MEASUREMENTS OF COMPRESSED BUNCH TEMPORAL PROFILE USING ELECTRO-OPTIC MONITOR AT SITF *

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Abstract

The SwissFEL Injector Test Facility (SITF) is an electron linear accelerator with a single bunch compression stage at Paul Scherrer Institute (PSI) in Switzerland. Electro-optic monitors (EOM) are available for bunch temporal profile measurements before and after the bunch compressor. The profile reconstruction is based upon spectral decoding technique. This diagnostic method is non-invasive, compact and cost-effective. It does not have high resolution and wide dynamic range of an RF transverse deflecting structure (TDS), but it is free of transverse beam size influence, what makes it a perfect tool for fast compression tuning.

We present results of EOM and TDS measurements with down to 150 fs short bunches after the compression stage at SITF.

INTRODUCTION

Hard X-ray FEL facilities are based upon multi-stage compression of electron bunches. Bunch temporal profile monitoring is normally done after each compression stage. The most common approach is to use an RF transverse deflecting structure (TDS) [1].

Electro-optic monitor (EOM) represents another method for bunch temporal profile measurements [2]. The transverse electric field component of a moving charged particle is enhanced by the Lorentz factor. For an ultra-relativistic particle the field lines are concentrated in a thin disk, approaching zero thickness with Lorentz factor growing to infinity. The disk circumference lies in a plane perpendicular to the propagation direction. An ultra-relativistic bunch of particles will induce an electric field which is localized in the longitudinal extent of the bunch itself. The bunch length can be measured by sampling the distribution of its electric field. In electro-optic monitor a traveling electric field pulse can be converted into a laser pulse modulation of the same duration in a non-linear crystal. A modulation is produced on the top of a chirped laser pulse (with time-to-wavelength correlation) by using the electro-optic spectral decoding (EOSD) method. It is sufficient to know the spectrum of the pulse and its chirp to reconstruct the temporal profile of a bunch.

Although achievable time resolution is limited, an EOM has some advantages when compared to a TDS, since it is an alternative non-invasive technique to measure the longitudinal bunch profile. It requires much less beamline space and it is only sensitive to a longitudinal distribution of charge. Both are time domain measurement approaches with absolute calibration. A TDS allows to measure bunch longitudinal profile in a larger dynamic range by changing the deflecting gradient. TDS has the best resolution achieved to date [3]. But it needs a separate RF system, and destroys the measured bunch.

* The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n.°290605 (PSI-FELLOW/COFUND)
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EOM SETUP AT SITF

The SwissFEL Injector Test Facility (SITF) is a 250 MeV linear accelerator with a single bunch compression stage. There are two EOMs installed at SITF: one in front of and one behind the bunch compressor. A TDS is installed 1 meter downstream of the second EOM.

The EOSD measurement scheme is shown in Fig.1. An in-house developed fiber laser oscillator generates about 1 nJ pulses with the wavelength of 1030 nm and the spectral bandwidth of 25 nm at 40 MHz. A pulse picker lowers repetition rate to 1 MHz in front of an amplifier, that boosts up the pulse energy to 5-10 nJ. A grating compressor pre-compensates dispersion caused broadening of the pulse in the long fiber to the tunnel.

A 2 mm thick GaP crystal is installed in the vacuum beam pipe on a specially designed actuator platform with all other optical elements responsible for laser transport and polarization control. In case the crystal is put in the whole assembly moves not disturbing the internal alignment. The laser enters the vacuum through an optical view port and is directed to the crystal by a mirror. Then it propagates through the crystal, and it is reflected back at the end facet. After this it moves against the direction of the electron bunch and is guided out of the beam pipe to a spectrometer.

The linearly polarized laser beam is almost blocked by nearly crossed polarizers configuration without external electric fields. The laser light polarization is changed due to the electro-optic effect in the crystal in presence of an electron beam. In perfect case laser pulse has to propagate in the crystal synchronously to the electric field envelope of an

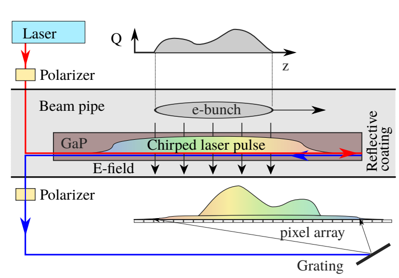


Figure 1: EOM setup scheme.

ISBN 978-3-95450-133-5

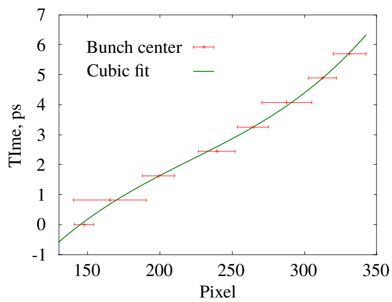


Figure 2: Spectrum to time calibration curve.

