Slice energy spread measurement in the low energy photoinjector

Houjun Qian, Mikhail Krasilnikov, Anusorn Lueangaramwong, Xiangkun Li, Osip Lishilin, Zakaria Aboulbanine, Gowri Adhikari, Namra Aftab, Prach Boonpornprasert, Georgi Georgiev, James Good, Matthias Gross, Christian Koschitzki, Raffael Niemczyk, Anne Oppelt, Guan Shu, Frank Stephan, Grygorii Vashchenko, and Tobias Weilbach

Deutsches Elektronen-Synchrotron, 15738 Zeuthen, Germany

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Slice energy spread is one of the key parameters in free electron laser optimizations, but its accurate measurement is not straightforward. Two recent studies from high energy (>100 MeV) photoinjectors at SwissFEL and European XFEL have reported much higher slice energy spread than expected at their XFEL working points (200 - 250 pC). In this paper, a new method for measuring slice energy spread at a lower beam energy (~20 MeV) is proposed and demonstrated at the PhotoInjector Test facility at DESY Zeuthen (PITZ), and the results for 250 pC and 500 pC are much lower than those measured at high energy injectors.

I. INTRODUCTION

High brightness electron beams are critical for many scientific instruments, such as electron microscopes and X-ray free electron lasers (XFEL), which have transformed modern research with unprecedented spatial, temporal and energy resolutions [1-4]. Beam brightness scales as beam density in the 6 dimensional (6D) phase space

\[ B_{6D} \propto \frac{\partial^3 Q}{\partial \varepsilon_{nx} \partial \varepsilon_{ny} \partial \varepsilon_{nz}} \propto \frac{I/\sigma_E}{\varepsilon_{nx} \varepsilon_{ny}}, \]  

(1)

where \( Q \) is the bunch charge, \( I \) is the peak current, \( \sigma_E \) is the uncorrelated energy spread or slice energy spread, \( \varepsilon_{nx}, \varepsilon_{ny} \) and \( \varepsilon_{nz} \) are normalized emittances. While the beam brightness directly measures the performance of electron microscopes, it indirectly determines the XFEL brilliance by affecting the amplification gain in the undulator [5]. Therefore, measurement of 6D beam brightness is an indispensable part of XFEL optimizations. For linac based XFELs, beam brightness optimization has to start from the injector due to the Liouville’s theorem. Both transverse emittance and beam peak current can be routinely measured in an XFEL injector, but accurate slice energy spread measurement is still not trivial. This is because photoinjector slice energy spread is expected to be on the 1 keV level, which is below the measurement resolution [6]. In the past, accurate slice energy spread measurement for XFEL injector was not that critical, because it is much lower than required and even causes micro bunching instability to reduce XFEL lasing [7-10]. Therefore, a laser heater is used to increase the injector slice energy spread to damp such an instability to improve FEL lasing [11]. With the improvement of electron source brightness and undulator technology, compact XFEL machines of lower beam energy were built and proposed, such as SACLA and SwissFEL [12-14].

Besides, the injector peak current is also getting lower to improve transverse emittance [15]. Due to the lower injector peak current and lower undulator beam energy, the threshold for injector slice energy spread gets much lower.

Recently, two dispersion based methods were proposed and demonstrated for accurate injector slice energy spread measurements with rms uncertainty down to the 0.1 to 0.3 keV level [16, 17]. Both measured much higher slice energy spread than expected for 200 to 250 pC bunch charge, which reduced the laser heater role in improving XFEL lasing [15]. Compared to SASE XFEL, seeded XFEL prefers even lower slice energy spread for high harmonic generation [19, 20], in which slice energy spread and energy modulation are typically measured with undulator radiation dependence over chicane strength after the modulator [21, 22]. A summary of high resolution slice energy spread measurements is shown in Table I and the two hard X-ray injectors show much lower longitudinal beam brightness than the two seeded FEL injectors.

| Method | Undulator radiation dispersion |
|--------|-------------------------------|

TABLE I. Summary of slice energy spread measurements.

| SDUV | FERMI | SwissFEL | Eu-XFEL | Unit |
|------|-------|----------|---------|------|
| Q    | 100   | 600      | 200     | 250  | pC   |
| \( E_k \) | 136   | 1320     | 100     | 130  | MeV  |
| \( I \) | 12    | 800      | 20      | 20   | A    |
| \( \sigma_E \) | 1.2   | 40       | 15      | 5.9  | keV  |
| \( I/\sigma_E \) | 10    | 20       | 1.3     | 3.4  | A/keV|

In this paper, we introduce a dispersion based method to measure the slice energy spread at the low energy (20 MeV) PhotoInjector Test facility at DESY Zeuthen (PITZ). In addition to the low beam energy, tungsten slit masks are used to reduce the beam transverse emittance, therefore energy spread measurement resolution improves compared to a high energy injector. The paper is organized as follows. First, the methodology is described in Sec. I. Then, the experiments for 250 pC and 500 pC are presented in Sec. II. Finally, a discussion
and summary is given in Sec. IV and V.

