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

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2019 DOE Basic Research Needs Study on HEP Instrumentation: Calorimetry

https://science.osti.gov/hep/Community-Resources/Reports

Priority Research Direction
PRD 1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements
PRD 2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments
PRD 3: Develop ultrafast media to improve background rejection in calorimeters and improve particle identification

Fast/ultrafast, radiation hard and cost-effective inorganic scintillators needed to achieve energy, spatial and timing resolution for future HEP calorimetry

2021 HEP CPAD Meeting: https://indico.fnal.gov/event/46746/timetable/#all.detailed

Bright & Fast Inorganic Scintillators

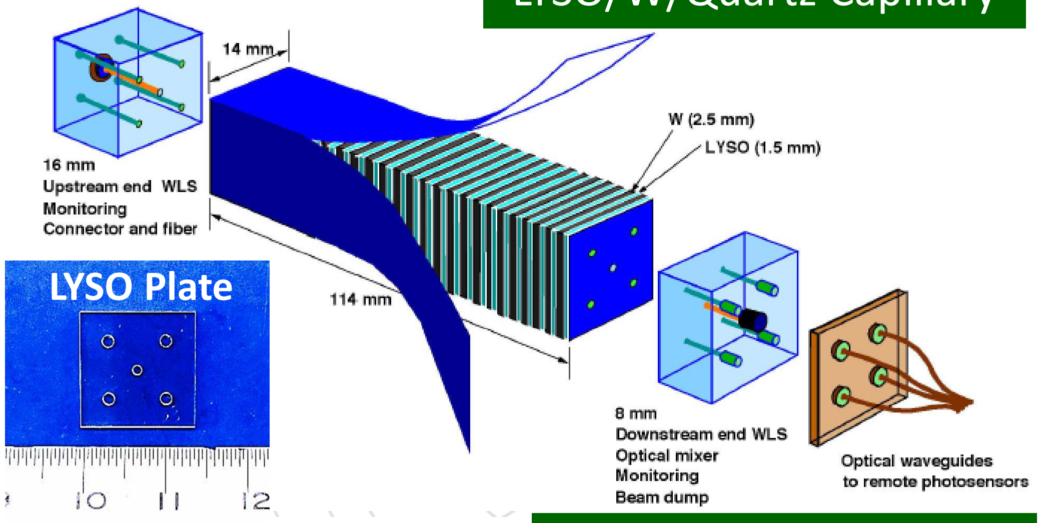
	LYSO:Ce	LSO:Ce,Ca[a]	LuAG:Ce[b]	LuAG:Pr[c]	GGAG:Ce[d]	GLuGAG:Ce[g]	GYGAG:Ce[h]	$SrHfO_3$:Ce[i]	$BaHfO_3$:Ce[i]	$CeBr_3$[k]	$LaBr_3$:Ce[k]
Density (g/cm^3)	7.4	7.4	6.76	6.76	6.5	6.80	5.80	7.56	8.5	5.23	5.29
Melting points (^oC)	2050	2050	2060	2060	1850[e]	>1900[e]	1850[e]	2730	2620	722	783
X_0 (cm)	1.14	1.14	1.45	1.45	1.63	1.38	2.11	1.17	0.98	1.96	1.88
R_M (cm)	2.07	2.07	2.15	2.15	2.20	1.57	2.43	2.03	1.87	2.97	2.85
λ_I (cm)	20.9	20.9	20.6	20.6	21.5	20.8	22.4	20.6	19.4	31.5	30.4
Z_{eff}	64.8	64.8	60.3	60.3	51.8	55.2	45.4	60.9	62.9	45.6	45.6
dE/dX	9.55	9.55	9.22	9.22	8.96	9.28	8.32	9.80	10.7	6.65	6.90
λ_{peak} (nm)	420	420	520	310	540	550	560	410	400	371	356
Refractive Index	1.82	1.82	1.84	1.84	1.92[f]	1.92[f]	1.92[f]	2.0	2.1	1.9	1.9
Normalized Light Yield	100	116	83	73	115	161	167	133	133	99	153
Total Light yield (ph/MeV)[a]	30,000	34,800	25,000	22,000	34400	48,200	50,000	5,000[j]	5,000[j]	30,000	46,000
Decay time (ns)[a]	40	31	46	20	53	84 148	100	42	25	17	20
Light Yield in 1st ns (photons/MeV)	740	950	540	1,100	640	570	500	120	200	1,700	2,200
Issues					high thermal neutron x-section			incongruent		hygroscopic	

[a] Spurrier, et al., *IEEE T. Nucl. Sci.* 2008,55 (3): 1178-1182
[b] Liu, et al., *Adv. Opt. Mater.*, 4: 731–739. doi: 10.1002/adom.201500691
[c] Yanagida, et al., *IEEE T. Nucl. Sci.* 2012, 59(5): 2146
[d] Luo, et al., *Ceram. Int.* 2016, 41(1): 873
[e] The melting point of these materials various with different composition from 1800 to 1980 ^oC. The data is based on reported values.
[f] Kuwano, et al., *J. Cryst. Growth.* 1988, 92: 17
[g] Wu, et al., *NIMA* 2015, 780: 45
[h] Cherepy, et al., *IEEE T. Nucl. Sci.* 2013, 60(3): 2330
[i] van Loef, et al., *IEEE T. Nucl. Sci.* 2007, 54(3):741
[j] Based on ^{137}Cs gamma-ray excitation (shaping time of 4 µs) light yield result in ref. i
[k] Data based on single crystals

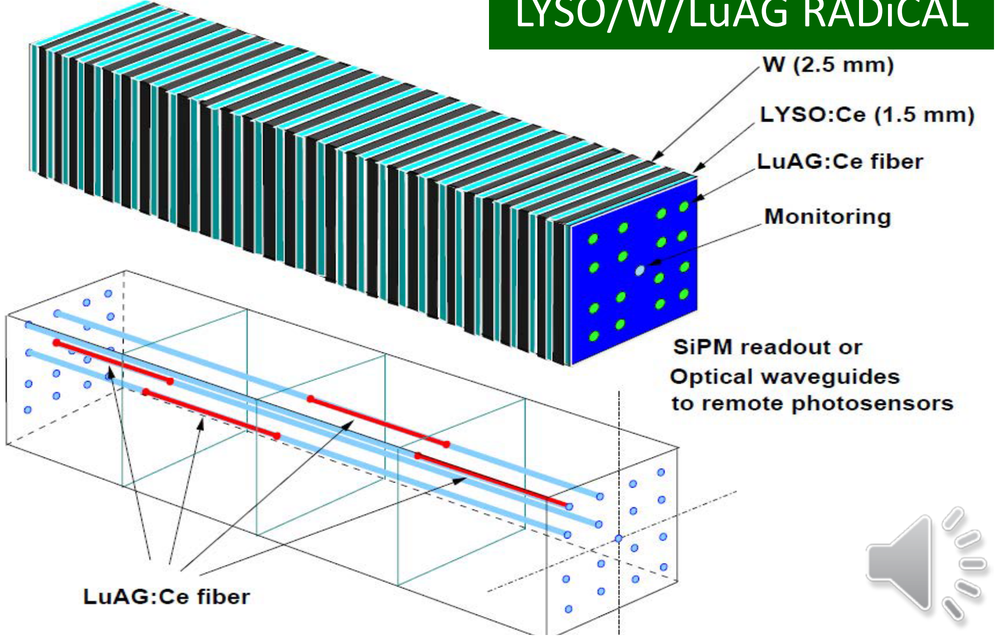
Why LuAG:Ce Ceramic Fibers?

- It meets the DOE BRN PRD for calorimetry:
  - Bright, fast and rad hard scintillators for HL-LHC & FCC-hh;
  - Cost-effective scintillators for lepton Higgs factory;
  - Ultrafast scintillators for high-rate experiment (Mu2e-II).
- An LYSO/W/Quartz Capillary Shashlik calorimetry has been under development in a decade for endcap calorimeter at the HL-LHC:
  - Absorbed dose: up to 100 Mrad,
  - Charged hadron fluence: up to 6×10^{14} p/cm^2,
  - Fast neutron fluence: up to 3×10^{15} n/cm^2.
- LuAG:Ce ceramic fibers are now proposed for the **RADiCAL** concept featured with ultra-compact, radiation hard and fast-timing:
  - Use LuAG:Ce to replace quartz capillary as WLS; and
  - A short LuAG:Ce segment at the shower maximum would provide precision timing.

