UPGRADE AND EVALUATION OF THE BUNCH COMPRESSION MONITOR AT THE FREE-ELECTRON LASER IN HAMBURG (FLASH)

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Abstract

The control and stabilization of RF systems for accelerators are of considerable importance. In case of high-gain free-electron lasers (FEL) with magnetic bunch compressors, the RF phases determine the attainable bunch peak current, which is a relevant parameter for driving the FEL process. In order to measure the bunch peak current in a simple and fast but indirect way, both bunch compressors at FLASH are equipped with compression monitors (BCM) based on pyroelectric detectors and diffraction radiators. They provide substantial information to tune the bunch compression and are used for a beam-based feedback to stabilize the RF phases. This monitor system became more important and more challenging after the installation of a third-harmonic RF system for longitudinal phase space linearization.

In this paper, we describe the hardware upgrade of the bunch compression monitor and show the expected performance by simulations of the CDR source and the radiation transport optics. Particle tracking simulations are used for generation of the simulated BCM signal for various compression schemes. Comparison with experimental data will be presented.

INTRODUCTION

The measurement of coherent diffraction radiation (CDR), generated by an electron bunch passing a metallic slit, is a simple and noninvasive method of relative bunch length and current determination. The experimental setup, including diffraction slit, transport optics, pyroelectric detectors (pyro) and readout electronics, is denoted by bunch compression monitor (BCM) in the following.

The BCM signals, which provide relative bunch length and current information, can be used in a beam-based feedback system to control the energy chirp by stabilization of the RF parameters of the accelerator modules in front of the bunch compressors (BC). This is not only relevant for compensation of slow drifts but also for intra-bunch-train compensation for long bunch train operation [1, 2].

The installation of a third-harmonic RF system for longitudinal phase space linearization in front of the BCs [3, 4] enables a new compression scheme with several possible working points. The proposed working points with moderate compression in the first BC produce too low radiation levels to be detected with the existing BCM [2].

The upgraded BCM setup offers an overall sensitivity increase by two orders of magnitude. In order to improve the dynamic range, it includes two individual detectors with different amplifications. A direct comparison between the old and new performance of the BCM setup will be shown.

EXPERIMENTAL SETUP

Behind the BC, the electron bunches pass the diffraction radiator. It consists of two aluminum-coated silicium screens ($20 \times 46\,\mathrm{mm}^2$) forming a horizontal slit of 5 mm. A tilt of 45 deg enables an extraction of the broad bandwidth diffraction radiation through a plane crystalline quartz window (d = 4.8 mm, diameter 60 mm). A periscope of two gold coated mirrors guides the radiation to the detectors.

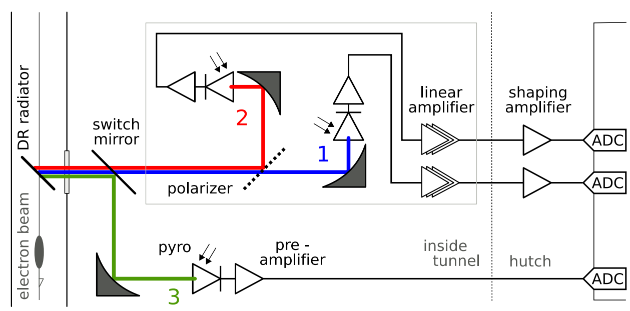

Figure 1: BCM setup at the first BC (see text). The new (1,2) and old detectors (3) are marked with different colors corresponding to graphs in other figures.

Optical Layout

In Fig. 1 a schematic overview for the new and old BCM setup is shown. The new setup is build next to the old one for a direct comparison between these. A motorized mirror deflects the DR into the different detectors.

For the old setup, the radiation transits 1.2 m in air and is focused with a parabolic mirror (f = 200 mm, clear aperture 100 mm) onto the pyro detector (3). The detectors can be adjusted by a motorized stage horizontally. By moving the switch mirror out of the beam path, the radiation enters the new setup. A polarizer (Microtech Instruments G30, diameter 90 mm) separates the radiation into vertical (1) and horizontal (2) field components in two symmetric detection arms. Each focus the DR with parabolic mirrors (f = 50.8 mm, diameter 3 inch) onto the pyroelectric elements. Motorized mirror mounts and in the optical axis

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movable detectors allow an accurate spatial overlap of radiation and pyro detector. The path length of the radiation is reduced by 0.3 m in respect to the old setup. All components are mounted on a breadboard and covered with a cardboard housing.

