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FIRST MEASUREMENTS OF THE TRANSIENT ELECTRICAL NEAR-FIELD OF ELECTRON BUNCHES IN THE FLUTE IN-AIR SECTION

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Abstract

The Ferninfrarot Linac- und Test-Experiment (FLUTE) at the Karlsruhe Institute of Technology (KIT) is a compact linac test facility providing sub-picosecond to femtosecond short electron bunches with energies up to several tens of MeV. The transient electric near-field of such bunches is relevant for understanding coherent THz emission and for developing compact field-sensitive beam diagnostics. Here, we present first electro-optical measurements of bunch-induced near-field signals in the FLUTE in-air section using a photonic-integrated Mach-Zehnder-interferometer sensor placed close to the beam axis. The measured delay-dependent response shows features consistent with electro-optical detection of the transient electric near field of the bunch. Our results establish a basis for future spatially resolved measurements with varying accelerator parameters.

INTRODUCTION

The FLUTE compact linac test facility at KIT provides access to short relativistic electron bunches and to their strong transient electric fields. In particular, the generation of intense THz radiation at FLUTE is closely linked to the temporal and spatial structure of the bunch-induced near field, making field-sensitive diagnostics relevant both for accelerator development and for beam studies.

Electro-optical (EO) sampling is a well-established method for time-resolved measurements of electric fields in the THz frequency band and has been applied to the diagnostics of relativistic electron bunches previously. For example, single-shot EO techniques have enabled sub-picosecond measurements of electron-bunch lengths by encoding the longitudinal bunch profile onto synchronized optical probe pulses [1]. More recently, near-field EO spectral decoding has also been used for high-throughput measurements of individual longitudinal bunch profiles in a storage ring environment at the Karlsruhe Research Accelerator (KARA) [2].

In conventional EO and THz measurements, the field is often sampled at a fixed position while the temporal waveform is reconstructed from the probe delay. Recent EO sampling experiments have demonstrated access to spatiotemporal electric-field profiles around relativistic electron beams [3]. The FLUTE in-air section [4] provides access to the region outside the vacuum tube where the bunch-induced field evolves in space and time after the bunch exits into the air.

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This makes the setup attractive not only for temporal sampling, but also for future spatially resolved studies of the transient near field.

At the same time, measurements close to the beam axis place strong constraints on detector size, access, and alignment. Conventional EO arrangements based on free-space optics can be comparatively bulky for such a geometry and are not always ideal for fast exploratory scans. A promising alternative is provided by compact photonic-integrated EO sensors based on thin-film lithium niobate. In particular, Mach–Zehnder interferometer (MZI) sensors with oppositely poled lithium-niobate waveguide arms have recently been demonstrated for time-domain detection of freely propagating THz fields [5, 6] and later used at KIT for measurements of coherent synchrotron radiation of electron bunches at KARA [7]. Here, the present work investigates a first application of such an integrated EO sensor to bunch-induced electric near field signals in the FLUTE in-air section.

In the following, we provide a brief overview of the general experimental setup, document the realized geometry, experimental parameters, and provide qualitative simulation results to visualize the expected evolution of the transient electrical fields in the in air-section. We then define the extraction metrics used for evaluation and show the resulting THz time-domain traces. We argue that these first results are consistent with near-field-sensitive detection of the electron bunch while detailed interpretations related to precise timing reconstruction remain part of an ongoing analysis.

EXPERIMENTAL SETUP

During the experiments, electron bunches with an energy of 30 MeV and a charge of (273 ± 5) pC were generated at a repetition rate of 10 Hz. Details about the FLUTE accelerator can be found elsewhere [8, 9].

In brief, FLUTE comprises an RF photoinjector, a traveling-wave linac, a magnetic bunch compressor, and finally the in-air experiment section. Electron bunches are generated by illuminating a copper photocathode with ultraviolet pulses derived from a Ti:sapphire laser system via third-harmonic generation. The bunches are then further accelerated to their final energy in a 3 GHz traveling-wave linac and subsequently transported through a four-dipole magnetic chicane for optional longitudinal bunch compression. During the experiments, the beam exited the vacuum system through a thin metal foil into an in-air section at the end of the beamline.

