Development of Novel Inorganic Scintillators for Future High Energy Physics Experiments

Chen Hu, Liyuan Zhang, Ren-Yuan Zhu

California Institute of Technology

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Why Crystal Calorimetry?

- Precision photons and electrons measurements enhance physics discovery potential in HEP experiments.
- Performance of crystal calorimeter is well understood for e/γ, and is investigated 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.
- The next generation crystal detectors for HEP experiments:
  - Bright, fast and rad-hard LYSO and LuAG ceramics at the HL-LHC;
  - BaF_2:Y with <1 ns decay: ultrafast calorimetry for unprecedented rate;
  - Cost effective crystals for the homogeneous hadron calorimetry.

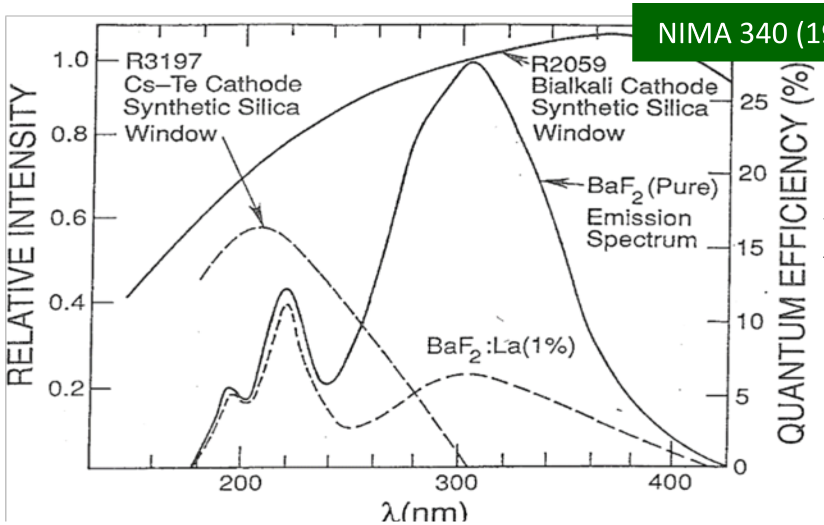
Why BaF_2:Y for Mu2e-II?

- Undoped CsI crystal used for the Mu2e calorimeter has a fast scintillation at 310 nm with 30 ns decay time and survives an ionization dose up to 100 krad.
- BaF_2 crystal has a ultrafast scintillation at 220 nm with 0.5 ns decay time and a similar intensity as CsI, and may survive 100 Mrad. Its slow scintillation at 300 nm with 650 ns decay time, however, causes pileup in a high rate environment.
- Two approaches have been used to suppress the slow scintillation in BaF_2: (1) rare earth doping and/or (2) dedicated photodetector. Yttrium doping in BaF_2 crystals is found effective, promising a ultrafast calorimeter.
- Mass production capability of BaF_2 exists in industry:
  - BGRI (China), Incrom (Russia) and SICCAS (China);
  - Hellma (Germany).
- Work on rare earth (La and La/Ce) doped BaF_2 crystals were reported in the last Mu2e-II workshop. Reported today is **ɣ-ray induced readout noise and damage in long BaF_2:Y crystals.**

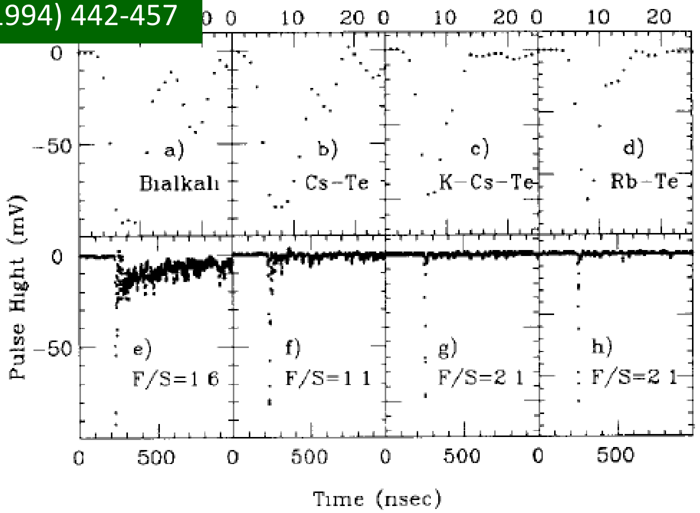
Ultrafast and Slow Light from BaF_2

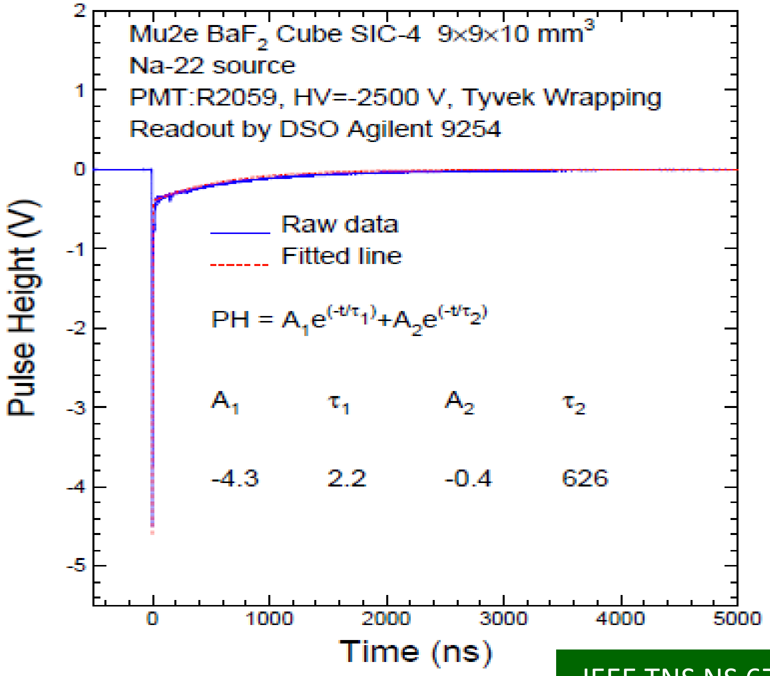
BaF_2 has a ultrafast scintillation component @ 220 nm with 0.5 ns decay time and an intensity similar to undoped CsI. It has also a factor of 5 larger slow component @ 300 nm with 300 ns decay time.

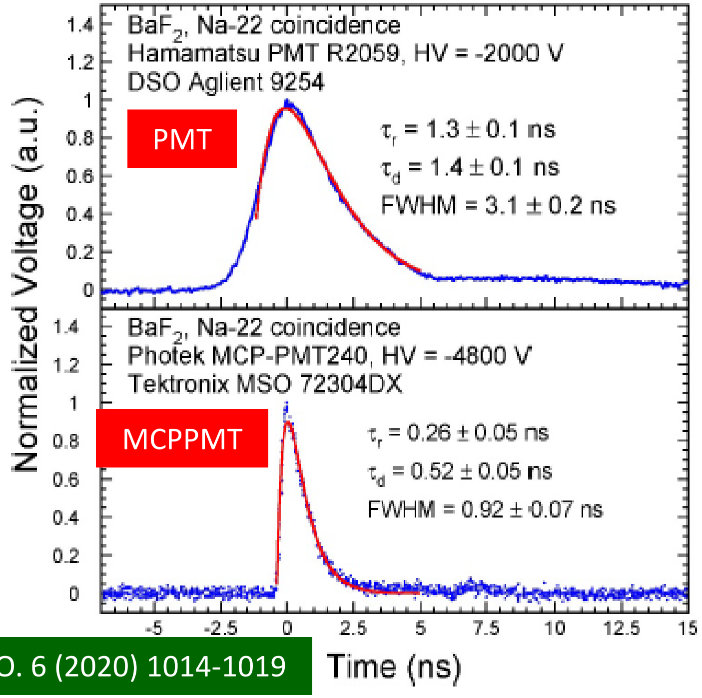
Slow suppression may be achieved by rare earth (Y, La and Ce) doping, and/or solar-blind photo-detectors, e.g. Cs-Te, K-Cs-Te and Rb-Te cathode



