# LONGITUDINAL BUNCH PROFIL MONITORING VIA ELECTRO-OPTIC SINGLE SHOT DIAGNOSTIC WITH LINEAR RESPONSE *

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*Abstract*

A new approach of electro-optic (EO) spectral encoding allows for the non-invasive characterization of the longitudinal electron bunch distribution at the ELYSE laser triggered ps pulse radiolysis facility: the transverse electric field of the relativistic bunch is encoded to the temporally dispersed spectrum of a supercontinuum whose wavelength dependent polarisation state is then analyzed with balanced detection. This method combines the spectral bandwidth of the probe (Fourier transform limit < 5 fs) with a direct signal response of the detection scheme. As a result, the field amplitude within the EO crystal can be determined in an absolute, undistorted manner with a time window several times longer than the electron pulse.

The diagnostic allows bunch monitoring at the 100 pC level even for low beam energy and brightness. The influence of the accelerator conditions on the bunch profile and its stability has been studied for the 4 - 8 MeV bunches at ELYSE with a 500 μm thick ZnTe crystal at a distance of 4 mm to the $e^-$-beam centre.

## INTRODUCTION

In the last years, the electro-optic (EO) sampling has become an important tool for the characterization of the longitudinal electron beam profile and bunch arrival time in different accelerator schemes. Its capability of non-invasive measurement has motivated great effort to improve the temporal resolution of single shot sampling schemes on the sub-ps scale. Particularly the known facilities of ultrafast bunch accelerators have advanced this development [1-3] and recently a diagnostic scheme for the high energetic $e^-$-bunches has been optimized [4]. As it is common to the existent EO single shot techniques the used detection schemes are based on crossed polarizer operated at near zero optical bias.

In this kind of polarization analyzer only one polarization state of the optical probe is recorded. This may facilitate the realisation of the setup. The signal response is however non-linear and depends on the intensity distribution of the probe $I_0(t)$, the optical bias $\Gamma_0(t)$ and the phase retardation $\Gamma(t)$ induced by the electric field under investigation:

$$I_S(t) = I_0(t)\sin^2(\Gamma(t) + \Gamma_0(t)) \qquad (1)$$

Scattering contributions are here neglected. Different terms of the signal function can dominate the signal response. This cross polarized configuration leads to well known distortions that affect the relative amplitude and even polarity of the detected signal [5,6]. These distortions can in general not be corrected, especially not without the knowledge of the electromagnetic field under investigation.

The sensitivity and operation range of such crossed polarizer detection is sufficient for the determination of the arrival time of $e^-$-bunches with a sharply defined distribution of charge and jitter. In contrast, for several applications the profile of the bunch has to be controlled and must therefore be monitored precisely. For example, the optimized operation of both the spontaneous amplified stimulated emission of free electron lasers (SASE FEL) and pulse-radiolysis require bunches compressed down towards their charge limited duration. A characterisation of such ps-electron accelerators or the low energetic accelerating lines in general has up to now not been performed in a non-invasive single shot manner. The corresponding EO-diagnostic must cover the sub-100 ps range to detect possible satellite pulses and to understand the EO-signal with possible artefacts. As an analysis of the different techniques suited for the fs-scale shows, their detection window can not be expanded to several 10 ps without severe restrictions and expense. For a comparison of the existent fundamental techniques, i. e. the spectral or spatial encoding [7,8] and a combination of them [9], see for example [10-12].

Here we apply a widely tunable and broadband EO single-shot technique with linear response to the electric field. It can be used both in the low and high energy parts of the accelerator line and allows for the first time the non-invasive monitoring of the longitudinal pulse shape of ps-$e^-$-bunches. With this online diagnostic the accelerator conditions can be optimized on the output bunch parameters. This capability is demonstrated in this paper for the arrival time distribution, i.e. the jitter. The different contributions to the EO-signals are discussed.

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## EXPERIMENTAL: EO-SAMPLING WITH SUPERCONTINUUM ENCODING IN BALANCED DETECTION

The presented studies have been performed at the experimental line EA-1 of ELYSE, a ps electron accelerator seeded by a photocathode gun (for details see [13] and references therein). The longitudinal pulse shape of ELYSE was studied 30 mm after the exit window of the accelerator line at a typical distance for radiolysis experiments. A ZnTe crystal of 500 µm thickness was placed at 3 mm from the electron beam axis. The birefringence induced by the transverse electric field of the $e^-$-bunch was probed collinearly to its propagation in about 4 mm to the electron beam centre.

