Performance evaluation of the upstream MEG II Radiative Decay Counter

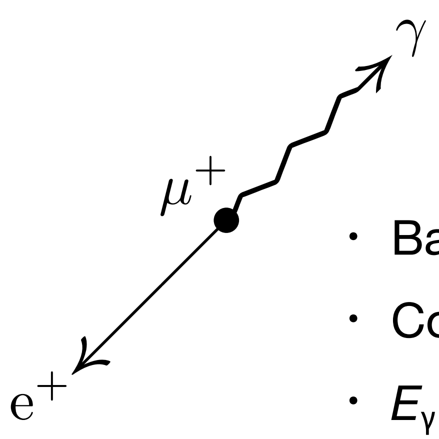
「大強度μ粒子ビーム上で運用するMEG II輻射崩壊同定用カウンターに期待される性能の評価」

岩井　遼斗 (東大理)

Introduction

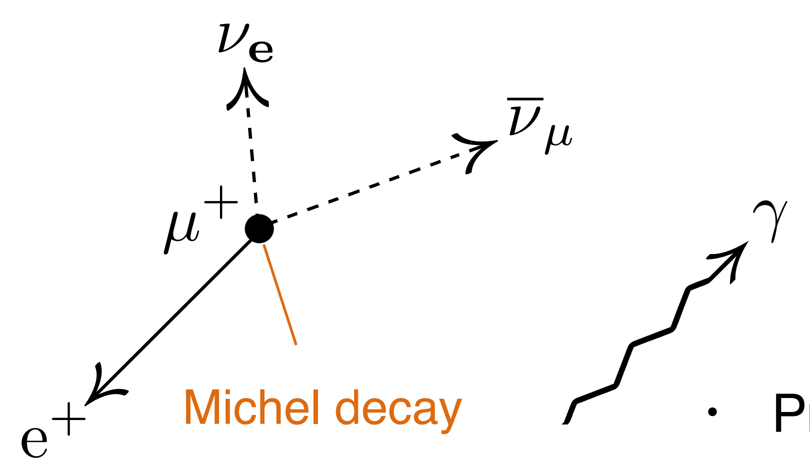
- Signal & background in MEG II experiment

μ→eγ decay



- Back-to-back
- Coincident in time
- $E_\gamma = E_e = 52.8$ MeV

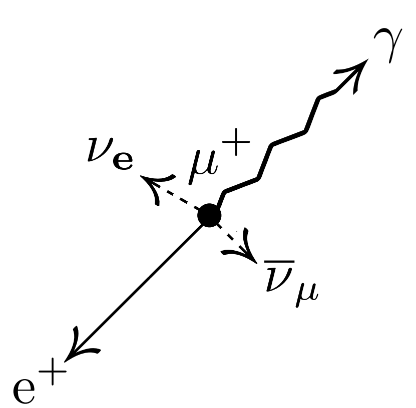
Dominant BG source (accidental BG)



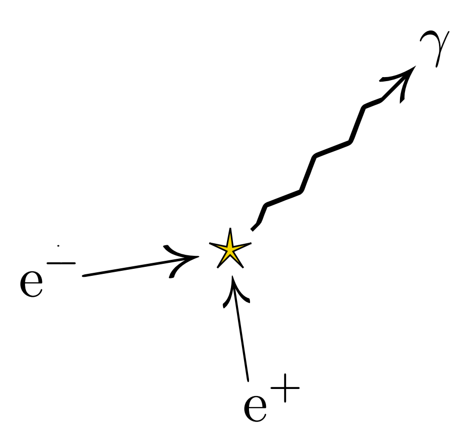
- Proportional to square of μ decay rate

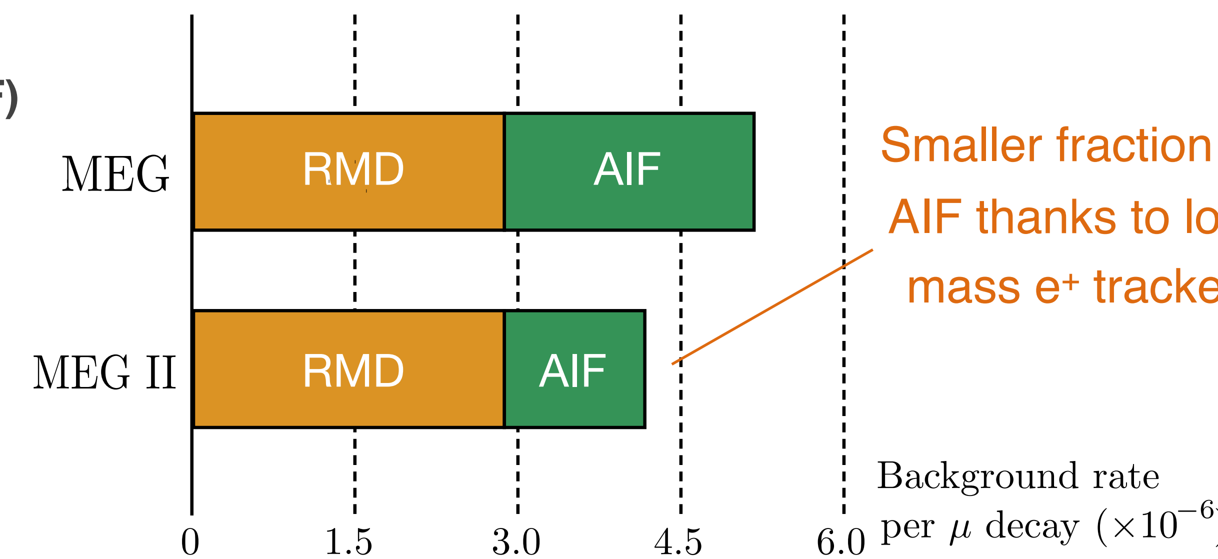
- Source of BG γ

① **Radiative Muno Decay (RMD)**



② **Annihilation in flight (AIF)**



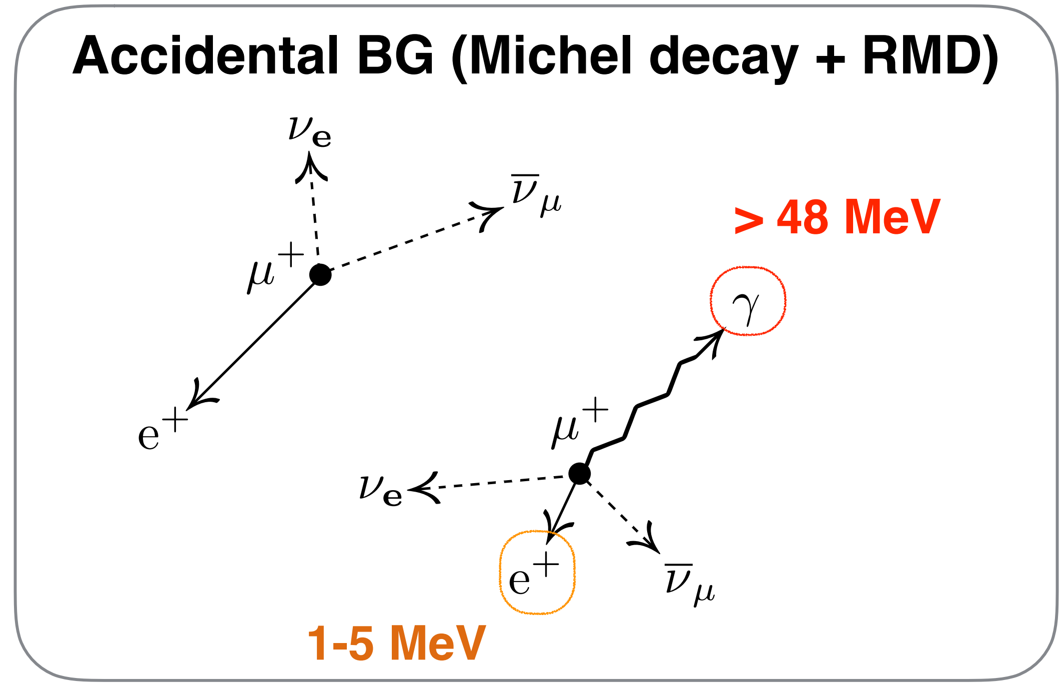


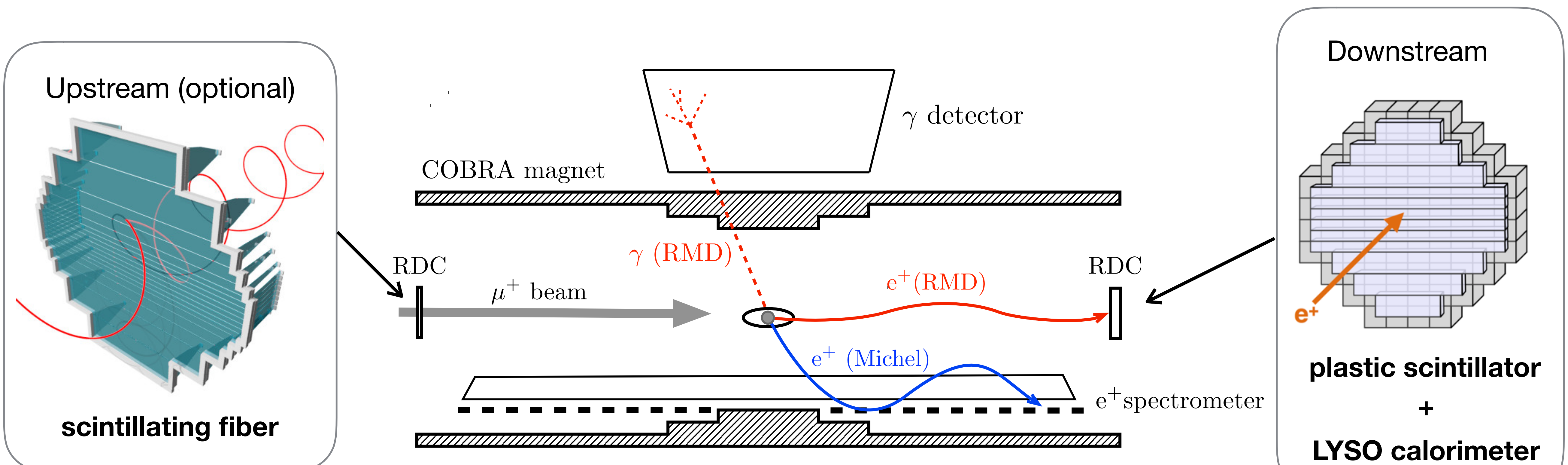
Smaller fraction of AIF thanks to low mass e⁺ tracker

- <u>Important to reduce BG γ from RMD</u>

Radiative Decay Counter (RDC)

- RDC identifies BG γ from RMD
  - Low momentum e^+ from RMD swept along the beam axis
  - RDC measures time coincidence of low momentum e^+ and BG γ on μ beam axis
- Detector requirement : Finely segmented, compact design (diameter ~20 cm)

