Impact of Non-Gaussian Electron Energy Heating upon the Performance of a Seeded Free-Electron Laser

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(Received 11 October 2013; published 21 March 2014)

Laser-heater systems have been demonstrated to be an important component for the accelerators that drive high gain free electron laser (FEL) facilities. These heater systems suppress longitudinal microbunching instabilities by inducing a small and controllable slice energy spread to the electron beam. For transversely uniform heating, the energy spread augmentation is characterized by a non-Gaussian distribution. In this Letter, we demonstrate experimentally that in addition to suppression of the microbunching instability, the laser heater-induced energy distribution can be preserved to the FEL undulator entrance, significantly impacting the performance of high-gain harmonic generation (HGHG) FELs, especially at soft x-ray wavelengths. In particular, we show that the FEL intensity has several local maxima as a function of the induced heating caused by the non-Gaussian energy distribution together with a strong enhancement of the power at high harmonics relative to that expected for an electron beam with an equivalent Gaussian energy spread at an undulator entrance. These results suggest that a single stage HGHG FEL can produce scientifically interesting power levels at harmonic numbers $m \geq 25$ and with current seed laser technology could reach output photon energies above 100 eV or greater.

DOI: 10.1103/PhysRevLett.112.114802 PACS numbers: 29.27.Bd, 41.60.Cr, 42.65.Ky

In recent years, short wavelength high gain free electron laser (FEL) [1] have been demonstrated to be powerful scientific tools enabling previously inaccessible information via new experimental techniques [2]. Following the ground-breaking operation of the FLASH facility [3] in the VUV to soft x-ray spectral range, LCLS [4] and SACLA [5] have made available $\geq$ 25-GW instantaneous power, sub-$100-\mathrm{fs}$ duration output pulses in the hard x-ray regime. More recently, successful commissioning of the FERMI user facility now provides scientists with the first seeded FEL pulses in the EUV [6], enabling deeper control of the output pulse's coherence and spectral properties [7,8]. A prerequisite for these high gain FELs are very high brightness electron beams, characterized by low transverse emittance and high peak current. Such high currents are normally obtained by longitudinal compression in one or more magnetic chicane compressors along the accelerator where collective effects may severely deteriorate the electron beam quality.

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A particularly problematic example is the longitudinal microbunching instability [9] whose existence has been confirmed in many FEL-driving accelerators (see, e.g., [10–12]). This instability creates both energy and density modulations on the electron beam, increasing the energy spread up to levels that can strongly degrade the FEL gain process. An accompanying and undesired effect is a large coherent optical transition radiation signal at intercepting diagnostic screens, often limiting the utility of beam profile imaging systems [13,14]. The application of a so-called laser heater (LH) [15] at the low energy ($\approx$100 MeV) part of the accelerator has been found [16] to be an efficient way to suppress the microbunching instability. Generally composed of a short undulator situated in a chicane where the electron beam interacts with an intense laser beam at the resonant wavelength of the undulator, a LH induces a modest and controllable increase in the beam's incoherent energy spread. This increase suppresses, via Landau damping, microbunching instability growth downstream in the remainder of the accelerator. In general, the LH-induced energy spread will not have a Gaussian distribution and in practice, will depend upon details of the transverse overlap between the laser beam and the electron beam in the LH undulator [17]. For the simple case of a transversally uniform field (i.e., very large laser size), the induced energy

spread is the projection of a simple sinusoid resulting in a bipeaked distribution, with the separation between the two energy bands depending upon the LH laser intensity and the specific undulator parameters [18]. However, the most efficient microbunching suppression is obtained for comparable spot sizes of the electron and laser beams in the LH undulator [16].

The control of the total energy spread and its distribution structure at the entrance to an FEL undulator are crucial factors for the successful operation of seeded high gain FELs in which harmonic upshift schemes are used to access wavelengths much shorter than the seed wavelength λ_S. For the case of high gain harmonic generation (HGHG) FELs [19], nearly all analysis to date presumed a Gaussian distribution for the full energy spread. The unattractive consequence is an exponential suppression of FEL gain at moderately high harmonic numbers and, equivalently, the shortest operation wavelengths. Various schemes (e.g., [20–22]) have been proposed to overcome some of these limitations. In particular, the echo-enabled harmonic generation [21] approach utilizes multiple stages of modulation and dispersion to introduce fine structure into the electron beam's longitudinal phase space, permitting efficient FEL radiation emission at quite high harmonic numbers despite a relatively large overall energy spread at undulator entrance.

