DESIGN OF TDS-BASED MULTI-SCREEN ELECTRON BEAM DIAGNOSTICS FOR THE EUROPEAN XFEL

J. Wychowaniak*
DMCS, Technical University of Łódź, Łódź, Poland
Ch. Gerth, M. Yan
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

Abstract

Dedicated longitudinal electron beam diagnostics is essential for successful operation of modern free-electron lasers. Demand for diagnostic data includes the longitudinal bunch profile, bunch length and slice emittance of the electron bunches. Experimental setups based on transverse deflecting structures (TDS) are excellent candidates for this purpose. At the Free-Electron Laser in Hamburg (FLASH), such a longitudinal bunch profile monitor utilizing a TDS, a fast kicker magnet and an off-axis imaging screen, has been put into operation. It enables the measurement of a single bunch out of a bunch train without affecting the remaining bunches. At the European X-ray Free-Electron Laser (XFEL) multi-screen stations in combination with TDS are planned to be installed. In order to allow for flexible measurements of longitudinal bunch profile and slice emittance, a configurable timing and trigger distribution to the fast kicker magnets and screen stations is required. In this paper, we discuss various operation patterns and the corresponding realization based on MTCA.4 technology.

INTRODUCTION

The performance of a hard X-ray free-electron laser (FEL), such as the European XFEL, depends critically on the transverse emittance of the electron beam [1]. Hence, it is important to generate electron beams with lowest possible emittance [2, 3] and efficiently preserve the emittance through acceleration and longitudinal bunch compression. Measurement and control of the transverse emittance is crucial for the optimisation and operation of the FEL as the beam emittance may be degraded due to non-linear effects, e.g. emission of coherent synchrotron radiation (CSR) or micro-bunching instabilities [4].

As the FEL amplification process takes place locally within longitudinal bunch slices, measurements of time-resolved properties, i.e. slice emittance, rather than time-averaged properties, i.e. projected emittance, are of interest. Excellent candidates for the measurement of the slice emittance with single-bunch resolution are transverse deflecting structures (TDS) [4, 5]. The electron bunch is streaked in transverse direction by the TDS and imaged with an imaging screen. The slice emittance can then be measured in the plane perpendicular to the streak direction by changing the phase advance between the TDS and the imaging screen. This can be achieved by either changing quadrupole currents between the TDS and imaging screen (quad-scan method) or by employing several screens (multi-screen method) [6]. A disadvantage of this direct time-domain method is that the emittance of the diagnosed bunch is drastically degraded due to the scatter process in the imaging screen and the bunch cannot be used for FEL operation.

CONCEPTUAL LAYOUT OF THE SLICE EMITTANCE MONITOR SETUP

The super-conducting accelerator of the European XFEL will operated with RF macro pulses of up to 650 μs at a repetition rate of 10 Hz. Each RF macro pulse can be filled with a train of up to almost 3000 bunches at a maximum repetition rate of 4.5 MHz. This offers the possibility of using several bunches of each bunch train for on-line measurements. A generic layout of a slice emittance monitor, employing a TDS followed by four fast kicker magnets and four screen stations equipped with off-axis screens, is depicted in Fig. 1. Four electron bunches out of the bunch train are streaked by the TDS and then deflected by the fast kicker magnets onto the off-axis screens without disturbing FEL operation of the remaining bunches in the bunch train. A longitudinal bunch profile monitor, comprising one kicker magnet and one off-axis screen, has been commissioned successfully at the Free-Electron Laser in Hamburg (FLASH) [7].

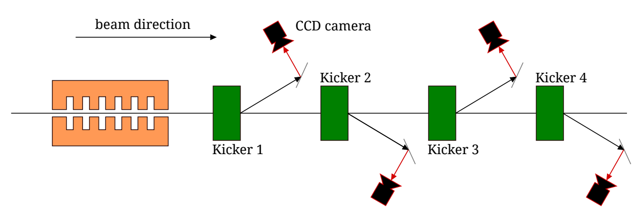


Figure 1: Generic layout of a slice emittance monitor.

