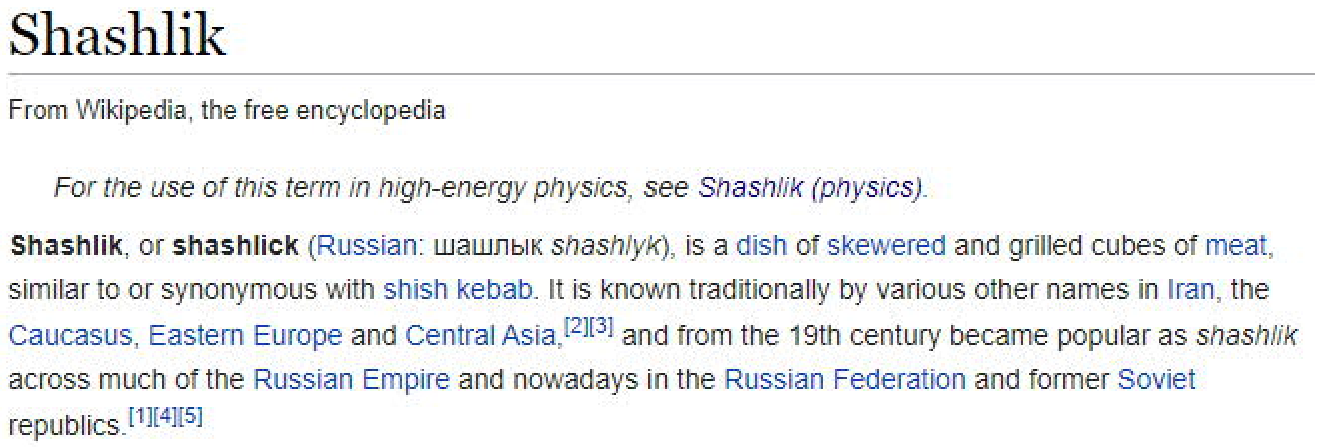
Shashlik for LHCb ECAL Upgrade 2



Shashlik

From Wikipedia, the free encyclopedia

For the use of this term in high-energy physics, see Shashlik (physics).

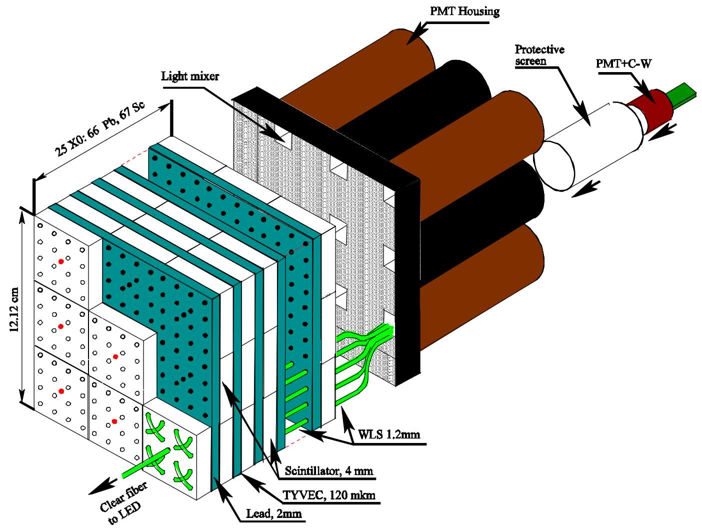
Shashlik, or **shashlick** (Russian: шашлык *shashlyk*), is a dish of skewered and grilled cubes of meat, similar to or synonymous with shish kebab. It is known traditionally by various other names in Iran, the Caucasus, Eastern Europe and Central Asia,[2][3] and from the 19th century became popular as *shashlik* across much of the Russian Empire and nowadays in the Russian Federation and former Soviet republics.[1][4][5]

Shashlik (physics)

From Wikipedia, the free encyclopedia

For the food, see Shashlik.

In high energy physics detectors, **shashlik** is a layout for a sampling calorimeter. It refers to a stack of alternating slices of absorber (e.g. lead, brass) and scintillator materials (crystal or plastic), which is penetrated by a wavelength shifting fiber running perpendicular to the absorber and scintillator tiles.[1]

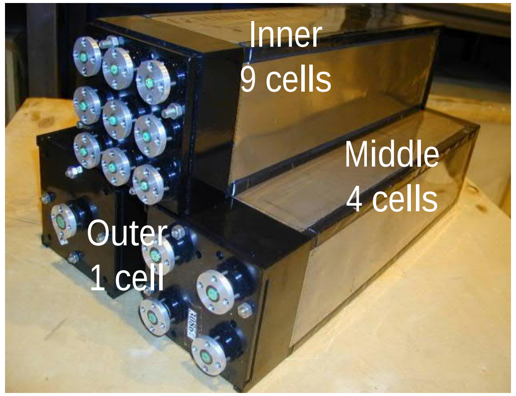


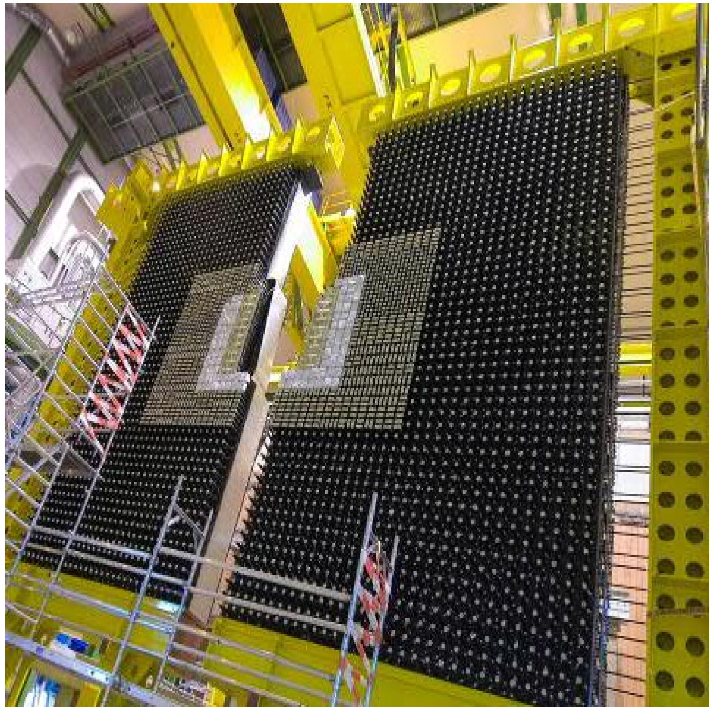
Present ECAL

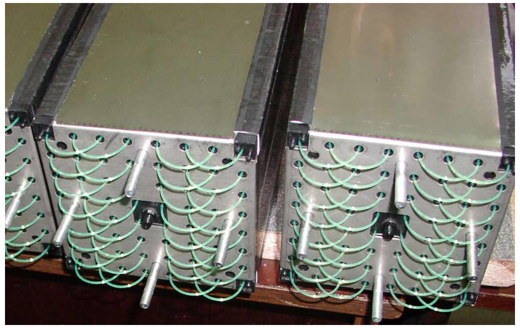
Shashlik technology – well known since 1990s

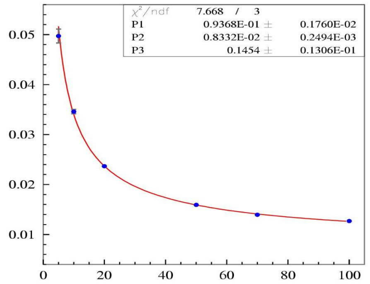
- 4 mm thick scintillator tiles and 2 mm thick lead plates, ~25 X_0 (1.1 λ_I);
- Moliere radius ~ 35 mm;
- modules 121.2 x 121.2 mm2;
- Segmentation: 3 zones → 3 module types,
    - 176 Inner (9 cells per module, 4x4 cm^2),
    - 448 Middle (4 cells, 6x6 cm^2),
    - 2688 Outer (1 cell, 12x12 cm^2).
- Total of 3312 modules, 6016 cells, (7.7 x 6.3) m^2.

- Light readout: PMT R-7899-20, HAMAMATSU.
    - An individual Cockcroft-Walton board at each PMT.
- PMT at the back of the module; WLS fiber loops at the front









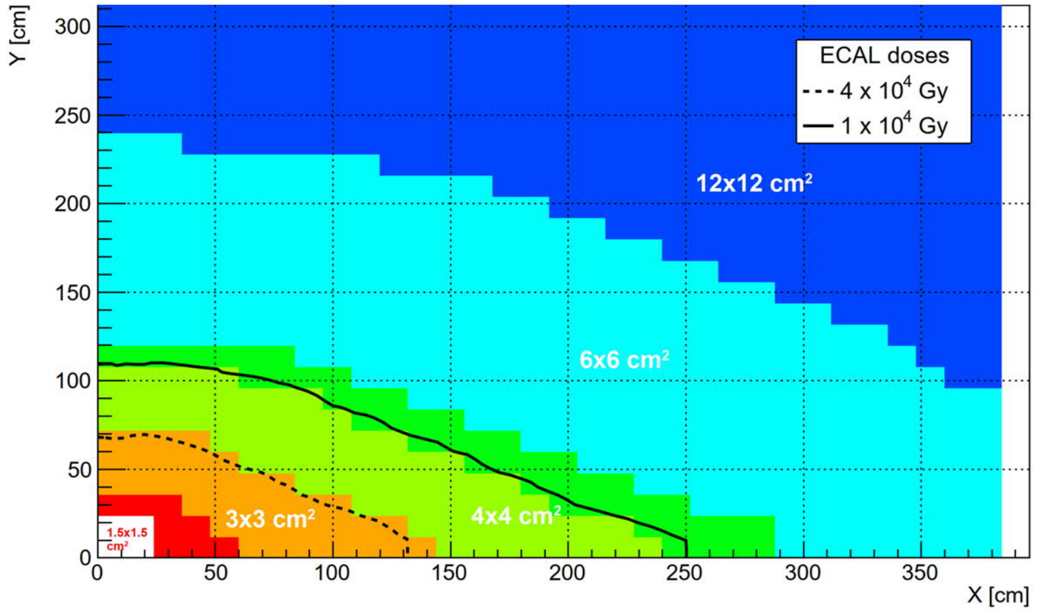
Average performance figures from beam tests (there is slight difference between zones):

