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$E_{\rm cm} = 500$ GeV CLIC $\gamma\gamma$ collider based on its drive Beam FEL

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Abstract

CLIC is a linear e^+e^- collider project which employs a drive beam to accelerate the main beam. Various portions of the drive beam provide RF power for corresponding units of the main linac through energy extracting RF structures. CLIC can operate over a wide range of center-of-mass energies, from 150 GeV to 3 TeV. In addition to e^+e^- collider, $\gamma\gamma$ and γe colliders based on CLIC can be realized. In order to generate high energy photons, a Free electron laser (FEL) produced from the CLIC drive beam linac can be used. In this paper we show that the CLIC drive beam parameters satisfy the requirements of the FEL mode of operation.

Key Words: CLIC, $\gamma\gamma$ collider, FEL.

1. Introduction

The idea of a $\gamma\gamma$ collider was proposed in the early 1980's [1]. It is well known that due to rigorous synchrotron-radiation limitations in storage rings, future e^+e^- colliders in the TeV energy region must be linear. Unlike storage rings, in linear colliders each bunch is used only once. This renders possible the use of electrons for the production of high-energy photons in order to obtain colliding $\gamma\gamma$ and γe beams. The high-energy gamma beam is produced by Compton backscattering of a laser beam off the electron beam. At the same time, it was suggested that a free-electron laser (FEL) could be used as the photon source of the $\gamma\gamma$ collider [2, 3].

There are two problems associated with $\gamma\gamma$ collider utilizing conventional lasers. One is the requirement of high peak power for optimum electron γ conversion efficiency. Another problem is the requirement of high repetition frequency. The repetition frequency and the peak power of the gamma beam can be adjusted with a FEL.

FEL is an attractive option to reduce the cost of the laser system for $\gamma\gamma$ collider [3, 4, 5]. In 1994, R. Corsini and A. Mikhailichenko [6] proposed the use of single drive-beam bunches in a free-electron laser for a $\gamma\gamma$ collider based on an earlier version of CLIC. The present paper extends this earlier work by considering the use of a MOPA (Master Oscillator Power Amplifier) FEL in a $\gamma\gamma$ collider for updated CLIC parameters, which greatly differ from those in 1994, and in particular imply low-charge bunch trains for the main beam. In this design, the radiation from a master laser is amplified in a FEL amplifier with tapered wiggler, and a solid-state laser serves as master laser. The brightness of FEL is limited only by diffraction [7]. Several physics opportunities for γe and $\gamma\gamma$ collisions at photon linear collider are listed in reference [8] and some examples are also described in reference [9].

2. Kinematic background

In this section, the kinematics of the laser and electron beam interactions is discussed. All the relations considered here are the same for both a conventional laser and FEL. The conversion of the FEL radiation to a high-energy γ beam at the conversion point, can be characterized by the dimensionless parameter x [1]:

$$x = \frac{4E_\mathrm{b}\omega_0}{m^2}\cos^2\frac{\alpha}{2} \tag{1}$$

where m and E_b are the electron rest mass and beam energy, respectively, and ω_0 denotes the laser photon energy and α is the angle between the FEL and the main-linac bunches. Crab crossing is considered for Interaction point and the crab angle is taken to be 15 mrad. The maximum energy of the backscattered photons, $\omega_{\max} = xE_\mathrm{b}/(x+1)$, grows with the parameter x, but the backscattered photons can be lost for $x > 4.8$ due to $\mathrm{e}^+\mathrm{e}^-$ pair creation in collisions of the produced photons with un-scattered FEL photons (Breit-Wheeler process). Thus, the optimum value for x is 4.8, translating to a maximum photon energy $\omega_{\max} = 0.81E_\mathrm{b}$.

The requirement of the peak power increases considerably for $n_\gamma > 0.65$. Therefore, the convenient value of conversion efficiency is 0.65. The conversion efficiency for generation of high energy photons per individual electron is formulated in reference [8]. Conversion efficiency is obtained as a function of P and Z_R, and it is illustrated in Figure 1. The required laser power and Z_R can also be inferred from Figure 1 [10].

