Development and Performance Test of Picosecond Pulse X-ray Excited Streak Camera System for Scintillator Characterization

Development and Performance Test of Picosecond Pulse X-ray Excited Streak Camera System for Scintillator Characterization

Takayuki Yanagida[1]*, Yutaka Fujimoto[1], Akira Yoshikawa[1], Yuui Yokota[1], Kei Kamada[1], Jan Pejchal[1,5], Varely Chani[1], Noriaki Kawaguchi[2], Kentaro Fukuda[2], Koro Uchiyama[3], Kuniyoshi Mori[3], Ken Kitano[4], and Martin Nikl[5]

[1]*Institute of Multidisciplinary Research for Advanced Materials, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan*
[2]*Tokuyama Corporation, Shibuya 3-chome, Shibuya, Tokyo 150-8383, Japan*
[3]*Hamamatsu Photonics Cooperation, 325-6 Sunayama-cho, Naka-ku, Hamamatsu 430-8587, Japan*
[4]*Vacuum and Optical Instruments, 2-18-18 Shimomaruko, Ota, Tokyo 146-0092, Japan*
[5]*Institute of Physics AS CR, Cukrovarnicka 10, Prague 6, 162-53, Czech Republic*

Received March 23, 2010; accepted April 13, 2010; published online May 14, 2010

To observe time and wavelength-resolved scintillation events, picosecond pulse X-ray excited streak camera system is developed. The wavelength range spreads from vacuum ultraviolet (VUV) to near infrared region (110–900 nm) and the instrumental response function is around 80 ps. This work describes the principle of the newly developed instrument and the first performance test using BaF_2 single crystal scintillator. Core valence luminescence of BaF_2 peaking around 190 and 220 nm is clearly detected by our system, and the decay time turned out to be of 0.7 ns. These results are consistent with literature and confirm that our system properly works.

DOI: 10.1143/APEX.3.056202

Scintillators have played a major role in ionizing radiation measurements in medical imaging, oil logging, astro/particle physics, security, and other non-destructive applications.[1)] Up to now, many scintillators have been developed and investigated. To evaluate the figure-of-merit of new material, properties like the decay time, emission wavelength, light yield, stopping power, and intrinsic radioactivity should be measured and discussed. To search for and develop new scintillators efficiently, namely the decay time kinetics must be measured and evaluated properly, as it contains important information about the energy migration processes.

To understand the scintillation decay kinetics one has to study the photoluminescence decay first, which enables to investigate the emission centers themselves by exciting them selectively with a proper excitation wavelength. Also the time-resolved emission spectra can be obtained which provide valuable information about the last stage of scintillation mechanism.[2)] However, the excitation energy is usually of a few to several eV, less than the material band-gap and the obtained decay kinetics does not include information about the energy migration processes in the host crystal which are of great importance in actual applications where the excitation photon/particle energies are in the keV–MeV range. In addition, emission caused by a transition between inner shells (e.g., core valence luminescence: CVL) cannot be excited by the photoluminescence measurements.

Classical method to study scintillation decay is based on time-correlated single photon counting (TCSPC) which uses the excitation by 511 keV γ-ray of ^{22}Na radioisotope[3,4)]. Positron emitting radio isotope (e.g., ^{22}Na) emits after electron–positron annihilation two γ-photons of 511 keV in the opposite directions. One γ-photon is detected by very fast scintillator coupled to photomultiplier tube (PMT) which generates the start trigger pulse. The other one excites the scintillator sample to be measured. Using a slit behind the sample, generated scintillation light is suitably attenuated to detect maximum one scintillation photon per an excitation event using a PMT again which generates a stop pulse. After many acquisitions and building the start-stop time histogram of this process, scintillation decay profile of the sample is build-up. The instrumental response function (timing resolution) of such a system is usually around 1 ns. Based on TCSPC, a modified method was reported. Instead of using a positron radio isotope, pulsed X-ray tube was used as an excitation source: such a measurement system can achieve the timing resolution of several tens of ps and allows the tiny or even powder samples examination.[5,6)] Under such X- or γ-ray excitation, actual scintillation decay kinetics can be obtained. Such a method has been developed by high energy physicists and is widely used. However, as it is mostly used in the spectrally-unresolved manner, it is difficult to identify each decay time constant and its origin with the center or a process in the overall scintillation mechanism.

