Investigations on the radiation hardness of the flat tile scintillators for the CMS HGCAL

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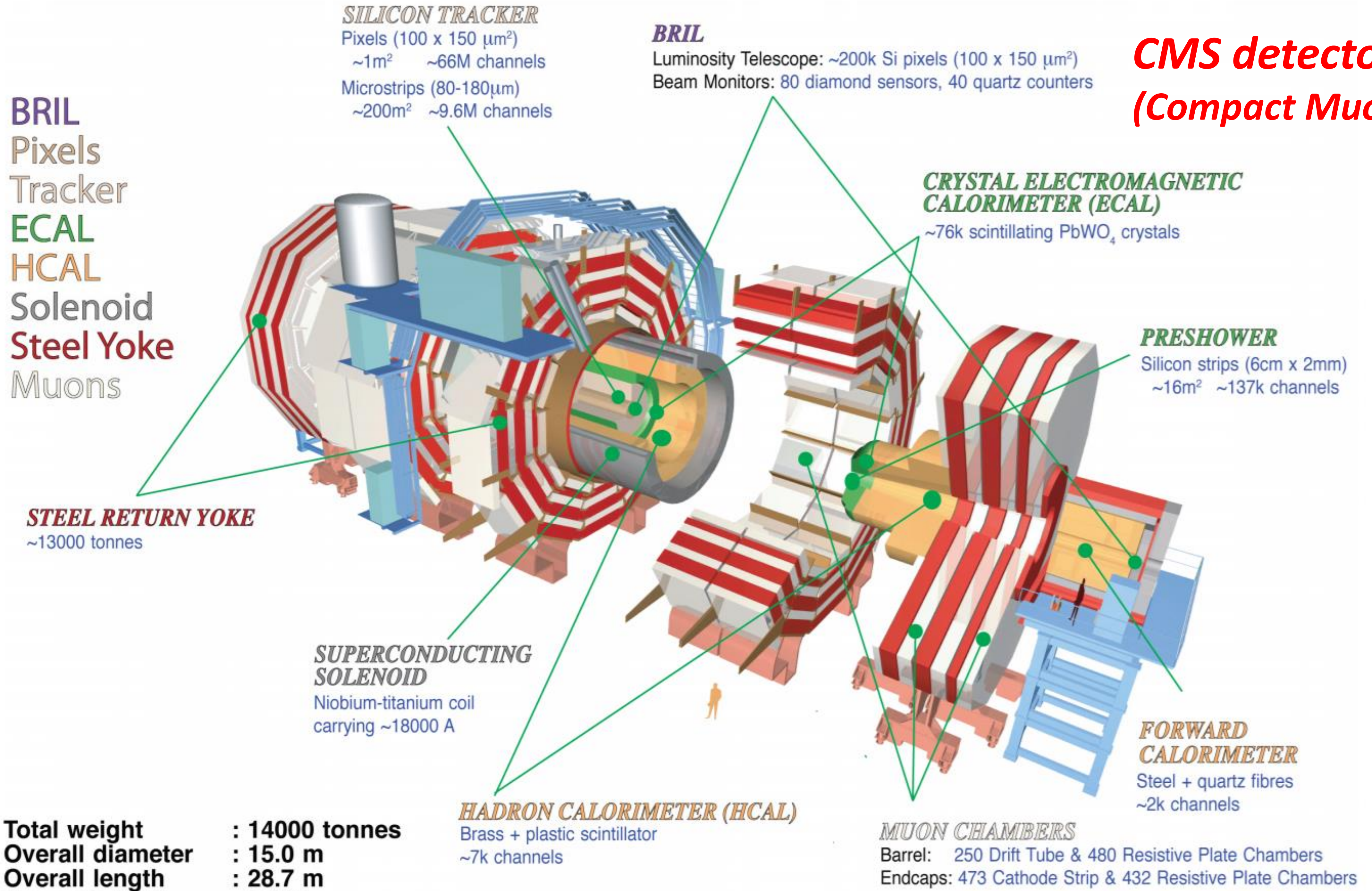
on behalf of S.V. Afanasiev, P. DeBarbaro, A.Yu. Boyarintsev, Yu.V. Ershov, I.A. Golutvin, N.V. Gorbunov, A.I. Malakhov, V.A. Smirnov, E.V. Sukhov, D.A. Tlisov*, N.I. Zamyatin

***** *deceased*

CMS detector
(Compact Muon Solenoid)



Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

HGCAL Parameters

A radiation load of 0.3 MRad is expected on scintillation part over 10 years of HGCAL operation (at the HL-LHC)

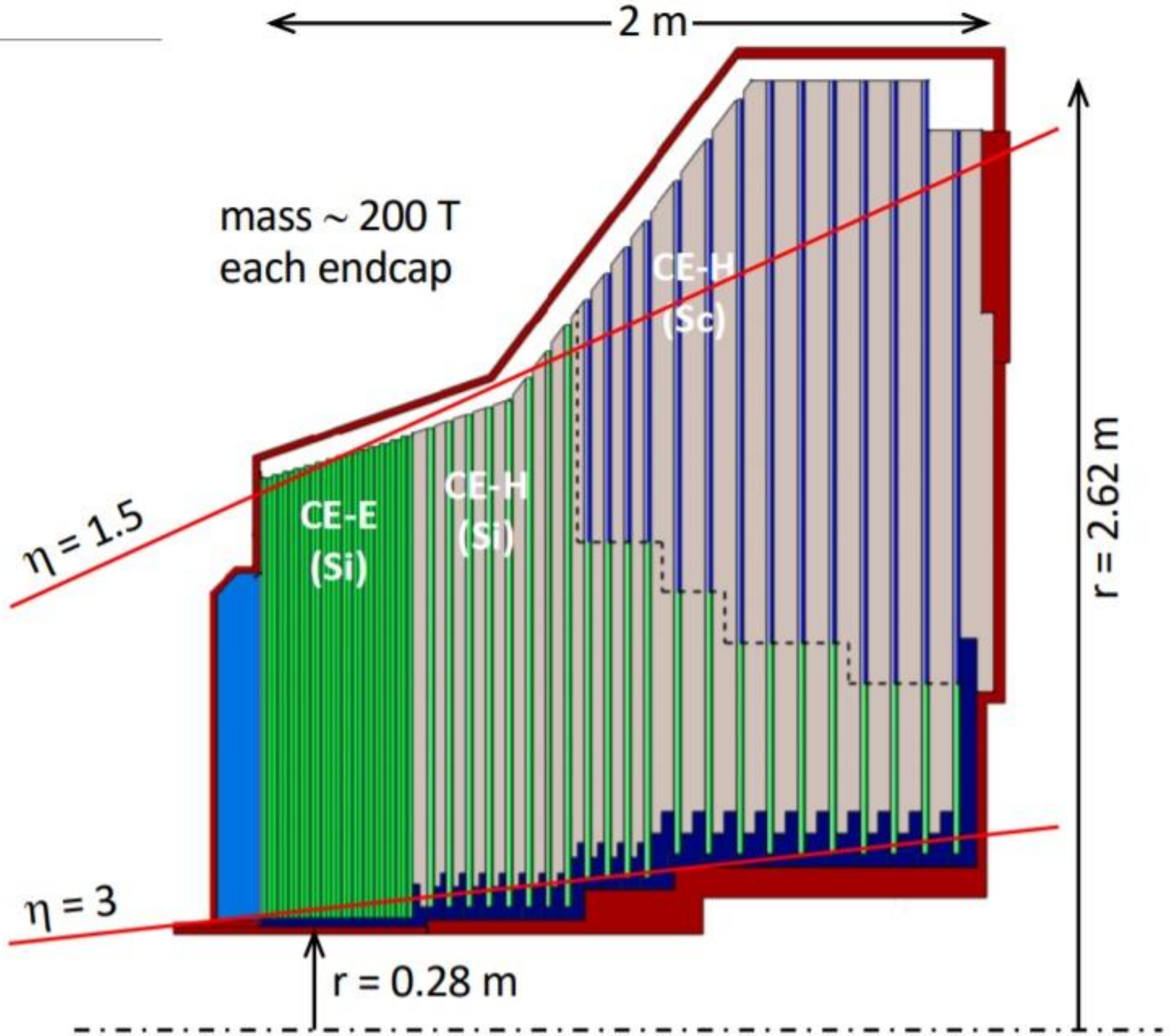
Key Parameters (updated from the TDR):

- HGCAL covers 1.5 < η < 3.0
- **Full system maintained at -30ºC**
- **~640 m²** of silicon sensors
- **~370 m²** of scintillators
- 6.1M Si channels, 0.5 or 1.1 cm² cell size (*6M*)
  240k scint-tile channels (η–ϕ)
  - Data readout from all layers
  - Trigger readout from alternate layers in CE-E and all in CE-H
- ~31000 Si modules (incl. spares)

Active Elements:

- Si sensors (full and partial hexagons) in CE-E and high-radiation region of CE-H.
- SiPM-on-Scintillating tiles in low-radiation region of CE-H

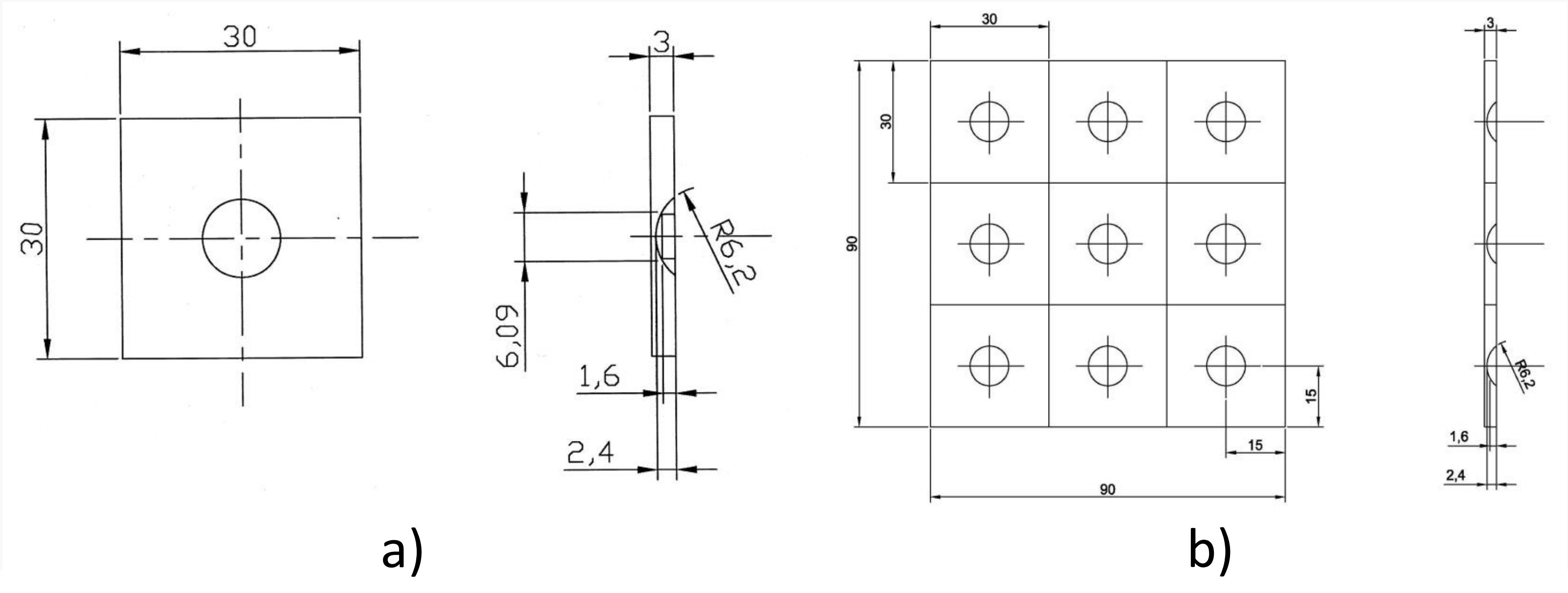
Electromagnetic calorimeter (**CE-E**): **Si**, Cu/CuW/Pb absorbers, 28 layers, 25.5 X_0 & ~1.7λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 22 layers, ~9.5λ (including CE-E)

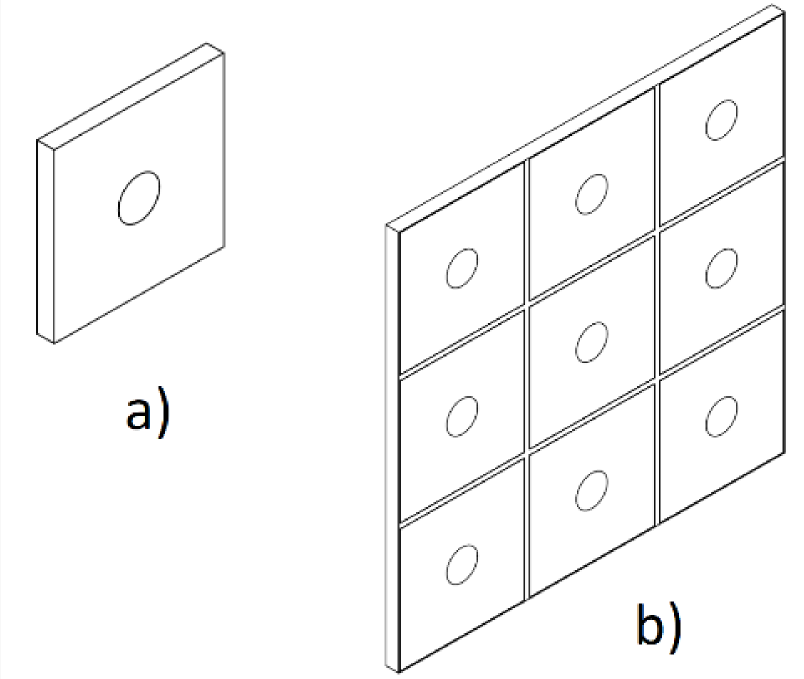


Samples of the scintillators for tests

Flat-tile configuration (Single samples)

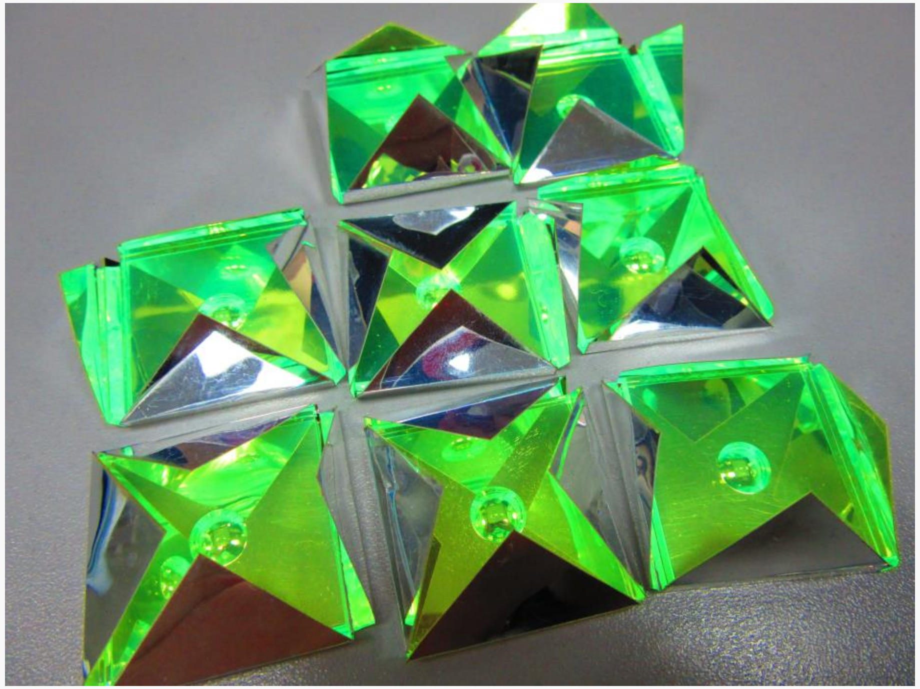
Block-area configuration (Block samples)