LYSO/W/Quartz Capillary

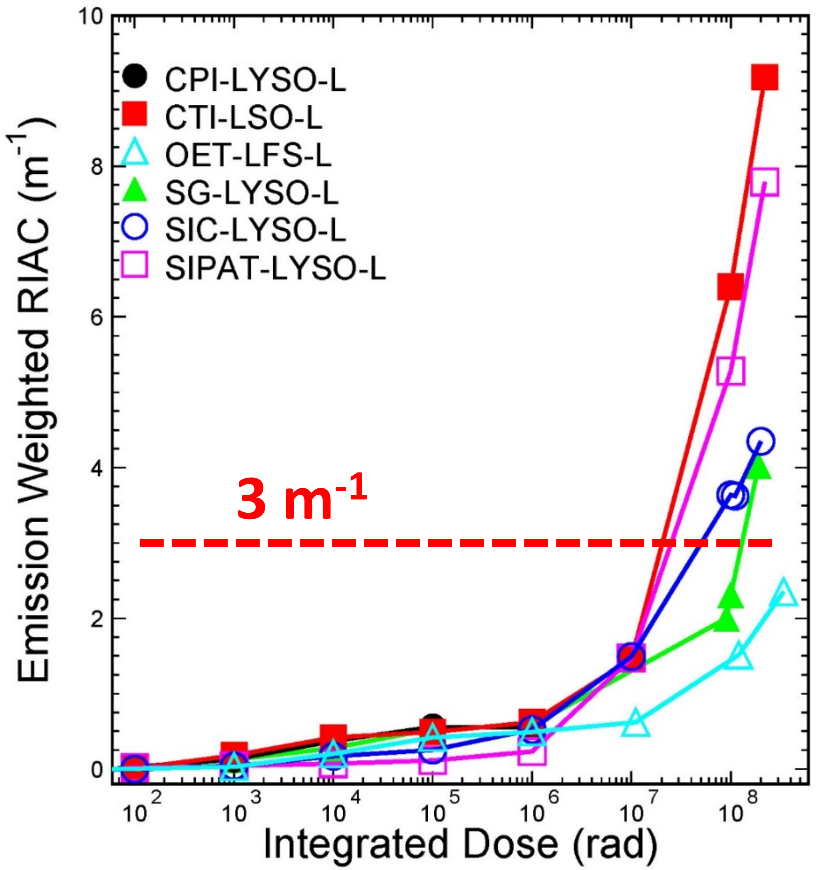


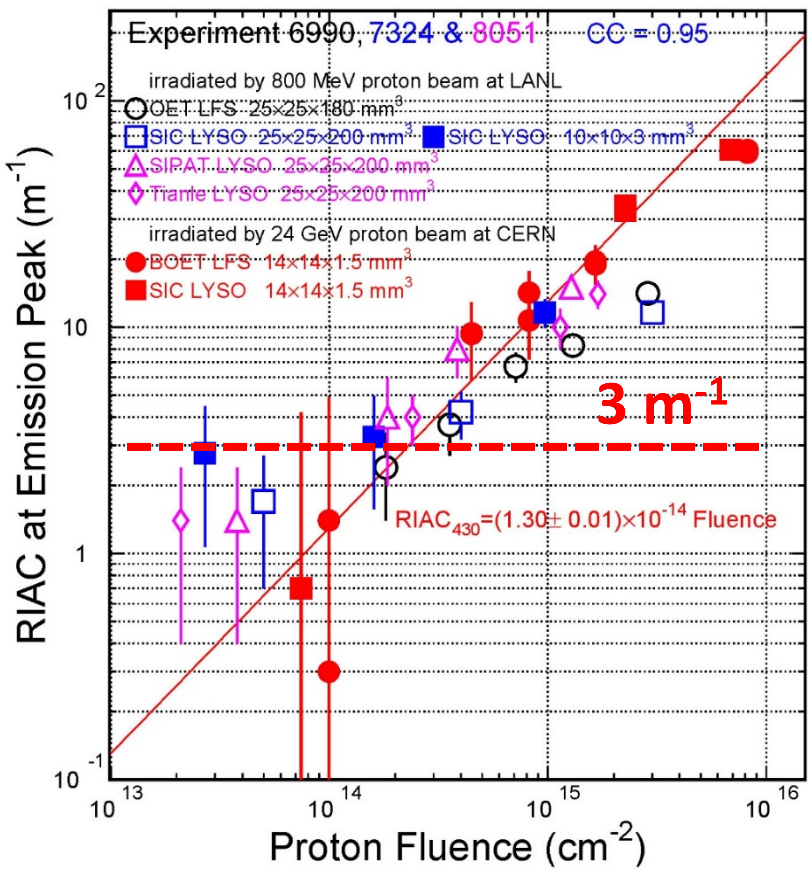
LYSO/W/LuAG RADiCAL

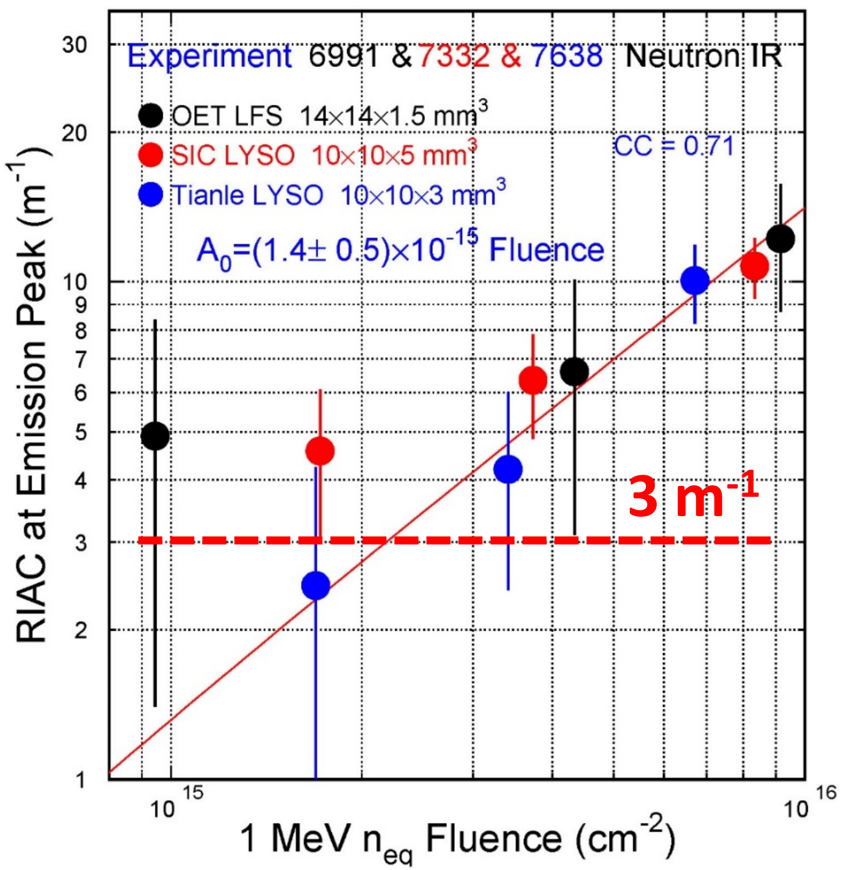


LYSO:Ce for CMS Barrel Timing Layer

CMS LYSO spec: RIAC < 3 m^{-1} after 4.8 Mrad, 2.5 x 10^{13} p/cm^2 & 3.2 x 10^{14} n_{eq}/cm^2



