

A SCHEME FOR STABILIZATION OF OUTPUT POWER OF AN X-RAY SASE FEL

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Abstract

Stability of XFEL radiation is naturally linked to stability of the linac RF system through bunch compression, leading to very tight tolerances for RF amplitudes and phases. We propose a stabilization scheme that allows to loosen these tolerances by an order of magnitude.

INTRODUCTION

Free-electron lasing at wavelengths shorter than the ultraviolet can be achieved with a single-pass, high-gain FEL amplifier. Due to lack of powerful, coherent seeding sources, short-wavelength FEL amplifiers work in the so called Self-Amplified Spontaneous Emission (SASE) mode, where the amplification process starts from shot noise in the electron beam [1]. Present acceleration and FEL techniques hold potential for SASE FELs to generate wavelengths as short as 0.1 nm [2, 3].

Pulse-energy stability of the radiation from a short-wavelength FEL might be challenging due to the fact that one deals with an exponential gain of many orders of magnitude. In particular, there exist both intrinsic and extrinsic fluctuations of the FEL pulse energy.

Intrinsic fluctuations are due to the start up from shot noise. In the exponential gain regime they scale as $\sqrt{l_{coh}/\sigma_z}$, where l_{coh} is the FEL coherence length and σ_z is rms bunch length. For hard X-ray FELs [2, 3] these fluctuations are not so large because of a short coherence length (of the order of 0.1 μm). Moreover, they are reduced when an FEL reaches saturation. In Fig. 1, the 1D version of the code FAST [5] was used to present the intrinsic rms fluctuations of FEL pulse energy versus undulator length (curve 1 on the lower plot) for the SASE1 undulator, operating at 0.1 nm [2]. Fluctuations are about 7% in the exponential gain regime before saturation, and about 2% at saturation.

Extrinsic fluctuations are due to jitter in amplitude and phase of the RF system. In the high-gain linear regime, the radiation power increases along the undulator length as $\exp(2z/L_g)$ where L_g is the field gain length, which depends on beam and undulator parameters. In the case when the beta-function in the undulator is optimized for the highest FEL gain and energy spread effects can be neglected, $L_g \propto \epsilon_n^{5/6}/I^{1/2}$ [4], where I is the beam current and ϵ_n is the normalized emittance. While the emittance is supposed to be a stable parameter in beam formation systems for X-ray FELs, fluctuations of the beam current are of major concern due to a large compression factor C in magnetic chicanes. For instance, in the case of the European XFEL [2], the beam current increases from 50 A to 5 kA,

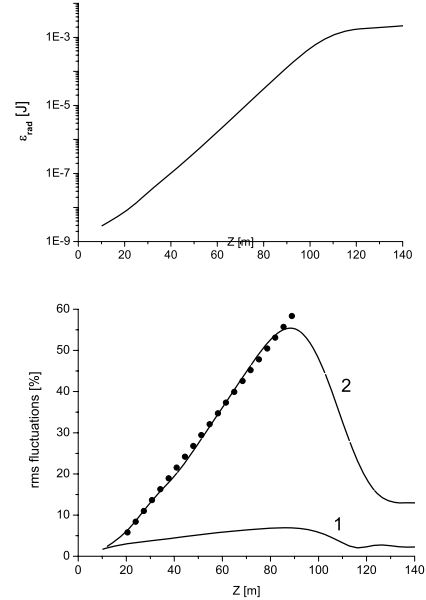


Figure 1: Results of numerical simulations with FAST. Radiation pulse energy (upper plot) and relative rms fluctuations (lower plot) versus undulator length for SASE1 undulator, operating at 0.1 nm [2]. Curve 1: intrinsic SASE fluctuations (stable electron beam), curve 2: with 10% rms fluctuations of bunch compression factor. Dots are calculated according to formula (1) with $L_g = 13$ m.

i.e. $C = 100$. Analysis in [6] shows that $\Delta C/C_0 \propto C_0 \Delta x$ where C_0 is the nominal compression factor and x is a fluctuating RF parameter. In other words, the larger the compression factor, the more sensitive it is to variations of the RF parameters. As a result, typical RF jitter tolerances are very tight, of order of a hundredth of a degree for phases and of 10^{-4} for amplitudes. The rms relative fluctuations of the FEL pulse energy, σ_ϵ , are plotted in Fig. 1 for rms relative fluctuations of compression factor $\sigma_c = 10\%$ (here and below we consider a flat-top distribution of compression factor variations). One can see that extrinsic fluctuations are much stronger than intrinsic ones. In the exponential gain regime, with $L_g \propto I^{-1/2}$ one can simply derive for small σ_c (accounting for variations of the pulse width):

$$\sigma_\epsilon \simeq \left(\frac{z}{L_g} - 1 \right) \sigma_c. \quad (1)$$

This dependence is shown in Fig. 1 with dots.

