OUTPUT POWER CONTROL IN AN X-RAY FEL*

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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 4th 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 pulse of coherent radiation in the 0.1 nm region of the spectrum [2,3].

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 changed by varying the laser intensity on the photocathode. The compression system is also flexible enough to provide a variable compression.

When varying the electron bunch charge, 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 as an example.

*Work supported in part by the US Department of Energy under grant DE-FG03-92ER40693

2 FEL SCALING

The gain length, saturation power, and saturation length of a SASE-FEL are defined by the FEL parameter ρ [4]

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

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;

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

the beam plasma frequency; r_e and c the classical electron radius and the light velocity; n_e the electron density; $\omega_u=2\pi c/\lambda_u$.

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 maximise ρ. The gain length is given, in the simple 1D theory, neglecting diffraction and slippage by

$$L_G = \lambda_u / 2\sqrt{3}\pi\rho \qquad (3)$$

Saturation occurs after about 10 gain lengths, and the radiation intensity at saturation is about ρ times the beam energy. Diffraction, energy spread 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. The beam density can be conveniently written as

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

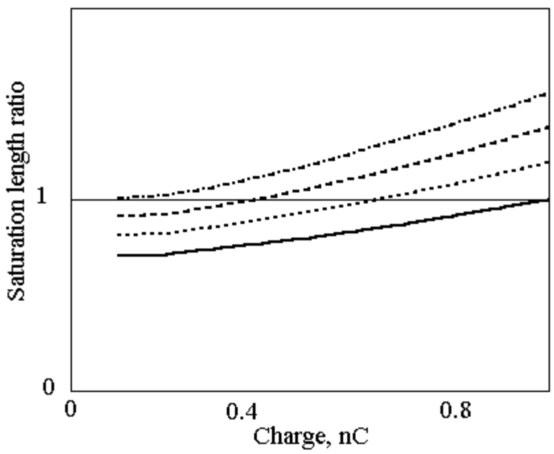

Fig. 1 Ratio of the saturation length to the reference case saturation length, as a function of electron bunch charge, and for different values of the compression coefficient. The reference case is defined as Q=1 nC and Cf=20. The curves show that it is possible to obtain the same saturation length when changing the charge from 0.1 to 1 nC, by changing the compression factor from 20 to 10.

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 emittance and pulse length with charge,

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

$$\sigma_L = 0.63\times10^{-3}Q^{1/3} \quad . \qquad (6)$$

where the charge is in nC, the emittance in mxrad, 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.

Table 1: LCLS Parameters. Energy spread, pulse length, emittance are rms values. Brightness is in number of photons per second, per (mm mrad)2, per 0.1% bandwidth. The energy spread is the local energy spread within a co-operation length. A correlated energy chirp of 0.1% is also present along the bunch.

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	
Period, cm	3
Field, T	1.32
K	3.7
Gap, mm	6
Total length, m	100
Radiation	
Wavelength, nm	0.15
FEL parameter, ρ	$5\text{x}10^{-4}$
Field gain length, m	11.7
Bunches/sec	120
Average brightness	$4\text{x}10^{22}$
Peak brightness	10^{33}
Peak power, GW	10^{9}
Intensity fluctuations, %	8

Notice also that from (4), (5), (6) it follows that 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.

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 [2], given in Table 1. The FEL radiation characteristics given in this table are for the case of 1nC electron charge and compression of 20. In what follows we will use this as the reference case. We simulate a situation with an 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.

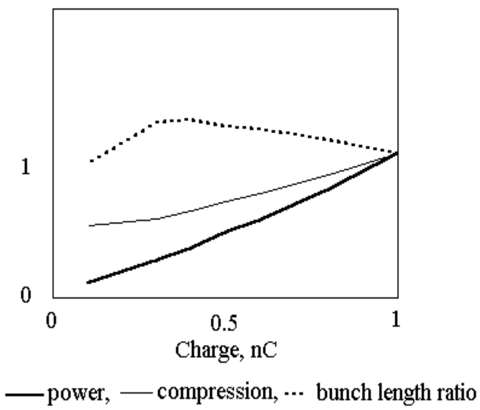

Fig.2 Ratio of peak power, bunch length, and compression factor, Cf, to that of the reference case, defined as Q=1 nC and Cf=20. The peak power changes almost linearly with charge, and is reduced by a factor of ten from 1 to 0.1 nC.

The results in figure 1 shows that it is possible, using the same LCLS undulator, to reach saturation at the undulator exit for a charge range between 1 to 0.1 nC, if one simultaneously reduces the compression factor by 2. The results in figure 2 show that in this situation the XFEL peak power is reduced by one order of magnitude, while the bunch length remain practically constant.

Figure 2 also shows that, when considering simultaneously the bunch length from the photoinjector and the compression, the final bunch length changes by no more than 25% when changing the charge. Hence the peak current for the XFEL scales almost linearly with charge, and is reduced to about 350 A at 0.1 nC.

2 CONCLUSIONS

We have shown that it is possible to change the output power of a XFEL, while keeping the same saturation length, by changing the electron bunch charge and the compression factor in the linac. This procedure can produce a large change in output power, as large as one order of magnitude in the LCLS case. This method is easy to implement and does not require additional hardware like the gas cell considered in ref. [2].

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