CERN – EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CLIC Note 543
PS/AE Note 2002-180

CERN-OPEN-2002-060
22 October 2002

STUDY OF THE FEASIBILITY OF AN X-RAY FREE ELECTRON LASER WITH A 15 GEV CLIC BEAM

M. Brandin
Luleå University of Technology, Sweden

R. Corsini
CERN, Switzerland

T. Ekelöf, A. Ferrari
Uppsala University, Sweden

Abstract

This note presents a study of the feasibility of a Free Electron Laser (FEL) using an electron beam from the Compact Linear Collider (CLIC). We first show that, with the nominal CLIC layout, the energy spread at 15 GeV would be too large to allow FEL saturation in an undulator of reasonable length. An alternative scheme was studied, with a dedicated source, with a by-pass of the damping rings and with magnetic compression between the various acceleration stages. With this scheme, the energy spread of the CLIC beam can be reduced from 1.5% to 0.1%, but the emittance is much larger and, although the power gain is better than in the nominal case, FEL saturation is still not reached. We show that the energy spread or the transverse emittance would have to be reduced by another order of magnitude in order to obtain FEL saturation.

Geneva, Switzerland
22nd October, 2002

1 Introduction

In order to achieve laser beams of ultrahigh brilliances and very short wavelengths, the development of an X-ray Free Electron Laser (FEL) presently shows great promise. The requirements on the electron beam needed to feed such a laser (very short bunch length, small emittances and high charge) are similar to what are needed for a high-energy and high-luminosity collider such as the Compact Linear Collider, CLIC [1]. This is illustrated by the fact that other development projects for linear electron-positron colliders are intimately connected to the development of FELs. The advantage of operating with very high gradients (150 MV/m for CLIC) is that it may involve a significantly smaller linear accelerator length. In this note, we present the first paper study of the feasibility to drive an X-ray FEL with a 15 GeV CLIC beam.

In Section 2, we present the basic principles of the FEL [2]. In Section 3, the simulation program used in this study and the input parameters are discussed. In Section 4, we show that the nominal CLIC parameters do not allow production of a 15 GeV electron beam that is suitable to feed an X-ray FEL, and we discuss possible ways to improve the beam parameters in order to get closer to the FEL saturation, but this requires some modifications of the injector complex. Finally, conclusions are drawn in Section 5.

2 Basic principles of the Free Electron Laser

The FEL is a very powerful coherent radiation source, with the potential of reaching regions of the electromagnetic spectrum that normal lasers do not reach. In particular, the X-ray regime is of great interest for research in many fields of science. Indeed, X-rays are valuable tools in the study of nature. Since the wavelength of the beam determines the smallest distance that can be examined, and since X-ray wavelengths are of the same order as atom sizes, X-rays are suitable for probing matter at the atomic level. Furthermore, if these X-rays can be produced with the same properties as lasers, they will be even more useful since they will have an increased brilliance, a shorter pulse length, and they will be much more coherent and much better collimated, as compared to the present synchrotron X-ray sources. Other advantages are that the radiation is highly polarised and that the wavelength is tunable. Nowadays, FELs are under development or operation in several places around the world. In particular, several international centres are developing facilities in the X-ray regime: SCSS (SPring-8 Compact SASE Source) at SPring-8 [3] in Hyogo (Japan), LCLS (Linac Coherent Light Source) at SLAC [4] in Stanford (USA), and TESLA X-FEL at DESY [5] in Hamburg (Germany). All of them are connected to research and development of high-energy linear colliders.

FELs make use of the synchrotron radiation, i.e. the fact that accelerated charges emit electromagnetic radiation. In an FEL, a high quality beam of relativistic electrons is injected into an undulator, i.e. a straight set-up of magnetic dipoles with an equal field strength and alternated polarities. These magnets are placed with a distance λ_u between two identical poles. The beam is deflected by each of the magnetic fields and travels through the undulator on a sinusoidal trajectory. Since the electrons have a high velocity, they emit radiation in a small cone, in the forward direction. The maximal trajectory angle (and thus the largest angle for the radiation) can be derived from the equations of motion for the electrons:

$$\theta_{max} = \frac{a_u}{\gamma} \ll 1,$$

where γ is the electron energy in units of $m_e c^2$ and where the undulator parameter a_u is defined as:

$$a_u = \frac{e \lambda_u B_u}{2\pi m_e c} \simeq 0.934\, \lambda_u(\mathrm{cm})\, B_u(\mathrm{T}).$$

Here, B_u is the rms field: if B_0 is the peak on-axis field, then $B_u = B_0/\sqrt{2}$ for a planar undulator and $B_u = B_0$ for a helical undulator.

When they travel through an undulator, electrons spontaneously emit radiation, creating a co-propagating radiation field, which then itself interacts with the beam, either by accelerating electrons in phase with the field or by decelerating electrons with an opposite phase. In this way, a longitudinal fine structure (micro-bunching) is created and the radiation is amplified, because the electrons in a micro-bunch emit photons coherently. The radiation stimulates the electrons to emit further photons of the same energy (wavelength), contributing to an exponential growth of the radiation power along the undulator. At some stage, the system reaches an equilibrium, where energy oscillates between the electron beam and the radiation field, see Figure 1.

