DEVELOPMENT OF ELECTRON BUNCH COMPRESSION MONITORS FOR SwissFEL

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Abstract

SwissFEL will be a hard X-ray fourth generation light source to be built at the Paul Scherrer Institute (PSI), Switzerland. In SwissFEL the electron bunches will be produced with a length of 1-3 ps rms and will then be compressed by a factor of more than 1000 down to a few fs in order to generate ultra short x-ray pulses. Therefore reliable, accurate and noninvasive longitudinal diagnostics is essential after each compressing stage.

In order to meet the requirements of this machine, new monitors have to be developed, in particular for low-charge operation at 10 pC. We will present recent results of setups that measure electro-magnetic radiation, namely edge, synchrotron and diffraction radiation, emitted by the electron bunches (far field, spectral domain). These monitors are tested in the SwissFEL Injector Test Facility, together with a state of the art S-band Transverse Deflecting Cavity.

INTRODUCTION

SwissFEL [1], a linac-driven X-ray free-electron laser operating in the wavelength range 0.1-7 nm is currently under construction at PSI. A photocathode gun will produce two electron bunches with a time delay of 28 ns and an overall repetition rate of 100 Hz. These electron bunches will then be accelerated up to 330 MeV by S-band Traveling Wave (TW) structures in the injector section and subsequently by C-band TW linacs up to the final energy of 5.8 GeV before reaching the undulator. To achieve a linearization of the longitudinal phase space, there is a X-band cavity included in the injector section. As indicated in Fig. 1, three magnetic chicanes which can be used for longitudinal compression will be part of the machine design.

Shifting the phase of the RF-field in the accelerating structures with respect to the electron bunch, will produce an energy chirp of the electron bunch. Due to this energy chirp the electron bunch gets longitudinally compressed while passing the magnetic chicane. The bunch lengths planned for SwissFEL are summarized in Tab. 1. To achieve the first compression stage, the S-band cavity is planned to operate around a nominal off-crest phase of approximately 23 deg. To reach the envisaged performance of SwissFEL, the phases of the accelerating structures have to be stabilized up to 0.02 deg [1].

Therefore, compression monitors will be installed after each of the bunch compressors (BC). Different detection schemes and detectors are under consideration to meet the required accuracy on a noninvasive single shot basis.

In order to demonstrate the capability of generating beam properties that are suitable for SwissFEL, the 250 MeV SwissFEL Injector Test Facility (SITF) is currently commissioned at PSI. In the following, results from the SITF are presented for compression monitors after BC1.

Table 1: RMS Electron Bunch Lengths After Each Bunch Compressor Stage for Four Planned Operation Modes of SwissFEL

Charge	BC1 [fs]	BC2 [fs]	BC3 [fs]
200 pC	500	25-75	25-75
200 pC	300	25	25
10 pC	250	3	3
10 pC	250	2	0.7

MONITORING BUNCH COMPRESSION

The longitudinal electron bunch shape determines the spectral content of the coherent radiation. By integrating the spectral intensity of the coherent radiation in a certain frequency range, variations in bunch compression lead to a variation in the detected intensity. Using detectors fast enough to resolve two consecutive bunches, enables single shot measurements.

To measure the longitudinal shape of electron bunches a RF transverse deflecting cavity (TDC) [2] in combination with a Screen Monitor is installed in the SITF. Furthermore, a Martin-Puplett interferometer is currently commissioned to measure the autocorrelation of coherent edge and synchrotron radiation.

The spectral density distribution radiated by a bunch of N electrons is given by

$$\frac{d^2P}{d\omega d\Omega} = \frac{d^2P_0}{d\omega d\Omega}\left(N + N(N-1)|F(\omega,\Omega)|^2\right) \quad (1)$$

where $d^2P_0/d\omega d\Omega$ is the single electron spectrum for the process under consideration and F the bunch form factor. For the parameters used at SITF, the influence of the transverse bunch shape can be neglected [3]. Therewith, F is exclusively given by the longitudinal form factor, defined by the Fourier transform of the longitudinal charge distribution.