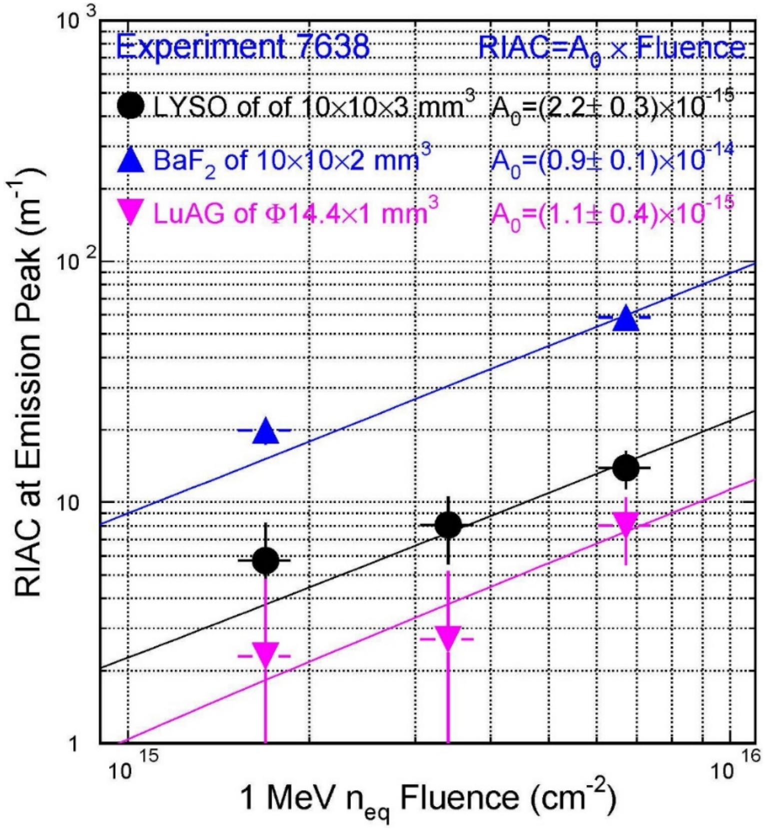


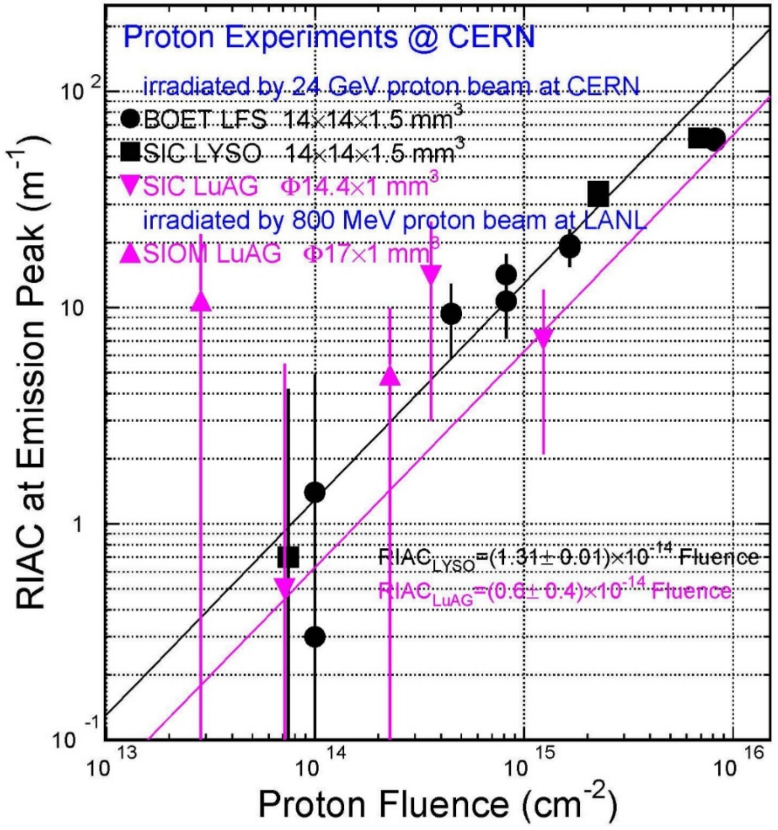


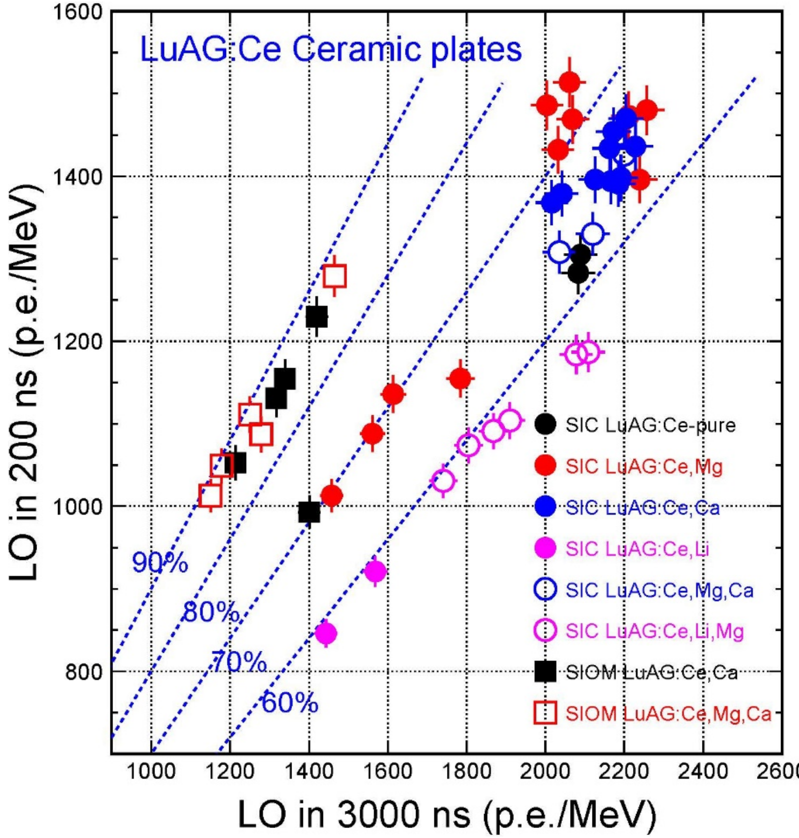
Damage induced by protons is an order of magnitude larger than that from neutrons
Due to ionization energy loss in addition to displacement and nuclear breakup

LuAG:Ce Ceramics Radiation Hardness

LuAG:Ce ceramics show a factor of two better radiation hardness than LYSO crystals up to 6.7×10^{15} n_{eq}/cm^2 and 1.2×10^{15} p/cm^2, promising for FCC-hh
Paper N18-05 in the 2020 NSS CR, DOI: 10.1109/NSS/MIC42677.2020.9507969

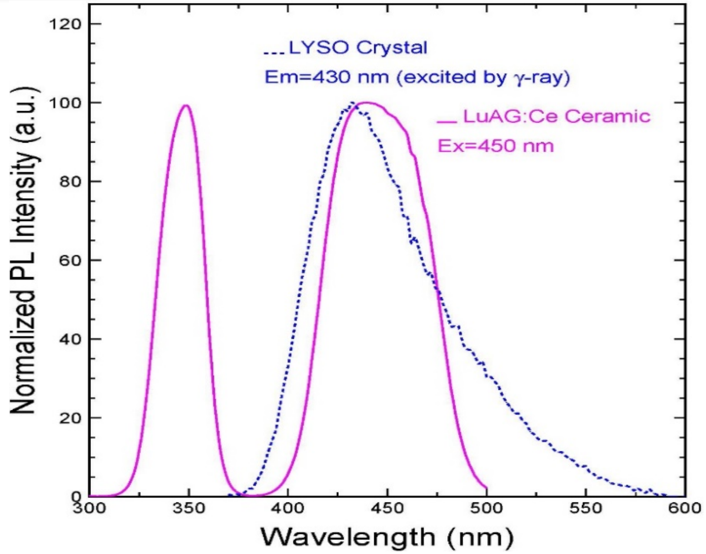






R&D on slow component suppression by Ca co-doping, and radiation hardness by ɣ/p/n

RADiCAL: LYSO/W/LuAG Shashlik ECAL

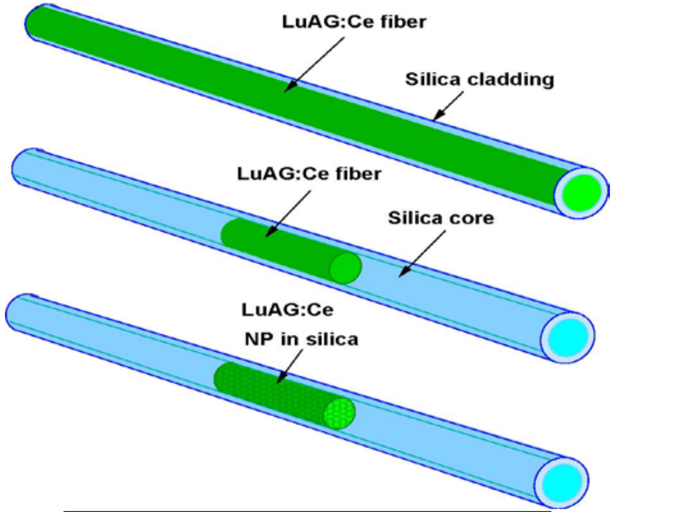


Excitation of LuAG:Ce ceramics matches well LYSO:Ce emission:

RADiCAL

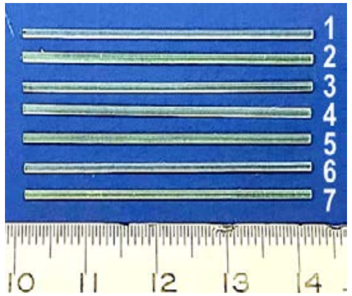
RADiation hard **i**nnovative **CAL**orimetry

See R. Ruchti, in the CPAD meeting

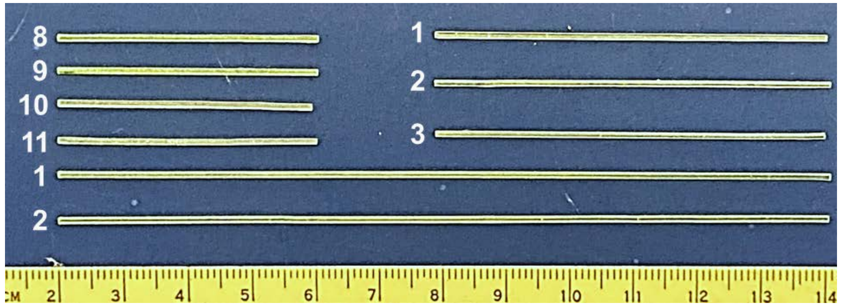


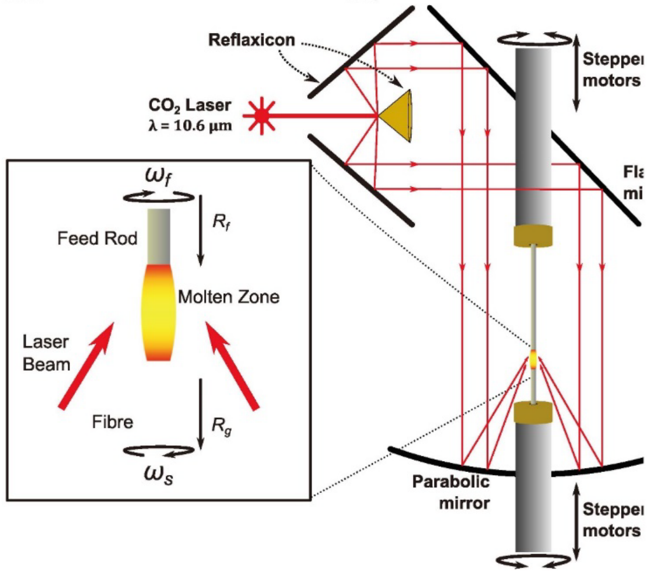
16 LuAG:Ce ceramic fibers
Laser Heated Pedestal Growth

