LOW CHARGE OPERATION OF SWISSFEL

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Abstract

The Paul Scherrer Institut is proposing an X-ray FEL facility, providing a wavelength range between 1 Angstrom to 7 nm. The major mode of operation is SASE with a supplemental seeding option for wavelength down to 1nm. In addition a low charge operation of about 10 pC is considered to achieve single spike operation in the soft X-ray regime and thus overcoming the limitation of seeding sources at that wavelength. This presentation discusses the basic operation as well as expected stability of the performance in in terms of pulse energy and spectral power.

INTRODUCTION

Free-electron Lasers (FEL) are a novel source for coherent radiation in the X-ray regime with several projects worldwide currently under construction or operation (e.g. LCLS [1], the European X-ray FEL [2], XFEL/Spring-8 [3] and SwissFEL [4]). They provide short, transversely coherent X-ray pulses with a radiation power above one Gigawatt, opening new areas of research in various branches of science.

Due to a lack of a coherent seeding source these FELs operate as Self-amplifying Spontaneous Emission (SASE) FELs [5], where the amplification process is started by the incoherent, spontaneous emission. Towards shorter wavelength in the Ångstrom range the degree of longitudinally coherence decreases due to the diminishing difference between the speed of light and the longitudinal velocity of the electrons. The radiation does not reach every point within the electron bunch over the finite distance of the undulator and slices of the electron bunch amplify the radiation independently.

Several methods have been proposed to achieve short FEL pulses down to a single, coherent spike in the SASE FEL radiation profile. The methods range from manipulating the electron beam by either spoiling the emittance of most part of the bunch [6], or to locally enhance the current [7] with a short conventional laser pulse, modulating the electron beam energy and then compressing it in a dispersive section prior to the undulator. A similar configuration allows to combine the induced energy modulation with a strong taper in the undulator [8] or a two-stage FEL with slightly detuned undulators [9] Other methods are using cascading High-Gain Harmonic Generation (HGHG) FELs [10] to start with either a short seed pulse or to use the contrast enhancement in the SASE spikes during the harmonic upconversion [11]. Finally, the FEL pulse can be manipulated after the FEL by either slicing a subsection of a chirped pulse with a narrow band monochromator [12] or by optical compression. However all of these scheme (except for the compression of the chirped FEL pulse) are not efficient because they only utilize a small fraction of the electron bunch for lasing. In addition, almost all of the schemes produce a background signal which is longer than the single coherent spike and might interfere with proposed measurements with a short, coherent laser pulse.

In this paper, we study an alternative approach by reducing the electron bunch length so that only one single spike is formed by the SASE process [13]. The process avoids any electron beam or radiation manipulation and is void of any pedestal background signal from the electron bunch which does not lase but still emits incoherently.

Besides utilizing the entire electron bunch in the FEL process, a low charge operation has the advantage that all incoherent and coherent effects along the beam line are significantly diminished. The impact of wakefields [14], coherent synchrotron radiation [15] in bends and space charge are negligible and the initial beam brightness is better preserved during the acceleration, compression and transport to the undulator.

The studies were done for the soft X-ray beamline of SwissFEL with a bunch charge of 10 pC. We present the expected performance as well as the intrinsic fluctuation in the FEL output in this single spike regime at around 1 nm wavelength.

LOW CHARGE OPERATION OF SWISSFEL

SwissFEL will cover the range of 200 pC down to 10 pC for the bunch charge to optimize the FEL performance for specific modes of operation. While the 200 pC case provides the highest photon number per pulse, lower charge allows for a higher beam brightness and shorter FEL pulses. In particular at 10 pC the electron pulse can be compressed to yield a sub-femtosecond FEL pulse without any background signal. In addition, the final pulse length is also chosen so that only one spike will occur in the full tuning range of the soft X-ray beamline between 0.7 to 7 nm. The resulting pulse has full longitudinal coherence and a duration of less than a femtosecond.