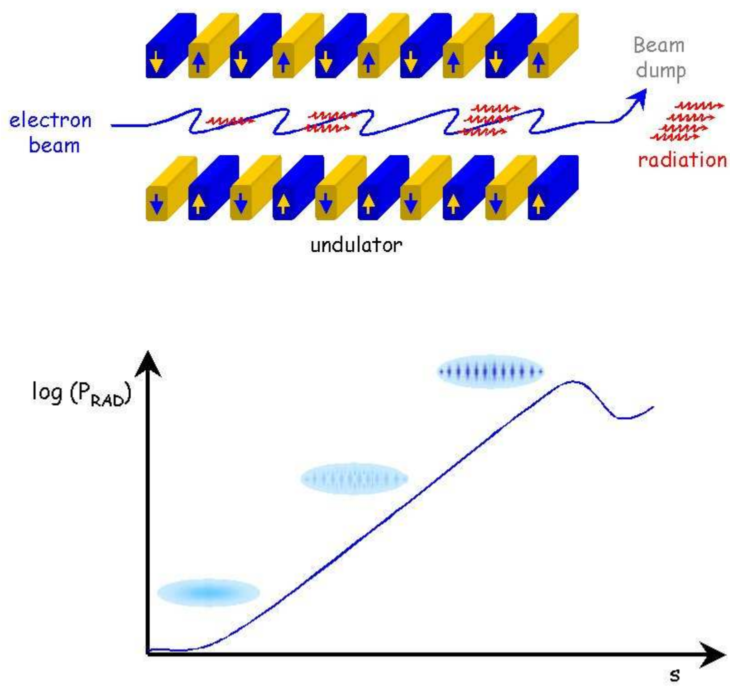

Figure 1: Free Electron Laser operating in the Self Amplified Spontaneous Emission (SASE) mode: the upper plot shows how the photon beam is built up along an undulator and the lower plot shows the exponential growth of the power up to the saturation, together with the micro-bunching process.

The strength of the interaction between the electron beam and the radiation field is characterized by the FEL-parameter ρ:

$$\rho \propto \gamma^{-1}\, J^{1/3}\, B_u^{2/3}\, \lambda_u^{4/3}\,,$$

where J is the electron peak current density.

Many important properties of the FEL directly depend on ρ. For example, if z is the distance along the undulator, then the growth of the radiation power before saturation is given by:

$$P(z) = P_0\, e^{z/L_g},$$

where the gain length L_g can be expressed as:

$$L_g \simeq \frac{\lambda_u}{4\pi\sqrt{3}\,\rho}.$$

The parameter ρ also gives the power extraction efficiency at saturation:

$$P_{sat} \simeq \rho P_{beam}.$$

The wavelengths to be emitted depend primarily on the energy of the beam, as well as the period and the strength of the magnetic field in the undulator:

$$\lambda_r \simeq \frac{\lambda_u}{2\gamma^2}(1 + a_u^2).$$

This resonance condition means that the difference in path length between the electrons and the radiation field over one undulator period λ_u must be equal to the wavelength λ_r of the spontaneously emitted light. It also means that the wavelength is tunable by changing the undulator parameters, λ_u and B_u, or the energy.

The previous equation is only valid for electrons which have an energy γ and which travel on the central trajectory in the undulator. However, in reality, there is an energy spread within the electron bunch, which may broaden the linewidth $\Delta f_r/f_r$ (i.e. the frequency spread of the radiation), and even interfere with the power gain mechanism of the FEL. In order to obtain the maximum possible gain, one should have:

$$\Delta\gamma/\gamma \lesssim \rho.$$

The transverse betatron motion of the electrons may also be responsible for the broadening of the linewidth, because a spread in transverse velocities leads to a spread in the longitudinal velocities as well, which induces an additional effective energy spread. Therefore, the beam emittance is also a critical parameter, especially for short radiation wavelengths.

The FEL process can be initiated by an external perturbation or by intrinsic density fluctuations in the beam. In the latter case, often referred to as the start-up from shotnoise, the perturbation is not uniform along the bunch, resulting in a different micro-bunching at each position inside the bunch. Consequently, the radiation spectrum may consist of independent regions, each of them transversally and longitudinally coherent, leading to the formation of spikes in the pulse. The length of these regions is the cooperation length, usually much smaller than the bunch length, and can be expressed as:

$$L_{coop} = \frac{\lambda_r}{4\pi\rho}.$$

Some problems may arise from the spiky time structure of the emitted radiation, such as strong intensity fluctuations from pulse to pulse. A possible solution is to initiate the SASE process by an external seed, for instance monochromatic light flashes which have the same length as the electron bunch.

