LONGITUDINAL COHERENCE IN AN FEL WITH A REDUCED LEVEL OF SHOT NOISE

Vitaliy Goryashko*, Volker Ziemann
Uppsala University, Sweden

Abstract

For a planar free electron laser (FEL) configuration we study self-amplified coherent spontaneous emission driven by a gradient of the bunch current in the presence of different levels of noise in bunches. We calculate the probability density distribution of the maximum power of the radiation pulses for different levels of shot noise. It turns out that the temporal coherence quickly increases as the noise level reduces. We also show that the FEL based on coherent spontaneous emission produces almost Fourier transform limited pulses and the time-bandwidth product is mainly determined by the bunch length and the interaction distance in an undulator. We also propose a scheme that permits the formation of electron bunches with a reduced level of noise and a high gradient of the current at the bunch tail to enhance coherent spontaneous emission. The presented scheme uses effects of noise reduction and controlled microbunching instability and consists of a laser heater, a bunch compressor, and a shot noise suppression section. The noise factor and microbunching gain of the overall proposed scheme with and without laser heater are estimated.

INTRODUCTION

Longitudinal (temporal) coherence of free-electron lasers (FELs) is important for a number of applications like coherent scattering, time-resolved spectroscopy, nonlinear science. Most existing short wavelength FELs are operated as single pass amplifiers so that the coherence of FEL output strongly depends on the coherence of an effective input signal. The latter can be a gradient of density or velocity modulations in electron bunches, or an external electromagnetic signal. In SASE FELs the gradient of electron density is caused by shot noise so that shot noise in electron bunches plays a role of an ultra-wide band effective seed. But shot noise has a random nature and as a result the output of SASE FEL is stochastic and presented by a series of random superradiant spikes with a large variation of intensities [1]. In order to mitigate this drawback and reach longitudinal coherence, a number of techniques like seeding with external quantum lasers, self-seeding and high-brightness SASE FELs [2] based on bunch-radiation manipulations were proposed. The idea of seeding techniques is to achieve the dominance of an initial coherent signal over an incoherent one at the FEL start-up. The input signal-to-noise ratio along with the FEL process define the longitudinal coherence at the output.

In order to reach high coherence with external seeding schemes, the energy of an external seed laser up to several millijoules [3] is typically required. That is achievable by commercially available quantum lasers. But the capability of seeding with a high repetition rate is questionable. For example, for FELs based on superconducting technology like the European XFEL, the energy of a quantum laser has to be of the order of kJ per second. This implies a laser system that is well beyond the existing state-of-the-art lasers. Then, it is beneficial to reduce an incoherent signal at the FEL start-up and correspondingly reduce the required coherent seed power. As we mentioned, the main contribution to the incoherent effective input signal comes from shot noise, so the latter must be suppressed.

To mitigate the shot noise effect several techniques have been proposed and FELs with a reduced level of shot noise are under active study [4, 5, 6]. At the same time, to the authors' knowledge only a linear theory of such FELs have been published. The problem to what extent the bunch noise has to be suppressed in order to obtain well-determined radiation pulses requires further studies and we address this question in our paper.

We study how the coherence of an effective input signal affects the FEL output coherence on the example of an FEL having an essential level of coherent spontaneous emission (CSE) and different levels of shot noise. Recall that the total spontaneous radiated power at wavenumber k is

$$P_{\text{spontaneous}}(k) = Q_b P_{\text{und}}(k) + Q_b^2 |F(k)|^2 P_{\text{und}}(k), \quad (1)$$

where the first term is the contribution from shot noise whereas the second one is that from coherent spontaneous emission. Here, Q_b is the number of electrons in a bunch, $P_{\text{und}}(k)$ is the power emitted by a single electron in an undulator, $F(k)$ is the bunch form-factor (Fourier transform of the longitudinal electron density) that at given wavelength depends on the bunch length and the gradient of the bunch current. By changing the level of shot noise one modifies the first term in (1) and changes the coherence of the FEL output radiadion.

