COHERENT RADIATION DIAGNOSTICS FOR LONGITUDINAL BUNCH CHARACTERIZATION AT EUROPEAN XFEL

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Abstract

European XFEL comprises a 17.5 GeV linear accelerator for the generation of hard X-rays. Electron bunches from 20 pC to 1 nC will be produced with a length of a few ps in the RF gun and compressed by three orders of magnitude in three bunch compressor (BC) stages. European XFEL is designed to operate at 10 Hz delivering bunch trains with up to 2700 bunches separated by 222 ns. The high intra-bunch train repetition rate offers the unique possibility of stabilizing the machine with an intra-bunch train feedback, which puts in turn very high demand on fast longitudinal diagnostics. Two different systems will be installed in several positions of the machine. Five bunch compression monitors (BCM) will monitor the compression factor of each BC stage and be used for intra-bunch train feedbacks. A THz spectrometer will be used to measure parasitically the longitudinal bunch profile after the energy collimator at 17.5 GeV beam energy. We will present concepts for fast longitudinal diagnostics for European XFEL based on coherent radiation, newest developments for high repetition rate measurements and simulations for the feedback capability of the system.

INTRODUCTION

European XFEL will be a linac-driven hard X-ray free electron laser operating at wavelength down to 0.1 nm [1]. The machine will produce up to 2700 short (2-100 fs) X-ray pulses per macro pulse (10 Hz) with a repetition rate of up to 4.5 MHz. The X-ray pulse generation requires kA peak current of the electron bunches which will be achieved by three stages of bunch compression (BC0, BC1 and BC2 in Fig. 1). The corresponding bunch lengths are indicated in Table 1 (source: start-to-end simulations [2]). A high power laser will generate 4 ps - 7 ps rms long electron bunches in the normal conducting photocathode gun. In the subsequent super conducting acceleration module (1.3 GHz) and the longitudinal phase space linearizer (3.9 GHz) the beam gets an energy of 130 MeV. In BC0 the bunches are compressed by a factor of three before they are accelerated to 700 MeV in the first part of the linear accelerator (L1). In the second compression stage (BC1) the length of the bunches is reduced by a factor of eight and they are accelerated to 2.5 GeV in L2. In BC2 the bunches are compressed to their final length (fs level) and in L3 they are accelerated to the maximum energy of 17.5 GeV. The electrons are then transported through an energy collimator to the distribution area and to SASE1 or SASE2 undulator beamlines, respectively.

Table 1: RMS electron bunch lengths in European XFEL for three different charges. Highlighted row: used in simulations.

Charge	Gun	BC0	BC1	BC2
20 pC	4.5 ps	1.5 ps	180 fs	5 fs
100 pC	4.8 ps	1.6 ps	200 fs	12 fs
1000 pC	6.8 ps	2.2 ps	300 fs	84 fs

Stable X-ray SASE output requires among other parameters precise control of the longitudinal shape of the electron bunches. The longitudinal shape is tailored only in the BCs. Bunch compression is achieved with an accelerating module running off-crest to induce an energy chirp in the electron beam and a magnetic chicane. In operation the compression level is mainly defined by the phase setting of the corresponding acceleration module. Five bunch compression monitors (BCM), three independent and two redundant, will measure at full repetition rate a quantity that is directly related to the current profile. The independent BCMs are the monitors of a feedback system controlling the RF phase settings. In addition one broadband infrared spectrometer is used to resolve accurately the final longitudinal bunch profile with single bunch resolution. It will be installed after the energy collimator where the electrons are fully compressed and have their final energy of 17.5 GeV. The spectrometer works best for short bunches producing short wavelength diffraction radiation.

In this paper, we will describe the requirements on the BCMs and feedback system in European XFEL as well as design considerations for the monitors. The performance of the whole system is estimated using simulation tools and operation experiences gained at the VUV Free-electron-LASer-Hamburg (FLASH).

MONITORING THE LONGITUDINAL BUNCH SHAPE

Requirements and Concepts

Table 2: Longitudinal diagnostic requirements overview (numbers in brackets: injector).