NIMA 340 (1994) 442-457



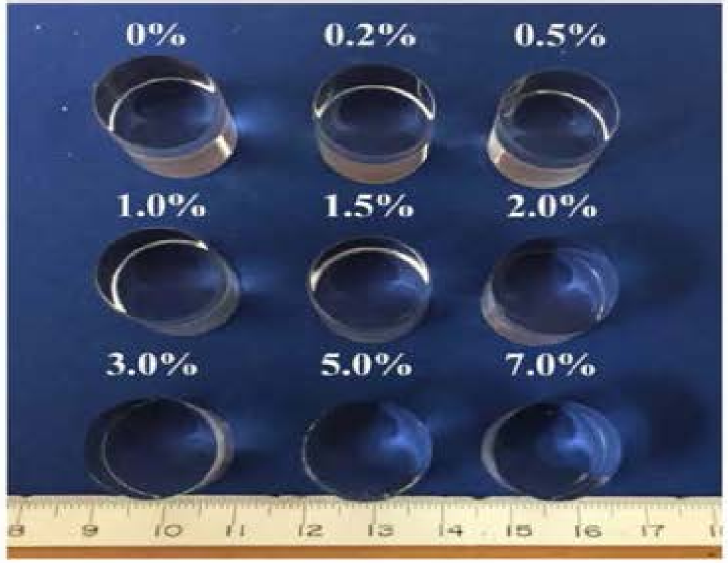


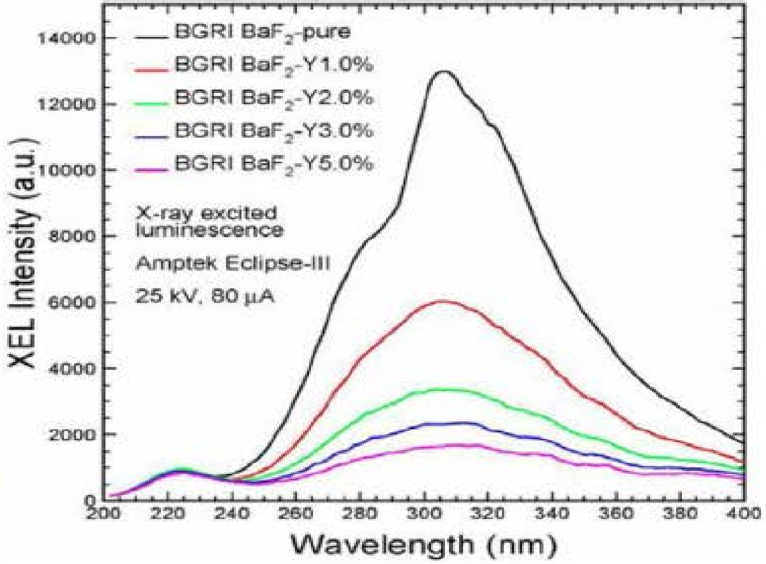


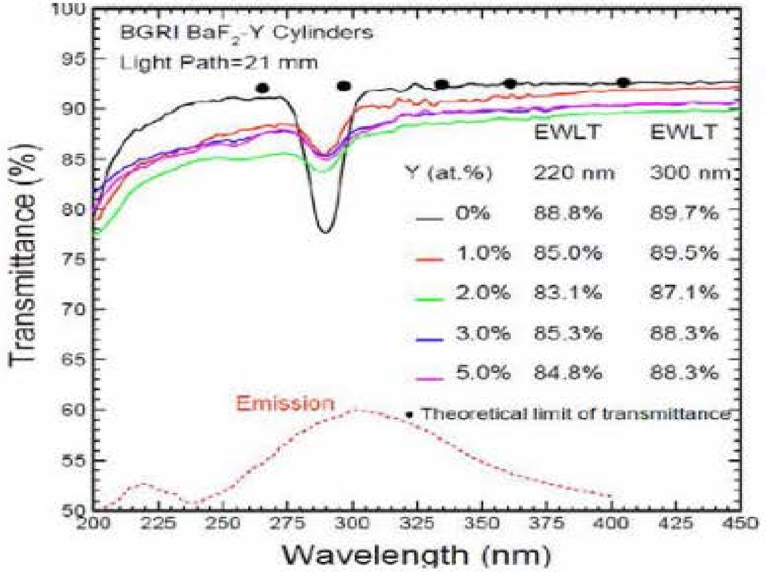
IEEE TNS NS 67, NO. 6 (2020) 1014-1019

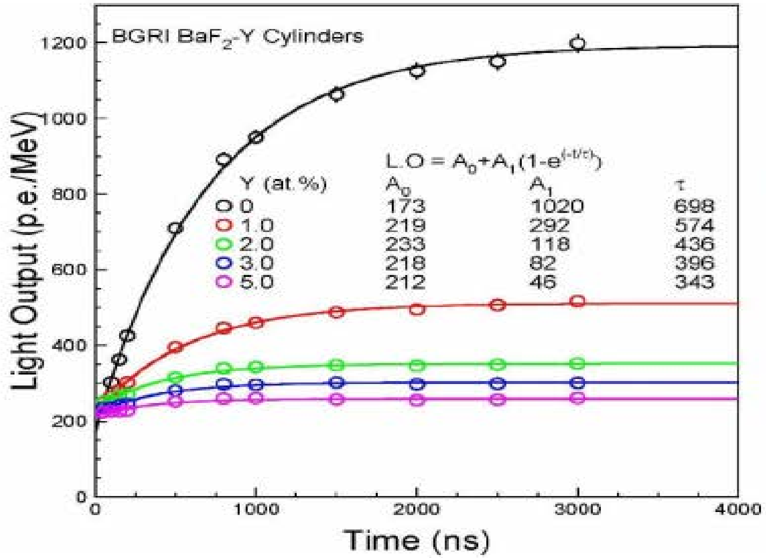
Yttrium Doped Small BaF_2 Samples

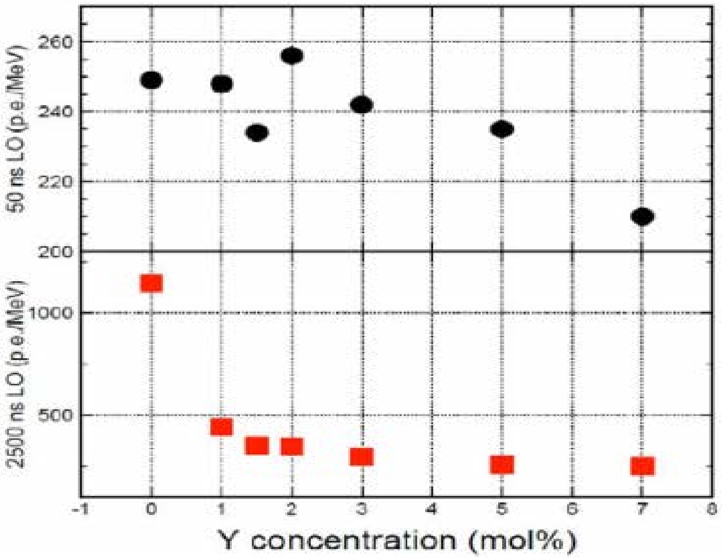
Increased F/S ratio observed in BGRI BaF_2:Y crystals, Proc. SPIE 10392 (2017)

