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Phase sensitive monitoring of electron bunch form and arrival time in superconducting linear accelerators

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In this Letter, we present a simple approach for monitoring electron bunch form and arrival time combining electro-optic sampling and phase and frequency sensitive signal detection. The sensitivity of the technique has the potential to allow online diagnostics to be performed down to bunch charges in the femto coulomb regime. The concept has high impact for the developments of the next generation of 4th generation x-ray light sources working with long pulse trains or continuous wave mode of operation. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3699025]

In the past decade, a new class of accelerator based light sources, so called 4th generation of synchrotron radiation facilities, has become available (see Ref. 1 and references therein), which allow the generation of femtosecond x-ray pulses with an unprecedented peak brightness for ultra-fast experiments in atomic and molecular physics, life sciences, and materials science. In these facilities, ultra-short, highly intense x-ray pulses are emitted by highly charged electron bunches, accelerated in radiofrequency driven accelerators to relativistic energies. Whilst a number of these x-ray facilities are working as user facilities (for a summary of recent experimental results, see, e.g., Ref. 2), work on the next upgrade of these facilities has already started. One focus of the planned developments is to increase the average brilliance of these sources by making use of superconducting radio frequency (RF) technology.[3,4] Thereby, repetition rates can be scaled from the present few hundred Hz to the few ten kHz and even GHz regime. Another focus of the efforts lies currently on the reduction of the x-ray pulse duration down to the few femtosecond (fs) level, which requires lowering the electron bunch charge by orders of magnitude.[5]

These new modes of operation ultimately require new approaches for the electron bunch diagnostic in particular concerning their form and arrival time as the presently available diagnostic approaches fall into two different groups, neither of which fit the requirements. Group one consists of bunch diagnostics developed for use at electron storage rings. Here, moderately short electron bunches, scaling from few hundred to few ps, at high repetition rate are typically analyzed by mean values of their properties, e.g., recording beam current instead of electron bunch charge. The developed techniques to determine bunch forms, e.g., streak cameras or analysis of the emitted coherent THz radiation,[6] provide the required sensitivity for low charges but lack the necessary femtosecond resolution. Arrival time measurements are typically not performed. Group two contains the diagnostics developed at the linear accelerators used to drive x-ray free electron lasers (FELs). Here, development has focused on single shot analysis of the arrival time and form of individual electron bunches. Although the available concepts (including electro-optic sampling techniques,[7,8] beam based arrival time monitors,[9] and transverse deflecting cavities[10]) are mature and much more diverse than at storage rings facilities, none of the concepts combines the required femtosecond resolution for form and arrival time with the necessary sensitivity for low charges. To this end, the large superconducting accelerator facilities like the European X-FEL (Ref. 3) or various energy recovery linacs[4] coming online in the next years require few femtosecond resolution of such diagnostics for form and arrival time for bunches with charges ranging between few pico coulomb and few hundred femto coulomb. Most importantly, these facilities will require robust schemes to control and feedback the accelerator online by utilizing appropriately designed error signals.

Our technique, developed at the prototype continuous wave superconducting RF (SRF) accelerator ELBE,[11] represents a robust solution for an arrival time feedback working with a time resolution of few hundred fs, on millisecond timescales and with low bunch charges. It is based on an adaption of the electro-optic based monitors for arrival time and bunch form measurements[7] to the requirements of superconducting accelerators working at low charge and high repetition rate. In our approach, we overcome the drawback of the limited sensitivity by making use of the long electron bunch pulse trains (up to continuous wave) available at ELBE and upgraded the electro-optic approach to include a phase and frequency sensitive detection scheme (see Fig. 1). The longitudinal electron bunch density at a certain position along the bunch can then be sampled over many bunches, and noise in the measurement is discarded, apart from that in a very narrow frequency band around the actual repetition rate of the electron bunches. Note that if necessary this frequency bandwidth $\Delta\nu/\nu$ can be made extremely small and reach values of 10^{-9} depending on the lock-in settings

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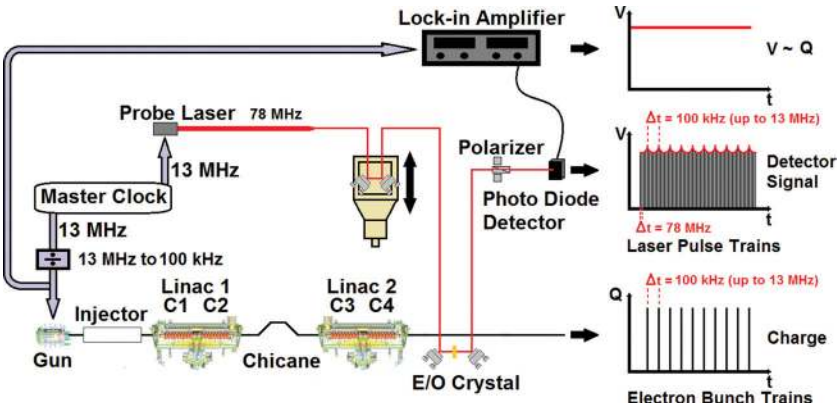

