Recent Progress of Inorganic Scintillators for Future HEP Calorimetry

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***Abstract*— Following the priority research directions for calorimetry documented in the DOE basic research needs for HEP instrumentation, the Caltech HEP Crystal Lab has been actively investigating novel inorganic scintillators along the following three directions. Fast and radiation hard inorganic scintillators to face the challenge of severe radiation environment expected by future HEP experiments at hadron colliders, such as the HL-LHC and a 10 TeV pCM collider, where radiation damage is induced by ionization dose, protons and neutrons. Ultrafast inorganic scintillators to face the challenge of unprecedented event rate expected by future HEP experiments searching for rare decays, such as Mu2e-II, and ultrafast time of flight (TOF) system at colliders. Cost-effective heavy inorganic scintillators for the homogeneous hadron calorimeter (HHCAL) concept to face the challenge of both electromagnetic and jet mass resolutions required by the proposed Higgs factory. We report recent progress in all these directions, such as LuAG:Ce ceramic fibers for the RADiCAL proposal, Lu_2O_3:Yb ceramics for TOF and ABS:Ce and DSB:Ce glass scintillators for HHCAL and the CalVision effort. The result of this investigation may also benefit nuclear physics experiments, GHz hard X-ray imaging, medical imaging and homeland security applications.**

Index Terms*— HEP calorimetry, fast and radiation hard scintillators, ultrafast scintillators, cost effective scintillators.

I. Introduction

Total absorption electromagnetic calorimeters (ECAL) made of inorganic crystals provide the best energy resolution and detection efficiency for photons and electrons, so are the choice for those HEP experiments requiring the ultimate energy resolution. Novel crystal detectors are being discovered in academic research and in industry, providing an important opportunity for future HEP calorimetry. Following the priority research directions for calorimetry in the DOE basic research needs for HEP instrumentation [1], we have been actively investigating novel inorganic scintillators along the following three directions: 1) fast and radiation hard inorganic scintillators to face the challenge of severe radiation environment expected by future HEP experiments at hadron colliders, such as the HL-LHC and a 10 TeV pCM collider, where radiation damage is induced by ionization dose, protons and neutrons, 2) ultrafast inorganic scintillators to face the challenge of unprecedented event rate expected by future HEP experiments searching for rare decays, such as Mu2e-II, and ultrafast TOF system at colliders, and 3) cost effective inorganic scintillators for the HHCAL concept to face the challenge of both electromagnetic and jet mass resolutions required by the proposed Higgs factory. In this paper, we report recent progress in all these directions, such as LuAG:Ce ceramic fibers for the RADiCAL concept [2], Lu_2O_3:Yb ceramics for TOF and ABS:Ce and DSB:Ce glass scintillators for the HHCAL and the CalVision concepts [3].

