AZERBAIJAN

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Different limitations on luminosity of linac-ring type colliders coming from beam dynamics issues are considered for the examples of the ep options of the THERA and Linac⊗LHC proposals. It is shown that \( L = 1.3 \times 10^{31} \) for THERA and \( L = 2.7 \times 10^{32} \) for Linac⊗LHC can be achieved for round beams case. Corresponding sets of parameters are given with the explanations.

I. INTRODUCTION

During the last decades, linac-ring type colliders are widely discussed concerning two purposes:
1. High luminosity particle factories [1],
2. High energy lepton-hadron colliders [2].

In these colliders, there are a number of unsolved problems, because of unconventional structure with respect to well studied ring-ring and linear colliders. There are a number of advantages which make linac-ring choice for ep collider preferable. First of all, this is the most effective way to reach TeV scale in ep collisions. Then, it is possible to construct TeV scale \( \gamma p \) colliders on their base [3]. In addition, linacs provide the possibility to obtain high degree of polarization of electron and positron beams, etc.

Today, the THERA proposal with \( \sqrt{s} \sim 1 \) TeV [4] is the most advanced one among the linac-ring type collider proposals and Linac⊗LHC with \( \sqrt{s} \sim 5 \) TeV [5] should be taken into account as the next step. In this study, we investigate limitations on parameters of the THERA and Linac⊗LHC ep colliders coming from intra-beam scattering (IBS), beam-beam tune shift, Laslett tune shift and beam beam kink instability. At this stage, we consider round beams (both matched and unmatched beam sizes).

II. FUNDAMENTAL LIMITATIONS ON THE LUMINOSITY

There are two most important collider parameters from physicist point of view, namely, center of mass energy and luminosity. In addition, beam polarization, energy spread, collision frequency and luminosity per collision could be important in some cases. Center of mass energy is given by \( \sqrt{s} = 2 \sqrt{E_e E_p} \) for ultrarelativistic colliding particles. The expression for luminosity is

\[
L = \frac{N_e N_p}{2 \pi \sqrt{(\sigma_{xe}^2 + \sigma_{xp}^2)(\sigma_{ye}^2 + \sigma_{yp}^2)}} f_c \tag{1}
\]

where \( N_e \) is number of electrons per bunch, \( N_p \) is number of protons per bunch, \( \sigma_{x,y} \) are horizontal and vertical beam sizes and \( f_c \) is collision frequency. For linac-ring colliders \( f_c = n_b f_{rep} \), where \( n_b \) is the number of electron bunches in pulse and \( f_{rep} \) is the pulse repetition rate. To obtain high luminosity, as far as possible high particle numbers and sufficiently small beam sizes are needed. In addition to this, while determining this parameters, one should consider limitations on them. Main limitations for electron beam and proton beam parameters are explained below.
A. Limitations on the electron beam parameters

1. Beam power

The first restrictive limitation for electron beam is beam power

\[ P_e = N_e E_e n_b f_{rep} \]  

which determines the maximum value of \( N_e f_c \) in Eq. (1). Taking into account the acceleration efficiency accessible value of \( P_e \) is several tens MW.

2. Beam-beam tune shift

The maximum number of electrons per bunch is determined by the beam-beam tune shift limit of the proton beam

\[ \Delta Q_p = \frac{N_p r_p}{2\pi\gamma_p}\frac{\beta_p^*}{\sigma_{xc}(\sigma_{xe} + \sigma_{ye})} \]  

where \( r_p = 1.534 \times 10^{-18} \text{ m} \) is the classical radius of proton, \( \gamma_p \) is the Lorentz factor of proton beam and \( \beta_p^* \) is beta function at collision point. Beam-beam tune shift value generally accepted for protons in case of ring-ring colliders is \( \Delta Q \lesssim 0.003 \). This limit value can be a little bit larger for linac-ring type colliders.

B. Limitation on the proton beam parameters

1. Intra-beam scattering (IBS)

One of the most important limitations comes from intrabeam scattering. IBS growth rates in energy spread, in the horizontal \( \varepsilon_x \) and vertical \( \varepsilon_y \) emittances are defined as following [6]:

\[ \frac{1}{\tau_p} = \left\langle A \frac{\sigma_h^2}{\sigma_p^2} f(a, b, c) \right\rangle \]

\[ \frac{1}{\tau_x} = \left\langle A \left[ f\left(\frac{1}{a}, \frac{b}{a}, \frac{c}{a}\right) + \frac{D_x^2 \sigma_x^2}{\sigma_p^2} f(a, b, c) \right] \right\rangle \]  

\[ \frac{1}{\tau_y} = \left\langle A \left[ f\left(\frac{1}{b}, \frac{a}{b}, \frac{c}{b}\right) + \frac{D_y^2 \sigma_y^2}{\sigma_p^2} f(a, b, c) \right] \right\rangle \]  

where the brackets \( \langle \rangle \) mean that the enclosed quantities, combinations of beam parameters and lattice properties, are averaged around the entire ring. In order to obtain beam size growth times one should multiply obtained values by factor two [6]. Parameters in Eq. (4) are:

