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Single shot electro-optic characterization of the ELYSE picosecond electron beam

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Abstract

The electron pulses delivered at ELYSE pulse radiolysis facility have been characterized using the non-invasive single-shot EO diagnostic designed in the DS1 task (*Electro-optical diagnostics for ELYSE: Single Shot Electro-Optic Sampling with a supercontinuum in balanced detection*. Schmidhammer et al., DS1 report n°38). The temporal profile and the shot to shot stability of the electron bunches have been measured for the first time using a non invasive device. The influence of the characteristics of the laser pulse on the photocathode (energy, pulse duration, intensity), of the accelerating HF field in the photogun and booster, and of the beam transportation were monitored.

Introduction

The required high brightness ($>10^{14}$) for future accelerators used as free electron laser sources in the X ray domain, is calling for ultra-short (100 fs) electron bunch length in order to increase the bunch peak current. One of the associated challenges is the control of the synchronization between the photo-injected electron bunch and the main laser pulse that could be used for a seed for harmonic generation, or for pump-probe user experiment at different stages of the accelerator. Such requirement implies the development of real-time high temporal resolution single-shot diagnostics. ELYSE [1] is the single picosecond photoinjector accelerator dedicated to radiolysis in Europe. It delivers an electron pulses with an energy tunable between 2 and 9 MeV, a charge up to several nC, at a repetition rate of 25 Hz. The radiation physico-chemists routinely used the facility to investigated ultrafast transient chemical processes in condensed media using pulse-probe methods. The chemical reaction is triggered by the electron pulse, while the induced changes are monitored using an optical probe beam synchronized to the electron bunch. So for pulse radiolysis facilities, as for FELs, good spatial and temporal stabilities of the electrons bunches are required.

ELYSE has been designed to operate in a mode with a time jitter between the electrons bunch and the laser pulse used to illuminate the photocathode less than 1 ps shot to shot. This has been indirectly validate through the time-resolved experiments, but so far this jitter has never been measured. Also, the electron bunch temporal profile is only known from invasive measurements with a streak camera, or indirectly from the deconvolution of the transient absorption signal obtained in pulse radiolysis experiments. One reason for the lack of single-shot diagnostics on ELYSE or similar photoinjector is that the developed EO devices, both in spatial or spectral encoding/decoding mode, are not adapted for pulses with picosecond duration, that are paradoxically too long. The newly designed EO device described in DS1 report [1] fills the gap. It allows a real-time non-invasive single shot encoding of the electron bunch electric field on a temporal window as large as 60 ps with a rise-time resolution better than 1 ps. The influence of the characteristics of the laser pulse on the photocathode (energy, pulse duration, intensity), of the accelerating HF field in the photogun and booster, and of the beam transportation were monitored.

Experimental arrangement

A scheme of the experimental arrangement is presented in figure 1. The ELYSE picosecond photoinjector accelerator [1] consist of a CERN/CTF type, 3 GHz RF gun, a solenoid, and a four cells booster, providing an energy up to 9 MeV. A frequency tripled ultra-short (120 fs) Ti:Sapphire laser (266 nm) generates at the photo-cathode a charge ranging from several hundred pC to 5 nC at a repetition rate ranging from 1 to 25 Hz. A fraction of the laser is used as a probe beam for the electro-optic diagnostic.

Three experimental areas are available at ELYSE [1]. For our measurements we used the experimental area I: the straight exit. After the booster, a triplet of quadrupoles focuses the beam while steerers can move it along the horizontal or vertical axis. The beam charge per pulse is measured with a moveable Faraday cup placed at the end of the transport line, 3 m downstream the photocathode. This Faraday cup is also used as a beam dump.

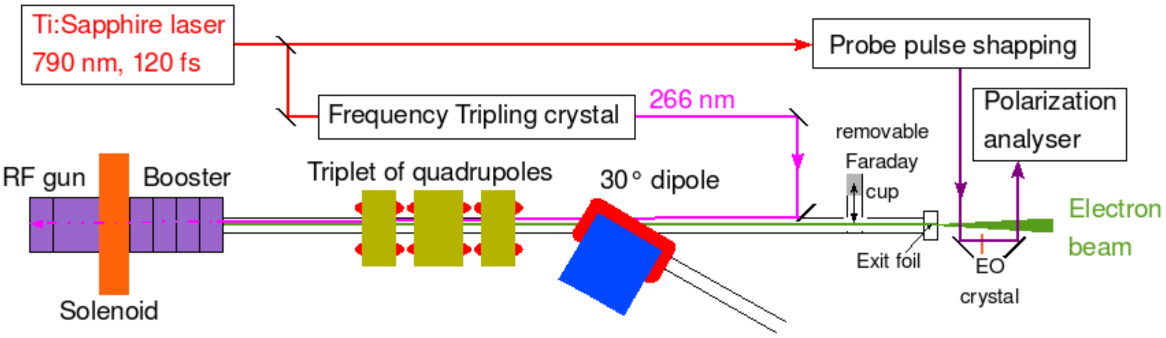


Figure 1. Implementation of the electro-optic diagnostic for the electron bunch duration at ELYSE.

The EO diagnostic has been described in details in a DS1 report [2]. It is based on the Pockels effect generated by the transverse electric field of the relativistic electron bunch propagating in the vicinity (mm) of a birefringent crystal (ZnTe).

Figure 2 shows details of the experimental set-up at the exit of the accelerator. The birefringent crystal was placed 25 mm away from the vacuum tube exit window (Al foil, 13 µm thick). It was protected from scattered electrons by a 6 mm copper plate, enough to stop completely a 9 MeV beam. The overall distance between the photocathode and the electro-optic crystal was 3.4 m, resulting in a 11.35 ns travelling time for the electron bunch.