At the European XFEL, installation of slice emittance monitors is foreseen at three different locations (see Fig. 2): in the injector and after the second and third bunch compressor chicane. Each TDS is followed by a matching section and a FODO lattice in which four screen stations are incorporated [8]. The screen stations will be equipped with off-axis scintillation screens made of 200 μm thick LYSO:Ce [9]. The scintillation screens will be installed at an angle of 0° with respect to the beam axis and imaged under 45° by a CCD camera in Scheimpflug arrangement. Micro-bunching instabilities can lead to the emission of coherent optical transition radiation (COTR) at the boundary of vacuum and the scintillator [10]. The imaging angle has been chosen to sup-

* jan.wychowaniak@desy.de

ISBN 978-3-95450-133-5

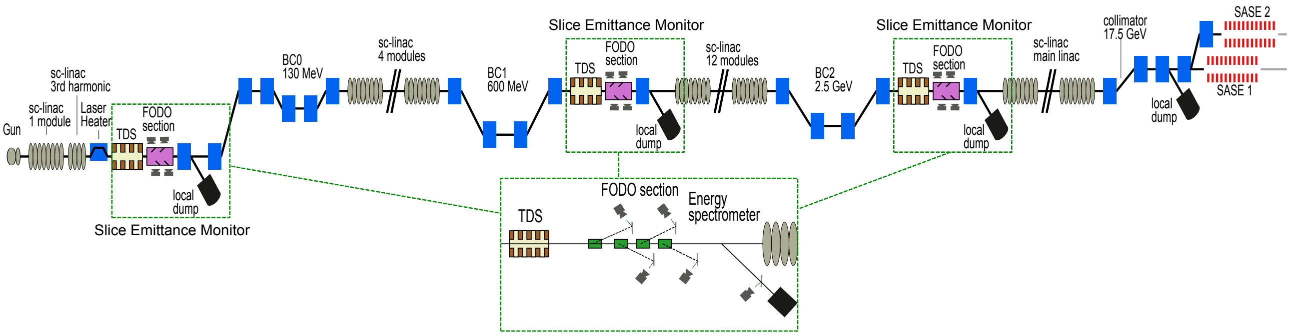


Figure 2: Accelerator layout of the European XFEL. Installation of TDS-based multi-screen slice emittance monitors is foreseen at three different locations along the accelerator.

press COTR, which has a strong angular dependence, while the incoherent isotropic scintillation light can be used for bunch profile measurements [4].

In order to deflect bunches out of the bunch train onto the off-axis screens, fast kicker magnets with a length of 350 mm will be installed downstream of each 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 = 380 ns 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 = 20 kV, respectively. The kick strength has been determined with a prototype kicker installed at FLASH and amounts to $k(\mathrm{mrad}) = 0.1\, U_p(\mathrm{kV})/E(\mathrm{GeV})$. The trajectories of the bunch centres induced by the four kickers and the respective positions on the imaging screens have been modelled for slice emittance monitor downstream of the second bunch compressor and are shown in Fig. 3. The kick directions alternate. As can be seen, the bunch deflected by the first kicker onto the first imaging screen also hits the third screen. As the screen stations will be equipped with CCD cameras (Basler aviator avA2300-25gm) with a minimum shutter time of 18 μs, the bunches deflected by the first and third kicker will overlap in the image of the third screen station.

