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ELECTRON BUNCH COMPRESSION MONITORS FOR SHORT BUNCHES - COMMISSIONING RESULTS FROM SwissFEL

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Abstract

In SwissFEL, by using three magnetic chicanes, 1–3 ps long electron bunches can be compressed by a factor of more than 100 down to a few fs in order to generate ultra short X-ray pulses. In order to meet the envisaged beam performance, noninvasive longitudinal diagnostic after each compression stage is essential. These bunch compression monitors measure relative bunch length changes on a shot-to-shot basis by detecting coherent edge, snychrotron or diffraction radiation emitted by the electron bunches. Here, we will report on the first commissioning results of the bunch compression monitors for the ultra short bunch mode.

INTRODUCTION

The Aramis beam line at the compact free electron laser user facility SwissFEL [1] at the Paul Scherrer Institut (PSI) in Villigen (Switzerland) produces tunable and coherent X-ray pulses in the wavelength range of 0.1–0.7 nm and is designed to run at 100 Hz.

As depicted in Fig. 1, SwissFEL is based on an S-band radio frequency (RF) photoinjector. An S-band injector in combination with an X-band structure is simultaneously generating the acceleration as well as the necessary linear energy chirp for the first bunch compression stage (BC1). To ensure the proper setup of the injector, the longitudinal electron bunch profile can be measured by means of S-band transverse deflection cavity (TDC).

Thereafter, the electron beam is further accelerated in C-band LINACs to the beam energy of 2.1 GeV. After a second bunch compressor (BC2), a C-band TDC is also providing the possibility to measure the longitudinal electron bunch profile. Two electron bunches with a time delay of 28 ns might be transported up to the switch-yard, where they are directed to the Aramis and Athos beam line respectively. The electron beam in the Aramis beam line can further be accelerated up to a beam energy of 5.8 GeV, before reaching the energy collimator (EC) and hence the undulators.

As indicated in Fig. 1, for one of the four nominal oper-ation modes of SwissFEL (Aramis), the energy collimator can be used as a third bunch compressor to achieve elec-tron bunch lengths of less than 1 fs (rms) (ultra short bunch mode).

The lasing performance of SwissFEL highly depends on the electron beam quality, in particular on the compression along the whole machine as well as on the stability over time. Therefore, an electron bunch compression monitor is installed after each possible compression stage (BC1, BC2 and EC).

While the first two monitors are used to stabilize the com-pression phase of the injector and LINAC1, respectively, the signal of the bunch compression monitor after the EC is expected to be used for an indication of full compression in the ultra short bunch mode.

In the subsequent sections, we provide first commission-ing results on the electron bunch compression monitors (BCM) for the ultra short bunch mode at 10 pC. To study the sensitivity of the monitors with respect to small changes in bunch length, the compression phases are scanned around the working point where the machine was set up to. In the in-jector (BC1), this is achieved by varying the off-crest phases of the last two S-band structures simultaneously, while keep-ing the beam energy via an energy feedback constant.

In contrast, the compression after BC2 is varied by alter-natingly shifting all RF stations of LINAC1 with respect to a fixed off-crest phase. This, to minimize multipacting in the RF structures.

Each of the three electron bunch compression monitors is briefly outlined and the experimental results are presented following the order along the machine.

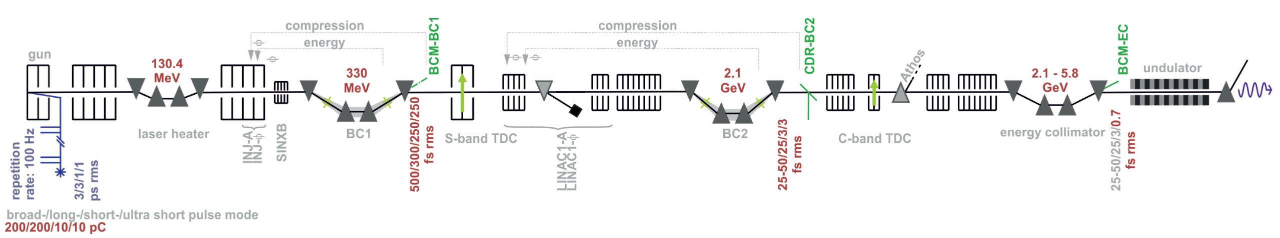

Figure 1: Layout of SwissFEL. After each possible compression stage, there is an electron bunch compression monitor installed. While BC1 (flexible bending angle to cover: 3–4°) and BC2 (flexible bending angle to cover: 1.5–3.8°) are constantly used for compression, the energy collimator (fixed bending angle of 1°) is only used as a third bunch compressor in the ultra short pulse mode. But only after the first two compression stages, the longitudinal electron bunch profile can be measured using a transverse deflecting cavity (destructively).