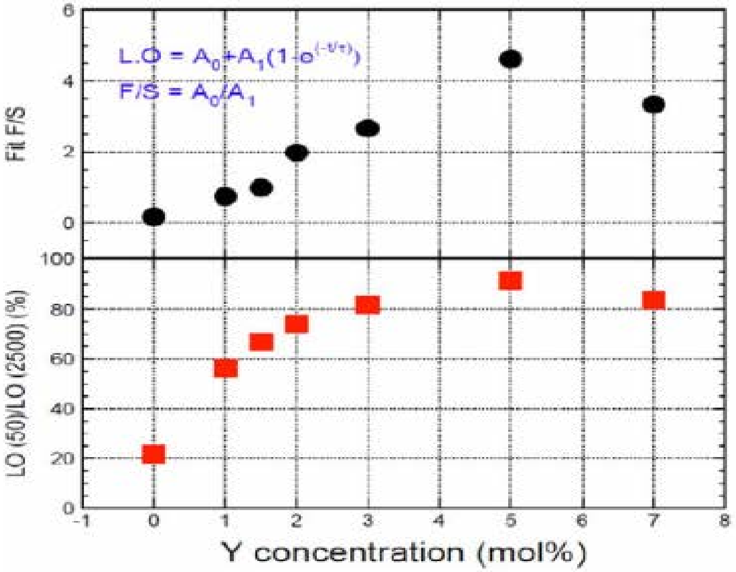




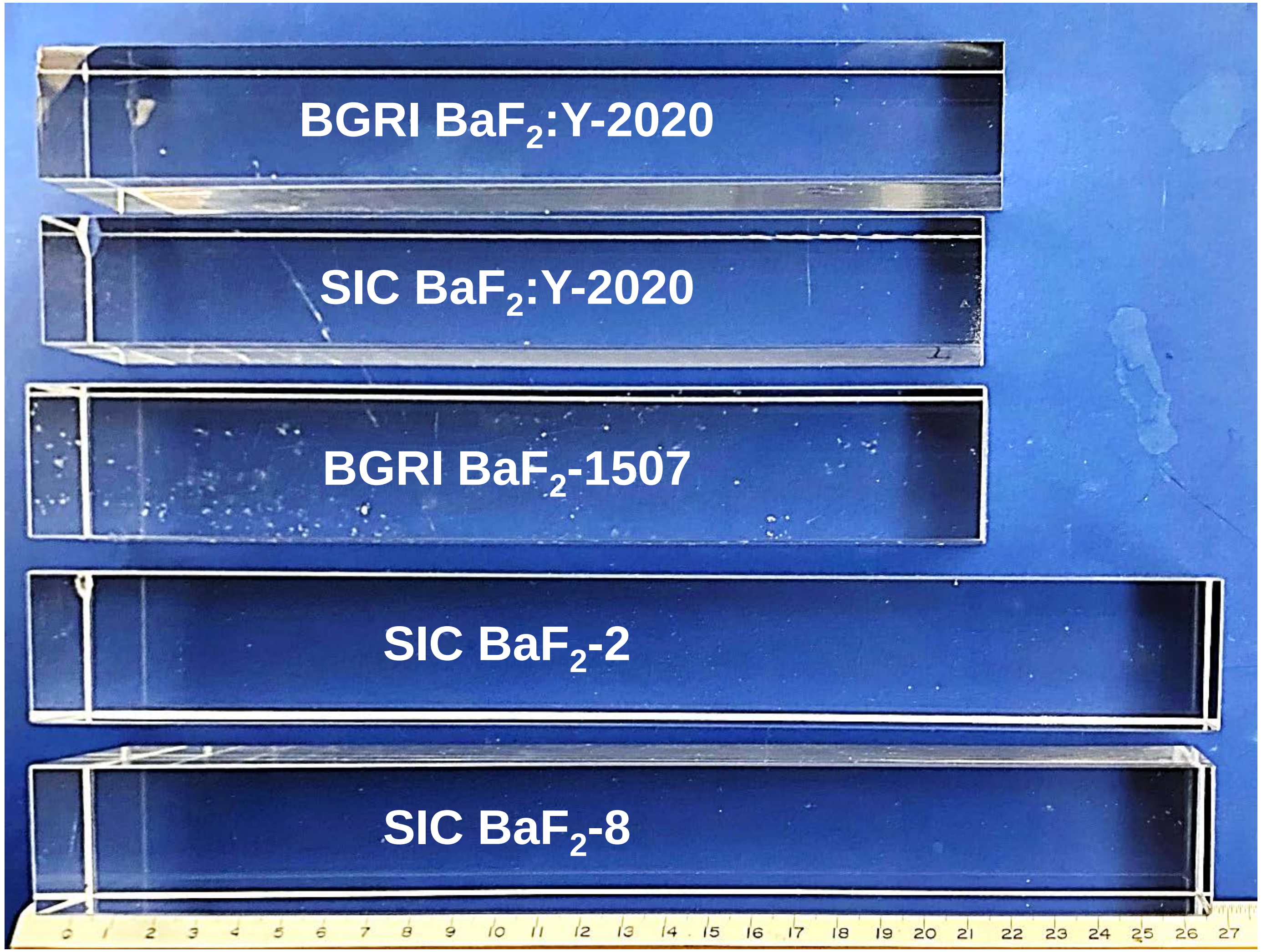








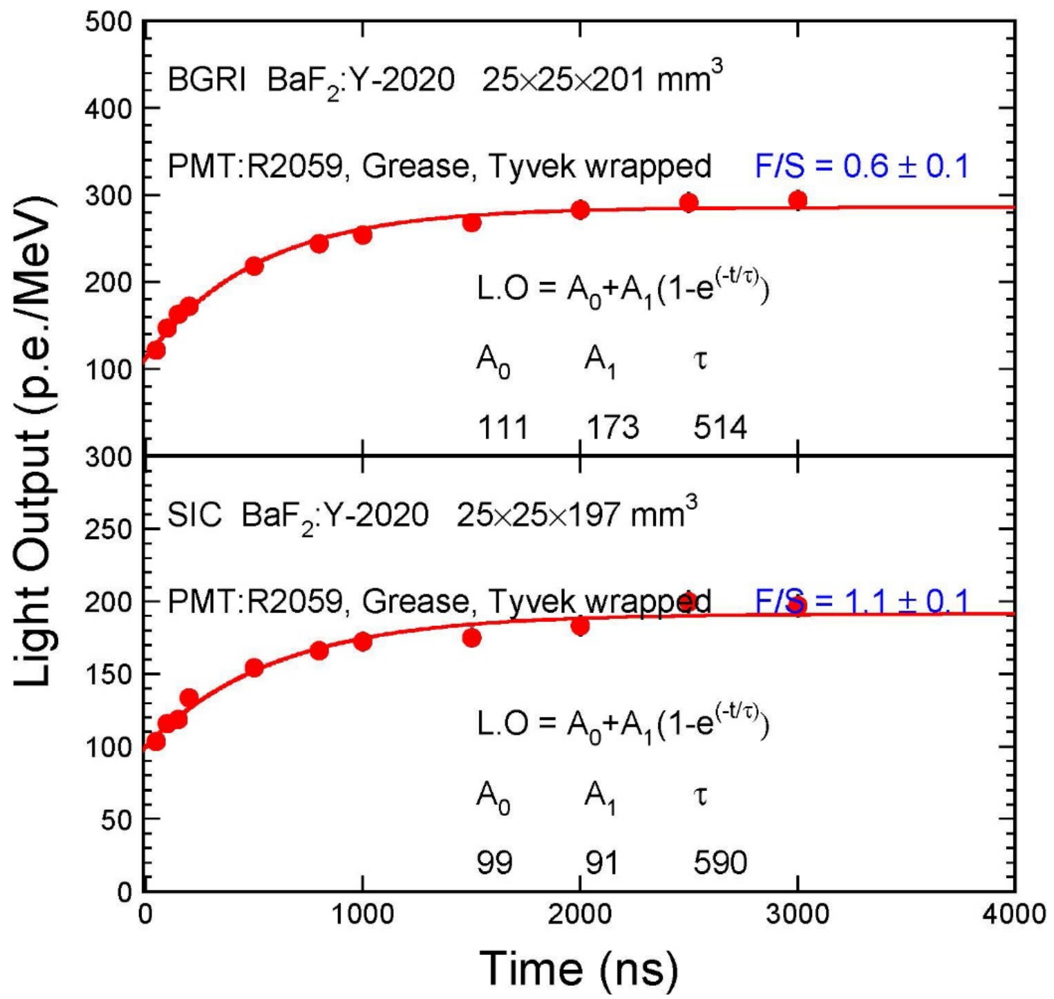
2020 BaF_2:Y and Three BaF_2 Crystals

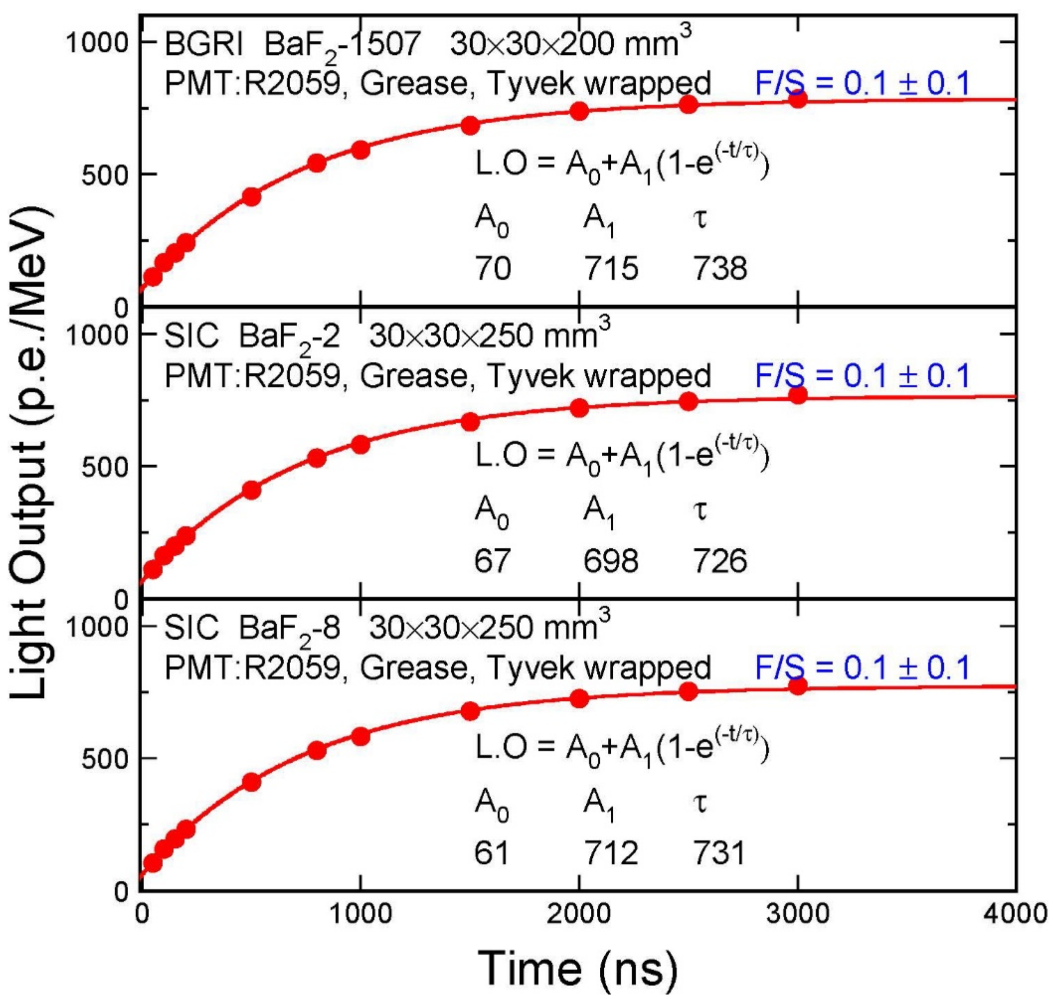


Sample ID	Dimension (mm^3)
BGRI BaF_2:Y-2020	25×25×201
SIC BaF_2:Y-2020	25×25×197
BGRI BaF_2-1507	30×30×200
SIC BaF_2-2	30×30×250
SIC BaF_2-8	30×30×250

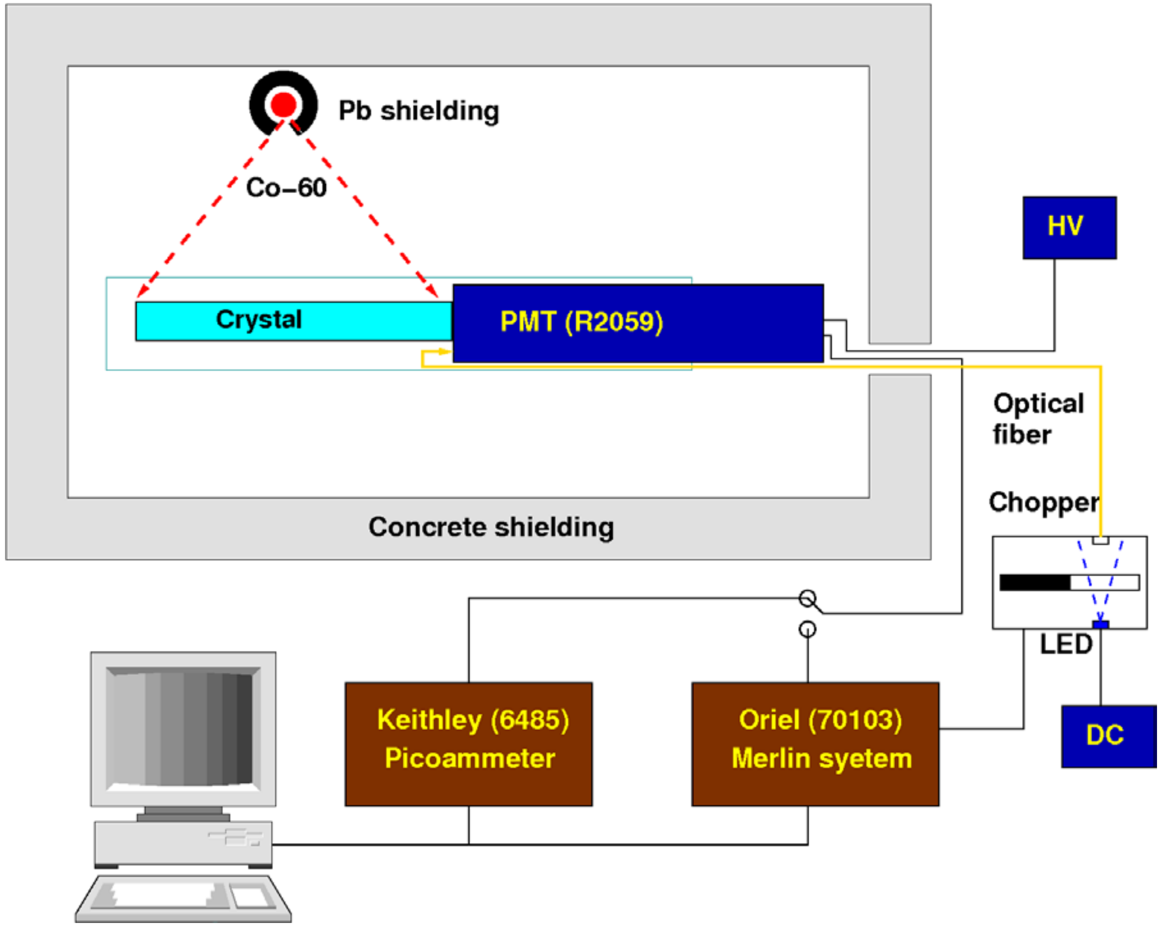
Light Output & Decay Kinetics

BaF_2 wrapped by Tyvek and coupled to a R2059 PMT via DC-200 fluid
Significant reduction in slow component observed in BaF_2:Y crystals





