# LUMINOSITY UPGRADE OF CLIC-LHC EP/γP COLLIDER*

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*Abstract*

An energy frontier or QCD Explorer ep and γp collider can be realized by colliding high-energy photons generated by Compton backscattered off a CLIC electron beam, at either 75 GeV or 1.5 TeV, with protons or ions stored in the LHC. In this study we discuss a performance optimization of this type of collider by tailoring the parameters of both CLIC and LHC. An estimate of the ultimately achievable luminosity is given.

## INTRODUCTION

Combination of a linear accelerator project, namely CLIC (Compact Linear Collider) with the LHC (Large Hadron Collider) offers an opportunity to build a linac-ring type ep collider. The ultimate energy-frontier ep and γp collider would employ a full 1.5 TeV CLIC linac colliding with the LHC. CLIC-1 comprises a single drive-beam unit which can accelerate the main beam to 75 GeV. The CLIC-1 x LHC based ep/γp collider is called QCD Explorer [1].

One advantage of a linac-ring type collider compared with a ring-ring type collider is the possibility of operating it as γp collider [2,3]. The physics potential of γp colliders has been discussed in references [1,2,3,4].

## LUMINOSITY

The luminosity for an electron-proton collider is

$$L = \frac{f_{call}}{2\pi}\frac{n_e n_p}{\sigma_e^2+\sigma_p^2} \quad (1)$$

where $n_e$ and $n_p$ are the number of particle in an electron bunch and proton bunch, $\sigma_e$ and $\sigma_p$ are the beam sizes of electron beam and proton beam at the interaction point, and $f_{coll}$ is the collision frequency.

In the proposed γp colliders, high energy photons are produced by Compton backscattering of an intense laser off the electrons provided by the linear accelerator. The dimensionless parameter characterizing Compton cross section is given by

$$x = \frac{4E_b\omega_0}{m_e^2}\cos^2(\frac{\alpha_0}{2}) \quad (2)$$

where $\alpha_0$ denotes the collision angle between laser beam and electron beam, $\omega_0$ the energy of a laser photon and $E_b$ the initial energy of electrons. In the case of head on collision and with practical units $x$=15.3$E_b[TeV]\omega_0[eV]$. The maximum energy of backscattered photons is

$$\omega_{\max} = E_b\frac{x}{x+1} \quad (3)$$

The energy of backscattered photons increases and the photon spectra become harder with increasing value of the parameter x, but if x is larger than 4.8, high energy photons can be lost due to $e^+e^-$ pair creation in collision with unscattered laser photons. Thus, x parameter should be lower than 4.8. For the optimum value of x parameter, the maximum energy of the backscattered photons is $\omega_{max}$=0.83$E_b$ [5,6,7,8,9]. The differential luminosity of γp collisions is [4,10]

$$\frac{dL_{\gamma p}}{d\omega} = \frac{f(\omega)0.65n_e n_p f_\gamma}{2\pi\left(\sigma_e{}^2+\sigma_p{}^2\right)}\exp\left[\frac{-z^2\theta_\gamma(\omega)^2}{2\left(\sigma_e{}^2+\sigma_p{}^2\right)}\right] \quad (4)$$

where $\omega$ is the energy of the high energy photons, z is the distance between the conversion point (CP) and the interaction point (IR), $\theta_\gamma(\omega)$ is the angle between high energy photons and electron beam direction. This angle is expressed as (for small $\theta_\gamma$)

$$\theta_\gamma(\omega) = \frac{m_e}{E_e}\sqrt{\frac{E_e x}{\omega}-(x+1)} \quad (5)$$

where $x = 4E_e\omega_0/m_e{}^2$ and $\omega$ is the laser photon energy. In Eq. (3), $f(\omega)$ is the normalized differential Compton cross section. The factor of 0.65 stems from the maximum value of the electron-to-photon conversion coefficient. The total γp collision luminosity is

$$L_{\gamma p} = \int_0^{\omega_{\max}}\frac{dL_{\gamma p}}{d\omega}d\omega \quad (6)$$

Making a change of variable in Eq. (4) and introducing the γp invariant mass

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$$W_{\gamma p} = 2\sqrt{\omega E_p} \quad (7)$$

with $E_p$ denoting the proton beam energy, the γp differential luminosity can be rewritten as [11]

$$\frac{dL_{\gamma p}}{dW_{\gamma p}} = \frac{W_{\gamma p}}{2E_p} \frac{f\left(\frac{W_{\gamma p}^2}{4E_p}\right) 0.65 n_e n_p f_\gamma}{2\pi\left(\sigma_e^2 + \sigma_p^2\right)} \exp\left[\frac{-z^2\theta_\gamma \left(\frac{W_{\gamma p}^2}{4E_p}\right)^2}{2\left(\sigma_e^2 + \sigma_p^2\right)}\right] \quad (8)$$

