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DEMONSTRATION OF AN ELECTRO-OPTIC SPECTRAL INTERFEROMETRY LONGITUDINAL PROFILE MONITOR AT CLARA

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Abstract

Electro-optic (EO) diagnostics are able to non-destructively resolve the longitudinal charge profile of highly relativistic bunches without complicated calibrations and ambiguous phase recovery techniques. The most implemented technique is EO spectral decoding as it is simple and reliable, and has an easy to interpret output. However, its resolution is limited, however, to the geometric mean of the transform limited and stretched probe laser durations. Until very recently, efforts to improve on this have resulted in designs that lose the attractive properties of spectral decoding. On the CLARA accelerator at Daresbury Laboratory we have demonstrated a new EO system that exploits common-path spectral interferometry, "EOSI", which removes the geometric mean limitation. The system was used to measure 35 MeV/c bunches ranging from 150 pC down to 2 pC, and at a range of compressions from several ps to ~300 fs RMS. We will explain the technique, describe the measurements, and outline issues and improvements. The technique differs from a spectral decoding system by only a single optical element, potentially allowing current EO systems to be upgraded.

INTRODUCTION

The Coulomb field of highly relativistic electron bunches closely resembles the longitudinal charge distribution. This field is similar to that of a THz-frequency electromagnetic wave (except it includes components down to DC), so many methods originating in the measurement of THz pulses have been adapted for its measurement. The commonly used temporal scanning methods do not translate well to particle accelerator requirements, where the jitter from shot to shot, both in arrival time and in profile, can be significant. To combat this a number of methods to encode the Coulomb field into a single laser pulse have been demonstrated. Perhaps the most popular technique is spectral decoding [1–3], where a chirped laser pulse is used to sample the field, and time to wavelength mapping of the chirped pulse allows a simple readout via an optical spectrometer. This method is considered nondestructive, simple and robust to implement, and straightforward to interpret, but has a well known limitation that the achievable resolution T_{min} is proportional to:

$$T_{\mathrm{min}} \approx \sqrt{T_{\text{trans-limited}} * T_{\text{chirped}}}$$

where $T_{\text{trans-limited}}$ and T_{chirped} are the transform limited and stretched probe laser widths [2]. This leads to a trade off between sampling window size and resolution for most practically accessible laser pulses.

The underlying principle of EO sampling is that the laser and Coulomb fields are multiplied together via the EO materials nonlinear polarisation response [4, 5], producing a new pulse in which the Coulomb field is encoded in the temporal envelope. When the instantaneous bandwidth of the Coulomb field is much less than that of the probe, the new pulse can interfere with the probe locally in time and be considered a phase (refractive index) change and can be recovered directly in a spectrum. When the rapidity of the changes in the Coulomb field causes the generation of frequencies outside those present co-temporally in the probe, a distortion of the recovered profile results.

Spatial [6] and Temporal [7] encoding methods that bypass the resolution limiting spectral decoding have been demonstrated, but rely on cascaded nonlinear processes making their laser and field strength requirements impractical (temporal decoding), or introduce other ambiguities/limitations due to the sampling geometry (spatial decoding). Recently a technique that overcomes the spectral limitation has been reported [8] that implements a phase diversity approach by combining ideas from photonic time stretch methods and RF communication theory. This method improves the potential resolution to effectively the compressed probe duration (with EO material bandwidths being the limit in practice), but to do so requires capturing two interaction spectra simultaneously, and also operates in a so-called "balanced detection" regime that is inherently less sensitive than operation using a "near extinction" regime [9, 10]. Here we present the application of spectral interferometry in an electro-optic profile monitor, this overcomes the resolution problem using a single spectrometer in a near-extinction geometry. It was implemented on the CLARA accelerator as part of a machine exploitation run in April 2022.

ELECTRO-OPTIC SPECTRAL INTERFEROMETRY

In the spectral interferometry technique "unknown" and "reference" pulses are combined with a known time delay between them. When measured in a spectrometer there is interference between the two pulse spectra described by:

$$S_{\mathrm{SI}}(\omega) = S_{\mathrm{ref}}(\omega) + S_{\mathrm{unk}}(\omega) + \ldots$$
$$2\sqrt{S_{\mathrm{ref}}(\omega)}\sqrt{S_{\mathrm{unk}}(\omega)} \times \cos(\phi_{\mathrm{unk}}(\omega) - \phi_{\mathrm{ref}}(\omega) + \omega_0\tau)$$

from which the relative phase between the pulses can be calculated via Fourier analysis [11]. This measurement can

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be combined with the known phase of the reference pulse to calculate that of the unknown pulse. Similarly the spectral amplitude can be recovered, giving full knowledge of the temporal profile. As this method is based on interference it can readily detect small signals, but is very sensitive to environmental conditions. It is crucial to arrange both beams to be perfectly collinear and mode-matched. This is very difficult to achieve stably in an accelerator hall. In this work we implement a common-path geometry, where the reference and unknown beams co-propagate along the exact same optical path but with orthogonal polarisation states. This particular arrangement has been proposed in the literature [12], but to the author's knowledge has not been demonstrated until now. This arrangement requires that the probe field is 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, choice of EO material (size of nonlinear coefficient), and increasing the distance to the sampling point to match the particle beam's properties. In this work the probe intensity modulation was kept to <1% to satisfy the approximation.