In this Letter we report measurements on FERMI's single stage HGHG FEL-1 [6] that show this presumption of a Gaussian distribution at undulator entrance is in fact far too pessimistic: much of the local, non-Gaussian structure induced by a laser heater is transported along an accelerator, including through a bunch compressor, and preserved up to the FEL. We have systematically characterized the impact of FERMI's LH by modifying the energy distribution shape upon the HGHG FEL process, comparing it with previously developed analytic theory by Huang *et al.* [16]. Our results, further supported by numerical simulations, show that using the energy spread distribution produced by the laser heater instead of a simple Gaussian distribution with the same rms can strongly improve the performance of a seeded single stage HGHG FEL, allowing one to reach quite high harmonics.

In an HGHG FEL configuration, an external seed laser interacts with a relativistic electron beam in a short undulator (the "modulator") producing a coherent energy modulation on the latter at the seed laser wavelength (normally in the UV). This energy modulation then develops into an associated density modulation (bunching) following passage through a short chromatic dispersive section. The modulated beam, which contains strong components at higher harmonics of the seed wavelength, then enters a long undulator (the "radiator") where the resonant wavelength is set to a particular harmonic. The resulting coherent emission can then be amplified through the normal FEL process, producing short wavelength output pulses characterized by excellent transverse and longitudinal coherence [6,23,24]. Presuming that the seed laser intensity is constant along the modulator, its radius σ_r is much greater than that of the electron beam σ_x, and finally, that the distribution of the electron beam's incoherent (i.e., "slice") energy spread σ_γ is Gaussian, Yu [19] derived the coherent microbunching fraction b_m at exit from the dispersion section

$$b_m = \exp\left(-\frac{1}{2}m^2\sigma_\gamma^2 D^2\right) J_m(m\Delta\gamma_S D), \tag{1}$$

where m is the harmonic number, $D \equiv 2\pi R_{56}/\gamma_0\lambda$, R_{56} is the dispersive section momentum compaction factor, $\lambda = \lambda_S/m$ is the emitted radiation wavelength, γ_0 the electron beam Lorentz factor, $\Delta\gamma_S$ is the seed laser-induced energy modulation amplitude, and J_m is the mth order Bessel function. Analysis of Eq. (1) shows that, in order to have significant bunching at harmonic m, $\Delta\gamma_S \geq m\sigma_\gamma$. However, in order for the FEL gain process to be effective in the downstream radiator, $\Delta\gamma_S/\gamma_0$ must be smaller than the FEL parameter $\rho \sim 10^{-3}$ [25], so a tradeoff needs to be found. This results in a requirement on the normalized energy spread $\sigma_\gamma/\gamma_0 \leq \rho/m$ that for FERMI's 1.2-GeV beam energy and characteristic energy spread of 150 keV limits $m \leq 8$.

However, if the shape of non-Gaussian energy spread distribution function is preserved from the LH exit through downstream bunch compression and additional transport to the FEL's modulator entrance, then application of analysis from Ref. [16] shows that Eq. (1) should be modified as

$$b_m = \exp\left(-\frac{1}{2}m^2C^2\sigma_H^2 D^2\right) J_m(m\Delta\gamma_S D) \times S_H(mC\Delta\gamma_H D, \sigma_r/\sigma_x) \tag{2}$$

where $C \sim \mathcal{O}(10)$ is the net longitudinal beam compression between the LH and the FEL, σ_H is the beam's slice energy spread entering the LH (presumed Gaussian), $\Delta\gamma_H \gg \sigma_H$ is the energy modulation induced by the LH, and S_H is a hypergeometric function (see [16] for details). Experiments performed at LCLS have shown the validity of the LH theory, demonstrating, in particular, that the shape of the energy spread distribution measured just after the laser heater does not follow a Gaussian distribution [17]. In the special case of $\sigma_r \gg \sigma_x$, $S_H = J_0(mC\Delta\gamma_H D)$, as already anticipated, this results in an energy spread with a double peak distribution. Although this particular distribution may significantly impact the bunching process, it is not the best suited for microbunching suppression. Consequently, LHs are typically operated in a condition with σ_r only slightly larger than σ_x.