II. METHODOLOGY

Slice energy spread is usually measured with an RF transverse deflecting structure (TDS) and a dipole magnet, which maps the longitudinal phase space (LPS) of the beam to the transverse distribution on a screen in a dispersion section. As was discussed in [10], the beam size along the energy dispersion direction consists of four contributions, i.e. screen spatial resolution, transverse emittance effect, TDS-induced energy spread and true slice energy spread. The convolution of the four contributions can be expressed as

\[ \sigma_{\text{total}}^2 = \sigma_{\text{scr}}^2 + \varepsilon_{n1} \beta_{\text{scr}} + \left( \frac{D \sigma_{\text{D}}}{\gamma} \right)^2 + \left( \frac{D \sigma_{\text{D, TDS}}}{\gamma} \right)^2 \]  

where \( \sigma_{\text{total}} \) is the total rms beam size, \( \sigma_{\text{scr}} \) is the rms screen resolution, \( \varepsilon_{n1} \) is the normalized slice emittance in the dipole bending plane, \( \beta_{\text{scr}} \) is the beta function at measurement screen, \( D \) is the dispersion section, \( \gamma \) is the beam Lorentz factor, \( \sigma_{\gamma, \text{TDS}} \) is the slice energy spread due to the transverse acceleration gradient in TDS, \( \sigma_{\gamma} \) is the net slice energy spread without the contribution of TDS.

The energy spread \( \sigma_{\gamma, \text{TDS}} \) depends linearly on the TDS deflection voltage, therefore it can be extracted by TDS voltage scan. After removing the TDS contribution, there are two methods to extract the net slice energy spread \( \sigma_{\gamma} \) from the other contributions. The first is demonstrated at the SwissFEL by scanning the beam energy [11]. The second is demonstrated at the European XFEL by scanning the dispersion function \( D \) [17]. Both methods require a constant slice emittance and constant beta function at the measurement screen, which is not easy to achieve for a space charge dominated low energy photoinjector like PITZ.

A. Energy spread resolutions: low energy vs high energy

The photoinjector slice energy spread is very low in free electron laser applications, expected to be few keV from simulations [24]. To reduce the measurement error of \( \sigma_{\gamma} \), the contributions from the other three terms in Eq. (2) cannot be much larger than \( \sigma_{\gamma} \), otherwise it puts a tight requirement on machine stability and other measurement errors. Therefore, contributions from screen resolution, transverse emittance and TDS should be as low as possible. The energy spread resolution due to screen resolution and transverse emittance can be expressed as

\[ \sigma_{\gamma, \text{scr}} = \frac{\sigma_{\text{scr}}}{D \gamma}, \]  

\[ \sigma_{\gamma, e} = \frac{\sqrt{\varepsilon_{n1} \beta_{\text{scr}}}}{D \gamma^2}. \]  

The best energy and time resolutions by TDS in the linear approximation are [25]

\[ \sigma_{\gamma, \text{TDS}} = \frac{e}{m_0 c^3} \sqrt{\varepsilon_{n2} \beta_{\text{TDS}}} \sqrt{\omega_{\text{TDS}} V_{\text{TDS}}}, \]  

\[ \sigma_t = \frac{m_0 c^2 \sqrt{\varepsilon_{n2} \beta_{\text{TDS}}} \omega_{\text{TDS}}}{\sin(\psi)} \sqrt{V_{\text{TDS}}}, \]  

\[ \sigma_t \sigma_{\gamma, \text{TDS}} = \frac{\varepsilon_{n2}}{c \sin(\psi)}, \]  

where \( e \) is elementary charge, \( c \) is speed of light, \( \varepsilon_{n2} \) is the normalized slice emittance in the TDS streaking plane, \( \beta_{\text{TDS}} \) is the beam beta function in the TDS, \( \omega_{\text{TDS}} \) is the TDS angular frequency, \( V_{\text{TDS}} \) is the TDS transverse voltage, \( \psi \) is the phase advance between TDS and the LPS measurement screen.

