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BEAM DYNAMICS STUDIES AND INSTRUMENTATION TESTS FOR BUNCH LENGTH MEASUREMENTS AT CLEAR

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Abstract

A new CERN Linear Electron Accelerator for Research (named CLEAR) has been installed as a general-purpose user facility to study novel accelerating techniques, high-gradient structures, instrumentation and irradiation experiments. CLEAR is a flexible accelerator that can provide high quality bunched electron beams with a wide range of beam parameters up to an energy of 220 MeV, offering several testing capabilities. Among all the potential applications, novel accelerating techniques, such as plasma acceleration and THz generation are considered. These applications require shorter bunches, down to the 100 fs level. This paper reports on beam dynamics studies and instrumentation tests to establish a bunch length of this order in CLEAR. The short bunches are generated using adiabatic bunching in the first accelerating structure. For bunch length diagnostic, CLEAR is equipped with a streak camera and a transverse deflecting cavity. Alternatively, a phase-scan of the last accelerating structure could be used as well to estimate the bunch length. The experimental results with respect to these different techniques are presented and compared with simulations.

INTRODUCTION

CALIFES (Concept d'Accélérateur LInéaire pour Faisceau d'Electron Sonde) [1] represented the electron probe beam injector for the CLIC Test Facility 3 (CTF3) [2] at CERN. Recently, this accelerator has been refurbished as a new general-purpose user facility for accelerator R&D and components tests for existing and future accelerator applications. CLEAR [3, 4] can provide high quality bunched electron beams from 60 to 220 MeV in single or multi-bunch configuration with a bunch spacing of 1.5 GHz. The test accelerator exhibits a broad range of capabilities, such as prototyping and validation of accelerator components (for the Large Hadron Collider upgrade and its injector), high-gradient acceleration studies (normal-conducting X-band structures), irradiation of electronic components and medical applications. Furthermore, novel concepts as plasma acceleration and THz generation [5] could profit from the CLEAR beam line optimized for short bunches and low emittance beyond the current performances achieved by the CALIFES photo-injector, in the past. The improvement of the electron bunches quality in terms of length and emittance would also be beneficial to AWAKE (Advanced WAKEfield Experiment) [6], which will need a new short-pulse electron source in view of the "Run 2" phase. Therefore, beam dynamics studies and instrumentation tests have been performed for both determining an accelerator injection configuration that allows bunch lengths less than 1 ps and its subsequent experimental measure.

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CLEAR LAYOUT AND DIAGNOSTICS

The accelerator is composed of the CALIFES injector (around 25 meters-long), which provides the electron beam to a subsequent 16 meters-long diagnostics and test lines. The electron photo-injector is composed of a 2.5-cell S-band RF gun [7] where the electrons are extracted and accelerated from a Cs_2Te cathode when illuminated by laser pulses. Two solenoids surround the gun for space charge emittance compensation. The RF gun is able to provide electron bunches with an energy of around 6 MeV, then three S-band LIL (LEP Injector Linac) [8] accelerating sections allow to boost the beam energy up to 220 MeV. An Integrated Current Transformer (ICT) [9] and a ceramic screen are installed right after the RF gun, for beam diagnostics. The first structure can be used to compress the bunch by using the velocity bunching technique. A matching section with a quadrupole triplet and a spectrometer line complete the accelerator. An S-band RF deflecting cavity is also installed along the beam line (Fig. 1). Bunch length measurements are possible by streak camera measurements [10] of Optical Transition Radiation (OTR) or by using an S-band RF deflecting cavity [11]. A transverse beam profile monitor [12] equipped with a Yttrium Aluminium Garnet (YAG) scintillator and an OTR screen is installed before the spectrometer. An additional ICT and YAG screen in the spectrometer line complete the longitudinal beam diagnostic capabilities. The beam-line ends about 20 cm after the spectrometer dipole with a 100 μm-thickness aluminium window, leaving about 1 meter-long in-air test stand. This area hosts the main THz radiation diagnostics [13].

