令和4年度

東北大学大学院理学研究科物理学専攻 修士論文発表会

高エネルギー光子・電子ビームプロファイルモニタの開発と加速器研究への応用

Development of high-energy photon and electron beam profile monitor and application to accelerator research

原子核物理研究室　修士2年

木野 量子

令和５年２月１日

Contents

- Motivation
- Design of the new Beam Profile Monitor (BPM)
- Measurement result
- Application to accelerator research
- Summary

Contents

- **Motivation**
- Design of the new Beam Profile Monitor (BPM)
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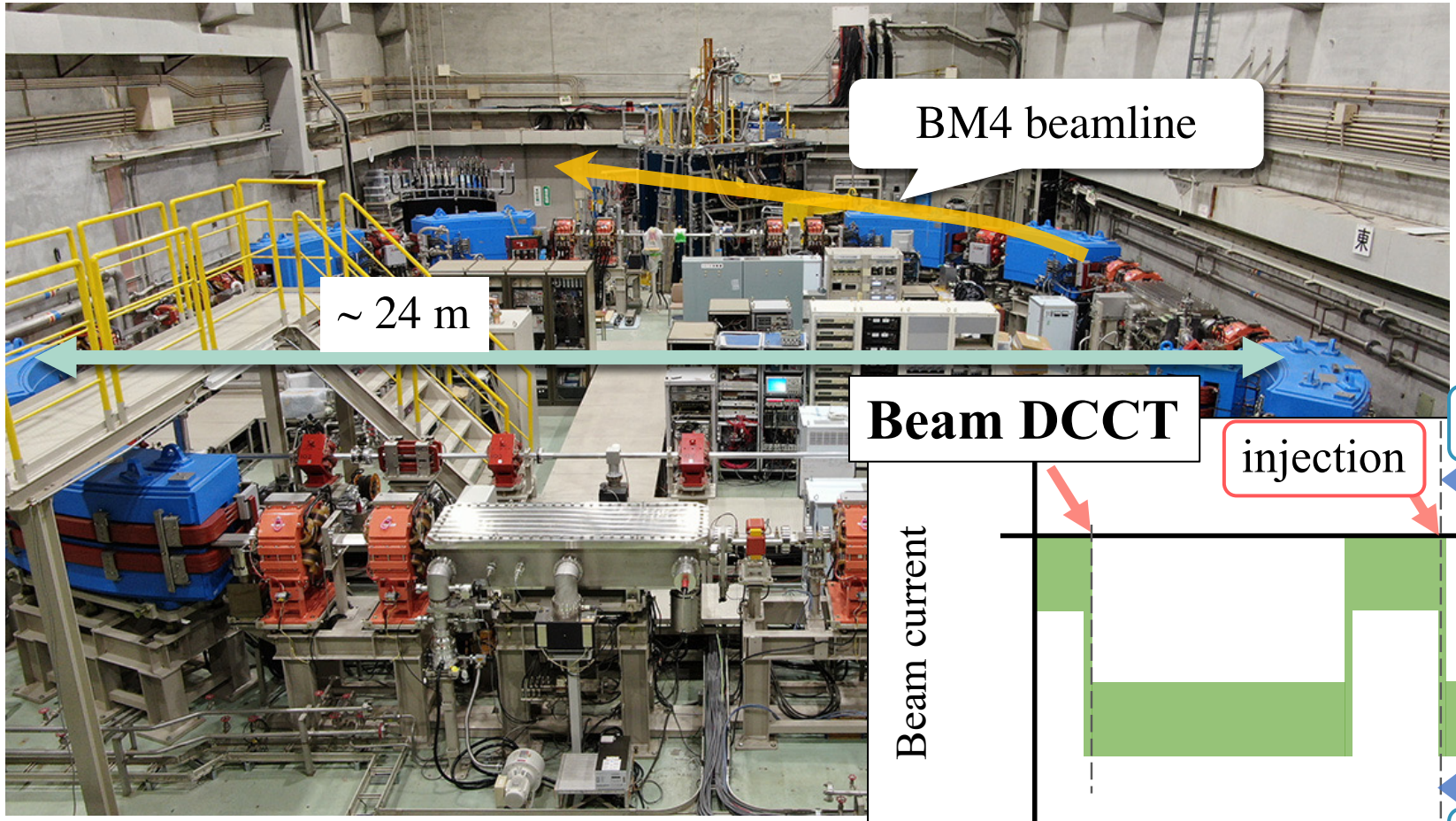
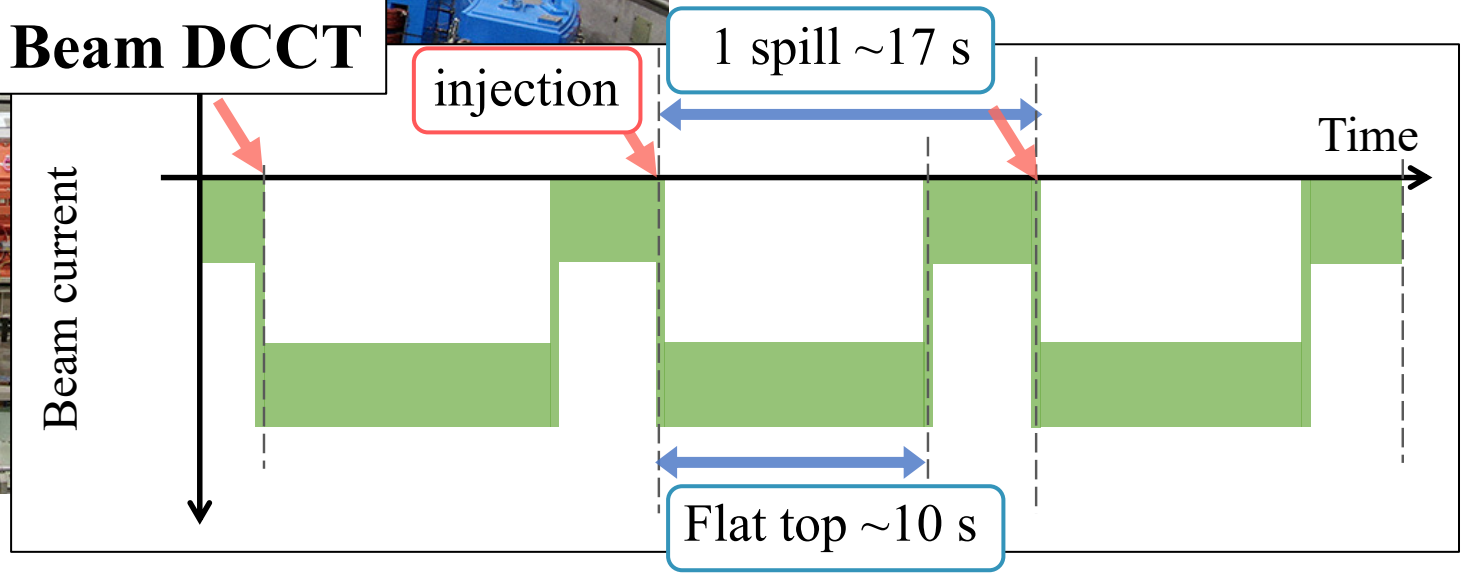
Booster STorage ring at ELPH, Tohoku Univ.



- Electron syncrotron
  Injection Beam : 90 MeV

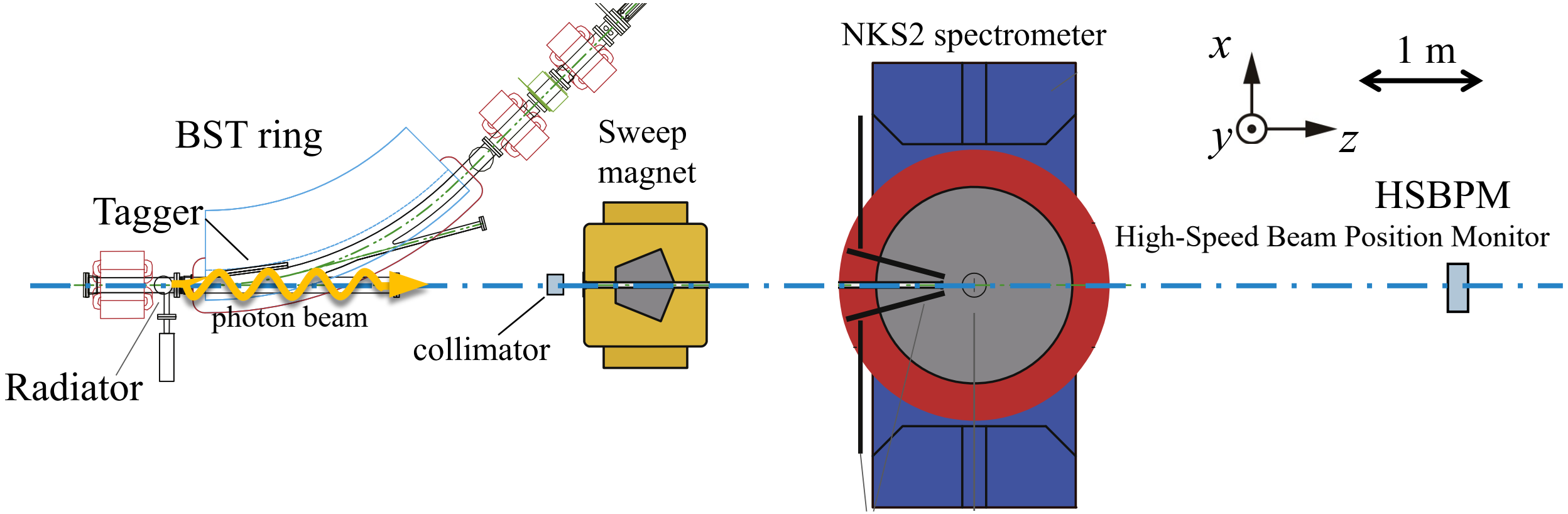
⬇

Ring Top Energy: **1.3** GeV

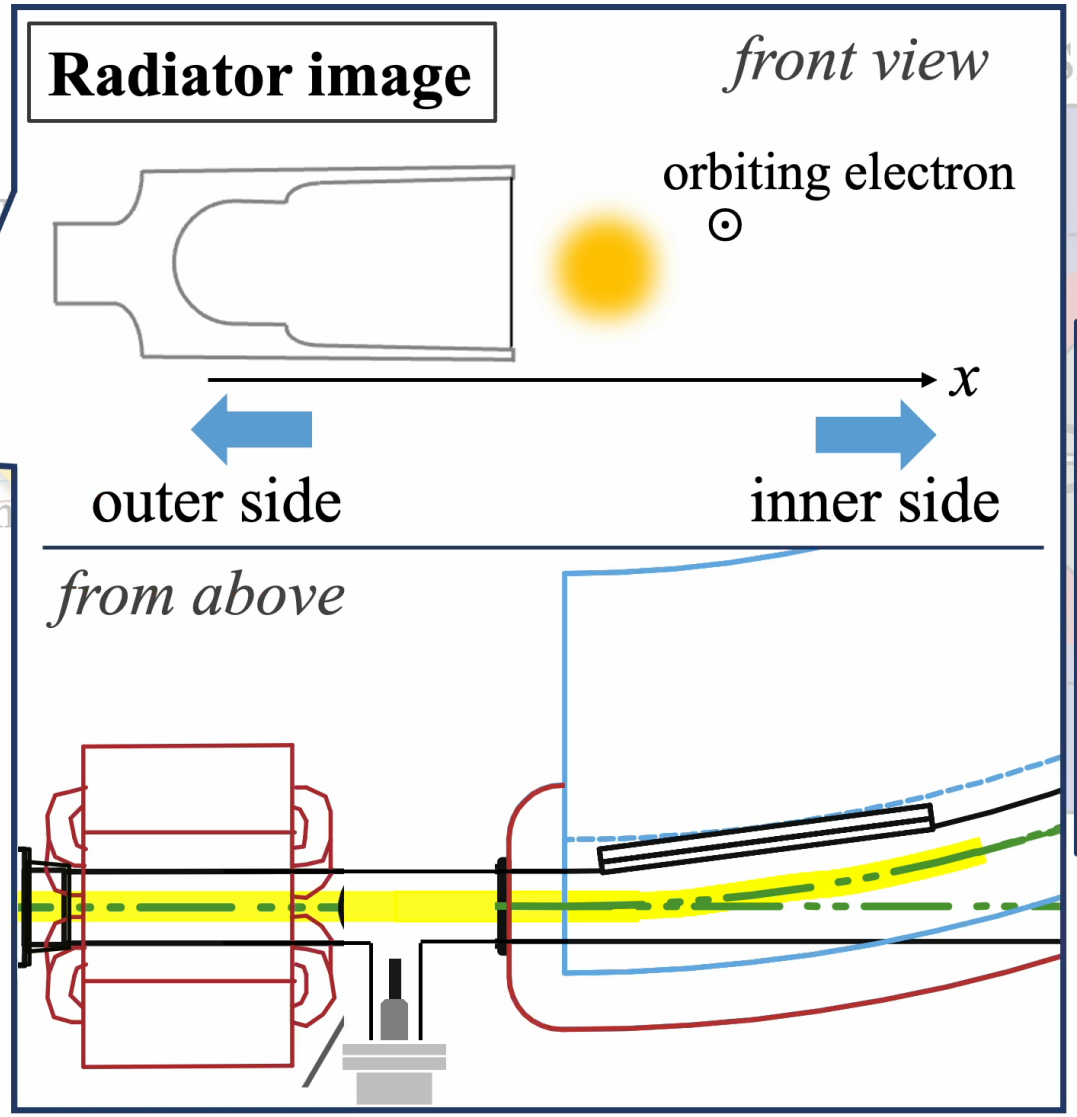


Booster **ST**orage ring (BST ring)
at Reserch Center for **EL**ectron **PH**oton Science (ELPH)

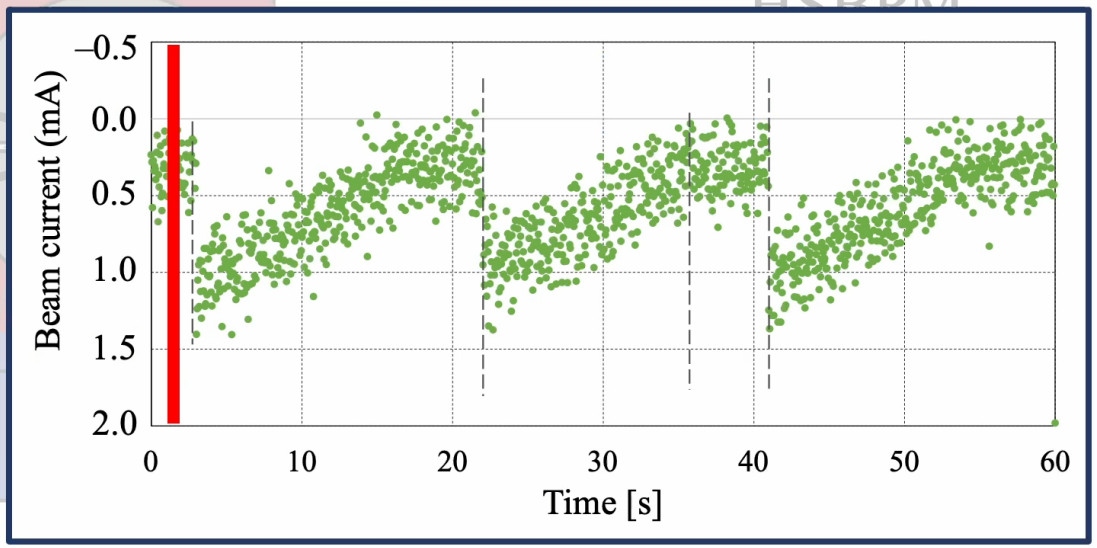
Characteristics of ELPH BM4 beamline



Characteristics of ELPH BM4 beamline



Beam DCCT



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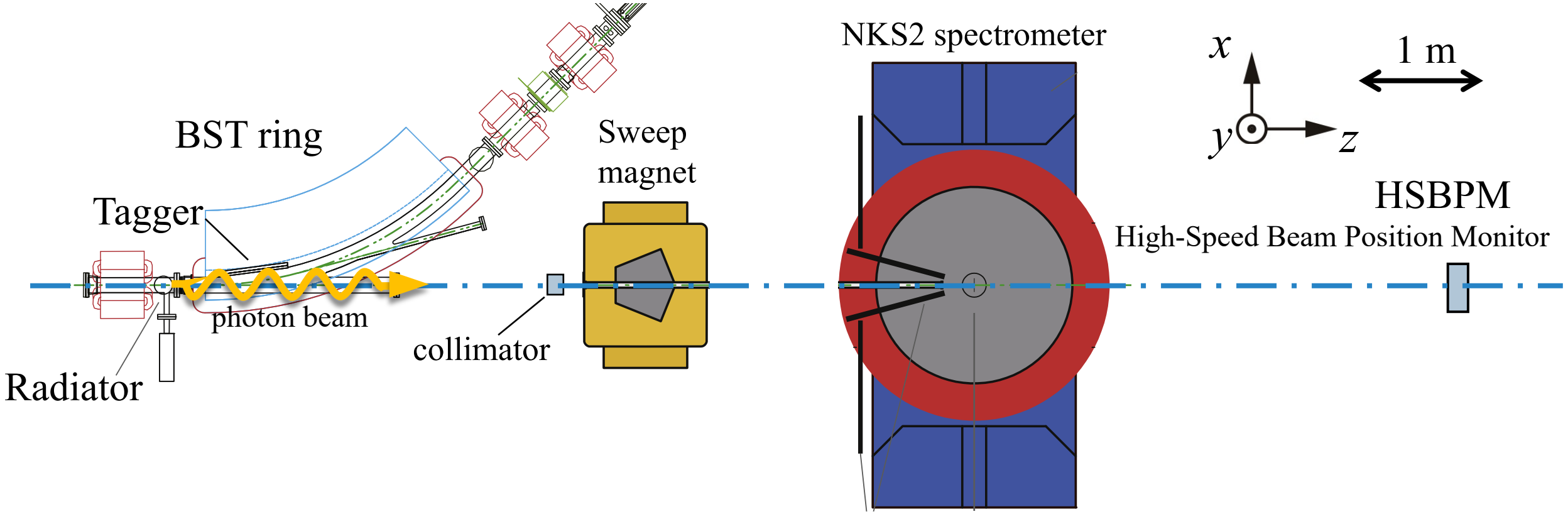