3 Basic assumptions and initial conditions

In order to investigate the feasibility of an X-ray FEL at CLIC, simulations were performed with the GENESIS 1.3 code [6]. The input parameters were derived from simulations of the CLIC injector complex and of the accelerating structures.

3.1 FEL simulation with GENESIS

The GENESIS program is a time-dependent and fully three-dimensional code, which solves the paraxial FEL-equations with the approximation of a slowly varying amplitude of the radiation field [6]:

$$\frac{d\gamma}{dz} = -k_r \frac{a_r a_u}{\gamma} \sin(\theta + \phi_r),$$

$$\frac{d\theta}{dz} = k_u - k_r \frac{1 + {p_\perp}^2 + {a_u}^2 - 2 a_r a_u \cos(\theta + \phi_r)}{2\gamma^2},$$

$$\frac{dp_\perp}{dz} = -\frac{1}{2\gamma} \frac{\partial {a_u}^2}{\partial r_\perp} \pm k_{foc} r_\perp,$$

$$\frac{dr_\perp}{dz} = \frac{p_\perp}{\gamma},$$

$$\left[2ik_r \frac{\partial}{\partial z} + {\nabla_\perp}^2\right] a_r e^{i\phi_r} = -\frac{eZ_0 I}{m_e c^2} \langle \frac{a_u e^{-i\theta}}{\gamma} \rangle.$$

Here, $k_r = 2\pi/\lambda_r$ is the radiation wavenumber, $k_u = 2\pi/\lambda_u$ is the undulator wavenumber, a_r is the dimensionless radiation field amplitude, ϕ_r is the radiation field phase, θ is the particle phase, $p_\perp$ is the transverse particle momentum, $r_\perp$ is the transverse particle position, Z_0 is the vacuum impedance, I is the beam current, and k_{foc} is the strength of the external focusing field. The brackets in the last equation denote the average with respect to the electron distribution function, which is normalised to unity.

The time-dependency is approximated with a variation along the electron bunch, since one has $z \simeq ct$, and all the other variables can be expressed in terms of z. The head and the tail of the electron bunch will reach a fixed point z at different times, which are Δt apart. As a result, the internal time-structure is directly related to the longitudinal position within the bunch. Simulations in time-dependent mode usually require a lot of CPU time. Hence, the whole bunch is not simulated, but only a number *NSLICE* of sample slices. These are one radiation wavelength long and are evenly separated along the bunch. They are then treated one by one, and the radiation field from one is transported to the next one as the simulation proceeds. The distance between the slices, referred to as *ZSEP* in the code, is an integer number of times the radiation wavelength. Every slice is filled with a certain number of macro-particles, each of them corresponding to a large number of electrons. This approach allows to save a lot of computational resources, since fewer particles have to be used. Still, the simulations take a large amount of CPU time. In the limit of infinite and uniform bunches and radiation fields, the steady-state approximation can be used for more straightforward investigations. Then, the time-dependency drops, and the FEL equations become much easier to solve.

3.2 Initial undulator and beam parameters

The main concern when designing an undulator is to choose the desired wavelength and beam energy. The wavelength shall be 1.5 Å in order to be consistent with other X-ray FEL projects. A suitable electron beam energy (15 GeV) and the undulator parameter have been chosen, so that the resonance condition is met at this wavelength. No detailed studies were performed in order to optimise the undulator for CLIC, but the wavelength, the energy and the undulator period have been chosen close to the ones used for the simulation of LCLS in reference [4], see Table 1. The undulator parameter was then calculated from the resonance condition.

Parameter	Unit	**CLIC**	**LCLS**
Wavelength, λ_r	Å	1.5	1.5
Energy	GeV	15	14.4
Undulator period, λ_u	mm	30	30
Undulator parameter, a_u	-	2.758	2.623
Magnetic field, B_u	T	0.985	0.937

Table 1: Parameters used for the undulator in the simulations for CLIC, compared to those used for LCLS.

In order to keep the beam on its path through the whole undulator, some focusing in a FODO lattice is needed. To determine the strength of, and the spacing between the quadrupoles, a good knowledge of the β-functions is needed. Again, the values that we use here are similar to those found for LCLS, and no additional study was performed for the CLIC beam.

Along the undulator, the energy of the electron beam is reduced by the energy transfer to the radiation field. Consequently, the resonance condition may not be well satisfied for the desired wavelength when the distance required for saturation is large. This can be compensated by a tapering of the undulator. By reducing the magnetic field along a part of the undulator where the beam energy has become smaller, the resonance condition can be satisfied at the right wavelength.

As far as the beam parameters are concerned, the transverse emittance and the energy spread at CLIC are quite different from what is expected for LCLS, while the electron bunch length and the peak current are of the same order, see Table 2 for details.

Parameter	Unit	**CLIC**	**LCLS**
Energy	GeV	15	14.4
Energy spread, $\frac{\Delta\gamma}{\gamma}$	10^{-4}	150	0.6
Emittance, ϵ_x/ϵ_y	μm · rad	0.6/0.01	1.2/1.2
Bunch length, l_b	μm	35	23
Peak current, I	kA	2.7	3.4

Table 2: Nominal parameters for the CLIC electron beam used in the simulations, as compared to those used for LCLS.