To achieve single spike operation for the hard X-ray beamline of SwissFEL a lower charge than 10 pC and even stronger compression would be required, which both are considered difficult due to the dynamic range of the diag-

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Table 1: Beam Parameters of SwissFEL for the nominal mode (1), the initial low charge mode (2) and the upgraded low charge mode with stronger compression (3).

Mode		1	2	3
Charge	pC	200	10	10
Current	kA	2.7	0.7	7.0
Bunch length	fs	31	6.2	2.4
Core energy spread	MeV	0.35	0.25	1.00
Core emittance	μm	0.43	0.18	0.25
Projected emittance	μm	0.65	0.25	0.45
Compression factor		125	240	2400

nostics and the RF stability for stable compression. However it seems that there is not a big demand for a single spike at wavelengths below 0.7 nm besides providing a sub-fs pulse. Therefore the charge range is limited to 10 pC as its lower limit.

Operation at 10 pC is approached in two stages. The first stage utilize less compression of the bunch to set-up and commission the electron beam diagnostic at low charges. Once the RF stability allows for stable operation, the bunch compression is increased, resulting in a peak current of about 7 kA and an rms pulse length of 2.4 fs. A summary of the expected beam parameters for SwissFEL [16] is shown in Table 1

The shortest wavelength of 0.7 nm in the soft X-ray beamline is achieved at a beam energy of 3.4 GeV and an undulator with a K-value of 1 and a period length of 4 cm. The undulator has a total length of 70 m with 4 m long modules and 80 cm long drift sections (for focusing and diagnostic). The average β-function is 10 m. The hard X-ray beamline has a similar layout though the undulator parameter is 1.2 and the period is 15 mm with an electron beam energy of 5.8 GeV for the shortest wavelength of 1 Å.

SINGLE SPIKE OPERATION

The regime of longitudinal coherence is defined by the cooperation length $L_c = \lambda/4\pi\rho$, where λ is the radiation wavelength and ρ is the FEL parameter. If the electron bunch is longer than twice the coorperation length multiple spikes in the radiation profile occur. Therefore the proper choice of the bunch charge and the compression factor provide an electron bunch length sufficiently short to allow only one spike. ASTRA, ELEGANT and GENESIS 1.3 based start-to-end simulations have shown that the initial stage of low charge operation is not sufficient to fulfill the goal at 0.7 nm and that further compression is required. The radiation profiles for the two cases are shown in Fig. 1. Comparing these two cases the single spike operation provides a pulse which is 3 times shorter, while the effective FEL parameter is twice as large. This is confirmed by the rms pulse length at saturation which is 2.3 fs and 0.25 fs for operation mode 2 and 3, respectively. The spectral width at saturation is a good measure for the effective FEL parameter. For the two stages the rms bandwidths are 1.4 and 6.2 eV, respectively. For the short electron pulse the product from rms FEL pulse length and bandwidth is 1.55 eVfs, which is reasonable close to the Fourier limit of a Gauss radiation profile of $\hbar/4 = 1.03$ eVfs. Note that an FEL spike has always an intrinsic chirp and that the Fourier limit can never be achieved in a single-spike mode. The longer electron pulse provides a product of 3.2 eVfs which is in very good agreement with the three spikes present in the profile.

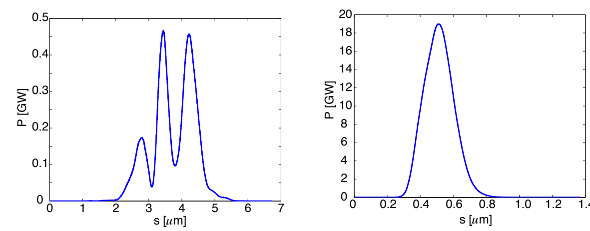

Figure 1: FEL pulse profile at saturation for mode 2 and 3 of Table 1(left and right plot, respectively).

