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FIBRE-COUPLED OSCILLATOR-DRIVEN ELECTRO-OPTIC SPECTRAL INTERFEROMETRY AS A LONGITUDINAL BUNCH PROFILE MONITOR

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Abstract

Electro-optic (EO) diagnostics offer non-destructive methods to resolve the longitudinal charge profile of highly relativistic bunches without the need for complex calibrations or ambiguous phase recovery techniques. The most common technique, EO spectral decoding (EOSD), is favoured for its simplicity, reliability, and straightforward output interpretation, however its resolution is constrained to the geometric mean of the transform-limited and chirped probe laser durations. We have introduced a new technique utilising spectral interferometry (EOSI), which overcomes this limitation by adding a single optical element to an EOSD setup, with successful measurements shown previously on the CLARA accelerator at Daresbury Laboratory. To further explore this technique, we have performed EOSI on the CLEAR accelerator at CERN (160 MeV, 40-70 pC and 0.7-3.5 ps FWHM) utilising a 3 nJ oscillator and optical fibre-coupled transport. Our results highlight the potential for low power, turn-key operation and flexible integration of EOSI systems for single-shot ultrashort bunch length and arrival time monitoring, with the laser and spectral characterisation occurring away from the accelerator.

INTRODUCTION

With improvements in RF technology, as well as potential novel terahertz (THz) or plasma-based acceleration mechanisms, particle bunches have the potential to be compressed to the 10 fs regime [1–3]. To complement these advances, more precise longitudinal beam diagnostics are required.

Electro-optical (EO) methods detect the Coulomb field of electron bunches, offering direct and non-destructive measurements of the profile of each bunch. A common method is Electro-Optic Spectral Decoding (EOSD) [4, 5], where a chirped laser pulse samples the field and reconstruction is achieved using time-wavelength mapping. This offers some substantial benefits - most notably for its simplicity in implementation and interpretation - but it has a temporal resolution limit of

$$T_{\text{min}} \approx \sqrt{T_{\text{trans-limited}} \cdot T_{\text{chirped}}}, \tag{1}$$

where $T_{\text{trans-limited}}$ and T_{chirped} are the transform limited and stretched probe laser widths [4]. This leads to a trade off between the sampling window size and the achievable resolution.

Several methods exist that overcome this resolution limitation, but they often require high laser power due to various non-linear processes (*e.g.* temporal encoding [6] or spectral upconversion [7]) or face additional limitations such as in their geometry (*e.g.* spatial encoding [8]). A recent approach has utilised phase diversity to overcome this limit, and is being actively developed [9]. We investigated an alternative technique: Electro-Optic Spectral Interferometry (EOSI) [10]. This adds only one optic to an existing EOSD setup to overcome the limits, with previous work at the CLARA accelerator at Daresbury laboratory measuring bunches as short as 190 fs RMS and showing potential to measure shorter. Here we show that this performance is sustained whilst using a low energy oscillator (3 nJ) with transport to the accelerator hall through long (~ 70 m) optical fibres, therefore demonstrating the ease of implementation and robustness of this diagnostic tool.

ELECTRO-OPTIC SPECTRAL INTERFEROMETRY

In all these methods, a laser probe pulse is passed through a zincblende crystal simultaneous to the electric field that is to be detected. Most of the probe passes through unchanged, but a small modulation is created with a polarisation orthogonal to the probe and with a magnitude [11]

$$E_{\text{mod}}(t) = B\frac{d}{dt}\left[E^{\text{eff}}_{\text{clmb}}(t)E_{\text{probe}}(t)\right], \tag{2}$$

where B is a constant accounting for crystal thickness and absorption, and $E^{\text{eff}}_{\text{clmb}}$ is the effective Coulomb field after accounting for the second-order non-linear susceptibility and phase-matching effects. This modulation has the same frequency as the probe, but the temporal envelope is now the same as the Coulomb field and therefore also proportional to the longitudinal charge density profile of the electron bunch.