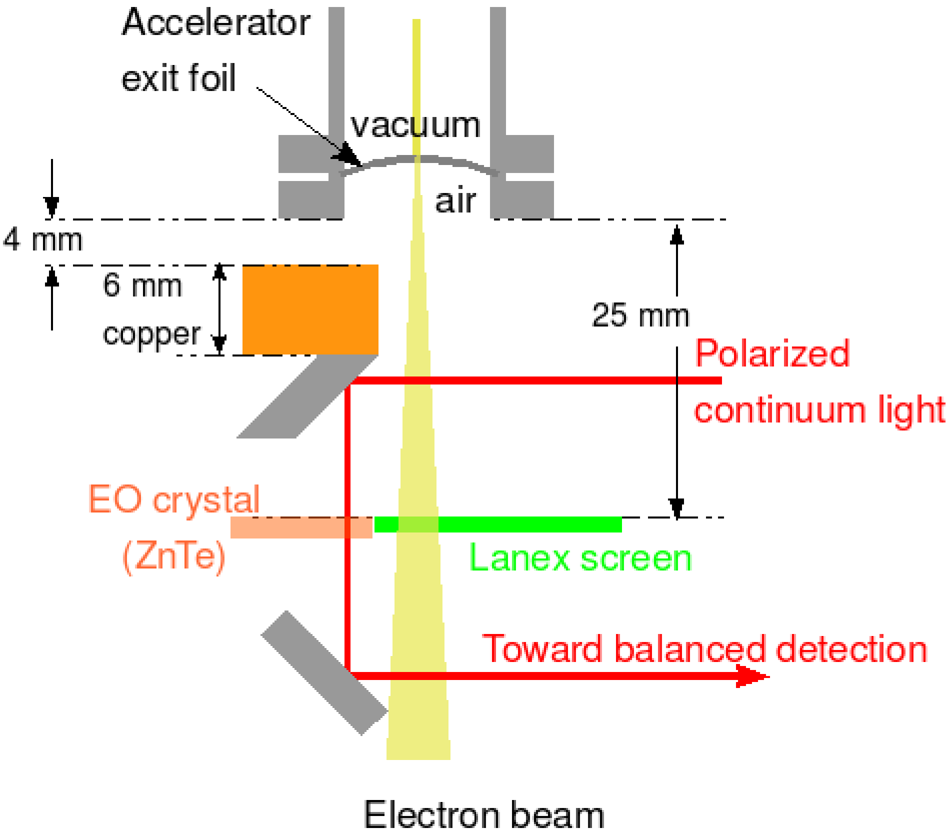


Figure 2. Top view of the details of the experimental set-up at the exit of the accelerator.

A LANEX® scintillator screen, placed beside the ZnTe crystal and imaged on a CCD camera, was used to measure the electron beam transverse profile. A BK7 plate has also been used in some cases in order to separate the electron beam static electric field and an EM contribution coming from transition radiation generated by the electron bunch at the exit window, as will be discussed below.

Typical electron beam parameters were a diameter varying from 2 to 4 mm (depending on the focussing and the charge), a distance of about 4 mm from the axis of the laser probing the electric field, and an energy of 7.9 MeV (factor $\gamma = 16.5$) We will precise those parameters for each of the presented measurements.

Electro-optic measurement

Phase retardation of the laser probe beam induced by the electric field of the electron bunches is given by :

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

where λ is the laser probe wavelength, d, n *and* r_{41} are respectively the thickness, the refraction index, and the electro-optic coefficient of the birefringent crystal.

As described above, the probe laser beam is time-frequency encoded. The differential signal we measured was:

$$S(\lambda) = [\, p(\lambda) - s(\lambda)\,] \,/\, [\, p(\lambda) + s(\lambda)\,],$$

where $p(\lambda)$ and $s(\lambda)$ are respectively the amplitudes at the wavelength λ of the spectrum of the horizontal and vertical polarisation. It is related to the polarisation rotation by $\sin(\Gamma(\lambda)) = S(\lambda)$, so that the transverse electric field E is related to the differential signal by:

$$E(\lambda) = \mathrm{asin}[S(\lambda)]\ \lambda\ /\ [2\pi\ d\ n(\lambda)^3\ r_{41}] \qquad (1)$$

The electric field temporal profile can be retrieved from the time-frequency relation in the probe pulse. This relation can be obtained from the dispersion relations of the different optical elements in the probe path. It can also be experimentally obtained by changing the delay between the probe pulse and the electron bunch and recording the frequency position of the maximum of the electro-optic signal. Figure 3 shows the good agreement between theoretical calculation and experimental determination of the dispersion relation.

