A PICOSECOND SAMPLING ELECTRONIC “KAPTURE” FOR TERAHERTZ SYNCHROTRON RADIATION

M. Caselle, M. Brosi, S. Chilingaryan, T. Dritschler, N. Hiller, V. Judin, A. Kopmann, A.-S. Müller, J. Raasch, L. Rota, L. Petzold, N. J. Smale, J., L. Steinmann, M. Vogelgesang, S. Wuensch, M. Siegel, M. Weber, KIT, Karlsruhe, Germany

Abstract

The ANKA storage ring generates brilliant coherent synchrotron radiation (CSR) in the THz range due to a dedicated low-a_c-optics with reduced bunch length. At higher electron currents the radiation is not stable but is emitted in powerful bursts caused by micro-bunching instabilities. This intense THz radiation is very attractive for users. However, the experimental conditions cannot be easily reproduced due to those power fluctuations. To study the bursting CSR in multi-bunch operation an ultra-fast and high-accuracy data acquisition system for recording of individual ultra-short coherent pulses has been developed. The Karlsruhe Pulse Taking Ultra-fast Readout Electronics (KAPTURE) is able to monitor all buckets turn-by-turn in streaming mode.

KAPTURE provides real-time sampling of the pulse with a minimum sampling time of 3 ps and a total time jitter of less than 1.7 ps. The KAPTURE system, the synchrotron operation modes and beam test results are presented in this paper.

INTRODUCTION

At the synchrotron light source ANKA, up to 184 electron bunches can be filled with a distance between two adjacent bunches of 2 ns corresponding to the 500 MHz frequency of the accelerating RF system.

Since a few years, special user operation with reduced bunch length in the order of a few picoseconds has been available to research communities. In this mode, coherent synchrotron radiation is generated for electro-magnetic waves with a wavelength in the order of or longer than the electron bunch length. Due to this, one usually observes a strong amplification of the radiation spectrum in the THz band. Moreover, above a certain current threshold, a coherent modulation of the longitudinal particle distribution (microbunching) occurs due to CSR impedance [1]. This particle dynamic effect changes the characteristics of the CSR tremendously. The microbunching structures fulfil a coherence condition for shorter wavelengths. This leads to an instantaneous increase of the radiated THz power. Observation in the time domain shows bursts of radiations which occur with different periodicities depending on the bunch current. The characteristics of the bursting patterns are unique for different sets of accelerator parameters [2].

The KAPTURE (KArlsruhe Pulse Taking and Ultrafast Readout Electronics) system opens up a possibility to monitor the THz radiation of all bunches in the ring over a principally unlimited number of turns, realising a new type of measurement at ANKA. In this paper we present the KAPTURE system, the synchrotron applications and the measurements of CSR at the ANKA synchrotron light source.

KAPTURE SYSTEM

The KAPTURE system records individual pulses continuously with a sub-millivolt resolution and a relative timing resolution between two consecutive pulses in the order of picoseconds. KAPTURE is a flexible system and can be easily configured for the requirements of others synchrotron facilities.

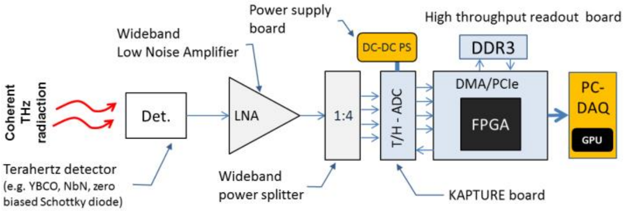

Figure 1: KAPTURE system for the detection of coherent THz radiation generated at ANKA.

