MEASUREMENTS OF SLICED-BUNCH PARAMETERS AT FLASH

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Abstract

The capability of the free-electron laser (FEL) user facility FLASH at DESY was expanded by several upgrades during the shutdown in 2009/2010. A key extension was the installation of a third-harmonic (3.9 GHz) RF system for the linearization of the longitudinal phase space in front of the bunch compressors. In order to control the bunch compression and make full use of the third-harmonic RF system, a new diagnostic section for the measurements of sliced-bunch parameters directly in front of the main undulators was designed and commissioned. In this paper, we describe the beam imaging systems and their optical performance. The achievable resolution of both time and energy is shown and compared to the design values. First measurements of the longitudinal phase space and the observation of coherent optical transition radiation during FEL operation with linear compression are presented.

INTRODUCTION

The installation of a third-harmonic (3.9 GHz) RF system was one of the major upgrades of the FEL user facility FLASH at DESY during the shutdown in 2009/2010 [1]. The third-harmonic (3.9 GHz) RF system has been installed in front of the first bunch compressor for the linearization of the longitudinal phase space (LPS). After successful technical commissioning, the applicability for LPS manipulation was demonstrated in a first test [2].

By linearizing the longitudinal phase space the fraction of the bunch that performs lasing is increased and higher FEL pulse energies are achieved. However, beam dynamics become more complex and several working points for the accelerator RF settings can be found by particle tracking simulations for best FEL performance. In order to check the validity of these simulations and set up the accelerator RF settings for FEL operation, a direct observation of the LPS is desirable. For this reason, a new measurement setup for sliced-bunch parameters was designed [3], which has been installed during the upgrade shutdown and commissioned in summer 2010.

In this paper, we describe the beam imaging systems of the measurement setups and their optical performances. The achieved time and energy resolution is presented and compared to the design values given in Ref. [3]. First measurements of the longitudinal phase space and observation of coherent optical transition radiation (COTR) during FEL operation with linear compression are presented.

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BEAM IMAGING SYSTEMS

The layout of the new diagnostics beamlines SMATCH and SDUMP at FLASH and their expected performance, evaluated by numerical simulations, were described in Ref. [3]. The numerical studies were based on theoretical accelerator optics of the designed lattice. In order to fully exploit the expected diagnostics performance and to be prepared for COTR, two new beam imaging stations were designed. The beam imaging stations consist of a vacuum chamber equipped with a motorized screen holder and a camera system. The setups and their performances are described in the remainder of this section.

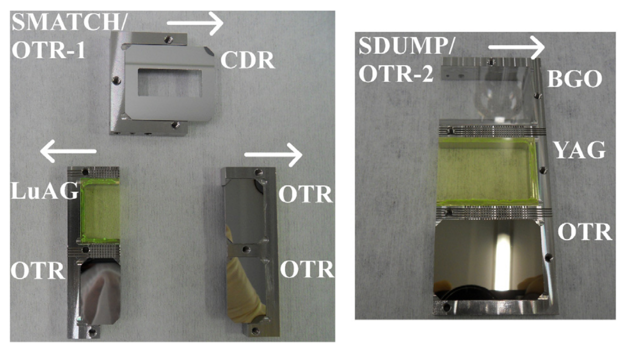

Figure 1: Screen holders and observation screens; emission directions are indicated by arrows. Left: SMATCH setup. Right: SDUMP setup.

Table 1: Properties of the Observation Screens

Screen material	Thickness (mm)
YAG:Ce ($Y_3Al_5O_{12}$:Ce)	0.1
LuAG:Ce ($Lu_3Al_5O_{12}$:Ce)	0.1
BGO ($Bi_4Ge_3O_{12}$)	0.1
OTR (Al coated silicon)	0.380 (150 nm Al)
CDR (Al coated silicon with cutout)	0.380 (150 nm Al)

The screen holders are equipped with different observation screens which are mounted at an angle of 45 deg with respect to the incoming electron beam. Images of the screen holders are shown in Fig. 1 with the emission direction indicated by arrows. The setup at SMATCH will also be used for THz spectroscopy of coherent transition and diffraction radiation. The screen materials and the corresponding thicknesses are listed in table 1. The OTR screens were intended to be used as standard screens, whereas the

