An X-ray image intensifier for microsecond time-resolved experiments

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ABSTRACT: Persistence of an X-ray image intensifier with a YAG (P46, Y₃Al₅O₁₂:Ce³⁺) phosphor in the output window was examined using X-ray pulses from a storage ring and a high-speed CMOS camera. Because of the fast decay of the YAG fluorescence (60 ns), persistence of CsI:Na⁺ in the input window dominates the decay of intensity of the image intensifier. As reported before, persistence of CsI:Na⁺ had two major components when fitted with two exponential functions, a fast one around 600 ns and a slow one about 7 μs. In addition, it was found that a slower component, which is small but takes tens of microseconds to decay, also exists. Thus, this detector should be used with caution at a time resolution higher than about 50 μs when high accuracy of measurement is required.

KEYWORDS: Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators); X-ray diffraction detectors; X-ray detectors
1 Introduction

An X-ray image intensifier is an area detector widely used for medical diagnosis. With its aluminium input window replaced with beryllium, it has been used as an X-ray detector for diffraction experiments at synchrotron radiation facilities [1–3]. In addition to its high sensitivity, one important advantage of an image intensifier is its flexibility. As it can be coupled to any camera, advent of imaging technologies has been helping it to survive even though use in medical diagnosis, its largest application, is declining. To the best of authors’ knowledge, it is the area detector with the highest time resolution (in a microsecond range) that is currently used in experiments at synchrotron radiation facilities. Although photon counting pixel array detectors with fast readout, such as PILATUS3 (DECTRIS, Baden, Switzerland), are available now, the frame rate is still limited to around 1,000 frames per second.

At the SPring-8 third-generation synchrotron radiation facility, X-ray image intensifiers have been modified for experiments at submillisecond time resolution. One important modification is changing the phosphor in the output window from GADOX (P43, Gd$_2$O$_2$S:Tb$^+$) to YAG (P46, Y$_3$Al$_5$O$_{12}$:Ce$^{3+}$) to reduce persistence: the fluorescence decay time of GADOX is 1–2 ms while that of YAG is 60 ns when the measured intensity is fitted with a single exponential function [4, 5]. This modified model has been used in several time-resolved X-ray diffraction experiments at SPring-8 [6–11]. In recent experiments, the X-ray image intensifier is coupled to a fast-framing CMOS camera such as those from Photron that can record up to 1,550,000 frames per second [11]. The X-ray image intensifier has phosphor in the input window (CsI:Na$^+$) as well as in the output window. Since the major decay component of CsI:Na$^+$ is known to be 550 ns [12], it is expected that the persistence of CsI:Na$^+$ dominates the decay of the image intensifier when YAG is used in the output window. However, since CsI:Na$^+$ in the image intensifier is a needle-shaped crystal sandwiched between beryllium and photocathode, its persistence may be affected by this structure. Also, most of the reported values of the persistence so far have been acquired using an electron beam or high energy $\gamma$-rays. Thus, the precise nature of the persistence of the image intensifier as a whole is unknown and now a concern in experiments at the time resolution of microseconds.

It used to be difficult to measure persistence of an X-ray image intensifier with low-energy X-rays because the signal of a single photon is too small to detect and there was not a suitable
monochromatic pulsed X-ray source that was readily available. Recently, we found a technique to measure persistence of a detector with synchrotron radiation. In a previous study, we measured the decay of scintillation from YAG induced by X-rays using a high-framing CMOS camera and found it to be 60 ns [5]. In this report, intensity decay of the X-ray image intensifier as a whole was studied with the same method.

2 Methods

An X-ray image intensifier with a beryllium window (V5445P, Hamamatsu Photonics, Hamamatsu, Japan) [1], was used (figure 1). The input window is 150 mm in diameter and needle-shaped 150 µm-thick crystals of CsI:Na$^+$ was directly grown on its back. A bialkali (RbCsSb) photocathode was evaporated onto CsI:Na$^+$. Electrons from the photocathode are accelerated by the electric field of 25 kV and hit a phosphor (YAG:Ce$^{3+}$) in the output window (non-browning glass with a diameter of 13 mm). The image intensifier was coupled to a high-speed CMOS camera (SA5, Photron, Tokyo, Japan) with a relay lens system. This camera has 1024×1024 pixels and a 12-bit analog-to-digital converter. The pixel size is 20 µm × 20 µm. A lens with $f = 50$ mm was attached to the image intensifier while one with $f = 85$ mm was used with the camera. Thus, the reduction ratio of the image on the CMOS sensor was about 6.8.

The experiment was made at the BL40XU beamline in SPring-8 [13] with a peak X-ray energy of 12.4 keV. The camera was operated at 1,302,000 frames per second which gives 768 ns time resolution. Between successive frames, there is a dead time of 210 ns [5]. A subarray of 64 × 8 was used. In the previous study, the direct X-ray beam from the undulator radiation was used [5]. However, since the X-ray image intensifier has much higher sensitivity than the plain phosphor-lens coupling, intensity of X-ray scattering from silica particles with an average diameter of 100 nm (Seahoster KE-P10, Nippon Shokubai Co. Ltd, Osaka, Japan) was measured (figure 2). Silica particles were chosen because they scatter strongly and are resistant to radiation. To achieve high accuracy and a large dynamic range in the measurement, intensity in the entire image was integrated. The background due to the offset of the analog-to-digital converter in the camera was measured in the absence of X-rays and subtracted from each image. Care was taken by choosing an appropriate area of scattering so that any pixel in the image does not saturate at the peak intensity.
Figure 2. Image of the scatter from silica particles recorded by the image intensifier and CMOS camera. The image size is 64 × 8 pixels.

