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ONLINE LONGITUDINAL BUNCH PROFILE AND SLICE EMITTANCE DIAGNOSTICS AT THE EUROPEAN XFEL

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Abstract

The longitudinal current profile and slice emittance are important bunch parameters for the operation of an X-ray free-electron laser. At the European XFEL, dedicated diagnostic sections equipped with transverse deflecting RF structures (TDS) have been installed for the control and optimisation of these parameters. Travelling-wave TDS in combination with fast kicker magnets and off-axis screens allow for the study of individual bunches without affecting the other bunches in the super-conducting linear accelerator which can generate bunch trains of up to 2700 bunches at 4.5 MHz within 600 microsecond RF pulses at a repetition rate of 10 Hz. The measurement of the slice emittance is realised in a static F0D0 lattice equipped with four individual screen stations.

Variations of the longitudinal bunch profile or slice emittance along the bunch train may lead to degraded FEL performance for parts of the train which reduces the effective available number of bunches for FEL operation. By gradually adjusting the timing, individual bunches along the bunch train can be measured in order to optimise the overall beam parameters for all bunches in the train. In this paper, we describe in detail the diagnostic concept and present first measurement results of the projected and slice emittance along the bunch train.

INTRODUCTION

The European XFEL, which is currently under commissioning, will deliver ultra-short X-rays in the photon energy range 0.25 keV to 25 keV [1]. The superconducting linear accelerator that will drive 3 FEL undulator beamlines will generate beam energies of up to 17.5 GeV. As is illustrated in Fig. 1, the RF accelerating field is pulsed at a frequency of 10 Hz with a flat-top duration of up to 600 μs, in which a train of electron bunches is accelerated. The bunch repetition rate can be up to 4.5 MHz (equal to a bunch spacing of 220 ns), which corresponds to a maximum of 2700 bunches per bunch train. In future, it is envisioned to operate the accelerator with constant bunch filling patterns that are advantageous in terms of operation stability. The photon pulse pattern can be chosen by sending unwanted electron bunches with fast kicker magnets into a local dump upstream of the FEL undulator beamlines.

Variations during the RF flat-top duration of either the laser pulse properties of the photo-cathode laser or the RF parameters of the accelerator modules in the injector may

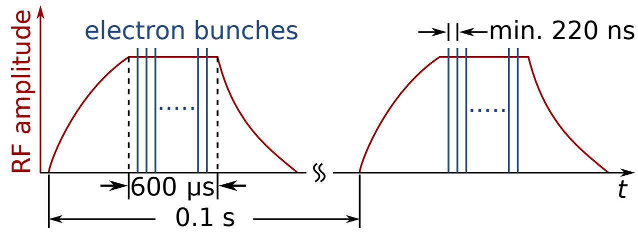

Figure 1: RF timing structure and electron bunch pattern of the European XFEL.

result in variations of beam matching or emittance of the bunches in the bunch train. This in turn may lead to substantial variations along the bunch train of the photon pulse energies of the X-rays that are delivered to the user experiments. Hence, there is a strong demand for diagnostic techniques with which electron bunch parameters such as the longitudinal current profile or slice emittance can be measured along the bunch train. This has been realised by utilising a transverse deflecting RF structure (TDS) in combination with kicker magnets and off-axis screens.

The RF field of the TDS induces a time-dependent transverse deflection of the electrons of one bunch in the bunch train by which the longitudinal bunch shape is transformed to the transverse plane. A fast kicker magnet downstream of the TDS is then used to deflect this bunch onto an off-axis screen without affecting the remaining bunches in the bunch train. The diagnosed bunch is taken out of the bunch train before the FEL undulators while the remaining bunches continue for the generation of FEL radiation. By utilising four kicker magnets with four off-axis screens in a static F0D0 lattice, the longitudinal bunch profile and slice emittance can be measured. Finally, these bunch parameters can be measured along the bunch train by properly adjusting the timing of the TDS, kicker magnets and camera systems of the screen stations. In this paper, we present the results of projected and slice emittance measurements obtained in the injector section of the European XFEL.