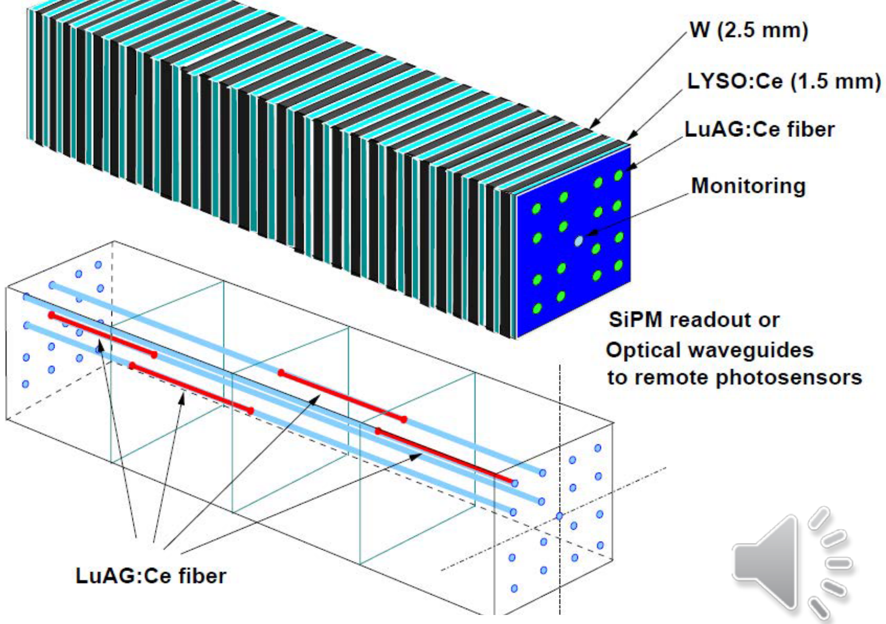
LYSO/W/LuAG RadiCal



11 Φ1x40 mm³
3 Φ1x60 mm³
2 Φ1x120 mm³
SIC LuAG:Ce
Ceramic LHPG fiber







WLS Ex./Em. with Edinburgh FLS920

Edinburgh FLS920

Edinburgh Sample Chamber

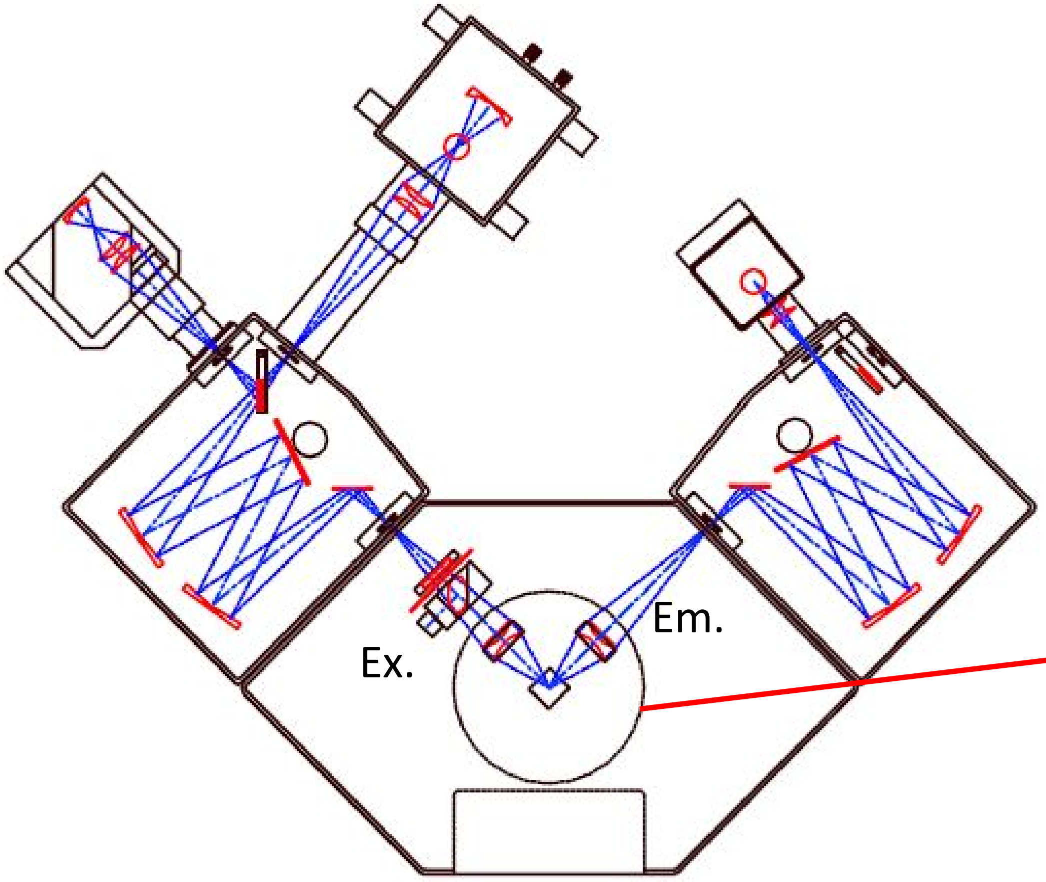
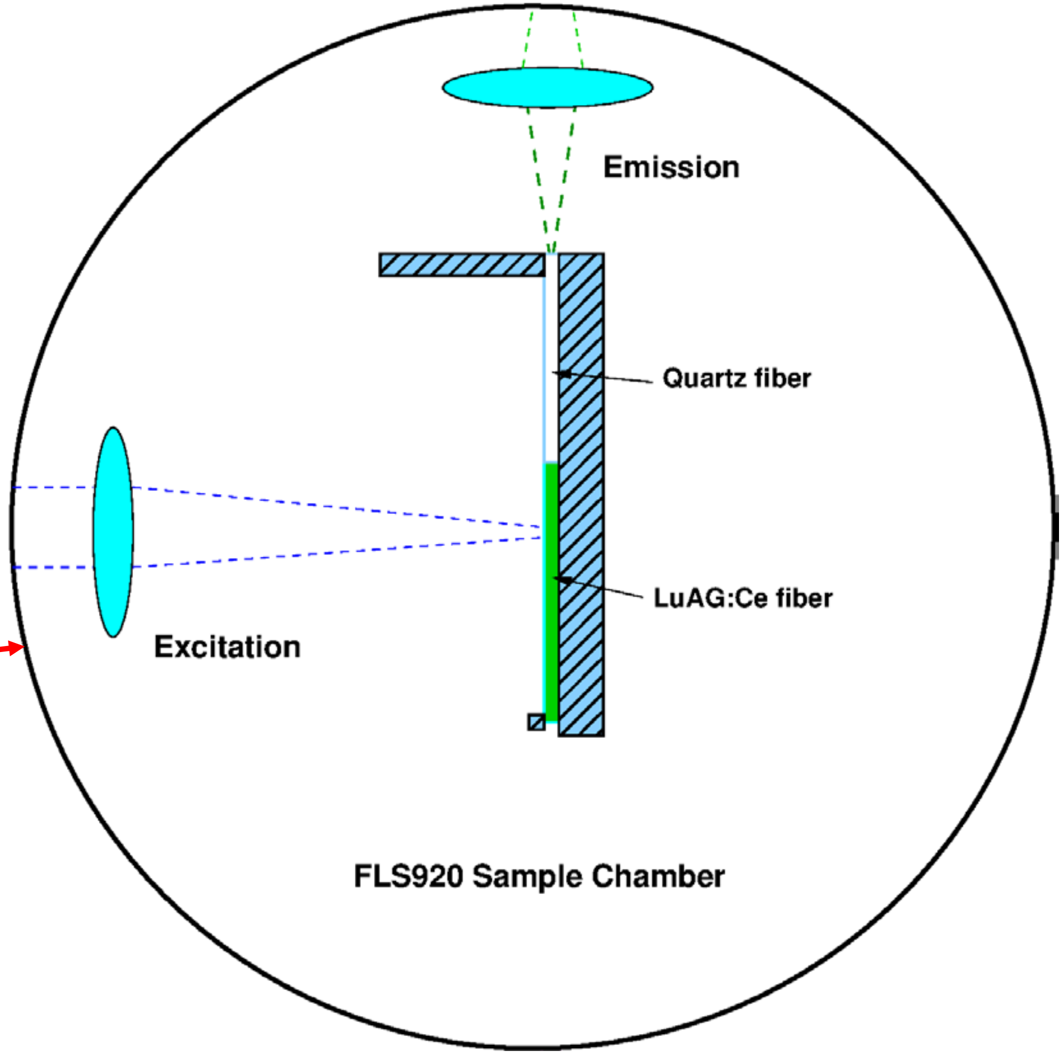
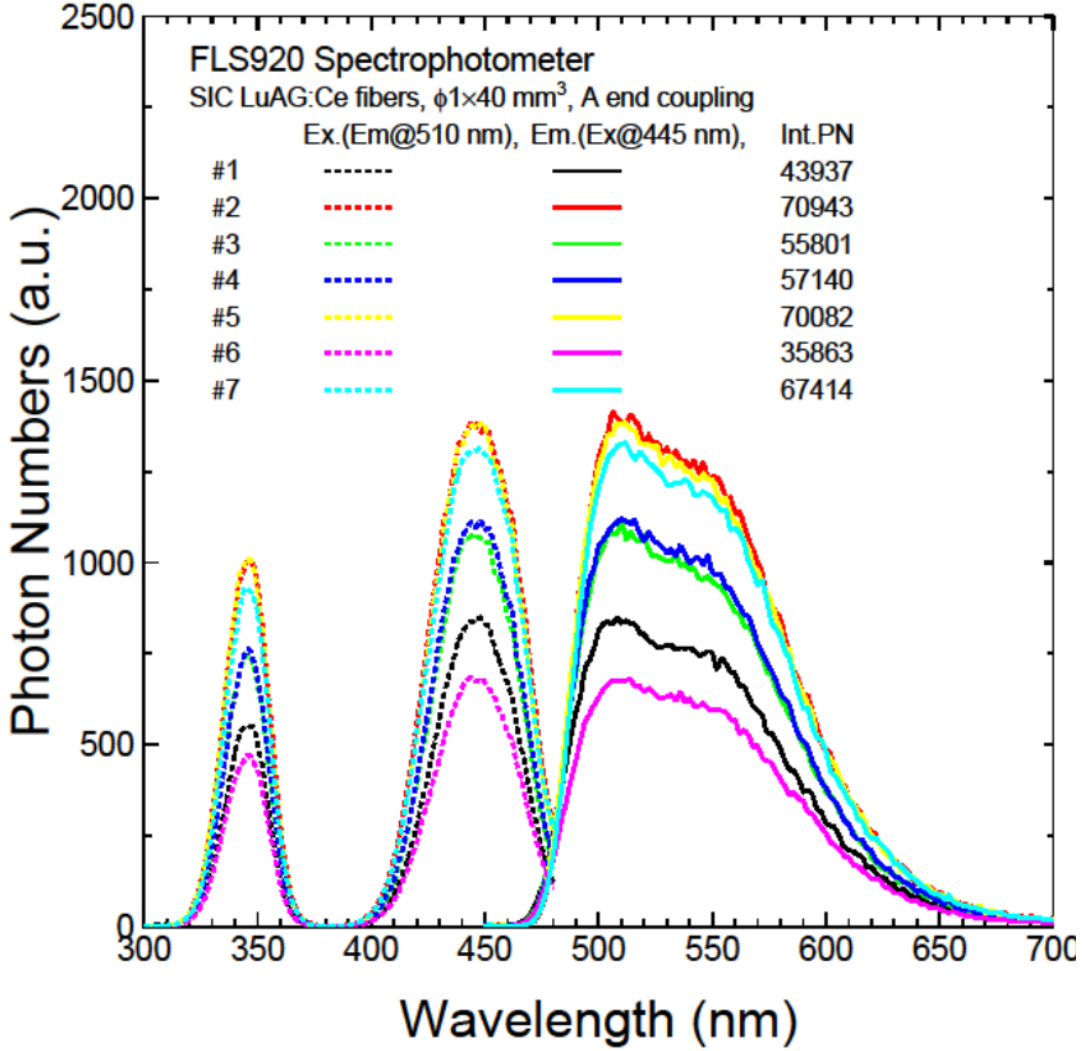