II. Samples and experiments

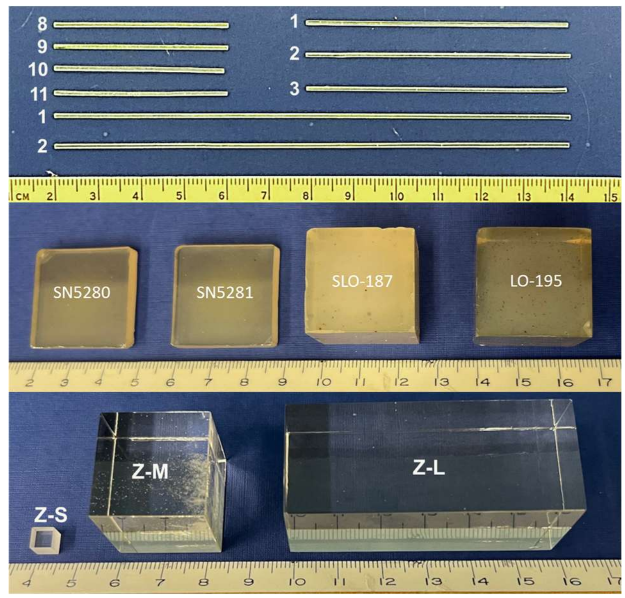

Fig. 1 *A photo showing novel inorganic scintillators investigated recently.*

Fig.1 shows some of the samples reported in this paper: Top: nine ϕ1 mm LuAG:Ce ceramic fibers produced by Shanghai Institute of Ceramics, including four 40 mm long, three 60 mm long and two 120 mm long. Middle: four Lu_2O_3:Yb ceramic samples produced by Radiation Monitoring Devices Inc., including two $27\times27\times5$ mm^3 (SN5280 and SN5281) and two 25 mm cubes (SLO-187 and LO-195). Bottom: three ABS scintillating glass samples provided by the Institute of High Energy Physics (IHEP), including a 5 mm cube (Z-S), a 24 mm cube (Z-M) and a $25\times25\times60$ mm^3 block (Z-L). We measured their photon-excited and X-ray-excited luminescence (PL and XEL), transmittance, pulse height spectra (PHS), γ-ray and α particle excited scintillation pulse profile, light output (LO) as a function of integration time, decay time (τ), longitudinal light response uniformity for long samples, and their degradation under γ-ray and proton radiation.

III. Results and discussion

One potential application of the LuAG:Ce fibers is the RADiCAL concept. Three $\phi1\times40$ mm^3 LuAG:Ce fibers, #10, #9 and #6, were irradiated by 800 MeV protons with fluence of 0.19, 3.0 and 18×10^{14} p/cm^2, respectively, in the proton irradiation experiment 9168 in the blue room of LANSCE. The

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left plot of Fig. 2 shows photoluminescence (PL) spectra of the sample #6 with 420 nm LED exciting at different positions before and after 18×10^{14} p/cm^2. The right plot of Fig. 2 shows the corresponding integrated PL intensity as a function of the excitation position. The average PL intensity decreases by 19%, 21% and 28% for the samples #10, #9, and #6, respectively, indicating excellent radiation hardness against protons up to 18×10^{14} p/cm^2, which is consistent with LuAG:Ce ceramics [4].

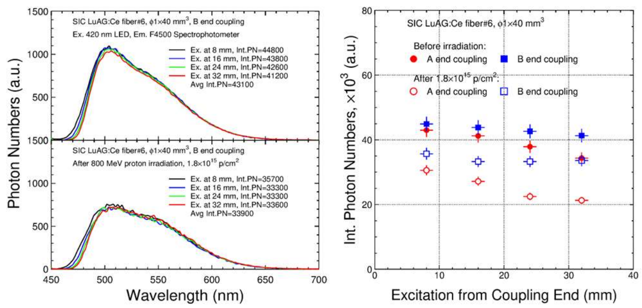

***Fig. 2** Left: PL spectra of the φ1×40 mm^3 LuAG:Ce cramic fiber #6 before (top) and after (bottom) 1.8×10^{15} p/cm^2 irradiation. Right: the integration of the PL strctra is shown as a function of excitation position (right).*

With high density (9.4 g/cm^3) and ultrafast decay (<1 ns) Lu_2O_3:Yb ceramics may find applications in future ultrafast TOF detectors and calorimeters. The left plot of Fig. 3 shows a pulse profile measured by a Photek MCP-PMT 240 with alpha particle excitation for a ϕ9×1 mm^3 Lu_2O_3:Yb ceramic sample, and the corresponding fit. The right plot of Fig. 3 shows consistent charge-transfer emission band at 300-400 nm for four Lu_2O_3:Yb ceramic samples and the peaks at longer than 400 nm presumably from rare earth elements in Lu_2O_3. The left plot of Fig. 4 shows PHS measured with Na-22 excitation, coincidence trigger and three integration gates for SN5280. The little change observed in the 511 keV photopeak between 45 ns, 200 ns and 1,000 ns integration gates confirms their ultrafast decay time.