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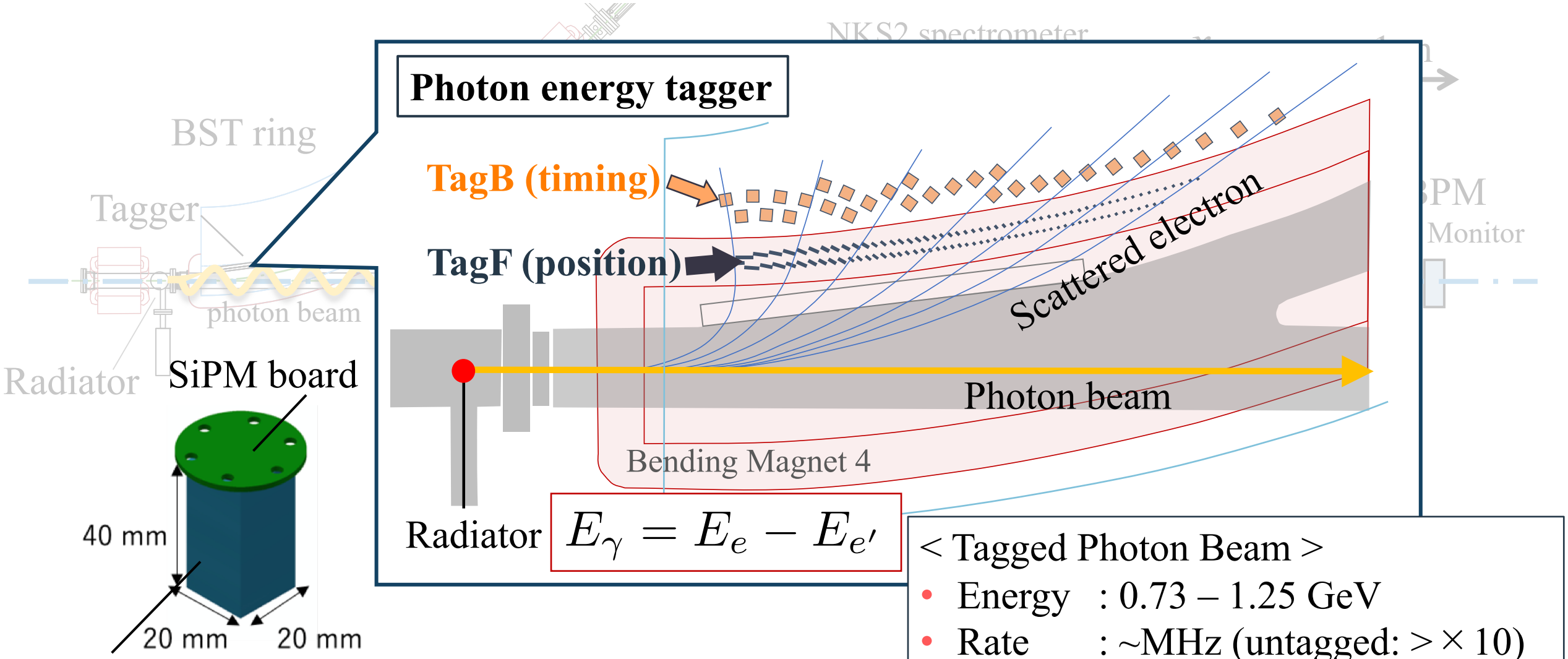
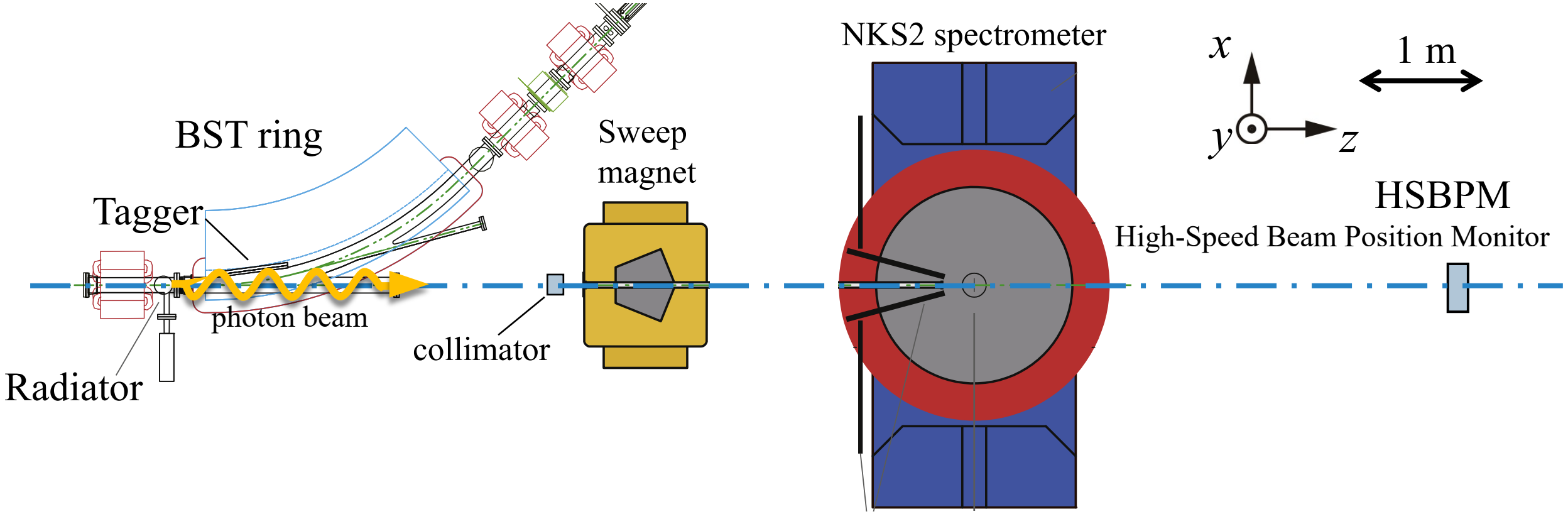


< Tagged Photon Beam >

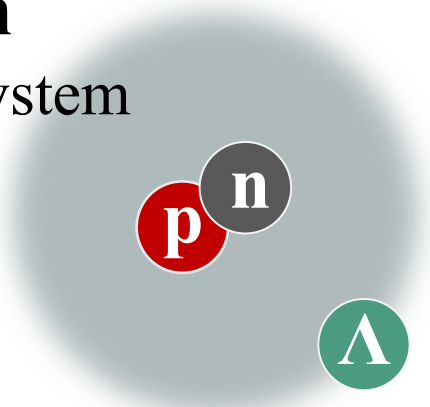
- Energy : 0.73 – 1.25 GeV
- Rate : ~MHz (untagged: > × 10)

Characteristics of ELPH BM4 beamline



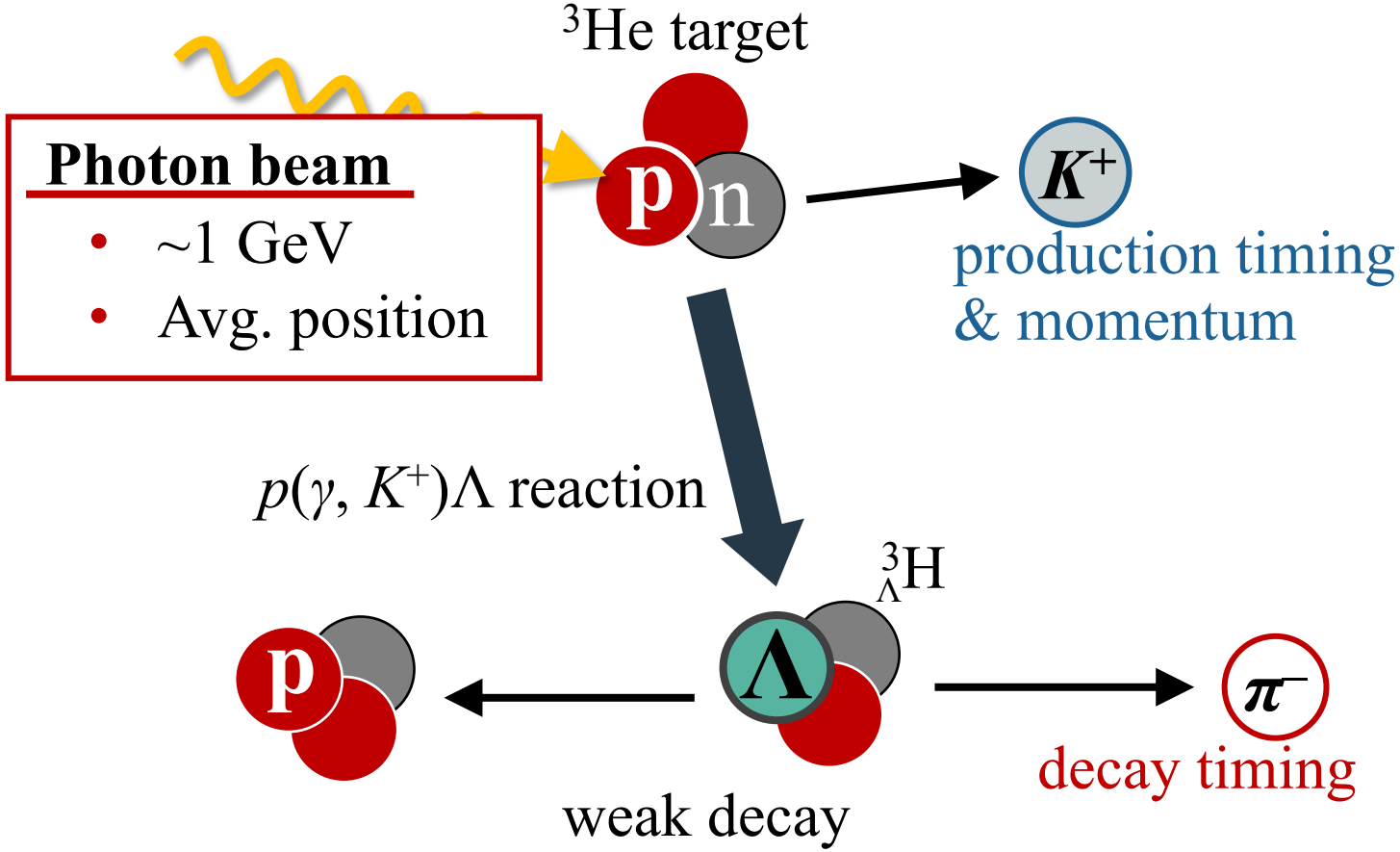
${}^{3}_{\Lambda}$H lifetime measurement at ELPH BM4 beamline

Hypertriton
d-Λ binding system

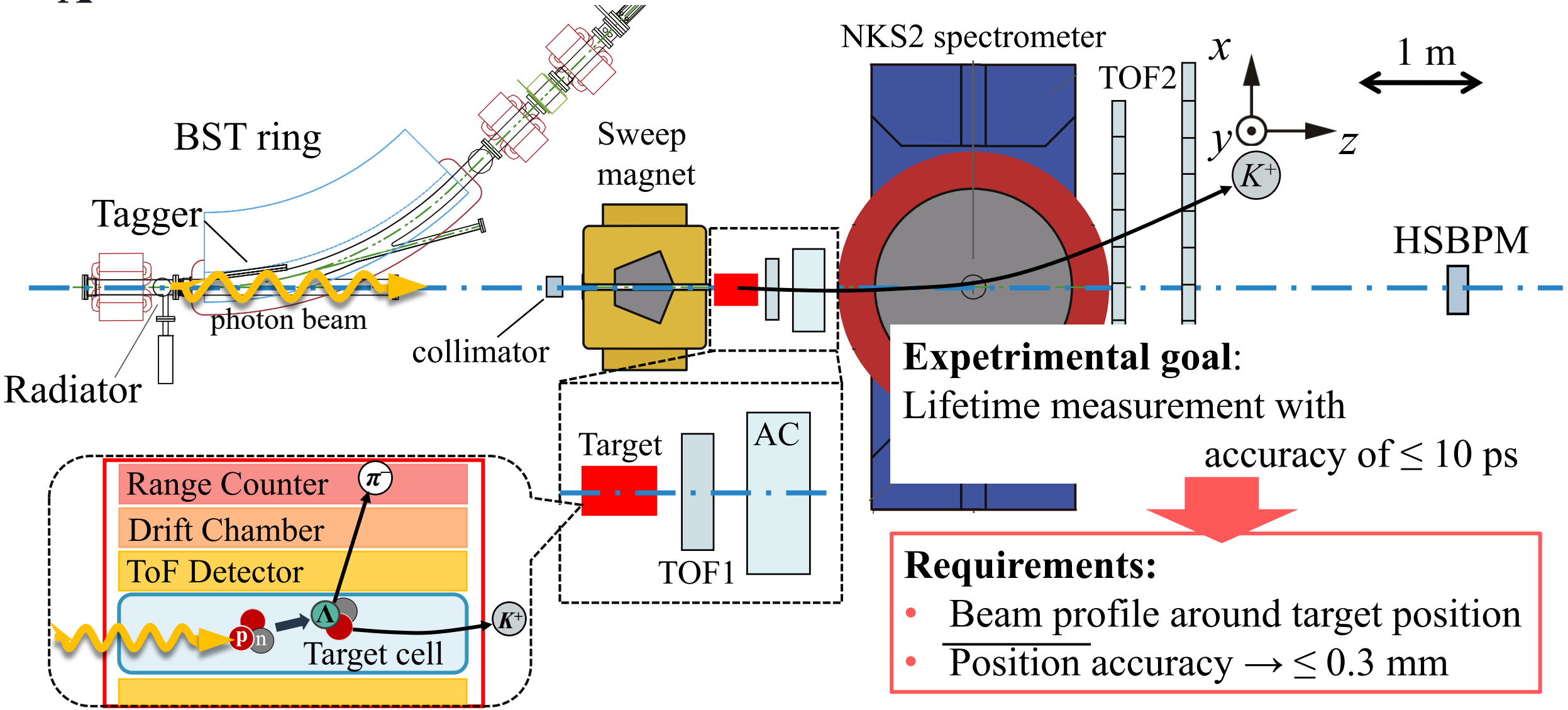


Lifetime: ~ 260 ps (~τ_{Λ})?

- Still large experimental uncertainties
- Precise measurement by the independent method is crucial



${}^{3}_{\Lambda}$H lifetime measurement at BM4 beamline

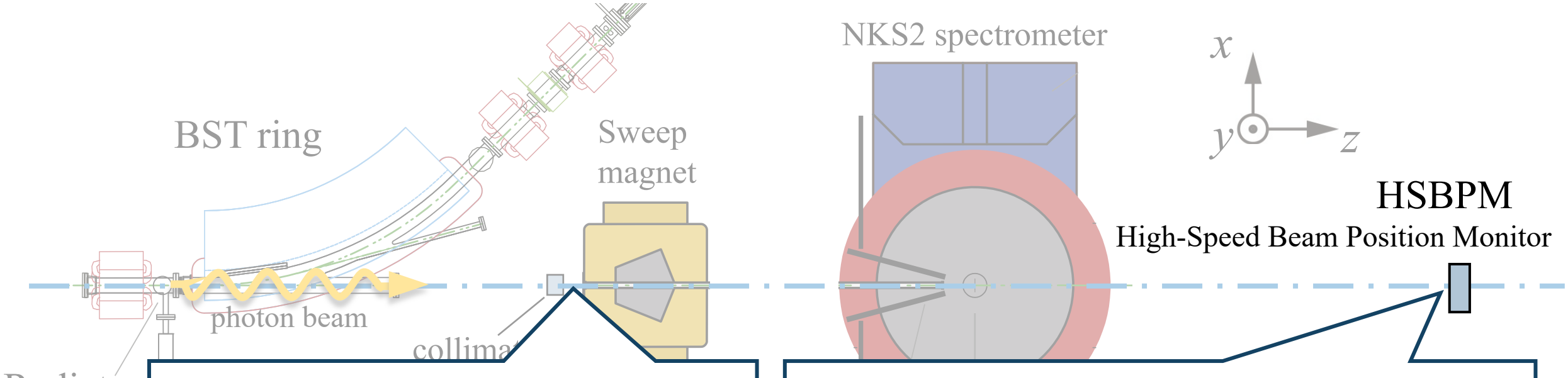


Expetrimental goal:
Lifetime measurement with accuracy of ≤ 10 ps

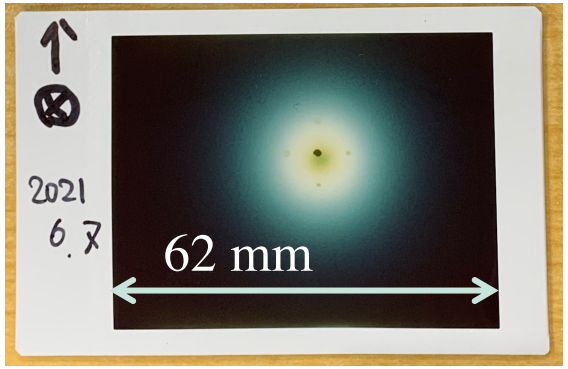
Requirements:

- Beam profile around target position
- Position accuracy → ≤ 0.3 mm

Beam profiling at ELPH BM4 beamline

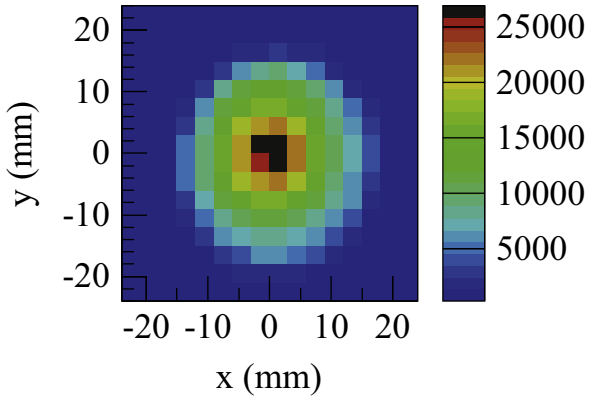


Instant camera & film



non-quantitative & time consuming

Scintillation fiber & Multi-anode PMT



- Used only for downstream of the beamline
- Averaged information of several spills

Motivation

- Beam profile monitoring for up~middle-stream of the beamline
- Quantitative and real time monitoring

- Accelerator parameter measurement at BM4 beamline
- Feedback to accelerator research

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Requirements for the Beam Profile Monitor

- Photon → ◎ detect　　charged particles → × remove
- Less material thickness
- Position resolution: $\sigma \leq 0.3$ mm
- Stable operation in a magnetic field (~ 0.3 T)
- Measurement on high rate (several MHz)
- Data acquisition synchronized with beam cycle