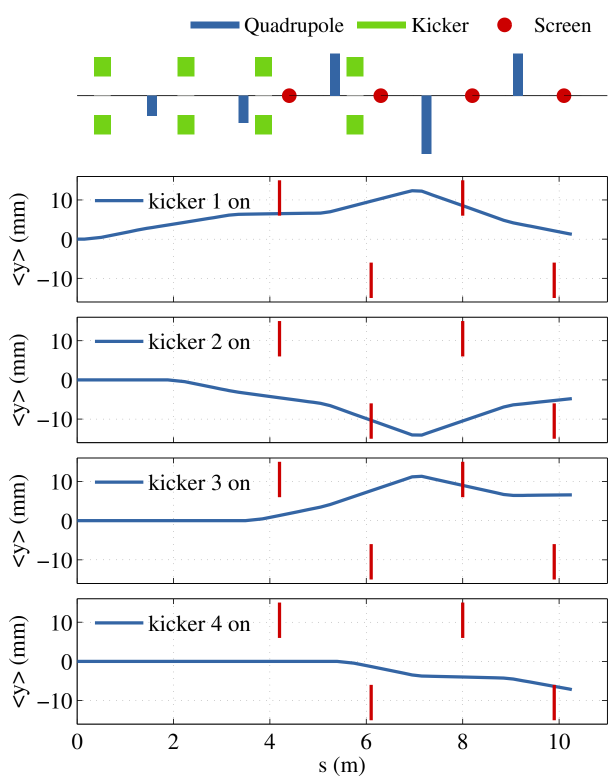


Figure 3: Top: Schematic layout of the beam line for on-line slice emittance measurements downstream of the second bunch compressor at European XFEL. Bottom: Trajectories of the bunch centres induced by for the four kicker magnets and respective beam positions on the off-axis screens.

OPERATION MODES

A slice emittance monitor that includes 4 pairs of kickers and screens allows for configurable operation modes, so that multiple bunch kick patterns can be employed.

Figure 4 illustrates a mode with four consecutive bunches being kicked out from a single bunch train for diagnostics. The kicked bunches hit the consecutive screens of the slice emittance monitor. They are marked in blue in the picture. This procedure is repeated for every bunch train. This is the typical kick pattern configuration for slice emittance measurements where the maximum data rate is required. Such configuration is used e.g. during the machine tuning phase, which requires the best possible operation statistics to be produced.

However, as mentioned above, the bunch deflected by kicker 1 (and designated for screen 1) hits also screen 3, which may result in disturbance of the beam size measurement. Here, simultaneous use of kickers 1 and 3 may be unwanted.

Figure 4: Typical bunch kick pattern for slice emittance measurements with maximum data rate.

ISBN 978-3-95450-133-5

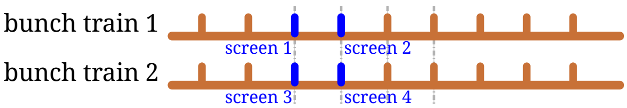


Figure 5: Possible pattern for kicking two bunches from a bunch train.

For such cases it is desirable to have the possibility of reducing the number of kicked bunches per bunch train. An example of such variation can be seen in Fig. 5. The number of bunches kicked per bunch train is reduced to two. This kick pattern can be seen as composed of two sub-patterns. One of them involves selected bunches designated together for being kicked from a bunch train with the use of kickers 1 and 2 (i.e. going towards screens 1 and 2). The other sub-pattern similarly (the same bunches), but with kickers 3 and 4 (towards screens 3 and 4). These two sub-patterns are then being applied alternately to consecutive bunch trains. Technically this means that for every sub-pattern only two out of four kickers are being triggered, and also two corresponding cameras collect images.

If even less data statistics is sufficient, then only one single bunch out of a bunch train may be taken out. As it can be seen in Fig. 6, the four kickers are configured with timing for the same single bunch in the bunch train, but triggered successively in four consecutive bunch trains. Such scenario is applicable e.g. to normal machine operation, where less statistics is required and the number of bunches sacrificed for beam diagnostics could be reduced.