EOSI measures this modulation by applying a small time delay between the modulation and the probe (in this setup $\tau \sim 1$ ps) using a birefringent crystal, before combining the two pulses with a polariser to create interference in the measured spectrum

$$S_{\text{SI}}(\omega) = S_{\text{probe}}(\omega) + S_{\text{mod}}(\omega) + 2\sqrt{S_{\text{probe}}(\omega)}\sqrt{S_{\text{mod}}(\omega)} \times \cos(\phi_{\text{mod}}(\omega) - \phi_{\text{probe}}(\omega) + \omega\tau), \tag{3}$$

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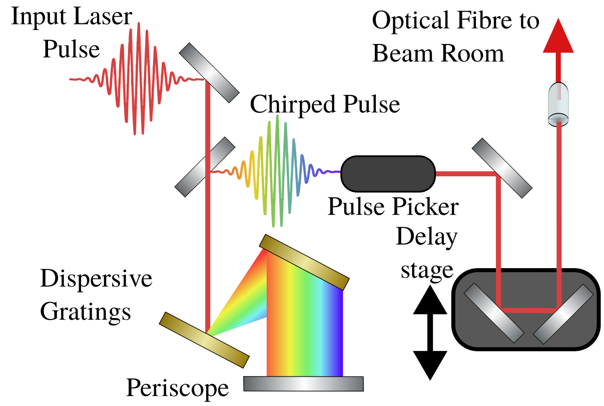
which is in essence a common-path Mach-Zehnder interferometer [12]. The phase difference can be determined from the spectrum through simple Fourier analysis, and can be compared to the known phase of the probe to obtain the phase information of the modulation. Similar analysis can obtain the amplitude of the modulation and so the Coulomb field can be reconstructed.

This method allows for highly sensitive measurements of the modulation amplitude due to operating close to the "crossed polariser" setup [13], and of the phase due to the inherent nature of interferometry. It also eliminates most issues caused by the sensitivity of Mach-Zehnder interferometers to the surrounding environment by using a common path for the two beams. This arrangement does require, however, that the probe field is largely unchanged by the EO interaction, but sum- and difference-frequency generation processes will extract energy from the probe. This effect can be made sufficiently small by optimising EO crystal length and choice of EO material.

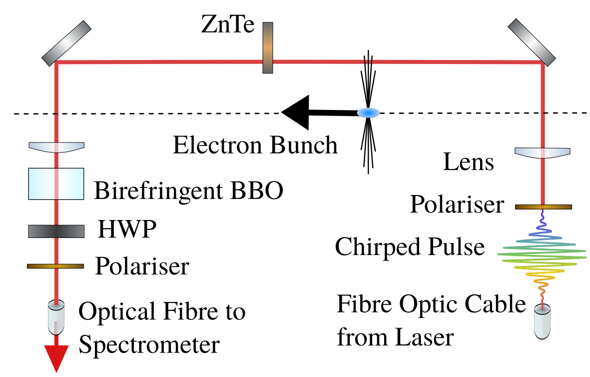
EXPERIMENTAL SETUP

This experiment was performed at the in-air test stand at the CLEAR facility at CERN; the layout used is shown in Fig. 1. The laser pulse was generated by an Erbium fibre laser (Toptica Photonics FemtoFibre, 37.5 MHz, 2.9 nJ, 100 fs, 780 nm) and then negatively chirped using a double pass through a pair of 1600 lines/mm gratings to compensate for the positive GDD accumulated through the ~70 m optical fibres used for transport. A pulse picker - formed of a Pockels cell and a polariser orthogonal to the incoming laser pulse - reduced the laser pulse rate to match the accelerator by both utilising the same trigger. Synchronisation between the laser and electron beam (160 MeV, 40-70 pC and 0.7-3.5 ps FWHM, 5 Hz) was achieved using a PID circuit comparing a 75 MHz sub-harmonic of the accelerator RF to the laser output, as measured with an internal photodiode. Precise timing overlap between the bunch and the laser was achieved using an OTR screen in the path of the laser/electron beam with the light focussed onto a fast photodiode, and adjusting the phase of the accelerator RF. This was fine tuned using the delay stage in a scan using EOSD/EOSI.