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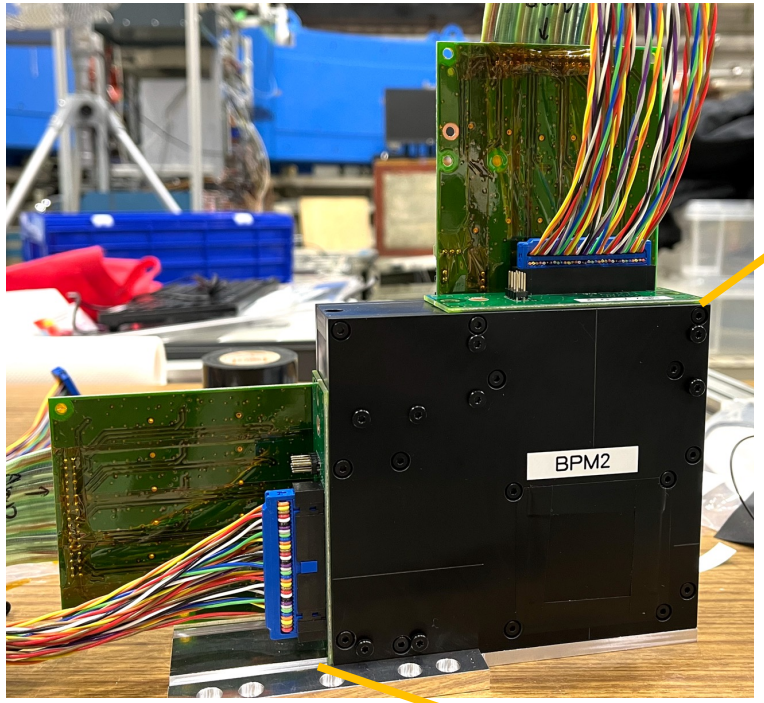
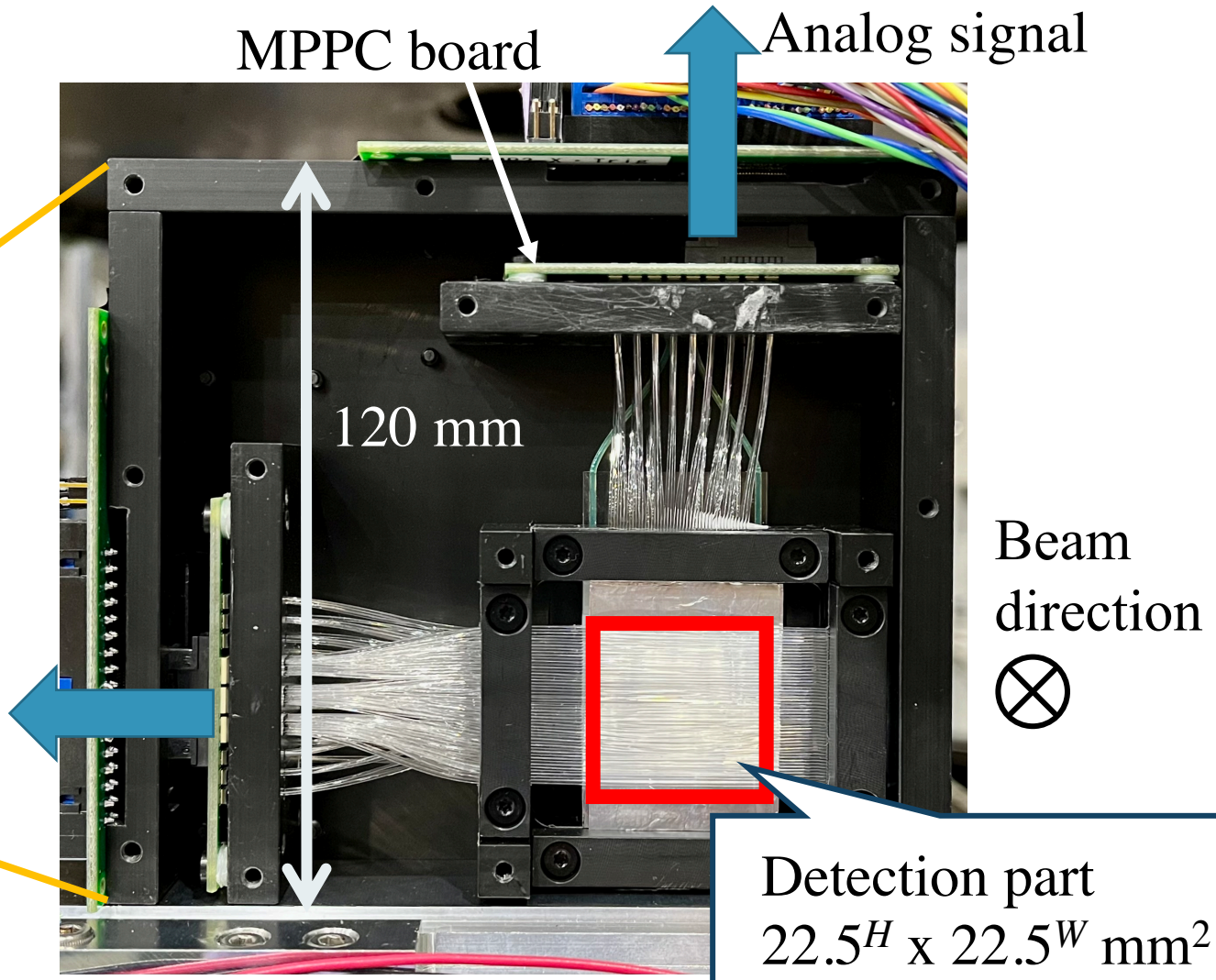
Basic design of the Beam Profile Monitor

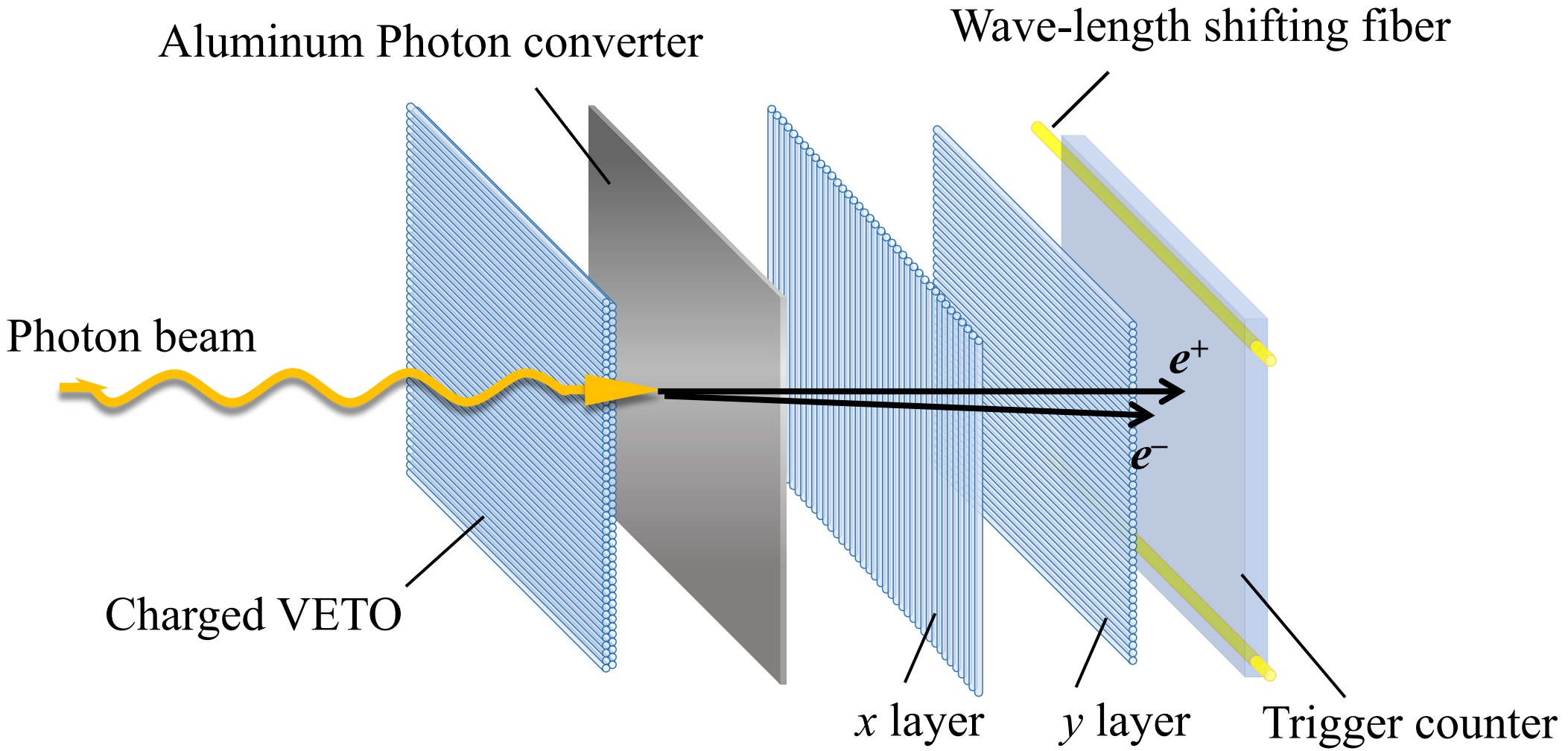




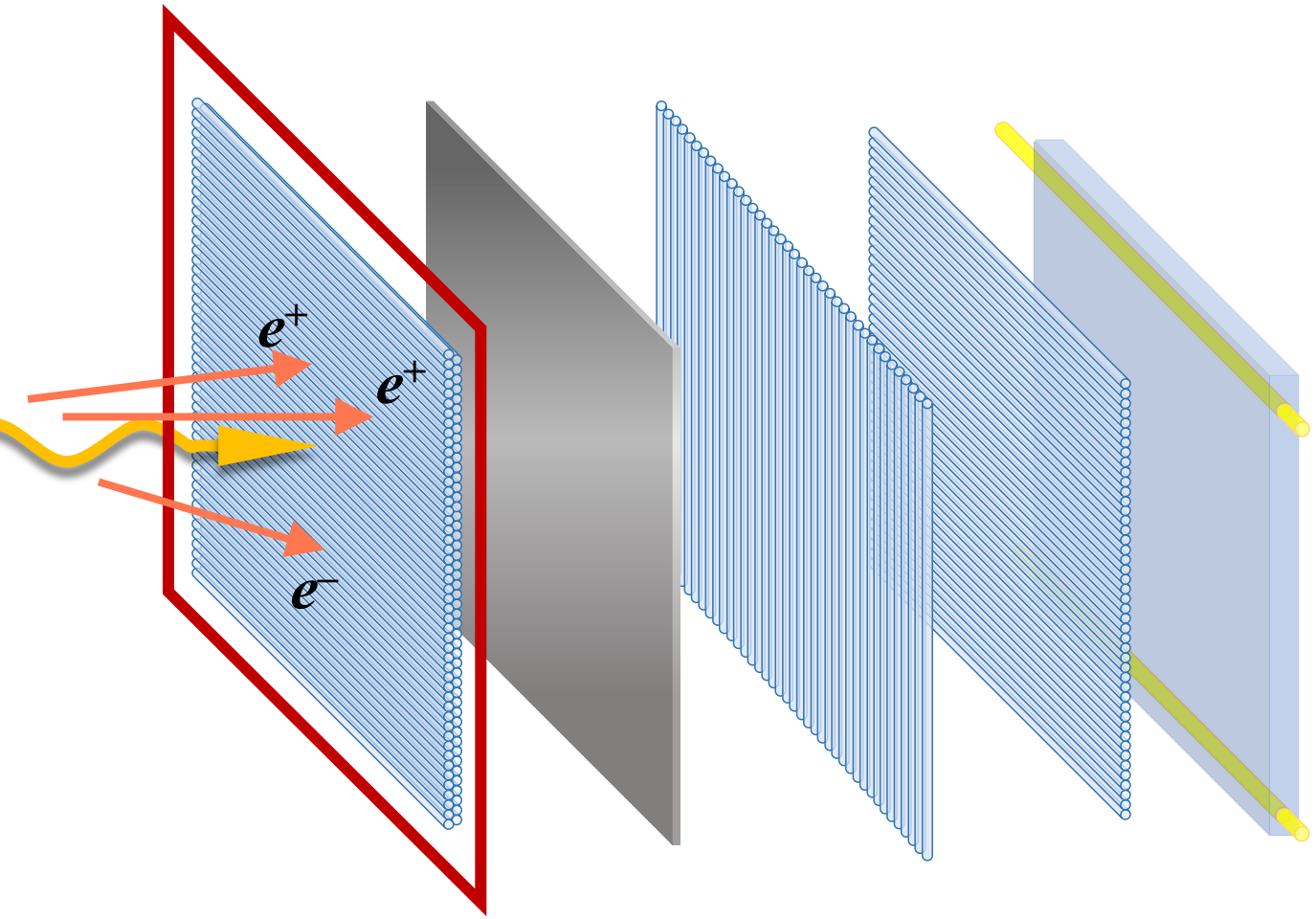
Basic Structure:

Scintillation Fibers + SiPM

Basic design of the Beam Profile Monitor

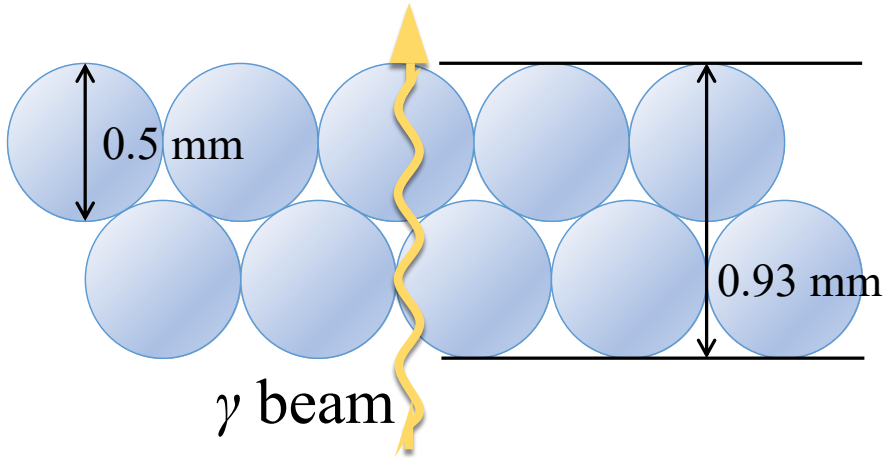


Basic design of the Beam Profile Monitor



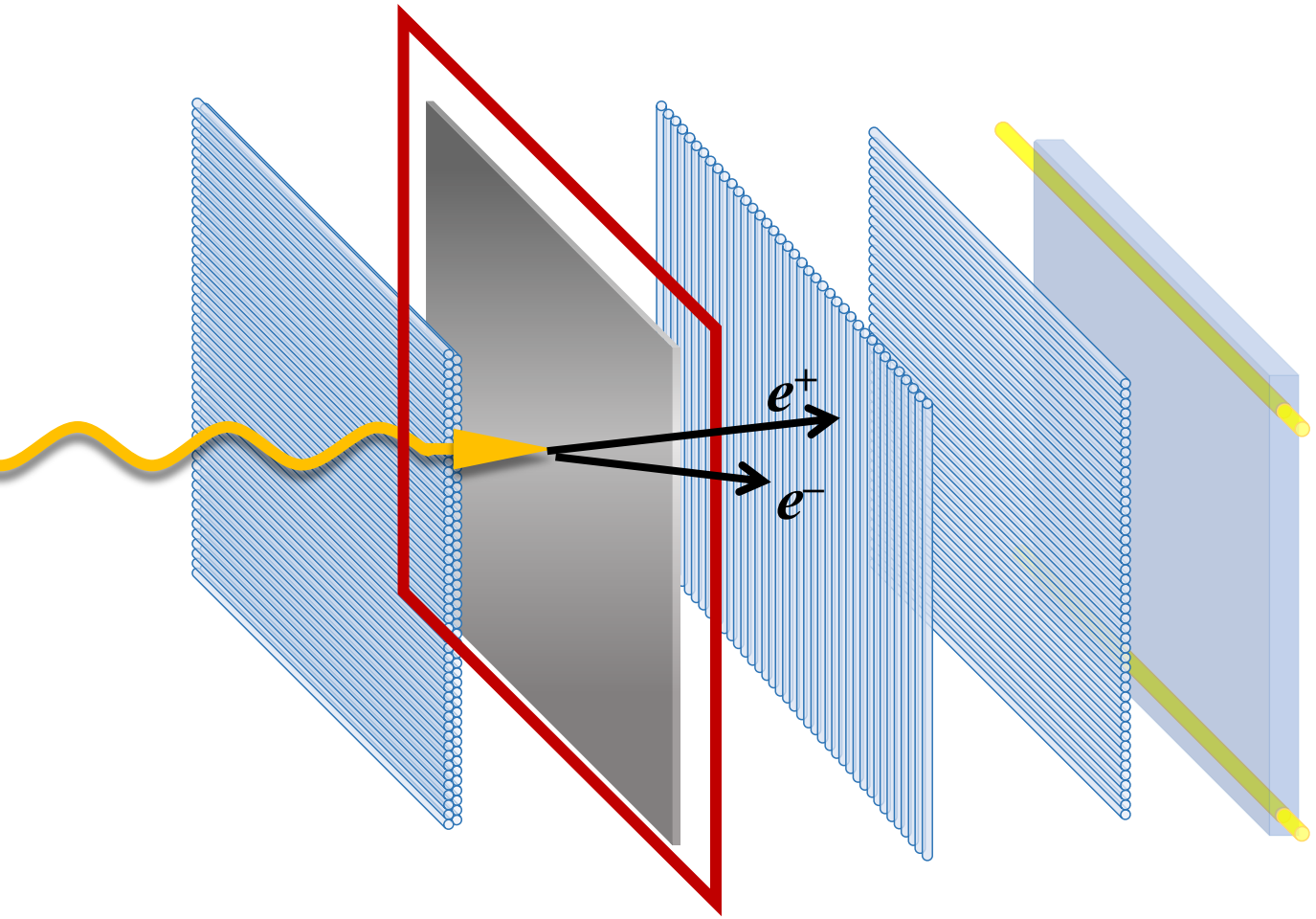
Charged VETO counter

- Detect BG events (charged particles)
- reduce thickness & high efficiency



99 Scintillation fibers
(kuraray SCSF-78, ϕ 0.5 mm)

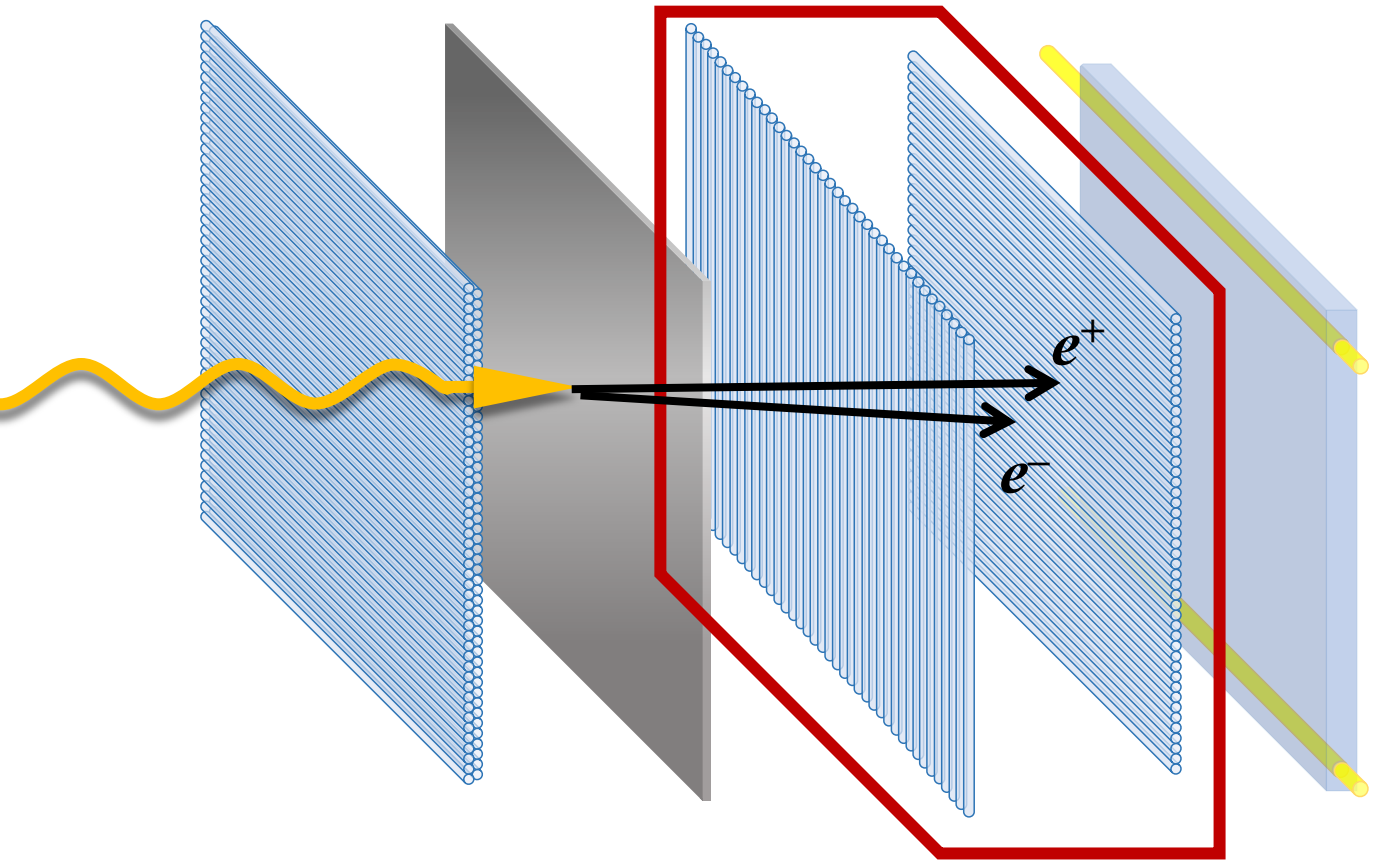
Basic design of the Beam Profile Monitor



Photon converter

- Production e^+/e^- pair
- Aluminum
- Thickness: 0.4 mm
- Convertion probability: ~ 0.3%