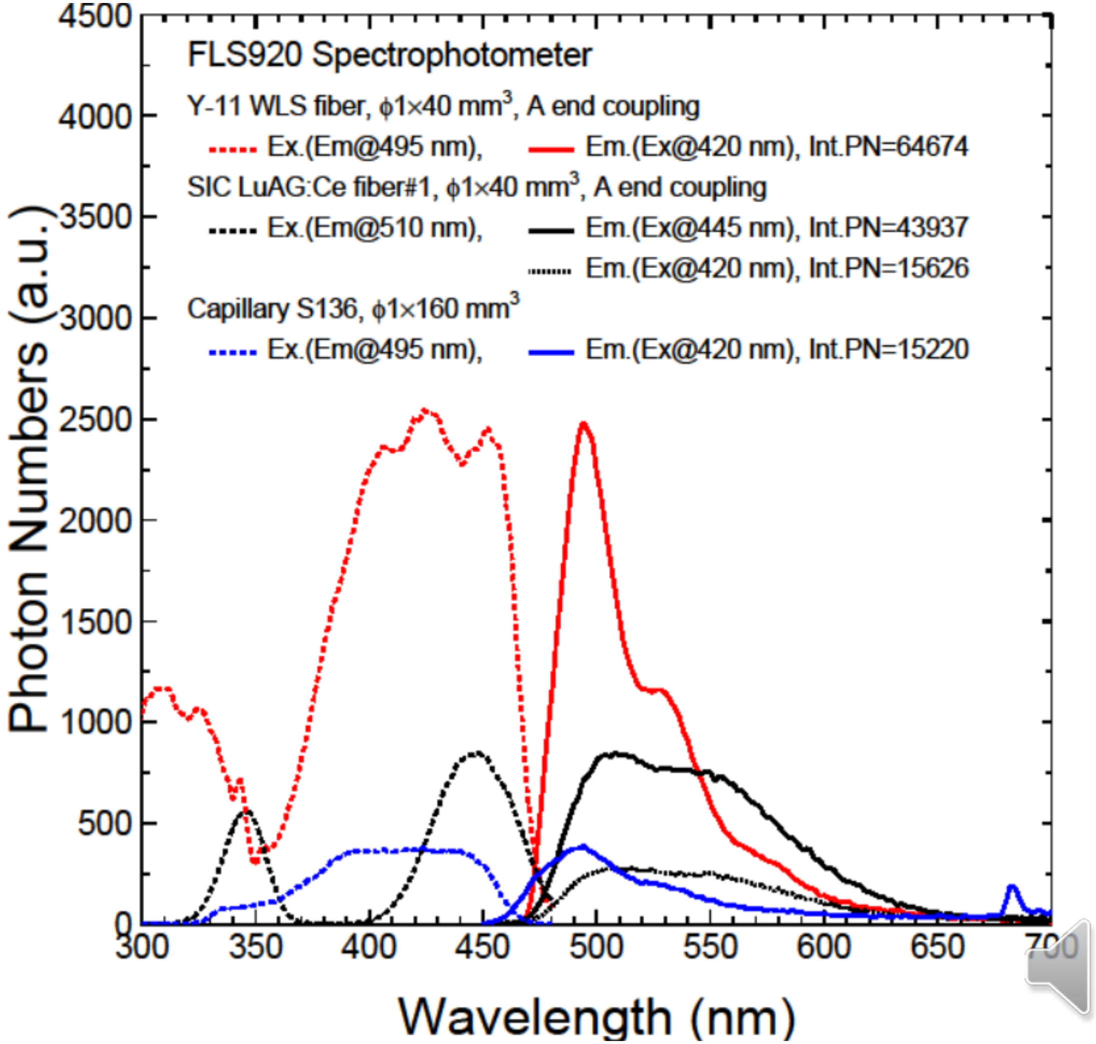
Figure 1-6: General layout of an FLS920



Ex/Em: LuAG:Ce, Y-11 and Quartz Capillary

7 Φ1×40 mm fibers: consistent excitation/emission spectra with different intensity
LuAG:Ce intensity: <Y-11 but comparable with capillary: ×3 @445 nm as @420 nm





WLS Quantum Yield with FLS920/Integrating Sphere

Edinburgh FLS920

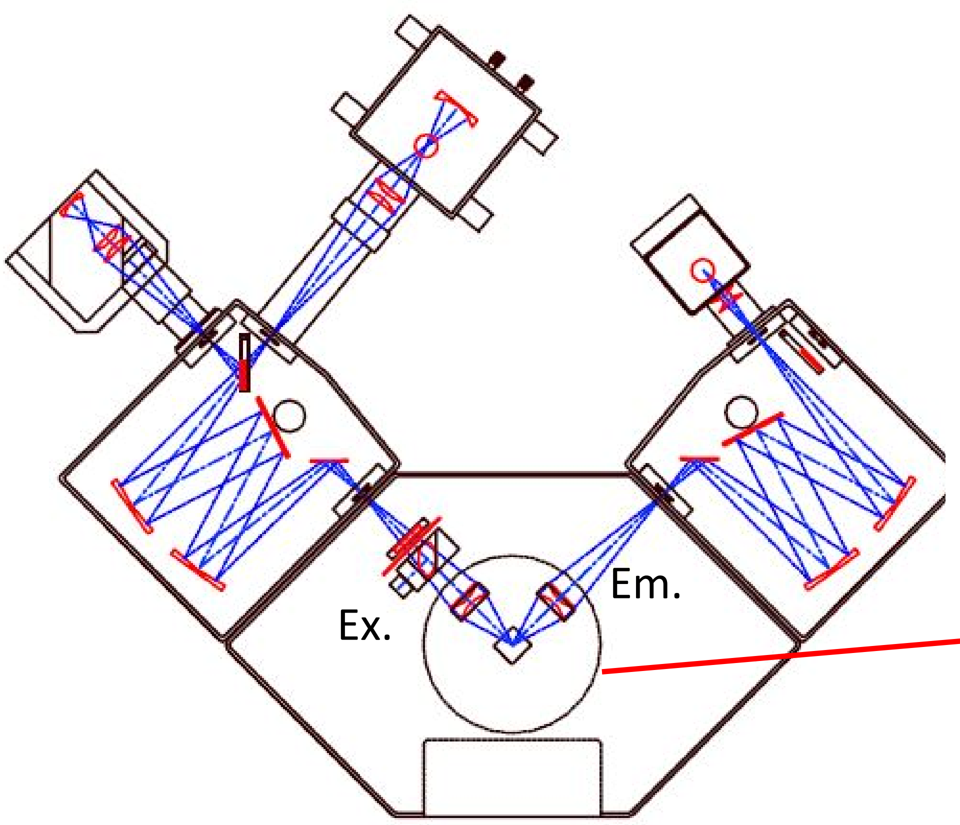
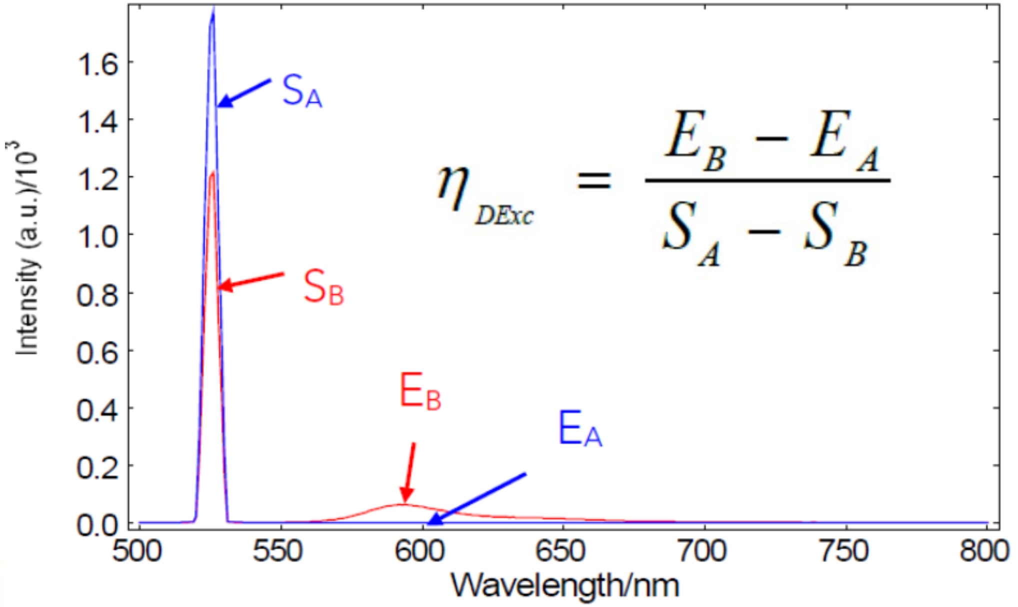