To design new scintillating materials, detailed information about the emission mechanism under the ionizing radiation excitation is necessary. Therefore, we have developed a new measurement and evaluation set-up which enables us to obtain simultaneously information about both the decay kinetics and emission wavelength under picosecond pulsed X-ray tube excitation and using the streak camera-based detector. Our system has some unique points, namely broad wavelength range (110–900 nm), fast response (instrumental response function of about 80 ps), and X-ray excitation, the features which are all essential for a scintillator evaluation. The aim of the present work is to describe the principles and performance test of the system by using a well-known superfast scintillator, namely BaF_2.[7)] BaF_2 exhibits core valence luminescence within vacuum ultraviolet–ultraviolet (VUV–UV) wavelength region with subnanosecond decay time.[8)] It is the ideal sample to test our equipment VUV sensitivity and fast response in time.

The whole system is sketched in Fig. 1. It consists of two main parts. One is the streak camera with the in-front light diffraction element, and the other one is pulsed X-ray tube. The overall size of the system is around $120 \times 50 \times 50\,cm^3$ and the total weigtht about 100 kg. To detect VUV photons, the chamber and vacuum pump are included in the spectrometer. As the system is not so big, it can be transported to some facilities if accelerators or beams should be used as an excitation source.

Figure 2 shows a schematic drawing of the system. The root of the excitation is a laser diode (PLP10-063) made by Hamamatsu. It emits at 638 ± 20 nm, pulse width of 50 ps

*E-mail address: t_yanagi@tagen.tohoku.ac.jp

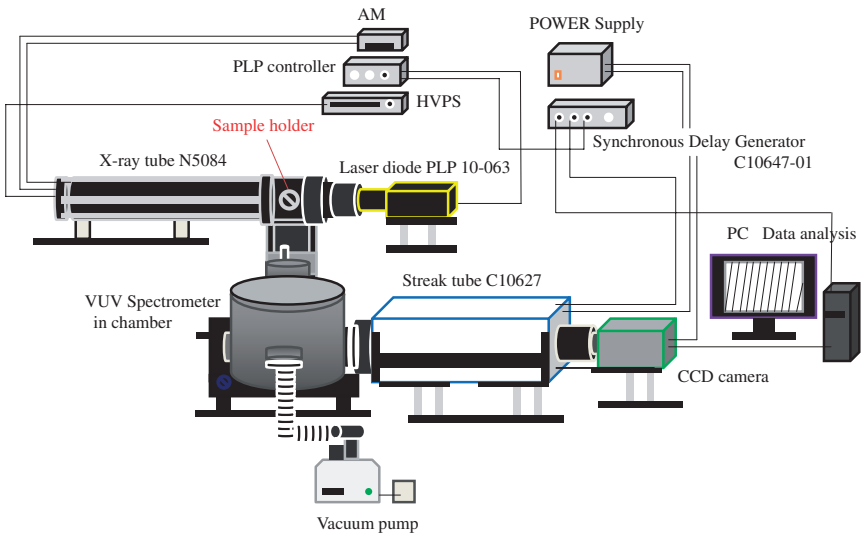

Fig. 1. Brief overview of the pulsed X-ray streak camera system. The size of the total system is compact as 120 × 50 × 50 cm^3 and 100 kg weight. PLP based X-ray tube generates pulsed X-ray which excites the sample and also PLP generates the trigger signal at the same time.

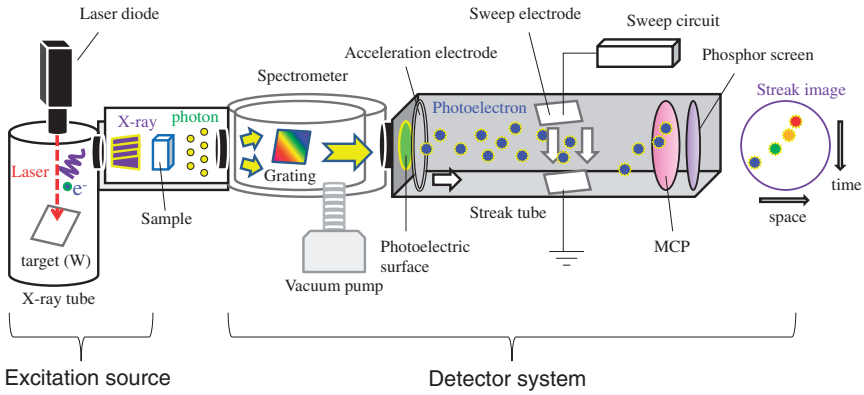

Fig. 2. Brief principle of the developed system. Laser diode hits the photocathode and generates electrons. Electrons are accelerated and bremsstrahlung X-rays are generated by the target. These X-rays excite the sample scintillator and through the grating, scintillation photons are detected by the streak system.

and with maximum 100 MHz repetition frequency. Emitted visible photons hit a multi-alkali photocathode of X-ray tube (N5084) made by Hamamatsu (e.g., ref. 4) and are converted to electrons. The photocathode quantum efficiency at 650 nm is around 3%. These electrons are accelerated by 30 kV of high voltage bias, and led to a tungsten target by a strong electric field. Then, bremsstrahlung X-rays are generated and led to the sample through 20 mmϕ × 0.5 mm thick Be window. The mean energy of X-ray quanta is ~20 keV and the endpoint energy of the bremsstrahlung spectrum is ~30 keV. At present, the X-ray pulse shows full width at half maximum (FWHM) of about 80 ps.