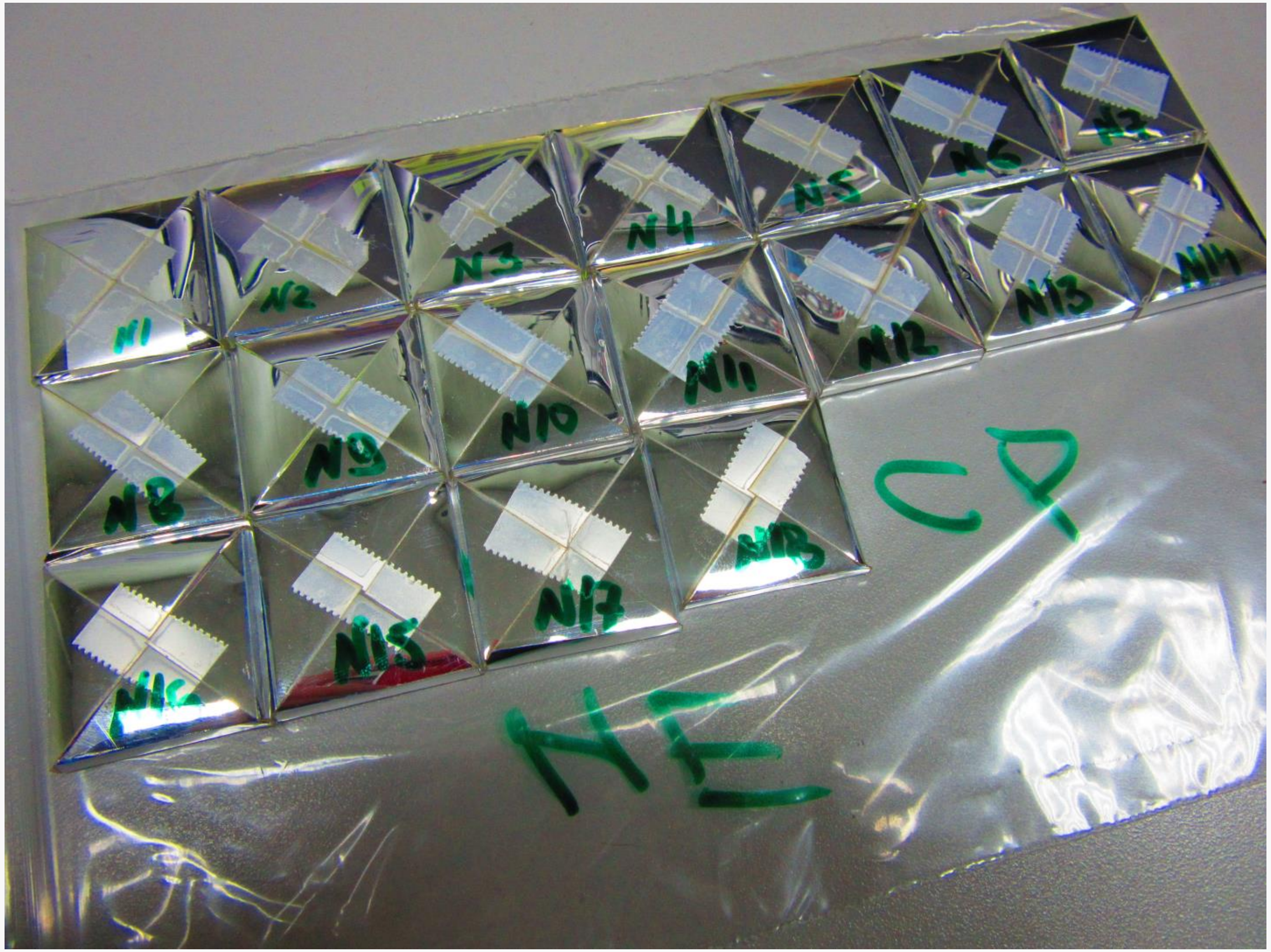




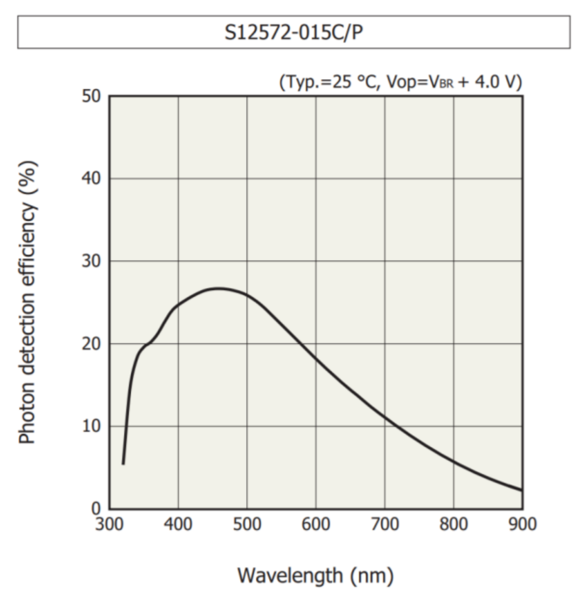
***BC-408 (BICRON)**, **EJ-260 (Eljen)**, **SCSN-81 (Kuraray)** and **UPS-923A (Ukraine)** were prepared by the Institute for Scintillation Materials (ISMA), Kharkov. There are made by milling commercially cast material down to the CE thickness (3 mm), then cutting the outline and the dimples.*

***SC-301** and **SC-307** were prepared by **Protvino (IHEP)**, Russia.*

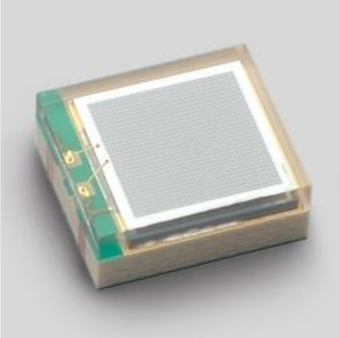




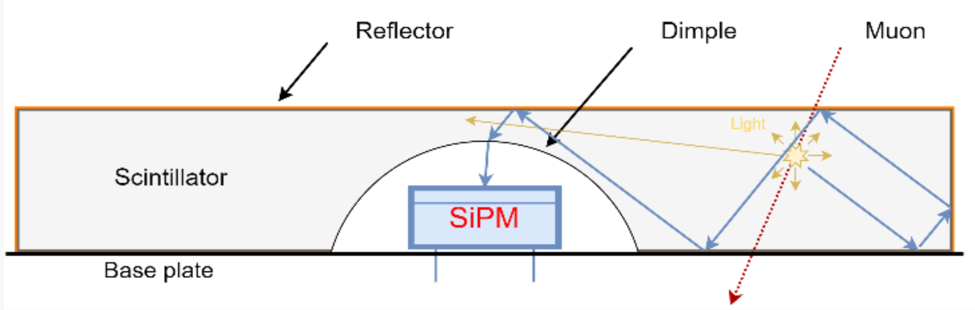
Silicon Photomultipliers (SiPMs) parameters



Parameter	S12572 -015P
Effective photosensitive area	3 × 3 mm
Pixel pitch	15 μm
Number of pixels	40000
Geometrical fill factor	53 %
Package	Surface mount type
Window	Epoxy resin
Window refractive index	1.55



18 Hamamatsu S12572-015P were used for light yield (LY) measurements in the special test bench. Gain is about $2.3 \cdot 10^5$ at $V_{op} = V_{br} + 3.0$ for all SiPMs.



Scintillators parameters

	BC-408	EJ-260	EJ-262	SCSN-81	UPS-923A	SC-301	SC-307
Light yield (relative to anthracene), %	64	60	57	50	60	55	69
Peak wavelength, nm	**425**	**490**	**481**	**440**	**425**	**420**	**416**
Decay time, ns	**2.1**	**9.2**	**2.1**	**2.5**	**3.3**	**2.4**	**2.2**
Base material	PVT	PVT	PVT	PS	PS	PS	PS

PVT – Polyvinyl toluene
PS – Polystyrene

Relative light yield of samples before irradiation

Single samples

30 x 30 x 3 mm^3

Scintillator	Max. emission, nm	Reflector	Number of tiles	Mean LY, p.e. (G fit)	Relative LY	R_{dimple}, mm	Readout by
BC-408	*425*	*ESR*	10	21.9 ± 0.9	1.0	6.2	Hamamatsu S12572-015P
EJ-260	*490*	*ESR*	10	25.3 ± 1.1	1.16		
UPS-923A	*425*	*ESR*	20	19.9 ± 0.7	0.91		
SC-301	*420*	*ESR*	10	26.7 ± 1.0	1.22		
SC-307	*416*	*ESR*	10	24.4 ± 0.7	1.12		
BC-408	*425*	*Tyvek*	10	11.2 ± 0.3	0.51		
EJ-260	*490*	*Tyvek*	10	10.2 ± 0.2	0.47		
UPS-923A	*425*	*Tyvek*	10	11.6 ± 0.5	0.53		
SCSN-81	*440*	*Tyvek*	10	12.0 ± 0.3	0.55		
EJ-260	*490*	*ESR*	7	23.0 ± 0.3	1.05	5.0	Hamamatsu 13360-1350PE
EJ-262	*481*	*ESR*	6	33.2 ± 0.5	1.52		
UPS-923A	*425*	*ESR*	9	20.5 ± 0.6	0.94		

Block samples

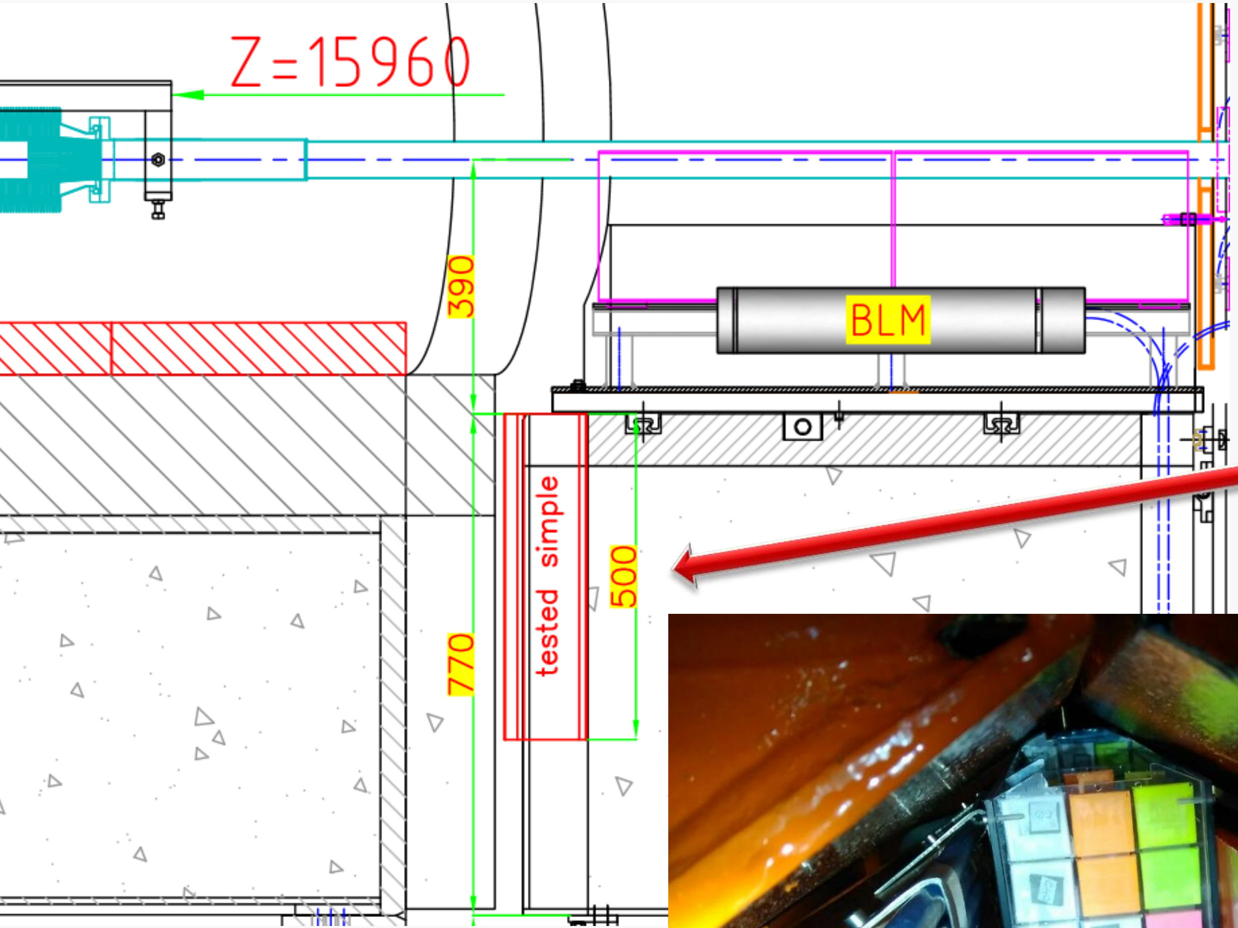
90 x 90 x 3 mm^3

Scintillator	Max. emission, nm	Reflector	Number of cells	Mean LY, p.e. (G fit)	Relative LY	R_{dimple}, mm	Readout by
BC-408	*425*	*ESR*	16	21.4 ± 0.5	0.98	6.2	Hamamatsu S12572-015P
BC-408	*490*	*Tyvek*	9	11.6 ± 0.6	0.53		
UPS-923A	*425*	*ESR*	17	18.3 ± 0.6	0.84		
EJ-260	*490*	*ESR*	5	33.8 ± 0.6	1.54	5.0	
UPS-923A	*425*	*ESR*	5	21.8 ± 0.2	1.0		

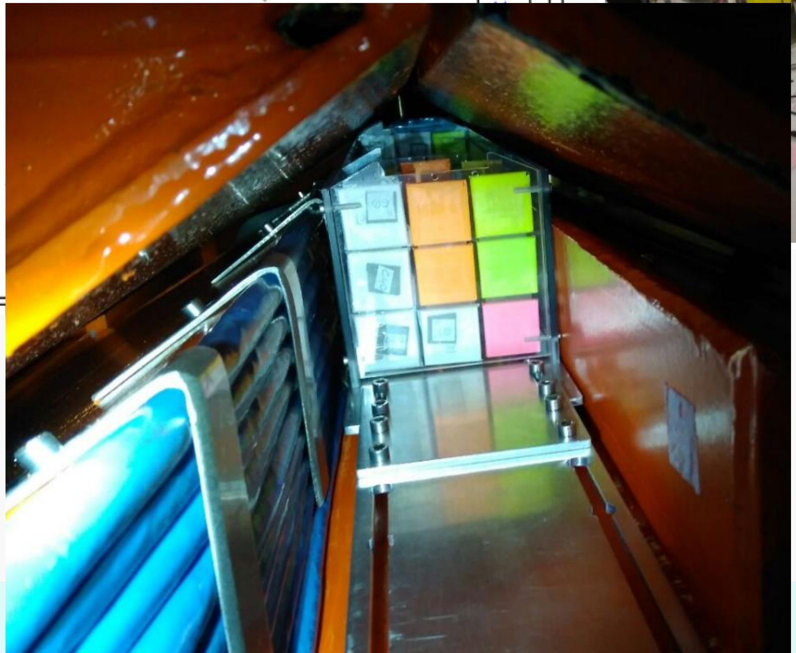
** The relative light yield (RLY) of all scintillators was normalized to the LY of ESR-wrapped BC-408.*

*** ESR foils were used for irradiation at the IBR-2. Tyvek was used for irradiation at the CMS.*

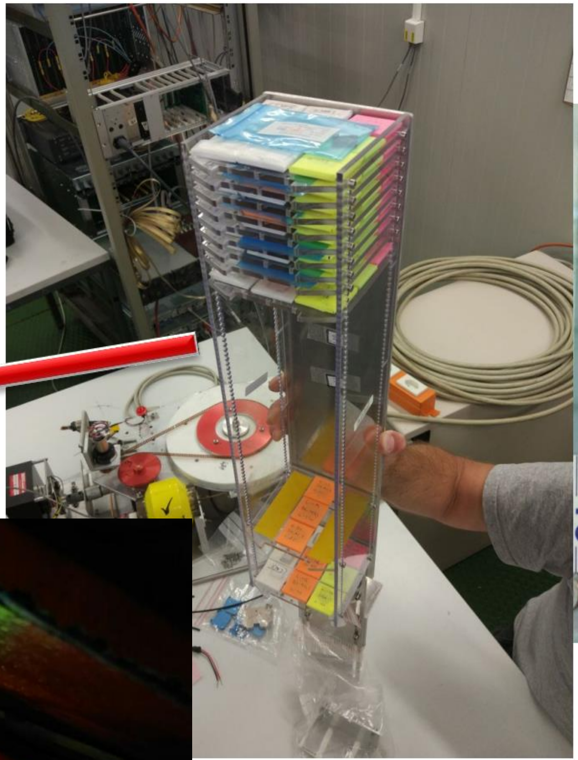
Castor Radiation Facility (CRF) and tower with samples