Basic design of the Beam Profile Monitor

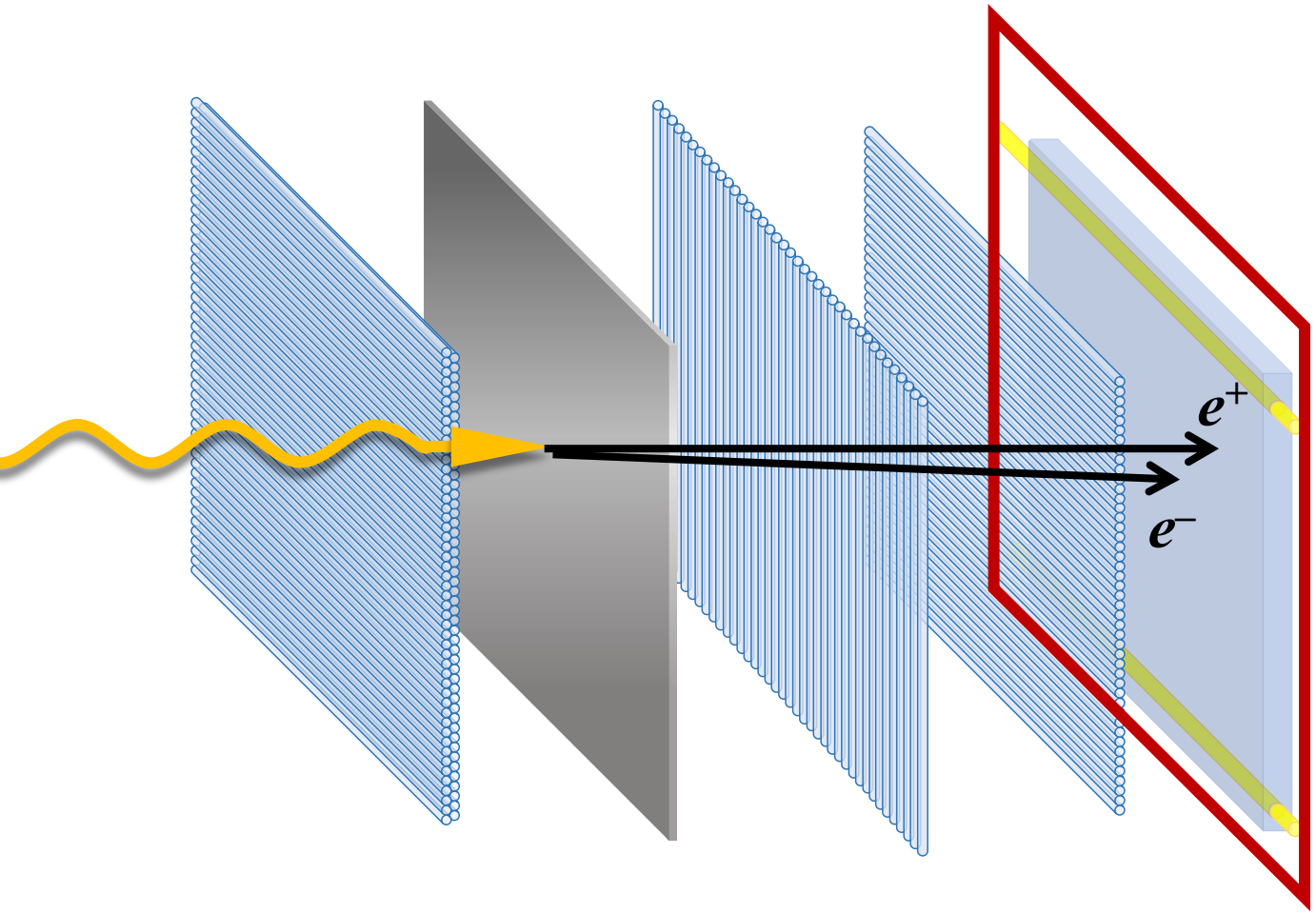


x layer & *y* layer

- Detect particle position
- Scintillation fibers (ϕ 0.5 mm)
  (Kuraray SCSF-78)
- 3 fibers / 1 ch = 1.5 mm / seg.
- 15 seg. / 22.5 mm

⟶ **achieve resolution 0.1 mm**
/ 1,000 events (simulation)

Basic design of the Beam Profile Monitor



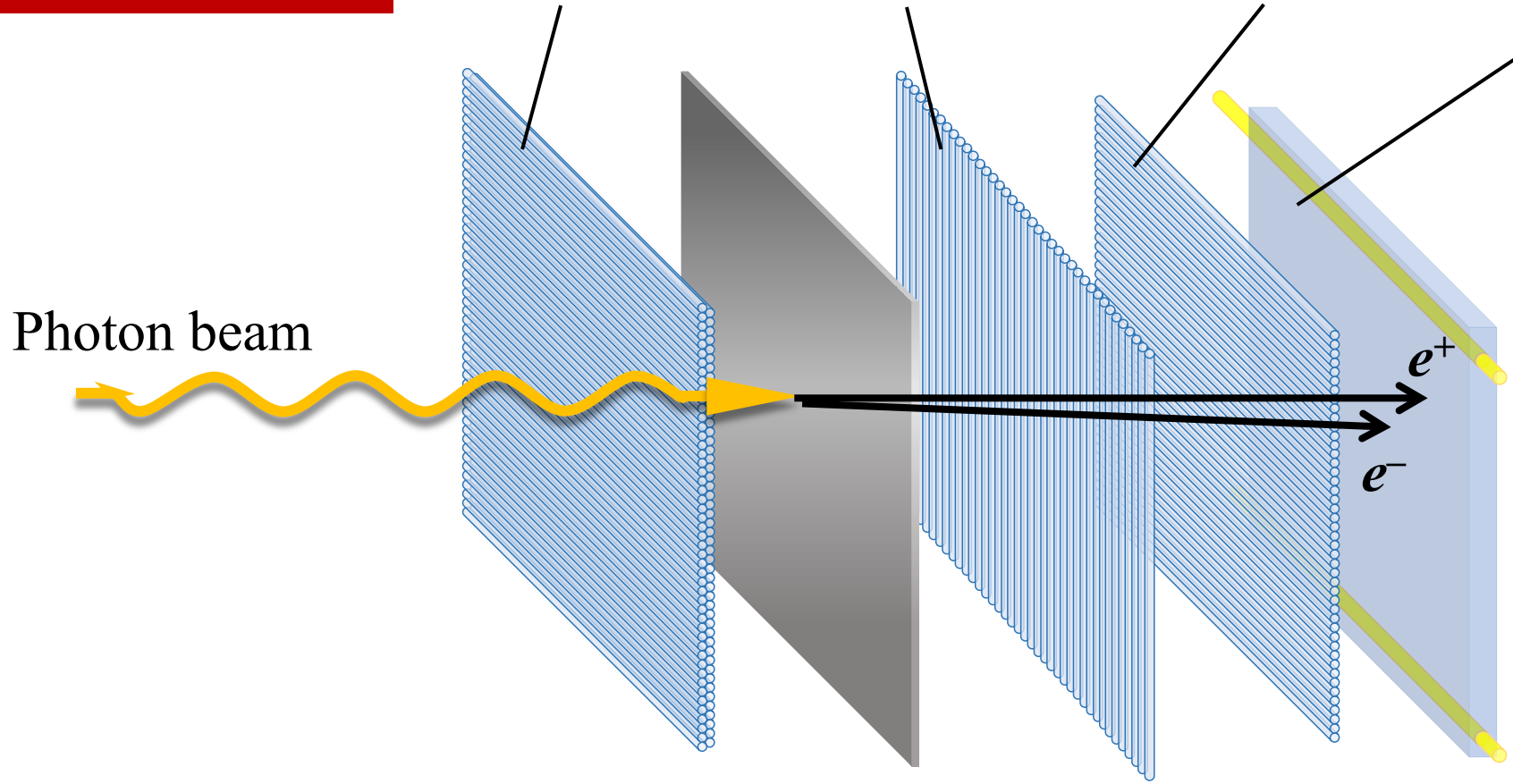
Trigger counter

- Event identification
- Time window
- Plastic scintillator
  (Eljen EJ-212, 2 mm)
- Wave-length shifting fiber
  (kuraray Y-11, ϕ 1 mm)

Basic design of the Beam Profile Monitor

Photon Event ID

$[\ \overline{\mathrm{VETO}}\ ] \otimes [\ x\ \text{layer}\ ] \otimes [\ y\ \text{layer}\ ] \otimes [\ \text{trig.}\ ]$



Only photon events can be extracted!

Requirements for the Beam Profile Monitor

- ✓ Photon → ◎ detect　　charged particles → × remove
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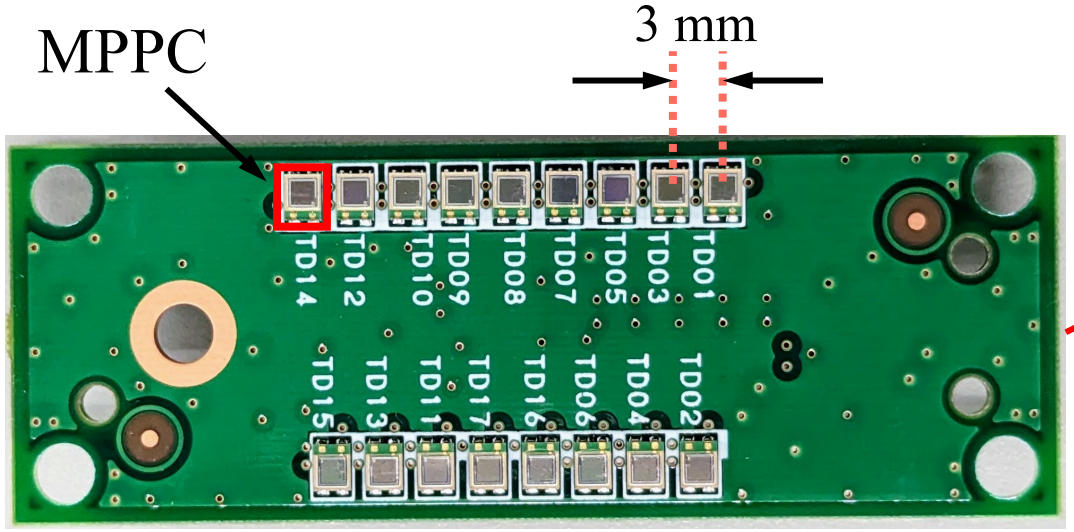
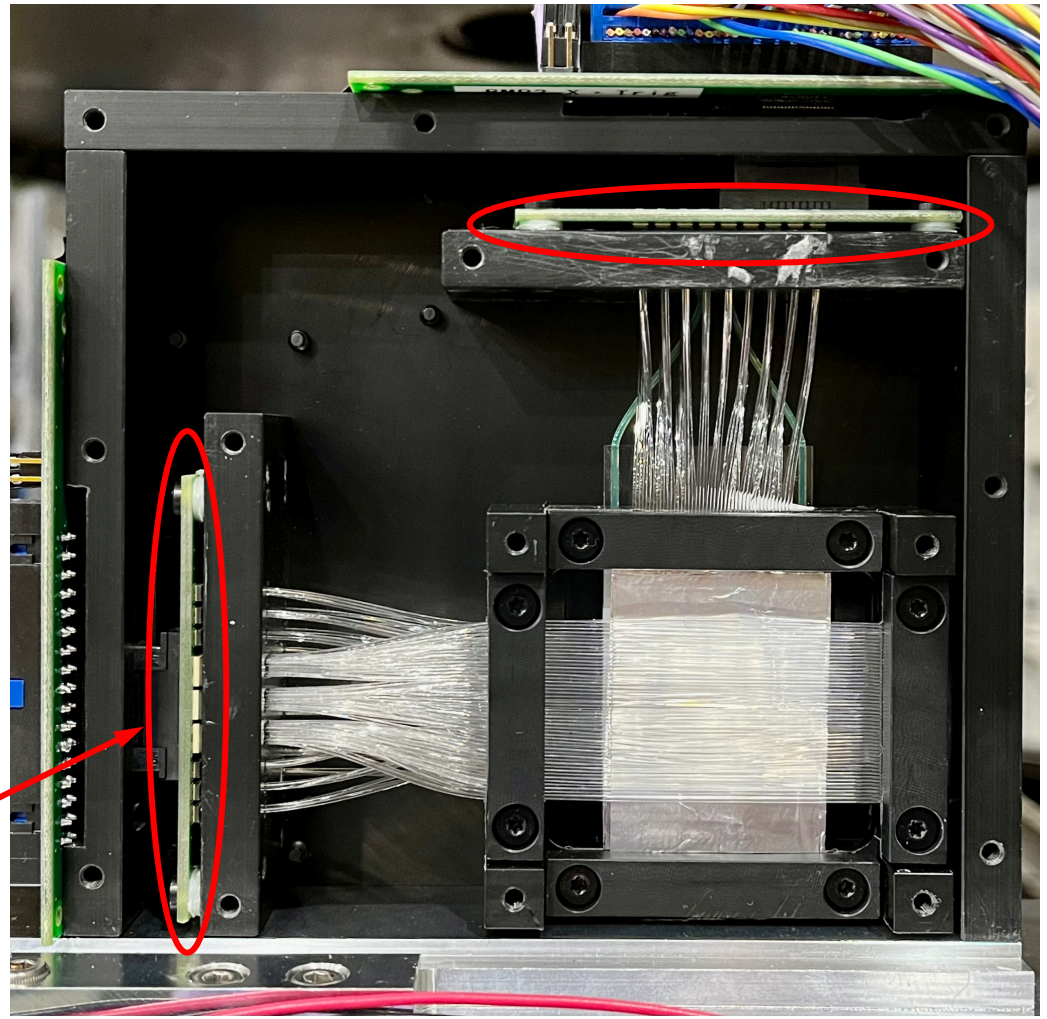
SiPM and the readout circuit

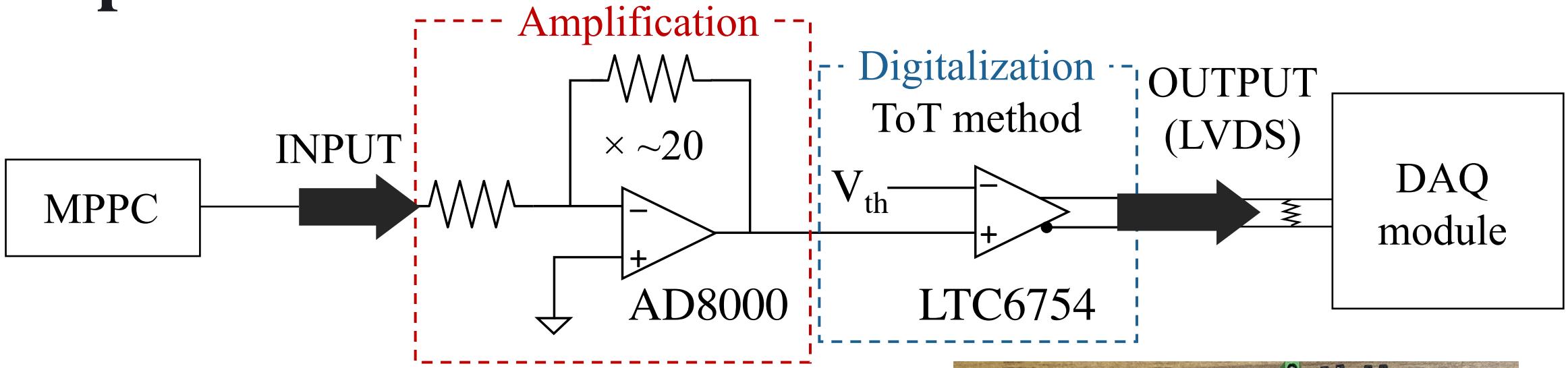
Multi-Pixel Photon Counter
S13360-1350PE / S13360-3050PE
(Hamamatsu Photonics K.K.)

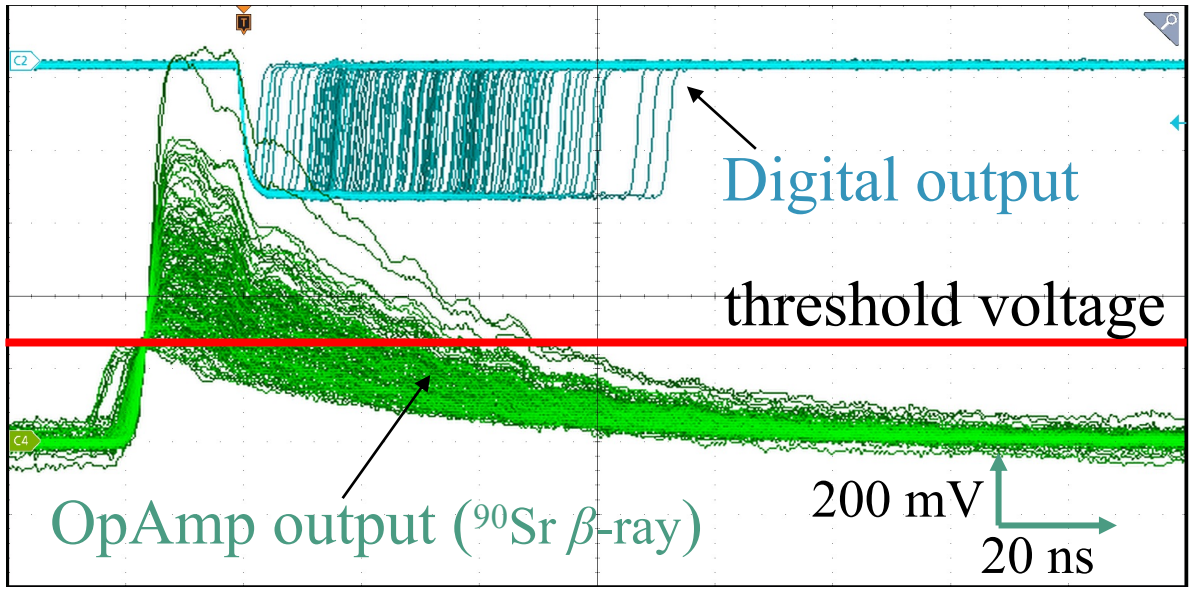
- Detect scintillation light
- Stable operation in magnetic field

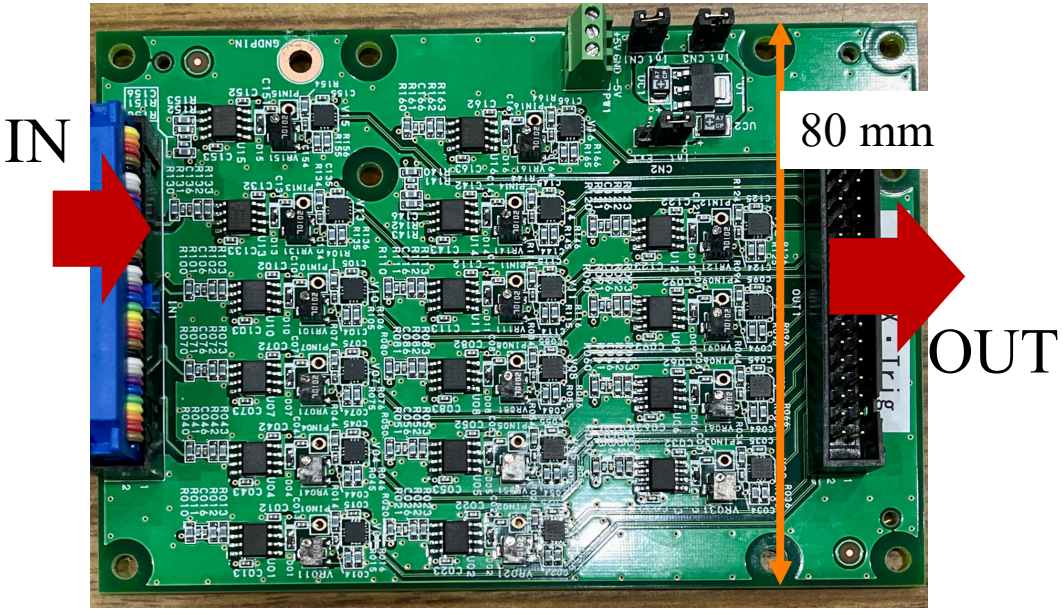




Amp. & ToT circuit







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- ❑ **Measurement on high rate (several MHz)**
- ❑ **Data acquisition synchronized with beam cycle**

