SINGLE-SHOT ELECTRON BUNCH LENGTH MEASUREMENTS USING A SPATIAL AUTO-CORRELATION INTERFEROMETER

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Abstract

A spatial, electro-optical auto-correlation (EOA) interferometer using the vertically polarized lobes of coherent transition radiation (CTR) has been developed as a single-shot electron bunch length monitor at an optical beam port downstream the 100 MeV pre-injector LINAC of the Swiss Light Source (SLS). This EOA monitor combines the advantages of step-scan interferometers (high temporal resolution) and THz-gating technologies (fast response) providing the possibility to tune the accelerator with an online bunch length diagnostics. While a proof of principle of the spatial interferometer was achieved by step-scan measurements with a Golay cell detector, the single shot capability of the monitor has been demonstrated by electro-optical correlation of the spatial CTR interference pattern with fairly long (500 ps) Nd:YAG laser pulses in a ZnTe crystal. In single-shot operation, variations of the bunch length between 2 and 4 ps due to different settings of the LINAC bunching cavities have been measured with sub-ps time resolution.

INTRODUCTION

As the first link of the "top-up" injection chain for the SLS storage ring, the 100 MeV pre-injector LINAC has been designed for highest reliability and long-term stability. In the "top-up" operation mode, it delivers excellent energy spread and transverse emittances at bunch charges of up to 1 nC and 3 Hz repetition rate [1]. For bunch length measurements, the LINAC has to be operated with a modified setting of the bunching section resulting in shorter bunches at the cost of slightly increased energy spread and reduced bunch charges of up to 0.6 nC. Tuning of the LINAC in the "short bunch" operation mode is usually accomplished by maximizing the integrated CTR intensity on a pyroelectric detector, benefiting from the fact that the CTR spectrum becomes broader for shorter bunches. However, this procedure is not unambiguous, since the occurrence of sub-structures within a bunch creates also high frequency components in the CTR spectrum, which may in some cases lead to a comparable increase of the integrated CTR intensity. It would thus be desirable to have a robust and reliable single-shot bunch length measurement to obtain real-time information for the adjustment of accelerator parameters. PARMELA simulations of the SLS pre-injector LINAC show that bunch lengths in the order of 1 to 5 ps can be expected for the "short bunch" operation mode. The present EOA monitor set-up has thus been optimized for this range, simultaneously aiming for sub-ps time resolution.

SPATIAL EOA INTERFEROMETER

The spatial EOA interferometer set-up and the confirmation of its functionality has been achieved in several steps, including the consideration of the long wavelength CTR emission characteristics, the confirmation of the interference fringe visibility in the focal plane of the interferometer, and the optimization of the electro-optical readout. This section gives a brief overview of the related activities.

Basic Design Considerations

An analytical model of the long wavelength CTR emission characteristics has been developed and could be experimentally verified at an optical port behind the 100 MeV SLS pre-injector LINAC [2,3]. As a result of these studies, two basic issues have been considered in the design of the spatial EOA interferometer at SLS.

a) The diameters of the optical components (wire grid polarizer, plane and toroidal mirrors) are chosen large enough to account for the angular broadening of the CTR emission with increasing wavelengths. The expected wavelength range for the ps long electron bunches from the SLS LINAC is above 0.5 mm (below 600 GHz). The cut-off of the optical components in the interferometer set-up is at 10 mm wavelength respectively 30 GHz.

b) The tilt of the TR screen by 45° results in an asymmetric emission pattern for the horizontal CTR polarization components. Thus, only the symmetric, vertically polarized CTR components were selected for the interferometer set-up.

Spatial Interferences – Proof of Principle

For two plane waves, a spatial auto-correlation interferometer produces a transverse fringe pattern in its focal plane according to the relationship:

$$I_{interf}(v, x) = (I_1 + I_2)\left[1 - \alpha \cdot Cos\left[4\pi v Sin(\theta)\frac{x}{c}\right]\right] \quad (1),$$

where θ is the incident angle between the wave vector k and the normal vector n on the focal plane respectively the EO-crystal (in our case 30°); x is the transverse plane,

where the interference occurs, α the modulation depth of the interferogram, which is depending on the CTR intensity I_i in each arm of the interferometer.

As a proof-of-principle for the actual set-up, the visibility of the transverse interference fringes in the focal plane of the interferometer was demonstrated in a laboratory measurement using monochromatic cw-sources in a range between 70 and 120 GHz [4]. The results are in very good agreement with GRASP [5] simulations showing a slight tilt of the interference fringes due to the asymmetric layout of the interferometer. For a broadband and pulsed source like CTR, spatial interference occurs only when the difference in the length of both interferometer arms is within the length of the ps long electron bunches (in the order of a millimeter). This is of course similar to conventional Michelson or Martin-Puplett interferometers. A longitudinal phase shift respectively a length change between the interferometer arms results in case of the spatial interferometer in a transverse position shift of the zeroth order fringe in the focal plane. This behavior, which is an indication of the set-up's single-shot capability, could be demonstrated with CTR, emitted at the ALIDI-SM-5 optical monitor behind the 100 MeV SLS pre-injector LINAC. A series of horizontal scans with a Golay-Cell detector in the focal plane of the spatial interferometer was performed for different longitudinal phase settings showing the expected transverse shift of the zeroth order fringe [2].

