OUTPUT POWER CONTROL IN AN X-RAY FEL

C. Pellegrini, X. Ding, J. Rosenzweig
UCLA Physics Department, Los Angeles, CA

Abstract

Recent theoretical and experimental advances of the high gain Self-Amplified Spontaneous Emission free-electron laser (SASE-FEL), have demonstrated the feasibility of using this system as a 4^{th} generation light source. This source will produce diffraction-limited radiation in the 0.1nm region of the spectrum, with peak power of tens of GW, subpicosecond pulse length, and very large brightness [1,2,3]. The peak power density in such a system is very large, and in some experiments it might damage the optical systems or the samples, or it might be simply larger than what is needed for the particular experiment being considered. Some options to reduce the power level, for example by using a gas absorption cell to reduce the X-ray intensity, have been studied [2]. In this paper we discuss another possibility to control the power output of an X-ray SASE-FEL by varying the charge from the electron source, and the longitudinal bunch compression during the acceleration in the linac.

1 INTRODUCTION

X-ray free-electron lasers (XFEL) based on the Self Amplified Spontaneous Emission (SASE) mode of operation can produce very large peak power and subpicosecond long pulses of coherent radiation in the 0.1 nm region of the spectrum [1,2].

In some experiments it may be useful to reduce the peak power to avoid damaging the sample under study, or some optical components. One method to do this is to use a gas cell to attenuate the X-ray pulse [2]. In this paper we discuss an alternative method based on changing the amount of charge in the electron pulse produced by the electron source. In the present design of XFELS the electron beam is produced in a photoinjector, and accelerated to 15 GeV in a linac. During the acceleration the electron bunch is also compressed to reach the peak current needed for FEL operation. The charge of the electron bunch can be easily changed by varying the laser intensity on the photocathode. The compression system is also flexible enough to provide a variable compression.

When changing the electron bunch charge and the initial laser spot radius on the photocathode, other beam parameters, like the emittance, pulse length and energy spread, also change. These changes have an effect on the XFEL gain length and output power.

To estimate the overall effect we need to consider the FEL scaling laws and the photoinjector-linac scaling laws. The scaling laws for these two cases will be discussed in the next section. We will then evaluate the XFEL performance using the LCLS, with a planar undulator, as an example.

2 FEL SCALING

The gain length, saturation power, and saturation length, of a SASE-FEL are a function of the FEL parameter ρ [4]. For a planar undulator ρ is given by

$$\rho = \left(\frac{K}{4\gamma}\frac{\Omega_p}{\omega_u}F(K)\right)^{2/3}, \tag{1}$$

where $K=eB_u\lambda_u/2\pi mc^2$ is the undulator parameter; B_u the undulator field and λ_u the undulator period; γ the beam energy in rest mass units;

$$\Omega_p = (4\pi r_e c^2 n_e/\gamma)^{1/2} \tag{2}$$

the beam plasma frequency; r_e and c the classical electron radius and the light velocity; n_e the electron density; $\omega_u=2\pi c/\lambda_u$; $F(K)=J_0(K^2/(2+4K^2))-J_1(K^2/(2+4K^2))$.

Since the FEL gain length and the saturation length are inversely proportional to ρ, and the output power is proportional to ρ, optimising the FEL is equivalent to maximising ρ. The gain length is given, in the simple 1D theory, neglecting diffraction and slippage by

$$L_G = \lambda_u / 2\sqrt{3}\pi\rho \tag{3}$$

Saturation occurs after about 10 gain lengths, and the radiation intensity at saturation is about ρ x beam energy. Diffraction effects, energy spread, σ_E , and slippage, $S=\lambda N_u$, can increase the gain length over the 1D value if the conditions $\varepsilon<\lambda/4\pi$, $\sigma_E<\rho$, $S<L$, $Z_R>L_G$ are not satisfied, where ε is the beam emittance, N_u the number of undulator periods, and Z_R the radiation Rayleigh-range.

