SUPPRESSING SHOT NOISE AND SPONTANEOUS RADIATION IN ELECTRON BEAMS*

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Abstract

Shot noise in the electron beam distribution is the main source of noise in high-gain FEL amplifiers, which may affect applications ranging from single- and multi-stage HGHG FELs [1] to an FEL amplifier for coherent electron cooling [2]. This noise also imposes a fundamental limit of about 10^6 on FEL gain, after which SASE FELs saturate [3]. There are several advantages in strongly suppressing this shot noise in the electron beam, and the corresponding spontaneous radiation. For more than a half-century, a traditional passive method has been used successfully in practical low-energy microwave electronic devices* [4,5] to suppress shot noise. Recently, it was proposed for this purpose in FELs [6]. However, being passive, the method has some significant limitations and is hardly suitable for the highly inhomogeneous beams of modern high-gain FELs. I present a novel active method of suppressing, by many orders-of-magnitude, the shot noise in relativistic electron beams. I give a theoretical description of the process, and detail its fundamental limitation.

INTRODUCTION

According to present understanding of electron beam generation at a cathode, at microscopic scale† the electrons emerge randomly from the cathode's surface. Specifically, for short-wavelengths FELs one can assume that the optical phases of individual electrons at the entrance are random, and, for a sample of N >> 1 of electrons that

$$h^o_\omega = \sum_{n=1}^{N} e^{i\varphi_n}; \quad \sqrt{\left\langle \left| h^o_\omega \right|^2 \right\rangle} = \sqrt{N}, \tag{1}$$

where $\langle a \rangle$ represents the statistical average of the value a. Simply, the total intensity of spontaneous radiation of such beams is proportional to the number of particles in the beam. It also is true about the time-averaged spectral intensity of the radiation:

$$\frac{d\mathcal{E}_\omega}{do \cdot d\omega} = \frac{e^2}{4\pi^2 c} \left| \sum_{n=1}^{N} e^{i\varphi_n} \int e^{i\left(\omega(t-t_n) - \vec{k}\cdot\vec{r}_o\right)} \left[\vec{k} \times d\vec{r}_o\right] \right|^2 \tag{2}$$

where $\mathcal{E}_\omega$ is the spectral density of radiated energy, $\vec{k} = \vec{n} \cdot \omega / c$ is the wave-vector of the radiation, and c is the speed of the light; the remainder of the variables are defined in [8]. The radiation integral is taken along the particle's trajectory $\vec{r}_o(t - t_n)$, where t_n is the arrival time of n-th electron into the radiator.

Generally, while the total integrated power‡ does not fluctuate depending on a random sample of electrons, the spectral density of the radiation fluctuates significantly. This effect, predicted theoretically, was observed experimentally in SASE FELs [9].

In this paper, I initially focus on a simple 1D model and later describe how the results can be applied to systems that are more realistic. A possible experimental test of such suppression is discussed in separate paper at this conference.

REMOVING SHOT NOISE

Being random by the nature, the shot noise cannot be removed by an external action/system whose reaction is independent of the sample. The action must depend upon the sample itself, i.e. information about the sample should be used to act on it.

1D theory

Let us consider a linear analytically solvable 1D high-gain FEL [10,11] with three well-defined eigen modes and eigen vectors for each Fourier harmonic component of the three-vector $[\mathrm{E}]_\nu^T = \{\tilde{E}_\nu, \tilde{E}'_\nu, \tilde{E}''_\nu\}$:

$$[\mathrm{E}]_\nu(\hat{z}) = \sum_{n=1}^{3} A_n \cdot [\mathrm{Y}_n(\nu)] e^{\lambda_n(\nu)\hat{z}} \tag{3}$$

where, $\tilde{E}_\nu$ is Fourier component of transverse (optical) electric field, A_n is a complex amplitude of the nth mode, $f' = df/d\hat{z}$, $\nu = \omega/\omega_r$ is the normalized frequency to the FEL resonance, and $\hat{z} = \Gamma z$ is the distance normalized to the 1D FEL growth length. Further§, the eigen functions $\tilde{\mathrm{Y}}_n(\nu,\hat{z}) = [\mathrm{Y}_n(\nu)] e^{\lambda_n(\nu)\hat{z}}$ satisfy a self-consistent third-order homogeneous differential equation [11], and the values are the solution of a simple cubic equation [12]:

$$\lambda\left(\left(\lambda + \hat{q} + i\hat{C}\right)^2 + \hat{\Lambda}_p^2\right) = i, \tag{4}$$

where $\hat{q} = \sigma_E / \rho E_o$ is the normalized energy spread, $\hat{C} = (1-\nu)/\rho\nu$ is normalized detuning from the FEL resonance, and $\hat{\Lambda}_p = \Lambda_p / \Gamma$ is the normalized space-charge (plasma wave-number) parameter (see [3] for details of definitions). Typically, (see Fig.1) only one of the eigen values has positive real part**, i.e., two other

* I.e., waiting for plasma oscillation to transfer shot noise in the density shot noise into the velocity spread. This technique is very successful for low-energy DC beams with constant peak current.

† i.e. at the scale mush shorter than correlation between electrons, such bunch length or Debay length [7].

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‡ i.e. integrated over the angles and the frequency

§ True for a Lorentzian energy-distribution in the beam, see [3], p.31

** For generality, I note that I am interested only in eigen solution whose growth rate is maximal. The rest of the eigen modes either decay or eigen solutions either decay or simply oscillate without amplification. For an FEL with a high gain, the weak decaying and oscillating terms can be neglected, and focus placed on the growing one, whose eigen value is chosen as λ_1.

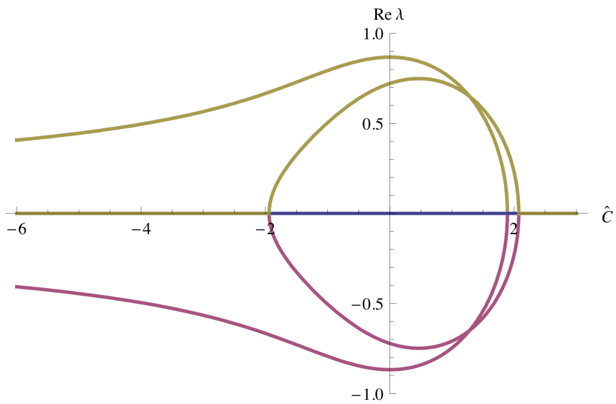

Figure 1: Real part of eigen values for $\hat{\Lambda}_p = 0$ and $\hat{\Lambda}_p = 0.5$ as functions of the detuning $\hat{C}$

Initial conditions at the entrance to the FEL-amplifier defining the Fourier content are the density modulation, energy modulation[††], and the EM field. In turn, these values determine the initial value of three-vector $[E_\nu(0)]$ through a set of self-consistent Vlasov-Maxwell equations. For example [13], the density (current) is connected directly with the first derivative of the electric field:

$$\tilde{E}_\nu{}'(z) = -\frac{2\pi}{c}\frac{K_w}{\gamma}\cdot\tilde{j}_\nu(z)$$

from where we can find $\tilde{E}_\nu{}'(0)$. Similarly, the second derivative connects with the initial conditions, details of which are given in [3].

In short, at the entrance of the FEL the amplitudes of the eigen modes can be found from a simple matrix inversion of eq. (3) at *z=0*:

$$[A]_\nu = [Y]^{1}\cdot[E]_\nu(0); \quad [Y] = \{Y_1, Y_2, Y_3\}. \quad (5)$$

Because I am interested only in the growing eigen vector, only A_1 is need to be known which is a linear combination of the initial conditions:

$$\begin{aligned} A_1(\nu) &= a_1\cdot\tilde{E}_\nu(o) + a_2\cdot\tilde{E}'_\nu(o) + a_3\cdot\tilde{E}''_\nu(o) \\ &= b_1\cdot\tilde{E}_\nu(o) + b_2\cdot j_\nu(o) + b_3\cdot\varepsilon_\nu(o) \end{aligned} \quad (6)$$

grow much more slowly than the dominant mode. This connects the 1D case with a generic 3D case.