FIG. 1. Schematic of the phase and frequency locked electro-optic monitor concept employed in the pilot experiments at ELBE. The present set up allows to work at repetition rates between 100 kHz and 13 MHz in both, continuous wave (cw) and macro pulse (mp) mode of operation, respectively.

and the reference frequency of choice. Scanning the arrival time of a fs laser with respect to the electron bunch allows the measurement of the mean electron bunch form with an extraordinary dynamic range and sensitivity. More importantly, the combination of two measurements at fixed delay-times of the fs laser will allow deriving two simple error signals for arrival time drifts and changes of the electron bunch form.

In the experiments, the electron bunch form was sampled with the 150 fs (FWHM) pulses from a 78 MHz/780 nm fiber based laser (TOPTICA Photonics). The accelerator was run in continuous wave (cw) and macro pulse (mp) mode of operation at a micro pulse repetition rate of 101.5625 kHz. The laser oscillator was phase locked to the 13 MHz base frequency of the accelerator masterclock at ELBE (Ref. 11) (see Fig. 1). A 0.8 mm thick ZnTe (110) crystal (INGCRAY Laser Systems Ltd.) was employed as electro-optic pick up crystal at a distance of 3 mm to the passing electron bunches. The electric field of the electron bunches causes a rotation of the linear polarization of the 150 fs laser pulses in the crystal via the electro-optic Pockels effect (for details, see Ref. 7 and references therein). All measurements were performed in the near crossed polarizer configuration.[7] The change of polarization is in our case quantified by means of a fixed polarizer in front of the silicon photodiode (THORLABS, DET10A/M) as an increase of the detected intensity. The electron bunches, passing the ZnTe crystal, cause a periodic modulation of the laser signal at the silicon photodiode. This photodiode signal is fed into a lock-in amplifier (Stanford Research SR844—in the cw measurements and Zurich Instruments HF2LI in some of the cw and all of the macro pulsed measurements). The lock-in amplifiers use the 128th sub harmonic of the accelerator master clock base frequency as a reference signal for a phase sensitive amplification of only a narrow frequency band around this frequency which in our case corresponds to the electron bunch repetition rate of 101.5625 kHz. Thereby, noise signals with frequencies outside the narrow frequency band are rejected, and the amplitude of the 101.5625 kHz modulation is transformed into a DC voltage and recorded (see Fig. 1).

All of the measurements presented were performed with a relatively short integration time of 300 ms of the lock-in amplifier, thereby virtually integrating over the signal of 30 469 electron bunches in the cw mode of operation. In this configuration, signals on the scale of few nV can be easily detected. The monitor enables to scan the electron bunch form of bunches containing charges as low as a few pC within only a few seconds (see Fig. 2). Even more importantly, the technique allows for an active stabilization of the arrival time and form of the electron bunches when measuring the electro-optic signal simultaneously at two distinct points of the longitudinal electron bunch distribution. As explained before, the fs laser is phase locked to the accelerator master clock, and its synchronization in modern accelerators can be kept stable on a few femtosecond timescale over hours (Ref. 12 and references therein). This is not true for electron bunch form and arrival time; here, e.g., thermal drifts of the accelerator RF phase can lead to a gradual change of both parameters that our proposed monitor would be able to detect online.

By folding the path of two fs laser pulses through the same electro-optic crystal and setting both working points to the half maximum of the rising and falling density, two numerical error values can be derived by the difference and sum of the measured voltages (see Fig. 3). The difference of signals A and B would be a direct monitor of the arrival time of the electron bunches with respect to the external laser system locked to the master oscillator and allows to actively feedback the accelerator RF phase. The sum of signals A and B would allow verifying that bunch form and charge are kept constant, which is particularly important when the feedback is actively adjusting the accelerator phase. Using the macro