BEAM DYNAMICS MODEL

A train of laser pulses, each one a few ps length spacing, impinges the photocathode. The number of pulses that constitutes the train can be controlled remotely. The number of pulses in the train was set to two, for most of the measurements. The RF gun is surrounded by two solenoids, the focusing and bucking coils. Three dimensional simulations have been performed using the Opera-3D FEA software. The latter allows to obtain the on-axis longitudinal magnetic field profile along the beam axis. The right current values

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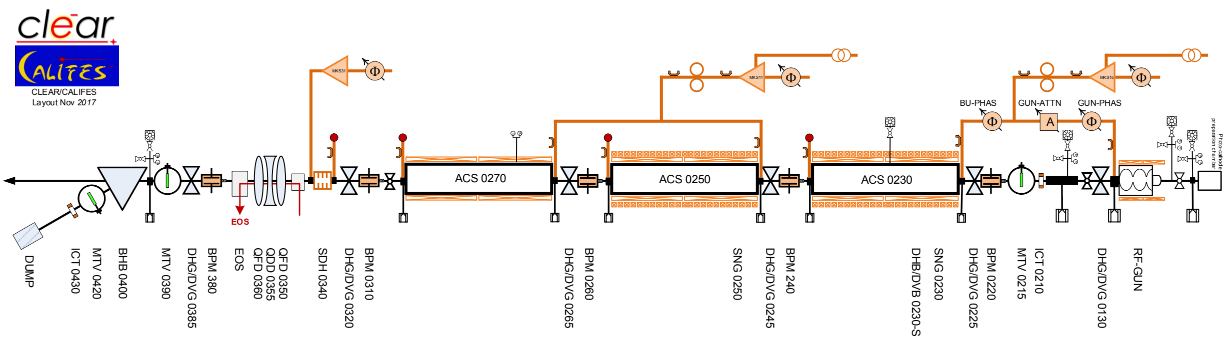

Figure 1: CLEAR accelerator layout.

of the coils is set in order to cancel the induced magnetic field (B = 0 T) at the photocathode location (z = 0 m). This allows to prevent beam transverse emittance degradation due to the residual angular momentum increase. The maximum current through the focusing coil can be set to 340 A. Also, the on-axis longitudinal electric field amplitude has been extracted from 2D Superfish simulation. These two field profiles are used as inputs for the tracking of electrons in the linac by ASTRA (A Space Charge Tracking Algorithm) [14] in order to have a close match between simulations and experimental data. Table 1 indicates the most relevant parameters that have been used for simulations.

Table 1: Simulation Parameters

Parameter	**Value**
Photocathode	Cs_2Te
Laser spot size $\sigma_{x,y}$	0.4 mm - Gaussian
Laser pulse duration σ_t	4 ps - Gaussian
Steerer position	0.305 m
ICT position	1.63 m
MTV position	1.825 m

We performed beam charge measurement using the ICT (see Fig. 2) as a function of the gun RF-phase. This so-called “phase scan” is usually used to characterize the electric field interacting with the photo-cathode triggering the charge extraction phenomenon. These experimental data are compared with the ASTRA beam dynamics model considering a gun peak accelerating fields of 90 MV/m and a suitable Schottky value. As we can see from Fig. 2 the ASTRA model is in good agreement with the experimental data for this set of parameters. Figure 3 shows the comparison between the experimental transverse beam size measured on the MTV screen at around 1.8 m after the cathode with ASTRA simulations. In this case, the trend of the simulated values looks in agreement with the experimental values. Some of the simulated values are within the experimental error bars. Even if the simulated position of the beam waist fits the experimental one, these values seem to underestimate the experimental values at the minimum.