[††] With a distribution function $F = F(\varepsilon, t, z=0)$, the harmonic of density modulation is defined as $n_\omega = \int e^{-i\omega t}dt \int F(\varepsilon,t,0)d\varepsilon$ and is directly connected to the current modulation, $\tilde{j}_\omega = e\mathrm{v}_z\cdot n_\omega\cdot\gamma/K_w$. The energy modulation $\varepsilon_\omega = \int e^{-i\omega t}dt\int \varepsilon\cdot F(\varepsilon,t,0)d\varepsilon$ is the Fourier harmonic of first moment of **F**.

Thus, eq. (6) represents the amplitude of the noise at the entrance of the FEL, which will be amplified, in some cases, to the decrement of usefulness of the FEL. For example, it would limit the attainable FEL gain to a few millions in power, and/or to a few thousands in amplitude[‡‡], because the amplified spontaneous radiation (viz., A_1) will saturate the FEL [14].

Furthermore, setting $A_1 = 0$ will remove the noise, and theoretically convert FEL into a noise-free amplifier whose gain is limited only by its length.

Let us discuss how this can be achieved in principle:

a) In normal systems there is no seed noise at the FEL entrance, i.e.. $\tilde{E}_\nu(o) = 0$

b) To eliminate the linear combination of the shot-noise in the density and the energy modulation.

We start from a system that can eliminate density modulation in the beam.

Suppressing the density noise

Here, I consider the simple case of a shot-noise suppressor shown in Fig. 2. This system, which at a first sight seems similar to one proposed for optical stochastic cooling (OSC) [15,16], has very different physics and functionality. In contrast to OSC, the self-interaction of a particle with its own radiation is not important in this scheme, while interaction with its neighbors, which is harmful in OSC, plays the key role and is the most important effect.

Briefly, the suppressor works as follows: The electron beam passes through the first wiggler where it spontaneously emits radiation proportional to the local values of shot noise.

This radiation goes through a high-gain, broadband laser amplifier. In the second wiggler, an electron interacts with the amplified radiation induced by the neighboring electrons, and accordingly, its energy is changed.

The energy change is transferred in a microscopic phase-shift (arrival time) in a buncher. The sum of these microscopic shifts with amplitudes of $\Delta\varphi_n = \omega\cdot\Delta t_n \propto 1/\sqrt{N}$ is equal to the amplitude and is opposite in sign to the initial shot-noise harmonic. The outcome is the suppression of this harmonic in the beam's density.

A simplified mathematical model of the process can be used, wherein (a sample of) N mono-energetic electrons interact with each other in the system[§§].

[‡‡] The amplitude of the saturation gain is estimated easily from first principles: let's consider an ensemble of $N \sim 10^6$ -10^8 particles in the coherence length of SASE FEL. The initial relative density modulation coming from the shot noise if $\delta n/n \sim 1/\sqrt{N}$ can be linearly amplified only to the level of $\delta n/n \sim 1$. This limits the gain to $g_{\max} < \sqrt{N}$.

[§§] i.e. they are within the correlation length of the radiation and interaction in the system, where they receive kicks from the fields induced by each other

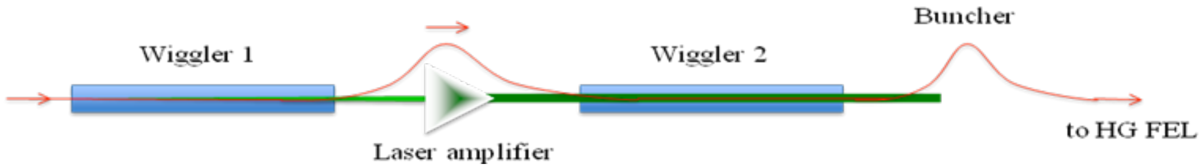

Figure 2: Layout of possible shot-noise suppressor based on a broad-band laser amplifier [17].