4 Results

4.1 Simulation with the nominal CLIC parameters

When running steady-state simulations with the undulator and beam parameters given in Tables 1 and 2, one obtains a very low power gain, compared to LCLS, see Figure 2.

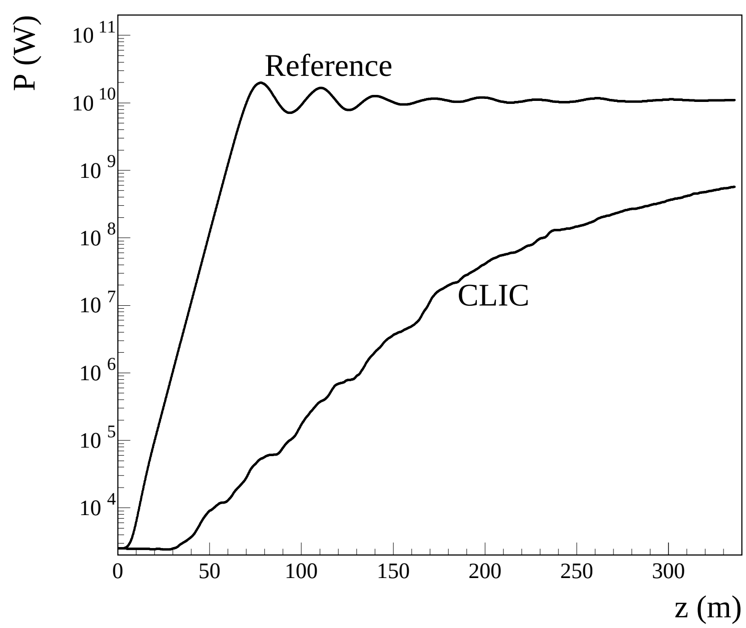

Figure 2: Evolution of the radiation power along the undulator for CLIC, compared to the reference case (LCLS).

The condition $\Delta\gamma/\gamma \lesssim \rho$ is not satisfied, as it should be for coherent light emission to occur: at CLIC, the energy spread is 1.5%, while the FEL-parameter ρ is about 10^{-3}. Because of the large energy spread, the linewidth $\Delta f_r/f_r$ is very broad, so there is no uniform interaction of the radiation with the electron beam. As a result, no micro-bunching can occur. The very low emittance of the CLIC beam does not compensate for the destructive effect of the large energy spread, and the nominal CLIC beam is thus a poor FEL driver.

4.2 Possible modifications of the CLIC injector complex

Studies were made on the possibility to adapt the CLIC injector complex for FEL operation through reasonably simple hardware modifications.

The large value of the energy spread is the major issue, while the value of the transverse emittance is well below what is required for the operation of CLIC as an FEL driver. The reason for this is that CLIC mainly aims at providing electron and positron beams with very small transverse emittances, especially in the vertical direction, in order to have a very high luminosity for the e^+e^- collisions at high energy (3 TeV). Since it is impossible to obtain very small transverse emittances directly from the source, it is necessary to use damping rings [7]. They were designed to deliver a 3 GHz beam with an energy of 1.98 GeV, an energy spread of 0.082% and a rms bunch length of 3 mm. Since the required bunch length in the main linac is 30 μm, a two-stage compression [8] is then performed, which leads to an energy spread of about 1.5% at the beginning of the main linac. This large relative energy spread is then reduced during the acceleration up to 1.5 TeV and it is therefore not a major limitation for the operation of CLIC as a high-energy e^+e^- collider.

For a possible operation of CLIC as an FEL driver, a strong reduction of the energy spread must be envisaged, even at the expense of a transverse emittance growth. The idea is thus to use a dedicated electron source, which generates bunches with a reasonably low emittance and then to by-pass the damping rings. By doing so, there is no reduction of the emittance. On the other hand, one can use much shorter bunches and therefore obtain a much smaller energy spread after the various compression stages.

An investigation of the energy spread limitations in the various sections of the injector complex and in the main linac was performed, considering the bunch extension along the accelerating RF cavities and the effect of the short-range wakefields. Three frequencies are used in CLIC: the pre-injector structures operate at 1.5 GHz with an accelerating gradient of 17 MV/m, the injector and booster linacs operate at 3 GHz with a gradient of 21 MV/m and the main linac operates at 30 GHz with a gradient of 150 MV/m. A Gaussian bunch (truncated at 3σ) with a charge of 1 nC was considered, as well as uniform distributions. The minimum rms energy spread obtainable in the various structures was calculated as a function of the rms bunch length after optimization of the RF phase, which is aimed at compensating for the effect of the wakefields by using the RF curvature of the accelerating field in the best way. The results of this study are shown in Figure 3.