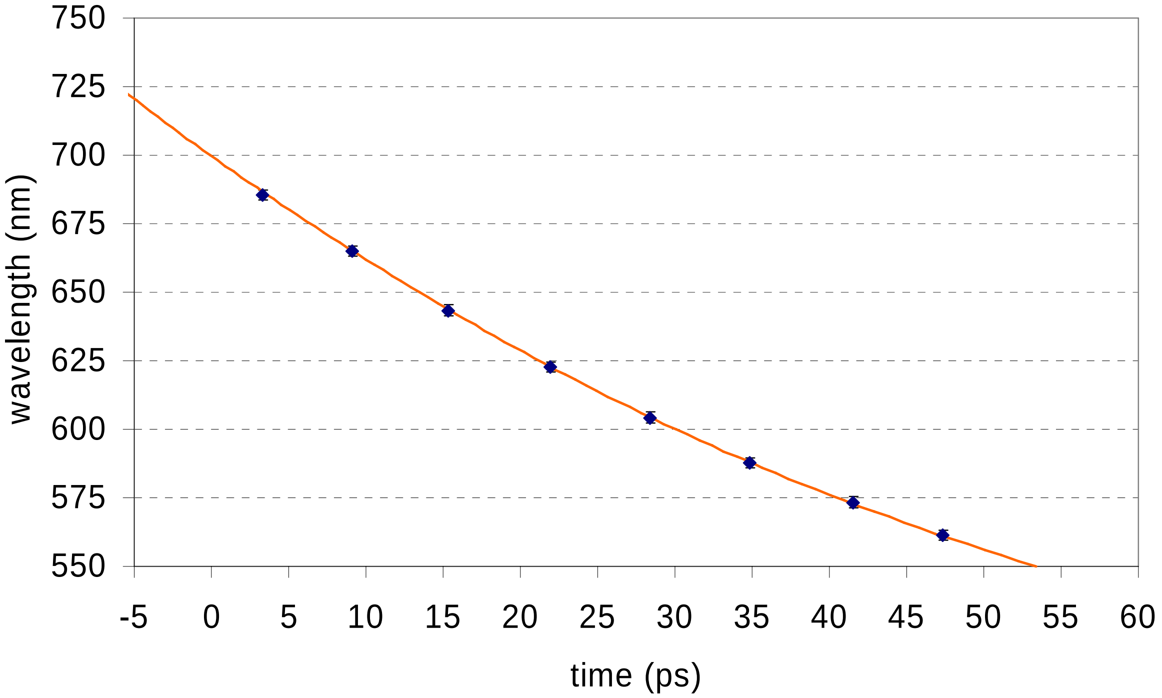


Figure 3. The theoretical (continuous line) and experimental (dots) dispersion relation. The temporal origin has been arbitrary associated with the wavelength 700 nm. The vertical error bars are the wavelength incertitude on the position of electro-optic maximum.

Figure 4 shows a typical temporal profile of the electric field measured with the single-shot EO diagnostic: an asymmetrical maximum, followed by a negative contribution.

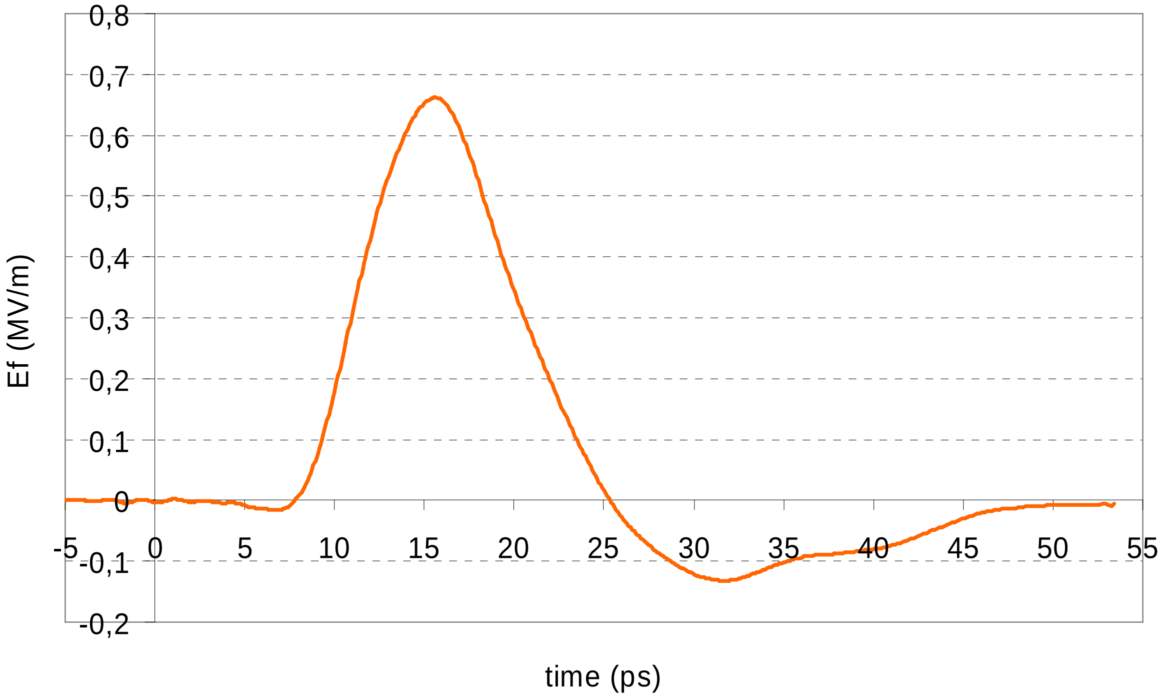


Figure 4. Typical temporal profile of the electric field obtained with the single-shot EO diagnostic and equation (1). The ZnTe crystal was 1.5 mm thick.

The negative part of the electric field could come from coherent transition radiation (CTR) generated by the electron bunch at the accelerator exit window (metallic foil) [3, 4].

Coherent Transition Radiation contribution

Transition radiation is produced by the electron bunch when it crosses the exit foil (metallic) at the end of the accelerator vacuum tube. Wavelength longer or of the order of the bunch length add coherently to form Coherent Transition Radiation (CTR) [5], which is an EM pulse with a duration equal to the bunch length. This CTR field can also trigger a Pockels effect in the EO crystal. Since it is an EM radiation, its sign could be opposite to the electron bunch Coulomb field.

To separate this two fields, we placed a glass (BK7) plate, between the accelerator exit plane and the crystal. That way, the CTR signal, which needs to cross the glass plate to reach the EO crystal, is delayed, while the timing of the electron beam (and its Coulomb field), which travels freely, is not affected (see figure 5).

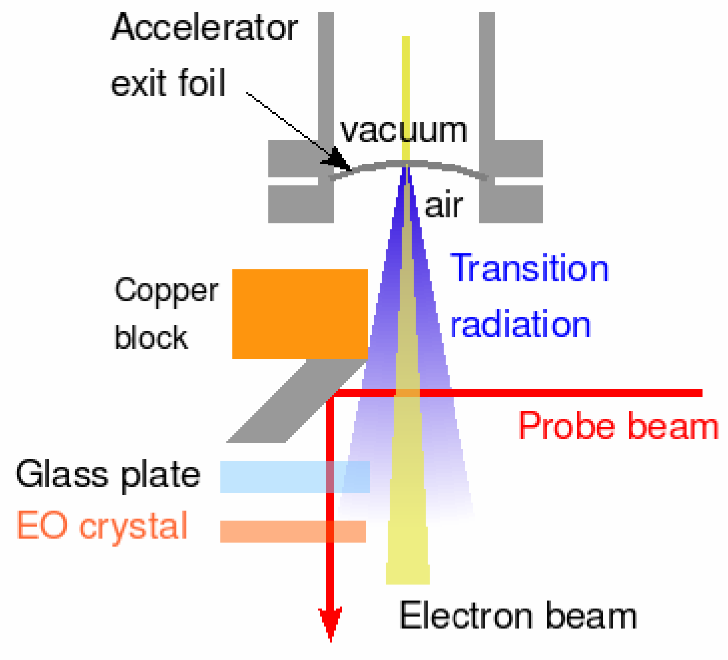


Figure 5: Experimental arrangement used to delay, with a 3 mm glass (BK7) plate, the CTR field generated by the electron bunch at the vacuum tube exit window, from the direct (coulomb) electron bunch field.

