Development of LuAG:Ce Ceramic Fibers for the RADiCAL Detector Concept

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1. Introduction

An ultra-compact, radiation hard and fast-timing electromagnetic calorimeter (RADiCAL, Fig.1) concept is proposed for the HL-LHC and the proposed FCC-*hh*, where an absorbed dose up to 100 Mrad and a 1 MeV equivalent neutron fluence up to 3×10^{16} n_{eq}/cm^2 are expected in the endcap region. Fig. 1 shows a RADiCAL module where cerium doped lutetium-aluminum garnet ($Lu_3Al_5O_{12}$:Ce or LuAG:Ce) ceramic fibers are used as wavelength shifter (WLS) for thin LYSO:Ce crystal plates. Fig. 2 shows the LuAG:Ce excitation spectrum (magenta lines) matches well the radioluminescence spectrum of LYSO:Ce crystals (blue dots). LuAG:Ce ceramics are known to have a factor of two better radiation hardness than LYSO:Ce crystals against hadrons.

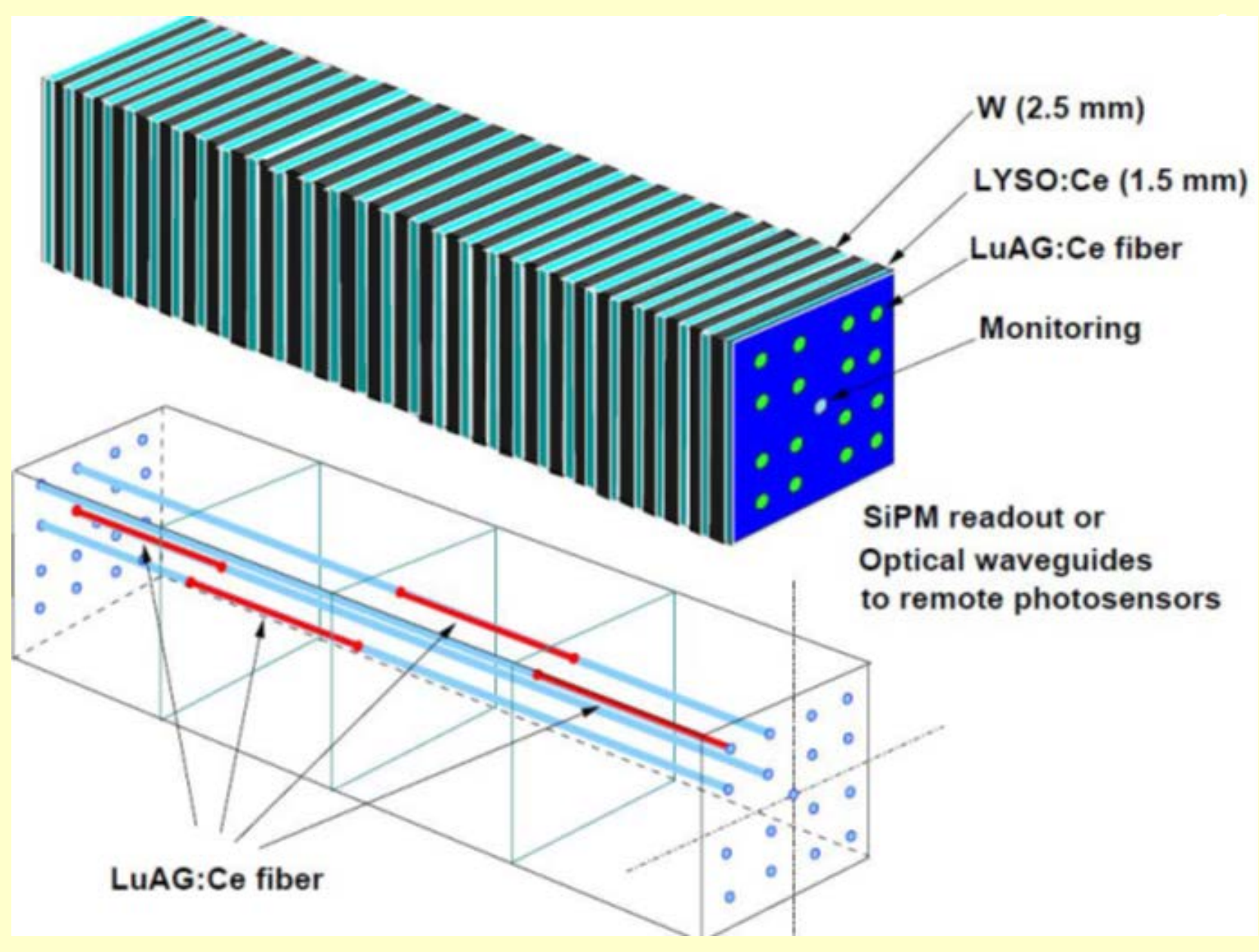

Fig. 1 A schematic showing a RADiCAL electromagnetic calorimeter module.