SELF-AMPLIFIED COHERENT SPONTANEOUS EMISSION

We analyse the properties of an FEL with a reduced level of shot noise using a 1D approximation for the electron bunch but still consider the longitudinal discreteness of the electrons and employ a non-averaged FEL model [7], [8]. The dependence of the bunch current and excited radiation field on the transverse coordinates is ignored in this approach. However, the 3D effects are taken into account in a phenomenological way by using an effective value of

* vitaliy.goryashko@physics.uu.se; vitgor06@gmail.com

ISBN 978-3-95450-126-7

Copyright © 2013 CC-BY-3.0 and by the respective authors

the FEL parameter $\rho_{\rm eff}$ calculated with Xie's fitting formula. Xie's formula accounts for the effects of emittance ('matched' bunch focusing is assumed in what follows), energy spread as well as for diffraction. The latter turns out to be the most severe factor of degradation of the FEL process such that the effective 3D FEL parameter $\rho_{\rm eff}$ is almost two times smaller than the 1D FEL parameter ρ.

The coherent spontaneous emission originates from the gradient of the beam current and reaches its maximal value for the current distribution of a rectangular shape. Although the rectangular current distribution is an idealized case, it makes the result more universal so we will adopt this approximation for our analysis. The impact of a finite rise time of the front of a current pulse can be estimated for a desired bunch current gradient by calculating an effective initial signal-to-noise parameter and comparing with the results presented below. The main parameters of the bunch and studied FEL are listed in Tables 1 and 2. The peak and

Table 1: Bunch Parameters After Bunch Compression

Parameter	Symbol	Value
Electron energy	$\gamma_r m_e c^2$	250 MeV
Bunch peak current	I_0	350 A
Transverse rms size	σ_b	55 µm
Energy spread	$\sigma_\gamma m_e c^2$	64 keV
Normalized emittance	ε_n	0.36 mm·mrad
Bunch duration	T_b	190 fsec

Table 2: Main Parameters of the FEL

Parameter	Symbol	Value
Undulator period	λ_u	4 cm
Undulator parameter	$\mathcal{K}$	3.2
Number of undulator periods	N_u	200
FEL wavelength	λ_r	0.511 µm
FEL parameter	ρ	0.0095
Cooperation length	L_c	4.29 µm
Gain length	ℓ_g	33.57 cm
Normalized bunch length	τ_b	13.3
Effective FEL parameter	ρ_{ef}	0.0053

average normalized radiation powers $|F|^2$ as a function of the interaction distance along the undulator are shown in Fig. 1. Here, $|F|^2 \propto P_{rad}/\rho_{\rm eff} P_{beam}$ with P_{rad} and P_{beam} being the radiation and peak electron beam powers, respectively. The peak radiation power is mainly determined by CSE whereas the average power strongly depends on shot noise. From Fig. 1 one can see that the low-gain regime extents to around $30\lambda_u$, the high-gain interaction occurs approximately in the region from $30\lambda_u$ to $80\lambda_u$ and the FEL saturates beyond this region. The dependence of power on time for different positions in undulator with and without shot noise in the electron bunch are presented in Fig. 2.

At the FEL start-up the interference of elementary electromagnetic impulses emitted by uniformly distributed electrons results in a series of radiation pulses that are one

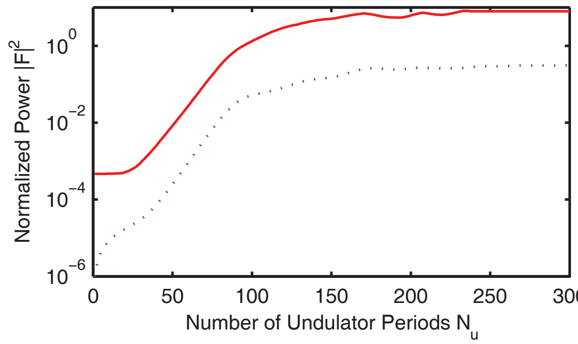

Figure 1: The peak (solid red curve) and average (dotted blue curve) power as a function of the undulator distance.

cycle in duration (plot for $N_u = 10$ in Fig. 2). This series of EM pulses results in a single wide pulse at the end of the high-gain regime (plot for $N_u = 100$ in Fig. 2) because of dispersion caused by the presence of the electron bunch. In the nonlinear regime (plots for $N_u = 200$ and $N_u = 300$ in Fig. 2) the radiation pulse has a clear spike with a duration

