FIRST REALIZATION AND PERFORMANCE STUDY OF A SINGLE-SHOT LONGITUDINAL BUNCH PROFILE MONITOR UTILIZING A TRANSVERSE DEFLECTING STRUCTURE

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Abstract

For the control and optimization of electron beam parameters at modern free-electron lasers (FEL), transverse deflecting structures (TDS) in combination with imaging screens have been widely used as robust longitudinal diagnostics with single-shot capability, high resolution and large dynamic range. At the free electron laser in Hamburg (FLASH), a longitudinal bunch profile monitor utilizing a TDS has been realized. In combined use with a fast kicker magnet and an off-axis imaging screen, selection and measurement of a single bunch out of the bunch train with bunch spacing down to 1 μs can be achieved without affecting the remaining bunches which continue to generate FEL radiation during user operation. Technical obstacles have been overcome such as suppression of coherent transition radiation from the imaging screen, the continuous image acquisition and processing with the bunch train repetition rate of 10 Hz. The monitor, which provides the longitudinal bunch profile and length, has been used routinely at FLASH. In this paper, we present the setup and operation of the longitudinal bunch profile monitor as well as its performance during user operation.

INTRODUCTION

High-resolution longitudinal electron beam diagnostics has been highly demanded for the control and optimization at FELs and can be utilized to provide an estimate on the FEL photon pulse length [1]. One of the challenging tasks is to provide diagnostics that is non-disruptive to the generation of FEL radiation with single-shot capability. At FLASH, an on-line longitudinal bunch profile monitor has been realized which is routinely used to assist in setting up the longitudinal compression of the electron bunches and monitor their bunch length variations during user operation.

The longitudinal bunch profile monitor, which is comprised of a TDS, fast kicker magnet, off-axis scintillation screen and imaging system, is located directly upstream of the FEL undulators. A schematic layout of the monitor is shown in Fig. 1. It is operated in bunch-stealing mode, in which one bunch out of each bunch train is taken for the measurement and the remaining bunches continue the generation of FEL radiation. The super-conducting accelerator is operated with RF macro pulses of up to 800 μs at a repetition rate of 10 Hz. Each RF macro pulse can be filled with a train of up to 800 bunches at a maximum repetition rate of 1 MHz. Stealing one bunch out of a bunch train with 1 μs bunch spacing puts stringent requirements on the technical realization of individual components. For the integration into the control system and machine operation, several technical aspects need to be considered and dedicated control software has to be implemented.

DIAGNOSTIC COMPONENTS

The 3.65 m long TDS is of LOLA-type [2] with a frequency of $f = 2.856$ GHz and induces deflection of the particles in the vertical plane. The particle motion of an electron is given by [3]

$$y(s) = y_0(s) + S \cdot z \cdot \cos(\phi) + S \cdot \frac{\sin(\phi)}{k}, \qquad (1)$$

$$S = \frac{eV_0 k}{pc} \sqrt{\beta_{y,\mathrm{TDS}}\, \beta_{y,\mathrm{Screen}}} \cdot \sin(\Delta\mu_y). \qquad (2)$$

The second term in Eq. (1) relates to a deflection depending on the longitudinal position z of the electron inside the bunch, and the last term denotes a constant offset for all electrons in the bunch, i.e. an offset of the bunch centroid. When operated at the zero-crossing of the RF phase ($\phi = 0$ or $\phi = 180$), the TDS performs a linear transformation of the longitudinal distribution into a vertical distribution, which can be imaged with the help of imaging screens and used to reconstruct the longitudinal distribution. The longitudinal resolution is given as σ_{y_0}/S. In order to simultaneously meet the requirement on a good longitudinal resolution and allow the matching into the undulator section, the accelerator optics has been carefully designed.

Downstream of the TDS, a fast kicker magnet generates a strong field with a pulse length of 1.2 μs and deflects the streaked bunch horizontally onto an off-axis screen. The imaging screen is a scintillation screen (CRY19 [4], $25 \times 20\,\mathrm{mm}^2$, 100 μm thickness) which is mounted at an angle of 35° between the screen normal and the beam axis with a horizontal offset of 15 mm. The scintillation light emitted in the direction perpendicular to the beam axis is captured by the imaging system consisting of an objective and a CCD camera with GiGE-Vision interface. The performance of the imaging system is characterized in Ref. [5].

