Hadron Induced Radiation Damage in Fast Heavy Inorganic Scintillators

Chen Hu, Christina Wang, Liyuan Zhang, Ren-Yuan Zhu

California Institute of Technology

Jon Kapustinsky, Xuan Li, Michael Mocko, Ron Nelson, Steve Wender, Zhehui Wang

Los Alamos National Laboratory

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Why Inorganic Scintillators?

- Precision photons and electrons enhance physics discovery potential in HEP experiments.
- Performance of crystal calorimeters is well understood for e/γ, and is promising for jets measurements :
  - The best possible energy resolution and position resolution;
  - Good e/γ identification and reconstruction efficiency;
  - Excellent jet mass resolution with dual readout, either C/S and F/S gate.
- Challenges at future HEP Experiments:
  - Radiation hard scintillators at the energy frontier: HL-LHC and FCC-hh;
  - Ultra-fast scintillators at the intensity frontier: Mu2e-II;
  - Cost-effective crystals for Higgs factory.

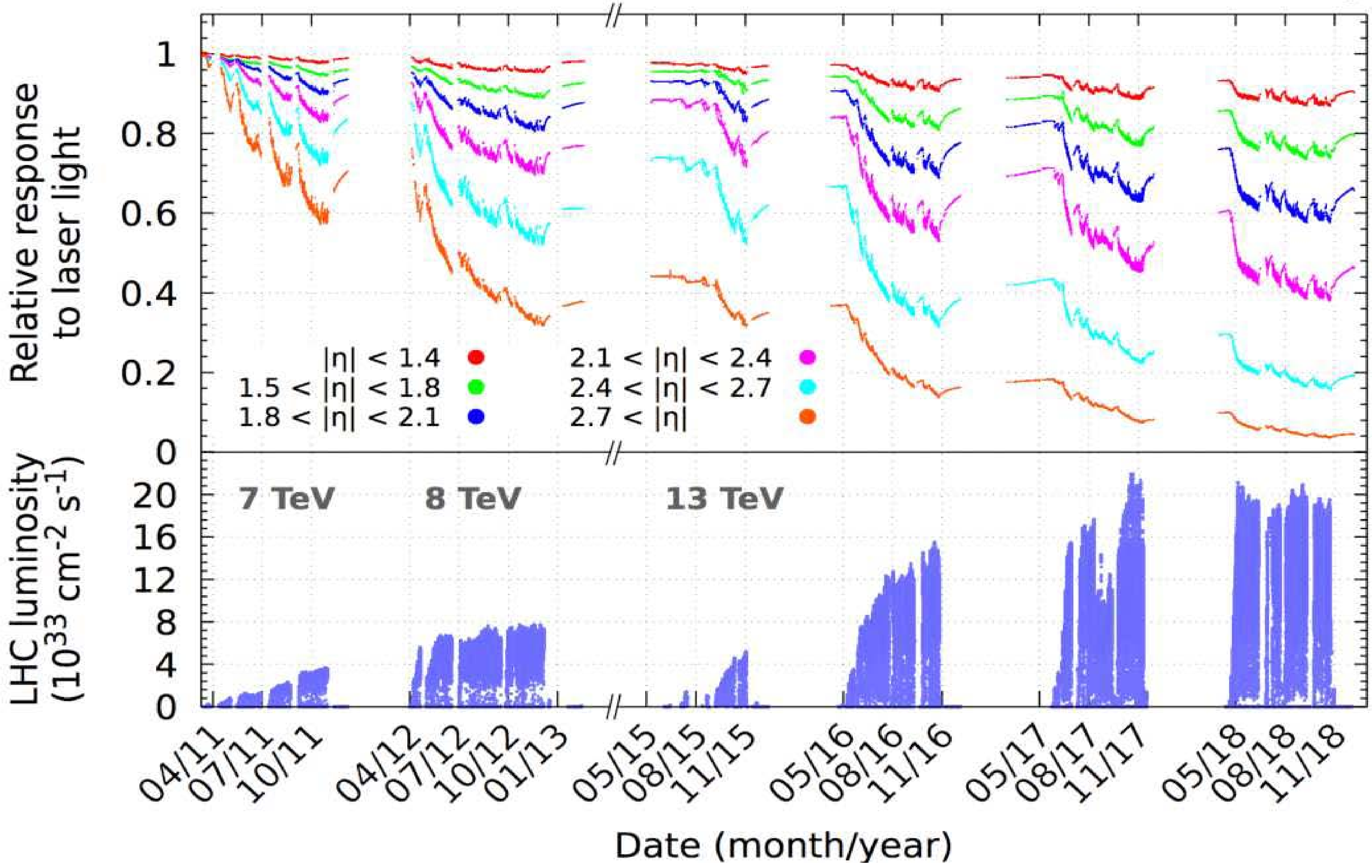
Motivation: 2019 DOE Basic Research Needs Study on Instrumentation: Calorimetry

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

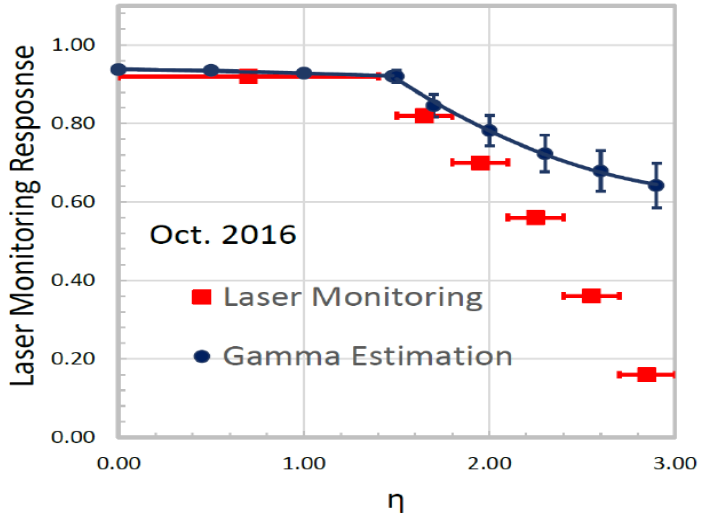
Goal: Development fast and ultrafast inorganic scintillators for future HEP and NP experiments: HL-LHC, FCC-hh and GHz Hard X-ray Imaging.
Snowmass 2022 White Paper: https://arxiv.org/abs/2203.06731

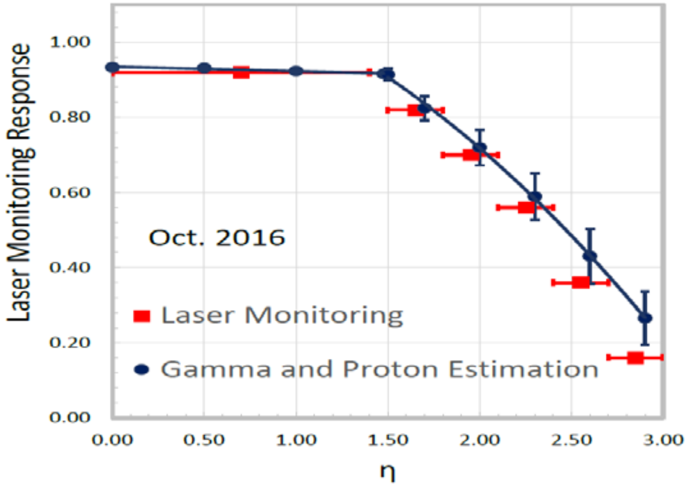
PWO: Damage by Gammas, Protons & Neutrons

F. Ferri, Calor 2022, https://indico.cern.ch/event/847884/timetable/#20220515



http://www.hep.caltech.edu/~zhu/talks/ryz_161028_PWO_mon.pdf

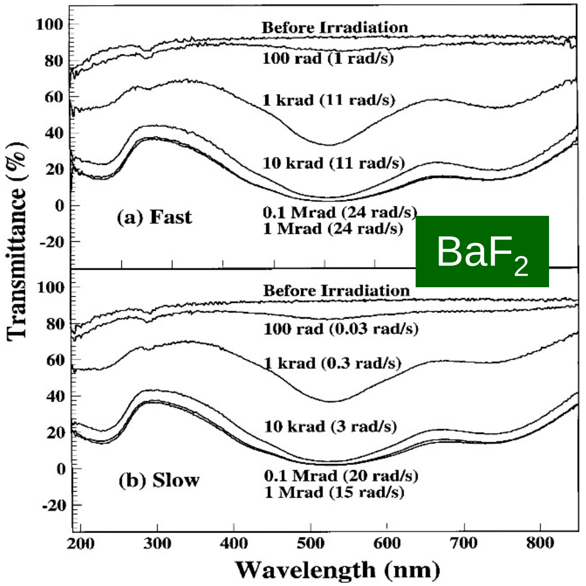


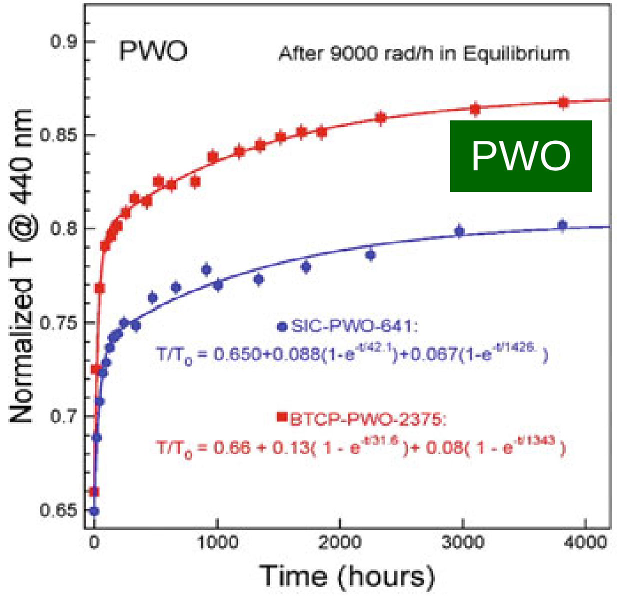


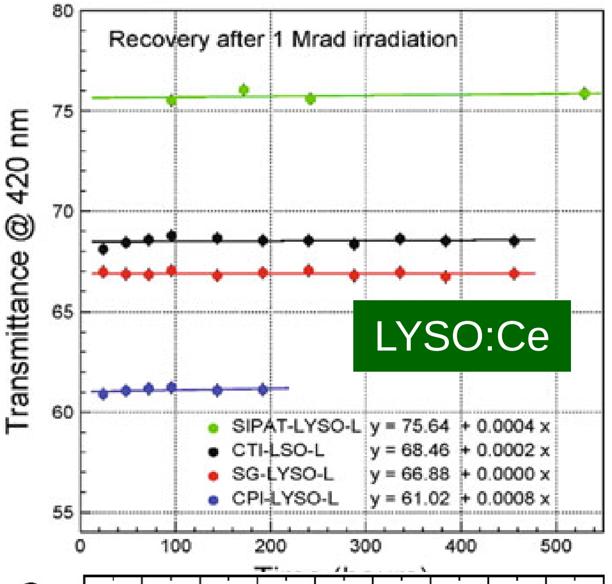
Use materials with monotonic damage: BaF_2, CsI, LYSO:Ce, LuAG:Ce

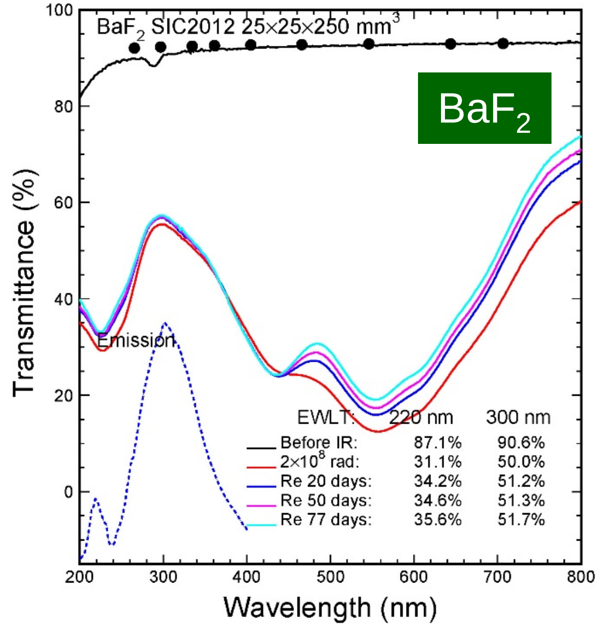
Neutron damage?