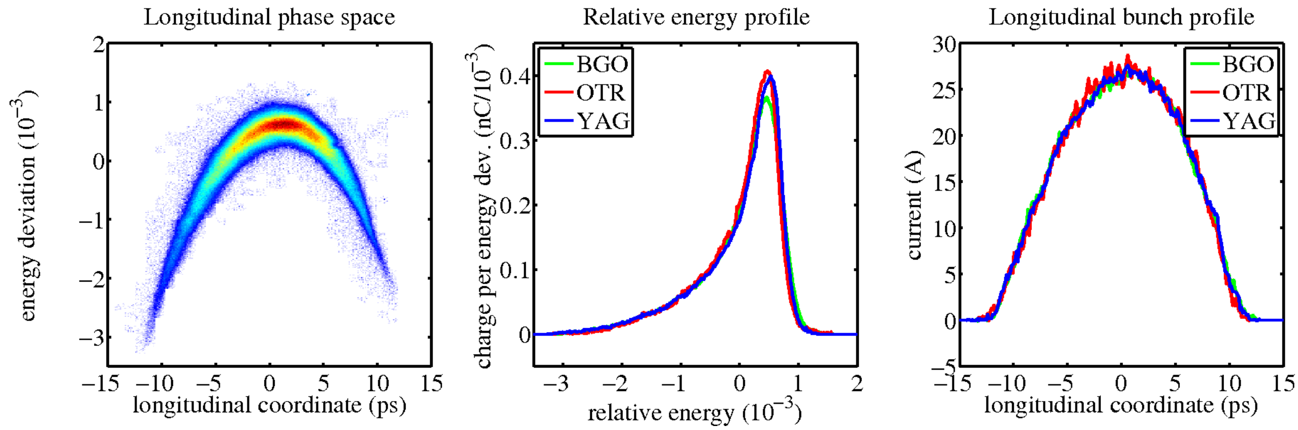

Figure 2: Comparison of longitudinal phase space measurements at SDUMP for different observation screens and bunches with a charge of 400 pC. Left: LPS with a YAG:Ce screen. Middle: Projection onto the "energy deviation"-axis for BGO, OTR and YAG:Ce. Right: Projection onto the "longitudinal coordinate"-axis for BGO, OTR and YAG:Ce.

scintillators are designed for suitability studies (see [4]) and as option in the case of existing COTR, which already was observed at FLASH [5] and may compromises diagnosis [6]. A first comparative investigation, using different observation screens for measurements of the longitudinal phase space, are presented in Fig. 2. The measurements were performed with a transverse deflecting structure (TDS) in the dispersive section SDUMP (see [3]). The sinusoidal curvature in the LPS is given by the on-crest RF phases of the accelerator modules. The projections onto the different axes show good agreement between the measurements with the different screens. In general, beam size measurements with scintillators tend to result in larger values (see [4]). The good agreement in this case may be connected to the relatively large beam sizes due to the shearing by the TDS and dispersion.

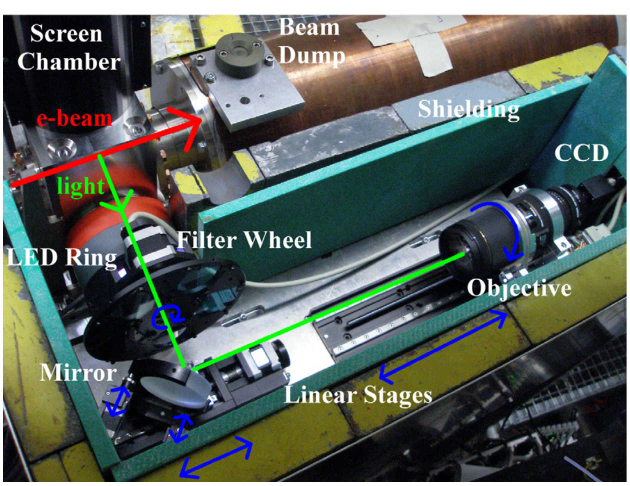

Figure 3: The camera system at SDUMP: The main components and paths are labeled, and motorized units are indicated by blue arrows which show the direction of motion.

The light from the observation screens are imaged via the camera system pictured in Fig. 3. The magnifications and lateral resolutions achieved with the motorized unit of CCD camera (1360 x 1024 pixels with 12 bit dynamic range and 6.45 x 6.45 μm^2 pixel size) and objective (macro lens (f = 180 mm and teleconverter (x 1.4)) is shown in Fig. 4 for both setups. The magnification was measured using calibration grids on the screen holders, and the resolution was estimated by an USAF-1951 test target. The area in the right plot of Fig. 4 determines the estimation uncertainty of the lateral resolution. It is the difference between the field of the USAF-1951 test target which is resolved and the next one which is not. Additional components are a ring of LEDs as light source for the calibration measurement, a movable mirror for alignment and a filter wheel equipped with a neutral density filter, longpass filter and two shortpass filters.