Charge	20 - 1000 pC
Energy	(0.005)0.13 - 17.5 GeV
Bunchlength	5 - 2000(7000) fs rms
RF phase stability	0.01 deg
Bunch spacing	min. 222 ns
Repetition rate	10 Hz

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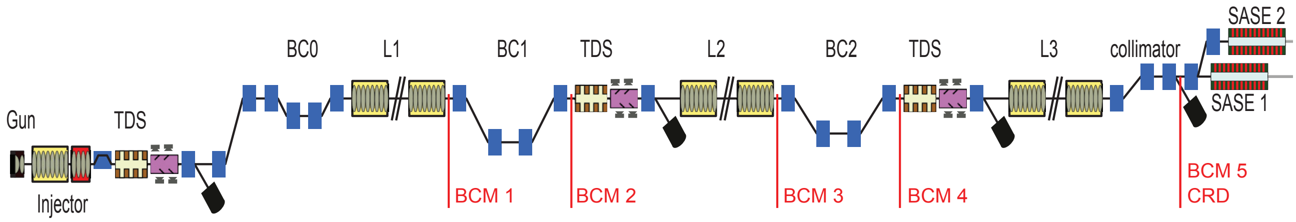

Figure 1: Main components of European XFEL.

Several longitudinal diagnostic systems have to be installed in European XFEL to cover the complete parameter range listed in Table 2. The current profile can be accurately monitored with a longitudinal profile monitor [3] consisting of a transverse deflecting structure (TDS, [4]) in combination with fast kicker magnets and off-axis screens. One bunch out of the bunch train is streaked in the TDS and kicked to the profile monitor where it is recorded by a camera. The TDS system offers direct profile measurement of a single bunch with femtosecond resolution. However, the system is destructive to the electron bunch and not capable of measuring all bunches in a bunch train. It is not sensitive to variations over the bunch train which may be caused by phase drifts of the low level RF (LLRF). The TDS based longitudinal profile monitor will be the reference system.

The longitudinal bunch shape determines the spectral content of the coherent radiation emitted by the electrons when passing a discontinuity such as Coherent Synchrotron Radiation (CSR), Coherent Diffraction Radiation (CDR), and Coherent Transition Radiation (CTR). The spectral density distribution of the coherent radiation emitted by a bunch composed of N electrons is given by Eq. 1, where $d^2P_0/d\omega d\Omega$ denotes the single electron spectrum for the process under consideration and $F(\omega,\Omega)$ the longitudinal bunch form factor. F is the normalized Fourier transform of the longitudinal current profile.

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

Spectrally resolved measurements of the coherent radiation with a spectrometer directly yield the absolute value of the (complex) formfactor (CRISP4). The actual longitudinal bunch shape can be derived by making certain assumptions and using mathematical reconstruction methods [5]. By integrating the spectral intensity in a certain frequency range, we get a single signal that is correlated to the current profile of the bunch (BCM). Small variations in bunch shape lead to variations in the detected signal and can be used as monitor signal for the feedback system.

The longitudinal current profiles of a bunch with 100 pC bunch charge at several positions in the machine are depicted in Fig. 2. The corresponding formfactors are shown in Fig. 3. Analyzing the curves in Fig. 3 we find that THz detectors have to be used after BC0, BC1 and BC2. There will be no system to measure the coherent radiation between the electron gun and BC0 (10 GHz range).

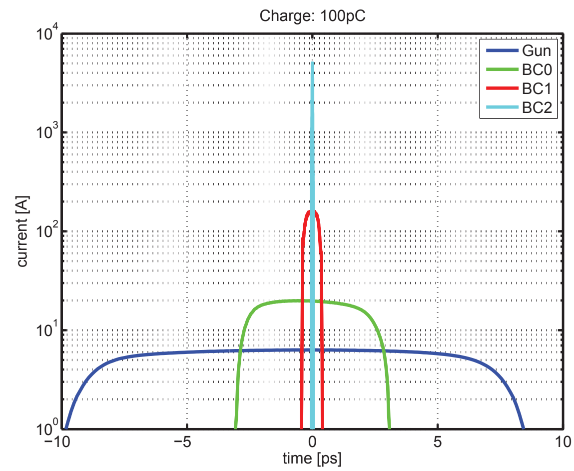

Figure 2: Longitudinal bunch profile from beam dynamics simulations.

