MAIN PARAMETERS OF LC⊗FCC BASED ELECTRON-PROTON COLLIDERS

Y. C. Acar∗ and B. B. Oner†

TOBB University of Economics and Technology, Ankara, Turkey

U. Kaya‡

TOBB University of Economics and Technology, Ankara, Turkey and Department of Physics, Faculty of Sciences, Ankara University, Ankara, Turkey

S. Sultansoy§

TOBB University of Economics and Technology, Ankara, Turkey and ANAS Institute of Physics, Baku, Azerbaijan

Abstract

Multi-TeV center of mass energy ep colliders based on the Future Circular Collider (FCC) and linear colliders (LC) are proposed and corresponding luminosity values are estimated. Parameters of upgraded versions of the FCC are determined to optimize luminosity of electron-proton collisions keeping beam-beam effects in mind. It is shown that $L_{ep} \sim 10^{32} \text{cm}^{-2}\text{s}^{-1}$ can be achieved with moderate upgrade of the FCC parameters.

∗Electronic address: ycacar@etu.edu.tr
†Electronic address: boner@etu.edu.tr
‡Electronic address: ukaya@etu.edu.tr
§Electronic address: ssultansoy@etu.edu.tr
I. INTRODUCTION

Our knowledge on deep inside of matter has been essentially provided by means of lepton-hadron collisions. For example, electron scattering on atomic nuclei reveals structure of nucleons in Hofstadter experiment [1]. Moreover, quark parton model was originated from lepton hadron-collisions [2]. Extending the kinematic region by two orders of magnitude both in high $Q^2$ and small $x$, HERA with $\sqrt{s} = 0.32$ TeV has shown its superiority compared to the fixed target experiments and provided parton distribution functions (PDF) for LHC experiments. Unfortunately, the region of sufficiently small $x$ ($< 10^{-6}$) and high $Q^2$ ($\geq 10 GeV^2$), where saturation of parton densities should manifest itself, has not been reached yet. Hopefully, LHeC $\sqrt{s} = 1.3$ TeV will give opportunity to investigate this region.

Construction of linear $e^+e^-$ colliders (or special linacs) and muon colliders tangential to the future circular collider (FCC) as shown in Fig. 1 will give opportunity to achieve multi-TeV center of mass energy in lepton-hadron collisions [4].

![Figure 1: Possible configuration for FCC, linear collider (LC) and muon collider (μC).](image)

FCC is the future 100 TeV center-of-mass energy pp collider proposed at CERN and supported by European Union within the Horizon 2020 Framework Programme for Research and Innovation. Main parameters of the FCC pp option [5] are presented in Table I. The FCC also includes an electron-positron collider option at the same tunnel (TLEP) [6], as well as several ep collider options [7].
Table I: Main parameters of proton beams in FCC.

| Parameter                                           | Value         |
|-----------------------------------------------------|---------------|
| Beam Energy (TeV)                                   | 50            |
| Peak Luminosity ($10^{34} \text{cm}^{-2}\text{s}^{-1}$) | 5.6           |
| Particle per Bunch ($10^{10}$)                      | 10            |
| Norm. Transverse Emittance ($\mu m$)                 | 2.2           |
| $\beta^*$ amplitude function at IP (m)              | 1.1           |
| IP beam size ($\mu m$)                              | 6.8           |
| Bunches per Beam                                    | 10600         |
| Bunch Spacing (ns)                                  | 25            |
| Bunch length (mm)                                   | 80            |
| Beam-beam tune shift                                | $5.6 \times 10^{-3}$ |

Energy recovery linac (ERL) with $E_e = 60\text{GeV}$ is chosen as the main option for LHeC. Same ERL can also be used for FCC based ep collider [7]. Concerning e-ring in the FCC tunnel [7] energy of electrons is limited ($E_e < 200\text{GeV}$) due to large synchrotron radiation. Higher electron energies can be handled only by constructing linear colliders tangential to the FCC. For the first time this approach was proposed for UNK@VLEPP based ep colliders [8]. Then, construction of TESLA tangential to HERA was considered [9]. This line was followed by consideration of the LC@LHC ep collider proposals (see reviews [10, 11] and references therein).