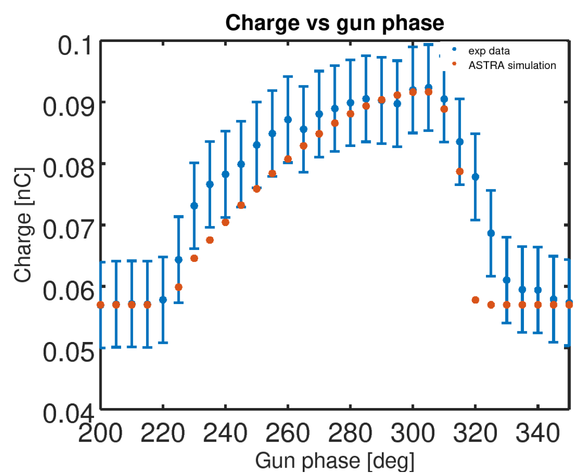

Figure 2: Comparison between the experimental extracted charge at ICT vs gun phase (blue line) and ASTRA simulation (orange line).

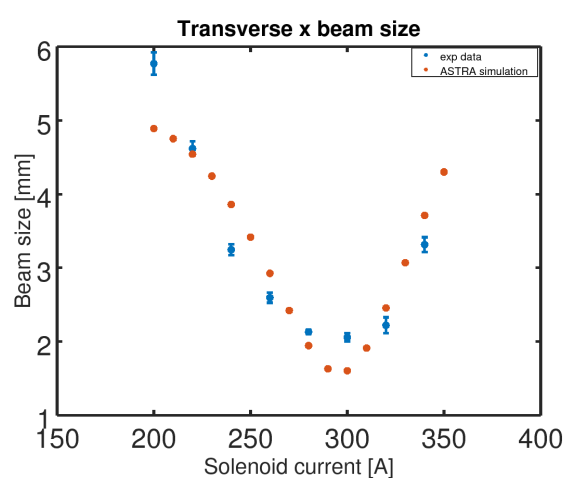

Figure 3: Comparison between the transverse beam size at ICT vs focusing solenoid current (blue line) and ASTRA simulation (orange line).

The discrepancy between the experimental data and simulations, especially at the minimum value, will be further investigated by improving the accuracy of the ASTRA model.

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BUNCH LENGTH MEASUREMENTS

The bunch length has been measured by different techniques aiming at testing the CLEAR instrumentation and potential for short bunches. First measurement has been performed by using an RF deflecting cavity, after the three accelerating sections. In Fig. 4, the data have been recorded for different gun-phases (blue) and compared with simulations (red). We considered a good match between measured and simulated charge as a reference for the gun-phases.

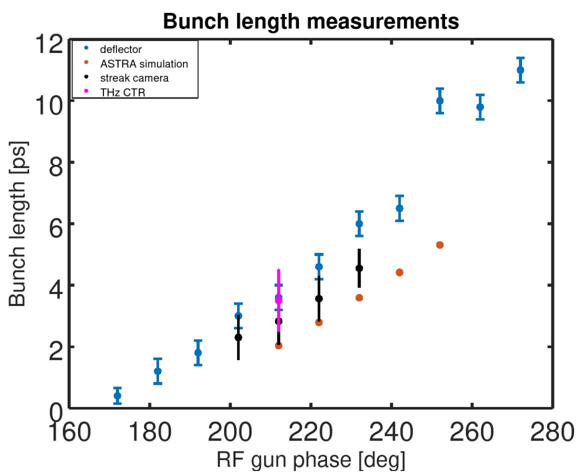

Figure 4: Bunch length experimental measurements with RF deflector, simulations, streak camera and THz radiation.

