ELECTRO-OPTICAL BUNCH LENGTH MONITOR FOR FLUTE: LAYOUT AND SIMULATIONS*

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Abstract

A new compact linear accelerator FLUTE is currently under construction at Karlsruhe Institute of Technology (KIT) in collaboration with DESY and PSI. It aims at obtaining femtosecond electron bunches (1 fs - 300 fs) with a wide charge range (1 pC - 3 nC) and requires a precise bunch length diagnostic system. Here we present the layout of a bunch length monitor based on the electro-optical technique of spectral decoding using an Yb-doped fiber laser system (central wavelength 1030 nm) and a GaP crystal. Simulations of the electro-optic signal for different operation modes of FLUTE were performed and main challenges are discussed in this paper.

MOTIVATION

The Karlsruhe Institute of Technology is currently constructing a linac-based light source named FLUTE (Ferninfrarot Linac-Und Test-Experiment - farinfrared linac and test experiment). It is a dedicated accelerator R&D facility with the main goals being to cover a large charge range and achieving very short electron pulses to generate THz radiation with high peak fields [1]. FLUTE will have a compact setup with a total length of around 15 m. Its electron source is a photo injector gun with an electron energy of 7 MeV. A subsequent linac increases the electron energy up to 42 MeV followed by a magnetic chicane for bunch compression. FLUTE will be able to operate with a wide range of electron bunch charges and lengths (see Tab. 1), which requires a sophisticated single-shot system for online bunch-length diagnostics.

Due to the limited available space and the wish for non-invasive, online diagnostics, a bunch length monitoring system based on the electro-optical technique of spectral decoding (EOSD) is proposed. Electro-optical (EO) techniques have proven to be a versatile and reliable tool for bunch length measurements at linacs [2, 3] and we have gathered in-house experience with such a system at the ANKA storage ring [4]. The underlying principle is to modulate the electric field of the electron bunch on a single, stretched laser pulse and subsequently analyze this pulse to reconstruct the longitudinal bunch profile [5]. The laser pulse receives a chirp when stretching it, introducing a correlation between time and wavelength inside the pulse. Thus by detecting the spectral modulation of the laser pulse with a single-shot spectrometer, the longitudinal bunch profile can be extracted after a calibration measurement is performed. For this publication, we performed numerical simulations of the expected EOSD signals for various locations of interest along the accelerator and various machine conditions of FLUTE to determine the optimum settings and parameters of the proposed EOSD system.

Table 1: FLUTE Key Parameters

Electron energy	42	MeV
Electron bunch charge	1 - 3000	pC
Electron bunch length (RMS)	1- 270	fs
Pulse repetition rate	10	Hz
Length	≈15	m

SIMULATION CODE

An EOSD system for bunch length diagnostics has a variety of parameters, which play a key role in the performance of the system and need to be adapted to the beam parameters. So in order to determine these optimum parameters, we performed numerical simulations. The code used for the simulation studies was originally developed by B. Steffen (DESY) and showed an excellent agreement with the experimental results [6]. Technically it is realized in MATLAB and it can logically be divided into three main parts, which are shown in the code-flow diagram in Fig. 1. The first part of the code covers the laser parameters and computes the chirp and length of the laser pulse by propagating the initial pulse through a dispersive medium. As dispersive medium, glass with a variable thickness was used in order to simulate the dispersion that is introduced inside the long fiber we use to stretch and chirp the laser pulse in the experiment. As result, we obtain the electric field of the chirped, stretched laser pulse $\mathrm{E}_{\mathrm{c,\ laser}}$. The second part calculates the radial electric field of a relativistic electron bunch - represented as a line charge density Q(t) - where the horizontal dimensions of the bunch, σ_x and σ_y, are neglected. The energy is given by the relativistic factor γ. The code then computes the radial electric field at a distance r_0 from the bunch $\mathrm{E}_{\mathrm{THz}}(\mathrm{Q(t)},r_0,\gamma)$. The last part of the simulation then calculates the modulation of the electric field of the laser pulse, $\mathrm{E}_{\mathrm{c,\ laser}}$, inside the EO material. For our case gallium phosphide (GaP) crystals of different thicknesses were investigated. The EO material acts as a field-dependent phase retarder and thus causes a modulation of the polarization, the so-called phase retardation. For ideal measurement conditions, this phase