DIAGNOSTIC SECTION

Three dedicated beamline sections equipped with TDS have been designed for the measurement of the longitudinal profile and slice emittance as well as the longitudinal phase space [2]. A schematic layout of the TDS diagnostics sections, which are located downstream of the laser heater system in the injector section and downstream of the second and third bunch compressor chicane, is depicted in Fig. 2. Each section comprises a TDS, four kicker magnets, four screen stations with off-axis and on-axis screens, one dipole

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magnet and one screen station in the dispersive section behind the dipole magnet [3]. The four screen stations are located in the subsequent drift sections of a F0D0 cell structure, which allows for projected emittance measurements [4]. When the TDS is switched on, slice emittance and longitudinal profile measurements can be performed. Longitudinal phase space measurements can be carried out in the dispersive section only when the dipole magnet is switched on and, as a consequence, the whole bunch train is deflected to the local dump and FEL operation is interrupted.

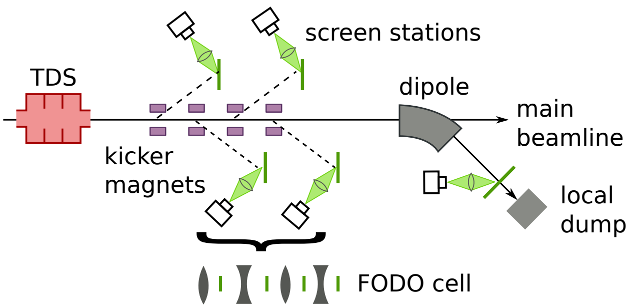

Figure 2: Schematic layout of the 3 TDS diagnostic sections at the European XFEL.

The TDS are disk-loaded S-band RF waveguide structures designed and manufactured by the Institute for Nuclear Research of the Russian Academy of Sciences (Moscow, Russia). They are operated in travelling wave $2\pi/3$ mode at a frequency of 2.997 GHz[1]. The TDS in the injector section comprises 16-cells and has a filling time below 110 ns, i.e. the RF pulse is short enough to act only on one bunch within the bunch train without affecting the other bunches.

The screen stations [5] are equipped with both full on-axis and half off-axis scintillator screens (LYSO:Ce) which are mounted perpendicular to the beam axis and imaged at an angle of 45° to the beam axis with CCD cameras in a Scheimpflug configuration. As a result, the screen stations provide a constant spatial (rms) resolution of 10 µm for the configuration with a magnification of 1 : 1 over the entire screen. The distance from the edge of the off-axis screen to the beam axis amounts to 6 mm.

As is illustrated in Fig. 3, the kicker magnets consist of a ceramic vacuum chamber, which has been sputtered at the inside with a layer of 1 µm thick stainless steel, and two flat copper bars outside the vacuum beam pipe at opposite sides with a length of 350 mm. One high-voltage pulser (up to 20 kV) is directly attached to each kicker magnet. The pulsers generate half cycles of a sine wave with a pulse duration of t_p = 380 ns at 10 Hz which enables deflection of single bunches onto the corresponding off-axis screens for diagnostics while the remaining bunches in the bunch train are not affected and proceed to the undulator beamlines for the generation of FEL radiation.

[1] The frequency of the TDS $f = 332/144 \cdot 1.3$ GHz= 2.997 GHz is generated from the master oscillator frequency of 1.3 GHz and is an integer multiple of the bunch repetition rate of 4.5 MHz.

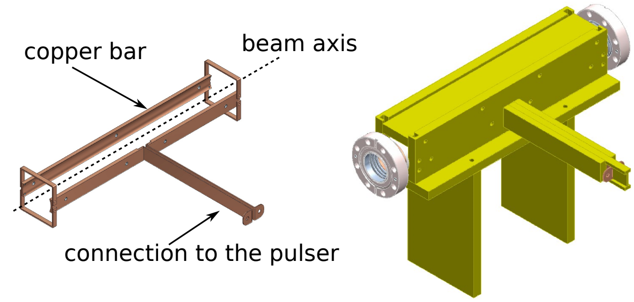

Figure 3: Schematics of a kicker magnet. The high-voltage pulser is not shown.