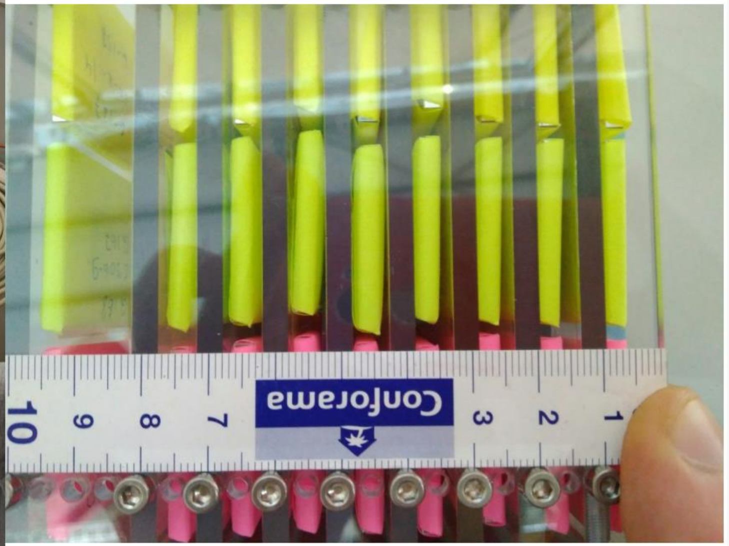


Total: 100 samples
Irradiation time: 138 days
(June-October 2018)

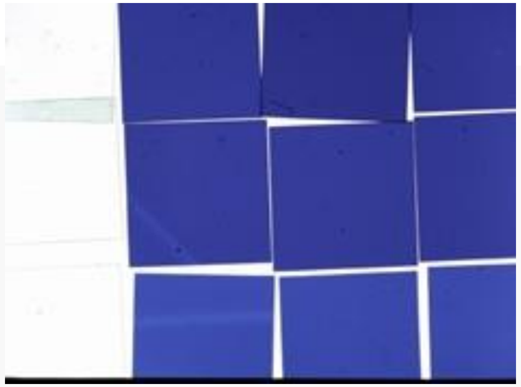


CRF Tower Assembled





FWT-60-00 Radiochromic Films



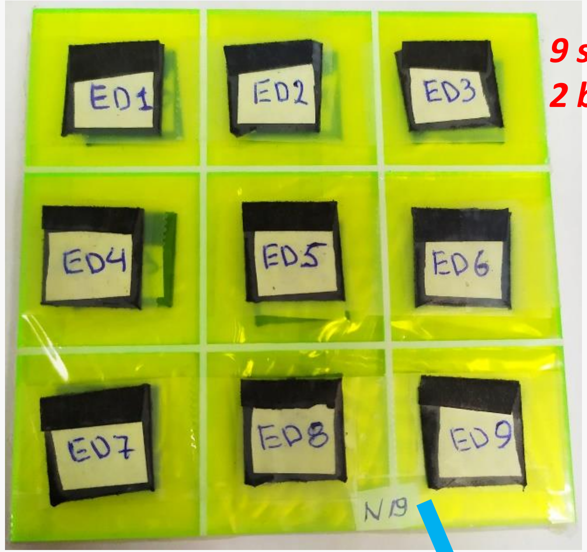
Investigation of radiation hardness of scintillators in IBR-2 reactor

Irradiation in March 11-22, 2019

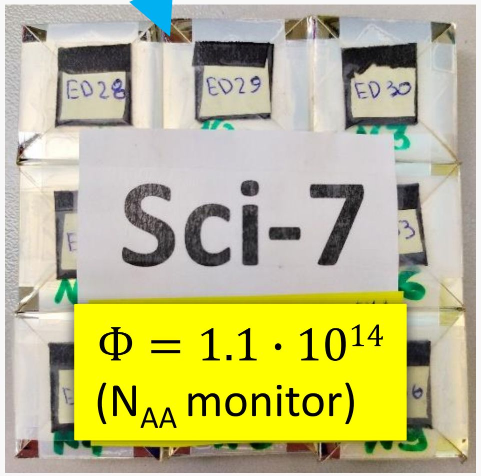
Irradiation in May 13-28, 2019

6 single samples
3 block samples

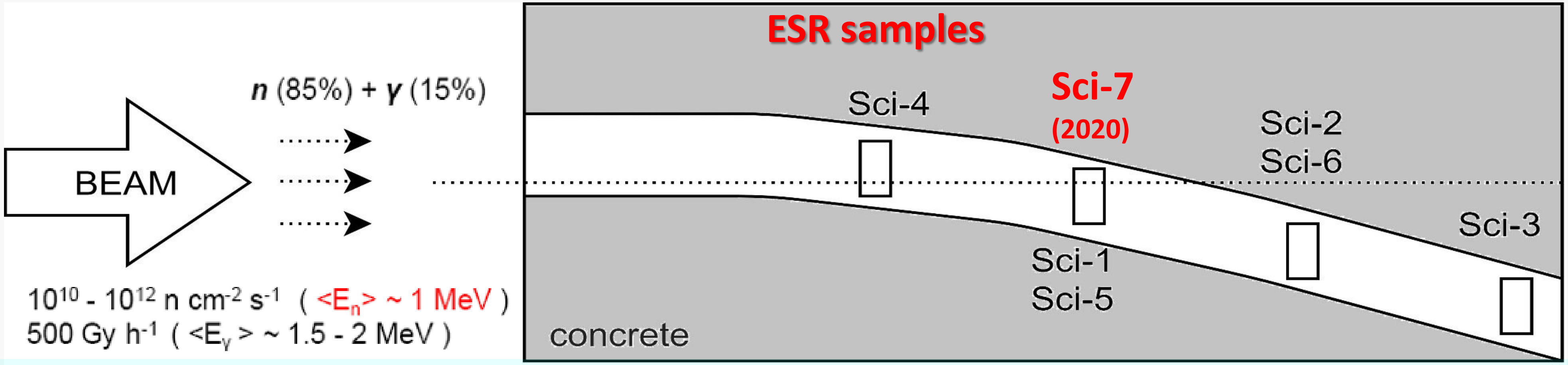
Irradiation in January 16-29, 2020



9 single samples
2 block samples

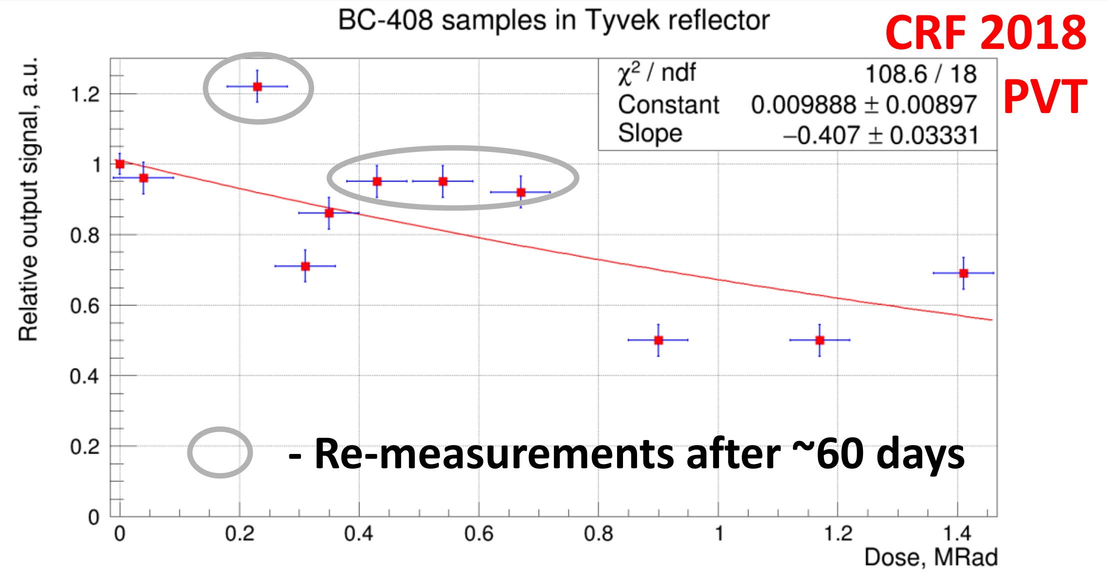


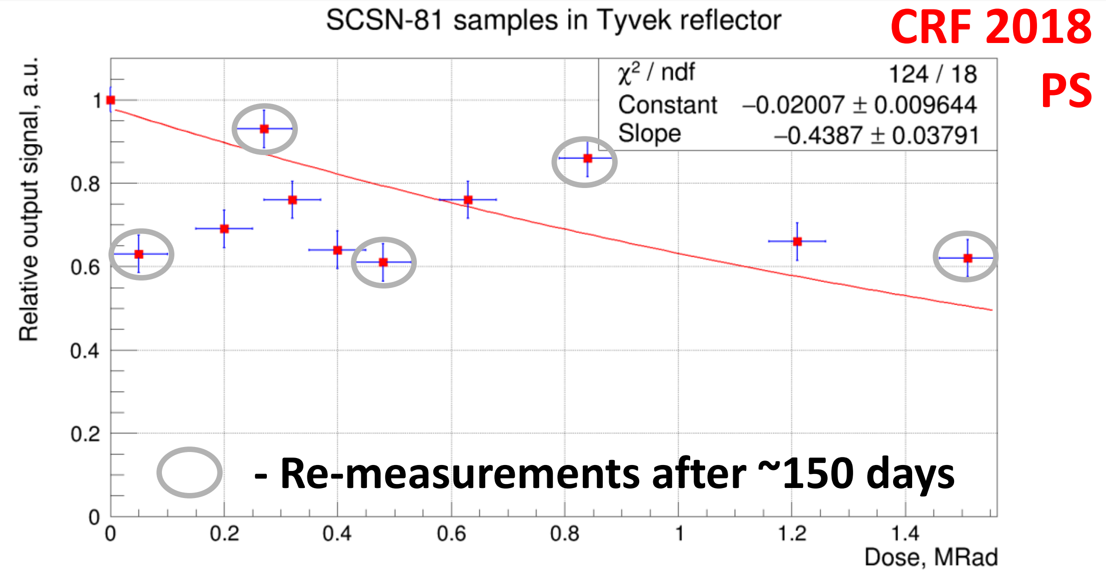
$\Phi = 1.1 \cdot 10^{14}$
(N_{AA} monitor)

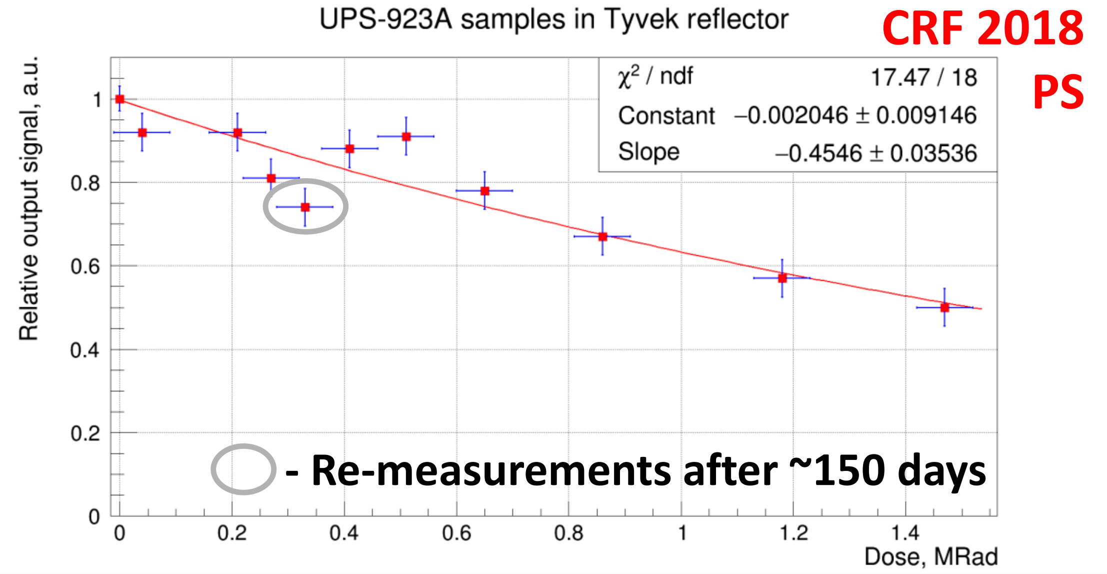


10^{10} - 10^{12} n cm^{-2} s^{-1} ($\langle E_n \rangle \sim 1$ MeV)
500 Gy h^{-1} ($\langle E_\gamma \rangle \sim 1.5 - 2$ MeV)

Radiation hardness of «blue» scintillators





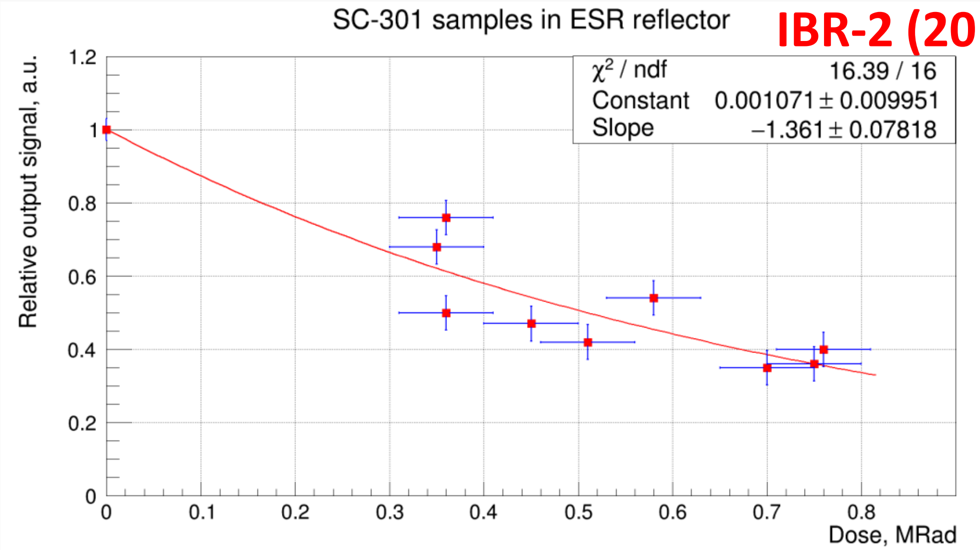


All Tyvek-wrapped samples degraded by two times at the absorbed dose of 1.5 Mrad (dose rate was about 0.9 kRad/hour). The results are valid for the PVT base as well as for the PS base.