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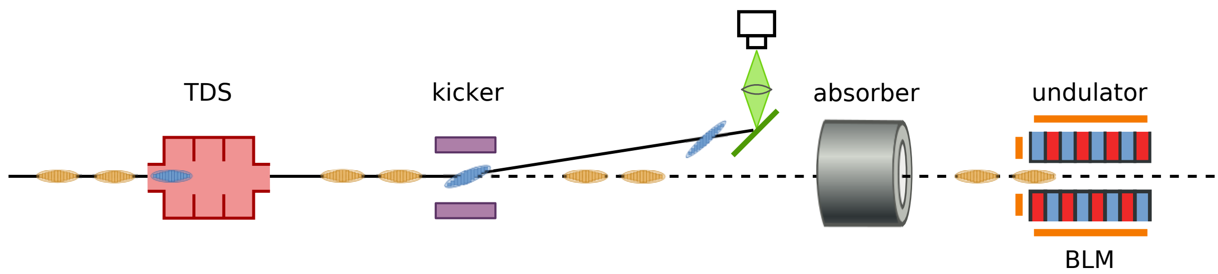

Figure 1: Schematic layout of the longitudinal bunch profile monitor consisting of a TDS, fast kicker magnet, off-axis scintillation screen and imaging system (not to scale). The set-up is located directly upstream of the FEL undulators. Quadrupoles and other components are omitted. The bunch-stealing mode is illustrated with blue (for the measurement) and yellow bunches (for the generation of FEL radiation).

By setting the trigger timings for the TDS, kicker magnet and camera to one and the same bunch, the on-line monitor is configured in bunch-stealing mode, in which one bunch out of the bunch train is streaked and deflected onto the off-axis screen for the measurement while the remaining bunches continue the generation of FEL radiation (see Fig. 1). Shifting the trigger timings for all components by the same amount allows for monitoring any bunch within the bunch train.

Fast Kicker Magnet

In order to deflect one bunch out of the bunch train onto the off-axis screen, a fast kicker magnet with a length of 542 mm has been installed downstream of the TDS. The kicker magnet consists of a ceramic vacuum chamber that has been sputtered at the inside with a layer of 1 μm thick stainless steel and a single air coil made of flat copper bars outside the vacuum. A pulser that generates a half cycle of a sine wave with a pulse duration of $t_p = 1.2\,\mu$s is directly attached to the kicker magnet. The maximum pulse current and high voltage generated by the pulser are $I_p = 5$ kA and $U_p = 16$ kV, respectively. The experimental result the a cross-calibration for the kicker magnet with a beam corrector magnet is shown in Fig. 2. The deduced kick strength amounts to k(rad)$= 0.41\,U_p$(kV)/E(MeV).

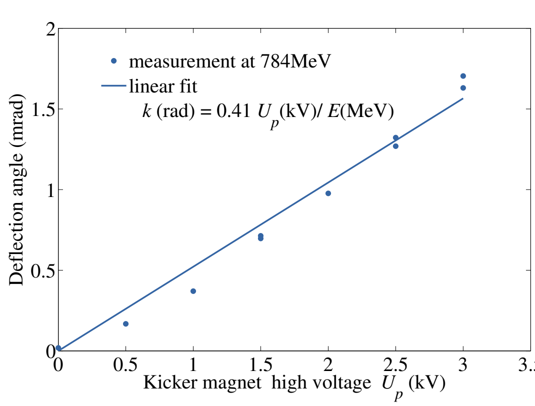

Figure 2: Cross-calibration of the kicker magnet with a corrector magnet for the determination of the kick strength k.

Suppression of COTR

Local peak or substructures inside the longitudinal current profile of the bunch may induce the emission of coherent optical transition radiation (COTR) at the boundary of vacuum and the scintillator, which renders the imaging of the bunch impossible. By applying the spatial separation technique, COTR with a strong angular dependence can be suppressed while the incoherent isotropic scintillation light can be used for bunch profile measurements [6]. The scintillation screen for the longitudinal bunch profile monitor is installed at an angle of 35° between the screen normal and the beam axis, which allows the imaging with scintillation light and strongly suppresses the detection of COTR.

CONTROL AND OPERATION

In addition to the diagnostic components described in the previous section, reliable operation of the longitudinal bunch profile monitor requires comprehensive measures concerning various technical aspects such as induced beam loss, image processing at a rate of 10 Hz and a slow TDS RF phase feedback for keeping the beam in the centre of the imaging screen.

