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Longitudinal coherence in an FEL with a reduced level of shot noise

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presented at

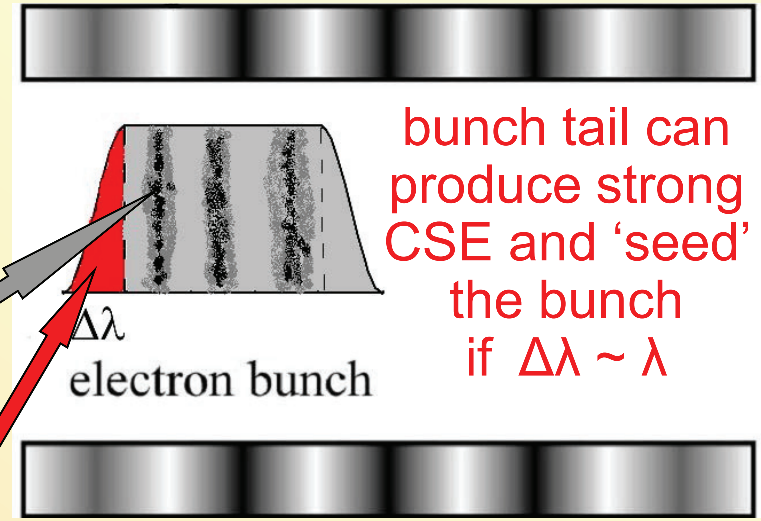
FEL 2013, New York, August 25-30, 2013

Spontaneous Undulator Radiation: SASE and SACSE FEL

$$\left(\nabla^2 - \frac{\partial^2}{\partial t^2}\right)\vec{E} = \frac{4\pi}{c}\frac{\partial \vec{j}}{\partial t}$$

$$\vec{j} = e\sum_{i}^{Q_b} \vec{\upsilon}_i\, \delta(\vec{r}-\vec{r}_i)$$

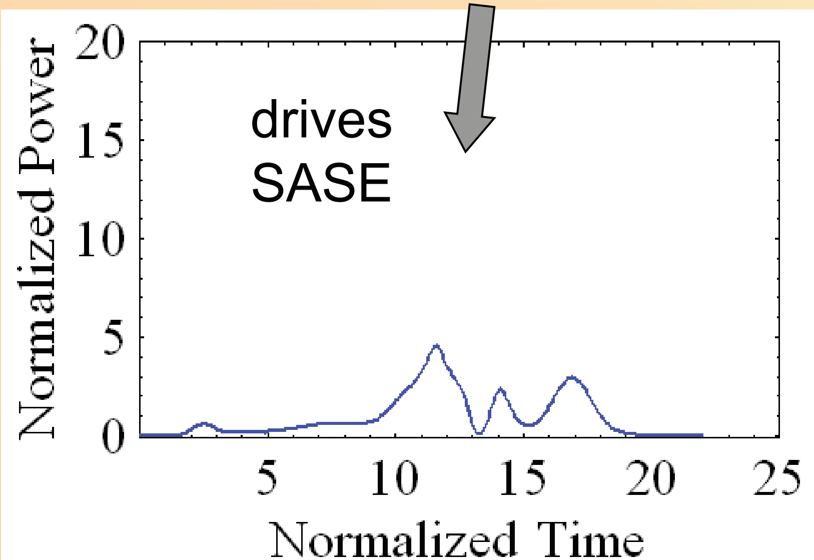
- the gradient of a current drives emission

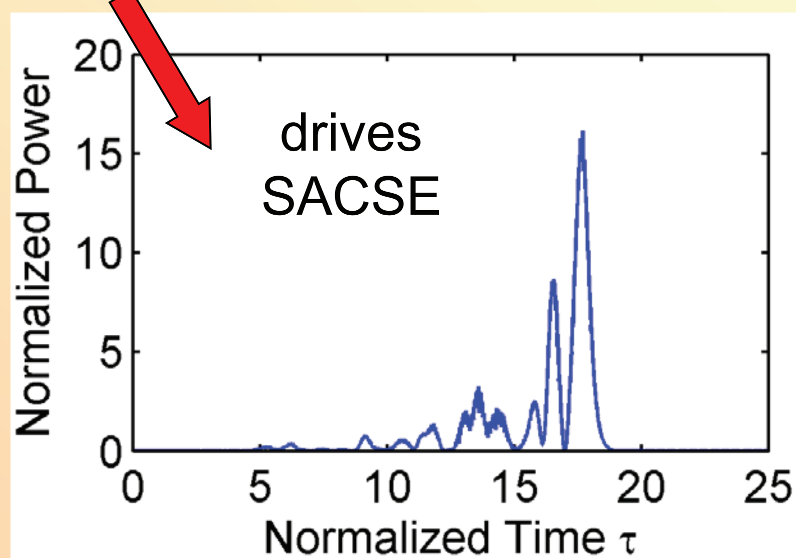


bunch tail can produce strong CSE and ‘seed’ the bunch if Δλ ~ λ

$$P_{spon}(k) = \underbrace{Q_b P_{und}(k)}_{\text{incoherent}} + \underbrace{Q_b(Q_b-1)\left|\bar{F}(\omega)\right|^2 P_{und}(k)}_{\text{coherent}}$$

incoherent *coherent*





Coherent and Incoherent Spontaneous Emission

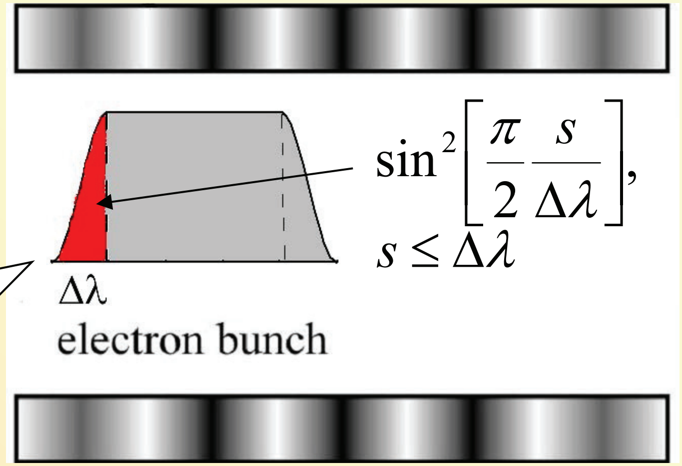
$$P_{\mathrm{spontaneous}}(k) = P_{\mathrm{incoh}}(k) g(S, \langle\Gamma\rangle) + P_{\mathrm{coh}}(k)$$

