Measurement of the average local energy spread of electron beam via coherent harmonic generation

Chao Feng,^{1,2} Tong Zhang,^{1,2} Jianhui Chen,¹ Haixiao Deng,¹ Meng Zhang,¹ Xingtao Wang,¹ Bo Liu,¹ Taihe Lan,¹ Dong Wang,¹ and Zhentang Zhao^{1,*}

¹Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China

²Graduate University of Chinese Academy of Sciences, Beijing 100049, China

(Received 21 March 2011; published 9 September 2011)

The local energy spread of electron beam is a very important parameter for high-gain free-electron lasers (FELs), especially the seeded FELs. Highly accurate measurement of the extremely small local energy spread is rather challenging. In this paper, a simple method to accurately measure the average local energy spread based on the coherent harmonic generation is proposed. A one-dimensional analytical estimation is given to show the principle of this method, and three-dimensional simulation codes have been used to verify the theory. This method has been demonstrated on the Shanghai deep ultraviolet FEL, and the results show that the average local energy spread is about only 1.2 keV at the exit of the 136 MeV linac, which agrees well with the numerical simulations.

DOI: 10.1103/PhysRevSTAB.14.090701

PACS numbers: 41.85.Ar, 41.60.Cr

I. INTRODUCTION

High-gain free-electron lasers (FELs) are being developed to serve as short-wavelength, wide-tunability, high-intensity, coherent radiation sources for advanced user applications. One of the most feasible ways for delivering FEL to the hard x ray is self-amplified spontaneous emission (SASE) [1]. However, SASE radiation starts from shot noise of the electron beam, and results in a poor temporal coherence and a long undulator system. With the growing interest in compact and fully temporal coherence sources, various seeded FEL schemes have been proposed for short wavelength on the basis of harmonic generation and seeding of external lasers. A typical scheme is the high-gain harmonic generation (HG) scheme [2], which has been demonstrated in the visible and ultraviolet region [3,4]. Since HG pursues the exponential growth in the radiator, it suffers from a limited frequency multiplication factor to avoid large beam energy modulation [5]. To improve the efficiency of frequency up-conversion and extend the seeded FEL to the x-ray region, some novel seed FEL schemes like cascading stages of HG [6] or echo-enabled harmonic generation (EEHG) [7,8] have been proposed in recent years.

Most present and future designs of linac driven high-gain FELs adopt high brightness photoinjectors to meet the requirements on the transverse and longitudinal beam quality [9–11]. One of the fundamental parameters in

photoinjectors is the local energy spread which has a strong impact on the FEL performance. When the local energy spread is larger than the Pierce parameter ρ [12] inside the FEL cooperation length, the FEL amplification process will reach saturation. For seeded FEL schemes, the contradictory requirements of large energy modulation and small local energy spread constrain the possibility of working at high harmonic number for a single stage. The study of local energy spread allows one to deeply investigate the details of the energy spread compensation method and to design and tune the FEL machine for best performance. Moreover, the knowledge of the local energy spread and the energy modulation amplitude induced by the seed laser will give a complete description of the seeded FEL process.

Significant efforts have been devoted in past decades to measurement of the realistic electron beam. Since the electron bunches are much shorter than the temporal resolution of measurement devices, standard electron beam diagnostics are routinely used in measuring the projected parameters like the beam charge, emittance, and energy spread of the full electron bunch, but they fail to measure the local parameters of the electron bunch. The local energy spread of electron beam produced by a photoinjector is believed to be in the order of few keV [13,14]. For accelerator research, it remains a challenge to measure the energy spread with high accuracy across a wide range. Driven by the urgent need for measuring the local energy spread of the beam, various instrumentations and methods such as transverse deflecting radiofrequency cavity [15], FEL gain curve based method [16], optical klystron (OK) based method [17], or optical replica synthesizer (ORS) based method [18] have been developed. The widely used method to measure the local energy spread of electron beam produced by a photoinjector is using a deflecting cavity followed by a horizontal dispersive region which