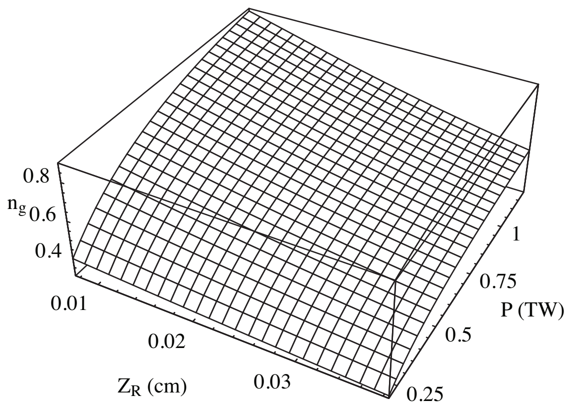

Figure 1. Conversion efficiency vs Z_R and peak power at $A = 2$ J

Full expression for the normalized energy spectrum of the high energy photons after conversion ($f(\omega) = \frac{1}{\sigma_c}\frac{d\sigma_c}{d\omega}$) is expressed in references [11, 12, 13, 14], where σ_c is Compton cross section. The spectrum depends on parameter x, electron (λ_e) and laser (λ_0) helicities. By varying the polarization of the main-beam electrons and the FEL photons, the polarization of the high-energy gamma beam can be tailored to fit the needs of the gamma-gamma collision experiments. Controlling the polarization is also important for sharpening the spectral peak in the $\gamma\gamma$ luminosity. Due to the dependence of the Compton scattering on the polarization, the peak in the luminosity spectrum is significantly enhanced by choosing opposite sign helicity for the laser photons and the electrons [1, 8, 12, 13]. An attractive feature of the FEL is circularly polarized output radiation which can be produced from a helical wiggler [4, 5, 15].

At the conversion point (CP), the density of FEL photons can lead to to a multiphoton processes. The associated nonlinear effects are described by the parameter ξ. If $\xi^2 \ll 1$, a single electron interaction with a single laser photon can lead to pure Compton scattering. Otherwise, multiphoton processes become dominant and the maximum photon energy decreases. This condition is fulfilled with the value shown in Table 1. ξ imposes a lower limit on the Rayleigh length (Z_R) and changes dimensionless parameter x by way of $x \to x/(1+\xi^2)$ [11].

3. Luminosity

CAIN 2.35 simulation code has been used to calculate spectral luminosity [16] using the electron parameters shown in Table 1. The luminosity spectra for different helicity states of FEL and e-beams are shown in Figure 2, where $W_{\gamma\gamma} = 2\sqrt{\omega_1\omega_2}$ denotes the center of mass energy of the colliding high energy photons. The figure shows the spectra without increment method. As can be seen from Figure 2, improved Luminosity spectrum is obtained in the case of opposite helicity states.

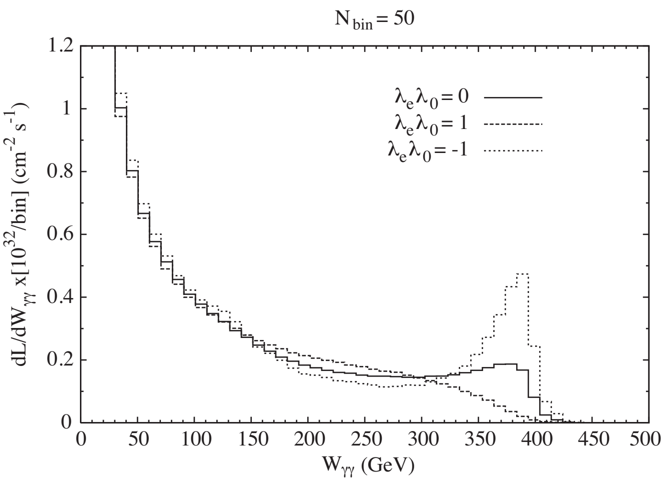

Figure 2. CLIC $\gamma\gamma$ Luminosity spectra at $E_{cm} = 0.5$ TeV for different helicity states of electron (λ_e) and FEL photons (λ_0).

4. FEL System for Proposed $\gamma\gamma$ Collider

4.1. CLIC main linac and drive linac

The CLIC drive beam complex consists of 2 combiner rings (CR) and a delay loop [17, 18]. Two CR compresses the drive beam 3 and 4 times, respectively, and the delay loop compresses the drive beam 2 twice. Initial bunch separation of 2 ns ($24 \times 24 \times 121$ bunches for $E_{\mathrm{cm}} = 3$ TeV, 139 μs total length) can be reduced to 0.5 ns with the 2$^{\mathrm{nd}}$ CR.