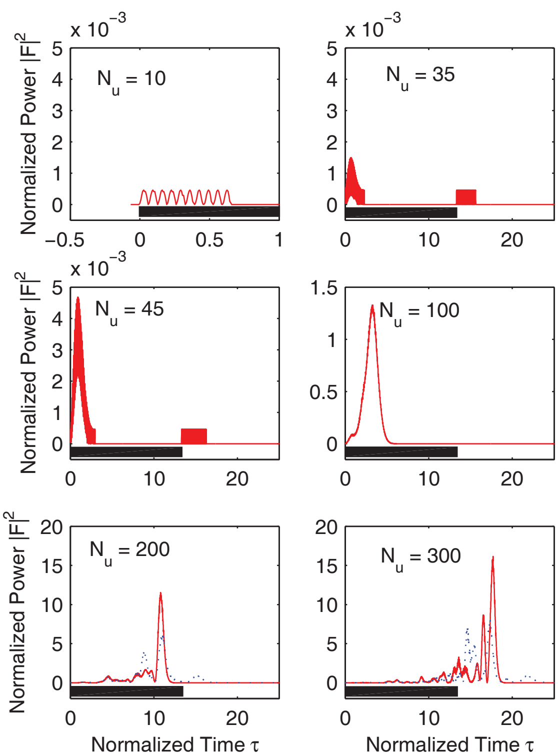

Figure 2: Normalized power vs. normalized time at different longitudinal positions in the undulator. The solid red curves depict the results for simulations without shot noise whereas the dotted blues curves depict the simulations that take into account shot noise. The arrival time of electrons is shown by the black boxes lying under the abscissas. Note that there are different scales on the plots.

Copyright © 2013 CC-BY-3.0 and by the respective authors

ISBN 978-3-95450-126-7

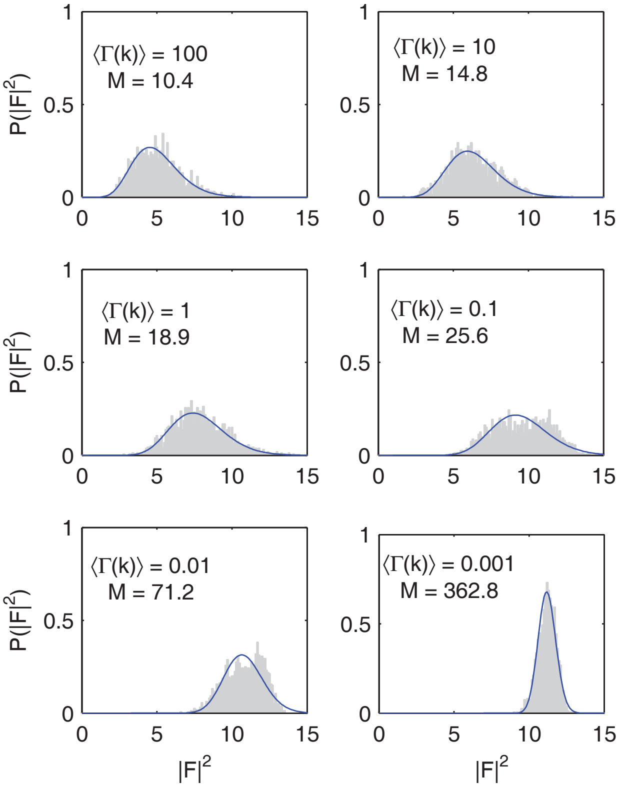

Figure 3: Histograms of the probability density distribution, $p(|F|)^2$, of the normalized maximal power $|F|^2$ for different levels of noise. The solid blue curves represent corresponding Gamma distributions. Calculations have been performed with 1600 statistically independent simulations.

of the order of the cooperation length. The maximum physical power is around 5.5 GW and the energy stored in the main radiation spike is some 100 µJ. Whereas shot noise has a negligible effect on the radiation pulse shape at the low-gain, in the high-gain regime it results in a substantial distortion of the radiation pulse and reduction of the emitted power in the nonlinear regime.

To characterize the level of noise at wavenumber k, we will follow Ref. [9] and define the noise factor as

$$\Gamma(k,z) = \frac{1}{Q_b} \sum_{q,p} e^{ik[s_q(z)-s_p(z)]}, \qquad (2)$$

where $s_q(z)$ is the longitudinal bunch coordinate of particle q at position z in the undulator and $k = 2\pi/\lambda$ is the wavenumber. If the particle positions are uncorrelated, this results in $\langle\Gamma(k,z)\rangle = 1$, where $\langle\ldots\rangle$ stands for the statistical averaging. The situation $\langle\Gamma(k,z)\rangle < 1$ corresponds to the case of anticorrelated ('quiet') bunches. In the case of microbunching instabilities $\langle\Gamma(k,z)\rangle \sim G$, where G is the microbunching gain.

