BEAM PROFILE MEASUREMENTS USING A FAST GATED CCD CAMERA AND A SCINTILLATION SCREEN TO SUPPRESS COTR

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Abstract

For standard beam profile measurements of high-brightness electron beams using optical transition radiation (OTR) screens, coherence effects induced by microbunching instability render direct imaging of the beam impossible. A technique of using a scintillation screen with a fast gated CCD camera has been demonstrated to have successfully suppressed coherent OTR (COTR) in transverse beam diagnostics at FLASH. Now the fast gated CCD camera has been employed for longitudinal bunch profile measurements with a transverse deflecting structure (TDS). Results obtained under operating conditions with and without COTR are compared to those from longitudinal phase space measurements in a dispersive arm, where no coherence effects have been observed so far. In this paper, we examine the performance of the fast gated CCD camera for longitudinal beam profile measurements and present further studies on the use of scintillation screens for high-energy electron beam diagnostics.

INTRODUCTION

High-brightness electron beams with small transverse and longitudinal emittance and high peak currents are required to drive high-gain free-electron lasers (FEL). A standard method for bunch profile measurements is to directly image the beam with OTR emitted from a viewing screen. Recently, coherence effects in the emission process of OTR due to microbunching instability [1, 2] in longitudinally compressed beams have been observed at LCLS, FLASH and other facilities [3, 4] and hampered beam diagnosis.

By using a scintillation screen with a fast gated CCD camera, suppression of COTR in transverse electron beam diagnosis has been achieved at FLASH [5]. The basic principle is to shift the camera gate so that the detection of the spontaneous COTR generated on the scintillator surface is excluded, thus imaging the electron beam only with delayed scintillation light which is emitted incoherently.

This technique has been recently employed for longitudinal beam profile diagnosis at FLASH. The measurements have been performed under operating conditions with and without COTR, and compared to results obtained at another section as reference. Furthermore, the correlation of radiation intensity from different viewing screens to the bunch compression is examined. When varying the bunch length by changing the RF phase of the accelerator at a fixed bunch charge, the intensity of emitted scintillation light and OTR should remain constant. On the other hand, strongly fluctuating OTR intensities are indication for coherence effects. In this paper, we present the successful application of using a fast gated ICCD camera in combination with a scintillation screen to suppress COTR in longitudinal bunch profile measurements, and prove the validation of this method in a wide range.

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EXPERIMENTAL SETUP

The longitudinal beam profile measurements have been carried out with a TDS (LOLA) [6], which transforms longitudinal information into transverse information by shearing the electron bunch in the transverse plane. The image of the sheared bunch on the viewing screen can be used to reconstruct the longitudinal profile. The whole experimental station is located directly upstream of the SASE undulator as shown schematically in Fig. 1.

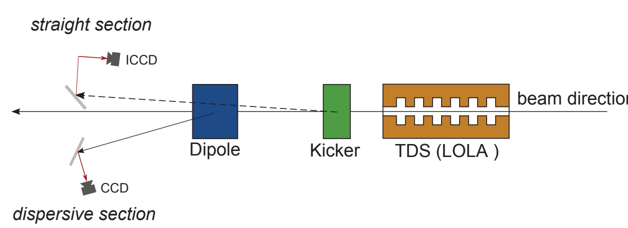

Figure 1: Layout of the experimental setup.

Downstream of the TDS, a fast kicker can kick one bunch out of the bunch train onto an off-axis screen in the straight section where the fast gated ICCD camera is installed. The ICCD camera is a commercial camera from PCO [8] and built up in 4 stages: 1. Incoming photons are converted to electrons by the photo cathode. 2. The electrons are amplified by a micro channel plate (MCP), which also regulates the delay of the camera gate. 3. A phosphor screen (S20) converts the electrons back to photons. 4. The photons are detected by the CCD chip. The ICCD camera was equipped with a macro lens (f = 150 mm) and a teleconverter (x 1.4), reaching a magnification of about 4:1. Apart from the kicker, a dipole magnet can deflect the beam into a dispersive section equipped with a normal CCD camera where longitudinal phase space measurements are performed, which give information about the energy spread. The setup in the dispersive section serves as a stable and reliable station for longitudinal phase space measurements

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at FLASH [7] where coherence effects have not been observed so far, allowing it to be used as a reference to our measurements in the straight section. The machine can be switched between operation in straight or dispersive section. Different viewing screens (see Table 1) at 45° w.r.t. the incoming beam are mounted at the two sections and the cameras are intstalled normal to the incoming beam (for details about the cameras see [5, 7]).

