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MEASUREMENTS OF CSR RADIATION AT KARA USING NOVEL THIN-FILM LITHIUM NIOBATE ELECTRO-OPTICAL SENSORS

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Abstract

Electro-optical detection provides a powerful method for characterizing the electric fields of relativistic electron beams and their emitted radiation. We report on the use of novel thin-film lithium niobate electro-optical sensors for the detection of freely propagating terahertz (THz) pulses and, for the first time, measurements of coherent synchrotron radiation (CSR) at the Karlsruhe Research Accelerator (KARA). The thin-film lithium niobate sensors, implemented as integrated Mach–Zehnder interferometers, combine a strong electro-optical response with engineered velocity matching and a compact device geometry, enabling sensitive detection of transient THz fields. Using these Mach–Zehnder interferometer waveguide structures, we demonstrate efficient coupling of CSR to the sensors and present first measurement results.

INTRODUCTION

Electro-optical (EO) detection is a well established tool for measuring pulsed THz electromagnetic radiation e.g. [1–3]. Regarding electron accelerators, EO detection has become an established diagnostic method for probing the longitudinal electric fields, and thus the longitudinal beam profiles, of electron bunches e.g. [4, 5], as well as for measuring the radiation emitted by relativistic electron beams e.g. [6]. In both cases the transient field induces a Pockels effect and thus a change in polarization on a synchronized optical probe laser beam, enabling single shot measurements of the pulse shape [7–9]. Recent studies include tomographic reconstruction of the full phase space distribution of electron bunches [10] and far-field EO detection of emitted radiation [11], underscoring the expanding role of EO techniques in electron accelerators.

While bulk EO crystals have traditionally been employed, integrated photonic sensors can simplify the detection chain, reduce the need for bulky free space optics, and improve system robustness. The EO sensor used for the present measurements consists of a photonic-integrated Mach–Zehnder interferometer with an arm length of 600 µm, fabricated in thin film lithium niobate (TFLN) [12]. The waveguide geometry is engineered for velocity matching between the THz wave and the laser probe. The optical probe beam is coupled to the chip via fibers and grating couplers (included in the packaged sensor), while free space coupling of the THz field enables a compact setup at the beamline. First measurements with high-intensity THz radiation pulses generated by optical rectification of femtosecond laser pulses on an organic crystal have been reported [13].

In this study, we present the first coherent synchrotron radiation (CSR) measurements obtained with the TFLN EO sensor at the Karlsruhe Research Accelerator (KARA). The TFLN EO sensor was positioned at the Infrared2 (IR2) beamline with the CSR radiation focused onto the sensor. A femtosecond probe laser was coupled to the EO sensor, and the CSR induced phase modulation converted into an intensity modulation was recorded. The results demonstrate efficient CSR coupling and sensitivity and validate measurements with the TFLN EO sensor as a diagnostic tool for CSR detection.

EXPERIMENTAL SETUP

The experiment was carried out at KARA operating in short-bunch mode (momentum compaction $\alpha_c = 2.6\times10^{-4}$) with two subsequently injected bunches separated by 2 ns, as required by another experiment conducted at the same time. The revolution frequency was 2.72 MHz and the beam energy 1.3 GeV. Measurements were performed with a total beam current of 0.36 mA, corresponding to a combined charge of 133 pC. The bunch-by-bunch system reported a ratio of 0.53 : 0.47 for the two bunches, which results in ≈71 pC for the first bunch, which was measured by the TFLN EO sensor.

Coherent synchrotron radiation (CSR) at the diagnostic port of the IR2 beamline was focused with a single off-axis parabolic mirror onto the TFLN EO sensor (see Fig. 1). A detailed description of the sensor concept can be found in [12, 13]. The sensor is pumped by a fiber coupled femtosecond laser (90 fs, 1560 nm central wavelength) running at 62.47 MHz and phase locked to KARA's 499.76 MHz master clock, allowing controlled frequency detuning and programmable phase shifts of the laser probe pulses (schematic illustration of the components and synchronization can be found in Fig. 2). Only every 23rd laser pulse is modulated because the laser pulses at a repetition rate of 62.47 MHz sampled the CSR at the much lower revolution frequency of 2.72 MHz. Although the filling pattern included two bunches, the laser pulse spacing of about 16 ns samples only one bunch.