Ph.el. yield: ~ 3000 / GeV

Energy resolution: $\frac{\sigma_E}{E} = \frac{(8 \div 10)\%}{\sqrt{E(GeV)}} \oplus 0.9\%$

Present LHCb ECAL Upgrade II plan

(see talk of Philipp)



The limit of radiation tolerance of the Inner type Shashlik modules is ~ 40 kGy

R&D is ongoing aiming to improve the intrinsic time resolution of Shashlik modules

Total of 3312 modules

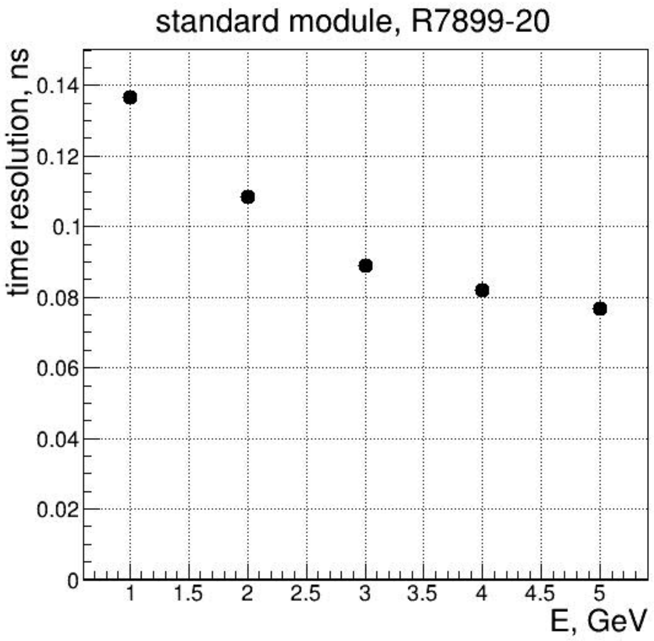
- 32 W-crystal or W-plastic Spacal (red in the figure)
- 144 Pb-plastic Spacal (orange)
- 3136 Shashlik modules (the rest)

<u>94.6% of the ECAL modules remain Shashlik</u>

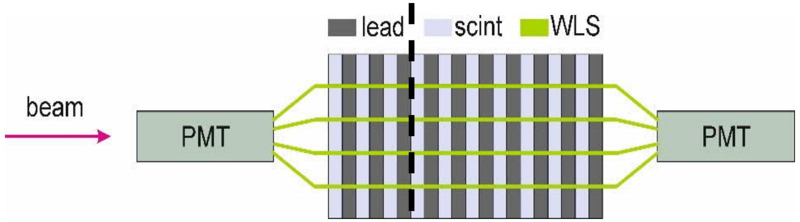
- LS3 consolidation – install the 32+144 Spacal modules and reorder existing Shashlik modules, no modification

- LS4 Upgrade II – we will need to
  - improve granularity -> produce 1168 additional Inner and Middle modules to replace part of Outer ones.
  - improve time resolution -> replace WLS fibers, …

Time resolution – present performance, ways to improve



standard Outer type module.
The time resolution is not far from required values, but improvement is needed



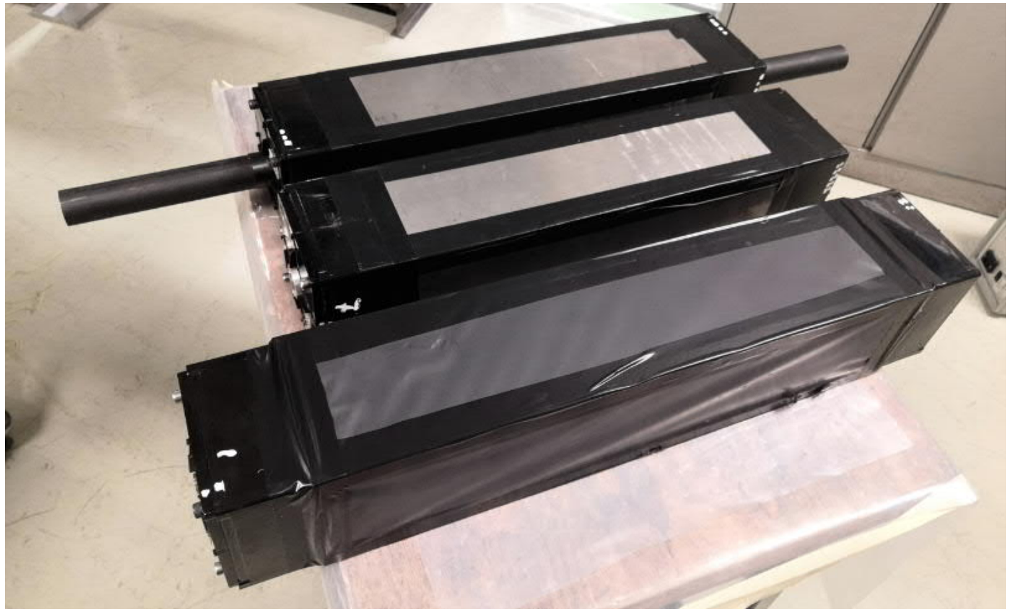
If split: mirror at the WLS fiber ends

Several ways:

1. Double side readout. Allows to mitigate the effect of longitudinal fluctuations of showers by using combination of the two measurements.
   - The WLS fibers can be either continuous or split (~@shower max). Both methods give similar time resolution
     - can also try single side readout (like in the present modules)
2. use better PMT (small transit time spread and transit time uniformity over the photocathode) – e.g., HAMAMATSU PMTs with metal channel dynodes (MCD)
   - linear focusing R7899-20: TTS is ~1-2 ns
   - Subsequent tests done with HAMAMATSU R7600U-20 (TTS < 0.35 ns)
3. use WLS fibers with shorter decay time
   - Y11 decay time is ~ 7 ns
   - faster fibers are available at KURARAY. We tested Shashlik modules with:
     - YS-2 (2.7 ns)
     - YS-4 (1.1 ns)
4. …

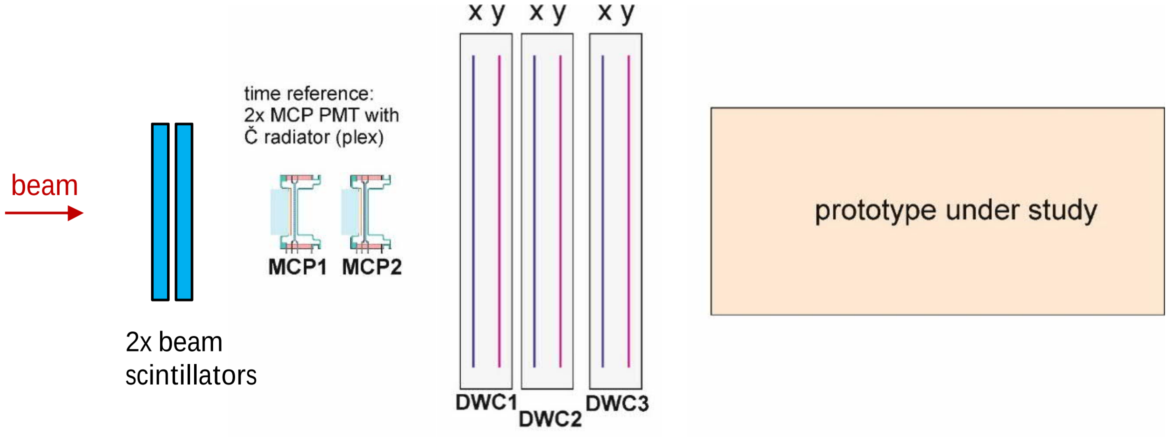
Prototypes

Several prototypes were produced on the basis of spare ECAL Outer modules by replacing the WLS fibers: with split and continuous fibers for double-side readout, with fiber loops for single-side readout



For time resolution, we use a small part of the module surface, ~1x1 cm^2. At this stage, it is sufficient to obtain an indication. In future more detailed studies will be performed.

