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LONGITUDINAL PHASE SPACE DIAGNOSTICS WITH CORRUGATED STRUCTURE AT THE EUROPEAN XFEL

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Abstract

Characterization of the longitudinal phase space (LPS) of the electron beam after the FEL process is important for its study and tuning. At the European XFEL, a single plate corrugated structure was installed after the SASE2 undulator to measure the LPS of the electron beam. The beam passing near the plate's corrugations creates wakefields, which induce a correlation between time and the transverse distribution of the beam. The longitudinal phase space of the beam is then analyzed on a scintillating screen monitor placed in the dispersion section. In this paper, we present the result of commissioning the corrugated structure and the first LPS measurement.

INTRODUCTION

Longitudinal phase space (LPS) measurements after the undulator are of high interest for FEL and beam dynamics studies and facility operation. The standard way to measure LPS is to use the Transverse Deflection Structure (TDS) [1, 2]. The TDS is powered by a klystron and streaks the electron beam in the transverse plane. The streaked beam is observed on a scintillating screen monitor. The TDS-screen system will allow observation of the longitudinal phase space of the beam if the screen is located in the dispersion section and the dispersion is orthogonal to the direction of TDS deflection. However, the size and complexity of such diagnostics grows with increasing electron beam energy. Therefore, the development and installation of TDS requires a significant investment of time (years) and manpower [3], especially for the European XFEL, which operates with the beam energies up to 17.5 GeV [4].

Another way is to use a corrugated structure. A corrugated structure - a corrugated pipe of small radius or two corrugated metal plates with an adjustable gap - has been proposed in [5] to remove linear energy correlation (chirp) in a relativistic electron beam and first confirmed experimentally in [6]. When an electron beam is displaced relative to the center of the corrugated structure and passes near the corrugated wall, it experiences a time-correlated transverse kick in the direction of the wall. However, the transverse kick is not linear unlike the TDS. This makes it difficult to analyze the measurements obtained due to non-linearity of the time axis, and the time resolution is poor at the beam head. A corrugated structure is a type of wakefield structure along with, for example, dialectic structures. Nevertheless, the simplicity of passive streamers based on wakefield structure is attractive for electron beam manipulation both for FEL techniques, e.g. [7], and for diagnostic purposes [8–10].

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LPS DIAGNOSTICS WITH CORRUGATED STRUCTURE

At the European XFEL, the development of LPS diagnostic based on a corrugated structure was started in October 2020 and commissioned in January 2022. The new device is a metal corrugated plate, consisting of 5 segments of length of 1 m each. The corrugated structure is installed after the SASE2 undulator and, together with the GAGG:Ce screen installed in the downstream arc, forms a diagnostic system for measuring the LPS of the electron beam. The strength of the transverse kick of the corrugated plate depends on the beam current distribution and the distance between the beam and the corrugated plate. Unlike the corrugated structures in PSI [10] or SLAC [11], which use movable jaws with appropriate mechanics to change the distance between the beam and the corrugated plate, we control the distance with a trajectory bump. This significantly simplifies the design of the entire system. The trajectory bump is created by 4 vertical correctors, with maximum amplitude 4 mm – distance between the plate and reference beam trajectory. A simplified layout of the diagnostic beam line is shown in Figure 1 and the corrugated structure installed in the tunnel is shown in Figure 2.

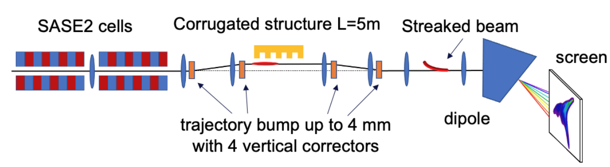

Figure 1: Simplified layout of the diagnostic beam line for LPS measurement after SASE2 undulator.

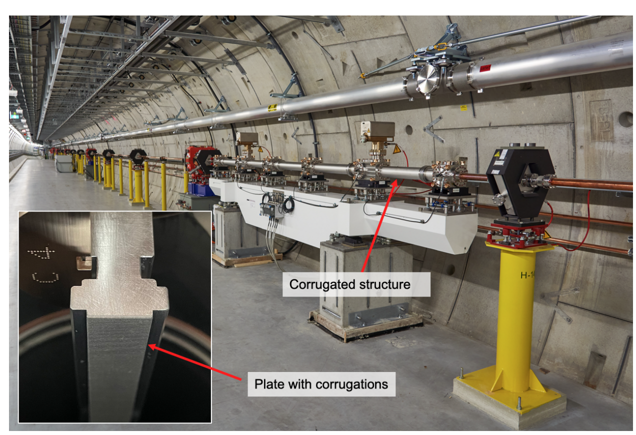

Figure 2: Installed corrugated structure in the tunnel.