$g(S,\langle\Gamma\rangle)$ is the noise reduction factor

$$P_{\mathrm{coh}}(k) = Q_b^2 |F(k)|^2 P_{\mathrm{und}}(k) \qquad P_{\mathrm{incoh}}(k) = Q_b P_{\mathrm{und}}(k)$$

$$\boxed{P_{\mathrm{coh}}(k) \gg P_{\mathrm{incoh}}(k)}$$

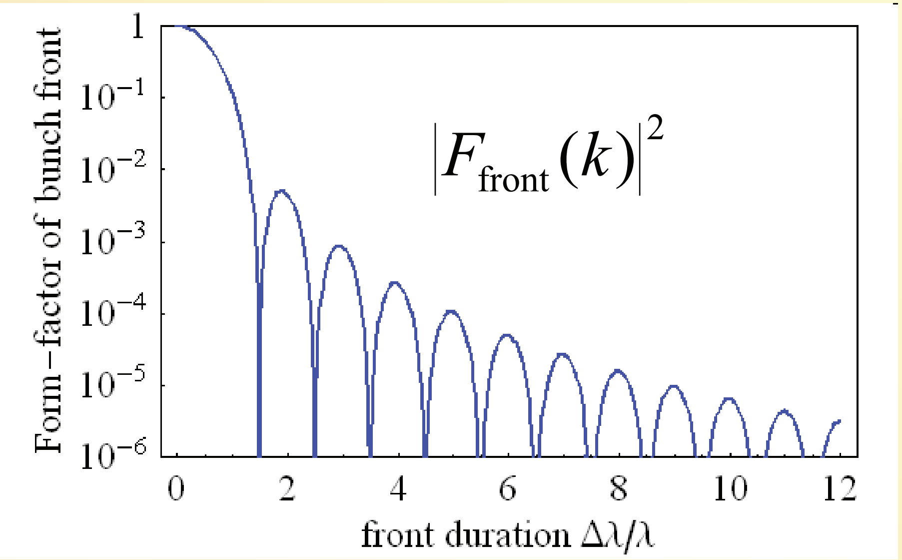
consider a bunch of special shape



$$|F(k)|^2 = |F_{\mathrm{rec}}(k)|^2 |F_{\mathrm{fron}}(k)|^2$$

$$|F_{\mathrm{rec}}(k)|^2 = \left(\frac{\sin[kL_b/2]}{kL_b/2}\right)^2$$

$$|F_{\mathrm{fron}}(k)|^2 = \left(\frac{\pi^2 \cos[k\Delta\lambda/2]}{\pi^2 - k^2\Delta\lambda^2}\right)^2$$



$$\boxed{\frac{4\pi^2 Q_b}{(kL_b)^2 (k\Delta\lambda)^4} \gg g(S, \langle\Gamma\rangle))}$$

By decreasing the front duration of a bunch and shot noise one can achieve the dominance of coherent spontaneous emission over incoherent emission.

Towards Strong Coherent Spontaneous Emission at Start-up

Can we prepare bunches with a sharp tail and a reduced level of shot noise?

$$\boxed{\frac{4\pi^2 Q_b}{(kL_b)^2(k\Delta\lambda)^4} \gg g(S, \langle\Gamma\rangle))} \quad ?$$

Let us try!

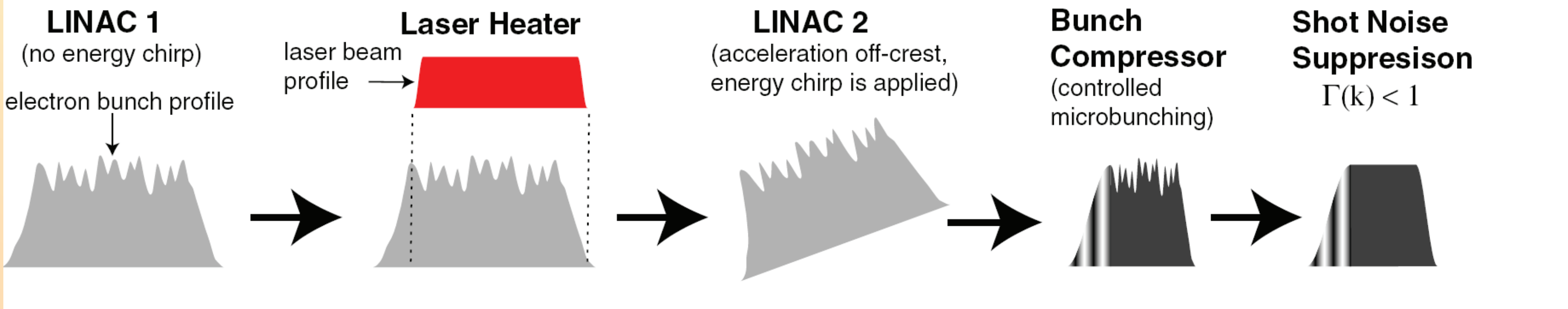
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **16**, 030702 (2013)

Self-amplified coherent spontaneous emission in a free electron laser with "quiet" bunches

