# MEASUREMENT OF THE LOCAL ENERGY SPREAD OF ELECTRON BEAM AT SDUV-FEL

C. Feng, T. Zhang, J.H. Chen, H.X. Deng, M. Zhang, X.T. Wang, B. Liu, T.H. Lan, D. Wang, Z.T. Zhao, Shanghai Institute of Applied Physics, CAS, Shanghai 201800, China

*Abstract*

In this paper, we introduce a versatile method to accurately measure the average local energy spread based on the coherent harmonic generation (CHG) scheme. This method has been demonstrated on the Shanghai deep ultraviolent FEL (SDUV-FEL), and the results show that the average local energy spread is about only 1.2keV at the exit of the 136MeV linac when the bunch compressor is off, and this value change to about 2.6keV when the bunch compressor is on.

## INTRODUCTION

The local energy spread of electron beam produced by a photo-injector is believed to be in the order of few keV [1-2]. For accelerator research, it remains a challenge to measure the energy spread with high accuracy at this range. The widely used method to measure the local energy spread of electron beam produced by a photo injector is using a deflecting cavity followed by a horizontal dispersive region which allows measuring the longitudinal trace space in a single shot basis [3]. The local energy spread can be extrapolated by slicing the beam vertically and measuring the beam thickness in energy as function of time. The resolution of this method is about a few keV, which is not accurate enough for FEL operation. Another method to characterize the local energy spread is optical replica synthesizer (ORS) first suggested by Saldin et al. in Ref [4]. This method was proposed 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 is 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.

A novel method for characterizing the local energy spread based on the coherent harmonic generation (CHG) has been developed at the Shanghai deep ultra-violent FEL (SDUV-FEL). 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.

## PRINCIPLE

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 nth harmonic in the radiator is given by

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

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, $\gamma$ is the relativistic parameter for the mean electron beam energy, $\sigma_\gamma$ 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

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

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

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 Eq. (2-3), it is found that $\Delta\gamma \propto \sqrt{P_{seed}}$.

For a longitudinally uniform distributed electron beam, the output power of a CHG can be simplified as [5]

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

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, $\Sigma$ 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.


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The output CHG energy should be the integration of the radiation power (Eq. (4)) along electron beam,

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

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

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

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

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

$$\overline{b_n} = J_n(nD\overline{\Delta\gamma})e^{-\frac{1}{2}(nD\overline{\sigma_\gamma})^2} \quad , \tag{8}$$

and Eq. (5) yields

$$E_{CHG} \approx \frac{(Z_0 K[JJ]_1 l\overline{b_n})^2}{32\pi\gamma^2 c}\int_0^{\sigma_z}\frac{I^2}{\Sigma^2}dz \quad . \tag{9}$$

It is clear that $E_{CHG} \propto \overline{b_n}^2$. Given a seed laser power, one can find the optimized DS strength to maximize the $E_{CHG}$.

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

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

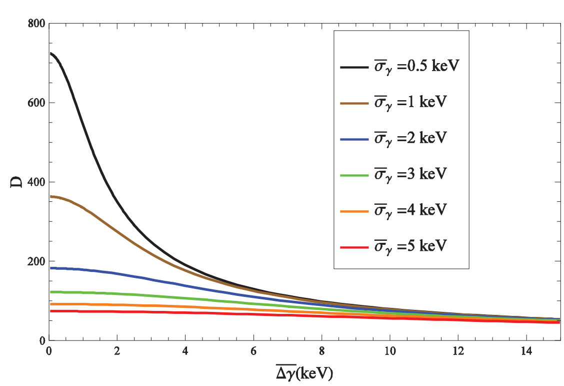


Figure 1: Optimized DS strength as a function of energy modulation amplitude for various values of local energy spread.

It is easy to find that among the infinite number of roots of Eq. (10), only the first root maximize the expression of bunching factor. Figure 1 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)

$$C = \overline{\Delta\gamma_1} / \overline{\Delta\gamma_2} = \sqrt{P_1 / P_2} \, , \tag{11}$$

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 to point out that the average local energy can also be solved out by scanning the seed laser power for different dispersion strengths. The equations for solving $\overline{\sigma_\gamma}$ and $\overline{\Delta\gamma}$ are as follows

$$\begin{cases} J_{n-1}(nD_1\overline{\Delta\gamma_1}) - J_{n+1}(nD_1\overline{\Delta\gamma_1}) = \dfrac{2n\overline{\sigma_\gamma}^2 D_1}{\overline{\Delta\gamma_1}}J_n(nD_1\overline{\Delta\gamma_1}) \\ J_{n-1}(nD_2\overline{\Delta\gamma_1}/C) - J_{n+1}(nD_2\overline{\Delta\gamma_1}/C) = \dfrac{2n\overline{\sigma_\gamma}^2 D_2}{\overline{\Delta\gamma_1}/C}J_n(nD_2\overline{\Delta\gamma_1}/C) \end{cases} \quad . \tag{12}$$

It is clearly seen from Eq. (12) the average local energy spread and energy modulation amplitude relies only on the ratio of two consequent seed laser power rather than their absolute values.

