Self-Amplified Spontaneous Emission Free-Electron Laser with an Energy-Chirped Electron Beam and Undulator Tapering

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We report the first experimental implementation of a method based on simultaneous use of an energy chirp in the electron beam and a tapered undulator, for the generation of ultrashort pulses in a self-amplified spontaneous emission mode free-electron laser (SASE FEL). The experiment, performed at the SPARC FEL test facility, demonstrates the possibility of compensating the nominally detrimental effect of the chirp by a proper taper of the undulator gaps. An increase of more than 1 order of magnitude in the pulse energy is observed in comparison to the untapered case, accompanied by FEL spectra where the typical SASE spiking is suppressed.

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Ultrashort x-ray pulses are of great interest for their promising applications in ultrafast time resolution studies [1]. Single pass SASE free-electron lasers are capable of generating x-ray pulses ranging from hundreds down to tens of femtoseconds, allowing the direct observation of structural dynamics, such as localized and collective motions in solids, molecular vibration, etc. [2,3]. However, to resolve faster processes, as for instance electronic rearrangements, probes in the femtosecond regime are required. Radiation production in a FEL is based on the passage of a relativistic electron beam through the periodic magnetic field of a planar undulator with maximum amplitude B_u and period λ_u, provoking emission at a resonant frequency $\omega_0 = 2\gamma^2\omega_u/(1 + K^2/2)$ and its harmonics, where $\omega_u = 2\pi c/\lambda_u$, $K = eB_u\lambda_u/(2\pi m_e c)$ is the undulator strength and $\gamma = E/m_0c^2$ is the Lorentz factor. The SASE FEL radiation is only partially coherent, being the result of the amplification of the electron beam shot noise. The output pulse structure is characterized by phase-uncorrelated coherent spikes extending over the electron beam pulse length. The property of longitudinal coherence may be improved by seeding the FEL with an external source [4,5]. This approach can be extended to higher harmonics with the harmonic generation process in a FEL cascade with two or more undulators, the latter being tuned with the resonance at one of the harmonics of the former [6,7]. FEL cascades operating at saturation can provide superradiant ultrashort pulses, where the spike length is determined by its peak intensity [8–10]. The two-step electron laser interaction in the echo-enabled harmonic generation scheme [11], can also generate ultrashort pulses at the attosecond time scale [12]. These solutions are constrained in wavelength tunability by the availability of a suitable seed source. Alternatively, one may use methods that rely only on the SASE mechanism. For example, the shaping of the longitudinal or transverse electron beam phase space preferentially enables the gain in a small longitudinal portion of the beam [13,14]. The single cooperation length (or single spike) regime can be achieved by using electron bunches shorter than the average distance between two adjacent SASE spikes [15–18], as demonstrated at LCLS [19]. Pulse shortening methods, that rely on phase space manipulations, depend on the degradation of the FEL gain when the radiation slips outside the effective gain region, leading to an increase of the gain length and a drop in FEL output, as well as pedestals. However, the single-pulse approach has very high performances (short gain length) due to the use of high brightness beams. Achieving this brightness requires use of small charge beams (< 10 pC), which implies efficient radiation production, but relatively small total photon output. On the other hand, introducing in the gain shaping a linear correlation (chirp) in the longitudinal phase space enables the preservation of FEL performance [20]. This scheme combines electron beam energy chirp with a judiciously-chosen undulator field taper, i.e., a smooth variation of peak magnetic field along the beam propagation axis. The energy chirp serves to detune the beam's local resonant frequency (in longitudinal position $s = z - \beta_z ct$, where the beam mean longitudinal velocity $\beta_z c = c(1 - (1 + K^2/2)/2\gamma^2)$). As the FEL radiation produced upstream propagates forward in s, it falls out of the local gain bandwidth. This effect can be compensated, however, by choosing the undulator taper to allow the continuous gain of a spike initiated in the rear of the bunch as it moves forward in s with the appropriate velocity, as illustrated in Fig. 1.

In case of a linear chirp on the electron beam, the mean "local" energy varies as $\gamma(s) = \gamma(s_0) + \alpha(s - s_0)$, with s_0 representing the center of the electron bunch in its drifting reference frame, and α quantifying the degree of energy chirp. The higher velocity of the light with respect to that of the electrons brings a radiation spike out of resonance, when it slips a distance of the order of $\delta s \sim \rho\gamma m_0 c^2/2\alpha$, being ρ the Pierce gain parameter [21]. Inhomogeneous gain broadening associated with the energy spread occurs even with a negligible local energy spread because of slippage.

