TRANSVERSE PROFILE MONITORS FOR SwissFEL

Rasmus Ischebeck, Eduard Prat, Volker Schlott, Vincent Thominet, PSI, Villigen, Switzerland
Minjie Yan, DESY, Hamburg, Germany
Patrick Krejcik, Henrik Loos, SLAC, Menlo Park, CA, USA

Abstract

We have developed a beam profile monitor that allows us to measure two-dimensional electron beam profiles for highly compressed electron bunches. Such bunches have plagued profile measurements in optical transition radiation monitors in the past, because coherent radiation entering the optical system has invalidated the images and even destroyed cameras. The present design makes use of a scintillating crystal, and directs coherent transition radiation away from the optical axis by careful choice of the angle. When observing Snell's law of refraction as well as the Scheimpflug imaging condition, a resolution better than the thickness of the scintillator can be achieved. We will present here measurements performed at the SwissFEL Injector Test Facility and at the Linac Coherent Light Source. The high resolution and excellent sensitivity of this monitor make it ideal for installation in SwissFEL.

REQUIREMENTS ON TRANSVERSE PROFILE MONITORS FOR FREE ELECTRON LASERS

The slice emittance of the electron beam is among the most important parameters when designing a free electron laser, because it has a direct influence on the gain length. Second-generation X-ray FELs such as SACLA [1] or SwissFEL [2] achieve a much more compact footprint by basing their design on a lower energy than what has been implemented in first-generation FELs. This scheme requires a shorter undulator period, possible with in-vacuum undulators, as well as a smaller normalized emittance. The generation of these beams, as well as the diagnostics for the emittance are thus of primary interest. Slice emittance measurements are based on a transverse deflecting radiofrequency cavity, a quadrupole magnet lattice to control the phase advance, and a two-dimensional transverse profile monitor. Measurements of projected emittance can be performed without the deflector, and using a one-dimensional profile measurement, but sources of projected emittance growth may not need to affect the slice emittance, which is central to the FEL process in the undulators.

Developments in photocathode as well as thermionic electron guns have resulted in the generation of smaller and smaller emittances, which result in progressively smaller beam sizes, putting ever tighter requirements on the transverse profile monitors. In addition to increased requirements on resolution, an effect has occurred in recent years, which has hampered transverse profile measurements using optical transition radiation: highly compressed electron bunches have a pronounced longitudinal structure at sub-micrometer length scales, resulting in the coherent emission of optical transition radiation [3–7]. This coherent OTR (COTR) is several orders of magnitude brighter than the incoherent light that is proportional to the particle density.

SwissFEL will use wire scanners [8], as well as two-dimensional profile monitors that image scintillators inserted into the beam. Profile measurements with wire scanners are not affected by coherent emission effects, because the scattering process is based on individual collisions of the electrons with particles in the wire. Similarly, the scintillation process in materials such as cesium doped yttrium aluminum garnet (Ce:YAG) originates from individual excitations of the scintillator by the primary electrons. One has to be careful, however, as coherent transition radiation generated on the scintillator surface, or in-vacuum mirrors, might affect the measurement. This can happen in one of two ways: either it enters the imaging system directly, or it generates radiation with a sufficient photon energy to excite the scintillator.

The first effect can be avoided by delaying the acquisition in the detector until the prompt transition radiation has disappeared. This requires an effective shutter that opens on a nanosecond scale to catch the tail of the scintillation light. Such shutters are implemented by using microchannel plates, a method that increases the complexity of the camera significantly, leads to more frequent service intervals, and most importantly, leads to a loss in image quality through smearing of the image, as well as a non-uniform response. Another method consists of choosing the observation geometry such that the COTR is directed away from the camera. Care has to be taken in this case to not artificially degrade the resolution by imaging radiation from a scintillator with finite thickness. Another issue to take into account is a possible saturation of the scintillator for high-density beams.

RESOLUTION OF PROFILE MEASUREMENTS

The SwissFEL design aims for a normalized slice emittance of 180 to 430 nm. This results in beam sizes down to about 30 µm FWHM at the location of the profile monitors. The resolution of the imaging system was verified according to the ISO 12233 standard. The limiting resolution was found to be better than 8 µm (Figure 1).