Figure 1-6: General layout of an FLS920

Edinburgh Integrating Sphere

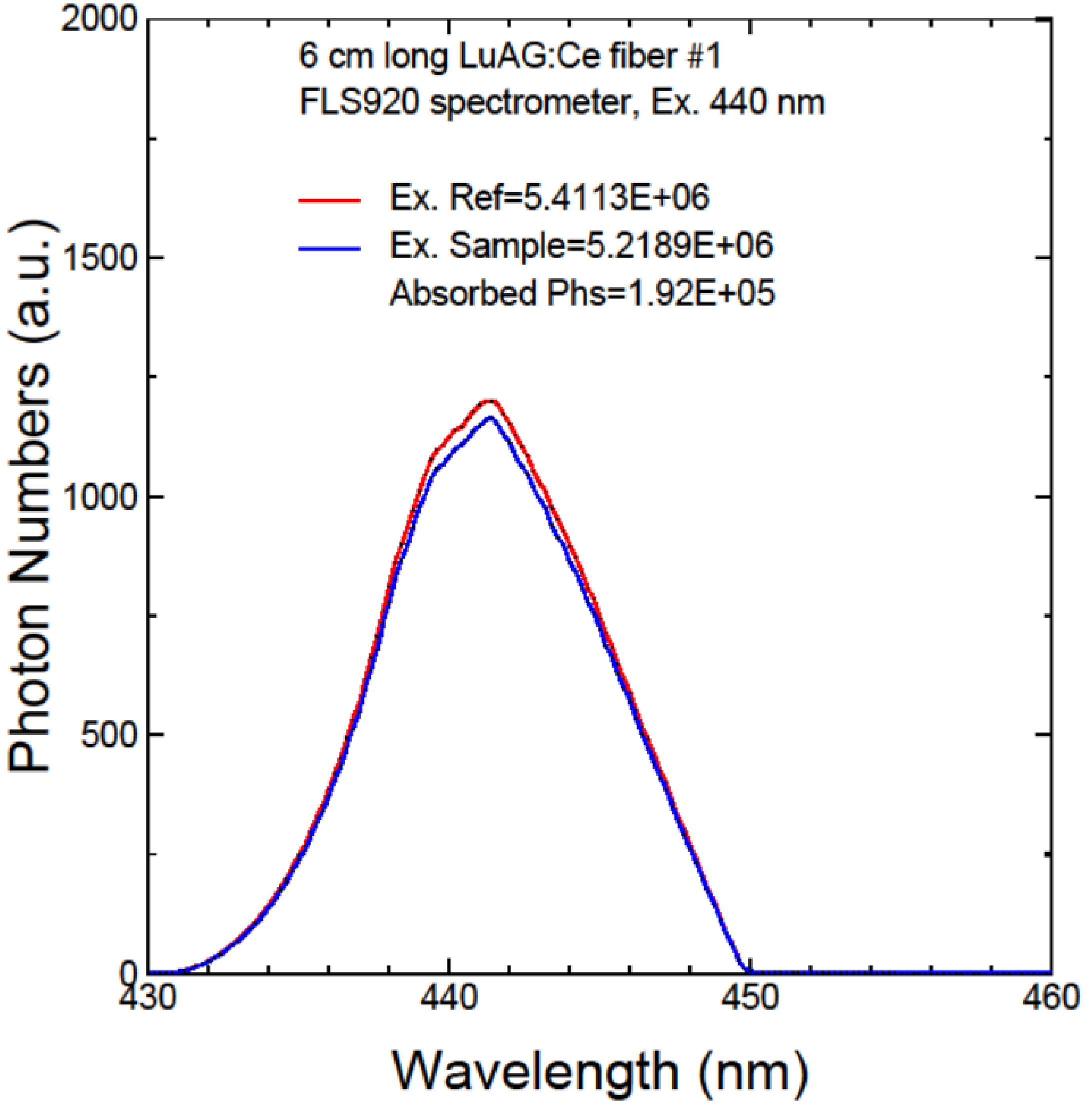
A: Reference: Φ1 mm Quartz Rod

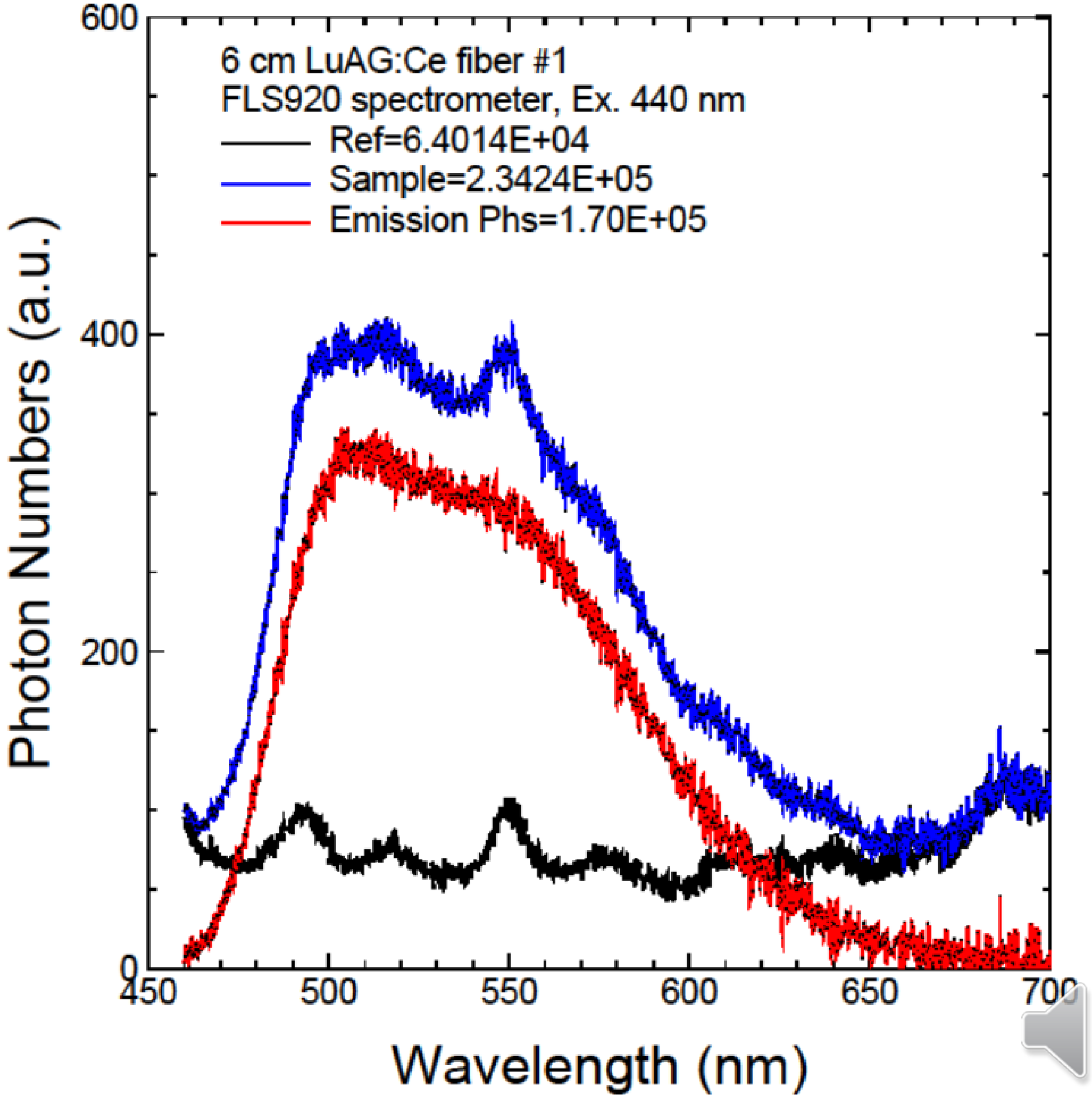


Broad emission: λ_{ex}=440 nm
S_A: ref. scattered excitation
S_B: WLS scattered excitation
E_A: ref. emission
E_B: WLS emission

Quantum Yield: Φ1×60 mm Fiber #1

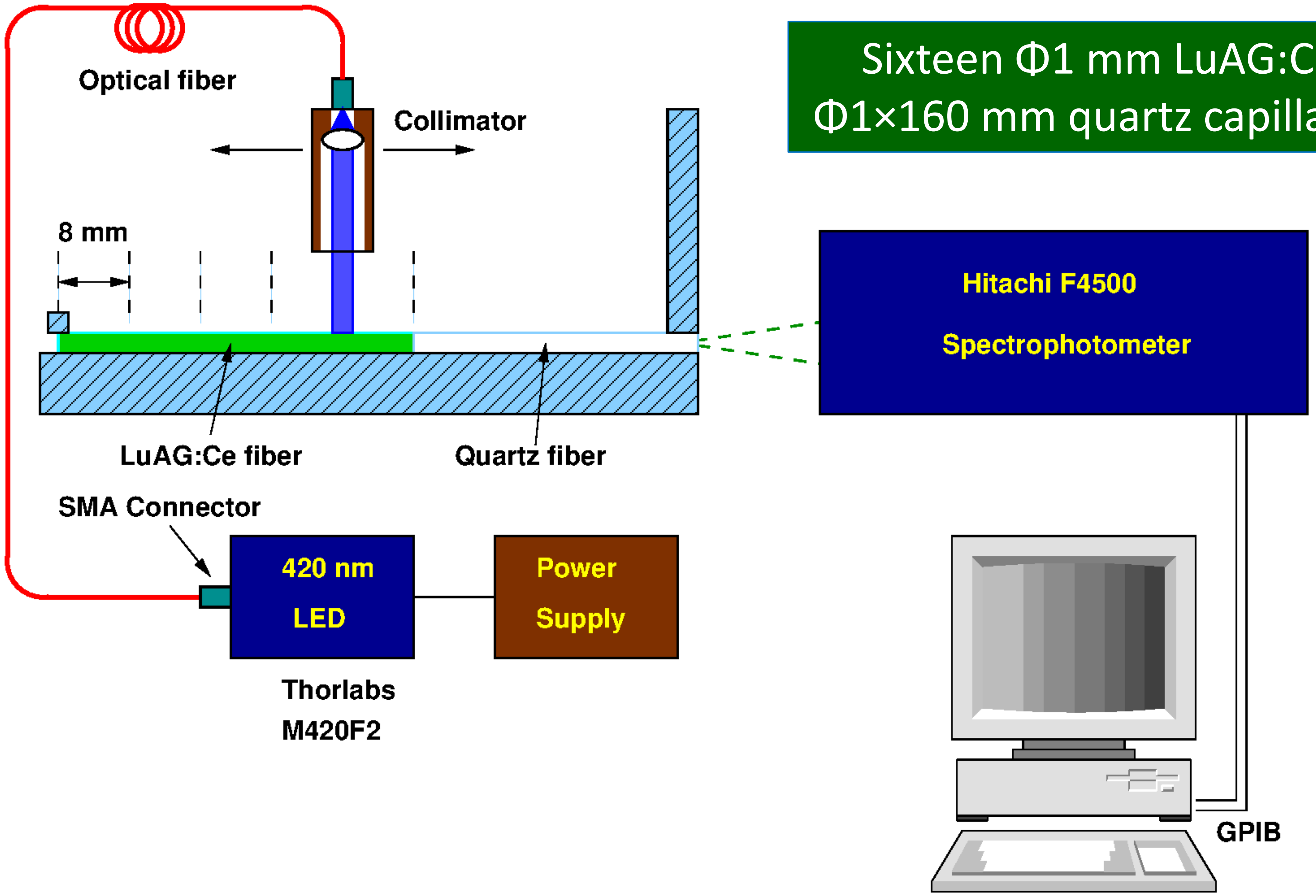
Consistent LuAG:Ce emission and QY = 0.88±0.05 with a quartz rod reference