Under such X-ray pulse excitation the BaF_2 scintillator sample emits VUV scintillation photons. Normally, such a sample must be set in a vacuum chamber to avoid absorption of VUV emission by the oxygen.[2)] In this time, we use more simple approach, a typical way in the high energy physics: the sample is directly coupled with MgF_2 window of the spectrometer chamber with a VUV transmitting optical grease (Dupont Krytox 16350). In the spectrometer chamber, a holographic grating on a Seya–Namioka mount is mounted. After diffraction at the grating, scintillation photons are led to the streak camera (Hamamatsu C10627) which forms the

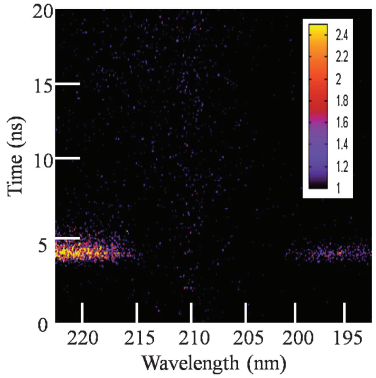

Fig. 3. Streak image of BaF_2. The horizontal axis shows the wavelength in units of nm and the vertical time in units of ns. In upper right region, the strength of the intensity in z-axis is represented.

streak image at the output charge coupled device (CCD) photodetector. The repetition frequency of the excitation source of the system is limited by the scanning speed of the streak camera. The maximum frequency is 14 MHz when the time range is set to be 0–1 ns, and the minimum one is 20 Hz when the time range is set to be 10 ms. The wavelength

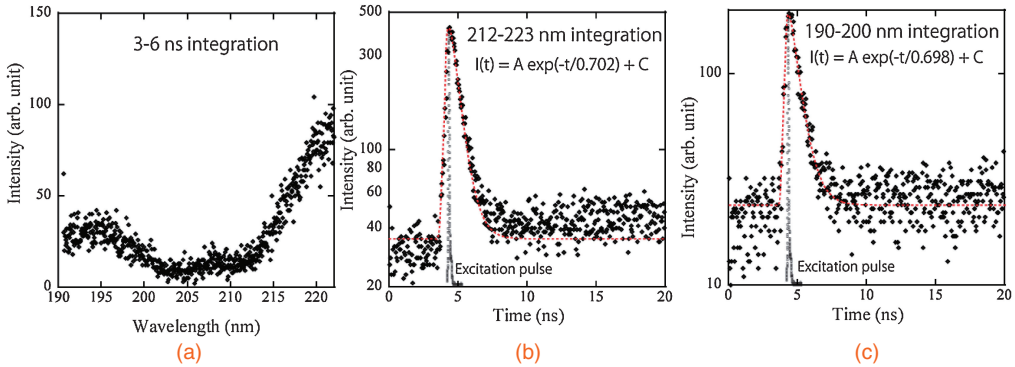

Fig. 4. Radio-luminescence spectra of BaF_2 (a), decay time profile accumulated from 213 to 223 nm (b), and decay time profile accumulated from 190 to 200 nm (c). Fitting results (dotted line) and instrumental response are also shown in (b) and (c), where A and C mean constant value.

range of the system is within 110 and 900 nm. The actually observed wavelength range is ~30 nm around the set value, which is given by the grating characteristics. In both timing and wavelength data, the resolution is limited by the CCD which has 640×480 channels. The detailed description of the detector part has been well explained already.[2] Compared with the F_2-laser based excitation apparatus,[2] our system becomes much more compact and easy-to-use because the sample manipulation occurs in air and excitation is provided by small X-ray tube ($\phi 8 \times 20$ cm).

Figure 3 shows the obtained streak image of BaF_2. The wavelength is set at 205 nm to include both core valence luminescence bands at once. The accumulation time of the present experiment is about 6 h. As shown in the figure, the core valence luminescence peaking around 190 and 220 nm is clearly observed. In the emission intensity profile, the 220 nm band is stronger than that of 190 nm one, which is consistent with the reported results.[7,8] In the decay time profile, luminescence decay within 3 to 6 ns is observed in both 220 and 190 nm bands. These fast emissions are attributed to the core valence luminescence of BaF_2 which has ~800 ps decay time constant.[7,8] Thus, from a visual image analysis, our new system is confirmed to work adequately. Additionally, this is the first experimental result of such a stand-alone fast X-ray pulse excited wavelength- and time-resolved spectroscopy performed at a scintillator material.