In this paper, we consider main parameters of the LC@FCC based ep colliders. In numerical calculations, we use parameters of ILC (International Linear Collider) [12] and PWFA-LC (Plasma Wake Field Accelerator - Linear Collider) [13]. In Section 2 we estimate $L_{ep}$ taking into account beam-beam tune shift and disruption effects. Finally, recommendations and conclusions are presented in Section 3.

II. LC@FCC BASED ep COLLIDERS

General expression for luminosity of LC@FCC based ep colliders is given by:

$$L_{ep} = \frac{N_e N_p}{4\pi max[\sigma_{xp}, \sigma_{xx}] max[\sigma_{yp}, \sigma_{yy}] min[f_{cp}, f_{ce}]}$$  (1)
where $N_e$ and $N_p$ are numbers of electrons and protons per bunch, respectively; $\sigma_{xp}$ ($\sigma_{xe}$) and $\sigma_{yp}$ ($\sigma_{ye}$) are the horizontal and vertical proton (electron) beam sizes at IP; $f_{ce}$ and $f_{cp}$ are LC and FCC bunch collision frequencies. $f_e$ is expressed by $f_e = N_b f_{rep}$, where $N_b$ denotes number of bunches, $f_{rep}$ means revolution frequency for FCC and pulse frequency for LC. In order to determine collision frequency of ep collider, minimum value should be chosen among electron and proton collision frequencies. Some of these parameters can be rearranged in order to maximize $L_{ep}$, but one should note that there are some main limitations that should be considered. One of these limitations is electron beam power, however only parameters of FCC proton beam is rearranged in this study and only nominal parameters of linear colliders are considered. Therefore, there is no change of electron beam power due to upgrades. Other limitations for linac-ring type ep colliders are due to beam-beam effects. While beam-beam tune shift affects proton beams, disruption has influence on electron beams. Beam-beam tune shift for proton beams is given by:

$$\xi_{xp} = \frac{N_e r_p \beta_p^*}{2\pi \gamma_p \sigma_{xe} (\sigma_{xe} + \sigma_{ye})} \quad (2.1)$$

$$\xi_{yp} = \frac{N_e r_p \beta_p^*}{2\pi \gamma_p \sigma_{ye} (\sigma_{ye} + \sigma_{xe})} \quad (2.2)$$

where $r_p$ is classical radius of proton, $\beta_p^*$ is beta function of proton beam at interaction point (IP), $\gamma_p$ is the Lorentz factor of proton beam. $\sigma_{xe}$ and $\sigma_{ye}$ are horizontal and vertical sizes of electron beam at IP, respectively. Disruption parameter for electron beam is given by:

$$D_{xe} = \frac{2 N_p r_e \sigma_{zp}}{\gamma_e \sigma_{xp} (\sigma_{xp} + \sigma_{yp})} \quad (3.1)$$

$$D_{ye} = \frac{2 N_p r_e \sigma_{zp}}{\gamma_e \sigma_{yp} (\sigma_{yp} + \sigma_{xp})} \quad (3.2)$$

where $r_e$ is classical radius of electron, $\gamma_e$ is the Lorentz factor of electron beam, $\sigma_{xp}$ and $\sigma_{yp}$ are horizontal and vertical proton beam sizes at IP, respectively. $\sigma_{zp}$ is bunch length of proton beam.
Considering ILC⊗FCC and PWFA-LC⊗FCC options, one should note that bunch spacing of electron accelerators are always greater than FCC, while proton beam sizes are always greater than the electron beam sizes at IP. Details and parameters of electron beam accelerators are given in further subsections. In numerical calculations, we use tranversely matched electron and proton beams at IP. Keeping in mind roundness of FCC proton beam, Eqs (1)-(3) turn into;

\[ L_{ep} = \frac{N_e N_p}{4 \pi \sigma_p^2} f_{ce} \]  

\[ \xi_p = \frac{N_e r_p \beta^*_p}{4 \pi \gamma_p \sigma_p^2} \]  

\[ D_e = \frac{N_p r_e \sigma_{ze}}{\gamma_e \sigma_p^2} \]

In order to increase luminosity of ep collisions moderate upgrade of the FCC proton beam parameters have been used. Namely, number of proton per bunch is increased 2.2 times, \( \beta \)-function of proton beam at IP is arranged to be 11 times lower (0.1 m instead of 1.1 m) which corresponds to THERA and LHeC designs. Therefore, IP beam size of proton beam, \( \sigma_p \), is decreased 3.3 times according to the relation \( \sigma_p = \sqrt{\varepsilon_p N_p \beta^*_p / \gamma_p} \). Details of the parameter calculations for ep colliders are given in further subsections.