This is demonstrated in Fig. 4 for the operation of 2 bunches, of which the second bunch is kicked. On the left hand side the image of the two bunches on an on-axis screen is shown while on the corresponding image of the off-axis screen on the right only the kicked bunch is visible (and reflections on the edge of the scintillator).

A bunch with a certain bunch number within the bunch train can be chosen for diagnostics via the timing system by adjusting appropriately the trigger delays of the TDS, kicker magnets and camera systems. The diagnosed bunch experiences a betatron oscillation due to the kicker magnet and may get lost along the accelerator. This bunch is marked by the timing system and taken out of the bunch train by the fast kicker magnets upstream of the FEL undulator sections or, in case of beam loss, ignored by the fast machine protection system, which would inhibit the generation of further electron bunches. For an emittance measurement, the kicker magnets are toggled subsequently and typically 20 beam images are recoded per screen. One emittance measurement takes less than 20 secods as the screens do not have to be moved. By scanning the bunch number, the projected or slice emittance as well as the longitudinal bunch profile can be measured along the bunch train. The diagnostic sections also serve as matching sections, in which the beam is routinely matched to the design accelerator optics for transport into the subsequent beamline sections equipped with accelerating modules.

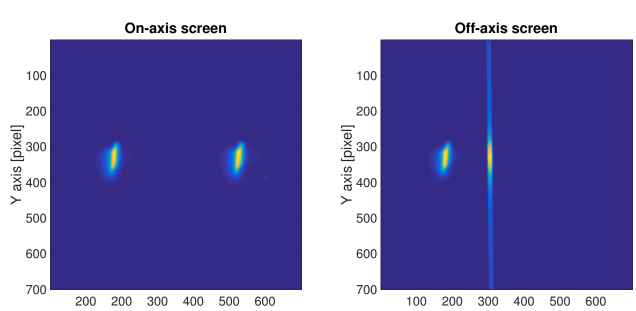

Figure 4: Beam operation with two bunches: the second bunch is kicked by a kicker magnet. Left: Image of on-axis screen with both bunches visible. Right: Image of off-axis screen with only the kicked bunch visible.

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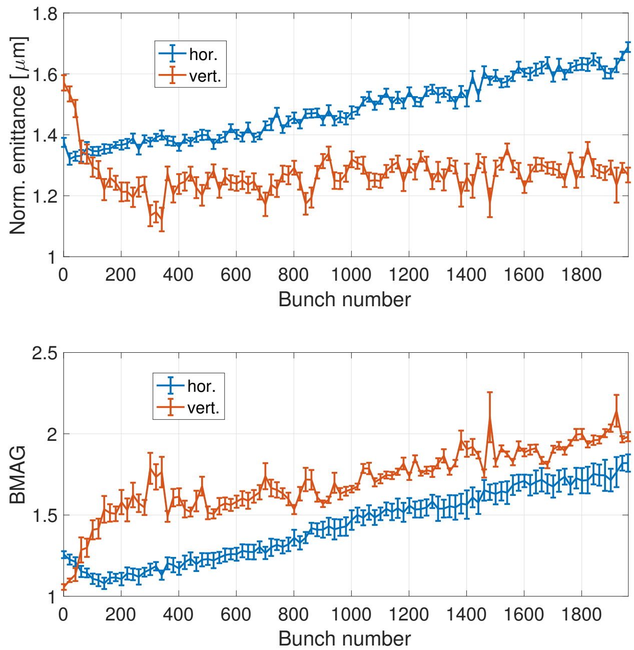

Figure 5: Intra-train emittance measurement for individual bunches along the train. Top: Projected normalized emittances. Bottom: Optics mismatch amplitude (BMAG) with respect to design optics.

