SUPPRESSION OF COHERENT OPTICAL TRANSITION RADIATION IN TRANSVERSE BEAM DIAGNOSTICS BY UTILISING A SCINTILLATION SCREEN WITH A FAST GATED CCD CAMERA

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Abstract

Microbunching instability in high-brightness beams of linac-driven free-electron lasers (FEL) can lead to coherence effects in the emission of optical transition radiation (OTR) used for standard transverse profile diagnostics, thus rendering it impossible to observe a direct image of the particle beam. By using a scintillation screen in combination with a fast gated CCD camera, coherence effects can be suppressed as OTR is created in an instantaneous process while scintillation light has a certain decay time. In addition, the emission of the scintillation light is a statistical process from many atoms which is completely insensitive to the longitudinal bunch structure and does not produce coherence effects. Gating the camera after the passage of the electron bunch should eliminate any influence of the coherent OTR (COTR). First experiments using this method have been performed successfully at the Free-Electron Laser in Hamburg (FLASH) as a proof-of-principle. In this paper, we study the applicability of scintillation screens for high-energy electron beams under operation conditions for which COTR is emitted. Experimental results together with simulations are presented and discussed in view of COTR suppression and spatial resolution.

INTRODUCTION

Transverse electron beam diagnosis based on OTR screens may be hampered by coherence effects in the visible regime due to microbunching instability in longitudinally compressed high-brightness electron beams [1, 2]. Observation of coherent OTR has been reported by several facilities [3, 4] and an example from FLASH is shown in Fig. 1. Possible concepts for suppressing coherence effects include, for instance, reducing the spectral COTR contribution by inserting band pass filters [6], using laser heaters to damp microbunching instability [7] or imaging the electron beam with scintillation screens.

The emission of the scintillation light is a statistical process from many atoms which is completely insensitive to the longitudinal bunch structure or the microbunching, and does not produce coherence effects. However, there is still OTR generated at the boundary of vacuum and scintillation screen. This undesired OTR from the scintillation screen surface can be separated from the scintillation light either spatially by suitable orientations of scintillation screen and camera, or temporally by delayed recording of images. Since the scintillation light has a certain decay time whereas OTR is emitted in an instantaneous process, gating the camera after the passage of the electron bunch should avoid the detection of OTR and therefore completely suppress COTR. In this paper we report the first successful experiments carried out at FLASH using this method of temporal separation, and study the applicability of scintillation screens for transverse beam diagnosis of high-energy electron beams in view of spatial resolution.

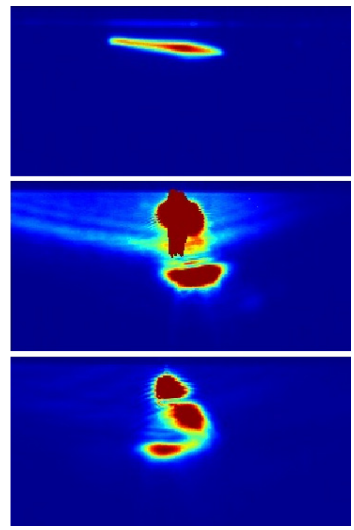

Figure 1: Top: Beam image without COTR (LuAG screen). Middle and bottom: Strong COTR effects lead to saturation in the beam images (OTR screen with shortpass and longpass filters). For more details see Ref. [5].

EXPERIMENTAL SETUP

The experiments were performed at the diagnostics section SMATCH upstream of the SASE undulators at FLASH. Light emitted from different imaging screens, mounted at a movable off-axis screen holder at 45° to the incoming beam, can be detected at 90° w.r.t. the incoming beam by a camera system consisting of a fast gated CCD camera (Dicam Pro, 1280 x 1024 pixels with 6.7 x 6.7 μm^2 pixel size) equipped with a macro lens (f = 150 mm) and a teleconverter (x 1.4). Figure 2 shows the top view of the SMATCH layout (right) and a picture of the screen holder with the emission directions indicated by arrows (left). In our experiment we used the OTR screen (Al coated silicon)

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and LuAG screen ($Lu_3Al_5O_{12}$:Ce, thickness of 100 μm) on the left. The screens on the right are used for THz spectroscopy. During machine operation one bunch out of the bunch train is kicked onto the screen by a fast kicker magnet upstream of the screen holder and the projected transverse beam profile is imaged. The resolution of the imaging system, estimated with a USAF1951 test target, amounted to about 100 μm and the magnification was determined to be 7:1.

