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STATISTICAL ANALYSIS OF 2D SINGLE-SHOT PPRE BUNCH MEASUREMENTS*

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Abstract

The pulse picking by resonant excitation (PPRE) method is used to realize pseudo single-bunch radiation from a complex filling pattern at the BESSY II storage ring. The PPRE bunch is excited in the horizontal plane by a quasi-resonant incoherent perturbation to increase the emittance of this bunch. Therefore, the synchrotron light of the PPRE bunch can be separated by collimation from the radiation of the main bunch train at dedicated beamlines for timing users. The properties of the PPRE bunch depend on the storage ring settings and on the excitation parameters. It is not trivial to distinguish between the wanted intrinsic bunch broadening and an additional position fluctuation of the PPRE bunch. Using the potential of the new diagnostics beamline with the possibility to observe an additional spatial dimension with a fast streak camera, we introduce a new method to study the properties of the PPRE bunch. Applying a statistical analysis to a series of single-turn images enables distinguishing between horizontal orbit motion and the broadening of the bunch due to the excitation. Measurements are presented and the results are compared with data from the BPM system.

INTRODUCTION

The BESSY II electron storage ring delivers synchrotron radiation to a very diverse user community providing a complex filling pattern and also special operation modes in low-α or single bunch weeks [1, 2]. In standard user operation the filling pattern features a bunch train for high flux users and several high current bunches, the camshaft bunch, multiple slicing bunches, and the Pulse-Picking by Resonant Excitation (PPRE) bunch, serving dedicated applications.

The PPRE bunch at BESSY II appears only once per revolution and is used to produce pseudo single-bunch radiation in a complex filling pattern. It is realized by exciting the bunch in the horizontal plane with a stripline kicker at a certain frequency to increase its emittance [3]. The radiation of this bunch can be separated in the beamline using collimators [4]. For the experiments it is essential that the PPRE bunch has a constant large emittance and a stable orbit, which is not fluctuating turn-by-turn.

While some progress has been made to understand the behaviour theoretically [3], machine diagnostics to fully characterize the PPRE bunch have been lacking. Since no bunch resolved beam size measurements were available yet, optimizing the PPRE settings relied on user feedback.

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A new beamline dedicated for bunch resolved longitudinal diagnostics equipped with a fast streak camera has been setup, commissioned and is now in full operation since mid 2020 [5]. The beamline and the streak camera are also capable to image an additional transverse dimension. Using this potential we present a new method to study the properties of the PPRE bunch.

METHOD AND EXAMPLE

The statistical 2D analysis of streak camera images is introduced in reference [5] and will only be outlined here for a short example on PPRE at standard conditions. The idea is to compare the photon distribution in two dimensions in single-shot streak camera images to obtain information on bunch movement and horizontal size of the PPRE bunch applying statistical knowledge. In Fig. 1, such a single-shot streak camera measurement of a single turn is shown.

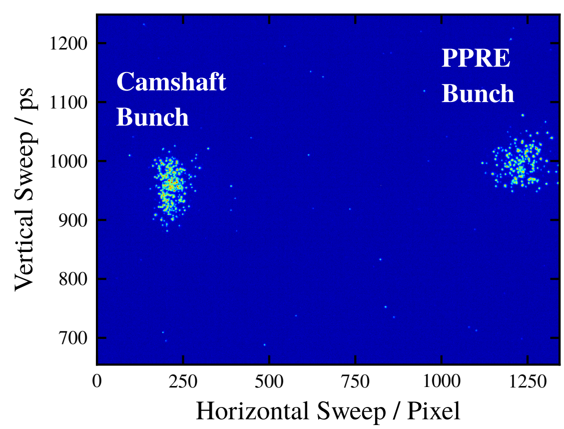

Figure 1: Single-shot single-turn streak camera measurement from the camshaft and the PPRE bunch at the new diagnostics beamline.

For each single shot the horizontal position, the longitudinal position (phase), the horizontal width and the longitudinal width (bunch length) of a bunch are obtained from fits of the respective 1D projections of the data. These four parameters are then acquired for a longer measurement series (e. g. 1000 images in this case). Histograms of the distributions are shown exemplarily for the horizontal position and width of the PPRE bunch in Fig. 2. The distributions match a normal distribution reasonably well and the standard deviation and the mean of the distributions will be used for further analysis. In contrast to reference [5], we use a direct statistical data treatment throughout this contribution to have a better comparability with the data obtained by the bunch-by-bunch feedback (BBFB) system.