Analysis of this slippage is complicated by the modification of the radiation spike's velocity in the presence of gain; the peak of a spike in the exponential gain regime moves at a velocity [8] $\beta_L = 3\beta_z/(2 + \beta_z)$. Approaching

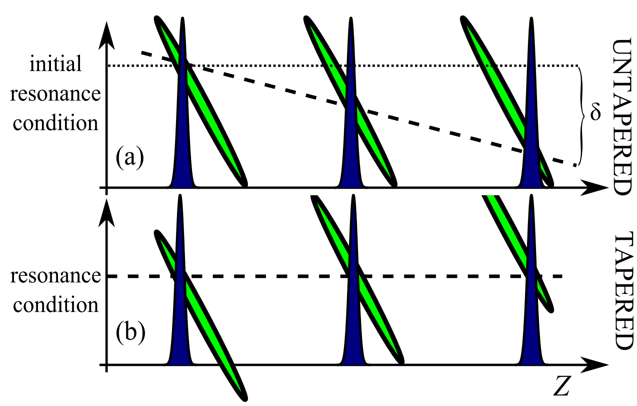

FIG. 1 (color online). Propagation of a field spike (blue) developing at the rear of a chirped e-beam (green) for (a) untapered case, and (b) tapered case as a function of z. Vertical axes indicate the resonant condition as a function of the relative position between the beam and radiation, δ is the final detuning in the untapered case. In (a) the slippage leads the spike out of resonance, when the chirp is combined with an appropriate undulator taper (b), the resonance can be preserved.

saturation, the radiation peak propagates at a higher velocity than β_L, closer or even higher than unity, because of the pulse shortening associated to the electron synchrotron oscillation [22]. Above saturation, the front of the pulse moves forward at c.

The chirp-taper combination discussed above also affects the spike propagation velocity. Indeed, the chirp-induced energy change observed at the peak of the radiation pulse may be expressed as $\gamma(z) = \gamma_s + \alpha z \eta \omega_u/\omega_0$ with z the coordinate along the undulator, γ_s the beam energy at the undulator entrance ($z = 0$) and at the position along the bunch where the spike will eventually grow, and η a coefficient accounting for an arbitrary propagation velocity of the radiation - β_r ($\eta = 1$ for $\beta_r = 1$ and $\eta = 1/3$ for $\beta_r = \beta_L$). Inserting $\gamma(z)$ in the resonant condition and solving for the undulator K provides a taper scaling which preserves the desired resonance condition during propagation as

$$K(z) = 2\sqrt{(\gamma_s + \alpha z \eta \omega_u/\omega_0)^2 \omega_u/\omega_0 - 1/2}. \quad (1)$$

In such a regime the correlated energy spread is compensated only for spikes drifting with the appropriate velocity associated to the taper. When the cooperation length is of the same order of the e-bunch length only a single radiation spike reaches full saturation.

In this Letter we report on the first experimental demonstration, at the SPARC FEL test facility, of the generation of short pulses in a single pass amplifier with this combined chirp-taper method [20]. The SPARC undulator is composed by six variable gap modules of 75 periods each (77 including termination periods), with a period length of 2.8 cm and a maximum $K = 2.2$ [23]. The FEL [24,25] is driven by an accelerator providing a high quality beam [26]. Longitudinal beam compression is achieved by electron beam injection off crest in the first linear accelerator (linac) section, close to the zero crossing phase, resulting in velocity bunching that leaves a strong chirp in the longitudinal phase space and subsequent increase of the peak current [27]. The measured longitudinal phase space at the linac exit after velocity bunching shows a residual chirp, of -8.7 ± 2 keV/μm, with the uncertainty arising mainly due to linac phase jitters of 1°, combined with the sensitivity of compression to injection phase errors. The experiment was done with a mean energy of 115.2 MeV, projected (slice) energy spread of 1.33 (0.7) MeV and rms e-bunch length of 0.42 ps, corresponding to a peak current of 380 A. In the transverse plane the beam was matched to the undulator with Twiss parameters (averaged over the undulator length) $\langle\beta_x\rangle = \langle\beta_y\rangle \sim 1.5$ m and with projected emittances $\varepsilon_x/\varepsilon_y = 2.7/3.0$ mm mrad. In these conditions the chirp with its associated gain degradation prevents the FEL from reaching deep saturation, in the absence of tapering. An in-vacuum spectrometer [28] represents the main radiation diagnostics. Calibrated gratings and CCD detector (Versarray, 1300B-Princeton