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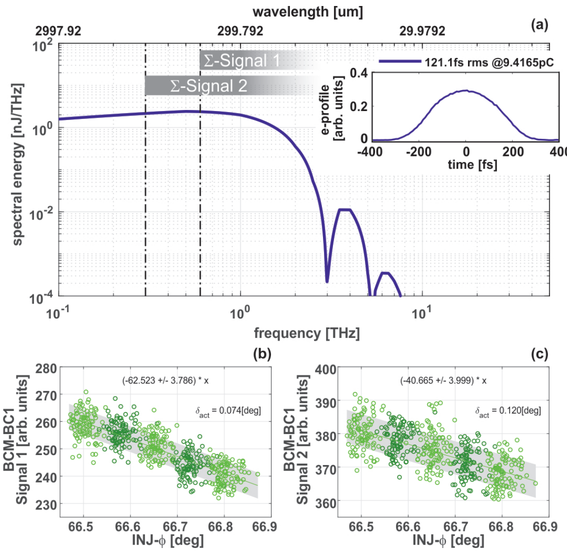

Figure 2: Top (a): Estimated spectral energy of measured longitudinal electron bunch profile at the working point after BC1. Also indicated are the spectral parts which are detected. (b) and (c): Measured signals with respect to the compression phase in the injector using a high pass filter at 0.6 THz and 0.3 THz respectively.

COMPRESSION MONITOR AFTER BC1

At the first bunch compression stage, the compression monitor using coherent edge (and synchrotron) radiation from the entrance edge of the 4th bending magnet of BC1 has originally been designed to provide a relative bunch length measurement for nominal rms bunch lengths of a few hundred femtoseconds (250–500 fs). As commonly done in compression monitors, the idea is to detect this spectral part of the emitted radiation, where the intensity of the coherently emitted radiation drops (see Fig. 2(a)). The more precise this spectral part is matched to the bunch length and bunch profile, the higher the sensitivity of the monitor with respect to small changes around these machine settings.

To meet the required dynamic range as well as the requirement to resolve two electron bunches with a time delay of 28 ns, this monitor is based on broadband Schottky diodes sensitive up to more than 2 THz. Since the sensitivity of these detectors is typically dropping with increasing frequencies, the THz intensity is split into two signal paths which are equipped with two different high-pass filters at 0.3 THz and 0.6 THz (as indicated in Fig. 2).

A typical electron bunch profile measured in the injector at the working point of the machine is depicted in Fig. 2(a) together with the estimated spectral energy deduced from the temporal profile. The electron bunch is significantly shorter than for which the monitor was originally optimized for. As expected, the sensitivity with respect to the compression phase (Fig. 2(b)) is considerably higher for the signal path using the 0.6 THz high pass filter. However, for these short electron bunch lengths, a high pass filter at a higher frequency could increase the sensitivity of the actually measured 0.07° S-band as we measured a significantly higher sensitivity for longer bunches [2].

COMPRESSION MONITOR AFTER BC2

After the second bunch compression stage, the compression monitor is based on coherent diffraction radiation (CDR; titanium foil, thickness 1 µm, hole diamter 4 mm) and designed for rms electron bunch lengths of 3–25 fs. For the expected electron bunch profiles, the coherent spectral intensity is expected to drop in the far infrared region. Since two signals with 28ns time delay are required to be detected also at this position, the monitor is based on a fast Mercury Cadmium Telluride (MCT) detector module which is sensitive in the wavelength range 2 µm–12 µm.

At the present working point, a typical longitudinal electron bunch profile is depicted in Fig. 3(a) together with the deduced spectral energy distribution.