The time structure of the FEL pulses should be same with the time structure of the e-bunches of the main linac. Therefore, drive linac e-beam, which produces FEL, should be modified to synchronize with main linac e-beam. In order to get the same time structure, it is necessary to use additional drive beam bunches from the drive linac gun. In that case, it is needed to use the bunches after the 2$^{\mathrm{nd}}$ CR without using first CR and delay loop. Therefore, both drive beam and main beam will have the same bunch separation (0.5 ns). The number of the main beam bunches per pulse is 312 and the number of drive beam bunches per sub-pulse (train) is 121 [19, 20].

If we take 3 more sub-pulses (short train) from the drive linac gun for each main linac section, we will obtain 363×2 additional bunches, at 0.5 ns. These additional bunches can be used in the wigglers. Before the wigglers, 51 bunches from each short train should be dumped to match the bunches. In this way, the number of the drive beam bunches are taken after the 2$^{\mathrm{nd}}$ CR can be decreased to 312. To obtain high peak power FEL, high beam peak current is needed. For this aim, before the 2$^{\mathrm{nd}}$ CR an additional bunch compressor can be used to compress drive beam 4 times which will increase peak current from 1 kA to 4 kA. The Wiggler can be installed parallel to final focusing system of main linac. A schematic view of the $\gamma\gamma$ collider is shown in Figure 3.

4.2. Luminosity increment method

CLIC at E_{cm}=3 TeV contains 24 drive beam decelerator units for each main linac section, however the $E_{\mathrm{cm}} = 0.5$ TeV option has only 4 decelerator units for each main linac section. In that case, the drive beam pulse length is reduced by a factor of 6. To increase the luminosity, 6×312 main beam bunches can be accelerated by using the full drive beam pulse length (139 μs). Consequently, the repetition frequency of the main linac increases by a factor of 6. CLIC main linac beam parameters are given in Table 1, where proposed modification of the repetition rate and corresponding luminosity are shown in parentheses. In the case of luminosity increment method we need a kicker after the second combiner ring which is faster than the E_{cm}=3 TeV option. Related drive beam parameters are given in Table 2.

4.3. FEL Amplifier and Master Laser

The laser power and Rayleigh length values ($P = 0.78$ TW and $Z_{\mathrm{R}} = 0.2$ mm) are chosen from Figure 1. The proposed photon beam generation scheme is a high-gain single pass FEL amplifier with a helical tapered wiggler. The interaction between the electrons and master laser leads to an exponential growth of the FEL power. First of all, the wiggler must satisfy the resonance condition [4]:

$$\lambda = \frac{\lambda_{\mathrm{w}}}{2\gamma_{\mathrm{e}}^2}(1 + K^2), \tag{2}$$

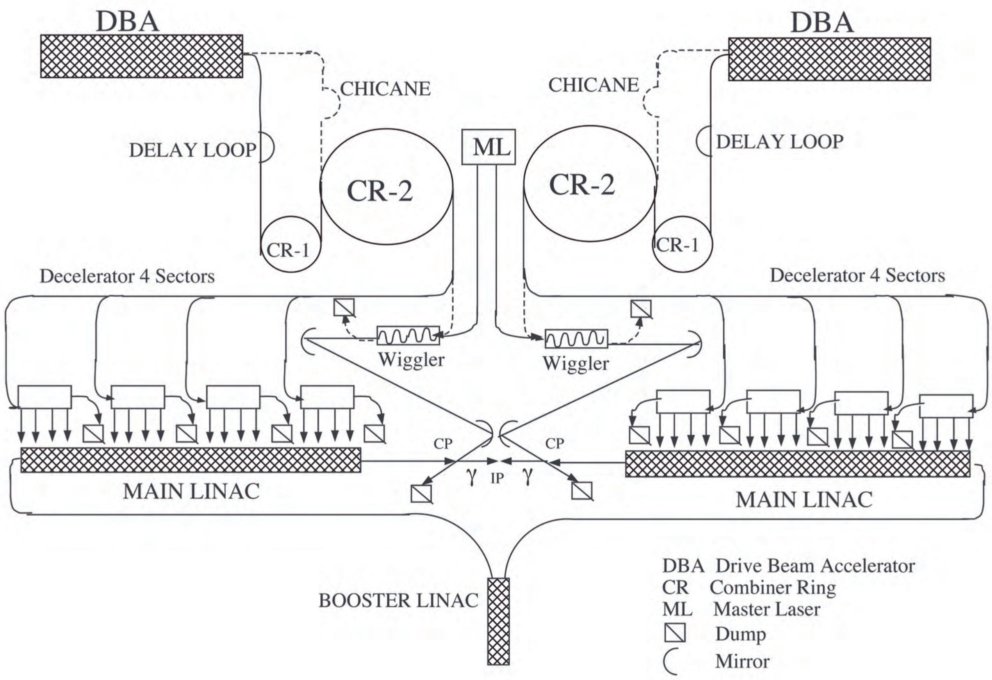

Figure 3. Layout of CLIC $\gamma\gamma$ collider and proposed laser system. Dashed line shows short train of the drive beam.