Beam Loss

In order to prevent damage to the accelerator in case of beam loss, a machine protection system [7], which includes beam loss monitors (BLM) and a toroid protection system (TPS) [8], is in operation at FLASH. The MPS stops the generation of electron bunches in case of beam loss by utilizing a fast shutter in the photo-cathode injector laser with a total response time below 4 μs. On-line TDS measurements in bunch-stealing mode utilizing an off-axis imaging screen in combination with a fast kicker magnet intentionally cause beam losses. The electron bunch that is kicked out of the bunch train onto the off-axis screen is stopped in a copper absorber behind the off-axis screen (see Fig. 1) and generates a shower of secondary particles. As a result, the BLMs in the FEL undulator section, which is located directly downstream of the copper absorber, generate alarms although these alarms do not represent unwanted beam loss inside the undulators. Furthermore, the absence

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of the kicked bunch downstream of the off-axis screen is detected by the TPS and an alarm is generated. Electronic circuits have been developed to mask both the analogue signals generated by the BLMs and a bunch gate received by the TPS for the duration of the kicked bunch ($\approx 1\,\mu$s). The timing of the BLM and TPS mask can be set in accordance with the kicked bunch used for diagnostics.

Data Acquisition and Slow Feedback

A simplified diagram which illustrates the data flow for the longitudinal profile monitor is depicted in Fig. 3. At FLASH, communication with hardware is realized by front-end servers of the distributed object-oriented control system [9]. The beam images taken with the camera and the bunch charge recorded with the toroid are read out by their corresponding front-end servers, and the data is transferred to the shared memory of the data acquisition system (DAQ) [10]. All front-end servers receive unique identifiers from the timing system for each bunch train, and collector processes take care that the data from all distributed front-end servers is sorted according to the bunch train in the shared memory of the DAQ. In case data is received, the DAQ delivers the raw image and bunch charge to the image processing server, which is a middle-layer server that runs on the same central processing unit (CPU) as the DAQ. After image processing, the current profile, root mean square (rms) bunch length and centre-of-mass position are calculated and sent back to the shared memory of the DAQ.

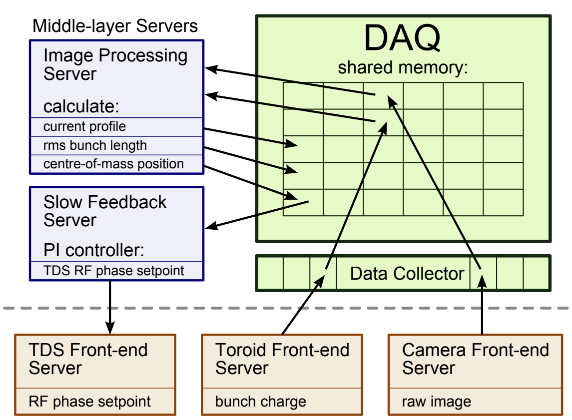

Figure 3: Simplified diagram of the data flow for the longitudinal bunch profile monitor and slow TDS RF phase feedback (for more detail see text).

In order to retrieve the bunch parameters for each kicked bunch, the image processing server has to reach a performance of 10 Hz. The raw image is first processed by subtracting an average background, which is recorded either during initialization of the monitor or on demand by the operator. A sophisticated algorithm is then applied to recognize the beam and remove noise. Figure 4 shows one example of an image after background subtraction (left) in comparison to the final processed image (right). The real beam has been successfully distinguished from the disturbances, e.g. the screen edges, and the noise around the beam has been removed. In case of an image without a beam, the image processing server recognizes the absence of the beam and halts sending results back to the DAQ. The longitudinal beam parameters are obtained from the processed image using the bunch charge read out by the nearest toroid and the calibration constant for the longitudinal (time) coordinate. A calibration of the longitudinal coordinate is performed once at the start-up of the monitor.

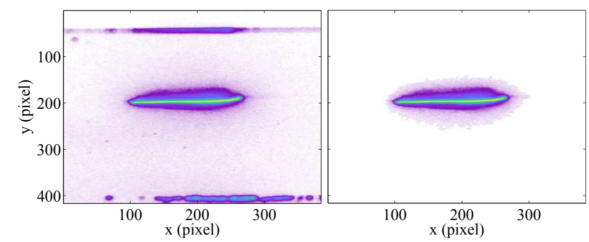

Figure 4: Example of the image processing algorithm with a raw image after background subtraction (left) and the final processed image (right).

Any timing change between the arrival time of the bunches at TDS and the TDS RF phase, i.e. change of the phase ϕ in Eq. (1), results in a centroid deflection of the bunches. Arrival-time changes can be caused by RF amplitude or phase changes of accelerating modules upstream of the bunch compressors that lead to path lengths changes in the magnetic chicanes. Changes of the TDS RF phase may originate from length changes of the RF cables due to temperature drifts. In order to keep the beam in the centre of the imaging screen, a slow TDS RF phase feedback has been implemented as a middle-layer server. The server is an adaptation of the slow phase feedback [11] for the accelerating modules. When the image processing server sends a centre-of-mass position to the shared memory of the DAQ, the centre-of-mass position is sent to the slow TDS RF phase feedback server as illustrated in Fig. 3. The value of the centre-of-mass position is compared to the target value, and a proportional-integral (PI) controller calculates the corrected TDS RF phase setpoint which is then written to the corresponding property of the TDS RF front-end server. The feedback loop as depicted in Fig. 3 can be operated at the 10 Hz bunch train repetition rate for a pre-selected region of interest of the CCD camera image.

