EXTRACTION OF THE LONGITUDINAL PROFILE OF THE TRANSVERSE EMITTANCE FROM SINGLE-SHOT RF DEFLECTOR MEASUREMENTS AT sFLASH*

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Abstract

The gain length of the free-electron laser (FEL) process strongly depends on the slice energy spread, slice emittance, and current of the electron bunch. At an FEL with only moderately compressed electron bunches, the slice energy spread is mainly determined by the compression process. In this regime, single-shot measurements using a transverse deflecting rf cavity enable the extraction of the longitudinal profile of the transverse emittance. At the free-electron laser FLASH at DESY, this technique was used to determine the slice properties of the electron bunch set up for seeded operation in the sFLASH experiment. Thereby, the performance of the seeded FEL process as a function of seed laser-electron timing can be predicted from these slice properties with the semi-analytical Ming-Xie model. The prediction is well in line with the FEL peak power observed during an experimental laser-electron timing scan. The power profiles of the FEL pulses were reconstructed from the longitudinal phase-space measurements of the seeded electron bunches that were measured with the transverse deflecting cavity.

INTRODUCTION

When starting a high-gain free-electron laser (FEL) from noise, properties of the generated photon pulses such as central wavelength and spectral shape are subject to fluctuations. Additionally, the longitudinal coherence of a SASE pulse is limited due to several longitudinal modes lasing independently from each other. One option to overcome these limitations is an FEL seeded by high-gain harmonic generation (HGHG). In this seeding scheme, an energy modulation is induced in the electron bunch by the interaction with an external seed laser. This sinusoidal modulation is then transfered to a density modulation when the electron bunch traverses a subsequent dispersive chicane. The electron density distribution shows micro-bunching with the periodicity of the seed laser and can efficiently start the FEL process in a downstream undulator on the seed laser wavelength and its harmonics [1].

For an HGHG-seeded FEL, it is essential to maintain the longitudinal and transverse overlap between the seed laser pulse and electron bunch. In the transverse plane, the laser pulse is usually larger than the electron bunch. This way, all electrons in a longitudinal slice of the electron bunch experience a similar amplitude of the electric field and a similar modulation amplitude. Longitudinally, however, the laser pulse is usually shorter than the electron bunch and the question arises which relative timing between them has to be chosen for optimum lasing performance.

While a straightforward method to optimize the longitudinal overlap is a scan of the relative timing between laser pulse and electron bunch, the optimum timing can also be determined from an analysis of single-shot measurements of the longitudinal phase-space distribution. This analysis reveals the longitudinal profile of the transverse emittance and reveals the longitudinal fraction of the electron bunch that supports best FEL performance. Here, profile refers to the physical quantity being a function that changes its value with the longitudinal coordinate in the electron bunch.

To measure the longitudinal phase-space distribution of the electron bunches, a transverse deflecting structure (TDS) is used in combination with a subsequent dispersive dipole spectrometer. While fields in the cavity kick electrons dependent on their arrival time in the vertical plane, the spectrometer deflects horizontally. On a screen downstream of the dipole, the longitudinal phase-space distribution can be measured with a time resolution below 10 fs.

At the seeding experiment sFLASH at FLASH in Hamburg the TDS is located downstream of the radiating undulator [2–4]. Here, the longitudinal phase-space distribution of seeded electron bunches can be measured. The energy drop of the seeded portion of the bunch can be used to extract seeded FEL pulse power profiles. While this method has been used before on an FEL process started from noise [5], this contribution shows its applicability to HGHG-seeded FEL pulses. Thus, when extracting the seeded power profiles, the seeding process can serve as a local probe to verify the emittance profile extracted from the TDS measurements and the derived performance prediction.

