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TOWARDS DIRECT DETECTION OF THE SHAPE OF CSR PULSES WITH FAST THz DETECTORS

J. L. Steinmann*, M. Brosi†, E. Bründermann, A. Mochihashi, P. Schreiber, A.-S. Müller
Karlsruhe Institute of Technology, Karlsruhe, Germany

Abstract

Coherent synchrotron radiation (CSR) is emitted when the emitting structure is equal to or smaller than the observed wavelength. Consequently, these pulses are very short and most detectors respond with their impulse response, regardless of the pulse length and shape. Here we present single-shot measurements performed at the Karlsruhe Research Accelerator (KARA) using a fast real-time oscilloscope and Schottky barrier detectors sensitive in the sub-THz range. The time response of this setup to CSR pulses emitted by electron bunches during the microbunching instability is shown to be sensitive to the shape of the electron bunch. Our results show how, in the future, the shape of electron bunches can be directly measured using a straightforward setup.

OVERVIEW

While incoherent radiation is independent of the electron distribution and the emitted optical power is therefore directly proportional to the bunch structure, coherent radiation, on the other hand, depends on the electron distribution, since the power for fully coherent radiation scales quadratically with the number of particles. In the past, our readout chain could not directly resolve the time structure of THz pulses but measured the total integrated pulse energy. Here we show for the first time direct time structure measurements of a short electron bunch suffering from the microbunching instability. During this instability, which was extensively studied in the past years [1], sub-structures on the bunch profile are created leading to a rich structure whose form factor extends up to several THz. With a commercial real-time oscilloscope and a fast sub-THz detector we were able to resolve some part of that structure.

SETUP AND CHARACTERIZATION

The optical measurement setup is quite simple as we used a single off-axis parabolic mirror to focus the synchrotron radiation at the KARA IR2 beamline onto the THz detector. The detector consists of a horn antenna coupling the radiation into a waveguide and onto a Schottky diode which rectifies the electric field pulse. Due to the filtering characteristic of the waveguide (WR2.2) and the diode itself, the detector is sensitive between 325 GHz to 500 GHz. Through a small hole in the parabolic mirror, some fraction of the optical light is transmitted and focused with an objective onto a photo diode detector sensitive in the visible range, thus measuring purely incoherent synchrotron radiation. This diode is specified with a rise time of 35 ps and a bandwidth of 10 GHz. The optical setup is shown in Fig. 1.

Each detector output is connected with a 1.2 m long RF cable to the 100 GHz, 256 GSa/s, 10-bit real-time oscilloscope. Apart from the oscilloscope, the equipment is not intended for this high frequency, which leads to some compromises that might affect the performance. The THz diode has a 2.92 mm K-connector where we connected a low-loss cable also with K-connectors to an K-to-V-Adapter and a V-to-1 mm-Adapter to the oscilloscope. The K connectors as well as the used Totoku Flexible Cable, TCF358, 1.2 m are specified only up to 40 GHz above which additional modes can propagate on the cable. The photo diode detector has an SMA connector but is limited to ~10 GHz bandwidth.

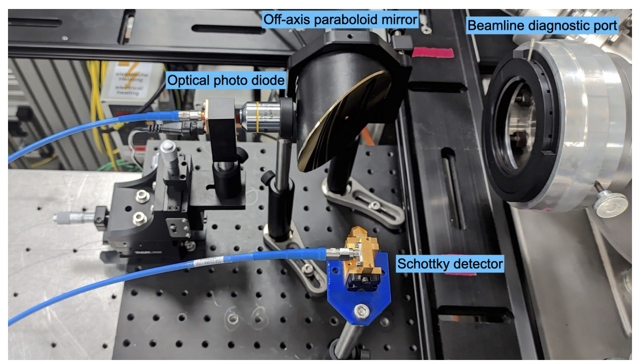

Figure 1: Optical setup: The radiation is coupled out via the diagnostic port of the IR2 beamline at KARA and focused with an off-axis parabolic mirror into the horn antenna of the THz detector. Through a hole in the mirror, visible light is guided through an objective onto a photo diode detector.

To characterize the THz detector setup and make sure we are not just seeing detector effects we measured a stable laser based THz source (TERA15-TX-FC) with a length of below 2 ps first, which is shorter than what our setup can resolve. Therefore, the impulse response of the system is probed. The photo diode detector was illuminated with incoherent synchrotron radiation in the visible range. To compensate for arrival time changes due to synchrotron oscillation, the pulses were aligned before averaging.