*Corresponding author.
zhaozt@sinap.ac.cn

Published by the American Physical Society under the terms of the *Creative Commons Attribution 3.0 License*. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

allows measuring the longitudinal trace space in a single shot basis. The local energy spread can be extrapolated by slicing the beam vertically and measuring the beam thickness in energy as a function of time. The resolution of this method is about a few keV [15], which may be not accurate enough for FEL operation. Analysis on the experimental gain curve of the FEL can give the local parameters of the lasing part. This method has been carried out at the SCSS Test Accelerator and the results show that the relative local energy spread should be lower than 6×10^{-4} [16]. Both the OK and the ORS based method use the coherent undulator radiation to find the information of the local energy spread. The OK based method was developed about two decades ago using the radiation spectrum from an OK to measure the energy spread in the storage rings [17,19]. The accuracy of this method was improved by a new fitting method in Ref. [20]. The relative energy spread was measured from 6×10^{-4} to 6×10^{-3} with an overall uncertainty of less than 5% in the Duke storage ring based on this method. The ORS based method was first suggested by Saldin *et al.* in Ref. [18]. The ORS technique is used for full measurement of the longitudinal profile of short electron bunches. Based on the information of the current profile, the local energy spread distribution can be determined from the dispersion section strength scan under the condition that the energy modulation amplitude is smaller than the local energy spread. The resolution of this method will be limited by the accuracy of the measurements of the current profile. In addition, it is practically not easy to guarantee the energy modulation induced by the seed laser is smaller than the local energy spread.

In this paper, a novel method for characterizing the local energy spread based on the coherent harmonic generation (CHG) [2,21] is proposed. Similar to the ORS based method, the information of the local energy spread is determined using the CHG. In contrary to the ORS based method, measurement of the current profile is not necessary and the energy modulation can be arbitrary with respect to the local energy spread. Instead, two measurements with different seed laser powers are needed. The energy modulation amplitudes induced by the seed lasers can be obtained at the same time.

An analytical estimation is present in Sec. II to describe the physical mechanism of the CHG based method. Then a 3D simulation is carried out to demonstrate its feasibility in Sec. III. Section IV presents the experimental results of energy spread measurement at the Shanghai deep ultraviolet FEL (SDUV-FEL) test facility using this method. Conclusions and prospects are given in Sec. V.

II. CHG BASED ENERGY SPREAD MEASUREMENT METHOD

The CHG is typically used to enhance the harmonic radiation gain by imprinting microbunching in the electron beam with an external seed laser [2,21]. A CHG scheme

normally consists of two undulators separated by a chicane. The electron beam is energy modulated by the seed laser in the first undulator called modulator and then sent through a chicane called dispersion section (DS) to convert the energy modulation into density modulation, after which the prebunched electron beam will generate powerful coherent harmonic radiation in the second undulator called radiator.

The density modulation of the electron beam can be quantified by the bunching factor, which has a maximum value of unity. Analytically, the initial bunching factor of the n th harmonic in the radiator is given by [2]

$$b_n = J_n(nD\Delta\gamma)e^{-(1/2)(nD\sigma_\gamma)^2}, \quad (1)$$

where J_n is the n th order first class Bessel function, $D = k_s R_{56}/\gamma$ is a dimensionless parameter related to the dispersive strength of the DS, k_s is the wave number of the seed laser, R_{56} is the dispersive strength, γ is the relativistic parameter for the mean electron beam energy, σ_γ is the local energy spread of the electron beam, and $\Delta\gamma$ is the energy modulation amplitude induced by the seed laser, which can be expressed as

$$\Delta\gamma = k_s a_s a_{um} l_m [JJ]_1 / \gamma \quad (2)$$

$$a_s = \sqrt{\frac{Z_0 P_{\text{seed}}}{\pi k_s Z_R (mc^2/e)^2}}, \quad (3)$$

where a_s and a_{um} are the dimensionless (rms) vector potentials of the spontaneous radiation and magnetic field of the modulator, respectively. l_m is the length of the modulator, $[JJ]_1$ is the polarization modification factor for a linearly polarized planar undulator, $Z_0 = 377 \Omega$ is the vacuum impedance, and Z_R is the Rayleigh length of the seed laser. From Eqs. (2) and (3), it is found that the energy modulation is in proportion to the square root of the seed laser power: $\Delta\gamma \propto \sqrt{P_{\text{seed}}}$. In order to get sufficient bunching factor, $nD\sigma_\gamma < 1$ should be satisfied, and the n th Bessel function will reach its first and absolute maximum when $nD\Delta\gamma \approx n + 1$ according to Eq. (1), which means that the energy modulation amplitude should be n times larger than the initial local energy spread.