V. A. Goryashko* and V. Ziemann

Uppsala University, Sweden

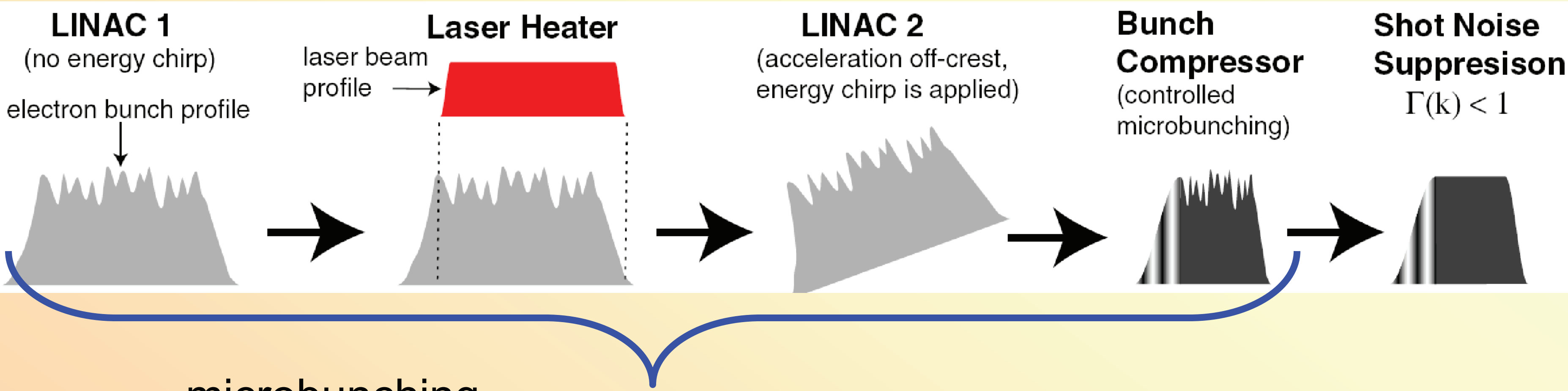
Formation of 'Quiet' Electron Bunches with High Current Gradient



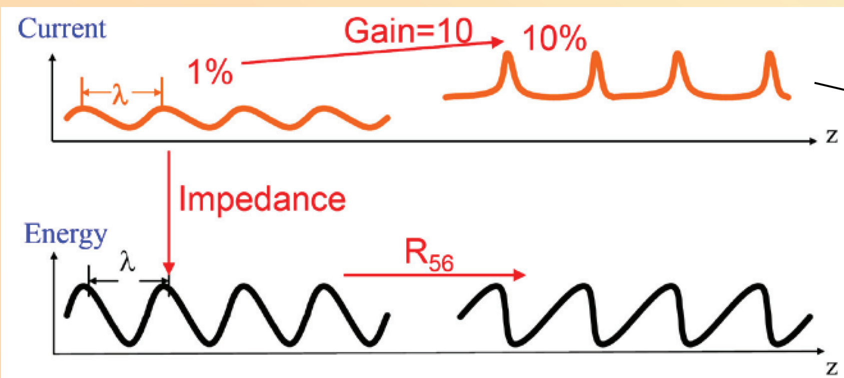
The schematic illustration of a possible formation of the quiet bunch with a high current gradient at the bunch tail.

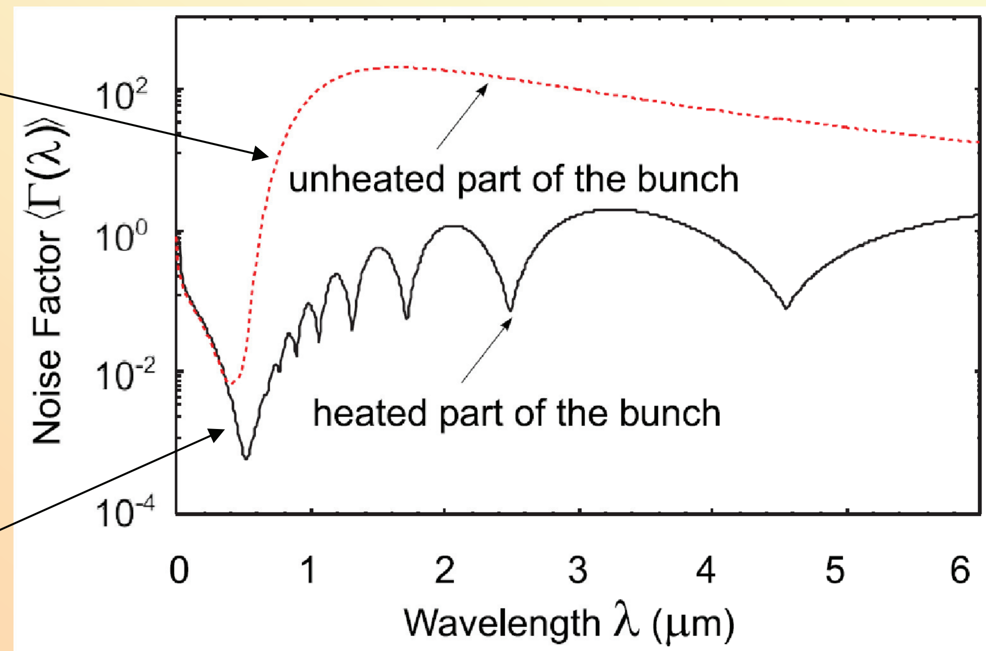
- the concepts of **Longitudinal Space Charge Amplifier** and **Laser Heater** are combined it order to produce partly microbunched bunch
- the main core of a bunch is heated by a laser heater and stable w.r.t. the microbunching instability
- the bunch tail is left unheated and is subject to the microbunching instability
- an energy chirp is applied in order to produce **wavelength compression**
- the microbunched tail is a source of CSE and 'seeds' the main bunch core
- the shot noise suppression is used in order to make the bunch core 'quiet'