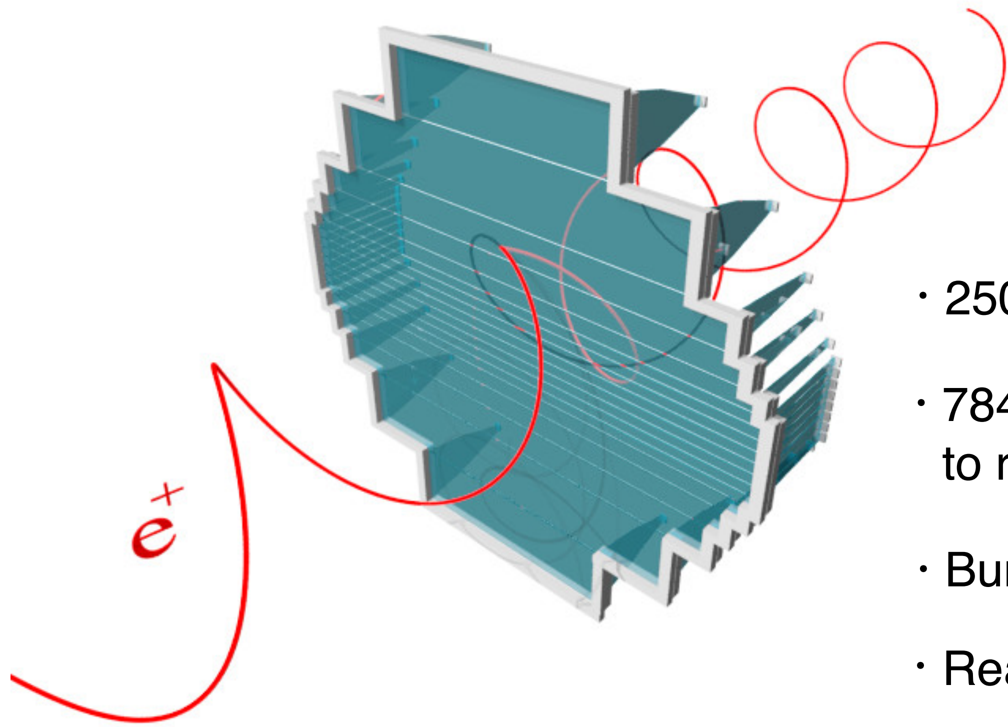




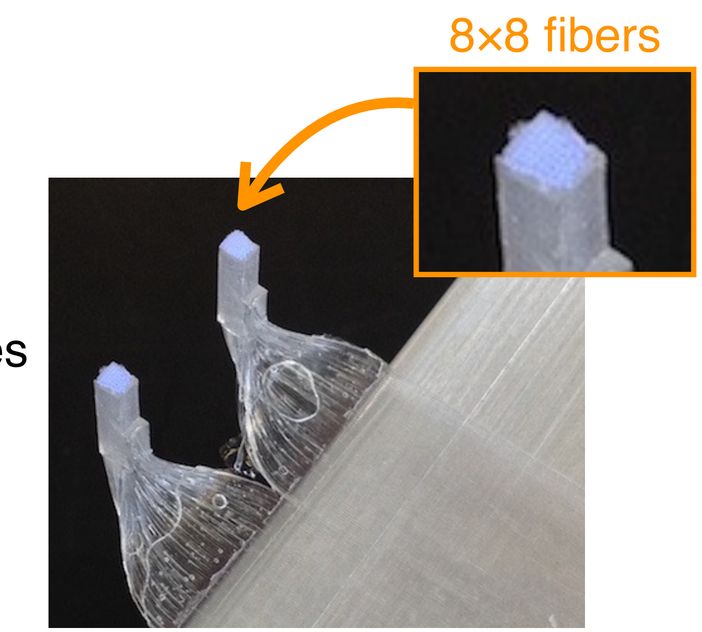
- Only downstream detector was constructed and tested with μ beam

Upstream detecter

- Upstream detector requires R&D concerning operation in high intensity μ beam (10^8 μ/s)
- Provisional design : Measure timing of e^+ with layer of multi-clad scintillating fibers

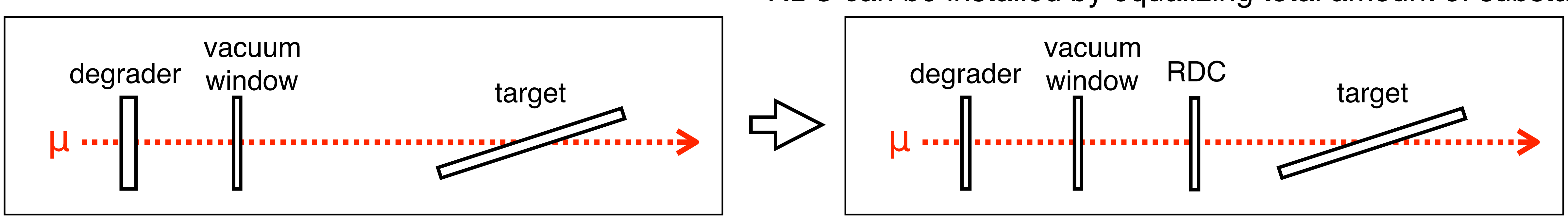


- 250 μm thick square shape fiber
- 784 fibers are grouped into 18 bundles to reduce number of channels
- Bundles are bent at right angles
- Readout bundle ends with SiPM



- 28 MeV/c μ beam slowed-down by degrader

RDC can be installed by equalizing total amount of substance



- <u>Influence on μ beam is expected to be small</u> (reported in previous JPS meeting)

Upstream detecter

- Sensitivity improvement with RDC (ideal case)

	MEGII sensitivity
w/o RDC	5.0×10^{-14}
w/ downstream	4.3×10^{-14}
w/ downstream + upstream	3.9×10^{-14}

16%

28%

Assuming detection efficiency :

100% (downstream)

90% (upstream)

Upstream detector has 10% efficiency loss due to fiber cladding

- In real case, detection efficiency of upstream RDC is limited by :

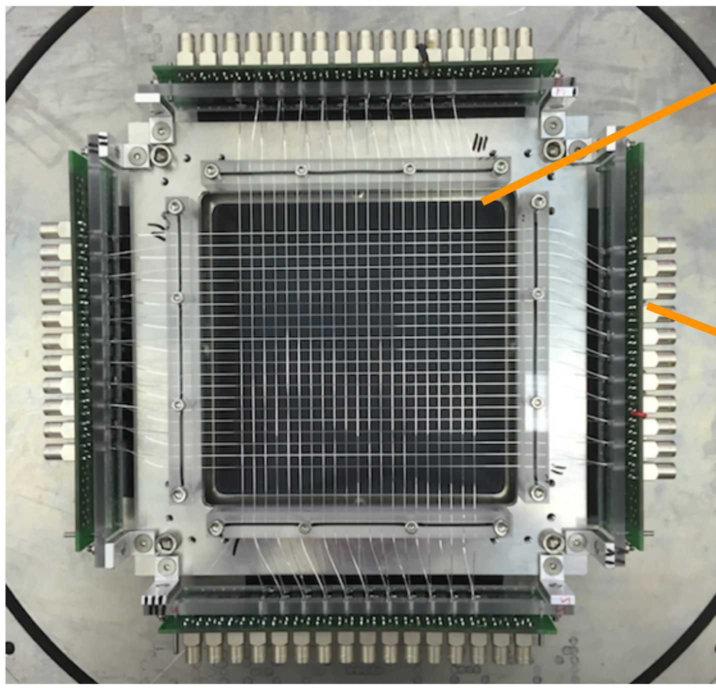
(1) Pile-up beam μ (large efficiency loss due to SiPM after-pulse in μ waveform)

(2) Small light yields of thin scintillating fiber

- In this study, total detection efficiency for e^+ is evaluated by considering pile-up and light yield

Light yield study

- In beam test with prototype, we observed small light yields of e^+



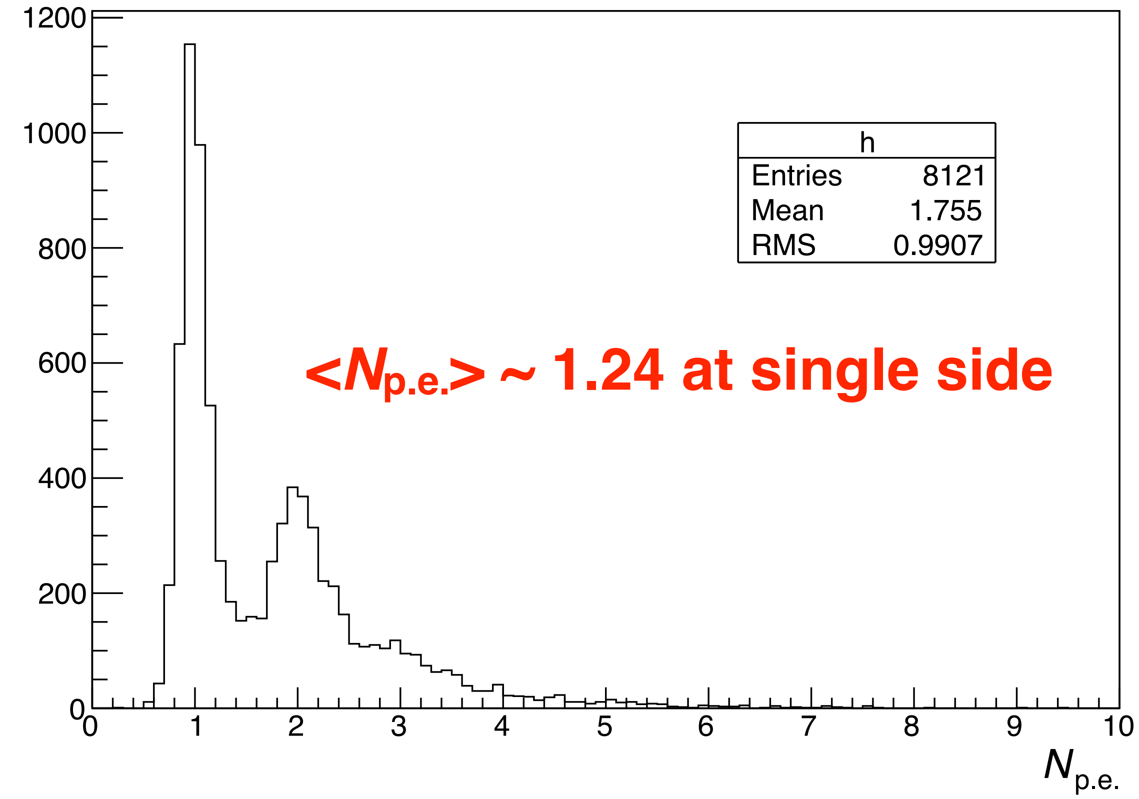
Scintillating fiber

- 20 cm length, multi-cladding
- 250 µm thick square shaped

Photosensor

- Double readout
- 1.3×1.3 mm² SiPM

Light yield of 28 MeV/c e^+ beam (single side)



- Probability to detect no photons ~29% (single side)

- Small light yields is probably due to short attenuation length of the fiber

$$I(x) = I_0(e^{-\frac{x}{\Lambda_1}} + e^{-\frac{x}{\Lambda_2}})$$

- I_0 : Light output of fiber core
- I : Measured light yield at x
- Λ_1,Λ_2 : Attenuation length of core or cladding light

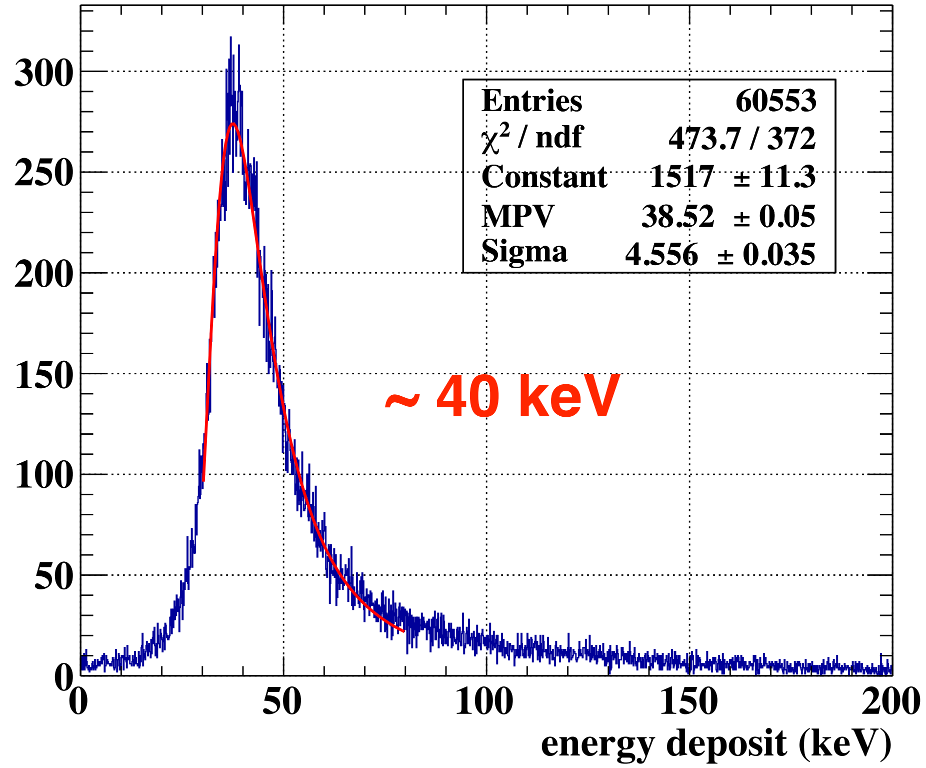
2.7 m in data sheet (fitted region : 1-3 m from fiber end)