Figures 4(a)–4(c) represent projections along the wavelength and time axes. By signal accumulation within 3 to 6 ns, we obtain the radio-luminescence spectrum as shown in panel (a). The core valence luminescence bands peaking around 220 and 190 nm are clearly seen. In addition to the wavelength accuracy, the ratio of peak intensities (roughly 220 nm : 190 nm = 2 : 1) is also consistent with the reported results.[7,8] Then, panel (b) shows the decay time profile integrated from 213 to 223 nm, and panel (c) shows the same plot integrated from 190 to 200 nm, respectively. Fitted by a single exponential function, the main component of the decay time turned out to be 700 ± 100 ps in both profiles. In this figure, the instrumental response function which is very fast is also represented. This decay time constant is also consistent with the literature results.[7,8] Thus, it is confirmed that newly developed pulsed X-ray excited streak camera system works adequately.

Although the above described system is very powerful tool to investigate fast scintillation materials in a wide spectral range, there is still a room for technical improvement. The major problem is the power of the X-ray tube, because the repetition frequency of the pulse is principally limited by the sweeping time of the streak camera which is difficult to improve. If we can apply higher bias voltage (e.g., 35 kV), the number of emitted X-ray photons will increase, and the accumulation (exposure) time can be shortened accordingly. In order to achieve such an improvement, higher resistance for high voltage bias is needed for the X-ray tube. Such an attempt is now under consideration. The other possibility is to collect/guide X-rays towards the sample. In the present setup, X-ray photons are emitted to 4π space angle uniformly. If we apply X-ray mirrors or other reflectors similarly as in the X-ray astrophysics,[9] the number of X-rays which can reach the sample will increase. In addition to these improvements, we are now planning to use the α-ray excitation in the same system, because scintillation phenomena under charged particle excitation are also actively studied. As scintillators exhibit huge differences in their spectra positions, decay times and light yields[10] this system will be surely helpful for further study and understanding the scintillation phenomena.

Acknowledgments This work was partially supported by the Ministry of Health and Welfare Japan, a Grant-in-Aid for the development of medical instruments. This work was also partially supported by the Ministry of Education, Culture, Sports, Science and Technology Japan, a Grant-in-Aid for Young Scientists (A), No. 19686001 (AY), and a Grant-in-Aid for Young Scientists (B), No. 15686001 (TY). Partial support of the Yazaki Memorial Foundation for Science and Technology, Japan Science Society, the Sumitomo Foundation, and Iketani Science and Technology Foundation, are also gratefully acknowledged.

1) M. Nikl: Meas. Sci. Technol. **17** (2006) R37.
2) Y. Furukawa, M. Cadatal, K. Yamanoi, S. Takatori, M. Pham, E. Estacio, T. Nakazato, T. Shimizu, N. Sarukura, K. Kitano, K. Ando, K. Uchiyama, Y. Isobe, K. Fukuda, T. Suyama, T. Yanagida, A. Yoshikawa, and F. Saito: Jpn. J. Appl. Phys. **48** (2009) 096503.
3) L. M. Bollinger and G. E. Thomas: Rev. Sci. Instrum. **32** (1961) 1044.
4) H. Takahashi, T. Yanagida, D. Kasama, T. Ito, M. Kokubun, K. Makishima, T. Yanagitani, H. Yagi, T. Shigeta, and T. Ito: IEEE Trans. Nucl. Sci. **53** (2006) 2404.
5) W. W. Moses, S. E. Derenzo, M. J. Weber, S. C. Blankespoor, M. H. Ho, and A. C. West: Radiat. Meas. **24** (1995) 337.
6) S. E. Derenzo, M. J. Weber, W. W. Moses, and C. Dujardin: IEEE Trans. Nucl. Sci. **47** (2000) 860.
7) C. W. E. van Eijik: Nucl. Tracks Radiat. Meas. **21** (1993) 5.
8) S. Kubota, J. Ruan, M. Itoh, S. Hashimoto, and S. Sakuragi: Nucl. Instrum. Methods Phys. Res., Sect. A **289** (1990) 253.
9) H. Awaki, K. Heike, Y. Misao, Y. Tawara, Y. Ogasaka, H. Kunieda, H. Ohmori, W. Lin, S. Moriyasu, Y. Ueno, S. Morita, K. Katahira, C. Liu, H. Honda, and S. Shioya: Adv. Space Res. **34** (2004) 2678.
10) P. A. Rodnyi: *Physical Processes in Inorganic Scintillators* (CRC, New York, 1997) p. 15.