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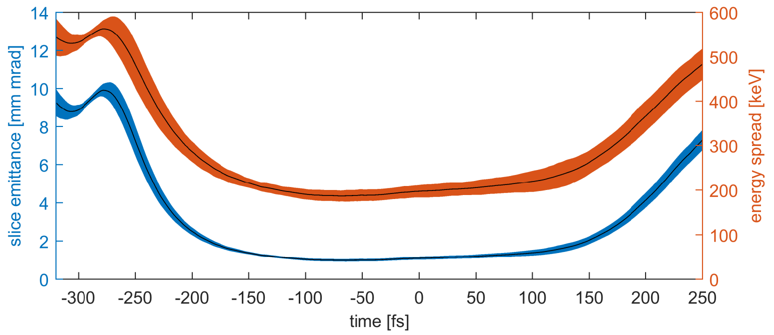

Figure 1: Longitudinal profiles of transverse slice emittance $\varepsilon_{\mathrm{mx}} = \sqrt{\varepsilon_{\mathrm{n,x}}\varepsilon_{\mathrm{n,y}}}$ and measured energy spread $\sigma_{\mathrm{E,m}}$ as a function of temporal position along the electron bunch. The colored areas show the statistical rms uncertainties of both profiles. Reprinted from [2] with permission by Scientific Reports under Creative Commons Attribution 4.0 International License.

EXTRACTION OF SLICE EMITTANCE

The energy spread $\sigma_{\mathrm{E,m}}$ is measured on the screen of the dispersive energy spectrometer. It is a superposition of different contributions, one is the actual energy spread of the electron bunch $\sigma_{\mathrm{E,0}}$, the other two are the heating from the deflecting fields σ_{PW} (along the lines of the Panofsky-Wenzel theorem [6]) and the transverse beam size on the screen σ_{geom}, also contributing to the width of the measured profile. Assuming that each contribution has a Gaussian profile, their widths can be added in quadrature [7]

$$\sigma_{\mathrm{E,m}}^2 = \sigma_{\mathrm{E,0}}^2 + \sigma_{\mathrm{geom}}^2 + \sigma_{\mathrm{PW}}^2. \qquad (1)$$

To reconstruct the emittance of the electron bunch, an assumption on the initial energy spread $\sigma_{\mathrm{E,0}}$ has to be made. Since, in seeded operation, the electron bunch is moderately compressed with a peak current of about 500 A to 600 A, it is assumed that the energy spread is dominated by the compression process. At FLASH, simulations show that the energy spread of the bunch is roughly given by $\sigma_{\mathrm{E,0}} = 100\,\mathrm{keV/kA} \cdot I_{\mathrm{peak}}$, where I_{peak} is the peak current [8].

Both, the contribution of the heating induced by the TDS fields as well as the beam size on the screen are functions of the transverse emittance. While the heating depends on the normalized vertical slice emittance $\varepsilon_{\mathrm{n,y}}$, the beam size on the measurement screen is a function of the normalized horizontal slice emittance $\varepsilon_{\mathrm{n,x}}$. By defining the ratio u between both transverse emittances, these can be written as $\varepsilon_{\mathrm{n,x}} = \varepsilon_{\mathrm{n}}$ and $\varepsilon_{\mathrm{y,n}} = u\varepsilon_n$. The Ming-Xie formalism used below to predict the FEL performance takes one normalized transverse emittance as a parameter. An estimate for the upper limit of this emittance is the geometric mean $\varepsilon_{\mathrm{mx}} = \sqrt{\varepsilon_{\mathrm{n,x}}\varepsilon_{\mathrm{n,y}}} = \varepsilon_{\mathrm{n}}\sqrt{u}$ of the transverse emittances [9, 10].

Equation (1) then gives the emittance:

$$\varepsilon_{\mathrm{n}}(t) = \frac{\sigma_{\mathrm{E,m}}^2(t) - \sigma_{\mathrm{E,0}}^2(t)}{\xi}, \qquad (2)$$

where $\xi = (K^2\beta_{\mathrm{y}}u + A^2\beta_{\mathrm{x}})\gamma m_0^2 c^4$. Here, $K = eV_0 k/pc$ is the kick parameter of the TDS, V_0 is the effective voltage of the rf field in the TDS, k is the wave number of the rf field, p is the electron momentum, e is the elementary charge, β_{y} and β_{x} are the local beta functions, and c is the speed of light. The parameter A is the calibration constant of the spectrometer that converts the density distribution on the screen to an energy distribution. The mean electron energy is γ and m_0 is the electron rest mass. For the moment $u = 1$ will be assumed. Any deviations will be treated later as systematic errors and will increase the uncertainties on derived emittances [2].