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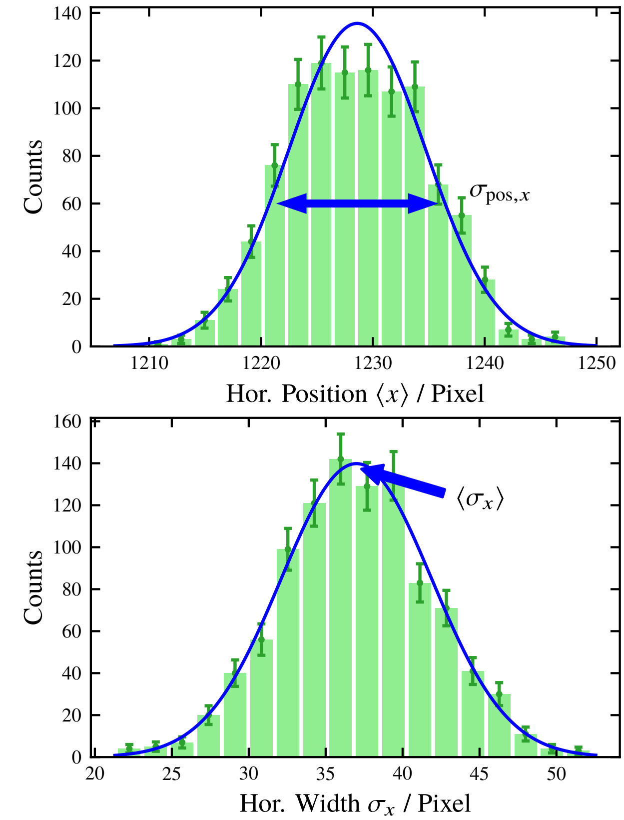

Figure 2: Histogram of the measured horizontal position (top) and the horizontal width (bottom) of the PPRE bunch from 1000 single-shot streak camera images. Additionally a Gaussian given by the mean and standard deviation of the distributions is shown.

From basic statistics we use now the property of the standard error of the mean: For an independent sample of N observations from a population with a given standard deviation σ the mean value will have the standard error of the mean value σ_{mean} given by

$$\sigma_{\text{mean}} = \sigma / \sqrt{N}. \tag{1}$$

So we need the fluctuation of the mean σ_{pos} for both dimensions and the average horizontal width or bunch length $\langle \sigma \rangle$ as an estimator for the standard deviation respectively. The evaluated results are shown in Table 1.

Table 1: Statistical Results for PPRE Distribution and Calculated Photon Number with Eq. (2)

	Hor. $\langle x \rangle$ / Pixel	**Ver. $\langle t \rangle$ / ps**
$\langle \sigma \rangle$	37.00 ± 0.15	25.69 ± 0.07
σ_{pos}	6.15 ± 0.14	2.91 ± 0.07
N_{eff}	–	78 ± 4

Accounting for non-binary photon response and varying photon number in each image we can calculate an effective photon number N_{eff}, which is the actual photon number times a constant depending on the streak response, the data evaluation and the photon number itself ($N_{\text{eff}} = cN_{\text{ph}}$), see reference [5] for details. Assuming that there are no additional turn-by-turn orbit fluctuations in the longitudinal dimension, we can solve

$$\sigma_{\text{pos},t} \approx \langle \sigma_t \rangle / \sqrt{N_{\text{eff}}}, \tag{2}$$

for N_{eff} and obtain 78 ± 4. In the horizontal case however, we cannot use Eq. (2) directly. We have to add an additional term to account for the horizontal turn-by-turn orbit fluctuation $\sigma_{\text{orbit},x}$ due to the excitation and Eq. (2) has to be modified

$$\sigma_{\text{pos},x} \approx \sqrt{\langle \sigma_x \rangle^2 / N_{\text{eff}} + \sigma^2_{\text{orbit},x}}. \tag{3}$$

We can calculate the orbit motion directly from Eq. (3) by substituting the photon number obtained in the longitudinal direction since the photon number in an image is valid for the analysis in both directions.