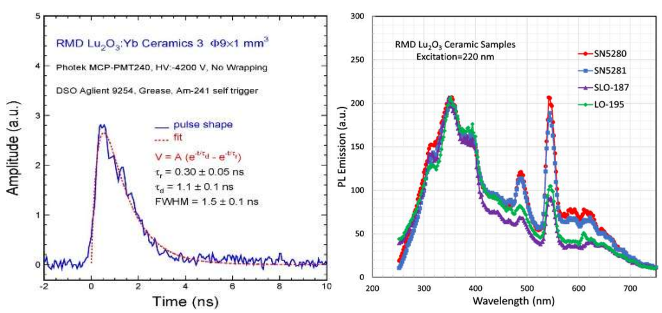

***Fig. 3** Left: Scintillation pulse profile of Lu_2O_3:Yb ceramic excited by α particle from Am-241. Right: PL spectra of four Lu_2O_3:Yb ceramic samples.*

With density of 6 g/cm^3 and an expected mass-production cost of less than \$1/cc, the ABS glass scintillator is promising for the HHCAL concept. The right plot of Fig. 4 shows the transmittance spectra and XEL emission for the 3 ABS samples (Z-S, Z-M and Z-L). Also listed in the figure are the numerical values of emission weighed longitudinal transmittance (EWLT) for different optical pathlength. Their pathlength dependence indicates that the optical quality of these glass samples needs to be improved. The left plot of Fig. 5 shows PHS for three ABS sample measured with 1 μs gate. The right plot of Fig. 5 shows the measured LO as a function of the integration time and the decay time of 1.2~1.4 μs extracted by exponential fits. The LO decreases significantly from Z-S to Z-L because of their poor optical quality.

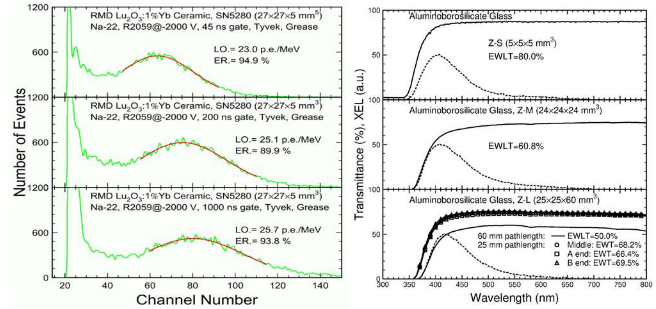

***Fig. 4** Left: PHS of the Lu_2O_3:Yb ceramic sample 5280 measured withdifferent integration time. Right: LO as a function of integration time for three ABS glass samples.*

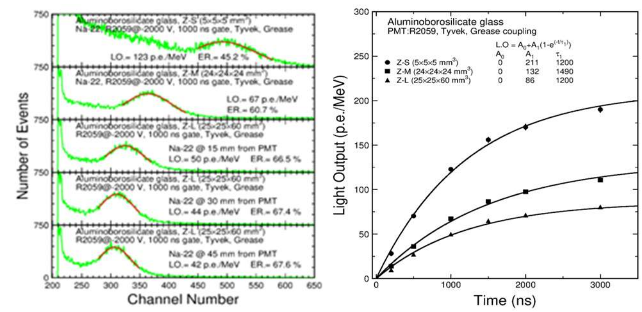

***Fig. 5** PHS (left) measured with 1 μs gate and LO as a function of integration time (right) are shown for three ABS glass samples.*

IV. Summary

The HL-LHC and FCC-hh require fast and radiation hard inorganic scintillator. The RADiCAL concept proposes an ultra-compact, fast timing and longitudinally segmented shashlik calorimeter with LuAG:Ce ceramics as wavelength shifter for LYSO:Ce crystals. Lu_2O_3:Yb ceramic scintillators are an ultrafast scintillator under development. The CalVision concept proposes a dual readout longitudinally segmented crystal ECAL combined with the IDEA HCAL promising excellent EM and hadronic resolutions for the proposed lepton Higgs factory. Novel cost-effective heavy scintillating glasses, such as ABS and DSB are under development for the homogeneous HCAL, which promises the best jet mass resolution by total absorption.

References

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