A. ILC⊗FCC

Main parameters of ILC electron beam are given in Table II [12]. One can see from the table that bunch spacing of ILC is 554 ns which is about 22 times greater than FCC bunch spacing of 25 ns. Therefore, most of the proton bunches coming from FCC ring accelerator would be dissipated unless parameters of FCC is rearranged. For FCC, the parameter \( N_p \) can be increased while number of bunches is decreased regarding the dissipation. Transverse beam size of proton is much greater than transverse beam size of electron for ILC⊗FCC. If beam sizes are matched, this leads \( L_{ep} \) to decrease since luminosity is inversely proportional
to $\sigma_p^2$ as can be seen from Eq. (4). To increase luminosity, upgraded value of $\beta^*_p$ parameter is set to be 0.1 m and therefore $\sigma_p$ to be 2.05 $\mu$m. Calculated values of $L_{ep}$, $D_e$ and $\xi_p$ parameters for ILC×FCC based ep colliders with both nominal and upgraded FCC proton beam cases are given in Table 3. In addition in Table 4, disruption parameter is fixed at the limit value of $D_e = 25$ and corresponding $N_p$ and $L_{ep}$ values are given.

Table II: Main parameters of electron beams in ILC.

| Beam Energy (TeV) | 250 | 500 |
|-------------------|-----|-----|
| Peak Luminosity ($10^{34} \text{cm}^{-2}\text{s}^{-1}$) | 1.47 | 4.90 |
| Particle per Bunch ($10^{10}$) | 2.00 | 1.74 |
| Norm. Horizontal Emittance ($\mu$m) | 10.0 | 10.0 |
| Norm. Vertical Emittance (nm) | 35.0 | 30.0 |
| Horizontal $\beta^*$ amplitude function at IP (mm) | 11.0 | 11.0 |
| Vertical $\beta^*$ amplitude function at IP (mm) | 0.48 | 0.23 |
| Horizontal IP beam size (nm) | 474 | 335 |
| Vertical IP beam size (nm) | 5.90 | 2.70 |
| Bunches per Beam | 1312 | 2450 |
| Repetition Rate (Hz) | 5.00 | 4.00 |
| Beam Power at IP (MW) | 10.5 | 27.2 |
| Bunch Spacing (ns) | 554 | 366 |
| Bunch length (mm) | 0.300 | 0.225 |

Table III: Main parameters of ILC×FCC based ep collider.

| $E_e$(GeV) | $\sqrt{s}$(TeV) | $L_{ep}$ = $10^{30}$ cm$^{-2}$s$^{-1}$ | $D_e$ | $\xi_p$ | $L_{ep}$ = $10^{30}$ cm$^{-2}$s$^{-1}$ | $D_e$ | $\xi_p$ |
|------------|----------------|-------------------------------|-----|-------|-------------------------------|-----|-------|
| 250        | 7.08           | 2.26                          | 1.0 | $1.09 \times 10^{-3}$ | 55.0 | 24   | $1.09 \times 10^{-3}$ |
| 500        | 10.0           | 2.94                          | 0.5 | $9.40 \times 10^{-4}$ | 70.0 | 12   | $9.40 \times 10^{-4}$ |
Table IV: Main parameters of ILC\(\otimes\)FCC based ep collider corresponding to the disruption limit \(D_e = 25\).

| \(E_e\) (GeV) | \(\sqrt{s}\) (TeV) | \(N_p\) \((10^{11})\) | \(L_{ep} = 10^{30}\text{cm}^{-2}\text{s}^{-1}\) | \(\xi_p\) |
|---------------|-------------------|-----------------|------------------|-------|
| 250           | 7.08              | 2.3             | 57               | 1.09 \times 10^{-3} |
| 500           | 10.0              | 4.6             | 149              | 9.40 \times 10^{-4} |