EXPERIMENTAL SETUP

The layout is shown schematically in Fig. 1. The probe is derived from a regeneratively amplifed Ti:sapphire laser (few µJ, 800 nm, 50 fs) that is synchronised with the (35 MeV/c, 1-150 pC, 10 Hz) electron beam [13]. It was chirped to an experimentally verified 8.1 ps by detuning the laser compressor. An adjustable telescope was used to focus the probe to a few 10s μm on the 0.5 mm thick GaP crystal (EO) to allow the probe to be positioned close to the electron beam. A retro-reflection geometry was used to avoid shadowing the Coulomb field. After the EO interaction in the crystal a new pulse with a fraction of a percent of the probe's intensity was created with an orthogonal polarisation, which co-propogated back with the probe. A quarter-wave plate ($\lambda/4$) was used to compensate for residual birefringence in the EO crystal, followed by a calcite birefringent plate (BRP) which added the required delay between polarisation states. A polariser (POL) was then used to extinguish the probe intensity to a level similar to that of the optically encoded pulse to maximise fringe visibility on a spectrometer (Spec). The SI algorithm is then applied to recover the temporal envelope of the pulse, and thereby the Coulomb field profile. Finding initial overlap between the laser and electron beams was aided by a spare beam pick-up installed near the interaction point, and a fast optical photodiode sampling the probe laser prior to entering the vacuum chamber. The laser was locked to the CLARA RF frequency using a commercial system (Synchrolock, Coherent) and fine scanning was achieved via an optical delay stage. Using GaP with an 800 nm probe limited the spectral response of the system due to poor phase-matching. ZnTe was originally specified, but the low optical quality of the crystals available (inhomogeneous birefringence and scattering from bubbles) made operating in a retro-reflection geometry and at near extinction of the probe made setting the system up very difficult. The quality of all available GaP crystals was much higher, and with the correct wavelength probe would actually provide a wider bandwidth than ZnTe. The system could be switched back to spectral decoding by removing the birefringent plate, and re-optimising the quarter-wave plate

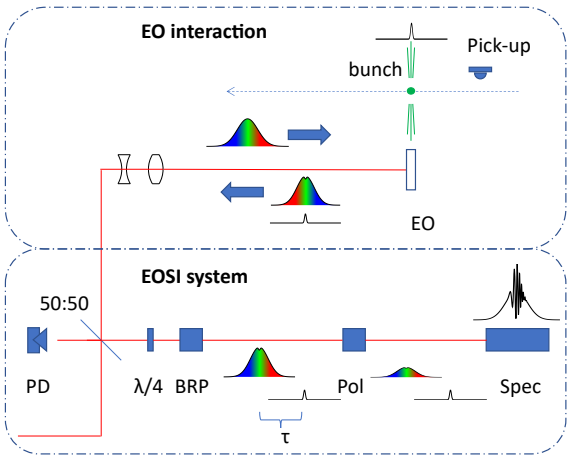

Figure 1: Experiment schematic.

RESULTS AND DISCUSSION

An example of a recovered temporal profile is shown in blue in Fig. 2.

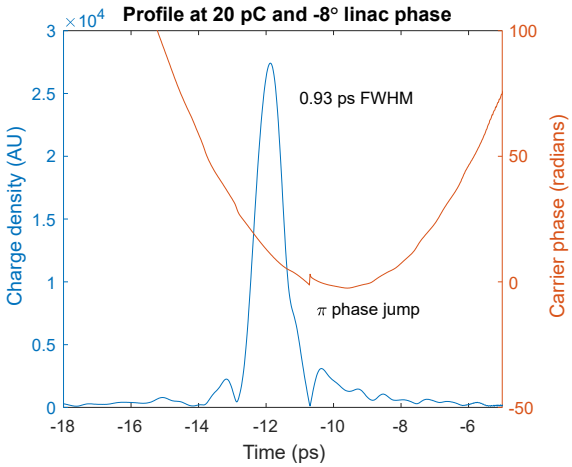

Figure 2: Example of a retrieved profile. the phase jumps indicate a sign flip in the profile.

The red curve shows the underlying phase of the optical carrier wave. The π phase jumps are equivalent to the envelope changing sign. This trace was observable live in the control room as the processing consists of a series of FFTs and matrix manipulations that are trivial on modern computing hardware.

