Abstract

The linac at the NSLS Source Development Lab (SDL) provides a high brightness electron beam for the DUV-FEL project with subpicosecond bunch length and several hundred Amperes peak current by means of a photoinjector and a magnetic bunch compressor. Previous diagnostics of the longitudinal bunch dynamics relied on the rf zero-phasing method and measurements of CTR spectra. In order to have a fast and non-intercepting longitudinal diagnostic available, the electro-optic measurement technique has been implemented with its major component, a synchronized 100 fs Ti:Sapphire laser coaligned with the electron beam, already in place as a seed for the FEL. The theoretical temporal resolution for a 100 um thick ZnTe crystal is limited to about 200 fs and the signal contrast to more than 1%. We present preliminary results of multi-shot scanning measurements and the single-shot diagnostics of the bunch shape as well as its application as a rf-laser jitter monitor.

INTRODUCTION

The DUV-FEL accelerator [1] consists of a photoinjector, four SLAC-type accelerating structures for up to 200 MeV beam energy, a magnetic chicane after the second linac tank compressing the beam to several hundred femtoseconds, and two undulators, a short modulator and NISUS, for self amplified spontaneous emission (SASE) and high gain harmonic generation (HGHG) experiments. The frequency tripled Ti:Sapphire laser for the photo-cathode generates several hundred pC of charge at a repetition rate of up to 10 Hz. A small fraction of the fundamental serves as a seed for the FEL experiment. The Coulomb field at distance \( r \) is

\[
\Delta \varphi = \frac{2\pi n_0 r_{41} E_{\text{vac}} l}{(1 + \sqrt{\epsilon}) \lambda},
\]

with crystal length \( l = 500 \mu m \), wavelength \( \lambda = 800 \text{ nm} \), refractive index \( n_0 = 2.853 \), dielectric constant \( \epsilon = 10.1 \), and electro-optic coefficient \( r_{41} = 4.04 \text{ pm/V} \). The Coulomb field of the electron beam at the ZnTe-crystal’s location are horizontally polarized. For a (110)-cut crystal with the [001]-axis oriented vertically, the induced phase change is

![Figure 1: Time profile of the compressed electron beam using zero-phasing method. The two profiles are taken with +90° and -90° phase in the last linac tank.](image-url)
\[ E_{\text{vac}} = \frac{Z_0 I}{2\pi r} , \quad (2) \]

with the time dependent beam current \( I \). The phase change is detected with a \( \lambda/4 \) plate as compensator and an analyzer cube, whose transmitted and reflected beams are either focused into a pair of photodiodes for the multi-shot experiment or into a pair of fibers and eventually a monochromator with CCD array for the single-shot set-up [5]. With the compensator set to balanced intensities, the asymmetry of the integrated photodiode signals or the spectra becomes

\[ A = \frac{S_T - S_R}{S_T + S_R} = \sin (\Delta \varphi + \varphi_0) , \quad (3) \]

and \( \varphi_0 \) accounting for any residual birefringence.

**SCANNING EXPERIMENT**

The accelerator and seed laser were operated at their usual settings for the HGHG experiment with 177 MeV beam energy, a bunch charge of 290 pC, and the seed laser chirped to 5.9 ps (FWHM) for good overlap with the 1 ps long electron bunches. The amplified difference signal of the photodiodes was averaged over 50 bunches for each data point, whereas the sum signal was measured only once. To eliminate electrical noise and background from electrons hitting the crystal, data was also taken with either the seed laser or the electron beam blocked. Figure 3 shows the effective electric field calculated from the signal asymmetry using Eq. (1) for different separations of laser and electron beam. Note that the obtained Coulomb field is reduced, since it is averaged over the much longer laser pulses. The solid curve shows Eq. (2) convoluted with the measured rms beam sizes of 300 \( \mu \)m and 600 \( \mu \)m for electron beam and laser, respectively. To fit the data points, the charge was assumed to be 230 pC, which is not far less than the 290 pC measured in the Faraday cup.

A scan of the seed laser delay relative to the electron beam is shown in Figure 4. The main peak has a FWHM of 6.7 ps which is slightly longer than the laser pulse. The solid curve is a corresponding gaussian distribution with satellites after multiples of 10 ps added, which is the round-trip time of THz waves in the ZnTe crystal. The peak height of the satellites is larger than expected which indicates the presence of trailing wake fields. No electric field ahead of the bunch could be observed.
**SINGLE-SHOT EXPERIMENT**

The raw spectra, with and without electron beam, from the two multi-mode fibers carrying the transmitted and reflected beams from the analyzer cube, are shown in Fig. 5. Both reference spectra differ significantly from each other and their difference varies with the compensator orientation. This indicates a large wavelength dependent intrinsic birefringence, which partly is stress induced in the ZnTe crystal and partly may originate from a crystalline quartz vacuum window. The static phase is determined from the asymmetry of the reference spectra without electron beam and subtracted from the phase including the electro-optic signal. The resulting current profile using Eqs. (1,2) is shown in Fig. 6 with a delay difference of 1.67 ps between the upper and lower part. The wavelength shift in the signal peak was used to obtain the time calibration to

$$\eta = (1.25 \pm 0.2) \text{ nm/ps}$$

which is close to the chirp in the seed laser of 1.15 nm/ps. The data in the lower part of the figure exhibits the expected single-sided shape of the Coulomb field, whereas each of the data in the upper part contains an additional pre- and post-pulse, which is not yet understood. Therefore, the following discussion only refers to the first set of data.

Considering the temporal resolution of the electro-optic set-up, the rms pulse width of this measurement of $(730 \pm 75)$ fs can be compared with the bunch length of $(625 \pm 50)$ fs obtained with the zero-phasing method, which has a resolution of tens of femtoseconds. The individual FWHM contributions for the the electro-optic method are the intrinsic duration of the Coulomb field in 2.1 mm distance of

$$\tau_r = r/((\gamma c)) = 20 \text{ fs},$$

the coherence frequency for the THz waves in the 500 µm thick ZnTe crystal of $f_{coh} = 2.8 \text{ THz}$ which corresponds to a coherence time of $\tau_{coh} = 210 \text{ fs},$ the resolution due to the chirped detection scheme [5] of

$$\tau_{BW} = \sqrt{T\tau_0} = 700 \text{ fs}$$

with chirped and unchirped length of $T = 5.2 \text{ ps}$ and $\tau_0 = 130 \text{ fs},$ and the spectrometer resolution $\tau_{\lambda} = \Delta \lambda/\eta = 190 \text{ fs}.$ This combines to a rms resolution of 320 fs. When applied to the bunch length from the zero-phasing method, this results in an expected rms length of 725 fs for the electro-optic signal, which is within the fluctuations of the actual measured length. The charge can be calculated to $(180 \pm 35) \text{ pC}$ compared to $(290 \pm 15) \text{ pC}$ from the Faraday cup.

**SUMMARY**

A nonintercepting single-shot electro-optic bunch length measurement has been installed at the DUVFEL accelerator and successfully demonstrated results which agree with theory and with results obtained by zero-phasing.

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**REFERENCES**