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RECENT UPGRADES OF LONGITUDINAL DIAGNOSTICS AT FLASH

M. K.Czwalinna*, J. Kral, J Roever, B. Steffen
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

Abstract

In the framework of the recent FLASH2020+ upgrade program, the longitudinal electron beam diagnostics of the FLASH accelerator had been modernized and extended by additional devices, including an electro-optical bunch length detector (EOD), as well as an additional bunch compression monitor (BCM) and a bunch arrival-time monitor (BAM) in the new direct seeding beamline FLASH1. Also, the THz intensity spectrometer (CRISP) received a modernized control interface that will allow non-experts to perform bunch profile measurements. The paper presents an overview on the current status of the longitudinal electron beam diagnostics at FLASH and the ongoing (re-)commissioning.

OVERVIEW

FLASH, the Soft X-Ray and Extreme-UV Free Electron Laser at DESY, has undergone a substantial upgrade and refurbishment within the framework of the FLASH2020+ project. In a previous phase the focus of upgrade had been on renewal of injector lasers for the photo-cathode and an energy upgrade of the linac section to reach 1.35 GeV total beam energy [1]. Within the recent shutdown phase, from June 2024 to August 2025, the FLASH1 beamline has been completely rebuild to allow externally seeded FEL operation [2]. A post-compression arc had been added in front of the IR undulator to further allow for superradiant THz pulse generation.

The remodeling of the FLASH1 electron beamline required, in addition to the primary objective of enabling seeding, the redesign of the electron beam diagnostics or their relocation inside the beamline. This placed significant demands on the beam dynamics engineers, the mechanical designers, and the technical staff who implemented the work. In this paper, we give a short overview of changes and upgrades applied to the following longitudinal diagnostic devices:

- BAM : Bunch Arrivaltime Monitor,
- BCM : Bunch Compression Monitor,
- EOD : Electro-optical Diagnostics,
- CRISP: Coherent Radiation Intensity Spectrometer.

These devices have in common the single-shot capability, mostly non-invasive measurement techniques and their suitability for implementation in beam-based feedback systems. Not covered in this work are destructive detection methods incorporating transverse deflecting structures (TDS) to measure the longitudinal phase space, such as the *LOLA* [3] in FLASH 1 beamline, and the *PolariX*-TDS [4] in FLASH2 as well as in FLASH3 (FLASH Forward) beamline.

* marie.kristin.czwalinna@desy.de

REQUIREMENTS ON BUNCH DIAGNOSTICS FOR FLASH

The stability level achieved with the previously established beam-based feedback systems is planned to be enhanced by additional beam diagnostics and more advanced algorithms [5]. The additional bunch compression chicanes in FLASH 1 beamline (in the seeding section and in the post-compression arc for THz generation) requires additional diagnostic devices to monitor the bunch compression rate and their timing, e.g. relative to the external seeding lasers. The adjustable current of magnetic bunch compressor chicanes in both, FLASH1 and FLASH2 beamlines, are leading to an arrival time variation from few fs to multiple 10 ps: any timing sensitive equipment thus needs to automatically follow or readjust to these changes. FLASH is operated in a 10 Hz burst mode, with up to 800 µs long bunch trains of 1 MHz intra-burst repetition rate. Comparable to European XFEL, also at FLASH the beam region concept had been implemented already before this shutdown, to allow for individual tunability of beam energy and compression for bunches with different beam destinations within the burst. This poses certain constraints for operation of bunch diagnostics and beam-based feedbacks which act on different bunches within the burst [6].

For the physical requirement reports of the FLASH2020+ project, the demands on beam diagnostics and feedbacks were reconsidered (also based on the optics design for the new FLASH beamline [7]); an extract is given in the Table 1.

Table 1: Operation Parameters, Measurement Accuracy and Stability Demands within Beam-Based Feedback (BBF) Operation at FLASH

Parameter	Value
burst rate	10 Hz
intra-burst rep. rate	0.05 MHz to 1 MHz
bunch charges	0.01 nC to 1 nC
beam regions (BR)	typ. 2 (up to 3)
time diff. between BR	±20 ps (max. ±200 ps)
arrival time stability	< 10 fs rms
arrival time accuracy	< 5 fs
compression accuracy	< 0.1 mrad (RF phase)

LONGITUDINAL DIAGNOSTICS DEVICES

This section briefly summarizes the changes applied to the mentioned beam diagnostic devices. Details can be found in the referenced articles. Figure 1 provides a schematic overview of the FLASH facility with its new FLASH1 beamline; highlighted are the locations of the longitudinal beam