The bunch structure of CLIC does not well match with the nominal bunch structure of the LHC. The mismatch in bunch spacing limits the achievable luminosity of ep and γp colliders. To remedy it partially, a 15-GHz CLIC option (CLIC-15) was proposed in reference [4]. Two methods can be applied to increase the luminosity of CLIC-LHC. The first one consists in changing the bunch structure of the LHC. The LHC bunch spacing would be reduced to half of the value which was proposed in ref 4. The reduction of bunch spacing is complicated by the electron-cloud effect expected for protons in the LHC. This upgrade leads to two times higher luminosity approximately.

The proton beam and electron beam parameters are given in Table 1, which shows CLIC parameters for 75 GeV and 1.5 TeV for an original 15 GHz rf frequency option ("CLIC-15") and for a 12 GHz option derived from revised CLIC parameters ("CLIC-12"). The proton-beam parameters for a decreased LHC bunch spacing are listed in parentheses.

The second method of raising the luminosity is using tuneable FFS (final focusing system) of CLIC which leads to a traveling IP waist position by changing the quadrupole strengths in the final focus system. Considering 72 cm interaction length, one proton bunch collides with 9 electron bunches of CLIC-15. In case of CLIC-12 option 6 collisions occur in 36 cm interaction length. If the tuneable FFS is used, all collisions would occur at the electron beam waist. By thismethod a significant increase can be achieved.

Figure 1 shows the projection of γp collision at conversion region and interaction region. All collisions occur at the electron beam waist thanks to the varying quadrupole strengths in the electron final focus system. High energy photons are produced at a distance z from interaction region.

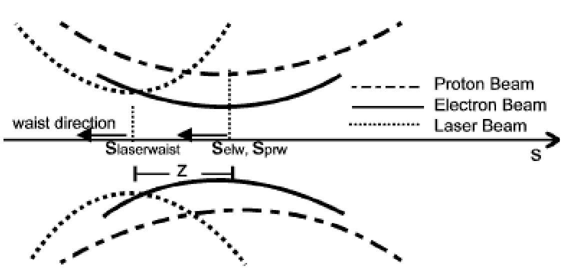


Figure 1: Projection of γp collision.

Table 1: Parameters of 75 GeV and 1.5 TeV for CLIC-15 (15GHz), CLIC(12 GHz) e-beam and LHC p-beam.

| Parameter | Electrons | Protons |
|---|---|---|
| Beam energy Eb (GeV) | 75 /1500 | 7 TeV |
| bunch population Nb 109 | 0.512 (0.278)** | 17 |
| Rms bunch length σz (Gaussian) | 31 μm | 37.8mm |
| bunch spacing Lsep (ns) | 0.534 (0.417)** | 5 (2.5)* |
| Number of bunches nb | 220 (146)** | 12 (24)* |
| IP beta function $\beta^*_{x,y}$ (m) | 0.003 | 0.25 |
| IP spot size $\sigma_{x,y}$ (μm) | 1 /0.3 | 11 |
| Rms emittances $\gamma\varepsilon_{x,y}$ (μm) | 73 | 3.75 |
| Repetition rate fcoll (Hz) | 450 (243)** | |
| Full interaction length *l* (cm) | 72 (36)** | |
| Distance between IP CP *z* | 5 cm | |
| $L_{\square p}$ (z = 5 cm, $\lambda_e\lambda_0$=-1) ($cm^{-2}s^{-1}$) | $7.5\ 10^{29}$ | |
| $L_{\square p}$ (z = 5 cm, $\lambda_e\lambda_0$=-1)* ($cm^{-2}s^{-1}$) | $4.9\ 10^{30}$ | |
| $L_{\square p}$(z = 5 cm, $\lambda_e\lambda_0$=-1)** ($cm^{-2}s^{-1}$) | $1.3\ 10^{30}$ | |
| $L_{ep}$* ($cm^{-2}s^{-1}$) | $7.8\ 10^{30}$ | |
| $L_{ep}$** ($cm^{-2}s^{-1}$) | $2.1\ 10^{30}$ | |
| $L_{ep}$ ($cm^{-2}s^{-1}$) | $1.2\ 10^{30}$ | |

*upgrade parameter
** 12 GHz CLIC parameter

The luminosity values for the 12 GHz and 15 GHz options shown in Table 1 are calculated for the upgraded LHC. The luminosity values of 1.5 TeV CLIC based colliders are approximately the same as for the 75 GeV option.