In case of same \( \sigma_{\text{scr}}, D, \varepsilon_{n1}, \beta_{\text{scr}}, \) Eq. (3) and Eq. (4) show better absolute energy spread resolution can be achieved with a lower beam energy. For LPS measurements, its best time and energy resolutions product is limited by the transverse emittance and phase advance only. A better time resolution from TDS will lead to a worse energy spread resolution for the LPS measurement.

Taking the parameters from the European XFEL injector as an example [17], beam energy is 130 MeV, dipole screen resolution is 28 µm with an energy dispersion of 1.2 m, nominal emittance is 0.4 µm for 250 pC [17] [26]. The screen-induced energy spread resolution is 3 keV, but it can be reduced to 0.5 keV if the beam energy is lowered to 20 MeV. The product of TDS time resolution and energy resolution is at least 0.68 keV ps based on Eq. (7). If temporal resolution of TDS measurement reaches a 1 ps (FWHM) resolution, i.e. 0.42 ps rms, TDS will induce an rms energy spread of at least 1.6 keV.

B. TDS voltage scan

Since \( \sigma_{\gamma, \text{TDS}} \) is linearly proportional to \( V_{\text{TDS}} \), Eq. (2) can be rewritten as

\[ \sigma_{\text{total}}^2 = \sigma_0^2 + (\sigma_1 \frac{V_{\text{TDS}}}{V_1})^2, \]  

where \( \sigma_0^2 \) is the sum of first three terms on the right hand side of Eq. (2), which are independent of TDS voltage. \( \sigma_1 \) is the beam size contribution from TDS voltage \( V_1 \). With a scan of \( \sigma_{\text{total}} \) versus \( V_{\text{TDS}} \) in experiment, \( \sigma_0 \) can be fitted.

Let us assume a 3% rms error for \( \sigma_{\text{total}} \) measurement. Here an numerical example is used to show the sensitivity of \( \sigma_0 \) fitting error on TDS voltage scan range. Let us assume TDS voltage scan has 6 voltages uniformly distributed between \( V_1 \) and \( V_{\text{max}} \). For each TDS voltage, \( \sigma_{\text{total}} \) is calculated based on Eq. (3), and a random relative error with a 3% rms value is added. With 6 TDS voltages and corresponding energy spread values, \( \sigma_0 \) can
be fitted. Such a process is repeated 1000 times, and the rms relative errors are shown in Fig. 1 for different measurement configurations. The simulations show that the fitting error depends critically on \( \sigma_1 \), i.e. \( V_1 \). To keep the fitting error of \( \sigma_0 \) below 10\%, \( \sigma_1 \) should be smaller than \( \sigma_0 \). With the TDS voltage scan range \( V_{\text{max}}/V_1 \) between 1.5 and 3, the fitting error is not sensitive to \( V_{\text{max}} \). Based on Eq. 7, a smaller \( \sigma_1 \) means a worse time resolution, which might increase the measurement error of \( \sigma_1 \) by including time correlated energy spread. Therefore, a low transverse emittance in the TDS streaking plane is also critical.

\[
\sigma^2_f = \sigma^2_0 + \left( R_{12y} \cdot \sigma_{y', \text{slit2}} \right)^2, \tag{9}
\]

where \( R_{12y} \) is the transfer matrix element from slit 2 to Disp3.scr1, \( \sigma_{y', \text{slit2}} \) is the beam divergence after slit 2 cut. The \( R_{12y} \) can be either calculated if a reliable lattice model is established, or measured directly by orbit response. By scanning \( R_{12y} \), using quadrupole group 3, and measuring vertical rms size on Disp3.scr1, the screen resolution can be fitted based Eq. 9.

For measuring emittance-induced horizontal beam size on Disp3.scr1, the vertical slit 2 is used, and the horizontal slit 2 is removed. The final slice energy spread is measured with a combination of horizontal slit 1 and vertical slit 2. To allow enough charge for the slice energy spread measurement, the vertical slit 2 opening is 50 \( \mu \)m. After slit 2 cut, the beam horizontal rms size is 14.4 \( \mu \)m, which is much smaller than horizontal beam size on High2.scr2 when dipole magnet is off, and can be neglected. So, the horizontal beam size at High2.scr2 equals

\[
\sigma^2_x = \sigma^2_{\text{scr}} + \left( R_{12x, \text{H2}} \cdot \sigma_{x', \text{slit2}} \right)^2, \tag{10}
\]

where \( R_{12x, \text{H2}} \) is the transfer matrix element from slit 2 to High2.scr2, \( \sigma_{x', \text{slit2}} \) is the beam divergence after slit 2 cut. Similar to screen resolution measurement, by varying \( R_{12x, \text{H2}} \), both screen resolution and beam divergence can be fitted. Then beam emittance-induced beam size at Disp3.scr1 can be calculated as \( R_{12x, \text{D3}} \cdot \sigma_{x', \text{slit2}} \).
where $R_{12x,D3}$ is the transfer matrix element from slit 2 to Disp3.scr1.