The resolution of the optical system is however not the only factor determining the resolution for beam profile measurements. One has to take into account also the broadening inside the scintillator [9], as well as the imaging of a scintillating crystal of finite thickness [10]. The SwissFEL profile monitor takes into account the Snell-Descartes law of refraction [11], as illustrated in Figure 2. The observation angle

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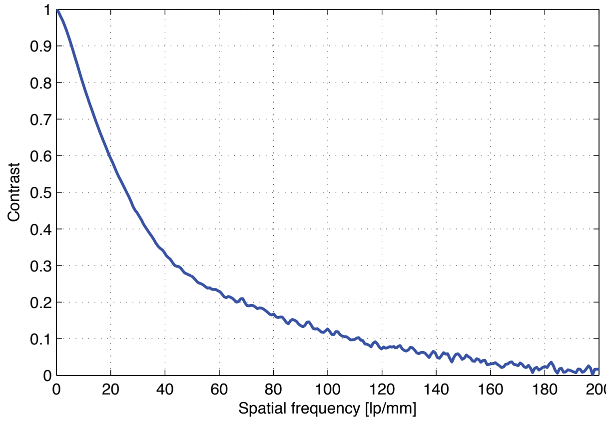

Figure 1: Measurement of the resolution of the imaging system used in the SwissFEL profile monitors.

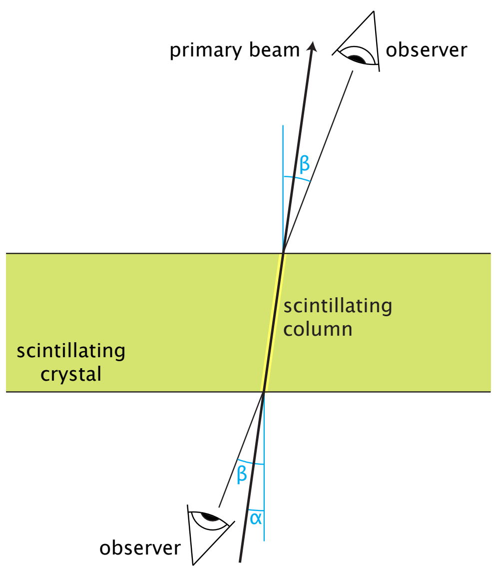

Figure 2: Imaging of the light-emitting column inside the scintillating crystal.

β is chosen such as:

$$\beta = -\arcsin(n \sin \alpha)$$

This minimizes the effect of the scintillator thickness on the image resolution.

By tilting the lens and/or the image detector (Figure 3), observing the Scheimpflug criterion [12], the entire scintillator can be imaged simultaneously. Considerations of lens aberrations and detector efficiency favor a small observation angle. The observation axis, on the same side to the normal of the crystal as the primary beam, is then relatively close to the beam, which may be difficult to set up if the primary beam is in vacuum and the detector in air. This difficulty has been overcome by using a flat in-vacuum mirror, shown in Figure 3 b.

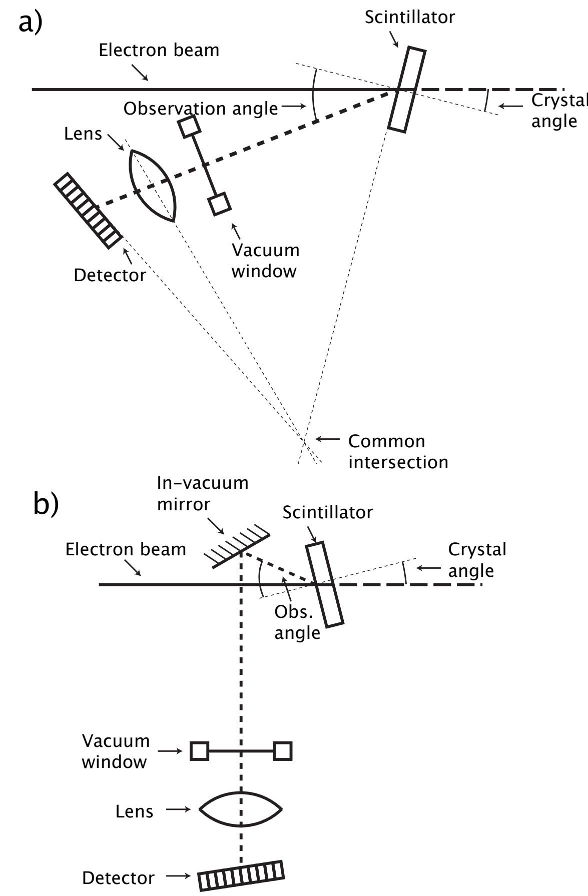

Figure 3: Imaging of scintillation radiation, observing the Snell-Descartes law of refraction as well as the Scheimpflug imaging condition.