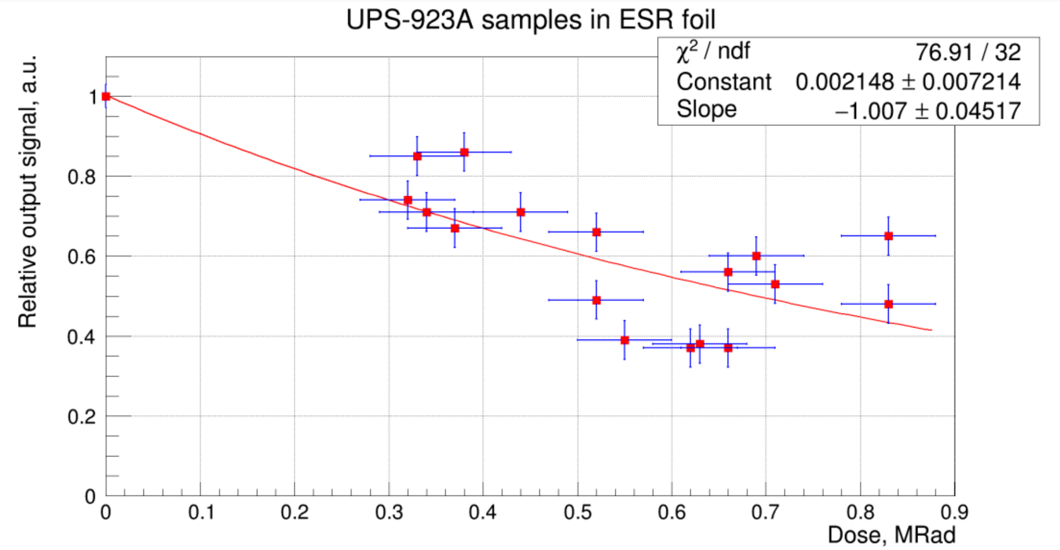
** Max. emission: BC, UPS - 425 nm; SCSN - 440 nm.*

*** CRF: Castor Radiation Facility at the CMS detector.*

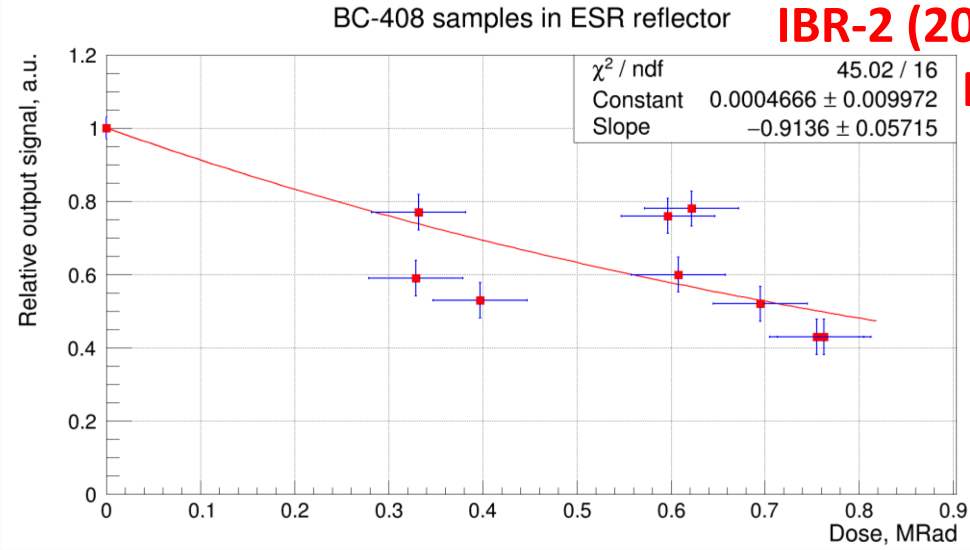
Radiation hardness of «blue» scintillators



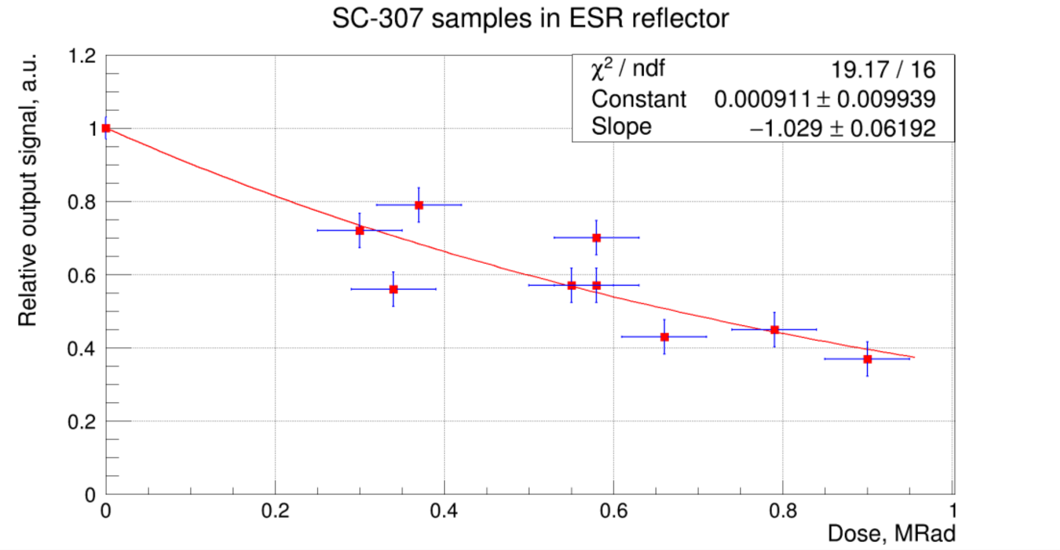
IBR-2 (2019)
PS



IBR-2 (2019)
PS



IBR-2 (2019)
PVT



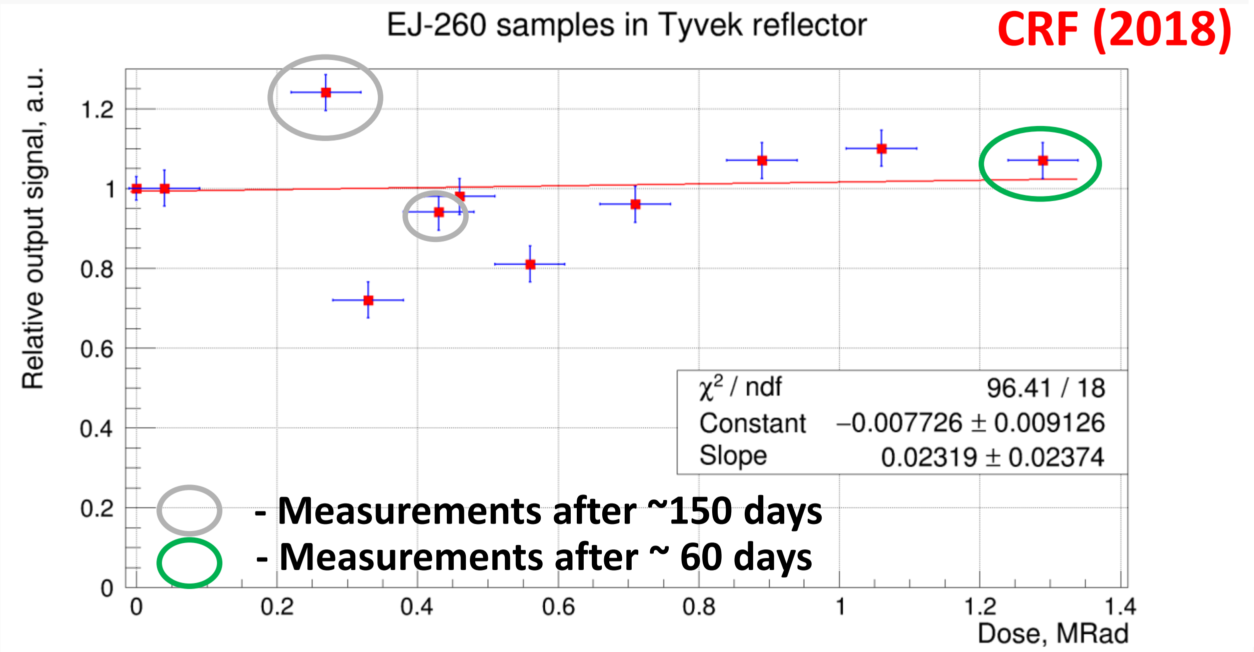
IBR-2 (2019)
PS

All ESR-wrapped samples were degraded by more then two times at dose of 0.9 Mrad.

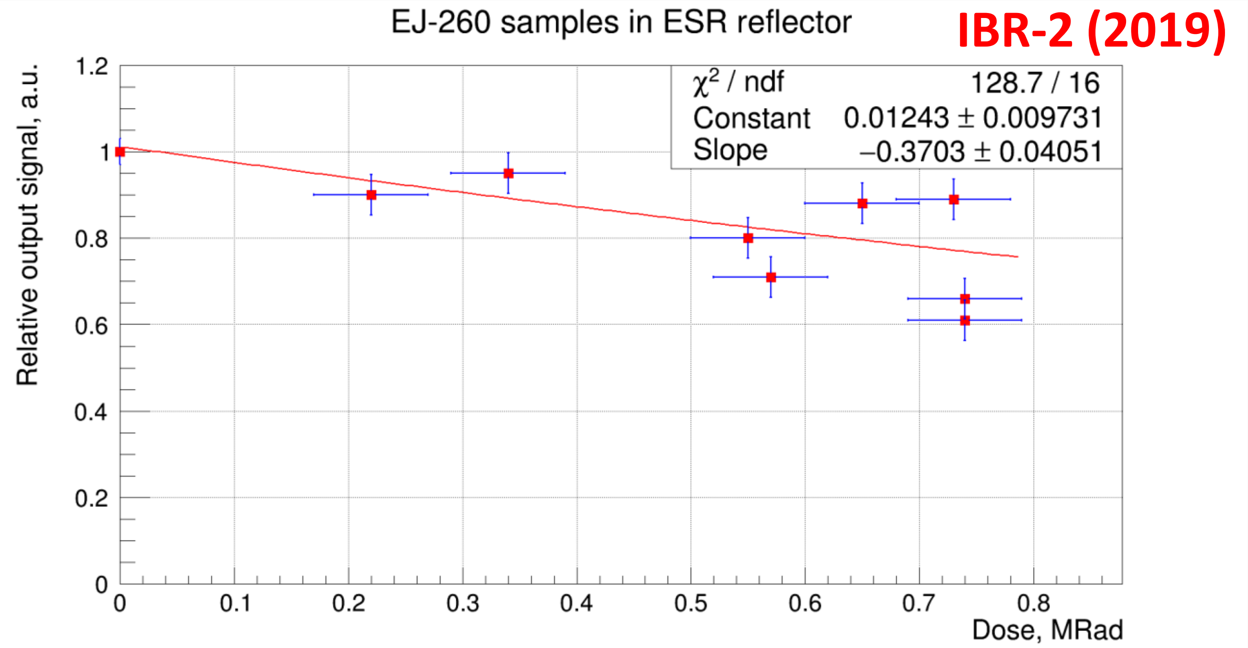
Radiation hardness of «green» scintillators

EJ-260: max. emission is 490 nm, PVT base
(Measurements were taken in 7-20 days after of irradiation)

CRF (2018)



IBR-2 (2019)

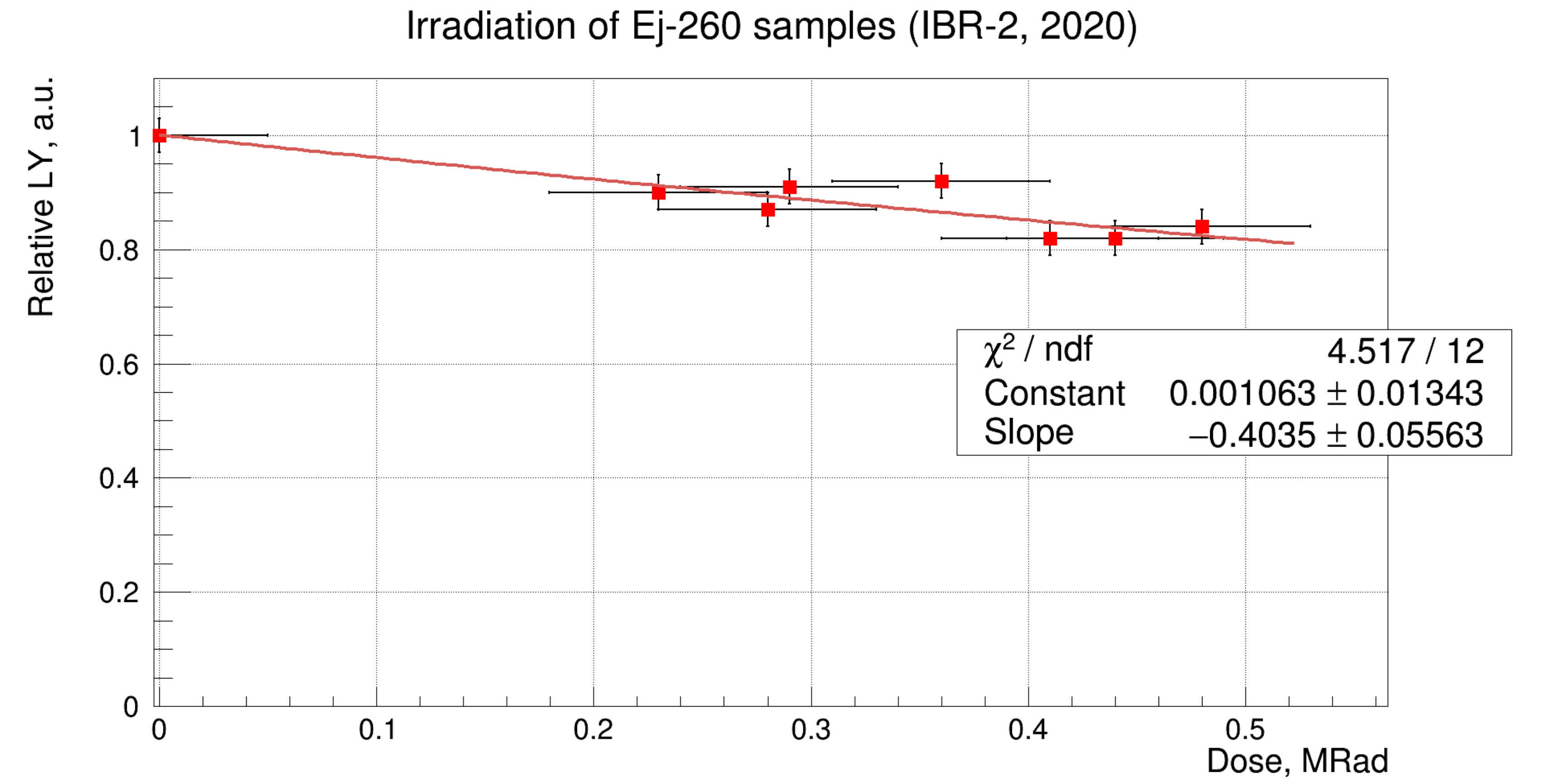


The green Tyvek-wrapped scintillators practically had no changes in the output signal (LY) up to the absorbed dose of 1.2 Mrad. ESR-wrapped samples had a small degradation. But we must take into account different irradiation conditions. IBR have more aggressive conditions relative to CMS detector.

Radiation hardness of «green» scintillators: additional tests

EJ-260: max. emission is 490 nm, PVT base

(Measurements were taken in 162 days after of irradiation due to COVID-19)



Irradiation conditions:

IBR-2, 2020 (Jan 16-29, 13 days)

Scintillator samples:

Dimension: 29.5 x 29.5 x 3 mm^3

Dimple: R_{dimple} = 5 mm

Wrapped: ESR foils

Initial LY of EJ-260 individual tiles:

Mean = 23.0 p.e.

RMS = 0.3 p.e.