With the bunch length optimized for the single-spike operation at around 0.7 nm, the electron bunch is too long for a singe-spike mode in the hard X-ray beamline at one Å due to the shorter cooperation length. The FEL parameter is about 3 times smaller while the wavelength is a factor 7 smaller, thus resulting in a reduction of the cooperation length by about 50%. According to this rough estimate there are about 2 to 3 spikes visible in the profile. Nevertheless a sub-fs pulse can still be very attractive for some user experiments, which do not rely on fully longitudinal coherence.

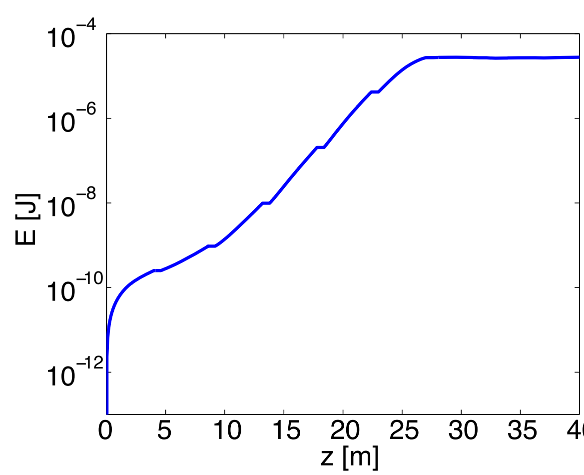

Figure 2: Average energy of the FEL pulse along the undulator at 0.7 nm for the single spike mode.

On the other hand the electron pulse is too short for operation at the longest wavelength at 7 nm. The radiation field slips out of the bunch before saturation is achieved. This acts effectively as a loss mechanism of the radiation field, increasing the gain length and thus the cooperation length. The FEL operates in a superradiant regime [17], where the FEL pulse length actually increases while the electron bunch length is decreased. For an optimum performance of a single spike with shortest possible pulse length the electron bunch length has to be roughly matched to about twice the coorperation length. Longer pulses yield more spikes while shorter bunches still generate a single spike but with less pulse energy and longer pulse length.

With the design parameters for the single-spike mode listed in Table 1 the FEL saturates after 25 m at 0.7 nm with a pulse energy of 15 μJ (as shown in Fig. 2). The peak power is 20 GW, the spot size is 24 μm rms and the divergence angle is 6 μrad. Note that the quoted values are the rms from both transverse dimension (rms radius). For a single plane, e.g. the size and divergence in the x-direction, the values have to be scaled with $1/\sqrt{2}$. The product is $7.2 \cdot 10^{-11}$ m as compared to a diffraction limited beam with $\lambda/4\pi = 5.6 \cdot 10^{-11}$ m. Similar to the intrinsic frequency chirp in the longitudinal direction, the FEL eigenmode has a phase front curvature which is stronger than a fundamental Gaussian beam. Therefore it can be expected that the product of size and divergence is larger. Fig. 3 shows the evolution of the radiation beam size and divergence angle. The fundamental FEL eigenmode is dominant after 15 m.

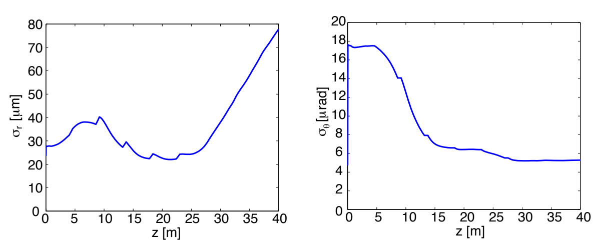

Figure 3: Average size and divergence of the FEL pulse along the undulator at 0.7 nm.

STATISTICAL FLUCTUATION

Despite achieving almost full transverse and longitudinal coherence, the single-spike mode is still the outcome of excitation of the FEL amplification process by a noisy source of the incoherent synchrotron radiation. Therefore it cannot be expected that the performance is identical for each shot, even if the electron beam parameters are stable. In this section we solely investigate the resulting fluctuation of the FEL performance from the SASE mechanism, excluding any jitter in the electron beam.

