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CONTINUOUS BUNCH-BY-BUNCH RECONSTRUCTION OF SHORT DETECTOR PULSES

J. L. Steinmann*, M. Martin, M. Brosi, B. Kehrer, M. M. Patil, P. Schreiber, M. Caselle and A.-S. Müller
Karlsruhe Institute of Technology, Karlsruhe, Germany

Abstract

The KAPTURE system (KArlsruhe Pulse Taking and Ultrafast Readout Electronics), developed at the Karlsruhe Institute of Technology (KIT), was designed to digitize detector pulses during multi-bunch operation at the KIT storage ring KARA (Karlsruhe Research Accelerator). KAPTURE provides digitization for pulses at rates of 500 MHz using up to 4 sampling points per pulse to record each bunch and each turn for potentially unlimited time. The new KAPTURE-2 system now provides eight sampling points per pulse, including baseline sampling between pulses, which allows improved reconstruction of the pulse shape. The advanced reconstruction of the pulse shape is realized with a highly parallelized implementation on GPU. The system will be used for the investigation of longitudinal beam dynamics e.g. by measuring instability induced CSR fluctuations or arrival time oscillations. This contribution will report on first results of the KAPTURE-2 system at KARA.

KAPTURE-2

The KAPTURE system has proven its great potential in several measurements in the last years. Among others, it enabled a snapshot technique [1, 2] to instantaneously map machine parameters to the resulting bursting spectrogram and was used to build a single-shot spectrometer recording 500 million spectra per second [3]. A synchronization scheme makes it possible to take measurements, which are synchronized to other experimental stations [4]. However, due to the limitation of four readout channels, a pulse reconstruction for a single-shot measurement of the amplitude, width and arrival time of a pulse was not feasible.

The new KAPTURE-2 was designed to facilitate the pulse reconstruction capabilities [5]. An incoming pulse is split by a wideband power divider into equal parts for every digitizing channel. Each channel consists of a track-and-hold (T/H) with 18 GHz analog bandwidth and a 12 Bit analog-to-digital converter (ADC). By setting the timing for the T/H, the individual sampling position of each channel can be set. KAPTURE-2 is synchronized to the storage ring RF system. Consequently, the exact sampling time can be adjusted relative to the RF phase by a set of three different delay stages. First, a global delay, with 6 steps of 330 ps each, can be set to sample in the region of the pulse. For fine adjustments a delay of up to 275 ps in steps of 25 ps can be added. Finally, the sampling time of each individual T/H can be set accurately by a 3 ps delay stage up to 93 ps. By using KAPTURE-2 as a sampling scope, i.e. averaging a signal for some turns and scanning every possible delay position allows to sample a pulse with high accuracy. Figure 1 shows the result of such a time scan for a short detector pulse.

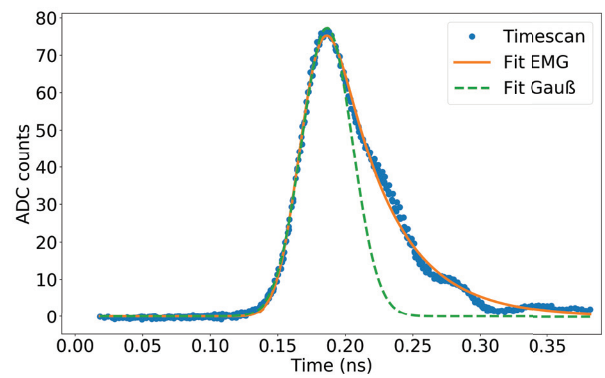

Figure 1: Time scan of a Schottky detector pulse of a single input channel. A Gaussian and an exponentially modified Gaussian (EMG) curve are fitted to the data.

PULSE RECONSTRUCTION

The time scan is needed to properly set the sampling points for the different readout channels. Then, each channel can be set to a different time point of the pulse to sample it. To reconstruct the original pulse from these eight points an interpolation is required. However, a full reconstruction is not needed to derive the pulse amplitude, the pulse arrival time, and the pulse width. Even if the optical pulse happens to be shorter than the impulse response of the detector, a correlation between them is observed. Only for much shorter pulses, they can be approximated as a delta peak to the detector.

As seen in Fig. 1, the signal shape of the used Schottky barrier diode detector is not purely Gaussian. Instead, it comprises a fast rise and an exponential decay. An exponentially modified Gaussian (EMG) fits the shape much better, however, it is also more complex and needs orders of magnitude longer to converge when such a function is fitted to the data. While this is suitable for an offline post-processing of the data, we are focusing on a method for online viewing by fitting purely Gaussians, nevertheless. Such a curve can be linearized by taking the logarithm, which greatly speeds up the fit as only a linear regression is required. Additionally, it can be directly implemented on the readout electronics itself more easily in the future.