The FEL parameter depends on the beam density in the undulator, and is proportional to the beam plasma frequency to 2/3, or $(Q/\sigma^2\sigma_L)^{1/3}$, Q being the electron bunch charge, σ the radius, and σ_L the length. We write the beam density as

$$n_e = \frac{N_e}{(2\pi)^{3/2}\varepsilon\beta\sigma_L}, \tag{4}$$

where N_e is the number of electrons in a bunch, ε the beam emittance, β the focusing function in the undulator. The beam density is determined by the electron source, and by the acceleration and compression processes. We assume the electron source to be a 1.6 cell photoinjector [5]. The scaling of the beam emittance, pulse length and energy spread with charge for this photoinjector has been studied and the results are presented in ref. [5]. We use the results of this paper, in particular the scaling of normalized emittance and pulse length with charge,

, $$\varepsilon_N = 1.45\times10^{-6}(0.38Q^{4/3} + 0.095Q^{8/3})^{1/2} \tag{5}$$

. $$\sigma_L = 0.63\times10^{-3}Q^{1/3} \tag{6}$$

where the charge is in nC, the emittance in m-rad, and the bunch length in m. The acceleration and compression process producing the beam used in the FEL is designed to preserve the transverse emittance, and reduce the pulse length by a compression factor C_f. As shown in [2] the emittance increase produced by wakefields is small, and we take it into account by using the additional factor 1.45 in (6).

During this acceleration and compression the wakefields in the linac and compressors increase the longitudinal emittance by a rather large factor. However the local energy spread, remains small. The term local refers in the FEL case to the energy spread within a slice of the beam corresponding to one co-operation length, defined as $L_c=L_g\lambda/\lambda_u$, the slippage in one gain length [6]. The local energy spread is maximum at the largest charge, 0.02% at 1 nC, and in our analysis we assume it to remain constant at lower charges, a pessimistic assumption. We use this assumption to evaluate the XFEL gain length, saturation length and output power.

3 XFEL PERFORMANCE

In this section we use the electron beam scaling with charge introduced before to evaluate the XFEL performance. We use a model based on the FEL code described in [7], which includes 3-dimensional effects.

The basic set of parameters used is those of the LCLS project, given in Table 1, and corresponding to a 1nC electron charge. In what follows we will use this as the reference case. We simulate a situation with a planar undulator of given, fixed length, and change the electron bunch charge and compression factor to keep the saturation length constant and equal to the undulator length. The main results are shown in fig. 1 and 2.

Notice also that from (4), (5), (6) it follows that for when the charge is in the range of 0.1 to 1 nC, the range that we consider in this paper, the beam density, and so the FEL parameter, is almost independent of charge.

The result in figure 1 shows that it is possible, using the same LCLS undulator, to operate the FEL with the same gain for a charge range between 1 to 0.1 nC, if one simultaneously changes the compression factor by less than a factor by 2. Similar results are obtained if we keep the saturation length constant. In fact the system is remarkably flexible, and offers a wide range of options and of control of the FEL operation and performance. The results in figure 2 show the change in peak power, bunch length, and compression factor, when we change the charge to keep the gain length constant. The XFEL peak power is reduced by almost one order of magnitude, while the bunch length remains practically constant.

Electron beam	
Electron energy, GeV	14.3
Emittance, nm rad	0.05
Peak current, kA	3.4
Energy spread, %	0.02
Bunch length, fs	67
Undulator	
Type	Planar
Period, cm	3
Field, T	1.32
K	3.7
Average β, m	18
Gap, mm	6
Total length, m	100
Radiation	
Wavelength, nm	0.15
FEL parameter, ρ	$4.7x10^{-4}$
Field gain length, m	11.7
Peak power, GW	10^{9}
Intensity fluctuations, %	8

Table 1: LCLS parameters. Energy spread, pulse length, emittance are rms values. The energy spread is the local energy spread within 2π co-operation lengths. A correlated energy chirp of 0.1% is also present along the bunch at 1 nC charge.