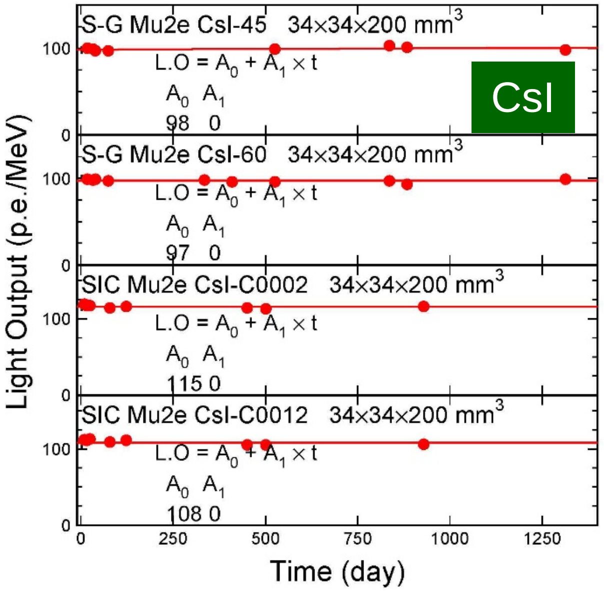
Damage Recovery after γ-rays

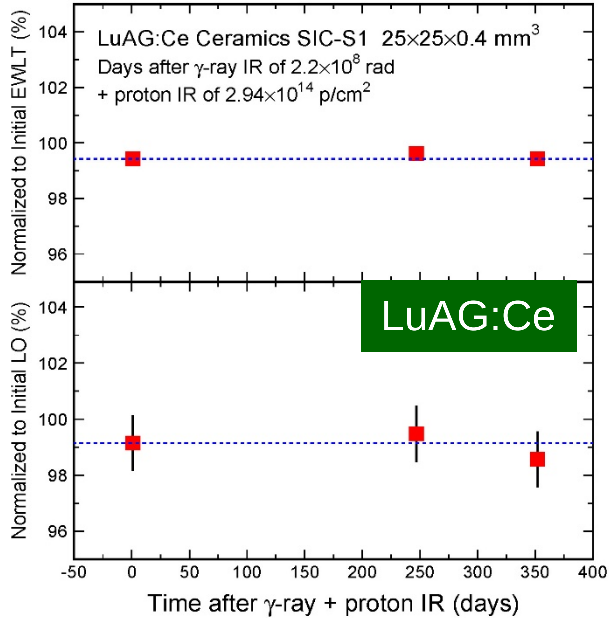












Damage in PWO recovers at room temperature, requiring frequent calibration/monitoring

No recovery in BaF_2, CsI and LYSO:Ce crystals, and LuAG:Ce ceramics, indicating dose-rate independent damage.

LANCE Experiments for Investigation on Hadron-Induced Damage in Inorganic Scintillators

Proton and Neutron irradiation carried out at the Blue Room & East Port of LANSCE starting 2014 and 2015, respectively

Year	2014	2015	2016	2017	2018	2022
800 MeV Protons at the Blue Room	6501	6990	7324	-	8051	9168
Broad Band Neutrons at the East Port	-	6991	7332	7638	-	-

Cancelled: Proton: 7640 (2017), 8362 (2019), 8588 (2020) & 8842 (2021) and Neutron: 8057 (2018), 8351 (2019) & 8507 (2020)

Thanks to the LANSCE PAC for awarding beam time for 9168 (2022)

Published Papers

Chen Hu, Liyuan Zhang, Ren-Yuan Zhu, Jin Li, Benxue Jiang, Jon Kapustinsky, Michael Mocko, Ron Nelson, Xuan Li, and Zhehui Wang, *Hadron-Induced Radiation Damage in LuAG:Ce Scintillating Ceramics*, IEEE TNS Nucl. Sci. **69** (2022) 181—186.

7638, 8051

Chen Hu, Fan Yang, Liyuan Zhang, Ren-Yuan Zhu, Jon Kapustinsky, Michael Mocko, Ron Nelson, and Zhehui Wang, *Neutron-Induced Radiation Damage in LYSO, BaF_2, and PWO Crystals*, IEEE TNS Nucl. Sci. **67** (2020) 1086-1092.

6991, 7332, 7638

Chen Hu, Fan Yang, Liyuan Zhang, Ren-Yuan Zhu, Jon Kapustinsky, Ron Nelson, and Zhehui Wang, Proton-Induced Radiation Damage in BaF_2, LYSO, and PWO Crystal Scintillators, IEEE TNS Nucl. Sci. **65** (2018) 1018-1024.

6501, 6990, 7324

C. Hu, F. Yang, L. Zhang, R.-Y. Zhu, J. Kapustinsky, R. Nelson and Z. Wang, "Neutron-Induced Radiation Damage in BaF2, LYSO and PWO Crystals“, paper N22-6 presented in NSS2017 and SCINT 2017 Conferences.

6991

F. Yang, L. Zhang, R.-Y. Zhu, J. Kapustinsky, R. Nelson and Z. Wang, “Proton-Induced Radiation Damage in Fast Crystal Scintillators”, SCINT 2017, IEEE Trans. Nucl. Sci, vol. **64**, (2017) 665-672.

6501, 6990

F. Yang, L. Zhang, R.-Y. Zhu, J. Kapustinsky, R. Nelson and Z. Wang, “Proton-Induced Radiation Damage in BGO, LFS, PWO and a LFS/W/Quartz Capillary Shashlik Cell”, paper N36-7 in NSS2016 Conference Record.

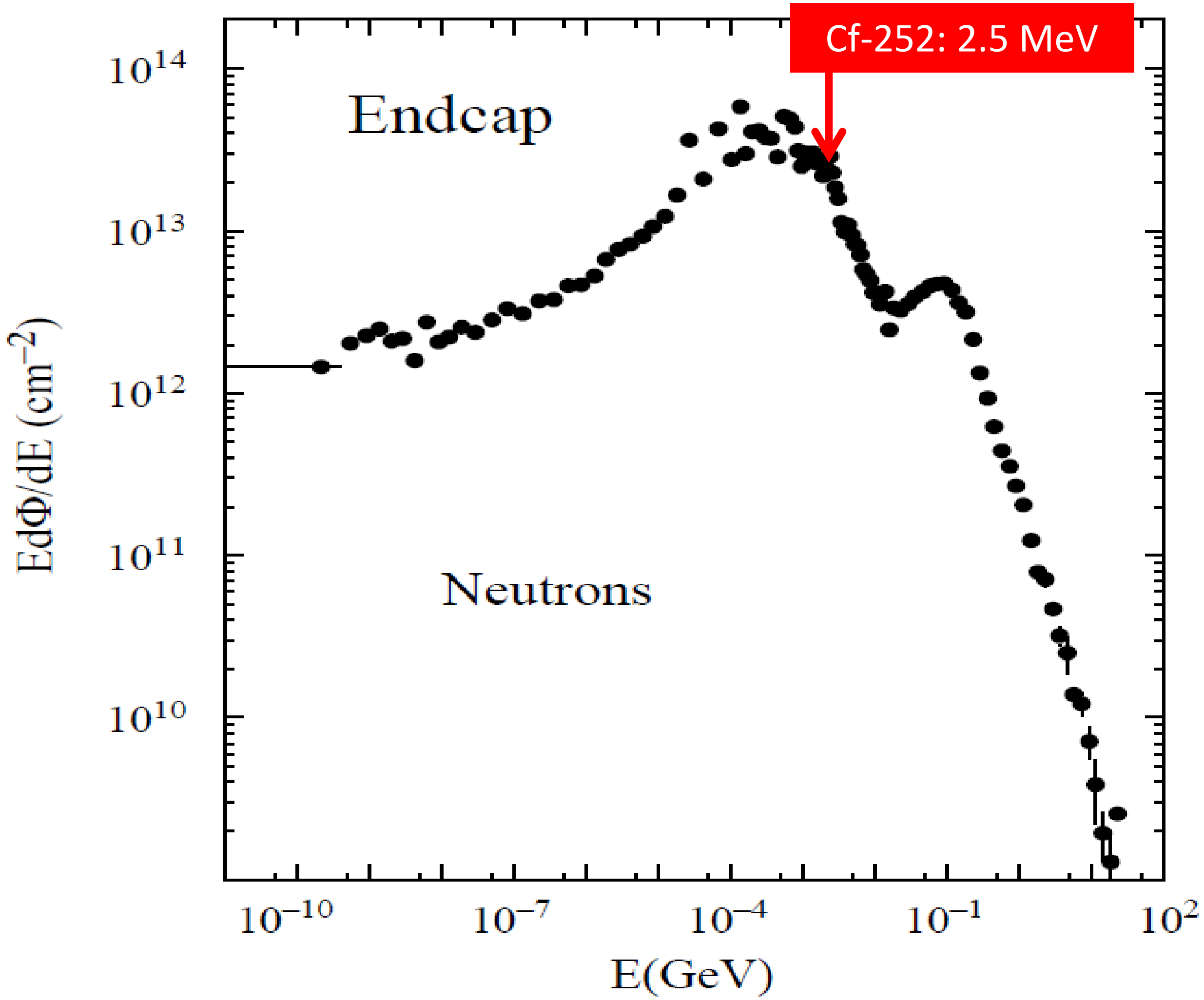
6501

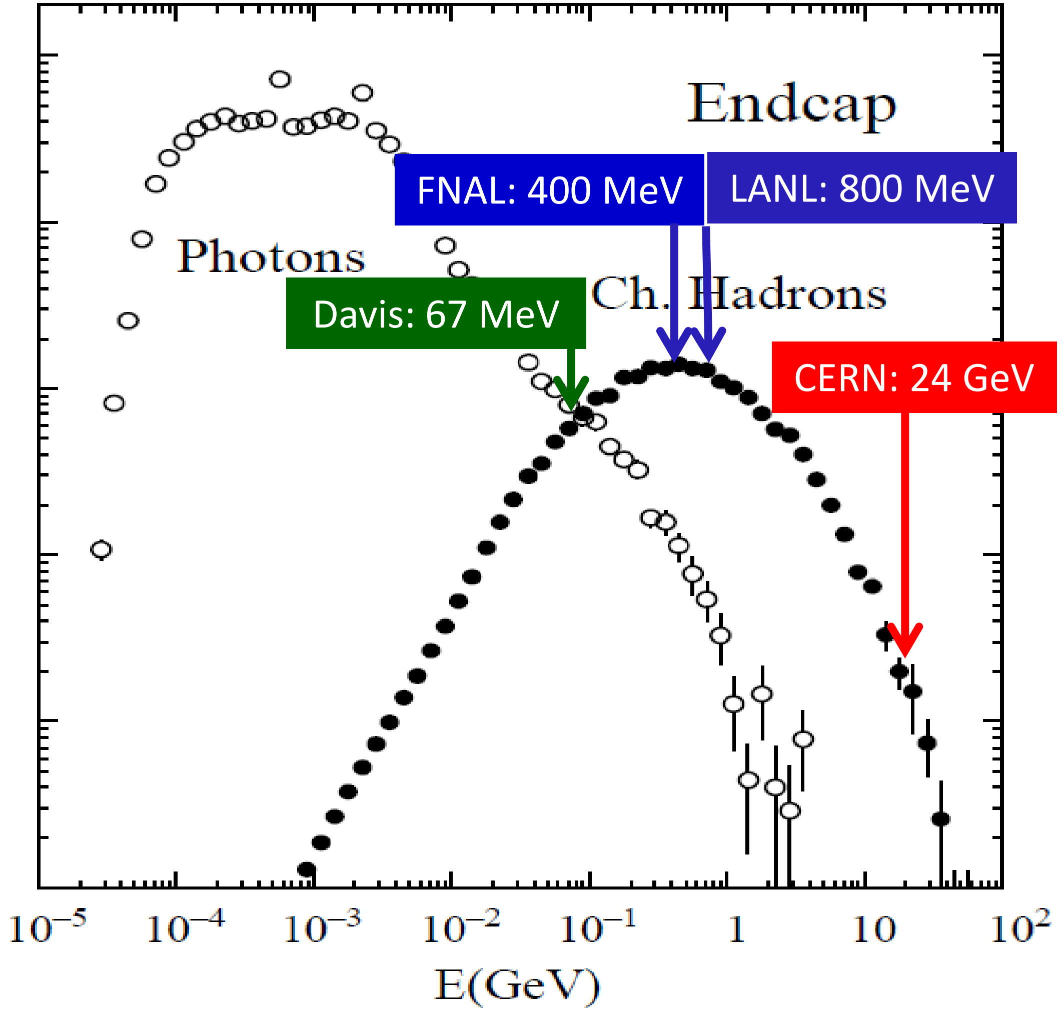
F. Yang, L. Zhang, R.-Y. Zhu, J. Kapustinsky, R. Nelson and Z. Wang, "Proton induced radiation damage in fast crystal scintillators," NIM A, vol. **824**, (2016) 726-728.