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The corrugated structure streaks the beam in vertical plane and a dipole magnet bends the electron beam in horizontal plane. The schematic view of corrugated plate is shown in Figure 3. The sizes of the corrugation are the same as for corrugated structure which is installed in LCLS [11] and can be seen in Table 1. The GAGG:Ce screen pixel dimensions are 5.5 × 5.5 μm^2.

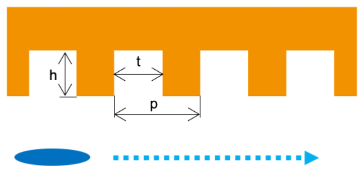

Figure 3: Schematic side view of the corrugated structure.

Table 1: Main Parameters of the Corrugated Structure

Parameter	Value
Depth, h	0.5 mm
Gap, t	0.25 mm
Period, p	0.5 mm
Width, w	12 mm
Number of segments	5
Total length, L	5 m

The new diagnostic does not have a dedicated beam line to dump the electron beam after the screen. Therefore, the diagnostics operates at a frequency of 1-3 Hz to reduce the radiation load.

Special Beam Optics

Two additional requirements are necessary for the LPS measurement: the betatron phase advance in vertical plane, plane of the dipole kick, between the corrugated structure and screen must be close to $\phi_y = \pi/2 + n \cdot 2\pi$, n is an integer, and maximal possible horizontal dispersion on the screen for better energy resolution. A new beam optics were developed to satisfy these requirements. In addition, a zero dispersion optics have been developed for the energy resolution measurement. All optics modes are presented in Figure 4 and Table 2.

Table 2: Optics Modes and its Main Parameters

Parameter	Design	Zero disp.	Max disp.
β_y^{WS}	56.4 m	56.4 m	56.4 m
D_x^{scr}	7 cm	<1 cm	40 cm
β_x^{scr}	5.6 m	5.26 m	5.5 m
β_y^{scr}	10.2 m	15 m	28.8 m
$\Delta\mu_y$	289 deg	283 deg	284 deg
R_{34}	-22.6	-39.2	-39.1

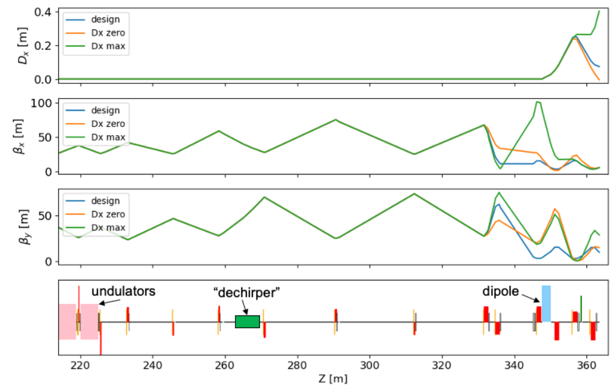

Figure 4: Beam optics modes for the diagnostic beam line.

Energy Calibration

In order to be able to measure the slice energy spread, it is necessary to calibrate the energy axis on the screen or, in other words, to measure the dispersion in the screen position. The horizontal dispersion in the screen position is measured by scanning the voltage of the last accelerator RF station and measuring the center of mass of the beam on the screen.

Energy Resolution Measurement

One of the features of our diagnostic beam line is the ability to set the dispersion at the screen position to zero, Figure 4 and Table 2. This makes it easy to measure the energy resolution of the diagnostic system. Figure 5 shows an example of such a measurement. In this particular case, the beam optics was set to the "zero dispersion" mode, and the measured dispersion was $D_x = 22$ mm. The beam current was about 0.5 kA, which allows us to estimate the slice energy spread of 0.2 – 0.3 MeV. Thus, the contribution of the energy spread to the measured size of the beam slices can be neglected. Figure 5 shows that the minimum beam size is 37 μm averaged over 20 pixels slice width. This corresponds to the maximum energy resolution of 1.43 MeV with a horizontal dispersion of $D_x = 0.45$ m, measured in the same measurement run.

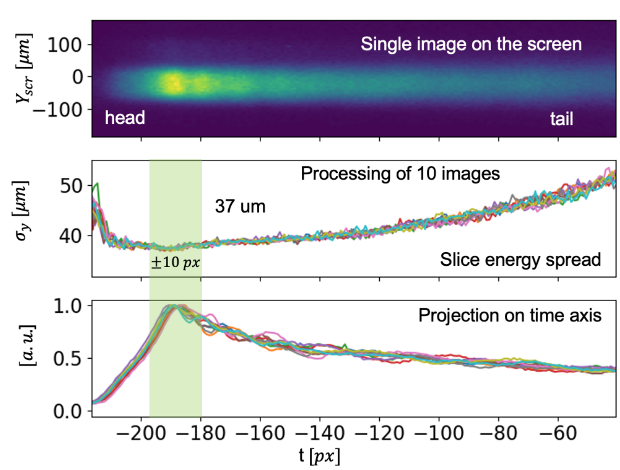

Figure 5: Example of the energy resolution measurement.