Figure 1 shows the longitudinal profile of the measured energy spread and the reconstructed geometrical mean of the transverse slice emittance. The emittance profile shows a minimum between −50 fs and −100 fs, where optimum FEL performance is expected.

PREDICTION OF FEL PERFORMANCE

With the extracted transverse slice emittance $\varepsilon_{\mathrm{mx}}$, the estimate of the uncorrelated energy spread $\sigma_{\mathrm{E,0}}$ and the current profile, all information to predict the gain length of the FEL is available. For this, the well established semi-analytical Ming-Xie model [11] has been used to calculate the gain length L_{g} and saturation power P_{sat} taking into account the HGHG-induced energy spread increase.

In an HGHG-seeded FEL, the FEL power evolution is a superposition of coherent emission of the pre-bunched beam at the beginning of the undulator and experimental FEL amplification [12]:

$$P(z) = P_{\mathrm{th}}\left[\frac{\frac{\zeta^2}{3}}{1+\frac{\zeta^2}{3}} + \frac{\frac{1}{2}\exp\left[\zeta-\sqrt{3}\right]}{1+\frac{P_{\mathrm{th}}}{2(P_{\mathrm{sat}}-P_{\mathrm{th}})}\exp\left[\zeta-\sqrt{3}\right]}\right], \qquad (3)$$

where $\zeta = z/L_{\mathrm{g}}$ is the normalized longitudinal coordinate, z is the distance traveled along the undulator and $P_{\mathrm{th}} = \rho_{\mathrm{FEL}}|b_{\mathrm{n}}|^2 P_{\mathrm{beam}}$ is the power threshold at which the behavior of the power gain changes from the quadratic z-dependence of coherent radiation to the exponential regime of the FEL. Here, b_{n} denotes the bunching factor on the n^{th} harmonic of the seed laser, which is be the fundamental of the FEL process in the radiator.

As stated above, all information is available to derive which longitudinal section of the electron bunch has the shortest gain length and might run into saturation. To give an absolute prediction of the radiated power, however, the

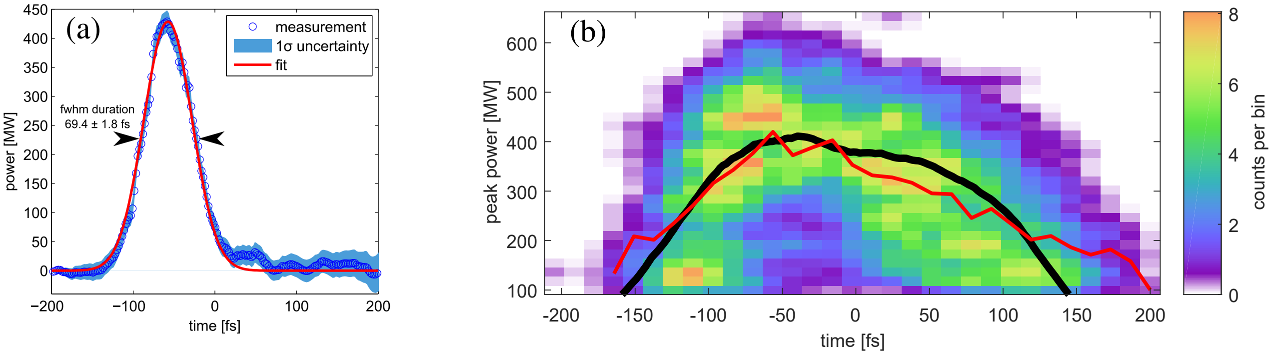

Figure 2: Measurements of FEL pulse power profiles. Panel *(a)* shows a single-shot power profile extracted from a TDS measurement. Panel *(b)* shows a two-dimensional histogram of the peak powers and longitudinal positions of FEL pulses extracted from TDS measurements smoothed by a Gaussian with an rms width of one pixel. See text for more information. Reprinted from [2] with permission by Scientific Reports under Creative Commons Attribution 4.0 International License.