Gamma-ray Induced Photocurrent



BaF_2 crystals, wrapped by Tyvek paper and coupled to the R2059 PMT via an air gap, were irradiated by ^{60}Co γ-rays under dose rates of 2 and 23 rad/h

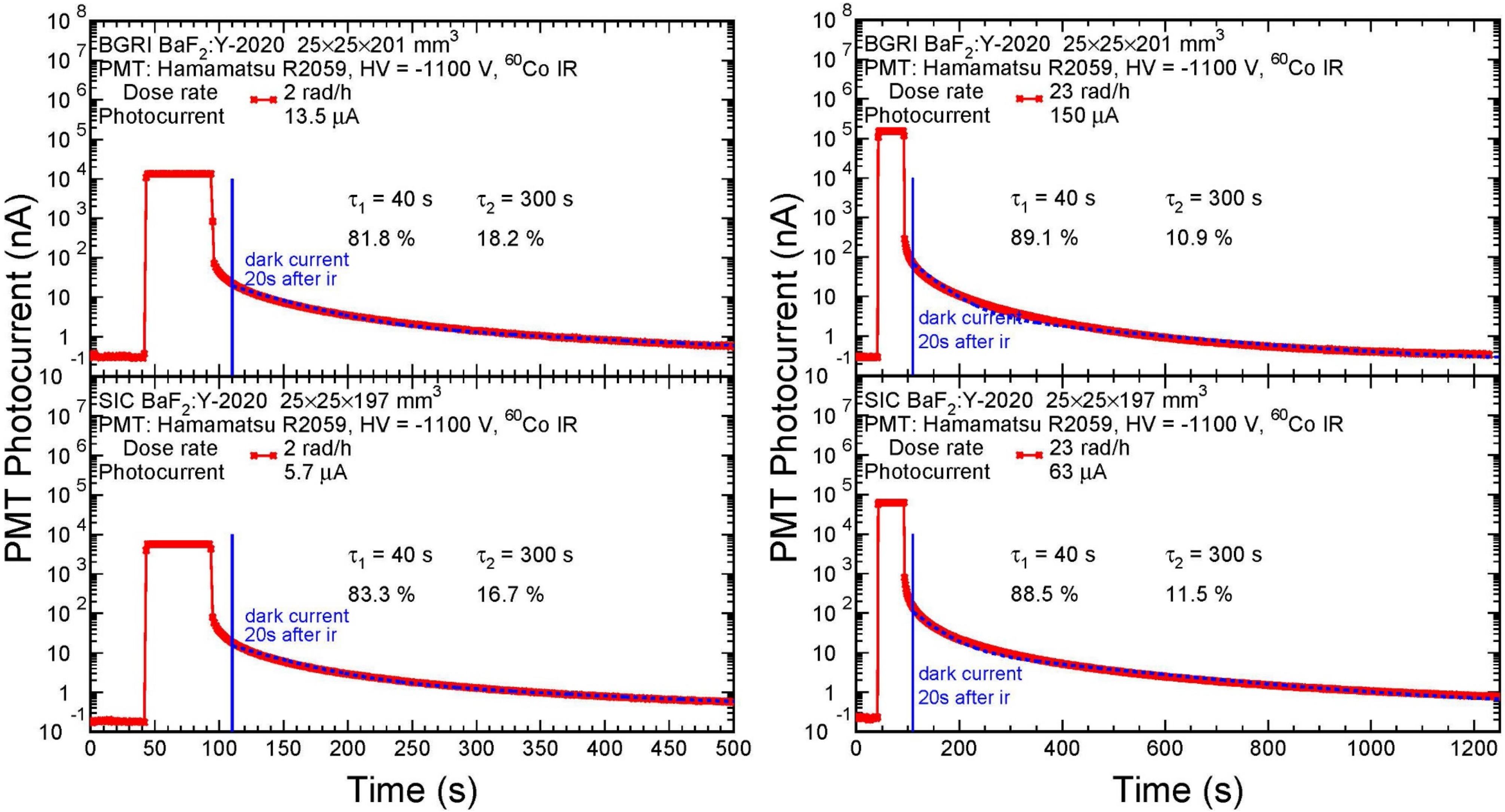
F is defined as the radiation induced photoelectron numbers per second, normalized to the dose rate.
RIN (σ) is defined as the fluctuation of photoelectron number (Q) in the readout gate normalized to the light output (LO) of BaF_2

$$F = \frac{\dfrac{Photocurrent}{Charge_{electron} \times Gain_{SiPM}}}{Dose\ rate_{\gamma-ray}\ or\ Flux_{neutron}}$$

$$Q = F \times Dose\ Rate \times Gate\ Length$$

$$\sigma = \frac{\sqrt{Q}}{LO} \quad \text{(MeV)}$$

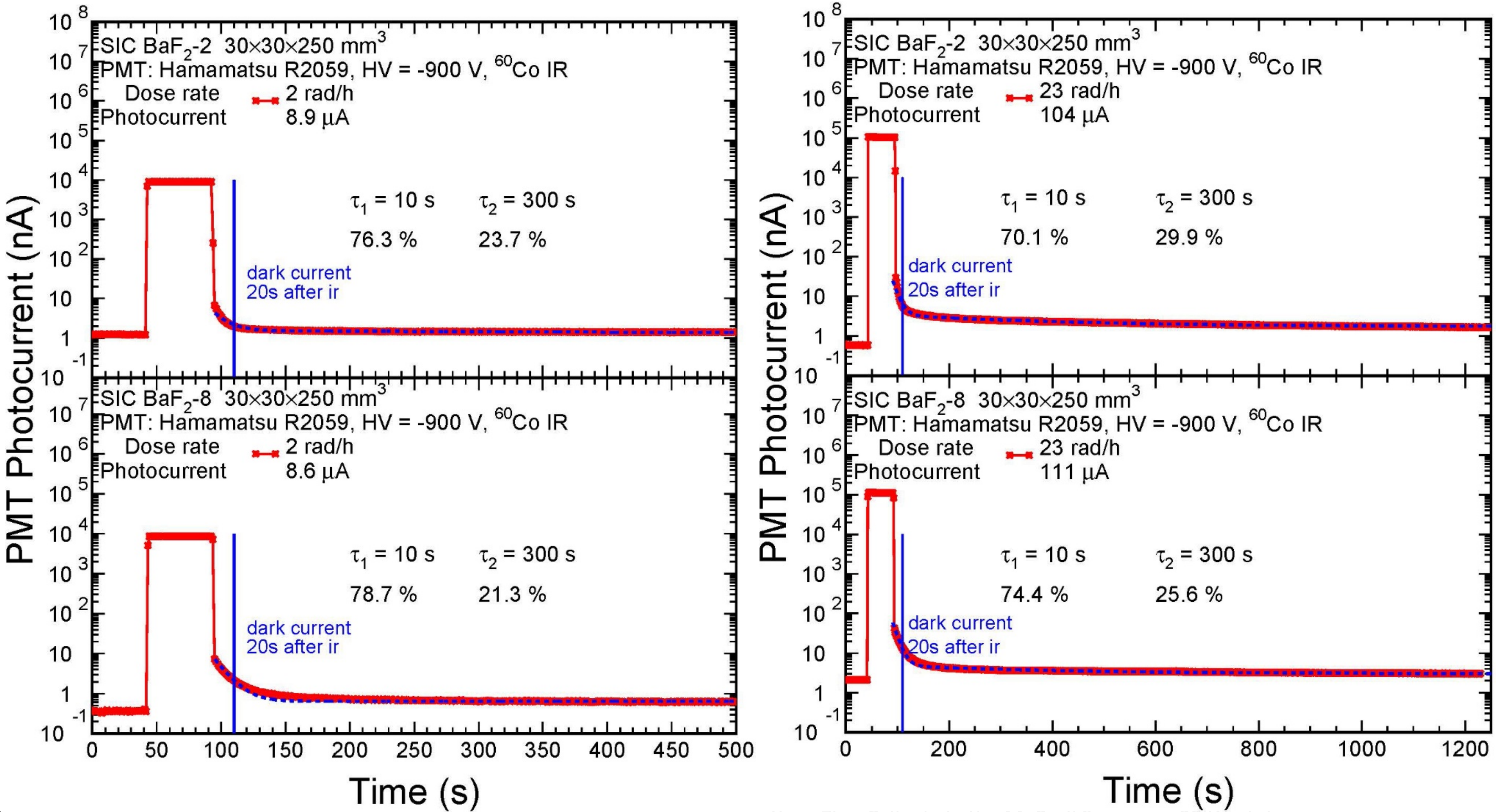
History of Photocurrent: Two BaF_2:Y under Dose Rates of 2 and 23 rad/h