6501

Hadron Energy Spectra at the HL-LHC

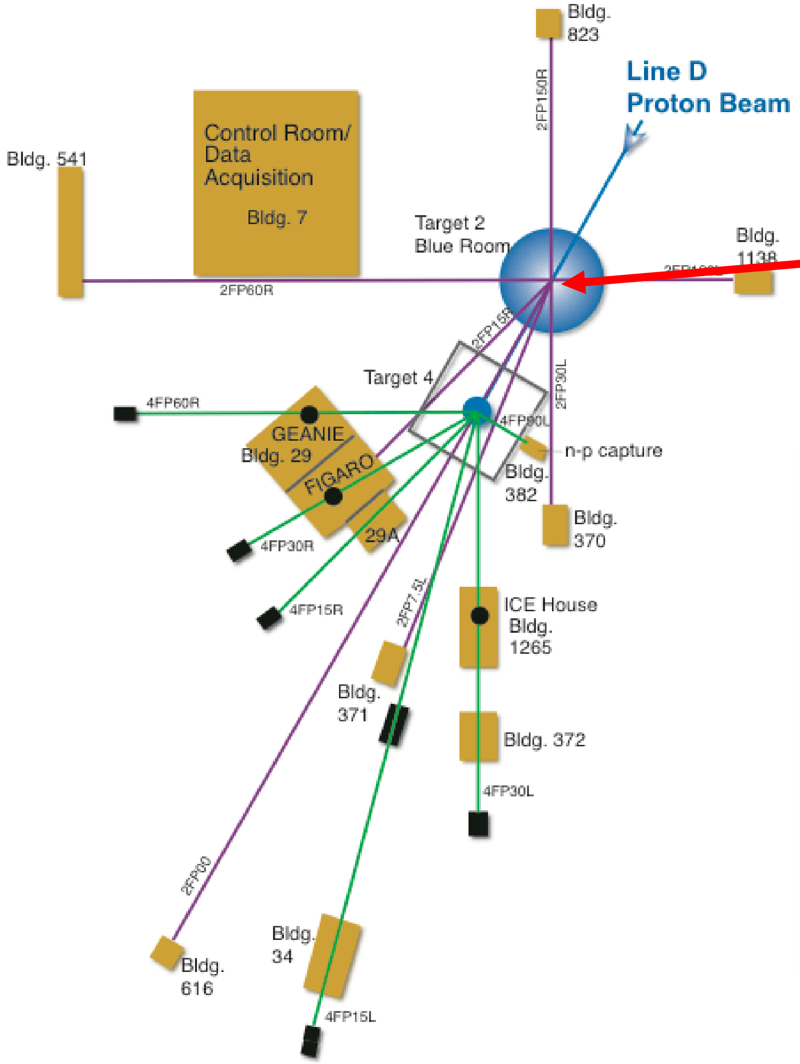
FLUKA simulations: neutrons and charged hadrons are peaked at MeV and hundreds MeV respectively
Proton and neutron irradiation was carried out in the Blue Room and East Port of LANSCE respectively





Proton Irradiation at the Blue Room

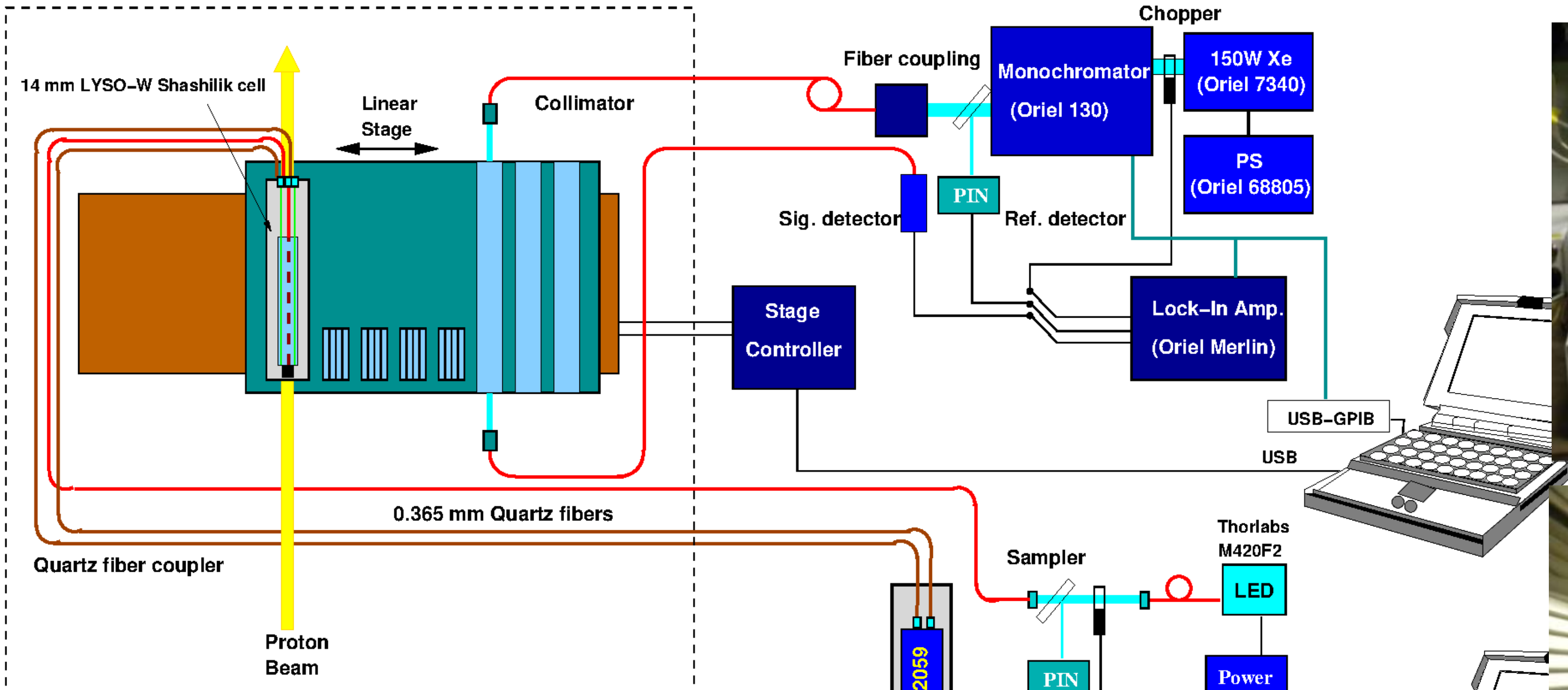
Los Alamos Neutron Science Center (LANSCE)

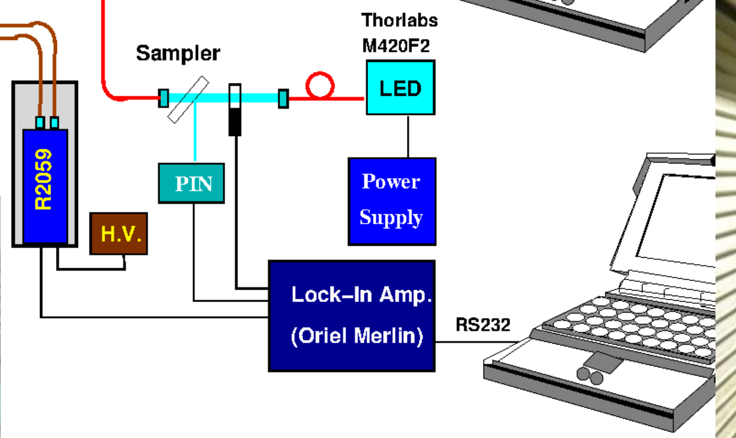


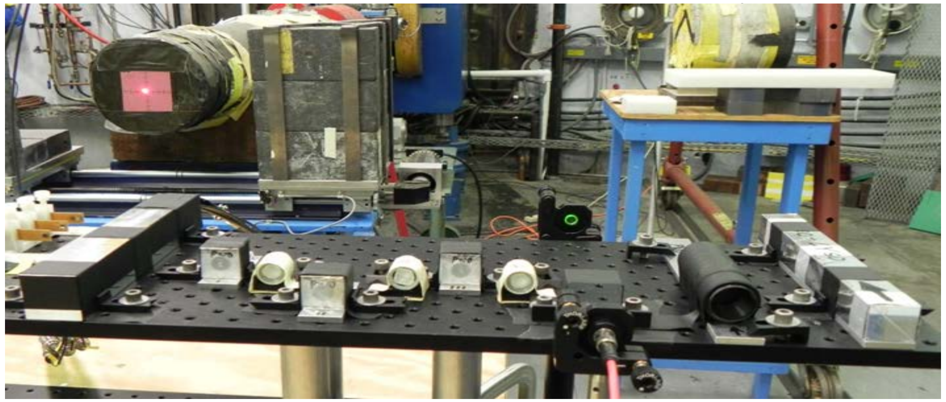
800 MeV proton beam (FWHM= 2.5 cm)

Environment/Source	Proton Flux ($p\ s^{-1}\ cm^{-2}$)	Fluence on Crystal ($p\ cm^{-2}$)
CMS FCAL (η=1.4) at HL-LHC	2.8×10^{5}	2.5×10^{13} / 3000 fb^{-1}
CMS FCAL (η=3.0) at HL-LHC	2.3×10^{6}	2.1×10^{14} / 3000 fb^{-1}
WNR facility of LANSCE	**Up to 2×10^{10}**	**Up to 3×10^{15}**