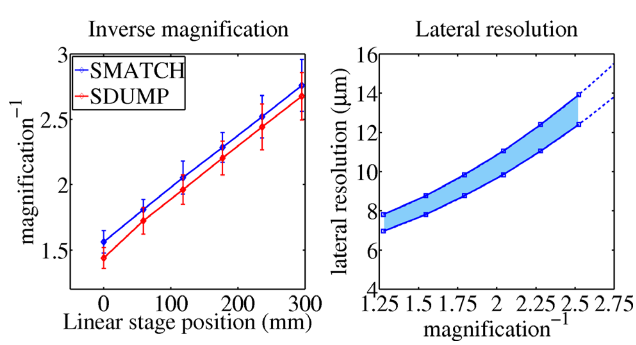

Figure 4: Performance of the camera optics at SDUMP and SMATCH. Left: Inverse magnification as function of the linear stage position (CCD camera + objective). Right: Lateral resolution as function of the inverse magnification.

TIME AND ENERGY RESOLUTIONS

The time and energy resolution of the new diagnostic section, estimated by particle tracking simulations [3], amounts to about 27 fs in time and $1.6 \cdot 10^{-4}$ in relative

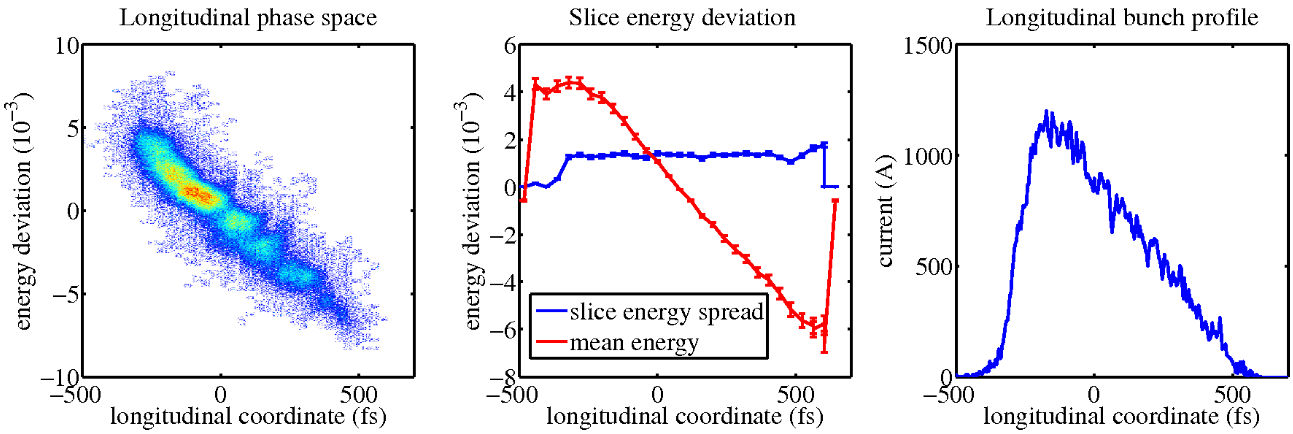

Figure 5: Longitudinal phase space measurement for a linearly compressed bunch with a charge of 400 pC using OTR. The mean energy deviation and slice energy spread are shown in the centre plot. The right plot shows the beam current.

energy. Using the formulas quoted in [7] and design optics values, the expected time resolution is even 20 fs. According to [7], the time resolution can be estimated by the beam size, without being sheared by the TDS, divided by the shear function or parameter S. The measurements in Fig. 6 show an example calibration with a resulting time resolution of 18 ± 3 fs during standard FEL operation without having to apply a special optics.