Data acquisition system

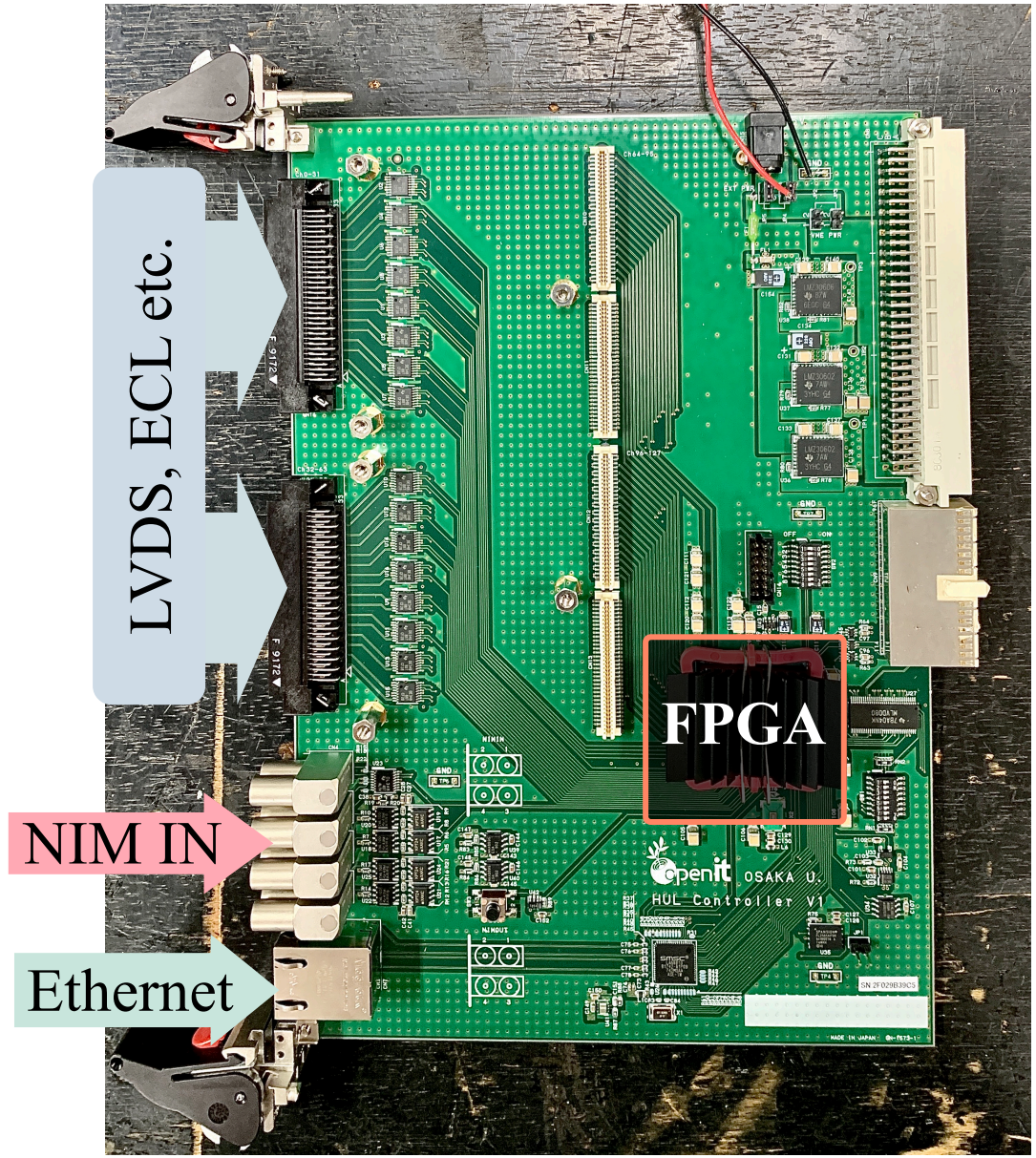
Expected event rate: ~ MHz / detector

→ Not possible with traditional trigger type TDC

Hadron **U**niversal **L**ogic firmware: Streaming TDC [1]

- ✓ 0.97 ns / channel
- ✓ measure elapsed time up to 33 s
- ✓ Trigger less data taking
- ✓ Offline event selection

[1] R. Honda *et al.*, Prog. Theor. Exp. Phys., Issue 12 (2021) 123H01.



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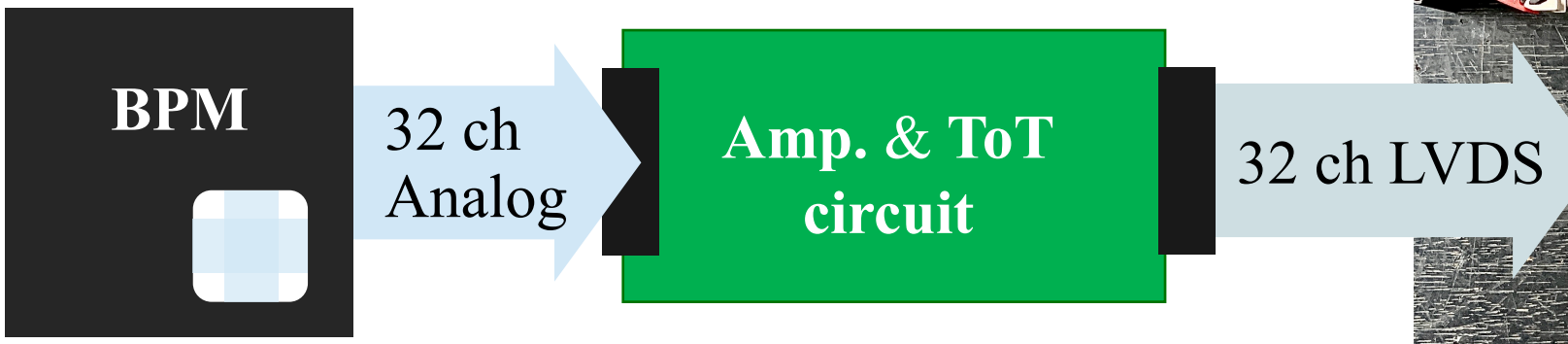
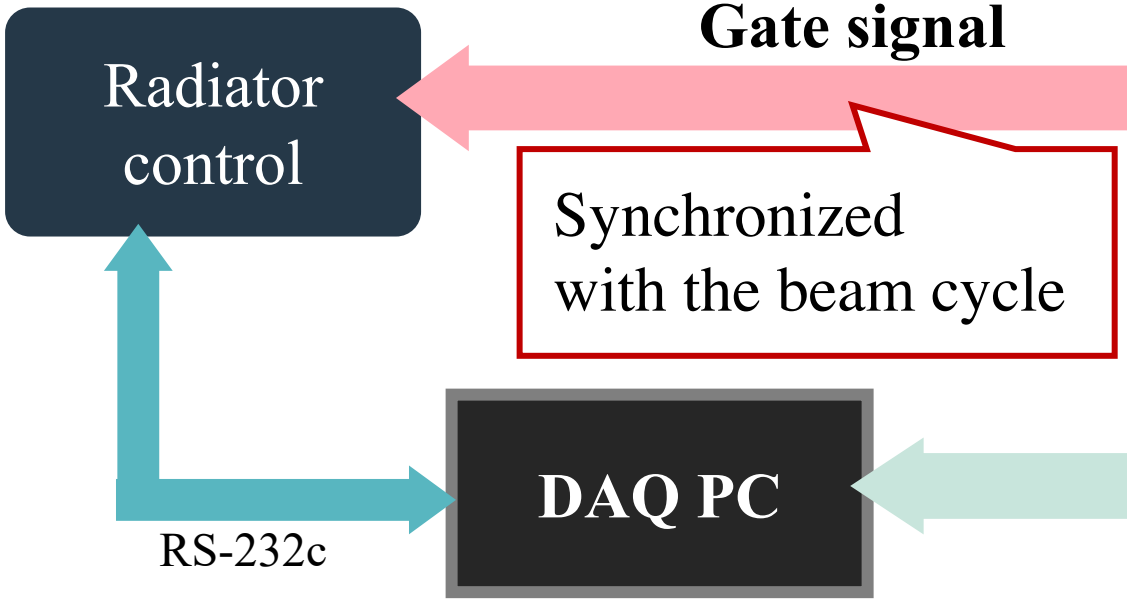
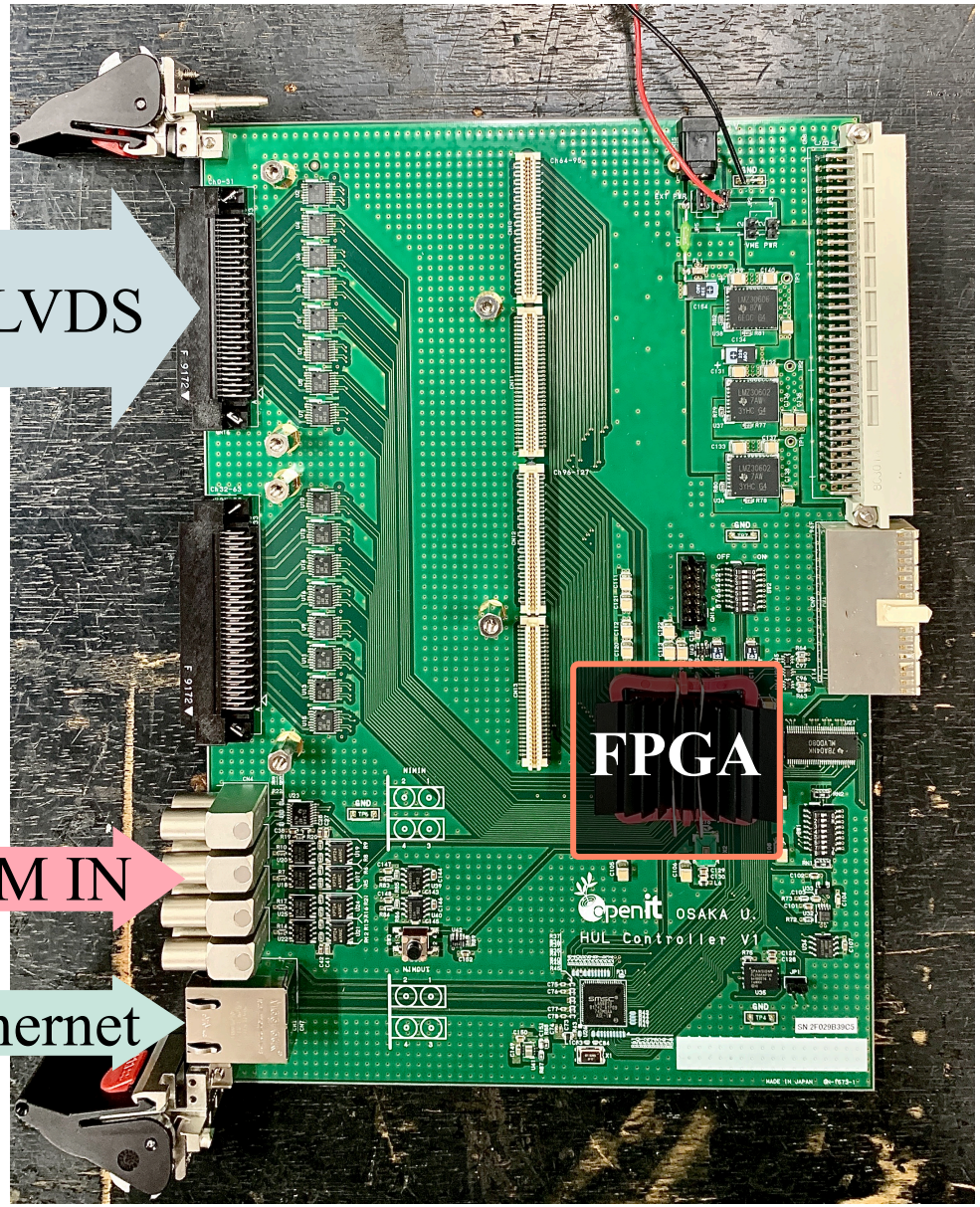
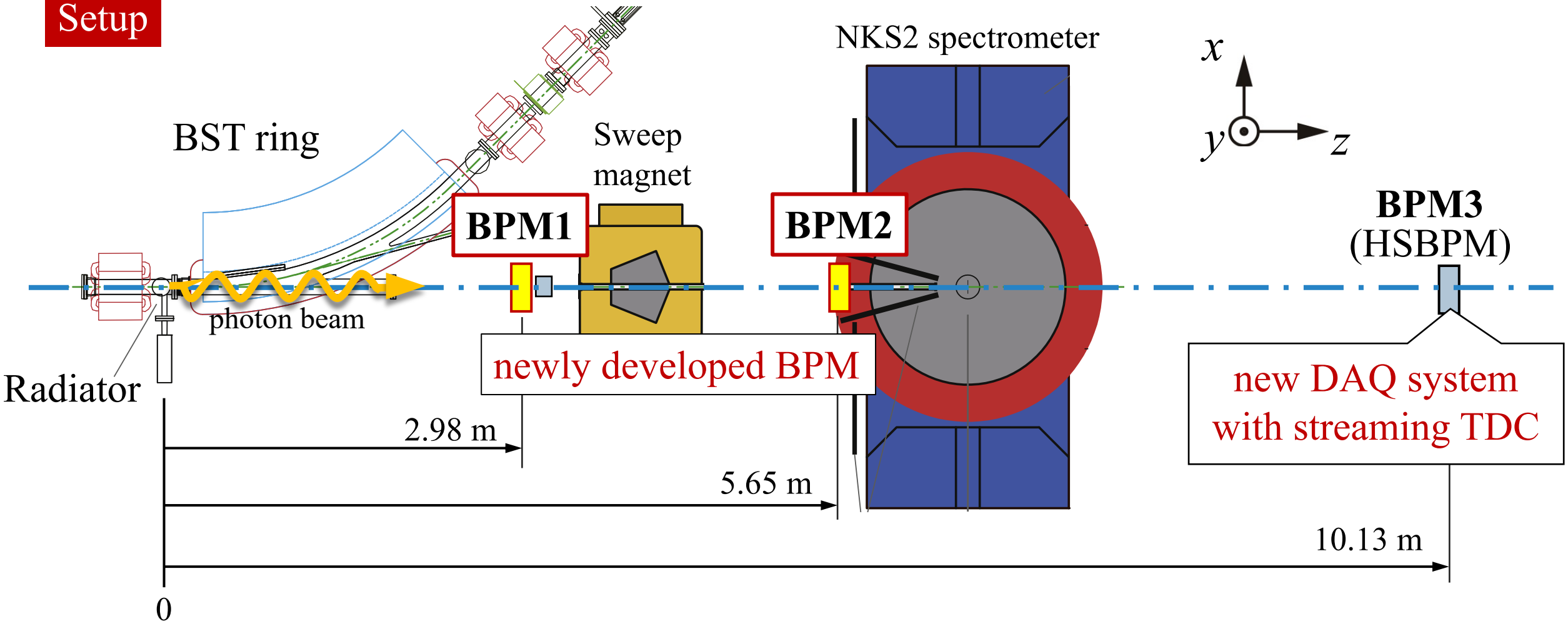






Photon beam monitoring at ELPH BM4 beamline

Setup



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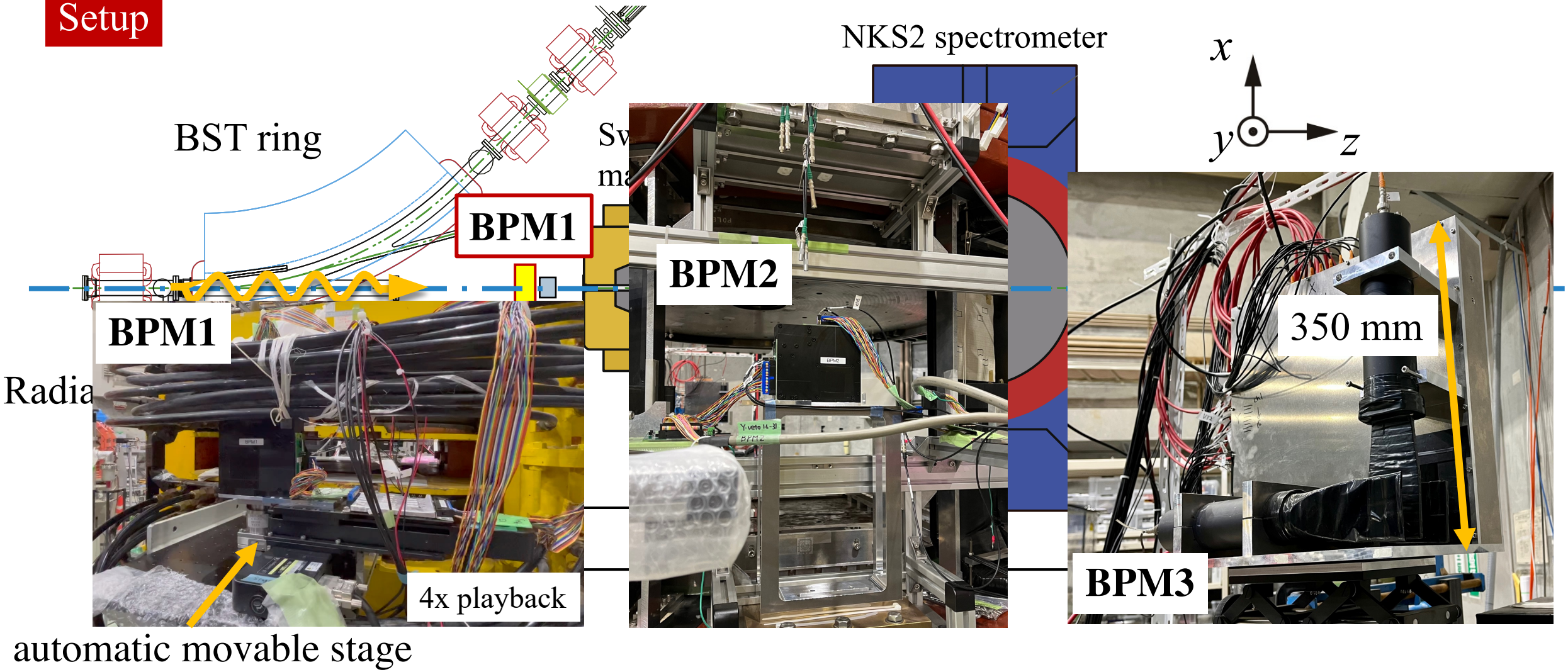