Regarding the operation modes for SwissFEL, after BC1, coherent radiation is expected up to the THz spectral region. To test different detection schemes, compression

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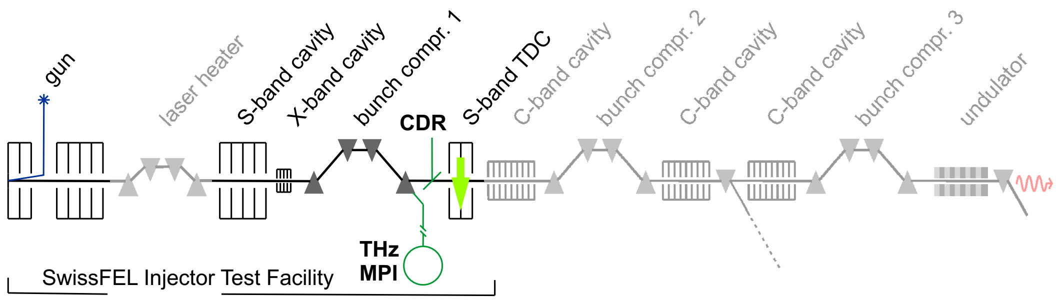

Figure 1: Schematic layout of SwissFEL with the indicated part which is currently in operation as the 250 MeV SwissFEL Injector Test Facility. The instrumentation under consideration: the THz-transfer line, imaging the coherent edge radiation (CER) of the entrance surface of the fourth bending magnet in the BC onto the roof of the tunnel where it can directly be measured or analyzed with a Martin Puplett Interferometer (MPI). The transverse deflecting cavity (TDC) and a port to extract coherent diffraction radiation (CDR).

studies were performed at the SITF based on coherent edge, synchrotron and diffraction radiation.

Edge and Synchrotron Radiation After the (First) Bunch Compressor

The edge radiation of the last dipole magnet of the bunch compressor is imaged via a THz transfer line onto the tunnel roof. The finite mirror sizes and the influence of the vacuum windows result in the spectral transmission, shown in Fig. 2. This simulation is based on Synchrotron Radiation Workshop (SRW) [4]. For a perfectly aligned system a transmission of roughly 20% is expected at 1 THz. For the bunch compression studies, one fourth of the trans-

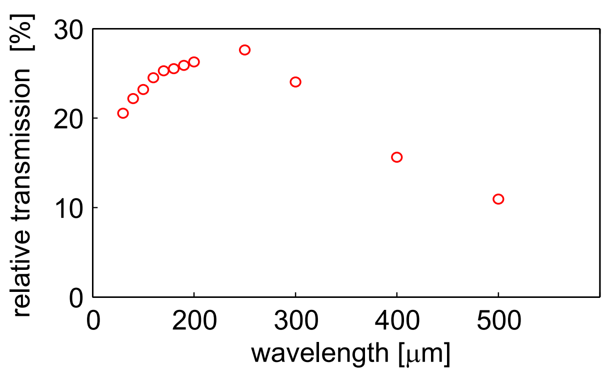

Figure 2: Relative spectral transmission of the THz transfer line, based on simulations using SRW [4].

fer line output is subsequently focused onto a fast, quasi-optical THz detector (ACST) which is sensitive up to more then 2 THz. For nominal SwissFEL parameters of a bunch charge of 10 pC and around a bunch length of 500 fs rms, the off-crest phase of the accelerating S-Band cavity was scanned. Figure 3a) shows, the integrated intensity over the whole spectral range of the detector (50 GHz-2 THz) for a beam energy of 200 MeV. The error bars indicate the standard deviation resulting of 100 single shot measurements for each compression phase. The horizontal error is given by the fluctuating read-back of the corresponding phase. For the same time period, Fig. 3b) indicates the charge fluctuation and Fig. 3c) depicts a rough estimate for the bunch length measured with the TDC and a Screen Monitor.

For this long bunch and low charge operation mode, a clear

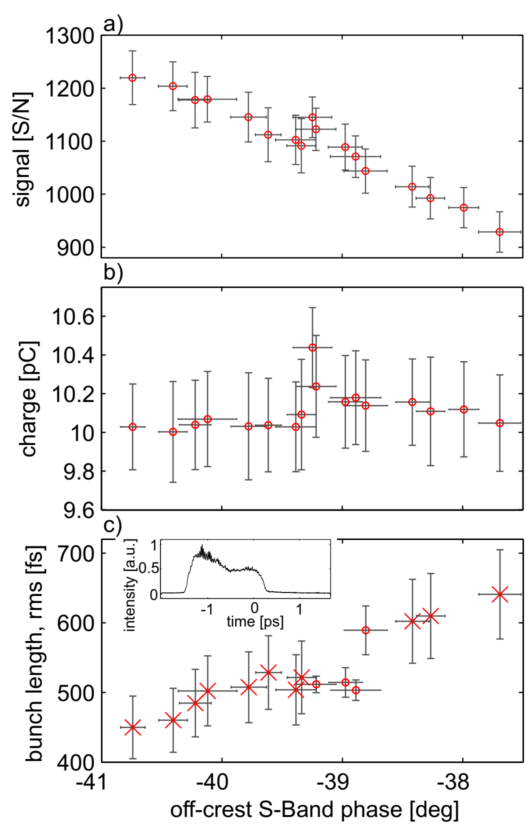

Figure 3: Measurements vs. compression around a bunch length of 500 fs for 10 pC, 200 MeV. a) One fourth of the edge and synchrotron radiation emitted at the fourth dipole magnet of the BC is imaged onto a quasi optical THz detector. b) corresponding measured charge. c) corresponding measured bunch length using the TDC. A typical longitudinal bunch profile is depicted as an inset.