Test conditions:

Source: cosmic rays

Type of SiPM: S13360-1350PE

Sensitive area: 1.3 x 1.3 mm^2

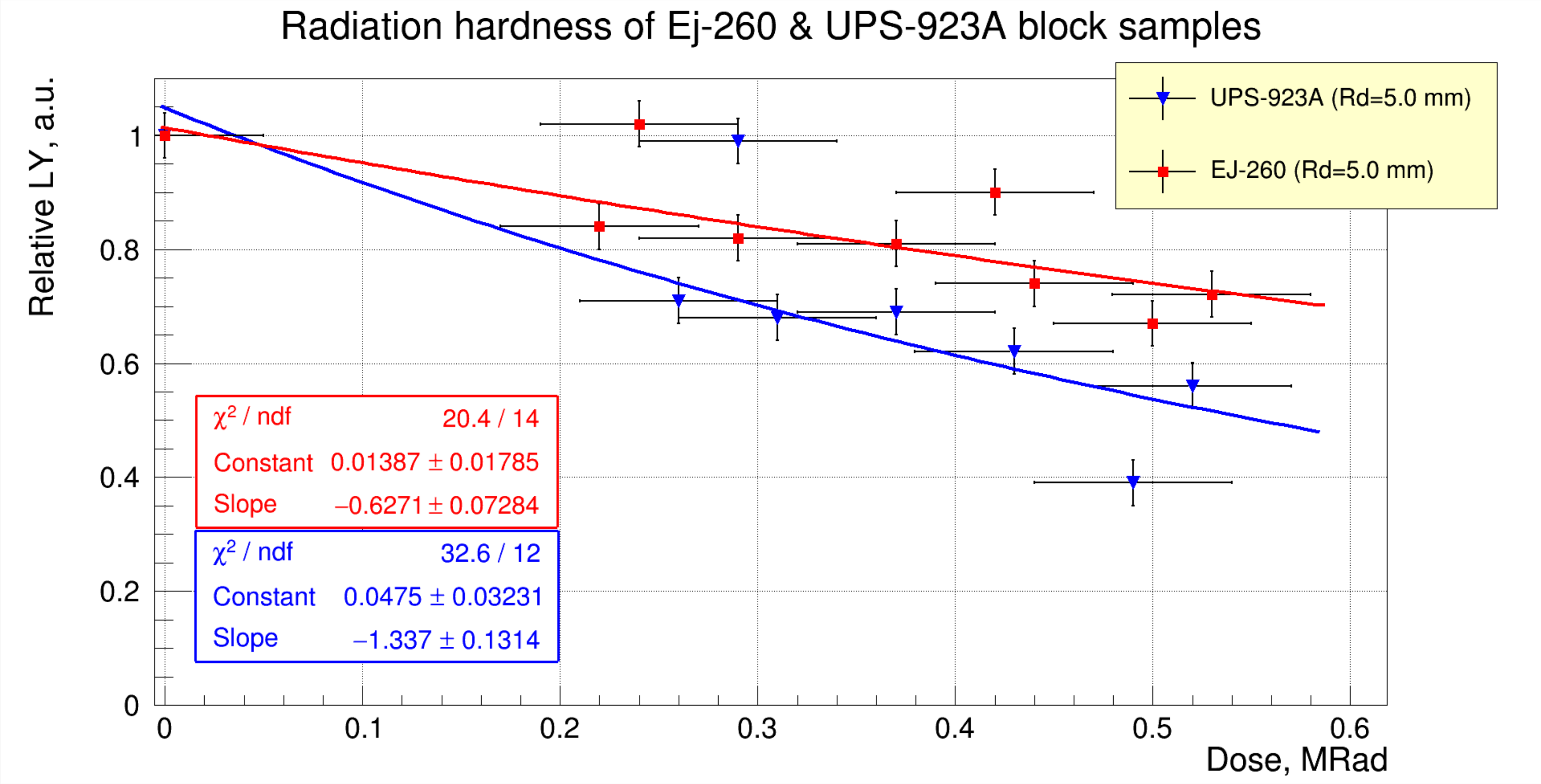
Operation voltage: $V_{op} = V_{br} + 1.0\ V$

Thermo-compensation mode:

$V_{op} = V_{(25\ °C)} + 0.06V \cdot \Delta T$

EJ-260 block samples vs UPS-923A block samples

(Measurements were taken in 160 days after of irradiation due to COVID-19)



Irradiation conditions:

IBR-2, 2020 (Jan 16-29, 13 days)

Scintillator samples:

Dimension: 90 x 90 x 3 mm^3

Dimples: R_{dimple} = 5.0 mm

Wrapped:

ESR sheets is main reflector

1 mm epoxy separator between cells

Initial LY of Ej-260 = **33.8 ± 0.6 p.e.**

Initial LY of UPS = **21.8 ± 0.2 p.e.**

Test conditions:

Source: cosmic rays

Type of SiPM: S12572-015P

Sensitive area: 3 x 3 mm^2

Operation voltage:

$V_{op} = V_{br} + 3.0$ V

Thermo-compensation mode:

$$V_{op} = V_{(25\,°C)} + 0.06V \cdot \Delta T$$

Relative light yield of samples after irradiation up to dose of 0.8 MRad

№	1.	2.	3.	4.	5.	6.	7.	8.	9.
	Type	Reflector	#	Mean (G fit) ± RMS, p.e.	LY	Irradiated on	Mean (G fit) ± RMS, p.e.	Dose rate, kRad/h	RLY after irradiation
Conditions: R_{dimple} = 6.2 mm, Hamamatsu S12572-015P, Dose is 0.8 Mrad									
1.	**BC-408**	*ESR*	*10*	**21.9 ± 0.9**	**1.0**	**IBR-2**	**9.3 ± 0.2**	2.63	**0.43**
2.	**EJ-260**	*ESR*	*9*	**25.3 ± 1.1**	**1.16**	**IBR-2**	**18.8 ± 0.8**	2.55	**0.74**
3.	**UPS-923A**	*ESR*	*17*	**20.1 ± 0.6**	**0.92**	**IBR-2**	**10.1 ± 0.1**	2.88	**0.5**
4.	**SC-301**	*ESR*	*10*	**26.7 ± 1.0**	**1.22**	**IBR-2**	**9.5 ± 0.2**	2.64	**0.36**
5.	**SC-307**	*ESR*	*10*	**24.4 ± 0.7**	**1.12**	**IBR-2**	**10.6 ± 0.8**	2.93	**0.43**
6.	**BC-408**	*Tyvek*	*10*	**11.2 ± 0.3**	**0.51**	**CMS**	**5.9 ± 0.1**	1.28	**0.53**
7.	**EJ-260**	*Tyvek*	*10*	**10.2 ± 0.2**	**0.47**	**CMS**	**10.2 ± 0.8**	1.14	**1.0**
8.	**UPS-923A**	*Tyvek*	*10*	**11.6 ± 0.5**	**0.53**	**CMS**	**7.3 ± 0.1**	1.22	**0.63**
9.	**SCSN-81**	*Tyvek*	*10*	**12.0 ± 0.3**	**0.55**	**CMS**	**9.7 ± 0.2**	1.2	**0.81**
Conditions: R_{dimple} = 5.0 mm, Hamamatsu S13360-1350PE, Dose is 0.5 MRad									
10.	**EJ-260**	*ESR*	*7*	**23.0 ± 0.3**	**1.05**	**IBR-2**	**19.0 ± 0.2**	1.47	**0.83**

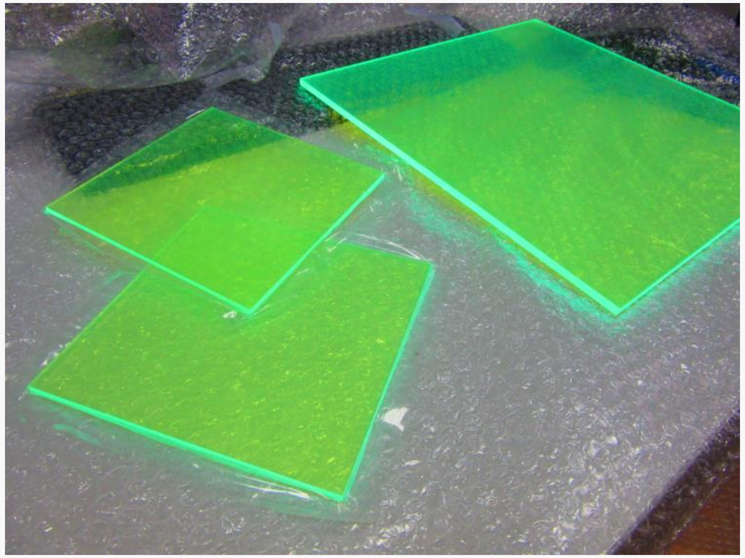
Additional
Reflectors results:

LY of all ESR-wrapped scintillators are practically independent of the irradiation dose of the own ESR foils. That is means what ESR foil is radiation-resistant reflector.

This result is valid for irradiated as well as non-irradiated scintillators using irradiated ESR foils.

** The relative light yield (RLY) of all scintillators was normalized to the LY of ESR-wrapped BC-408 before irradiation.*

New fast «green» scintillator materials for tests: IBR-2 (Nov 2020, 6 tiles)



EJ-262 samples:

LY relative anthracene: **57%**
Max. Emission: **481 nm**
Decay time: **2.1 ns (instead of 9.2 ns like Ej-260)**
Base material: PVT
Dimension: 29.5 x 29.5 x 3 mm^3
Dimple: $\mathbf{R_{dimple} = 5.0\ mm}$
Wrapped: ESR foils

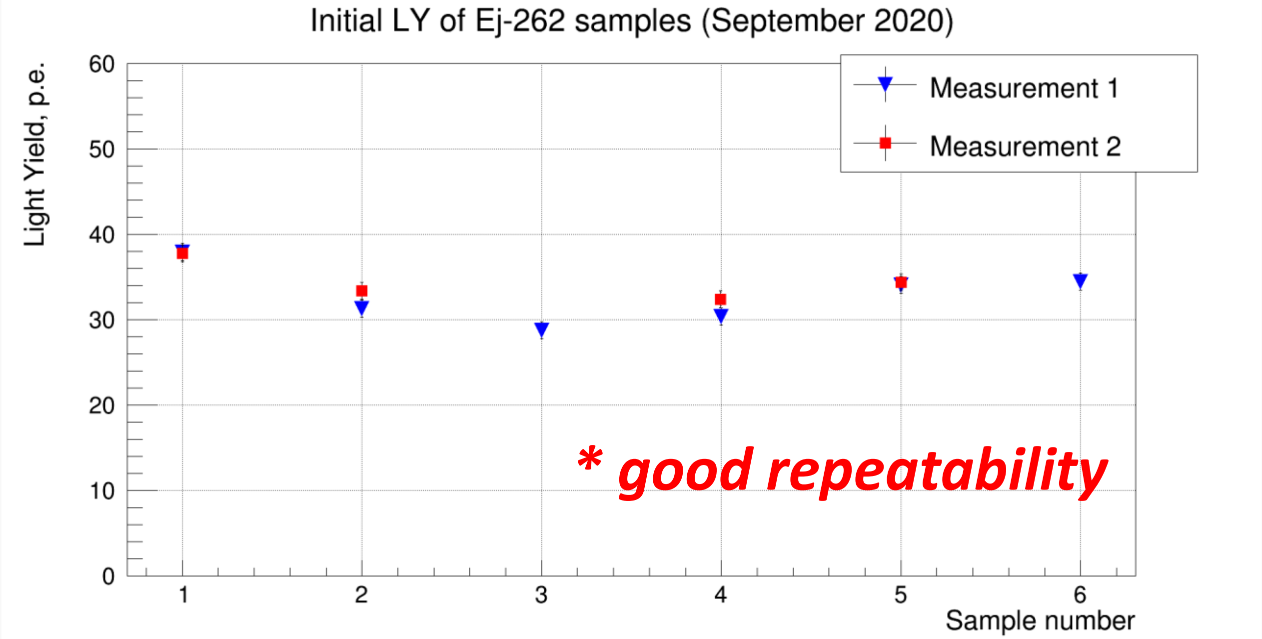
Initial LY of EJ-262 individual tiles:

Mean = 23.0 p.e.
RMS = 0.6 p.e.

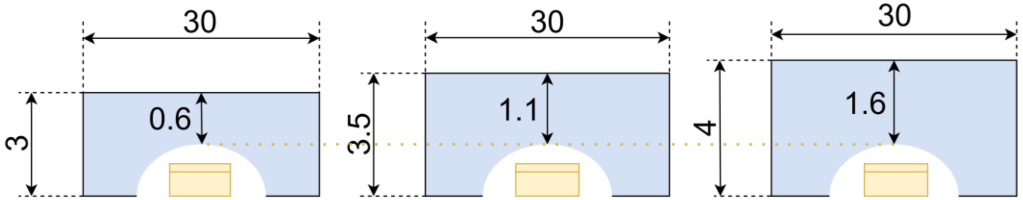
Test conditions:

Source: cosmic rays
Type of SiPM: **S13360-1350PE**
Sensitive area: 1.3 x 1.3 mm^2
Operation voltage: $V_{op} = V_{br} + 1.0\ V$
Thermo-compensation mode:

$$V_{op} = V_{(25\,^{\circ}\mathrm{C})} + 0.06V \cdot \Delta T$$



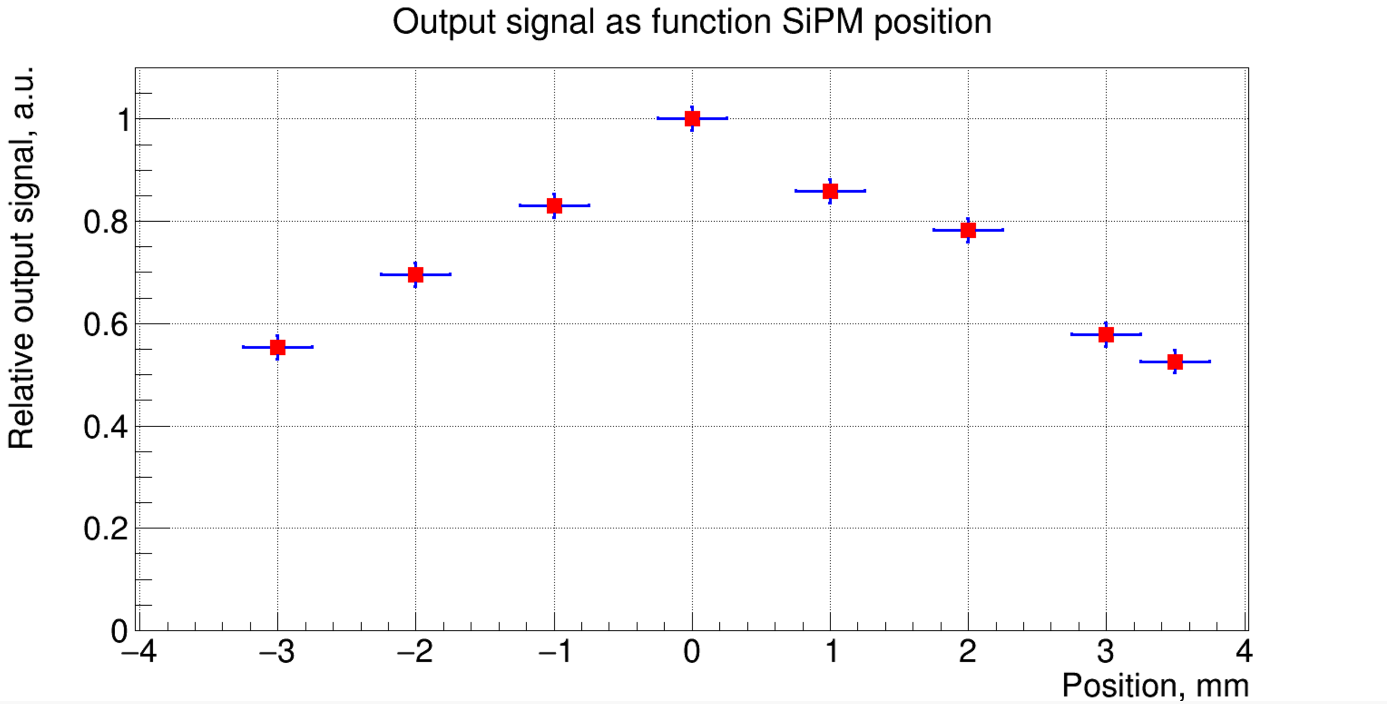
Dependence of the light yield on the thickness of scintillator



Thickness	Average value of p.e. in all cells	The ratio of the values of photoelectrons
3 mm	17.39 p.e.	100%
3.5 mm	22.65 p.e	130%
4 mm	23.21 p.e.	134%