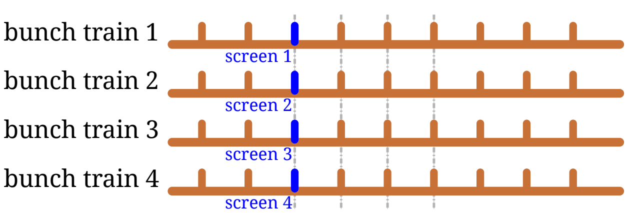
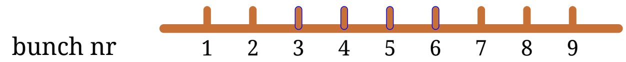


Figure 6: Possible pattern for kicking a single bunch from a bunch train.

Figure 7 provides a summary of the scenarios described above. They are just selected examples of how a TDS-based slice emittance monitor can be set up, in terms of its kicker and camera trigger configurations, in order to accommodate diverse patterns of kicked bunches. This configuration scheme is flexible and, as a result, numerous combinations of bunches designated for kicking are possible to be configured.

BUNCH PATTERN CONCEPT

The machine operation allows for a configurable number of bunches within a bunch train. Also, the spacing between bunches can vary, depending on the operating frequency that is configured. The maximum operating frequencies for FLASH and the European XFEL are 1 MHz and 4.5 MHz, respectively, while lower frequencies (wider bunch spacing) are also configurable. The description of number of bunches within a bunch train and their spacing in the machine timing system is referred to as bunch pattern. The bunch pattern concept is based on a 9 MHz structure, so that maximum operating frequencies of both XFEL and FLASH can be accommodated (see Fig. 8).



	Screen 1 a) / b) / c)	Screen 2 a) / b) / c)	Screen 3 a) / b) / c)	Screen 4 a) / b) / c)
bunch train 1	3 / 3 / 3	4 / 4 / -	5 / - / -	6 / - / -
bunch train 2	3 / - / -	4 / - / 3	5 / 3 / -	6 / 4 / -
bunch train 3	3 / 3 / -	4 / 4 / -	5 / - / 3	6 / - / -
bunch train 4	3 / - / -	4 / - / -	5 / 3 / -	6 / 4 / 3

Figure 7: Summary of most typical operation modes of slice emittance monitor.

The bunch pattern concept is implemented in a form of a table of integer numbers (referred to as pattern table words), and as such is exchanged across the machine timing system. The number of bunches within a bunch train and their spacing are described by appropriate values within a table word corresponding to a given time position. As illustrated in Fig. 8 (lower part) for the European XFEL, values indicating bunch presence (red) are set for every second word which corresponds to an operation frequency of 4.5 MHz .

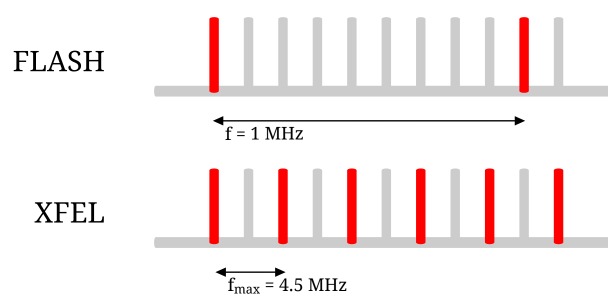


Figure 8: Bunch pattern describing maximum frequencies for FLASH (top) and XFEL (bottom).

The information contained in a pattern table word is composed on a bit basis (see Fig. 9). Appropriate bits within a word have meanings determined by the design of the timing system. Three most significant bits serve for the purpose of marking a given bunch to be kicked by one of the slice emittance monitor stations (TDS injector, TDS BC1 or TDS BC2). In Fig. 9 (middle) the pattern table words corresponding to presence of a bunch at given time position are marked with brown boundary. The pattern table words indicating bunches to be kicked by one of the slice emittance monitors (color code blue in the top), are marked red.

If a particular bunch is intended to be kicked, the pattern word corresponding to this bunch has one of its TDS bits set, depending on which slice emittance monitor is configured to take the bunch out.