Since there is a TDC behind the bunch compression monitor after BC2 the compression signal can be correlated to the measured rms electron bunch length as shown in Fig. 3(b). The machine jitter induced a bunch length fluctuation of +/-10 % over 60 consecutive electron bunches. Part of this jitter can be attributed to the jitter of the X-band phase.

Changing the phase of LINAC1 by +/-0.5°, the induced bunch length change from 4–11 fs (rms) already led to a nonlinear behavior in the compression monitor signal. At the working point, the sensitivity of the compression monitor can be estimated at 8 % relative bunch length change.

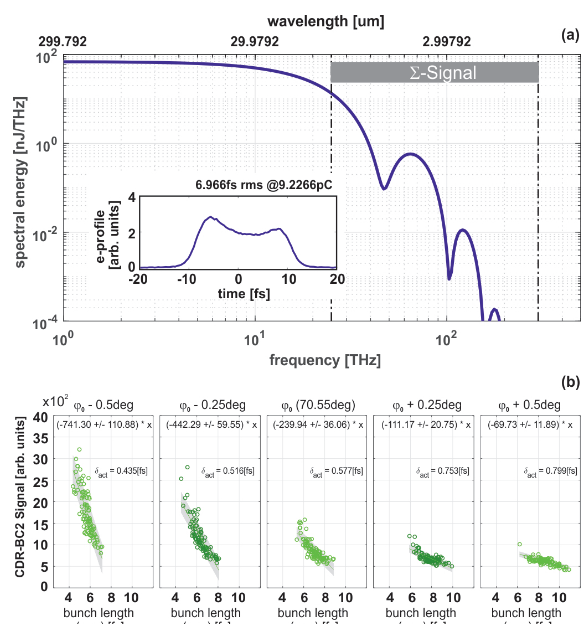

Figure 3: Top (a): Estimated spectral energy of measured longitudinal electron bunch profile at the working point after BC2. Also indicated is the spectral part which is detected. (b): Measured signal with respect to to the synchronously measured bunch length at five different compression phases in LINAC1.

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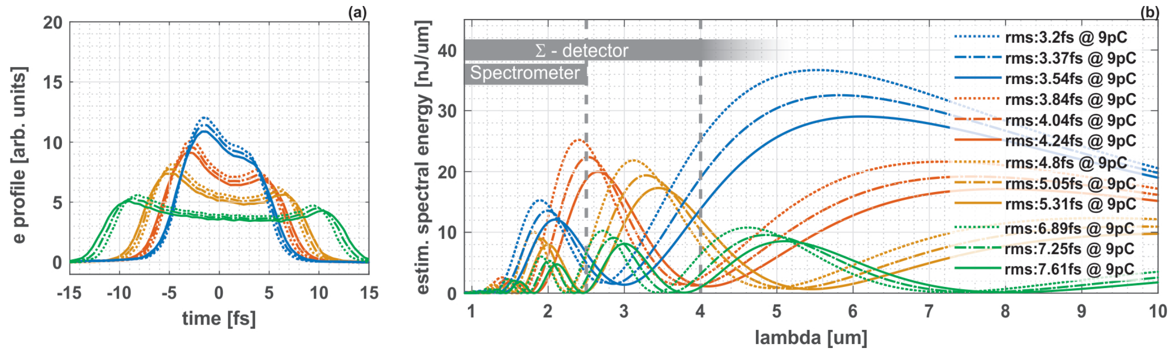

Figure 4: Left (a): Typical longitudinal profiles estimated after the energy collimator (dash-dotted lines) with indicated profiles of +/- 5 % deviation (dotted and solid lines). (b): Corresponding estimated spectral energy. Indicated is the spectral part which is detected by a sum-detector as well as the spectral part measured via a spectrometer.

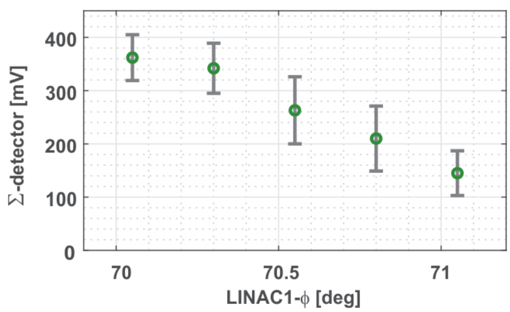

Figure 5: Measured signal from the sum-detector with respect to the phase of LINAC1.