The theory of SASE FEL predicts that the energy of an FEL pulse varies according to a Gamma- distribution with the only fitting parameter M [18]. The meaning of M can be seen as the number of modes in the signal, which is the

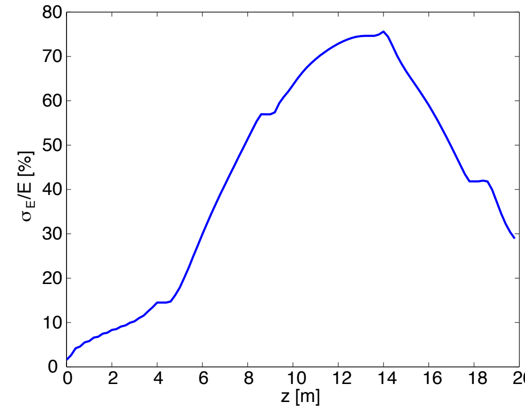

Figure 4: Fluctuation of the FEL pulse energy along the undulator at 0.7 nm.

number of spikes in the case of transverse coherence. The extrapolation towards a single spike operation would assume $M = 1$ with a 100% fluctuation, following a negative exponential distribution. However simulation with 500 independent seeds for the shot noise shows an rms maximum fluctuation of about 75% (as shown in Fig. 4), corresponding to $M = 2.3$. Towards saturation and beyond the rms fluctuation drops down to about 30% ($M = 11$) while only a single spike is visible in the profile. This can be understood by the fact that from shot-to-shot the effective shot noise power, seeding the FEL, varies but that the final radiation energy is defined by the number of electrons in the bunch, all emitting coherently. A low shot noise sample just require more undulator length to reach saturation.

It is also very instructive to compare the rms fluctuation of the energy with the rms fluctuation of the peak power, which is about 90% in the linear regime after transverse coherence has achieved. Because the power fluctuates stronger than the energy there has to be a correlation between radiation power and FEL pulse length, as clearly shown in Fig. 5. Towards saturation the fluctuation of power and energy becomes similar (between 30 – 40%) and the correlation between power and pulse length is less pronounced.

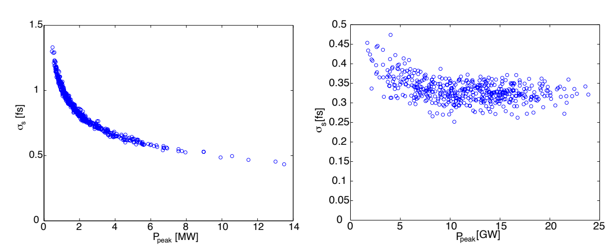

Figure 5: FEL pulse length vs FEL peak power at 10 and 20 m (left and right plot, respectively).

The strongest rms fluctuation remains at a spectral component in the FEL spectrum. Almost all the way up to sat-

Table 2: Fluctuation in the FEL parameters of the single-spike mode at 0.7 nm at SwissFEL after 20 m.

Parameter	Mean	Fluctuation
Energy	10 μJ	30%
Power	20 GW	30%
Pulse Length	0.25 fs	8%
Bandwidth	0.25%	15 %
Size	24 μm	10 %
Divergence	6 μrad	11%
Central Spectral Component	$6 \cdot 10^{-22}$ Js	70%
Peak Brilliance	$2.8 \cdot 10^{31}$ #/s·mm^2·mrad^2·0.1%	40%

uration it stays around 100% till it drops to 55% at saturation and then rises up again to larger rms fluctuation (e.g. 70% at 2 m after saturation). The corresponding distribution are shown in Fig. 6. The strong fluctuation in the linear regime can be explained that longitudinal coherence is builded up while the rms bandwidth is still larger than at saturation. In this case the different modes can interfere at a given frequency. Towards saturation the FEL bandwidth has narrowed down so that the spike fills out the full envelope of the FEL amplification. However the fluctuation remains high because the frequency component is very sensitive to the post saturation regime and the interference with the sideband instability.