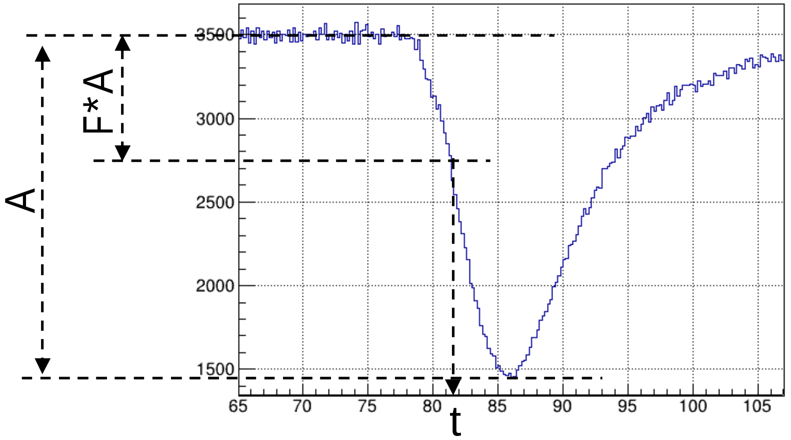
test beam



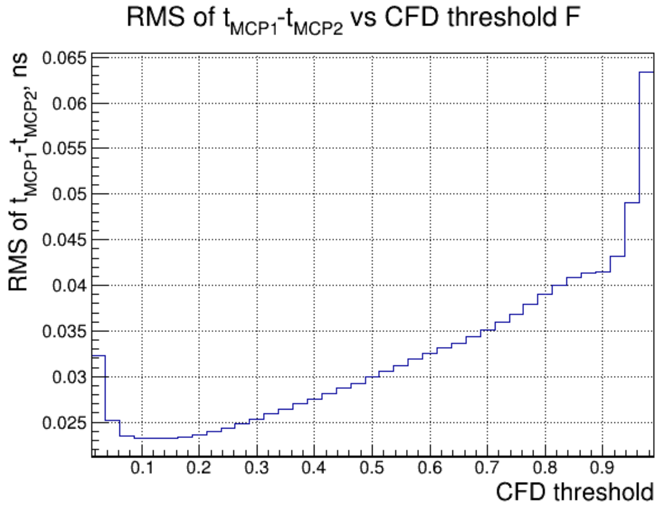
- 2 scint. counters coincidence for a beam trigger
- 3 Delay Wire Chambers (DWC) for track measurements
- 2 Cerenkov counters (plex) read out by MCP PMTs for time reference(*)(**)

- CAEN TDC V1290N - DWC readout
- LeCroy ADC 1182 – amplitude measurements
- CAEN 742 series digitizer – 5 GHz waveform recording

(*) The time reference $t_0=(t_{MCP1}+t_{MCP2})/2$*, precision 12-14 ps*
(**) The MCP PMTs are kindly provided by A. and M. Barnyakov, BINP, Novosibirsk

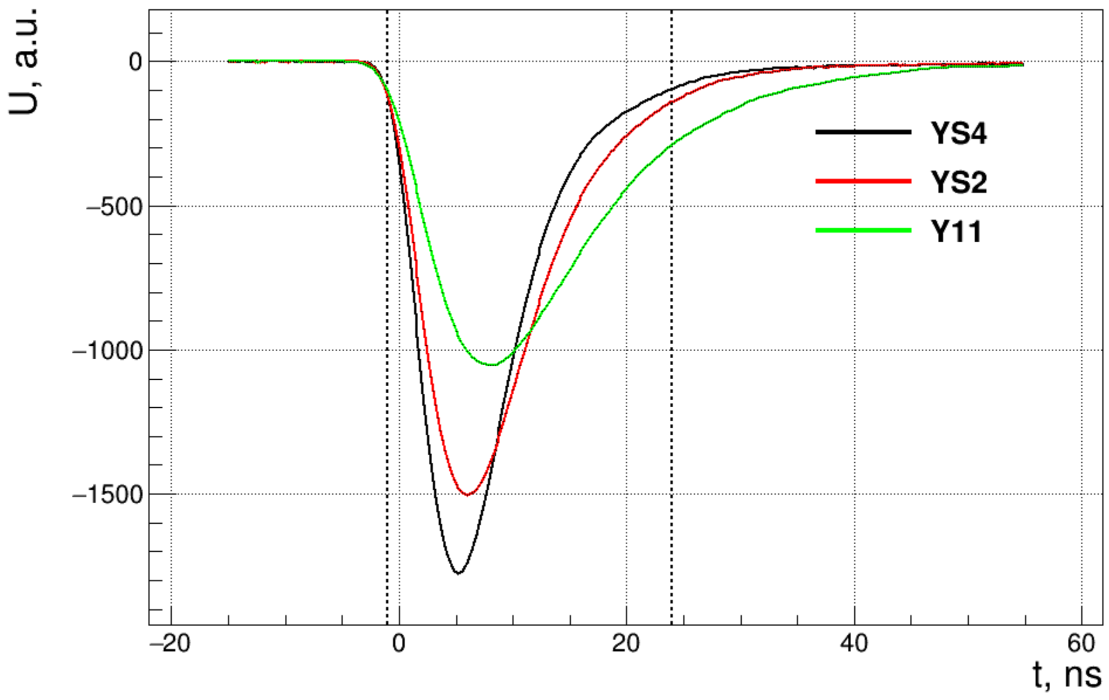


The time measurement: moment of time corresponding to crossing of certain fraction *F* of amplitude (“offline CFD”).

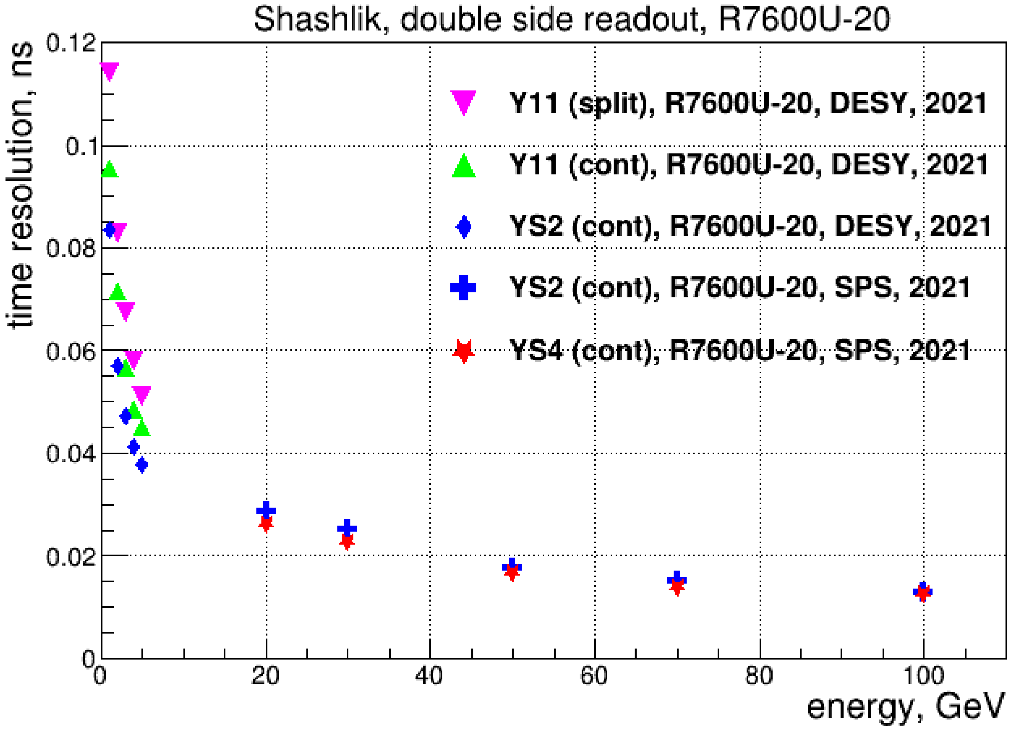


The optimal CFD threshold is in most cases ~0.2 (determined by noise)

Results with Y11, YS-2 and YS-4



Pulse shapes with Y11, YS-2, YS-4 (normalized area). Indeed, with YS-4 and YS-2 it is faster than with Y11, and the time resolution is expectedly better.



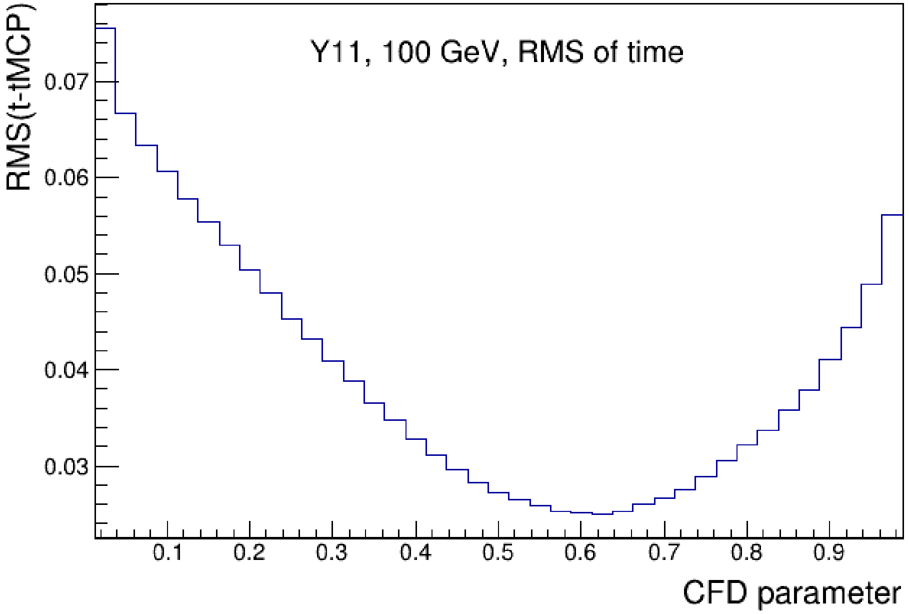
The time resolution with double-side readout.