Figure 2 and 3 show the differential luminosity spectra of γp collider based 75 GeV CLIC-LHC and γp collider based 1.5 TeV CLIC-LHC, respectively.

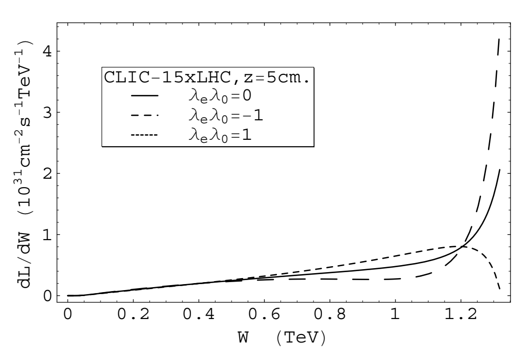


Figure 2: Differential luminosity of QCD Explorer based γp collider vs. centre of mass energy.

 

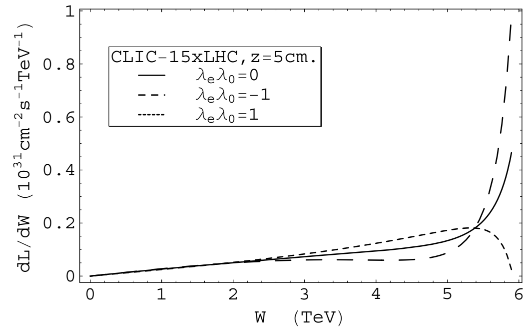


Figure 3: Differential luminosity of Energy Frontier based γp collider vs. centre of mass energy.

The variation of the total luminosity with the distance between conversion point and interaction point of QCD Explorer based γp colliders for two different options is presented in Figures 4 and 5.

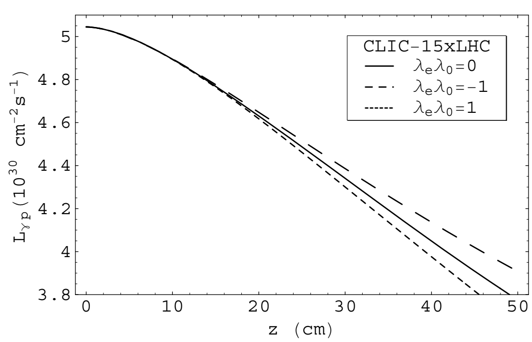


Figure 4: Total luminosity of CLIC-15 (15 GHz) based QCD Explorer (75 GeV CLIC electron beam) vs. the distance between interaction point and conversion point z.

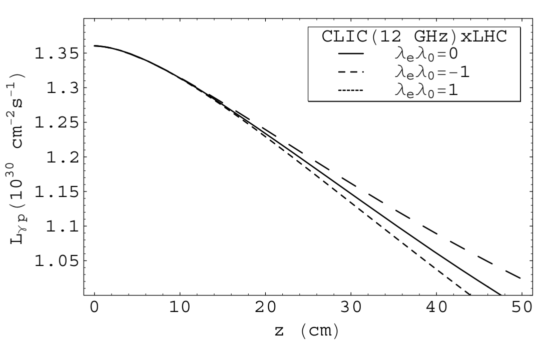


Figure 5: Total luminosity of CLIC (12 GHz-75 GeV) based QCD Explorer vs. the distance between interaction point and conversion point z.

## CONCLUSION

Two different solutions were proposed to increase the Luminosity of CLIC-LHC based ep and γp colliders. Changing of the bunch spacing of LHC and using tuneable FFS, the luminosity value of γp collider is increased from $7.5\text{x}10^{29}$ cm$^{-2}$s$^{-1}$ to 5 $10^{30}$ cm$^{-2}$s$^{-1}$. Also, ep luminosity can be increased up to 7.8 $10^{30}$. Thus, a seven times higher luminosity value can be achieved for the QCD Explorer and the Energy Frontier based γp and ep colliders by using TFFS and by changing the LHC proton beam bunch spacing. For the 12 GHz option of CLIC, the luminosity value of ep collider is a more moderate $2.1\text{x}10^{30}$ cm$^{-2}$s$^{-1}$ and the luminosity achievable in the γp collider mode is $1.3\text{x}10^{30}$ cm$^{-2}$s$^{-1}$.

This type of collider offer crucial advantages for exploring both Standard Model (SM) particles and the physics beyond the SM.

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