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LONGITUDINAL INTRA-TRAIN BEAM-BASED FEEDBACK AT FLASH

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Abstract

The longitudinal intra-train beam-based feedback has been recommissioned after major upgrades on the synchronization system of the FLASH facility. Those upgrades include: new bunch arrival time monitors (BAMs), the optical synchronization system accommodating the latest European XFEL design based on PM fibers, and installation of a small broadband normal conducting RF cavity. The cavity is located prior to the first bunch compressor at FLASH and allows energy modulation bunch-by-bunch (1 μs spacing) on the per mille range. Through the energy dependent path length of the succeeding magnetic chicane the cavity is used for ultimate bunch arrival time corrections. Recently the RF cavity operated 1 kW pulsed solid-state amplifier was successfully commissioned. First tests have been carried out incorporating the fast cavity as actuator together with SRF stations for larger corrections in our intra-train beam-based feedback pushing now arrival time stabilities towards 5 fs (rms). The latest results and observed residual instabilities are presented.

INTRODUCTION

The free-electron laser in Hamburg (FLASH) at DESY is a research facility which provides laser radiation in the soft X-ray range with tunable wavelengths down to 4.2 nm. The accelerator operates in pulsed mode with a repetition rate of 10 Hz. The laser radiation is generated by the self-amplified spontaneous emission (SASE) process. The electron bunch trains with a variable length and repetition rate are accelerated by superconducting radio frequency (SRF) cavities up to the electron beam energy of 1.25 GeV, with a maximum number of 800 bunches per pulse and a bunch repetition rate of 1 MHz [1].

A high precision synchronization in the range of femtoseconds between an external laser and the free-electron laser (FEL) pulses is required, e.g., for pump-probe experiments. An intra-train beam-based feedback is used to correct arrival time fluctuations of the electron bunches in the magnetic bunch compression chicane in order to improve the bunch arrival time stability, which contributes to the photon beam quality delivered to the experiments. The important signal for the beam-based feedback is provided by the bunch arrival time monitors (BAMs) [2].

The low level radio frequency (LLRF) controller, regulating the 1.3 GHz RF field in amplitude A and phase Φ of the SRF cavities, includes different control strategies like a learning feedforward controller to minimize repetitive amplitude and phase errors from pulse to pulse and a second order multiple-input multiple-output (MIMO) controller to react within a pulse. The LLRF control system is based on the MicoroTCA.4 standard. The RF field regulation typically reaches an amplitude stability of $\Delta A/A \approx 0.008$ % and a phase stability of $\Delta\Phi \approx 0.007$ deg for the SRF cavities [3]. In addition, the superposition of the RF field information with beam-based measurements, e.g. the arrival time measured by the BAMs, is included in the control strategy of the RF field [4, 5].

The control strategy with the superposition of the RF-field and the beam-based information is called longitudinal intra-train beam-based feedback. This beam-based feedback control strategy and the controller design is already introduced in [5, 6].

In addition to the recent upgrades of the BAMs [4, 7, 8] and optical synchronization system [9], now using the latest European XFEL design based on PM fibers, a normal conducting cavity has been integrated into the beamline as a fast energy corrector cavity to further improve the arrival time stability to reach the goal of an arrival time stability of about 5 fs (rms). This cavity is called “Bunch Arrival Corrector CAvity” (BACCA). The latest measurement results will be presented in this paper.

SYSTEM DESCRIPTION

Figure 1 shows a scheme of FLASH with the above mentioned diagnostic units and beam-based feedback loops marked with the colored areas. The measured arrival time data of the second BAM (BAM2) after the first bunch compressor (BC2) is transmitted via a high-speed optical link to the LLRF controller and used for the arrival time regulation by adjusting the RF field at the SRF module ACC1. The same arrival time signal is used for the regulation of the fast feedback cavity BACCA. The first BAM (BAM1) is not affected by the beam-based feedbacks and measures the incoming arrival time jitter. After the second bunch compressor the accelerator modules ACC4 to ACC7 increase the beam energy but do not influence the bunch arrival time. Marked in grey and dashed lines are the bunch compression monitors (BCMs) and the additional feedback loop for the regulation of the SRF modules ACC2 and ACC3 by using the arrival time measurements of the third BAM (BAM3). These parts are planned as add-ons in the future for the beam-based control strategy.

Bunch Arrival Time Monitors

The intra-train beam-based control strategy uses the arrival time of every single bunch for the regulation. The bunch arrival time monitors consist of three main parts, the RF unit, the electro-optical unit and the data acquisition (DAQ) unit. The readout electronics according to the MicroTCA.4 standard are in operation since 2013 [10].