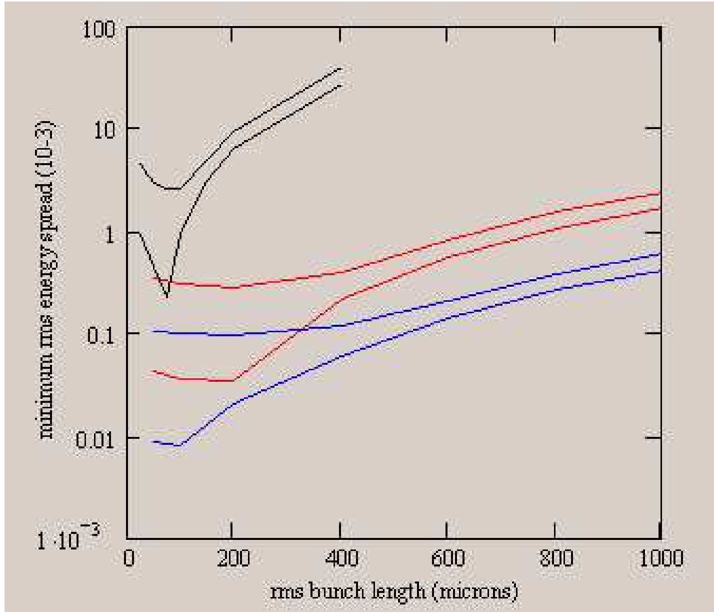

Figure 3: Minimum rms energy spread for 1.5 GHz (blue), 3 GHz (red), and 30 GHz (black) acceleration. The two lines for each colour correspond to a Gaussian (upper) and a uniform (lower) time profile of the bunch.

In the 30 GHz acceleration structures, the longitudinal short-range wakefields induce a large energy spread, which is a strong limitation for the X-ray FEL. However, since the acceleration up to 9 GeV is performed at RF frequencies of 1.5 GHz and 3 GHz, CLIC still may be able to deliver a useful beam for FEL operation at 15 GeV. If the bunch length is optimised for the various accelerating sections, the energy spread can be kept minimal. Let us assume that a photo-injector similar to the one proposed for TESLA is used [9]: the initial bunch length is 300 μm and the (uncorrelated) initial energy spread is 1.5%. We calculated the evolution of the longitudinal phase-space for a Gaussian distribution of 1000 macro-particles. Bunch compression sections were simulated between some of the acceleration stages and at 15 GeV (just upstream of the undulator) in order to reach a bunch length of about 30 μm at the entrance of the FEL. The initial longitudinal phase-space distribution is shown in Figure 4.

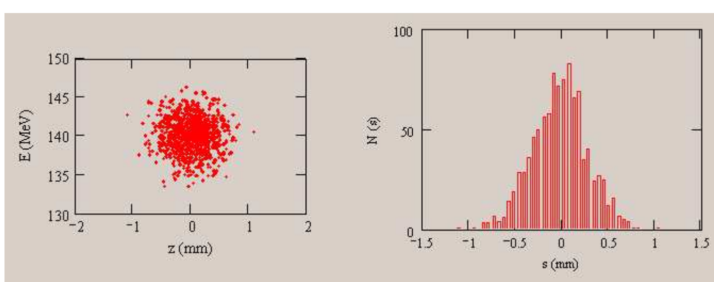

Figure 4: Initial longitudinal distributions, in the phase-space (left), and when projected along the beam propagation axis (right).

The first acceleration stage at 1.5 GHz, brings the energy up to 2 GeV. The energy spread is dominated by the initial value of $\Delta\gamma$. No particular growth of the absolute spread occurs, thus reducing the relative energy spread to about 10^{-3} (see Figure 5).

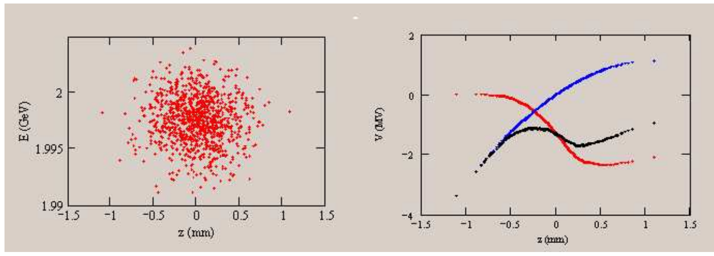

Figure 5: Longitudinal phase-space distribution after the first acceleration stage (left) and integrated voltages normalised to the average phase during acceleration (right): the wakefield contribution (red), the accelerating field contribution with an RF phase of -2 degrees (blue), and the total integrated voltage (black) are shown.

No compression is needed between the 1.5 GHz and the 3 GHz acceleration stages. The bunch length, although not optimal, is short enough for acceleration at 3 GHz with a decent growth of the energy spread. A compression would produce a larger energy spread than the one generated in the linac. The energy reached in this second stage is 9 GeV. At this point, the energy spread is mainly coming from the combined effects of the wakefields and of the RF acceleration. The rms energy spread has now increased to about 1.25×10^{-3}. Here, the bunch can be linearly compressed down to an rms bunch length of about 90 μm (see Figure 6).