The horizontal orbit motion calculated using Eq. (3) is $\sigma_{\text{orbit},x} = 4.5 \pm 0.3$ Pixel. Note that the orbit motion is small compared to the measured horizontal bunch size $\langle \sigma_x \rangle$ of about 37 Pixel at the streak camera, which is necessary for stable PPRE user experiments.

MEASUREMENTS VS. EXCITATION AMPLITUDE & FREQUENCY

The method was used to further study the properties of the PPRE bunch as a function of the excitation amplitude and frequency. For this the horizontal bunch size and motion data from the streak camera are converted into physical units at the bunch orbit via an orbit calibration (1 Pixel corresponds to about 10 µm at the orbit). The results are also compared to data from the BBFB system, which uses a bunch resolved readout and online analysis of a beam position monitor [6].

The horizontal size and motion of the PPRE bunch measured with the streak camera are shown in Figs. 3 and 4 as a function of the PPRE excitation amplitude (standard value is 0.5 V). The horizontal PPRE bunch size increases for higher excitations until it reaches a saturation above 300 µm. Note that the measured size is not corrected by the resolution limit of the streak camera, for direct measurements it is estimated

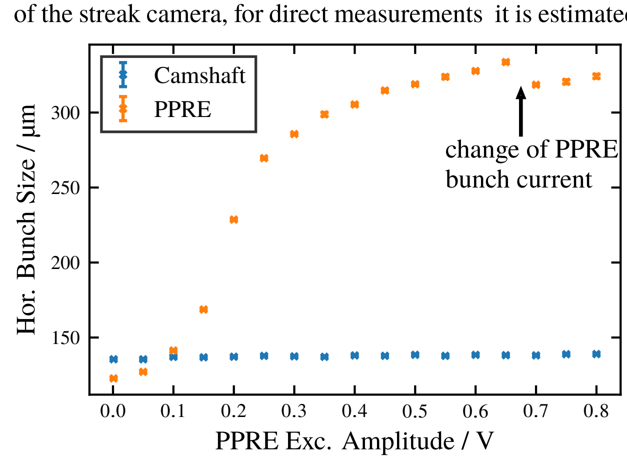

Figure 3: Measured horizontal size of the PPRE and the camshaft bunch as a function of the PPRE excitation amplitude.

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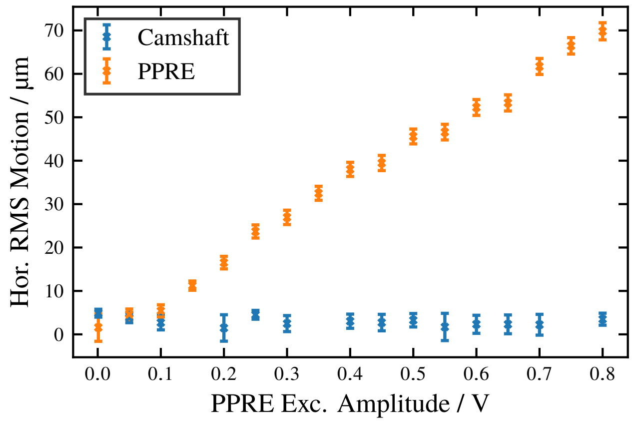

Figure 4: Measured horizontal orbit motion of the PPRE and the camshaft bunch as a function of the PPRE excitation amplitude.

to be around 100 µm. For comparison also the results for the camshaft bunch are shown. Its bunch size stays constant and has minimal or no horizontal motion.

In Fig. 5 the PPRE bunch motion is compared with data from the BBFB system, normalized by the horizontal β-function at the respective source points. The data from both systems agrees very well except for a slight bump in the BBFB data for intermediate excitations.