Figure 6 presents the result of such a test. The signal in blue has been obtained without the glass plate, and exhibit the ‘typical’ form. With the 3 mm thick BK7 plate (orange line) two maxima are observed: one at the same time than the maximum without the glass plate, and a second one delayed by 15 ps. This value is in good agreement with the expected delay of a THz pulse propagation in BK7 ($n_{\mathrm{BK7}} \sim 2.5$) [6]. The transmission in amplitude expected for a sub-THz pulse should be of the order of 20 % (17 % for a 8 ps FWHM pulse), However, a direct comparison of the amplitude ratio is difficult since the CTR radiation is an EM pulse (oscillating field), while the Coulomb field is static. One possible way the improve the separation of these two components could be to increase the distance between the exit window and the detection plane: the CTR diverges faster than the electron beam (the Coulomb field). Another way is to change the bunch charge: the Coulomb field is linear with the charge, while CTR, due to the coherent addition, is quadratic.

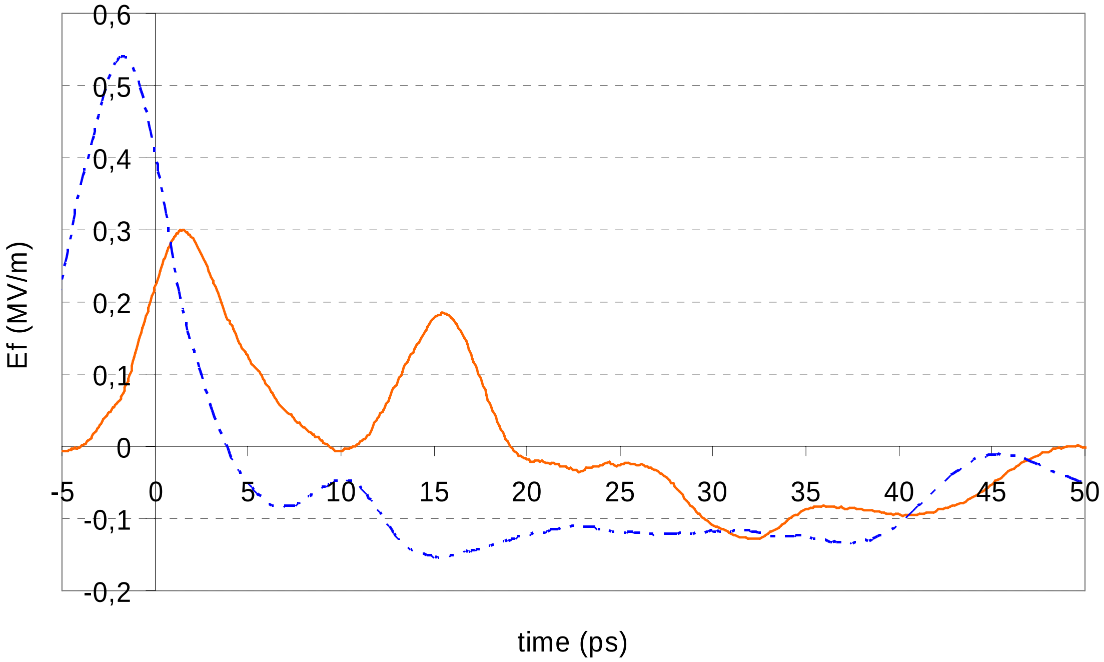


Figure 6. Separation of the CTR and Coulomb field contributions by adding a 3 mm thick BK7 glass plate between the accelerator exit plane and the crystal. With a 3 mm BK7 plate (orange curve) and without (blue curve).

Comparison between EO and streak camera measurements

Another temporal diagnostic used at ELYSE is based on Cherenkov light measurement [7]. A 500 µm sapphire plate mounted on a translator can be placed in the electron beam path, just before the Faraday cup (see figure 1). The Cherenkov (prompt) radiation emitted at 90° from the electron beam direction was focused at the entrance of a spectrograph (CHROMEX 250IS) coupled to a streak camera (HAMAMATSU C7700) triggered by the laser. Time response of this complete device is 5.2 ps (FWHM). In order to get a good signal to noise ratio, 20 shots were taken. The shot-to-shot temporal jitter of the streak camera was corrected on each of these 20 shots before adding them a get the average electron bunch profile. The experimental procedure was to first make few (20) measurements with the EO device, and then, without changing the accelerator parameters, inserting the sapphire plate in the beam path and recording Cherenkov light. Typical results of this measurements are presented on figure 7.

