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First single-shot and non-intercepting longitudinal bunch diagnostics for comb-like beam by means of Electro-Optic Sampling

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ABSTRACT

At SPARC-LAB, we have installed an Electro-Optic Sampling (EOS) experiment for single shot, non-destructive measurements of the longitudinal distribution charge of individual electron bunches. The profile of the electron bunch field is electro-optically encoded into a Ti:Sa laser, having 130 fs (rms) pulse length, directly derived from the photocathode's laser. The bunch profile information is spatially retrieved, i.e., the laser crosses with an angle of 30° with respect to the normal to the surface of EO crystal (ZnTe, GaP) and the bunch longitudinal profile is mapped into the laser's transverse profile. In particular, we used the EOS for a single-shot direct visualization of the time profile of a comb-like electron beam, consisting of two bunches, about 100 fs (rms) long, sub-picosecond spaced with a total charge of 160 pC. The electro-optic measurements (done with both ZnTe and GaP crystals) have been validated with both RF Deflector (RFD) and Michelson interferometer measurements.

1. Introduction

Single-shot and non-intercepting bunch length measurements with 50 fs order resolution are of high interest for future plasma-based accelerators, in order to monitor the beams to be injected in the plasma. In particular, the particle-driven wakefield acceleration (PWFA) require multi-bunches schemes where two or more subsequent bunches, sub-100 fs long and sub-picosecond spaced, can enhance the plasma transformer ratio R and generate the proper accelerating field [1] able to accelerate the last one with low energy spread [2].

The technique of electro-optical sampling (EOS) [3] provides the possibility of measuring the longitudinal charge distribution by means of nonlinear crystals placed near the moving electron beams and it is able to reach high temporal resolutions, determined by the width of the optical laser pulse and the EO crystal length. The working principle is based on the induced birefringence in a nonlinear crystal (like ZnTe and GaP) by the high electric fields of the relativistic electron bunch (with temporal profile $E_{bunch}(t)$), which propagate in the crystal like a THz-field [4] (see Fig. 1). Since the crystal becomes anisotropic (biaxial), the electric field of a polarized laser passing in the crystal is decomposed along the two optical axes, with characteristic refractive indices $n_i = n_1, n_2$. Because the two components travel at different velocities $v_i = c/n_i$, at the end of the crystal their relative phase delay Γ is

$$\Gamma(t) = \frac{\omega d}{c}(n_1 - n_2) \propto E_{bunch}(t) \quad (1)$$

where ω is the laser's pulse frequency and d is the crystal thickness. Therefore the time information contained in $\Gamma(t)$ is a replica of $E_{bunch}(t)$.

At the SPARC-LAB facility [5] (see Fig. 2) a Ti:Sa IR laser ($\lambda = 800$ nm, 130 fs pulse length, rms) is used to sample the birefringence which is induced in the nonlinear optical crystal by the co-moving electric field of a 110 MeV electron bunch. The laser is directly derived from the photocathode's one, resulting in a natural synchronization with the electron beam, having a repetition rate of 10 Hz. The initial linear polarization of the laser pulse is converted into a slightly elliptical polarization which is then converted into an intensity modulation by placing a polarizer after the crystal, with its polarization axis rotated by 90° with respect to the initial laser polarization. To encode the bunch longitudinal profile into the laser, we used the spatially encoding EOS technique [6], in which the laser crosses the nonlinear crystal with an

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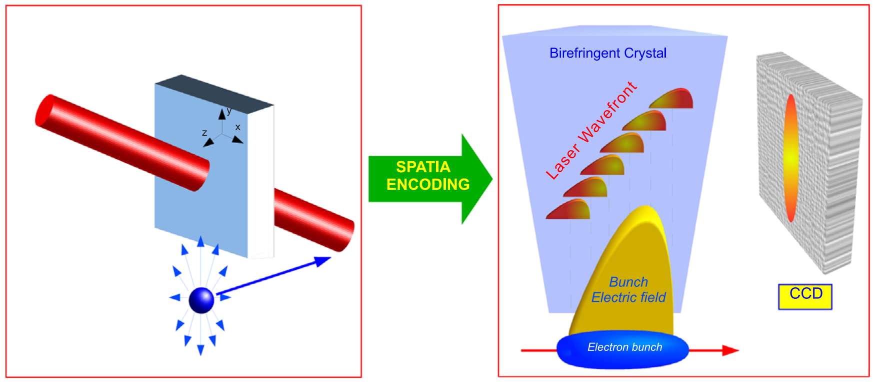

Fig. 1. Spatial decoding for the Electro-Optic Sampling. The laser crosses the EO crystal with angle $\theta = 30^\circ$. By inserting a polarizer whose axis is 90° with respect to the laser linear polarization, the longitudinal bunch profile is directly retrieved on the CCD.