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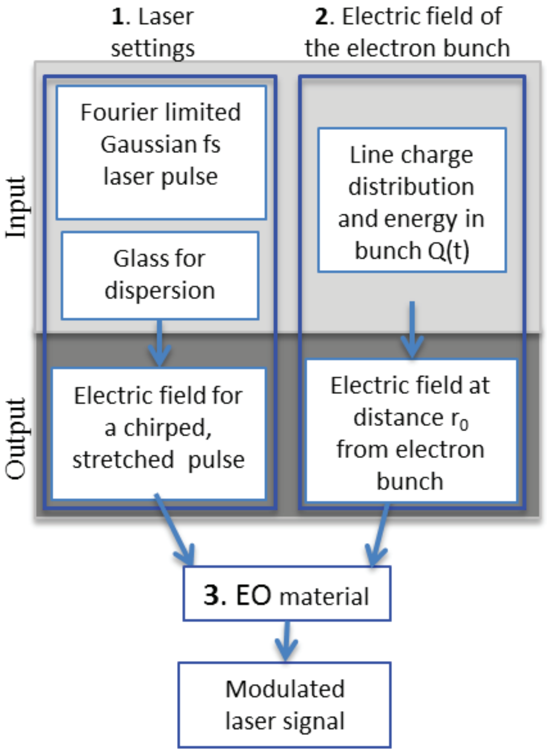

Figure 1: Code-flow diagram for the simulation.

retardation is directly proportional to the electric field of the bunch. For more details see [p. 74-75 in 7].

Figure 2, shows three curves representing the different stages of the simulation. The first one (black dashed line) shows the initial charge distribution of the electron bunch Q(t). From this charge distribution the electric field (pink dashed line) is computed taking into account the relativistic factor γ which determines the opening angle. In this plot, the simulation is presented for a 7 MeV electron bunch and a RMS bunch length of 1200 fs. The electric field is computed at a distance of 5 mm away from the bunch. The widening of the electric field is clearly visible due to the comparatively low gamma factor. The green solid line shows the resulting phase retardation Γ after passing the EO crystal. We take the peak value of the phase retardation as a measure of the signal intensity, which plays a role to check if the signal is above the detection limit.

SIMULATION RESULTS

We plan to operate FLUTE in different charge regimes: a low charge mode at 1 pC, a medium charge mode at 100 pC and a high charge mode with up to 3 nC. For each of the modes, a maximum bunch compression is desired. Beam dynamics simulations with ASTRA [8] allow the prediction of the transverse and longitudinal beam parameters along FLUTE. While space charge is limiting the maximum compression for higher charges, for very low charges around 1 pC we aim to achieve a bunch length < 10 fs. To obtain this optimum compression for the different operation modes, the monitoring of the bunch length in three different locations is of interest: first right after the gun at an electron energy of only 7 MeV, secondly after the linac (42 MeV), and thirdly after the chicane. All the corresponding beam parameters in these three locations can be found in Tab. 2. In a first step, these values for the RMS bunch length and bunch charge were used as input parameters for the simulation, applying the following procedure:

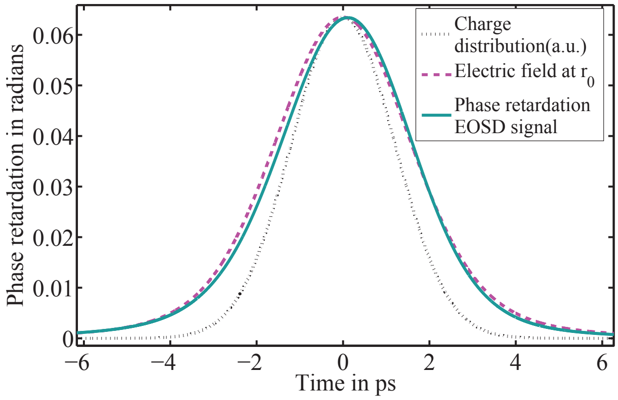

Figure 2: Simulation stages results.

a.) The minimum distance between EO crystal and electron bunch needs to be determined. Because of the 1/r decay of the electric field we want to bring the crystal as close as possible to the bunch to obtain a high signal, without influencing the bunch. To take into consideration that the transverse beam sizes vary for different machine settings, we take a minimum distance of $r_0=4\sigma_y$.

b.) Determination of the crystal parameters: For our simulations we considered only GaP as crystal material, because we plan to use an Yb-doped fiber laser system operating at 1050 nm central wavelength [9, 10] and there the optimum phase matching between the electric fields of the laser and the electron beam is achieved in GaP. While thicker crystals yield a larger signal, they also limit the temporal resolution due to finite phase matching. We performed simulations for the following different crystal thicknesses: 5 mm, 2.5 mm, 1 mm. For the location after the chicane, where charge densities in the bunches are much higher due to the compression, also crystal thicknesses of 0.1 mm and 0.5 mm were considered.

c.) The laser pulse length was set by varying the thickness of the dispersive medium. It was set in a way to obtain laser pulse widths (FWHM) in a range from 700 fs to 12 ps.

d.) Once all the parameters are set, the resulting modulation of the bunch electric field on a laser pulse is calculated.