The complex amplitude of the amplified field of the spontaneous radiation from such a system is a direct linear superposition of the complex amplitudes of individual particles:

$$E = \mathrm{Re}\left(ae^{i\omega t}\right);\quad a = a_o \sum_{n=1}^{N} e^{i\varphi_n} \tag{7}$$

where a_o is the amplitude of the electric field from a single electron that combines both the processes of radiation from the wiggler and the laser's amplification***. In the second wiggler, the electron's energy will change accordingly with its interaction with the field:

$$\frac{d\mathrm{E}_n}{dz} = -eE(t_n)\cdot x'(z) \tag{8}$$

where $-e$ is the charge of the electron, $x(z)$ is the transverse trajectory of electrons in the wiggler. The resulting energy kick is

$$\delta \mathrm{E}_n = -ea_o L_w \cdot \frac{K_w}{2\gamma} \cdot \mathrm{Im}\sum_{m=1}^{N} e^{i(\varphi_n - \varphi_m)} \tag{9}$$

where K_w is the wiggler parameter, L_w is its length, and $\gamma = \mathrm{E}/mc^2$ is the relativistic factor of electrons. While passing through a buncher with longitudinal dispersion $D = -\frac{c\cdot dt_{buncher}(\mathrm{E})}{d\ln \mathrm{E}}$ the optical phase of each electron is adjusted by

$$\delta\varphi_n = g_o \cdot \mathrm{Im}\sum_{m=1}^{N} e^{i(\varphi_n-\varphi_m)};\ g_o = \frac{kD\cdot ea_o L_w \cdot K_w}{2\gamma^2 mc^2} \tag{10}$$

resulting in the harmonic modification to

$$h_\omega = \sum_{n=1}^{N} e^{i(\varphi_n+\delta\varphi_n)} \cong \sum_{n=1}^{N} e^{i\varphi_n}\left(1+i\delta\varphi_n\right)$$

wherein I used the fact that $|\delta\varphi_n| << 1$:

$$h_\omega = \sum_{n=1}^{N} e^{i\varphi_n} + \frac{g_o}{2}\sum_{n=1}^{N}\sum_{m=1}^{N} e^{i(2\varphi_n-\varphi_m)} - \frac{g_o}{2}\sum_{n=1}^{N}\sum_{m=1}^{N} e^{i\varphi_m} = \left(1-\frac{g_o N}{2}\right)\cdot h_\omega^o + \frac{g_o}{2}\sum_{n=1}^{N}\sum_{m=1}^{N} e^{i(2\varphi_n-\varphi_m)}. \tag{11}$$

where h_ω^o is the density harmonic at the entrance of the system (eq. (1)) The first term in eq. (11) denotes the correlated reduction of the shot-noise. Choosing $g_o = 2/N$ reduces remaining shot-noise level to

$$h_\omega = \frac{1}{N}\sum_{n=1}^{N}\sum_{m=1}^{N} e^{i(2\varphi_n-\varphi_m)}. \tag{12}$$

A simple evaluation of eq. (12) reveals that

$$\sqrt{\left\langle |h_\omega|^2 \right\rangle} = 1 \tag{13}$$

i.e., such system will reduce the amplitude of shot-noise by the factor $\sqrt{N}$, and the power of shot-noise (spontaneous radiation) by a factor of N.

Therefore, this proposed noise-suppression scheme offers the potential of reducing power of the shot nose by four-to-eight orders-of-magnitude.

Effect of energy spread in the electron beam

Let us consider that the electron beam has a Gaussian energy-distribution with relative RMS energy-spread of σ_δ:

$$f(\delta) = \frac{1}{\sqrt{2\pi}\sigma_\delta}\exp\left(-\frac{\delta^2}{2\sigma_\delta^{\ 2}}\right);\quad \delta = \frac{\mathrm{E}-\mathrm{E}_o}{\mathrm{E}_o}. \tag{14}$$

The phase change in the buncher eq. (10) will have an additional term related the initial energy deviation of the n^th electron δ_n^o

$$\delta\varphi_n = g_o \cdot \mathrm{Im}\sum_{m=1}^{N} e^{i(\varphi_n-\varphi_m)} + kD\cdot\delta_n^o. \tag{10'}$$

The evaluation of modified eq. (11) is similar to that used in theory of optical klystron [18] giving

$$h_\omega = \left(1-\frac{g_o N}{2}e^{-\frac{(kD\sigma_\delta)^2}{2}}\right)\cdot h_\omega^o + noise \tag{11'}$$

i.e., the effect remains similar, with slight modification of the required gain $g_o = 2e^{\frac{(kD\sigma_\delta)^2}{2}}/N$ and of residual shot-noise.