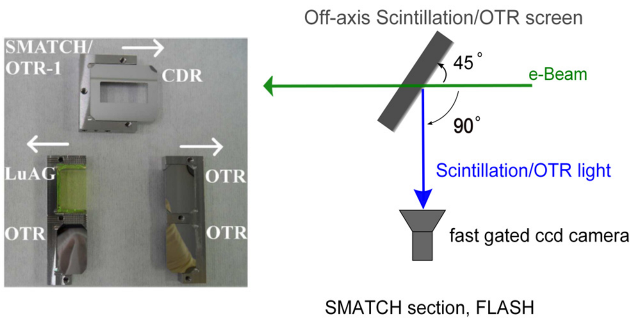
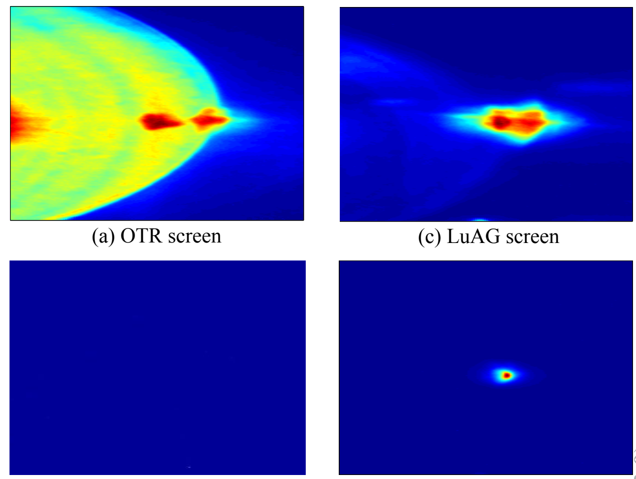


Figure 2: Left: Screen holder with imaging screens at diagnostics section SMATCH; emission directions indicated by arrows [5]. Right: Top view of the layout of the experimental setup.

EXPERIMENTAL RESULTS

The measurements were performed at a beam energy of 700 MeV and bunch charge of 0.5 nC. In order to see COTR effects the electron bunches were compressed.

Figure 3(a) shows a beam image measured with the OTR screen and a camera exposure time of 100 ns. There appears to be two undefined saturated structures in the middle part of the image due to strong COTR. The large half circle in yellow color code can be attributed to synchrotron radiation which is reflected on the surface of the OTR screen. Even with the camera gain adjusted to the minimum value, the image was still in saturation, rendering any diagnosis impossible. Then the camera gate was delayed until the OTR signal disappears. Since the emission of OTR is an instantaneous process, vanishing of OTR image was expected after the passage of the bunch, which means a camera delay time of under 1 ns. However, due to the trigger-jitter, the gate had to be delayed by at least 100 ns to completely block the OTR signal (Fig. 3(b)). Both measurements were repeated with the LuAG screen under the same conditions as for the OTR screen. The image shown in Fig. 3(c) was taken with the LuAG screen and without camera delay. The origin of the light signal is both COTR, generated at the boundary of screen and vacuum, and scintillation light, exited by the electron bunch. Most part of synchrotron radiation has now passed through the scintillator crystal, thus leaving only very low intensity in the background. Still, the camera image is saturated by strong COTR and gives no quantitative information about the transverse beam profile. Finally, the camera gate was delayed again by 100 ns and the image is shown in Fig. 3(d). According to Fig. 3(b), COTR is excluded after this delay time and only scintillation light contributes to the signal. Now a quantitative analysis of the beam spot becomes possible, and the measured horizontal and vertical beam sizes are 226 μm and 496 μm, respectively. Unfortunately, due to the lack of a reference measurement of the beam profile, the accuracy of this measurement cannot be determined.



(a) OTR screen (c) LuAG screen

(b) OTR screen, +100ns delay (d) LuAG screen, +100ns delay

Figure 3: Camera images of the beam with (a) OTR screen, (b) OTR screen with 100 ns camera delay, (c) LuAG screen, (d) LuAG screen with 100 ns camera delay.

RESOLUTION STUDIES

Simulations with the ray-tracing program ZEMAX© [8] revealed that the relative angles (i) between incoming beam and camera, and (ii) between incoming beam and screen have a large influence on the spatial resolution of transverse beam sizes measured with scintillation screens. The horizontal beam sizes of simulated images from BGO ($Bi_4(GeO_4)_3$, blue line) and LuAG screens (red line) are plotted in Fig. 4 as a function of screen tilt θ (angle between screen normal and beam). The green line indicates the reference beam size. Each curve corresponds to an observation geometry with a camera orientation of 22.5°, 45° or 90° w.r.t. the incoming beam. There exists an optimum setting for the screen tilt in each observation geometry and, surprisingly, placing the camera normal to the beam (typical configuration for beam size measurements), shows the worst resolution among the three geometries. This behaviour has been confirmed in test experiments with a BGO screen performed at the Mainz Microtron (MAMI), Mainz. Two images from that experiment are included in Fig. 4 for the corresponding simulations. The beam image is strongly enlarged when the screen tilt is changed from 15° to 45°, indicating the worsening resolution.

