ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-MOPB038

VARIABLE POLARIZATION SELF-LOCKED STREAKING OF ELECTRONS IN TIME WITH A PAIR OF CORRUGATED STRUCTURES

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Abstract

Corrugated structures have recently been utilized for the time-resolved diagnostics of electron bunches and free-electron-laser (FEL) pulses across several FEL facilities: SwissFEL at PSI and European XFEL at DESY. This approach is simple and cost-effective, based on the self-streaking of electrons with a transverse wakefield enhanced in such structures. In this work, we optimize the design of a corrugated streaker for the wide range of beam parameters of the CERN Linear Electron Accelerator for Research (CLEAR). We report on the fabrication of corrugated plates with various corrugation parameters and their initial installation for in-air measurements at CLEAR. Variable polarization streaking can be achieved either by mechanically rotating the plates or by utilizing two pairs of corrugated streakers. Additionally, we emphasize that when streaking in the vertical (or horizontal) direction with one structure, the undesired quadrupole wakefield can be compensated by the second orthogonally oriented streaker. This allows for a significant improvement in the resolution of the method.

INTRODUCTION

CLEAR is a user facility providing an electron beam with a wide range of parameters for user experiments, summarized in Table 1 [1–4]. The layout of the CLEAR beamline is shown in Fig. 1 featuring several Test Areas for the experiments. Characterization and control of the bunch length, temporal profile distribution, and longitudinal phase space of the electron bunch are of great importance for several user experiments. Currently, such diagnostics are realized by utilizing an S-band transverse deflector driven by a dedicated klystron. The transverse deflector has a footprint of around 20 cm, excluding the waveguides, and provides a temporal resolution of ~100 fs for 200 MeV electron beams when measuring the streaked beam at the MTV390 screen [5].

All test areas are located downstream of the transverse deflector and the first measurement screen. Therefore, non-invasive shot-to-shot online diagnostics of the bunch length are currently not available at CLEAR, although experiments could benefit from such capabilities. Moreover, temporal diagnostics may be of significant interest for monitoring beam properties in the second beamline planned to be implemented at CLEAR, using the bending magnet BHB0400 to direct the beam in the opposite direction from the Vesper Test Area. In this work, we explore a cost-effective and elegant approach of employing a corrugated passive streaker for temporal diagnostics, which was successfully implemented at SwissFEL [6] and EXFEL [7].

Table 1: CLEAR Beam Parameters

Parameter	Value
Bunch charge	0.005 – 1.6 nC
Bunch length RMS	0.1 – 10 ps
Beam Energy	30 – 220 MeV
Beam Energy Spread	< 0.2% rms (< 1 MeV FWHM)
Bunch frequency	1.5 or 3.0 GHz
Norm. emittance	1 – 20 µm
Bunches per pulse	1 – 150
Max. pulse charge	~90 nC
Repetition rate	0.8333 – 10 Hz

SIMULATION RESULTS

Each corrugated streaker installed at SwissFEL is approximately 1 m long, consisting of two pairs of corrugated streakers attached to micron-precision moving motors, with the entire setup integrated into a vacuum chamber [6, 8]. The approximate cost of a single unit is around 110 kCHF, which is roughly an order of magnitude less than that of an active C-band or X-band deflecting cavity with a power supply [6]. However, even this amount is still a significant investment for a single diagnostic system in a small medical accelerator or an electron linac at an irradiation facility such as CLEAR.

In comparison to the 6 GeV beam energy at SwissFEL, the maximum beam energy at CLEAR is limited to 200 MeV. For this energy, and considering that the shortest bunch length at CLEAR is approximately 100 fs, we optimized the design of the corrugated plates to minimize production cost and footprint. Another characteristic worth comparing is the active S-band deflector installed at CLEAR, which is approximately 20 cm long, excluding the waveguides and power supply system. We performed a series of numerical simulations assuming a corrugated plate length of only 10 cm and validated that the streaking effect, even for the shortest bunches at CLEAR, is well-pronounced and would enable reconstruction of the temporal profile of the electron bunch with a resolution similar to that of the active S-band deflector.

Figure 2 shows the results of numerical simulations at a measurement screen placed 0.5 m downstream from the corrugated streaker. In these simulations, we use the analytical model from [9] for plates with 500 µm corrugation,

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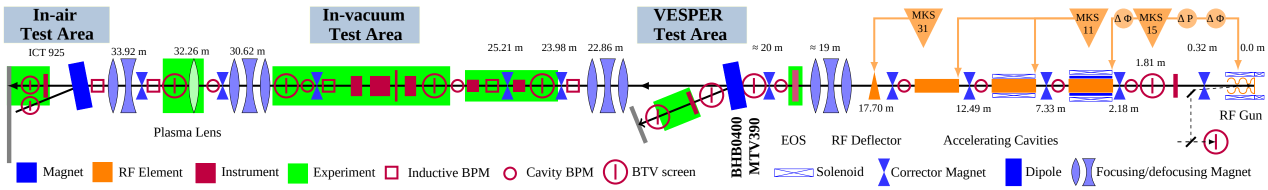

Figure 1: Schematic of the CLEAR layout featuring three test areas for user experiments. In the diagram, the beam travels from right to left.