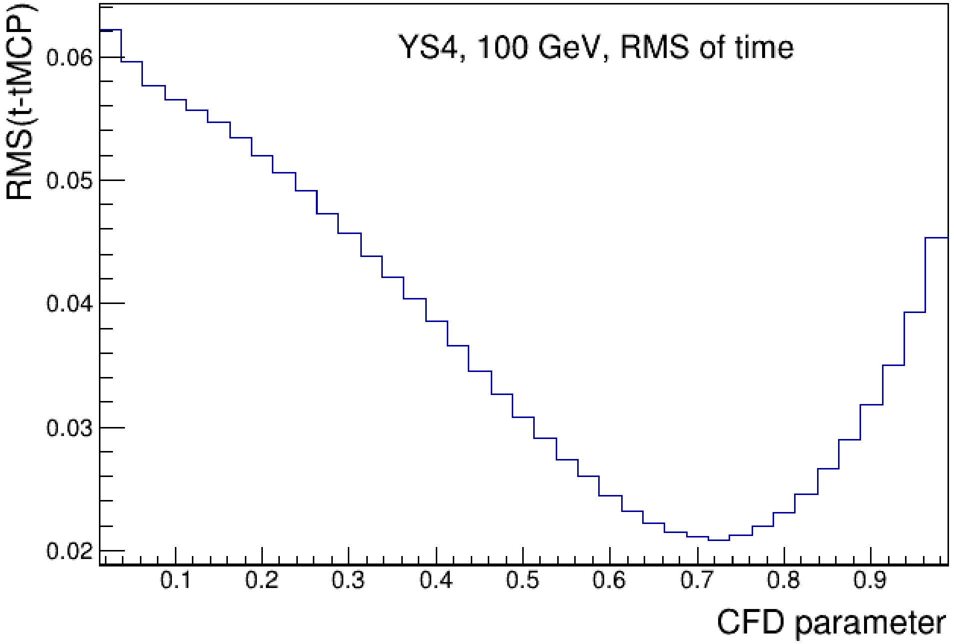
- with YS-2 and YS-4, not so bad.

Single side readout

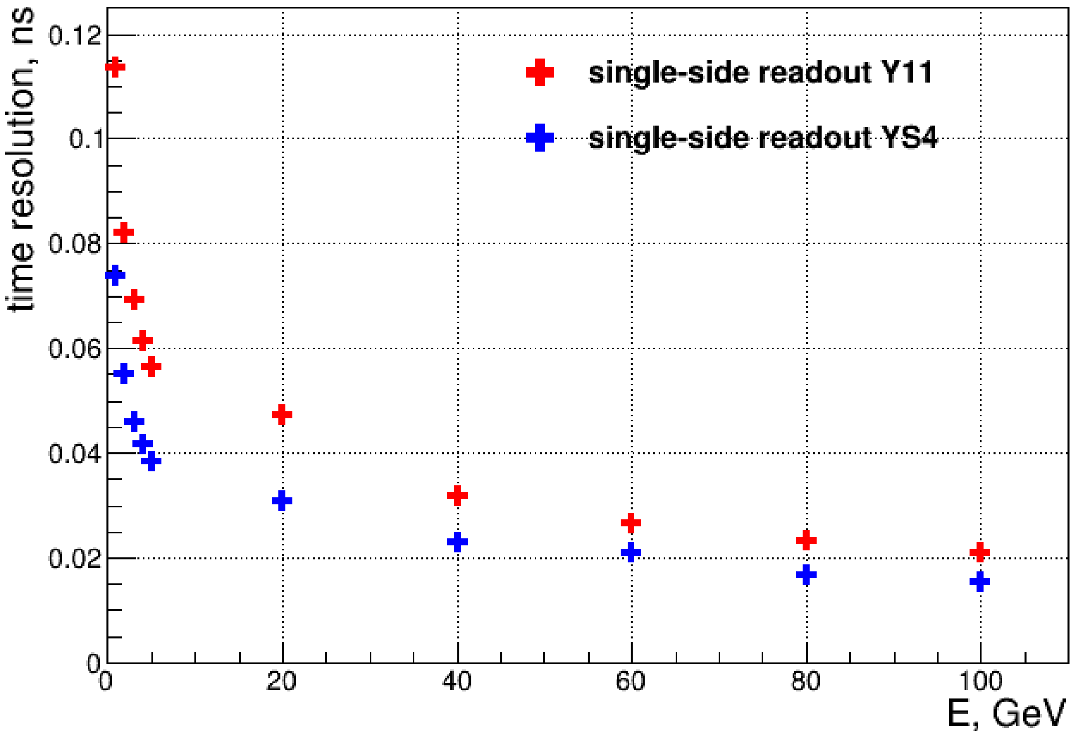
As in the present ECAL: PMT readout at one side, fiber loop at the other side. We spare one PMT.
The idea is: as the signal is a sum of direct and returned light, a compensation of shower longitudinal fluctuation can occur at a certain CFD threshold (the optimal threshold is not determined by noise in this case)

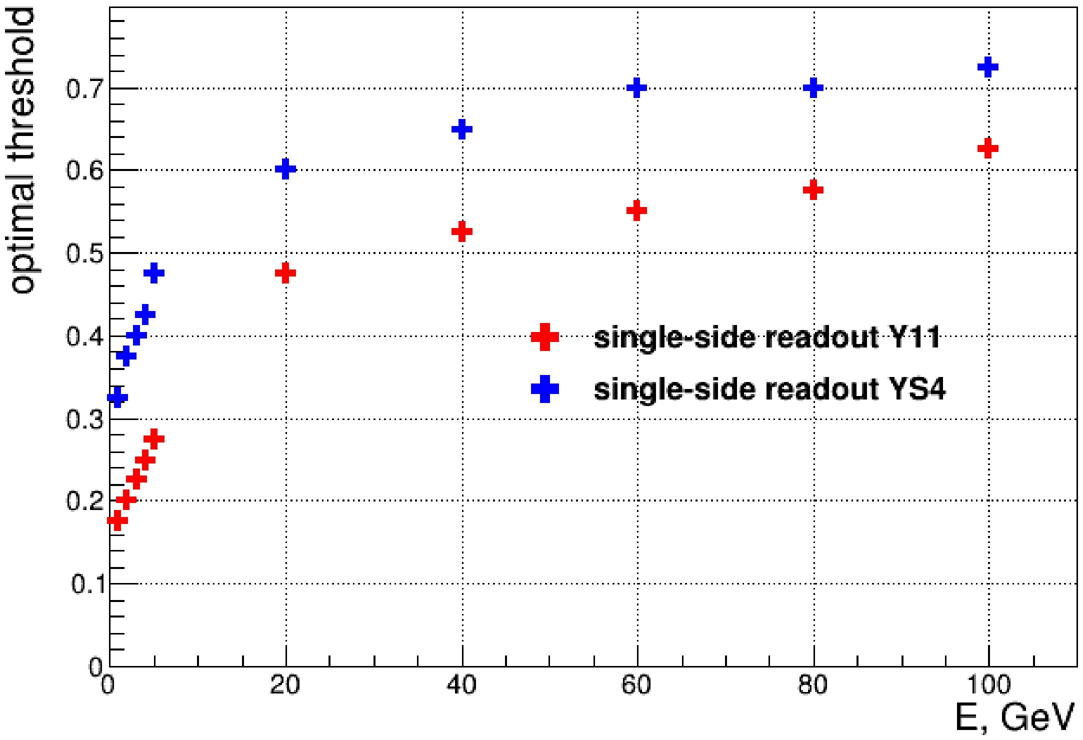
Indeed, there is a well defined optimum: e.g., @ 100 GeV the best threshold is 0.6 for Y11 and 0.7 for YS4.





Single side readout

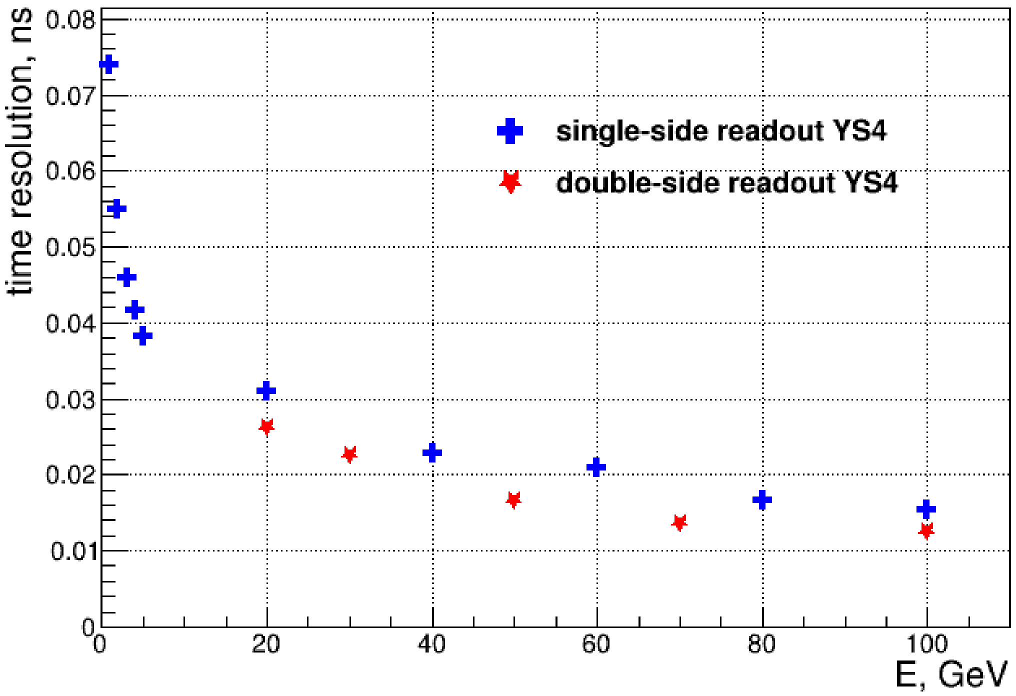




time resolution of prototypes with single side readout, Y11 and YS4, R7600-20. At each energy, an optimal threshold parameter was determined, which gives the best time resolution.