Afterglow tail with two decay time: 40 s and 300 s

Y doping increases afterglow with short decay time

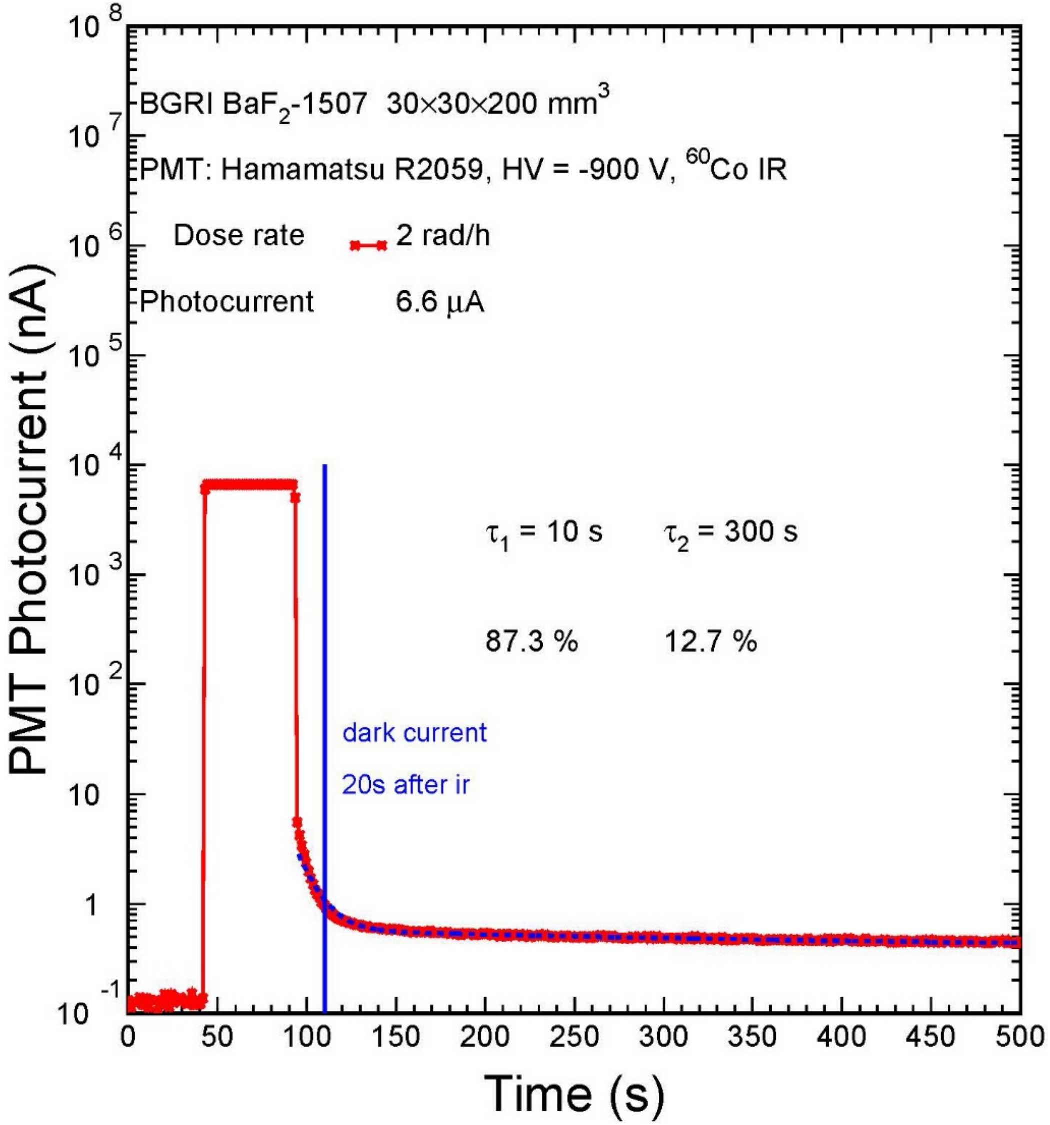
History of Photocurrent: Two SIC BaF_2 Crystals under Dose Rates of 2 and 23 rad/h

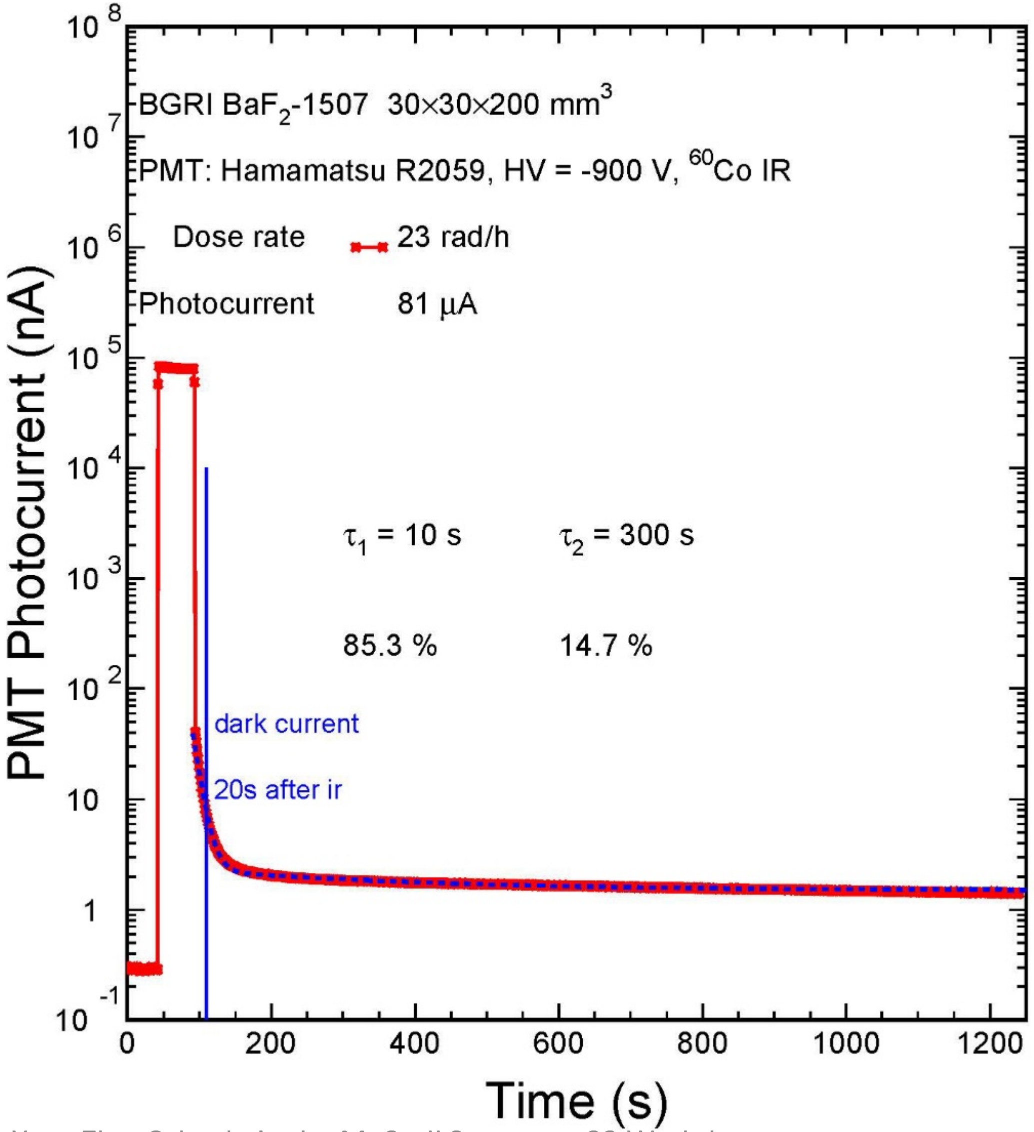


Afterglow with two decay time of 10 s and 300 s

Y doping reduces afterglow with long decay time

History of Photocurrent: BGRI BaF_2 Crystal-1507 under Dose Rates of 2 and 23 rad/h