Equation (2) makes two important predictions. First, the energy spread measure relevant to the exponential

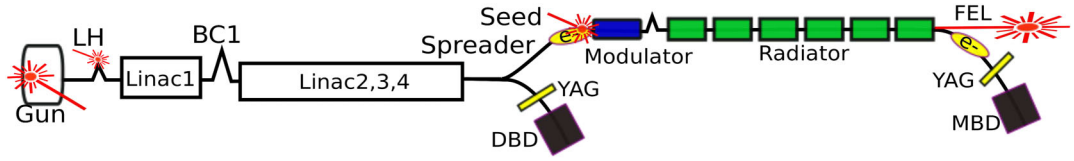

FIG. 1 (color online). FERMI FEL-1 experimental setup. Electrons extracted by a photoinjector (GUN) pass through a laser heater system (LH) and then a bunch compressor (BC1). Following final acceleration to 1.2 GeV, they are bent through an achromatic spreader to the FEL-1 undulators or, alternatively, can be sent to a diagnostic beam dump (DBD) system where their time-resolved energy distribution can be measured.

suppression term is the (compressed) slice energy spread at the LH, whose typical value is $C\sigma_H \approx 30$ to 50 keV, *rather than* the much larger, overall measured energy spread at linac exit (100 to 300 keV). Second, for usual case ($\sigma_r \approx 2\sigma_x$) as at FERMI, the amplitude of the harmonic microbunching at radiator entrance will oscillate as the laser heater power is increased, decaying more slowly than an exponential. Our experimental data support these predictions.

The data presented in this Letter were obtained at FERMI's FEL-1; Fig. 1 displays a schematic of the experimental setup. Electrons extracted from the photoinjector [26] are accelerated up to 100 MeV, at which point they enter the LH chicane within whose undulator a near infrared laser pulse is centered both in time and space on the e-beam pulse. The laser pulse is ~3 times longer than the electron bunch and its energy is tunable via a remotely controlled polarimeter, up to a maximum value of 70 μJ. FERMI's LH system has been successfully commissioned and is now routinely used in FEL operations [27,28]. After heating, electrons are accelerated to 300 MeV, longitudinally compressed ~10 times in a magnetic chicane (BC1) and then further accelerated up to a final energy of 1.2–1.5 GeV. Table I reports the main machine and FEL parameters. The FEL output pulse energy and spectral properties were measured by means of calibrated gas cells and an online spectrometer [29].

The electron energy distribution was determined by a bending magnet spectrometer with an intercepting screen system placed at the diagnostic beam dump (DBD) just beyond the linac end. The longitudinal phase space here can be measured by coupling the DBD spectrometer with an rf-deflecting cavity located just before the DBD dipole bend [30]. The slice energy spread measurement has an estimated resolution of about 70 keV, including the spectrometer resolution and the rf deflector induced energy spread. Figure 2(a) shows the measured longitudinal phase space for a narrow time slice near the temporal center of the electron beam as a function of the LH pulse energy. One sees that although at zero LH heating, the energy distribution is similar to a Gaussian in shape, as the heating is increased the distribution widens and flattens out in the center. Figure 2(b) shows details of the energy distribution for the case where the LH energy was 42 μJ. As shown by the curves of Fig. 2(c), it is readily apparent that energy distribution does not closely follow a Gaussian curve but is much flatter in the center and the tails drop faster to zero. While theory predicts that a similar shape should also characterize the beam with a weaker laser heater power, such a difference between the measured slice energy distribution and a Gaussian is not evident experimentally at low LH energy due to the limited electron beam spectrometer resolution.

We now turn to the dependence of FEL output on the laser heating. As previously demonstrated at LCLS [17], a very small heating by FERMI's LH is enough to suppress microbunching instability growth resulting in a significant improvement in FEL performance [27]. Figure 3(a) shows the FEL output pulse energy at 32.5 nm wavelength as a function of the heating energy: one observes a threefold enhancement between operating with laser heater off and the optimal LH energy setting of 0.6 μJ that suppresses the microbunching and minimizes the energy spread of the beam entering the undulator. Increasing the LH energy beyond this optimum to 3 μJ drops the FEL output back to the LH-off level, because the increased energy spread begins to suppress FEL gain. However, when the LH heating is increased much further, an interesting FEL behavior begins with the output pulse energy showing a

TABLE I. Measured electron beam, laser, and undulator parameters used in the experiment. For the FEL undulators, the first number refers to the modulator, the second to the radiator.