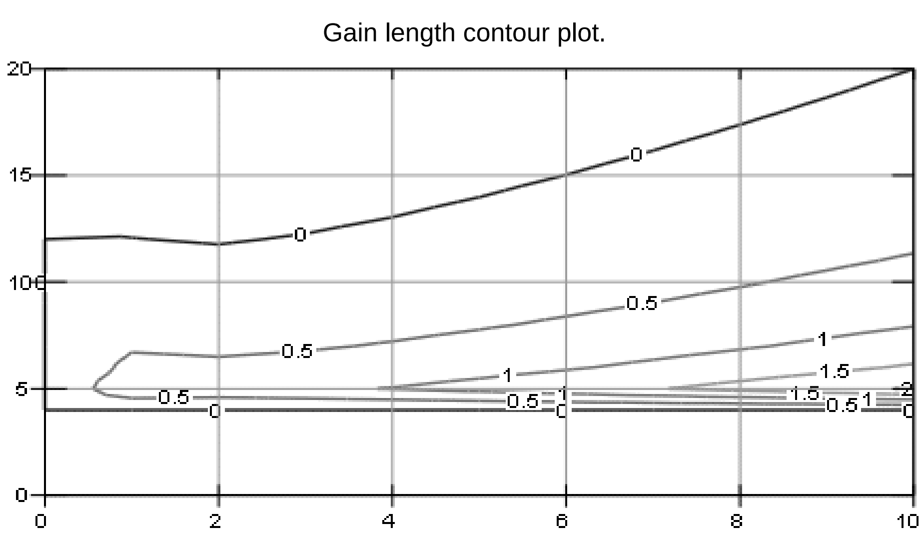

Fig. 1 Contour plot of {$L_g(Q,C_f)/ L_g(1nC,20)$}-1. The x-axis represents the charge in units of 0.1 nC, the y-axis the compression factor. The line corresponding to zero gives the values of charge and compression for constant gain length, equal to the reference case gain length..

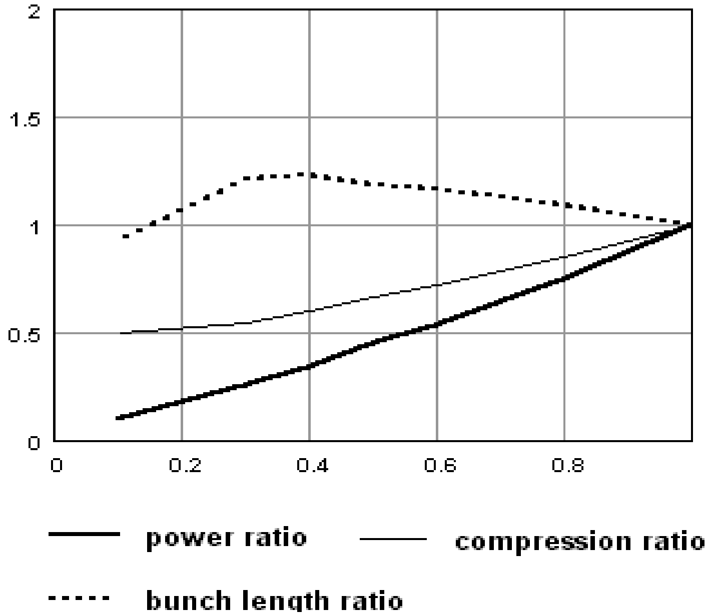

Fig.2 Ratio of peak power, bunch length, and compression factor, C_f, to that of the reference case, defined as Q=1 nC and C_f=20.

Similar results are obtained if we keep the saturation length constant. In fact the system is remarkably flexible, and offers a wide range of options and of control of the FEL operation and performance. The results in figure 2 show the change in peak power, bunch length, and compression factor, when we change the charge to keep the gain length constant. The XFEL peak power is reduced by almost one order of magnitude, while the bunch length remains practically constant.

4 CONCLUSIONS

We have shown that it is possible to change the output power of a XFEL, while keeping the same gain length, by changing the electron bunch charge and the compression factor in the linac. This procedure can produce a large change in output power, almost one order of magnitude in the LCLS case. This method alleviates the need for additional hardware like the gas cell considered in ref. [2]. Operating LCLS at low charge can also make easier to control of bunch length, energy spread, and emittance during the acceleration, as discussed in ref. [8].

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