* johannes.steinmann@kit.edu

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DECORRELATION OF FIT PARAMETERS

As described above, a Gaussian fit does not perfectly represents the detector response. Therefore, the effect of different input pulse properties like arrival time, amplitude and width on the fit parameters needs to be evaluated. A detector response has been simulated by taking an exponentially modified Gaussian with the data analysis (sampling and fitting a Gaussian to the sample points) applied to it to retrieve the parameters of the simulation.

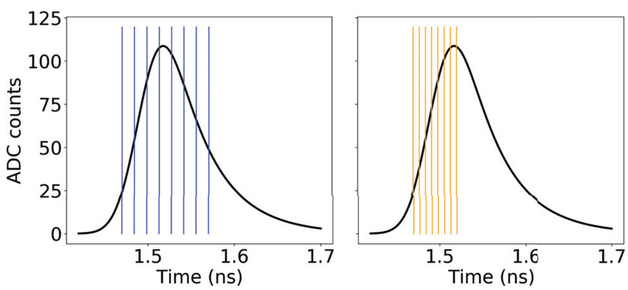

Figure 2: Different distributions of sampling points. A sampling at the tail of the pulse (left), which is not Gaussian, will lead to artifacts in the following Gaussian fit function. To be used with a Gaussian fit, a distribution as shown on the right is advantageous.

The quality of the fit greatly depends on the distribution of the sampling points over the pulse. Figure 2 visualizes the effect of different distributions. It becomes clear that a bad choice of the sampling times will lead to a degraded fit quality and to correlations of the fit parameters. For example, if an arrival time change will shift the sampling times to the tail of the bunch, the Gaussian fit would result in a changed width and amplitude, too.

To analyze the correlation between a variation of the physical parameters like arrival time and amplitude and the extracted values from the fit, the pulses of Fig. 2 were shifted in arrival time for different pulse widths. As expected, different correlations are observed for both cases. In order to decorrelate the different values, a three-step procedure is used. First, a second-order polynomial is used to correct the arrival time μ according to Eq. (1). Afterwards, a two-dimensional second-order polynomial (Eq. (2)) corrects the width (σ) and finally, a three-dimensional second-order polynomial (Eq. (3)) is applied to correct the amplitude (A).

$$\mu_c = p_0 + p_1\,\mu + p_2\,\mu^2 \tag{1}$$

$$\begin{aligned}\sigma_c = {} & p_{00} + p_{01}\,\sigma + p_{02}\,\sigma^2 \\ & + p_{10}\,\mu_c + p_{11}\,\mu_c\sigma + p_{12}\,\mu_c\sigma^2 \\ & + p_{21}\,\mu_c^2\sigma + p_{22}\,\mu_c^2\sigma^2 \end{aligned} \tag{2}$$

$$A_c = p_{000} + p_{001}\,A + \cdots + p_{222}\,\mu_c^2\sigma_c^2A^2. \tag{3}$$

The polynomial parameters are retrieved by a fit to the simulations. The sampling times chosen for the experiment are used in the simulation, so that the retrieved polynomials can be used to correct the experimental data. This method is only applicable, if the retrieved arrival time does not depend on the width and the amplitude of the signal. This is dependent on the choice of sampling times. The chosen times have to sample mostly the Gaussian part of the pulse. For a quantitative study of the decorrelation, the correlation coefficients between the fit parameters are calculated for the chosen sampling times of the experiment. They are summarized in Table 1.

Table 1: Correlation Coefficients

	raw	**decorrelated**
Amplitude A / Arrival time μ	0.199	0.015
Amplitude A / Width σ	0.122	0.026
Arrival time μ / Width σ	0.294	0.003

FIRST MEASUREMENTS

The measurements were carried out at the KIT storage ring KARA (Karlsruhe Research Accelerator) in the short-bunch mode. This operation mode is in vicinity of the microbunching instability which leads to turbulent bunch lengthening above a bunch current threshold. All measurements were performed above that threshold. First, a time scan of the detector pulse is done in a multi-bunch environment as KAPTURE-2 allows the continuous recording of all bunches in parallel. Figure 3 shows the time scan of bunches with different charges. In this first measurement, six out of the eight channels were used for the fit. Their sampling times were chosen according to Fig. 3.