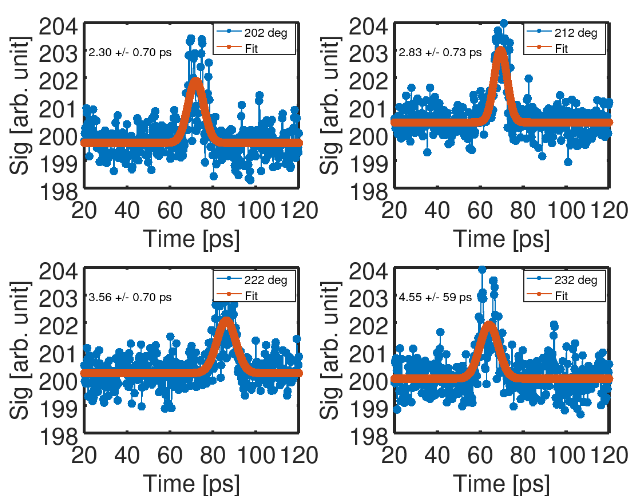

Figure 5: Bunch experimental temporal profiles recorded by the streak camera, for different RF gun phases.

Figure 5 shows the profiles recorded by the streak camera for measuring the bunch duration. By means of the Gaussian fit we can extrapolate the bunch length taking into account also the slit aperture contribution. As we can see from the Fig. 4, the bunch length values are in agreement with those obtained by the deflector measurements for the same gun phases. We point out that all measurements with the streak camera have been taken with band-pass filter (centered at 450 nm, 35 nm bandwidth) and that experimental errors have been evaluated doing statistics over tens of pictures for each gun phase. Moreover, the bunch length measurements have been performed with Coherent Transition Radiation (CTR) in the region of mm-waves (see Fig. 6). The data has been recorded wit a set of four zero-biased Schottky diodes each one coupled to a waveguide band–pass filter. The frequencies studied have been 36, 60, 72 and 84 GHz, respectively. A model has been used for fitting the data, taking into account the finiteness of the radiator (Aluminium disk, 10 cm diameter), the angular distribution of the CTR at the plane of the detectors and assuming that the bunch has a gaussian longitudinal shape. The bandwidth of the CTR spectrum is inversely proportional to the bunch length. Experimental errors come from shot-to-shot statistical fluctuations (measurements recorded with a train of twenty bunches), depending in turn on charge fluctuations and background noise from other metallic parts located on the table around the detectors. From Figure 5 the bunch length is 3.5 ± 1 ps in agreement with the value obtained by the RF deflector (3.6 ± 0.4 ps) for the same gun-phase (212 deg).

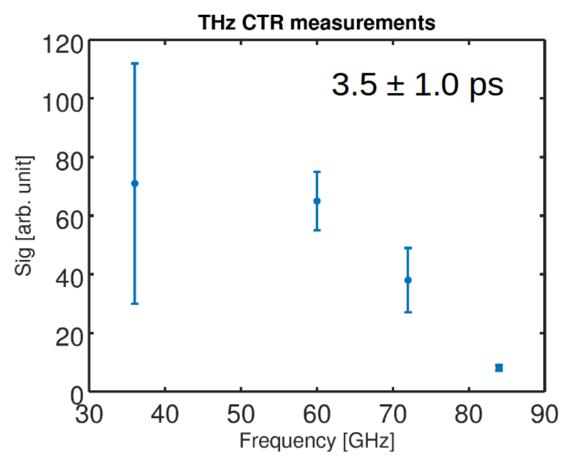

Figure 6: Bunch length experimental measurements from coherent transition radiation (CTR) recorded by zero-biased Schottky diodes.

CONCLUSION

The CLEAR user facility is devoted to R&D for accelerators and instrumentation in a broad range of applications. Beam dynamics studies, bunch length measurements and instrumentation tests have been carried out. The ASTRA code has been used to perform simulations and their comparison with the experimental data demonstrated a promising starting point toward a solid tool for predicting the best configuration for very short electron bunches. Bunch length measures have been performed with three different techniques: RF deflecting cavity, streak camera and THz coherent transition radiation. Although the experimental data exhibit good agreement for different techniques, in order to produce electron bunches of length of 100 fs further improvements are needed.

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