A screenshot of the operator control panel of the slow TDS RF phase feedback can be seen in Fig. 5. The upper plot shows a history of the centre-of-mass position of the beam image on the imaging screen over 8 hours and the lower plot the corresponding TDS RF phase setpoint. During the first hour the accelerator settings were optimized for FEL operation and the slow TDS RF phase feedback was switched off. Until about 17:00 hours, the TDS measurement setup was optimized and the slow TDS RF phase feedback switched on. As can be seen, the TDS RF phase setpoint was changed by the slow feedback by about 4 degrees over a period of 5 hours. At around 22:00 hours, the accelerator settings were again tuned for FEL operation.

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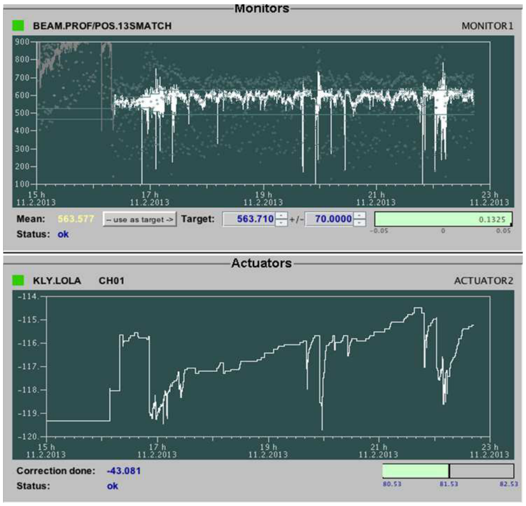

Figure 5: Operator control panel of the slow TDS RF phase feedback showing histories of the centre-of-mass position of the beam image on the imaging screen (top) and TDS RF phase setpoint (bottom).

Figure 6 shows a screenshot of the operator panel for the longitudinal bunch profile monitor: Processed single-shot image (upper left), current profile (lower left), history of bunch length (upper right) and history of peak current (lower right). The period shown from 15:00 hours to 23:00 hours is the same as in Fig. 5. During this user operation run, the energy and wavelength of the FEL radiation were about 7 μJ per photon pulse and 31 nm, respectively. From a bunch train with 401 bunches, the last one is used for the monitor. The local spikes in the histories are due to the absence of the beam, which are not displayed appropriately. After tuning around 17:00 hours, a stable bunch length of about 150 fs and a peak current of 325 A were reached.

CONCLUSION

The longitudinal bunch profile monitor, based on a transverse deflecting structure, a fast kicker magnet and an off-axis imaging screen, has been established at FLASH in front of the FEL undulators. The beam optics in this section has been optimized for measurement performance as well as matching into the FEL undulators. The monitor operates in the bunch-stealing mode in which one bunch is deflected out of the bunch train onto the off-axis screen for diagnostics. As this cannot be distinguished from an unwanted beam loss, masking of single alarms generated in the beam loss and toroid protection system has been realized to prevent the machine protection system from stopping beam operation. A slow TDS RF phase feedback that keeps the beam in the centre of the imaging screen has been implemented, e.g. to act against TDS RF phase changes due to temperature drifts. The monitor has an update rate of 10 Hz and is routinely being used during FEL user operation to monitor possible bunch length variations.

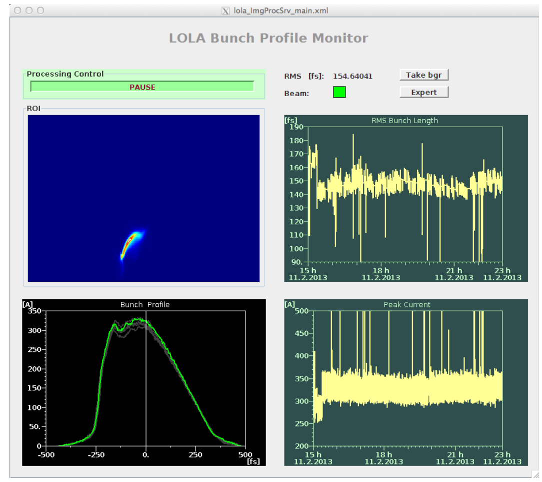

Figure 6: Operator panel for the longitudinal bunch profile monitor: Processed single-shot image (upper left), current profile (lower left), history of bunch length (upper right) and history of peak current (lower right).

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