



Generation of Coherent Broadband Photon Pulses with a Cascaded Longitudinal Space-Charge Amplifier

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The longitudinal space-charge amplifier has been recently proposed by Schneidmiller and Yurkov as an alternative to the free-electron laser instability for the generation of intense broadband radiation pulses [Phys. Rev. ST Accel. Beams **13**, 110701 (2010)]. In this Letter, we report on the experimental demonstration of a cascaded longitudinal space-charge amplifier at optical wavelengths. Although seeded by electron beam shot noise, the strong compression of the electron beam along the three amplification stages leads to emission of coherent undulator radiation pulses exhibiting a single spectral spike and a single transverse mode. The on-axis gain is estimated to exceed 4 orders of magnitude with respect to spontaneous emission.

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The successful lasing of the Linac Coherent Light Source [1] and the Spring-8 Angstrom Compact free-electron LASer [2] has established the high-gain free-electron laser (FEL) as the brightest source of monochromatic, hard x-rays, allowing the exploration of nature with unprecedented temporal and spatial resolution [3,4]. While the narrow bandwidth of FELs is a desirable feature in applications such as imaging and spectroscopy, it ultimately limits the ability of the FEL to generate few-cycle pulses for ultrafast experiments. As an alternative, the longitudinal space-charge amplifier (LSCA) has recently been proposed as a powerful broadband coherent radiation source [5]. In a LSCA, a relativistic electron beam (e beam) becomes modulated in density (i.e., microbunched) by the interaction with its own collective space-charge forces, combined with longitudinal dispersion in transport. This microbunching instability process was first identified as a detrimental effect in the context of FEL injectors [6–12]. However, as pointed out in [5], it can be optimized and cascaded through several amplification stages to yield strong microbunching for the emission of intense broadband coherent light. Because of its unique spectral properties, the LSCA is a natural candidate for the generation of intense attosecond radiation pulses [13]. Furthermore, the LSCA presents several advantages in terms of compactness and robustness to nonideal beam conditions.

In this Letter, we report on the experimental demonstration of the LSCA as a new type of broadband, fully coherent radiation source at the Next Linear Collider Test Accelerator (NLCTA) of the SLAC National Accelerator Laboratory. Our experimental setup is shown in Fig. 1, and exploits the existing three-chicane echo-enabled harmonic generation seeding beam line [14,15] as a cascaded three-stage LSCA seeded by shot noise. Through the proper tuning of the bunch compression, we demonstrate the

generation of an intense, single mode pulse with an intensity gain of 4 orders of magnitude over the spontaneous emission level.

The physical mechanism of the space-charge instability can be modeled as a two-step process. An e beam with an initial density perturbation at the longitudinal spatial frequency k travels through a transport channel (drift) of length L_d . During transport, the modulated longitudinal space-charge fields induce a corresponding energy modulation in the e beam. Afterwards, the electrons travel through a longitudinally dispersive transport element (e.g., a magnetic bending chicane) which transforms the energy modulation back into a density modulation, but with an amplitude larger than the initial value. This process can start from shot noise or from a coherent microbunching induced by interaction with an external laser, and can be repeated in several amplification stages to enhance the density modulation amplitude.

The microbunching instability has been investigated in detail elsewhere [9–12,16,17]. To provide a dynamical description of the cascaded LSCA setup explored experimentally here, it is useful to follow the matrix formalism of Gover *et al.* [18] for a simple one-dimensional (1D), cold beam model. The beam density modulation can be quantified by the beam bunching factor, given by $b = \sum_n \exp(-ikz_n)/N$, where z_n is the longitudinal position of

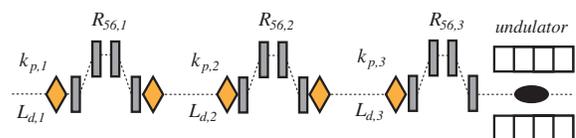


FIG. 1 (color online). Overview of the beam line for the NLCTA experiment. Three chicanes separate three drift sections within an alternating-gradient focusing channel defined by quads (diamonds).