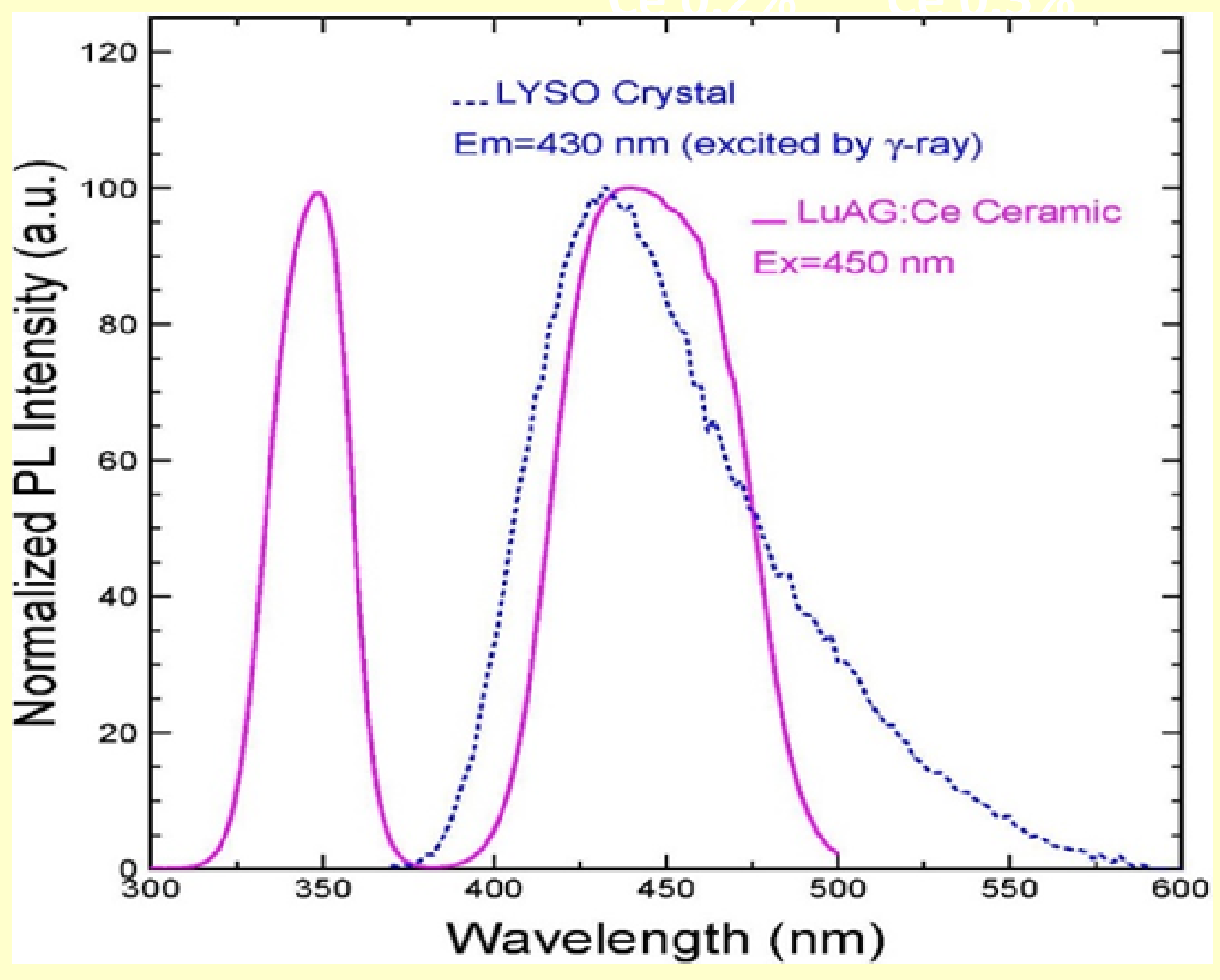

Fig. 2 The LYSO:Ce radioluminescence matches well the LuAG:Ce excitation spectrum.

