ELECTRO-OPTICAL METHODS FOR MULTIPURPOSE DIAGNOSTICS

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Abstract

Electro-Optical Sampling (EOS) based temporal diagnostics allows to precisely measure the temporal profile of electron bunches with resolution of few tens of fs in a non-destructive and single-shot way. At SPARC_LAB we adopted the EOS in very different experimental fields. We measured for the first time the longitudinal profile of a train of multiple bunches at THz repetition rate, as the ones required for resonant Plasma Wakefield Acceleration (PWFA). By means of the EOS we demostrated a new hybrid compression scheme that is able to provide ultra-short bunches ($<$ 90 fs) with ultra-low ($<$ 20 fs) timing-jitter relative to the EOS laser system. Recently we also developed an EOS system in order to provide temporal and energy measurements in a very noisy and harsh environment: the electrons ejected by the interaction of a high-intensity (hundreds TW class) ultra-short(35 fs) laser pulses with solid targets by means of the so-called Target Normal Sheath Acceleration (TNSA) method.

INTRODUCTION

The research activity of the SPARC_LAB test-facility [1] (LNF-INFN, Frascati) is currently focused on advanced acceleration techniques for electrons, protons and heavier ions. The demand to accelerate particles to higher and higher energies is currently limited by the effective efficiency in the acceleration process that requires the development of large facilities. By increasing the accelerating gradient, the compactness can be improved and costs reduced.

For the acceleration of electrons, the technique that guarantees gradients of the order of GV/m relies on plasma acceleration [2, 3]. In this case a *driver* pulse, consisting in an electron bunch (Plasma Wakefield Acceleration, PWFA) or a laser pulse (Laser Wakefield Acceleration, LWFA), excites a wakefield in a plasma. Such wakefield is then used in order to accelerate electron coming directly from plasma (so-called self-injection schemes [4–6]) or a subsequent *witness* bunch, externally injected by a linac [7, 8]. Both in the particle and laser driven schemes, ultra-short bunches are required in order to produce larger wakefields and avoid an excessive growth of emittance and energy spread. In the latter one, in particular, a very demanding task is represented by the synchronization between the laser and the witness bunch, that requires relative timing-jitters of the order of few femtoseconds [7].

In the field of protons and ions acceleration, energies in multi-MeV range have been obtained in the past decade by means of the so-called Target Normal Sheath Acceleration (TNSA) method [9–11], in which an high-intensity short-pulse laser interacts with solid targets. The typical timescale for particle emission is on the sub-picosecond level but so far no direct and time-resolved measurement was able to determine the exact mechanism of the acceleration process and cross-check the developed theoretical models [12].

From the previous considerations it follows that precise time-resolved measurements with sub-picosecond resolution are of great interest for different aspects of particle acceleration. In the following we report about the use of electro-optic methods in such fields, showing that it represents a valuable tool for a deeper understanding of the physical processes involved.

TEMPORAL MEASUREMENT FOR TRAINS OF ELECTRON BUNCHES

The Electro-Optical Sampling (EOS [13]) is a temporal diagnostics that allows to measure the bunch longitudinal charge distribution by means of nonlinear crystals like ZnTe and GaP. Being a single-shot and non-intercepting device able to provide temporal resolution of the order of few tens of fs [14, 15], it is widely used in accelerator facilities [16–19]. Its working principle relies on the electro-optic (or Pockels) effect induced in such crystals by the Coulomb field generated by a relativistic bunch. The crystal becomes birefringent, i.e. characterized by two refractive indices $n_{1,2}$ along its principal optical axes. If at the same time a linearly polarized laser crosses the crystal, the crystal birefringence makes its polarization elliptical, i.e. the two orthogonal components of the laser electric field cumulate a relative phase delay given by

$$\Gamma(t) = \frac{\omega_L d}{c}(n_1 - n_2) \propto E_b(t)\,, \qquad (1)$$

where ω_L is the laser central frequency and d is the crystal thickness. From eq. 1 it follows that the bunch temporal profile $E_b(t)$ is imprinted on the phase delay $\Gamma(t)$.