In order to study the effect of noise on FEL performance, we have calculated the probability density distribution of the maximum power in the radiation pulse for different values of the noise factor $\langle\Gamma(k)\rangle$, see Fig. 3. Recall that the normal level of shot noise corresponds to $\langle\Gamma(k)\rangle = 1$. It turns out that just as for the SASE FEL the envelope of the probability density distribution of the self-amplified CSE pulses can be accurately approximated by the Gamma distribution with an appropriate value of the M parameter as it is shown in the same Fig 3. The M parameter is defined as $1/\sigma^2(|F_{\max}|^2)$, where $\sigma^2(|F|^2)$ is the relative dispersion of the normalized power of radiation pulses. As the noise level decreases the M parameters increases and the probability density distribution tends to a Gaussian distribution.

As one can see in Fig. 4 the noise reduction is accompanied by an increase in the mean maximum power $\mathrm{E}(|F_{\max}|^2)$ and by a decrease in the rms width $\sigma(|F_{\max}|^2)$ of distribution function of the normalized maximum power. It turns out that for $\langle\Gamma(k)\rangle \ll 1$, $\sigma(|F_{\max}|^2)$ is proportional to $\langle\Gamma(k)\rangle^{1/3}$. The decrease of $\sigma(|F_{\max}|^2)$ is of importance since the rms width of the distribution function directly determines the FEL coherence. Namely, $\sigma(|F|^2)$ is related to the second-order correlation function of zero argument, $g_2(0)$, by [1]

$$g_2(0) = 1 + \sigma(|F|^2). \qquad (3)$$

It follows from the theory of statistical optics that the cases of $g_2(0) = 1$ and $g_2(0) = 2$ correspond to stabilized single-mode laser radiation and to completely chaotic radiation from a thermal source, respectively. As the noise factor decreases $g_2(0)$ tends to unity. For example, given $\langle\Gamma(k)\rangle = 10^{-3}$ the normalized rms deviation of the maximal power is 5.25% and $g_2(0) \approx 1.003$. Thus, quiet bunches produce near single-mode pulses.

The Fourier transform limited pulses are important in many applications and it turns out that an FEL based on CSE is capable of producing such pulses. We found that the time-bandwidth product (defined in this paper as a product of the pulse rms width in the time domain, σ_f, and the pulse rms width in the frequency domain, σ_t) depends weakly on the noise level and is close to unity in the nonlinear regime. We also found that the time-bandwidth product is mainly determined by the bunch length and strongly depends on the interaction distance. It attains its minimal value ap-

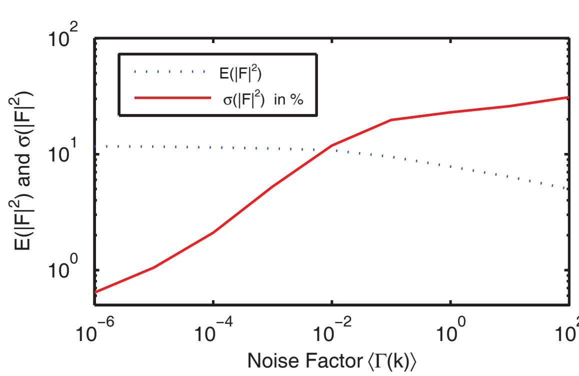

Figure 4: The mean and standard deviation of $|F|^2$ versus noise factor. Both axes are in a logarithmic scale.

ISBN 978-3-95450-126-7

Copyright © 2013 CC-BY-3.0 and by the respective authors

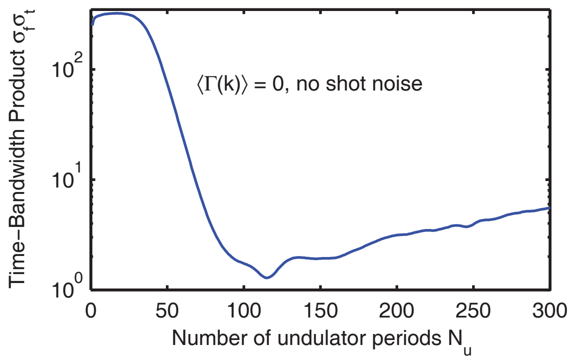

Figure 5: The time bandwidth product vs. undulator distance. There is no shot noise in the simulations.

proximately at the beginning of the nonlinear stage of the bunch-wave interaction as one can see in Fig. 5.