Table 1: Properties of the Viewing Screens

section	Screen material	Thickness(mm)
straight	LuAG:Ce($Lu_3Al_5O_{12}$:Ce)	0.1
straight	OTR(Al coated silicon)	0.380
dispersive	YAG:Ce($Y_3Al_5O_{12}$:Ce)	0.1

DATA ANALYSIS

The measured data were analyzed as demonstrated in Fig. 2. The example here was taken from the ICCD camera in the straight section with LuAG screen.

The original camera image of the beam is shown in Fig. 2 left. The background, which is recorded when the beam is switched off, is subtracted from the original camera image. Then the image is processed to obtain a region of interest (ROI). Since the sheared bunch has an arbitrary shape, a simple ROI of a fixed shape is not applicable in our case, thus demanding a sophisticated algorithm to define the beam. The basic principle is the combined use of gaussian filtering, noise estimation and flood fill algorithm. Noises outside the ROI are set to zero (color code white in Fig. 2 middle). For details see [9]. With projection of the processed image onto the longitudinal coordinate, the longitudinal profile is obtained, from which the rms value can be calculated.

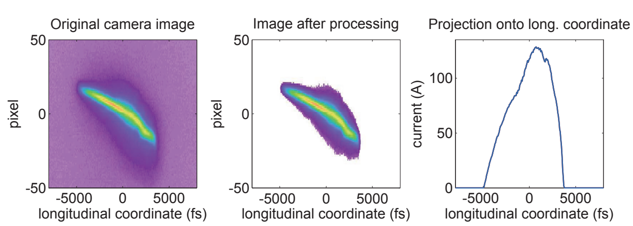

Figure 2: Example of data analysis. Image taken with ICCD camera in the straight section with LuAG screen. Left: original camera image. Middle: ROI of the image after processing. Right: longitudinal profile.

SUPPRESSION OF COTR

The measurements have been performed at FLASH, with the accelerator setting of beam energy 700 MeV and bunch charge 0.5 nC. Different compression settings were chosen which covered operating conditions with and without COTR.

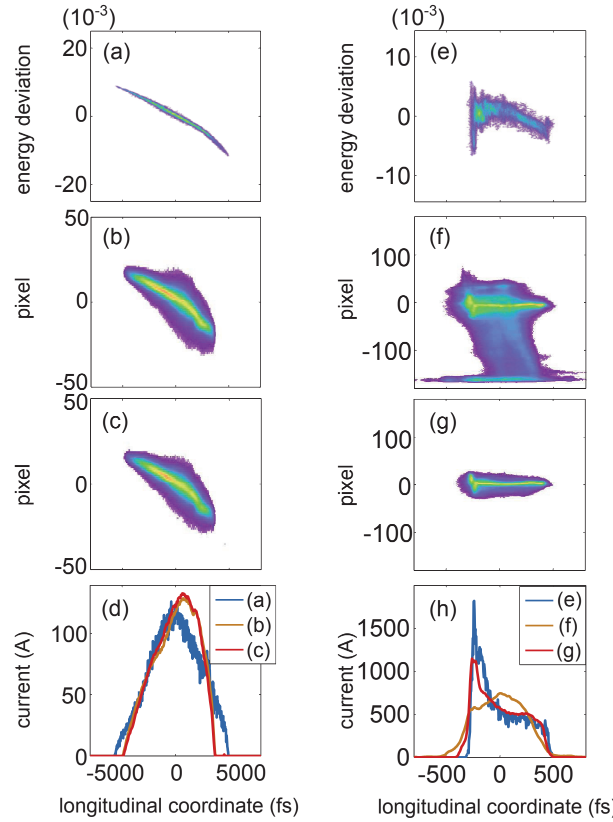

Figure 3: Camera images from longitudinal profile measurements under slight (a-d) and strong (e-h) compression settings using (a,e) CCD camera in dispersive section with YAG screen, (b,f) ICCD camera in straight section with LuAG screen, (c,g) ICCD camera in straight section with LuAG screen and camera delay. The longitudinal profiles are compared in (d,h).

The first measurement (see Fig. 3(a-d)) was performed at a slight compression setting where no coherence effect was expected. A longitudinal phase space measurement in the dispersive section using YAG screen was taken as a reference, which is shown in Fig. 3(a). Then the machine was switched to operate in the straight section. The image taken with the ICCD camera using LuAG screen without the camera gate being delayed is shown in Fig. 3(b). Both scintillation light and OTR light generated on the screen surface contribute to the image intensity. At last the camera gate of the ICCD was delayed to avoid detection of OTR on the chip (Fig. 3(c)).

The longitudinal profiles of the results obtained in the 3 setups are compared in Fig. 3(d). The area of the profiles are normalized to the bunch charge measured with a toroid to provide information about beam current. All three profiles, with rms values of (a) 2290±8 fs, (b) 1977±6 fs and (c) 1910±13 fs, are in good agreement. The one from the dispersive section is slightly wider than those from the

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straight section, which may be due to machine instabilities during the switching between the two sections.