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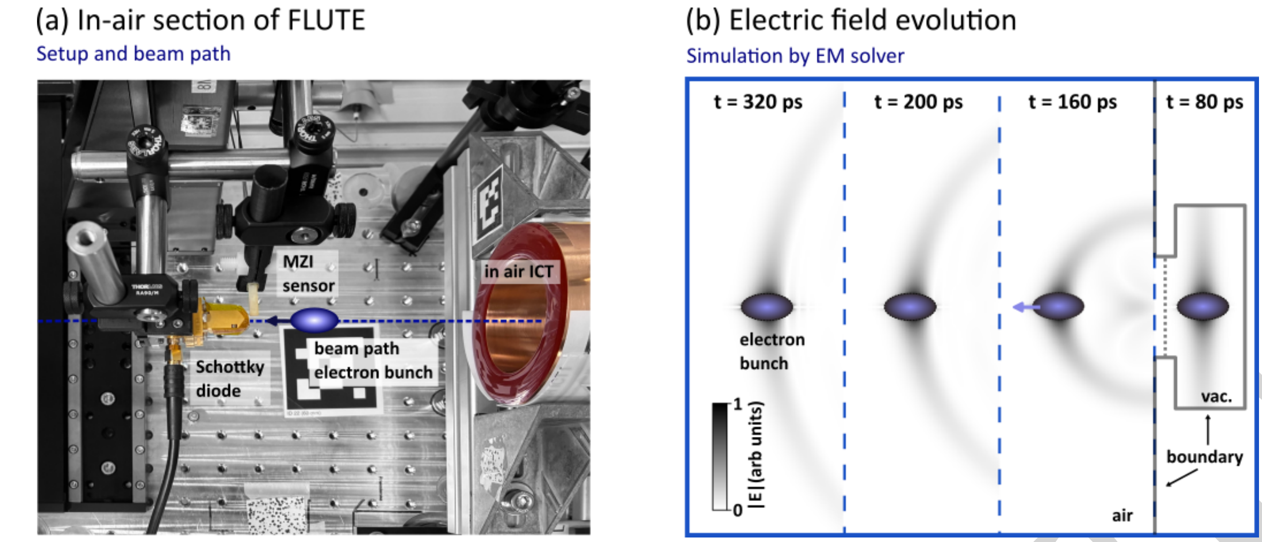

Figure 1: (a) Photo of the experimental setup and beam path in the FLUTE in-air section. The Schottky barrier diode is visible as the gold-colored detector, while the MZI EO sensor is enclosed in the white housing mounted perpendicular to the diode. During the measurements, the electron bunch propagated below the detectors towards the beam dump at the end of the in-air section. (b) Qualitative CST simulation of the transient electric-field evolution near the vacuum-to-air transition in the FLUTE in-air section (see also [3]). The gray outline indicates boundaries of the simplified cylindrical model.

Figure 1(a) shows a top-view photograph of the beam path in the FLUTE in-air section. For the near-field measurements, a Schottky barrier diode detector sensitive in the 500 GHz to 750 GHz frequency range and the integrated EO sensor were mounted on a movable x-y translation stage, while the electron bunch propagated along the z-direction. For both detectors, the orientation with respect to the polarization of the transient electric near-field is relevant. In the configuration used here, the integrated sensor was primarily sensitive to the electric-field component perpendicular to the optical table, with the electron bunch passing below the mounted sensor.

For time-resolved measurements on the picosecond scale, the integrated sensor was operated with a pulsed probe laser at a wavelength of 1560 nm. The laser repetition rate was 62.5 MHz and was synchronized with a reference repetition rate close to 500 MHz derived from the accelerator's master clock. The fiber-coupled pulse train was guided to the integrated sensor, where the optical probe pulses overlapped with the bunch-induced transient near field in a MZI [5]. Through the Pockels effect, the transient electric field modulates the optical phase in the interferometer, which is converted into a signal with an amplified balanced photodetector (PDB450C, Thorlabs) operated at a transimpedance gain of 1×10^7 V A^{-1} with a nominal bandwidth of 0.1 MHz. Finally, we digitized the signal with a 2 GHz oscilloscope (MXO54C, Rohde&Schwarz) which was synchronously triggered to the 10 Hz bunch generation.

EVALUATION AND FIRST RESULTS

To obtain a qualitative picture of the field evolution in the FLUTE in-air section, we performed a coarse-grained transient electromagnetic simulation in CST Studio Suite [10] using a simplified geometry of two cylindrical volumes representing the beam-pipe / vacuum section and the in-air section, connected by a small aperture. The maximum simulation frequency was set to 100 GHz.

As shown in Fig. 1(b), the bunch field is compressed perpendicular to its motion in a pancake like structure before the transition and evolves into an expanding curved wavefront after entering the in-air section. This curvature may be relevant for spatially resolved EO measurements, since different transverse positions can correspond to different local arrival times of the transient field. Because of the strongly simplified geometry and the artificial boundary conditions imposed by the outer cylinder, the simulation is used here only as a qualitative illustration of a potentially measurable effect.

Figure 2(a) shows representative oscilloscope traces of the balanced detector signal recorded with the photonic-integrated MZI sensor for two different probe-pulse delays. Each trace is obtained by averaging 10 oscilloscope acquisitions, corresponding to a total acquisition time of 1 s at the 10 Hz bunch repetition rate. The residual sinusoidal modulation is attributed to incomplete cancellation in the balanced detection scheme and follows the 62.5 MHz repetition rate of the probe laser, corresponding to a period of 16 ns. For a delay setting close to the maximum response, the balanced detector signal exhibits a step-like change followed by a slower relaxation. The blue trace represents a reference timing away from the main response, whereas the orange trace corresponds to the delay setting with the largest extracted signal amplitude in this scan.

