FIRST DEMONSTRATION OF A SLIPPAGE-DOMINANT SUPERRADIANT FREE-ELECTRON LASER AMPLIFIER

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Abstract

We report the first experimental demonstration of a slippage-dominant superradiant free-electron laser (FEL) using an ultrafast seed-laser pulse. We measured the evolution of the longitudinal phase space in the slippage-dominant superradiant regime. With a roughly 1% variation in the electron beam energy, we observed a seed-like fully longitudinal coherence, and a 2% wavelength shift from the seed. The temporal and spectral evolution of the slippage-dominant FEL radiation as predicted by a numerical simulation was experimentally verified for the first time.

INTRODUCTION

With the recent successful commissioning of the Linac Coherent Light Source (LCLS) at SLAC, FELs hold great promise of becoming the premier source of tunable, intense, coherent photons for either ultra-short time resolution (single pass amplifier) or ultra-fine spectral resolution (oscillator), from THz to the hard X-ray regime. Among several major approaches for single-pass FELs, Self-Amplified Spontaneous Emission (SASE) FELs have excellent tunability, and transverse coherence, but typically poor temporal coherence since the lasing process starts from the shot noise of the electron beam [1,2]. Laser-seeded FEL amplifiers have the highest temporal coherence since an external coherent seed initiates the FEL process [3,4]. However, the external seed determines the wavelength of the output radiation [5]. Therefore, the tunability of such a FEL depends upon the seed.

In this paper, we experimentally demonstrate a novel spectro-temporal regime of a laser-seeded FEL, similar to superradiance in the slippage regime, as analytically and numerically described by Bonifacio [6−8]. The wavelength of the output FEL radiation is centered at the spontaneous radiation wavelength, $\lambda_r = \frac{\lambda_u}{2\gamma_r^2} \cdot \left(1+\frac{K^2}{2}\right)$, determined by the electron beam energy $mc^2\gamma_r$, rather than by the seed laser wavelength, λ_{SEED}. Here, K and λ_u are the undulator parameter and period respectively. We provide numerical and experimental evidence for the spectral overlap between the seed pulse and the FEL gain bandwidth (GBW), which initiates the FEL process. The FEL output preserves the tunability of SASE while maintaining the longitudinal coherence of the seed laser. This dynamical behavior occurs in seeded FELs with short seed pulse duration and large slippage that we have dubbed as the slippage-dominant superradiance, which may be relevant for the next generation of tunable high-power seeded FELs. However, the ultimate limit on the spectral tuning range is set by the seed bandwidth; the tunable short-wavelength limit λ_{sl} and FEL power amplification are set by the slippage. Here, the slippage $L_s=N_r\cdot\lambda_r$ is defined as the displacement of the optical pulse with respect to the electron beam at the end of the N_r periods of the undulator. In an electron beam energy detuning case ($\lambda_r\neq\lambda_{SEED}$), the spectral overlap between the seed and the FEL GBW provides the initial seed to coherently bunch the electrons in the slippage region before they start to emit coherent light, identical to the superradiant spike in the slippage regime (SRSPIKE). The length of the slippage region, L_s, determines the number of electrons contributing to the coherent emission, and is proportional to the pulse length of SRSPIKE before the saturation, ~$0.5L_s$. Eventually, the slippage determines the FEL power amplification and the short wavelength limit λ_{sl} at which the superradiant spiking process becomes less efficient, i.e., when its intensity is less than that of the seed pulse.

We report the first experimental demonstration of the slippage-dominant superradiant spiking phenomenon using a short seed-laser pulse (140fs FWHM) at a fixed central-wavelength (793.5nm), and a variable energy electron beam (100.7–102.8MeV). The pulse length of SRSPIKE measured by frequency-resolved optical gating (FROG) technique [9] is determined by the slippage, ~$0.5L_s$. Simultaneously, we observed the FEL spectrum centered at the resonance wavelength and having a distribution of single spike which indicates good longitudinal coherence. Our experiment demonstrates a significant spectral tuning range, 778nm to 810nm, about ±2%, limited by the maximum of 1% seed-laser bandwidth (FWHM). The tunability range is defined by wavelengths for which the FEL output exceeds by tenfold the output energy of the SASE FEL. In addition, the FEL output power is up to three-orders of magnitude higher than that generated by the SASE FEL. Our experimental findings agree reasonably well with the results of our simulations using the PERSEO code [10].