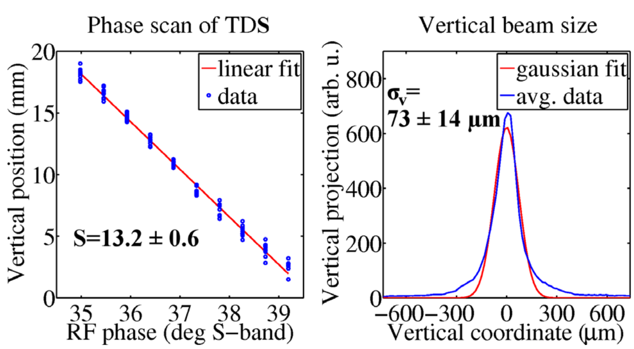

Figure 6: Calibration measurement for the TDS with an electron beam energy of 1.2 GeV. Left: RF phase scan to determine the shear function S at YAG-screen position. Right: Vertical beam profile without shearing by the TDS.

The relative energy resolution was estimated by measurement of the slice energy spread for on-crest RF conditions, where almost no bunch compression takes place. By this, the energy spread is not increased due to non-linear effects during compression and should be the same as measuered in the injector where it is about a few keV [8]. The plots in Fig. 7 show the mean energy deviation and the slice energy spread, whose minimal value is approximately $1.4 \cdot 10^{-4}$, which corresponds to 100 keV at a beam energy of 700 MeV. This value is resolution limited and gives an estimation for the energy resolution. The dispersion in SDUMP, which is the basis for energy resolved measurements, is about 750 mm during standard operation and can be tuned by an additional quadrupole magnet if necessary.

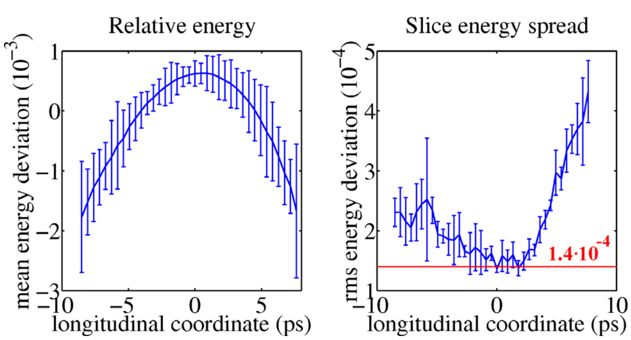

Figure 7: Energy deviation of on-crest bunches with a charge of 400 pC measured with OTR + shortpass filter and averaged over 5 consecutive bunches. Left: Mean energy deviation. Right: Slice energy spread.

FIRST RESULTS AT FEL OPERATION WITH LINEARIZED COMPRESSION

The diagnostic and tuning section SDUMP have been proven to be a very helpful and robust tool for adjusting the accelerator RF settings of the third-harmonic (3.9 GHz) system by directly measuring the LPS and comparing it to expected beam dynamics simulations. First dedicated approaches to get lasing with a conditioned LPS for linear compression using the SDUMP setup have been performed successfully. The plots in Fig. 5 show the first results for a linear compressed bunch for which lasing was observed. The left plot shows the longitudinal phase space for a bunch charge of 400 pC measured with OTR. The middle plot shows the energy deviations and in case of the mean value (red curve), an almost perfect linear energy chirp along the entire bunch is visible. The right plot shows the longitudinal bunch profile with moderate peak current above 1 kA. Another measurement with the same accelerator conditions and YAG as observation screen can be seen in Fig. 8, where intensity modulations are visible in the LPS (left plot) and also in the projection onto the energy

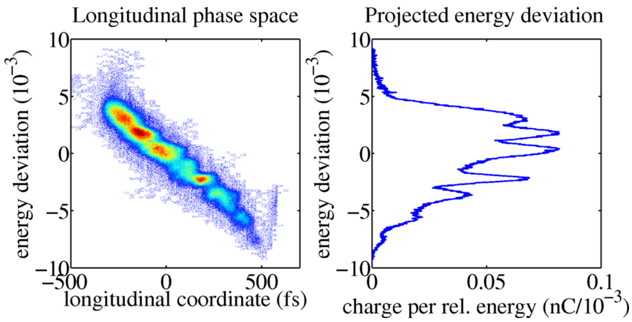

Figure 8: Longitudinal phase space measurement with YAG screen for the same accelerator settings as for plots in Fig. 5. A more pronounced substructure is visible. The right plot shows the projection onto the energy axis.

axis (right plot). These intensity spikes or modulations are independent of the observation screen and more or less stable in number and amplitude. These kind of modulations appear during FEL operation with linear compression and are a hint for microbunching instabilities [5].