One should distinguish, here, between jitters and slow

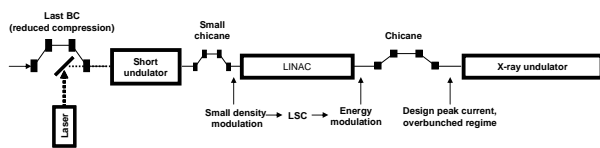


Figure 2: Conceptual scheme for stabilization of SASE FEL operation.

drifts of RF parameters. Slow drifts can be compensated by a beam-based slow feedback, as it is done at FLASH, a precursor of the European XFEL. At FLASH, coherent diffraction radiation produced by compressed bunches is used to regulate the phase of accelerating module upstream of the bunch compressor. However, pulse-to-pulse variations (jitters) cannot be compensated in this way. In this paper we propose a scheme that allows to dramatically reduce the sensitivity of the FEL pulse energy on the RF parameters variation by developing, in practice, a single-bunch feedback.

STABILIZATION SCHEME DESCRIPTION

Our scheme is based on the exploitation of an optically modulated electron beam. The concept has similarities with a current-enhanced SASE scheme [7], although there are essential differences. A sketch is shown in Fig. 2.

First, we reduce the compression factor in the main compression system, thus already relaxing tolerances by the same factor. Second, we modulate the electron beam in energy by interaction with a laser in a short undulator just behind the last bunch compressor (BC). Third, we convert energy modulation into a relatively small density modulation in a dispersion section (small chicane). Fourth, the beam propagates through accelerator, accumulating energy modulation due to longitudinal space charge (LSC), this modulation being much larger than that induced by the laser. Fifth, somewhere in front of the X-ray undulator we insert one more dispersive element (e.g. a chicane) to get density spikes with the design current. The transformation of the longitudinal phase space is nonlinear here, so that the density modulation includes also harmonics of the laser wavelength. It is important that we overbunch the beam, i.e. that the energy modulation is larger than what is needed to get maximal current for a given uncorrelated energy spread and R_{56} of the chicane.

This treatment has the effect of achieving a reduced sensitivity of the FEL output on RF jitters. In fact, when the compression factor in the main compression system C_0 increases (decreases) due to RF jitters, the energy modulation due LSC is stronger (weaker) than in the case of nominal compression. As a result, the beam is more strongly (or weakly) overbunched in the last chicane. As a consequence, the enhancement of the current is smaller (larger). It follows that the product of the current enhancement by C_0 remains nearly constant over a wide range of a compression factor change.

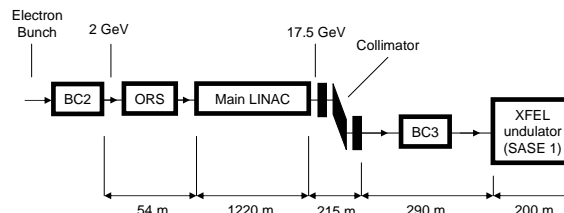


Figure 3: Possible realization of the stabilization scheme at the European XFEL.

We illustrate the operation of the stabilization scheme with a numerical example for the European XFEL (see Fig. 3). We consider the "standard" compression case [2], and we assume that the beam after the last bunch compressor (BC2) consists of a linearly compressed (by factor 100) Gaussian bunch with peak current of 5 kA, rms length of 15 μm , and uncorrelated energy spread of 1 MeV.

We reduce the compression by factor 1.7, thus getting 3 kA, 25 μm and 0.6 MeV after BC2. We suppose that an optical replica synthesizer (ORS) [8] is installed after BC2. Then, we modulate the beam in energy, with an amplitude of 100 keV, in the first undulator of ORS by a Ti:S laser with the wavelength of 800 nm and a few MW peak power. When the beam passes the ORS chicane (with $R_{56} = 150 \mu\text{m}$), the energy modulation is converted into 5.5% density modulation.

The radiator of the ORS is not used, and the beam is subsequently accelerated in the main linac from 2 GeV to 17.5 GeV. Due to LSC, an energy modulation of about 1.6 MeV is accumulated at the nominal current of 3 kA. Calculations were performed as described in [9].

We propose to install another chicane (BC3) after the collimation system (see Fig. 3). Setting $R_{56} \simeq 3.3 \text{ mm}$ we can obtain density spikes with a current of about 5.2 kA and full width about 430 nm in overbunched regime.