The KAPTURE system is shown in Fig. 1. It consists of a Low Noise Amplifier (LNA), a power splitter, a picosecond pulse sampling stage called “KAPTURE board”, a high throughput readout board and a high-end Graphics Processing Unit (GPU). The signal from the detector is fed into a LNA and then divided in four identical pulses by a wideband power splitter. The KAPTURE board acquires each pulse with 4 sample points at a programmable sampling time between 3 and 100 ps. The basic concept of the picosecond KAPTURE board and the architecture have been reported previously [3,4]. The high throughput readout board uses a new bus master DMA architecture connected to PCI Express logic [5] to transfer the digital samples from the KAPTURE board to a high-end GPU server. For continuous data acquisition a bandwidth of 24 Gb/s (12 bits @ 2 ns * 4 digital samples) is necessary. The DMA architecture has been developed to meet this requirement with a high data throughput of up to 32 Gb/s. The GPU computing node is used for real-time reconstruction of the pulse from the 4 digital samples. Afterwards, the peak amplitude of each pulse and the time between two consecutive pulses/buckets with a picosecond time resolution are calculated. The GPU node performs also an on-line Fast Fourier Transform (FFT) for the frequency analysis of the CSR fluctuations.

ISBN 978-3-95450-141-0

The internal organization of the KAPTURE system and its components is shown in Fig. 2. The detector signal is connected to the LNA by a wideband V-connector and then propagated to the power divider by a tee-bias device.

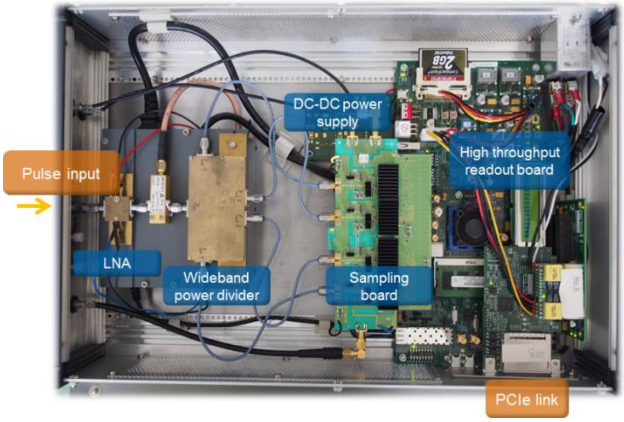

Figure 2: View inside the KAPTURE system.

Matching of the high bandwidth required to design a novel wideband power divider architecture [6]. The LNA gain has been developed in order to compensate the power divider insertion loss with minimum additional noise contribution. The readout board is equipped with a Virtex 6 FPGA that receives the digitalized samples, tags them with the current bunch number, and sends the data to the GPU server via the PCIe data uplink.

KAPTURE PERFORMANCE

The KAPTURE system is designed for continuous sampling of very short pulses (minimum FWHM of few tens of picosecond) with a trigger frequency synchronous with the RF-system of synchrotron machines (500 MHz for ANKA). Moreover, the amplitude of the pulses are typically in the order of some tens of millivolts. Due to ultra-fast and low amplitude pulses, KAPTURE has been designed with special precautions regarding component selection and layout technologies. The RF/ microwave analog front-end is operating at an analog input frequency range of DC - 50 GHz. The RF technologies used are described in previous work [6]. For a better control of the characteristic impedance of the line, especially at high frequency, special wideband coplanar waveguide transmission lines have been designed using a via fence technique. To achieve this performance special substrates have been used, respectively Duroid 5880 for the analog front-end and Roger 4003 for digitalization circuits [3,6].

The digitizer circuits use a picosecond time chip to control the timing between two adjacent samples. In this way, the picosecond sampling time can be programmed by FPGA. Low skew sampling time and clock distributions have been optimized with a total skew that does not exceed 6 ps.