After slice energy spread contributions from TDS, screen resolution and transverse emittance are measured, the real slice energy spread can be extracted via Eq. 2.

III. MEASUREMENTS

As mentioned already, recent slice energy spread measurements at the photoinjectors of SwissFEL and European XFEL have shown slice energy spread much higher than expected from simulations [16, 17]. This is either due to high slice energy spread already from the low energy section, or due to slice energy spread growth during the high energy acceleration and transportation. This motivated us to measure the slice energy spread in the low energy (20 MeV) injector at PITZ, which has the same RF gun as the European XFEL.

In the experiment, the RF gun and the cathode laser mimic the 250 pC working point of the European XFEL injector [26, 34, 35]. The photoelectron beam is generated by UV laser illuminating the Cs$_2$Te cathode. Cathode laser diameter is 1 mm with a quasi-uniform distribution. Temporally, the laser is 7 ps (FWHM) with a Gaussian distribution. The RF gun accelerates the beam to 6.3 MeV/c with a cathode gradient of 58 MV/m. Then, the beam is matched into the booster linac by solenoid focusing for optimum emittance at the booster exit. Finally, the 20 MeV beam is sent to the diagnostic beamline for slice energy spread measurement. The beam peak current is measured by the TDS to be 20 A.

As discussed in Sec. II C, the high resolution LPS measurement is done with both slit 1 and slit 2. Slit 1 is used to reduce vertical emittance to increase TDS resolution, and slit 2 is used to reduce horizontal emittance-induced energy spread resolution on Disp3.scr1. Both slits have 50 µm opening. In order to measure the low charge beams, 500 µm thick LYSO:Ce is used as screen material at High2.scr2 and Disp3.scr1 [36]. Quadrupole group 1 reduces the vertical beam size in the TDS to lower the TDS-induced energy spread, and quadrupole group 2 optimizes the time resolution of LPS measurement. Quadrupole group 3 varies vertical $R_{12y}$ and horizontal $R_{12x}$ for measuring screen resolution and emittance-induced energy resolution, respectively.

The slit 1 effect on vertical beam emittance is shown in Fig. 3. In the optimum emittance compensation working point, the beam is diverging at slit 2, and the normalized vertical RMS emittance is around 0.5 µm. The beam profile without slit 1 cut is measured near quadrupole group 1 when they are off, shown in Fig. 3(a). After the slit 1 insertion, the beam profile is shown in Fig. 3(b). The charge of the reduced beamlet is estimated to be 25 pC, and vertical rms size is reduced to 0.17 µm. The drift distance from the slit 1 to the beam profile measurement screen is 3.1 m, so the reduced vertical emittance is calculated to be 32 nm. The vertical emittance is reduced by a factor of 15.6 compared to the nominal case, which improved the LPS resolution significantly.

![FIG. 3. Beam images measured at 3.1 m downstream slit 1, near quadrupole group 1, when quadrupole group 1 is off, (a) without slit 1 cut, (b) with slit 1 cut.](image-url)
FIG. 4. TDS voltage scan with and without vertical emittance reduction by slit1.

FIG. 5. LPS vs TDS voltage with both slit 1 and slit 2 inserted.

and both the screen resolution and beam divergence can be fitted based on Eq. (10). Here, the beam rms size $\sigma_x$ at High2.scr2 is measured for the same time slice as that used for slice energy spread calculation. The measurement results are displayed in Fig. 6. When quadrupole group 3 is off, the measured beam size on High2.scr2 is $99 \pm 1 \mu m$, but this is dominated by the screen resolution of $73 \pm 1 \mu m$. Therefore, the real beam size is only $67 \pm 1 \mu m$, which translates to a beam divergence of $37 \pm 1 \mu rad$, corresponding to a horizontal normalized emittance of 21 nm. $R_{12x,3}^x$ is measured by orbital response to be 0.81 m, so the emittance-induced energy spread resolution is $0.65 \pm 0.02$ keV. The screen resolution of Disp3.scr1 is measured at the non-dispersion direction when TDS is off, so vertical slit 2 is changed to horizontal slit 2. The measurement is based on Eq. (9), and $R_{12y}$ is varied by quadrupole group 3. The screen resolution is $69 \pm 1 \mu m$ as shown in Fig. 7 and this translates to an energy spread resolution of $1.50 \pm 0.02$ keV.