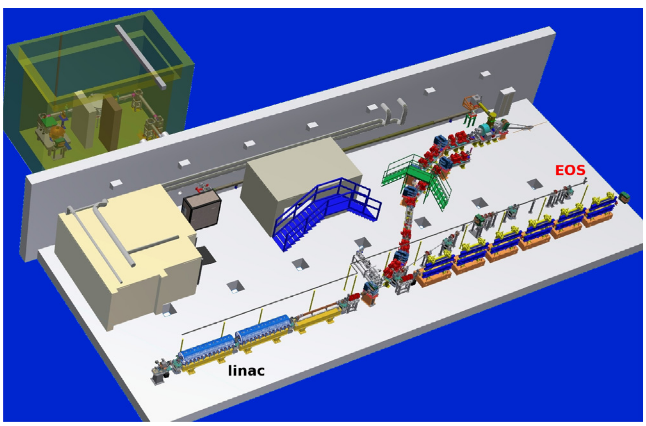

Fig. 2. SPARC-LAB layout. The EOS station is located at the end of the 2nd beamline.

angle of $\theta = 30^\circ$ (see Fig. 1). In such a way, being x the spatial coordinate along the laser transverse profile and t the time coordinate for the longitudinal bunch profile, we have

$$t = \frac{x}{c} \tan\theta \tag{2}$$

where c is the vacuum speed of the light. From Eq. (2), the total time window Δt is directly proportional to the laser's spot diameter d, i.e., $\Delta t = (d/c)\tan\theta$. In the presented measure, a 5 mm wide laser has been used, resulting in a time window of about 10 ps.

Previous accelerator-related EOS experiments have been carried out at FELIX [7], DESY [8] and SLAC [9], in each of which the EOS has been tested on a single (short or long) electron bunch. Here we report the recent results achieved at SPARC-LAB measuring, for the first time, the longitudinal profile of comb-like beams, consisting of two bunches, about 100 fs (rms) long, sub-ps spaced with a total charge up to 160 pC.

2. Two bunches comb-like beam at SPARC-LAB

The comb-like beam consists of two approximately equal electron bunch, generated by properly shaping trains of UV laser pulses illuminating the metallic photo-cathode in the RF gun [10]. A diagnostics transfer line allows to fully characterize the accelerated beam by measuring transverse emittance [11] and the longitudinal profile through a Radio-Frequency Deflector (RFD) [12], located at the linac exit. Fig. 3(a) and (b) shows, respectively, the longitudinal phase space and the corresponding longitudinal profile for a 160 pC total charge beam. The two consecutive

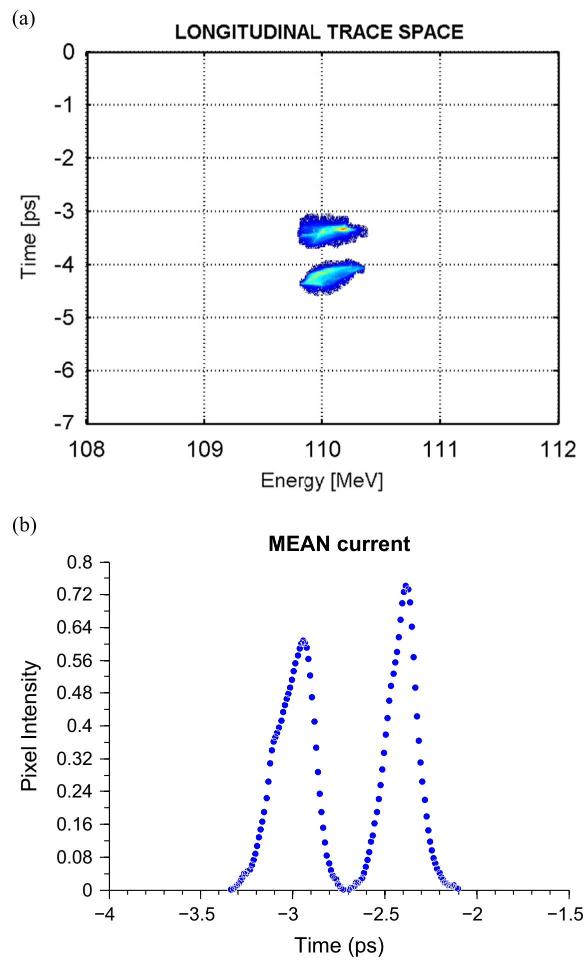

Fig. 3. (a) Longitudinal phase space retrieved by using a RF Deflector (time) and a bending magnet (energy) of a comb beam consisting of two consecutive bunches with a mean energy of 110.0 ± 0.1 MeV, with a total charge of 160 pC (77 pC and 83 pC for each bunch). (b) Projected profile (along the time axis), resulting in bunch lengths of 100 ± 12 fs and 70 ± 17 fs (both rms), separated by 846 ± 15 fs.

bunches have lengths of 100 ± 12 fs and 70 ± 17 fs (rms), with respective charges of 77 ± 6 pC and 83 ± 7 pC, separated by 846 ± 15 fs with a mean energy of 110.0 ± 0.1 MeV.

Because the EOS station is located at the end of a dogleg transfer line, we have to take care to the fact that the longitudinal phase space evolution in the dogleg is dominated by nonlinearities given by high order chromatic terms [13,14]. In order to evaluate the bunch properties after this line, a Michelson interferometer, analyzing the coherent transition radiation (CTR) from an