For a longitudinally uniform distributed electron beam, the output power of a CHG can be simplified as [11]

$$P = \frac{(Z_0 K [JJ]_1 l_r I b_n)^2}{32 \pi \Sigma^2 \gamma^2}, \quad (4)$$

where K is the dimensionless undulator parameter, l_r is the length of the radiator, I is the local current, b_n is the n th local bunching factor, and Σ is the local transverse beam area. For a realistic electron beam, when the slippage length is much shorter than the bunch length, the output radiation profile will be coupled strongly with the local beam current, bunching factor, and transverse beam area. The output CHG energy should be the integration of the radiation power [Eq. (4)] along the electron beam,

$$E_{\text{CHG}} \approx \frac{(Z_0 K [JJ]_1 l_b)^2}{32 \pi \gamma^2 c} \int_0^{l_b} \frac{I^2 b_n^2}{\Sigma^2} dz, \quad (5)$$

where c is the speed of the light and l_b is the full length of the electron bunch. Considering the weight factor of the local beam current, transverse beam area, and bunching factor, the average local energy spread $\overline{\sigma}_\gamma$ and the average energy modulation amplitude $\overline{\Delta\gamma}$ are defined as

$$\overline{\sigma}_\gamma = \frac{1}{nD} \ln^{1/2} \left\{ \int_0^{\sigma_z} \left(\frac{J_n(nD\Delta\gamma)I}{\Sigma} \right)^2 dz / \int_0^{\sigma_z} \left(\frac{J_n(nD\Delta\gamma)I}{\Sigma e^{(1/2)(nD\overline{\sigma}_\gamma)^2}} \right)^2 dz \right\} \quad (6)$$

$$J_n(nD\overline{\Delta\gamma}) = \int_0^{\sigma_z} \left(\frac{J_n(nD\Delta\gamma)I}{\Sigma} \right)^2 dz / \int_0^{\sigma_z} \left(\frac{I}{\Sigma} \right)^2 dz. \quad (7)$$

Following these expressions, the average bunching factor can be written as

$$\bar{b}_n = J_n(nD\overline{\Delta\gamma}) e^{-(1/2)(nD\overline{\sigma}_\gamma)^2}, \quad (8)$$

and Eq. (5) yields

$$E_{\text{CHG}} \approx \frac{(Z_0 K [JJ]_1 l_b \bar{b}_n)^2}{32 \pi \gamma^2 c} \int_0^{\sigma_z} \frac{I^2}{\Sigma^2} dz. \quad (9)$$

It is clear that $E_{\text{CHG}} \propto \bar{b}_n^2$. Given a seed laser power, one can find the optimized DS strength to maximize the E_{CHG} . Figure 1 shows the theoretical results of the second harmonic bunching factor as a function of the DS strength for different local energy spreads and energy modulation amplitudes, it is clearly shown that the optimized values of D will be quite different under different conditions.

To find the parameters that maximize the bunching factor, we differentiate Eq. (8) with respect to D , and set the derivative equal to zero,

$$J_{n-1}(n\overline{\Delta\gamma}D) - J_{n+1}(n\overline{\Delta\gamma}D) = \frac{2n\overline{\sigma}_\gamma^2 D}{\overline{\Delta\gamma}} J_n(n\overline{\Delta\gamma}D). \quad (10)$$

FIG. 1. Bunching factor squared as a function of DS strength for different conditions. Solid line: $\overline{\sigma}_\gamma = 1$ keV, $\Delta\gamma = 10$ keV; dot dashed line: $\overline{\sigma}_\gamma = 2$ keV, $\Delta\gamma = 10$ keV; dashed line: $\overline{\sigma}_\gamma = 1$ keV, $\Delta\gamma = 3$ keV; dotted line: $\overline{\sigma}_\gamma = 2$ keV, $\Delta\gamma = 3$ keV.