A small aperture in the parabolic mirror diverts a fraction of the beam to an optical photodiode that serves as a timing reference. Measurements of the free space CSR beam, cable lengths, and fiber lengths enabled a rough estimate of the tim-

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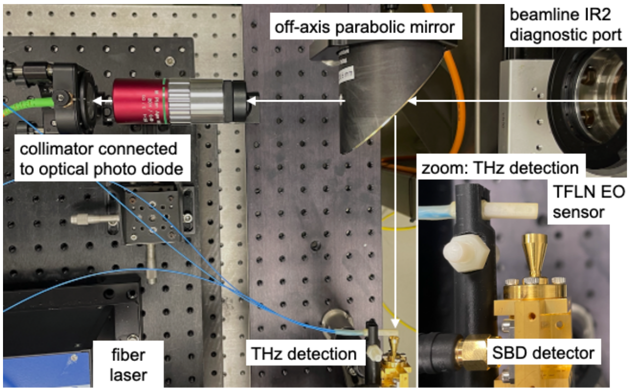

Figure 1: Experimental setup at the IR2 Beamline of KARA: upper right side is the window of the beam diagnostics port, the CSR radiation is focused by an off-axis parabolic mirror onto the THz detection, while a small fraction is delivered through a lens onto a collimator connected to a optical photo diode for timing reference. The THz detection consists of the TFLN EO sensor (packaged in a white cuboid plastic housing with a length of 20 mm) and a SBD detector behind it to enable efficient positioning. The TFLN EO sensor is pumped by a fiber laser with 90 fs pulses and around 1560 nm central wavelength.

ing difference shown on the reference oscilloscope between the photodiode signal and the laser pulses. Additionally, a Schottky Barrier Diode (SBD) detector positioned behind the EO sensor monitors the residual THz radiation, providing a convenient alignment signal. Observing the diode's output on the reference oscilloscope, the sensor position could be optimized without the timing constraints that affect the EO signal. For comparison, details of measurements using an optical diode and an SBD detector can be found in [14].

The two sensor fiber outputs were combined on a balanced photodiode (Thorlabs, PDB450C opterated at transimpedance gain of 10^{-5} V/A with 4 MHz bandwidth) and the differential signal was fed to a lock-in amplifier referenced to the 2.72 MHz revolution frequency and recorded on an oscilloscope.

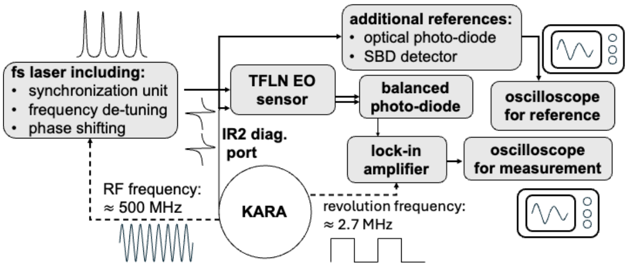

Figure 2: Schematic illustration of the components and synchronization during the measurements.

MEASUREMENT RESULTS

The laser repetition rate was slightly detuned from the RF frequency, thereby creating a constant drift between laser pulse and CSR pulse (ASOPS technique), leading to a 2 ps/s scan rate. The lock-in amplifier operated with a 300 ms time constant and a 30 mV sensitivity.