KAPTURE is very flexible and can operate in both real time and equivalent sampling modes. In the real time mode each pulse is acquired by four sample points with a flexible sampling time between 3 and 100 ps. In the equivalent sampling method the KAPTURE is able to acquire a periodical waveform with a sampling rate that exceeds 300 GS/s with a total observation time up to 2.2 ns. A very low noise layout design guarantees a Gaussian shape of the total time jitter with a standard deviation (Std-Dev) measured to be less than 1.7 ps [4]. The picosecond time characterization is fundamental for understanding the performance of the KAPTURE system. For this purpose, very short pulses with a FWHM of few tens of picosecond and a time jitter of few picoseconds are required. Due to limitations of commercial pulse generators, we have performed the characterization using short pulses generated by an YBCO detector [7] illuminated with coherent synchrotron radiation. The input pulse with a FWHM of 42 ps and an amplitude of 45 mV was previously measured with a real-time oscilloscope. For the time characterization we configured the KAPTURE system to operate in an equivalent sampling mode with a sampling time of 3 ps. In this way, we have acquired the input pulse with an equivalent sampling rate of more than 300 GS/s. The acquired pulse shape is in agreement with the previous measurement by a real-time oscilloscope; all results are reported in the previous work [6].

The analog channel and the ADC circuits exhibit a wide dynamical range of ± 2.5 V with a noise below 2 mV (RMS) [4].

To sustain a continuous data acquisition a bandwidth of 32 Gb/s is necessary. A high-throughput readout system is used to transfer the sampled data from the digitizer stage to the high-end GPU-DAQ system. The readout architecture and the FPGA firmware are presented [6].

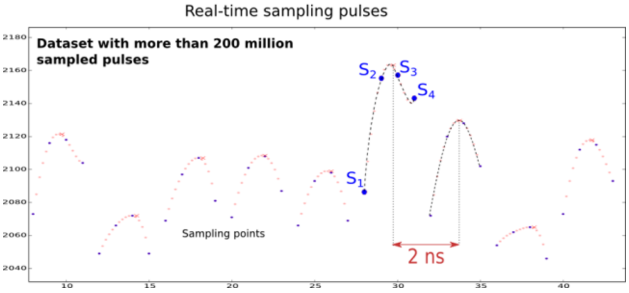

Figure 3: Details of reconstructed pulses, the x-axis shows the sampling points and the y-axis the ADC counts.

The real time data analysis is based on GPU node. The GPU is used for the pulse reconstruction; the measurements of the pulse amplitude and the time of arrival of each pulse, and also performs an on-line fast Fourier Transform (FFT) for the frequency analysis of the coherent synchrotron radiation fluctuations. Fig. 3 shows a dataset acquired in real time acquisition mode by a fast cryogenic YBCO detector. For each pulse the four sampling points S1, S2, S3 and S4 are acquired with a time distance of 15 ps respectively between the first sample S1 and the second S2, 9 ps between S2 and S3 and 15 ps between S3 and S4, while the time distance between two consecutive pulses is 2 ns.

ISBN 978-3-95450-141-0

KAPTURE – OPERATION MODES

The KAPTURE system has been designed with four individual wideband analog inputs. In this way, the system is flexible and can be used to acquire the fast detector signal from one or up to four detectors in parallel. Additional data flow logic can be instantiated in the FPGA for an additional real-time data processing on the detectors pulses. Fig. 4 shows the possible configurations and the number of sampling points per individual pulse.

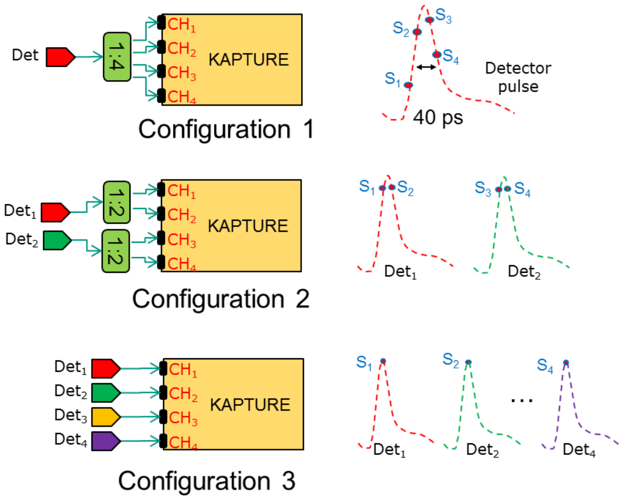

Figure 4: KAPTURE configuration modes, the connection between the detectors, power splitter and KAPTURE are made by wideband cables.