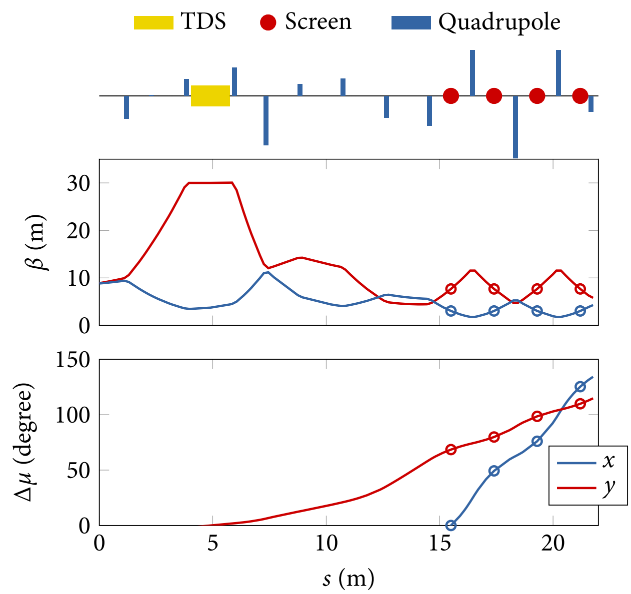

Figure 6: Accelerator optics for slice emittance measurements. Top: Schematic beamline layout; the quadrupole strengths are indicated by the height of the bars. Middle: Beta-functions. Bottom: Phase advances.

EMITTANCE MEASUREMENTS

The layout of the diagnostic sections and time structure of the electron bunches allow for novel phase space measurements of individual bunches along the train. In Fig. 5 an example of such a train emittance scan is shown. Each data point represents a transverse phase space measurement with the four screen stations in the F0D0 lattice. For each measurement a bunch is selected by the kicker magnet timing and sequentially kicked onto the four off-axis screens, and 20 beam images are recorded per screen station. A symmetric F0D0 optics with a phase advance of 76° per cell was chosen to give best results for the reconstruction of the projected emittances in both the x and y plane [6]. Phase space properties such as the beam Twiss parameters or transverse emittance are determined by a least square method using known beam transport functions [7]. The beam moments are varied at a reference point upstream of the F0D0 screen stations to best reproduce the measured beam spot sizes on the screens. A single emittance measurement for a certain bunch number takes less than 20 s.

For a train emittance scan, this procedure is repeated for bunches with different bunch numbers in the train. For the results shown in Fig. 5, every 20th bunch of the about 450 µs long train has been selected for a measurement. The measurements have been carried out in the injector section at on-crest operation with a beam energy of 130 MeV, bunch charge of 0.5 nC and bunch repetition rate of 4.5 MHz. In this particular example, the projected emittance and optics mismatch is not constant along the bunch train. The vertical emittance and optics mismatch exhibit a strong slope up to about bunch number 200. The horizontal emittance and optics mismatch increase slowly along the bunch train. This behaviour could be attributed to thermal effects in a part of the photo-cathode laser system, which could easily be corrected after being identified. This illustrates the utility of such a diagnostics setup which allows for optimising the phase space properties of each bunch in order to establish uniform FEL performance for all bunches in the train. The measurement time for this train emittance scan (measurement for every 20th bunch number) amounted to about 15 minutes.

Dispersion may be generated in the emittance measurement plane at the screen locations, when the kicker magnets are utilized for online emittance measurements. For relative energy spreads below $\sigma_\delta \sim 10^{-3}$, as is the case for on-crest operation, the relative error contribution in the calculated emittance is below 1%. A detailed error analysis of statistical and systematic errors that may contribute in the emittance measurement has been carried out in Ref. [6].