Controlled Microbunching

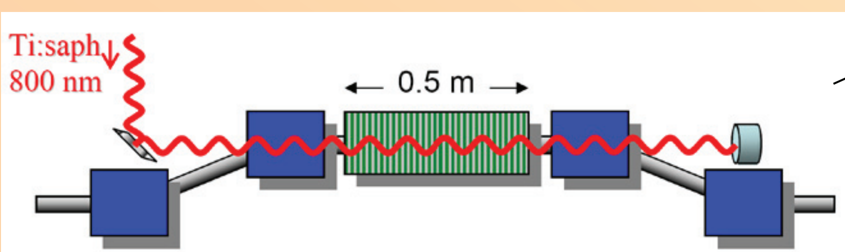


microbunching

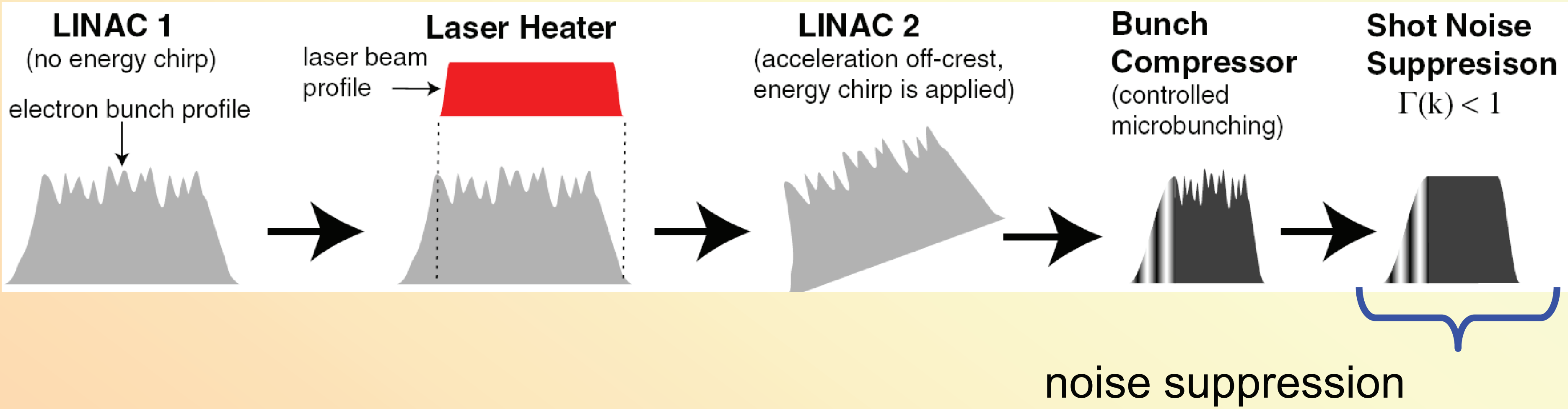


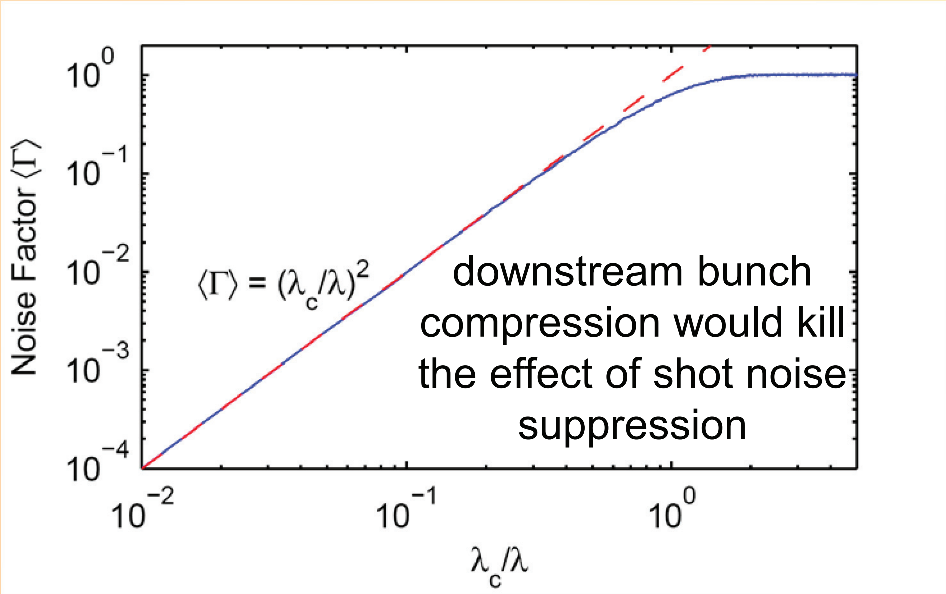


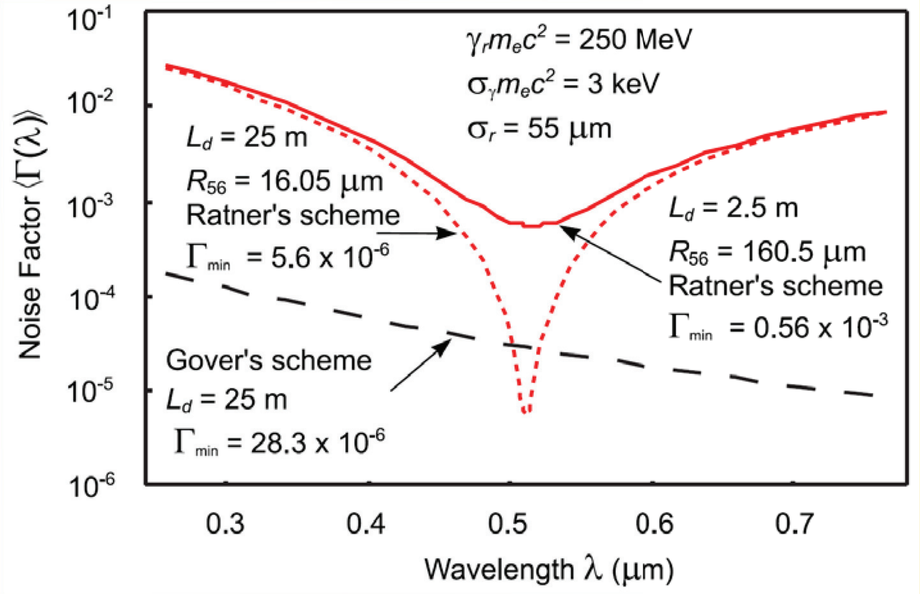
laser heater



Shot Noise Suppression







at 0.5 µs wavelength the maximum shot noise suppression for realistic bunch parameters is four orders of magnitude for both schemes