The optimal threshold parameter depends on energy

Single side readout



comparison double-side readout vs single, YS4

The time resolution with single side readout turns out to be not much worse than with double side readout. It could be a viable baseline solution.

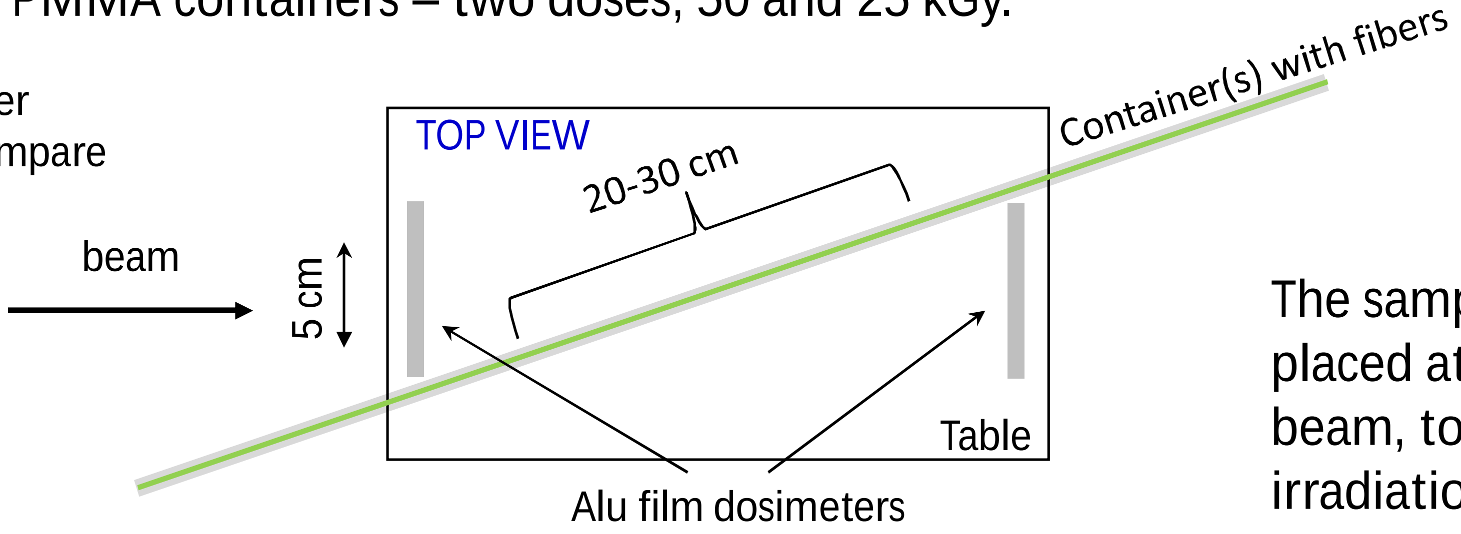
Note that it is not simple to use the optimal threshold as a function of energy – the time bias will also depend on energy (signal rising edge is few ns). A dedicated calibration is needed. Also, the optimal threshold may depend on (radiation) degradation of the module – recalibration.

More studies are needed to determine the best algorithm of time reconstruction.

WLS fiber radiation tolerance, tests at PS IRRAD

The idea was to irradiate central 20-30 cm of the 1m long fiber samples.
Two batches of fibers in two PMMA containers – two doses, 50 and 25 kGy.

fibers of different types in one container receive same dose -> convenient to compare the degradations



The samples were placed at ~20° to the beam, to reduce the irradiation time

The result is that *YS-2 and YS-4 degrade with radiation ~3 times faster than Y11*.

- the resulting radiation tolerance of the modules should be studied – not 3 times worse of course (scintillator contribution is significant), but some effect is expected
- we can modify the layout of ECAL zones accordingly
  - either equip more central modules with Y11
  - or replace them with Pb-Spacal

conclusion and further studies

- Shashlik part of the ECAL Upgrade II is large (94.6% of modules)
  - the energy resolution like in the present ECAL is OK
  - for UII, it is important to improve its time resolution
- The production of new modules is not foreseen by LS3
- By LS4 we will have to produce ~1168 modules
- For LS4/Run 5, it is possible to have Shashlik modules with better time resolution
  - optimal WLS fibers and PMTs
    - new fast KURARAY WLS (e.g, YS-4)
    - HAMAMATSU PMTs with metal channel dynodes (MCD)
    - possibly double side readout
  - However the radiation tolerance of YS-2, YS-4 is worse than Y11
    - the tolerance limit may be lower than 40 kGy
    - we can either equip certain part of Inner Shashlik modules with Y11
    - or replace them with Pb-Scint Spacal modules

conclusion and further studies

- The R&D results are optimistic; many further details have to be studied
  - light guides/mixers, PMT holders, HV system, LED system, …
  - radiation hardness of modules with new WLS fibers
    - KURARAY may even further improve the WLS fibers meanwhile
      - also the rad tolerance
  - reconstruction and calibration algorithms for time (and energy)
    - an Inner type (9 cells, 4x4 cm^2) double side readout module is produced and tested at SPS, data are being analyzed

conclusion and further studies

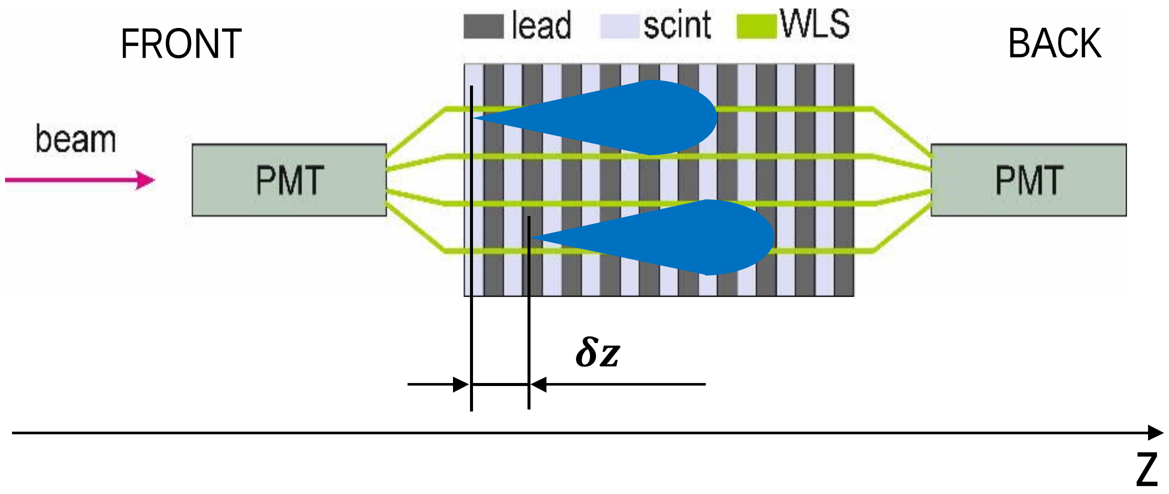
- By LS4 we will have to produce ~1168 modules
- It is still premature to discuss plans for mass production; however by now there are more than one option:
  - several centers in Russia (Protvino, Vladimir, …) with big experience
  - scintillating tiles can also be produced in Kharkiv (Ukraine)
    - lead plates – Germany
  - Tsinghua (China)
  - …

thank you !

spares

double readout with continuous fibers

The correlation between t_{FRONT} and t_{BACK} shown at the previous slide manifests the effect of shower longitudinal fluctuations. The biggest contribution comes from the variation of the *z* coordinate of the shower starting point (first interaction).



Let us assume that there are two identical showers which have *z* positions different by $\boldsymbol{\delta z}$. For the first shower the time measured at front and back are t_{FRONT} and t_{BACK}. Then for the second shower these times will be:

$$t_{FRONT} \rightarrow t_{FRONT} + \frac{\delta z}{c} + \frac{\delta z}{v}$$
$$t_{BACK} \rightarrow t_{BACK} + \frac{\delta z}{c} - \frac{\delta z}{v}$$

, where *c* is speed of light in vacuum and *v* is the *average* speed of propagation of photons along the *z* axis.