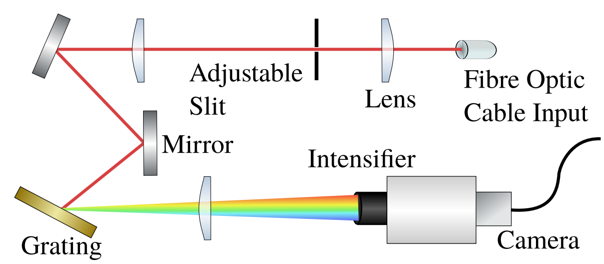
The laser pulse was transported to the accelerator hall through single-mode, polarisation maintaining fibres, where the pulse then passed through a Glan-Taylor polariser to ensure the laser pulse was horizontally polarised. Dispersion in the fibres compressed the pulse to a negatively chirped 6 ps FWHM. A co-propagating geometry with a 2 mm thick ZnTe crystal (the EO crystal) was used, situated 2 mm away from the electron beam (1 mm RMS transverse width). The first mirror was positioned 40 cm upstream to reduce the effects of Coulomb shadowing [14]. A 2.5 mm thick Barium Borate (α-BBO) crystal was placed in the laser beam path when operating as EOSI, with an optical axis precisely aligned to the polarisation of the probe, and this was removed from the setup when operating as EOSD. A half-wave plate was



(a) Initial pulse preparation



(b) Setup in accelerator hall



(c) Spectrometer

Figure 1: Experimental Schematic. Each section was connected to the next using an optical fibre with standard collimators/couplers in and out of the fibres not shown in the diagram.

positioned prior to the polariser to maintain coupling into the fibre.

The spectrum was analysed with a spectrometer using a gated and intensified camera to measure the weak signal, whilst also eliminating any light that leaked through the pulse picker.

RESULTS AND DISCUSSION

Initial bunch length measurements were performed using the EOSD setup (*i.e.* without the BBO crystal). The bunches provided were measured to be about 0.7 ps FWHM using an RF deflecting cavity with 40 pC of charge and an energy of 170 MeV. Figure 2 shows an example of the traces taken.

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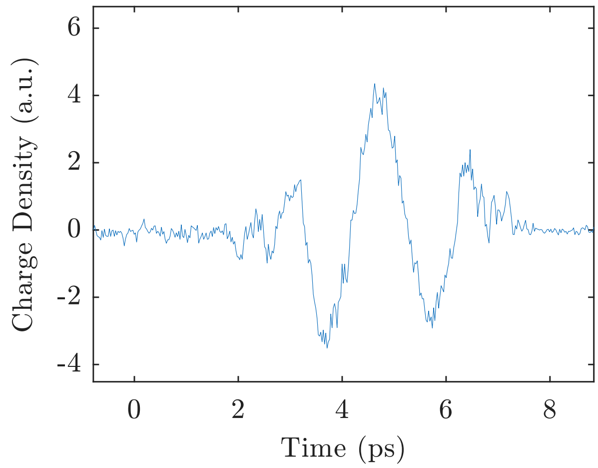

Figure 2: An EOSD trace taken of a 0.7 ps FWHM bunch.