In the case of strong compression setting, which produces more COTR, the longitudinal profile measurements were repeated with these 3 setups as well (see Fig. 3 (e-h)). The image taken with ICCD camera using LuAG screen without camera delay failed to give quantitative information about the beam due to the coherent OTR generated from the scintillator surface, as shown in Fig. 3(f). One can see a much expanded illuminated area and the images fluctuated from shot to shot. After the delay of camera gate was introduced to exclude COTR, a direct imaging of the sheared bunch with only scintillation light became possible Fig. 3(g). Compared with the reference profile (rms 210±3 fs) measured in the dispersive section, the longitudinal profile measured with this technique (rms 219±2 fs) shows a good agreement, while the profile of the image taken with ICCD without delay (rms 228±15 fs) differs largely from them.

It is worth pointing out that the profile measured with ICCD camera has lower peak intensity than reference Fig. 3(h). Some parts of the intensifier in the ICCD camera saturated before the CCD chip did. This problem is described at the end of this paper and is now under investigation.

COTR STUDIES

The intensity of COTR depends strongly on the longitudinal bunch compression, that means the RF phase settings of the accelator [3]. To verify the performance and ability of our method to suppress COTR, further measurements using the ICCD camera with different viewing screens have been carried out for various RF settings. As shown in Fig. 4, the radiation intensity (top) and relative intensity fluctuation (bottom) were measured at different compression settings by changing the RF phase of the first accelerating module ACC1.

The radiation intensity from OTR screen (black line) increases dramatically starting from the RF phase of 3.55 deg due to strong coherence effects. Although the enhancement of the OTR intensity at smaller phases is relative small, the relative intensity fluctuation calculated from 20 single shots lies between 10−15%, which is a typical indication of the existence of COTR. With an intensity enhancement of a factor up to 12 over the whole RF phase range, beam diagnosis with OTR screen in the straight section is not possible.

In the case of LuAG screen without camera delay (yellow line), the radiation intensity which consists of OTR and scintillation light stays constant at smaller phases and starts to fluctuate at RF phase of 3.75 deg. Compared to the case of the OTR screen, the scintillator screen mitigates partly the coherence effects, but is still impeded by COTR with an intensity enhancement factor of 2 in the measured phase range.

A very stable radiation intensity with rather low fluctuation is seen as expected when the ICCD camera gate is

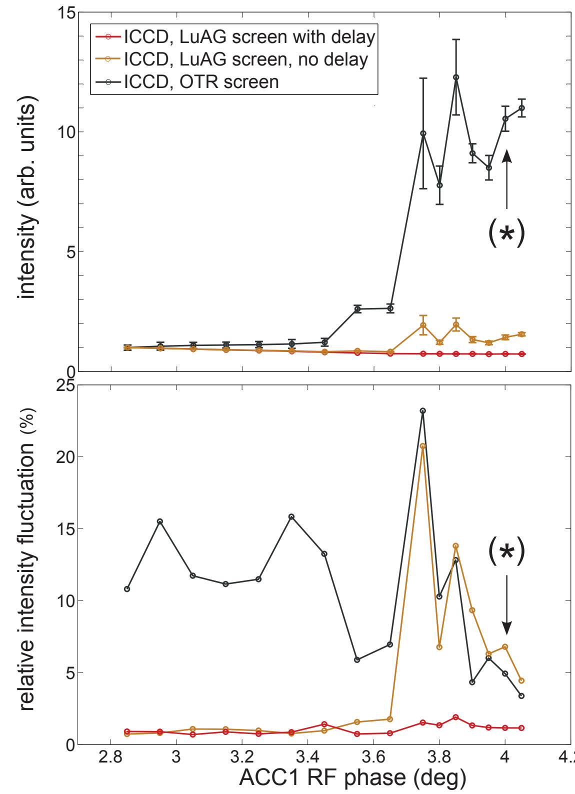

Figure 4: Phase scan for ICCD camera with different screens and camera gate settings. Top: radiation intensity measured for various ACC1 RF phases. Bottom: relative intensity fluctuation measured for various ACC1 RF phases. The profiles measured at * are shown in Fig. 5

delayed (red line). Since OTR is excluded, the radiation intensity, which has now only the contribution from scintillation light, is no longer correlated to the longitudinal compression, thus remaining constant over the entire RF phase range.