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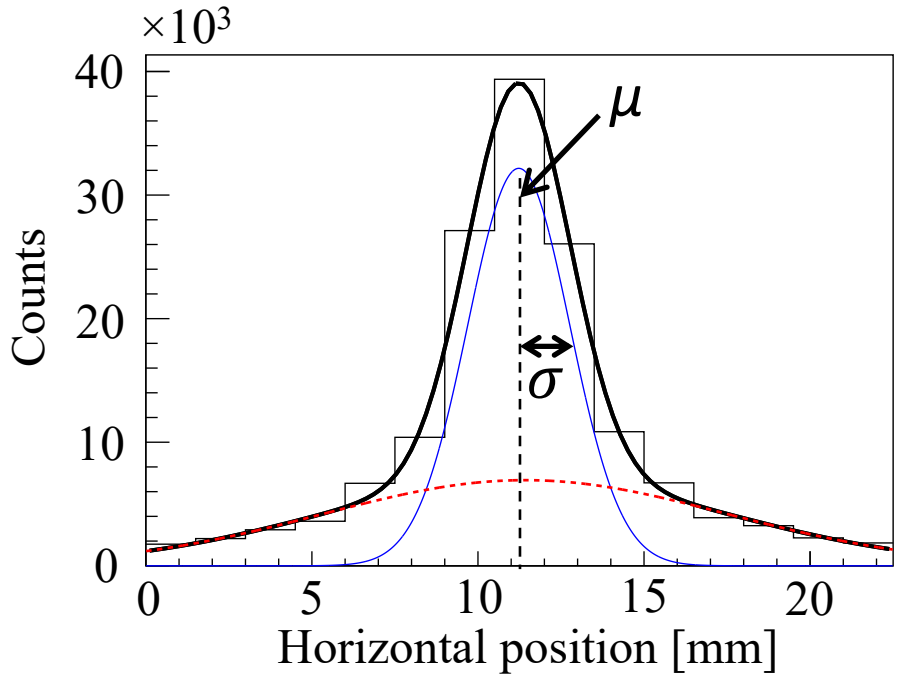
Quantitative beam profiling

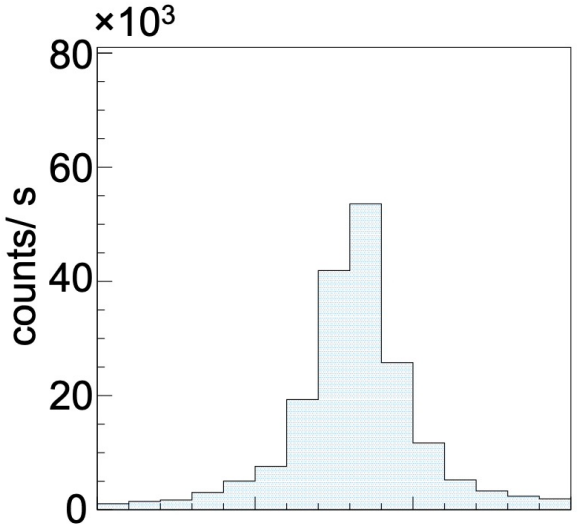
Fitting function: Gaussian + Gaussian

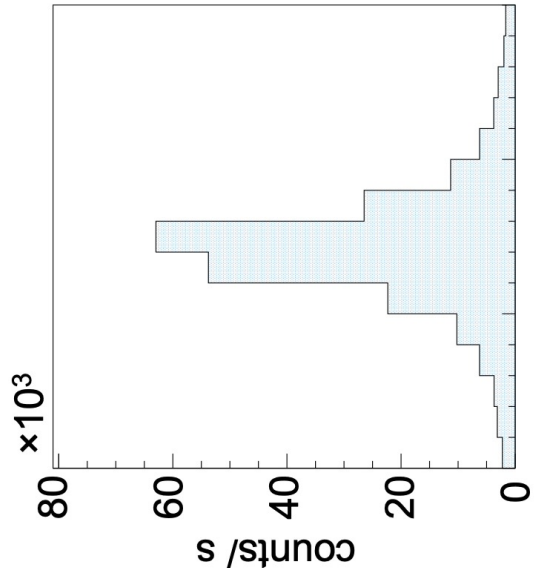
- Beam center position (μ)
- Beam size (σ)

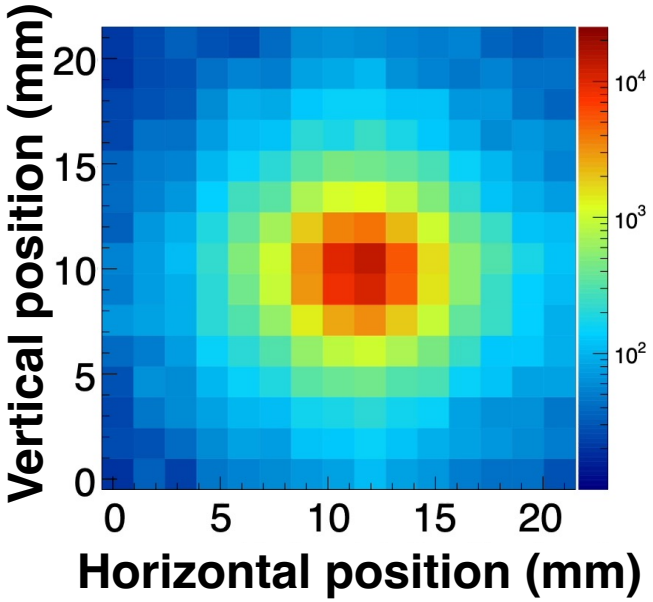


Position precision: $\Delta\mu$, $\Delta\sigma$ < 10 μm

Hit distribution /1.0 sec





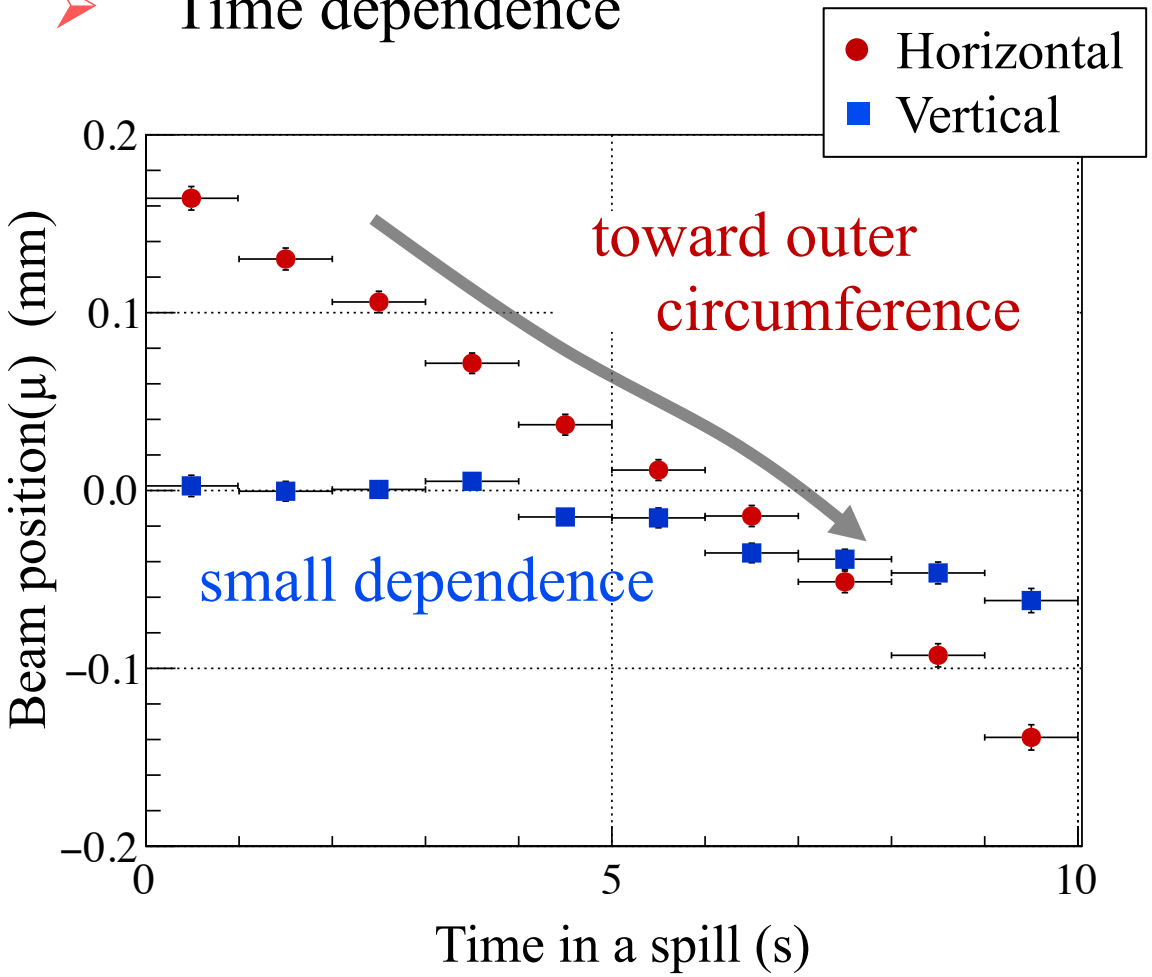


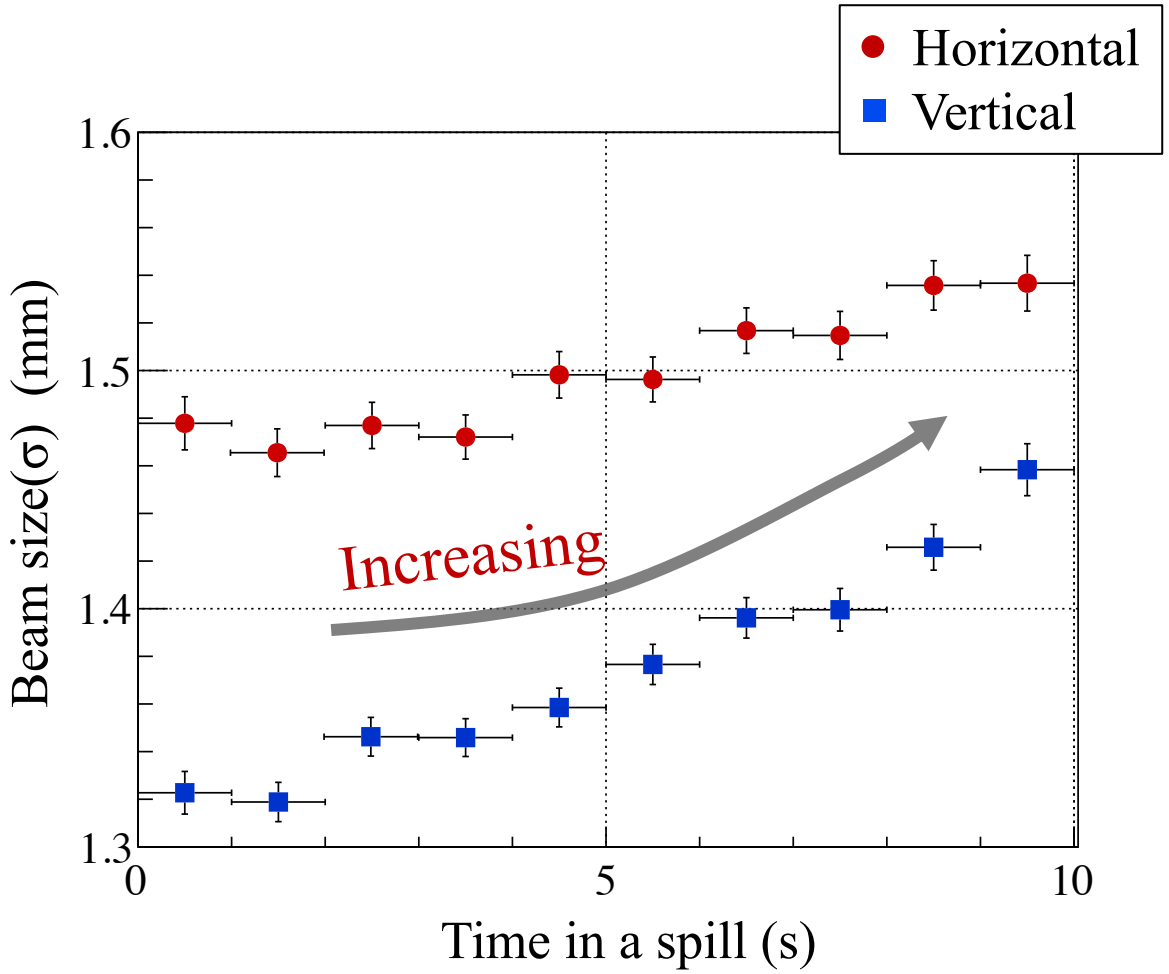
Measurement Results

	Beam Position(μ)	Beam size(σ)
Beam energy dependence	No dependencies	No dependencies
Beam intensity dependence	No dependencies	Increasing with the beam intensity
Time dependence		
Radiator position dependence		

Measured photon beam profile

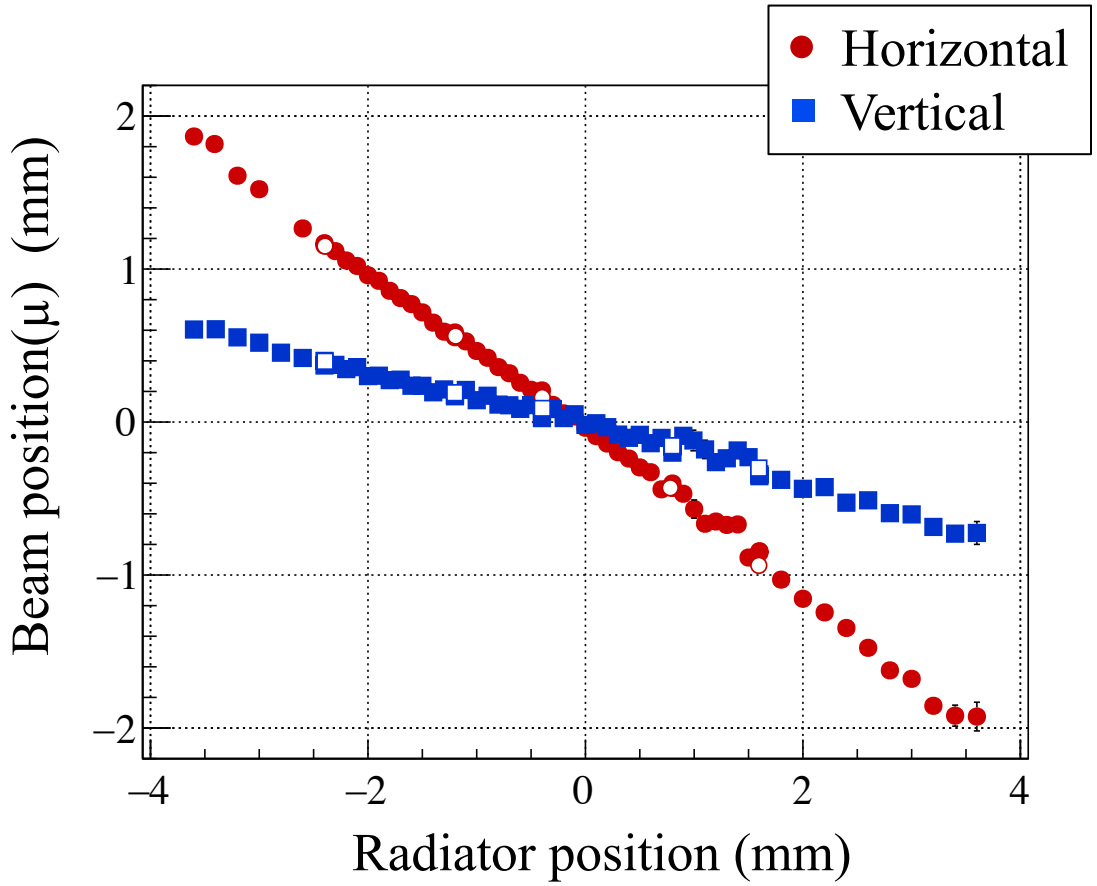
- Time dependence

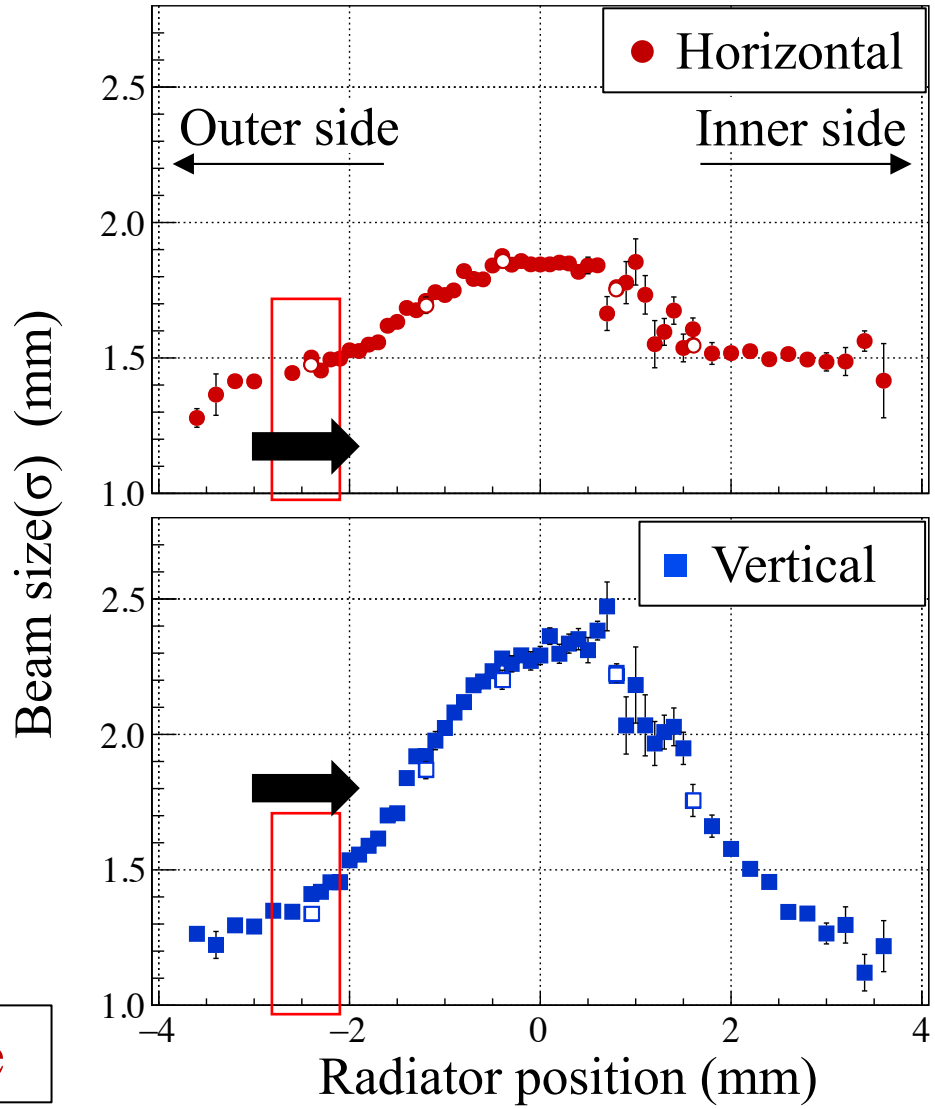




Measured photon beam profile

- Radiator position dependence





consistent with the result of time dependence

Measurement Results

- ✓ Profiling accuracy: ≤ 10 μm for only 1 second profile
- ✓ Real-time monitoring
- ✓ The first measuring of ELPH BM4 photon beam

	Beam Position(μ)	Beam size(σ)
Beam energy dependence	No	No
Beam intensity dependence	No	No
Time dependence	Yes	Yes
Radiator position dependence	Yes	Yes

