

# PICOSECOND SAMPLING ELECTRONIC FOR TERAHERTZ SYNCHROTRON RADIATION

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## Abstract

The ANKA storage ring generates brilliant coherent synchrotron radiation (CSR) in the THz range due to a dedicated low- $\alpha_c$ -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 attractive for users. However, due to the power fluctuations, the experimental conditions cannot be easily reproduced. To study the bursting CSR in multi-bunch operation an ultra-fast and high-accuracy data acquisition system for recording of individual ultra-short 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. In this paper we present the KAPTURE system, the performance achieved and the integration in the ANKA control system.

## INTRODUCTION

At the ANKA synchrotron light source, up to 184 electron buckets 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, we observe 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. Observations in the time domain show bursts of radiation that 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 the 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 and the integration in the ANKA environment.

## KAPTURE SYSTEM

The KAPTURE system records individual pulses continuously with a sub-millivolt resolution and a timing resolution in the order of picoseconds. KAPTURE is a flexible system and can be easily configured for the requirements of any synchrotron facility.

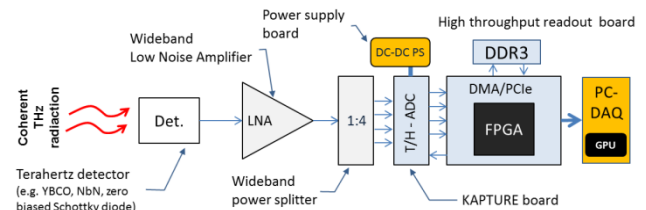


Figure 1: KAPTURE system for the detection of coherent THz radiation generated at ANKA.

The architecture of 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. Matching of the high bandwidth required to design a novel wideband power divider architecture [3]. The LNA gain compensates the insertion loss due to the power divider with a minimal additional noise. The KAPTURE board consists of four parallel sampling channels each operating at 500 MS/s [4]. Each sampling channel receives one of the four pulses from the power splitter and acquires it with one sampled point. The sampling time between the channels is settable with an accuracy of 3 picoseconds. The final result is that each detector pulse will be sampled with 4 sample points at a programmable sampling time between 3 and 100 ps. The basic concept and the architecture of the picosecond KAPTURE board have been reported previously [5]. The high throughput readout board uses a new bus master DMA architecture connected to PCI Express logic [6] 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 are calculated with picosecond time resolution. The GPU node performs also an on-line Fast Fourier Transform (FFT) for a frequency analysis of the CSR fluctuations.

The internal organization of the KAPTURE system and its components are 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.

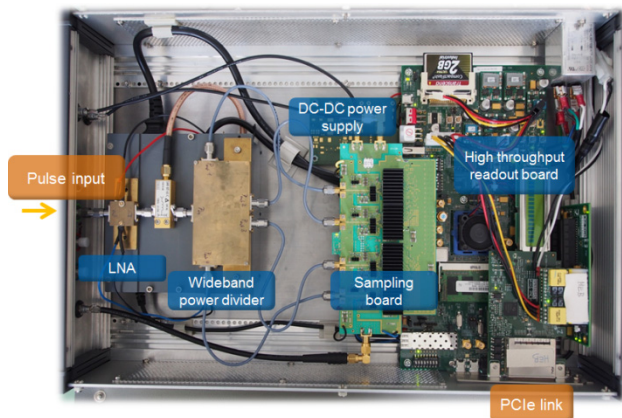


Figure 2: View inside the KAPTURE system.

The high data throughput readout board is equipped with a Virtex 6 FPGA that receives the digitized samples, tags them with the current bunch number, and sends the data to the GPU server via the PCIe data link.

### PERFORMANCE

The KAPTURE system is designed for continuous sampling of very short pulses (minimum FWHM of a few tens of picoseconds) with typical amplitude 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 technologies and the circuits have been reported previously [3]. The RF/microwave analog front-end is operating at an analog bandwidth of DC - 50 GHz. For a better control of the characteristic impedance of the transmission lines, especially at high frequencies, special wideband coplanar waveguide transmission lines have been designed using a via fence technique. To achieve this performance special substrates have been used, Duroid 5880 for the analog front-end and Roger 4003 for digitalization circuits respectively [3,4].

The picosecond time delay chip, used to distribute the sampling signals at the four channels can be programmed by FPGA with a picosecond resolution.

KAPTURE is flexible and can operate in both real-time and equivalent sampling modes. In the equivalent time sampling mode KAPTURE is able to acquire a periodical waveform with a sampling rate that exceeds 300 GS/s and a total observation time of up to 2.2 ns. The low noise layout guarantees a Gaussian time jitter distribution with a measured standard deviation (Std-Dev) of 1.7 ps [5].