SHOT NOISE SUPPRESSION AND CONTROLLED MICROBUNCHING

CSE is driven by the gradient of the bunch current and bunches with a steep rise of the electron density at the tail are preferable to drive the FEL. To create such bunches also having a reduced level of noise we propose the scheme shown in Fig. 6 that uses effects of noise reduction and controlled microbunching instability in a way similar to the longitudinal space charge amplifer [10], and consists of a laser heater, a bunch compressor as well as a shot noise suppression section. First, the bunch passes through the laser heater and bunch compressor. In our scheme the tail of the bunch is sensitive to the microbunching instability whereas the main core of the bunch is stable against the instability. This is realized by using a laser heater with a partial overlap between the electron and laser pulses such that the bunch tail remains unheated. Then, in the bunch compressor the bunch undergoes the longitudinal compression and the microbunching of its tail occurs as well. In Fig. 7 we present the results of calculations of the microbunching gain for the system with and without laser heater. Without heating of electrons, an appreciable microbunching gain is observed approximately at a compressed wavelength of 2.7 μm. Therefore, if we modulate the bunch tail with a period of around 40 μm (the compression factor is 16) by means of a photocathode laser (or laser modulator), then we

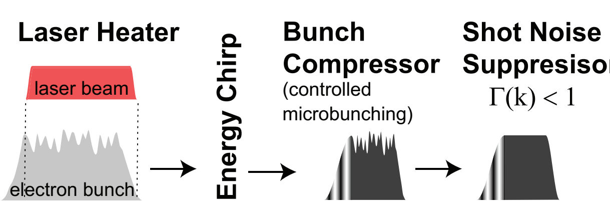

Figure 6: The schematic illustration of a possible formation of the 'quiet' bunch with a high current gradient at the bunch tail.

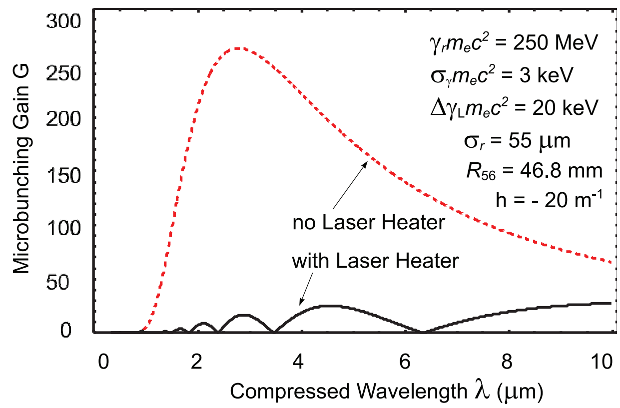

Figure 7: Microbunching gain vs. wavelength after compression with and without taking into account the effect of the laser heater.

have the microbunched tail resulting in a steep variation of the electron density.

Downstream the bunch compressor, we use a shot noise suppression section in order to make the main bunch core quiet. Shot noise suppression is achievable by employing either the scheme proposed by Gover and Dyunin [11] or the scheme proposed by Ratner et al. [9]. The first scheme uses only a drift channel of around a quarter of the plasma wavelength $L_d \approx \lambda_p/4$ so that the density modulation converts into the velocity modulation via collective plasma oscillations. In Ratner's scheme the noise reduction occurs in a chicane, where the energy modulation gained in the particle-to-particle interaction region, is translated into a homogenization of the bunch density. Ratner's scheme allows obtaining stronger noise suppression for the same drift length compared to Gover's scheme. The maximal noise suppression in both schemes is limited by the uncorrelated energy spread and emittance.

The noise factor calculated analytically for Gover's and Ratner's schemes at the wavelength region from $\lambda_r/2$ to $3\lambda_r/2$ is presented in Fig. 8. Recall that λ_r is the FEL resonant wavelength. The relativistic plasma wavelength λ_p is around 25 meters so that the required interaction length in Gover's scheme is around 6.25 meters and the maximum noise suppression factor is around 10^2. One can see from Fig. 8 that the same noise reduction is achieved in Ratner's scheme with a shorter drift length of 2.5 m. Because of the finite transverse size of electron bunches, the noise factor at Ratner's scheme strongly depends on the wavelength and we chose dispersive strength R_{56} to minimize $\langle\Gamma(k)\rangle$ at $\lambda = \lambda_r$ whereas for other wavelengths R_{56} is not optimal. At the same time, the noise reduction is quite uniform around the desired frequency as is demonstrated in Fig. 8 (dotted red curve) because the first derivative of $\langle\Gamma(k)\rangle$ with respect to λ is equal to zero.