2. Samples and Experiments

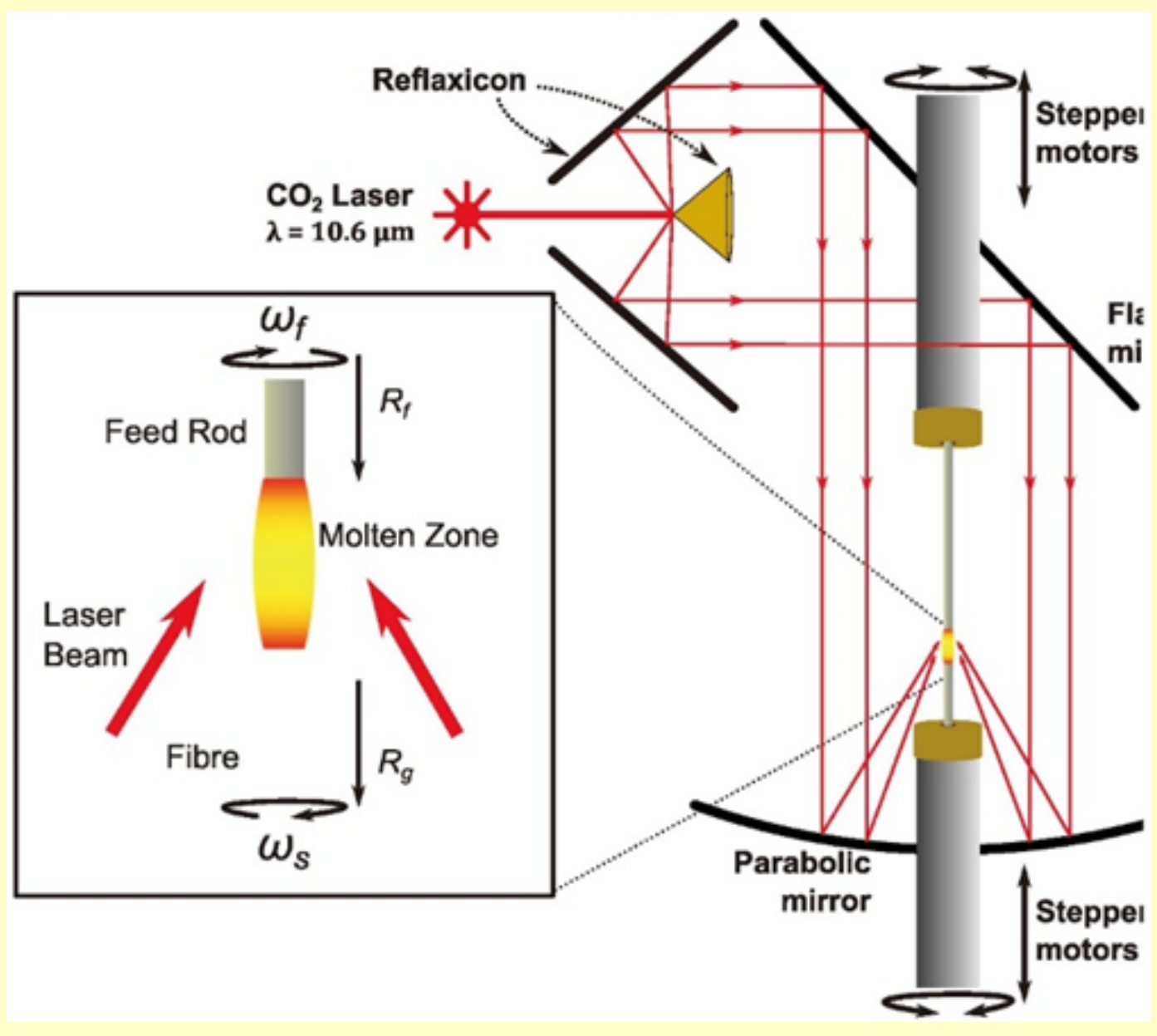

Fig. 3 A schematic showing laser heated pedestal growth for LuAG:Ce fibers.

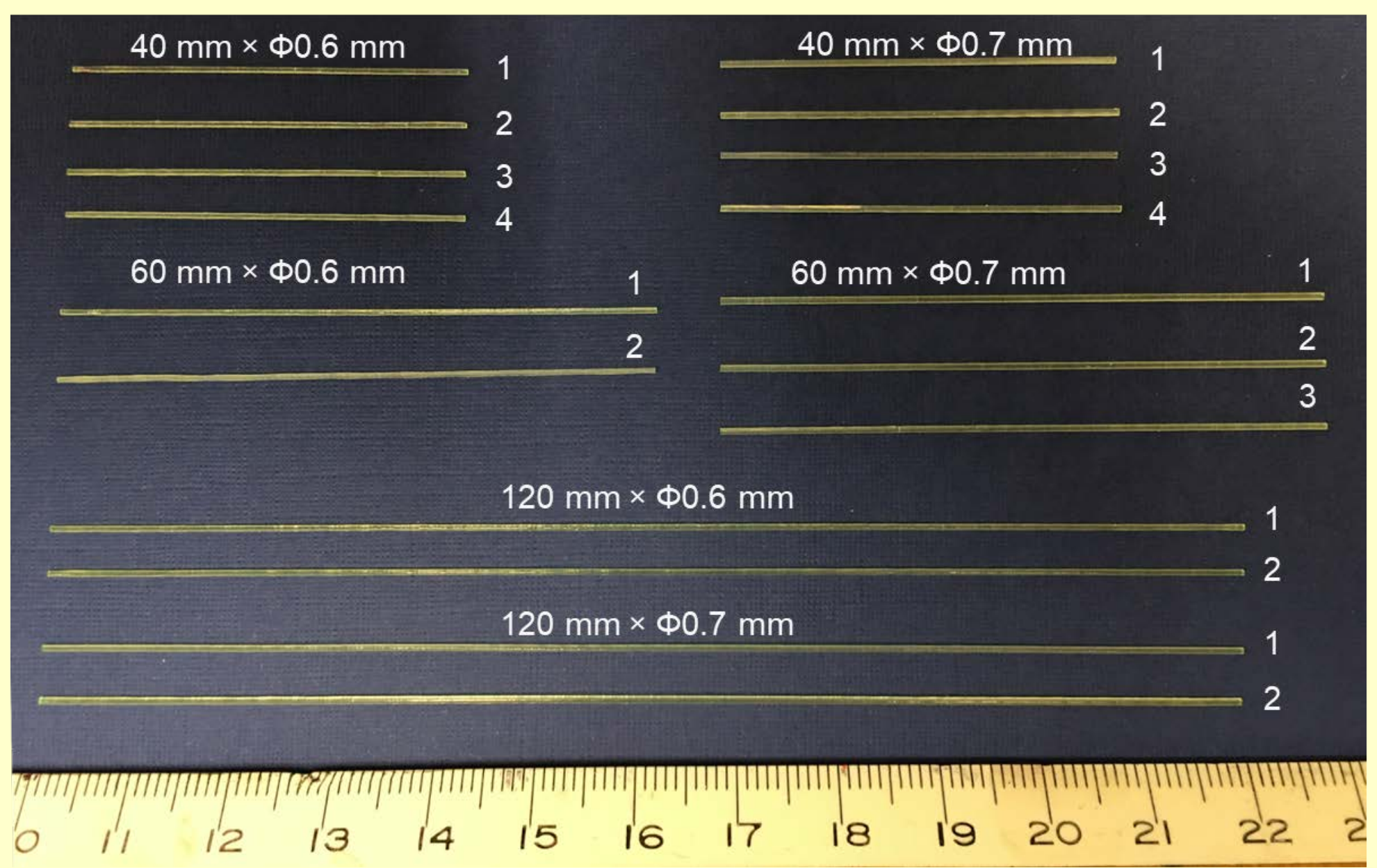

Fig. 4 A photo showing Φ0.6 and 0.7 mm LuAG:Ce ceramic fibers of 40, 60 and 120 mm long.