By varying the compression factor in the main compression system and calculating the current distribution after BC3, one can see from Fig. 4 that the variations of peak current are only a few per cent when the compression factor after BC2 changes by $\pm 30\%$.

The FEL process with our modified beams has been calculated with FAST, taking into account the energy chirp induced by LSC both in front of and in the X-ray undulator. For each $\Delta C/C_0$ in the main compression system we calculated the FEL pulse energy (averaged over an ensemble of shot noise realizations) for a standard compression case and for the case when the stabilization scheme is applied. The results for the end of the exponential gain regime (where the SASE fluctuations are the strongest) are presented in Fig. 5. For fair comparison one should remember that for the same variations of RF parameters, the variations of compression factor are smaller by a factor 1.7 when our scheme is used. Thus, for the same RF jitters one would reduce SASE pulse energy fluctuations (not including intrinsic fluctuations) by a factor 10. Alternatively, one

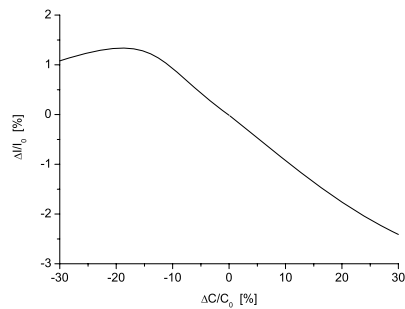


Figure 4: Deviation of peak current after BC3 versus deviation of the compression factor in the main compression system (after BC2).

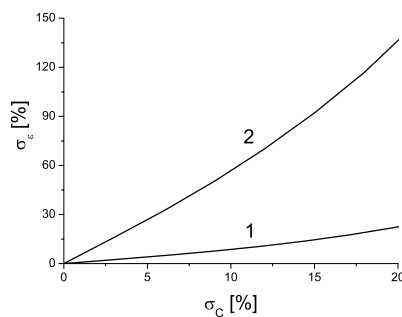


Figure 5: Rms fluctuations of FEL pulse energy at the end of exponential gain regime ($z = 90$ m) versus rms fluctuations of bunch compression factor for two cases. Curve 1: stabilization scheme is applied, curve 2: standard compression scheme. Intrinsic SASE fluctuations are excluded.

can compare RF jitter tolerances for the same SASE fluctuations. For given SASE fluctuations, the ratio of σ_c for the two considered cases is 5–6 in Fig. 5, depending on the allowed σ_e . Thus, in the numerical example considered here, the application of the stabilization scheme would allow to loosen tolerances by a factor of $(5-6) \times 1.7 \simeq 8-10$.

DISCUSSION

In this paper we did not consider enhancement of the current [7], keeping it at the XFEL design value of 5 kA for fair comparison with the standard compression scheme. Note that such an enhancement is easily possible (for instance, just by increasing the compression factor in the main compression system back to its original value, and/or by changing parameters of the optically modulated beam and the chicane). An important feature of our scheme is that the energy modulation due to LSC is much larger (more than factor 10) than that induced by the laser. In other words, the laser power can be reduced by more than two orders of magnitude with respect to a case where no LSC is present.

Also note that we did not consider a specific design of

the chicane. In fact, this might be influenced by coherent (CSR) and incoherent (ISR) synchrotron radiation. The length of the chicane will mainly be determined by ISR effects: for a chosen operating point and the considered R_{56} it cannot be shorter than 15–30 m (but can be reduced for a different operating point, for instance with larger energy spread and modulation). CSR effects on longitudinal and transverse dynamics are greatly reduced due to R_{51} effect, so that, according to our estimates, decrease of the final peak current and increase of emittance are small corrections. Subsequent reduction of the FEL gain can be compensated by an increase of the current as described above.

A possible challenge for the XFEL beam formation system is the LSC driven microbunching instability [10]. A laser heater [10] is supposed to suppress such an instability and it is included in the European XFEL design. It must be remarked that introducing one more chicane, as in our scheme, would increase the microbunching instability gain, so that larger energy spread might have to be generated in the heater. In this case, the R_{56} of the BC3 should be reduced proportionally, and the density modulation generated in the ORS should be increased by the same factor. At the considered operation point the energy spread was smaller than that generated in the undulator due to quantum diffusion and gave very weak correction to the FEL gain. With an increased energy spread the FEL gain reduction can be compensated by a moderate increase of beam current.

Finally, note that the realization of the proposed scheme would automatically allow to use a method for timing an XFEL source to high-power lasers [9]. Since the amplitude of the density modulation necessary in the stabilization scheme is an order of magnitude larger than that used in [9], the power of visible radiation produced after an X-ray undulator would increase by two orders of magnitude.

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