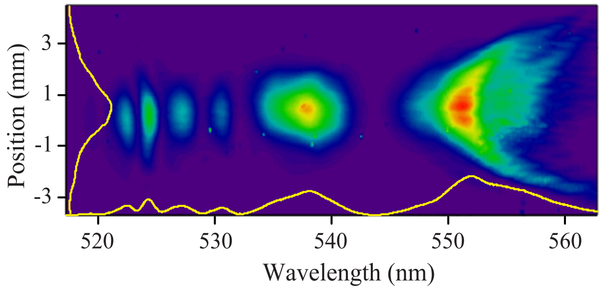

FIG. 2 (color online). Single shot spectrum acquired with all undulators set at nominal resonance of 540 nm, with spectrometer entrance slit opened at 100 μm, corresponding to a resolution of $\sim$0.17 nm. The vertical axis represents the nondispersive dimension at the slit.

Instruments) enables the simultaneous determination of spectral properties of the observed FEL radiation and of the pulse energy [29].

Figure 2 shows a typical single shot spectrum obtained with the untapered undulator, i.e., six sections tuned at the resonance of 540 nm for the mean beam energy. The strong chirp in the electron bunch produces a broadband spectrum extended over the full spectral window. The analysis of a sequence of 100 spectra gives an average ($\pm$ rms) pulse energy of 7.8 ± 8 μJ, a mean central wavelength of 537 ± 5 nm and an rms linewidth of 8.8 ± 2 nm.

In order to compensate the chirp, each undulator module was progressively tuned, commencing with the first, while minimizing the spectral width (see Fig. 3 Taper A).

This process results in an increase of the pulse energy, in a narrowing of the spectrum and in a shift of the mean wavelength down to 521 ± 3.7 nm. The central wavelength was restored to 540.1 ± 4.4 nm by tuning the undulator gaps to the values corresponding to the solid curve in Fig. 3 (Taper B). The black dashed line in Fig. 3 indicates the trend of a taper compensating a spike traveling at the velocity c ($\eta = 1$), as given by Eq. (1). Discrepancies between this last curve and Taper B in the final part of the undulator may be ascribed to nonlinearities in the energy chirp, but also to the fact that the taper is simultaneously compensating the electron energy loss. This is confirmed by the extracted energy per pulse. The analysis of the sequence of 100 spectra, as shown in Fig. 4, gives a pulse energy of average value of 139 ± 97 μJ and rms linewidth of 4.3 ± 1.3 nm.

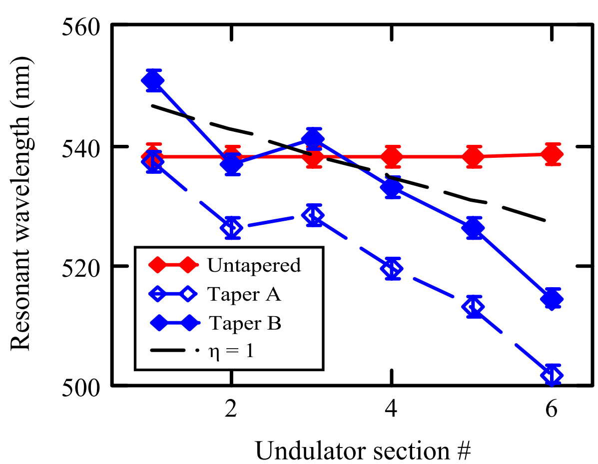

FIG. 3 (color online). Resonant frequency for a 115.2 MeV electron beam in the six undulators, untapered and tapered case (Taper A). Taper B after compensation of the observed wavelength blueshift.

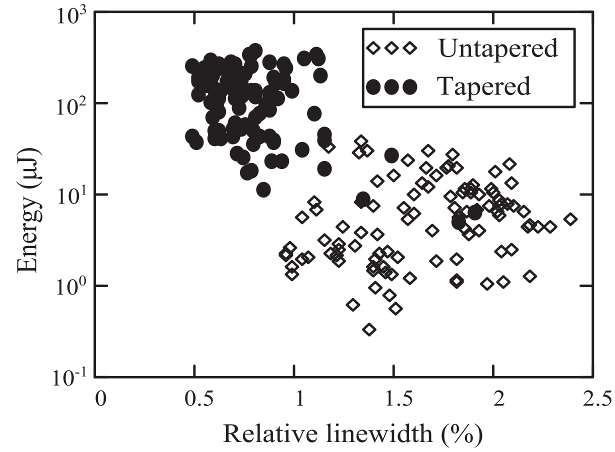

FIG. 4. Energy vs relative spectral width for untapered and tapered cases.