Effect of the energy spread noise

Even though many arguments hold that the shot-noise in the energy distribution of electron beam is less important than that in the density distribution (in [6] and references thereof), there are no conceptual problems with accounting for its effect in the proposed scheme. As discussed in the previous paragraph, a propagating electron beam through a buncher with longitudinal dispersion D_B will change its optical phase by $\delta\varphi_n = kD_B\cdot\delta_n^o$, i.e., it will introduce the

*** For simplicity I consider a planar wiggler, i.e., the E-field has only one component. Finding a_o is a trivial but elaborate task. Hence, details are not given here.

corresponding density noise even in a completely quiet beam:

$$h_\omega^\delta = \sum_{n=1}^{N} e^{ikD_B\cdot\delta_n^o}; \quad (1')$$

Therefore, adding an additional buncher, phase-shifter and, if necessary another wiggler and amplifier, will ensure that at the exit of such s system there is no shot-noise in the amplified mode:

$$\mathrm{A}_1(\nu) = b_2\cdot j_\nu(o) + b_3\cdot\varepsilon_\nu(o) = 0. \quad (6')$$

Time-domain (finite bandwidth) considerations

Up to now, I have focused on a single frequency, taking it for granted that the shot-noise can be suppressed in a rather wide bandwidth that includes the FEL gain bandwidth. Even though this issue can be discussed in terms of the frequency domain, considering the time domain is much more illustrative and also more elegant. In a linear system, both the FEL and the shot-noise suppressor can be described by a Green-function, which describes reaction of the system on a single electron (here and later in the text, N is the total number of electrons in the bunch)†††:

$$\delta\varphi_n = \sum_{m=1}^{N} K_{NS}(\varphi_n-\varphi_m); \quad E_{FEL}(\varphi) = E_o\sum_{m=1}^{N} K_{FEL}(\varphi_m-\varphi); \quad (15)$$

$$K_{NS} = \mathrm{Im}\left[A_{NS}(\varphi)e^{i\varphi}\right] \quad K_{FEL} = \mathrm{Re}\left[A_{FEL}(\varphi)e^{i\varphi}\right] \quad \left|\frac{d}{d\varphi}\ln A\right| << 1,$$

wherein the complex amplitudes A (envelopes) are slow-varying functions (see example in Fig.3).

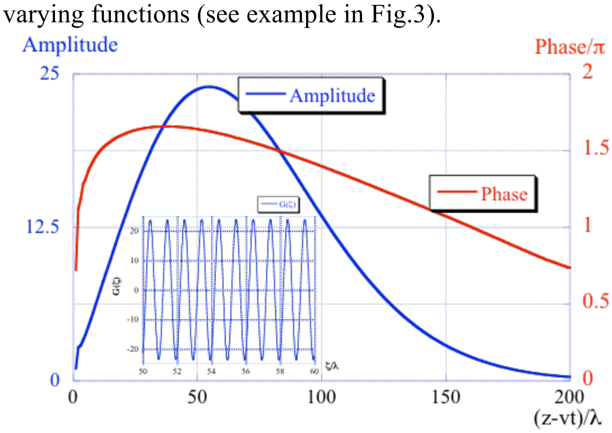

Figure 3: Sample Green-function of an FEL amplifier [2].