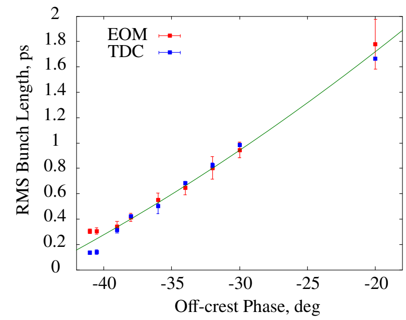


Figure 3: Bunch length measurements with EOM and TDS.

electron bunch. On practice the crystal bandwidth is substantially limited, hence the synchronicity with respect to the laser cannot be supported for the entire spectral range of the envelope.

The electron bunch temporal profile is now imprinted into a polarization modulation of the chirped laser pulse. It is converted into an intensity modulation after the second polarizer. An optical spectrometer is used to record the modulated laser spectrum. The laser pulse chirp calibration is required to map the spectrum into time. It is done by shifting the laser pulse arrival time by a known amount and registering the modulation shift in terms of wavelength. The final calibration (Fig. 2) is derived from a fit of time versus wavelength data with at least 3-4 points, generally depending on the fit model.

EXPERIMENTAL RESULTS

All bunch duration values are root mean square (RMS) values of a fitted gaussian distribution. Error bars indicate statistical error of 10 consequent measurements for TDS and 100 for EOM both at 2-3 Hz repetition rate with stable operation conditions. Bunch charge was kept at 100 pC during the entire period of measurements. Profile plots are showing the amplitude of the relative laser pulse modulation of the EOM, the TDS signal is normalized to match its peak with the EOM data. EOM and TDS do not have synchronous readout and the corresponding measurements are done in sequence one after the other.

RMS bunch length after the electron gun is 2.9 ps and down to about 100 fs after compression. Bunch energy is 200 MeV for all of the experiments described below. The phase of the last acceleration module is varied to control the bunch length. The energy reduction due to stronger off-crest phases is compensated by a higher gradient of another accelerating module.

Comparison with TDS

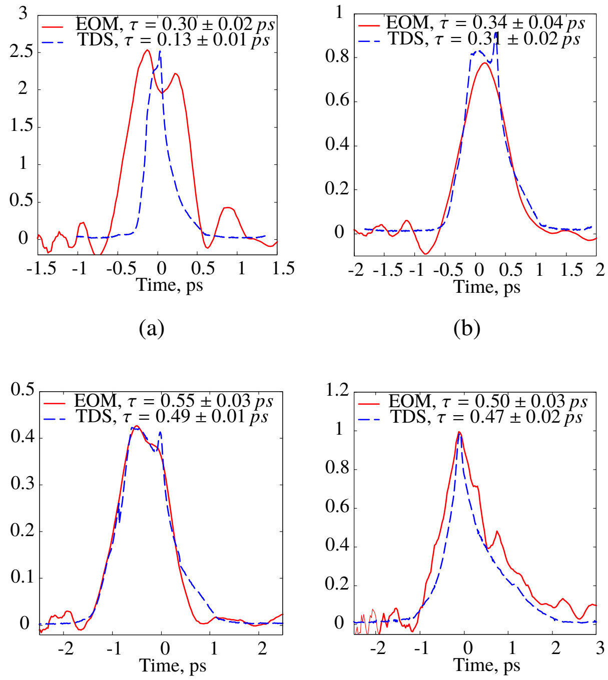
The aim is to study the dynamic range and resolution of the EOM behind the SITF bunch compressor. Reference measurements are done using the TDS. The measurement overview is in Fig. 3 in terms of bunch duration. The EOM bunch length results agree with the TDS in the range from 340 fs to 1.8 ps. The measured bunch profile is strongly distorted beyond the lower margin. Frequency mixing effect is responsible for laser pulse spectrum deformations in case the frequency content induced by EO modulation is comparable with that of the probing laser pulse [4]. One solution is to reduce the laser pulse chirp at the crystal. In our experiment the full available compression of the laser pulses was applied to achieve the minimum chirp. Each additional grating compressor reduces the pulse energy by one third, therefore it would need more pulse energy from the laser. A feasible way is to reduce dispersion by using a shorter fiber to the tunnel.

The longest bunch was measured with stronger chirped laser pulses. Signal to noise ratio falls down to one in this case and no reliable fitting can be applied for bunches longer than 1.8 ps. The laser spectrum stability can be improved to increase signal to noise ratio. The situation becomes better for the nominal 200 pC bunch charge. Thicker EO crystal would result in larger modulations, but it would decrease the resolution due to stronger THz envelope dispersion. One could equip a in-vacuum actuator with several EO crystals of different thickness to cover broader bunch length range.