Therefore

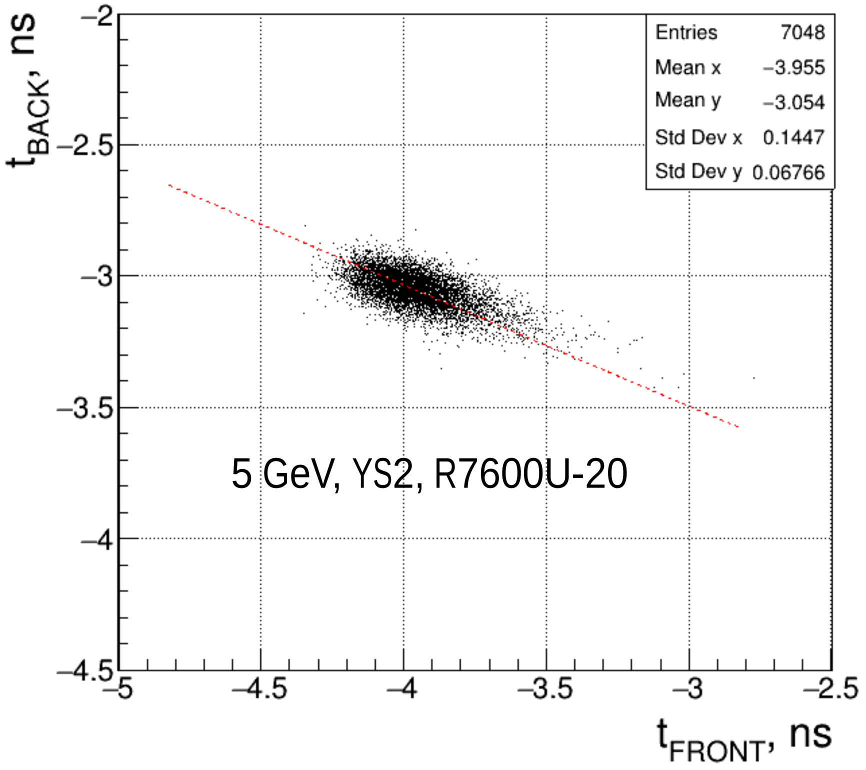
$$\Delta t_{FRONT} = \frac{\delta z}{c} + \frac{\delta z}{v}$$
$$\Delta t_{BACK} = \frac{\delta z}{c} - \frac{\delta z}{v}$$

, and

$$\frac{\Delta t_{FRONT}}{\Delta t_{BACK}} = \frac{c+v}{c-v}$$

, which determines the slope of the correlation. Obviously this does not depend on energy.

double readout with continuous fibers



5 GeV, YS2, R7600U-20

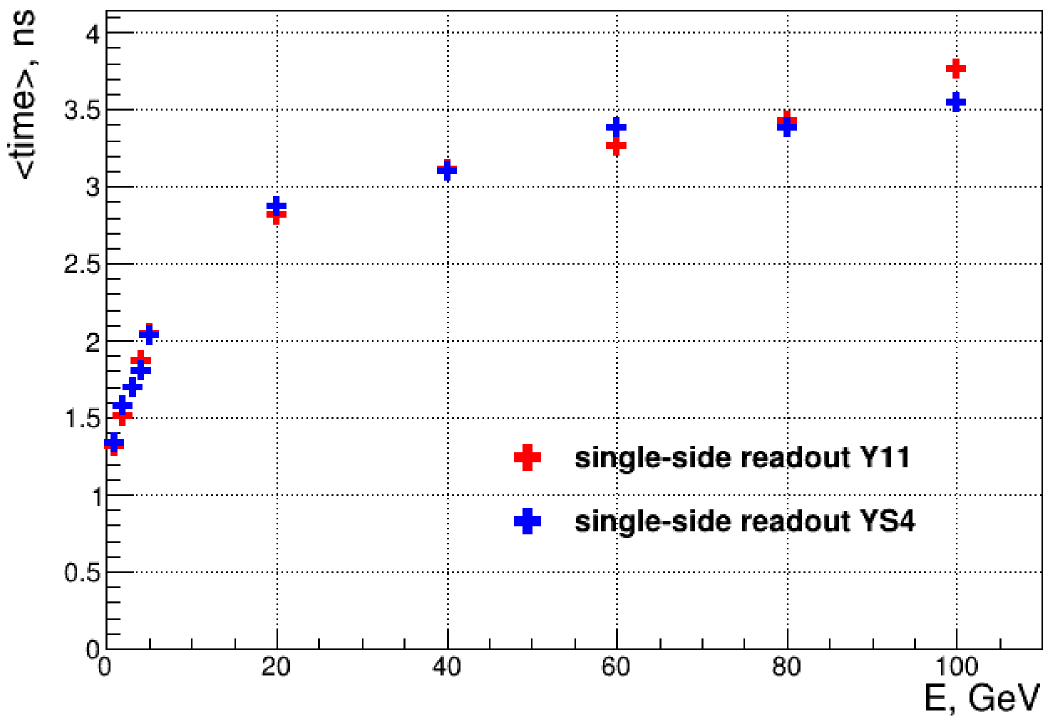
For the configuration with continuous WLS fibers, the combined time,

$$t_{COMB} = 0.7 \cdot t_{BACK} + 0.3 \cdot t_{FRONT}$$

, has best resolution, 38 ps

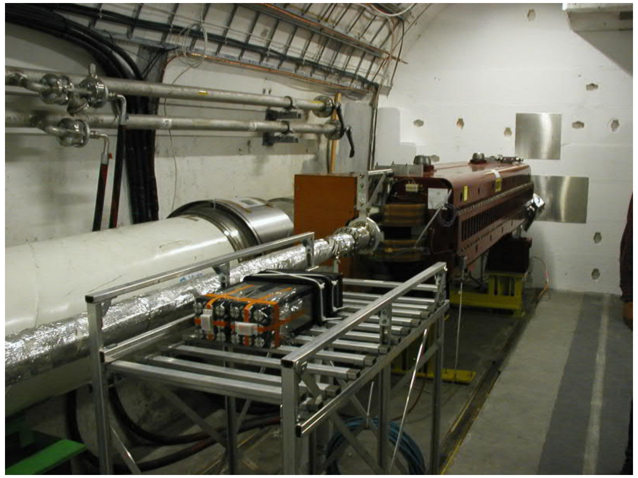
(36 after corrections for the MCP resolution)

single side readout



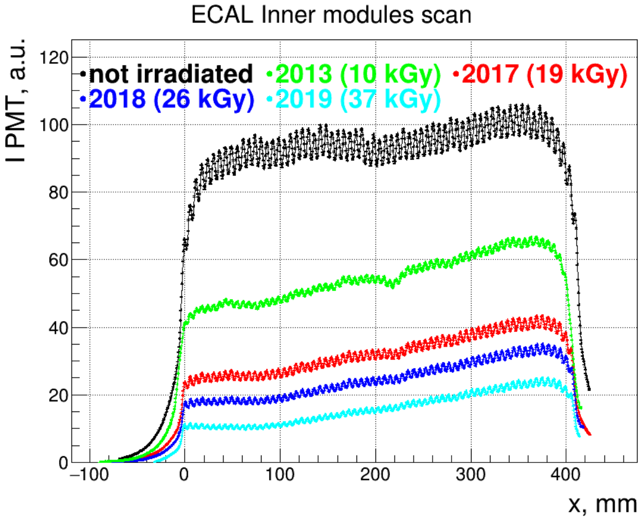
the variation of the optimal CFD threshold with energy leads to variation of the time measurement

ECAL (Inner) modules degradation

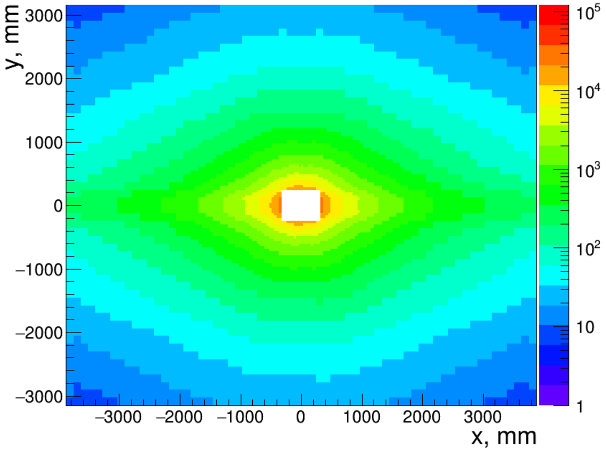


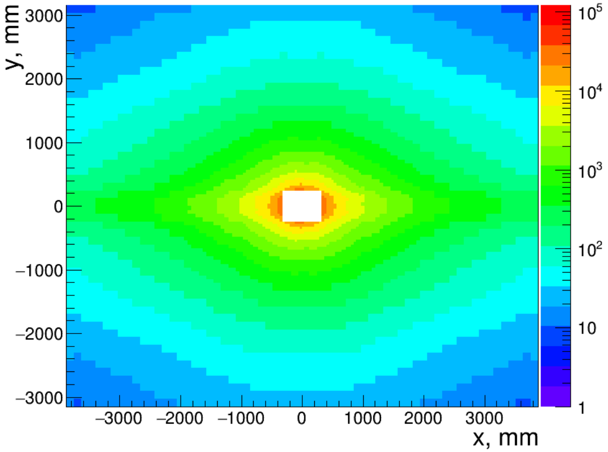
- The most relevant test was performed with Inner type modules installed ~4m upstream of the LHCb IP
  - installed in 2009, before the (re-)start of LHC
  - tested in 2013, 2017, 2018, 2019
- The degradation of the light yield was measured using the longitudinal scan with ^{137}Cs source.
  - always compared to a non-irradiated module

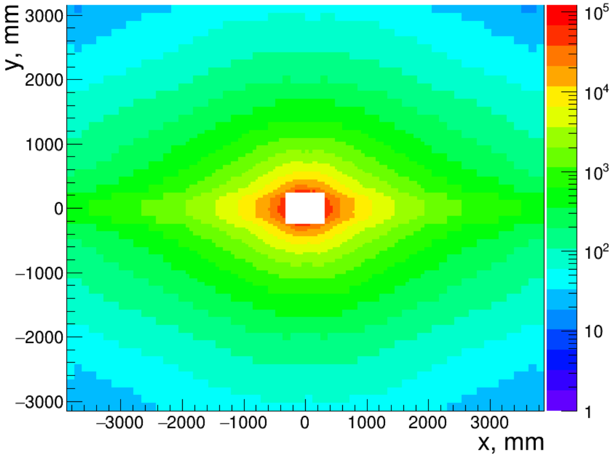
- After 40 kGy modules can be considered dead
  - however to use them for the LS3 consolidation one should take into account their previous degradation (e.g., place further away from the beam).