At SPARC-LAB facility we used Ti:Sa IR laser (λ = 800 nm, 70 fs rms pulse duration) in order to measure the longitudinal profile of a 110 MeV comb-like electron beam [20] consisting in two consecutive bunches of 80 pC delayed by 800 fs. The laser is directly derived from the photo-cathode laser system, resulting in a natural synchronization with the electron beam. The bunch longitudinal profile is retrieved by means of the spatially encoding technique [18], in which the laser crosses the nonlinear crystal with an angle of 30°.

Fig. 1(a) shows an electro-optic signal measured by using a 100 μm-thick GaP crystal. By projecting the signal along

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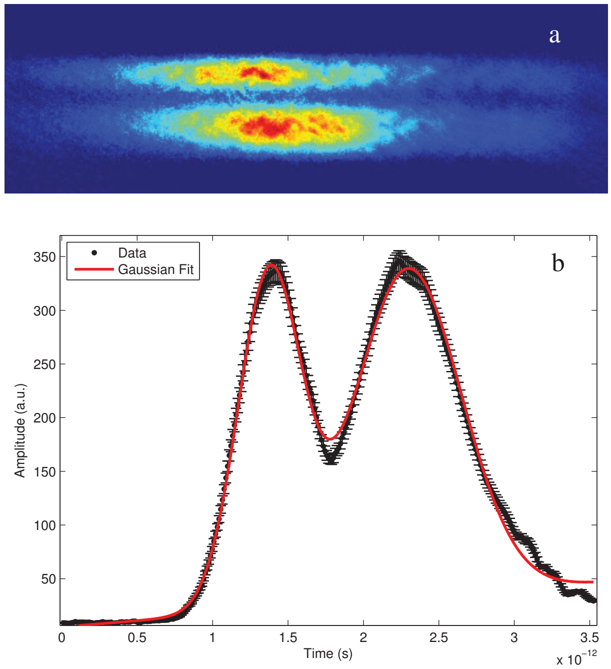

Figure 1: (a) Electro-optic signal of a comb-like bunch obtained with a 100 μm-thick GaP crystal. (b) Corresponding temporal profile obtained by projecting the signal in (a).

the vertical axis, the time profile of fig. 1(b) is obtained. A Gaussian fit has been calculated on such profile, resulting in bunch durations of 160 fs and 200 fs (rms), in agreement with results obtained with a RF-Deflector device [21]. This represents the first measurement done with the EOS diagnostics of an electron beam consisting in multiple bunches.

TIME-OF-ARRIVAL MONITOR

As anticipated, one of the most stringent requirements regarding the external injection of a linac-accelerated witness bunch in a laser-driven plasma accelerator concerns the ultra-low timing-jitter between the ultra-short bunch and the laser pulse. For instance, with plasma densities of $n_e \approx 10^{17}$ cm^{-3} (corresponding to 30 GV/m peak accelerating field) the timing-jitter must be below 30 fs, i.e. much smaller than the plasma oscillation period. Recently we demonstrated a new hybrid compression scheme able to simultaneously compress the bunch duration and reduce its arrival timing-jitter (ATJ) relative to the photo-cathode (PC) laser [22]. Our results prove that bunches with duration below 90 fs (rms) and relative ATJ lower than 20 fs (rms) can be obtained by combining RF-based compression by velocity-bunching (VB) with magnetic compression (MC) in a non-isochronous dogleg line. The proposed method could be of great interest for all experiments foreseeing a fs-level synchronization between an electron beam and a laser pulse, as seeded-FEL [23] and x/γ-rays production by Thomson scattering [24, 25].