B. PWFA-LC\(\otimes\)FCC

Beam driven plasma wake field technology made a great progress for linear accelerators recently. This method enables an electron beam to obtain high gradients of energy even only propagating through small distances compared to the radio frequency resonance based accelerators \[13\]. In other words, more compact linear accelerators can be built utilizing PWFA to obtain a specified beam energy. In Table V, main electron beam parameters of PWFA-LC accelerator are listed \[13\]. As in ILC\(\otimes\)FCC case, transverse beam size of proton is greater than all PWFA e-beam options. Same upgrade for the proton beam is handled and final values of luminosity, disruption and beam-beam parameters are given in Table VI for both nominal and upgraded FCC proton beam cases. In Table VII, disruption parameter is fixed at the limit value of \(D_e = 25\) and corresponding ep collider parameters are given.
Table V: Main parameters of electron beams in PWFA-LC.

| Beam Energy (TeV) | 125  | 250  | 500  | 1500 | 5000 |
|-------------------|------|------|------|------|------|
| Peak Luminosity ($10^{34} \text{ cm}^{-2}\text{ s}^{-1}$) | 0.94 | 1.25 | 1.88 | 3.76 | 6.27 |
| Particle per Bunch ($10^{10}$) | 1    | 1    | 1    | 1    | 1    |
| Norm. Horizontal Emittance (m) | $1.00 \times 10^{-5}$ | $1.00 \times 10^{-5}$ | $1.00 \times 10^{-5}$ | $1.00 \times 10^{-5}$ | $1.00 \times 10^{-5}$ |
| Norm. Vertical Emittance (m) | $3.50 \times 10^{-8}$ | $3.50 \times 10^{-8}$ | $3.50 \times 10^{-8}$ | $3.50 \times 10^{-8}$ | $3.50 \times 10^{-8}$ |
| Horizontal $\beta^*$ function at IP (m) | $11 \times 10^{-3}$ | $11 \times 10^{-3}$ | $11 \times 10^{-3}$ | $11 \times 10^{-3}$ | $11 \times 10^{-3}$ |
| Vertical $\beta^*$ function at IP (m) | $9.9 \times 10^{-5}$ | $9.9 \times 10^{-5}$ | $9.9 \times 10^{-5}$ | $9.9 \times 10^{-5}$ | $9.9 \times 10^{-5}$ |
| Horizontal IP beam size (m) | $6.71 \times 10^{-7}$ | $4.74 \times 10^{-7}$ | $3.36 \times 10^{-7}$ | $1.94 \times 10^{-7}$ | $1.06 \times 10^{-7}$ |
| Vertical IP beam size (m) | $3.78 \times 10^{-9}$ | $2.67 \times 10^{-9}$ | $1.89 \times 10^{-9}$ | $1.09 \times 10^{-9}$ | $5.98 \times 10^{-10}$ |
| Bunches per Beam | 1    | 1    | 1    | 1    | 1    |
| Repetition Rate (Hz) | 30000 | 20000 | 15000 | 10000 | 5000 |
| Beam Power at IP (MW) | 6    | 8    | 12   | 24   | 40   |
| Bunch Spacing (ns) | $3.33 \times 10^4$ | $5.00 \times 10^4$ | $6.67 \times 10^4$ | $1.00 \times 10^5$ | $2.00 \times 10^5$ |
| Bunch length (m) | $2.00 \times 10^{-5}$ | $2.00 \times 10^{-5}$ | $2.00 \times 10^{-5}$ | $2.00 \times 10^{-5}$ | $2.00 \times 10^{-5}$ |

Table VI: Main parameters of PWFA-LC@FCC based ep collider.