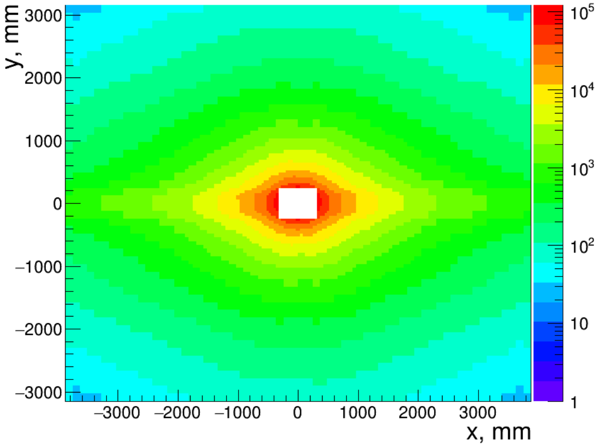


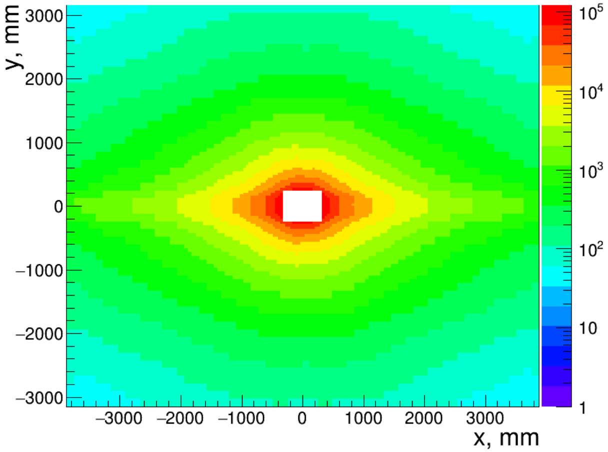
Radiation dose in ECAL cells


cell dose after 2021, Gy


cell dose after 2022, Gy


cell dose after 2023, Gy


cell dose after 2024, Gy


cell dose after 2025, Gy

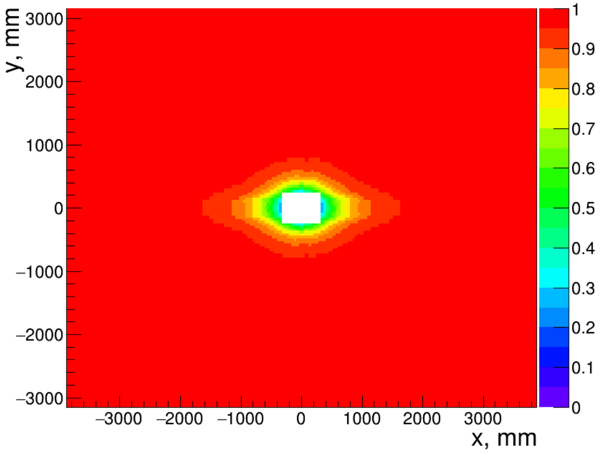
	N cell >40 kGy	N mod >40 kGy	Ncell >20 kGy	Nmod >20 kGy
2021	0	0	16	8
2022	0	0	36	16
2023	36	16	201	36
2024	111	28	368	56
2025	201	36	514	76

(Inner modules have 9 cells, 3x3).

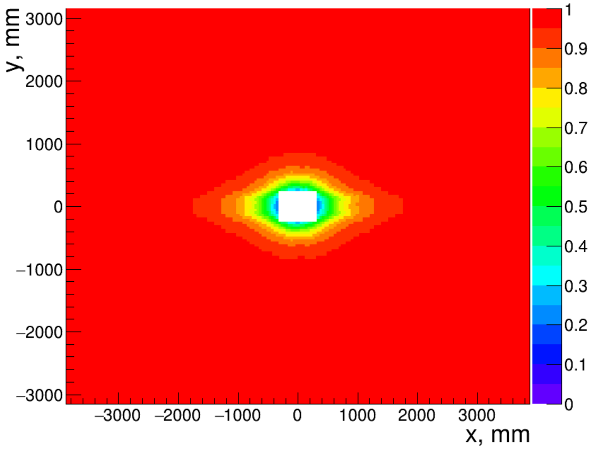
After 2025, out of 176 Inner modules, 36 will receive >40 kGy. Other 40 will receive 20-40 kGy.

Radiation degradation in ECAL cells

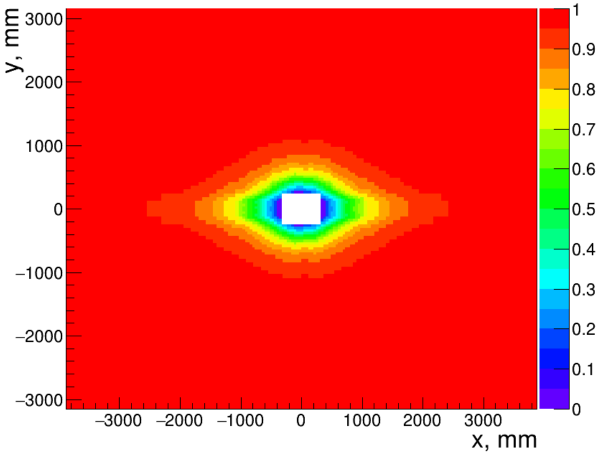
cell degradation after 2021 (10/fb)



cell degradation after 2022 (12/fb)

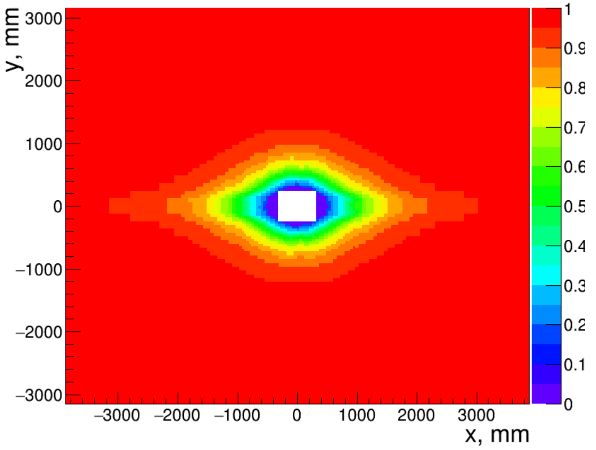


cell degradation after 2023 (24/fb)

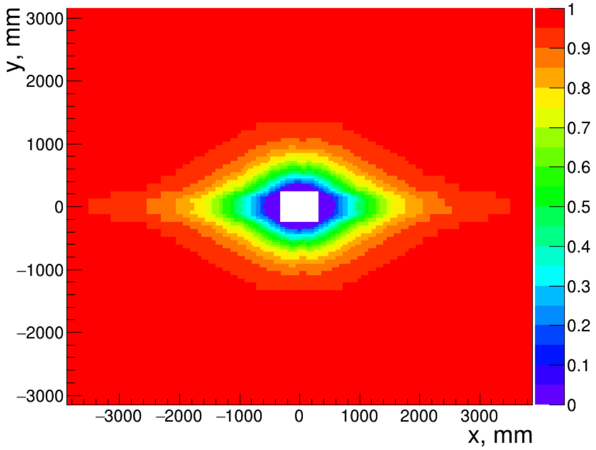


in violet: central cells with >40 kGy

cell degradation after 2024 (36/fb)



cell degradation after 2025 (48/fb)



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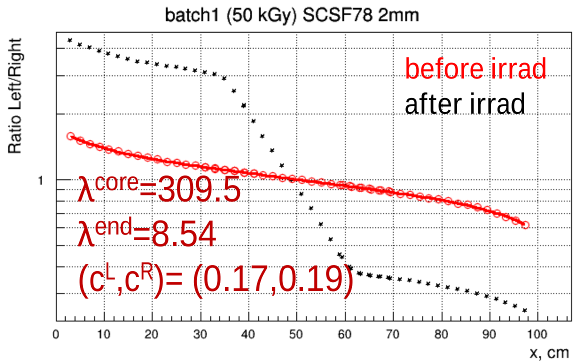
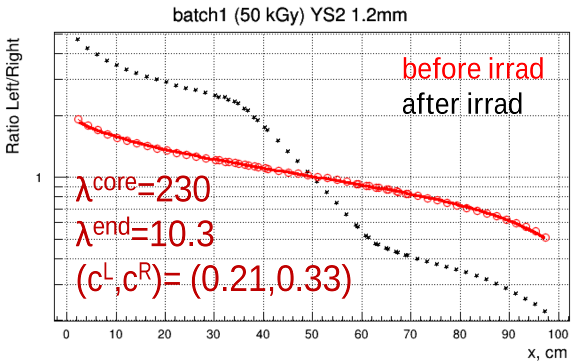
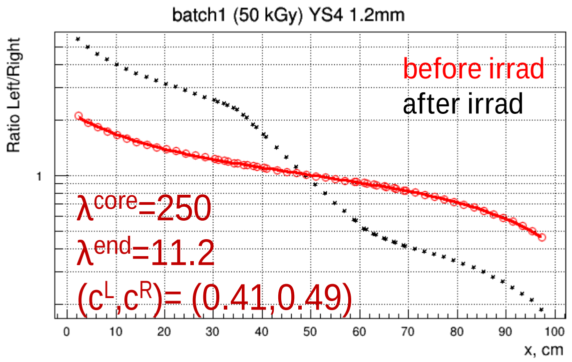
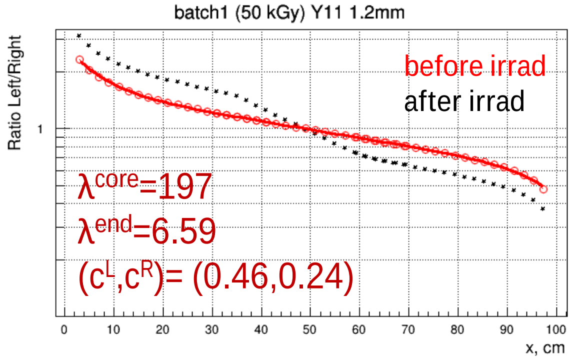
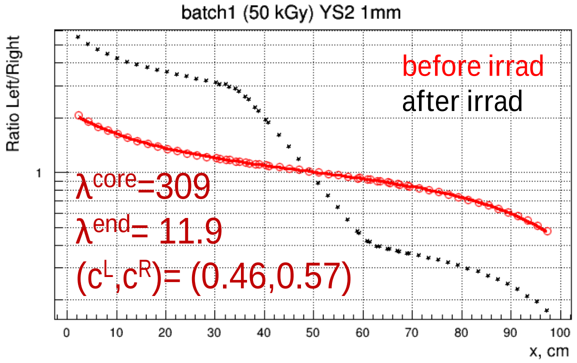
results from 2022, batch 1 (~50 kGy to the central segment)