\[ A = \frac{\gamma_p^2 c N_p}{64\pi^2 \beta \gamma^4 \varepsilon_x \varepsilon_y \sigma_x \sigma_p} \]

\[ \frac{1}{\sigma^2} = \frac{1}{\sigma_p^2} + \frac{D_x^2 \sigma_x^2}{\sigma_p^2} + \frac{D_y^2 \sigma_y^2}{\sigma_p^2} \]

\[ \sigma_{x,y}^2 = \sigma_{x,y}^2 + D_{x,y}^2 \sigma_p^2 \]  

\[ a = \frac{\sigma_h}{\gamma \sigma_{x,y}}, \quad b = \frac{\sigma_h}{\gamma \sigma_{y,x}}, \quad c = \frac{\sigma_h \beta_v}{\sqrt{2d/r_p}} \]
The function \( f \) is given by:

\[
f(a, b, q) = 8\pi \int_0^1 \left\{ 2\ln \left[ \frac{q}{2} \left( \frac{1}{P} + \frac{1}{Q} \right) \right] - 0.577... \right\} \frac{1 - 3x^2}{PQ} dx
\]

\[
P^2 = a^2 + (1 - a^2)x^2, \quad Q = b^2 + (1 - b^2)x^2
\]

(6)

where \( \sigma_p \) is rms energy spread, \( \sigma_x \) is rms bunch length, \( \varepsilon_x \) and \( \varepsilon_y \) are horizontal and vertical emittances, respectively. Remaining parameters are relative velocity \( \beta \), energy factor \( \gamma \) and velocity of light \( c \). \( D_x \) and \( D_y \) are dispersion functions. Parameter \( d \) represents a cut off for the IBS force, which is taken equal to vertical beam size.

2. Beam-beam kink instability

A relative offset between the heads of the proton and electron bunches causes to a beam-beam force, which deflects electrons. Interaction between deflected electrons and the tail of the proton bunch causes beam-beam kick, which can drive proton beam unstable. A stability criterion under linear approximation is \([7, 8]\),

\[
D_e \Delta Q_p \leq 4\nu_s,
\]

(7)

where \( D_e \) is disruption parameter and \( \nu_s \) is the synchrotron tune of the proton beam.

3. Laslett tune shift

Luminosity of \( ep \) collisions is constrained also by Laslett tune-shift, which leads to upper limit on the ratio \( N_p/\varepsilon_p^N \) at injector stage. For operating proton rings (HERA, Tevatron) and LHC injector systems \( N_p/\varepsilon_p^N \approx 10^{17} \). However, this limit can be overcame by a several methods; namely, higher injection energy in the booster, smaller booster ring, appropriate cooling of the proton beam, etc. For example, increasing of DESY III energy from 50 MeV to 120 MeV can be achieved by moderate expenses \( \sim 10 \) M\$ [9]. It seems quite realistic that \( N_p/\varepsilon_p^N \approx 10^{18} \) can be achieved by using a combination of mentioned methods.

III. THERA

THERA parameters given in TESLA TDR [10] are shown in the first column of Table I. The second column shows how to improve IBS rates for the matched electron and proton beam sizes without changing \( N_p/\varepsilon_p^N \) value. The third column deals with unmatched beam sizes, in which upper limit on luminosity is imposed by beam-beam tune shift and beam beam kink instability. Synchrotron tune for HERA is \( 5.12 \times 10^{-4} \) and we have used this value to estimate upper limit imposed by beam-beam kink instability. The fourth column gives a possible limit on luminosity improvement by changing injector Laslett tune shift limit with various methods mentioned above. In this case, IBS growth time becomes main limiting factor for matched beams, whereas beam-beam kink instability limits the luminosity for unmatched beam case, as seen from the fifth column of the Table I. Table I shows that in the case of matched round beams \( L = 1 \cdot 10^{31} \text{ cm}^{-2}\text{s}^{-1} \) seems realistic for THERA and luminosity \( L = 1.3 \cdot 10^{31} \text{ cm}^{-2}\text{s}^{-1} \) can be achieved for unmatched round beams.

IV. LINAC⊗LHC

In this case, following [5] (see also R. Brinkmann et al. in [2]) we consider TESLA-like accelerator as a "linac". A possible use of CLIC as a "linac" requires separate consideration, because of unmatched bunch spacing for CLIC (\( \sim ns \)) and LHC (\( \sim 25 ns \)). In the first column of Table II we consider LHC parameters designed for \( pp \) collider option, except bunch spacing, which is taken equal to 100 \( ns \) in order to match with TESLA beam structure. It is seen that \( L = 5 \cdot 10^{30} \text{ cm}^{-2}\text{s}^{-1} \) can be achieved. In next two columns LHC beam brightness is taken to be \( N_p/\varepsilon_p^N = 10^{17} \)
We see that $L = 2 \cdot 10^{31} \text{cm}^{-2} \text{s}^{-1}$ can be achieved for matched beam sizes and this value is 1.5 times greater for unmatched case. Main limitation for last case comes from beam-beam tune shift. In difference from THERA where proton beam brightness in the main ring is limited by IBS, Linac⊗LHC allows $N_p/\varepsilon_p^N$ up to $10^{18}$ due to 7 times larger value of $\gamma_p$. In this case, $L = 2(2.7) \cdot 10^{32} \text{cm}^{-2} \text{s}^{-1}$ can be achieved for matched (unmatched) beams.