Table 1. CLIC main linac beam parameters. The parameters of the increment method are shown in parentheses.

Parameter	Value
Beam energy $E_{\rm b}$ (GeV)	250
RF frequency (GHz)	12
Number of particles per bunch(10^9)	3.72
Number of bunches per train	312
Bunch train length (ns)	156
Bunch separation (ns)	0.5
Repetition frequency $f_{\rm rep}$ (Hz)	50 (300)
Twiss parameter $\beta^*_{\rm x}/\beta^*_{\rm y}$ (mm)	2/0.045
Normalized emittance (μm rad)	2.4/0.025
Bunch length $\sigma_{\rm z}$ (μm)	44
Distance between CP and IP (mm)	2.5
Crab angle (mrad)	15
Nonlinear parameter ξ^2	0.25
Total luminosity $L_{\gamma\gamma}$ (10^{33} cm^{-2}s^{-1}) ($\lambda_{\rm e}\lambda_0 = \ \ 0$)	2 (12)
Total luminosity $L_{\gamma\gamma}$ (10^{33} cm^{-2}s^{-1}) ($\lambda_{\rm e}\lambda_0 = +1$)	1.93 (11.6)
Total luminosity $L_{\gamma\gamma}$ (10^{33} cm^{-2}s^{-1}) ($\lambda_{\rm e}\lambda_0 = -1$)	2.14 (13)

where $K = 0.934 B_{\rm w}[{\rm T}]\lambda_{\rm w}[{\rm cm}]$ is the dimensionless wiggler parameter, $\lambda_{\rm w}$ is the wiggler period, $B_{\rm w}$ is the peak magnetic field inside the wiggler and $\gamma_{\rm e}$ is the drive beam relativistic factor. The choice of the optimum $\lambda_{\rm w}$, $B_{\rm w}$

pair can be made by minimizing the gain length (e-folding length for the radiation growth). The fundamental FEL parameter ρ describes the maximum efficiency. When maximum efficiency is reached, kinetic energy loss of the electron beam is no longer possible for constant wiggler parameters and the output power saturates [21]. After saturation, further extraction of energy from the electron beam is possible by tapering i.e. varying the K parameter by changing the wiggler peak field, the wiggler period, or both. We recommend self-tapering obtained by GINGER code, varying the peak wiggler field while keeping constant the wiggler period. This tapering is more efficient than the constant K [5, 4, 22].

During amplification, a number of characteristics affect the gain: electron beam energy spread, emittance effect, diffraction losses and slippage effect [3, 5]. An exact evaluation of all these phenomena has been made with simulation code GINGER [23]. The required amplifier parameters are shown in Table 3.

The simulation results show that the required output power can be obtained in a 55 meter wiggler with an initial 15 m untapered section. In Figure 4, FEL pulse power is plotted as a function of wiggler length. The output power starts to grow with the introduction of tapering around 15 m. Higher input master laser power would help to decrease total wiggler length. As the resonant condition is satisfied along the full wiggler length, the output power of the FEL increases although the B_w itself decreases. It is possible to decrease wiggler length using different design of wiggler. The related wiggler peak field variation along the wiggler is shown in Figure 5.

Parameters of the FEL amplifier with tapered wiggler are presented in Table 3. In this table, output FEL pulse length is calculated. Slippage ($N_{\mathrm{w}}\lambda$) plus e-beam length is 2.5 ps, as shown in Table 3.

4.4. Master laser

The master laser power must be higher than the FEL amplifier noise at the entrance of the wiggler [15]. The master laser (for which the parameters given in Table 3) is focused at the entrance of the wiggler. A Nd:YAG laser can be used as a master laser. Chirped Pulse Amplification (CPA) technique can be used to obtain required 1 MW peak power. Furthermore, the master laser has to be synchronized with drive linac e-bunches.

Table 2. Modified drive beam parameters to produce FEL. Increment method parameters are shown in parenthesis.