A series of experiments were performed to verify that the EOSI method was recovering traces accurately. An example is shown in Fig. 3, where the bunch profile was measured at

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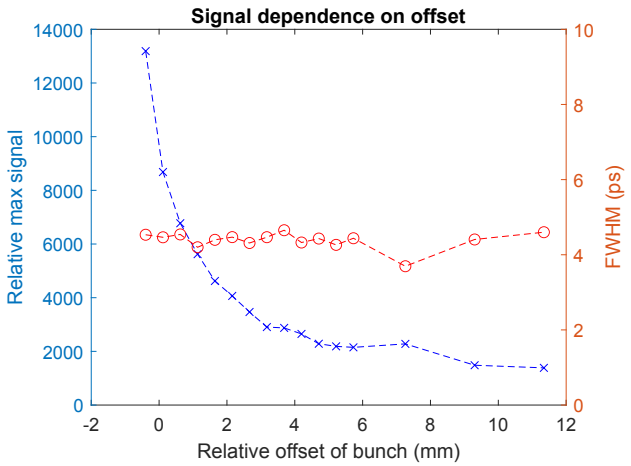

Figure 3: Plot showing the detection of the signal out to >1 cm sampling distance.

different separations between the probe and electron beams. The expected $1/r$ decay of the Coulomb field was observed, and whilst the temporal profile became noisier, the FWHM was still recovered accurately out to >1 cm offset. The temporal calibration was also verified by scanning the laser delay stage and verifying the same delays were measured in the recovered profile.

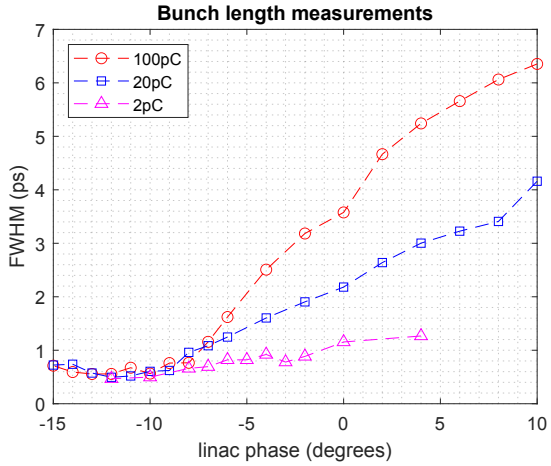

Figure 4: Bunch length characteristics for varying charge and linac phase.

The system was used to investigate the variation of bunch length against linac phase (w.r.t. crest) for different bunch charges. Results for 3 different beam set-ups are shown in Fig. 4. In order to maintain the bunch energy of 35 MeV/c the RF power was increased when off-crest to compensate the reduced field. The convergence and "bottoming out" of the measured bunch lengths at the lower linac phases is attributed partially to the phasematching limitation introduced by having to use GaP as the EO medium, and could also have been affected by residual high order spatial dispersion of the electron profile at these settings. This was expected with this amount of "over compression" and large energy spread and was visible on the interaction point YAG. The phase could not be scanned further off crest to see the length increase again as there was no more headroom on the RF power. The rolling-off of the longer 100 pC bunch widths is attributed to the length approaching that of the probe field. In this case the Gaussian pulse probe field is no longer effectively flat across the Coulomb field profile, and effectively shortens the recovered profile. This can be mitigated by using a longer stretching of the probe pulse without losing the potential to measure short features.

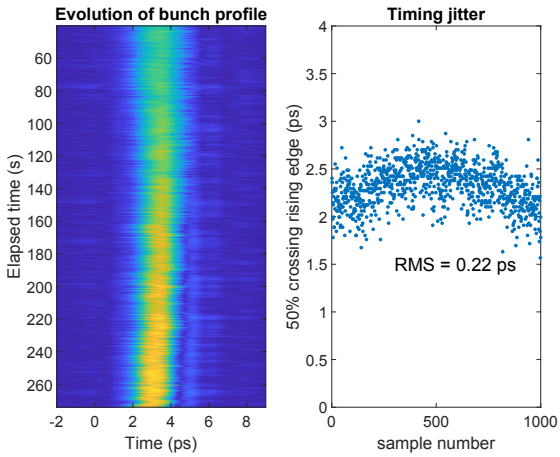

Figure 5: Bunch profile evolution over several minutes

A study of the laser-bunch arrival time jitter was also performed by capturing 1000 profiles over several minutes. The data is shown in Fig. 5, and shows the evolution of the bunch during the sampling period. Although there is some drift in bunch compression the arrival jitter between the two was 0.22 ps rms, which is in agreement with independent experiments and the expected performance of the laser locking system (Coherent Synchrolock). The collection rate was approximately 5 Hz due to the lack of optimisation of the data capture software. The raw data is simply spectra, which in principle can be captured at much higher rates.

CONCLUSIONS AND OUTLOOK

Electro-Optic Spectral Interferometry was demonstrated in an accelerator environment and used to make informative measurements of the electron bunch. Although limited by phasematching conditions, bunches as short as 0.45 ps FWHM were recovered, and the system was demonstrated capable of measuring electron bunch profiles with charge and duration varying over more than an order of magnitude. In future a probe wavelength optimised to GaP should be used, and a new 2D spectrometer arrangement. Importantly, the system comprises only one more optic than a spectral decoding system, and is based on calculation rather than iterative algorithms, implying that currently implemented EOSD systems could be upgraded whilst maintaining the system's advantages.

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