With configuration 1 the power splitter can be mounted internally within the system as shown in Fig. 2. This configuration allows for the acquisition of a very short pulse coming from a detector with a very high temporal resolution (e.g. YBCO). In configuration 2 and 3, KAPTURE uses a wideband power splitter with two outputs which have been developed for these measurements. These configurations are suitable for the acquisition with two or more detectors in parallel. Configuration 2 has been used for the measurements of the CSR with two zero-biased Schottky diodes. For the correct measurements of the detector pulse the sample points must be located in the peaking time region. The system assists the user to select the correct timing for the best position of the sample points for each analog input. Moreover, this configuration allows for additional real-time data processing between signals if necessary.

MEASUREMENTS AT ANKA

All measurements were performed at ANKA's infrared beamlines IR1 and IR2, which have an acceptable transmission grade for THz radiation. Fig. 5 shows a typical data set taken by KAPTURE. It shows the bursting regime in multi-bunch mode with four trains consisting of 33-35 bunches. The colour density plot shows the evolution of the intensity of all 184 buckets in the time domain. Only around 120 thousands turns are displayed here for the better visualisation of the bursting behaviour. The whole data set contains about 1 second of data, corresponding to 2.7 million turns. On the left side the calculated mean of the THz intensity and the measured bunch currents are shown. For the determination of bunch current a single photon counting method is implemented at ANKA [8].

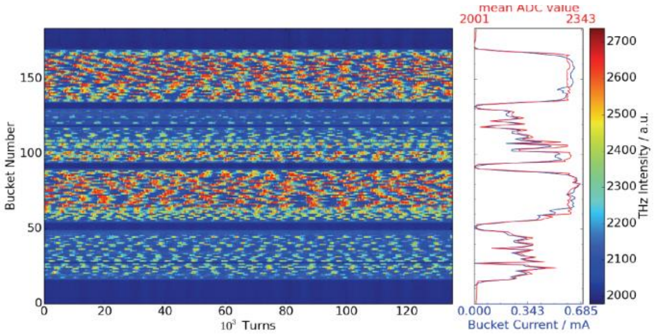

Figure 5: The THz signal measured with a fast Schottky Diode detector by the KAPTURE system with four trains consisting of approx. 33 bunches are shown on the left side for around 140 thousands consecutive turns. The intensity is colour coded. At the right side the corresponding bucket current is shown in blue and the mean THz signal in red by KAPTURE.

The filling pattern was tailored using the recently installed Bunch-by-Bunch Feedback system [9]. The measurement shows different bursting behaviours (Fig. 5, left) at different bunch currents (Fig. 5, right). For the investigation of bursting effects a frequency analysis using an FFT of the time domain data can be performed. These frequency domain data sets displayed for long-term decaying bunch currents in 2D gives a spectrogram. In Fig. 6, spectrograms of three arbitrarily chosen buckets within the similar properties. For the same time range are shown with the dashed line marking the same bunch current in every picture. Only marginal differences can be observed. It seems that the bunches show similar bursting behaviour for similar bunch currents. The investigation of similarities and differences of bursting spectrograms will provide a useful tool for the study of bunch-bunch interactions.