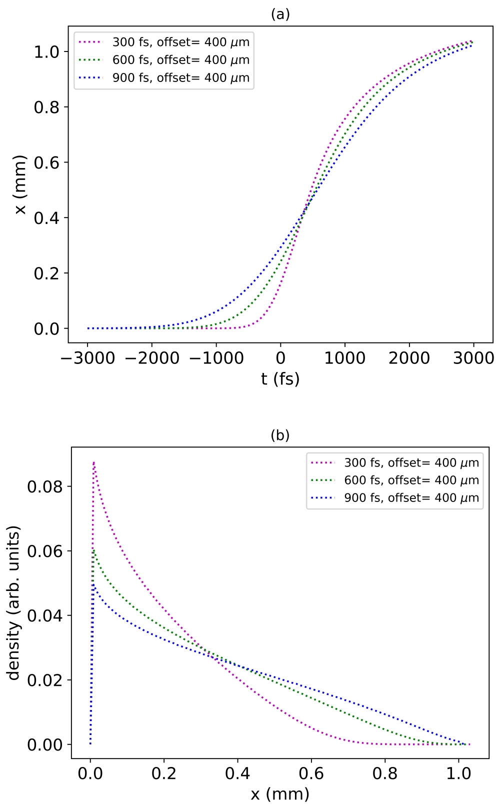

Figure 2: Simulation results for the corrugated streaker with 500 µm corrugation: (a) mapping of time, t, to the horizontal coordinate, x, at the measurement screen located at 0.5 m from the passive streaker plate; (b) predicted profile at the measurement screen for the corresponding cases.

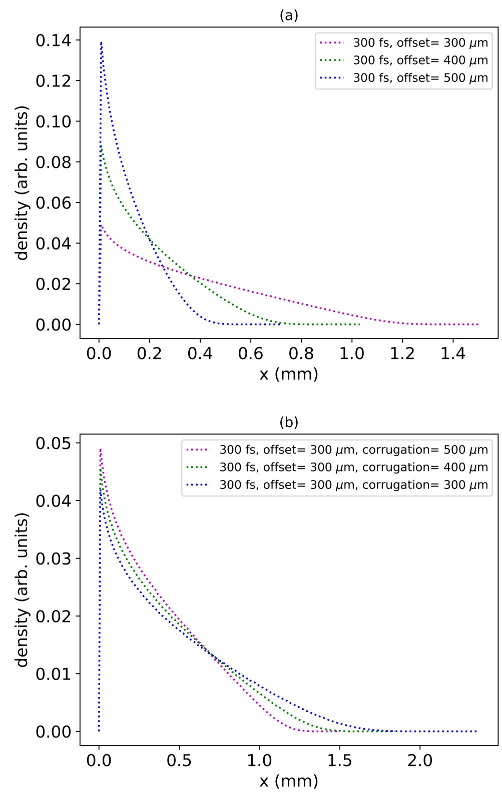

Figure 3: Predicted profile at the measurement screen: (a) for 500 µm corrugation and different offsets of the beam; (b) for various corrugation parameters.

assuming a Gaussian electron beam with a 300 pC charge at 200 MeV energy for various bunch lengths. Figure 2 (a) depicts the longitudinal-to-transverse mapping of the temporal coordinate onto the measurement screen. Using this mapping, the predicted streaked transverse profiles for different bunch durations, while neglecting the natural transverse beam size, are shown in (b). Even for a short bunch of 300 fs, the streaked size is larger than the typical natural beam size (~100 µm), suggesting that the 10 cm long corrugated plate placed 400 µm from the beam would provide sufficient resolution capabilities.

The dependence of the streaking effect on the distance between the beam and the corrugated plates is shown in Fig. 3 (a). The corrugation depth and half-period of 500 µm were initially chosen to simplify and reduce the cost of mechanical fabrication by enabling the use of widely available simple milling methods. A corrugation depth of 300 µm can still be relatively easily achieved at the CERN Mechanical Workshop without a significant price increase. Figure 3 (b) shows that using plates with 300 µm corrugation would be more beneficial for shorter bunches than the 500 µm counterpart in enhancing the streaking effect.

Two pairs of corrugated plates with corrugation parameters of 300 and 500 µm were fabricated in the CERN Mechanical Workshop in July 2024 at minimal cost, according to the mechanical drawings shown in Fig. 4. The M4 threaded holes, distributed along the plates, allow for easy attachment to electro-mechanical moving stages for in-air installation. With dimensions of only 40 mm in width and 10 mm in thickness, the plates can be easily accommodated in a standard vacuum pipe. Connection to in-vacuum micron-precision motors is planned through a standard, commercially avail-