Details of our single shot EO-sampling technique can be found in reference [12] including a discussion of its stability, sensitivity and signal response. Briefly, the electric field is encoded to the temporally dispersed spectrum of a supercontinuum (SC) whose wavelength dependent polarization state is analyzed in balanced detection. The combination of the spectral bandwidth that corresponds to a Fourier Transform limit <5 fs and the direct signal response of the detection scheme allows the determination of the local electric field without distortions over a temporal window several times longer than the electron pulse. Due to the ultrabroad frequency bandwidth of the probe pulse, the fs-range becomes accessible also for the spectral encoding technique. The minimum detection window is defined by the temporal dispersion of the optical setup to about 700 fs leading to a resolution < 100 fs. The detection window can be adjusted just by adding glass in the optical path.

For the characterization of ELYSE, the SC was generated by focusing ~1 µJ of a Ti:Sapphire laser slightly into a sapphire plate. The duration of the initial laser pulse at the SC-generation was about 200 fs. A highly stable single filament SC was obtained that covers the visible spectrum down to the near UV. The spectral part that is transmitted by the ZnTe is stretched to 60 ps through 20 cm of SF57. This detection window and the Fourier transform limit of the remaining spectrum of 6.6 fs lead to a temporal resolution of the spectral encoding of ~ 1 ps [12,14]. The effective time resolution is limited to 1.2 ps by the geometric configuration, i. e. the distance between the probe and the $e^-$-beam with its diameter of typically 2 mm.

From the well defined signal function of the balanced detection the induced phase retardation can be determined in an absolute manner from the recorded perpendicular polarization state components Ia and Ib:

$$\sin\Gamma = \frac{Ia - Ib}{Ia + Ib} \qquad (2)$$

With $\Gamma(\lambda)$ the electric field $E(\lambda)$ can be calculated via

$$\Gamma(\lambda) = \frac{2\pi d n^3(\lambda) r_{41} E(\lambda)}{\lambda} \qquad (3)$$

where d, n and $r_{41}$ are respectively the thickness, refractive index and electro-optic coefficient of ZnTe. Finally, $E(\lambda)$ can be transformed to $E(t)$ with the calculated and experimentally verified dispersion function of the optical path between SC-generation and EO-crystal.

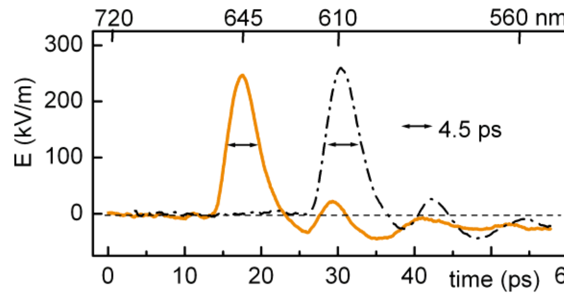


Figure 1: Two single shot measurements of the local electric field at a charge of 140 pC and $\gamma = 16$ in different spectral parts of the probe. The optical delay of the SC-probe was increased between the two shots by 13 ps.

## SINGLE SHOT MONITORING OF LOW ENERGETIC ELECTRON BUNCHES

Figure 1 shows the local electric field deduced via equation (3) from EO single shots that have been recorded for identical accelerator conditions but different optical delays of the probe: the field peak is encoded in the red respectively yellow part of the SC. Beam shape and amplitude of the field are independent of the probe delay. Even for the moderate electric fields at ELYSE with $\gamma$*Q ~ 2000 a good signal-to-noise ratio can be obtained: The maximum at 645 nm corresponds to 0.14 rad in 500 µm ZnTe and can be resolved by the shot noise limited diagnostic with an accuracy better than 0.005 rad or 100 V / cm.

Besides the transverse electric field that is directly linked to the passing $e^-$-bunch, the ZnTe is also exposed to parts of the coherent radiation created by the transition (CTR) of the bunch through the exit window, a 13 µm thick Al foil. The CTR field gets partially reflected inside the ZnTe with its refractive index n ~ 3 in the THz regime and causes so the damped oscillations lasting after the electron pulse. As simple simulations with equation (1) based on the measured $\Gamma(t)$ demonstrate, these signatures are artificially reduced to the limit of recognition due to the non-linear response of crossed polarizer operated near zero optical bias.