V. CONCLUSION

It is shown that in the round beam case $L = 1 \cdot 10^{31} \text{cm}^{-2} \text{s}^{-1}$ for THERA and $L = 2 \cdot 10^{32} \text{cm}^{-2} \text{s}^{-1}$ for Linac⊗LHC ep options can be achieved within the reasonable upgrade of proton beam parameters. These values may be essentially larger for flat beam case which will be analyzed in the forthcoming paper.

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| Parameters | TESLA TDR | Upgraded THERA (1) | Upgraded THERA (2) |
|------------|-----------|-------------------|-------------------|
| $E_e$ (GeV) | 250       | 250               | 250               |
| $E_p$ (TeV) | 1         | 1                 | 1                 |
| $N_e$ ($10^{10}$) | 2 | 2                 | 2                 |
| $N_p$ ($10^{11}$) | 1 | 5                 | 9                 |
| Bunch length $\sigma_{se}$ (mm) | 0.3 | 0.3               | 0.3               |
| Bunch length $\sigma_{sp}$ (cm) | 10 | 10                | 10                |
| $\varepsilon_x^e$ ($\mu$m rad) | 92 | 460               | 197.8             |
| $\varepsilon_x^p$ ($\mu$m rad) | 1 | 5                 | 2.15              |
| Beta func. at IP $\beta_{e,y}^*$ (m) | 0.5 | 0.5               | 0.5               |
| Beta func. at IP $\beta_{p,y}^*$ (cm) | 10 | 10                | 10                |
| $\Delta Q_p$ ($10^{-3}$) | 2.44 | 0.49              | 2.94              |
| IBS $\tau_s/\tau_x$ (hour) | 1.9/2.8 | 3.1/23            | 1.35/8.5          |
| Disruption | 0.6       | 0.6               | 1.4               |
| Bunch Spacing (ns) | 211.87 | 211.87            | 211.87            |
| Repetition rate (Hz) | 5 | 5                 | 5                 |
| Number of bunches in e pulse | 5600 | 5600              | 5600              |
| $\Delta Q_p D_{e}/4$ ($10^{-4}$) | 3.75 | 0.75              | 4                 |
| $N_p/\varepsilon_p^*$ ($10^{11}$) | 1 | 1                 | 2.33              |
| $L_{geo}$ ($10^{31}$) ($cm^{-2}s^{-1}$) | 0.48 | 0.48              | 1.1               |
| $L$(inc. Hourglass) ($10^{31}$)($cm^{-2}s^{-1}$) | 0.43 | 0.43              | 1.29              |
| Parameters                                      | Designed LHC | Upgraded LHC (1) | Upgraded LHC (2) |
|------------------------------------------------|--------------|------------------|------------------|
| Parameters matched                             |              | matched          | unmatched        |
| $E_e$ (TeV)                                    | 1            | 1                | 1                |
| $E_p$ (TeV)                                    | 7            | 7                | 7                |
| $N_e$ ($10^{10}$)                              | 0.7          | 0.7              | 0.7              |
| $N_p$ ($10^{11}$)                              | 1.05         | 1                | 8.6              |
| Bunch length $\sigma_{se}$ (mm)                | 1            | 1                | 1                |
| Bunch length $\sigma_{sp}$ (cm)                | 7.5          | 7.5              | 7.5              |
| $\varepsilon_e$ ($\mu$m rad)                  | 46.9         | 12.5             | 3.79             |
| $\varepsilon_p$ ($\mu$m rad)                  | 3.75         | 1                | 0.86             |
| Beta func. at IP $\beta_{c,e,yc}^+$ (m)         | 2            | 2                | 2                |
| Beta func. at IP $\beta_{c,p,yp}^+$ (m)         | 0.1          | 0.1              | 0.1              |
| $\Delta Q_p$ ($10^{-3}$)                       | 0.24         | 0.9              | 2.97             |
| IBS $\tau_p/\tau_x$ (hour)                     | 108/26.3     | 23/15            | 22.9/14.9        |
| Disruption                                     | 0.22         | 0.8              | 0.08             |
| Bunch Spacing (ns)                             | 100          | 100              | 100              |
| Repetition rate (Hz)                           | 10           | 10               | 10               |
| Number of bunches in e pulse                   | 5000         | 5000             | 5000             |
| $\Delta Q_p D_e/4$ ($10^{-4}$)                 | 0.135        | 1.8              | 0.6              |
| $N_p/\varepsilon_p$ ($10^{17}$)                | 0.28         | 1                | 1                |
| $L_{seo}$ ($10^{11}$) ($cm^{-2} s^{-1}$)       | 0.6          | 2.13             | 3.23             |
| $L$(inc. Hourglass) ($10^{11}$) ($cm^{-2} s^{-1}$) | 0.56        | 2                | 3.03             |

TABLE II. Main parameters of an ep collider based on Linac-LHC