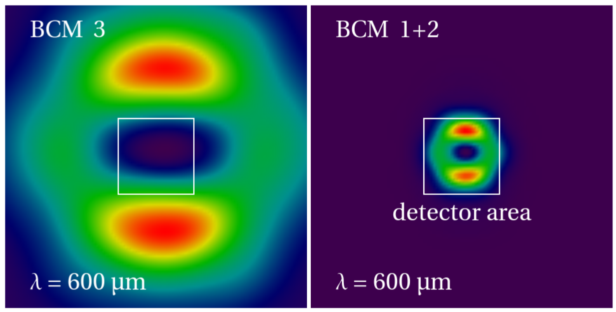

Figure 2: Simulation of the transverse profile (both polarizations) in the focal plane of old and new setup for $\lambda = 600\,\mu$m. The white rectangles indicate the size of the pyroelectric element of $2 \times 2\,\text{mm}^2$.

The benefit of the new optical layout is demonstrated in Fig. 2. For both polarizations the transverse profile of the radiation in the focal plane at the wavelength $\lambda = 600\,\mu$m is shown in comparison to the detector surface area of $2 \times 2\,\text{mm}^2$. Due to the shorter focal length the radiation profile in the new setup is better collimated. Fig. 3 displays on the left the single electron diffraction spectrum for all BCMs integrated over the detector surface. The peak intensity of the vertical field component by its own exceeds the maximum of both polarizations for BCM 3. Above 500 μm, the integrated intensity is more than 40 times larger for BCM 1 and 6 times for BCM 2, see Fig. 3 on the right plot. The optic simulations were done with the *Mathematica* package *THzTransport* and includes the radiator geometry, transmission of the quartz viewport and finite size of focusing optic. The absorption in humid air is neglected.

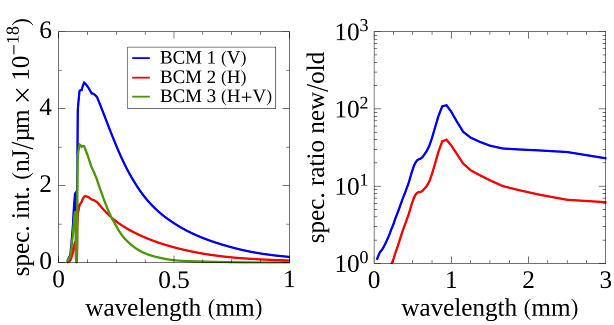

Figure 3: Spatially integrated intensity. Left: Single electron DR spectrum for all BCMs. Right: Intensity ratios of BCM 1/2 with respect to BCM 3.

Radiation Detection

The detectors are commercial pyroelectric elements (InfraTec LIE-301-X004). The used material is $LiTaO_3$ showing a broadband wavelength response from a few micro- up to several millimeter. The induced charges on the crystal surface are converted by a current sensitive preamplifier into a voltage pulse featuring a sharp rise and a exponential decay with the time constant τ. In the case of BCM 3, we used non-commercial preamplifier (VV50-3[1]) with a decay time of $\tau = 300$ ns enabling a discrimination between two successive electron bunches with a common spacing of 1 μs. This signal is lead over about 30 m into a hutch, where an ADC with 1 MHz sampling and a range of ± 1 V is located, Fig. 1. For the new setup we use commercial preamplifiers (Cremat CR110/CR111) with $\tau = 1.4\,\mu$s and an improved signal-to-noise ratio (S/N) by a factor of 2. Linear and Gaussian shaping amplifier allow to adjust the length and the height of the pulse more easily. The shaping amplifier (Cremat CR-200) with $\sigma = 250$ ns (rms) is used to prevent an overlap of successive pulses. To increase the dynamic range, the sensitivity of the preamplifiers of the two new detectors differs by a factor of 10.

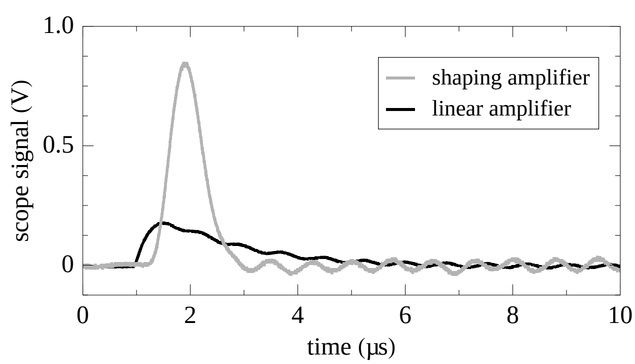

Figure 4: Example of oscilloscope trace of a single pulse.