The time characterization of the KAPTURE system is a crucial part in the evaluation of the performance. 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 was previously measured with a real-time oscilloscope and shows a FWHM of 42 ps as well as an amplitude of 45 mV. In addition, we configured the KAPTURE system to operate in equivalent sampling mode with a sampling time of 3 ps, thus achieving a sampling rate of more than 300 GS/s. The pulse shape acquired with the KAPTURE system is in agreement with the measurements done with the real-time oscilloscope; all results are reported in the previous work [3]. KAPTURE is designed to work in real-time sampling mode where each pulse is acquired by four sampling points. 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.

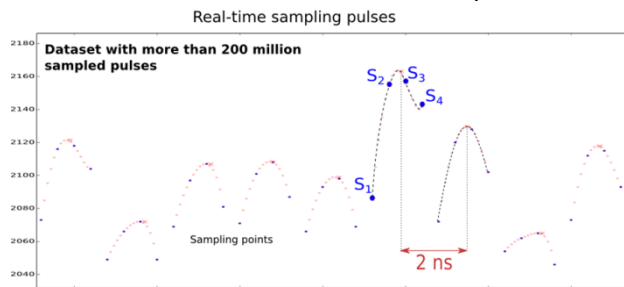


Figure 3: Details of reconstructed pulses, the x-axis shows the sampling points and the y-axis the ADC counts.

The real-time data analysis is based on a GPU co-processor. The GPU is used to reconstruct each pulse and measure its amplitude and time of arrival. It also performs an on-line Fast Fourier Transform (FFT) for a frequency analysis of the CSR fluctuations.

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 in [3].

The KAPTURE system, combined with different terahertz detectors (e.g. YBCO, NbN, Zero Biased Schottky Diode), has been proven to be an indispensable tool for analysis of CSR fluctuations in single- and multi-bunch mode. This method with a very high potential opens up new diagnostics possibilities such as the instantaneous measurement of the bursting threshold and chromaticity effects on longitudinal particle dynamics. Several important physics results have been published in the field of synchrotron terahertz radiation like the CSR behaviour at different current ring condition, the bunch-to-bunch interactions, the dependency of bursting threshold and momentum compaction [8, 9].

## INTEGRATION OF THE KAPTURE SYSTEM AT ANKA

The KAPTURE system has been designed to acquire datasets for a long observation time. The normal current decay in the synchrotron ring offers the possibility to study the CSR emission at different storage ring currents. For long-term observations taking several hours we implemented a data reduction method in KAPTURE. Only every 10th turn is saved, thus limiting the instability dynamics frequency to 270 kHz. Moreover, only one second out of 10 seconds is stored, resulting in 1 Hz frequency resolution. With these settings we are able to observe simultaneously two different effects: the dynamics of the high frequency changes in the kHz-range due to electron bunch phase space rotations and the slowly changing beam-current depending on the bursting behaviour.

To keep the information between each individual dataset and the beam condition consistent, the KAPTURE acquisition system has been integrated in a hierarchical software architecture shown in Fig.4.

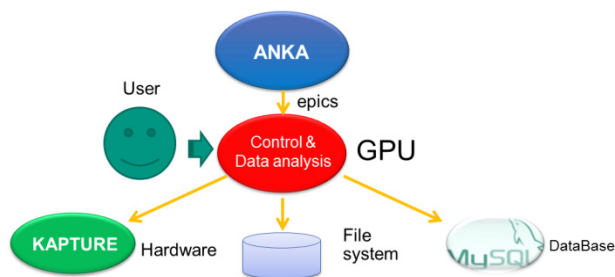


Figure 4: Integration of the KAPTURE system at ANKA.

This architecture integrates the control system, the DAQ and the on-line data quality check sub-systems in a single environment. The “Control and Data analysis unit” is the main software component. It receives the ANKA beam configurations/conditions by means of EPICS [10] and configures the KAPTURE hardware for the desired data readout (Control mode). This unit is running at the GPU server, it receives the readout data from KAPTURE with a data rate of 32 Gb/s and performs the real-time data analysis (Data analysis mode). A data quality check is included in the units in order to trigger specific actions in case of wrong data format. Optionally, an on-line FFT can be used also for a fast verification of the quality of the data acquired. The “Control and Data analysis unit” provides a high level and lightweight Graphics User Interface (GUI) that offers access to most of the system configuration in a controlled fashion and also offers basic functionality to view and analyse the data.

A MySQL database has been integrated to tag each individual dataset with the current accelerator parameters values. In this way, each measurement is automatically correlated with the exact beam condition that has generated the CSR measured by KAPTURE. This is

useful for an easy and fast identification of the interesting files for the off-line data analysis.

## CONCLUSION

In this paper we have presented the KAPTURE system, designed for sampling bunch-by-bunch CSR pulses with fast THz detectors over long observation times. The system is able to measure amplitude and timing of individual pulses with a rate of 500 MHz. A low noise design and a wide dynamic range resulted in a timing accuracy of less than 3 psec. We have also presented the integration of the KAPTURE system in the ANKA synchrotron machine environment. The KAPTURE system allows scientists to study a variety of physical phenomena at the ANKA storage ring.

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