Attenuating length is not measured in short region (< 1m)

Light yield study

- Items to be considered in calculation

(1) Simulated energy deposit of RMD e+

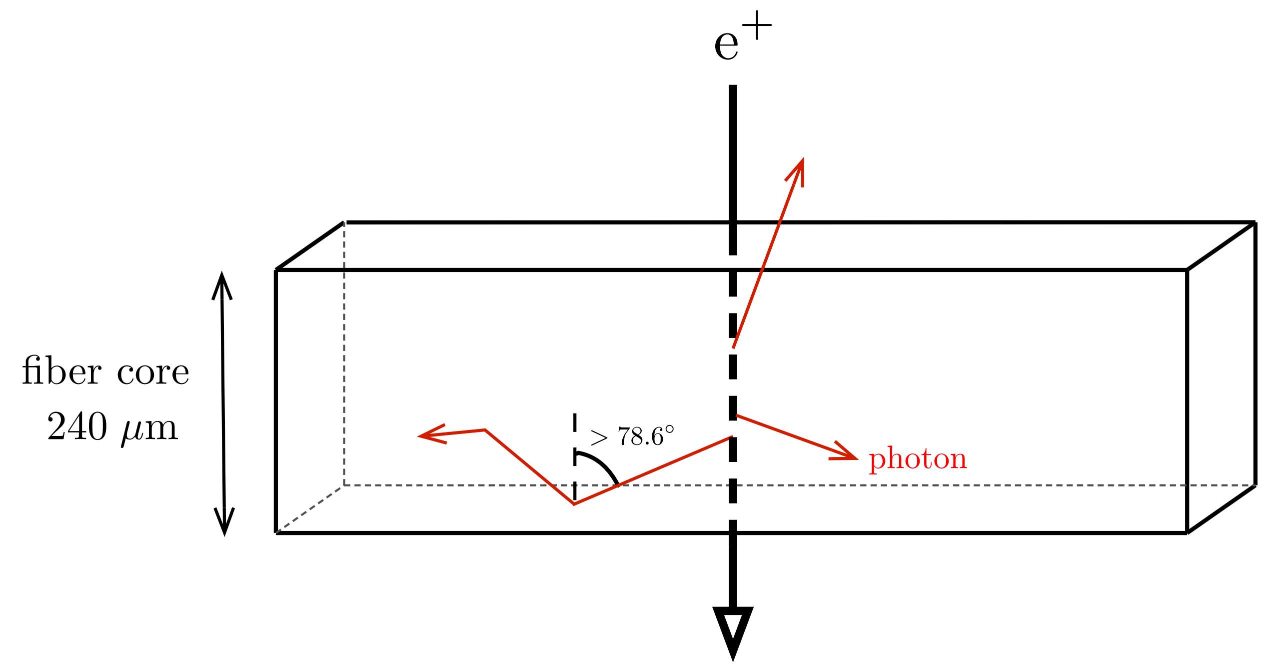


(2) Light out put of fiber core

8000 photon/MeV

* from data sheet

(3) Reflection angles to cladding wall



(4) Attenuation length of fiber

Further investigation is needed

(5) PDE of SiPM

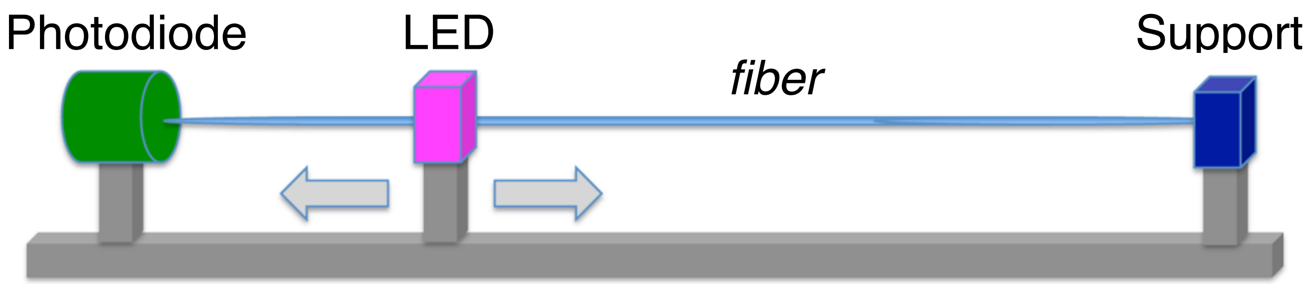
40%

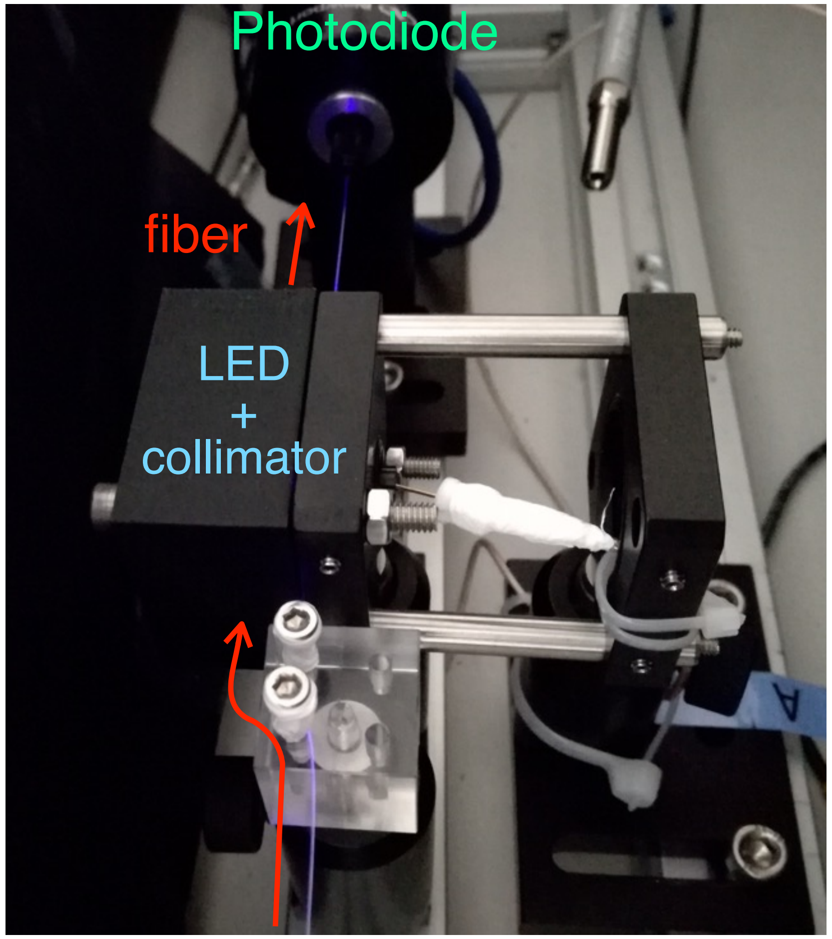
* from data sheet

- Calculation reproduces the observed light yield by assuming attenuation length ~7 cm

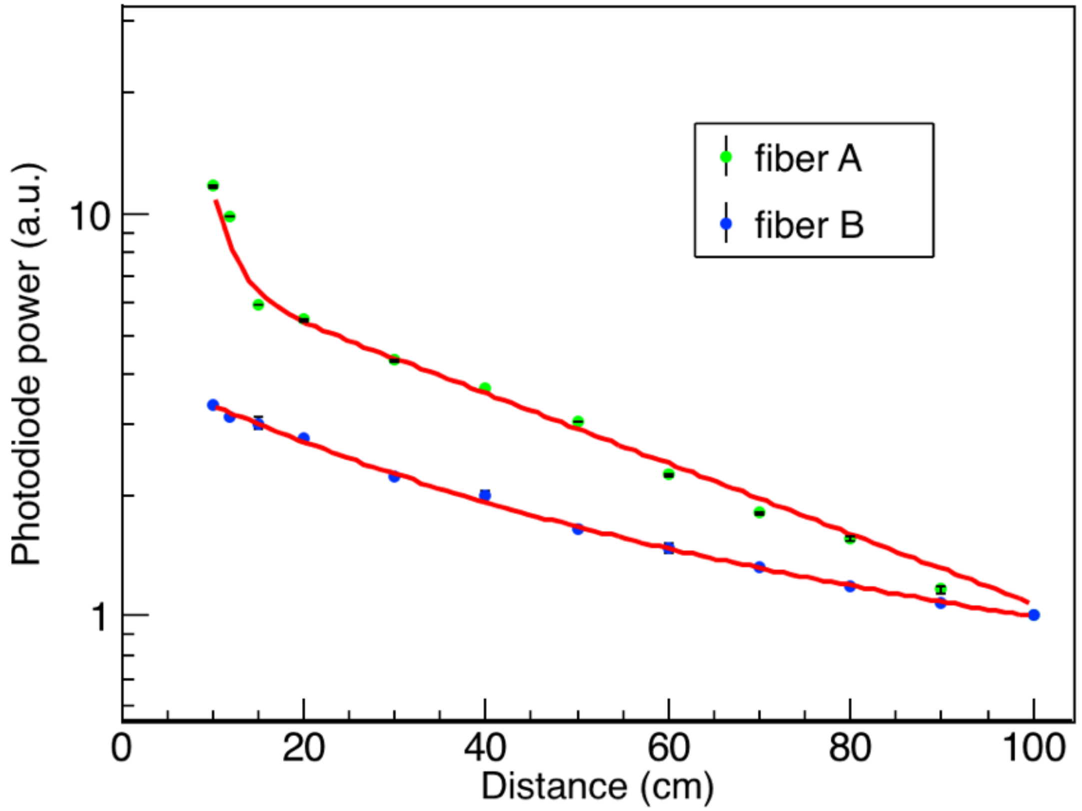
Light yield study

- Attenuation length was measured for few fiber samples





Each sample was measured 3 times (0→100 cm)



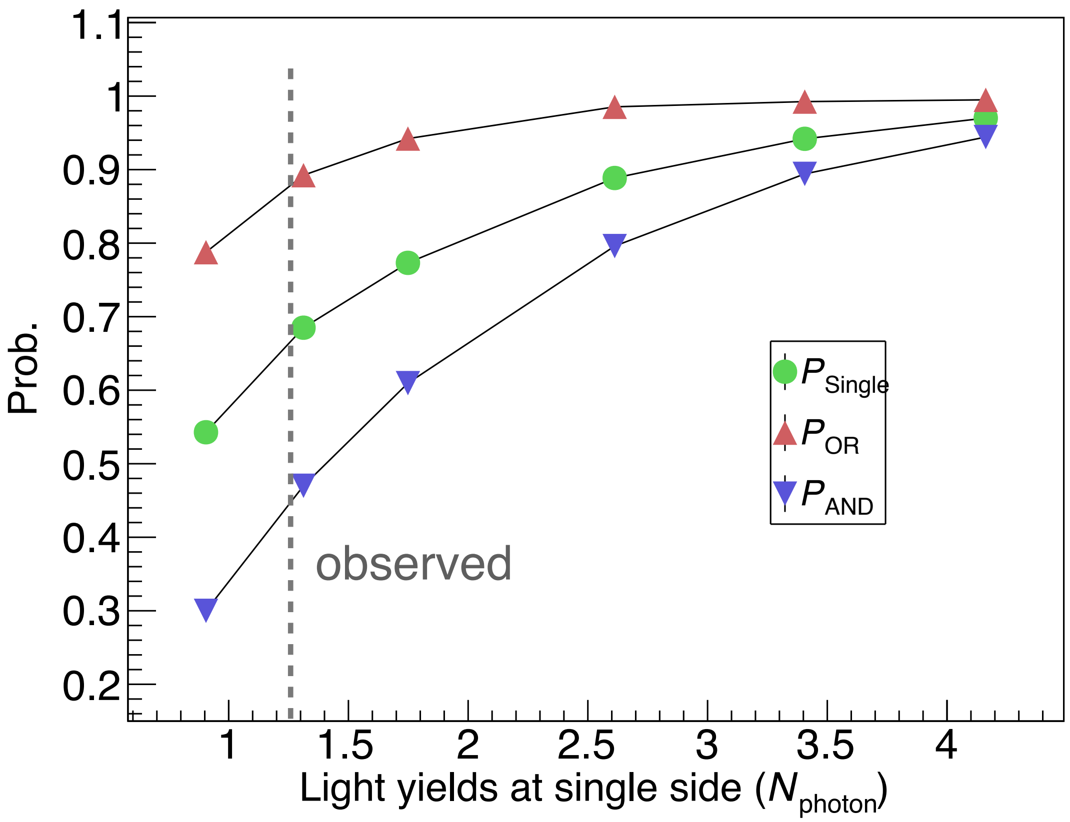
Attenuation length

	short	long
fiber A	2.2 cm	50.0 cm
fiber B	25.2 cm	145.1 cm

- Large attenuation in short region was measured
  - Variation between sample needs to be investigated
  - Shorter region (<10 cm) should be measured