the n th particle and N is the number of particles. The energy modulation is defined similarly as $\mu = \sum_n \eta_n \exp(-ikz_n)/N$, where $\eta_n = \delta\gamma_n/\gamma$ is the relative energy deviation and γ the beam's Lorentz factor. In the linear approximation (i.e., when $b \ll 1$) for a single-stage LSCA, the evolution of the two collective variables (b , μ) under the influence of space-charge forces and dispersion is described by the transport matrix

$$\begin{pmatrix} b_1 \\ \mu_1 \end{pmatrix} = \mathbf{R}\mathbf{M} \begin{pmatrix} b_0 \\ \mu_0 \end{pmatrix}, \quad (1)$$

where

$$\mathbf{M} = \begin{pmatrix} \cos(k_p L_d) & -\frac{ik}{\gamma^2 k_p} \sin(k_p L_d) \\ \frac{k_p \gamma^2}{ik} \sin(k_p L_d) & \cos(k_p L_d) \end{pmatrix}$$

is the space-charge evolution matrix, $k_p = \sqrt{e^2 n_0 / \epsilon_0 m c^2 \gamma^3}$ is the relativistic spatial plasma frequency, n_0 is the beam density, e is the electron charge, ϵ_0 is the vacuum permittivity, m is the electron mass, and c is the speed of light. The linear transport through the chicane is described by the transport matrix $\mathbf{R} = \begin{pmatrix} 1 & -ikR_{56} \\ 0 & 1 \end{pmatrix}$, where R_{56} is the longitudinal dispersion in the chicane. In general, if N_s amplification stages are used in series, the final variables can be computed by simple chain multiplication of the evolution matrices in each stage

$$\begin{pmatrix} b_{N_s} \\ \mu_{N_s} \end{pmatrix} = \mathbf{R}_{N_s} \mathbf{M}_{N_s} \dots \mathbf{R}_2 \mathbf{M}_2 \mathbf{R}_1 \mathbf{M}_1 \begin{pmatrix} b_0 \\ \mu_0 \end{pmatrix}. \quad (2)$$

The gain in the l th section is then defined as $g_l = b_l/b_{l-1}$. Assuming that the amplification process starts from a beam with negligible initial energy modulation ($\mu_0 = 0$), use of the single stage evolution matrix yields the microbunching gain,

$$g_1 = b_1/b_0 = \cos(k_p L_d) - \gamma^2 R_{56} k_p \sin(k_p L_d). \quad (3)$$

Under conditions of high gain ($|g_1| \gg 1$), the $\cos(k_p L_d)$ term can be neglected and the gain is proportional to the longitudinal dispersion in the chicane, $g_1 \approx -\gamma^2 R_{56} k_p \sin(k_p L_d)$. The overall gain in a cascaded system is given by the product of the microbunching gain in each stage,

$$g = g_1 g_2 \dots g_{N_s} = b_{N_s}/b_0. \quad (4)$$

Note that this formula is valid only if a significant amount of energy modulation is developed in each stage. Consider the simplified case of a two-stage LSCA ($N_s = 2$). In the high-gain approximation, the gain at the exit of the second stage is $g \approx \gamma^4 R_{56,1} k_{p,1} \sin(k_{p,1} L_{d,1}) R_{56,2} k_{p,2} \sin(k_{p,2} L_{d,2})$. On the other hand, if no energy modulation is developed in the second drift (namely, if $k_{p,2} L_{d,2} \rightarrow 0$), then the two-stage gain formula from Eq. (2) reduces to $g \approx \cos(k_{p,1} L_{d,1}) - \gamma^2 (R_{56,1} + R_{56,2}) k_{p,1} \sin(k_{p,1} L_{d,1})$. The

latter is essentially the single stage formula in Eq. (3), where the energy modulation from the first stage is converted into a density modulation by the sum total dispersion from each stage. Note that the microbunching still grows from one stage to the next, but the gain is additive rather than multiplicative. We will therefore refer to the first case as *cascaded* microbunching gain, and to the second case as *additive* microbunching gain. The distinct advantage of the cascaded arrangement is the potential for much larger gain for the same total dispersion. This concept can be generalized to multiple stages, and the signature of cascading is that the gain is dependent on the way the total R_{56} is partitioned.

The 1D theory can be easily modified to include 3D effects, energy spread, and beam compression. Following the approach of [19], it can be shown that the plasma frequency for a cold beam is given by replacing $k_p \rightarrow k_p^{(3D)} = k_p \Omega$, where $\Omega < 1$ is the normalized plasma frequency, which accounts for the finite size of the e beam and transverse betatron motion. The explicit dependence of Ω depends on the transverse beam distribution that one considers (see, e.g., [9,20]). In general, Ω is a decreasing function of the 3D parameter $D = k\sigma_x/\gamma$, where σ_x is the beam rms transverse size. For a transversely laminar e beam we have that $\Omega \rightarrow 1$ for $D \gg 1$ while $\Omega \rightarrow 0$ for $D \ll 1$, and thus microbunching gain is suppressed by 3D effects for long wavelengths. At short wavelengths, on the other hand, the gain process is dominated by energy-spread effects, according to an exponential suppression factor $\exp[-(k\sigma_\eta R_{56})^2/2]$ for a beam with a Gaussian relative energy spread σ_η . Finally, in the presence of a linear energy chirp, the effect of wavelength compression during dispersion has to be taken into account. For a given linear energy chirp $h = d\gamma/\gamma dz$, the wavelength changes as $\lambda \rightarrow \lambda/C$, where $C = 1/(1 + hR_{56})$. The gain formula then has to be modified as