Afterglow with two decay time of 10 s and 300 s

Y doping reduces afterglow with long decay time

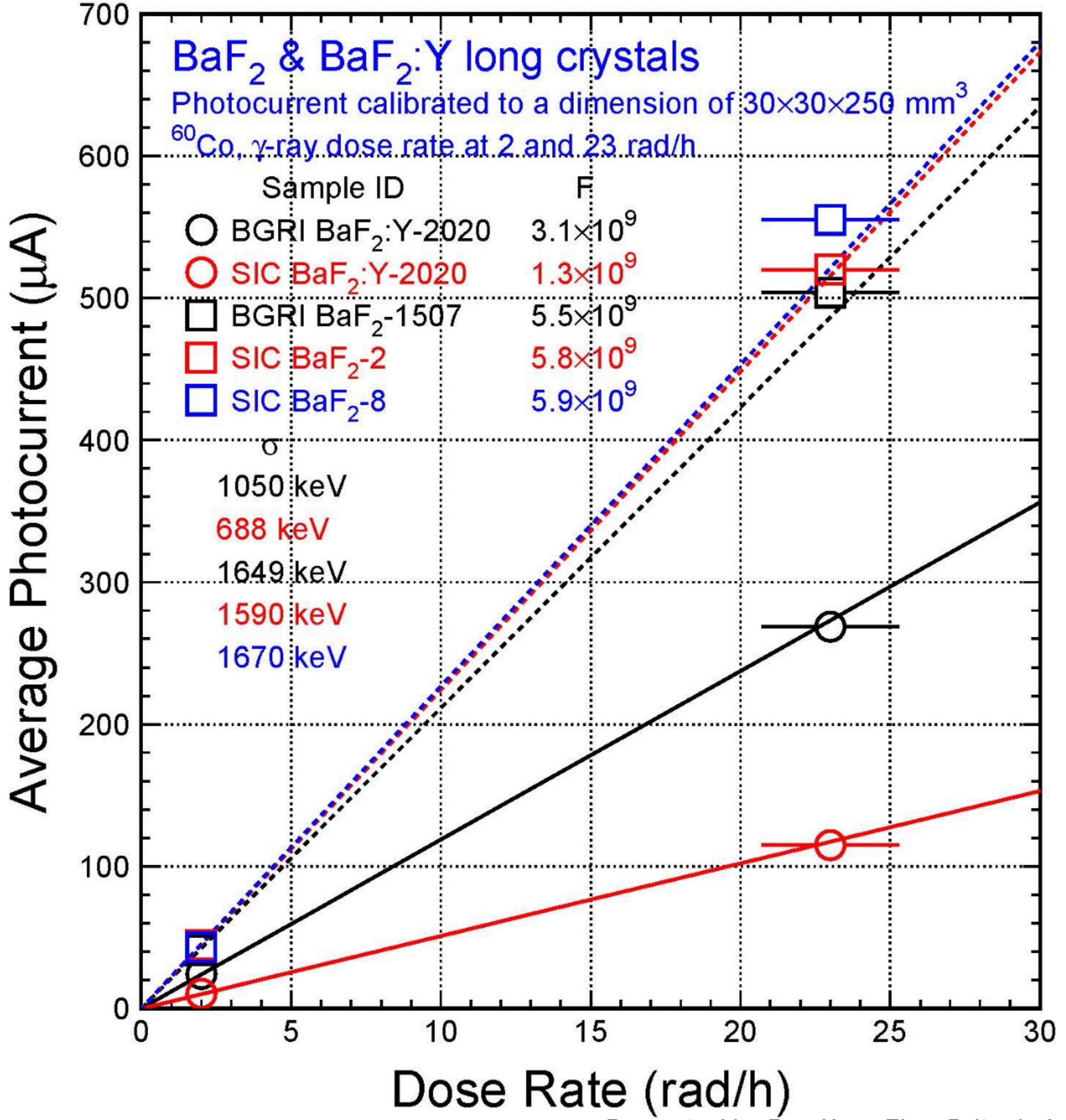
RIN:ɣ for 50 ns gate and 20 rad/h Dose Rate

Current values scaled to: BaF_2 crystal dimension of 30×30×250 mm^3 and PMT gain of 2.4×10^4 for R2059 @ -1100 V (4.8×10^3 @ -900 V); LO values scaled to air gap.

Crystal ID	L.O. corrected to air gap (p.e./MeV)*		F/S	Dose rate (rad/h)	Dark cur. before irrad. (nA)	Photo cur. (μA)	Dark cur. 20s after irrad. (nA)	Dark cur after 20s/Photo cur. (×10^{-4})	Dark cur. after 1000s –before irrad. (nA)	F (p.e./s/(rad/h))	RIN: ɣ (keV)
	50 ns	2500 ns									
BGRI BaF_2:Y-2020	53	127	0.64	2	0.5	24	34	14	0.05	3.1×10^9	1050
				23	0.5	269	122	4.5	0.22		
SIC BaF_2:Y-2020	45	87	1.08	2	0.4	10	30	29	0.03	1.3×10^9	810
				23	0.4	115	245	21	1.0		
BGRI BaF_2-1507	46	328	0.10	2	0.8	41	5.7	1.4	1.6	5.8×10^9	1650
				23	1.8	504	43	0.9	7.5		
SIC BaF_2-2	48	326	0.10	2	6.0	45	10	2.1	0.92	5.8×10^9	1590
				23	3.0	520	24	0.5	5.9		
SIC BaF_2-8	46	328	0.09	2	2.0	43	10	2.3	1.1	5.9×10^9	1670
				23	11	555	63	1.1	5.3		

Compared to CsI spec of 0.6 MeV, a shorter gate and/or solar blind photodetector are need