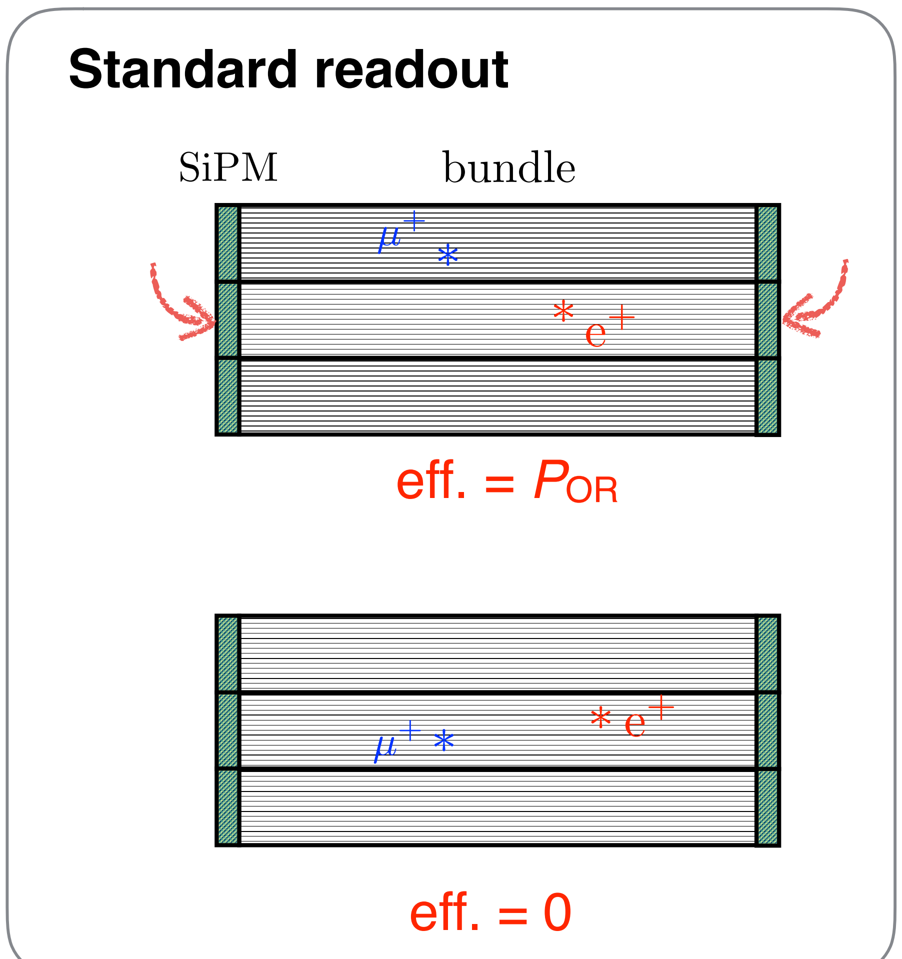
Detection efficiency & sensitivity

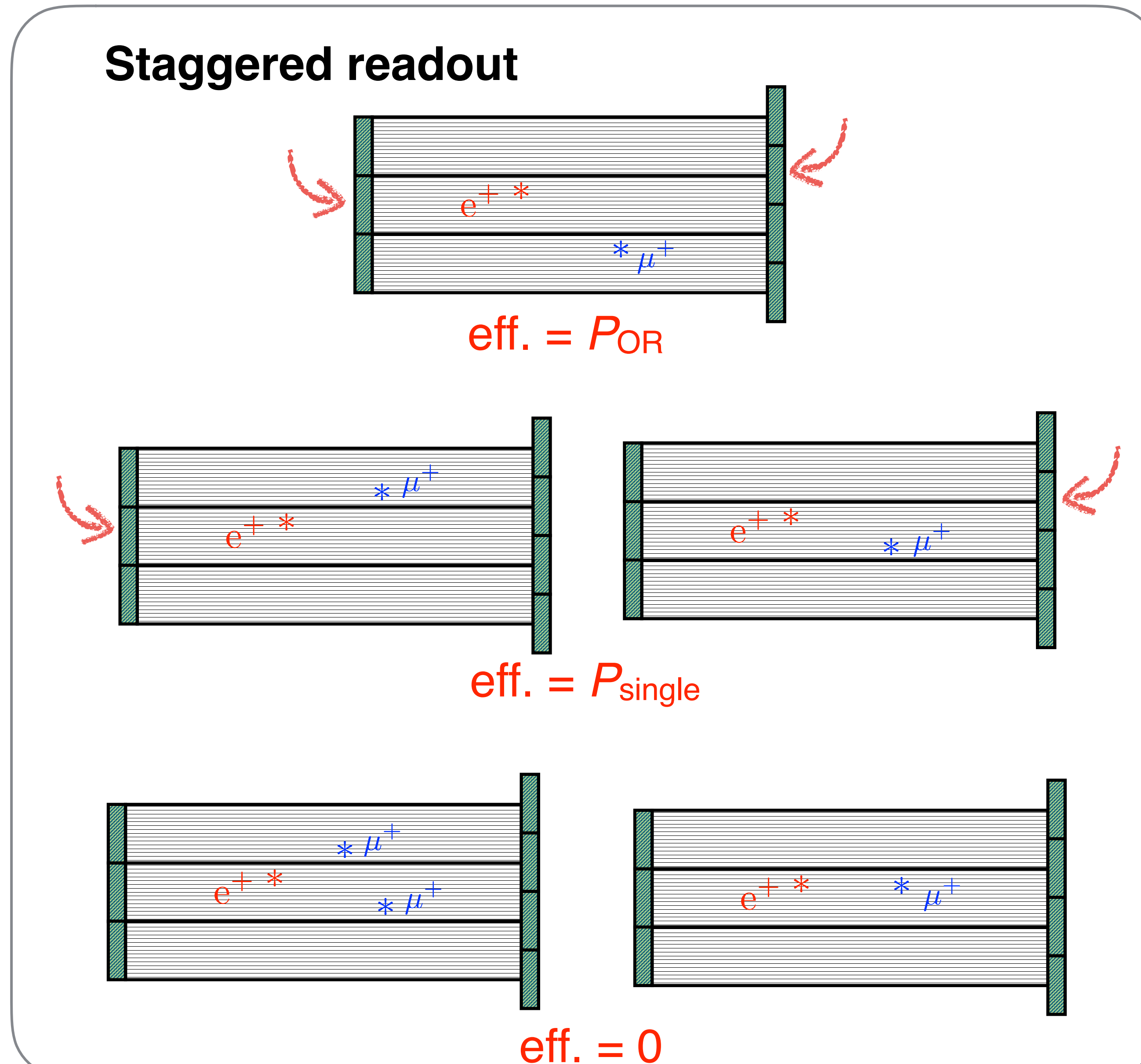
- Probabilities to detect e^+ signal with several light yields
  - P_{single} **: detect at single side**
  - P_{OR} **: detect at either side**
  - P_{AND} **: detect at both ends**



Detection efficiency & sensitivity

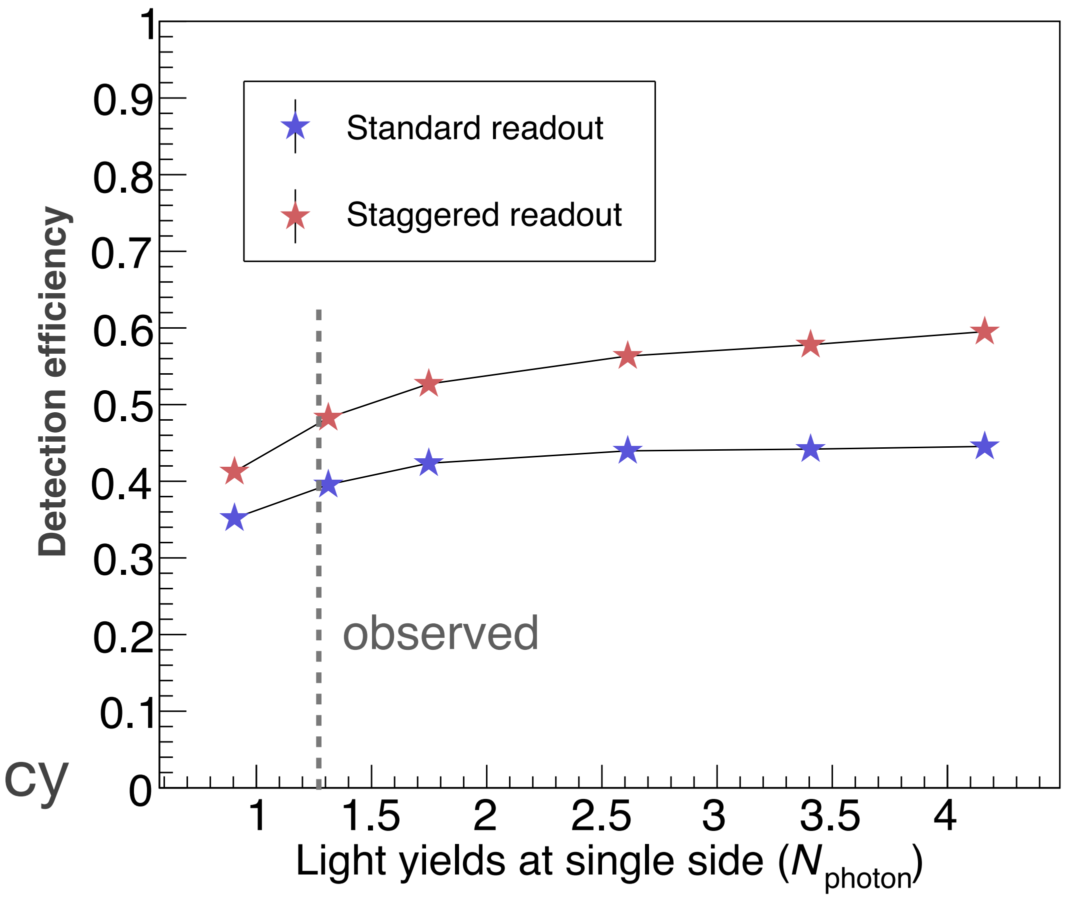
- Detection efficiency was evaluated by considering light yield and pile-up
  - Simulated hit timing, position of μ
  - $|T(e^+) - T(\mu)| < 60$ ns in same bundle→ pile-up
- Probability to detect signal at either fiber end was calculated for each event
- Hit pattern & event by event efficiency
  - Assuming 18 bundles





Detection efficiency & sensitivity

- Detection efficiency of e+ (E_γ > 48MeV)