Fig. 4 shows a signal of the new setup after the linear amplifier and after the shaping amplifier. Beside the initial signal of both, the traces display oscillations with a frequency of around 1.1 MHz. The reason are piezoelectric vibrations of the pyro crystal. Since the oscillations are amplitude and phase stable, it is planned to correct them by using fast digital signal processor boards.

MEASUREMENTS

After the successful hardware upgrade of the BCM was done, the commissioning of the new setup with compressed electron bunches started. The alignment was done by optimization of the spatial overlap of the CDR and the pyroelectric detector using motorized mirror mounts and linear stages. The main measurement parameters during the commissioning are listed in table 1. They are also valid for the measurements presented in the following.

[1] developed at Physikalisches Institut Heidelberg, Germany

Table 1: Main measurement parameters.

Parameter	Value
Bunch charge (nC)	0.5
Energy in first BC (MeV)	150
R56 of first BC (mm)	181
Third-harmonic RF system	off
RF-gun settings	nominal

Phase Scan and Simulation

The amplitude of the BCM signal as function of the RF phase has a clear signature with a characteristic dependency on the RF phase, which is depicted in Fig. 5. The maximum of the the BCM signal occurs at an RF phase of about -11 deg with respect to on-crest. This simple and fast measurement can be used for setting up the absolute RF phase of the first accelerator module for FEL-operation.

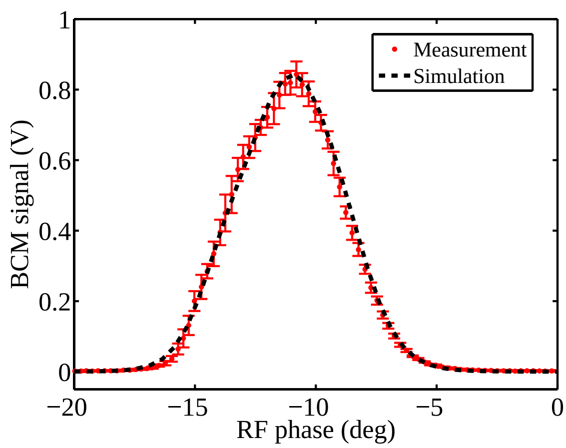

Figure 5: Measurement and simulation of the BCM 2 signal during an RF phase scan of the first accelerator module.

The measured data are compared with simulations on the bunch compression process, diffraction radiation source and transport optics of the BCM (presented above). The bunch compression was simulated using an one-dimensional particle tracking [2], i.e. linear tracking of the longitudinal phase space, including collective effects. The simulated BCM signal includes the longitudinal form factor from the particle tracking, the characteristics of the transport optics and the pyroelectric detector response. The result of this simulation is in perfect agreement with the measurements (Fig. 5).

Detector Comparisons

The old BCM setup with one detector was replaced by the new BCM with two detector channels with increased sensitivity. Figure 6 shows the S/N of the three detectors, during the phase scan explained before, on a semilogarithmic scale. Comparing the BCM signals at the RF phase of about -5 deg reveals the significant improvement of the both new detectors (blue and red). This improvement of S/N comes along with an increased detectable phase range and a broader dynamical range due to the two detectors, which can be operated simultaneously. In terms of beam-based feedbacks, BCM 2 can be used in case that BCM 1 saturates.

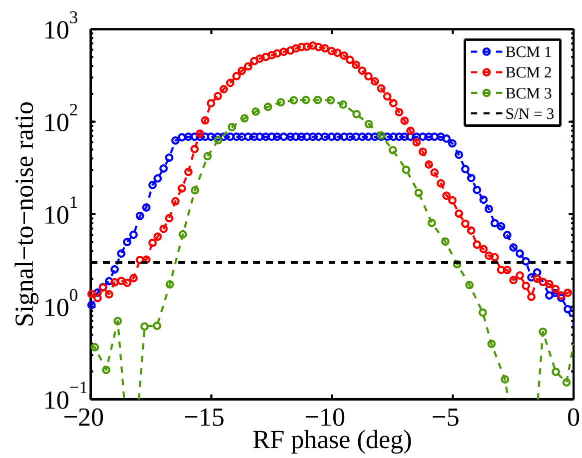

Figure 6: Signal-to-noise for the three detectors during an RF phase scan of the first accelerator module. BCM 1 shows saturation due to its high sensitivity.

CONCLUSIONS AND OUTLOOK

The BCM setup at the first BC was expanded by two new detectors, which are foreseen for parallel operation. The hardware upgrade and commissioning of the new setup have been successful, and a significant improvement of the S/N and dynamical range could be shown. Detailed simulations show that the BCM behaves as predicted. In the near future, the second BC will also be equipped with the new BCM.

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