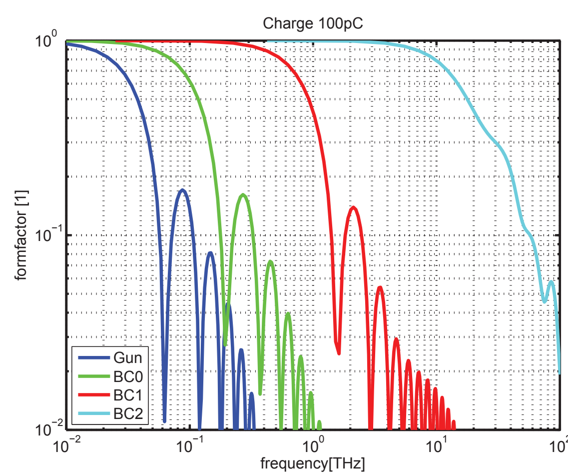

Figure 3: Longitudinal form factor derived from beam dynamics simulations.

Bunch Compression Monitor (BCM) and 4stage Coherent Radiation Infrared Spectrometer (CRISP4)

The BCMs have to be simple and reliable monitors providing robust signals from each bunch to be used for the RF phase feedback system. The signal generation should not depend on the beam orbit and must not disturb the beam itself. The monitors are composed of a cubic vacuum chamber, a screen mover and an in-vacuum diffraction radiation

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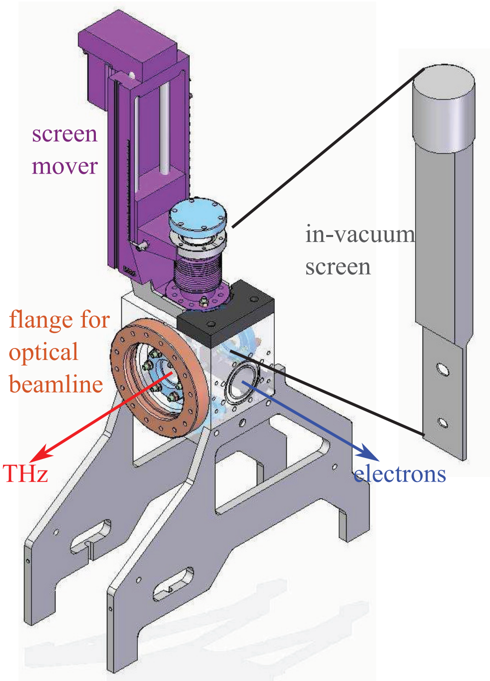

Figure 4: 3D CAD model of screen station for BCMs and CRISP4. Courtesy of N. Leuschner, DESY.

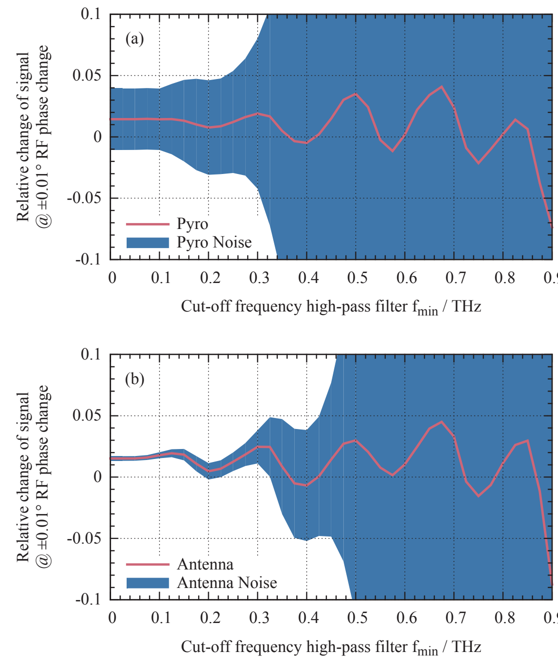

Figure 5: Simulation of relative detector response when changing RF phase by ±0.01 deg versus edge frequency of THz high-pass filter. (a) pyro-electric sensor, (b) quasi optical detector (Schottky-diode with antenna).

screen. The image export of the 3D CAD model of the vacuum station is shown in Fig. 4. The generated THz/infrared radiation is transported through an optical beamline to the detectors.The BCMs for European XFEL will be very similar to the proven systems installed at FLASH [6]. There the BCMs are used for slow RF phase feedback.