$$g_1 = (\cos(k_p^{(3D)} L_d) - C\gamma^2 R_{56} k_p^{(3D)} \sin(k_p^{(3D)} L_d)) \times \exp\left(-\frac{(Ck\sigma_\eta R_{56})^2}{2}\right), \quad (5)$$

where k is the microbunching frequency before the chicane and Ck is the frequency after the chicane. With this expression, the total gain in a cascaded LSCA can be computed from the product in Eq. (4), taking into account the wavelength shift due to compression, as well as the corresponding R_{56} , $k_p^{(3D)}$, and L_d in each stage.

The cascaded LSCA experimental setup shown in Fig. 1 is composed of three-magnetic chicanes each separated by drifts, with an undulator used as a radiator after the final chicane. The e beam is generated by an S-band photoinjector and accelerated as high as 120 MeV by two X-band accelerating structures (named linac 0 and linac 1). The three magnetic chicanes (C1, C2, and C3) have tunable longitudinal dispersion in the range $0.8\text{mm} < R_{56} < 10\text{mm}$. The radiator employed is a helical

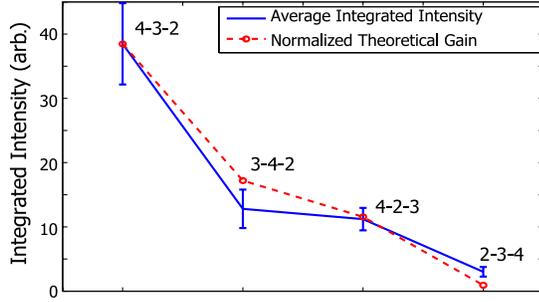


FIG. 2 (color online). Integrated camera intensity for three different R_{56} (marked in mm for C1-C2-C3, respectively) configurations, total $R_{56} = 9$ mm. For comparison the theoretical microbunching power gain is shown, normalized to the first experimental point. The error bars represent the uncertainty on the mean intensity ($\pm 3\sigma$) averaged over 250 shots.

undulator with $N_w = 11$ periods of length $\lambda_w = 1.9$ cm and an undulator parameter $K = 0.58$. The operating beam energy in this experiment was 72 MeV ($\gamma = 141$), corresponding to a resonant emission wavelength of $\lambda_r = 640$ nm. Beam compression was achieved by operating linac 0 on crest to an energy of 40 MeV and varying the phase of linac 1 forward of crest. The space-charge interaction evolves as follows. Before C1, most of the interaction happens in a drift of length $L_{d,1} = 10$ m where the beam has an average beam size of $\sigma_{x,1} = 220$ μm , while the drifts between C1 and C2, and C2 and C3 have lengths of $L_{d,2} = L_{d,3} = 2$ m with a beam size of $\sigma_{x,2} = 160$ μm and $\sigma_{x,3} = 150$ μm , respectively. The initial beam current is ≈ 10 A, with an uncorrelated energy spread of $\sigma_E \approx 1.5$ keV. The space-charge instability is seeded by shot noise, which gives a broadband initial microbunching power of $\langle |b_0|^2 \rangle = 1/N$.

To explore cascaded amplification, the coherent undulator radiation intensity was measured for different R_{56} configurations, each yielding the same total dispersion of 9 mm. Figure 2 shows the integrated undulator radiation signal measured with a near-field camera, as well as a comparison with the theoretical prediction for the 3D microbunching gain, calculated under the assumptions of three-stage cascaded gain, a Gaussian transverse distribution, and linear compression, using the measured beam parameters. For ease of comparison, the radiation intensity for the theoretical curve is normalized to the first experimental point. The plot shows good agreement between the measured and predicted intensity variation with different chicane dispersions.