Figure 5 compares the experimental output energies with the results of 100 cases simulated with GENESIS 1.3 [30]. The rms pulse energy fluctuation is $\sim$70% in the experiment, while it is $\sim$11% in the GENESIS 1.3 simulations including only the intrinsic e-beam shot noise. This value increases up to $\sim$50% [distribution (A) in Fig. 5] when a correlated stochastic variation of 28% in the pulse peak current and time duration, compatible with a phase jitter in the first linac section of $\sim 1°$, is introduced. Distribution (B) in Fig. 5 results from the additional

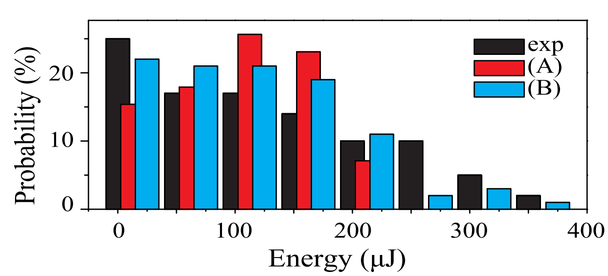

FIG. 5 (color online). Histogram of the pulse energy distribution given by 100 measurements (exp), and by 100 GENESIS 1.3 simulations, where statistical fluctuations of peak current and bunch length (A) and also emittances and energy spread (B) were introduced. The listed beam or undulator parameters were used, except for the slice emittances (1.4 mm mrad) and relative slice energy spread (1.7×10^{-3}) which were chosen to match measured mean pulse energy.

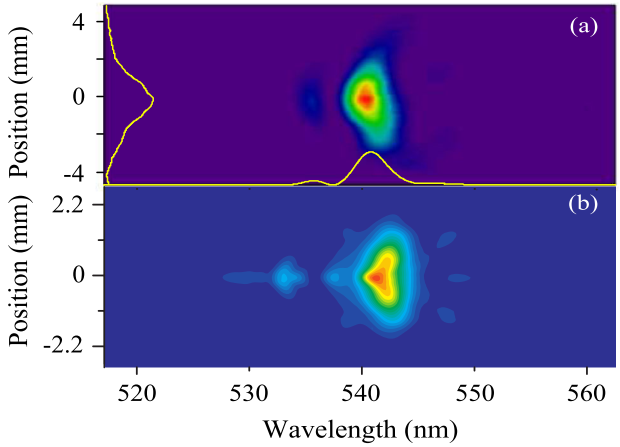

FIG. 6 (color online). Typical FEL spectrum showing a single spike from the experiment (a) and from the GENESIS 1.3 simulation (b). The total pulse energy is ~300 μJ.

fluctuation of emittances (50%) and slice energy spread (13%) which can be attributed to this phase jitter. About 50% of the acquired spectra were characterized by a pattern similar to that shown in Fig. 6 [image (a)], where typical SASE spikes are absent and the spectrum is composed by a single coherence region. Image (b) in Fig. 6, obtained by postprocessing the GENESIS 1.3 simulation data with an algorithm introduced to model the spectrometer input slit or grating transformations to reproduce the image on the CCD camera, exhibits a similar form. While the number of single spike events in the simulations (~ 30%) was lower than in the experiment, the agreement in the details of the reconstructed spectra in these cases is striking. A Gaussian profile fitting the main structure in the spectrum of Fig. 6 has a standard deviation of 1.45 nm. It likely results from the contribution of a partially nonlinear chirped radiation field spike [31]. A Fourier limited pulse with the same width would have a rms duration of ~50 fs and a peak power of about 2 GW.

In this Letter, we have demonstrated the possibility of generating isolated spike radiation pulses in a single pass FEL operating in SASE mode, by combining a chirped electron beam with a tapered undulator. This was obtained without increase in the gain length or loss of efficiency, but in fact yielding an increase by a factor of ~20 in the pulse energy due to the involvement of the entire beam in the FEL gain. This higher efficiency is accompanied by a narrowing of the spectral width. These studies provide a further insight into ways for controlling the longitudinal coherence of SASE FELs that are of particular interest for sub-fs x-ray radiation applications.

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