Simulation results for all the locations are shown in the Tab. 2. The deviation shows the difference in % between the set bunch length value and the reconstructed value. A positive sign shows that we overestimate real bunch length and negative means that the simulated system underestimates the set bunch length. For every setpoint closest possible distance between crystal and electron bunch was changed

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from $4\sigma_y$ to $4\sigma_y$+4 mm with a step of 1 mm (see Fig. 3) - to observe the signal change with distance.

Additionally, we estimated the influence of the opening angle of the resulting electric field of the electron bunch, that is the convolution of the single electron field with the charge distribution. For a single 7 MeV electron, the electric field is 300 fs(rms) longer at 5 mm distance from the electron bunch and around 940 fs longer at 10 mm distance. For 42 MeV electrons, this effect is less prominent: the electric field is longer by 30 fs (rms) at 5 mm distance and less than 10 fs longer at 2 mm distance from the bunch.

Table 2: Simulation Results

	1 pC	100 pC	3 pC
After the gun [7 Mev]			
Input σ_z, fs	520	1200	2500
Reconstructed σ_z, fs	690	1500	3700
Deviation, %	+20	+20	+50
Optimum crystal thickness, mm	5	5	5
Optimum laser pulse length (FWHM), ps	6.14	6.14	12.28
r_0, mm	2.8	5.6	12.5
After the linac [42 Mev]			
Input σ_z, fs	450	1080	2300
Reconstructed σ_z, fs	448	1060	2270
Deviation, %	-0.5	-2	-0.3
Optimum crystal thickness, mm	5	5	5
Optimum laser pulse length (FWHM), ps	6.14	6.14	12.28
r_0, mm	0.8	1.2	4.8
After the chicane [42 Mev]			
Input σ_z, fs	1	67	200
Reconstructed σ_z, fs	70	95	235
Deviation, %	unresolved	+45	+15
Optimum crystal thickness, mm	5	1	0.1
Optimum laser pulse length (FWHM), ps	0.768	0.768	0.768
r_0, mm	0.6	1.6	2.4

At the measure point after the gun, we could see that the "measured" bunch lengths for all charges are higher than the set bunch lengths. This is explained by the wide opening angle of the electric field of the bunch due to the low energy of 7 MeV (see Fig. 3). The deviation from a set bunch length is 20% for a 1 pC bunch and up to 50% for a 3 nC bunch. At this position the bunch charge density is low, compared to the compressed bunches after the chicane. This requires a relatively thick crystal, we consider a 5 mm thick crystal to be optimal.

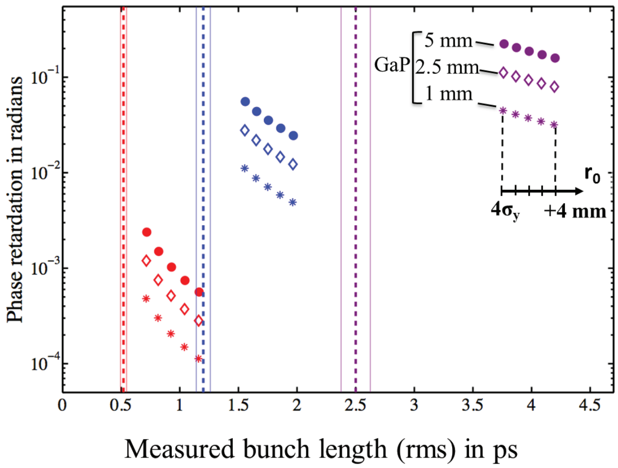

Figure 3: Measured bunch lengths after the gun. Circles: 5 mm thick crystal. Rectangles: 2.5 mm thick crystal. Stars:1 mm thick crystal. Blue: 1 pC. Red: 100 pC. Purple: 3 nC

After the linac the measured bunch length for all the bunch charges lies within ± 2% of the input value, allowing for an accurate bunch length reconstruction. As the charge density is still comparably low, a thick crystal is preferable and does not limit the temporal resolution.

After the chicane the reconstruction of the bunch lengths is most troublesome because the resolution limit of the technique is reached and even a thin crystal of just 0.1 mm thickness yields a 15% longer reconstructed bunch length for an input bunch length of 200 fs. For a 100 pC bunch of 67 fs the reconstruction overestimates the real bunch by up to 45%.

SUMMARY

To investigate the influence of various parameters we simulated the EO signal expected at different positions along FLUTE. The simulation allows us to understand the requirements and desired layout of the EO monitors. We identified the parameters that will affect the measured signal. For very short bunches (less than 40 fs) we are limited by the resolution of the technique. At low electron energies we are limited by widening of the signal because of an opening angle of the Coulomb field. Next steps include the study of alternative materials to improve the resolution and the design of the EO setup using the emitted CTR.

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