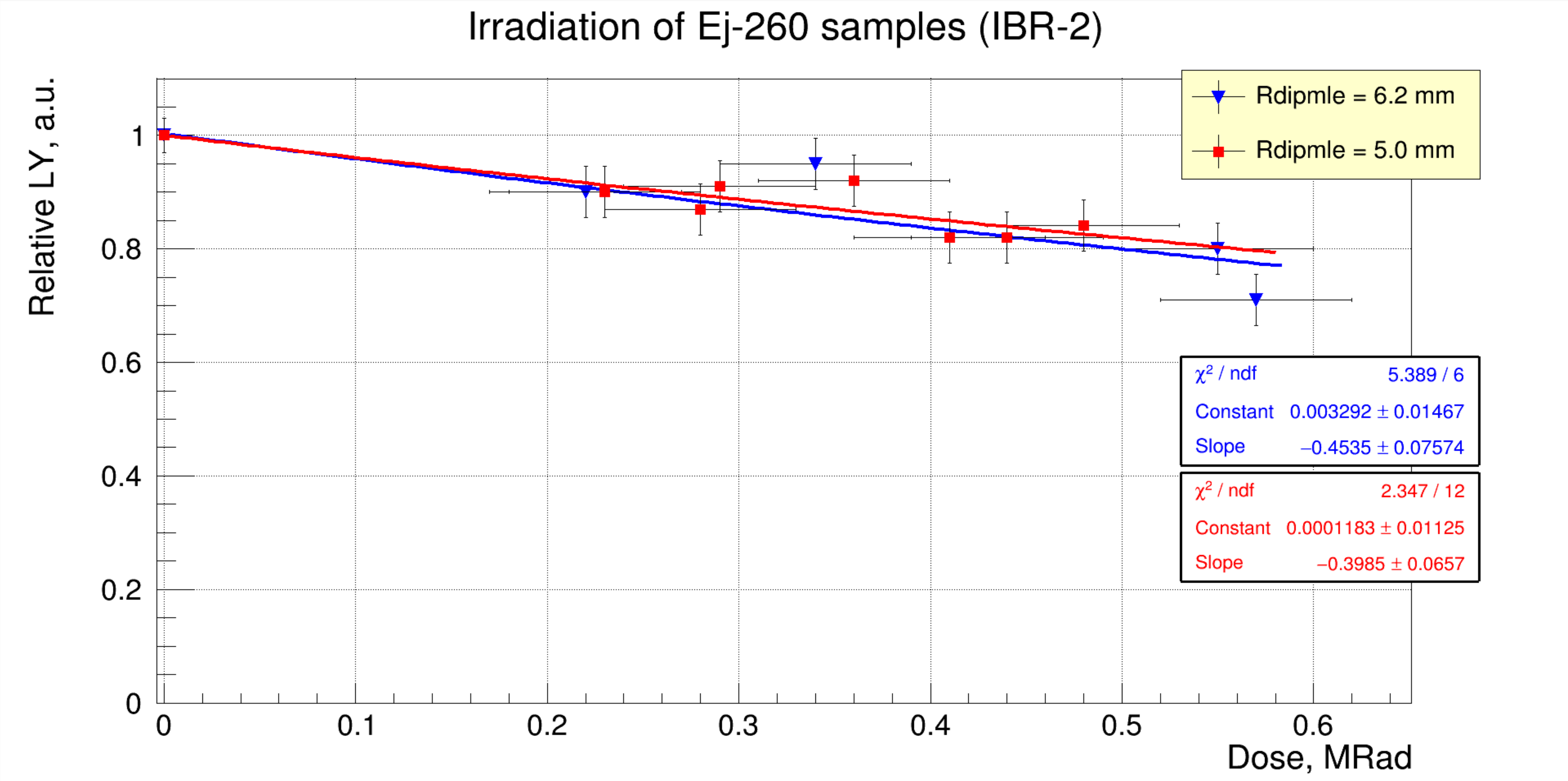
* UPS-923A block samples were used. All samples had ESR reflectors. Detection of light was carried out by Hamamatsu MPPC S12572-015P with photosensitive area 3x3 mm^2.

Dependence of the output signal (LY) on the position of 1 mm^2 SiPM (S12571-015P) in the dimple



- *Position is a shift relative to the center of the dimple*
- *ESR-wrapped CALICE type scintillator (30x30x3 mm^3 tile)*
- *Source of particle is ^{90}Sr*
- *R_{dimple} = 4.0 mm*

Positive dynamics in radiation hardness at decreasing R_{dimple}

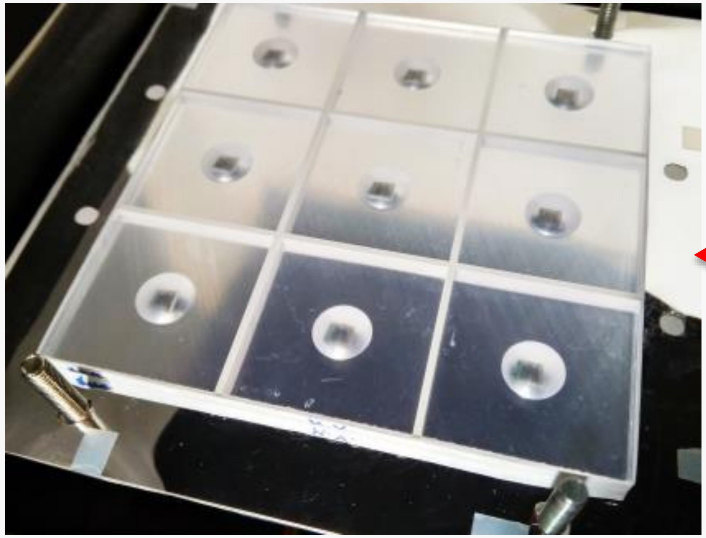


Summary:

- Radiation hardness of blue scintillators is almost identical for all types.
- EJ-260 scintillators (green) have minimal degradation of LY at different irradiation facilities.
- Radiation hardness of scintillators not depends on the base material (PVT or PS), but it depends on peak emission wavelength.
- Additional EJ-260 scintillators were irradiated in January 2020. Results show similar behavior relative to earlier studies.
- New EJ-262 scintillators were formed and tested in autumn 2020. Samples are being irradiation in IBR-2 reactor now.

Thank you for attention !

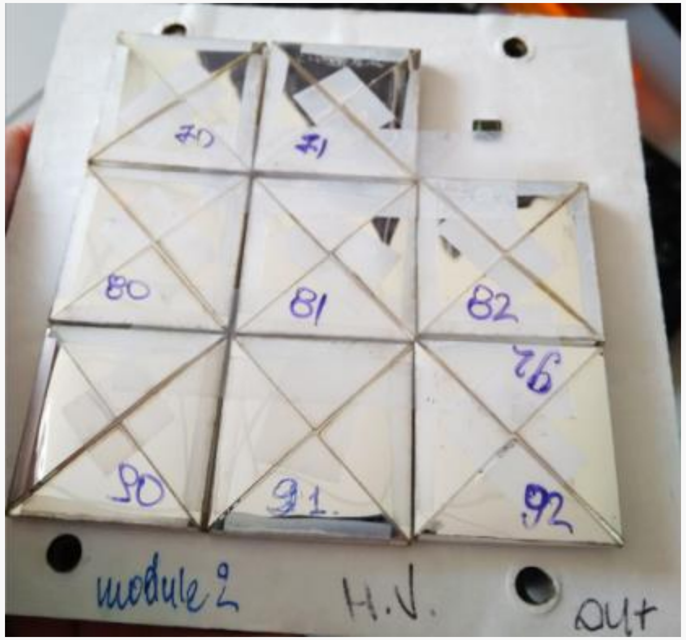
Back up slides

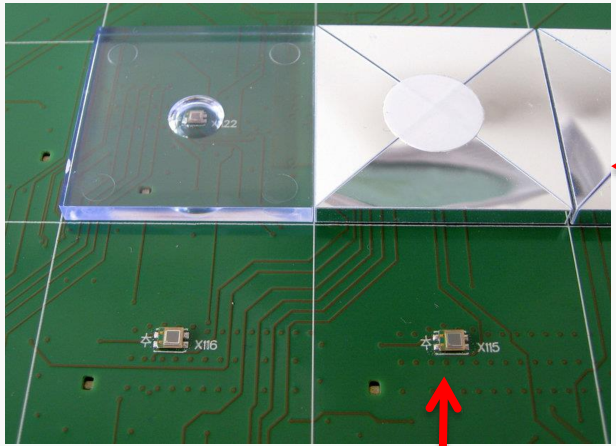


Block samples
3x3 cells

<u>More details in :</u>
Stand for the investigation radiation hardness of the plastic scintillators // CEUR Workshop proceedings, Vol-2507 - pp. 418-422 (2019)