SLICE EMITTANCE MEASUREMENTS

By utilizing a TDS, the longitudinal bunch profile is transformed to one transverse plane while in the perpendicular plane the spot sizes can be measured for the longitudinal slices and slice emittances can be evaluated with the least square fit technique described in the latter section.

Figure 6 depicts an example of an accelerator optics optimised for a slice emittance measurement in the TDS diagnostic section with the beta-functions (middle) and phase advances (bottom) for both the emittance measurement plane x and TDS streak plane y. For a good longitudinal resolution

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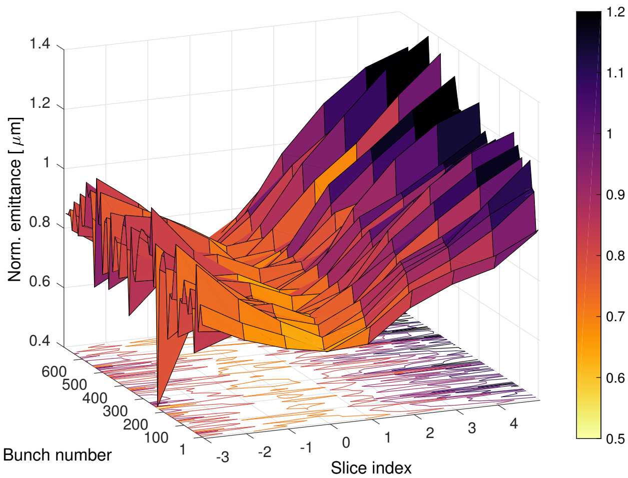

Figure 7: Nomalised horizontal slice emittance measured along the bunch train (in steps of 10 bunch numbers). Slice index 0 corresponds to the central slice with maximum bunch current.

in the streak plane, the accelerator optics has been optimised for a large beta-function $\beta_y = 30$ m at the TDS, a phase advance of $\Delta\mu_y = 90°$ from the TDS to the centre of the F0D0 lattice (i.e. the centre of the second and third screen) and a small phase advance of $\Delta\mu_y = 30°$ per cell in the F0D0 lattice. For the reconstruction of the slice emittance, a phase advance of $\Delta\mu_x = 76°$ per cell has been chosen in the emittance plane as in the case of the projected emittance measurements.

Figure 7 shows the results of online slice emittance measurements scanned along the bunch train. The slice emittance measurements have been carried out for bunch numbers 1 to 671 in the train in steps of 10 bunch numbers, i.e. a total of 67 measurements. For each emittance measurement, 16 beam images have been recorded for each of the four screen stations. Each emittance measurement took about 20 s and the total measurement time for the scan amounted to about 25 min. The data has been taken in the injector section at on-crest operation with a beam energy of 130 MeV, bunch charge of 0.5 nC and bunch repetition rate of 1.125 MHz.

The slice index 0 corresponds to the central slice of the bunch with maximum bunch current. The results for the slices in the head and tail of the bunch have been omitted from the plot for better illustration as they exhibit large error bars due to a large beam optics mismatch and low image intensities. All individual measurements display a similar distribution of the normalised slice emittance along the bunch train for the slice indices plotted. The individual normalised slice emittances vary between 0.6 μm and 1.3 μm with the minimum value at the central index 0 and increasing values towards bunch head and tail. Before the scan, the beam optics was matched to the central slice of the bunch with bunch number 1.

CONCLUSION

The combined utilization of a TDS with fast kicker magnets and off-axis screens is a versatile diagnostics implementation to analyse individual bunches in a bunch train without affecting the remaining bunches. In this paper we presented the results of measurements of the projected and slice emittance along the bunch train. This is especially helpful when it is required to achieve uniform FEL performance along the bunch train as it is the case for the European XFEL which operates in a 10 Hz pulsed mode. Compared to the maximum number of bunches in a bunch train (2700 at a repetition rate of 4.5 MHz), the bunches sacrificed for diagnostics purpose are negligible, and the method can be regarded as semi-parasitic on-line diagnostics.

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