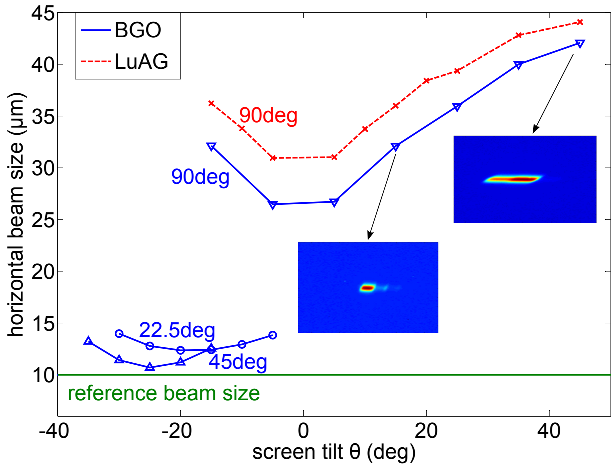


Figure 4: Horizontal beam size of simulated images from BGO (blue) and LuAG (red) screens. The angles between camera and incoming beam are 22.5°, 45° and 90°, respectively. Two images from test experiments are included.

Further experiments have been performed at MAMI with a well-focused uncompressed CW beam using LYSO screens ($Lu_{2-x}Y_xSiO_5$:Ce, thicknesses of 300 μm and 500 μm), which are assumed to have better resolution according to Ref. [9]. The camera system was orientated at 22.5° w.r.t the incoming beam (Fig. 5 (top)). The measured horizontal (lower left) and vertical (lower right) beam sizes as a function of screen tilt are plotted in Fig. 5 (bottom) in comparison with simulations. The measurement with the OTR screen is included as reference since there is no coherence effects observed at MAMI. The general behaviour of the measured results is in good agreement with the simulations. The thicker screen shows a worse resolution in both planes. Since the screen is rotated in the horizontal plane, the horizontal beam size is largely influenced by the screen tilt, whereas the vertical one is relatively insensitive to it. For beams with larger transverse size the influence of screen tilt is assumed to become less critical. It is necessary to emphasize that the optimum resolution is achieved when the screen is rotated away from the camera, which has also been observed in Ref. [9]. A possible explanation for the deviation between the measurement results and the simulations shown here could be the fact that the beam had a tilted elliptical spot size which complexes the simulations.

CONCLUSION

The first experiments using a scintillation screen in combination with a fast gated CCD camera to suppress COTR have been performed successfully at FLASH as a proof-of-principle. With studies at MAMI, the applicability of scintillation screen for high-brightness electron beam diagnostics has been investigated. Good spatial resolution of scintillation screen is achievable in certain observation geometries.

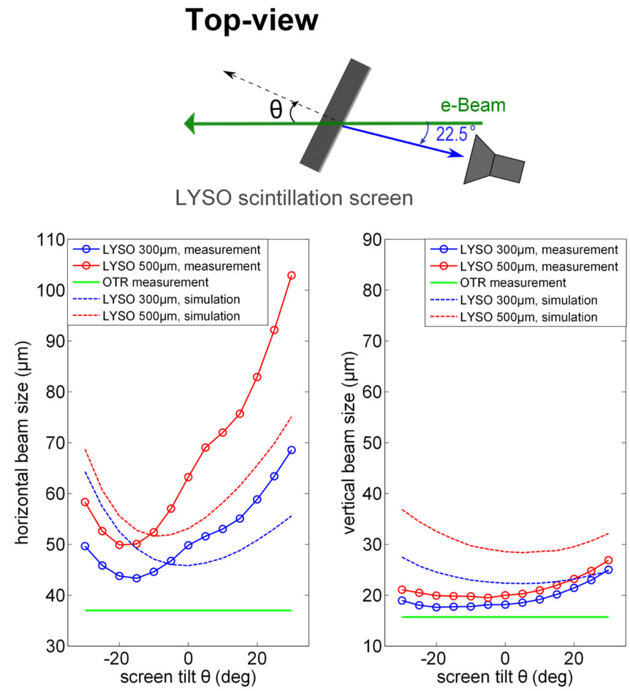


Figure 5: Top: Layout of the experimental setup for measurements at MAMI. Bottom: the measured horizontal (lower left) and vertical (lower right) beam sizes in comparison with simulations.

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