COMPRESSION MONITOR AFTER EC

While the two compression monitors after BC1 and BC2 are used to stabilize the compression phases, the BCM after the energy collimator is intended to be used for indication of full compression. Similar to BC1, it is based on coherent edge (and synchrotron) radiation from the entrance edge of the last bending magnet of the energy collimator. A mechanical aperture due to a quadrupole magnet limits the proper propagation of the edge radiation to wavelengths <4 µm.

This monitor is designed to measure relative electron bunch length changes of 5 % for bunch lengths in the range of 0.7–3 fs (rms).

Since the bandwidth of this monitor is more relaxed because there is only one electron bunch to be detected at 100 Hz, the monitor is equipped with a pyroelectric sensor used as a sum-detector and an additional spectrometer covering the wavelength range 0.9–2.5 µm.

Some possible temporal electron bunch profiles are assembled in Fig. 4(a). The estimated spectral energy for the different profiles are depicted in Fig. 4(b). Given the typical temporal shape, for bunch lengths >4 fs, the spectral region of 0.9–4 µm contains exlusively side maxima of the coherent spectra. This enhances the sensitivity of the monitor with respect to shape, but not bunch length changes. Only for shorter bunches, the main part of the coherent spectral intensity (see Fig. 4(b), blue spectra) is moving into the spectral region of 0.9–4 µm.

For first tests, measurements with the sum-detector were performed using an oscilloscope. The behavior with respect to the LINAC1 phase (see Fig. 5) indicates that the machine was not optimized at full compression. This is emphasized by the spectrometer data depicted in Fig. 6. Long electron bunches lead to faster oscillating spectral intensity distributions (Fig. 6(a)) and a lower sum-detector signal (Fig. 5). The shorter the electron bunch length, the broader are the characteristic signatures in the spectral intensity distribution (see also Fig. 4).

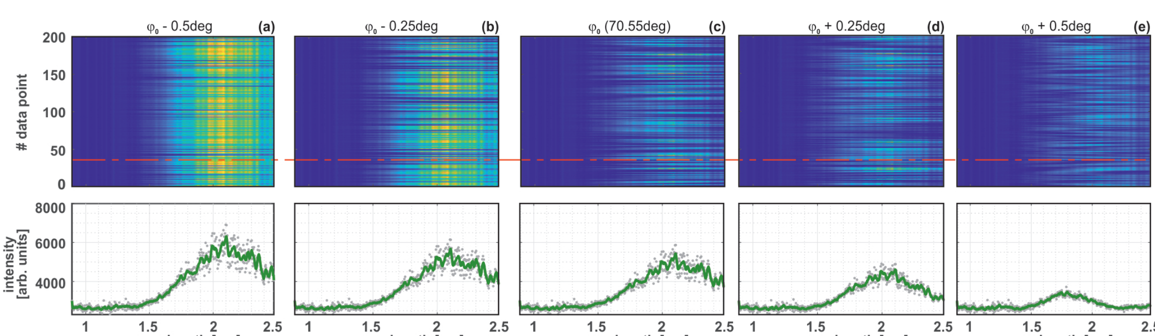

Figure 6: Measured spectral energy for five different phases of LINAC1 (a)–(e). Top row: measured spectra of 200 consecutive electron bunches. Bottom row: spectra of red indicated bunches. The gray dots are corresponding to the raw data, the green line to a binned (6 pixel) spectra.

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Further studies are planned to allow a more quantitative analysis of the behavior of this third bunch compression monitor.

CONCLUSION AND OUTLOOK

All compression monitor signals were successfully measured while scanning the compression in the injector as well as in LINAC1 during the first commissioning of the ultra short bunch mode at 10 pC. While TDCs in the injector and in the LINAC provide valuable measurements for comparison, the longitudinal profile after the energy collimator has to be simulated based on the machine settings. To allow this more quantitative analysis, the required machine parameters are planned to be measured/checked during the next, dedicated shift.

Moreover, the overall machine settings to reach the nominal electron bunch length for this ultra short bunch mode is planned to be optimized in the near future.

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