Non-Averaged Code for Simulation of SACSE FEL

Vector-potential *A* is expanded into a complete set of transverse modes (waveguide modes, Hermite-Gaussian modes, optical-waveguide modes). The mode amplitude satisfies a 1D Klein-Gordon equation

$$\left(\frac{\partial^2}{\partial z^2}-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}-k_\perp^2\right)\vec{A}_\perp=-\frac{4\pi}{c}\vec{I}_\perp,$$

$I_\perp$ is the effective current density

$$A_\perp(z,t)=\frac{1}{c}\int_{-T_e}^{t}dt'\int_0^z dz' G(z-z',t-t')I_\perp(z',t'),$$

$G(z-z',t-t')$ is the Green function

In 1D approximation and free space the electric field reads

$$E_\perp(z,t)=-\frac{\tilde{\varrho}}{c^2}\sum_q^{Q_e}\int_0^z dz'\,\frac{v_{\perp|q}(z')}{v_{z|q}(z')}\,\delta\left[(ct-ct'_q(z'))-(z-z')\right]U[t-t_q(z')]U[t_q(z')+T_e].$$

Quasi- recurrence relation has place

$$E_\perp(z_k+\Delta z,ct_j)=E_\perp(z_k,ct_j-\Delta z)+\int_{z_k}^{z_k+\Delta z}f[z_k,z',ct_j,ct_q(z')]dz'$$

Features of the Non-Averaged FEL Code

- an algorithm based on the Green function approach is unconditionally stable;
- EM field is calculated only in the space-time domain of interest;
- one needs to keep in memory bunch parameters and EM fields values only for one undulator position;
- numerical implementation of boundary conditions is straightforward;
- algorithm allows for successive calculation of the field along an undulator.

Time consumption:

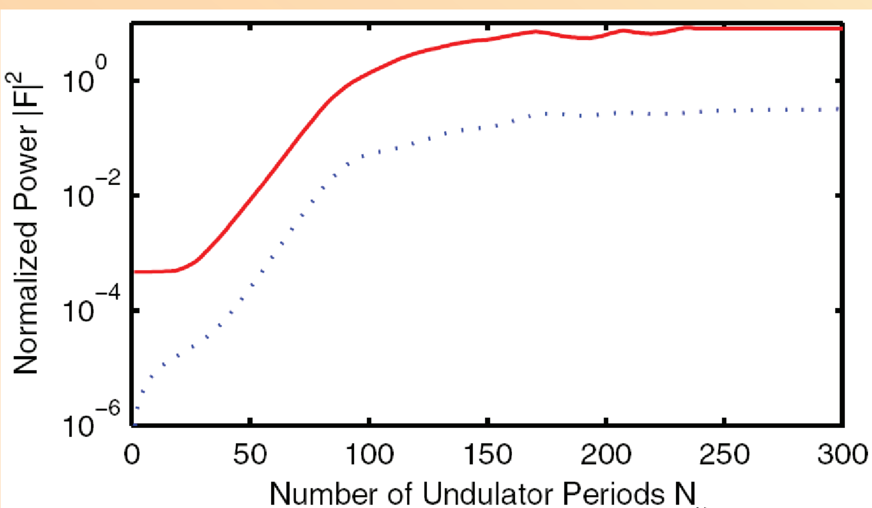
- several thousands particles
- undulator length ~ 30 gain length
- bunch length ~ 10 cooperation length
- 1D approximation
- discretization step ~ $\lambda_u/10$