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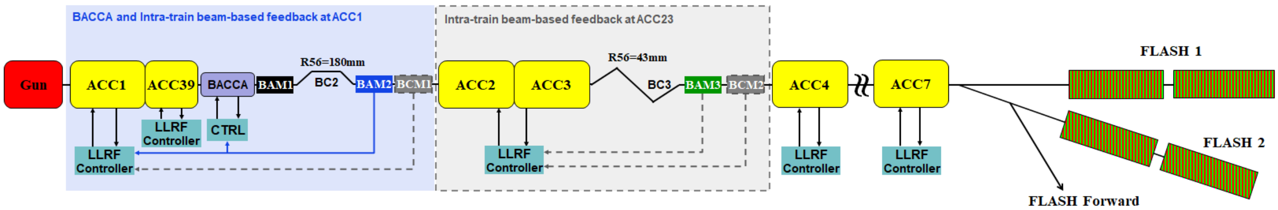

Figure 1: Scheme of FLASH with the superconducting modules ACC1-ACC7, the third harmonic module ACC39, the normal conducting cavity BACCA and the mentioned diagnostic units, as well as the beam-based feedback loops.

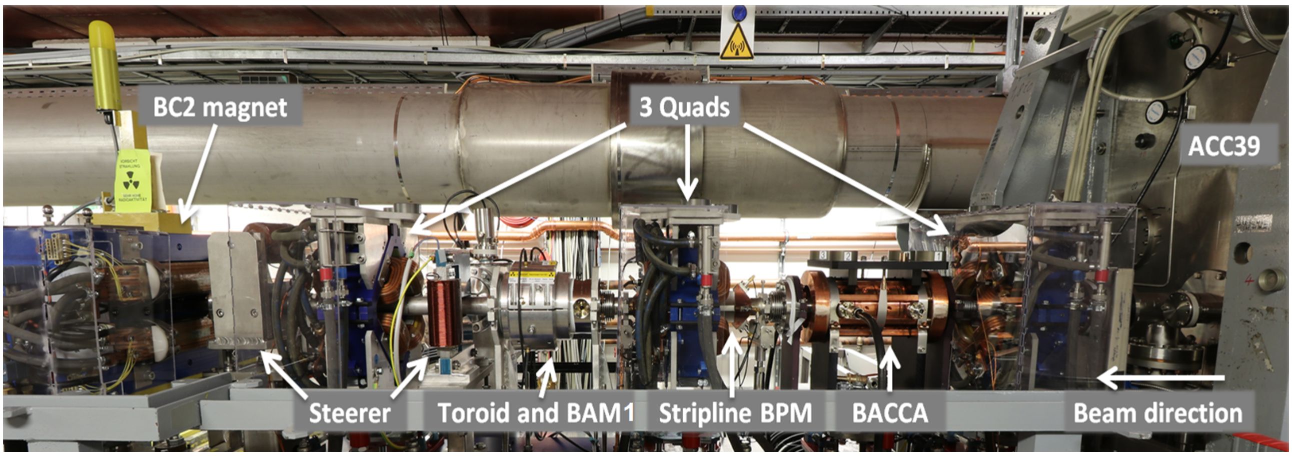

Figure 2: Picture with the part of the beamline where BACCA is located. With the third harmonic module (ACC39) on the right side and the beginning of the first bunch compressor (BC2) on the left side. The beam direction is right to left. [12]

The RF unit includes four pickups to capture the electromagnetic field induced by the electron bunch. For the electro-optical unit timing-stabilized laser pulses are provided as reference signal by the optical synchronization system [9]. The laser pulses are modulated by the signal of the RF unit and these modulations are used to calculate the arrival time. The new designed RF and electro-optic units allow using the full bandwidth of up to 40 GHz and a resolution in the sub-10 femtosecond range which has been evaluated for different FEL facilities [8]. The reference laser pulses are also used as clock for the DAQ system. A more detailed description of the BAM can be found in [2,4,7].

BACCA

The normal conducting feedback cavity BACCA with four cells is used as fast energy corrector cavity to improve the arrival time stability. The cavity is located after the third harmonic module (ACC39) and in front of the first bunch compressor (BC2). The specifications and technical design of BACCA are given in [11]. Two important requirements are an energy modulation range of about ±50 keV and a maximum feedback loop latency of 700 ns. The cavity operates at 2.9972 GHz to keep the cavity length short, due to limited beamline space for the installation. Figure 2 shows a picture of the accelerator part where BACCA is located.

Details about the installation, commissioning and first measurements with and without beam can be found in [12].

The normal conducting cavity is driven by a 1 kW high power RF amplifier. The arrival time variations measured by the BAM (BAM2) behind the first bunch compressor are used to control the driver input of the high power RF amplifier. A MIMO controller similar to a proportional-integral (PI) controller is used.