| $E_e (GeV)$ | $\sqrt{s}(TeV)$ | $L_{ep} = 10^{30} \text{ cm}^{-2}\text{ s}^{-1}$ | $D_e$ | $\xi_p$ | $L_{ep} = 10^{30} \text{ cm}^{-2}\text{ s}^{-1}$ | $D_e$ | $\xi_p$ |
|-------------|-----------------|----------------------------------|------|-------|----------------------------------|------|-------|
| 125         | 5.00            | 5.16                             | 2.00 | $5.47 \times 10^{-4}$ | 124   | 48   | $5.47 \times 10^{-4}$ |
| 250         | 7.08            | 3.44                             | 1.00 | $5.47 \times 10^{-4}$ | 82.6  | 24   | $5.47 \times 10^{-4}$ |
| 500         | 10.0            | 2.58                             | 0.50 | $5.47 \times 10^{-4}$ | 61.9  | 12   | $5.47 \times 10^{-4}$ |
| 1500        | 17.3            | 1.72                             | 0.17 | $5.47 \times 10^{-4}$ | 41.3  | 4.0  | $5.47 \times 10^{-4}$ |
| 5000        | 31.6            | 0.86                             | 0.05 | $5.47 \times 10^{-4}$ | 20.8  | 1.2  | $5.47 \times 10^{-4}$ |
Table VII: Main parameters of PWFA-LC⊗FCC based ep collider corresponding to the disruption limit $D_e = 25$.

| $E_e$(GeV) | $\sqrt{s}$(TeV) | $N_p$(10¹¹) | $L_{ep} = 10^{30} cm^{-2} s^{-1}$ | $\xi_p$ | IBS Growth Time (Horizontal) (h) |
|------------|-----------------|-------------|---------------------------------|--------|---------------------------------|
|            |                 |             |                                 |        | $L_c=106.9$ m | $L_c=203.0$ m |
| 125        | 5.00            | 1.15        | 65.0                            | $5.47 \times 10^{-4}$ | 721    | 149 |
| 250        | 7.08            | 2.30        | 86.0                            | $5.47 \times 10^{-4}$ | 360    | 75.0 |
| 500        | 10.0            | 4.60        | 129                             | $5.47 \times 10^{-4}$ | 180    | 37.0 |
| 1500       | 17.3            | 13.8        | 258                             | $5.47 \times 10^{-4}$ | 60.0   | 12.0 |
| 5000       | 31.6            | 45.8        | 433                             | $5.47 \times 10^{-4}$ | 18.0   | 3.90 |

As one can see from the third column of the Table VII number of protons in bunches are huge in options corresponding to the highest energy electron beams, therefore one may wonder about IBS growth times. For this reason we estimate horizontal IBS growth times using Wei formula [14]. Obtained results are presented in the last two columns of the Table VII. In numerical calculations we used FODO cell lengths values $L_c=106.9$ m (same as LHC) and $L_c=203.0$ m considered in [15]. It is seen that IBS growth times are acceptable even for $E_e = 5000$ GeV case.

III. CONCLUSIONS

In this study it is shown that for ILC⊗FCC and PWFA-LC⊗FCC based ep colliders luminosity values up to $L_{ep} \sim 10^{32} cm^{-2} s^{-1}$ are achievable with moderate upgrade of the FCC proton beam. Even with these luminosity values BSM search potential of ep colliders essentially exceeds that of corresponding linear colliders and is comparable with search potential of the FCC pp option for a lot of BSM phenomena. In principle, “dynamic focusing” scheme [16], which was proposed for THERA, could provide $L_{ep} \sim 10^{33} cm^{-2} s^{-1}$ for all ep collider options considered in this study. Concerning ILC⊗FCC based ep colliders, a new scheme for energy recovery proposed for higher-energy LHeC (see Section 7.1.5 in [3]) may give an opportunity to increase luminosity by an additional one or two orders, resulting in $L_{ep}$ exceeding $10^{34} cm^{-2} s^{-1}$. Unfortunately, this scheme can not be applied at PWFA-LC⊗FCC. Acceleration of ion beams at the FCC [15] will give opportunity to provide multi-TeV center
of mass energy in electron-nucleus collisions. In addition, electron beam can be converted to high energy photon beam using Compton back-scattering of laser photons (see [17] and references therein) which will give opportunity to construct LC⊗FCC based γp and γA colliders (see [18] and references therein).

In conclusion, construction of ILC and PWFA-LC tangential to the FCC will essentially enlarge the physics search potential for both SM and BSM phenomena. Therefore, systematic study of accelerator and detector, as well as physics search potential, issues of LC⊗FCC based lepton-hadron and photon-hadron colliders are essential to foreseen the future of high energy physics.

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