Proton Irradiation at the Blue Room



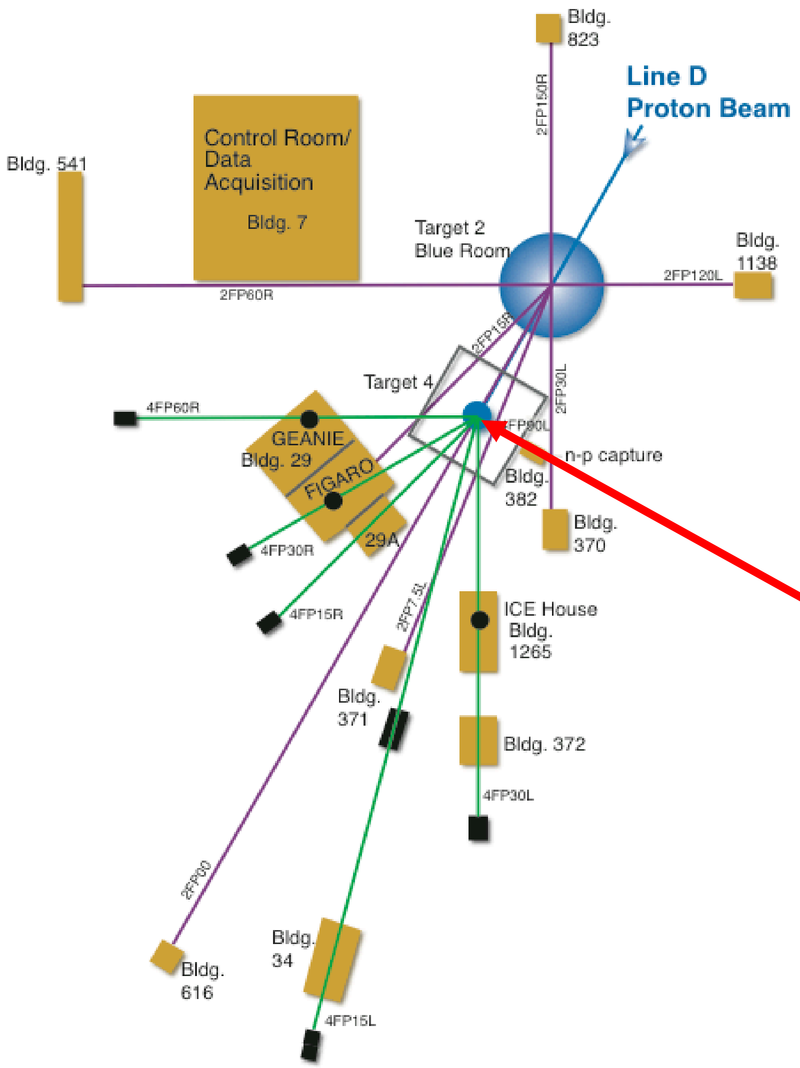




Setup of Experiment 7324

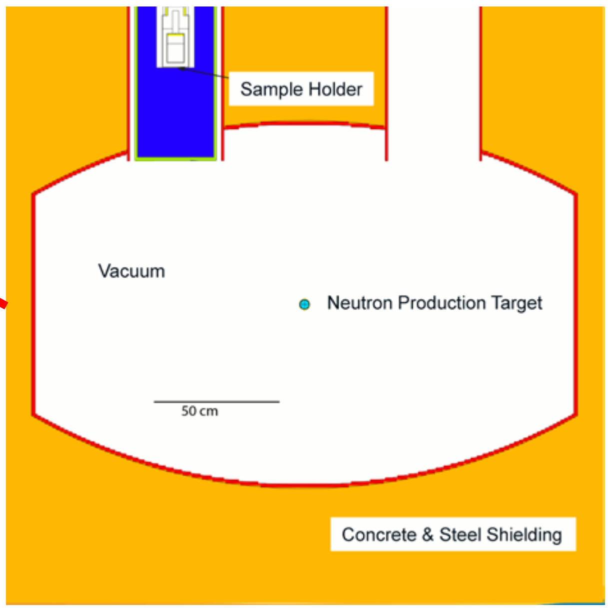
Neutron Irradiation in the East Port

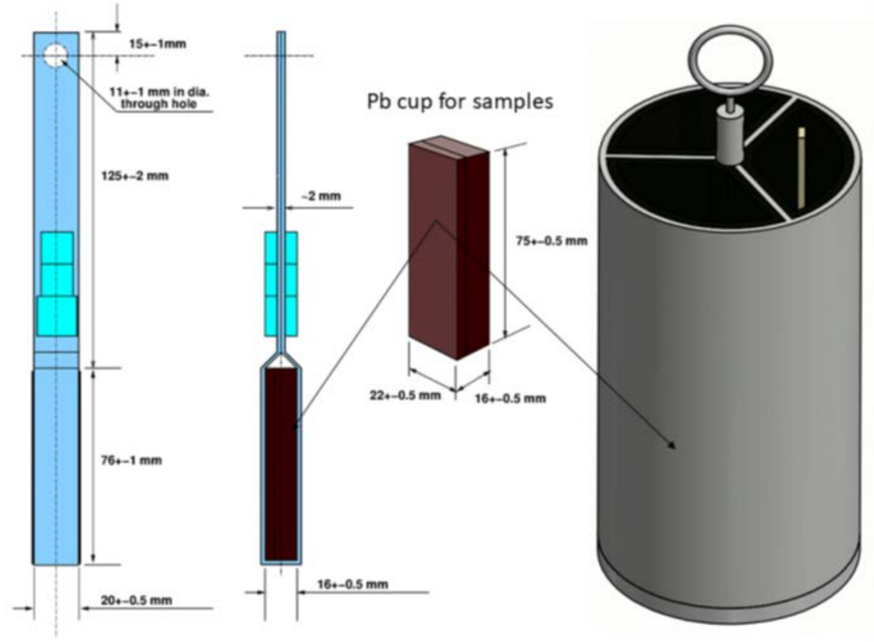
Los Alamos Neutron Science Center (LANSCE)



All samples in three groups were loaded at the beginning of beam run into the East Port of Target-4 at about 1.2 m away from the neutron production target. They were taken out one by one after reaching certain neutron fluence.

East Port

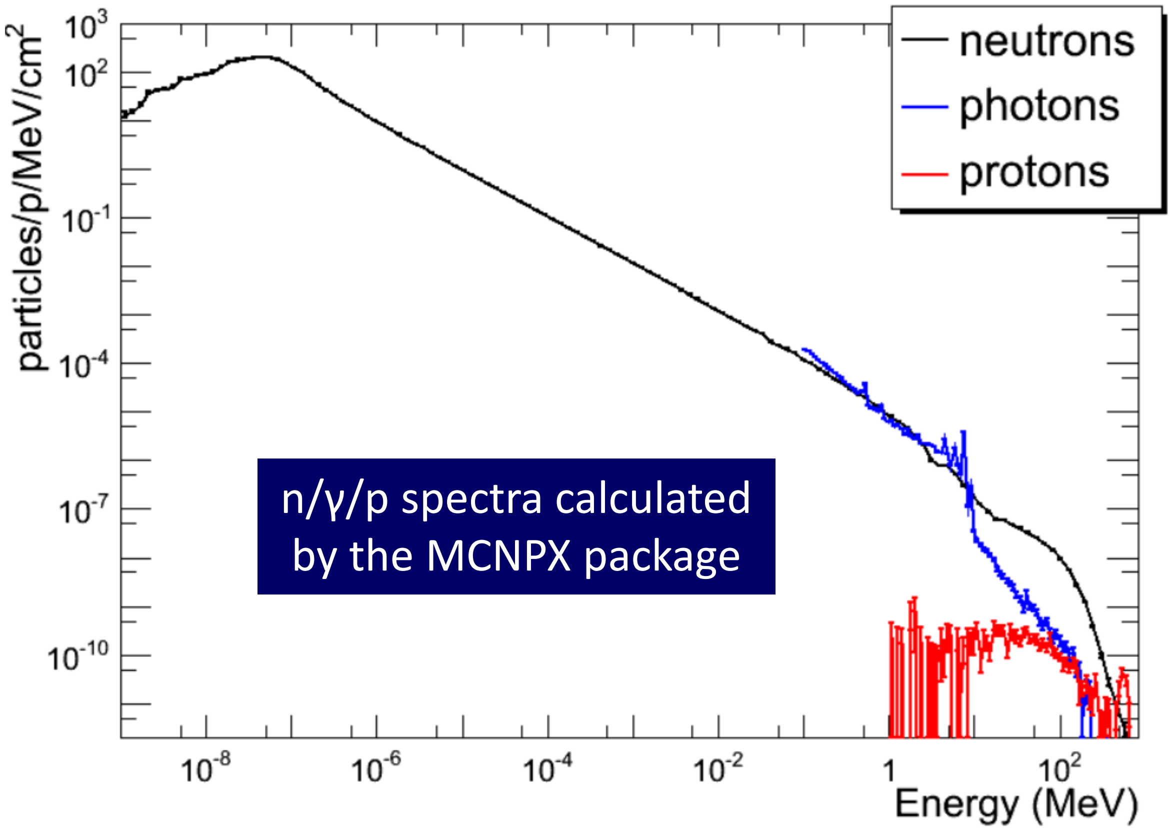


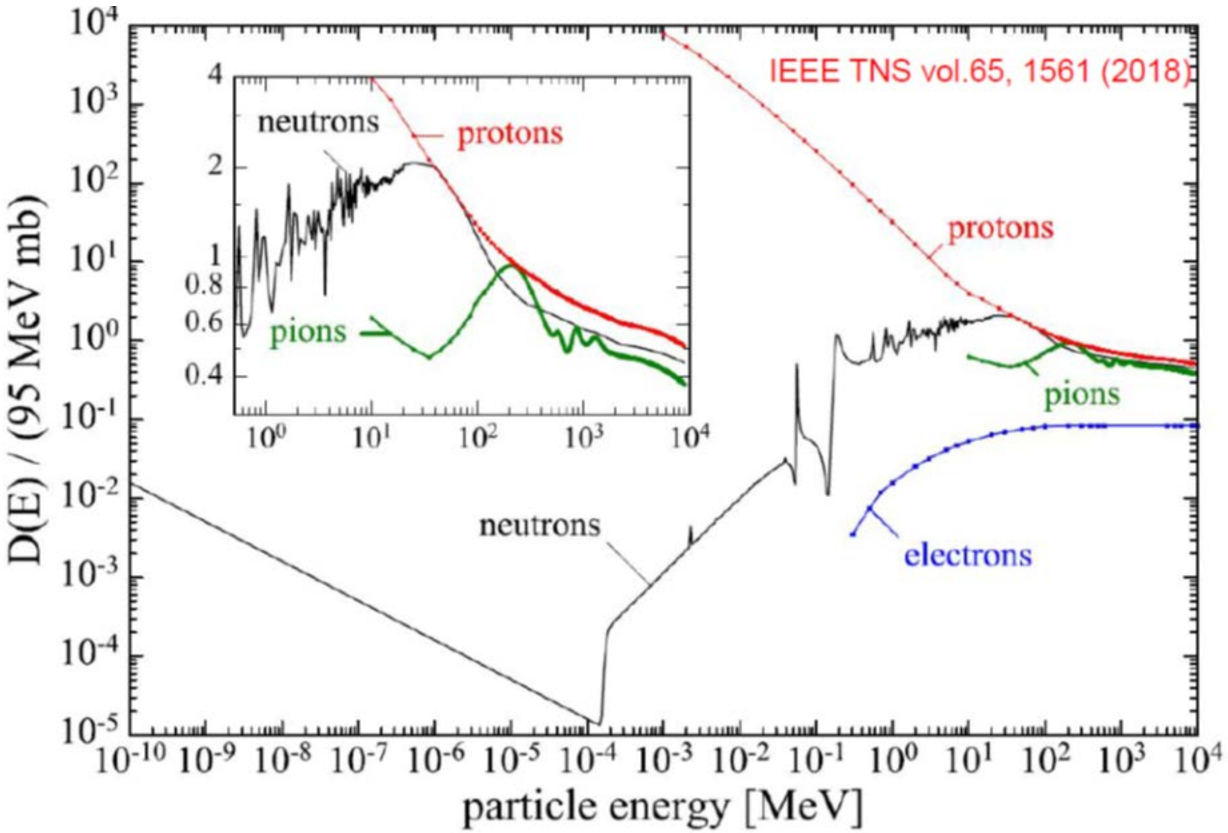


Setup of Experiment 7332

n/γ/p Spectra and 1 MeV n_{eq}

MCNPX (Monte Carlo N-Particle eXtended) package used to calculate the n/γ/p spectra tallied in the largest sample volume (averaging) with 1 MeV equivalent (n_{eq}) fluence calculated by using the damage factor in Silicon





Fast and Ultrafast Inorganic Scintillators

ANL APS: NIM A 940 (2019) 223-229 & Snowmass 2022 white paper https://doi.org/10.48550/arXiv/2203.06788

