

# Temporal Response of Fast and Ultrafast Inorganic Scintillators

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**Abstract**—Ultrafast inorganic scintillators with excellent radiation hardness are required for future HEP experiments at the energy and intensity frontiers as well as GHz hard X-ray imaging for the proposed MaRIE project. In this paper, we present an investigation on temporal response of fast and ultrafast inorganic scintillators. Temporal response of BaF<sub>2</sub>:Y, BaF<sub>2</sub>, YAP:Yb, YAG:Yb, ZnO:Ga, Ga<sub>2</sub>O<sub>3</sub>, YAP:Ce, LYSO:Ce, LuYAP:Ce, LuAG:Ce, YSO:Ce and GAGG:Ce was measured by ultrafast MCP-PMTs using cosmic rays and 510 keV  $\gamma$ -rays from a Na-22 source at Caltech, and by 30 keV X-ray bunches of 27 and 50 ps length at the Advanced Photon Source facility of Argonne National Laboratory. Their application for future HEP experiments and GHz hard X-ray imaging is discussed.

**Index Terms**—Crystal, hard X-ray imaging, light output, scintillators, transmittance, ultrafast decay time

## I. INTRODUCTION

FAST and ultrafast inorganic scintillators with excellent radiation hardness are demanded by future HEP experiments at the energy and intensity frontiers, such as the HL-LHC [1] and Mu2e-II upgrade [2], and GHz hard X-ray imaging for the proposed MaRIE project [3]. At the Caltech HEP crystal lab we investigated optical and scintillation properties for a set of fast and ultrafast inorganic scintillators [4], including direct-gap semiconductor crystals, such as gallium-doped ZnO (ZnO:Ga), core-valence luminescence crystals, such as BaF<sub>2</sub>, and BaF<sub>2</sub>:Y, Yb<sup>3+</sup> activated crystals featured with fast decay time and thermal quenching, such as YAlO<sub>3</sub>:Yb (YAP:Yb) and Y<sub>3</sub>Al<sub>5</sub>O<sub>12</sub>:Yb (YAG:Yb), Ga<sub>2</sub>O<sub>3</sub> and Ce<sup>3+</sup> activated bright and fast scintillators, such as lutetium yttrium oxyorthosilicate (Lu<sub>2(1-x)</sub>Y<sub>2x</sub>SiO<sub>5</sub>:Ce or LYSO:Ce) and yttrium oxyorthosilicate (Y<sub>2</sub>SiO<sub>5</sub>:Ce or YSO:Ce), LuYAP:Ce, LuAG:Ce and GAGG:Ce etc. In this paper, we report their temporal response to pulsed 30 keV x-ray bunches of 27 and 50 ps measured by ultrafast MCP-PMTs at the 10-ID-B beam line of the Advanced Photon Source (APS) facility of Argonne National Laboratory (ANL).

## II. SAMPLES AND EXPERIMENTAL SETUP

Fig. 1 is a photo showing a dozen of inorganic scintillator samples. Fig. 2 shows a schematic of the measurement setup. The experiment was performed at the beamline 10-ID-B running in hybrid fill pattern [5]. A single bunch of 50 ps length

is isolated from 8 septuplet bunches by symmetrical 1.594  $\mu$ s gaps. The 8 groups of septuplet bunches, with a bunch length of 27 ps and a bunch spacing of 2.83 ns, has a periodicity of 68 ns and a gap of 51 ns between groups. The 27 and 50 ps bunch length has a negligible effect to the temporal response.