Fig. 3 shows the laser heated pedestal growth (LHPG) setup used to produce LuAG:Ce ceramic fibers. Fig. 4 shows Φ0.6 and 0.7 mm LuAG:Ce ceramic fibers produced at Shanghai Institute of Ceramic (SIC). While the 12 cm long fibers are used for energy measurement, short fibers are used to measure precision timing for electromagnetic showers at the shower maximum. In addition, Φ1 mm LuAG:Ce ceramic fibers of different length are also produced for the RADiCAL concept.

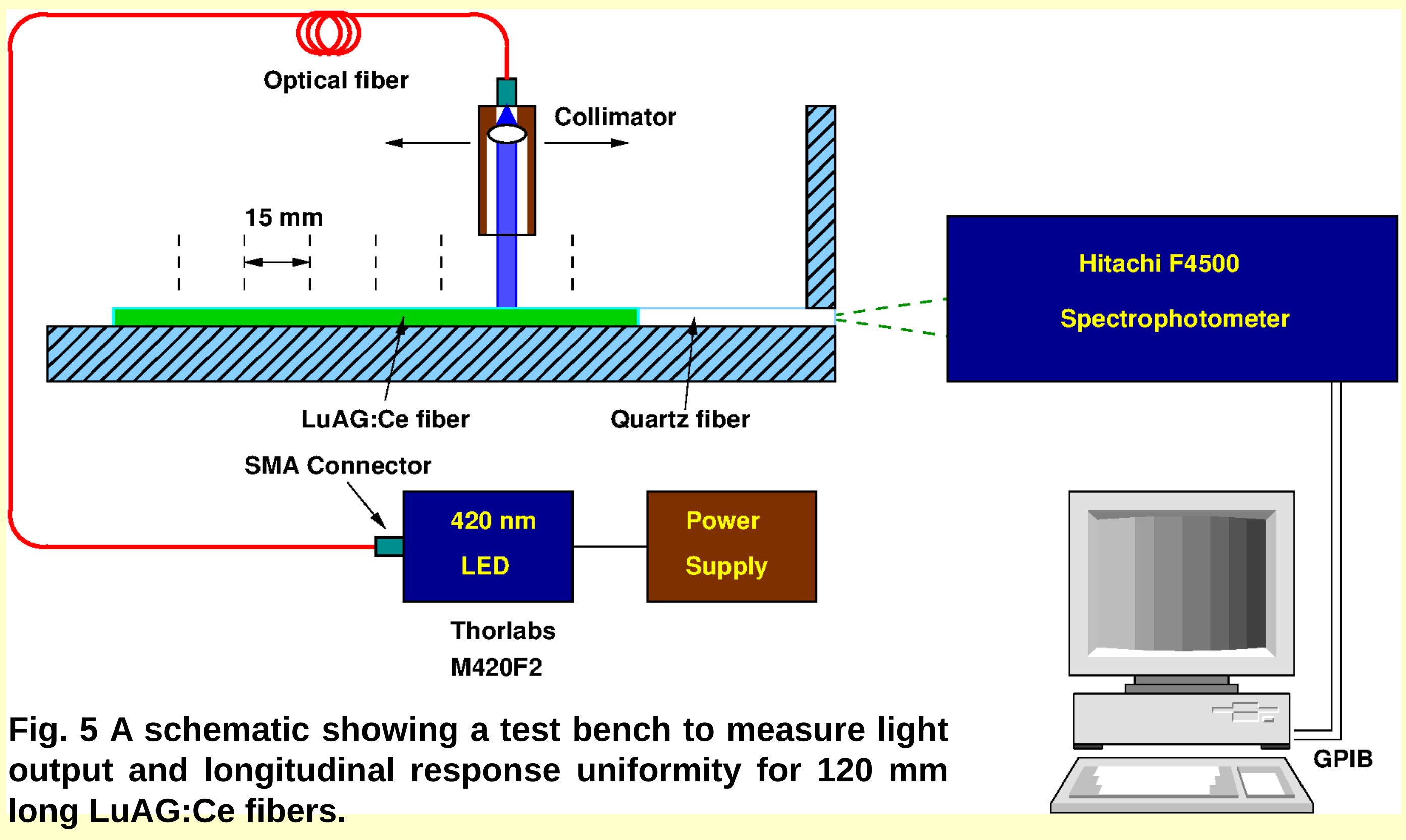

Fig. 5 A schematic showing a test bench to measure light output and longitudinal response uniformity for 120 mm long LuAG:Ce fibers.

Fig. 5 shows a test bench used to measure light output (LO) and longitudinal response uniformity (LRU). LuAG:Ce fibers were excited by a 420 nm LED at different longitudinal locations and with a solid coupling to a quartz fiber, mimicking its practical application in a RADiCAL module. Each fiber was measured twice with two alternative ends (A or B) couped to the quartz fiber.