	BaF_2	BaF_2:Y	ZnO:Ga	YAP:Yb	YAG:Yb	β-Ga_2O_3	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm³)	4.89	4.89	5.67	5.35	4.56	5.94	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (°C)	1280	1280	1975	1870	1940	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	2.51	2.77	3.53	2.51	1.14	1.45	2.77	1.63	1.37	3.10
R_M (cm)	3.1	3.1	2.28	2.4	2.76	2.20	2.07	2.15	2.4	2.20	2.01	2.93
λ_I (cm)	30.7	30.7	22.2	22.4	25.2	20.9	20.9	20.6	22.4	21.5	19.5	27.8
Z_{eff}	51.6	51.6	27.7	31.9	30	28.1	64.8	60.3	31.9	51.8	58.6	33.3
dE/dX (MeV/cm)	6.52	6.52	8.42	8.05	7.01	8.82	9.55	9.22	8.05	8.96	9.82	6.57
λ_{peak} [a] (nm)	300 220	300 220	380	350	350	380	420	520	370	540	385	420
Refractive Index[b]	1.50	1.50	2.1	1.96	1.87	1.97	1.82	1.84	1.96	1.92	1.94	1.78
Normalized Light Yield[a,c]	42 4.8	1.7 4.8	6.6[d]	0.19[d]	0.36[d]	6.5 0.5	100	35[e] 48[e]	9 32	115	16 15	80
Total Light yield (ph/MeV)	13,000	2,000	2,000[d]	57[d]	110[d]	2,100	30,000	25,000[e]	12,000	34,400	10,000	24,000
Decay time[a] (ns)	600 0.5	600 0.5	<1	1.5	4	148 6	40	820 50	191 25	53	1485 36	75
LY in 1st ns (photons/MeV)	1200	1200	610[d]	28[d]	24[d]	43	740	240	391	640	125	318
LY in 1st ns/Total LY	9.2%	60%	31%	49%	22%	2.0%	2.5%	1.0%	3.3%	1.9%	1.3%	1.3%
40 keV Att. Leng. (1/e, mm)	0.106	0.106	0.407	0.314	0.439	0.394	0.185	0.251	0.314	0.319	0.214	0.334

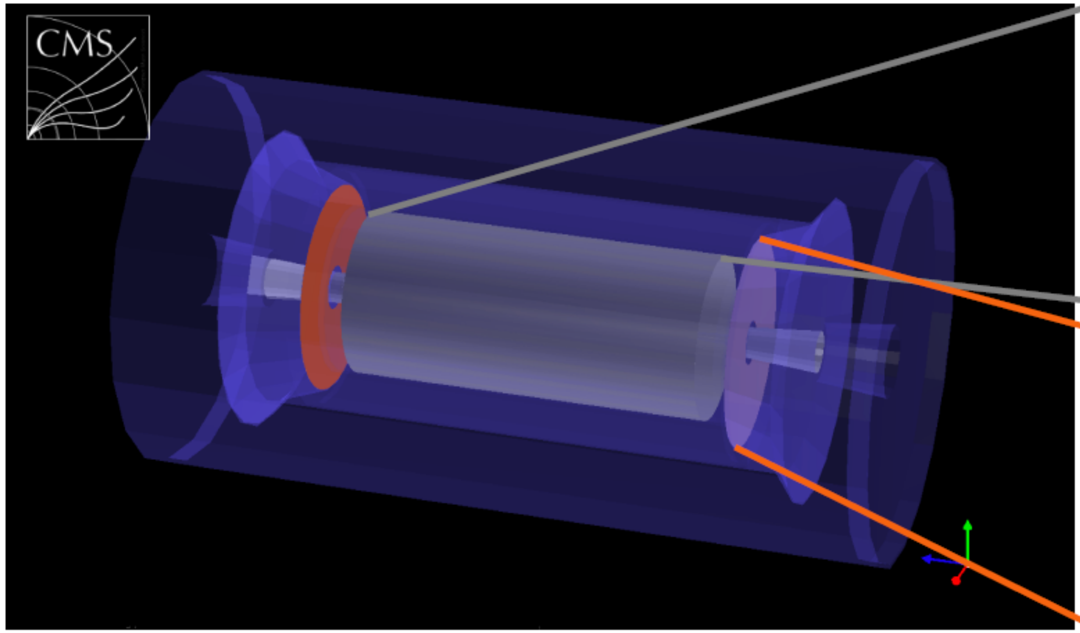
[a] top/bottom row: slow/fast component; [b] at the emission peak; [c] normalized to LYSO:Ce; [d] excited by alpha particles;
[e] ceramic with 0.3 Mg at% co-doping; [f] density for composition $Lu_{0.7}Y_{0.3}AlO_3$:Ce

LYSO:Ce for CMS Barrel Timing Layer

MTD performance goal: 30-40 ps at the start degrading to < 60 ps at 3000 fb^{-1}

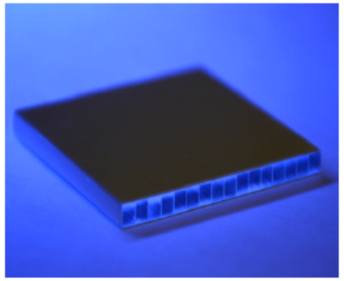
Barrel Timing Layer: arrays of LYSO crystal bars connected to SiPMs at both ends and readout by TOFHIR

Ultrafast inorganic scintillators would help to break the pico-second time barrier



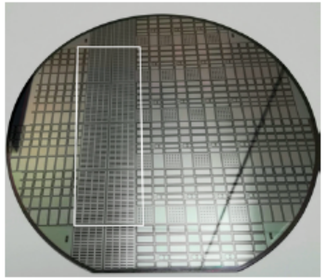
BTL: LYSO bars + SiPM read-out

- TK / ECAL interface ~ 45 mm thick
- $|\eta|$< 1.45 and p_T > 0.7 GeV
- Active area ~ 38 m^2 ; 332k channels
- Fluence at 3 ab^{-1}: 2×10^{14} n_{eq}/cm^2



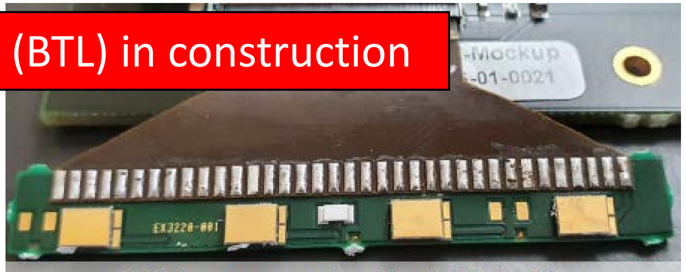
ETL: Si with internal gain (LGAD)

- On the HGC nose ~ 65 mm thick
- 1.6 < $|\eta|$ < 3.0
- Active area ~ 14 m^2; ~ 8.5M channels
- Fluence at 3 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2



LYSO + SiPM with Thermal Electric Cooler (TEC) for CMS Barrel Timing Layer (BTL) in construction

SiPM array prototypes from FBK



SiPM arrays mockup for TECs testing

Expected Radiation at the HL-LHC

CMS BTL/ETL: 4.8/68 Mrad, $2.5\times10^{13}/2.1\times10^{14}$ p/cm^2 & $2.9\times10^{14}/2.4\times10^{15}$ n_{eq}/cm^2

CMS MTD	η	n_{eq} (cm^{-2})	n_{eq} Flux ($cm^{-2}s^{-1}$)	Proton (cm^{-2})	p Flux ($cm^{-2}s^{-1}$)	Dose (Mrad)	Dose rate (rad/h)
Barrel	0.00	2.5E+14	2.8E+06	2.2E+13	2.4E+05	2.7	108
Barrel	1.15	2.7E+14	3.0E+06	2.4E+13	2.6E+05	3.8	150
Barrel	**1.45**	**2.9E+14**	**3.2E+06**	**2.5E+13**	**2.8E+05**	**4.8**	**192**
Endcap	1.60	2.3E+14	2.5E+06	2.0E+13	2.2E+05	2.9	114
Endcap	2.00	4.5E+14	5.0E+06	3.9E+13	4.4E+05	7.5	300
Endcap	2.50	1.1E+15	1.3E+07	9.9E+13	1.1E+06	26	1020
Endcap	**3.00**	**2.4E+15**	**2.7E+07**	**2.1E+14**	**2.3E+06**	**68**	**2700**

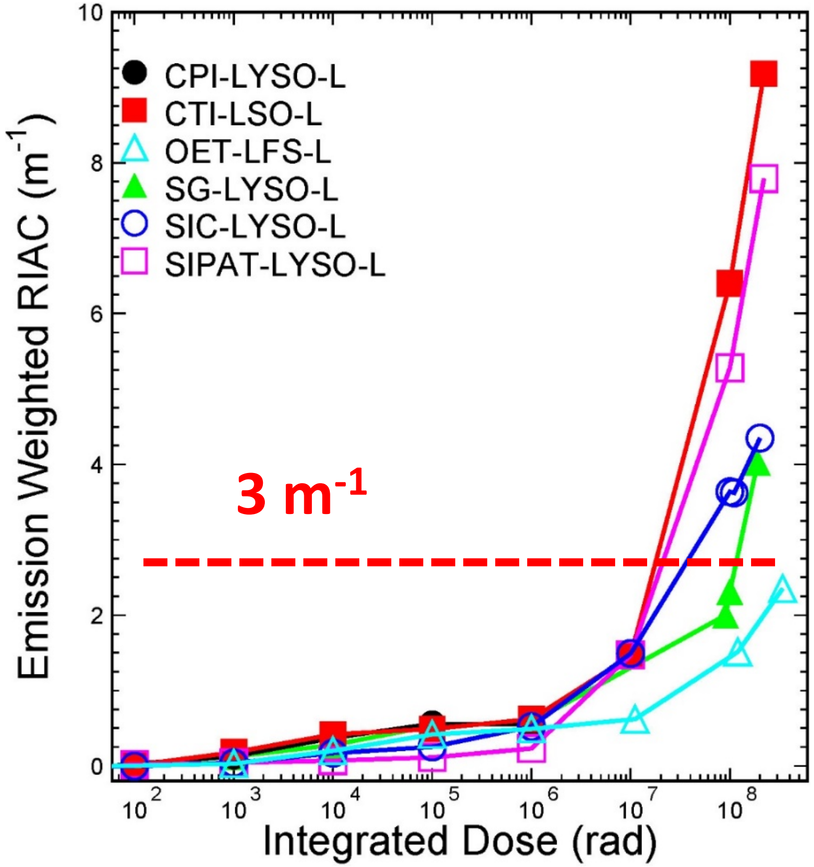
FCC-hh: up to 0.1 & 500 Grad and 3×10^{16} & 5×10^{18} n_{eq}/cm^2 at EMEC & EMF, respectively