ISBN 978-3-95450-133-5

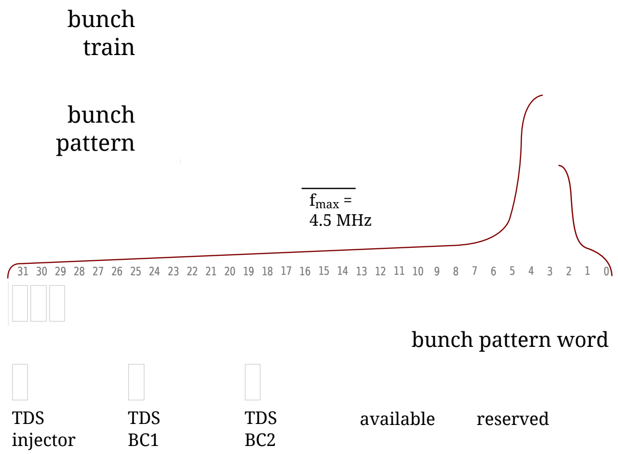


Figure 9: Concept of the MTCA-based timing system and structure of bunch pattern table word.

Figure 10: Schematic layout of the hardware and software setup of slice emittance monitor.

MTCA.4-BASED IMPLEMENTATION

The timing system is implemented in MTCA.4 standard [11]. It is designed as double size AMC modules, referred to as X2Timer cards. Each slice emittance monitor is provided with a dedicated MTCA.4 crate equipped with a X2Timer receiver, together with custom DOOCS server software [12] for controlling the card and slice emittance monitor hardware (see Fig. 10). For each bunch train the card:

- sets the TDS bits for the bunches to be kicked. This information is then propagated to the interested parties, e.g. the machine protection system (which needs to be aware that this beam loss is intentional),
- supplies the correct trigger to the kickers and cameras for bunches to be kicked.

By means of the DOOCS control software, a machine operator can configure the kick pattern for a given slice emittance monitor.

CONCLUSION

TDS-based multi-screen slice emittance monitors employing fast kicker magnets in combination with off-axis screens will be installed at the European XFEL. A flexible design of the timing system for the kickers and cameras, which allows for configuring different kick patterns depending on the desired operation modes, has been presented. The appliances based on the slice emittance monitor concept are presently in the design and construction phase. The required control software for the MTCA.4-based monitor hardware is under development, with corresponding laboratory tests being performed.

Commissioning of the injector of the European XFEL will start in mid 2015. This will provide the opportunity to operate the slice emittance monitor in the injector and gather experience with the concept presented in this paper under real operating conditions.

REFERENCES

[1] F. Zhou et al., Phys. Rev. Lett. 102, 254801 (2009).

[2] F. Stephan et al., Phys. Rev. ST Accel. Beams 13, 020704 (2010).

[3] F. Zhou et al., Phys. Rev. ST Accel. Beams 15, 090701 (2012).

[4] Z. Huang et al., Phys. Rev. ST Accel. Beams 13, 020703 (2010).

[5] M. Röhrs et al., Phys. Rev. ST Accel. Beams 12, 050704 (2009).

[6] M. Yan et al., "Comparison of Quadrupole Scan and Multi-screen Method for the Measurement of Slice Emittance at SwissFEL Injector Test Facility", THP088, *These Proceedings*, FEL'14, Basel, Switzerland (2014).

[7] 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`

[8] M. Röhrs, Ch. Gerth, "Electron beam diagnostics with transverse deflecting structures at the European X-ray free electron laser", FEL'08, Gyeongju, August 2008, MOPPH049, p. 90, `http://www.JACoW.org`

[9] Ch. Wiebers et al., "Scintillating Screen Monitors for the Transverse Electron Beam Profile Diagnostics at the European XFEL", IBIC'13, Oxford, September 2013, WEPF03, p. 807, `http://www.JACoW.org`

[10] C. Behrens et al., Phys. Rev. ST Accel. Beams 15, 062801 (2012).

[11] PICMG - MTCA.4 and other xTCA standards homepage, `http://www.picmg.org`

[12] DOOCS homepage, `http://doocs.desy.de`

ISBN 978-3-95450-133-5