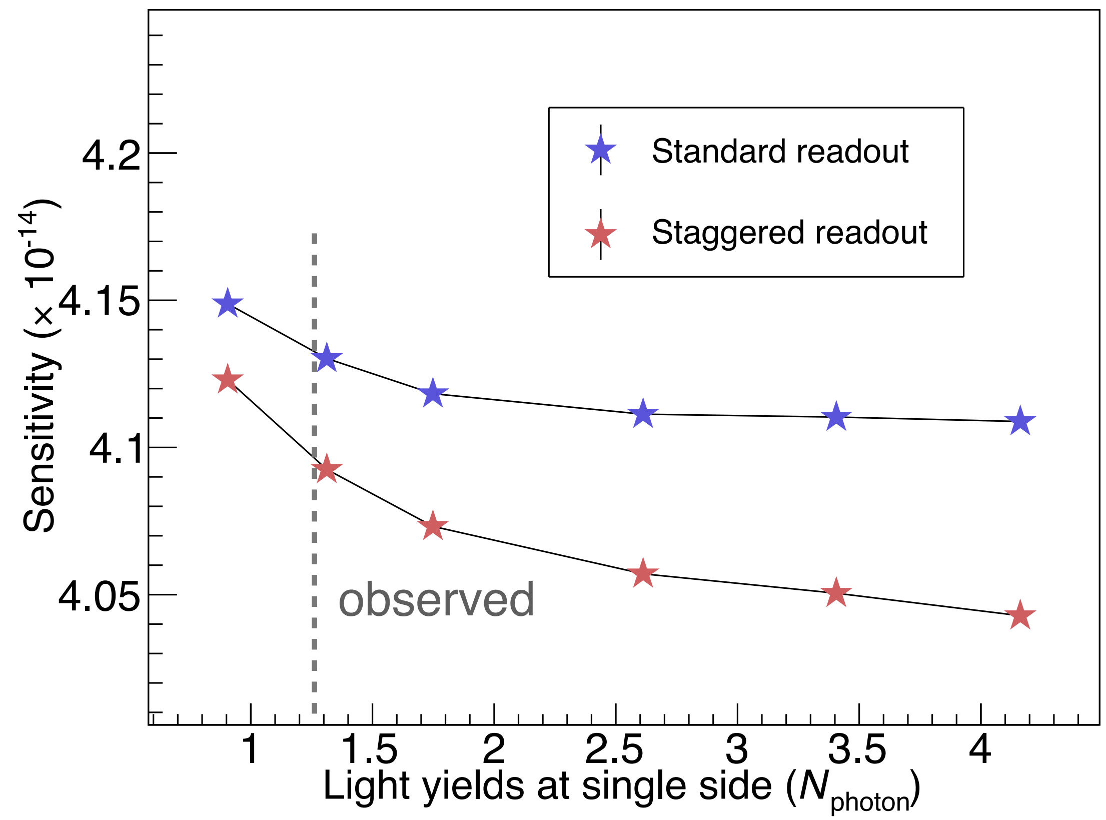


- Sensitivity was evaluated with detection efficiency
  - 4.3×10^{-14} only with downstream RDC
  - Sensitivity improvement

    w/ downstream : 16%

    w/ downstream + upstream : 22%

    *at observed light yield

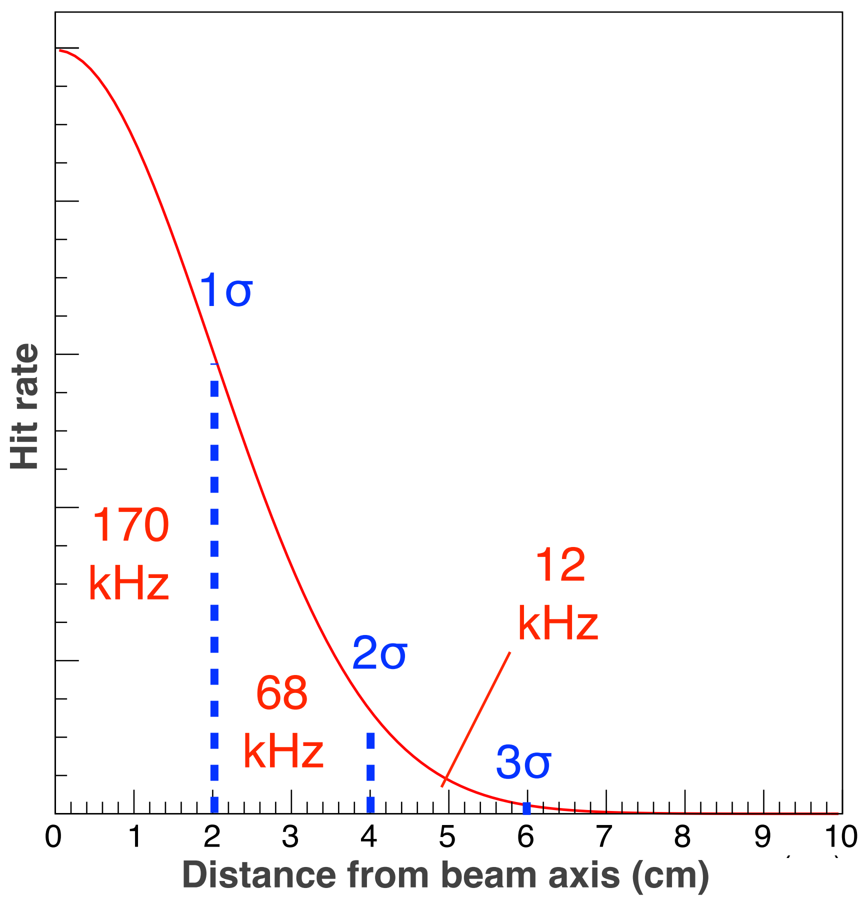


- Further improvement is possible by increasing light yield or higher segmentation

Radiation hardness of scintillating fiber

- Another potential issue is radiation damage on scintillating fiber

μ hit rate in central fiber



Dose in central fiber

Region	0-1σ	1-2σ	2-3σ
Dose (Gy/day)	2200	880	160

* energy deposit of μ ~600 keV

Effect 1 : Light output degradation of fiber core

48% after 16 days operation

Yu. M. Protopopov et al NIM B95 (1995)

Effect 2 : Change of attenuation length

Region	0-1σ	1-2σ	2-3σ
Attenuation length ratio after 16 days	0.46	0.52	0.63

K. Hara, et al NIM A411 (1998)

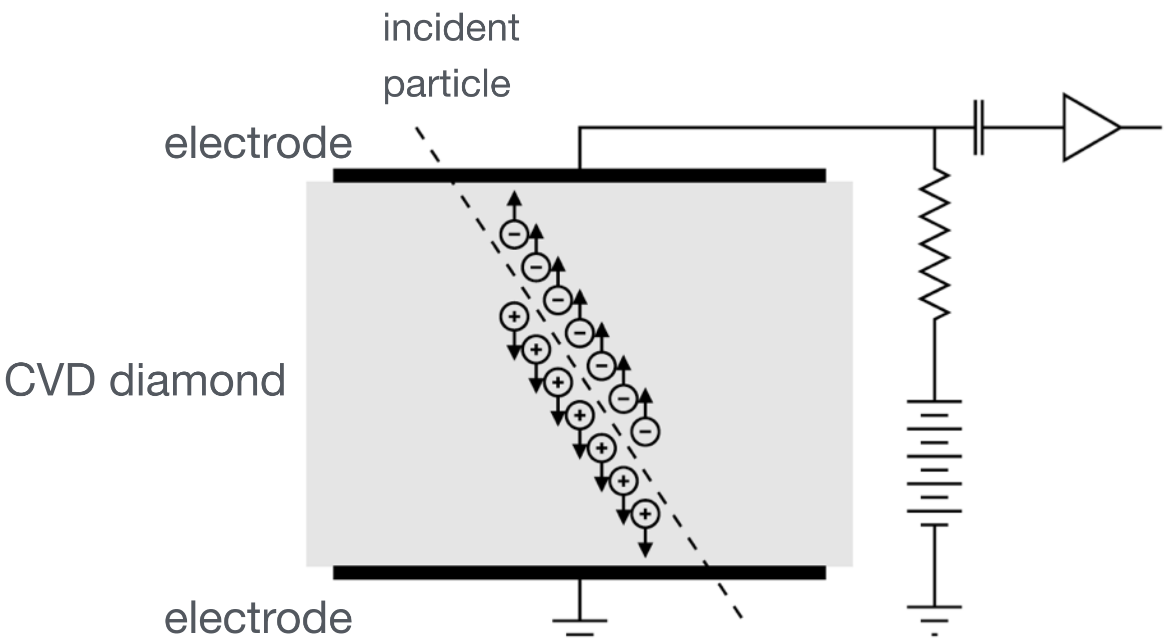
- Light yield is expected to largely drop down (~1/4 after 16 days operation)

- Actual irradiation test in high dose environment (10^5 Gy) is needed
    - Irradiation test at proton irradiation facility at PSI is planned

Radiation hardness of scintillating fiber

- If light yield drop due to radiation damage is correct, upstream RDC based on scintillating fiber is not realistic

- We are also considering detector based on CVD diamond
  - 85 μm thick single-crystal diamond mosaic
  - Radiation tolerance (~MGy)



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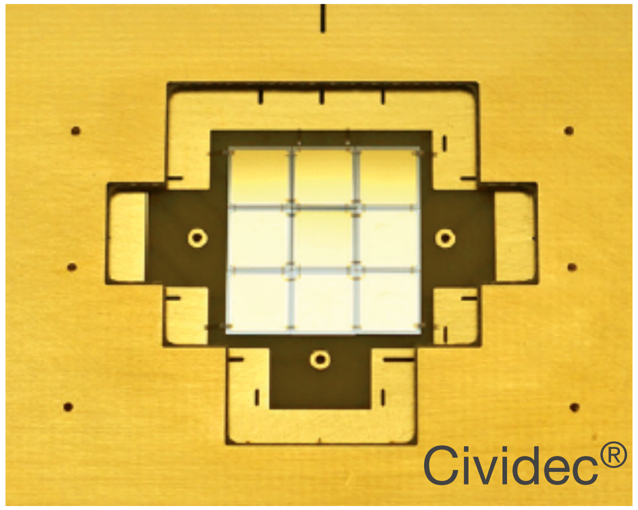
Diamond mosaic detecter (4.5 × 4.5 mm^2 tile ×9)
@CERN n_TOF facility



- Difficulty : Low charge collection of e^+ signal (~3000 e-h pairs)
  - In principle possible with commercial charge sensitive amplifier

Summary

- RDC identifies dominant source of background by detecting low momentum e^+
- We are considering further improvement of sensitivity by installing scintillating fiber based detector in μ beam
- Detection efficiency of e^+ was evaluated by considering light yields of fiber and pileup μ
    - e^+ detection efficiency ~50% (at observed light yield)
    - MEG II sensitivity improvement with downstream + upstream RDC ~22%
- Further study on attenuation length of scintillating fiber is necessary to better understand performance
- Light yield is expected to largely drop due to high radiation dose (2.2 kGy/day)
    - Literatures say light yield become ~1/4 after 16 days
    - Actual irradiation test is planned
    - We are also considering to use diamond mosaic detector