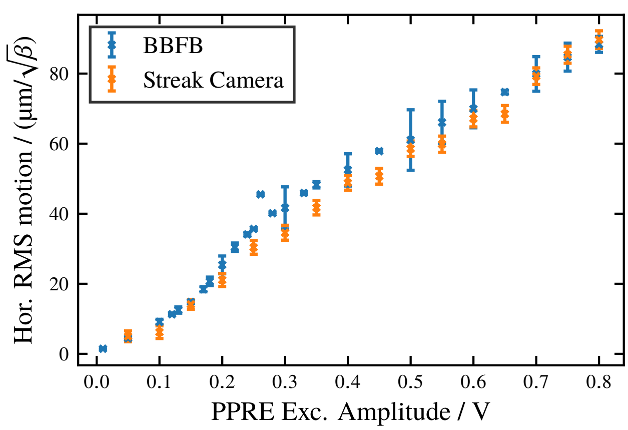

Figure 5: Horizontal PPRE bunch motion measured with the streak camera and the BBFB system as a function of the PPRE excitation amplitude, normalized by the horizontal β-function at respective source points.

The PPRE bunch size and motion were also measured as a function of the excitation frequency (standard working point is at 1 057.607 kHz) at the standard excitation amplitude. The time averaged bunch size measured with the streak camera (including width and orbit motion) is shown together with the horizontal motion from the BBFB system in Fig. 6. The normalized RMS bunch motion measured with both systems is shown in Fig. 7 and again agree quite well. However, one has to be aware that the distributions of the horizontal PPRE position and thus the motion quite severely deviate from a Gaussian distribution for some frequencies.

The peak structure arising from the horizontal tune at around 1 060 kHz and the sidebands of the synchrotron tune can clearly be seen in the PPRE bunch motion and bunch

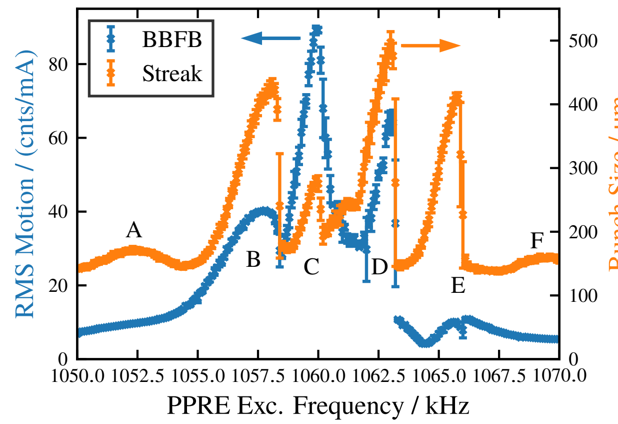

Figure 6: Horizontal size of the PPRE bunch measured with the streak camera and PPRE bunch motion measured with the BBFB system as function of the excitation frequency.

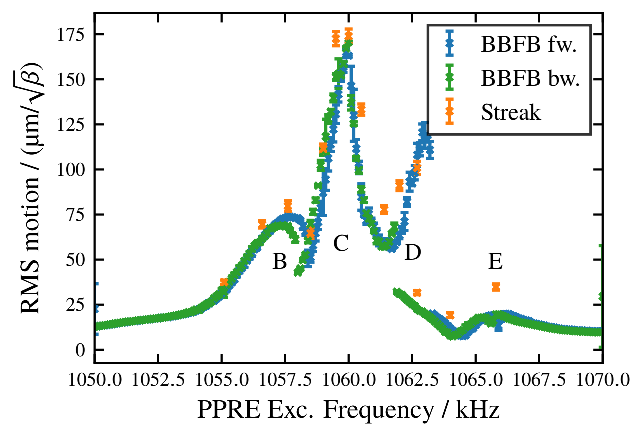

Figure 7: Horizontal PPRE bunch motion measured with the streak camera and the BBFB system (for two scanning directions) as a function of the PPRE excitation frequency, normalized by the horizontal β-function at respective source points.

size. The bunch motion reaches its maximum near the horizontal tune. The bunch size reaches very high values up to 500 µm at three different frequencies (peaks B, D, and E in Fig. 6). For peak D, high bunch sizes are only reached with specific parameter settings of the machine and the excitation is inconstant. In contrast, the excitation is more stable for the sidebands at peaks B and E, where the bunch motion is lower. The left sideband (peak B) is chosen as working point for user operation as it gives the most robust excitation properties.

CONCLUSION

Using the introduced statistical method the horizontal motion and size of a bunch can be detected simultaneously with the streak camera. At BESSY II this is now an important tool to ensure small PPRE orbit motion compared to bunch size in user operation. In addition, measurement series of the PPRE excitation amplitude and frequency were performed and the results agree with data obtained with the BBFB system.

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