## EXPERIMENT

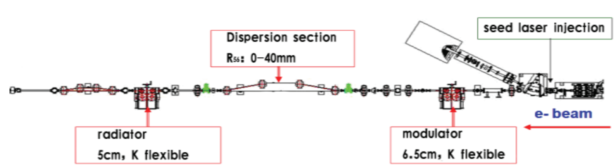


Figure 2: Layout of the SDUV-FEL scheme with CHG setup.

The SDUV-FEL is originally designed as an HGHG FEL test facility for generating coherent radiation with wavelength down to the deep UV region [6]. It is later realized that SDUV-FEL is also a suitable platform for CHG or echo-enabled harmonic generation (EEHG) [7-8] schemes. The schematic layout and parameters of SDUV with CHG setup are shown in Fig. 2 and Table 1, respectively.

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Table 1: 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 [μJ] | 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 |
| **Disperation** | |
| R56 [mm] | 0 ~ 40 |

The resonant wavelength of the modulator can be tuned to the seed laser wavelength by adjusting the gap and the radiator is set at its 2nd harmonic. The beam-laser interaction in the modulator is achieved when the electron and laser beam overlap both spatially and temporally. The 2nd harmonic radiation produced by the radiator is reflected out by an OTR screen and recorded by a CCD with a 400-800nm band pass filter, which is used for the CHG radiation from the intense seed laser pulse. The $R_{56}$ of the DS can be easily scanned from 1mm to 40mm.

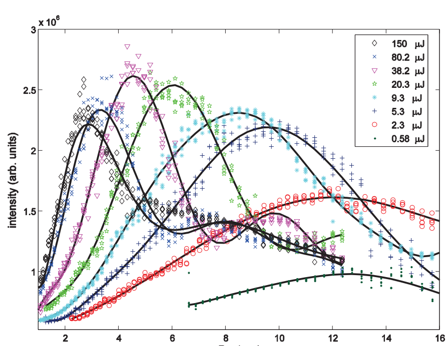


Figure 3: Experimental data and fit lines for various values of seed laser energy.

The seed laser energy was changed from 150μJ to 0.58μJ and the strength of the DS was scanned from 1mm to 16mm for each energy. The experimental data and fit lines for each curve are shown in Fig. 3. Every two curves can be used to solve out one value of average local energy spread and two values of energy modulation amplitude for both seed laser powers by Eq. (11-12). When the two seed laser powers are too close to each other, the scanning curves will be difficult to be clearly separated. In order to separate these curves and minimize the observation error, it is found in Fig. 1 that the ratio of seed laser powers should be large enough. The calculated results of both local energy spread and energy modulation amplitude are summarized in Fig. 4. The energy modulation amplitude shown in Fig. 4(a) is proportional to the square-root of the laser energy. The data points of the local energy spread that satisfy the criterion that the ratio of the seed laser powers is larger than 10 are shown in Fig. 4(b). Averaging over these points, one can find that the average local energy spread is about 1.2keV with the standard deviation about 0.054keV.

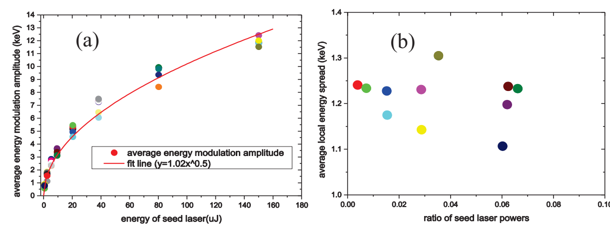


Figure 4: Calculated results for all the combinations of experimental curves. (a) Average energy modulation amplitudes for various seed laser energies and the fit line of these points. (b) Average local energy spreads for ratios of seed laser powers less than 0.1.

The average local energy spread was also measured by the same way when the bunch compressor is on and the bunch is compressed by a factor of about 2. The local energy spread is about 2.6keV at the exit of the linac. The maximal energy modulation amplitude induced by the first seed laser is about 25.6 keV which is approximately 10 times larger than the local energy spread.

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