3. Results and Discussions

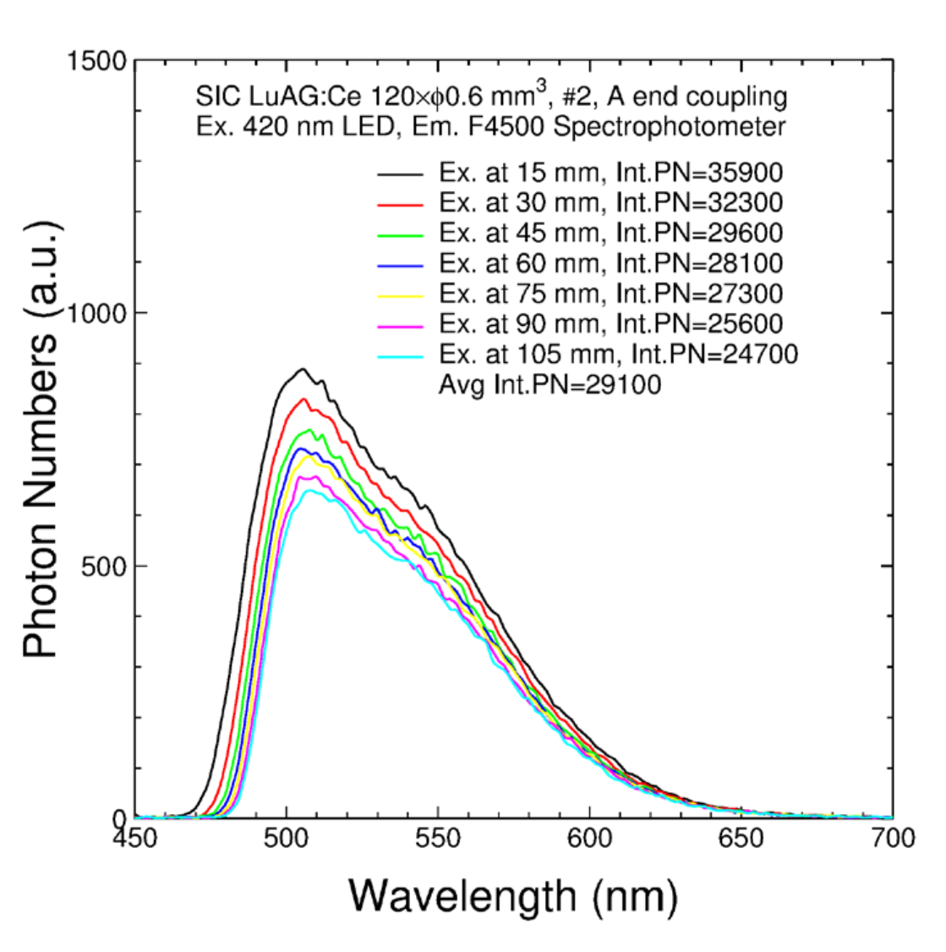

Fig. 6 PL spectra with excitation at different locations are shown for the Φ0.6 ×120 mm³ LuAG:Ce fiber #2 with the A-end coupling.