Electro-Optical Readout

An active mode-locked Nd:YAG laser ($\lambda_{1,2}$ = 1064 nm, 532 nm and τ = 500 ps) is guided through an optical transfer line from the SLS technical gallery onto an optical table at the location of the ALIDI-SM-5 optical monitor in the LINAC bunker. One part of the laser beam is split and focused onto a photomultiplier (PM), where a coarse synchronization with optical TR from the target screen is achieved. The main part of the laser beam passes a Glan Laser polarizer before being reflected onto a ZnTe crystal (10 mm x 10 mm x 1 mm) placed in the focal plane of the interferometer. In case of coincidence between the CTR and the laser pulses, the polarization of the laser light is rotated due to the CTR induced birefringence in the ZnTe crystal. The transmitted laser intensity passes the second (analyzing) polarizer and is focused in the vertical direction by a cylindrical lens onto an InGaAs linear image sensor (LIS) with 256 pixels and 50 μm pitch, providing the horizontal signal distribution of the residual laser light. A schematic view of the experimental set-up is shown in Fig. 1. The use of 500 ps long Nd:YAG laser pulses facilitates the synchronization with the short CTR pulses and turns the EOA monitor into a very robust and quite easy to handle bunch length instrumentation. However, the required extinction levels of the cross-polarization arrangement to obtain a sufficient signal to background ratio for the long laser pulses have to be in the order of 10^{-5} to 10^{-6}. This is fairly difficult to achieve, since even the highest quality EO-crystals degrade the total extinction by about one order of magnitude due to strain induced birefringenge. The best achieved extinction levels in our experiments were $4 \cdot 10^{-5}$.
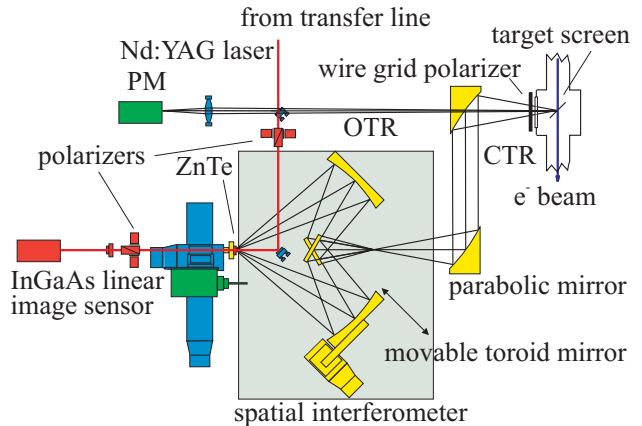

Figure 1: Schematic view of the EOA bunch length monitor at the ALIDI-SM-5 optical monitor behind the 100 MeV SLS pre-injector LINAC. The quasi-optical components including the spatial interferometer are marked in yellow, the laser path and EO readout in red.

BUNCH LENGTH MEASUREMENTS

After minimization of the extinction level with the ZnTe crystal in place has been obtained, the bunch length measurements are usually performed in two steps.

Synchronization

Coarse synchronization to a level of about 200 ps is achieved by overlaying the optical part of the TR, which passes through a central hole in the first out-coupling parabolic mirror, with part of the Nd:YAG laser pulses onto a PM. The signal on the LIS detector can then be optimized by subsequent fine-tuning of the laser-CTR timing and the adjustment of both EOA interferometer arms to equal lengths. When optimum conditions for coincidence are accomplished, the wanted signal level rises typically by a factor of 3 to 5.

Signal Analysis

If the longitudinal phase of the EOA interferometer is well adjusted, the spatial interference pattern can already be observed in the LIS raw data. However, the single-shot interference patterns $S(x)$ shown in Fig. 2 are the result of some basic data treatment according to equation (2), including background subtraction and normalization:

$$S(x) = I_{laser} \int_0^\infty d\nu \left(I_{interf}(x,\nu) - I_{\alpha \to 0}(x,\nu) \right) \quad (2)$$

where I_{interf} is the spatial fringe pattern expressed in equation (1) and $I_{\alpha \to 0}$ is the horizontal profile on the LIS taken at an "out-of-phase" interferometer setting (large arm length difference).