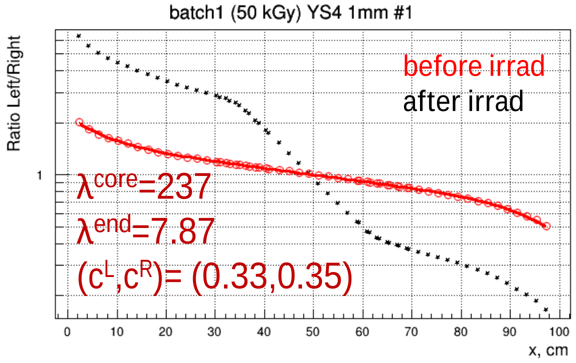


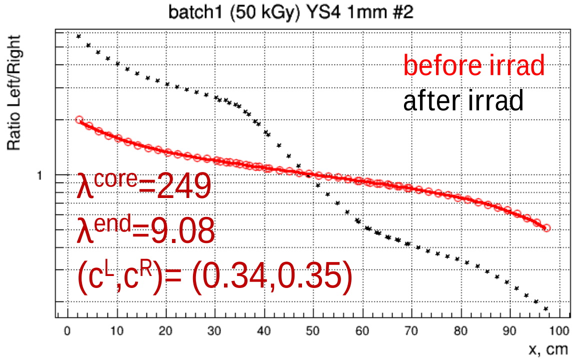










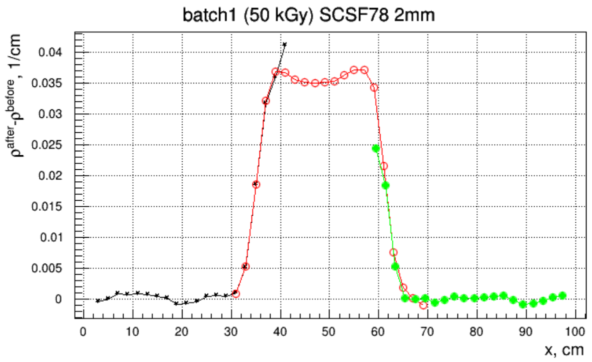


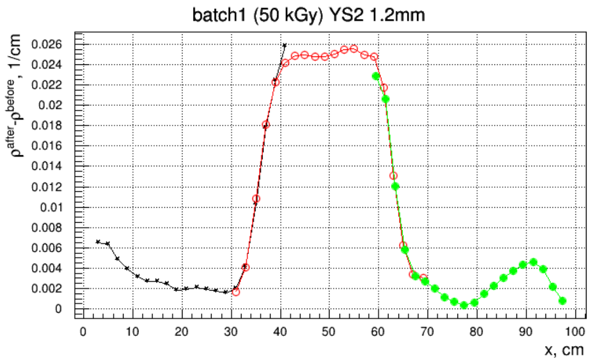
after irradiation:

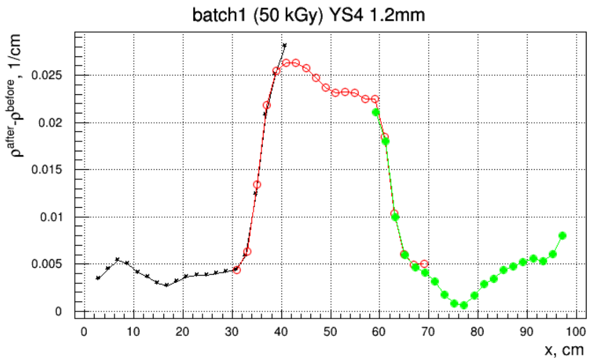
- degradation is visible;
- Y11 is better than others
- YS2 and YS4 are similar
- SCSF78 (scintillator) is worst

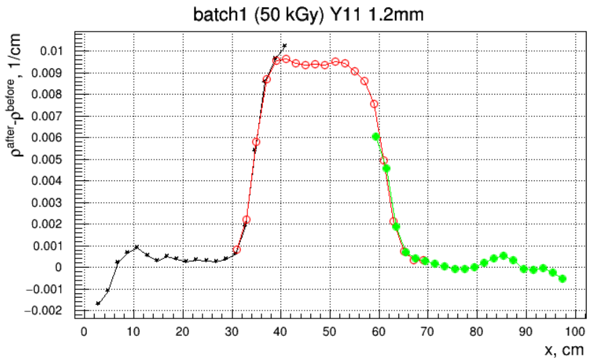
need to quantify (next slides)

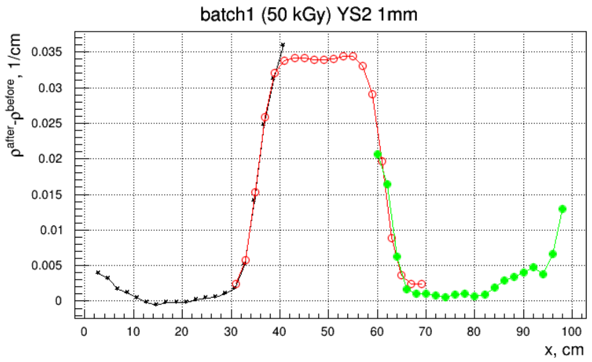
results from 2022 , batch 1 (~50 kGy to the central segment)

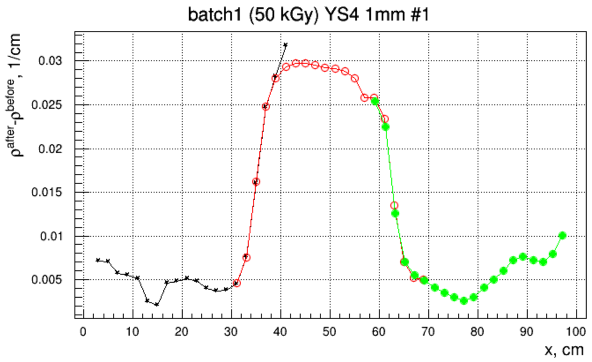

batch1 (50 kGy) SCSF78 2mm

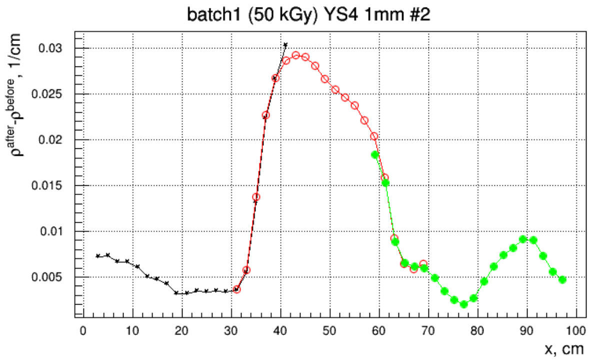

batch1 (50 kGy) YS2 1.2mm


batch1 (50 kGy) YS4 1.2mm


batch1 (50 kGy) Y11 1.2mm


batch1 (50 kGy) YS2 1mm


batch1 (50 kGy) YS4 1mm #1


batch1 (50 kGy) YS4 1mm #2

Fiber radiation tolerance, tests at PS IRRAD

batch 1, ~50 kGy			batch 2, ~25 kGy		
Fiber	att. len., m before / after	degradation 1/cm	fiber	att. len., m before / after	degradation 1/cm
SCSF78, Ø2mm	3.1 / 0.26	0.036	SCSF78, Ø2mm	2.7 / 0.40	0.021
Y11, Ø1.2mm	2.0 / 0.66	0.009	Y11, Ø1.2mm	2.1 / 1.2	0.005
YS2, Ø1.2mm	2.3 / 0.35	0.025	YS2, Ø1.2mm	2.5 / 0.50	0.015
YS2, Ø1mm	2.5 / 0.27	0.034	YS2, Ø1mm	1.7 / 0.40	0.020
YS4, Ø1.2mm	2.5 / 0.33	0.025	YS4, Ø1.2mm #1	1.5 / 0.50	0.016
			YS4, Ø1.2mm #2	1.7 / 0.65	0.010
YS4, Ø1mm #1	2.5 / 0.30	0.029	YS4, Ø1mm #1	2.5 / 0.55	0.014
YS4, Ø1mm #2	2.5 / 0.32	0.029	YS4, Ø1mm #2	2.5 / 0.51	0.015

Radiation degradation of YS-2 and YS-4 is ~2-3 times faster than of Y11