The underlying principle for the simultaneous bunch compression and relative ATJ reduction relies on the differences in dynamics between particles in the same bunch and bunches in different shots. By means of the hybrid scheme we used VB in order to shorten the duration of the low energy (5.3 MeV) beam exiting from the gun. In these conditions space-charge forces strongly affect the beam LPS. On the contrary, the time-of-flight and mean energy are not perturbed. Starting from the gun, the bunch time of arrival is mainly linked to the release time from the cathode but after VB compression its timing is strongly linked to the RF field phase-jitter. It follows that at the end of the linac the bunch is no more linked to the PC laser timing. The measured jitter is in this case $\sigma_t \approx 60$ fs. At this point, the correlation between the PC laser and the time-of-flight is restored by the dogleg. The different dynamics between the bunch inner structure and its longitudinal centroid allows us to reduce the ATJ relative to the PC laser in the dogleg while preserving its duration. Fig. 2 shows the bunch time-of-arrival measured with an EOS system installed at the end of the dogleg line. Since the employed probe laser is directly split from the PC laser system, the histogram represents the relative timing-jitter between the bunch and PC laser. By collecting 330 consecutive shots, the resulting ATJ is $\sigma_t \approx 19$ fs, about three times smaller than the one obtained at linac exit. The bunch duration downstream the dogleg is about 86 fs. Measurements on the bunch duration, conducted both at the end of the linac and the dogleg, show that it is possible to take control of the longitudinal beam dynamics while reducing down to about 19 fs(rms) the relative ATJ between the electron bunch and the external PC laser system.

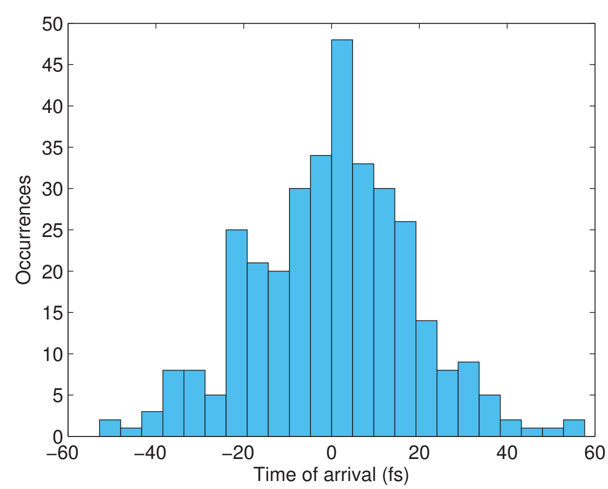

Figure 2: Collected time of arrival for 330 consecutive shots measured by the EOS. The resulting ATJ is $\sigma_t \approx 19$ fs.

TEMPORAL EVOLUTION OF THE ACCELERATING FIELD IN TNSA PROCESS

The interaction of a high-intensity short-pulse laser with thin solid targets [26, 27] generates jets of electrons that are emitted by the target and positively charge it, leading to

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the formation of the electrostatic potential that in turn governs the ion acceleration [9–11] in the TNSA process [28]. The typical timescale of such phenomena is on the sub-picosecond level. So far only indirect evidences of the escaping electron component have been recorded but a detailed and time-resolved study of the release mechanism has not been carried out yet. We employed the Electro-Optical Sampling diagnostics also in this field with the goal to measure the energy and temporal evolution of the ejected electrons.

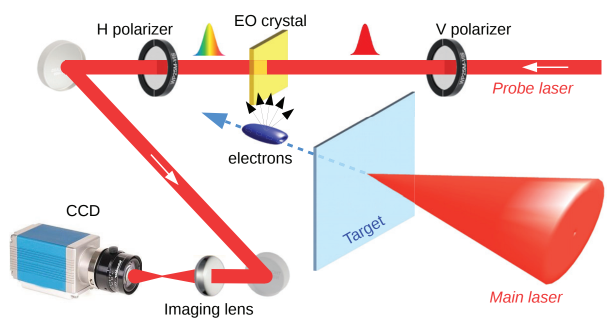

Figure 3: Setup of the experiment. The FLAME laser is focused on a metallic target that ejects electrons. The EOS diagnostics, based on a ZnTe crystal located 1 mm downstream the target, measures the temporal profile of the emitted electrons by means of an ultra-short probe laser.