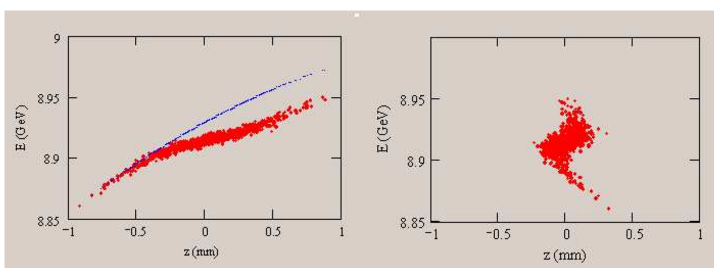

Figure 6: Longitudinal phase-space distribution after the 3 GHz acceleration (left) and after the first compression (right). The blue line in the left-hand side plot is the integrated 3 GHz voltage, obtained with an RF phase of -8 degrees for the accelerating field.

Finally, the beam is accelerated up to 15 GeV in the 30 GHz CLIC main linac and the bunch is linearly compressed before being sent into the undulator. The rms bunch length is reduced down to 80 μm and it is thus not significantly changed during this compression. It is mainly the core of the bunch which is compressed down to a shorter length (see Figure 7). At the end of this process, a Gaussian bunch could be obtained with an rms energy spread of the order of 10^{-3} and an rms length of about 30 μm, as shown in Figure 8.

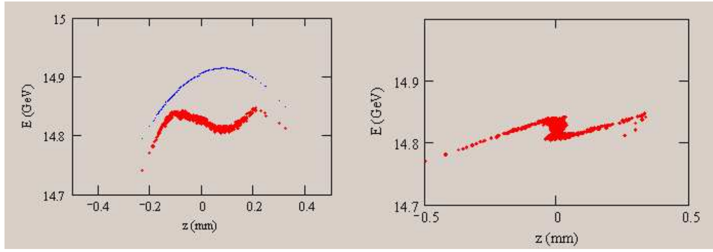

Figure 7: Longitudinal phase-space distribution after the 30 GHz acceleration (left), and after the last compression (right). The blue line in the left-hand side plot is the integrated 30 GHz voltage, obtained with an RF phase of -3 degrees for the accelerating field.

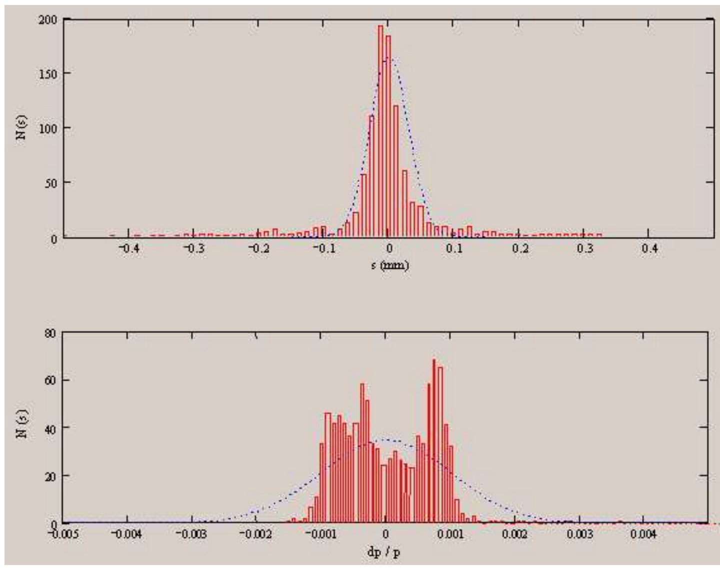

Figure 8: Longitudinal distribution (top) and energy distribution (bottom) obtained after the final compression, and comparison with a Gaussian distribution having an rms bunch length of 30 μm or an rms energy spread of 10^{-3}.

4.3 Results with a modified CLIC injector complex

New GENESIS simulations were performed with the Gaussian distributions obtained in the last section, after modification of the injector complex. The new beam parameters are given in Table 3 under column CLIC-II. The emittance for CLIC-II in Table 3 is obtained by assuming that there is no growth of the emittance along the accelerating structures (this may be quite optimistic). The value of the peak current I is derived from:

$$I = \frac{q}{\sqrt{2\pi}(l_b/c)},$$

with $q = 1$ nC and $l_b = 30$ μm. It is likely to be an upper limit only. In reality, one should perform time-dependent simulations in order to take into account the real current distribution.

Parameter	Unit	**CLIC**	**CLIC-II**
Energy	GeV	15	15
Energy spread, $\frac{\Delta\gamma}{\gamma}$	10^{-4}	150	10
Emittance, ϵ_x/ϵ_y	μm· rad	0.6/0.01	1/1
Bunch length, l_b	μm	35	30
Peak current, I	kA	2.7	4.0

Table 3: Parameters for the nominal CLIC electron beam and with a modified injection system (CLIC-II).