M. Aleksa *et al.*, Calorimeters for the FCC-hh CERN-FCCPHYS-2019-0003, Dec 23, 2019

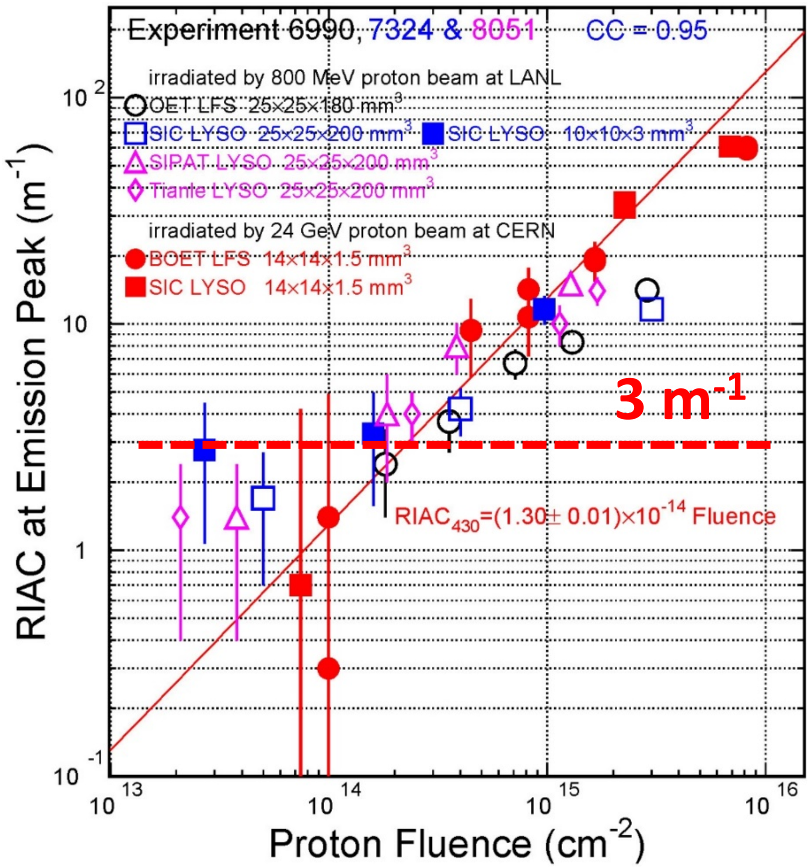
LYSO Radiation Hardness

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

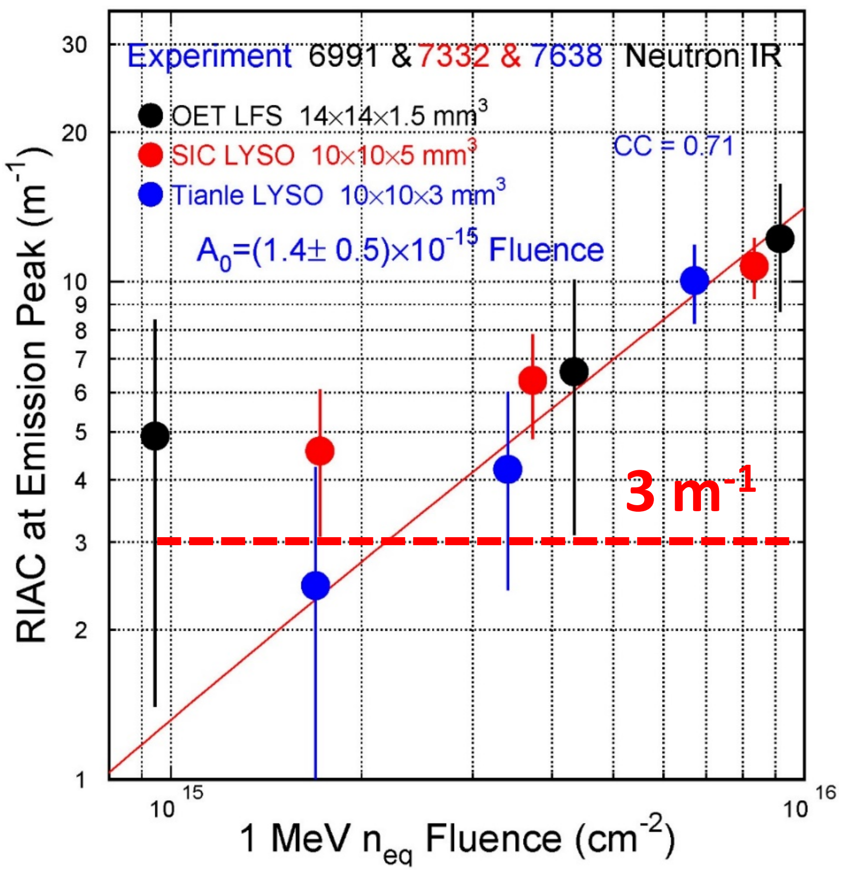
NIM A **824** (2016) 726-728



IEEE TNS **64** (2017) 665-672 , **65** (2018) 1018-1024



IEEE TNS **67** (2020) 1086-1092

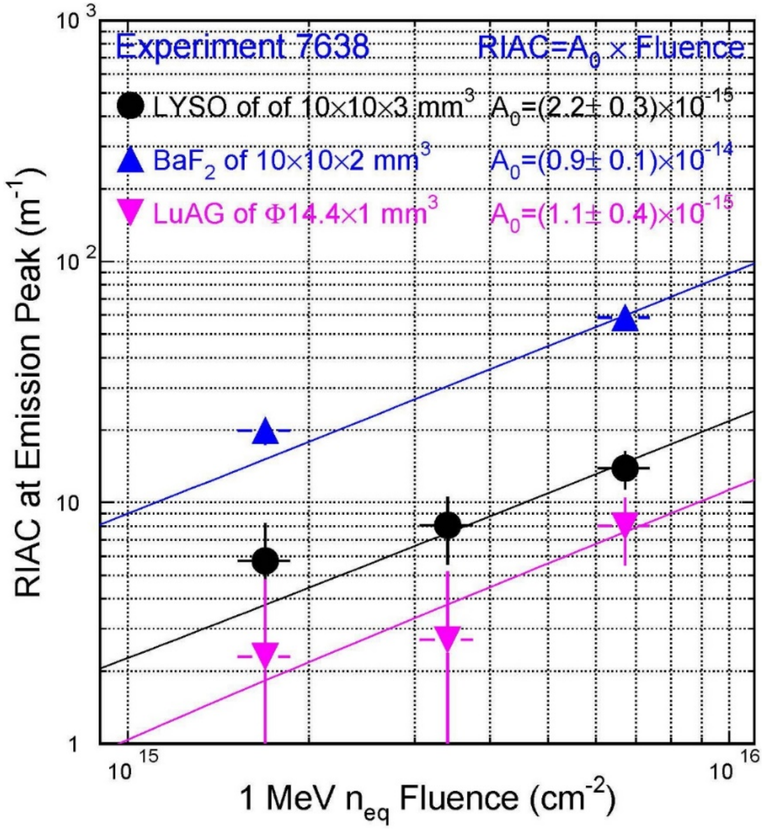


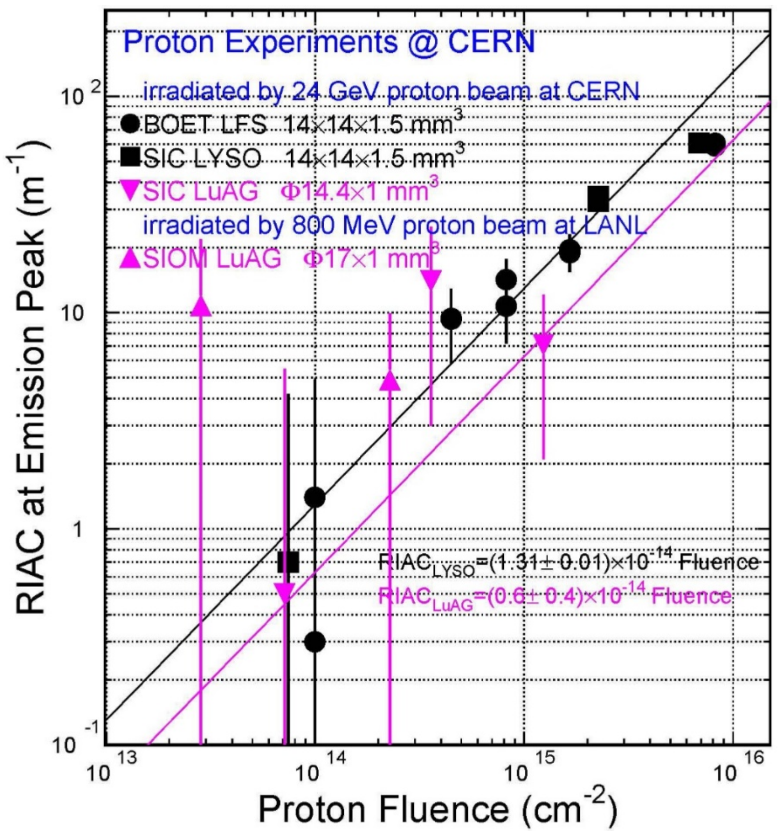
Crystals damaged by both proton and neutron. Damage by proton is larger than that from neutrons because of ionization energy loss in addition to displacement and nuclear breakup

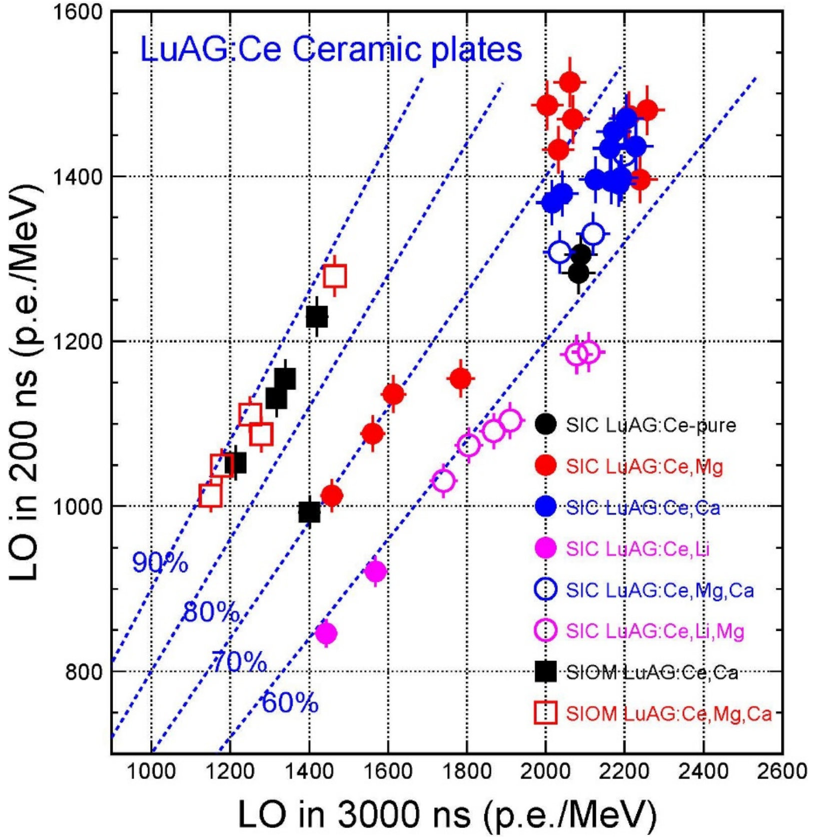
LuAG:Ce Ceramics Radiation Hardness

LuAG:Ce ceramics show a factor of two smaller RIAC values than LYSO:Ce up to 6.7×10^{15} n_{eq}/cm^2 and 1.2×10^{15} p/cm^2, promising for FCC-hh

IEEE TNS **69** (2022) 181-186

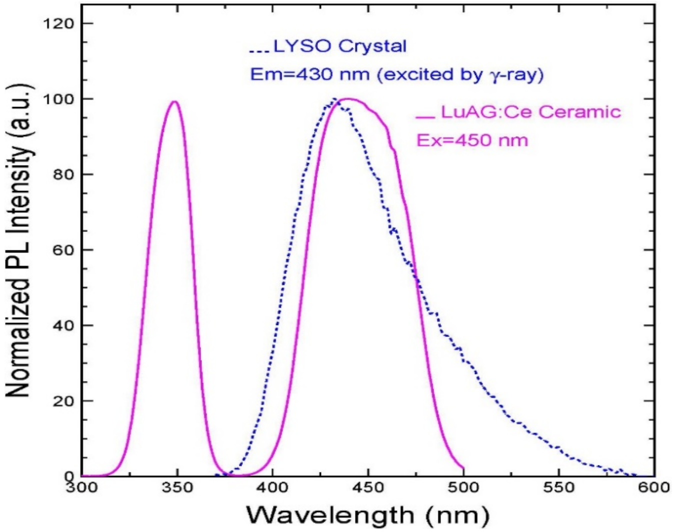






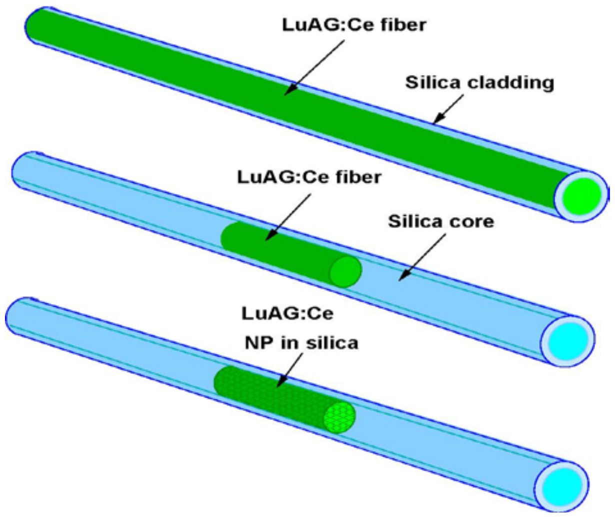
R&D on slow component suppression by Ca co-doping, and radiation hardness by ɣ/p/n