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FIRST RESULTS

It takes about a couple of minutes to prepare for LPS measurements and the same amount of time to restore normal operation, thanks to software designed to work with the new diagnostics. The tool also analyzes the acquired images, and an example LPS image of an electron beam with and without the SASE can be seen in Figure 6. The slice energy spread is shown at the bottom of the figures. Zero on the time axis here and in the next figures corresponds to the center of mass of the image. Note, that time axis is non linear due to non-linearity of the transverse kick of the corrugated structure.

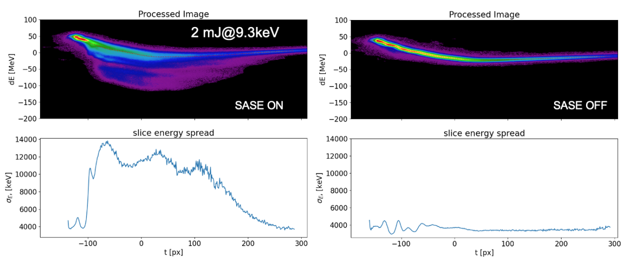

Figure 6: Observation of the LPS of the electron beam w/o SASE.

If the electron beam has an energy chirp and if dispersion is introduced into the undulator, this enables the dispersion-based fresh slice techniques [12]. By controlling the orbit in the SASE2 undulator, we were able to control the position of the lasing slice in the beam. LPS diagnostics, based on the corrugated structure, was used to observe the lasing of the different beam slices, Figure 7.

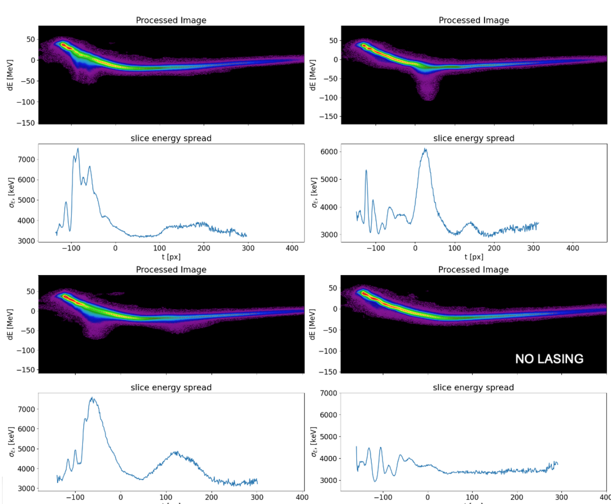

Figure 7: Observation of the lasing of the different slices in the beam.

Another example of an LPS image obtained with the new device is the observation of the microbunching instability, Figure 8. The microbunching instability was observed for long beam with the current amplitude around 0.5 kA and the laser heater in the injector was turned off.

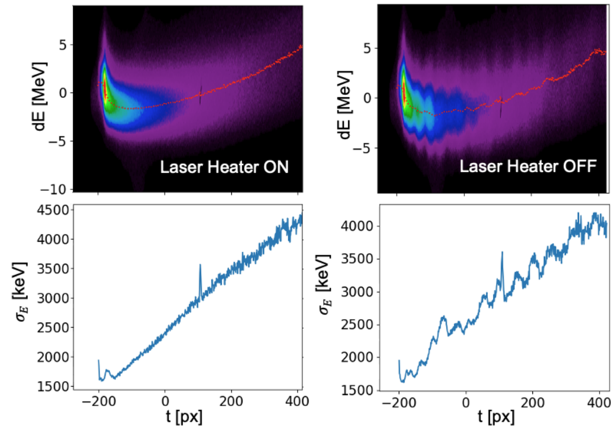

Figure 8: Observation of the microbunching instability with low beam current.

CONCLUSION

At the European XFEL, the development of LPS diagnostic based on a corrugated structure was started in October 2020 and commissioned in January 2022. To simplify the corrugated structure design, we abandoned the use a movable jaw with in-vacuum mechanics in favor of a trajectory bump to control the distance between the corrugated plate and the beam. At this point, we see no disadvantages of this solution. In this work, we have demonstrated that corrugated structure-based diagnostics are widely used in the European XFEL.

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