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increase in signal is observed as the longitudinal bunch gets more compressed. The main contribution to the vertical error bars might be due to charge fluctuations.
The high responsivity of the detector allows to use spectral filters for simultaneous detection of multiple spectral bands. This configuration would then allow for distinguishing between a variation in charge and a variation in bunch length, respectively in the phase of the accelerating structure.

Diffraction Radiation

After the bunch compressor, a 1 μm thick titanium foil with a hole diameter of 3 mm has been installed in the electron beam pipe to produce coherent diffraction radiation [3]. Here, the coherent radiation is focused onto a pyro-electric detector. To increase the sensitivity of the measured signal with respect to small (0.02 deg) variations in the accelerating phase, a THz high-pass filter was tested in front of the detector. As illustrated in the inset in Fig. 4, the high pass filter consist of hexagonally arranged holes in a thick, conducting plate [5]. The spectral transmission (see Fig. 4b)) of the THz filter was simulated by COMSOL.
As in the previous case, the spectral density distribution of the CDR is given by Eq. 1. For various bunch compressions, the longitudinal bunch profile was measured with the TDC (see Fig. 4a)). The longitudinal form factor derived therefrom was then multiplied by the radiation which was modeled with the $Mathematica$ package $THzTransport$ (developed by B. Schmidth, DESY). In Fig. 4b), the resulting spectral intensities are depicted. The spectrally integrated intensities with filter as a function of compression shows a steeper slope as the unfiltered integration shown in Fig. 4c). For a better comparison, the traces are normalized to the value for an off-crest S-Band phase of 47 deg. The measurements agree well with the expected increase by using the high-pass THz filter under consideration.

CONCLUSION AND OUTLOOK

The dependency of the spectrally integrated CER and CSR on the longitudinal electron bunch compression have been studied experimentally at the 250 MeV Injector Test Facility at PSI. Also for the two bunch mode (time delay of 28 ns) foreseen for SwissFEL operation, the fast response of the quasi optical THz detector allows for single shot measurements of the bunch compression after BC1. Due to the high responsivity, also for 10 pC charge, the use of THz highpass filters are under study to enhance the sensitivity with respect to very small (0.02 deg) S-band phase changes in the accelerating structure.

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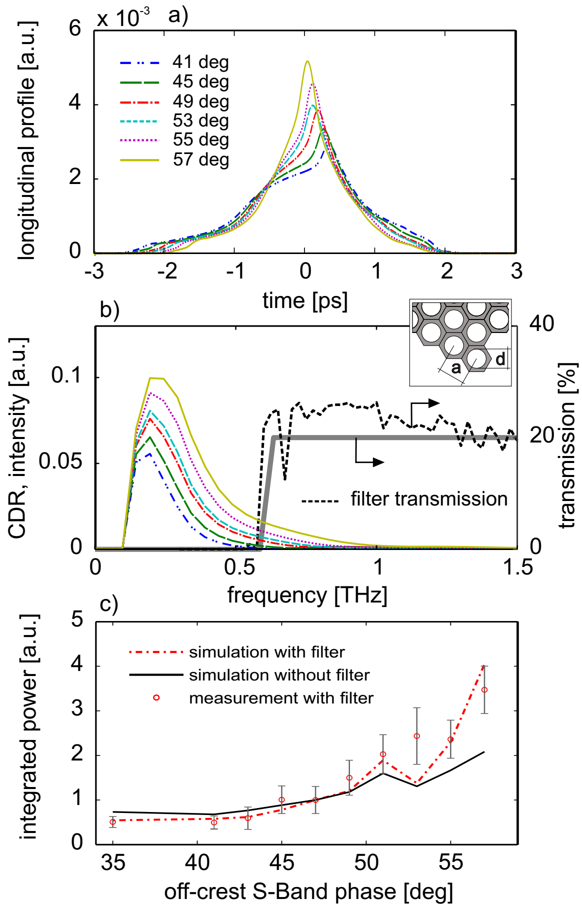

Figure 4: For different electron bunch compressions, the longitudinal bunch profile for 65 pC and 200 MeV is measured with the TDC a). Therewith, the corresponding CDR spectrum is derived b). Moreover the simulated transmission of a high-pass THz filter is shown in b). The inset illustrates the air filled hole array in a thick copper plate, used as the highpass THz filter (a=600 μm, d=300 μm). The resulting characteristic of the spectrally integrated signal as a function of the electron bunch compression angle is depicted in c). This data was taken without X-band.

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