	Parameter	at LH	at FEL
e^- beam	Charge	500 pC	500 pC
	Energy	95 MeV	1.2 GeV
	Slice energy spread (rms)	5 keV	100–300 keV
	Bunch length (rms)	3 ps	300 fs
	Size (at undulator, rms)	100 μm	100 μm
Laser	Wavelength	783 nm	260 nm
	Pulse duration (rms)	8 ps	80 fs
	Energy	< 70 μJ	~ 50 μJ
	Size (at undulator; rms)	150 μm	300 μm
Undulator	Period	40 mm	100 mm / 55 mm
	Number of periods	12	30 / 6 x 42
	Strength parameter (K)	0.8–1.17	3.8–4.1 / 0.6–2.8
	Dispersion (D)	···	3.5–7

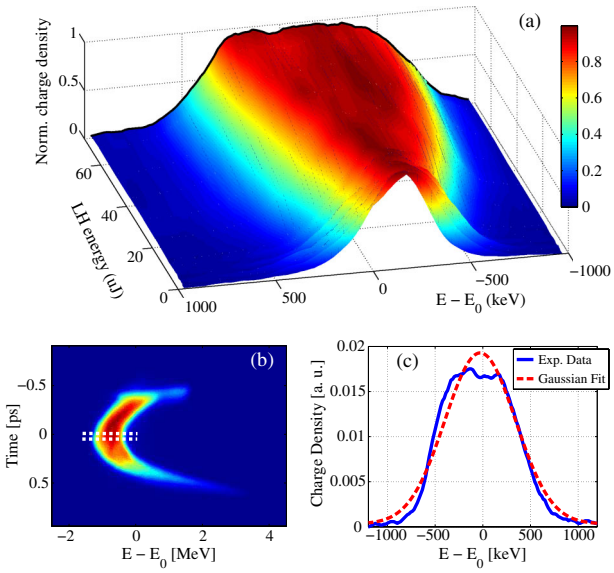

FIG. 2 (color online). (a) Measured slice energy spectrum of the electron beam in DBD as a function of the laser heater pulse energy. (b) Electron beam longitudinal phase space in DBD, measured for a laser heater energy of 42 μJ. (c) Projected energy distribution of the highlighted portion [dashed region in (b)] together with a Gaussian fit with the same second moment and integral area.

series of slowly damped oscillations [Figs. 3(b) and 4]. This happens even at heating levels that would have been expected to have strongly suppressed FEL gain if Eq. (1) applied directly.

To compare experimental measurements with theoretical predictions of the bunching, we then operated the FEL with only three of the total six radiators in resonance with the desired harmonic. In this configuration, the net FEL gain is small and the emission should be almost exactly proportional to the square of the bunching fraction, which, in principle, should allow a meaningful comparison to Eqs. (1) and (2). The results are shown in Fig. 4. Here, the FEL output energy at $\lambda = 32.5$ nm ($m = 8$) measured as a function of the laser heater pulse energy is plotted

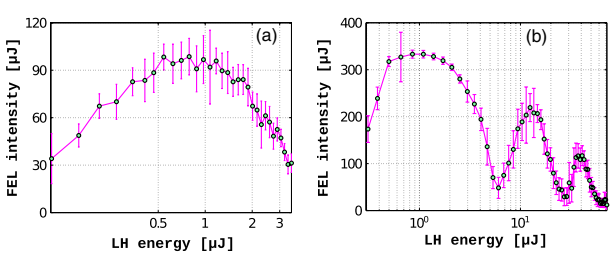

FIG. 3 (color online). FEL output pulse energy at $\lambda = 32.5$ nm (a, $m = 8$) and $\lambda = 52$ nm (b, $m = 5$) as a function of LH energy over a small (a) and large (b) energy range. The results show that optimized laser heating nearly triples the FEL output relative to no heating, but in (b), the FEL pulse energy also oscillates for much larger values of LH energy. The machine parameters during the experiments are summarized in Table I.

together with the theoretical predictions evaluated using relevant laser heater and electron beam parameters of Table I. The locations and amplitudes of the oscillation maxima are in excellent agreement with the predictions of Eq. (2) (filled line in Fig. 4) for a non-Gaussian energy spread distribution as observed at the linac end. Note that the drop in FEL power at very low LH pulse energy is due to the energy spread increase associated with poorly controlled microbunching instability growth [which is not considered in either Eqs. (1) or (2)].