The measured detector outputs are shown in Fig. 2 (top). The THz detector shows a significantly lower standard deviation (compare the noise before the pulses) and a very stable pulse signal and corresponding readout. Though, small afterringing and reflections are visible where not necessarily all of them have to come from the detector or the readout, as some are also visible in the THz time-domain spectroscopy

* steinmann@kit.edu
† now at MAX IV Laboratory, Lund

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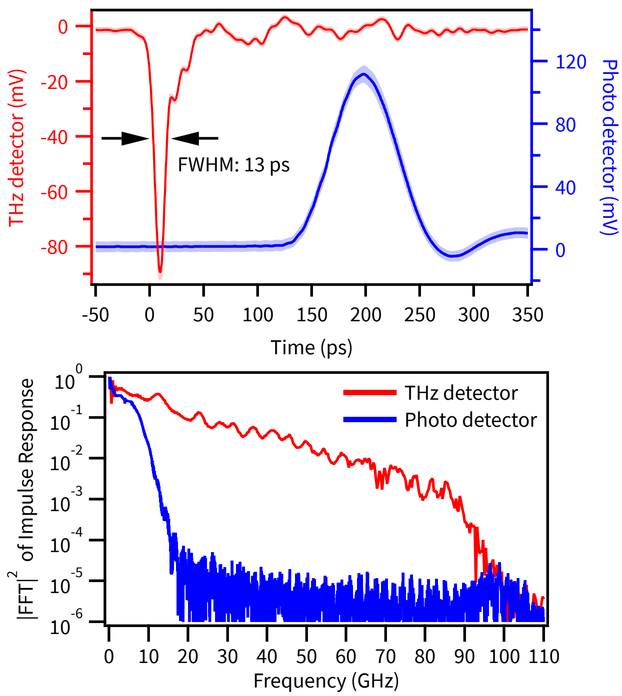

Figure 2: Top: Impulse response of the THz detector (red) and the photo diode detector (blue). The THz detector was probed with a >2 ps short, laser based THz pulse, the photo diode detector with incoherent synchrotron radiation. The solid line denotes the mean and the shaded area the standard deviation of 16 384 single shots. To compensate for timing drifts due to synchrotron oscillation, the photo diode detector signal was aligned at the rising edge at the half maximum, which is why at this reference point no deviation is seen. Bottom: Fourier transform of the impulse response of the THz detector (red) and of the visible photo diode detector (blue). Transmission properties of cable and connectors were not taken into account.

(TDS) system reference measurements of the test pulse and thus could be caused from the generating THz antenna.

Fourier transforms of the impulse responses are shown in Fig. 2 (bottom). The transmission properties of cable and connectors could not be taken into account as we have no means to measure them up to the high frequencies. As a guide, at 40 GHz the cable is specified with an insertion loss of 2.8 dB and the two connectors of 0.3 dB each. A detector response of up to 90 GHz is visible, so that we expect to be able to resolve structures in the time range of above 10 ps.

The used equipment is summarized in Table 1, and the used machine parameters are summarized in Table 2.

MEASUREMENTS

Measurements were performed during short-bunch operation with a momentum compaction factor α_c of 3.2×10^{-4} and a zero-current rms bunch length of below 7 ps. With a bunch current above the threshold, the microbunching instability leads to bunch lengthening and the rise of sub-structures on the blown up bunch profile. Under this condition, the instability with its sawtooth behavior can lead to rms bunch lengths of 10 ps to 20 ps with low picosecond to sub-picosecond short structures on top.

The measured pulse is shown in Fig. 3 for 20 consecutive turns where one turn takes (368.2 ns) at KARA. If the detector and readout device were not able to temporally resolve the CSR pulses, identical shapes with different amplitudes would be expected as we see it with "slow" detectors with response times in the lower GHz range. However, a signal of almost 50 ps full width at half-maximum (FWHM) can be seen with clear substructures. The incoherent photo diode detector signal variations are within the expected range of the standard deviation (cf. Fig. 2). Since the detectors bandwidth was measured to be below 20 GHz, the seen faster oscillations are due to noise.

Table 1: Used Equipment

Oscilloscope	Keysight UXR1004A [2]
THz Detector	VDI WR2.2 WM570R8 [3]
Photo diode detector	Alphalas UPD-35-UVIR-P [4]
Cable	Totoku TCF358 1.2 m [5]
Adapters	SHF KPC185F100M KPC292F185M [6]

Table 2: Machine Conditions

Energy	1.3 GeV
Filling pattern	Single bunch
Bunch current	0.53 mA
Bunch charge	196 pC
Synchrotron frequency	6.9 kHz
Accelerating Voltage	884 kV
Revolution Frequency	2.716 MHz
Zero-current bunch length	6.8 ps
Momentum compaction α_c	3.2×10^{-4}

SUMMARY

During the micro-bunching instability, a lengthened bunch with (sub-)picosecond sub-structures emits coherent THz radiation. In this paper we have shown that the time structure of this radiation can be directly resolved by a fast THz detector and a fast, 100-GHz real-time oscilloscope. In the future, this can be exploited more favorably by dedicated readout electronics, which can be used for live analysis and long-term turn-by-turn diagnostics [7, 8]. In addition, it can be used to verify the far-field electro-optical measurement techniques that we are currently setting up [9].