Backup

Optical attenuation length measurements of scintillating fibers

N.A. Amos, A.D. Bross and M.C. Lundin

Particle Detector Group, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

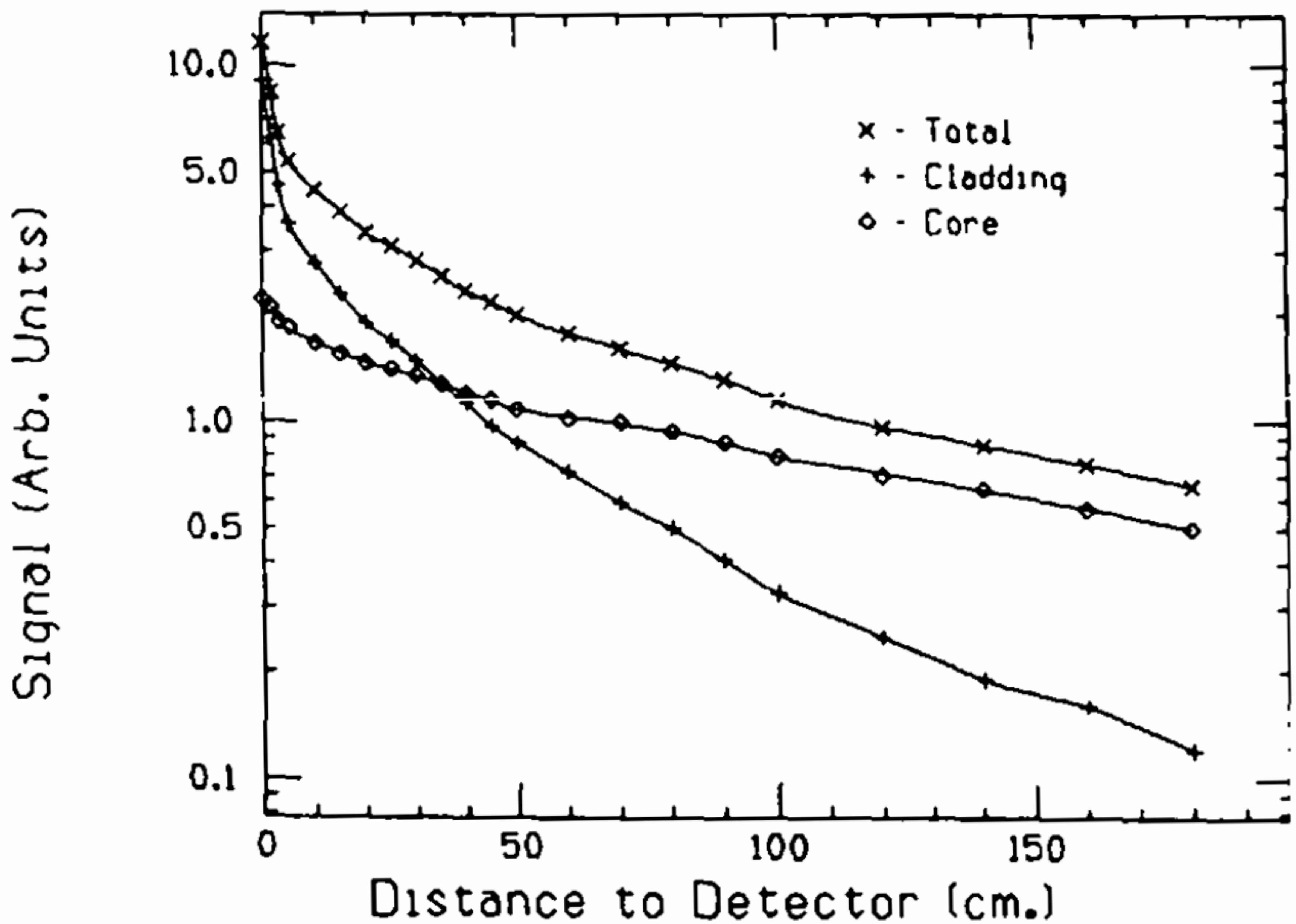


Fig. 13. Attenuation length curves for "core," "cladding," and "core + cladding" light.

Total detection efficiency

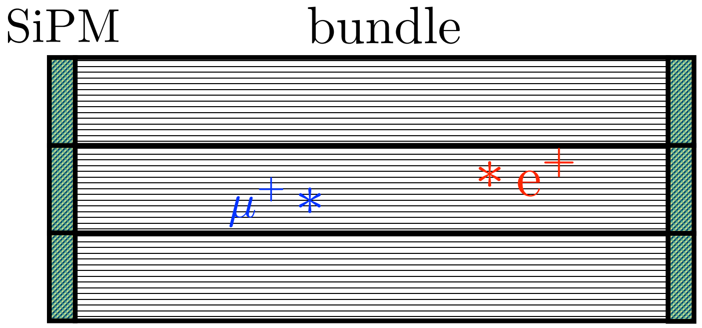
- Probabilities to detect scintillation photons and pileup were considered

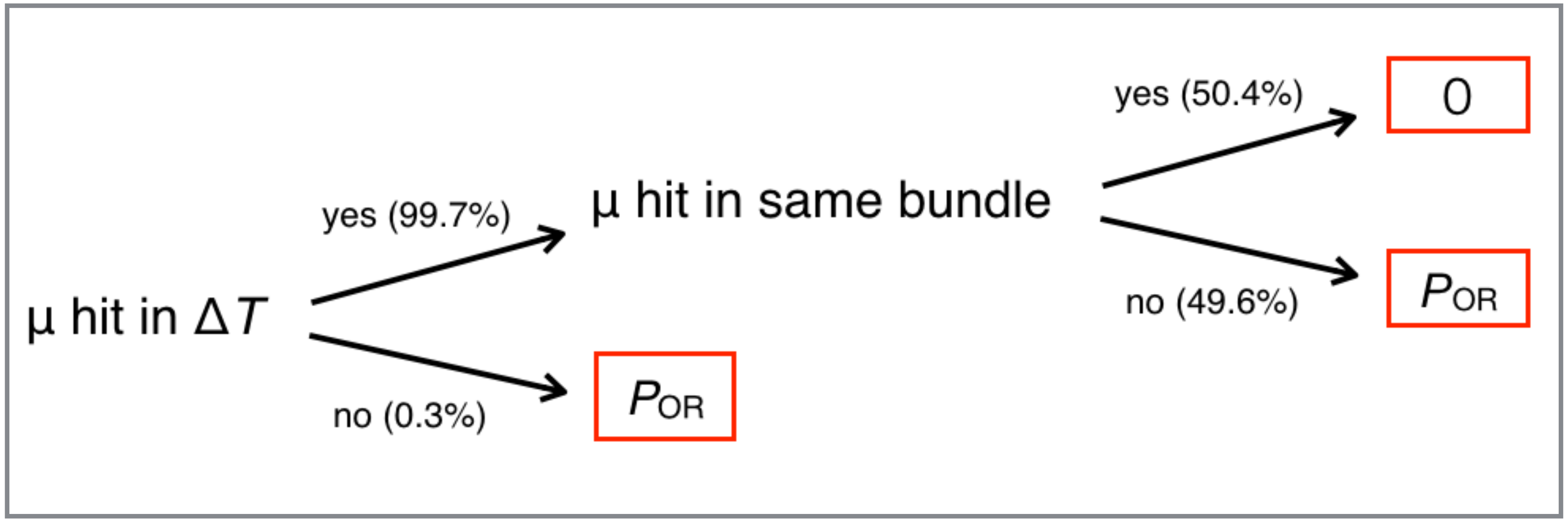
$$\text{Efficiency} = \frac{\text{Number of detected events by the SiPMs (either side)}}{\text{Number of entered positrons in the upstream RDC}}$$

- Simulated hit timing, position

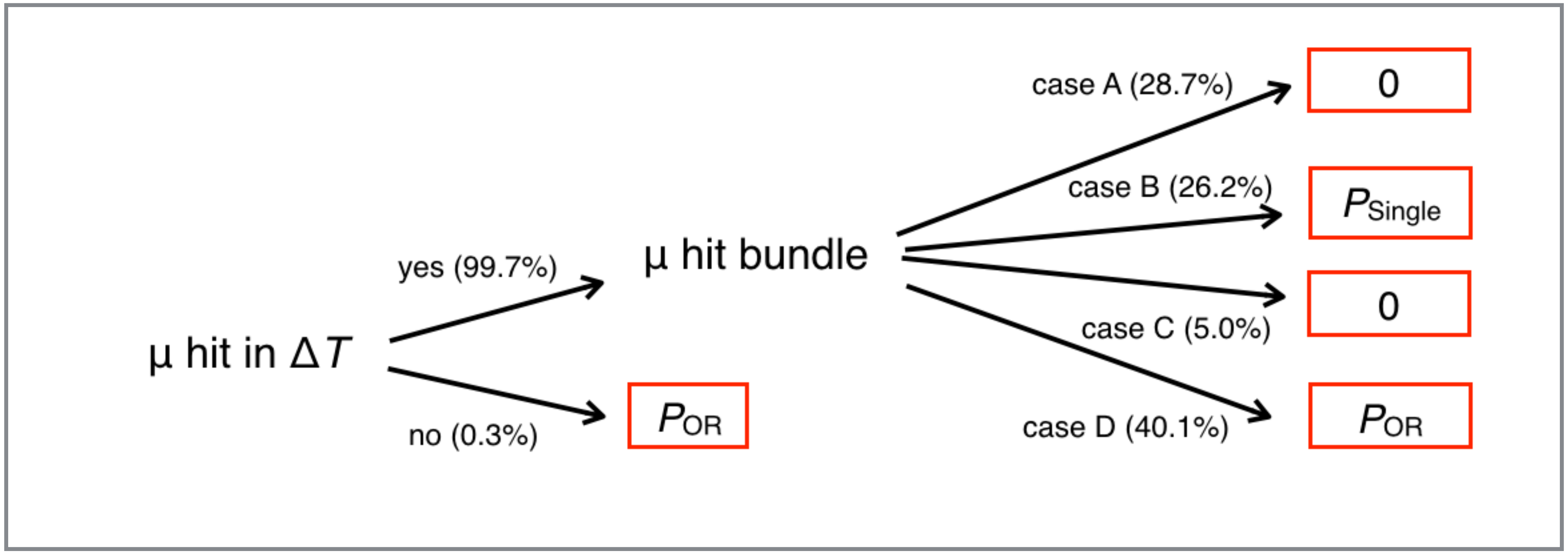
- Standard readout

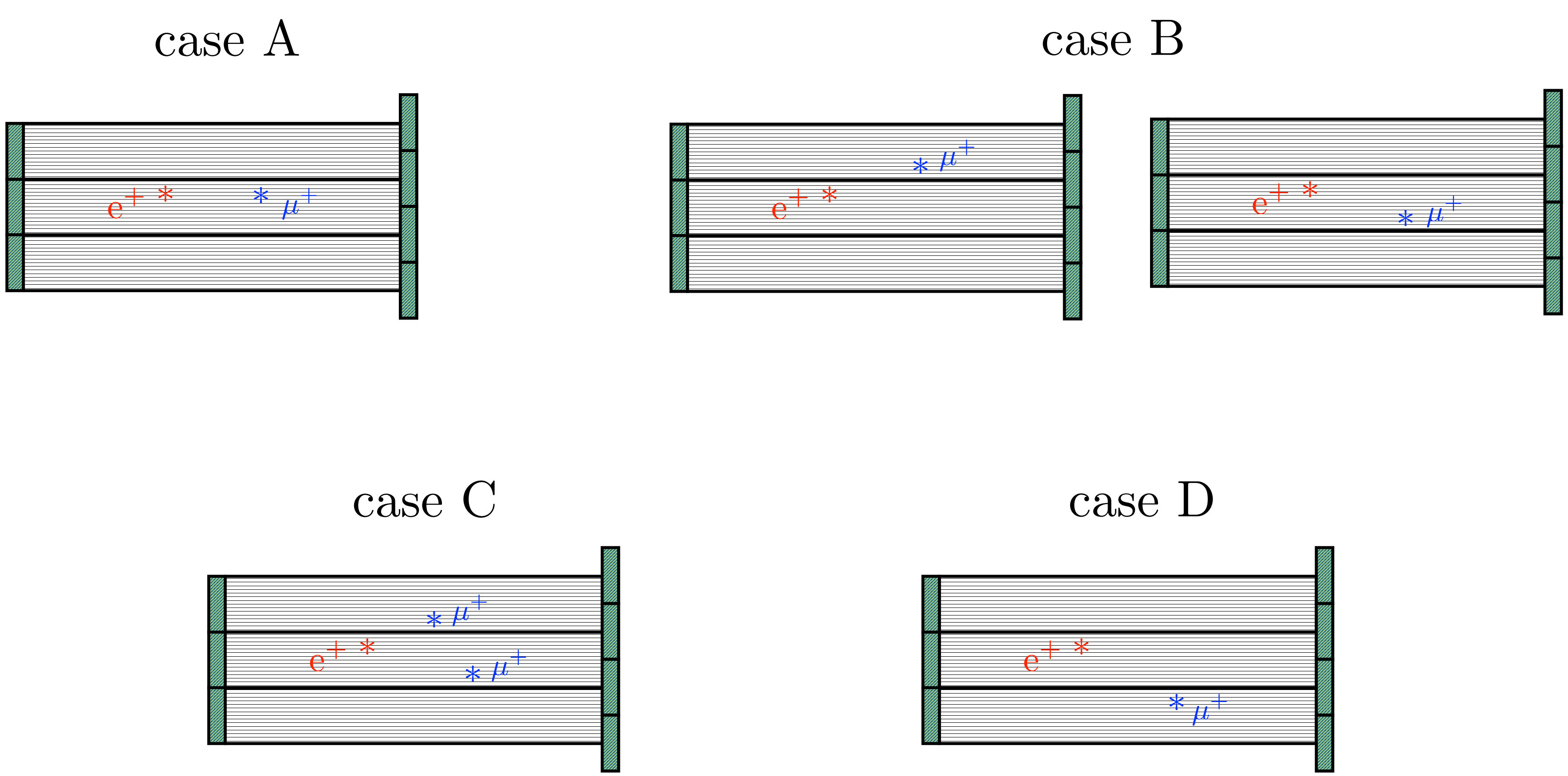
scp filename.xxx
muegamma@meg.icepp.s.u-tokyo.ac.jp:./html/docs/talks/JPS/2016a/name_jps2017s.xxx