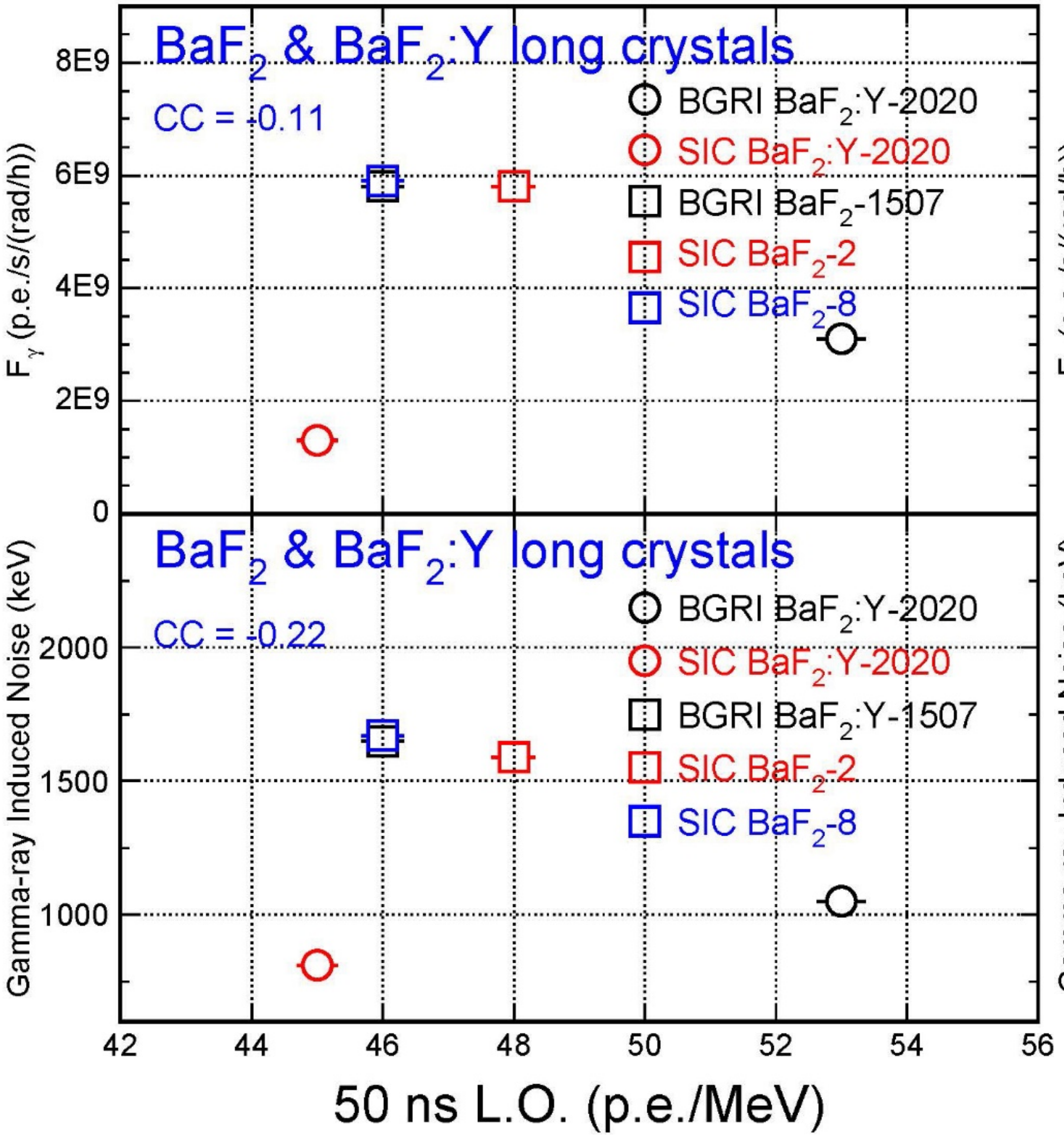
γ-Ray Induced Photocurrent vs Dose Rate

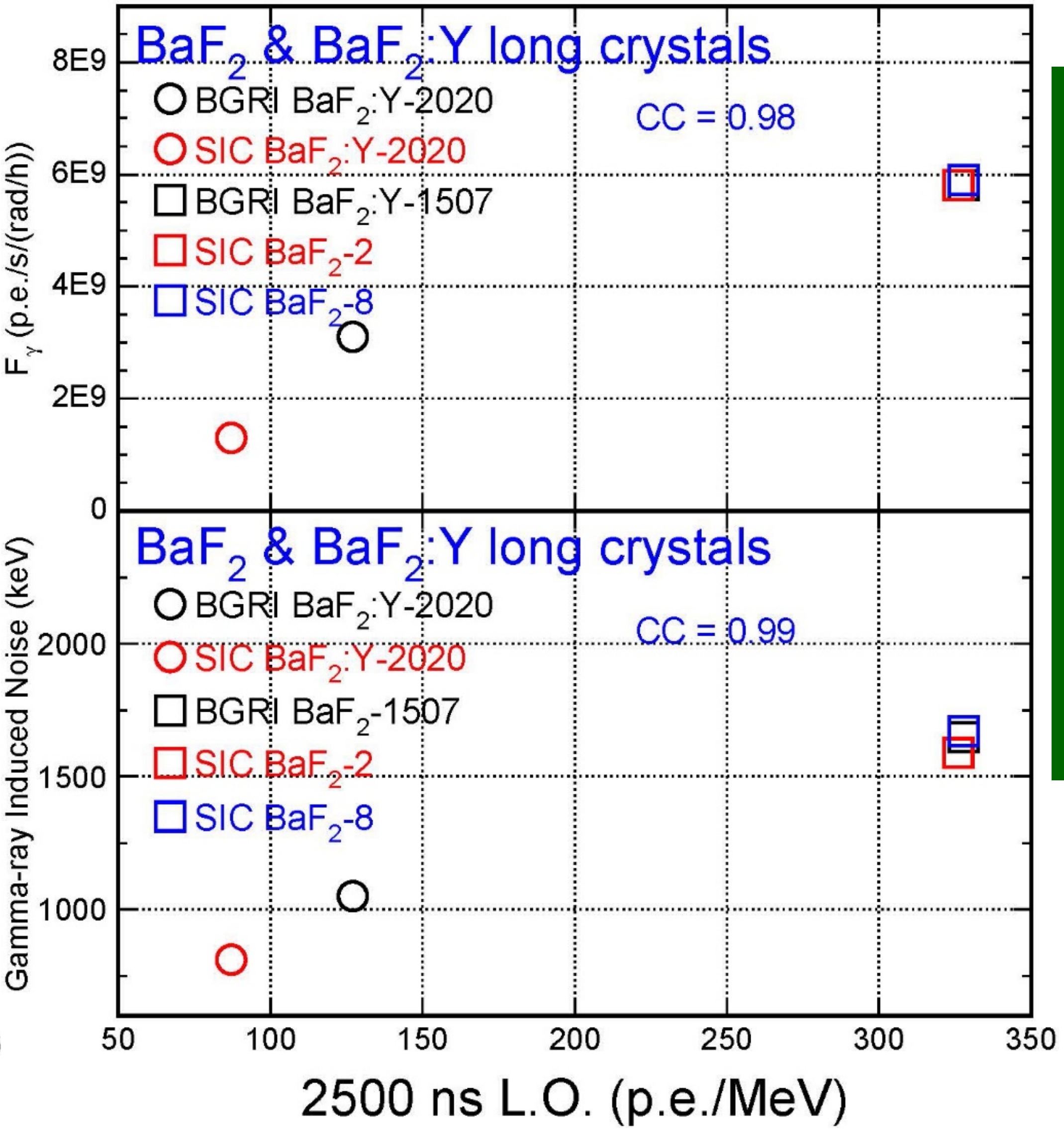


Good linearity between the γ-ray induced photocurrent and the dose rate

Yttrium doping in BaF_2 reduces the γ-ray induced photocurrent significantly

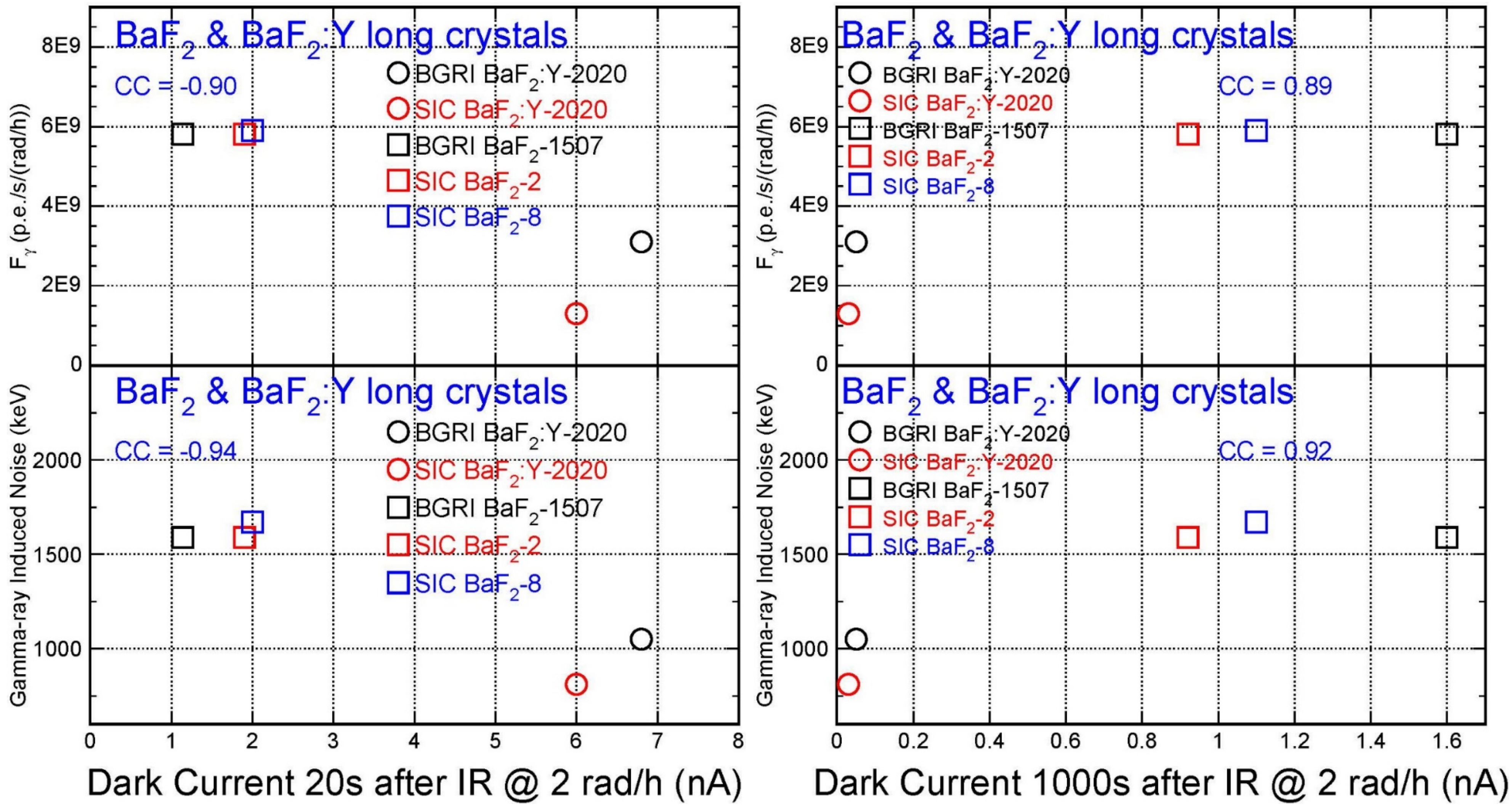
F and RIN:ɣ vs. LO in 50 ns and 2.5 µs





ɣ-ray induced photocurrent and readout noise are correlated to the LO in 2.5 µs gate, but not 50 ns gate

F and RIN:γ vs. Afterglow



Good correlations between F/RIN and the afterglow

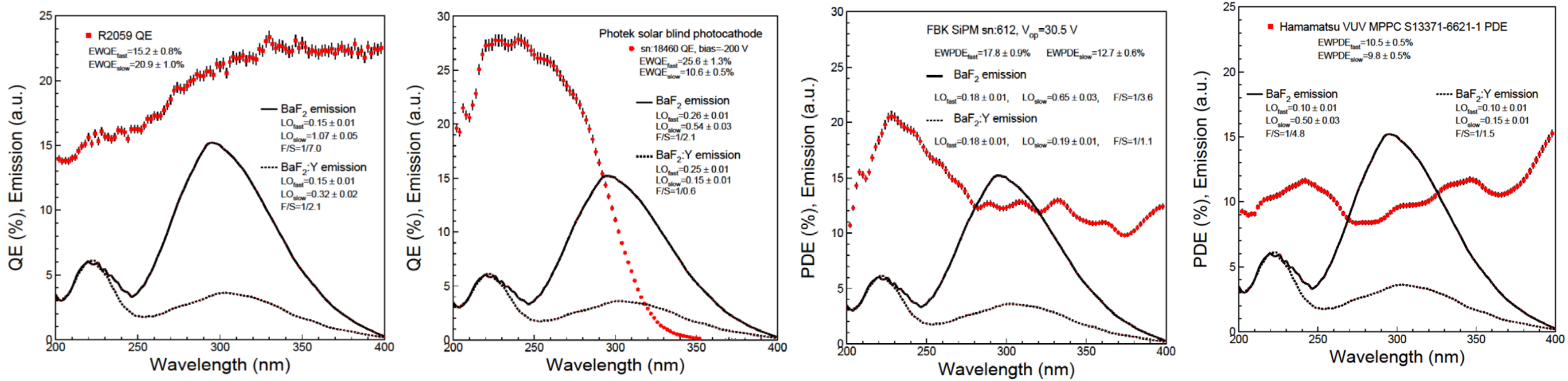
Y doping reduces F, RIN and afterglow with long decay time, but increases afterglow with short decay time

RIN:γ affected Photodetector QE/PDE Response

QE/PDE of four VUV photodetectors for BaF_2 and BaF_2:Y

Paper N05-03 in the virtual IEEE NSS/MIC 2020 Conference Record (2020)

Photodetector	$EWQE/PDE_{fast}$ (%)	$EWQE/PDE_{slow}$ (%)	$EWQE/PDE_{BaF}$ (%)	$EWQE/PDE_{BaF:Y}$ (%)	Relative LO (50 ns)	Relative F_{BaF}	Relative $F_{BaF:Y}$
Hamamatsu R2059	15.2	20.9	20.0	18.7	1.00	1.00	1.00
Photek Solar-Blind	25.6	10.6	13.0	16.1	1.68	0.65	0.86
FBK SiPM w/UV Filter-I	17.8	12.7	13.5	14.7	1.17	0.68	0.79
Hamamatsu MPPC	10.5	9.8	9.9	10.2	0.69	0.50	0.55