Parameter	Value
E_{db} (GeV)	2.37
Peak current (kA)	4.04
Bunch length (σ_{z}) (mm)	0.25
Bunch separation (ns)	0.5
Bunch charge (nC)	8.4
Beam size entrance of wig.(σ_{x} and σ_{y}) (μm)	380
Number of bunches/short trains	312 (6×312)
Repetition frequency f_{rep} (Hz)	50
Normalized emittance, RMS (μm rad)	150
Energy spread $\sigma_{E_{\mathrm{db}}}/E_{\mathrm{db}}$	0.2%
Beam power P (MW)	311
Pulse duration (μs)	23 (139)

Table 3. Master laser, FEL amplifier and optical system parameters.

Parameter	Value
Master laser	
Power (MW)	1
Wavelength (μm)	1.06
Pulse duration (ps)	1.56
Rayleigh length (m)	0.57
Repetition frequency $f_{\rm rep}$ (Hz)	50
FEL amplifier	
Wiggler Type	planar
Period $\lambda_{\rm w}$(cm)	11
Length of wiggler (m)	55
Number of sections $N_{\rm w}$	500
Length of untapered section(m)	15
FEL parameter ρ	7.5 10^{-3}
Entrance magnetic field (T)	1.74
Rayleigh length* (m)	121
FEL pulse length (FWHM) (ps)	2.5
FEL Power (TW)	0.78
Optical system parameters	
$F_{\rm N}$ number	12
Rayleigh length (mm)	0.2

*wiggler output value

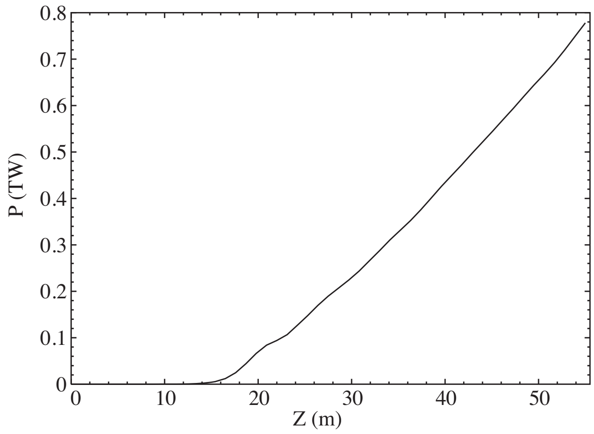

Figure 4. FEL Power as a function of wiggler length.

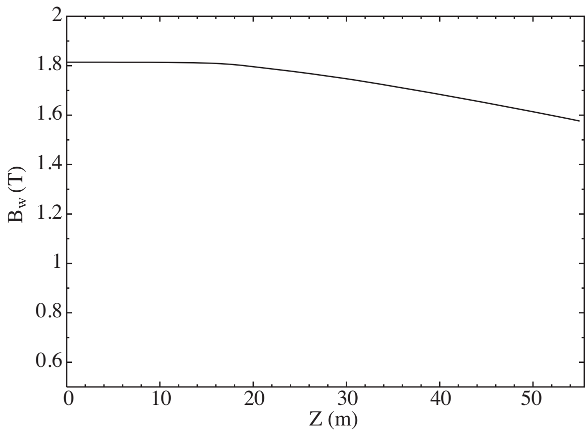

Figure 5. Magnetic field on the wiggler axis vs wiggler length.

4.5. Optical system

Prior to the CP, the FEL passes through an optical system. The FEL spot size at the CP must be larger than the electron beam transverse size. The final FEL spot size is defined by the optical system. The Rayleigh length is $Z_{\rm R} = \frac{4}{\pi}\lambda F_{\rm N}^2$, where $F_{\rm N}$ is the ratio of the focal length to the diameter of FEL on the last focusing mirror. In order to decrease the Z_{R} —which is initially 121 m from the FEL simulation result—to the desired value (0.2 mm), a detailed optical design study is required. F_{N} should be equal to 12 on the last mirror of the optical design.

5. Results and conclusions

The present paper shows that the CLIC project can provide the laser requirement itself for $\gamma\gamma$ collider option. The required laser power is 0.78 TW and it can be obtained from the drive linac with 55 m wiggler. The required modifications are explained in the text. Master laser pulse ($\lambda \sim 1\mu$m) which is synchronized with the drive beam, is also injected in to the wiggler.

Circularly polarized photons can be obtained with helical wiggler. Even including some effects degrading the peak power made of the FEL, it is possible to realize $\gamma\gamma$ or γe collider based on CLIC drive beam FEL. Reachable luminosity for opposite helicity states of FEL and e-beam in $\gamma\gamma$ collider is 2.14×10^{33} cm^{-2}s^{-1} and it can be upgraded to 1.3×10^{34} cm^{-2}s^{-1} with the "increment" method.

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