Because of the X-band accelerating field curvature, the global chicane compression results in a high-current leading spike. Figure 3 shows the result of a one-dimensional particle transport simulation performed with the ‘‘LOSCA’’ approach described in Ref. [13]. For a strongly compressed bunch, the microbunching gain is confined to the leading current peak, resulting in the emission of a

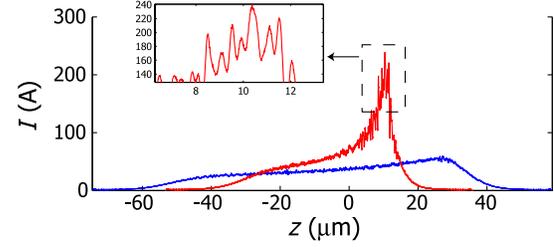


FIG. 3 (color online). Simulated beam current profile for a moderately compressed beam (blue line, $\phi_1 \approx 36^\circ$) and for a strongly compressed beam (red line, $\phi_1 \approx 41^\circ$).

pulse notably shorter than the total bunch length; conversely, for moderate compression the length of the microbunched fraction of the bunch is comparable to the entire bunch length. Figure 4 shows typical single-shot coherent undulator radiation spectrometer images from the LSCA with $R_{56,1} = 4$ mm, $R_{56,2} = 2.5$ mm, $R_{56,3} = 1.5$ mm for two scenarios: moderate gain (phase of linac 1 $\phi_1 \approx 36^\circ$), and maximum gain ($\phi_1 \approx 41^\circ$). The observed angular and spectral structure of the coherent radiation can be understood by examination of the far-field differential spectrum of the helical undulator,

$$\frac{dU}{dkd\Omega_s} = \frac{dU}{dkd\Omega_s} \Big|_{\text{sp}} N^2 |B(\vec{k})|^2, \quad (6)$$

where Ω_s is the solid angle and $(dU/dkd\Omega_s)|_{\text{sp}}$ is the single-particle differential spectrum [21]. The form factor $B(\vec{k}) = (1/N)\sum_j \exp(-i\vec{k} \cdot \vec{x}_j)$ is the 3D Fourier transform of the charge distribution, where the forward angle is related to the cartesian coordinates of \vec{k} by $\cos\theta = \sqrt{k_x^2 + k_y^2} / \sqrt{k_x^2 + k_y^2 + k_z^2}$. At a given angle θ , electrons traversing the undulator emit near the wavelength $\lambda_r = \lambda_w(1 + K^2 + \gamma^2\theta^2)/2\gamma^2$ with a FWHM spectral bandwidth of $\delta\lambda/\lambda \approx 1/N_w$. If the instability is seeded by shot noise, the microbunching spectrum is composed of several uncorrelated spikes with relative width given

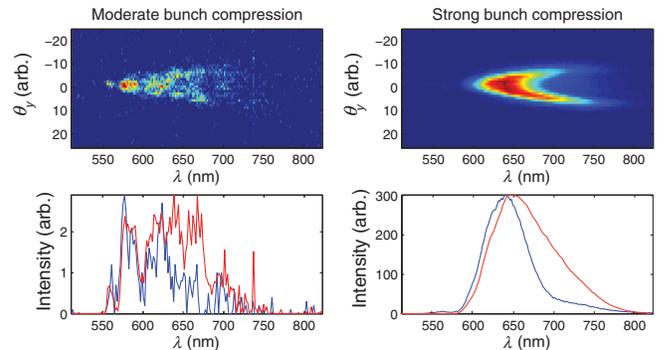


FIG. 4 (color). Single-shot spectrometer image (upper images), on-axis spectrum (lower images, blue line), and integrated spectrum (lower images, red lines) from a strongly compressed beam (right images) and for moderate compression (left images).

roughly by $\delta\lambda_{\text{spike}}/\lambda \simeq \lambda/L_b$, where L_b corresponds to the length of the microbunched distribution. Note that L_b can be shorter than the actual length of the e beam if a leading current peak dominates the microbunching process (see the high current peak in Fig. 3, red curve). If the bandwidth of the undulator is larger than the bandwidth of a single spectral spike, the coherent radiation spectrum from the LSCA shows several uncorrelated spikes. This corresponds to the slippage length in the undulator $L_s = N_w\lambda_r$ being shorter than the length L_b of the density modulated fraction of the beam (see the quasiuniform current distribution in Fig. 3, blue curve). In the opposite case, if the slippage length is longer than the microbunching structure ($L_s > L_b$), the radiation spectrum is characterized by a single coherent spike composed of $\sim N_w$ optical cycles. These cases are borne out from the measurements in Fig. 4. The intermediate gain configuration (left) corresponds to a weaker current compression than the peak gain. For this value of compression, the spectrum exhibits a spiky structure, as the slippage length in the undulator is shorter than the fraction of the e beam contributing to coherent emission. In the optimal compression case (right), the microbunched fraction of the e beam becomes shorter than the slippage length, and the emission is characterized by a single spectral spike. The measured on-axis FWHM bandwidth of the coherent emission distribution is $\Delta\lambda_r/\lambda_r \simeq 9\%$, in agreement with the on-axis emission bandwidth of the undulator. The measured angular integrated spectrum has a wider bandwidth $\Delta\lambda_r/\lambda_r \simeq 14\%$ since longer wavelengths are emitted off axis.