WLS Uniformity with 420 nm LED

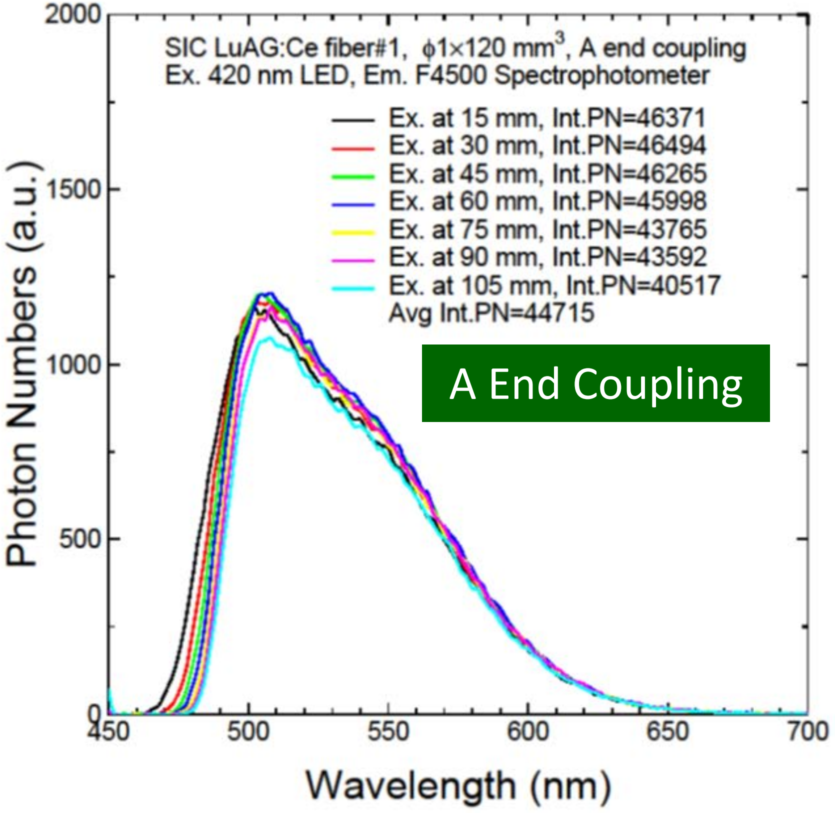
Sixteen Φ1 mm LuAG:Ce fibers, compared to a Φ1×160 mm quartz capillary and a Φ1×40 mm Y-11

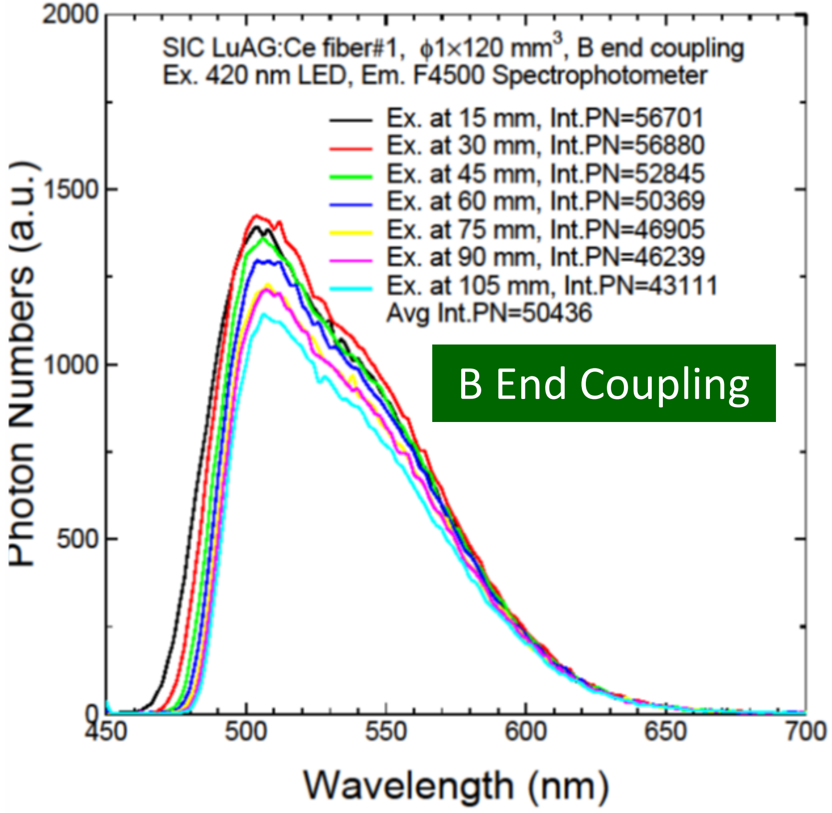


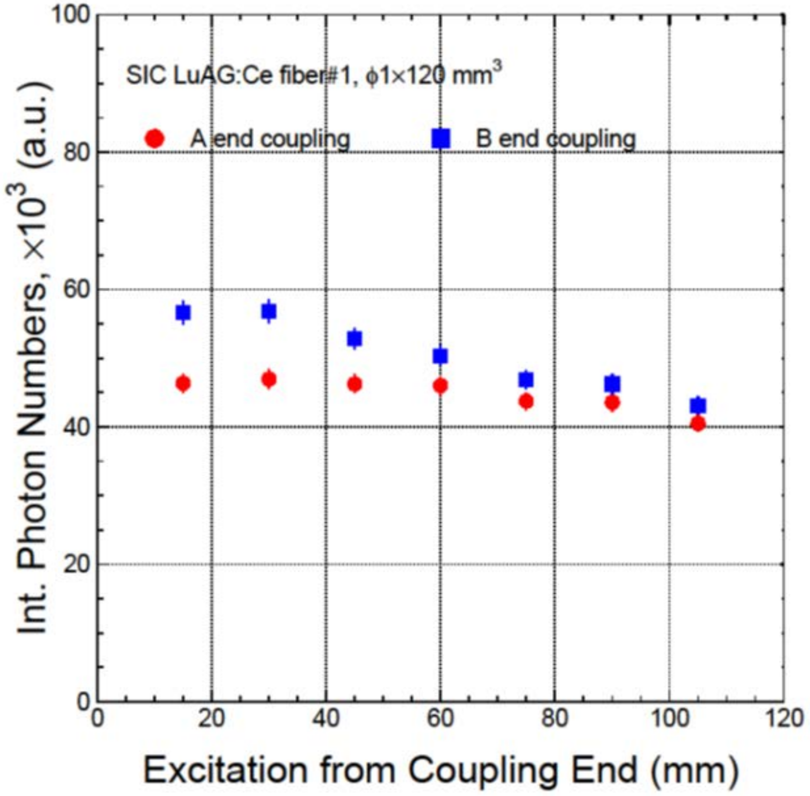
Light output measured for two alternative ends coupled to a F4500 spectrophotometer via a Φ1 mm quartz fiber with excitation at several positions along the LuAG fiber