Following the method used in the previous section, I calculate both the amplitude and the power of radiation from such a system:

$$E = E_o\,\mathrm{Re}\sum_{n=1}^{N} A_{FEL}(\varphi_n-\varphi)e^{i(\varphi_n-\varphi)}\left(1 + i\,\mathrm{Im}\sum_{m=1}^{N} A_{NS}(\varphi_n-\varphi_m)e^{i(\varphi_n-\varphi_m)}\right) \quad (16)$$
$$+ O(A'_{FEL}\delta\varphi)$$

Opening the *Im*, combing the terms, and changing the summation index yields the following term for suppressing shot-noise:

$$h_{sr} = \sum_{n=1}^{N} e^{i(\varphi_n-\varphi)}\left(A_{FEL}(\varphi_n-\varphi) - \frac{1}{2}\sum_{m=1}^{N} A^*{}_{NS}(\varphi_m-\varphi_n)\cdot A_{FEL}(\varphi_m-\varphi)\right) \quad (17)$$

There also is a non-removable shot-noise similar to that shown in eq. (12)

$$c = \sum_{n=1}^{N} A_{FEL}(\varphi_n-\varphi)\frac{e^{-i\varphi}}{2}\sum_{m=1}^{N} e^{i(2\varphi_n-\varphi_m)}A_{NS}(\varphi_n-\varphi_m),$$

which is of the same order as in eq(13) with $|h_\omega| \sim 1$.

Evaluating the RMS value of eq. (17) gives the following:

$$\left\langle |h_{sr}|^2\right\rangle = \sum_{n=1}^{N}\int d\varphi\left|A_{FEL}(\varphi) - \eta\int A^*{}_{NS}(\chi)\cdot A_{FEL}(\varphi+\chi)d\chi\right|^2 \quad (18)$$

where η is the number of electrons per a half of radian of the optical phase. In general, this suppression is trivially calculated numerically for a specific case. Analytically, a broad-band shot-noise suppression can be considered, with a symmetric Gaussian Green-function:

$$A_{NS}(\varphi) = \frac{\alpha}{\sqrt{2\pi}\sigma_\varphi}\cdot\exp\left(-\frac{\varphi^2}{2\sigma_\varphi^2}\right)$$

where σ_φ is its RMS length (in terms of optical phase). Further, I assume that HG FEL Green function is significantly longer than σ_φ. Expanding A_{FEL} $A_{FEL}(\varphi+\chi) = A_{FEL}(\varphi) + A'_{FEL}\chi + A''_{FEL}\chi^2/2 + O(\chi^3)$ allows reducing eq. (18) to

$$N\cdot\int d\varphi\left|A_{FEL}(\varphi)(1-g) + gA''(\varphi)\frac{\sigma_\varphi^2}{2}\right|^2; g = \alpha\eta; \quad (19)$$

with optimal value of g determined by

$$g = \frac{\int |A_{FEL}(\varphi)|^2 d\varphi - \sigma_\varphi^2/2\int A_{FEL}(\varphi)A''^*(\varphi)d\varphi}{\int |A_{FEL}(\varphi)|^2 d\varphi - \sigma_\varphi^2\,\mathrm{Re}\int A_{FEL}(\varphi)A''^*(\varphi)d\varphi + \sigma_\varphi^4/4\int |A''(\varphi)|^2 d\varphi}.$$

In the incompletely optimized test case of $g = 1$, the suppression of shot noise is given by

$$R = \frac{\sigma_\varphi^4}{4}\frac{\int d\varphi|A''|^2}{\int d\varphi|A|^2} \le \frac{1}{4}\left(\frac{\sigma_\varphi}{\sigma_{FEL}}\right)^4 \quad (20)$$

where σ_{FEL} is the RMS duration of the FEL Green-function. Optimization supports an additional factor of two- to-four reduction in noise beyond eq. (19). For FEL response in Fig. 3 $\left\langle |A|^2\right\rangle / \left\langle |A''|^2\right\rangle \cong 1.3\cdot 10^9$, and a noise suppressor with 5% relative RMS bandwidth (12% FWHM), i.e. $\sigma_\varphi = 20$, eq.(20) yields $1/R \cong 3.3\cdot 10^4$, i.e. one can expect suppression of the power of SASE emissions by a factor ~ 10^4.