It is easy to find that, among the infinite number of roots of Eq. (10), only the first root maximizes the expression of the bunching factor. Figure 2 shows the optimized dispersive strength with respect to energy modulation amplitude for different local energy spread. The optimized DS strengths tend to be a similar value when the energy modulation amplitude is much bigger than the initial local energy spread but become quite different as the energy modulation amplitude decays for different local energy spreads. There are two unknown parameters: $\overline{\Delta\gamma}$ and $\overline{\sigma}_\gamma$ in Eq. (10), it is necessary to change the condition once to solve them out. The energy modulation amplitude can be easily varied by changing the seed laser power. The ratio of the average energy modulation amplitudes is calculated by Eq. (2),

$$C = \overline{\Delta\gamma}_1 / \overline{\Delta\gamma}_2 = \sqrt{P_1 / P_2}, \quad (11)$$

where P_1 and P_2 are seed laser powers, $\overline{\Delta\gamma}_1$ and $\overline{\Delta\gamma}_2$ are the corresponding average energy modulation amplitudes. The best operating condition can be found by scanning the DS strength for different $\Delta\gamma$. It is worth pointing out that the average local energy spread can also be solved out by scanning the seed laser power for different dispersion strengths. The simultaneous equations for solving $\overline{\sigma}_\gamma$ and $\overline{\Delta\gamma}$ are as follows:

$$\begin{aligned} & J_{n-1}(nD_1\overline{\Delta\gamma}_1) - J_{n+1}(nD_1\overline{\Delta\gamma}_1) \\ &= \frac{2n\overline{\sigma}_\gamma^2 D_1}{\overline{\Delta\gamma}_1} J_n(nD_1\overline{\Delta\gamma}_1) \\ & J_{n-1}(nD_2\overline{\Delta\gamma}_1/C) - J_{n+1}(nD_2\overline{\Delta\gamma}_1/C) \\ &= \frac{2n\overline{\sigma}_\gamma^2 D_2}{\overline{\Delta\gamma}_1/C} J_n(nD_2\overline{\Delta\gamma}_1/C). \end{aligned} \quad (12)$$

FIG. 2. Optimized DS strength as a function of energy modulation amplitude for various values of local energy spread. The $\overline{\sigma}_\gamma$ is changed from 0.5 to 5 keV and the optimized value of D is obtained by numerically solving the first root from Eq. (10). Solid line: $\overline{\sigma}_\gamma = 0.5$ keV; dot-dashed line: $\overline{\sigma}_\gamma = 1$ keV; dashed line: $\overline{\sigma}_\gamma = 2$ keV; dotted line: $\overline{\sigma}_\gamma = 5$ keV.

FIG. 3. Calculation results of average local energy spread and average energy modulation amplitude according to Eq. (12) for different conditions as shown in Fig. 1.

It is clearly seen from Eq. (12) that $\overline{\sigma}_\gamma$ and $\overline{\Delta\gamma}$ rely only on the ratio of two consequent seed laser power rather than their absolute values. In the case of Fig. 1, the optimized conditions are $D_1 = 76$ for the solid line, $D_2 = 217$ for the dashed line, $D_1' = 73$ for the dot-dashed line and $D_2' = 152$ for the dotted line. The ratios of the seed laser powers are $C = C' = 3/10$. The solutions of Eq. (12) based on these parameters are the crossover points of the curves with the same type shown in Fig. 3. The results show that the $\overline{\sigma}_\gamma$ is 1 keV and $\overline{\sigma}_\gamma'$ is 2 keV, the $\overline{\Delta\gamma}_1$ and $\overline{\Delta\gamma}_1'$ are both 3 keV. These results coincide with the conditions shown in Fig. 1.

III. 3D SIMULATION RESULTS

The analytical calculations in Sec. II only give a precise estimate of local energy spread in some degree, numerical start-to-end simulations are necessary to account for various aspects of beam dynamics during the process. The main parameters of the SDUV-FEL facility, shown in Table I, are used in this simulation. Particle tracking through the SDUV-CHG beam line is done in three stages. The first stage applies the code ASTRA [22] for tracking from the cathode to 34 MeV at the injection point into the linac. Then the electron beam was tracked through the main accelerator with help of ELEGANT [23] taking into account the synchrotron radiation and the space charge effect. The CHG FEL process in the undulators is simulated with GENESIS [24] based on the output of ELEGANT.

TABLE I. Parameters of SDUV-FEL with CHG setup.