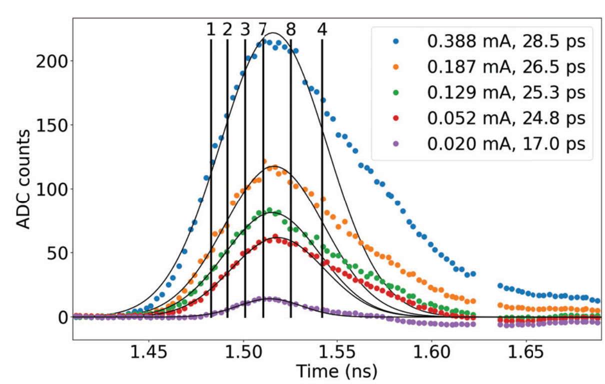

Figure 3: Time scan of differently charged bunches in a multi-bunch fill. The pulse lengths are determined by the Gaussian fit in solid lines. A longer pulse for higher bunch currents is expected due to the bunch-lengthening effect of the microbunching instability. The chosen sampling times are indicated by vertical lines.

From the Gaussian fit, the arrival time, pulse width and pulse amplitude is extracted for every bunch at each turn. Note, that the pulse width is dominated by the detectors low-pass behaviour and not directly by the bunch length. To visualize the dynamics of the microbunching instability, so-called *bursting spectrograms* are used [6]. They show

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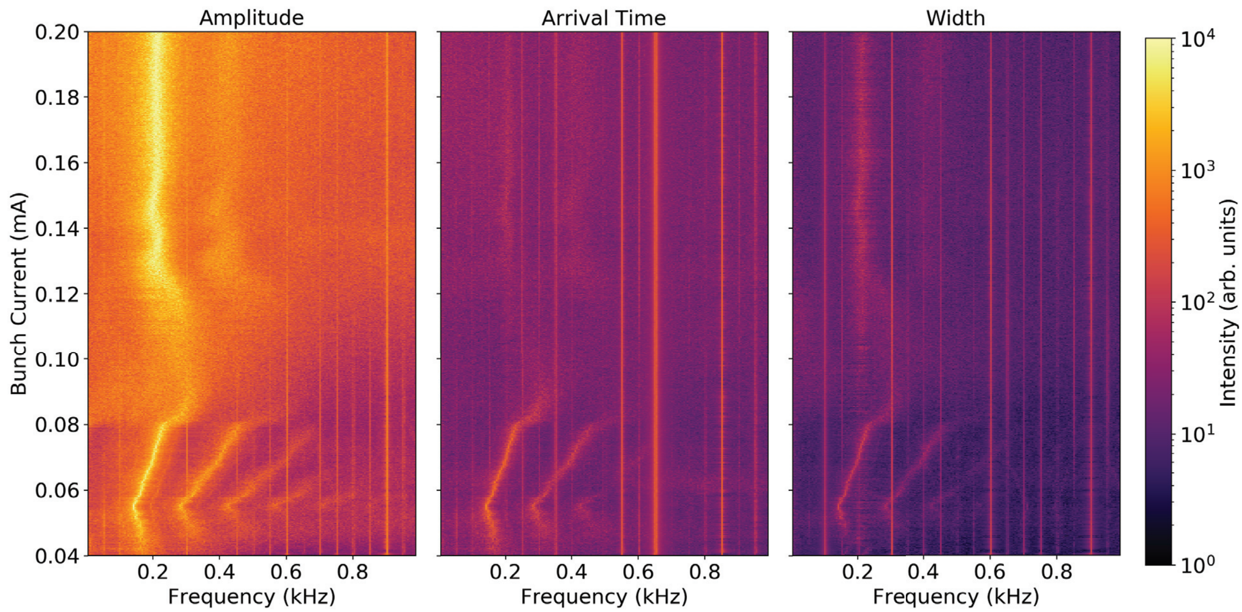

Figure 4: (from left to right): spectrograms of the extracted amplitude, arrival time and width of a bunch signal over charge. The behaviour of the amplitude is typical for the microbunching instability. The effect on the arrival time and width could not be studied before.

the signal fluctuations in dependence of the bunch current and are a fingerprint of the machine settings. The pulse reconstruction method allows the investigation of not only the amplitude signal, but also of the pulse width and arrival time as shown in Fig. 4. Straight vertical lines, which are visible in the spectrogram and separated by 50 Hz are due to electrical interferences. Even after applying the decorrelation, the same pattern, already known for the amplitude, can be seen on the arrival time and pulse width, too. A similar behaviour of the arrival time is also reported in [7].

SUMMARY

KAPTURE-2 allows a continuous turn-by-turn sampling of fast detector pulses with up to eight sampling points. We achieved an online analysis, almost in real-time, by using a heavily parallelized GPU algorithm based on linearized Gaussian curve fitting to the data. We successfully demonstrated the ability to retrieve the pulse width, amplitude and arrival time from the measured data by applying linearized Gaussian fits and a correction to the fit parameter for a decorrelation. The first results are promising and allow a study of the turn-by-turn arrival times of the bunches, for example, to investigate the microbunching instability. Additionally, with fast enough detectors and readout system, continuous direct bunch length measurements on a bunch-by-bunch and turn-by-turn level become possible with this system.

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