SIMULATION

The principal parameters in PERSEO simulation are the same as the ones in the experiments. In the short-pulse mode, the seed-laser pulse length L_{SEED}=42μm is on the order of the cooperation length L_c=21μm, given by the slippage in one gain length ($\lambda_r/4\pi\rho$). Here, $\rho=3.0\cdot10^{-3}$ is the Pierce parameter. We use a Gaussian temporal profile model for the electron bunch, cut_off at six-sigma, and the same time window for the seed laser pulse. In the simulation, three distinct FEL processes always coexist: SASE, direct amplification from the seed (ASEED), and SRSPIKE. ASEED, identical to the laser-seeded FEL in the steady-state regime, describes the seed-laser pulse itself temporally evolving through the undulator. SRSPIKE is the FEL radiation from the electrons in the

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slippage region. Their radiation output can be qualitatively described as $P_{out}(Z) \approx P_{ini} \cdot \int_0^L e^{\Gamma(\delta,s)\cdot Z} ds$, where $\Gamma(\delta,s)$, L, P_{ini}, and P_{out}, are the growth rate, interaction length, initial seed power, and output radiation power of an FEL, respectively. Longitudinal coordinates Z along the undulator and s along the electron bunch are defined within $0<Z<L_u$ and $0<s<L_e$ respectively, where L_u and L_e are the undulator length and the electron bunch length. The detuning parameter, $\delta=(E-E_s)/(\rho E_s)=\delta_e/\rho$, describes the off-resonance of the electron beam energy E relative to the seed resonance energy E_s. In the SASE case, the growth rate is always at the maximum $\Gamma(0,s)$, L is equal to the electron bunch length L_e, and the FEL process starts from the shot noise of the electron beam P_{SN}. Therefore, SASE FELs have infinite tunability but rather poor longitudinal coherence. In the ASEED case, L is equal to the seed pulse length L_{SEED}, P_{ini} is equal to the seed power P_{SEED}, and the growth rate $\Gamma(\delta,s)$ sharply falls down when δ is large. ASEED has no spectral tunability [5]. In the SRSPIKE case, the growth rate is also at the maximum $\Gamma(0,s)$, L is equal to the slippage L_s, and $P_{ini}=P_{SRSPIKE}$ is the fraction of the seed power that falls within the FEL GBW. Depending on P_{SEED}, $P_{SRSPIKE}$ could far exceed P_{SN} once the electron beam energy detuning is well within the seed bandwidth, so SASE is negligible. Furthermore, the linear analysis predicts that the steady-state region, related to ASEED, is negligible even when the detuning parameter $\delta = 0$ [11], once the slippage $L_s(\geq 10L_c$ normally) is significantly greater than the seed pulse length, which is satisfied by the short pulse condition. Therefore, only one SRSPIKE should be observed.

To produce fully coherent tunable FEL sources through SRSPIKE, we are interested in the large detuning case. In the high-gain steady-state limit, when $\delta > 3/2^{2/3} \approx 1.89$, the, steady-state interaction terminates and the seed pulse is effectively unperturbed when it slips through the electron bunch along the undulator, except that a portion of the seed spectrum overlapping with the FEL GBW provides the initial seed to coherently bunch the electrons in the slippage region. Both simulation and experiment were performed at the electron beam energy detuning $\delta_e=(E-E_s)/E_s=0.91\%$, corresponding to $\delta=2.7$. In PERSEO simulation, only one spike is observed in the slippage region, as shown in Fig. 1(a). Similarly, a single spike appears in the spectral evolution along the undulator, as shown in Fig. 1(b). We observe the spike evolving through the exponential gain regime ($v_g \sim c/3$) before arriving at the superradiant regime ($v_g \sim c$) at the end of the undulator, where v_g is the group velocity of FEL radiation pulse.

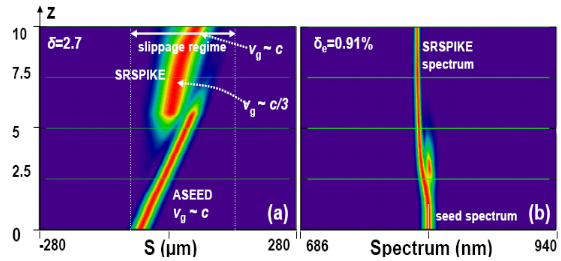

Figure 1: (color). (a) Normalized longitudinal profile of the radiation power along the electron beam coordinates "s" as it evolves along the undulator with coordinate z, and (b) spectral evolution along the undulator, as determined by a numerical simulation with PERSEO using the experimental parameters and δ=3.0.

In the FEL process, starting from the lethargy region through the exponential gain region, a majority of the seed spectrum stays the same, except that the part overlapping with the FEL GBW participates in the FEL interaction by providing the initial seed to coherently bunch the electrons in the slippage region. Because the detuning parameter δ=2.7 is large, the seed pulse maintains its temporal shape, shown as ASEED with in Fig. 1(a), and also, a single SRSPIKE in the slippage region starts to grow, until it dominates over the seed. The energy gain of the SRSPIKE relative to the seed-laser is ~100 at the end of exponential gain region. Besides reproducing superradiant spiking phenomena, we observe numerically the single spike spectral behavior and the pulse width (FWHM) of a SRSPIKE, ~$0.5L_s$ before the saturation.