- Staggered readout



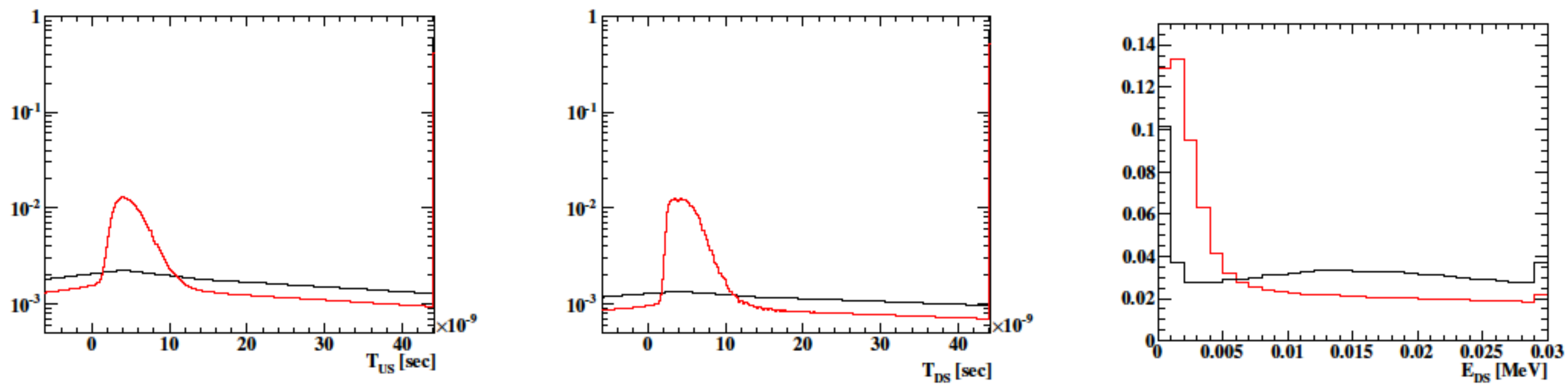


RDC data in physics analysis

- MEG II uses Maximum likelihood analysis to decide number of signals

$$\mathcal{L}\left(N_{\mathrm{sig}}, N_{\mathrm{RMD}}, N_{\mathrm{BG}}\right)$$

- RDC makes PDF of 3 observables (t_{ds}, E_{ds}, t_{us}) and implement in likelihood function



(a) T_{us} (b) T_{ds} (c) E_{ds}

Figure 27: Projection of RDC PDF. The red and black line shows the accidental background and the signal PDF, respectively.

Dose in fiber

- Fiber at 1 sigma region (~2 cm)

Mass = 0.025 [cm] * 0.025 [cm] * 2.0 [cm] * 1.05 [g/cm^3]

= 1.3e-6 [kg]

ΔE/s = 0.6 [MeV] * 500 [kHz] * 0.68

= 2.04e5 [MeV/s]

= 2.04e5 [MeV/s] * 1.0e6 [eV/MeV] * 1.6e-19 [J/eV] ⟶ 2.82e-3 [J/day]

= 3.26e-8 J/s

Dose = 3.26e-3 [J/day] / 1.3e-6 [kg]

= 2.5e-2 [Gy/s] ⟶ 2.2e3 [Gy/day]

Radiation effect

- Peter reported degradation of light yield of plastic scintillator

- Yu. M. Protopopov et al NIM B95 (1995) 496-500
γ-irradiation compare Sr-90 source

Table 4
Scintillation light yield of different types of plastic scintillators before and after irradiation and their recovery in time

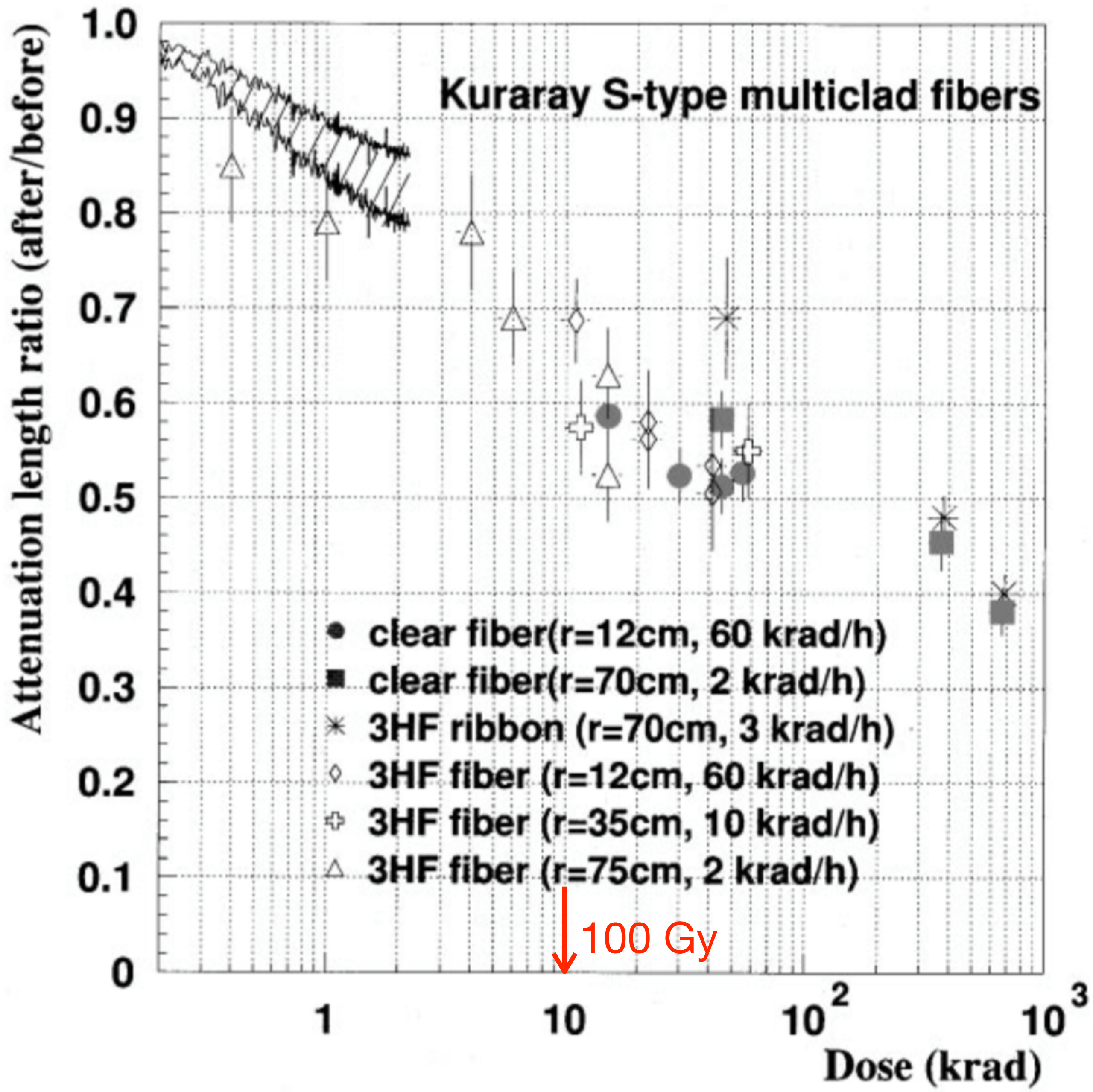
N	Scintillator	I_0 [%]	I/I_0 [%] (3.4×10^4 Gy)	I/I_0 [%] (1×10^5 Gy)	I/I_0 [%] (after 23 days of recovery)
1	PS [a]	100	48	23	52
2	PSM-115 [b]	90–100	92	60	72
3	NE-102a [c]	120	60	45	61
4	NE-110 [c]	120	63	48	59
5	BC-400 [d]	126	56	39	61
6	BC-404 [d]	126	63	53	57
7	BC-408 [d]	124	61	46	57

[a] Bulk-polymerizated polystyrene (2% pTp + 0.05% POPOP), IHEP, Protvino, Russian Federation.
[b] PSM-115-based polystyrene made by injection into the mold technology (2% pTp + 0.03% POPOP), IHEP, Protvino, Russian Federation.
[c] Nuclear Enterprises Ltd., Edinburgh, Scotland.
[d] Bicron Corp., Newbury, Ohio, USA.

- 48% light yield after 3.4e4 [Gy]
- US-RDC reaches 3.4e4 [Gy] after 16 days

Radiation effect

- Influence on attenuation length of fiber should be also considered
- **K. Hara, et al.,** ***Radiation hardness and mechanical durability of Kuraray optical fibers,*** **NIM A411 (1998)**



3HF fiber : Scintillating fiber with wavelength shifter for radiation hardness

Shortened attenuation length was observed even with small dose (~100 Gy)

Both optical fiber & scintillating fiber were characterized by..

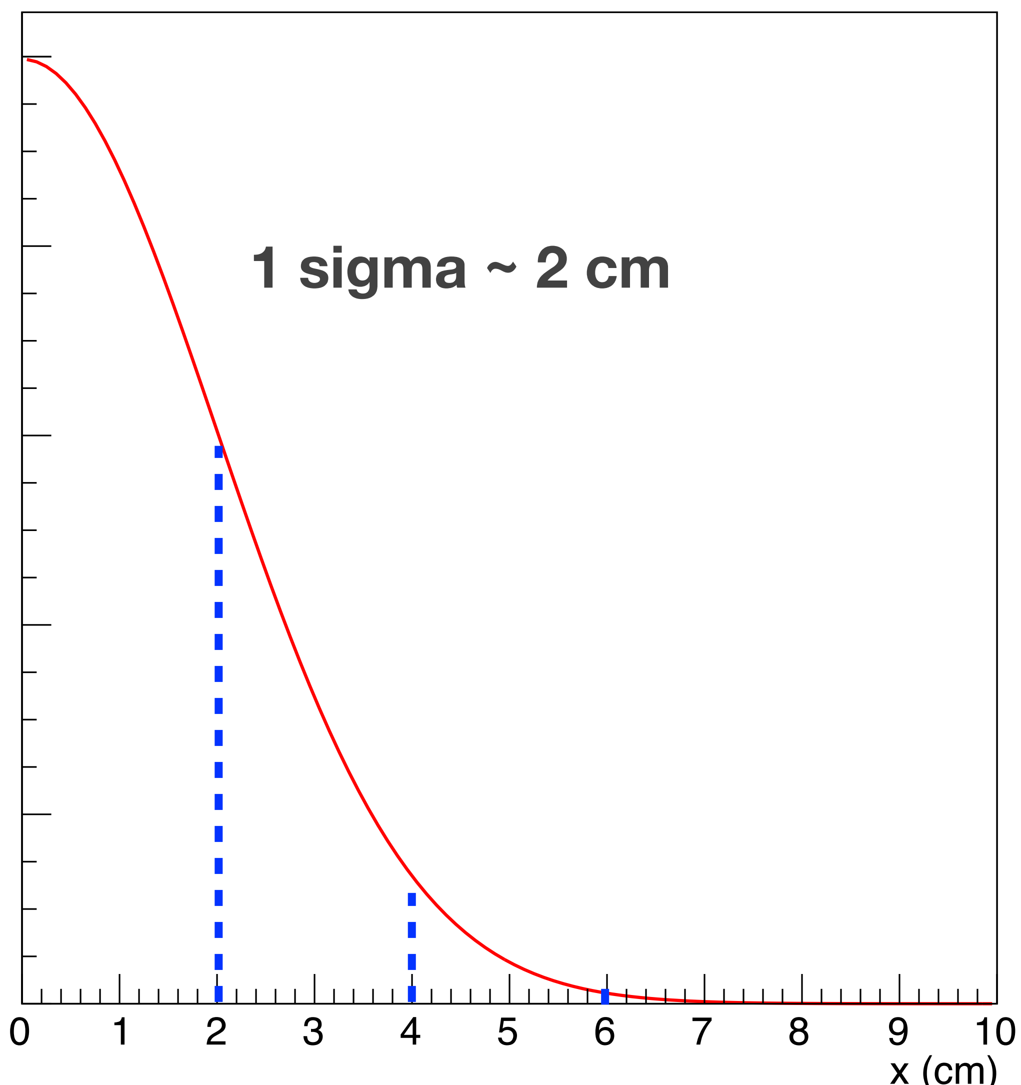
$$\lambda/\lambda_0 = (0.80 \pm 0.01) - (0.144 \pm 0.007)\log_{10} D$$