Uniformity of Φ1×120 mm Fiber #1

Good intensity and uniformity observed for one coupling end

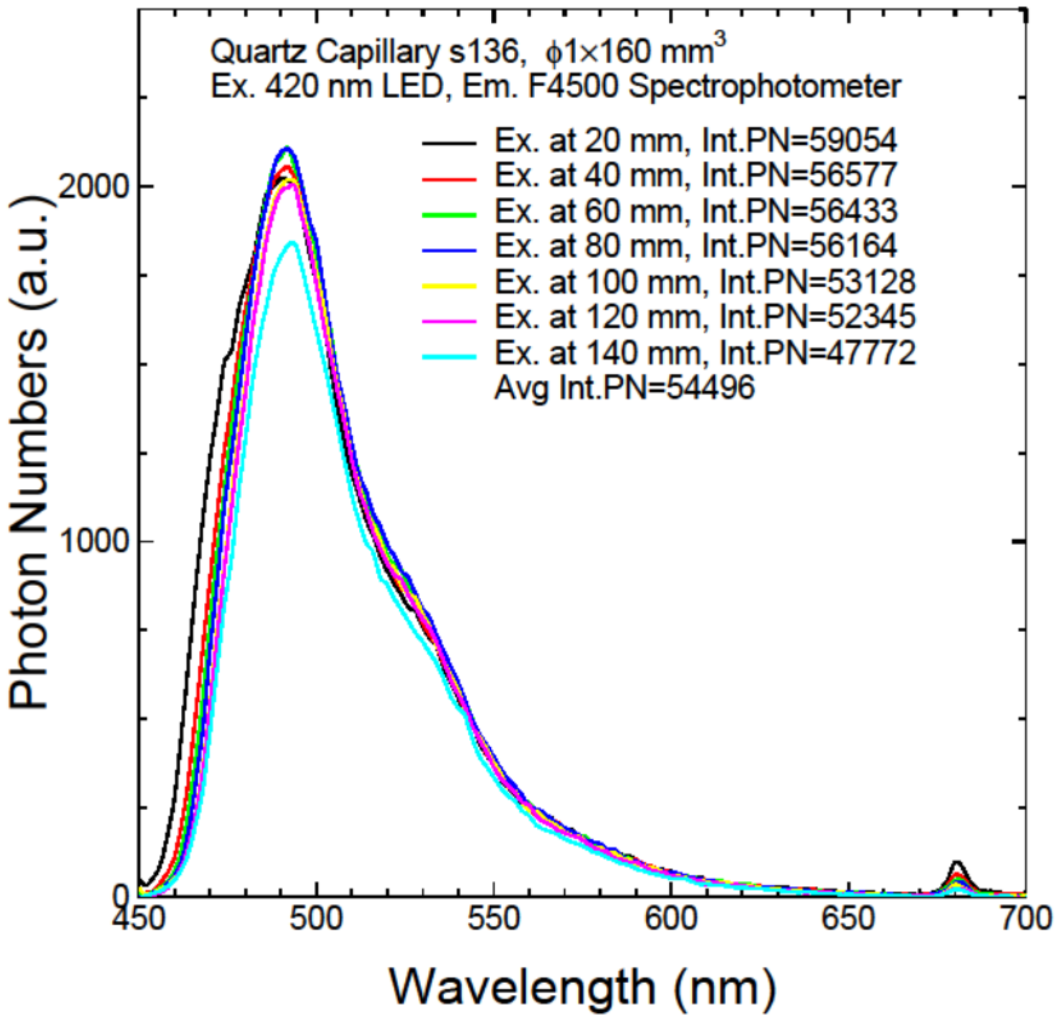


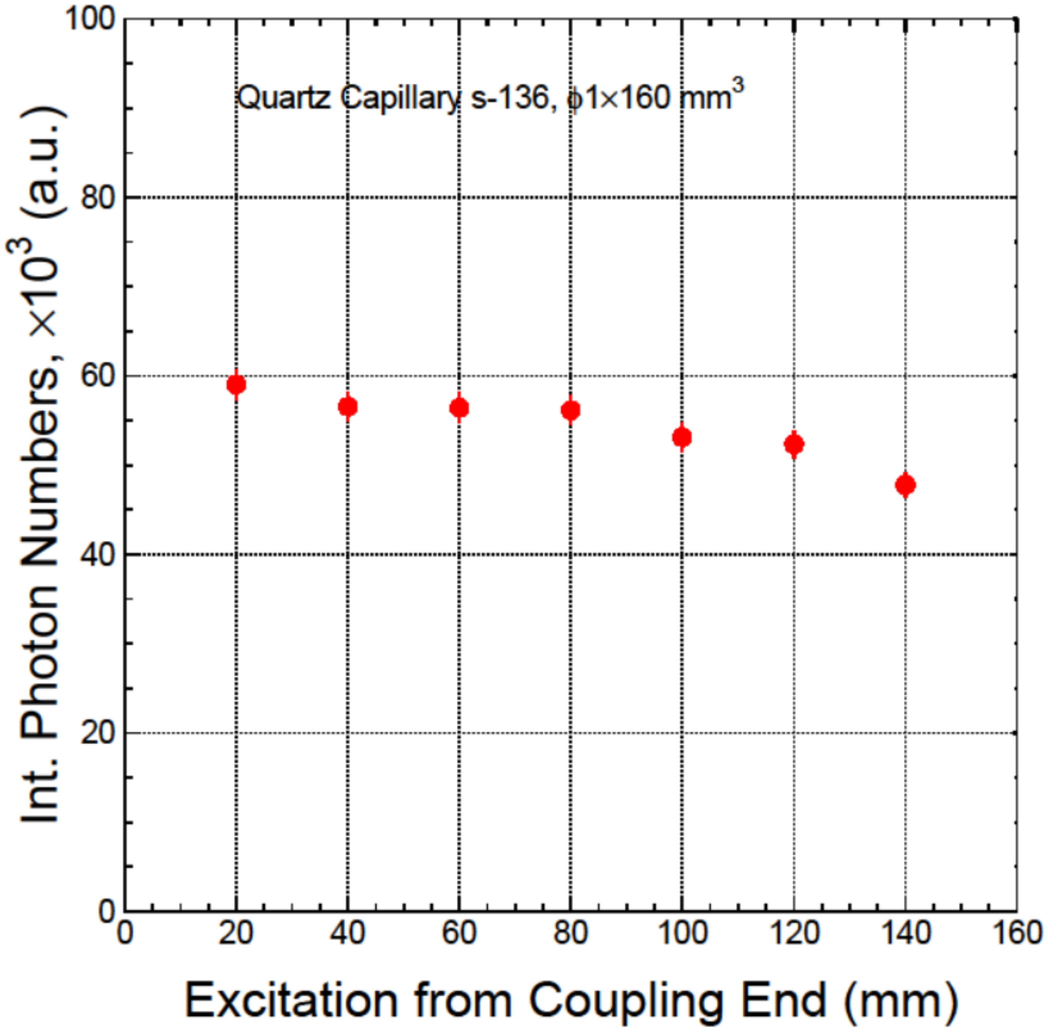




Uniformity of Φ1×160 mm Quartz Capillary

Good intensity and uniformity observed





Summary: 16 Φ1 mm LuAG:Ce Fibers

LuAG:Ce has comparable intensity and uniformity with Quartz Capillary

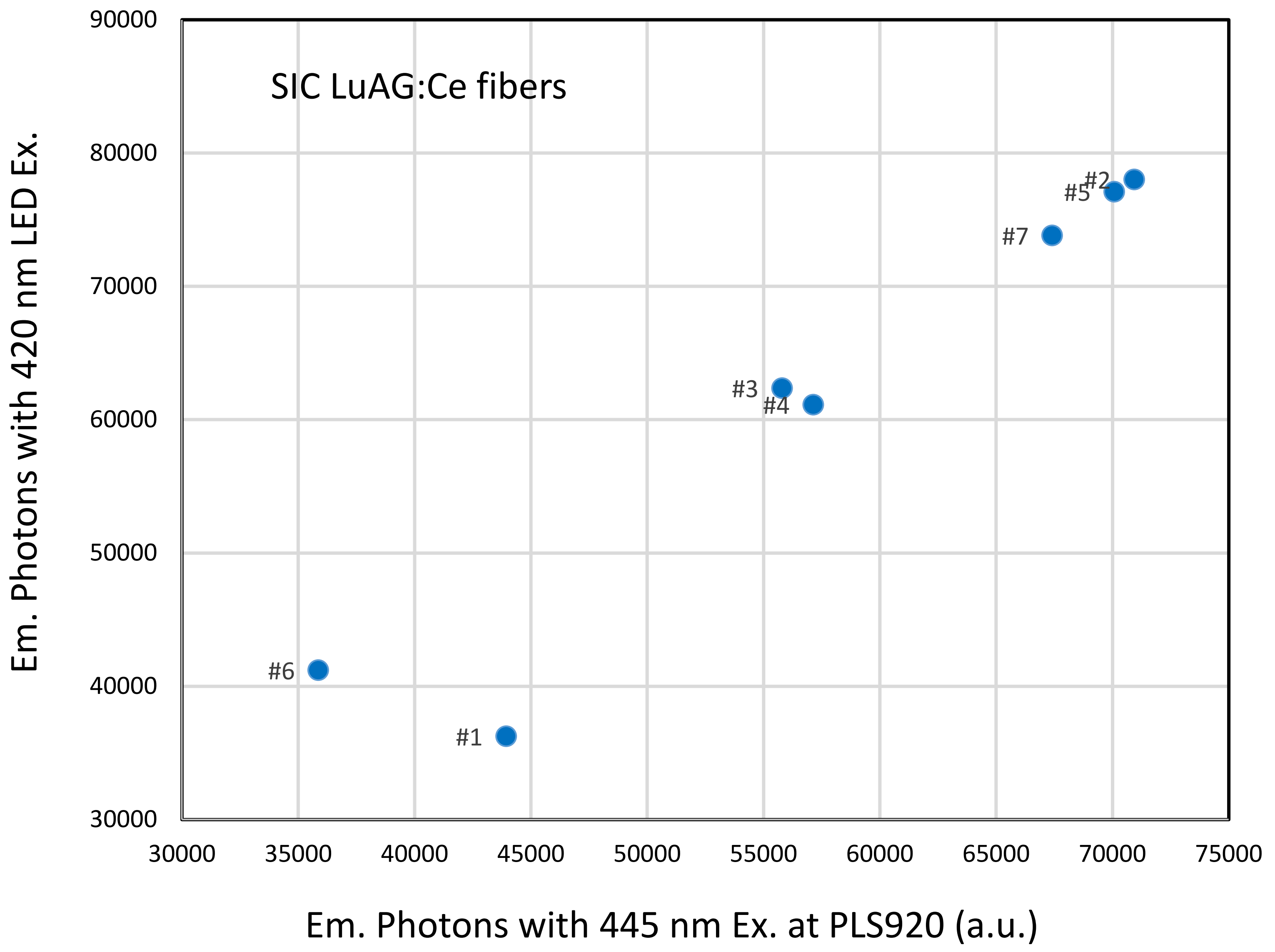
ϕ 1 mm LuAG:Ce Fibers	Length (cm)	Quantum Yield	A end coupling Ph# (a.u.)		B end coupling Ph# (a.u.)	
			Average	RMS (%)	Average	RMS (%)
#1	4	0.78 ±0.05	36099	1.9	43365	5.4
#2	4		71524	6.4	79592	3.6
#3	4	0.82 ±0.05	61897	1.5	62084	6.5
#4	4	0.78 ±0.05	61181	1.8	63105	4.0
#5	4		75425	2.6	78344	4.0
#6	4	0.85 ±0.05	39110	9.8	43159	3.6
#7	4		71058	6.8	75216	4.6
#8	4	0.82 ±0.05	75235	7.7	76735	0.9
#9	4	0.76 ±0.05	34032	2.7	48300	14.4
#10	4	0.78 ±0.05	36836	8.2	43566	9.1
#11	4	0.81 ±0.05	71689	12.5	73922	8.9
Y11 WLS	4	0.87 ±0.05	184690	35.6	232682	22.7
#1	6	0.88 ±0.05	48103	11.2	56280	2.6
#2	6	0.88 ±0.05	21229	69.0	23829	58.1
#3	6	0.79 ±0.05	34796	18.7	41303	24.0
#1	12		44715	5.0	50436	10.6
#2	12		36313	22.8	43746	20.5
Capillary s136	16		54496	6.8		

Summary

- Future HEP experiments require fast and radiation hard calorimetry. The **RADiCAL** concept utilizes bright, fast and radiation hard LYSO:Ce crystals and LuAG:Ce ceramic wavelength shifters for an ultra-compact, radiation hard and fast-timing shashlik calorimeter for the HL-LHC and FCC-hh.
- A total of 16 Φ1 mm LuAG:Ce ceramic fibers of 4, 6 and 12 cm were fabricated by using Laser Heated Pedestal Growth technique at SIC.
- The 1st batch LuAG:Ce WLS fibers show a quantum yield up to 88% with light output and uniformity comparable to quartz capillary.
- R&D will continue to improve optical quality of LuAG:Ce ceramic fibers. Beam tests are planned for a 3 × 3 LYSO/W/LuAG RADiCAL matrix to measure energy and timing resolution, and for individual cells to verify their radiation hardness against γ-rays and hadrons.

Work supported in part by the US Department of Energy Grants DE-SC0011925

Emission Intensities: 420 vs. 445 nm Ex.



Good correlation observed between emission intensities with 420 nm and 445 nm excitation.
A factor of three more light is observed with 445 nm excitation as compared to 420 nm