RESULTS

The presented results are related to the FLASH 1 beamline. The measurements are presented with 340 bunches, due to a limited RF field pulse length of the RF gun, a repetition rate of 1 MHz and a charge of 0.4 nC. The intra-train beam-beased feedback at the SRF module ACC1 operates together with the feedback of BACCA. Figure 3 shows the mean free arrival time of BAM2. The grey lines show the measured arrival time for the entire bunch train of 340 bunches and 600 pulses. As an example the measurements of pulse 100 and 550 are highlighted. The blue solid lines represent the standard deviation $\sigma(t_{\mathrm{Arrival}})$ of 600 pulses for each bunch. The beginning of the bunch train illustrates how the beam-based feedback influences the arrival time. The peak-to-peak value of the arrival time is reduced from bunch to bunch in a significant manner (grey lines) and thus, the arrival time jitter is minimized (blue solid lines). It takes $\approx 10\ \mu s$ (10 bunches with a repetition rate of 1 MHz) to reach the steady state value of ≈ 8.5 fs (rms). Figure 4 presents the changes of the arrival time jitter for the same set of data along the accelerator, which means the changes

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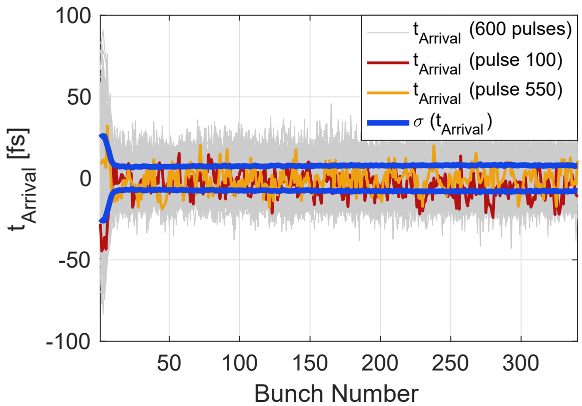

Figure 3: Mean free arrival time of BAM2. The grey lines show the arrival time of 600 pulses and the blue solid line the standard deviation $\sigma(t_{\text{Arrival}})$. The intra-train beam-based feedback at ACC1 runs together with BACCA.

from BAM1 to BAM3. The incoming arrival jitter is ≈ 32 fs (rms) (BAM1 - black solid line). After the first bunch compressor the arrival time jitter starts at around 25 fs (rms) and is pushed down by the beam-based feedbacks at ACC1 and BACCA to ≈ 8.5 fs (rms) (BAM2 - blue solid line). This value increases a little, while the beam passes the accelerator modules ACC2 and ACC3, which results in a jitter of ≈ 14 fs (rms) after the second bunch compressor (BAM3 - green dashed line).

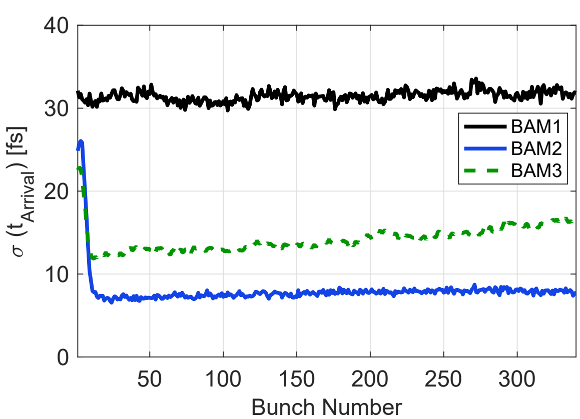

Figure 4: Standard deviation of the arrival time (600 pulses) for all three BAMs (BAM1, BAM2, BAM3). The intra-train beam-based feedback at ACC1 runs together with BACCA.

CONCLUSION AND OUTLOOK

The results show that the arrival time stability can be improved in a significant manner by using the intra-train beam-based feedback at the SRF module ACC1, together with the fast feedback cavity BACCA. The arrival time stability after the first bunch compressor can be improved from 25 fs (rms) for the first bunches to 8.5 fs (rms). The steady state value of the arrival time stability is reached within the first 10 bunches, which corresponds to the time of 10 μs for the repetition rate of 1 MHz. The arival time jitter increases a little, while the bunch train passes the accelerator modules ACC2 and ACC3, which results in an arrival time stability after the second bunch compressor of ≈ 14 fs (rms).

Next steps: (1) Finding the optimal closed loop bandwidth and optimal gain of ACC1 and BACCA, which is depending on the noise figure of the signals to be controlled. Low frequency distortions should be compensated with ACC1 while the high frequency regulation is done by BACCA. (2) Using the additional intra-train beam-based feedback loop at the SRF modules ACC2 and ACC3 with the arrival time information of BAM3 in order to improve the arrival time stability after the second bunch compressor. Furthermore, it is foreseen to use the bunch compression signals provided by the BCMs as additional beam information for the intra-train beam-based feedback.

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