The use and control of the energy spread shape offers an exciting possibility to extend the tuning range of a single stage HGHG FEL down to wavelengths associated with very high harmonics, e.g., for a 260-nm seed laser, harmonics $m \geq 25$ and wavelengths smaller than 10 nm. These wavelengths had been thought to be out of reach for a device like FERMI's single stage HGHG FEL-1, presuming that the electron beam entering the FEL had a Gaussian distribution $\sigma_\gamma \sim 150$ keV. We have explored this possibility by performing a series of numerical FEL simulations with the GINGER code [31], using FERMI FEL-1 parameters and considering beams with both Gaussian energy distributions and those corresponding to Eq. (2). In each case, the distribution is characterized by the same rms value of the energy spread ($\sigma_\gamma = 150$ keV); this value corresponds to the one measured at FERMI for the LH setting that maximizes the FEL power (LH $\simeq 1$ μJ).

The results, reported in Fig. 5, show that there is no significant difference in the emitted FEL power between the two distributions down to $\lambda = 26$ nm ($m = 10$). However, at shorter wavelengths, the non-Gaussian distribution shows much higher output powers. At $\lambda = 10$ nm ($m = 26$) the ratio between the two cases is more than 30:

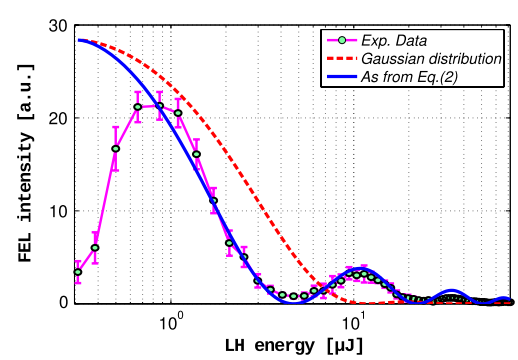

FIG. 4 (color online). Comparison between experimental data (dots) at $\lambda = 32.5$ nm ($m = 8$) and theoretical predictions of the FEL intensity as a function of the laser heater energy. In order to reduce total FEL gain, only three radiators were used; in this condition, the FEL emitted energy is almost proportional to the square of the bunching b_m^2. The dashed curve shows the standard prediction, Eq. (1) for b_m^2 that assumes a Gaussian energy spread at undulator entrance, while the filled curve was obtained using Eq. (2) for b_m^2 and includes non-Gaussian LH heating effects. The machine parameters during the experiments are summarized in Table I.

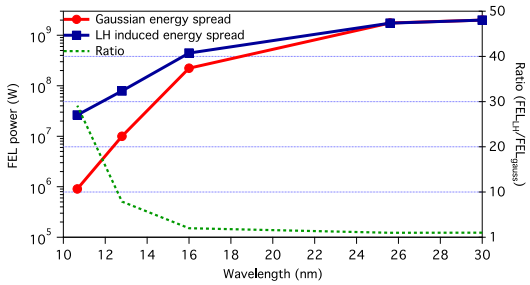

FIG. 5 (color online). Simulations for the FERMI setup. The HGHG emitted power is plotted as a function of the harmonic number, in the case of a Gaussian slice energy spread distribution (dots) and the measured distribution induced by LH (squares). Both distribution have the same rms σ_γ and for each point, the FEL was optimized in terms of the seed laser power and dispersion. The intensity ratio is reported (dashed line).

less than 1MW is predicted for the case of a Gaussian energy spread, while about 30 MW can be produced by adopting the LH-induced energy spread distribution. The better performance associated to the non-Gaussian energy spread is mainly due by the fact that a similar bunching level is obtained with a weaker seed laser and, hence, a smaller seed induced energy spread. Consequently, for the non-Gaussian case, the electron beam enters in the final radiator with a smaller energy spread and has a significantly shorter FEL gain length.

This is a tantalizing result as it suggests that controlling (and even further manipulating) details of the energy spread distribution induced by the laser heater may allow one to cover a much larger tuning range with a single stage HGHG configuration than what was initially predicted, without having to rely on more complicated seeding schemes such as echo-enabled harmonic generation or a two-stage HGHG [21,32]. This might be already the case at FERMI FEL-1, which despite an expected lower wavelength limit of 20 nm, has been operated successfully at 10 nm and shorter wavelengths [33]. This result suggests the scientifically useful operation range of the single stage HGHG scheme might be far better than previously expected.

This work was funded by the FERMI project of Elettra-Sincrotrone Trieste, partially supported by the Ministry of University and Research under Grants No. FIRB-RBAP045JF2 and No. FIRB-RBAP06AWK3, and supported by U.S. Department of Energy Contract No. DE-AC02-76SF00515.

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