initial bunching or modulation amplitude from the seed laser has to be known. In the following, this parameter will be used to fit the prediction of the FEL power to the measurements.

EXPERIMENTAL VERIFICATION

To experimentally determine the position of the electron bunch that shows best lasing performance, the FEL process is started from an initial bunching in the HGHG seeding setup. In this experiment, a 266 nm laser pulse modulates the electron bunch in a 5-period electromagnetic undulator. The radiator is tuned to the 7th harmonic of the seed laser [3].

Seeding allows to selectively start the FEL process in a longitudinally confined region of the bunch. The lasing electrons then lose energy to the radiation field. This is visible on measurements of the longitudinal phase-space distribution that can be obtained with the TDS setup at sFLASH. This energy drop of the electrons due to the FEL process enables the extraction of the FEL pulse power profile as shown for a single-shot in Fig. 2a From these reconstructions the peak power of the pulse and its longitudinal position within the electron bunch are available.

Figure 2b shows a two-dimensional, color-coded histogram of these two properties acquired in a laser-electron timing scan. The highest peak power and thus the best FEL performance is found between −50 fs and −100 fs where the emittance is minimal. While the red curve shows the mean peak power of every timing bin, the black curve shows a fit of the Ming-Xie-based prediction to the red curve.

As described above, the experimental data shown in the figure has been extracted from measurements of the longitudinal phase-space distribution after lasing has taken place. Pulses with low peak powers, however, cannot be evaluated reliably with an automatic algorithm. This is due to fluctuations in both, accelerating and TDS radio-frequency fields, that slightly change the energy profile of the electron bunch. When compared to reference bunches, this may induce false power signals below 100 MW. Thus, pulses with peak powers lower than 100 MW are omitted and the mean curve (red) above ±130 fs from the center shows a higher value than the prediction (black).The fit parameter for the shown black curve is $\Delta\gamma = 0.777 \pm 0.001_{\mathrm{stat}} \pm 0.154_{\mathrm{sys}}$, corresponding to $b_7 = (3.22 \pm 0.03_{\mathrm{stat}} \pm 1.70_{\mathrm{sys}}) \cdot 10^{-2}$, where statistical errors originate from the fitting process and systematical errors are derived from the uncertainty of the emittance reconstruction. For a more detailed error analysis refer to Ref. [2]. Measurements of the longitudinal phase-space distribution of uncompressed electron bunches, show a modulation amplitude of $\Delta\gamma = 0.79 \pm 0.09$. Here, the impact of collective effects is minimal, since the peak current of the generated micro-bunches is small and the change of the energy spread due to longitudinal space-charge forces is small [13, 14]. This measurement, thus, gives an estimate for the modulation amplitude and is well in line with the modulation amplitude derived here.

SUMMARY AND OUTLOOK

In this contribution a simple method to extract the longitudinal profile of the transverse emittance from single-shot measurements of the longitudinal phase-space distribution is presented. The extraction was verified with a seeded FEL that is used to longitudinally resolve the FEL performance along the electron bunch. The method is well suited for moderately compressed electron bunches, where collective effects only play a minor role.

These measurements allow to predict the FEL performance along the electron bunch and enable the optimum choice of laser-electron timing in an HGHG-seeded FEL. Additionally, an on-line extraction of the emittance on a shot-by-shot basis allows the tuning of the accelerator components to generate a flat emittance profile that improves the stability of the seeded signal. A more general description of the results presented here can be found in Ref. [2].

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