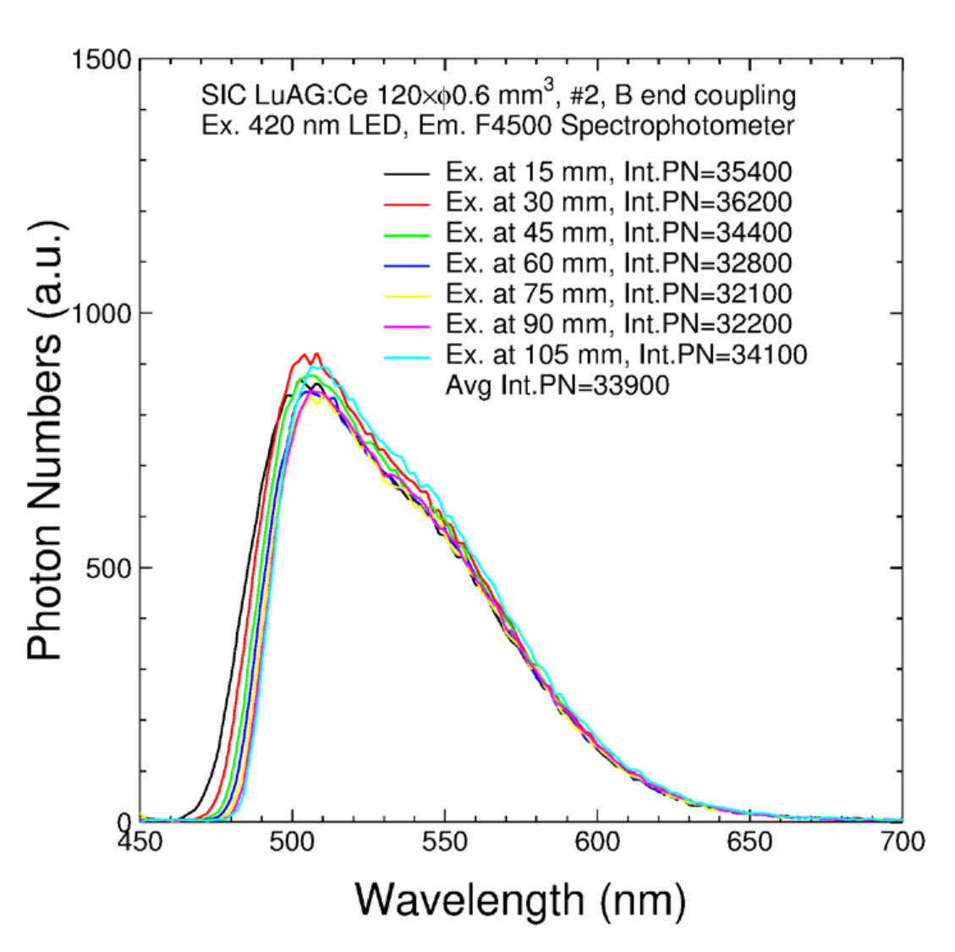

Fig. 7 PL spectra with excitation at different locations are shown for the Φ0.6 ×120 mm³ LuAG:Ce fiber #2 with the B-end coupling.

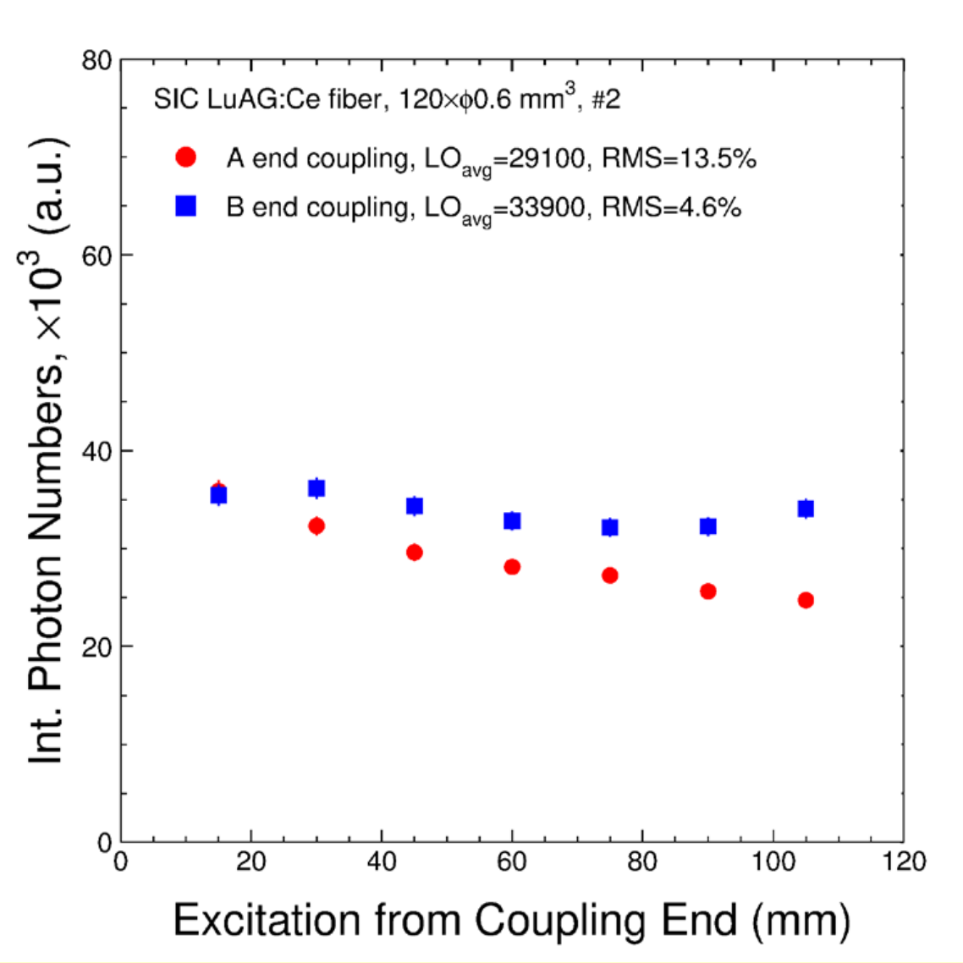

Fig. 8 The LO as a function of the excitation location from the coupling end for the Φ0.6 ×120 mm³ LuAG:Ce fiber #2.