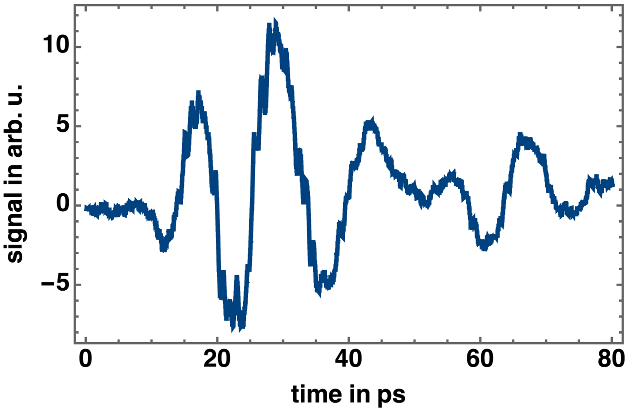

Figure 3: Scan of the CSR signal recorded with the thin-film lithium-niobate (TFLN) sensor at the KARA IR2 beamline (diagnostic port), showing the time-dependent waveform of the CSR field.

Figure 3 shows the EOS scan obtained with the TFLN EO sensor. A separate background run was performed with an iris closed at the exit window of the beamline. The mean of the background data was subtracted from the signal data. The processed trace displays a broad modulation spanning several tens of picoseconds: A modest signal dip, two prominent maxima/minima, followed by smaller fluctuations can be seen. Using the background run to evaluate the standard deviation, the signal-to-noise ratio was calculated as S/N ≈ 27.

Figure 4 displays the Fourier-transformed amplitude spectrum of the EOS scan with the TFLN EO sensor. Because the time domain scan is 80 ps, the spectral resolution is limited to approximately 12.5 GHz. A maximum appears at approximately 90 GHz. Following, the amplitude steadily decreases. The Fourier amplitudes observed for frequencies above 500 GHz are attributed to noise.

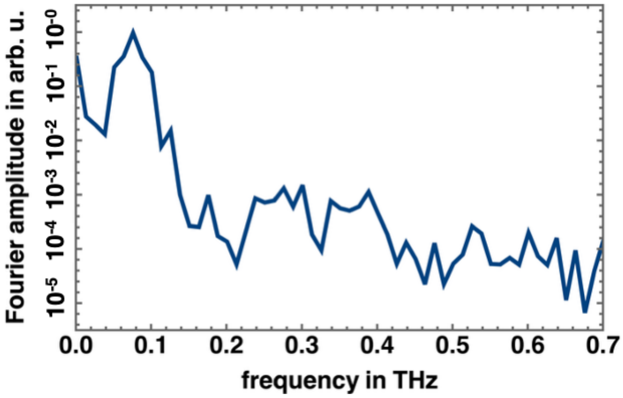

Figure 4: Amplitude spectrum of the CSR signal recorded with the TFLN EO sensor shown in Fig. 3. The 80 ps time window limits the spectral resolution to approximately 12.5 GHz.

CONCLUSION AND OUTLOOK

The present work shows that a compact, fiber-coupled TFLN EO sensor can successfully record CSR emitted by KARA, providing a new diagnostic tool. The measured spectrum displays a dominant peak just below 100 GHz, which is reasonable due to the CSR spectrum in the short bunch mode at KARA [15]. Nevertheless, a much wider CSR spectrum is expected, but remains hidden by the limited SNR. Previous experiments with table-top sources suggest a higher sensitivity, suggesting possible improvements of the setup at the beamline. For example, improvement of the optics to focus the CSR to the TFLN EO sensor is expected to increase the SNR.

Another improvement can be forseen by matching the repetition rate of the femtosecond laser to the 2.72 MHz to fit the revolution frequency (instead of the present 62.47 MHz repetition) so that every laser pulse samples a modulated CSR burst, eliminating the 23-fold laser pulses. In this context, evaluating the handling of the signal without the need of a lock-in amplifier is an option.

With improved SNR, the potential to employ chirped pulses and to go towards single-shot detection can be investigated. These upgrades would allow us to resolve fast CSR dynamics, study micro-bunching instabilities in real time, and provide a versatile diagnostic tool.

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