Figure 3. Electron filling pattern in the 2011A D-operation mode of SPring-8. A train of 684.3 ns duration contains 85 mA of electrons, while each of the five separated single bunches contains 3 mA.

To realize short X-ray pulses, operation of the SPring-8 storage ring with an asymmetric filling of electrons was utilized [5]. In this filling pattern, 85% of electrons is in 1/7 of the orbit (684.3 ns) while the rest is in five equally separated bunches (figure 3). To avoid radiation damage on the image intensifier, a rotating-slit X-ray shutter with an opening time of 45.1 µs was used [14]. The beam size at the shutter was about 0.25 mm in width and 0.10 mm in height. Since the circulation time of electrons in SPring-8 is 4.8 µs, there were about 10 repeated intensity changes within one opening. The circulation of the electrons in the storage ring and the opening of the X-ray shutter were not in synchrony.

3 Results

Figure 4 shows a typical result of the intensity measurement (blue curve). The peak intensity corresponds to the 684.3-nsec continuous zone of electrons in the storage ring. The variation in peak heights is due to different sampling of the zone by the 768-ns frames of the camera. The peaks are separated by 4.8 µs that is the circulation time of the SPring-8 storage ring. Between the peaks, the intensity decays to a level approximately 20% of the peak height. Five isolated bunches are not resolved. Compared to the similar plot in the previous study on the persistence of YAG scintillator alone [5], the level of intensity between peaks is much higher, showing that the persistence of the CsI:Na⁺ phosphor (including the photocathode) dominates the intensity decay. The level between peaks rises gradually after repeated pulses but seems to settle to a constant level. The integrated intensity decays to zero over a time range of 50 µs after the shutter is closed.

To analyze the decay kinetics, a numerical simulation was performed on the assumption that the intensity decay of fluorescence of CsI:Na⁺ is composed of two exponentially decreasing components. This assumption was made to analyze the data following a conventional method and there
Figure 4. Integrated intensity recorded by the X-ray image intensifier and CMOS camera at a time resolution of 768 ns (blue curve) compared with simulated intensity (red curve). Radiation from about ten circulations of electrons around the SPring-8 storage ring were recorded within one opening of a rotating X-ray shutter. (a) Data fitted with exponential decay components of \( t_1 = 550 \) ns and \( t_2 = 4000 \) ns [12]. (b) Data fitted with \( t_1 = 590 \) ns and \( t_2 = 7033 \) ns.

is no theoretical reason to expect that the decay can fitted perfectly with a sum of exponential functions. When the shutter is opening and closing, i.e. when an edge of the slit of the shutter is crossing the beam, the intensity rises or falls gradually. This was taken into account by assuming that the beam intensity increases or decreases linearly when the edge of the slit is crossing the beam. Since the slit height of 3.4 mm is much larger than the beam height of 0.1 mm, the entire beam can pass through the slit in the shutter. Figure 4(a) shows a comparison between the observed intensity (blue curve) and a results of simulation (red curve) with \( t_1 = 550 \) ns and \( t_2 = 4000 \) ns, with the amplitude of \( t_1 \) about 20 times larger than that of \( t_2 \), which are reported values [12]. The fit is generally reasonable but there is a discrepancy particularly after the shutter is closed. In figure 4(b), a modified Levenberg-Marquardt algorithm was used to fit the simulated intensity to the experimental data. The red line was obtained with time constants of \( t_1 = 590 \) ns and \( t_2 = 7033 \) ns with the amplitude of \( t_1 \) about 20 times larger than that of \( t_2 \). With a larger value of \( t_2 \), the fit after the closing of the shutter is better than in figure 4(a), but there is still a small but significant difference that cannot be accounted for. The observed intensity shows that there is another very minor component that persists for tens of microsecond.

4 Discussion

Since the decay time of YAG in the output window was estimated to be 60 ns when fitted with an exponential function [5], the persistence in the X-ray image intensifier is dominated by that of the CsI:Na⁺ phosphor in the input window. This is in contrast to the image intensifier with GADOX in which the persistence (about 1 ms) is determined by GADOX in the output window [4]. However, because CsI:Na⁺ has slower time decay components, it cannot be used at high time resolution that may be expected from the published time constants. The origin of the slower components is not clear. Presence of the second component has been reported previously but the third, very
weak component has not been known. It should be noted that there is no reason to assume that
the persistence is composed of a sum of exponentially decaying components because fluorescence
due to excitation of an inner shell electron is a complex process involving transition between many
energy levels. For example, it is known that P20 (ZnS:Ag\textsuperscript{+}) has a long-lasting persistence that
cannot be fitted with an exponential function [15, 16]. The data in figure 4 suggest that a long low
intensity may also exist in CsI:Na\textsuperscript{+} after a long excitation.

When this image intensifier is used in time-resolved experiments faster than about 50 µs, a
precise intensity measurement may be difficult because of the long persistence. However, in ex-
periments such as X-ray diffracting tracking [17–19] in which a diffraction peak is continuously
followed to measure its position and velocity, it may be used at a time resolution higher than 10 µs
depending on the required accuracy.

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