λ/λ_0 : Ratio of attenuation length

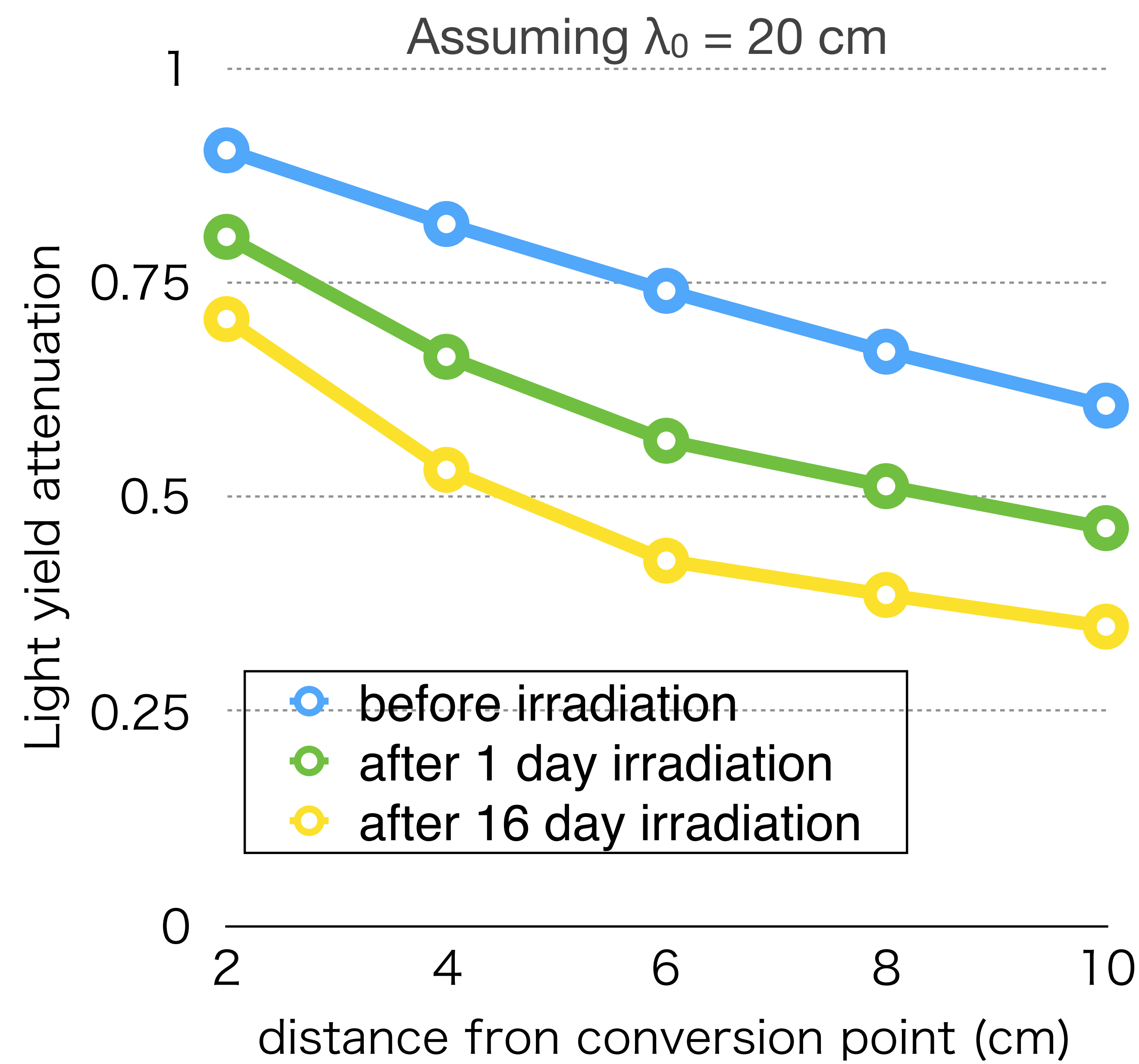
D : Dose in krad

Radiation effect

- Attenuation length in RDC



hit rate (kHz)	170	68	12
dose (Gy/day)	2200	880	160
λ/λ_0 (1 day)	0.46	0.52	0.63
λ/λ_0 (16 day)	0.29	0.35	0.45



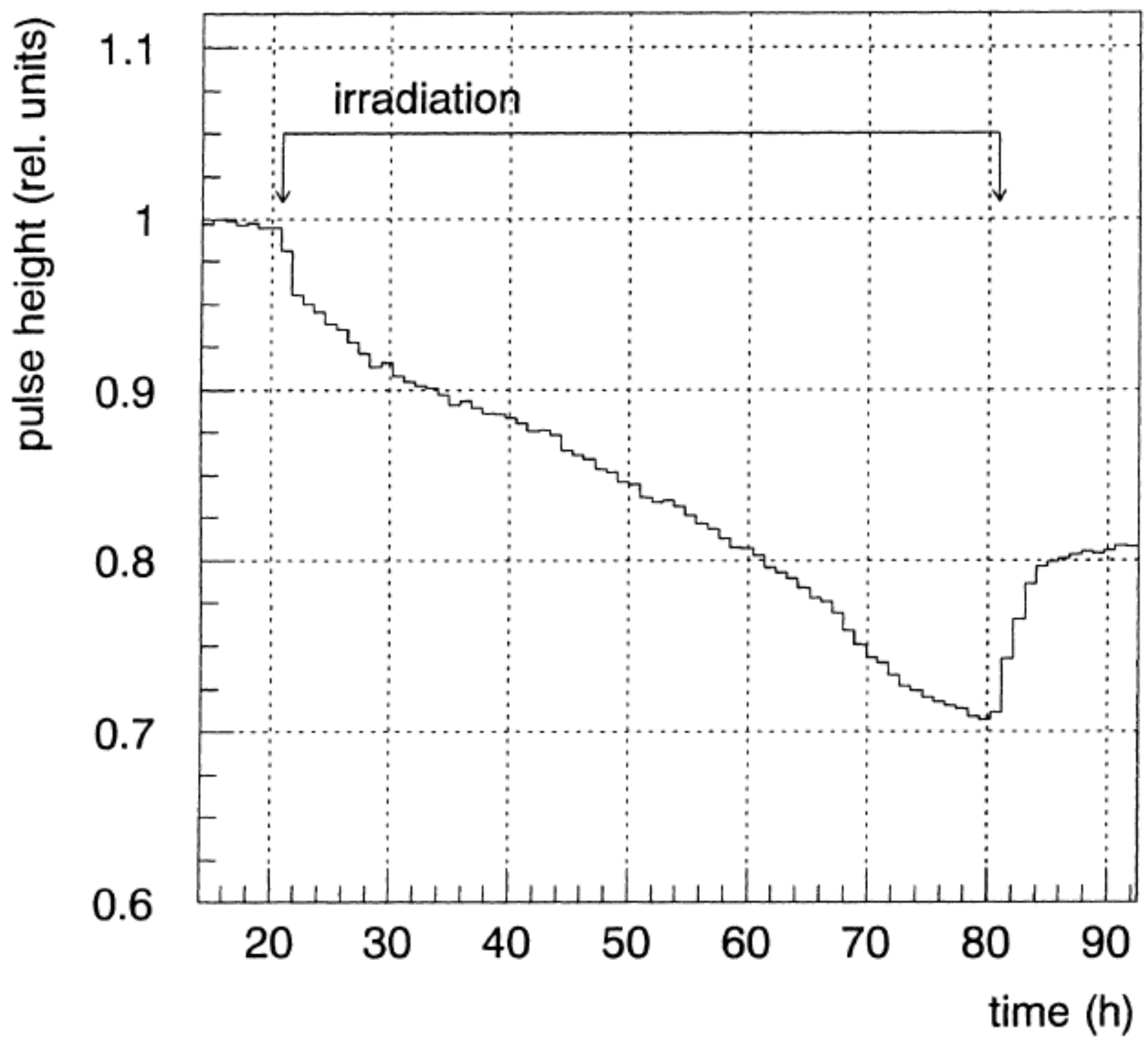
Assuming fiber length ~20 cm, total light yield will be ~1/4 after 16 days

Radiation effect

- **W. Busjan, et al.,** *Shortlived absorption centers in plastic scintillators and their* infuence on the fuorescence light yield, **NIM 152 (1999)**

- Irradiation test with **BCF-12** (planned to be used in RDC)
- 30 cm long fiber was uniformly irradiated with X-ray source (42 Gy/h)

Pulse heigh of particles penetrate middle of fiber

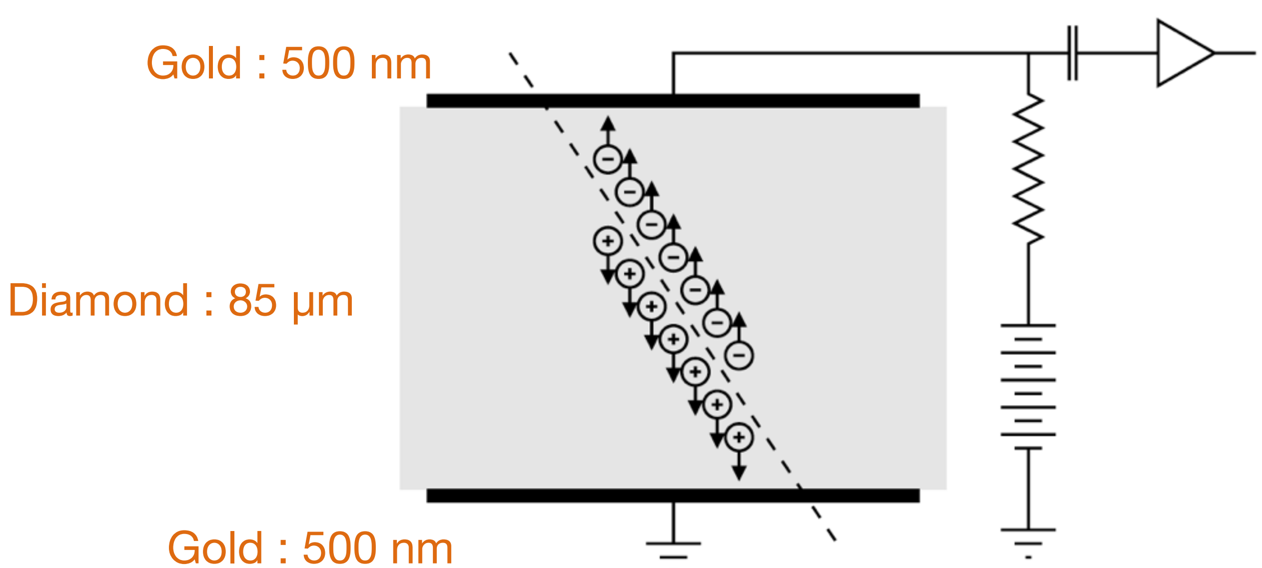


Current measured short component of attenuation length has large uncertainty (15-60 cm)

Result is consistent with previous calculations if λ^0 (attenuation length before irradiation) is 35-40 cm

Altenative plan

- CVD diamond based RDC is considered
  - Discussing about design with E. Griesmayer (TU Wein, Cividec®)
  - 85μm thick, multiple single crystal CVD diamond
- Advantages :
  - Radiation tolerance (~MGy)
  - High detection efficiency (~100%) & Fast signal (~10ns)
  - Space limitation for photosensor can be solved
  - 2D continuous μ beam monitoring
- Difficulty
  - Readout of positron signal (3300 e-h pairs)
  - Manufacturing large area & thin mosaic detector (cost, mechanical stability)
  - Effect on μ beam should be carefully studied
- Possible readout : Charge sensitive amplifier (~5 mV/fC) + broadband amplifier (40dB~)



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Diamond mosaic detecter @CERN n_TOF facility