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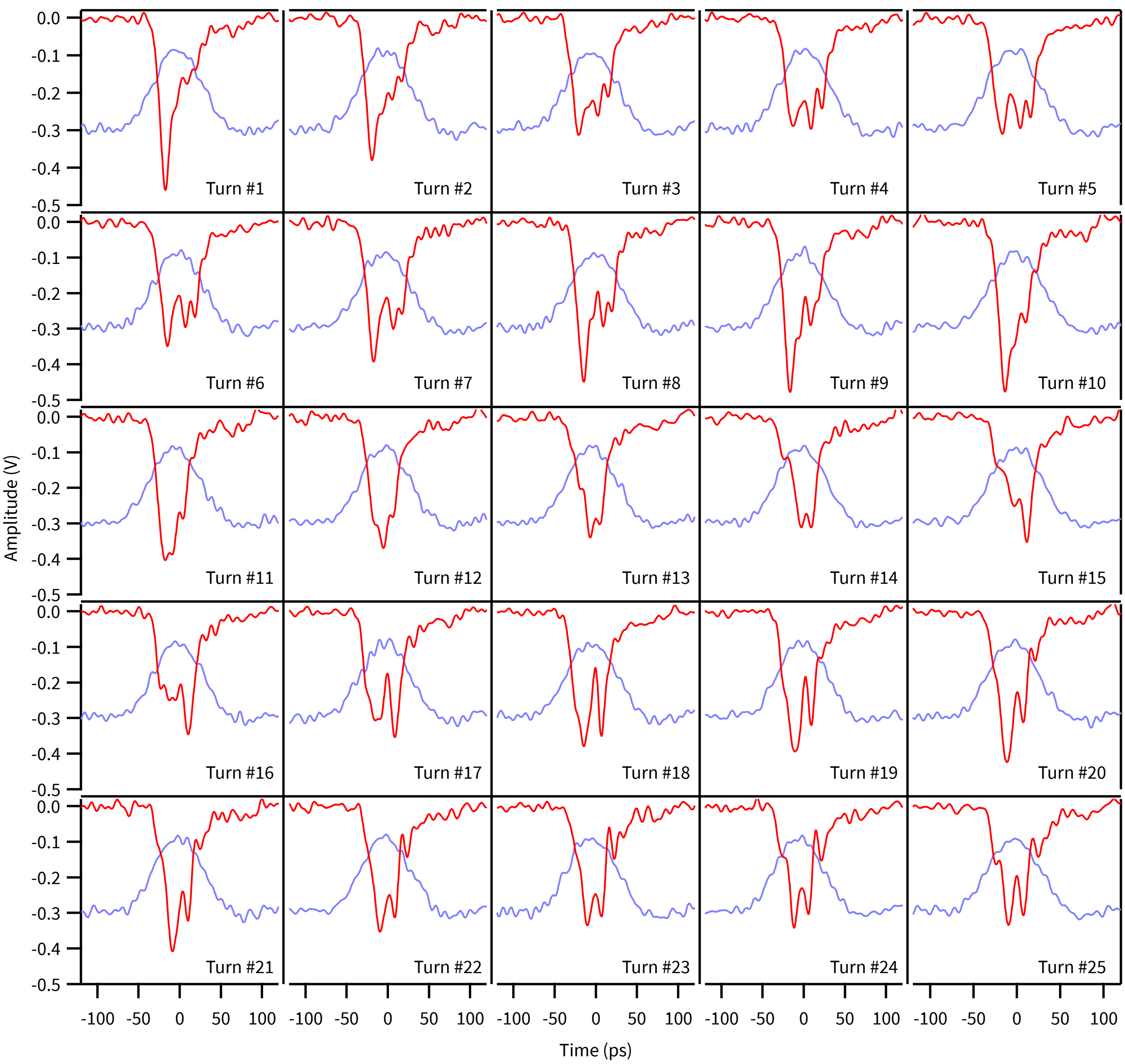

Figure 3: Evolution of the detector signal over 20 consecutive turns (spacing between each turn is 368.2 ns). The Schottky diode signal (in red) corresponds to the measurement of THz coherent synchrotron radiation (CSR). The photo diode detector signal (in blue) reflects the measurement of incoherent visible light at the same time. The photo diode detector data is scaled by a factor of 2 and shifted by −300 mV for better visibility. Note that due to different optical path lengths the synchrotron light hits the photo diode detector slightly earlier than the THz detector.

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