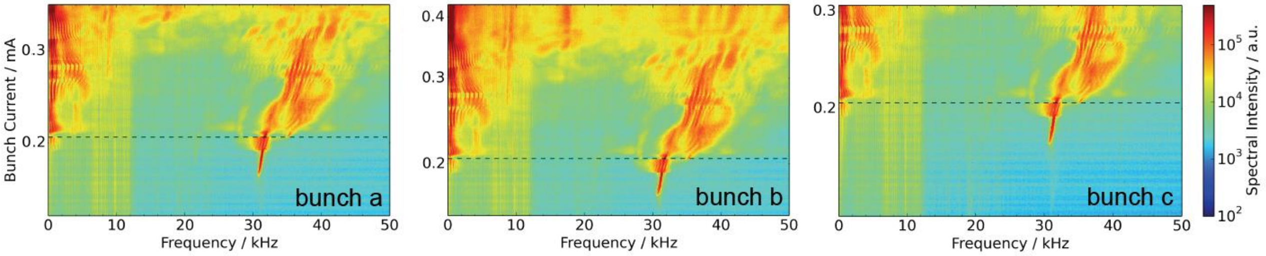

Figure 6: A frequency analysis of the time domain signal taken simultaneously for different bunches in the same fill gives insight into the bursting behaviour of each bunch in a multi-bunch environment. Here three bunches with different initial currents were taken. The horizontal dashed lines mark the different points in time where the bunches have the same current. The differences in the spectrograms are not obvious and have to be investigated thoroughly. The studies of bunch-bunch interactions are in progress.

Dependency of Bursting Threshold and Momentum Compaction Factor

Another measurement studies is the bursting threshold at different momentum compaction factor (a_c) and at constant RF settings based on KAPTURE. The bursting threshold is defined by the current at which the emitted CSR intensity starts to fluctuate. If the single-bunch mode is used, the complete bunch current range needs to be observed. Instead of waiting for a single bunch to pass through the whole current range, it is also possible to use multiple bunches with different bunch currents to save time. This kind of instant bursting threshold measurement method using the mean of the THz signal for all 184 buckets and corresponding single bunch currents has been used in the past with KAPTURE [10]. However another method using the standard deviation of the THz signal has shown higher reliability. Above the threshold, the standard deviation is increasing significant due to the initiated fluctuations. This allows to scan the machine parameters and to observe almost in real-time the change of the bursting threshold.

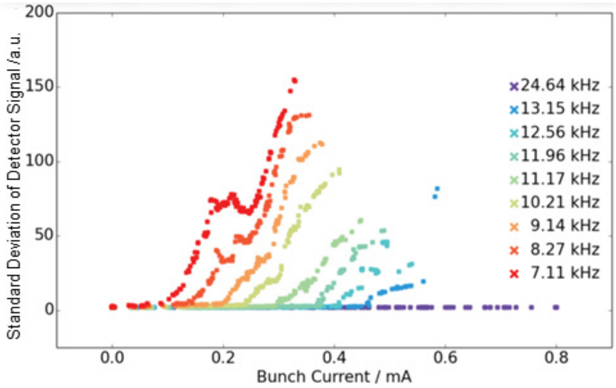

Figure 7: The bursting threshold study for different momentum compaction factors at constant RF-conditions is shown. The KAPTURE system allows monitoring of the bursting threshold during changes of the beam optics.

The standard deviation of the signal in dependence of the single bunch current is displayed in Fig. 7 during a reduction procedure of α_c at ANKA, where the strengths of focusing magnets are changed in steps while keeping the RF-voltage constant. Each colour indicates a data set, which corresponds to beam optics with the given synchrotron frequency f_s. For beam optics with lower a_c (corresponds to a lower f_s) the instability threshold is significantly reduced. Due to different bursting regimes the standard deviation does not increase constantly. Especially for f_s = 7.11 kHz, a change of bursting regime is visible at 0.2 mA.

Simultaneous Measurement with two Detectors

Operating KAPTURE in configuration 2 (see Fig. 4) we are able to measure simultaneously with two detectors. Bursts of radiation emitted due to micro-bunching instabilities in the ANKA storage ring have been observed continuously with both detectors for every bunch and every turn. Radiation split by a wire grid and detected with two Schottky diodes is shown in Fig. 8.