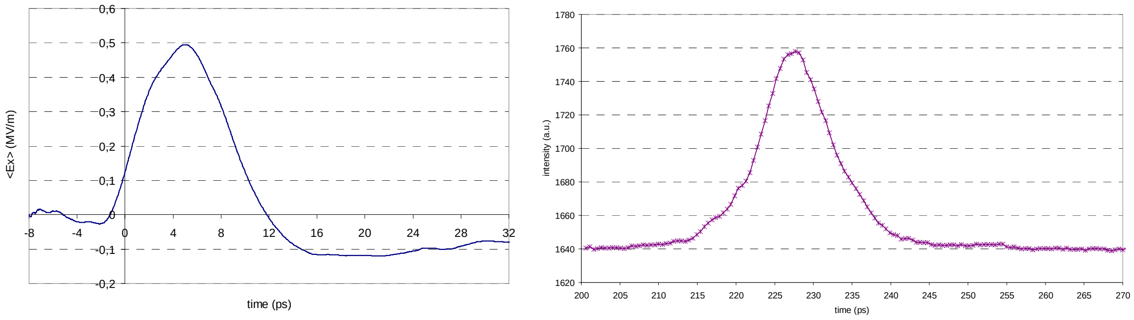


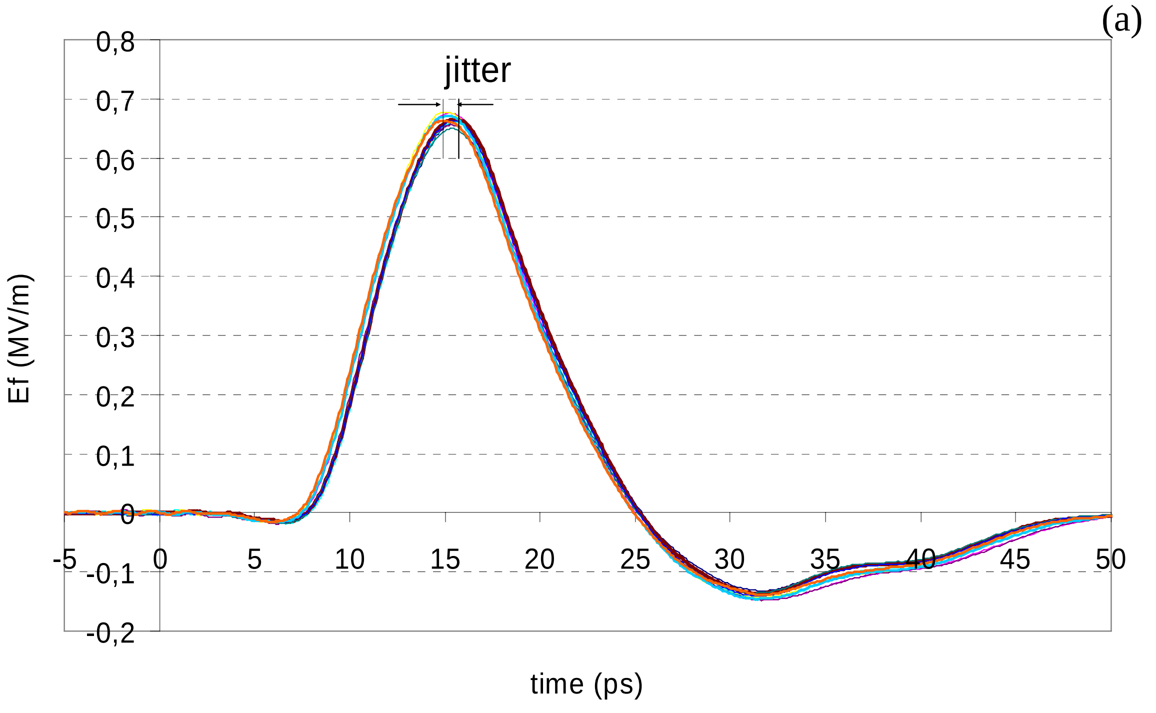
Figure 7. Measurements of the average electron bunch duration using: the electro-optic device (left); the Cherenkov light dispersed with a spectrometer and analysed with a streak camera (right). Each curve is the average over 20 shots.

As explained above, the falling edge measured with the EO diagnostic can be affected by CTR, or by reflections of the electric field in the crystal. Also, the profile measured with the streak camera is affected by the instrumental response. So a detailed comparison between these two diagnostics is difficult. However, after instrumental response deconvolution, both diagnostic indicate similar durations of the leading edge: 4 ps (half width at half maximum) from EO, and 4.3 ps from Cherenkov.

Measurement of the temporal jitter between the electron bunch and the laser

We made series of shots to measure the temporal jitter of the electron bunch at the exit of the accelerator. During this study, the accelerator was run at 5 Hz, and each temporal profile of 20 consecutive shots (bunches) was recorded. The arrival time of the electron bunch was defined as the position of the maximum of the EO temporal profile.

Figure 8 presents measurements made for two accelerator configurations. The left graph has been obtained for a configuration giving the maximum electron energy, that is a phase between the booster and the RF gun such that the electrons are at the maximum of the accelerating electric field (on the RF crest). In that case, the jitter is lower than 1 ps peak-to-peak (0.223 ps rms), in agreement with the electronic synchronisation jitter. When the energy is changed by modifying the booster phase, the electron bunch experiences a larger slope of the sinusoidal RF field, leading to an increase of the jitter, as observed on the graph on the right, were it reaches a value of 3.4 ps peak-to-peak (0.786 ps rms).