The detailed origin of the observed response function, including possible contributions from the EO sensor, the readout electronics, and electromagnetic reflections, is still under investigation. For the present preliminary analysis, we define a relative EO signal amplitude for each delay set-

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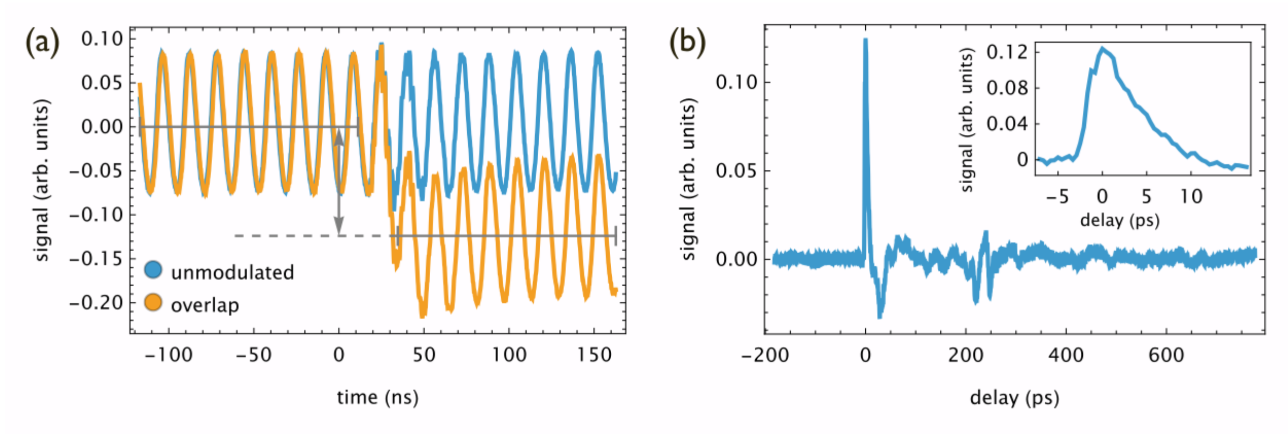

Figure 2: (a) Oscilloscope traces of the balanced photo-diode signal recorded for two different timing conditions of the EO probe pulse. The periodic modulation originates from the residual imbalance of the balanced detection and follows the 62.5 MHz probe-laser repetition rate. The beam-induced signal is quantified by the difference between the mean signal levels before and after the observed step-like change, as indicated by the arrow. The blue trace shows a reference timing without temporal overlap, while the orange trace corresponds to a delay setting near the maximum beam-induced response. (b) Delay-dependent EO signal amplitude obtained from the extraction procedure shown in (a). The pronounced peak (see inset) at a delay $t_0 = 0$, the baseline at negative delays and the residual modulations at positive delays support the interpretation of a beam-induced EO signal.

ting as the difference between the mean balanced-detector signal levels in two fixed oscilloscope-time windows before and after the step-like response, as indicated by the arrow in Fig. 2(a). These windows were chosen to cover approximately integer multiples of the 16 ns period of the residual oscillatory baseline, thus reducing its influence on the extracted amplitude. It should be noted that the delay scan changes the relative phase between the probe-pulse train and the bunch-induced field on the ps scale, whereas the oscilloscope traces are evaluated on the ns scale. Because the 62.5 MHz probe-pulse train is periodic, the sampling condition maps onto itself after one 16 ns period. Consequently, the fixed-window extraction may still contain a weak envelope imposed by the residual comb structure, the sensor response, or slower relaxation processes in the detection chain.

Applying this extraction procedure while scanning the relative delay between the probe pulse and the electron bunch yields the delay-dependent EO signal amplitude shown in Fig. 2(b). The delay axis was shifted so that the maximum signal amplitude occurs at $t_0 = 0$. At negative delays, the extracted signal remains close to a baseline, consistent with the situation before the arrival of the bunch-induced transient field at the sensor position. At t_0 a pronounced peak is observed (see inset). The apparent temporal width of this peak is on the order of the expected bunch duration for the machine settings during the experiment. Together with the baseline before the peak and the residual modulations at positive delays, this provides strong evidence for the detection of the transient electric near-field of the electron bunch.

SUMMARY

We demonstrated first near-field-sensitive EO measurements of electron-bunch-induced transient signals in the FLUTE in-air section using a photonic-integrated MZI sensor. The observed response provides strong evidence for the EO detection of the transient electric near-field of the electron bunch. At the present stage, the extracted signal is interpreted as a relative EO signal amplitude that is expected to scale with the electric field, while details of the absolute timing, sensor response, and field waveform remain part of the ongoing analysis.

A simplified CST simulation was used to qualitatively visualize the electric-field evolution near the transition from the vacuum section into the in-air section, indicating a curved wavefront in the sensor region.

Further measurements with extended spatial sampling and different accelerator parameters, such as bunch charge and bunch length, are being investigated to clarify the observed response function. In addition, the frequency-dependent response of the balanced photodetector chain, in particular with respect to residual signals at the 62.5 MHz probe-laser repetition rate despite the nominal low-bandwidth setting, remains to be characterized in detail. Such studies, together with comparisons to complementary diagnostics such as Schottky barrier diode measurements and refined electromagnetic simulations, may provide a better understanding of both the integrated sensor response and the transient fields generated by the relativistic electron bunches.

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