EXPERIMENT

The experiments reported here were performed at the Source Development Laboratory (SDL) of the Brookhaven National Laboratory (BNL). The SDL consists of an rf photoinjector, a 250MeV linac, a 10-meter undulator, and a Ti:sapphire laser system. The single Ti:sapphire laser system with two separate optical compressors is used both to drive the rf gun and to seed the FEL. To explore the slippage-dominant superradiance regime, the seed laser is adjusted to be Fourier-transform limited with an unchirped pulse duration of 140fs and a bandwidth of 7.5nm (FWHM), as shown in Fig. 2(a). The key experimental parameters are list in Table I.

Table I: Experimental Parameters at the SDL

Undulator period λ_u	3.89 cm
Undulator parameter K	1.1
Undulator length L_u	10 m
Electron energy E	102.8 MeV
Electron bunch length (FWHM)	1.1 ps
rms energy spread σ_E/E	0.1%
Maximum peak current I	300 A
Seed laser wavelength λ_{SEED}	793.5 nm
Seed laser bandwidth (FWHM) $\Delta\lambda_{SEED}$	7.5 nm
Seed laser duration (FWHM) τ_{SEED}	140 fs
Peak power of seed laser	1 MW

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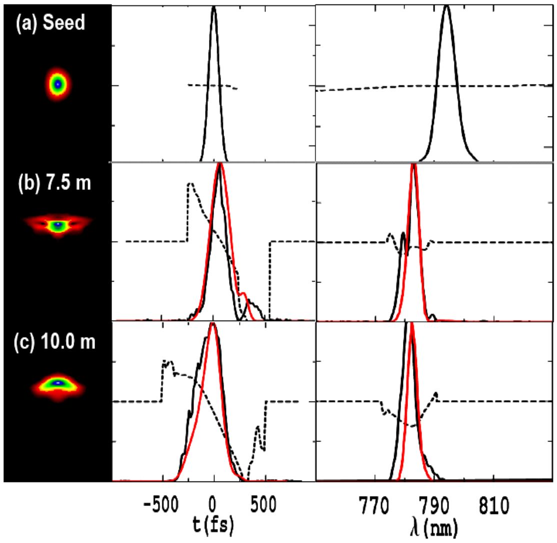

Figure 2: (color). Each FROG result is a row in the figure labeled by the longitudinal position in the undulator where the FEL interaction was terminated when the data being taken. Starting from the left, the three columns are: retrieved FROG images, temporal and spectral distributions including phase. Measured FROG amplitudes (—) and phase (--) are plotted from -6 to +6 radians and PERSEO simulation results (—). Seed power is 0.1μJ.

The longitudinal phase space distribution of the radiation is measured using a commercial Grenouille configuration FROG. At the electron beam energy detuning δ_e=0.91%, the retrieved FROG images of the FEL light are shown in the first column of Fig. 2, where the horizontal axis is the delay [τ] and the vertical axis is the frequency [ω]. The FROG image of the input seed laser is shown in the top row of Fig. 2. The resulting temporal and spectral distributions, including the phase are shown in columns 2 and 3 of Fig. 2 along with a label which highlights the longitudinal position in the undulator where the FEL interaction was terminated while we were taking the FROG data. The FEL interaction was terminated by using a trim coil located at various points along the undulator to kick the beam off the ideal trajectory. The measured FROG images (—) and the simulated temporal and spectral distributions (—) agree reasonably well.

Since the slippage regime is dominant when δ_e=0.91%, we experimentally confirm that a single SRSPIKE is observed, as shown in the column 2 of Figs. 2(b) and 2(c), and it dominates over the seed when z ≥ 7.5m. At z=10m, the pulse duration of the SRSPIKE measured using the FROG is ~330fs (FWHM) which is much wider than the seed-laser pulse (140fs FWHM) and is about half of the seed-laser slippage (680fs). In the temporal domain, those electrons being slipped over by the seed-laser pulse are coherently bunched before they start to emit coherent FEL light. The products of time-bandwidth Δτ·Δν, reconstructed from those FROG images, are close to 0.5, implying that the FEL pulse is nearly Fourier transform limited and has good longitudinal coherence.

CONCLUSION

In conclusion, we report the first experimental demonstration of the slippage-dominant superradiant FEL using an ultrafast seed-laser pulse. For a FEL amplifier operating in this regime, we experimentally and numerically characterize the evolution of its longitudinal phase space along the undulator, and show that the FEL spectrum is tunable while its temporal distribution is determined by the slippage. We also provide numerical and experimental evidence for the spectral overlap between the seed pulse and the FEL GBW, which initiates the slippage-dominant FEL process, rather than the shot noise of the electron beam. For the 140fs seed laser pulse at a fixed central wavelength of 793.5nm and ~1.1ps electron bunch duration, ±2% spectral tunability was experimentally demonstrated at the NSLS SDL. Furthermore, we observe a near Fourier-transform limit radiation pulse at δ_e=0.91% using a FROG. Both simulations and experiments reveal virtually fully longitudinal coherence of the FEL output compared to that of SASE. Also, the FEL output power is up to three orders of magnitude higher than that generated by a SASE FEL. These results agree well with our numerical simulations. How to apply this scheme as a broad-band tuning technique and further extend it towards the short wavelength will be our future work.

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