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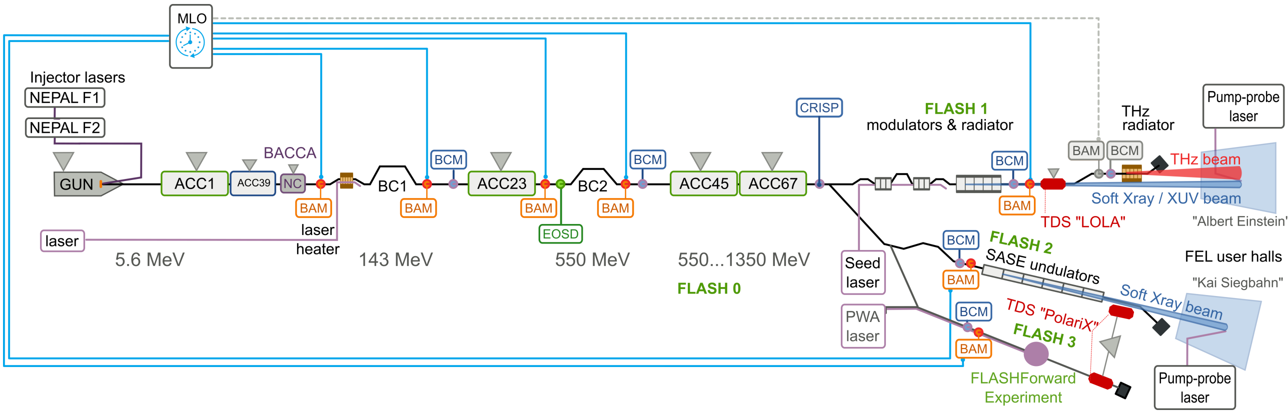

Figure 1: Drawing with longitudinal diagnostics at FLASH: 7× BAM (synchronized to the main laser oscillator, MLO), 5× BCM, 1× EOSD, 1× CRISP and 3× TDS. The BAM and BCM to be installed in 2026 depicted in grey colors.

diagnostic devices (installed and planned) as well as connection of the BAMs to the optical synchronization system.

BAM

The bunch arrival time monitor (BAM) utilizes a broadband (40 GHz) electro-optical mixing scheme to detect the center of charge timing relative to an ultra-stable optical reference laser [8]. It measures with sub-5 fs time resolution over a large range of bunch charges of 0.1 nC to 1 nC and with sub-10 fs even down to 20 pC. This technique has matured over the past decades such that the BAM is an inevitable diagnostics for all timing sensitive applications at FLASH: for active timing jitter reduction [9] as well as for data sorting in pump-probe experiments [10]. Further improvements, especially in the server and automation routines have now been implemented [11]. In the final stage, a total number of 8 BAMs will be operated at FLASH.

BCM

The BCM is a simple and robust monitor, which is composed of a cubic vacuum chamber with an in-vacuum diffraction screen, an in-air optic transport, detectors, pulse-shaping electronics and ADCs for a simple peak-sampling method. The pyro-electric detector type requires additional pile-up and background correction algorithms [12], which have been implemented directly on firmware level. Previously, the MTCA.4 based signal processing was kept in short distance to the detector output, but given the close vicinity to the exit of the bunch compression chicanes the electronics often suffered from failures caused by increased radiation dosage (gamma or neutrons) despite a radiation shielding. We are therefore currently developing a radiation tolerant analog front-end for the detector to digitize and stream out the raw data via optical low-latency links to a MTCA.4 signal processing unit located outside of the accelerator tunnel. In parallel, we have launched a development project in cooperation with THM Friedberg for an advanced, broadband THz detector as a replacement for the pryo-electric sensors, which offer a better signal-to-noise ratio and high sensitivity to facilitate a high precision intra-burst compression feedback.

EOD

The electro-optical detection (EOD) device for an online bunch profile monitoring is implemented using an advanced method of electro-optical spectral decoding (EOSD) [13]. Within a collaboration between DESY and Universite de Lille (PhLAM institute), a new EOSD optical design and analysis algorithms have been developed, and tested at European XFEL [14]. Based on these results, within the FLASH2020+ project, a completely new EOD setup has been realized upstream of bunch compressor BC2 (see Fig. 1). The EOD is currenlty under commissioning, and will include advanced servers for front-end control and automation algorithms to provide an easy-to-use interface to the machine operators and to facilitate its usage in beam-based feedback systems [15].

CRISP

The Coherent Radiation Intensity Spectrometer (CRISP) is a single-shot capable spectrometer operating over 8 octaves from 0.7 THz to 60 THz, using to two sets of five consecutive gratings, which can be interchanged by remote control. The spectral intensity is recorded simultaneously in 120 channels [16]. Utilizing an iterative phase retrieval Gerchberg-Saxton algorithm, a bunch profile and value for bunch length can be deduced from the spectral measurement [17]. At FLASH, the original CRISP setup, including the cubic screen chamber and interconnecting THz transport beamline, controls for vacuum and motorized mirror mounts required some refurbishment, which has partly been concluded in parallel to the work within FLASH2020+ project. Currently, it is only possible to measure individual bunches being kicked within the burst onto an conductive off-axis screen, generating coherent transition radiation, which is guided via the THz transport beamline to the CRISP chamber located in a lab alongside the FLASH tunnel. We are planning to exchange the screen chamber to again provide

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the optional use of a diffraction radiator, thus allowing the non-invasive measurement of all bunches within the burst.

CONCLUSION

FLASH is equipped with 4 different types of non-invasive, longitudinal bunch diagnostics with in total 16 installed devices and 2 in preparation. These devices, which are currenlty under commissioning with beam, allow for single-shot measurements of bunch arrival-time, bunch compression and bunch profile. Most of these devices are already implemented in beam-based feedback sysem for drift and jitter reduction. Projects are on-going to further enhance the device and feedback capabilities.

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