DESIGN OF TRANSVERSE PROFILE MONITORS FOR SWISSFEL

We have completed the design of transverse profile monitors for SwissFEL. These monitors use a cerium doped yttrium aluminum garnet (Ce:YAG) scintillator, which is polishedon both sides. To avoid charge-up, the YAG is coated with indium tin oxide (ITO). The scintillator has a diameter of 20 mm, and two different observation geometries are implemented, to balance resolution with field-of-view.

For those monitors requiring high resolution, the scintillating crystal is positioned at an angle of 8.1° to the primary beam, and the in-vacuum mirror is placed such that the normal of the crystal has an angle of 15° to the optical axis of the camera. The screens are imaged by an $f = 200$ mm macro lens[1] to a CCD[2] or CMOS detector[3]. The magnification of the imaging system is 1 : 1.22, resulting in an effective pixel size on the scintillator of 7.9 µm. To fulfill the Scheimpflug imaging condition, the normal of the CMOS

[1] Nikon, Tokyo, Japan
[2] Basler AG, Ahrensburg, Germany
[3] PCO AG, Kelheim, Germany

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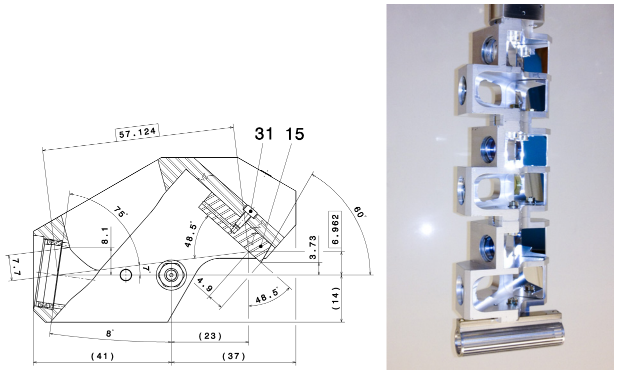

Figure 4: Screen holder for scintillating crystals. Left: technical drawing, including the scintillator to the left and the in-vacuum mirror to the top right. Right: photograph of the in-vacuum assembly of the first prototype, including two scintillators, two OTR screens and two alignment and calibration targets. At the bottom, an RF shield continues the beam pipe when the screen is not in use.

detector is tilted by 14° to the optical axis. At this angle, the microlens array on the chip can be used with only minor loss in efficiency. The field of view is horizontally constrained by the in-vacuum mirror[4] to ±3 mm.

A larger field of view is implemented by choosing an angle between the beam axis and the normal of the scintillator of 14.6°, and a corresponding observation angle of 30°. In this geometry, the in-vacuum mirror can be mounted at a distance of 8 mm to the beam axis, allowing to cover a field of view of 16 mm diameter.

The two monitors differ only in the screen holder, and in the placement of the lens and camera. A third model has been designed for use in the laser heater of SwissFEL, where light of a wavelength of 1040 nm is imaged with a hyperspectral lens[5] onto an IR-optimized CMOS detector[6].

The screens are mounted to an aluminum holder, shown in Figure 4. They can be positioned into the beam by means of a UHV translation stage. For the first prototype, installed in the SwissFEL Injector Test Facility, different scintillators (Ce:YAG[7], boron doped diamond[8], CRY019[9], and Cromox[10]) were compared to optical transition radiation generated on a 5 µm thick silicon wafer[11]. Out of these scintillators, the best resolution was achieved with Ce:YAG. The measured beam sizes were found to be comparable to the OTR measurements.

Two prototype monitors were built. One was installed in the SwissFEL Injector Test Facility, and one in the LCLS linac-to-undulator line [13]. Tests of the resolution were performed in the SwissFEL Injector Test Facility [14], and

[4] LT Ultra, Herdwangen-Schönach, Germany
[5] Jenoptik Optical Systems, LLC, Jupiter, FL, USA
[6] Basler AG, Ahrensburg, Germany
[7] Crytur Ltd., Turnov, Czech Republic
[8] Diamond Materials GmbH, Freiburg, Germany
[9] Crytur Ltd., Turnov, Czech Republic
[10] BCE Special Ceramics, Mannheim, Germany
[11] University Wafers, South Boston, MA, USA

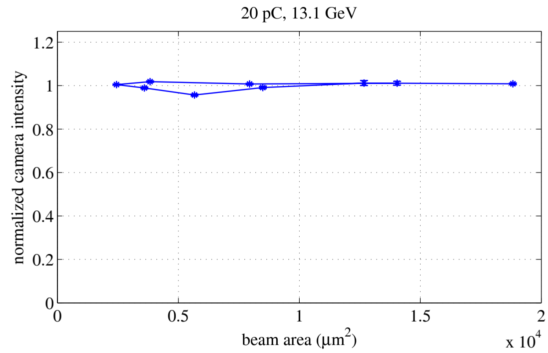

Figure 5: Total light emitted as a function of beam size.

saturation of the scintillators as well as the effectiveness of COTR suppression was studied at the Linac Coherent Light Source (LCLS).