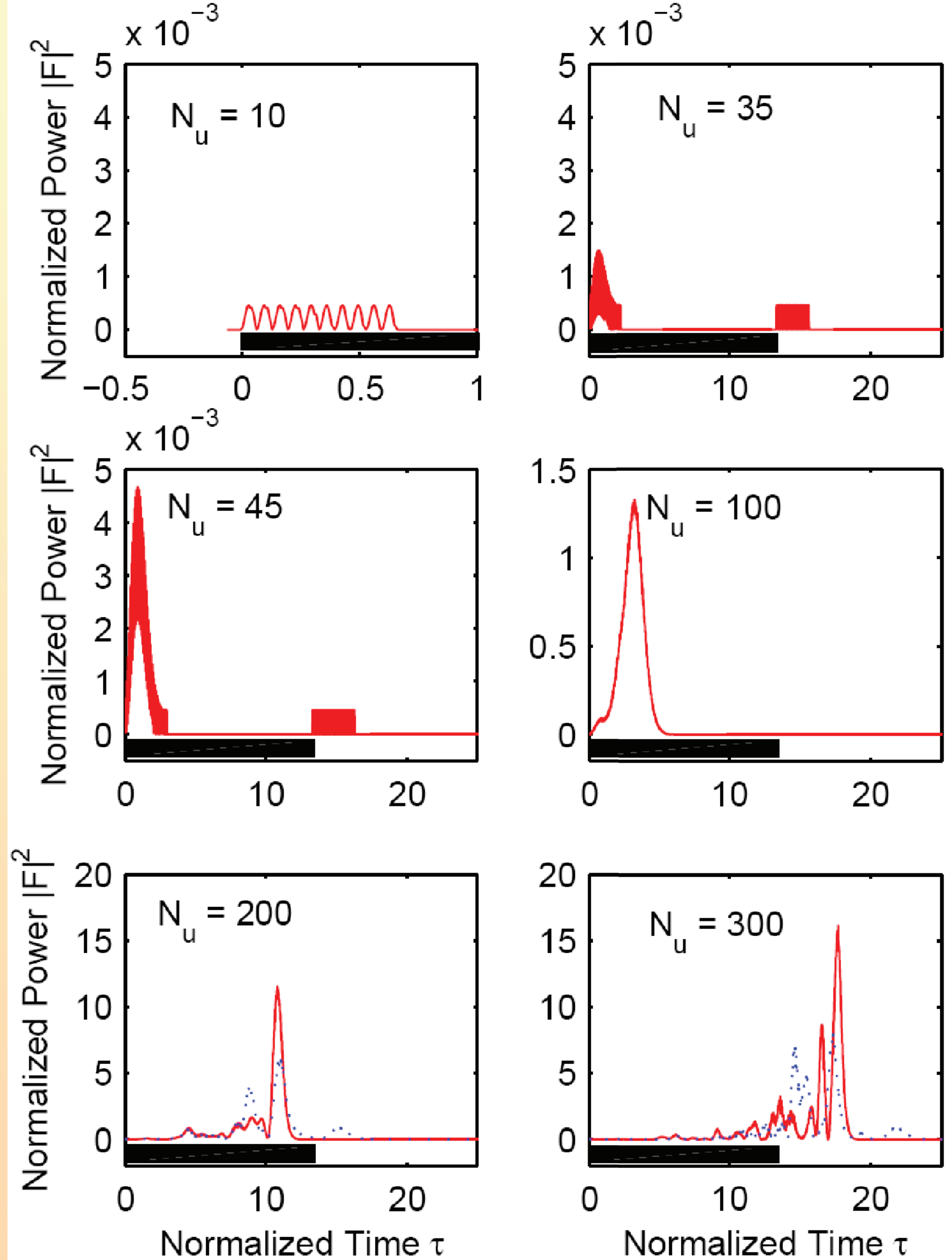
One run in Matlab takes around 100 sec. The code is fast enough to get statistically valid results within reasonable time.

Self-Amplified Coherent Spontaneous Emission

Bunch and FEL parameters

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
Undulator period	λ_u	4 cm
Undulator parameter	$\mathcal{K}$	3.2
FEL wavelength	λ_r	0.511 μm
FEL parameter	ρ	0.0053
Cooperation length	L_c	4.29 μm
Gain length	ℓ_g	33.57 cm
Normalized bunch length	τ_b	13.3





Noise in Electron Beams: Shot Noise Parameter*

In what follows the momentum noise and quantum noise are assumed to be small and I focus only on the position noise. We will limit ourselves to the case $k\lambda_D$<<1 so that the position noise can be reduced**.

$$\Gamma(k,z) = \frac{1}{Q_b}\sum_{q,p}^{Q_b} \exp\{ik[s_q(z) - s_p(z)]\}, \quad s_q(z) \text{ is the electron position in a bunch}$$

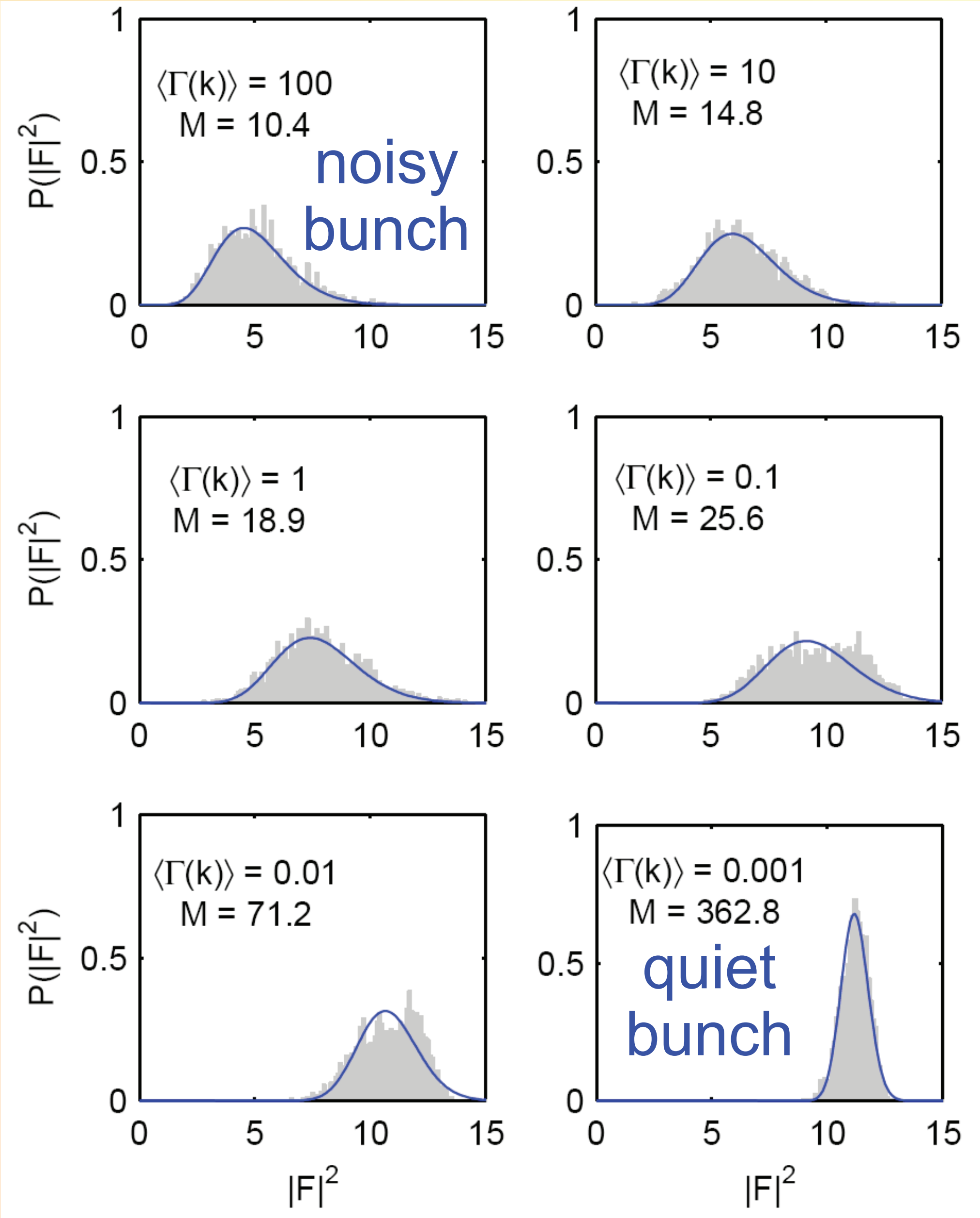
$$\Gamma(k,z) = Q_b\left|b(k,z)\right|^2, \quad b(k,z) = \frac{1}{Q_b}\sum_{q}^{Q_b} \exp[iks_q(z)];$$