Even with these modifications, no FEL-saturation can be obtained, as shown in Figure 9.

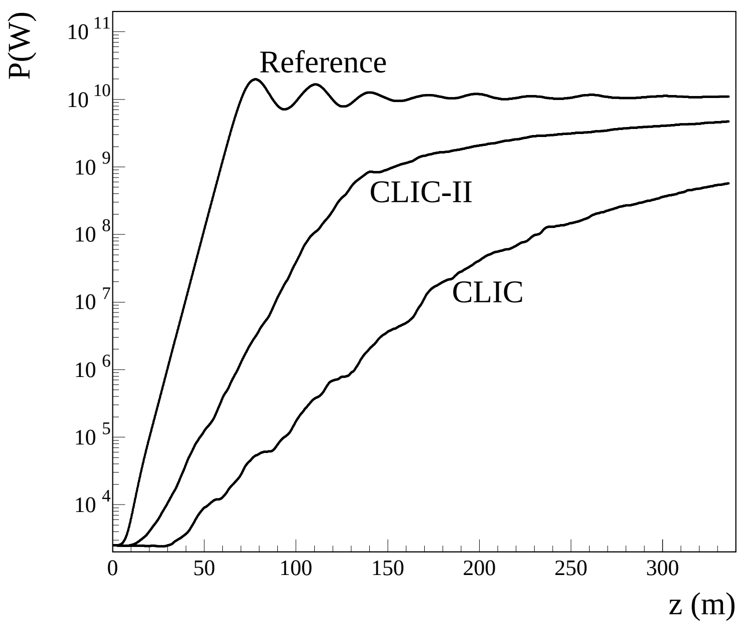

Figure 9: Power profiles for the nominal and modified CLIC layouts, as compared to the reference case.

The energy spread may still be too large for a proper micro-bunching and coherent light emission to occur. Also, the emittance has now become higher than when the damping rings are used, which may induce an additional effective energy spread, due to the larger transverse betatron oscillations.

Therefore, a further reduction of the energy spread and/or the transverse emittance is needed if one wants to use the CLIC beam in an FEL undulator, as it is shown in Figure 10. If only one parameter is modified, then a large reduction is needed, by about one order of magnitude. However, if both the energy spread and the emittance are reduced together, a factor two for each may be sufficient. However, the value of the emittance seems already quite optimistic and a higher value could be expected, because of the emittance growth along the acceleration structures. Therefore, the most probable solution seems to be a further reduction of the energy spread, which is what both the LCLS and the TESLA X-FEL projects are expecting to control.