Electron beam	
Beam energy [MeV]	136
Global energy spread [MeV]	0.2
Charge [pC]	100
Emittance [mm-mrad]	4.5
Pulse length (FWHM) [ps]	8
Seeding laser	
Wavelength [nm]	1047
Energy [μ J]	0–150
Pulse length (FWHM) [ps]	8.7
Modulator	
Period length [mm]	65
Period number	10
K	1.6
Radiator	
Period length [mm]	50
Period number	10
K	0.98
Dispersion	
R_{56} [mm]	0–40

The local beam properties are shown in Fig. 4. These parameters' distributions can be used to calculate the average local energy spread by the 1D theoretical definition in Eq. (6) and the result is about 1.7 keV.

With the electron beam input from ELEGANT, we run GENESIS with the seed laser power of 5 and 20 kW. The temporal profiles of the seed laser power are all assumed to be Gaussian. Figure 4(B) shows the distributions of local energy spread and the corresponding energy modulation amplitude for the power of 5 kW. The R_{56} of the DS is scanned from 0.1 to 20 mm for each laser power and the radiation energies are recorded in Fig. 5(A). Two set values (power, optimize R_{56}) of about (20 kW, 6.7 mm) and (5 kW, 9.1 mm) can be found from these two curves. Applying these values in Eqs. (11) and (12), one can get the average local energy spread value of about 1.5 keV, which agrees with the 1D calculation result of 1.7 keV. The average energy modulation amplitudes of about 2.1 and 4.2 keV for the seed laser powers of 5 and 20 kW are also obtained. Figure 5(B) shows the output radiation pulses of the CHG under the condition that the DS strengths are optimized for the corresponding seed laser powers. It is found that output radiation is produced mainly by the central part of the electron beam. We zoom in this central part in Fig. 4(B) and find that the initial local energy spread is within the range of 1 to 3 keV. The average value of energy spread and energy modulation amplitude in this part is about 1.5 and 2.0 keV which are consistent with the results of the CHG based method.

FIG. 4. Simulation results of the parameters' distributions along the electron beam. (A) Beam current (triangles) and transverse beam size (dots). (B) Local energy spread before (crosses) and after (dots) the modulator and energy modulation amplitude (triangles) for $P_{\text{seed}} = 5$ kW.

FIG. 5. Simulation results of the CHG radiation signals for both $P_{\text{seed}} = 5$ kW (dots) and $P_{\text{seed}} = 20$ kW (triangles). (A) FEL pulse energies as a function of the DS strength. (B) Output radiation pulses for the corresponding maximal pulse energies in (A).

IV. EXPERIMENTAL RESULTS

The Shanghai deep ultraviolet FEL (SDUV-FEL) is originally designed as an HGHG FEL test facility for generating coherent radiation with wavelength down to the deep UV region [25]. It is later realized that SDUV-FEL is also a suitable platform for the CHG or the EEHG operation [26]. The schematic layout and parameters of SDUV with CHG setup are shown in Fig. 6 and Table I, respectively.

The accelerator system of the SDUV-FEL test facility consists of a photoinjector and a linac. The gun is equipped with a Cu cathode surface, and electrons are extracted by illuminating the photocathode with an 8.7 ps (FWHM), 262 nm drive laser pulse. The energy of the electron bunch at the gun exit is around 4 MeV and the repetition rate is 2 Hz. This gun can provide 100 pC electron bunches with a normalized emittance of about 4 mm mrad. The electron beam is then accelerated to 136 MeV with the S-band linac.

The bunch compressor is off and the global energy spread is measured to be about 0.2 MeV at the exit of the linac. The electron beam is then transported to the CHG beam line to generate coherent radiation at the second harmonic of the seed laser.

The laser system of SDUV is a combined system which provides both the rf gun pulse and the seed laser pulses for HGHG, CHG, or EEHG. A laser oscillator is placed in the gun hutch and locked to the 2856 MHz signal generated for

FIG. 6. Schematic layout of the SDUV-FEL scheme with CHG setup.

FIG. 7. (A) Radiation intensity on an OTR screen downstream of the radiator, the radiation was recorded by a CCD with a 400–800 nm bandpass filter. (B) Single shot second harmonic CHG spectrum detected by a miniature fiber-optic spectrometer.

the linac system. The pulse of the oscillator is stretched and split in three branches. One is used as the driven laser for the gun; the other two are sent through a bow-tie polarization-maintaining optical fiber and delivered by a 40 meters long beam transport system for the seeding purpose. We use one of them for the CHG experiment. The total energy of the seed laser is over 150 μJ which can be attenuated by a rotatable polarizer placed at the exit of the oscillator. As mentioned above, only the ratios of these seed laser powers are of concern in this experiment.