$$\langle\Gamma(k,z)\rangle = \begin{cases} >1, & \text{microbunched bunch} \\ 1, & \text{normal level of shot noise} \\ <1, & \text{"quiet" bunch (noise suppression)} \end{cases}$$

* *D. Ratner, Z. Huang, and G. Stupakov, PRSTAB 14, 060710 (2011).*

** *K.-J. Kim, "Irreducible Quantum and Classical Noise in High-Gain FEL Amplifier," 4th Microbunching Workshop (2012).*

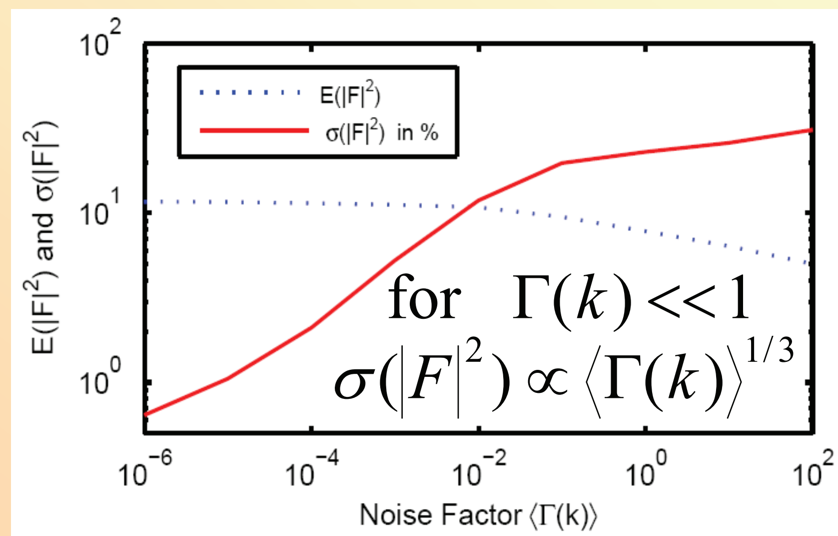
Self-Amplified Spontaneous Coherent Emission: Statistics



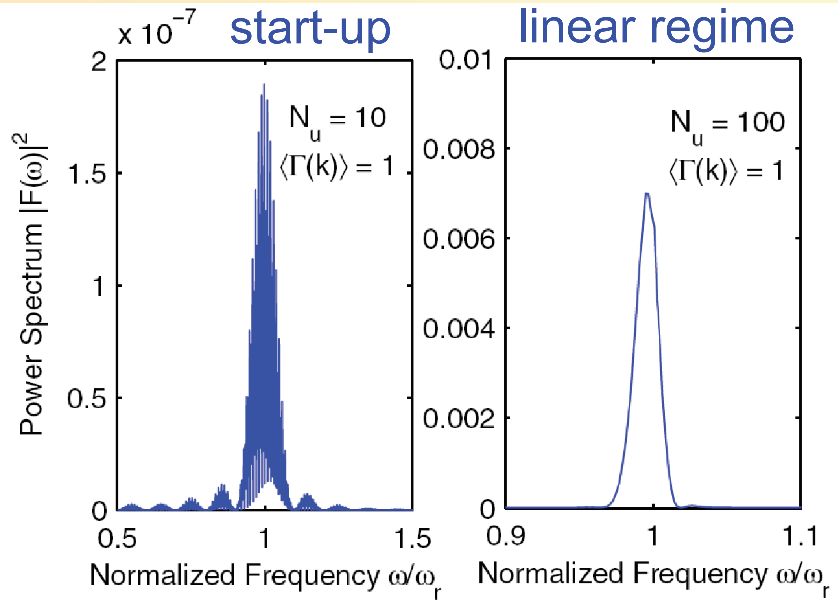
rms width of the probability density distribution determines FEL coherence

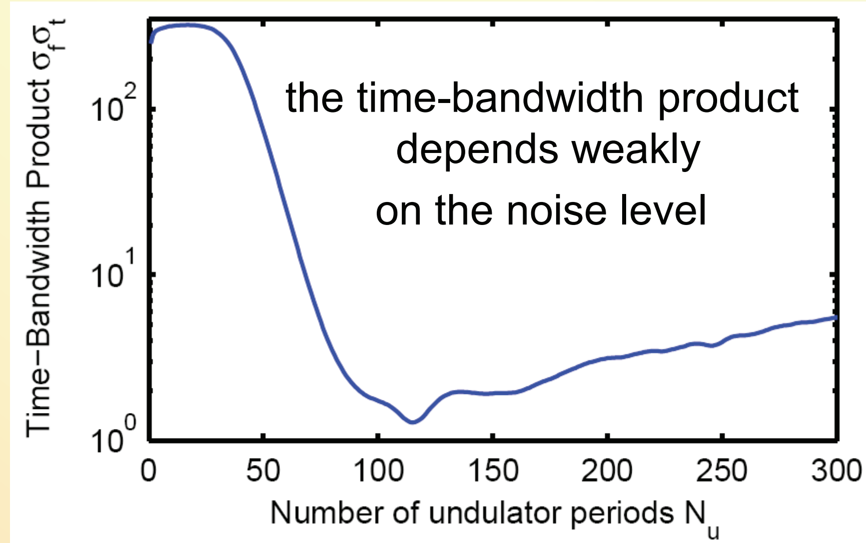
$$\boxed{g_2(0) = 1 + \sigma^2(|F|^2)}$$

$$g_2(0) = \begin{cases} 1, & \text{stabilized single-mode laser radiation,} \\ 2, & \text{chaotic radiation from a thermal source.} \end{cases}$$