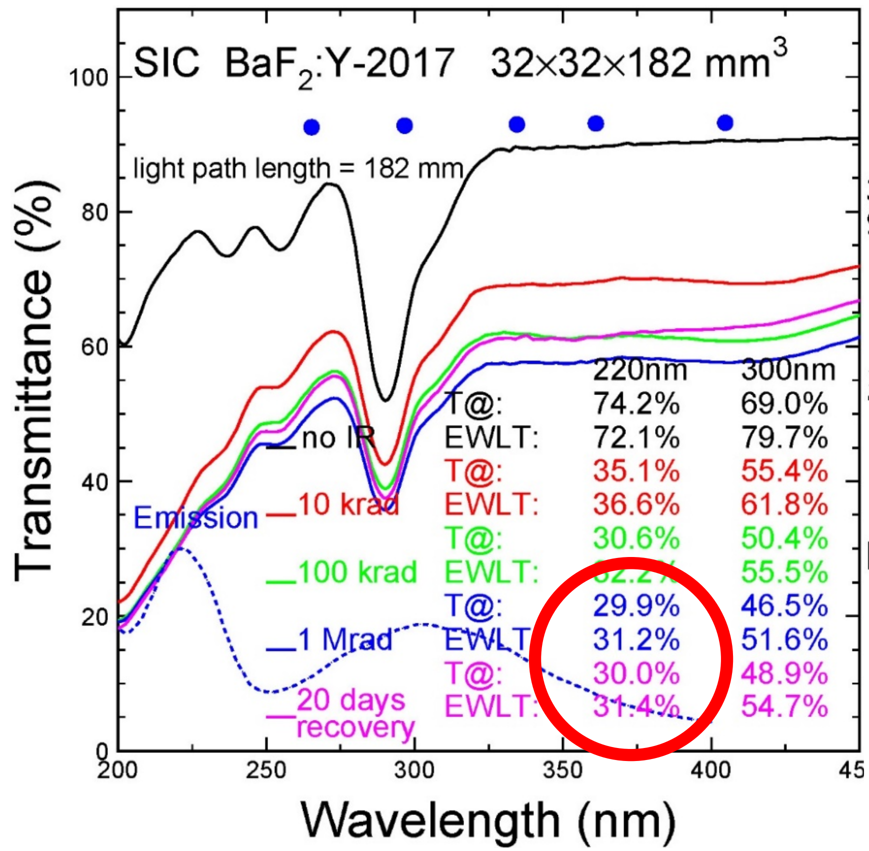
RIN:γ for Four VUV Photodetector

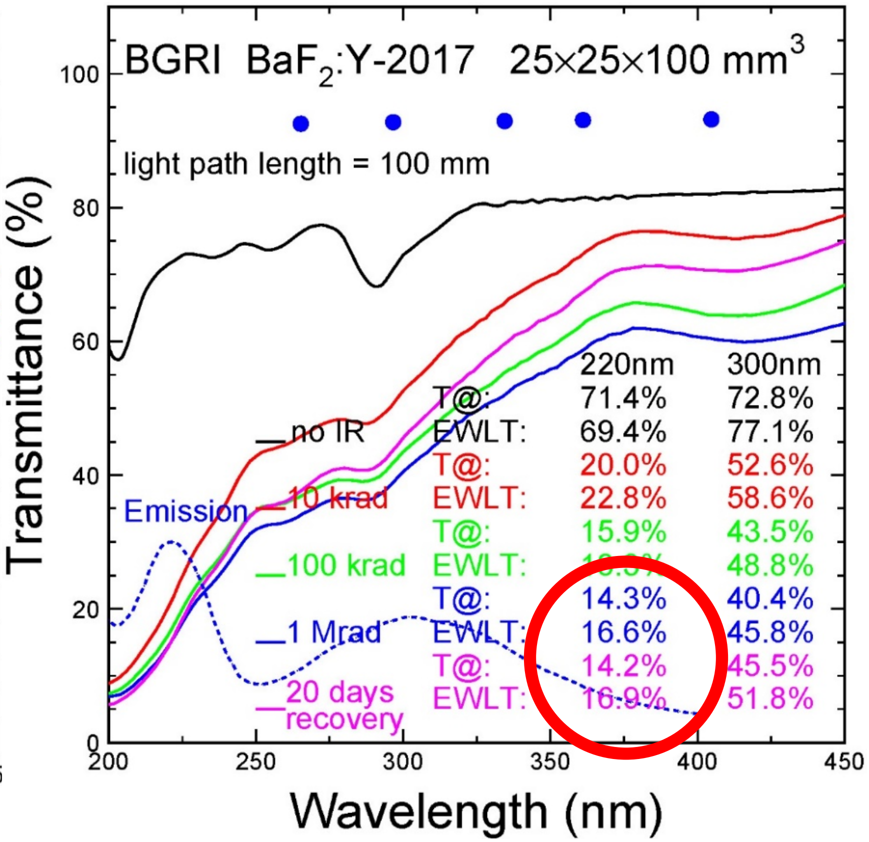
Photodetector	EWQE/PDE$_{fast}$ (%)	EWQE/PDE (%)	LO(50 ns) p.e./MeV	F	RIN:γ (keV)
BGRI BaF_2:Y-2020					
Hamamatsu R2059 PMT	15.2	18.7	53	3.1×10^9	1050
Photek PMT Solar Blind	25.6	16.1	89	2.7×10^9	580
FBK SiPM w/UV Filter-I	17.8	14.7	62	2.4×10^9	800
Hamamatsu VUV MPPC	10.5	10.2	37	1.7×10^9	1120
SIC BaF_2:Y-2020					
Hamamatsu R2059 PMT	15.2	18.7	45	1.3×10^9	810
Photek PMT Solar Blind	25.6	16.1	76	1.1×10^9	450
FBK SiPM w/UV Filter-I	17.8	14.7	53	1.0×10^9	610
Hamamatsu VUV MPPC	10.5	10.2	31	7.1×10^8	870
BGRI BaF_2-1507					
Hamamatsu R2059 PMT	15.2	20.0	46	5.8×10^9	1650
Photek PMT Solar Blind	25.6	13.0	77	3.8×10^9	790
FBK SiPM w/UV Filter-I	17.8	13.5	54	3.9×10^9	1160
Hamamatsu VUV MPPC	10.5	9.9	32	2.9×10^9	1680
SIC BaF_2-2					
Hamamatsu R2059 PMT	15.2	20.0	48	5.8×10^9	1590
Photek PMT Solar Blind	25.6	13.0	81	3.8×10^9	760
FBK SiPM w/UV Filter-I	17.8	13.5	56	3.9×10^9	1120
Hamamatsu VUV MPPC	10.5	9.9	33	2.9×10^9	1620

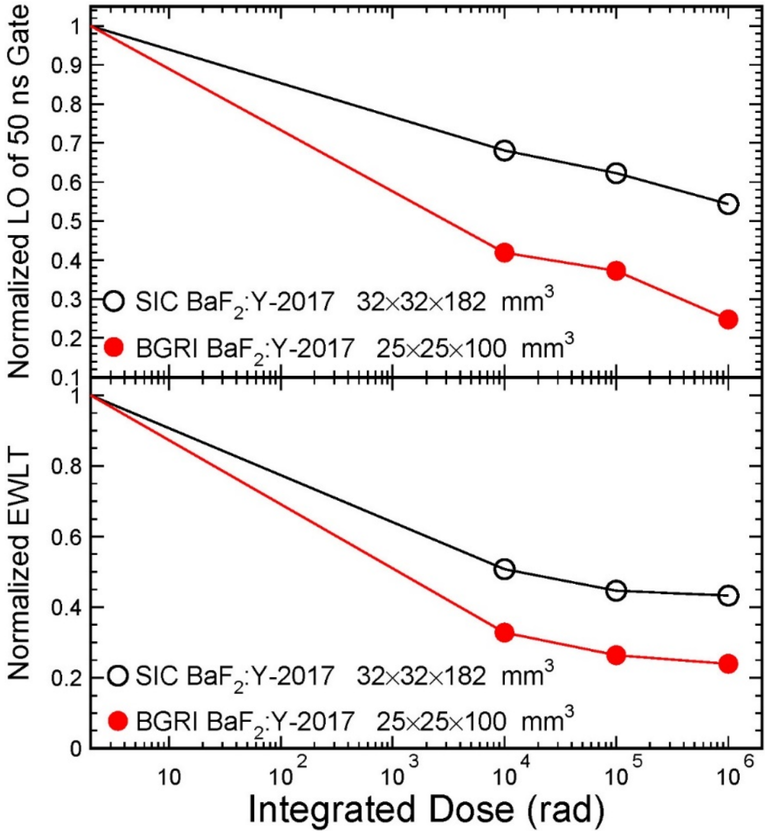
Solar blind photodetector reduces RIN:γ significantly
Taking into account the area coverage, a shorter gate is needed

1 Mrad Damage in BaF_2:Y Crystals

SIC 2017 BaF_2:Y sample shows a similar performance as BaF_2 crystals
Recovery is small for the fast component







Crystal quality is diverse at this stage R&D needed for improvement

Summary

- BaF_2 crystals provide ultrafast light with 0.5 ns decay time. Yttrium doping increases the F/S ratio while maintaining the ultrafast light intensity. With sub-ns pulse width BaF_2:Y promises a ultrafast calorimeter.
- RIN:ɣ was measured for two BaF_2:Y and three BaF_2 large size crystals under dose rates of 2 and 23 rad/h. While it is at a level of about 1.6 MeV for BaF_2 samples of $30\times30\times250$ mm^3 readout by R2059 PMT in 50 ns gate, a factor of two reduction is observed for BaF_2:Y crystals.
- RIN:ɣ is highly correlated to the LO in 2.5 µs gate not 50 ns gate, indicating dominance of the slow scintillation component. Yttrium doping reduces RIN:ɣ, and increases/reduces afterglow with short/long decay time. Both solar blind photodetector and a shorter integration gate are required to further reduce the RIN:ɣ values to less than 0.6 MeV.
- ɣ-ray induced damage in BaF_2:Y crystals is sample dependent. R&D is needed for improvement. Measurements are on way for ɣ-rays and neutrons.

Acknowledgements: DOE HEP Award DE-SC001192

Cost of Mass Produced Crystals (March, 2019)

Scaling to X_0, order of crystal cost: PWO, BGO, CsI, BSO, BaF_2:Y, LYSO

Item	Size	1 m^3	10 m^3	100 m^3	Scaled to X_0
BGO	22.3×22.3×280 mm	$8/cc	$7/cc	$6/cc	1.23
BaF_2:Y	31.0×31.0×507.5 cm	$12/cc	$11/cc	$10/cc	2.28
LYSO:Ce	20.7x20.7x285 mm	$36/cc	$34/cc	$32/cc	1.28
PWO	20x20x223 mm	$9/cc	$8/cc	$7.5/cc	1.00
BSO	22x22x274 mm	$8.5/cc	$7.5/cc	$7.0/cc	1.29
CsI	35.7x35.7x465 mm	$4.6/cc	$4.3/cc	$4.0/cc	2.09