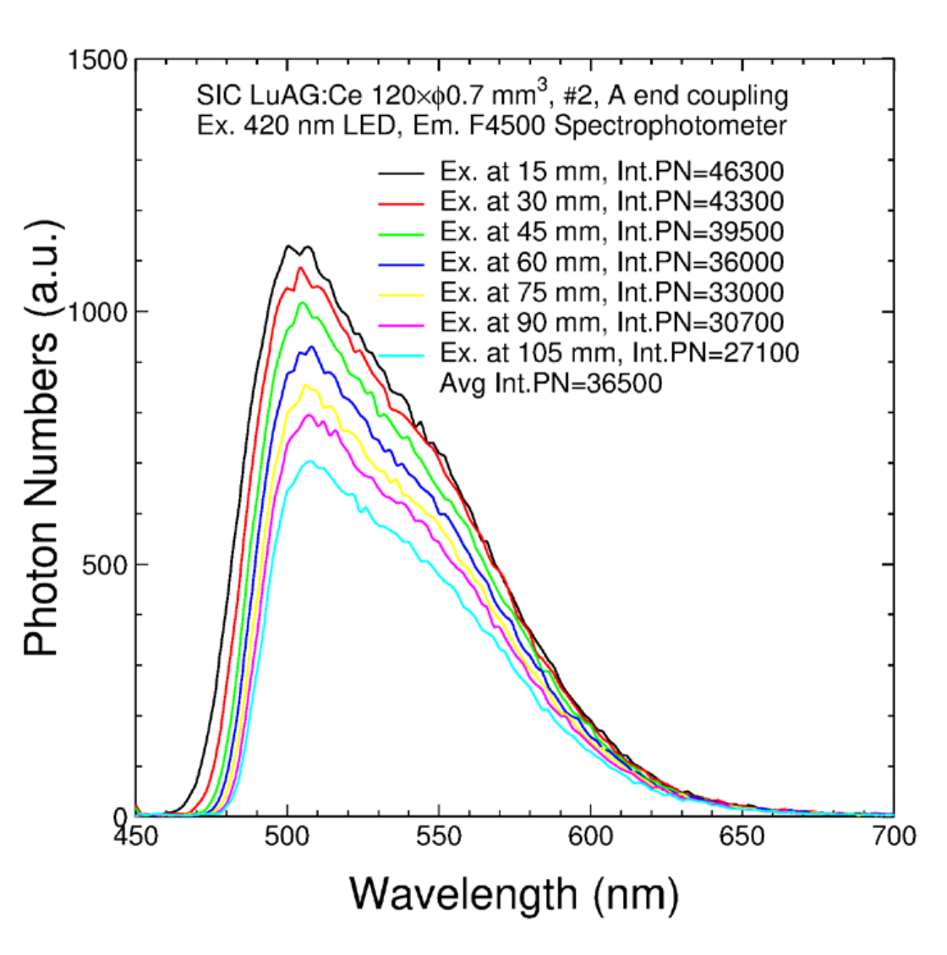

Fig. 9 PL spectra with excitation at different location are shown for the Φ0.7 ×120 mm³ LuAG:Ce fiber #2 with the A-end coupling.

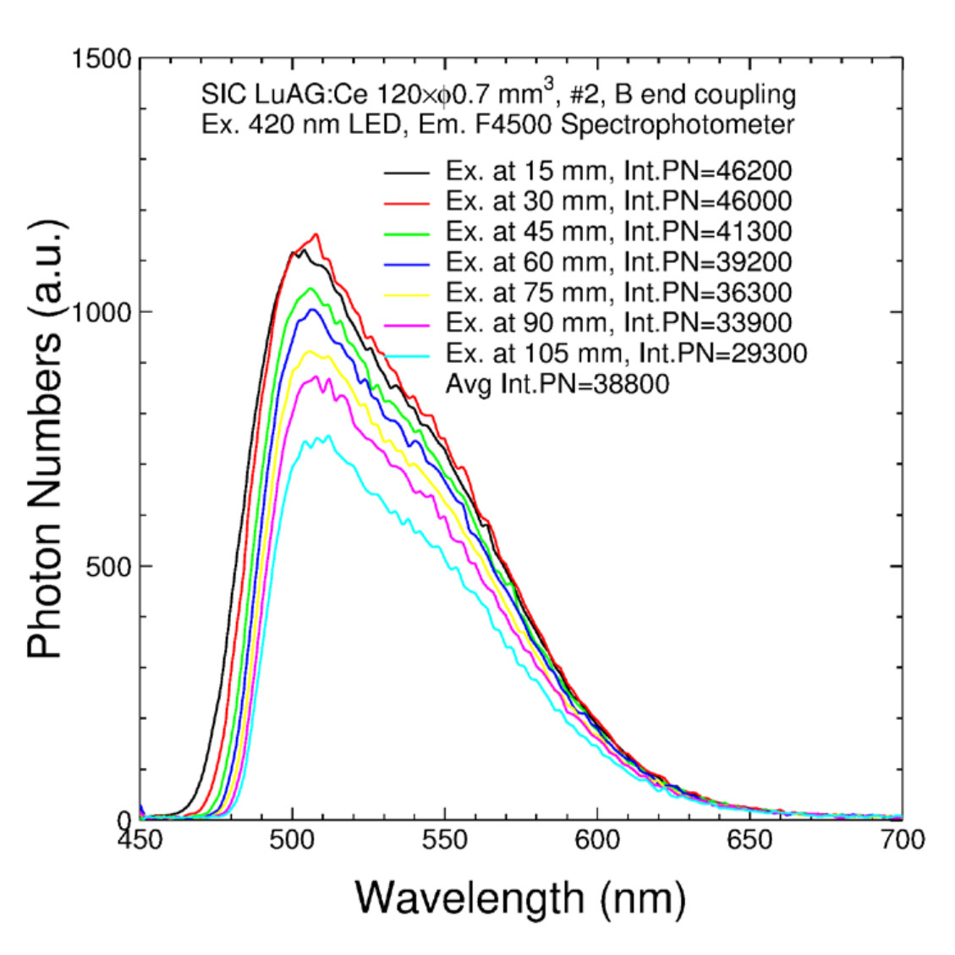

Fig. 10 PL spectra with excitation at different location are shown for the Φ0.7 ×120 mm3 LuAG:Ce fiber #2 with the B-end coupling.