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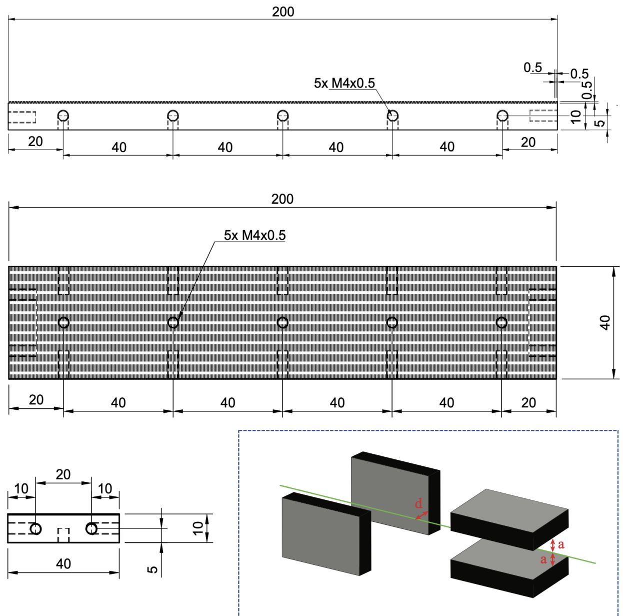

Figure 4: Mechanical drawings for the corrugated plates with 500 µm corrugation and the schematic of the installation of the two pairs of the corrugated streakers to compensate undesired quadrupole effects.

able vacuum cross fitting aligned with the center of the plate. If there is a need to adjust the tilt of the plates with respect to the beam axis, a pair of moving motors can be attached to opposite sides of the plates to facilitate this adjustment.

Variable polarization streaking in air can be achieved by mechanically rotating a single plate with respect to the beam axis. This would require an advanced moving stage or a combination of several moving stages. Alternatively, especially for in-vacuum installations, streaking in any arbitrary direction in the transverse plane can be achieved by using a linear combination of two orthogonally oriented plates. These simple modifications, combined with a series of quadrupole magnets and a dispersive section for energy measurements, can enable multi-dimensional phase space reconstruction similar to that demonstrated with the highly advanced active deflector system, PolariX [10, 11].

In addition, numerical simulations (not shown) of the quadrupole wakefield from a single plate offset at a distance d from the beam, as well as from two orthogonally oriented plates centered with respect to the beam and having a semi-gap a, as schematically shown in Fig. 4, suggest that nearly complete compensation of the quadrupole effects on the beam is possible with this configuration. This will significantly improve the temporal resolution of the method by maximizing the transverse beam size at the streaker location while simultaneously reducing its angular divergence.

INITIAL EXPERIMENTAL RESULTS

Immediately after fabrication, a single corrugated plate with 500 µm corrugation was installed in Vesper in-air Test Area for initial tests with a horizontal orientation for streaking in the vertical plane, as shown in Fig. 5. Moving the corrugated plate closer to the beam path resulted in a small but observable streaking effect at the energy spectrometer screen located in the close proximity to the streaker end. Due to small distance to the screen, various undesirable effects from the bending magnet vacuum chamber, dispersion effects as well as limited time, we did not performed systematic studies at this location. After the summer shutdown, we anticipate moving the plates to the In-Air Test Area (which was originally occupied by other experiments) for systematic studies and to benchmark the simulation results with experimental measurements.

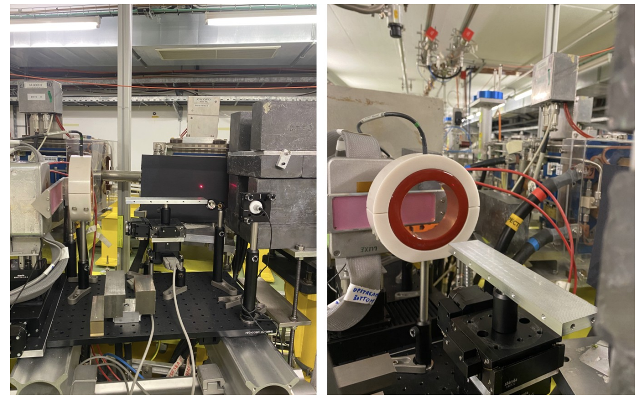

Figure 5: Photographs of a single corrugated plate with 500 µm corrugation installed in Vesper Test Area for initial tests.

DISCUSSION

Successful commissioning of the designed passive streaker, if installed at the end of the beamline, will enable online shot-to-shot diagnostics at CLEAR for upstream experiments.

Rotating a single corrugated plate along the beam axis will allow for variable polarization streaking, which can alternatively be achieved with a pair of corrugated streakers. According to simulation studies, compensating for the undesired quadrupole effects from the first streaker is feasible by adjusting the gap between the plates of the second streaker, which is oriented orthogonally. If confirmed experimentally, this would significantly enhance the resolution of the method, which is essential at lower beam energies where the projected emittance of the beam is quite large.

This design can be effectively adapted for existing irradiation facilities, future compact FEL facilities, and medical electron accelerators. Due to its compactness and cost-efficiency, it offers an elegant alternative to conventional active deflectors that require an RF power source for the temporal characterization of electron beams. In particular, if future experimental tests at CLEAR are successful, we strongly recommend incorporating a similar passive streaker for temporal diagnostics in the Deep Electron FLASH Therapy facility planned to be built and installed at the University Hospital of Lausanne (CHUV) [12].

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