The resonant wavelength of the modulator was tuned to the seed laser wavelength by adjusting the gap and the radiator was set at its second harmonic. One of the key issues for the seed experiment is to achieve temporal and spatial overlap of the electron bunches and the seed laser pulses in the modulator. The spontaneous emission from the electron beam passing through the modulator and the seed laser pulse were sent to a fast photodiode (2 GHz) to find the initial coarse temporal overlap. A high resolution oscilloscope with 6 GHz bandwidth was used to synchronize the two signals with an accuracy of 30 ps. Then the exact temporal overlap can be obtained by fine-tuning the delay line of the seed laser. The time jitter of our system is smaller than 1 ps, which is much shorter than the pulse lengths of the seed laser and the electron beam. The transverse overlap was achieved by observing the electron beam and the laser beam on optical transition radiation (OTR) screens located upstream and downstream of the modulator and placing both beams on the same transverse position. The transverse size of the laser spot was adjusted to be at least 5 times larger than the transverse size of the electron beam to keep the modulation amplitude the same along the electron bunch. The second harmonic radiation produced by the radiator is reflected out by an OTR screen and recorded by a CCD with a 400–800 nm bandpass filter, which is used to distinguish the CHG radiation from the intense seed laser pulse. The CHG image was clearly

observed as shown in Fig. 7(A). Figure 7(B) shows the spectrum of the radiation detected by a miniature fiber-optic spectrometer close to the window of the OTR chamber. The CHG radiation is fully coherent and the center wavelength is about 521 nm. The R_{56} of the DS can be easily scanned from 1 to 40 mm. The experimental data of second harmonic radiation intensity as a function of R_{56} is shown in Fig. 8. To further reduce the affection of the time jitter to our measurement, five points of radiation pulse intensities were recorded for each R_{56} . The experimental data shown in Fig. 8 can be fitted well with several theoretical curves with quite different parameters, which means

FIG. 8. Intensity of the second harmonic radiation as a function of the DS strength. The experimental data (black dots) can be fitted with theoretical lines with different parameters. Solid line: $\sigma_\gamma = 0.5 \text{ keV}$, $\Delta\gamma = 7.6 \text{ keV}$; dot-dashed line: $\sigma_\gamma = 1.0 \text{ keV}$, $\Delta\gamma = 7.4 \text{ keV}$; dashed line: $\sigma_\gamma = 1.5 \text{ keV}$, $\Delta\gamma = 7.0 \text{ keV}$.

FIG. 9. Experimental data and fitted curves for various values of seed laser energy. The radiation intensity was recorded by a CCD when scanning the DS strength. The energy of the seed laser is changed from 0.58 to 150 μJ . Different symbols stand for different seed laser energies; the black lines are the fitted lines for different symbols.

that the local energy spread cannot be determined by one measured curve.

To get an accurate value of the local energy spread and analyze the causes of measurement error of this method, a number of experimental curves were measured. The seed laser energy was changed from 150 to 0.58 μJ and the strength of the DS was scanned from 1 to 16 mm for each laser energy. The measurement results and fitted curves are shown in Fig. 9. Every two curves can be used to obtain one value of average local energy spread and two values of energy modulation amplitudes for both seed laser energies by using Eqs. (11) and (12). All these calculation

FIG. 11. Calculation results of the average local energy spread based on the measurement curves with the ratios of seed laser powers are less than 0.1 (or bigger than 10).

results are summarized in Fig. 10. The energy modulation amplitude shown in Fig. 10(A) is proportional to the square root of the laser energy. The maximum energy modulation is over 12 keV and the minimum value is less than 1 keV. In Fig. 10(B), the deviation of the measured local energy spread is small when the ratios of the two seed laser powers are less than 0.1 (or greater than 10). The scanning curves will be difficult to be clearly separated when the two seed laser powers are too close to each other, as shown in Fig. 9. In order to separate these curves and minimize the observation error, it is found in Fig. 2 that the ratio of the seed laser powers should be large enough and one of the energy modulation amplitudes should be close to the local energy spread. The data points that satisfy these criteria in Fig. 10(B) are shown in Fig. 11. Averaging over these

FIG. 10. Calculation results for all the combinations of experimental curves according to Eq. (12). (A) Average energy modulation amplitudes for various seed laser energies and the fitted curve of these points. (B) Average local energy spreads for various ratios of seed laser powers.

points, one can find that the average local energy spread is about 1.2 keV with the standard deviation about 0.054 keV. The result also agrees well with the numerical simulations in Sec. III.