Single tiles
30x30x3 mm^3

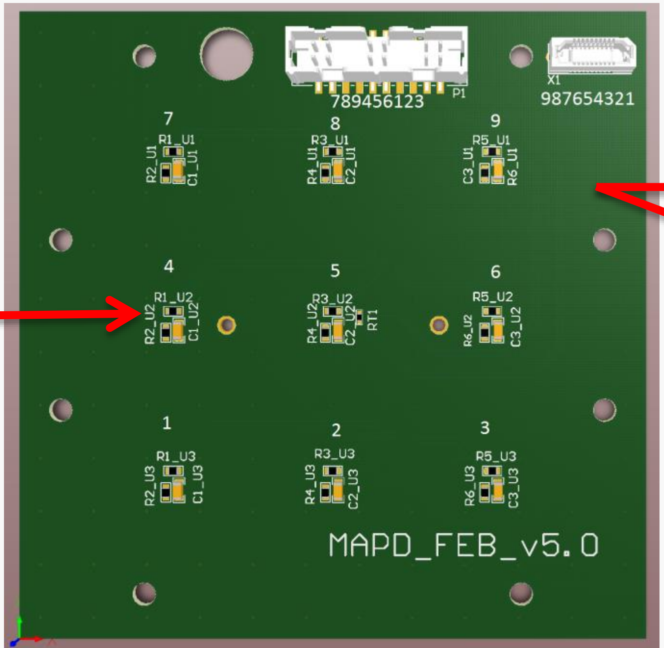


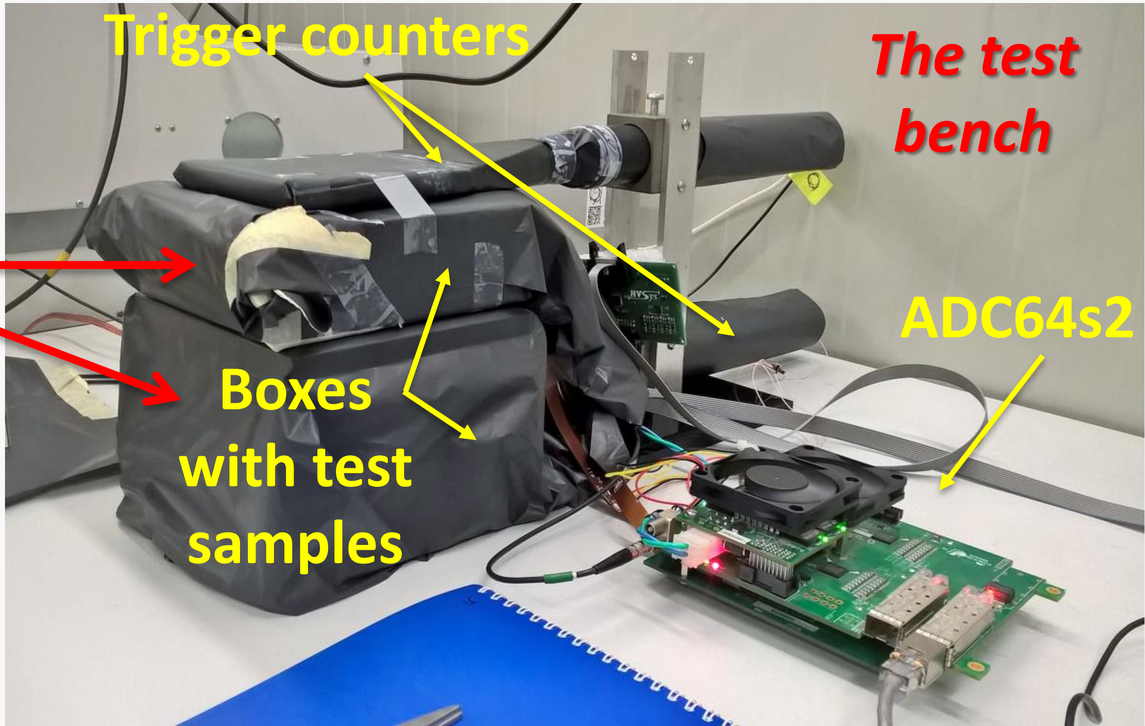


(un)wrapped SiPM-on-tile

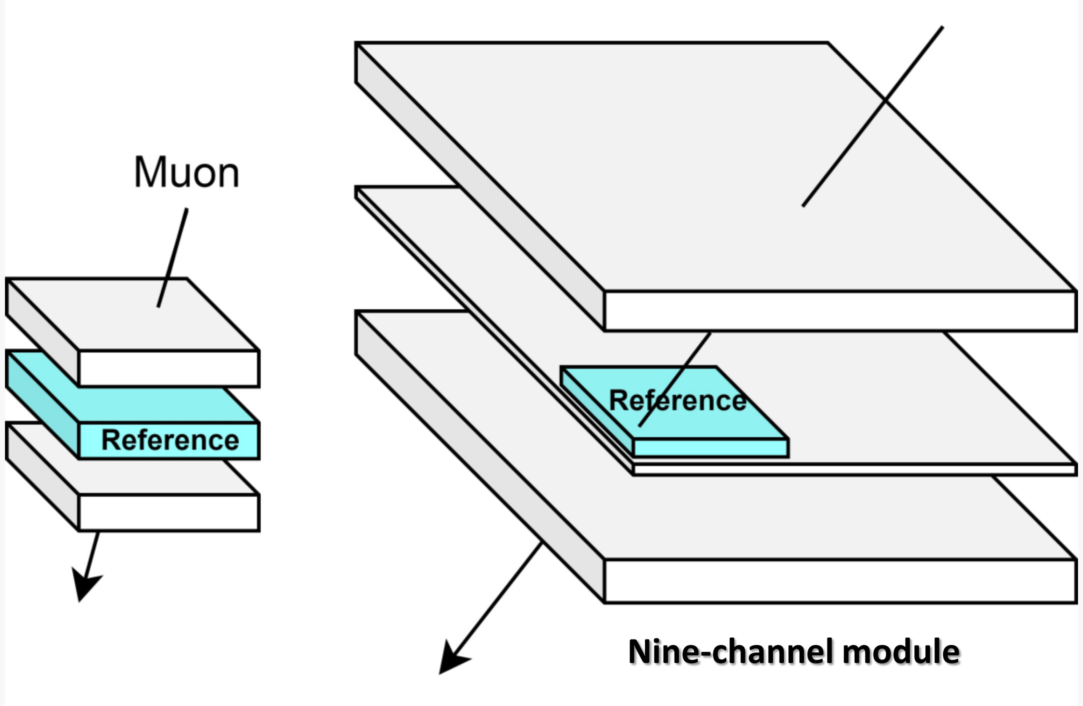
SiPMs

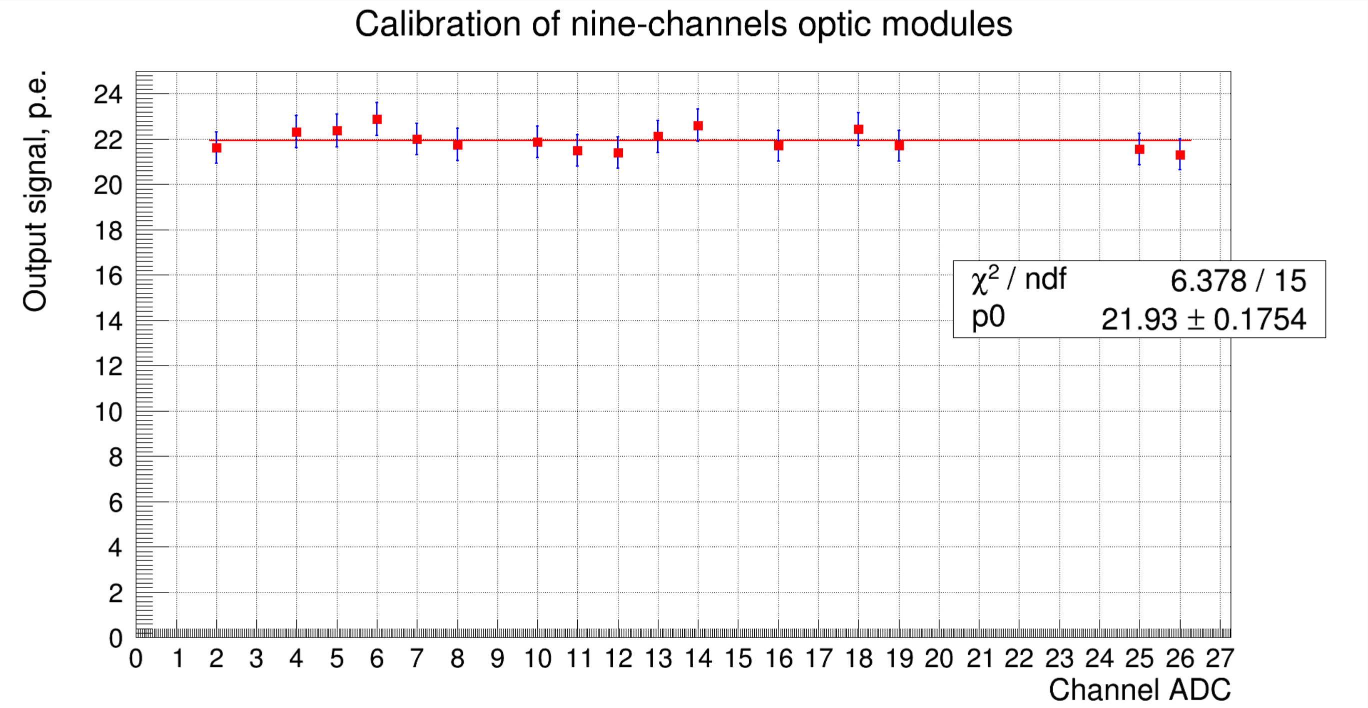
Multi-channel optic module





Cross calibration and multi-channels measurements

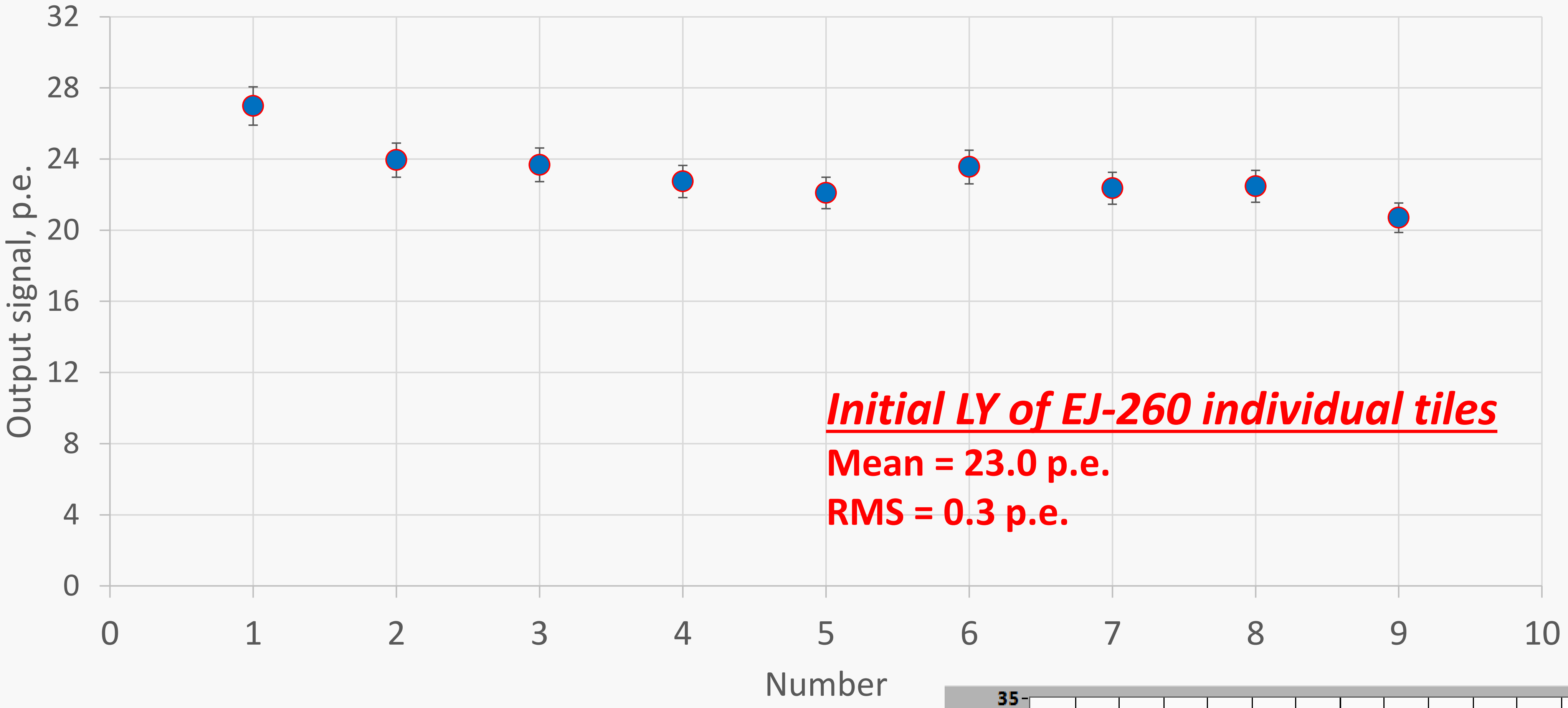




$\delta_{ref} = 0.7\%$ $\delta_{9ch} = 0.3\text{–}1.2\%$ $\delta_{sys} = 3.2\%$

$$\delta = \delta_{ref} + \delta_{9ch} + \delta_{stat} + \delta_{sys} = 4.5\text{–}4.8\%$$

Ej-260 single samples before irradiation in 2020



R_{dimple} = 5.0 mm

1.3 x 1.3 mm² SiPM (Hamamatsu S13360-1350PE)

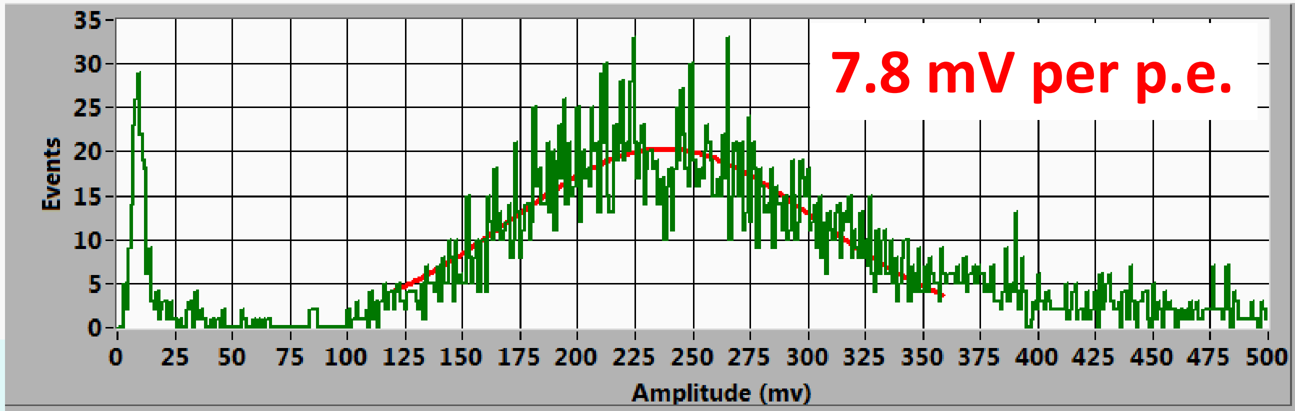
Conditions:

Source of irradiation is cosmic rays

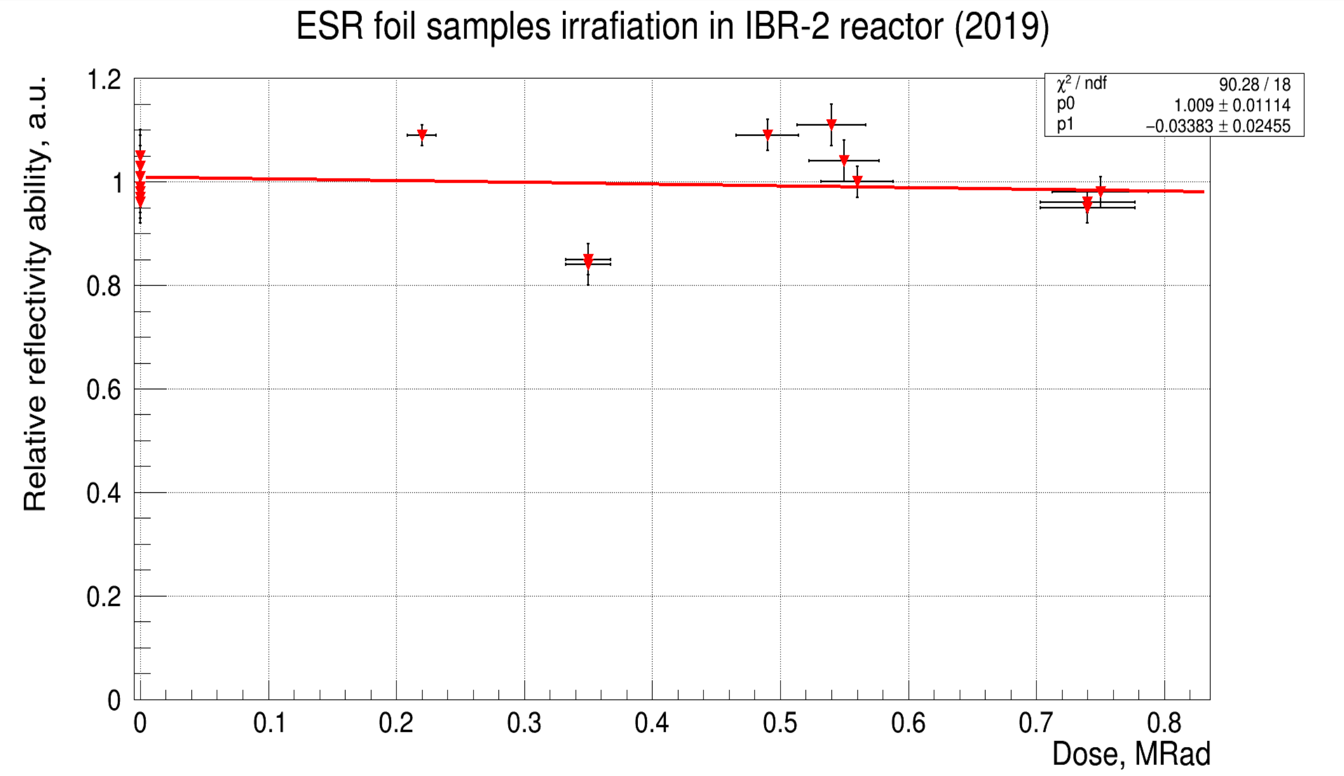
$V_{op} = V_{br} + 1.0\ V$

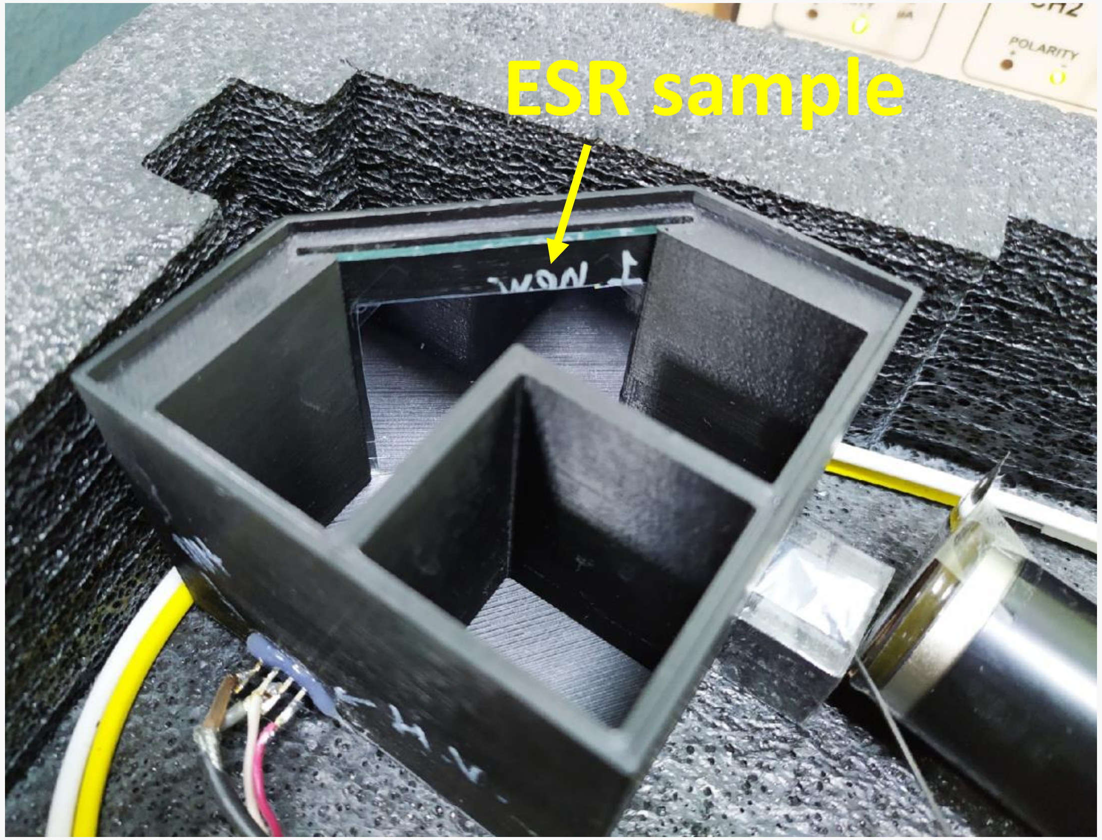
Standard thermo-compensation of Hamamatsu

$V_{op} = V_{(25\,°C)} + 0.06V \cdot \Delta T$



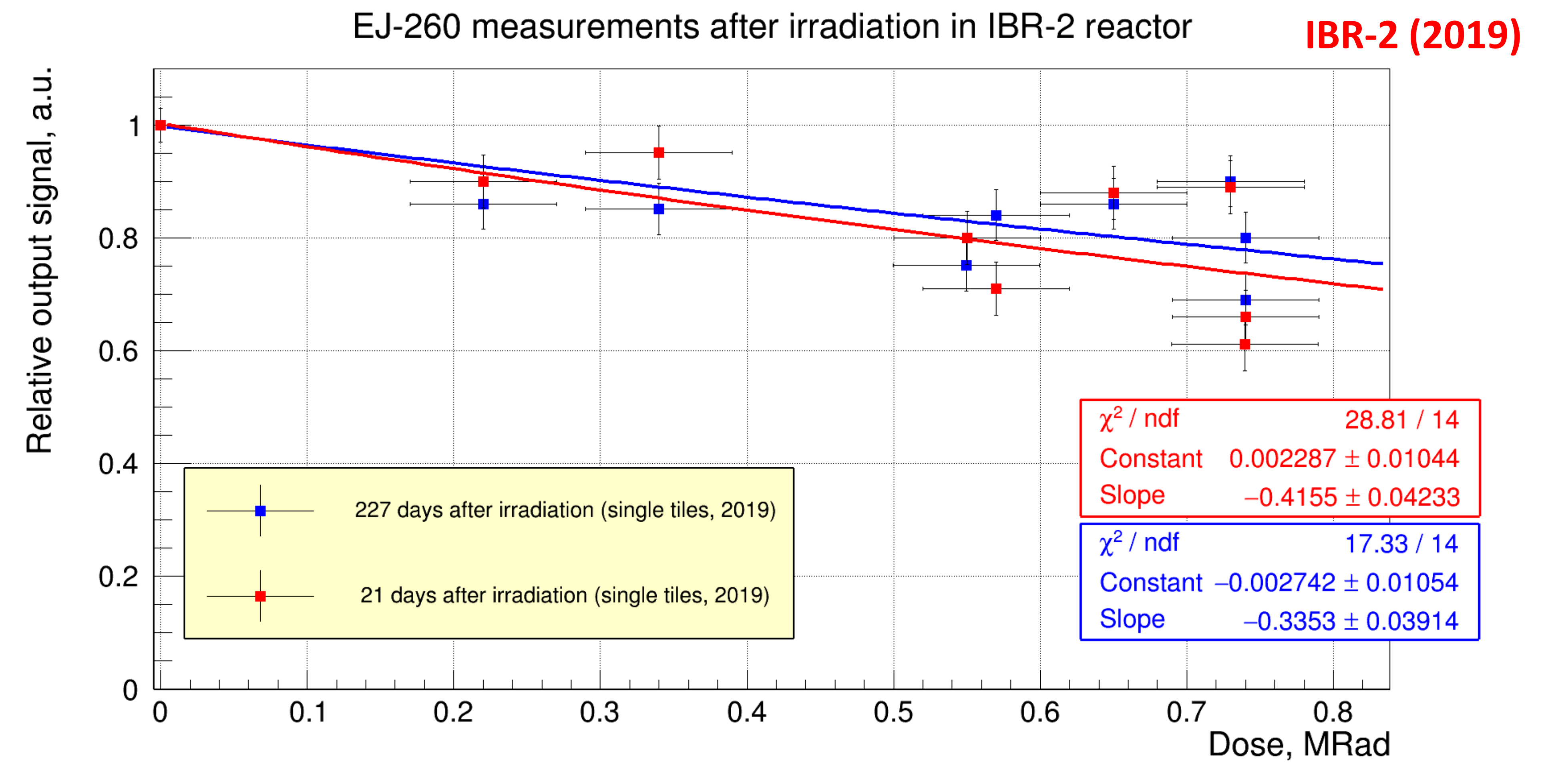
Irradiation of ESR reflectors (4x4 cm² samples)