For moderate compression the radiation intensity distribution also exhibits speckles in the transverse dimension, while for stronger compression, a single, coherent transverse mode is observed (see the intensity dependence on θ_y in the upper images in Fig. 4). This behavior is anticipated from theoretical predictions [20]. The space-charge transverse eigenmodes of a laminar beam are fully degenerate for large values of the 3D parameter $D = k\sigma_x/\gamma$, i.e., for short wavelengths. As a consequence of the full degeneracy, the transverse distribution of microbunching in this limit is composed of several uncorrelated speckles [12,16], resulting in the emission of a transversely incoherent mode in the radiator. This effect limits the operation of an unchirped LSCA to wavelengths $\lambda > 2\pi\sigma_x/\gamma$ for transverse coherence. For the typical operating condition of the NLCTA, this is in the midinfrared. The observed transition to transverse coherence was therefore obtained as a consequence of bunch compression. For the case of strong compression, the optical microbunching generated at the last stage of the LSCA is the result of long-wavelength microbunching amplified in the first stage and frequency upshifted to optical wavelengths by compression in the second and third chicanes. As a result the beam radiates a single coherent transverse mode in the undulator, as shown in Fig. 5.

Finally, to accurately measure the integrated intensity gain, we used a high dynamic range photodiode detector.

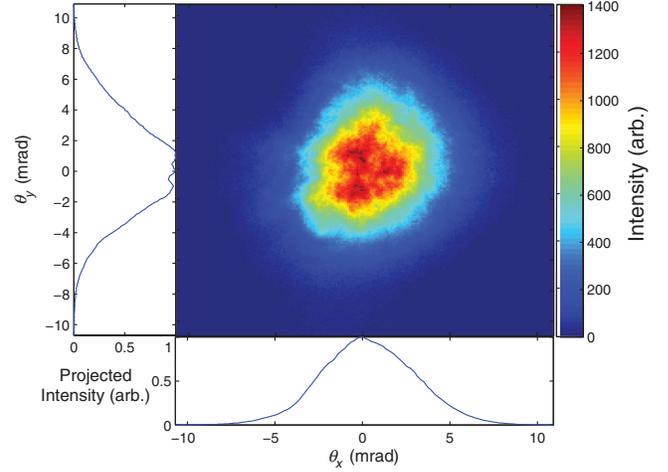


FIG. 5 (color). Far-field undulator radiation image and projected intensity in θ_x and θ_y at maximum compression.

With 12 pC of total beam charge, the average gain in the integrated intensity over the spontaneous emission background was measured to be $U_{\text{max}}/U_{\text{inc}} \simeq 600 \pm 30$, with a shot-to-shot intensity fluctuation of $\sigma_U/U_{\text{inc}} = 480$. The e -beam form factor $B(\vec{k})$ decays rapidly for angles larger than the coherent angle $\theta_c > \lambda_r/2\pi\sigma_x$, while the width of the spontaneous undulator radiation is $\theta_{\text{sp}} \simeq (1 + K^2)^{1/2}/\gamma$. For the typical operating conditions in our experiments $\theta_{\text{sp}} > \theta_c$, which means that the angular width of the coherent radiation is dominated by the geometry of the e beam. Since the angular width of the incoherent far-field distribution is measured to be $2.2 \times$ larger than that of the coherent distribution, the on-axis intensity gain is significantly higher, approximately 3000. Furthermore, only a fraction of the e beam contributes to the coherent emission, while the entire e beam contributes to incoherent emission. From the numerical simulations we estimate that the current peak that drives the microbunching process contains roughly 20% of the bunch charge. It follows that the peak power emitted on axis can be estimated to be 4 orders of magnitude above the shot-noise level [22].

In conclusion, in this Letter we have discussed the first experimental demonstration of a cascaded LSCA. In our experiment, the space-charge microbunching instability was controlled and optimized to generate intense broadband coherent undulator radiation pulses. Strong bunch compression due to a chirped beam results in coherent radiation pulses with a single transverse mode, consistent with our theoretical understanding of the amplification and compression processes. Because of the short duration of the current peak, a single spectral mode has been observed under conditions of strong compression. Finally, the cascading process enabled by use of three chicanes has been investigated by scanning the relative values of the three R_{56} 's while keeping the total compression constant. This experiment provides a proof-of-principle demonstration for

the generation of broadband coherent radiation at fourth generation light sources, and potentially extends the operation of FEL user facilities into new and unexplored regimes.

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