Parameters, which are less sensitive to fluctuation, are the FEL pulse length, the overall bandwidth, the radiation size and divergence. Each of the parameters have an simulated rms fluctuation of no more than 15%. A list of all parameters and fluctuation are shown in Table 2.

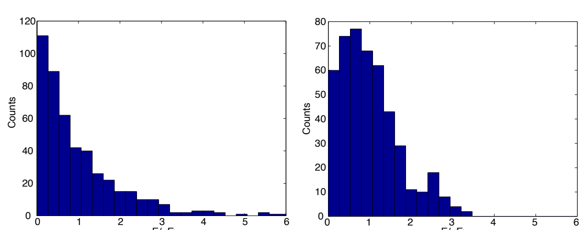

Figure 6: Propability distribution of the central frequency component in the spectrum at 10 and 20 m (left and right plot, respectively).

CONCLUSION

Single spike operation can be achieved when the bunch length of the electron bunch becomes comparable to the coorperation length of the FEL process. Longer pulses will produce multiple spikes while shorter pulses have a reduced efficiency and less energy. Therefore the electron bunch length and charge should be optimized for the given wavelength of the FEL, which are difficult if the tuning range of the FEL is large or if the linac serves multiple FEL bemlines.

For SwissFEL the single spike operation is optimized for the soft X-ray beamline with a shortest wavelength of 0.7 nm. The corresponding electron bunch charge is 10 pC requiring a significantly stronger compression than the nominal point of operation at 200 pC. Using the same configuration there are up to 3 spikes noticible at 1 Å, though the rms pulse length is 250 as, which makes the mode of operation still attractive at short wavelengths.

Due to the stochastic nature of a SASE FEL, even in the single-spike mode, the FEL exhibits intrinsic fluctuation in the FEL parameters. In particular the effective fitting parameter M to the fluctuation looses its meaning as the number of longitudinal modes. At saturation the power and energy fluctuates by about 40% rms, while the rms fluctuation at a given frequency component is still above 70% when the electron beam is extracted directly at saturation.

We are investigating input of jitter in the electron beam on the FEL performance for the single spike mode. Additionally we are further optimizing the bunch length and charge for the mode of operation.

REFERENCES

[1] *LCLS CDR*, SLAC Report No. SLAC-R-593, 2002

[2] *XFEL TDR*, DESY Report No. DESY-2006-097,2006

[3] T. Shintake *et al*, "SPring-8 Compact SASE Source", SPIE2001, San Diego, USA, June 2001

[4] B.D. Patterson (editor), *Ultrafast Phenomena at the Nanoscale: Science opportunities at the SwissFEL X-ray Laser*, PSI-SwissFEL Science Case, to be published

[5] C. Pellegrini, Nucl. Inst. & Meth. **A475** (2001) 1

[6] P. Emma *et al*., Phys. Rev. Lett. **92** (2004) 074801

[7] A. Zholents, Phys. Rev. STAB **8** (2005) 040701

[8] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, Phys. Rev. STAB **9** (2006) 050702

[9] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, Opt. Comm. **237** (2004) 153

[10] L.-H. Yu *et al*, Science **289** (2000) 932

[11] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, Opt. Comm. **212** (2002) 377

[12] C. Schroeder *et al*., J. Opt. Soc. Qm. B **19** (2002) 1782

[13] R. Bonifacio, L. De Salvo, T. Pierini, N. Piovella and C. Pellegrini, Phys. Rev. Lett. **73** (1994) 70

[14] S. Reiche *et al*., Nucl. Inst. & Meth. **A483** (2002) 70

[15] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, Nucl. Instr. & Meth. **A490** (2002) 1

[16] Y. Kim *et al*., *Beam Diagnostics and RF Systems Requirements for the SwissFEL Facility*, presented at the DIPAC '09 Conference, Basel, Switzerland (2009)

[17] R. Bonifacio, N. Piovella,B. McNeil, Phys. Rev. **A44** (1991) 3441

[18] E.L. Saldin *et al*., Nucl. Inst. & Meth. **A507** (2003) 106