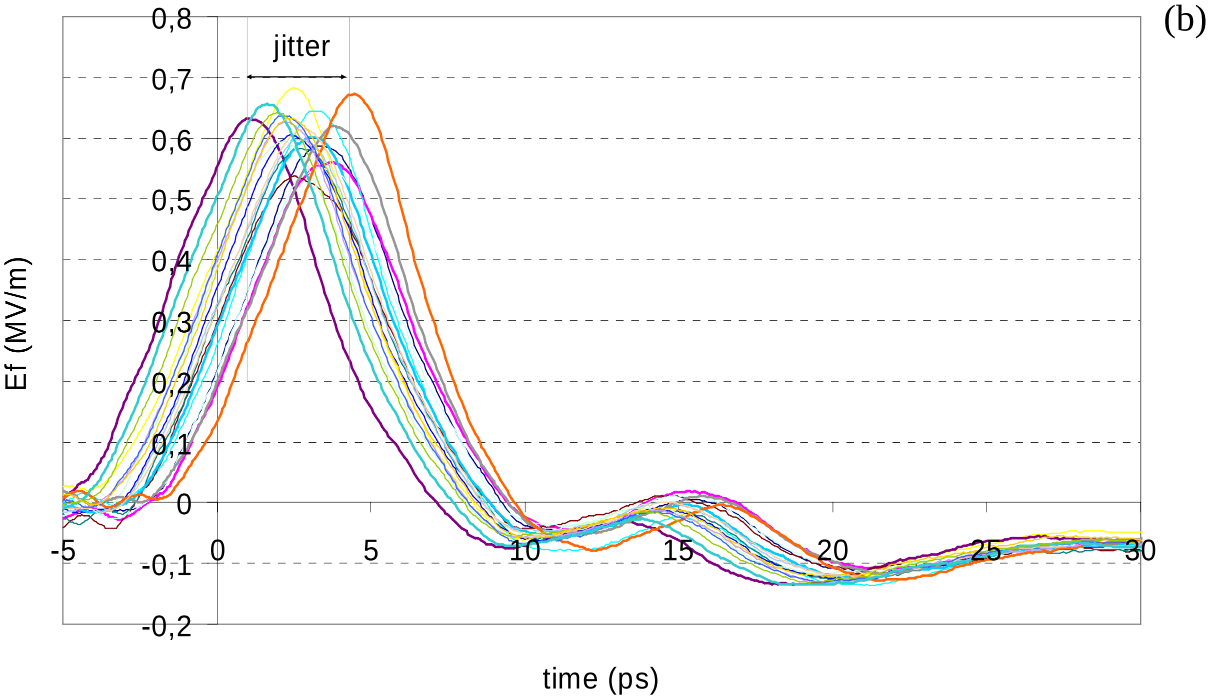


Figure 8. Measurement of the jitter for two different phasing of the booster relative to the RF gun. 8a : electron bunch on the crest of the RF accelerating field, leading to 7.9 MeV electrons and jitter of 0.9 ps peak-to-peak (0.22 ps rms); 8b : electron bunch out of the crest, leading to 6 MeV electrons and a jitter of 3.4 ps peak-to-peak (0.79 ps rms). The ZnTe crystal was 0.5 mm thick, and the transverse distance between the electron beam and the probe laser axis was 4.2 mm.

Influence of the solenoid current

The solenoid placed between the RF gun and the booster (cf. Fig. 1) is used to control the electron beam divergence at the exit of the RF gun. Therefore, it affects the entrance conditions in the booster, and so the electron bunch duration. This is illustrated in Fig. 9 where temporal profiles for two solenoid currents are presented. One can observe very different temporal profiles. Simulations with a transport code (such as ASTRA) would be necessary to better understand this temporal deformation. However, this measurement demonstrates the need, for picosecond accelerators, of such a real-time temporal diagnostic, which allows a direct optimization of the accelerator parameters (solenoid current in that case) in order to get the shortest bunch length.

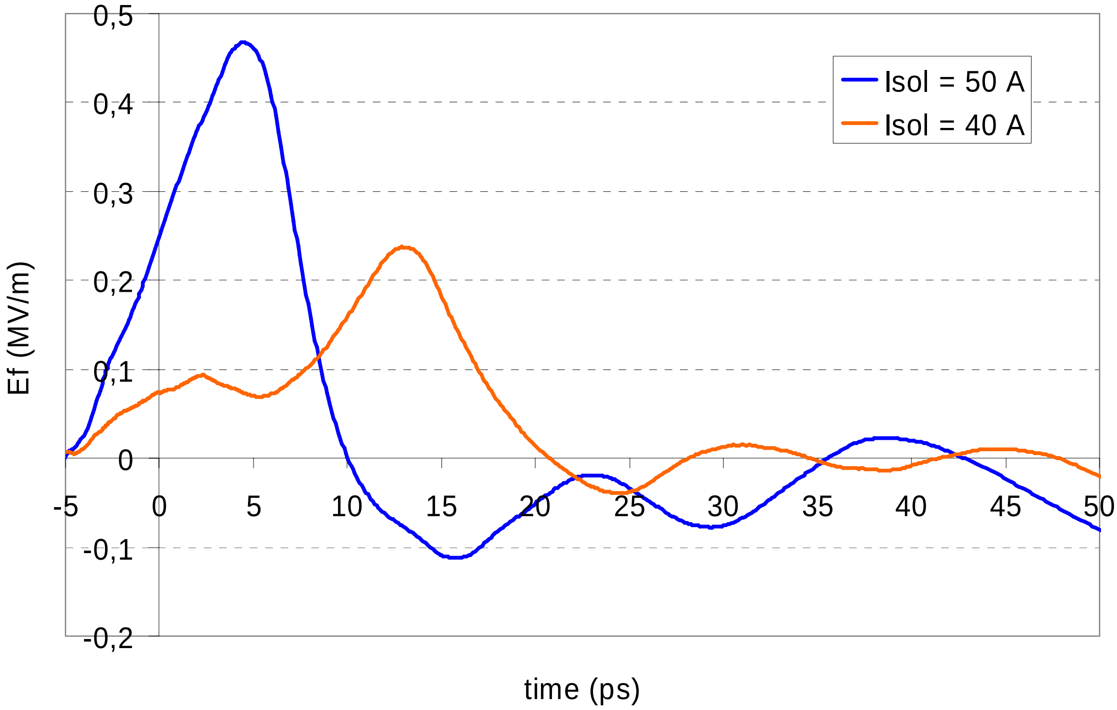


Figure 9. Effect of the solenoid current on the electron bunch temporal profile.

Influence of laser energy on photocathode

Laser energy on the photocathode is an important parameter. If the electron bunch charge can be limited by the photocathode saturation at high laser energy, Coulomb explosion at high charge also affect the electron bunch longitudinal (temporal) and transverse profiles. To study these different effects, we changed the laser energy by inserting neutral densities in the path of the 266 nm laser pulse. Figure 10 shows the non-linear behaviour of the bunch charge (measured with the Faraday cup) versus laser energy on photocathode. One can clearly see a saturation of the maximum number of electrons that can be extracted from the photocathode.