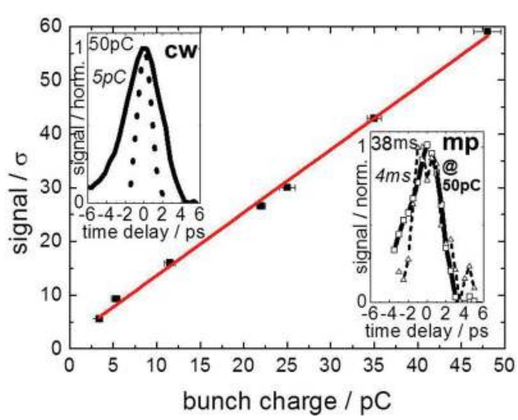

FIG. 2. EOS-signal in units of the standard deviation σ for different bunch charges utilizing 300 ms integration times. (*Inset top left*): Measurements at a bunch charge of 50 pC (solid) and 5 pC (dashed) in continous wave (cw) mode of operation. (*Inset bottom right*): Measurements in macro pulsed (mp) mode of operation at a charge of 50 pC, a repetition rate of 25 Hz (macro pulses)/100 kHz (micro pulses), and a macro pulse duration of 38 ms (squares) and 4 ms (triangles).

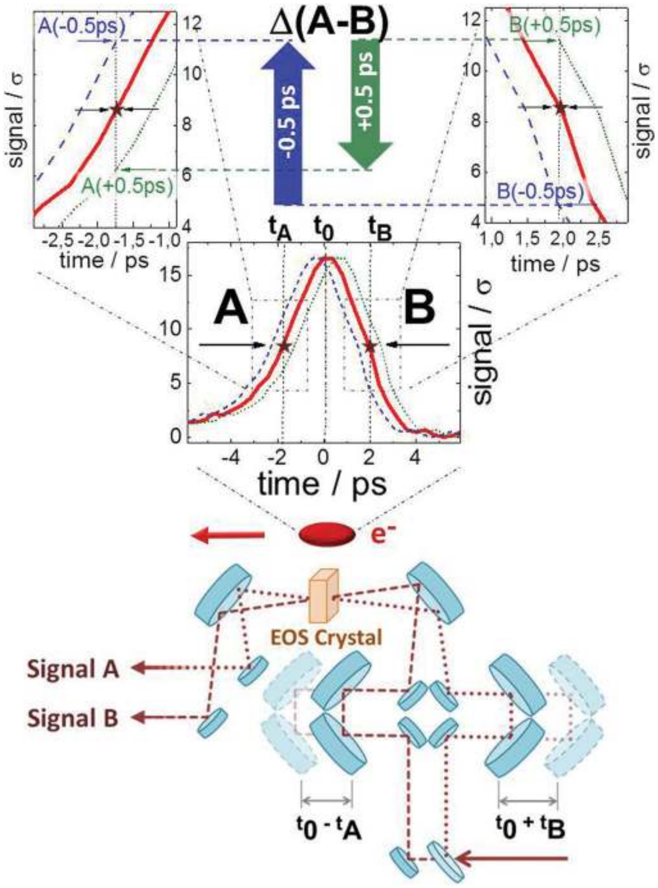

FIG. 3. Concept for a simple arrival-time drift monitor at ELBE with bunch form control based on phase sensitive detection at two distinct time delays t_A and t_B. (Bottom) The incoming fs laser pulse is split into two pulses. The two pulses are then guided on slightly different angles through the same electro-optic crystal and detected as signals A and B. The arrival times with respect to the arrival time of the electron bunches can be set independently to times t_A and t_b. (Middle) A good working point is the arrangement when signals A and B are set to times where the electro optic signal reaches one half of the peak value on the rising and falling edge, respectively, and Δ(A-B) is zero. (Top) In this case, the sign of the error signal Δ(A-B) directly indicates the sign of the arrival time drift. Note that the relative magnitude of the error signal also depends on the bunch form and may be different for positive or negative drifts. A change of error signal $\Delta(A+B)$ at the working point indicates a change of the bunch form (not shown).

pulse option of the ELBE accelerator, we could furthermore prove that the concept can also be used during macro pulse operation provided that the macro pulse trains are long enough (see inset of Fig. 2). The current detection limit lies here at the equivalent of 400 electron bunches per macro pulse, a number that fits well with the mode of operation currently employed at FLASH or planned for the European X-FEL.[1,3]

To summarize, we present a robust electro-optic monitor concept based on phase sensitive detection for electron bunch form and arrival time that is matched to the requirements of high repetition rate linear electron accelerators. Our concept requires two essential instrumental prerequisites: (i) a fs laser system with a repetition rate at least a factor of 2 higher than the electron bunch repetition rate and (ii) a phase sensitive amplifier working at the repetition rate of the electron bunches.

The monitor can easily be utilized for a robust slow feedback for drifts of the arrival time of the electron bunches at ELBE on a few hundred millisecond timescale, and at the same time, it can also verify that the overall electron bunch form is kept. Electron bunch charges in the few hundred femto-coulomb regime require longer sampling times on the order of seconds per data point. The concept will have high impact for future high repetition rate accelerators such as energy recovery linacs.[4]

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