Since this data treatment is done automatically by the experimental controls software package, shot by shot spatial auto-correlation profiles can be recorded online

during a measurement period, providing the possibility of tuning the LINAC's bunching section for shortest bunch lengths.

Bunch Lengths vs. 3 GHz Pre-Buncher Phase

In case of the "short bunch" operation mode of the SLS pre-injector LINAC both, bunch length and energy spread depend quite sensitive on the relative phase settings of the three buncher cavities (500 MHz sub-harmonic pre-buncher (SBU), 4-cell (PBU) and 16-cell (FBU) 3 GHz travelling wave bunchers). Fig. 2 shows auto-correlation profiles for different PBU settings, resulting in 2σ bunch widths between 1.6 and 3.4 ps assuming Gaussian longitudinal bunch configurations. The transfer functions of the experimental set-up as well as the frequency dependent CTR and laser spot sizes have been considered in the data analysis.
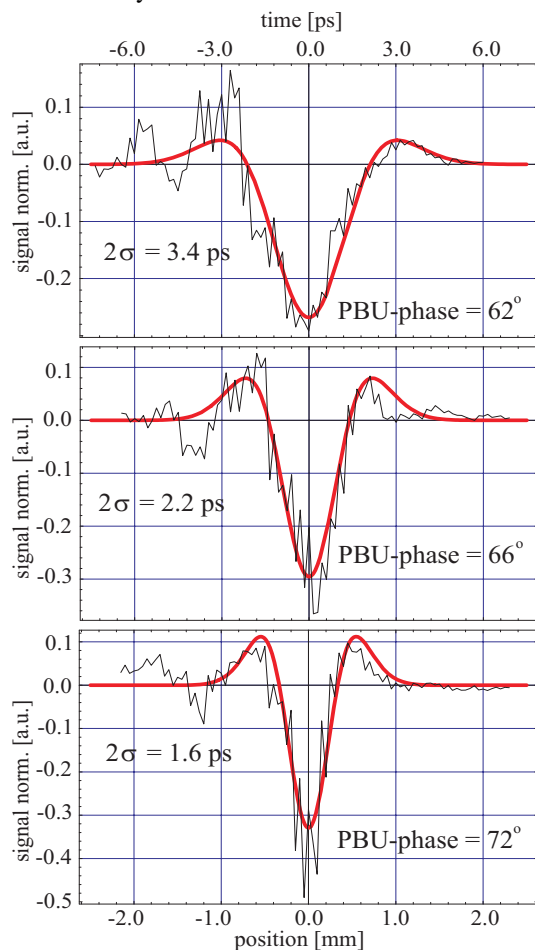
Figure 2: Single-shot, spatial auto-correlation profiles for different phase settings of PBU. Top: PBU-phase of 62° results in a 2σ bunch length of 3.4 ps. Middle: PBU-phase of 66° results in 2.2 ps. Bottom: PBU-phase of 72° results in 1.9 ps. In all three cases, a simple Gaussian has been assumed for the longitudinal bunch configuration.

The time resolution of the EOA interferometer as presently installed at the SLS pre-injector LINAC has been evaluated by determining the standard deviation of several single-shot measurements for different phase

settings of the PBU. Apart from systematic limitations of the set-up, which are still under investigation, the results depend mainly on the CTR signal intensity respectively the signal to background ratio of the EO readout, the LINAC and the Nd:YAG laser stability. The minimum time resolution of the present set-up is in the order of 200 fs.
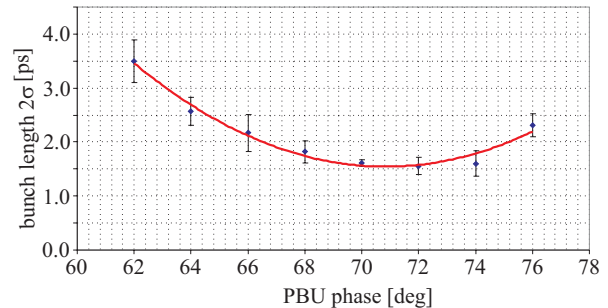
Figure 3: Average of ten single shots with standard deviation for different PBU phase settings. Minimum time resolution is in the order of 200 fs.

CONCLUSIONS AND OUTLOOK

A novel, spatial EOA interferometer for single-shot bunch length measurements has been developed and successfully implemented at the 100 MeV SLS pre-injector LINAC. The long pulses of the Nd:YAG probe laser eases synchronization between electron bunch and laser resulting in a robust bunch length monitor. For different settings of the PBU pre-buncher, electron bunch widths in the order of some ps have been measured with sub-ps time resolution.

An improved EOA monitor is planned to be set-up at the THz transfer line of the SLS femto-second pulse slicing project [6] to measure sub-ps long electron bunches using coherent synchrotron radiation.

ACKNOWLEDGEMENT

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