DISCUSSION

3D FEL effects

While the time-correlation issues described in the previous section are fully applicable to a real 3D FEL case, the transverse dimension adds degrees of freedom. Typically, there is a dominant transverse mode (looking-like TEM_{oo}) that has a maximum growth increment. I assume that the dominant mode is used to amplify the signal of interest; for example, a weak seed-wave from

††† Adding energy deviations (noise) is a trivial extension and omitted here for compactness

external laser, or density modulation from a modulator in the CeC scheme. For the dominant mode, one finds (numerically in practice) the analog of eq. (6) and sets $A_1 = 0$. This will suppress SASE radiation in the dominant mode, but the other modes would not necessarily exhibit similar suppression of shot noise, and could grow, though at lower increments, and might interfere with the amplified seed.

The way around this problem lies in exploiting the fact that the other modes have larger transverse extents, and so can be collimated.

Sensitivity to beam parameters

In practice, the longitudinal beam density (i.e. peak current) is not uniform, and therefore, noise reduction may not extend throughout the entire bunch. Naturally, the focus of the noise compensation should be on the portion of the beam where FEL gain is maximal. To suppress SASE power by a factor of 100, the peak current should remain within ± 10% of the range of interest (the seed location). Suppression by 10,000 will require establishing a challenging ±1% stability of the beam current. Surprisingly, these requirements are very similar to those needed for single- and multi-stage seeded HGHG FEL amplifiers.

For example, ±10% variation of peak current a single-stage seeded FEL amplifier with gain of 10^6 will cause three-fold shot-to-shot fluctuations of the delivered power. In three-stage seeded amplifier, these fluctuations would grow to about 40-fold, and render questionable the usefulness of such a source.

More reasonable performance of such devises can be attained with ±1% variation of peak current. In a single-stage seeded FEL amplifier with gain of 10^8 this will entail reasonable ±7% shot-to-shot power fluctuations. Even in a three-stage HGHG seeded amplifier, fluctuation would be about ±25%.

Therefore, the requirements on the beam parameters for high-gain seeded FEL amplifiers are similar to those needed for effectively suppressing shot-noise.

To prevent the unused portion of the beam from radiating and amplifying undesirable SASE power, one of the time-resolving suppression techniques can be employed, such as local laser-heating [19].

Very short wavelengths

So far I discussed using an external broad-band laser amplifier to suppress the shot-noise and spontaneous radiation at the laser's frequencies. While low-noise high-gain lasers are available from near-IR to UV-ranges of spectra, there are none in the X-UV and X-ray spectral ranges. Meanwhile, the main interest for seed amplification is the very short (X-ray) wavelength range. An important question is whether my suggested mode of suppression can be extended to wavelengths beyond reach of conventional laser-amplifiers? I believe it can be done in two ways:

1. Compression

One possible scenario is to use a visible/near IR shot-noise suppressor at the intermediate stage of electrons' acceleration in HG FEL system where the electron beam is long. Longitudinally compressing the beam will compress proportionally the wavelength at which the shot-noise is suppressed. Hence, using 1 μm shot-noise suppressor, followed by 1,000 compression of the electron beam can curtail shot noise and SASE at 1nm.

2. Using pre-amplifying DOK-FEL

This DOK-FEL shot-noise-suppression system potentially is very versatile, indeed, as flexible as the FELs themselves. Such a system combines up to three wigglers and bunchers/phase shifters. It also may require a methodology for delaying optical radiation: using grazing reflection optics is one possibility. The goal of such system is to excite and control amplitudes and phases of radiation, density, and energy harmonics to ensure that the amplitude of the dominant mode eq.(6) is zero. While it is, in principle, similar to the system discussed in this paper, details of DOK-FEL shot-noise suppressor system are elaborate and well beyond the scope of this short paper.

Proof-of-principle

I have suggested approach that may offer very significant suppression of spontaneous radiation in 3D FEL. While it seems feasible, its performance and applicability should be evaluated properly. Hence, this is one of the reasons we propose a proof-of-principle experiment using elements of the VISA FEL at BNL's Accelerator Test Facility [20].

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