SATURATION STUDIES

A possible disadvantage of scintillators as compared to optical transition radiation monitors is the saturation of the scintillator at high beam energies and densities. A measurement was performed by varying the transverse size of the electron beam while keeping the bunch charge constant. The measurement was performed with settings used for emittance measurements by a quadrupole scan. Scintillation light was collected by a camera, and integrated over a field of view large enough to cover the beam spot. The beam energy was 13.1 GeV, and a charge of 20 pC was used Saturation would show as a decrease of the total emitted light. As shown in Figure 5, the variation is less than 10% for the studied beam densities.

SUPPRESSION OF COHERENT OTR

The LCLS linac-to-undulator line is known for intense coherent OTR. Light intensities four orders of magnitude larger than the incoherently emitted light have been observed at this location, and focusing this light onto a CCD has resulted in a damaged sensor.

Since the scintillator is oriented at an angle of 8.1°, transition radiation from the front surface is emitted in a cone around an angle of 16.2°. The scintillation light is observed via the in-vacuum mirror, which is located on the other side of this emission cone.

The geometric suppression of coherent OTR has been tested by measuring the total emitted light as a function of compression. The charge for the present measurement was 20 pC, the beam energy 13.1 GeV. The compression was varied by changing the chirp of the acceleration, while keeping the beam energy constant. The resulting curve (blue line in Figure 6) shows no significant variation during this measurement.

The situation was somewhat different when the laser heater was switched off (red line in Figure 6). Here, an increase of 20% of the total emitted light was observed. It should be noted that this is not relevant to the nominal oper-

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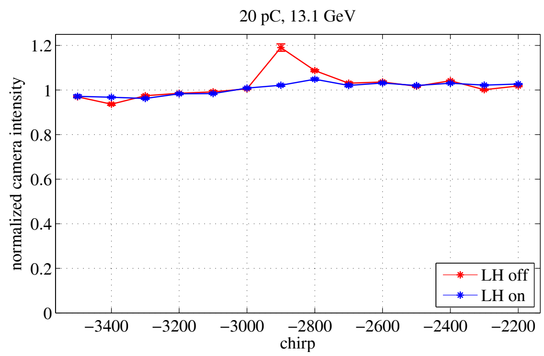

Figure 6: Total light emitted as a function of compression. Blue curve: nominal operation (laser heater on), red curve: laser heater off.

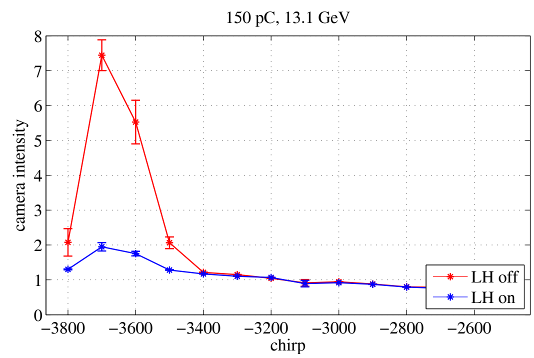

Figure 7: Total light emitted as a function of compression. Blue curve: nominal operation (laser heater on), red curve: laser heater off.

ation mode of LCLS, but it will be interesting nevertheless to explore what causes this increase. One theory is the emission of coherent radiation in the ultraviolet, which would cause the crystal to fluoresce. A comparison of different scintillating materials would allow further insight into this question.

For a bunch charge of 150 pC, the increase in light yield for full compression is more significant. Figure 7 shows a measurement with laser heater on (blue curve) and laser heater off (red curve). The light yield increases by almost an order of magnitude in the latter case.

CONCLUSION AND OUTLOOK

We have designed a transverse profile monitor for SwissFEL, which images light from a fluorescent crystal onto a CCD / CMOS detector. The resolution, saturation and COTR suppression of this monitor have been tested at the SwissFEL Injector Test Facility and at the LCLS linac-to-undulator line. Based on the results, we are confident that we can use this monitor to measure slice emittance at SwissFEL. Nonetheless, we will install wire scanners along the SwissFEL linac, as additional monitors to measure the projected emittance.

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