Three single shot profile pairs are shown in Fig. 4 (a,b,c) and one profile taken with a bunch after non-linear compression (Fig. 4(d)). Figure 4(a) indicates the situation when frequency mixing distorts the profile shape and limits the EOM resolution to about 300 fs. Bunch profiles of a gaussian shape were obtained in the measurement with 310 ± 20 fs pulses (plot (b)). The EOM bunch length value is 10% higher with respect to the value acquired by TDS. The profile peculiarities are completely smeared out by frequency mixing. Plots (c) and (d) represent bunch temporal profiles in case of linear and non-linear compression correspondingly. The triangular shape in the second plot has more high frequency content, which is more sensitive to broadening by frequency mixing.

EOM profiles in Fig. 5(a) are obtained from single shot measurement series. Bunch arrival time jitter is excluded by matching centers of all distributions to make comparison easier. The spread of amplitudes is 12 %, the bunch charge stability is better than 1 %. The modulation amplitude is clearly correlated to arrival time (Fig. 5(b)), but the modulation duration is not as much correlated. Therefore it cannot be related to the bunch current fluctuation, but rather some internal EOM modulation efficiency which drops towards the trailing part of the laser pulse.

ISBN 978-3-95450-133-5



(a) (b)

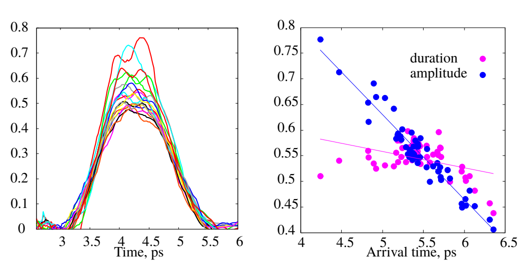
(c) (d)

Figure 4: Bunch temporal profiles.

Role of Transverse Beam Size

The EOM measures longitudinal charge distribution and should not be influenced by transverse beam parameters. This assumption was tested by measuring with transversely defocused bunches after compression. The quadrupole magnet to the EOM distance is 1.6 m, the magnet to TDS distance is 2.5 m. TDS measurements are presented with and without beam size subtraction. This procedure subtracts a transverse profile of unstreaked beam from the streaked beam size quadratically. The results are summarized in Fig. 6.

Blue line and points represent TDS results without beam size subtraction. The unstreaked beam contribution is negligible when the beam optics is optimized for the best temporal resolution at the TDS screen ($I_{quad} = 1\,A$). Now we change the quadrupole magnet current and observe the growth of the unstreaked distribution up to almost 3 times the streaked beam size matched to the screen. The value measured with EOM goes only slightly down. It can be caused by transverse-longitudinal coupling of the bunch due to residual dispersion. The main conclusion is that EOM measurements do not require transverse matching in very broad range of transverse parameters.



(a) Set of 15 bunch profiles (b) Correlated amplitude

Figure 5: 15 consequent shots, settings like in Fig.4(c).

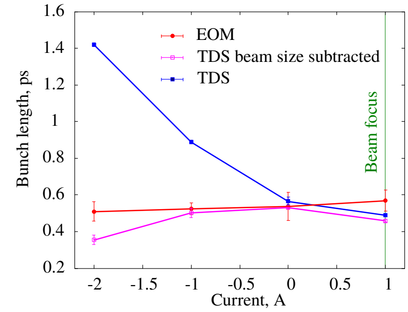


Figure 6: Bunch duration versus transverse size.

CONCLUSIONS

EOM measurements of temporal profile with compressed bunches were successfully carried out at SITF. A direct comparison to TDS has shown that in current state the EOM system is capable to cover the range between 300 fs and 1.8 ps. Measured temporal profiles agree well with TDS in the mentioned range. Frequency mixing deforms spectrum already at the modulation length of 340 fs and it also smears out shorter profile features of longer bunches.

SwissFEL will require to resolve about 200 fs pulses after the first bunch compressor in nominal mode, which is not yet covered by the EOM. The resolution can be improved by using 3 times as small pulse chirp as currently.

An experimental test was performed to demonstrate that EOM requires no transverse optics matching prior to bunch length measurements. This fact makes it a perfect tool for fast tuning of bunch compression, while transverse re-matching time can be spared for the final setup.

An electro-optic monitor possesses several advantages over TDS. It is a compact, non-invasive, much cheaper diagnostic equipment for bunch temporal profile measurements. Nowadays it can be built utilizing a reliable commercial femtosecond laser. It certainly lacks the dynamic range and resolution of TDS, but better laser spectrum stability and a shorter fiber to the tunnel can already contribute significantly to improving the resolution range.

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ISBN 978-3-95450-133-5