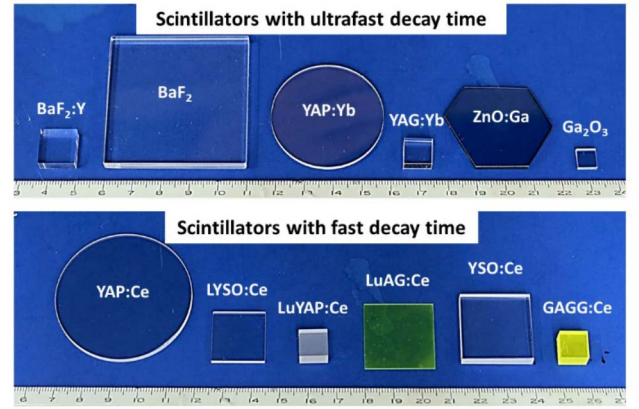


Fig. 1. A photo showing samples investigated in this work.

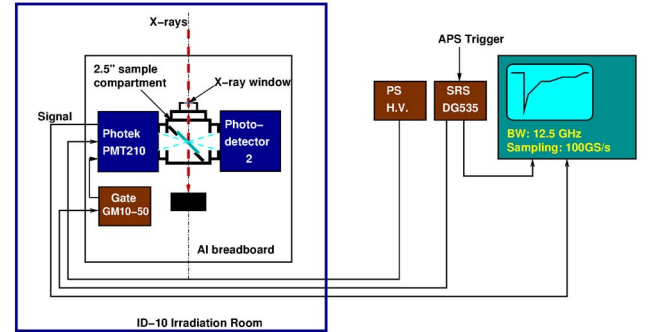


Fig. 2. A schematic showing the setup used in measurements.

Two Photek MCP-PMTs 110 and 210 with a rise time/FWHM of 65/110 ps and 95/170 ps respectively were used to measure the scintillation pulse. A gate unit GM10-50 was used to select measurement window and reduce the trigger rate. The output of the MCP-PMTs was recorded in a Tektronix DPO 71254C (12.5 GHz, 100 GS/s) scope through a 15 m SMA cable.

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### III. EXPERIMENTAL RESULTS

BaF<sub>2</sub>:Y and BaF<sub>2</sub> show the highest amplitude and fastest response to singlet, which is consistent with the calculated light output in the 1<sup>st</sup> ns. Fig. 3 shows temporal response of BaF<sub>2</sub>:Y (top) and BaF<sub>2</sub> (bottom). The consistent temporal response indicates that yttrium doping does not compromise ultrafast scintillation at 220 nm. Because of the 15 m cable, the measured rise, decay and FWHM width at APS are slightly longer than that measured with a  $\gamma$ -ray source at Caltech. Fig. 4 shows that both BaF<sub>2</sub>:Y and BaF<sub>2</sub> are able to distinguish the seven bunches in septuplet with a bunch spacing of 2.83 ns. BaF<sub>2</sub>, however, shows a saturation effect from the first to the eighth septuplet caused by pile-up of the slow scintillation component.

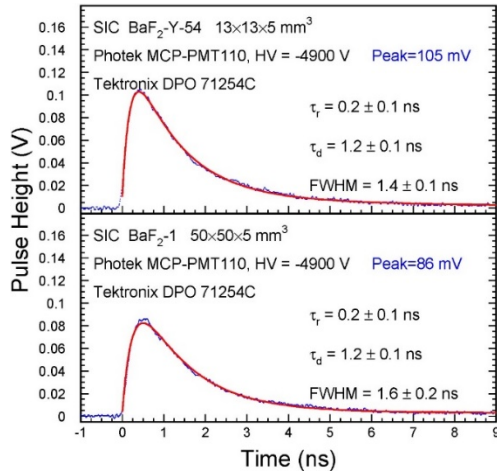


Fig. 3. Singlet bunch measured by BaF<sub>2</sub>:Y (top) and BaF<sub>2</sub> (bottom) coupled to the Photek MCP-PMT110.