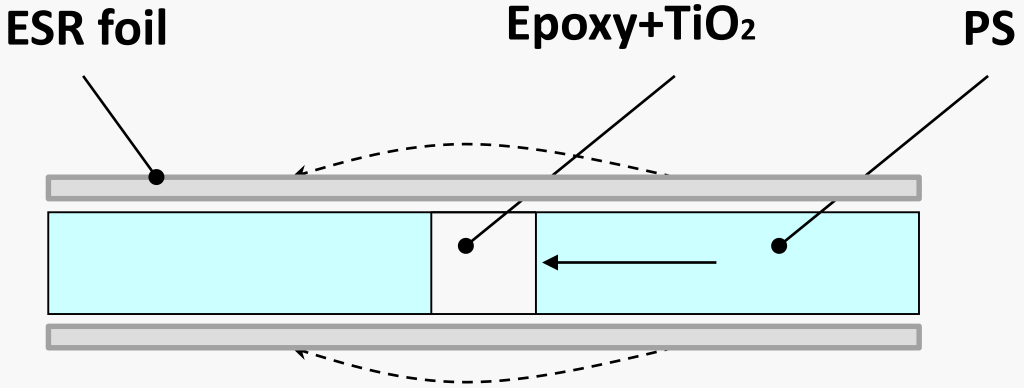
** Tests were taken in a special test bench. Source is 455 nm picosecond laser. Trigger from PMT-85.*

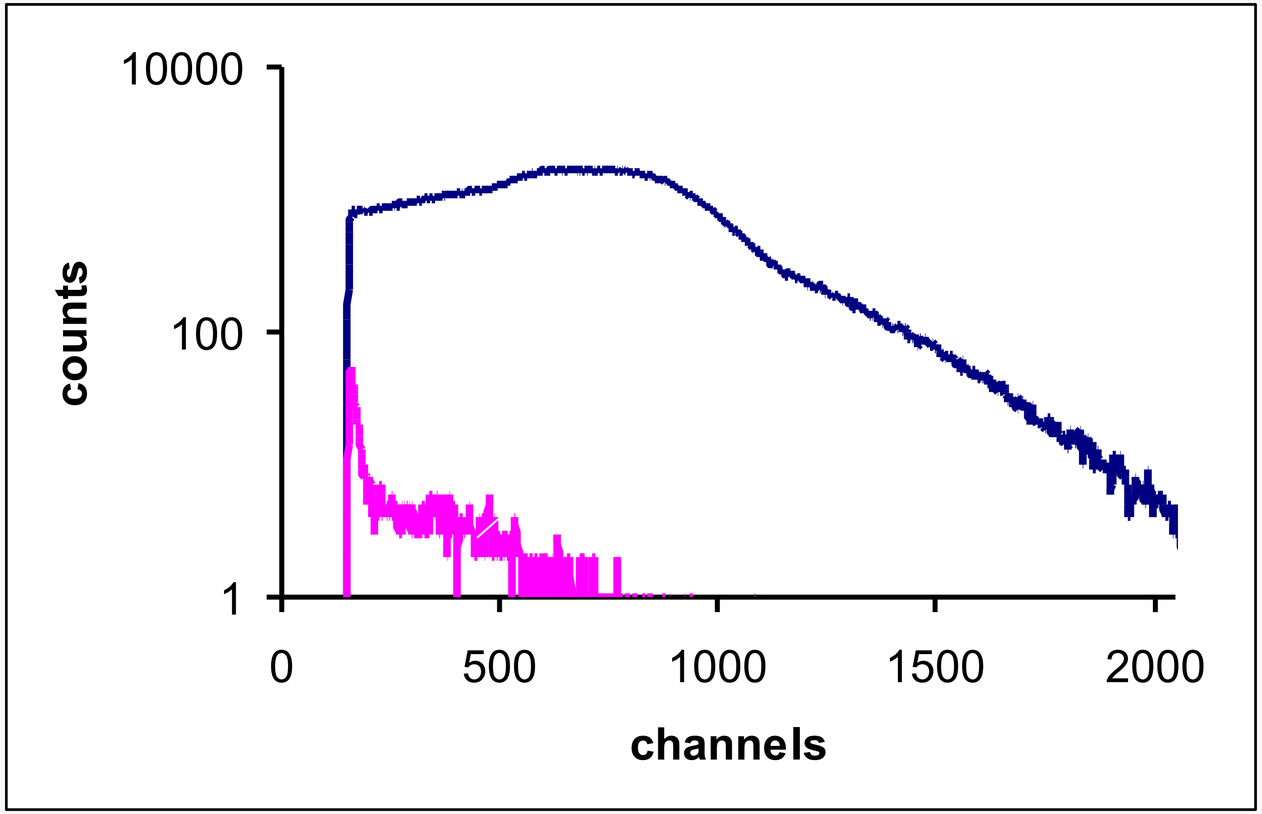
Long-time annealing of the EJ-260



The common decrease of the LY level is highly likely is results of the aggressive atmosphere of the IBR-2 reactor.

Optical cross talk





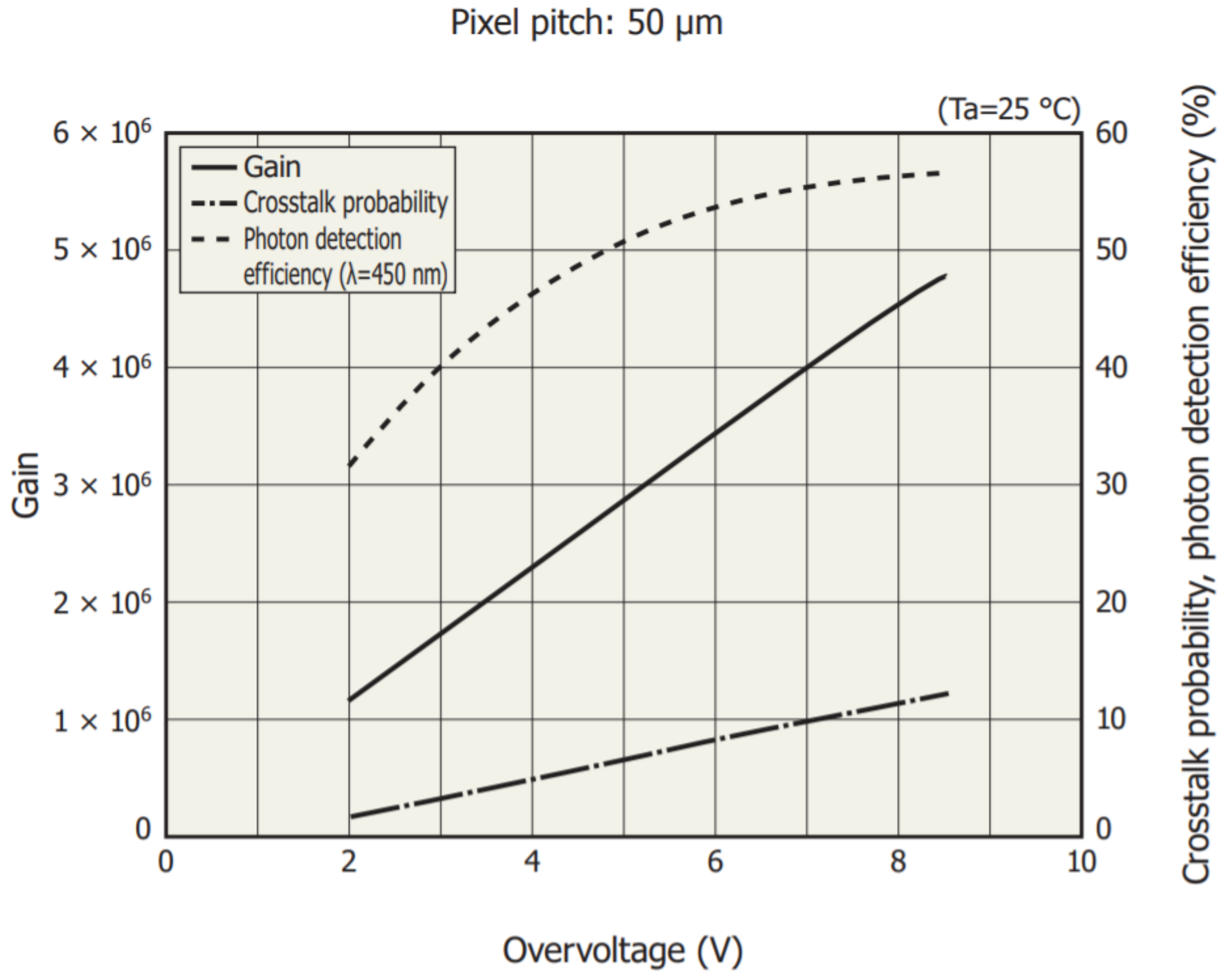
A beta radioactive source and cosmic rays were used to measure cross talk.

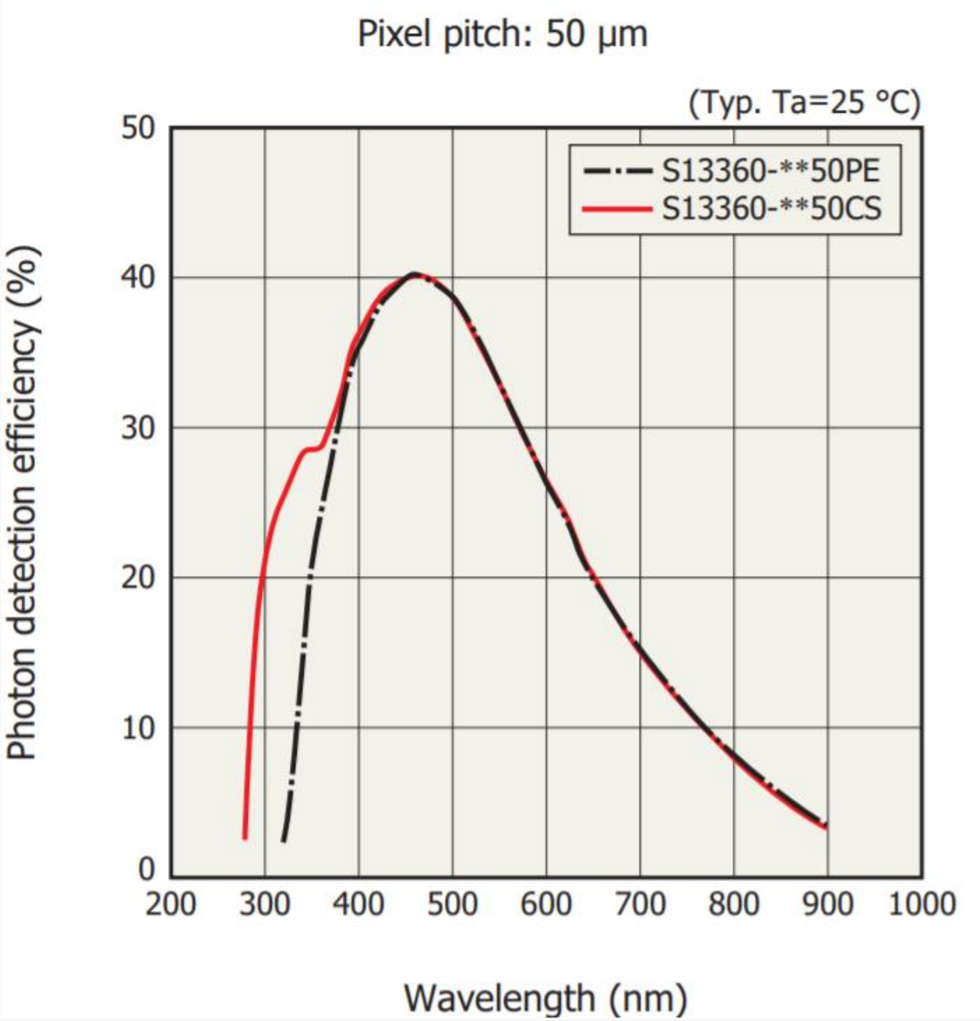
The signal in the adjacent scintillator was no more than:

0.15 % on Sr-90

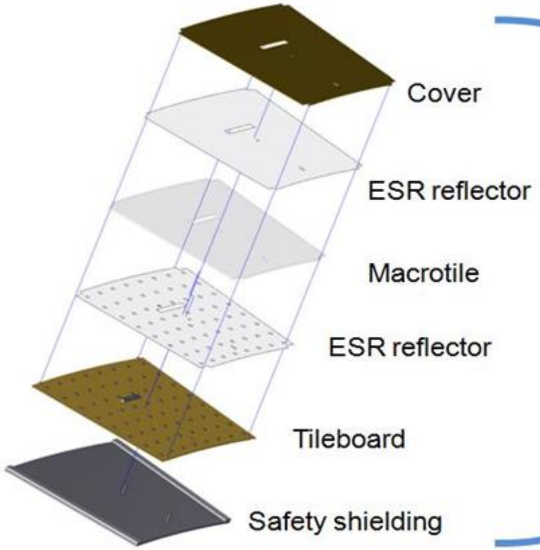
0.2 % on cosmic rays

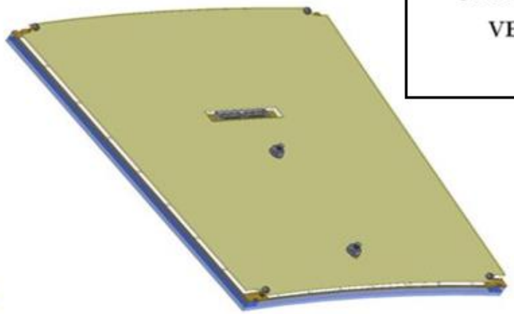
Hamamatsu S13360-1350PE





Realization of item #5 of theme “CMS. Comact Muon Solenoid at the LHC” (02-0-1083-2009/2019)
TOPICAL PLAN FOR JINR RESEACH AND INTERNATIONAL COOPERATION 2019





5. Development and investigation of the scintillator module prototype of the CMS Hadron Calorimeter	I.A. Golutvin A.I. Malakhov	Realization
VBLHEP	S.V. Afanasiev, Yu.V. Ershov, N.V. Gorbunov, A.M. Kurenkov, V.A. Smirnov, E.V. Sukhov, T.V. Trofimov, V.V. Ustinov N.I. Zamyatin	

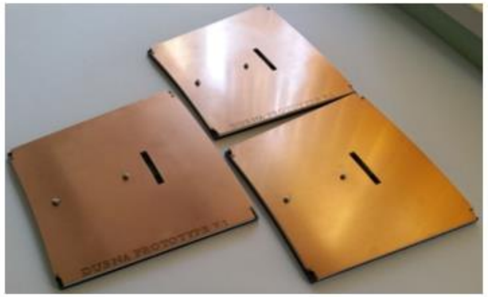
A. Zarubin, 51st meeting of the PAC for Particle Physics
http://indico.jinr.ru/event/892

- Design of prototype of scintillator module (macrotile option) has been developed
- 4 prototypes of scintillator module are made
- Study and testing of samples and prototypes are in progress

SiPMs, scintillator and reflector samples irradiated at IBR and tested

One prototype scintillator module is being tested at JINR

+



3 prototype scintillator modules sent for study to CERN, DESY and US(FNAL…) for testing.

3.3	Scintillator design and selection	15 Nov 2017	25/07/2020
3.3.1	Scintillator material testing	2 Jan 2018	06/07/2019
3.3.2	Scintillator assembly technique evaluation	15 Nov 2017	06/10/2019
3.3.3	Scintillator and tile board assembly technique selected (HL)	13 Oct 2019	13/10/2019

13 Oct 2019 Scintillator and tileboard assembly technique selected (Milestone CE.SC.1 3.3.3)