RADiCAL: LYSO/LuAG Shashlik ECAL

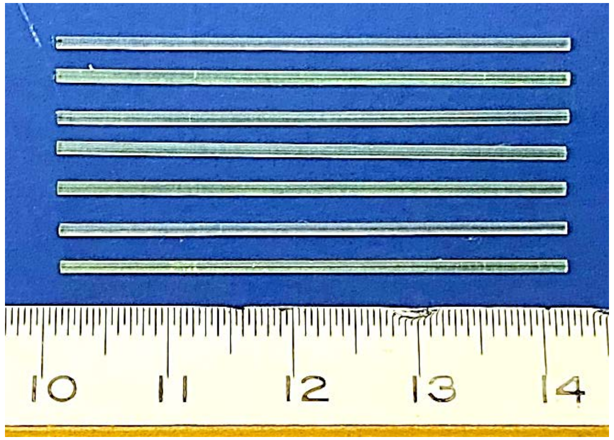


Excitation of LuAG:Ce ceramics matches well LYSO:Ce emission:

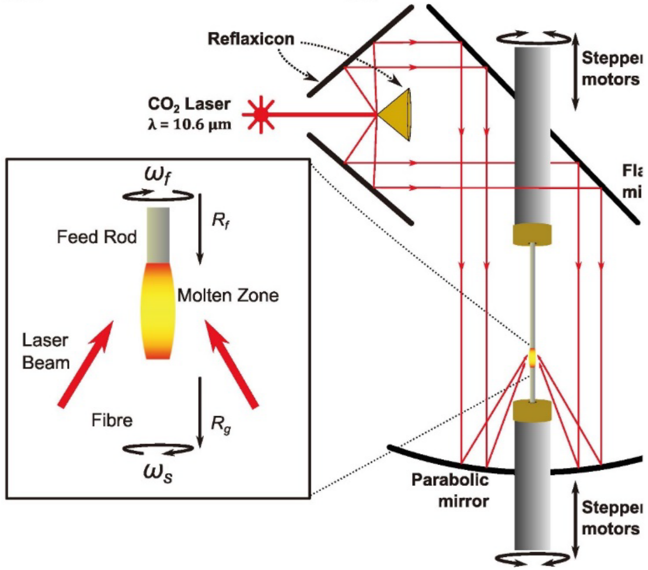
RADiation hard **i**nnovative **CAL**orimetry Snowmass 2022 White Paper: https://doi.org/10.48550/arXiv.2203.12806

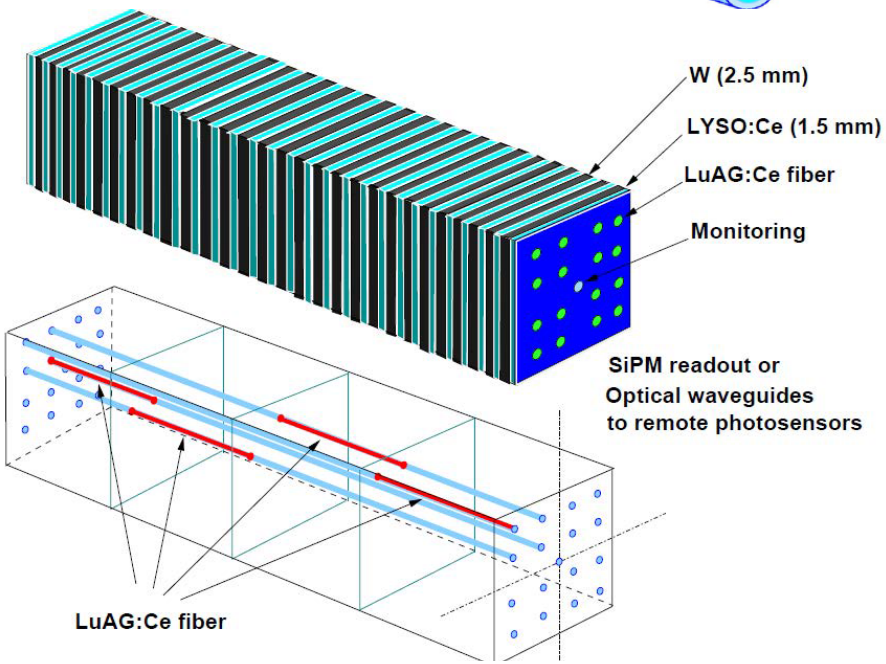


Φ1x40 mm³ SIC LuAG:Ce Ceramic LHPG fibers



Laser Heated Pedestal Growth

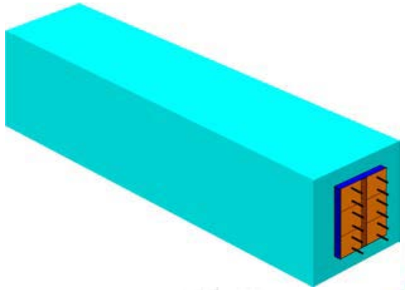




Mu2e Calorimeter Requirements

Mu2e-I: 1,348 CsI of 34 x 34 x 200 mm^3

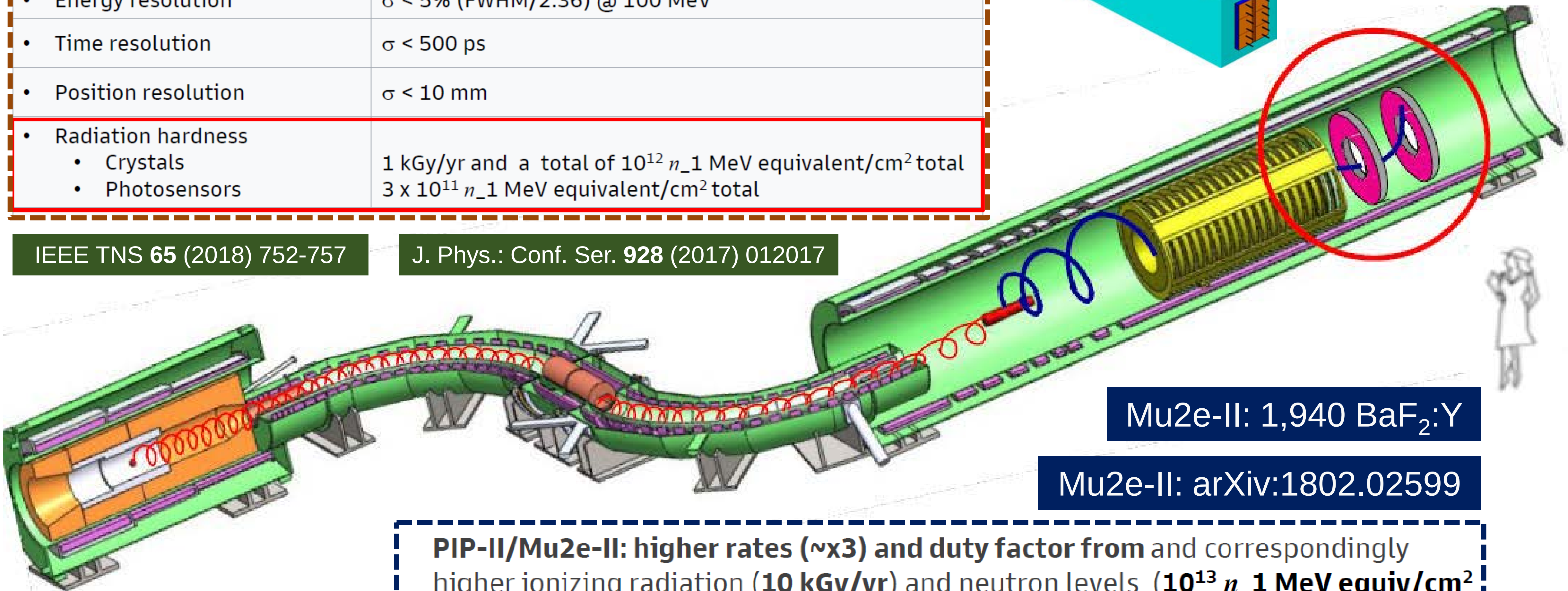
CsI+SiPM



• Energy resolution	σ < 5% (FWHM/2.36) @ 100 MeV
• Time resolution	σ < 500 ps
• Position resolution	σ < 10 mm
• Radiation hardness • Crystals • Photosensors	 1 kGy/yr and a total of 10^{12} n_1 MeV equivalent/cm^2 total 3 x 10^{11} n_1 MeV equivalent/cm^2 total

IEEE TNS **65** (2018) 752-757

J. Phys.: Conf. Ser. **928** (2017) 012017



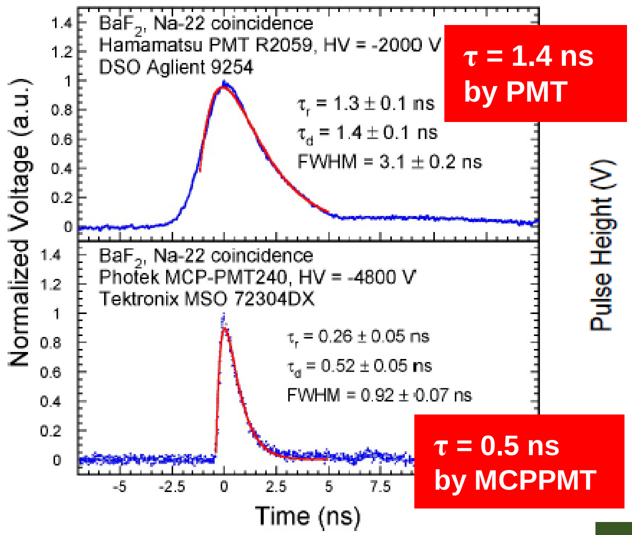
Mu2e-II: 1,940 BaF_2:Y

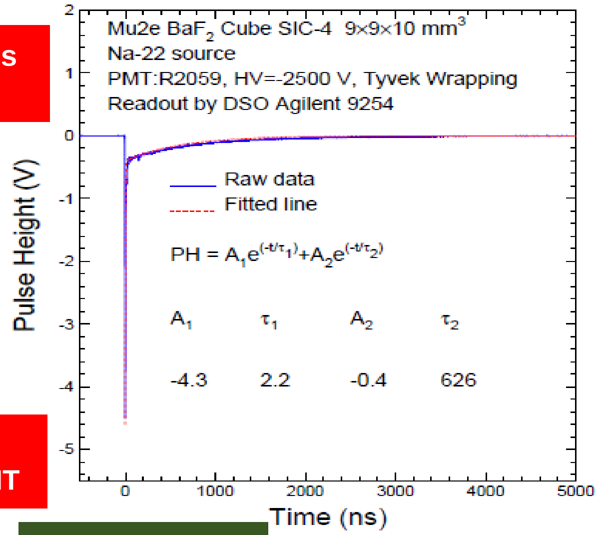
Mu2e-II: arXiv:1802.02599

PIP-II/Mu2e-II: higher rates (~x3) and duty factor from and correspondingly higher ionizing radiation (**10 kGy/yr**) and neutron levels (**10^{13} n_1 MeV equiv/cm^2 total**), which are particularly important at the inner radius of disk 1