In order to separate the CTR from the longitudinal field distribution of the $e^-$-bunch, a 3mm thick BK7 substrate was inserted in front of the ZnTe. The CTR has to cross the substrate before entering into the EO-medium and is

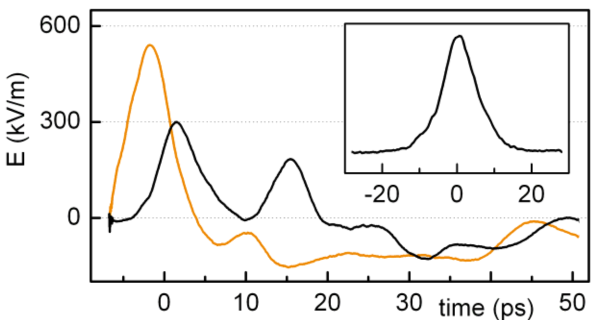


Figure 2: Separation of the Coulomb field and the CTR by adding 3 mm Bk7 as optical delay between the tube exit and the EO-crystal: with (black) and without (orange) delay for the CTR. The charge was ~ 0.8 nC. The inset shows the Cherenkov radiation of an $e^-$ bunch of 2 nC.

therefore delayed relative to the $e^-$-bunch whose propagation is not affected. In figure 2 the EO-measurement with CTR-delay (black) is compared to the one without: An additional strong maximum is revealed that is delayed by 15 ps relative to the first in good agreement with the theoretical value. In this configuration, the contributions of the CTR and the $e^-$-bunch field are separated for short bunch duration. So the shape of the first maximum should reflect the longitudinal bunch distribution. For a charge of ~0.8 nC and an energy of 6.5 MeV as depicted in figure 2 the FWHM was found to be 5.2 ps. A charge of 110 pC leads to a value of 3.0 ps due to the reduced Coulomb repulsion inside the bunch.

The measurement of Cherenkov radiation with a streak camera provides a reference for bunch durations distinctly beyond 5 ps, i.e. the apparatus function (for technical details see [13]). Such an invasive characterisation via the light generated by the $e^-$-bunch passing through a 500 µm sapphire plate is shown in the inset of figure 2 for a signal averaged over 20 shots. While the FWHM is around 10 ps due to the high charge of 2 nC, the beam shape is similar to the first peak of the black EO-single shot.

Using the EO-setup as online monitor of the accelerator operation, we have investigated the arrival time distribution dependent on the phase between the electric fields of the RF gun and the booster. A minimized jitter of 1.3 ps was found when the phase is tuned near to the maximum field strength of the booster resulting in maximum electron energy (see figure 3a). This value is close to the fundamental limit of 1 ps given by the synchronisation jitter between the accelerating fields and the laser source seeding the photogun. As expected, the initial jitter is amplified in the slope of the sinus dependence of the electric field on the phase. The increased energy dispersion in this regime has got also a compressing effect that reduces the FWHM duration as depicted from 8 to 5 ps.

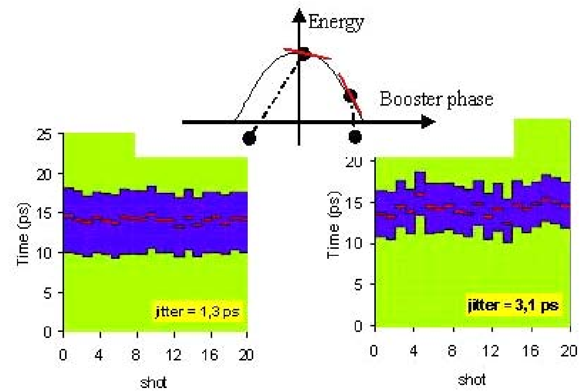


Figure 3: Arrival time (red) and FWHM pulse length (blue) of a series of 20 $e^-$-bunches that have been accelerated a) near to the maximum and b) in the falling slope of the booster field.

## CONCLUSION

The EO-sampling with supercontinuum encoding in balanced detection enables the first non-invasive single shot study of the longitudinal electron distribution at a ps-accelerator. The e-bunches have been characterized at the facility ELYSE outside the beam tube at the place of radiolysis experiments with a resolution of ~ 1 ps and a detection window of 60 ps. The accuracy of one single shot is better than 0.005 rad corresponding to 100 V / cm in 500 µm ZnTe. The linear response of the balanced detection allows the optimization of the accelerator parameters on its output including the bunch shape. For the first time, the phase dependence of the jitter has been measured directly.

The presented diagnostic is compatible to ultrafast laser sources in the Vis or Nir as the required intensity for supercontinuum generation can be achieved at different wavelengths with fs to ps pulse durations. The setup is easily tunable on the fs- and ps-scale and can be used both in the low and high energy parts of an accelerator line.

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