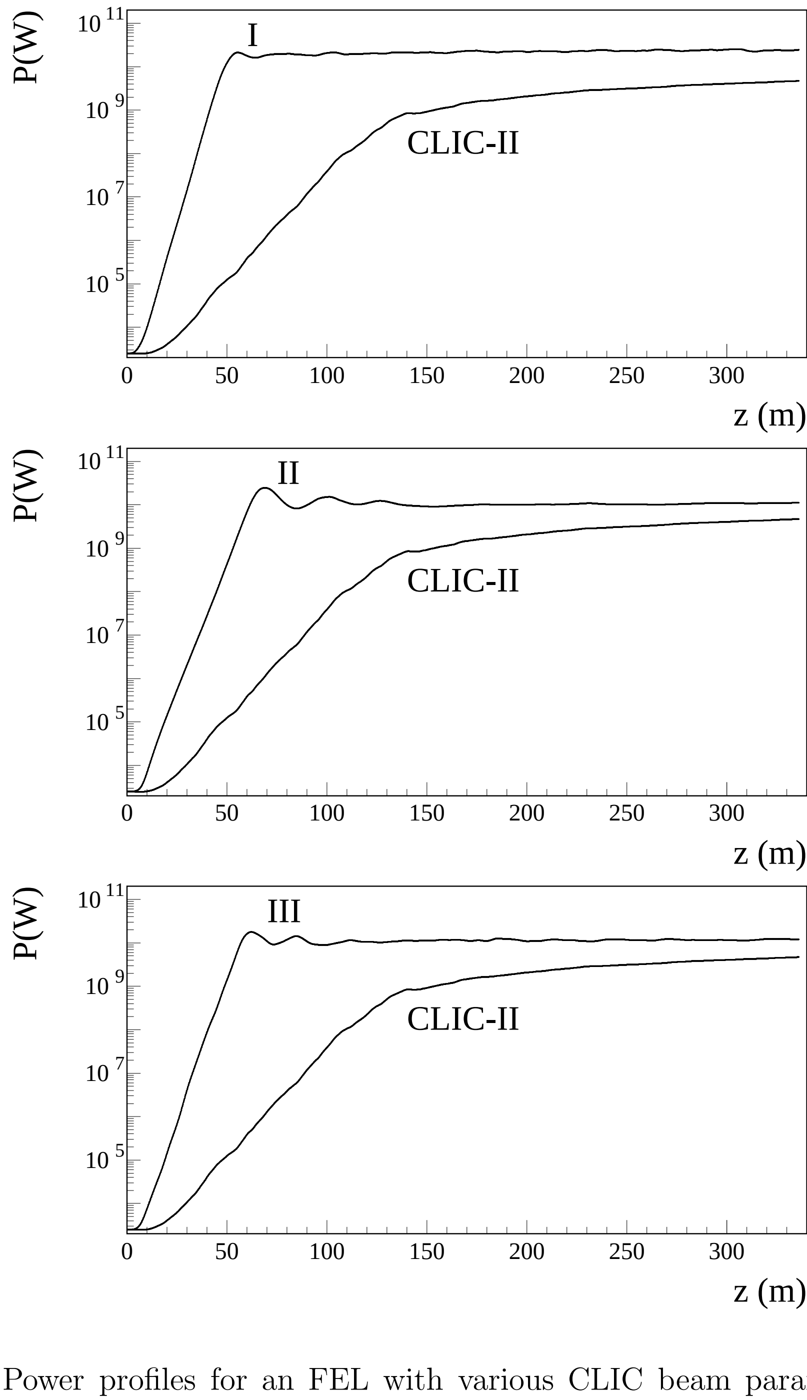

Figure 10: Power profiles for an FEL with various CLIC beam parameters. In I, the transverse emittance has been reduced by a factor 10, down to 0.1 μm.rad, as compared to the CLIC-II case. In II, the energy spread has been reduced by a factor 10, down to 10^{-4}, as compared to the CLIC-II case. Finally, in III, both the transverse emittance and the energy spread have been reduced by a factor 2, as compared to the CLIC-II case.

5 Conclusions

In this study, we have first shown that the nominal CLIC layout cannot be used as an X-ray FEL driver at 15 GeV, because of a too large energy spread. This comes from the fact that a long electron bunch is required in the damping ring, and that a large energy spread is generated in the compression stages needed thereafter. By using an alternative injection set-up, which by-passes the damping ring and uses a dedicated electron source, the energy spread can be reduced down to 10^{-3}. However, this is still not enough to drive an X-ray FEL with satisfying performances. In particular, it was shown that the 30 GHz accelerating structures are not well suited to deliver a beam with a very low energy spread. In order to reach FEL saturation at a power comparable to other FEL projects, the energy spread and/or the emittance would have to be reduced further (by about one order of magnitude).

More investigations are thus needed in order to find an alternative scheme compatible with the CLIC technology. For instance, one should consider the use of a lower RF frequency, e.g. 15 GHz, in the acceleration structures. It would also be interesting to perform time-dependent simulations in order to investigate the effects of a locally reduced energy spread, after a different optimization of the compression scheme. In that latter case, the total energy spread may be too large and the emitted wavelength could change slightly along the pulse, but a part of the bunch may radiate coherently at the expected wavelength.

Acknowledgements

The authors wish to thank S. Reiche for his help with the GENESIS simulation program.

The research of A. Ferrari has been supported by a Marie Curie Fellowship of the European Community Programme "Improving Human Research Potential and the Socio-economic Knowledge Base" under contract number HPMF-CT-2000-00865.

References

[1] G. Guignard (Ed.) *et al.*, "A 3 TeV e+e- Linear Collider Based on CLIC Technology", CERN 2000-008.

[2] R. Bonifacio, F. Casagrande, G. Cerchioni, L. de Salvo Souza, P. Pierini and N. Piovella, "Physics of the High-Gain FEL and Superradiance", La Rivista del Nuovo Cimenta Volume 13, Serie 3, Numero 9, 1990.

[3] T. Shintake, "Soft X-ray SASE-FEL Project at SPring-8, Japan", Proceedings of the Second Asian Particle Accelerator Conference, Beijing, September 2001.

[4] S. Reiche, C. Pelligrini, J.B. Rosenzweig, P. Emma and P. Krejcik, "Start-to-end simulation for the LCLS Xray-FEL", Nucl. Instr. Meth. A483 (2002) 70-74.

[5] G. Materlik and T. Tschentscher (Ed.) *et al.*, "The X-Ray Free Electron Laser", TESLA Technical Design Report - Part V, DESY 2001-11, TESLA Report 2001-23, TESLA-FEL 2001-05.

[6] S. Reiche, "Manual for GENESIS 1.3 Version 0.1", 1998.

[7] J.P. Potier and T. Risselada, "Fundamental design principles of linear collider damping rings, with an application to CLIC", EPAC2000, Vienna, June 2000.

[8] E.T. D'Amico, G. Guignard and T.O. Raubenheimer, "The CLIC main linac bunch compressor", Proceedings of the 6th European Particle Accelerator Conference (EPAC98), Stockholm, 1998.

[9] R. Brinkmann, K. Flöttman, J. Roßbach, P. Schmüser, N. Walker and H. Weise (Ed.) *et al.*, "The Accelerator", TESLA Technical Design Report - Part II, DESY 2001-11, TESLA Report 2001-23, TESLA-FEL 2001-05.