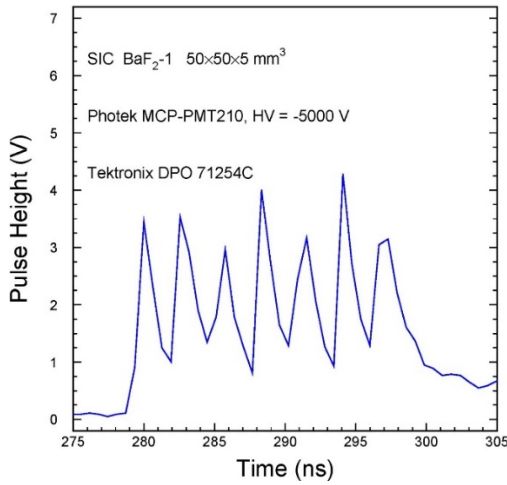


Fig. 4. Septuplet with 2.83 ns bunch spacing observed by BaF<sub>2</sub> coupled to the Photek MCP-PMT 210.

Table I is a summary of the temporal response for all crystals measured by the Photek MCP-PMT 210. Samples are ordered based on their FWHM values to the singlet bunch. Compared to BaF<sub>2</sub>, ZnO:Ga, YAP:Yb and YAG:Yb have a slower response, but with FWHM less than 3 ns. Conventional cerium doped fast inorganic scintillators, such as LYSO:Ce, LuAG:Ce and GAGG:Ce, however, are a way too slow to observe a clear septuplet structure with 2.83 ns bunch spacing. Replacing 15 m

cable with 1 m cable, BaF<sub>2</sub>:Y and BaF<sub>2</sub> show sub-ns FWHM pulse width, which is the shortest among all samples.

It is also interesting to note that cerium doped crystals are featured with a slow rise time, which may limit their timing resolution.

Table I Temporal Response of Fast Crystals Scintillators

| Crystal                        | Emission Peak (nm) | LO (p.e./MeV) | Rise Time (ns) | Decay Time (ns) | FWHM (ns) |
|--------------------------------|--------------------|---------------|----------------|-----------------|-----------|
| BaF <sub>2</sub> :Y            | 220                | 258           | 0.2            | 1.0             | 1.4       |
| BaF <sub>2</sub>               | 220                | 209           | 0.2            | 1.2             | 1.5       |
| YAP:Yb                         | 350                | 9.1*          | 0.4            | 1.1             | 1.7       |
| ZnO:Ga                         | 380                | 76*           | 0.4            | 1.8             | 2.3       |
| YAG:Yb                         | 350                | 28.4*         | 0.3            | 2.5             | 2.7       |
| Ga <sub>2</sub> O <sub>3</sub> | 380                | 259           | 0.2            | 5.3             | 7.8       |
| YAP:Ce                         | 370                | 1605          | 0.8            | 34              | 27        |
| LYSO:Ce                        | 420                | 4841          | 0.7            | 36              | 28        |
| LuYAP:Ce                       | 385                | 1178          | 1.1            | 36              | 29        |
| LuAG:Ce                        | 520                | 1531          | 0.6            | 50              | 40        |
| Ceramic                        |                    |               |                |                 |           |
| YSO:Ce                         | 420                | 3906          | 2.0            | 84              | 67        |
| GAGG:Ce                        | 540                | 3212          | 0.9            | 125             | 91        |

\* Excited by Alpha particles.

### IV. SUMMARY

Temporal response of a dozen fast and ultrafast inorganic scintillators was measured at the APS 10-ID-B test beam site by using 30 keV x-ray bunches with ps bunch length. BaF<sub>2</sub> shows the highest amplitude and fastest response. Septuplet structure with 2.83 ns spacing are clearly observed by both BaF<sub>2</sub>:Y and BaF<sub>2</sub> coupled to Photek MCP-PMT, indicating the feasibility of an ultrafast scintillator and photodetector-based front imager concept for the proposed MaRIE project. BaF<sub>2</sub>:Y shows no pile-up for multiple septuplets, demonstrating importance of slow component suppression. Other ultrafast inorganic scintillators, such as YAP:Yb, ZnO:Ga and YAG:Yb, show a wider pulse width than BaF<sub>2</sub>. Development of ultrafast inorganic scintillators will continue along these lines for future HEP experiments and GHz X-ray imaging.

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