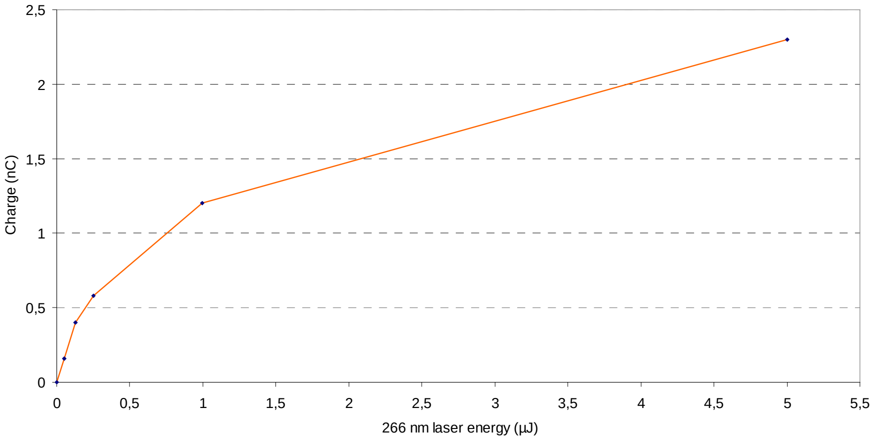


Figure 10. Maximum electron bunch charge versus laser energy on the photocathode. Since charge emitted by the RF gun depends on the RF phase at the laser arrival, charge plotted here is at optimum phase for a charge maximum.

The electric field associated with the electron bunch and detected by the EO device should be linear with the bunch charge. However, as said above, Coulomb explosion at high charge can increase the transverse and longitudinal (temporal) extend of the bunch, and so its electric field. This is clearly observed in Figure 11 where is presented the evolution of the maximum of this electric field (peak of the EO profile) with the bunch charge.

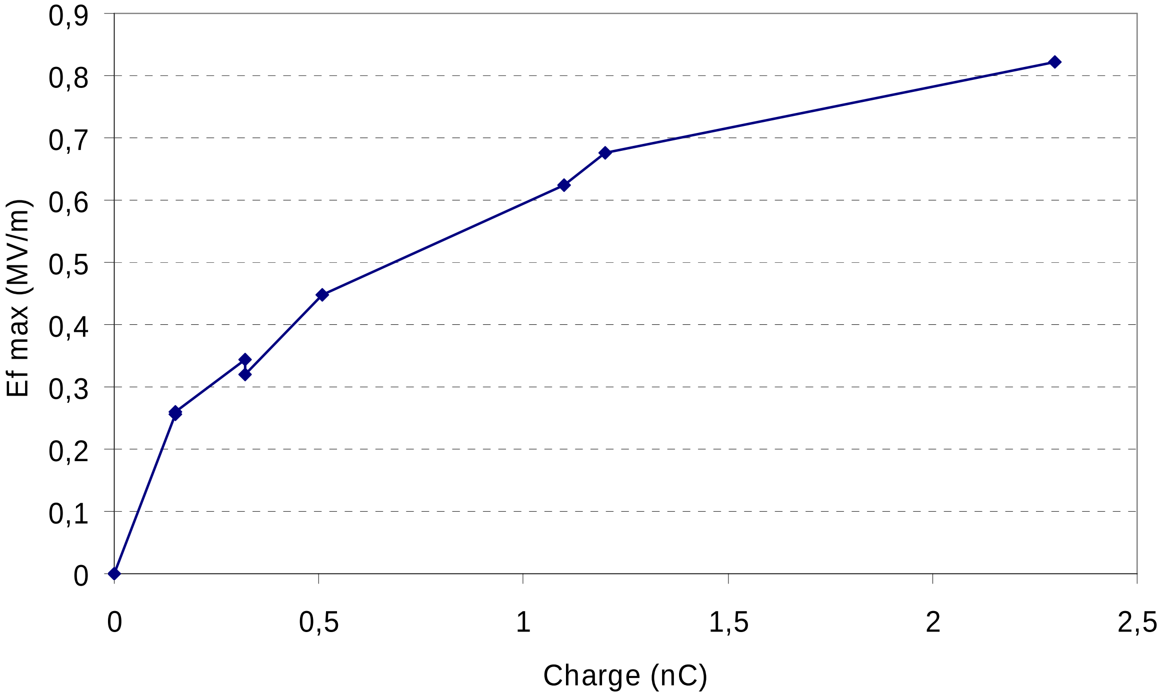


Figure 11. Maximum electric field versus electron bunch charge. The ZnTe crystal was 0.5 mm thick. The distance between the electron beam and the probe laser was kept constant (4 mm), as well as the accelerator RF and transport conditions (energy of 7.9 MeV).

Let us underline that the observed saturation of the signal when charge is increased indicates that the CTR contribution on the EO signal is much lower than the Coulomb field: a CTR dominated signal should have a quadratic dependence with charge.

Let us also note that in a another set of measurements, we reduced the charge down to 60 pC, and get a “reasonable” EO signal giving a maximum electric-field of E_f = 80 kV/m, which is an above limit of the detection threshold of our EO device.

The electric field (electron bunch) duration as a function of the bunch charge is presented in Fig. 12. One can observe that the lower the charge, the shorter the bunch. This is an another indication that the electron bunch shape is dominated by the space-charge effects, as can be expected at this quite low (7.9 MeV) electron energy.