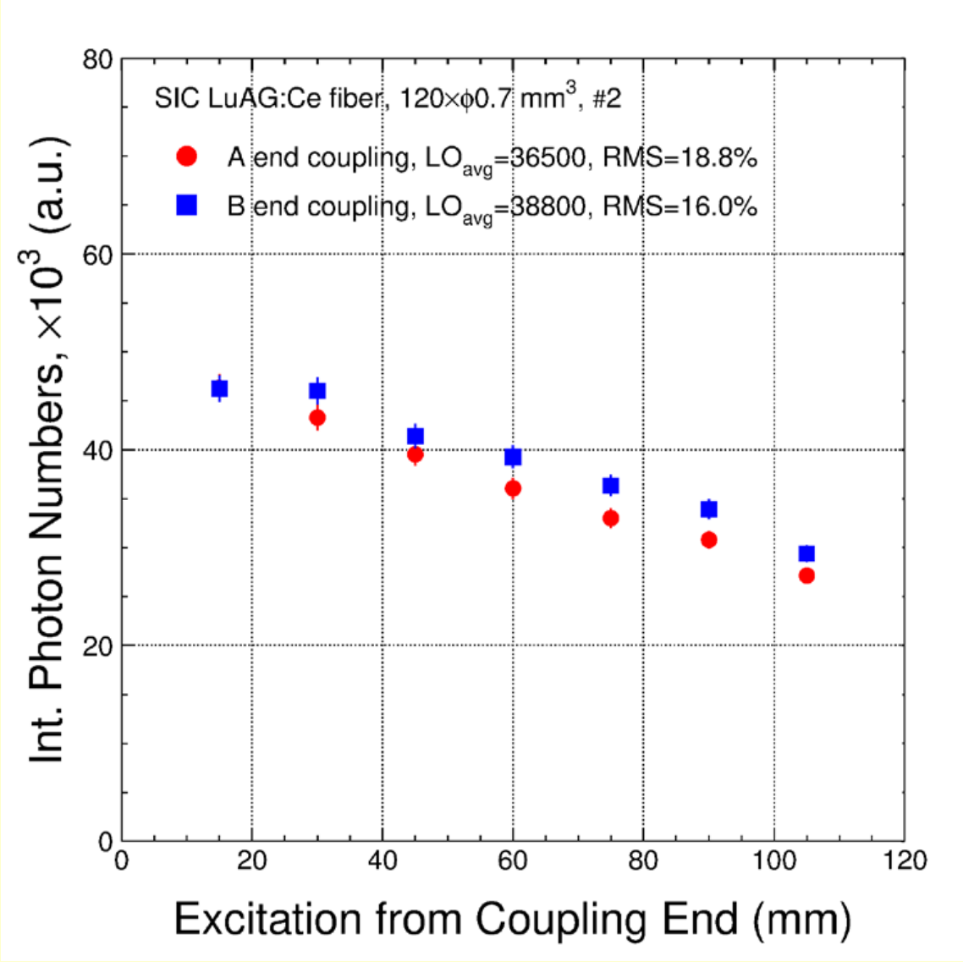

Fig. 11 The LO as a function of the excitation location from the coupling end for the Φ0.7 ×120 mm3 LuAG:Ce fiber #2.

Figs. 6 and 7 show the photoluminescence (PL) spectra of the Φ0.6 × 120 mm³ LuAG:Ce fiber 120-0.6-2 with A and B ends coupling respectively for LED excitation at 7 longitudinal positions. Also listed are the integrals of each emission spectrum, which represent LO. Fig. 8 shows the LO as a function of the distance of the LED excitation light from the coupling end for two alternative coupling ends. The slightly different average LO values with different coupling ends are due to the absorption and scatter centers in the fiber. The relative rms (%) value of the seven LO values represents the LRU of the fiber. Figs. 9-11 show the corresponding results for the Φ0.7 × 120 mm³ LuAG:Ce fiber 120-0.7-2.

Table 1: Summary of LO and LRU for 120 mm long LuAG:Ce ceramic fibers.

ID	Φ (mm)	A end LO (a.u)	A end rms (%)	B end LO (a.u)	B end rms (%)
120-0.6-1	0.6	28900	11.0	37800	19.4
120-0.6-2	0.6	29100	13.5	33900	4.6
120-0.7-1	0.7	24300	41.8	27100	38.5
120-0.7-2	0.7	36500	18.8	38800	16.0
120-1.0-1	1.0	44700	5.0	50400	10.6
120-1.0-2	1.0	36300	22.8	43700	20.5
Capillary s136	1.0	58200	3.2		

Table 1 summarizes the LO and LRU values for a total of six 120 mm long LuAG:Ce fibers with diameter of 0.6, 0.7 and 1.0 mm for two alternative coupling ends. The average LO is proportional to the fiber diameter since fiber of large diameter would absorb more excitation photons from the excitation LED light with a fixed FWHM of about 5 mm. The average LO is less than quartz capillary s136 of 160 mm long, which uses an organic WLS DSB. R&D will continue to improve quantum yield and LRU for LuAG:Ce ceramic fibers, and to investigate their radiation hardness.

Summary

Future HEP experiments require fast and radiation hard calorimetry. The RADiCAL concept proposes an ultra-compact, radiation hard and fast-timing electromagnetic calorimeter for the HL-LHC and the proposed FCC-hh, where bright, fast and radiation hard LYSO:Ce crystals and LuAG:Ce ceramic wavelength shifters are used. LuAG:Ce ceramic fibers of 0.6, 0.7 and 1 mm in diameter of up to 120 mm long were fabricated by using Laser Heated Pedestal Growth technique at SIC. Beam tests are planned for a LYSO/W/LuAG RADiCAL prototype to measure its energy and timing resolution, and for individual modules to measure their radiation hardness against ɣ-rays and hadrons. R&D will continue to improve quality of LuAG:Ce ceramic fibers.

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