With both screen resolution and emittance contribution measured, the slice energy spread deconvolutions are summarized in Table II. The slice energy spread for the 250 pC beam is $1.65 \pm 0.06$ keV. The longitudinal peak brightness, defined by the ratio of peak current over slice energy spread, equals 12.1 A/keV.

FIG. 6. Screen resolution and beam divergence measurements at High2.scr2.

FIG. 7. Screen resolution measurements at Disp3.scr1.

Slice energy spread of the 500 pC beam was also measured with the same methods. The cathode laser diameter was changed to 1.3 mm for the best transverse emittance. The other configurations, such as laser temporal profile, gun and booster energy, were the same as for the 250 pC beam. The best emittance is about $0.65 \mu m$ with a peak current of 34 A. The slice energy spread deconvolutions are summarized in Table III. The slice energy

| Component   | Resolution (mm) | Emittance (µm) | Real Slice Energy Spread (keV) |
|-------------|-----------------|----------------|-------------------------------|
| Non-TDS     | 69 ± 1          | 30 ± 1         | 76 ± 2                        |
| Screen      | 69 ± 1          | 30 ± 1         | 76 ± 2                        |
| Emittance   | 69 ± 1          | 30 ± 1         | 76 ± 2                        |
| Unit        | µm              | µm             | keV                           |

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| Unit        | µm              | µm             | keV                           |
spread for the 500 pC beam is $2.84 \pm 0.07$ keV, and the longitudinal peak brightness equals 12.0 A/keV.

### TABLE III. Summary of 500 pC slice energy spread measurement components, both in beam size measured at Disp3.scr1 and in energy spread.

| Non-TDS contribution | Screen resolution | Emittance resolution | Real slice energy spread |
|----------------------|------------------|---------------------|--------------------------|
| $149 \pm 3$          | $69 \pm 1$       | $15 \pm 1$          | $131 \pm 3$ µm           |
| $3.23 \pm 0.06$      | $1.50 \pm 0.02$  | $0.32 \pm 0.03$     | $2.84 \pm 0.07$ keV      |

### IV. DISCUSSIONS

For the 250 pC working point, $1.65 \pm 0.06$ keV slice energy spread was measured at the low energy (~20 MeV) photoinjector at PITZ. This is a factor of 3.6 lower than that measured at high energy (130 MeV) photoinjector at European XFEL, and a factor of 9 lower than that measured at SwissFEL injector for the 200 pC working point. All three injectors operate with the Cs$_2$Te photocathode, and have similar peak current of 20 A. Our result demonstrates the expected 1-2 keV energy spread from the Cs$_2$Te based photoinjector for the first time. This indicates a slice energy spread growth in the high energy photoinjector, which is worth further studies [17].

ASTRA simulations of the PITZ photoinjector shows 1.3 keV and 2 keV slice energy spread for the 250 pC and the 500 pC respectively [37]. Simulation values are lower than measurement results by 20% to 30%. This discrepancy can be caused by laser temporal modulations [38], or simplified physics model in ASTRA simulations, such as intra beam scattering effect [17], self consistent space charge modelling close to the saturation photoemission regime [39][41].

### V. SUMMARY

Longitudinal phase space mapping by TDS and dipole magnet is used for direct slice energy spread measurement, but its energy resolution is limited by screen resolution, emittance-induced beam size and TDS-induced energy spread. Analytical analysis shows, a low energy beam can achieve better energy resolution than high energy beam with the same normalized emittance, beta function, dispersion function and screen resolution. The product of time and energy resolution of TDS streaking is limited by the beam emittance. Therefore, we used a beam of lower energy and reduced horizontal and vertical emittance by slit cutting to enhance the LPS resolutions.

Numerical simulations show the lowest TDS-induced energy spread during a TDS voltage scan should be as small as possible to minimize the fitting uncertainty of non-TDS related energy spread. Direct measurement of energy spread resolutions due to screen resolution and emittance-induced beam size were suggested and demonstrated by using slit and lattice scans, which does not require a constant beta function like previous methods used for high energy injectors [16][17].

Finally, we demonstrated the new methods by measuring the slice energy spread at PITZ, which mimic the best emittance working point for European XFEL at 20 MeV. The slice energy spread results are $1.65 \pm 0.06$ keV and $2.84 \pm 0.07$ keV for 250 pC and 500 pC, respectively. The value for 250 pC is a factor of 3.6 to 9 lower than high energy injector results at European XFEL and SwissFEL, indicating slice energy spread growth in the high energy injector, which is worth further studies.

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