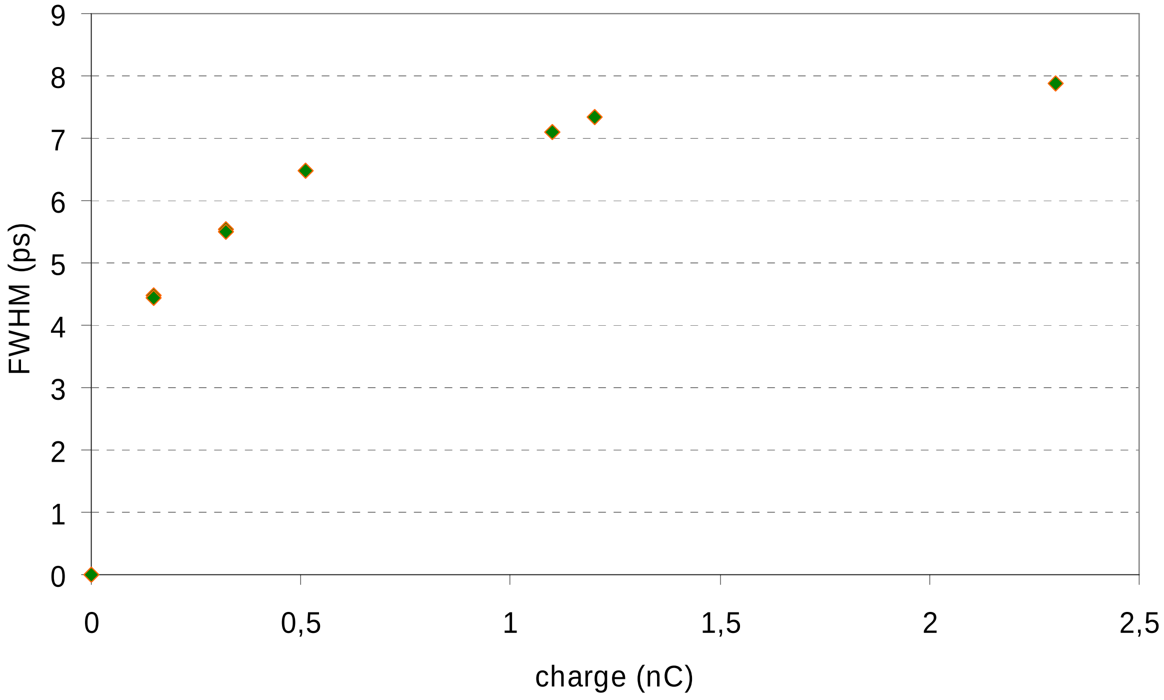


Figure 12. Electric field (electron bunch) duration versus bunch charge. Same parameters as in Fig. 11.

Influence of the laser pulse duration at the photocathode

In the context of laser pulse shaping for high brightness RF photoinjector, the duration of the laser producing the electron bunch has been varied from 120 fs to 1.5 ps. This was done by chirping the laser inside fused silica glass plates of different thickness (~ 250 fs/cm @ 266 nm). The plates, mounted on a translator, were placed on the 266 nm laser beam path, after the frequency tripling crystal (see Fig. 1). Thickness of 20, 40 and 60 mm were available, leading to laser pulse durations of about 120 fs (no silica), 0.5 ps, 1.0 ps and 1.5 ps. For each of these laser durations, measurements were also made at two charges: 0.15 and 2 nC. Figure 13 presents the electron bunch duration (measured with the EO device) versus the laser pulse duration at the photocathode.

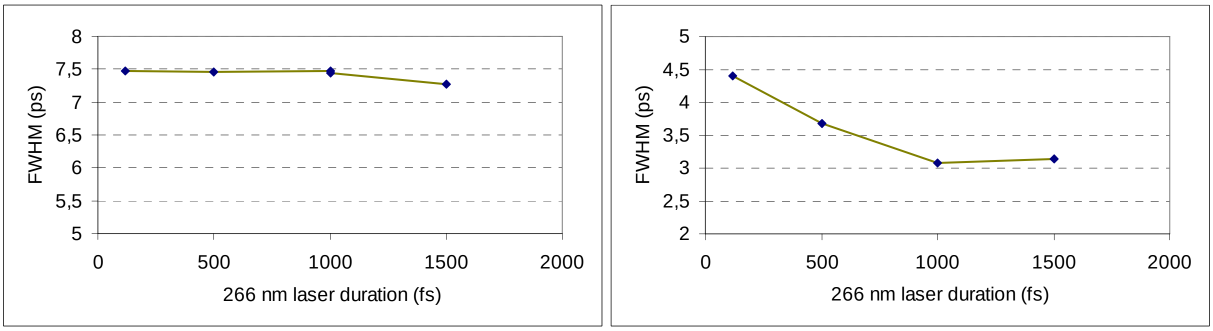


Figure 13. Variation of the electric field (electron bunch) duration with the duration of the 266 nm laser pulse at the photocathode, for high charge (left, 2 nC) and low charge (right, 0.15 nC).

At high charge (Fig. 13 left), the bunch duration does not depend (in the range we explored) on the laser pulse duration, and is always longer than this one. This is again an indication that the electron bunch duration is mostly dictated by space-charge. At low charge, the situation is different (Fig. 13-right). The bunch duration seems to become shorter as the laser pulse becomes longer. However, this behaviour is strongly influenced by the fact that as the laser duration was increased (putting more silica) the laser energy on the photocathode was decreased (laser absorption), so that the charge was decreasing form 150 pC (120 fs) down to 60 pC (1.5 ps). As we saw in Fig. 10, at these low charges the duration of the bunch rapidly decreases with its charge, so that concluding on the behaviour observed in Fig. 13 left is not obvious.

Conclusion

We have used the newly developed single-shot high sensitivity non-invasive electro-optic diagnostic described in the EUROFEL DS1 report [1] for single-shot characterization of the electrons bunches delivered by ELYSE. Even if the accelerator parameters were not offering the easier conditions (electron bunch duration of a few picoseconds, low electron relativistic factor, measurements made outside the beam pipe, large beam diameter leading to a large distance between the probe and the electron beams), the jitter measurement has been possible (0.9 ps peak-to-peak, or 0.22 ps rms). The influence on the electron bunch duration of various accelerator tunings have also been tested, such as : bunch charge, focussing current of the solenoid, laser pulse duration, or energy on the photocathode. These measurements demonstrate that the electron bunch temporal profile is very sensitive to the electron beam tuning.

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