The experiment was carried out with the FLAME laser at SPARC_LAB. It consists a 130 TW Ti:Sapphire laser system delivering 35 fs (FWHM), up to 4 J pulses at 800 nm central wavelength and 10 Hz repetition rate. The laser beam was focused $f/10$ off-axis parabolic mirror with focal length $f = 1$ m. The setup of the experiment is shown in Fig. 3. Once the electron cloud is emitted by the target, its temporal charge profile is spatially imprinted along the transverse profile of the probe laser, temporally synchronized with the electrons in correspondence of the ZnTe crystal.

A typical electro-optic signal is shown in fig. 4(a). The geometry of our EOS setup (the bunch is moving below the crystal and normally to it while the probe laser propagates laterally from right to left) determines the curved shape of the retrieved signals. The snapshots show that the escaping energetic electrons present a secondary broadened temporal structure, as reported in fig. 4(b). The first emitted bunch has approximately 1.2 nC charge and it is followed by a second broadened structure carrying a larger amount of particles (about 3 nC). The delay between the two structures is about 1.5 ps. This result represents the first measurement with sub-picosecond resolution ever done of the fast electron component released in laser-matter interactions.

CONCLUSIONS

Electro-Optical sampling represents a valuable tool allowing to measure the temporal profile of particle beams with high temporal resolution. The results presented here show that it can be adapted to very different experimental conditions. Its non-destructive feature is a key requirement

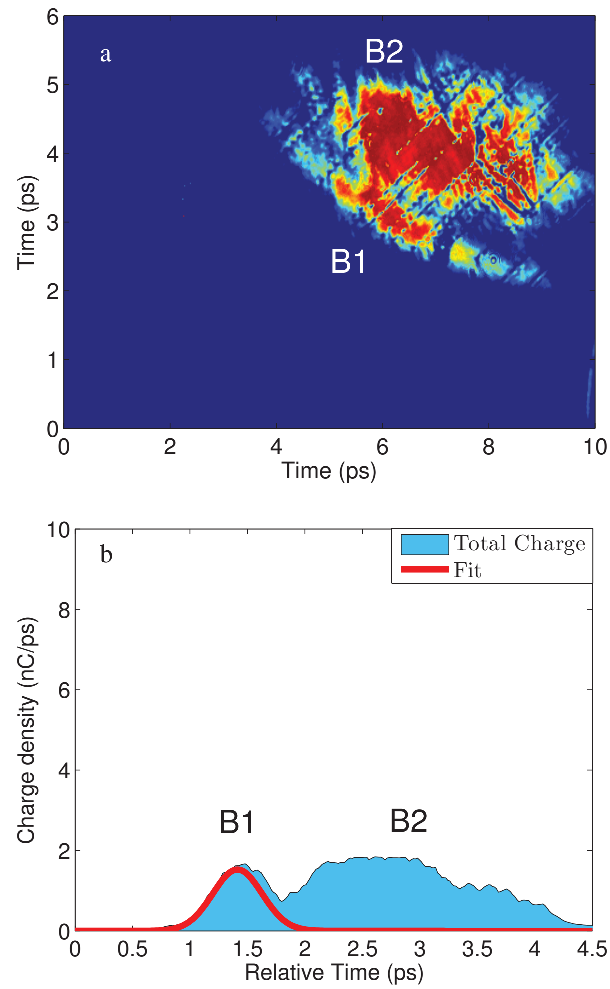

Figure 4: (a) Signature of the escaping electrons from target. The emitted charges are, respectively, 1.2 nC (B1) and 3 nC (B2). The gaussian envelopes represent the extrapolated charge profiles of each bunch. (b) Corresponding longitudinal charge profiles.

for a temporal diagnostics that has to be used to monitor, for instance, the injection of electron beams (consisting in multiple bunches) in a beam-driven plasma accelerator. Being single-shot, it allows to measure the time of arrival of electron beams with respect to the employed laser in order to estimate the overall timing-jitter. Finally, it can provide time-resolved measurements in laser-driven experiments as, for instance, the interaction of high intensity laser with solid targets, in order to fully understand the physical process of TNSA.

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