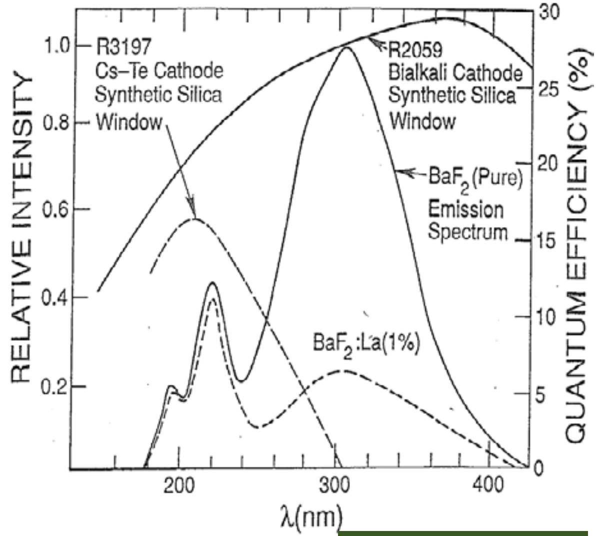
Ultrafast and Radiation Hard BaF_2

IEEE TNS **67** (2020) 1014-1019



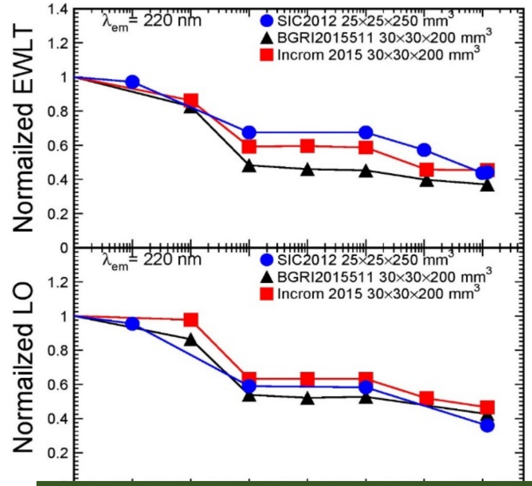


NIMA **340** (1994) 442-457



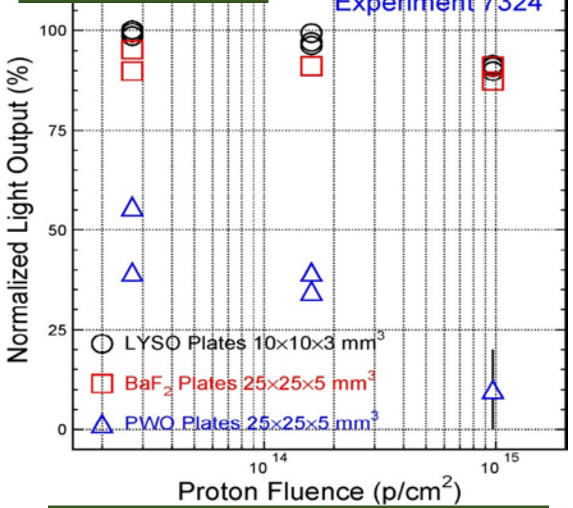
BaF_2 has an ultrafast scintillation component @ 220 nm with **0.5 ns** decay time and a much larger slow component @ 300 nm with 600 ns decay time.

Slow suppression may be achieved by rare earth doping, and/or solar-blind photo-detectors



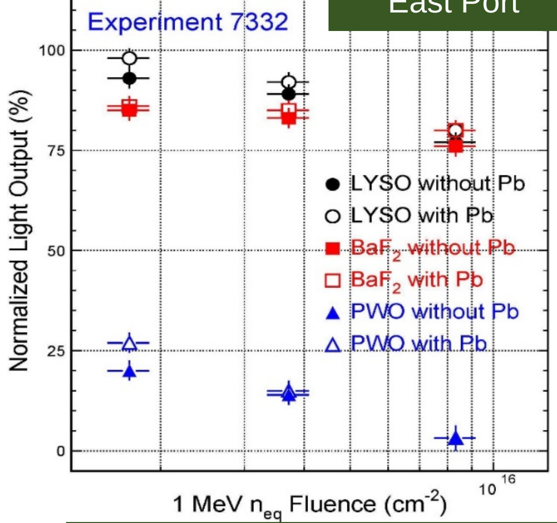
IEEE TNS **63** (2016) 612-619

Blue Room



IEEE TNS **65** (2018) 1018-1024

East Port



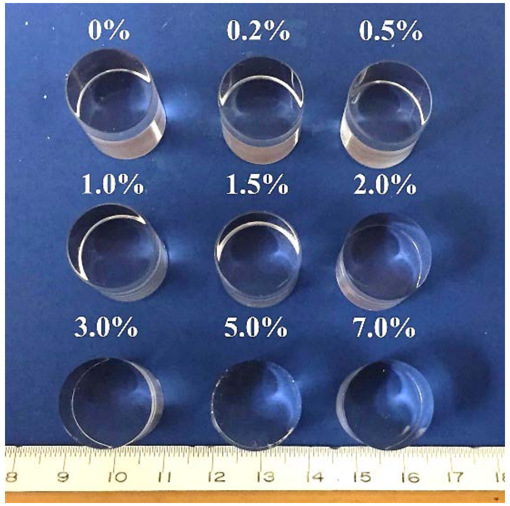
IEEE TNS **67** (2020) 1086-1092

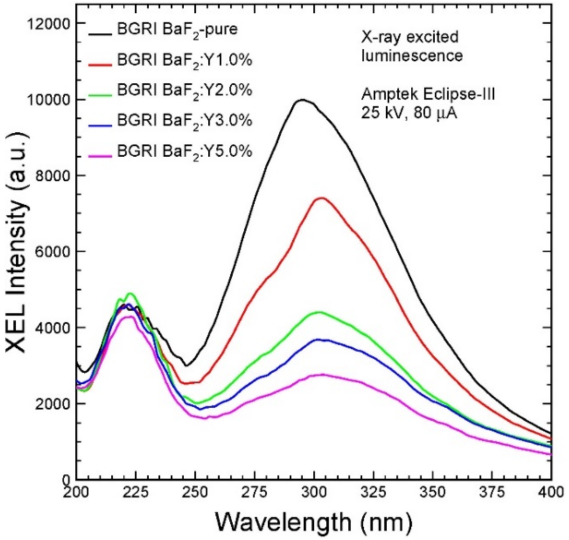
BaF_2 shows saturated damage from 10 krad to 100 Mrad, indicating good radiation resistance against ɣ-rays

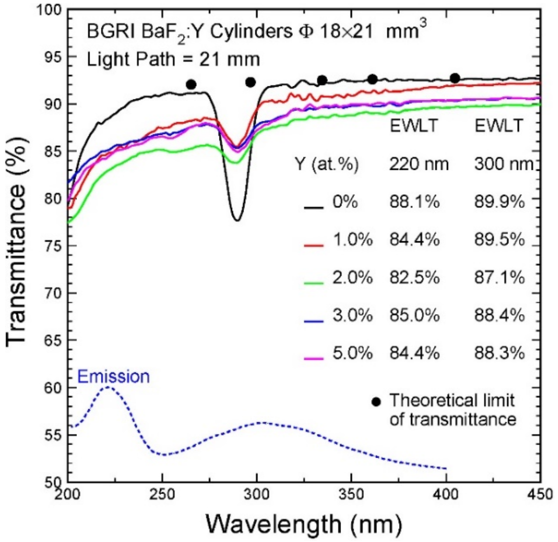
BaF_2 also survives after proton irradiation up to 9.7×10^{14} p/cm^2, and neutron irradiation up to 8.3×10^{15} n_{eq}/cm^2

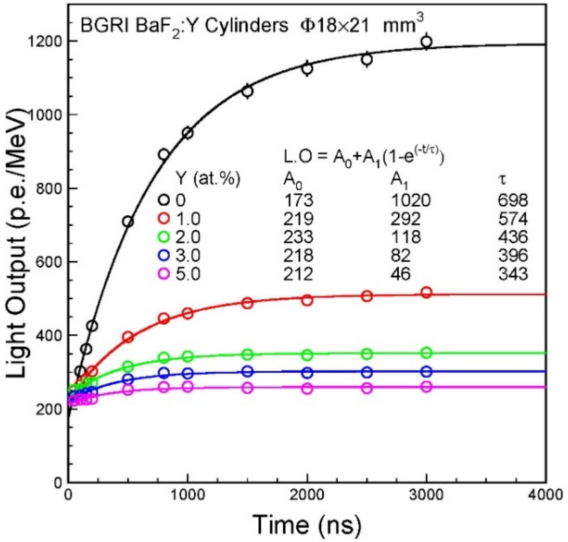
BaF_2:Y for Ultrafast Calorimetry

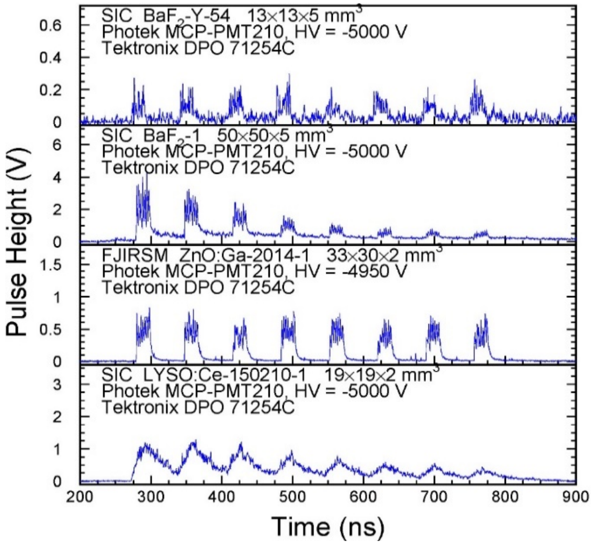
Increased F/S ratio observed in BGRI BaF_2:Y crystals: Proc. SPIE 10392 (2017)

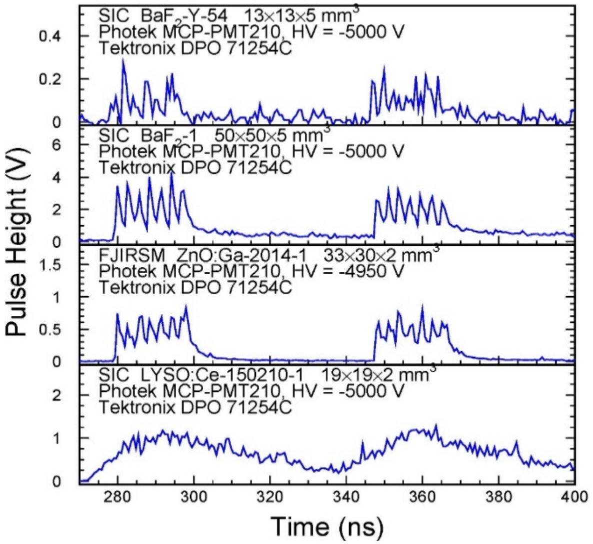


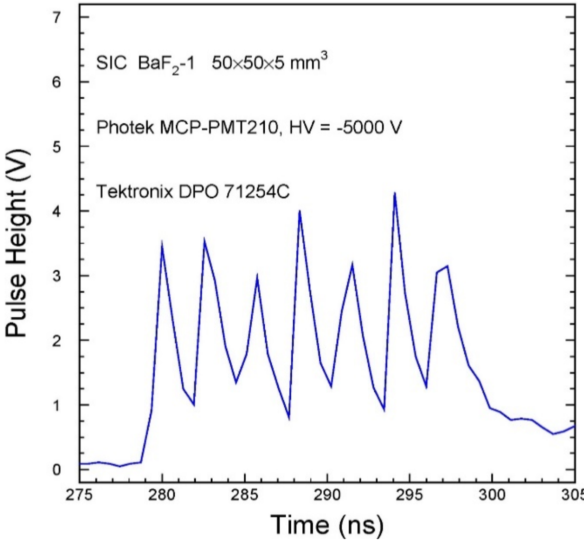












IEEE TNS **66** (2019) 1854-1860

NIMA **940** (2019) 223-239

X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF_2:Y and BaF_2 crystals: for GHz Hard X-ray Imaging

Summary

Inorganic scintillators were irradiated at LANSCE by 800 MeV protons and broad-band neutrons in the Blue Room and East Port respectively. Radiation damage induced by both protons and neutrons is observed. Proton-induced damage is larger than that from neutron because of ionization energy loss in addition to displacement and nuclear breakup.

Proton-induced damage in LYSO:Ce crystals from various vendors is consistent for 800 MeV from LANSCE and 24 GeV from CERN. It is also the same for one MeV equivalent neutrons. These results provide a solid foundation for using LYSO:Ce crystals in the CMS Barrel Timing Layer (BTL) project for the HL-LHC. Crystal QC for the CMS BTL project is on-going.

LuAG:Ce ceramics show a factor of two smaller RIAC than LYSO:Ce crystals against both neutrons and protons. This material is promising for the HL-LHC and FCC-hh. BaF_2 plates shows similar light output loss as LYSO:Ce at high fluence, consistent with the ɣ-ray result.

Our investigation will continue for on-going HEP experiments, and for understanding hadron-induced damage in various inorganic scintillators. The LANSCE facility at both the Blue Room and the East Port are important for such an investigation. **Availability is crucial.**

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