OBSERVATION OF COTR

The beam imaging station in the non-dispersive section SMATCH, which was designed for longitudinal on-line bunch profile measurements using a TDS and fast kicker magnet, has also been commissioned. The upper image in the left part of Fig.9 shows a bunch sheared by the TDS which was recorded parasitically during FEL operation. A slight change of the RF phase of about $\Delta\Phi \approx 0.5$ deg (1.3 GHz) of the accelerator module upstream of the first bunch compressor resulted in the lower images in the left part of Fig.9. Strong COTR was observed which makes any quantitative analysis impossible. Even after reducing the gain of the camera to a minimum or using short- or long-pass filter the CCD images were still saturated. Undefined structures and ringlike structures, typical for COTR, were observed with different observation screens. The lower image in the right part of Fig.9 shows COTR from a LuAG scintillator. All the observed coherent emission was present within a sharp RF phase range of ± 0.2 deg (1.3 GHz) and showed large shot-to-shot fluctuations. COTR was not observed in the images of bunches recorded with the same accelerator settings in the dispersive section SDUMP. Only the intensity modulations shown in Fig. 8 give a hint for microbunching effects.

CONCLUSIONS

The new diagnostic sections for slice-bunch parameters at FLASH have been commissioned successfully and used for first LPS measurements. The designed and expected resolutions in both time and energy domain were achieved, and the beam imaging stations have proven to work reliably. During FEL operation, linearly compressed bunches have been investigated which indicate microbunching instabilities by means of COTR and occur as substructures in the longitudinal phase space measurements.

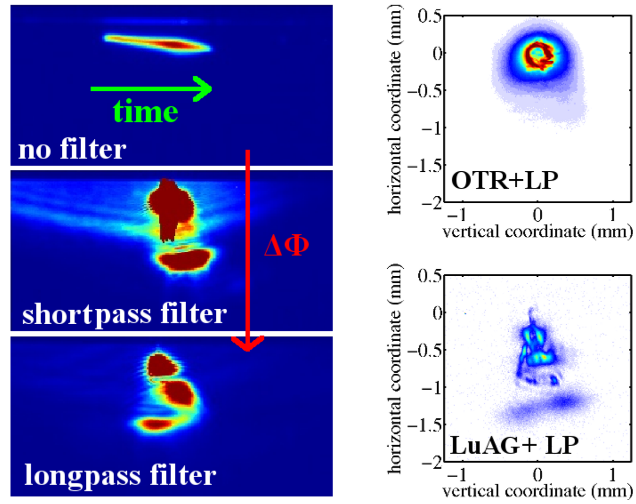

Figure 9: Observation of COTR. Left: Logbook entries with sheared bunches measured by OTR and two RF phase settings with 0.2 deg (1.3 GHz) difference. Top: Diagnosis possible. Middle: No diagnosis possible with shortpass filter. Bottom: No diagnosis possible with longpass filter (LP). Right: Measured images with OTR and a LuAG screen, both with longpass filter. Top: OTR with ring structure. Bottom: LuAG with undefined structure.

REFERENCES

[1] K. Honkavaara *et al.*, "FLASH Upgrade", PAC'09 , Vancouver, May 2009, TU5RFP059

[2] E. Vogel *et al.*, "Test and Commissioning of the Third Harmonic RF System for FLASH", IPAC'10, Kyoto, May 2010, THPD003

[3] C. Behrens, Ch. Gerth and I. Zagorodnov, "Numerical Performance Studies on the new Sliced-Beam-Parameter Measurement Setup for FLASH", FEL'09, Liverpool, August 2009, WEPC45

[4] G. Kube, C. Behrens and W. Lauth, "Resolution Studies of inorganic Scintillation Screens for high energetic and high brilliant Electron Beams", IPAC'10, Kyoto, May 2010, MOPD088

[5] S. Wesch *et al.*, "Observation of Coherent Optical Transition Radiation and Evidence for Microbunching in Magnetic Chicanes", FEL'09, Liverpool, August 2009, WEPC50

[6] H. Loos *et al.*, "Observation of Coherent Optical Transition Radiation in the LCLS Linac", FEL'08, Gyeongju, August 2008, THBAU01

[7] C. Behrens and Ch. Gerth, "On the Limitations of Longitudinal Phase Space Measurements using a Transverse Deflecting Structure", DIPAC'09, Basel, May 2009, TUPB4

[8] M. Huening and H. Schlarb, "Measurement of the Beam Energy Spread in the TTF Photo-injector", PAC'03, Portland, May 2003 , WPAB017