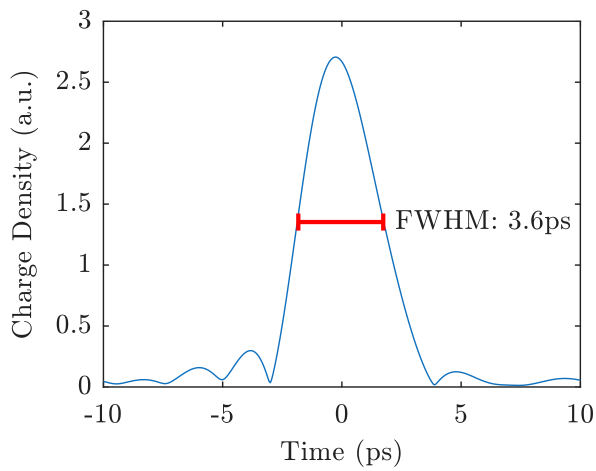

Figure 3: Bunch profile calculated from EOSI.

Several scans were taken with varying angles of the half-wave plate to maximise the sensitivity of the signal and therefore the signal-to-noise ratio (SNR).

These traces have substantial fringes and appear to be measuring negative charge densities. This is due to the fact that the bunches being measured are shorter than the resolution limit of EOSD (~ 800 fs from Eq. (1)) with the current length of chirped laser pulse. The short Coulomb field generates a wider bandwidth modulation pulse which interferes with the probe upon recombination at the half-wave plate and thereby violates the requirements for wavelength-time mapping.

To overcome this issue, the frequency spectrum of the modulated pulse was measured by adding only the BBO crystal to the setup (EOSI). A reconstruction of the bunch profile is shown in Fig. 3 with beam parameters of 3 ps (measured with the RF cavity), 160 MeV, and 70 pC.

Whilst we were unable to reproduce the short bunches used for the EOSD scans, EOSI has previously been shown capable of measuring ultrashort bunches [10]. Here we have shown its potential to be used practically as a diagnostic tool

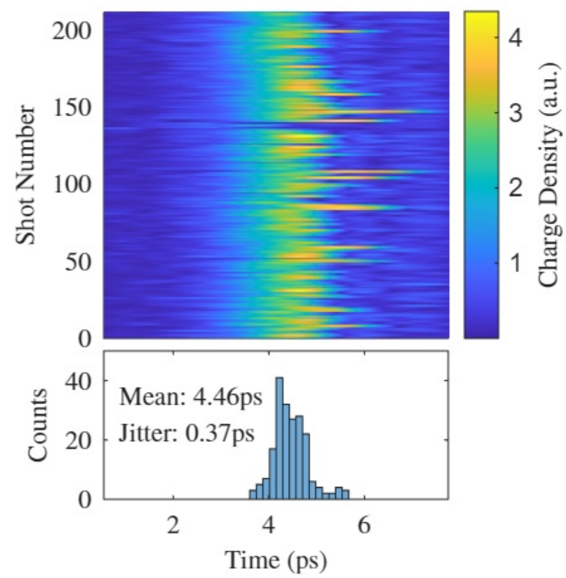

Figure 4: Bunch profile over time. Histogram is of the peak positions for the shots showing arrival time and corresponding jitter.

on accelerators that use ultrashort bunches - *e.g.* the injector beam at AWAKE [15].

Due to the single shot nature of these bunch measurements, they also offer insight into drift and jitter, for both the arrival time and the bunch profile. A scan of over 200 shots is shown in Fig. 4, and the arrival time jitter (determined by the position of the maximum charge density) is shown in a histogram below. Some jitter was also seen in the bunch width, likely because the bunches were compressed by moving off the crest of the accelerating field. Any jitter in time relative to the RF would also affect the bunch length.

CONCLUSIONS AND OUTLOOK

Electro-Optic Spectral Interferometry was demonstrated as a practical diagnostic tool for use directly measuring the longitudinal bunch profile of individual ultrashort electron bunches and their corresponding jitter. This was shown using a low energy oscillator with optical fibres transporting the beam, making a versatile monitor capable of being implemented on accelerators with limited space and without the need for permanent and cumbersome optical transfer lines.

We are developing an in-vacuum, turn-key EOSI instrument, with first applications planned at AWAKE and CLARA [15, 16].

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