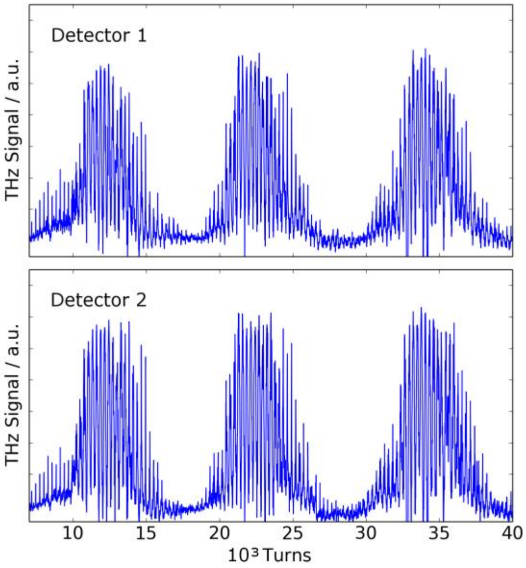

Figure 8: Simultaneous measurement of bursting instabilities with Schottky detectors.

For long-term observations over several hours we implemented a data reduction method in KAPTURE's. Only every 10th turn is saved, which limits the instability dynamics frequency to 270 kHz. Also only one second out of 10 seconds is stored, resulting in 1 Hz frequency resolution. With these settings, we are able to observe both, the dynamics of the high frequency changes in the kHz-range due to electron bunch phase space rotations as well as the slowly changing beam-current depending on the bursting behaviour. The resulting data rate is kept below 100 MB/s and can easily be stored on standard hard disks.

ACKNOWLEDGMENT

The authors would like to acknowledge the infrared group at ANKA for their support during the beam times at the infrared beamlines IR1 and IR2. This work is supported by the German Federal Ministry of Education and Research (Grant No. 05K13VKA) and the Helmholtz Association (Contract No. VH-NG-320).

REFERENCES

[1] G. Stupakov and S. Heifets, “Beam instability and microbunching due to coherent synchrotron radiation”, Phys. Rev. STAB, 2002, Vol. 5, Nr. 5, DOI:10.1103/PhysRevSTAB.5.054402.

[2] M. Schwarz et al., “Bursting Patterns of Coherent Synchrotron Radiation in the ANKA Storage Ring”, WEPEA011, IPAC’13, Shanghai.

[3] M. Caselle et al., “Ultra-fast data acquisition system for coherent synchrotron radiation based on superconducting terahertz detectors”, WEOBB202, IPAC 2013, Shanghai.

[4] M. Caselle et al. “An ultra-fast data acquisition system for Coherent Synchrotron Radiation with terahertz detectors “, TWEPP 2013, Perugia, *JINST* **9** C01024 doi:10.1088/1748-0221/9/01/C01024.

[5] L. Rota, M. Caselle et al. “A New DMA PCIe Architecture for Gigabyte Data Transmission", 19th Real-Time conference IEEE-RT, Nara, Japan.

[6] M. Caselle et al. “An Ultra-fast Digitizer with Picosecond Sampling Time for Coherent Synchrotron Radiation”, 19th Real-Time conference IEEE-RT, Nara-Japan.

[7] P. Thoma et al., “High-speed Y-Ba-Cu-O Direct Detection System for Monitoring Picosecond THz Pulses”. IEEE Transactions on terahertz science and technology, vol. 3, NO.1, January 2013.

[8] B. Kehrer et al., "Filling Pattern measurements at the ANKA storage ring", TUPC087, IPAC’11, San Sebastián.

[9] E. Hertle et al., "First Results of the New Bunch-by-bunch Feedback System at ANKA", TUPC087, IPAC’14, Dresden.

[10] A.-S. Müller et al., "Studies of Bunch-bunch Interactions in the ANKA Storage Ring with Coherent Synchrotron Radiation using an Ultra-fast Terahertz Detection System", MOPEA019, IPAC’13, Shanghai.