The shot noise suppression section based on Ratner's scheme proposes a good compromise between the noise suppression efficacy and system size. Note that Ratner's theory does not take into account the noise reduction due

Copyright © 2013 CC-BY-3.0 and by the respective authors

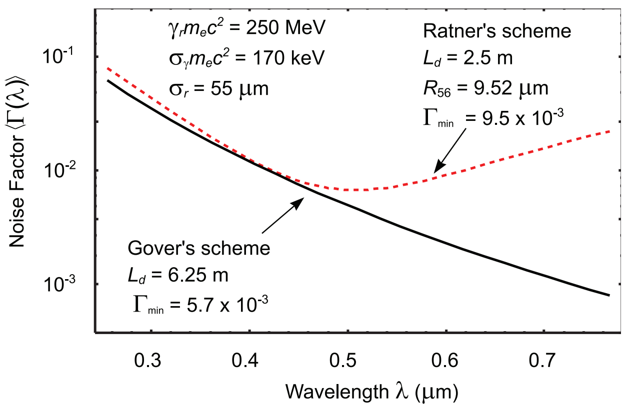

Figure 8: Noise factor vs. wavelength for two noise suppression schemes. The black solid line stands for the noise factor for the scheme employing only a drift channel (Gover's scheme) whereas the red dotted curve stand for the noise factor for the scheme employing a drift channel and a chicane (Ratner's scheme).

to the plasma oscillations in a drift channel so that Gover's and Ratner's scheme cannot be compared for a quarter plasma wavelength drift channel. The bunching factors at the end of the bunch compressor and noise suppression section, $b_0(k)$ and $b_s(k)$, are related by $|b_s(k)|^2 = \langle\Gamma(k)\rangle|b_0(k)|^2$ so that noise suppression means a decrease in the bunching factor.

SUMMARY AND DISCUSSION

We found that the shot noise suppression in electron bunches is an efficient way of increasing the longitudinal coherence of FELs. However, the studies show that shot noise has to be suppressed by three orders of magnitude in order to decrease the relative dispersion of radiation power by one order of magnitude. This finding impose a challenge on shot noise suppression techniques. At the same time, as we demonstrate the output pulses can be made completely coherent and Fourier transform limited.

We proposed a scheme of formation of electron bunches with a high current gradient at the bunch tail and a reduce level of shot noise in the bunch core. Such bunches result in strong CSE and might extend SACSE FEL towards VUV region. In our scheme the longitudinal space charge amplifier (LSCA) is used in order to produce bunches with a tail microbunched at a desired wavelength. The main core of a bunch is stable w.r.t microbunching instability due to its heating with a laser heater. Recent experimental evidence [12] confirms the possibility of formation of bunches with a high current gradient. After the controlled microbunching the suppression of shot noise is applied. We found the shot noise suppression in realistic bunches at the optical region to be four orders of magnitude both for Gover's and Ratner's schemes.

REFERENCES

[1] E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, The Physics of Free Electron Lasers (Springer, Berlin, Germany, 2000).

[2] B.W.J. McNeil, N. R. Thompson, and D.J. Dunning, Phys. Rev. Lett. 110, 134802.

[3] "Realizing the Potential of Seeded FELs in the Soft X-Ray Regime," Final Report, SLAC and LBNL Workshop, 2011.

[4] A. Gover and E. Dyunin, IEEE J. Quantum Electron. 46, 1511 (2010).

[5] V.N. Litvinenko, Proc. of the 31st FEL Conference (FEL 09), Liverpool, UK.

[6] K.J. Kim and R. Lindberg, Proc. FEL2011, Shanghai, China, p. TUOA2.

[7] S. Krinsky, Phys. Rev. E 59, 1171 (1999).

[8] V.A. Goryashko, V. Ziemann, Phys. Rev. ST Accel. Beams 16, 030702 (2013).

[9] D. Ratner, Z. Huang, and G. Stupakov, Phys. Rev. ST Accel. Beams 14, 060710 (2011).

[10] E.A. Schneidmiller and M.V. Yurkov, Phys. Rev. ST Accel. Beams 13, 110701 (2010).

[11] A. Gover and E. Dyunin, Phys. Rev. Lett. 102, 154801 (2009).

[12] A. Marinelli et al., Phys. Rev. Lett. 110, 264802 (2013).

Copyright © 2013 CC-BY-3.0 and by the respective authors

ISBN 978-3-95450-126-7