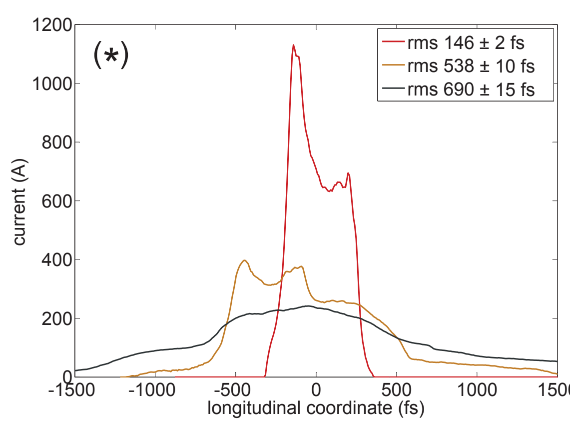

Figure 5: Comparison of the longitudinal beam profiles at ACC1 RF phase of 4.0 deg (corresponding to the point marked with * in Fig. 4).

A comparison of the longitudinal profiles measured with

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these three setups at RF phase of 4.0 deg (*) is shown in Fig. 5. The profiles taken with the OTR screen and LuAG screen without camera delay give overestimated bunch lengths and underestimated peak currents. From 20 single shots, a bunch length of 146 ± 1.6 fs is measured with the ICCD camera using LuAG screen with camera delay.

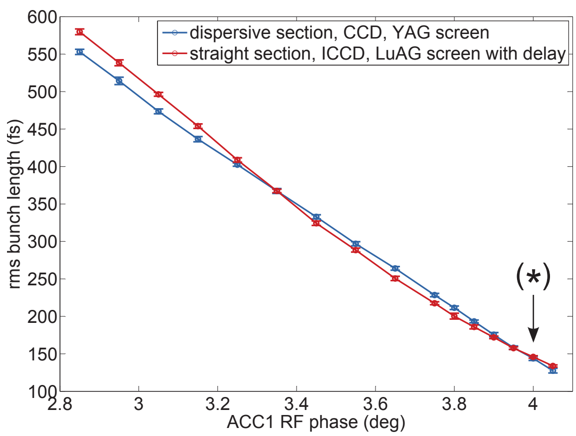

Figure 6: Phase scan for (red) ICCD camera with LuAG screen and delay, (blue) CCD camera in the dispersive section with YAG screen as reference. The calculated bunch lengths are plotted as function of ACC1 RF phase. The profiles measured at * are shown in Fig. 7

The rms bunch lengths for different RF phase settings has been calculated and compared with the reference bunch lengths obtained in the dispersive section. As shown in Fig. 6, the results are in good agreement for each phase setting. With increasing RF phase, the bunch length reduced from 580 fs to 130 fs. A slightly shorter bunch length measured in the dispersive section at smaller RF phase could be caused by the fact that longer bunches are more likely to lose electrons due to energy spread when passing through the dispersive section, thus showing a shorter bunch profile.

From the comparison of the longitudinal profiles measured at RF phase 4.0 deg (Fig. 7), one can see that the profile from the new technique (red line) has almost the same shape as that from the reference (blue line). The calculated bunch lengths, 144 fs and 146 fs respectively, are consistent with each other taking into account the standard deviation.

The lower peak on the negative coordinate side could be due to non-linearized intensification correlated to saturation in the intensifier system (consisting of photo cathode, micro channel plate and phosphor screen) of the ICCD camera. When the incoming beam is centered in a relatively small area on the CCD chip, higher intensity will be less intensified than lower intensity. This issue of the ICCD camera is currently under investigation in the laboratory.

CONCLUSION

We successfully suppressed COTR in longitudinal beam profile measurements by using a fast gated ICCD camera

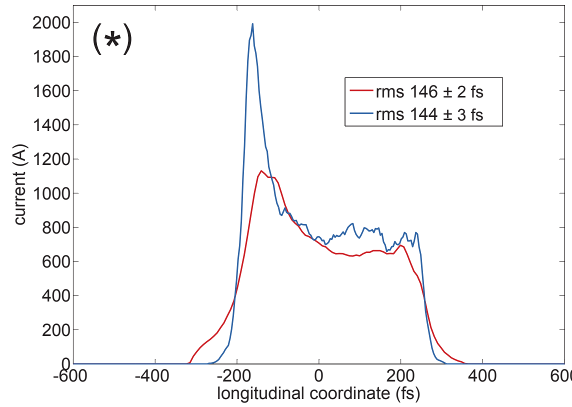

Figure 7: Comparison of the longitudinal beam profiles at ACC1 RF phase of 4.0 deg (corresponding to the point marked with * in Fig. 6).

in combination with a scintillation screen. The results are in good agreement with those obtained in another setup in the dispersive section as references. During further COTR studies, the consistency and reliability of this technique have been demonstrated, proving it to be a solution for COTR suppression. To understand the characteristics and performance of the ICCD camera, camera tests in the laboratory are ongoing.

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