CRISP4 was also developed for FLASH [5] and a copy will be installed in European XFEL. The grating spectrometer was designed to cover the wavelength range from 4 µm to 440 µm with two sets of gratings. 120 pyro-electric sensors convert the radiation in the respective frequency band into an electrical signal. At FLASH, CRISP4 is mainly operated with an off-axis transition radiation screen and fast kicker magnets. CTR is much more intense than CDR for the same electron beam parameters but it is destructive to the electron bunch. Therefore, the system is limited to measure one single bunch of the bunch train. At European XFEL, CRISP4 will get the radiation of each bunch of the bunch train from a diffraction screen. Sufficient intensity is generated by coherent diffraction due to the high energy and the high peak current of the electron bunches. CRISP4 will provide CDR spectra taken with one set of gratings at full repetition rate.

SIMULATIONS AND RESULTS

In order to design each monitor station and to choose the most appropriate detectors, the longitudinal bunch properties, radiation process, radiation transport and detector response have to be taken into account. We developed a simulation tool which combines different codes and inputs. We are now able to calculate the expected signal depending on the RF phase of the accelerating modules and the BC chicane setting. And therefore we are able to assess the required sensitivity of the sensors in order to provide reliable monitor signals to the feedback system.

Starting from the nominal acceleration module phase and amplitude settings we varied the phases by a small amount and calculated the according BCM response for two different detectors: pyro-electric sensor (Fig. 5 (a)) and quasi optical detector based on a Schottky-diode with antenna (Fig. 5 (b)). The scan range was chosen ±0.01 deg. The expected signal change was then compared to the noise of the detectors. With intent to improve the response of our systems, we also include spectral THz filters into our simulations [7]. The longitudinal formfactors (Fig. 3) are close to one for low frequencies and therefore small changes in bunch length will only affect the slope of the formfactors at higher frequencies. In order to increase the sensitivity of the BCMs to small changes in bunch length at the expense of lower signal amplitude, a high-pass spectral THz filter is used to suppress the low frequencies. The results of the calculations for BC0 are summarized in Fig. 5. The red curves in both plots denote the relative change of the signal of the respective detector when changing the acceleration phase by ±0.01 deg versus the edge frequency of a high-pass THz filter. The blue band denotes the absolute signal divided by the noise of the detector.

The relative signal change can slightly be improved when introducing THz filters, but the noise grows much more. The signal to noise ratio cannot be improved significantly. In addition we find that the Schottky-diode with antenna is

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the detector of choice at this location. The oscillations of the signals correspond to the structure of the longitudinal formfactor depicted in Fig. 3.

CONCLUSION

The coherent radiation diagnostics for European XFEL is based on the monitors installed in FLASH. Several properties have to be improved or adapted. The main improvement necessary is the modification towards the higher bunch repetition rate (4.5 MHz). The mechanical design is completely new and has to comply with European XFEL design and vacuum specifications. A rigid full metal diffraction radiation screen (-holder) will be integrated in all monitors.

Several software tools are available to simulate the complete path: from RF phase setting to detector signal. Simulation results and experience from FLASH showed that uncooled detectors like pyro-electric elements (all wavelengths) and Schottky-diodes with antennas (long wavelengths) are well suited to provide feedback capable signals for a fast intra-bunch train feedback.

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REFERENCES

[1] M. Altarelli et al., “The European X-Ray Free-Electron Laser Technical design report,” (DESY 2006-097).

[2] G. Feng et al., “Beam Dynamics Simulations for European XFEL,” (TESLA-FEL 2013-04).

[3] M. Yan et al., “First Realization and Performance Study of a Single-Shot Longitudinal Bunch Profile Monitor utilizing a Transverse Deflecting Structure”, IBIC’13, Oxford, September 2013, TUPC36, p. 456, http://www.JACoW.org

[4] P. Emma, J. Frisch, and P. Krejcik, “A Transverse RF Deflecting Structure for Bunch Length and Phase Space Diagnostics,” LCLS Technical Note, 12, (2000).

[5] S. Wesch et al., “A multi-channel THz and infrared spectrometer for femtosecond electron bunch diagnostics by single-shot spectroscopy of coherent radiation,” Nuclear Instruments and Methods in Physics Research Section A 665.0, pp. 40 to 47 (2011).

[6] H. Delsim-Hashemi et al., “Single-Shot Longitudinal Diagnostics with THz Radiation,” WG512, Proc. FLS2006, Hamburg, Germany (2006).

[7] F. Frei et al., “Development of Electron Bunch Compression Monitors for SwissFEL”, IBIC’13, Oxford, September 2013, WEPC36, p. 769, http://www.JACoW.org

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