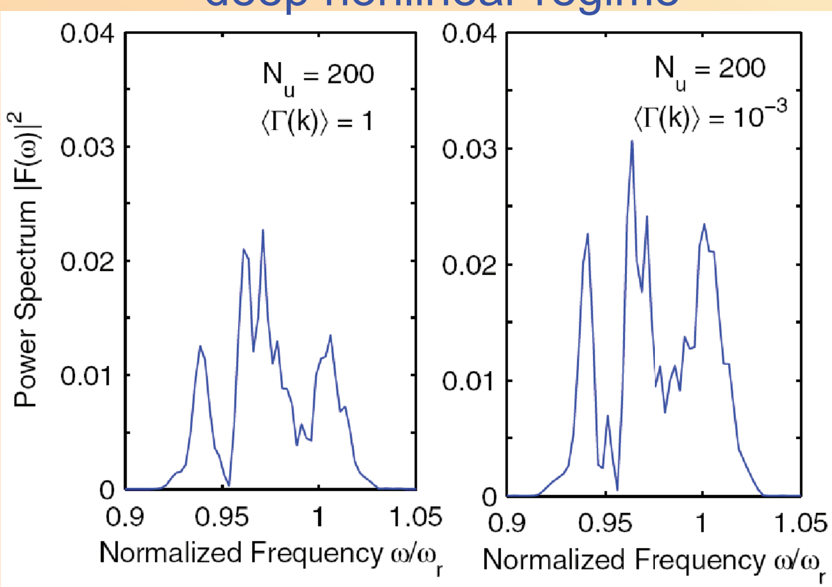


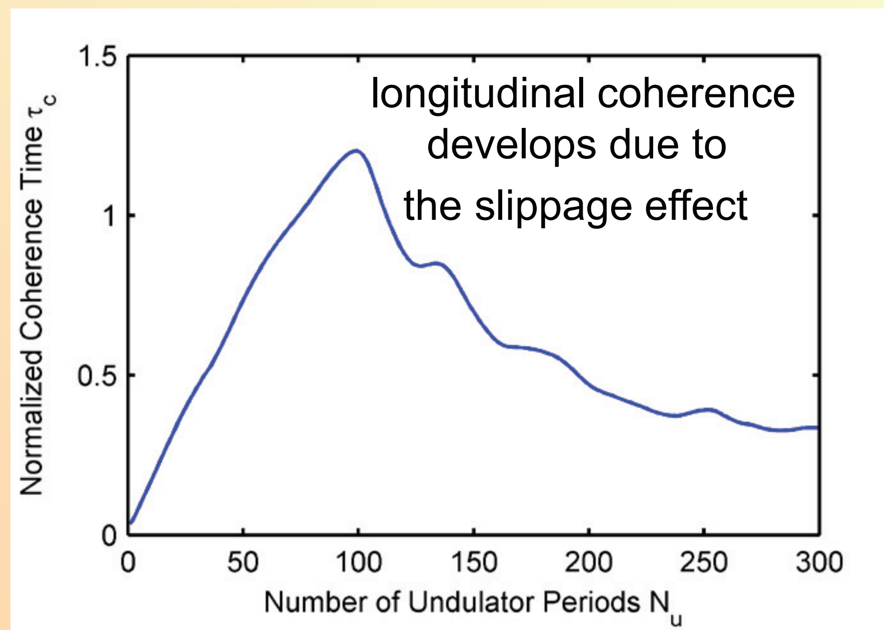
Spectrum and Time-Bandwidth Product





deep nonlinear regime





List of Relevant Publications

SACSE FEL:

- A. Doria et al., IEEE J. Quantum Electron. 29, 1428 (1993).
- D. A. Jaroszynski et al., Phys. Rev. Lett. 71, 3798 (1993).
- S. Krinsky, Phys. Rev. E 59, 1171 (1999).
- B.W. J. McNeil, G. R. M. Robb, D. A. Jaroszynski, Opt. Commun. 165, (1999).

Longitudinal space-charge amplifier:

- E.A. Schneidmiller and M.V. Yurkov, PRSTAB 13, 110701 (2010).
- A. Marinelli et al., Phys. Rev. Lett. 110, 264802 (2013).

Shot noise suppression:

- A. Gover and E. Dyunin, Phys. Rev. Lett. 102, 154801 (2009).
- V. N. Litvinenko, FEL 09, Liverpool, UK
- D. Ratner, Z. Huang, and G. Stupakov, PRSTAB 14, 060710 (2011).
- D. Ratner and G. Stupakov, Phys. Rev. Lett. 109, 034801 (2012).
- A. Gover, A. Nause, E. Dyunin, M. Fedurin, Nat. Phys., 8, 877 (2012).

Summary

- the shot noise suppression in electron bunches is an efficient way of increasing the longitudinal coherence of FELs;
- the output pulses can be made completely coherent and Fourier transform limited;
- 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;
- we propose a novel scheme of formation of ‘quiet’ bunches with a sharp tail to drive coherent spontaneous emission in FELs;
- the proposed scheme of bunch formation may extend SACSE FELs to the VUV region;
- details can be found in paper “V.A. Goryashko, V. Ziemann Phys. Rev. ST Accel. Beams 16, 030702 (2013)”.