V. CONCLUSIONS AND PROSPECTS

A novel method for local energy spread measurements is proposed and demonstrated on the SDUV-FEL. The results show that the average local energy is about 1.2 keV at the exit of the linac with beam energy of 136 MeV and beam charge about 100 pC. This method can also be used to characterize the local energy spread distribution along the electron beam by using a short pulse seed laser. This kind of measurement provides a fairly important tool for quick machine tuning and optimization of seeded FELs. The information of the local energy spread and the energy modulation amplitude will be very useful for the parameters setting of an EEHG experiment. Further investigations on its potential applications will be performed in the future.

ACKNOWLEDGMENTS

We would like to thank L. H. Yu (BNL) for helpful discussions and comments. This work is supported by National Natural Science Foundation of China (Grant No. 10935011) and Major State Basic Research Development Program of China (973 Program) (Grant No. 2011CB808300).

-
- [1] R. Bonifacio, C. Pellegrini, and L. M. Narducci, *Opt. Commun.* **50**, 373 (1984).
 - [2] L. H. Yu, *Phys. Rev. A* **44**, 5178 (1991).
 - [3] L. H. Yu *et al.*, *Science* **289**, 932 (2000).
 - [4] L. H. Yu *et al.*, *Phys. Rev. Lett.* **91**, 074801 (2003).
 - [5] E. L. Saldin, E. A. Schneidmiller, and Y. M. Yurkov, *Opt. Commun.* **202**, 169 (2002).
 - [6] J. H. Wu and L. H. Yu, *Nucl. Instrum. Methods Phys. Res., Sect. A* **475**, 104 (2001).
 - [7] G. Stupakov, *Phys. Rev. Lett.* **102**, 074801 (2009).
 - [8] D. Xiang and G. Stupakov, *Phys. Rev. ST Accel. Beams* **12**, 030702 (2009).
 - [9] The LCLS Design Study Group, SLAC Report No. SLAC-R-593, 2002.
 - [10] M. Altarelli *et al.*, “The European X-Ray Free-Electron Laser Technical Design Report,” DESY, 2007.
 - [11] R. Ganter *et al.*, “Swiss FEL Conceptual Design Report,” PSI, 2010.
 - [12] R. Bonifacio, C. Pellegrini, and L. M. Narducci, *Opt. Commun.* **53**, 197 (1985).
 - [13] Z. Huang *et al.*, *Phys. Rev. ST Accel. Beams* **7**, 074401 (2004).
 - [14] Yujong Kim *et al.*, in *Proceedings of the 9th European Particle Accelerator Conference, Lucerne, 2004* (EPS-AG, Lucerne, 2004).
 - [15] M. Hüning and H. Schlarb, in *Proceedings of the 20th Particle Accelerator Conference, Portland, OR, 2003* (IEEE, New York, 2003).
 - [16] Tsumoru Shintake *et al.*, *Phys. Rev. ST Accel. Beams* **12**, 070701 (2009).
 - [17] G. A. Kornukhin *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **237**, 281 (1985).
 - [18] E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, *Nucl. Instrum. Methods Phys. Res., Sect. A* **539**, 499 (2005).
 - [19] P. Elleaume, *J. Phys. (Paris)* **44**, C1-333 (1983).
 - [20] B. Jia *et al.*, *Phys. Rev. ST Accel. Beams* **13**, 080702 (2010).
 - [21] B. Girard *et al.*, *Phys. Rev. Lett.* **53**, 2405 (1984).
 - [22] K. Floettmann, ASTRA User’s Manual [http://www.desy.de/mpyflo/Astra_dokumentation/].
 - [23] M. Borland, ANL Advanced Photon Source Report No. LS-287, 2000.
 - [24] S. Reiche, *Nucl. Instrum. Methods Phys. Res., Sect. A* **429**, 243 (1999).
 - [25] Z. T. Zhao *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **528**, 591 (2004).
 - [26] J. H. Chen *et al.*, *Chinese Phys. C* **33**, 706 (2009).