Radiator position is a significant factor in determining beam profile

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  - Beam direction and the Twiss parameter
  - Estimation of the electron beam profile
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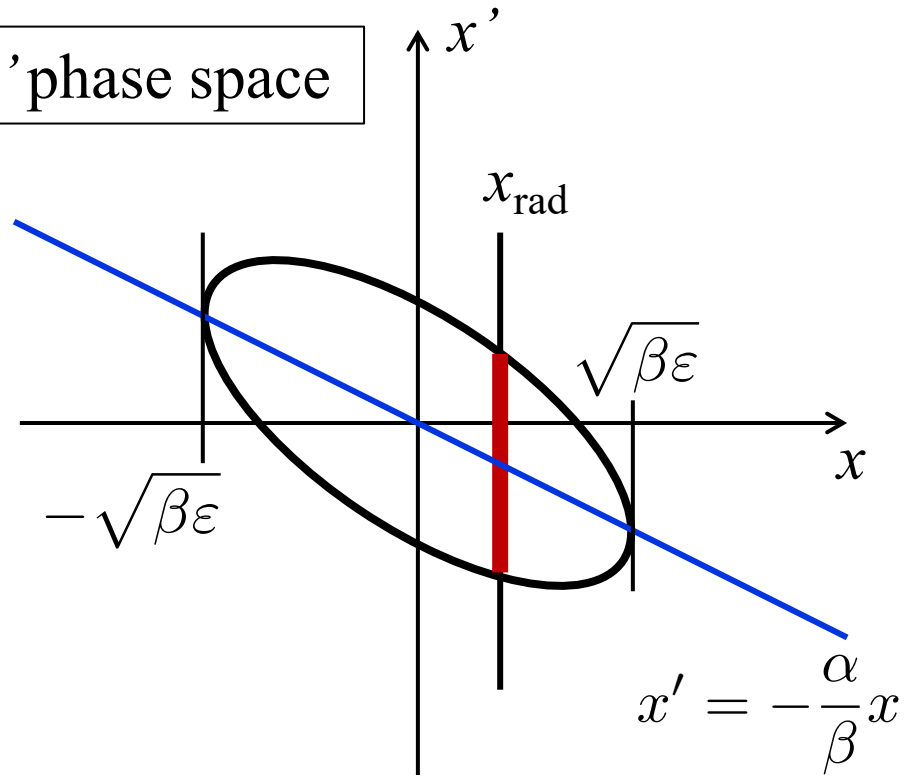
Beam direction and Twiss parameter

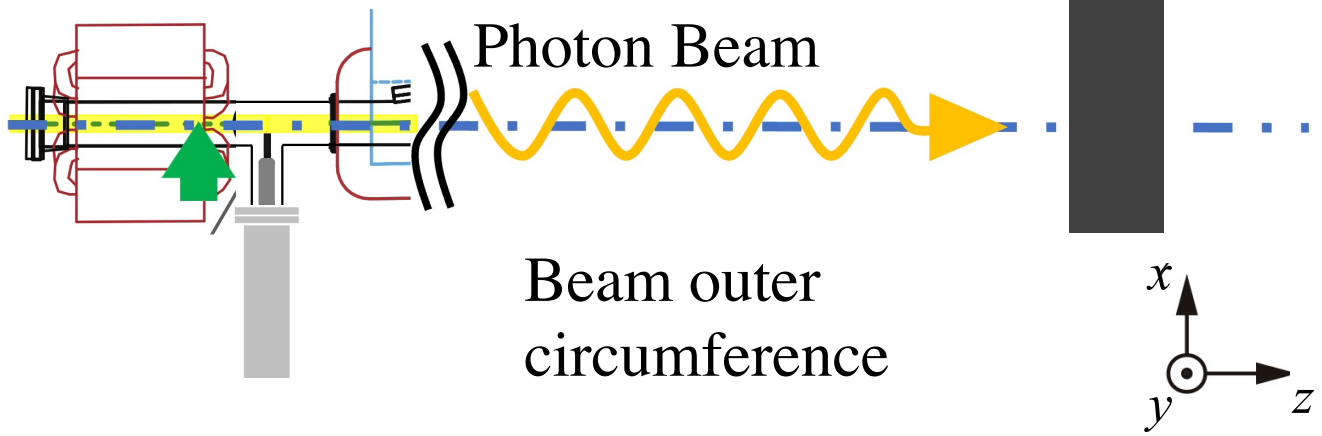
x-x' phase space



emittance

$$\gamma x^2 + 2\alpha x x' + \beta x'^2 = \varepsilon$$

Radiator movement direction



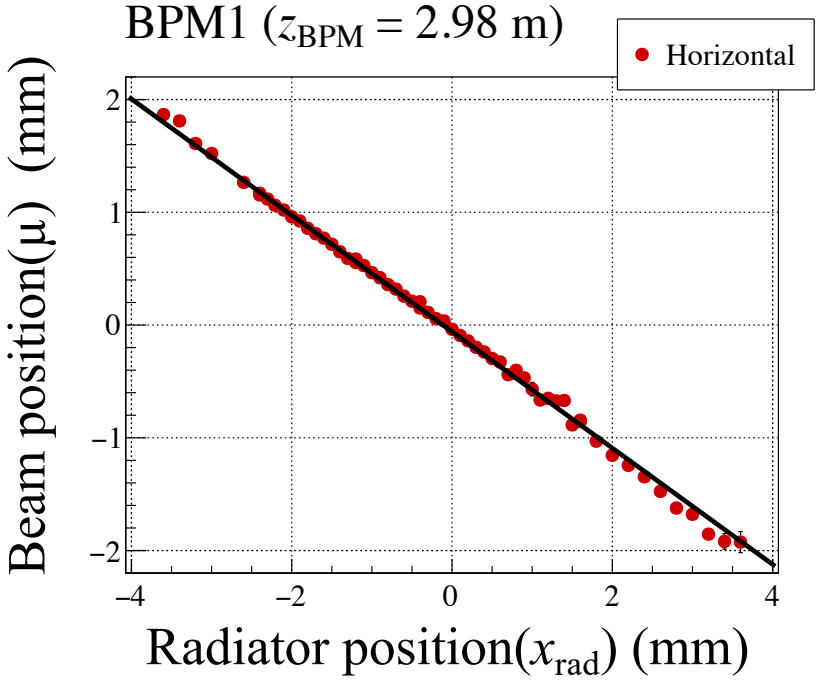
Photon beam direction can be predicted from the Twiss parameter of the electron beam.

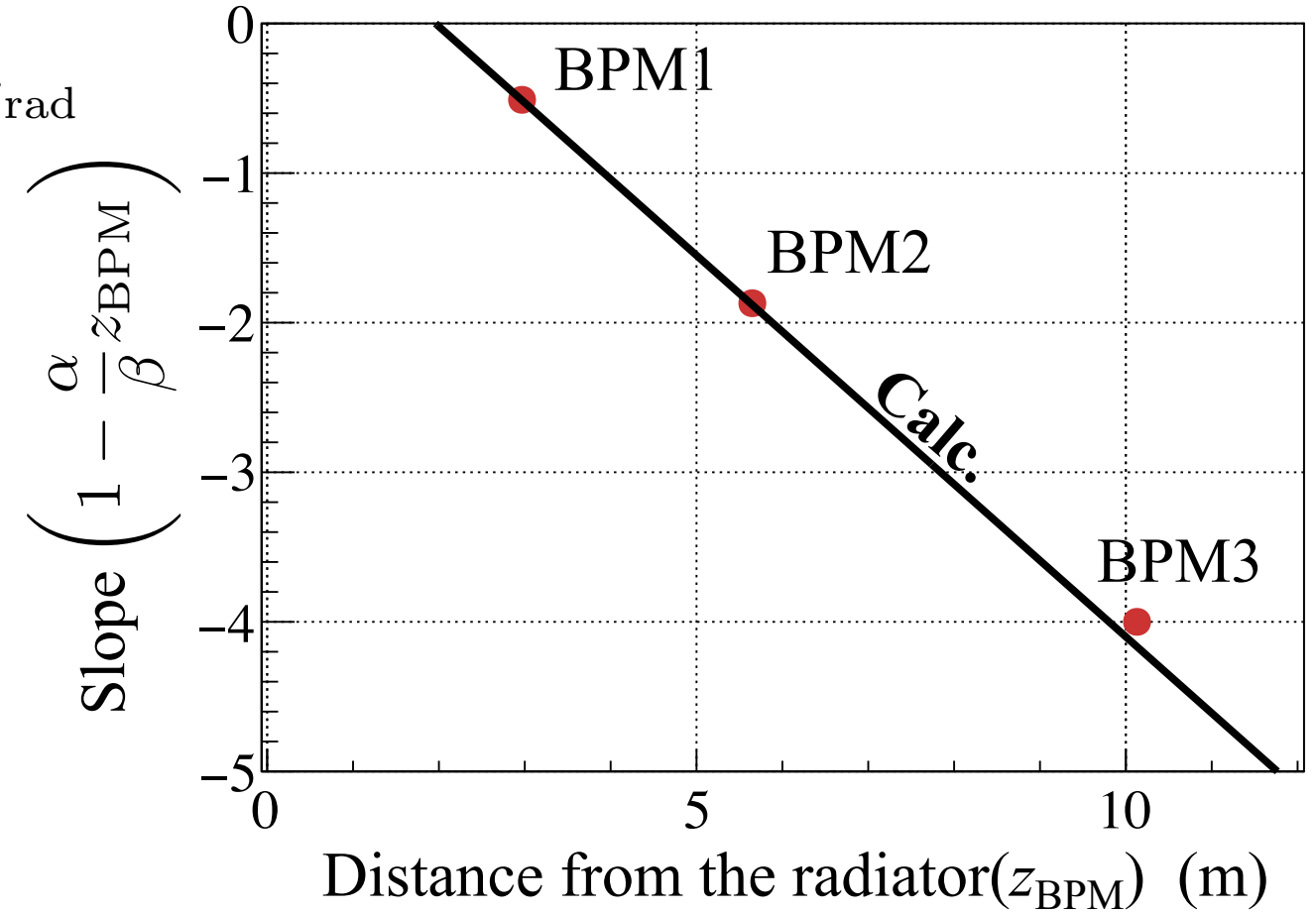
$$\mu = x_{\mathrm{rad}} - \frac{\alpha}{\beta} z_{\mathrm{BPM}} x_{\mathrm{rad}} = \left(1 - \frac{\alpha}{\beta} z_{\mathrm{BPM}}\right) x_{\mathrm{rad}}$$

Evaluation the measured profile (Horizontal)

Fitting function: $\mu = \left(1 - \frac{\alpha}{\beta} z_{\mathrm{BPM}}\right) x_{\mathrm{rad}}$

Fit param.





Twiss parameter@BM4

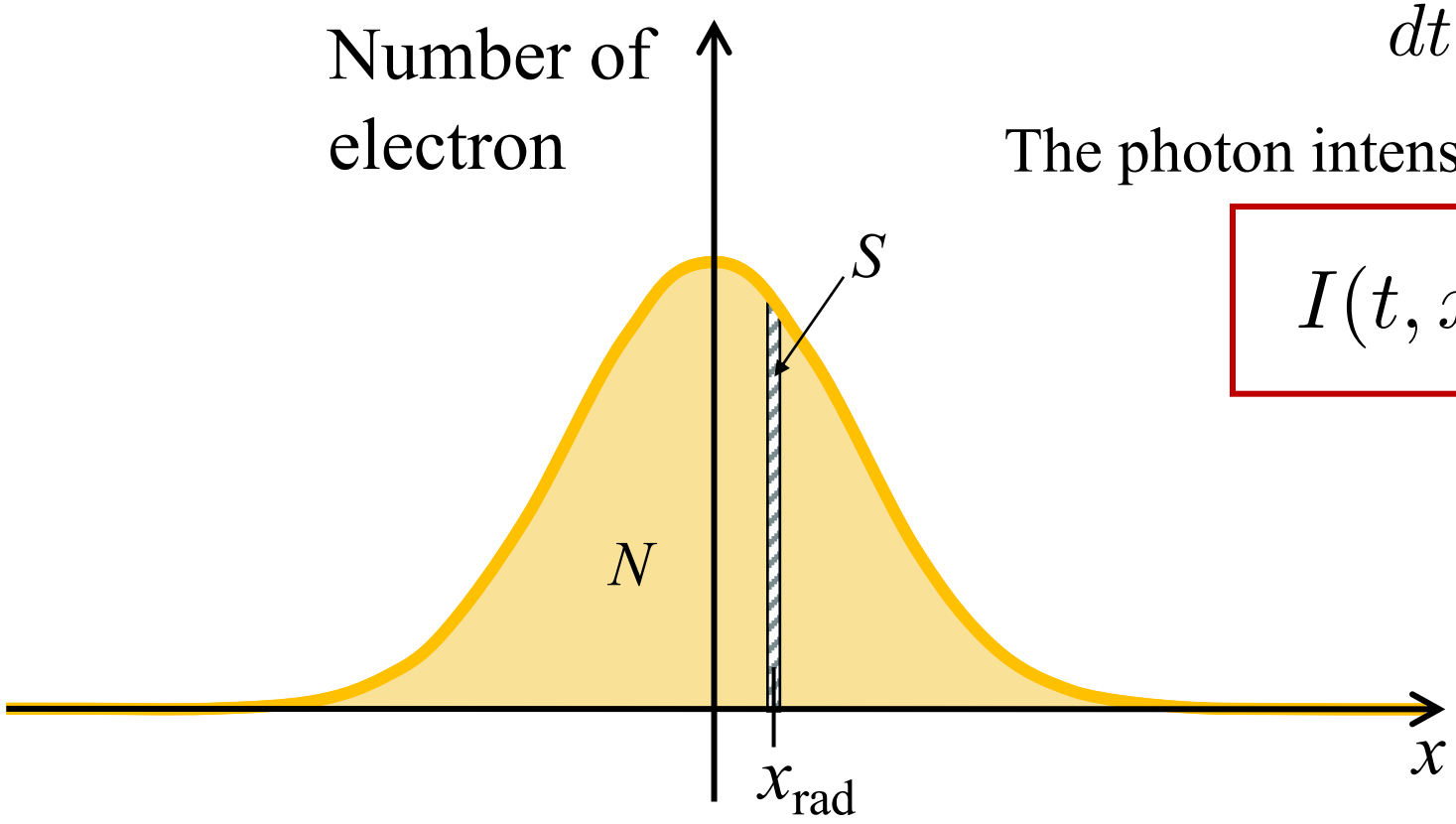
$(\alpha_x, \beta_x) = (1.18, 2.30) \longrightarrow -\alpha_x/\beta_x = -0.51$

Photon beam position can extract the information of the Twiss parameter

Contents

- Motivation
- Design of the new Beam Profile Monitor (BPM)
- Measurement result
- **Application to accelerator research**
  - Beam direction and the Twiss parameter
  - Estimation of the electron beam profile
- Summary

Estimation of the electron beam profile



$$\frac{dI}{dt} = -\frac{S}{N}\alpha I \qquad (\alpha\text{: constant})$$

The photon intensity I as a function of the elapsed time t;

$$I(t, x_{\mathrm{rad}}) = I_0 \exp(-\Gamma(x_{\mathrm{rad}})t)$$

$$\Gamma(x_{\mathrm{rad}}) = -\frac{S}{N}\alpha \ : \text{Decay constant}$$

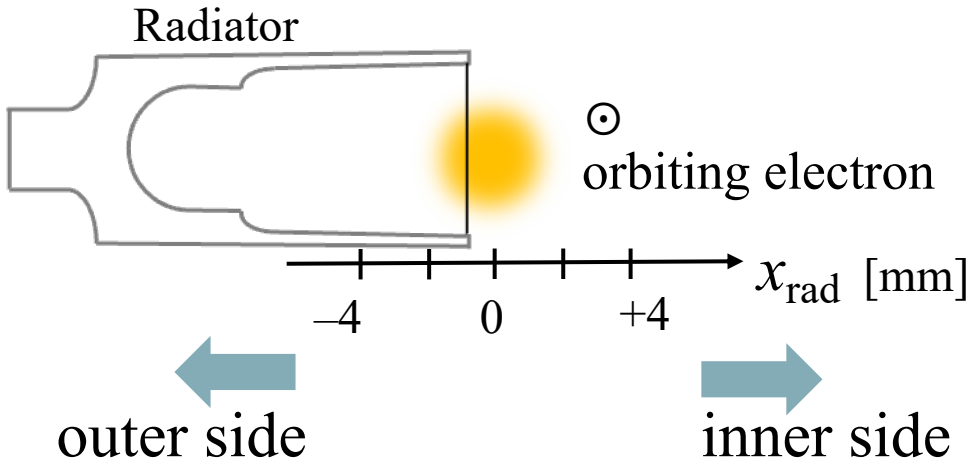
Electron beam intensity distribution

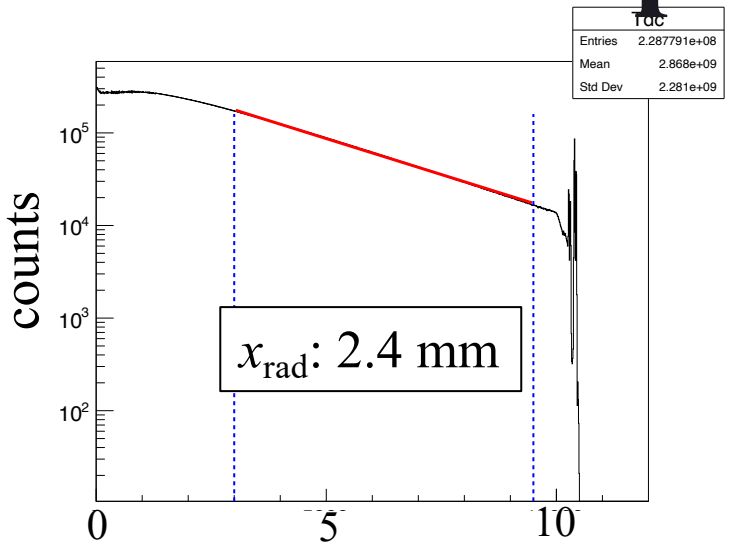
Estimation of the electron beam profile

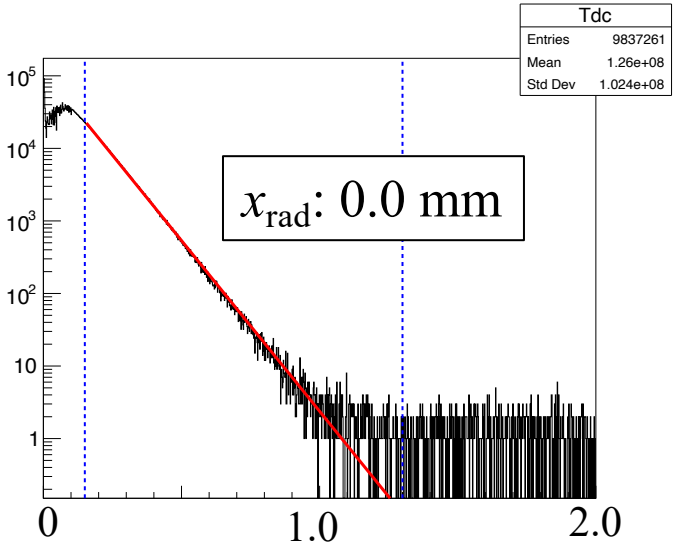
Fit on BPM's count rate

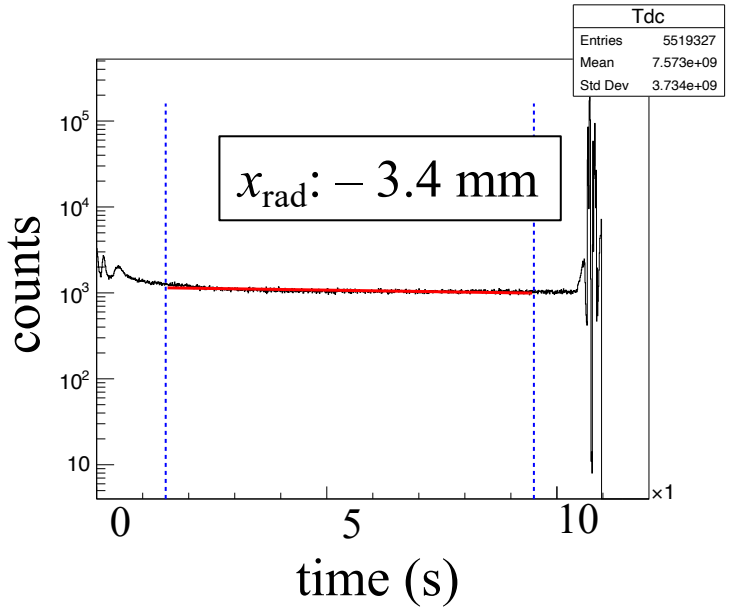
Fitting function:

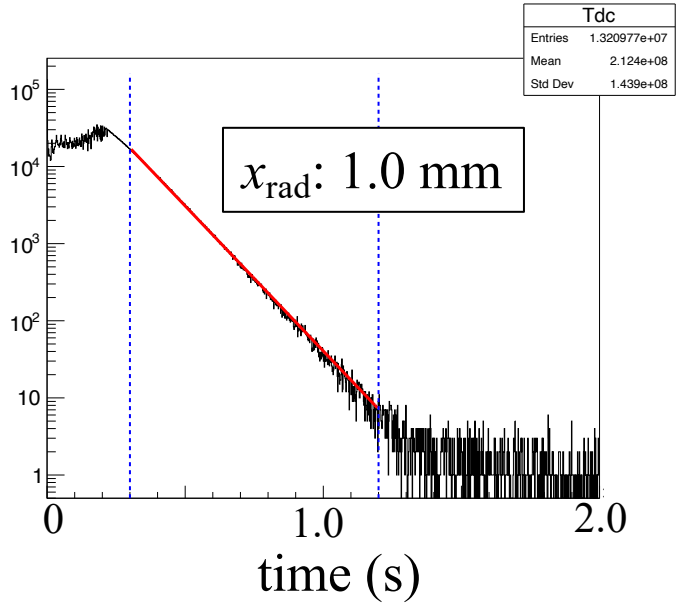
$$I(t) = I_0 \exp(-\Gamma t)$$



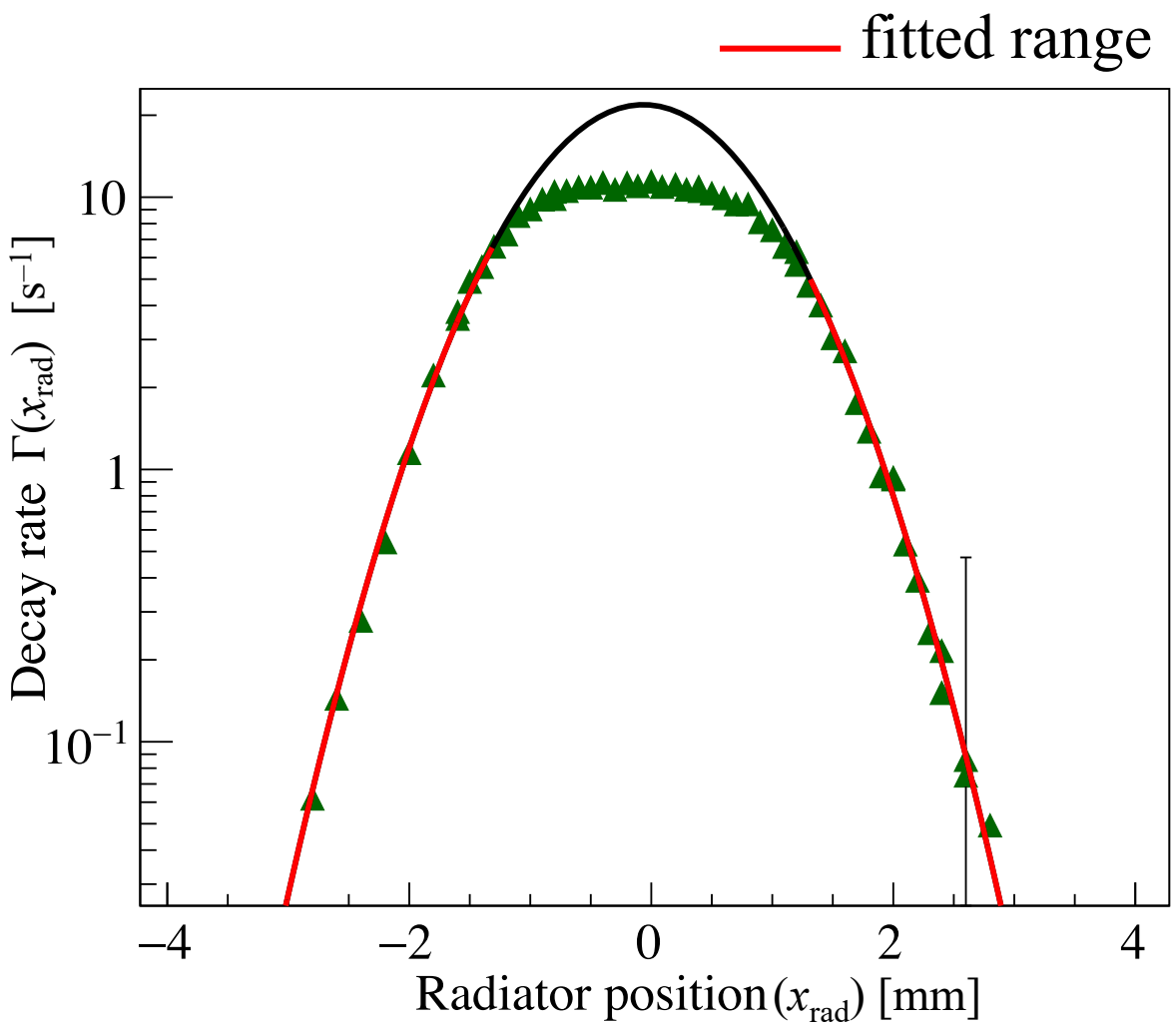








Result of the electron beam profile



Fitting function: Gaussian

position μ_x	– 0.066 +/– 0.001 mm
size σ_x	0.803 +/– 0.002 mm

Expected σ_x (@BM4) 0.76 mm

$$\sigma_x = \sqrt{\beta_x \varepsilon_x + \left(\eta_x \frac{\Delta p}{p}\right)^2}$$
$$\simeq \sqrt{2.30 \times 13.75 \times 10^{-8} + (0.82 \times 6.28 \times 10^{-4})^2}$$
$$\simeq 0.76 \ \mathrm{mm}$$

- Possibility that inserting the radiator affects the electron beam intensity distribution
- Obtain information of electron beam by BPM

Summary

- **Developed the new Beam Profile Monitor for BM4 beamline**

- **Beam Profile Monitor (BPM)**
  - Basic design: scintillation fibers and SiPMs
  - DAQ: Streaming TDC (FPGA module (HUL))
- **Measured photon beam profile**
  - Position precision: 10 μm for 1 second profile
  - Radiator position decides photon beam profile
- **Applicable to accelerator research**
  - Twiss parameters information can be deduced by beam direction
  - Electron beam profile at BM4 was successfully measured

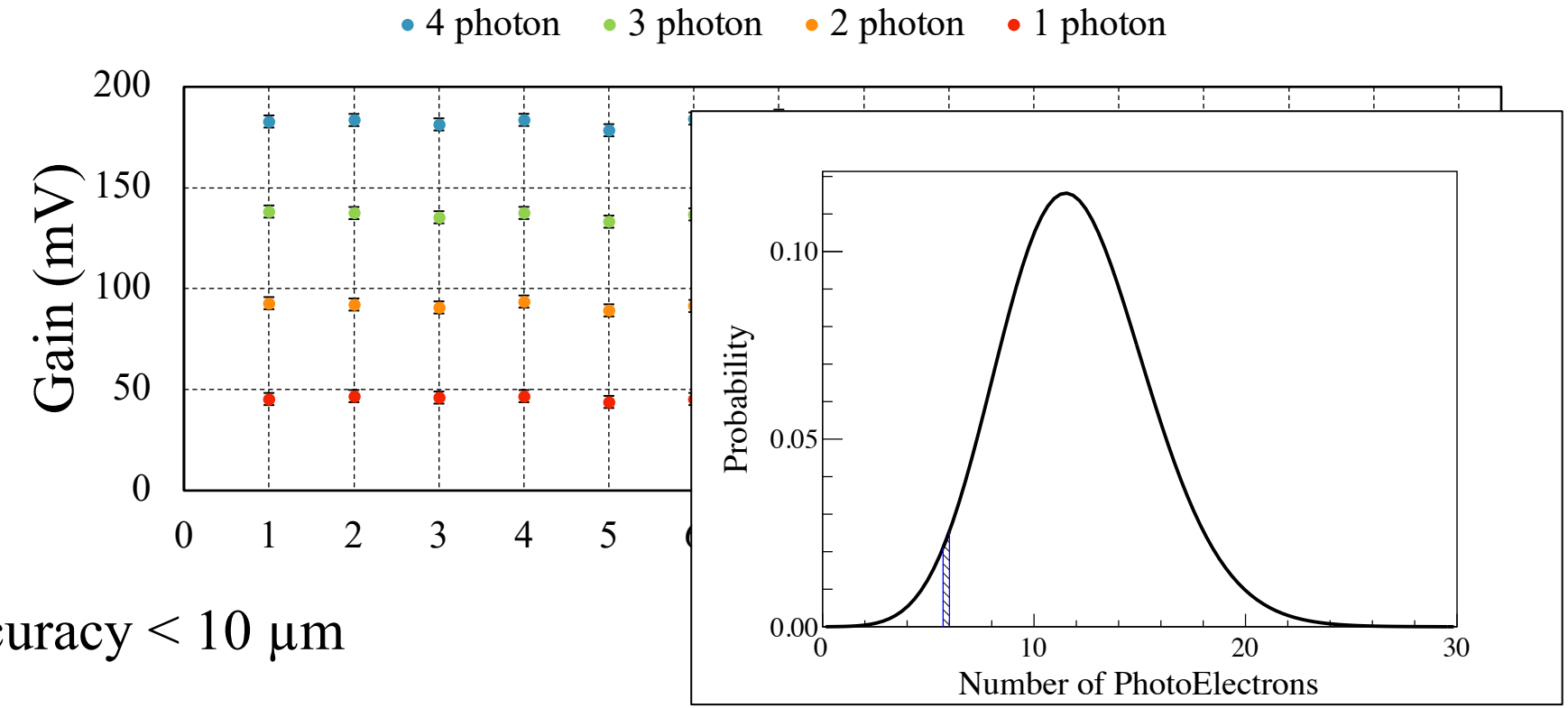
Back Up

Gain of each channels

MPPC gain ≤ 10%

efficiency /ch ~1%

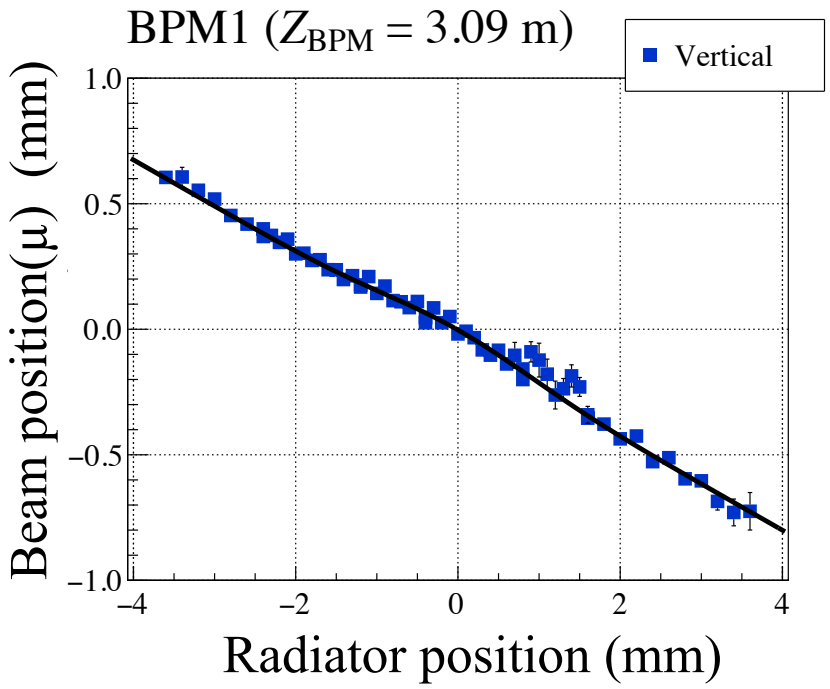
Absolute position accuracy < 10 μm

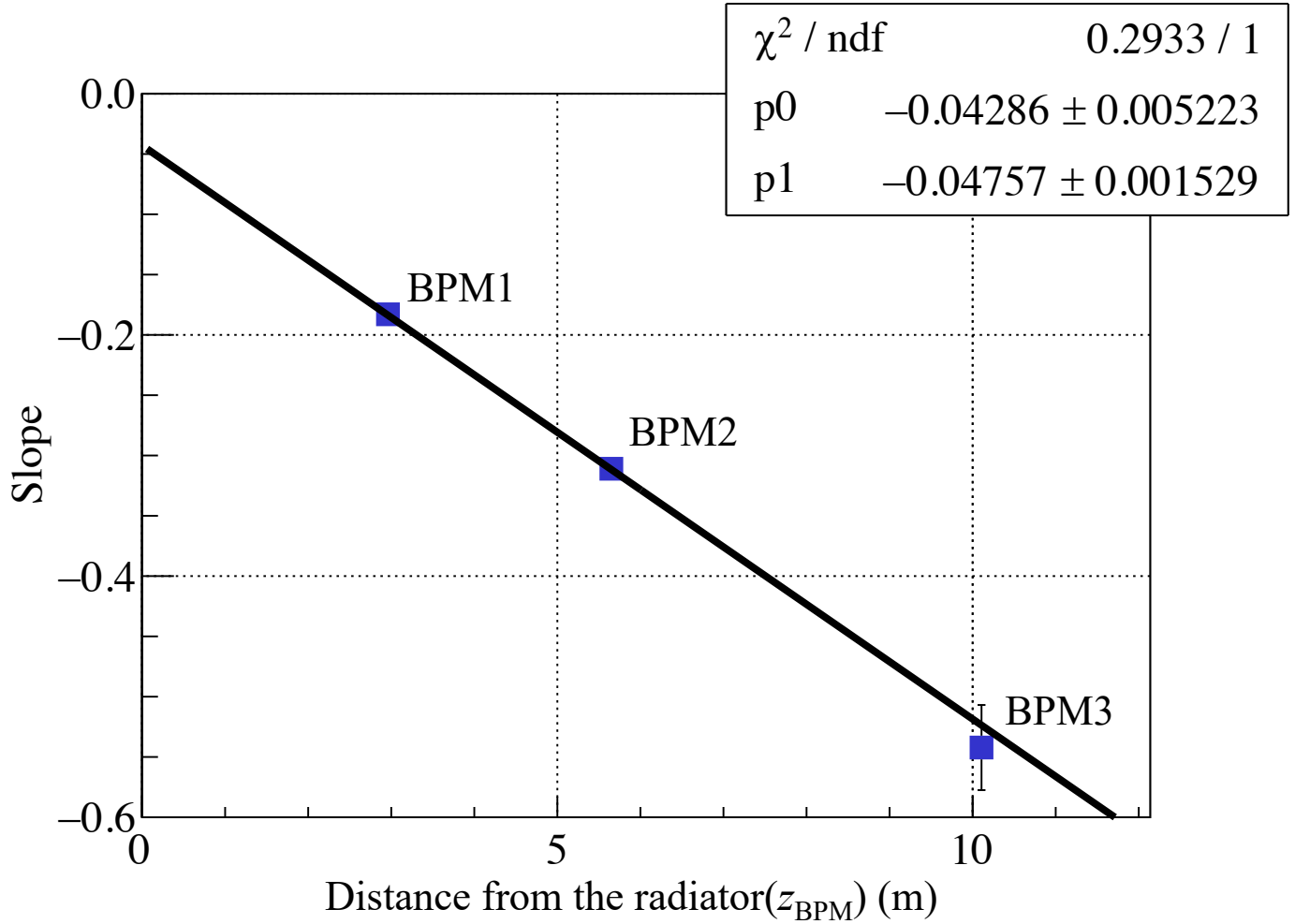


◎ Relative position < 10 μm (movable stage: 3 μm)

Evaluation the measured profile (Vertical)

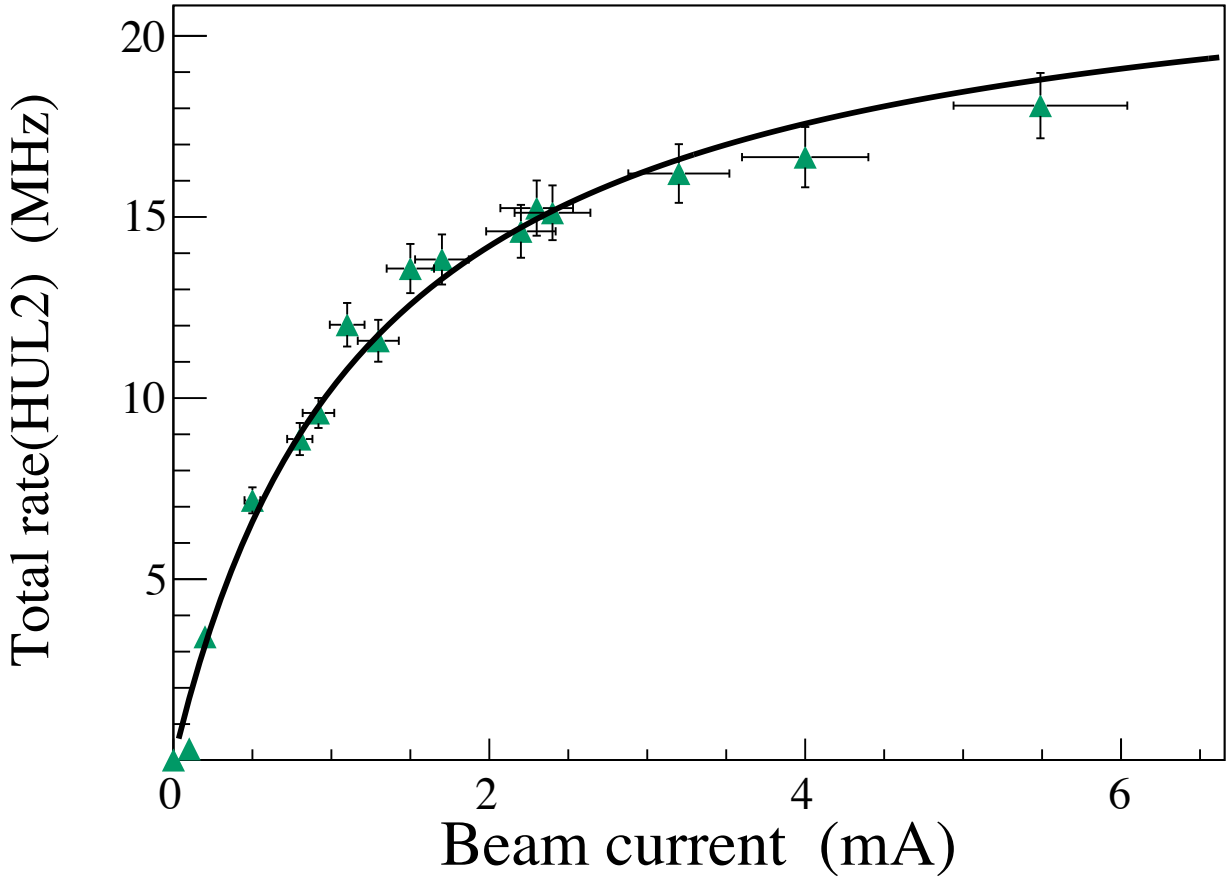
Fitting function: linear + gaussian





electron beam has *x*–*y* coupling
at BM4 radiator

Rate tolerance of the DAQ system



non-paralyzed correction function

$$mT = \frac{k/T}{1 - (k/T)\tau}$$

m: true count rate
k: number that the detector count in a time T
τ: dead time

Fit function: $y = \dfrac{p_0 x}{1 + p_0 p_1 x}$ $\begin{pmatrix} p_0 x = m \\ p_1 = \tau \end{pmatrix}$

Dead time: 43.3 +/– 2.0 ns

Previous measurement of electron beam size[4]

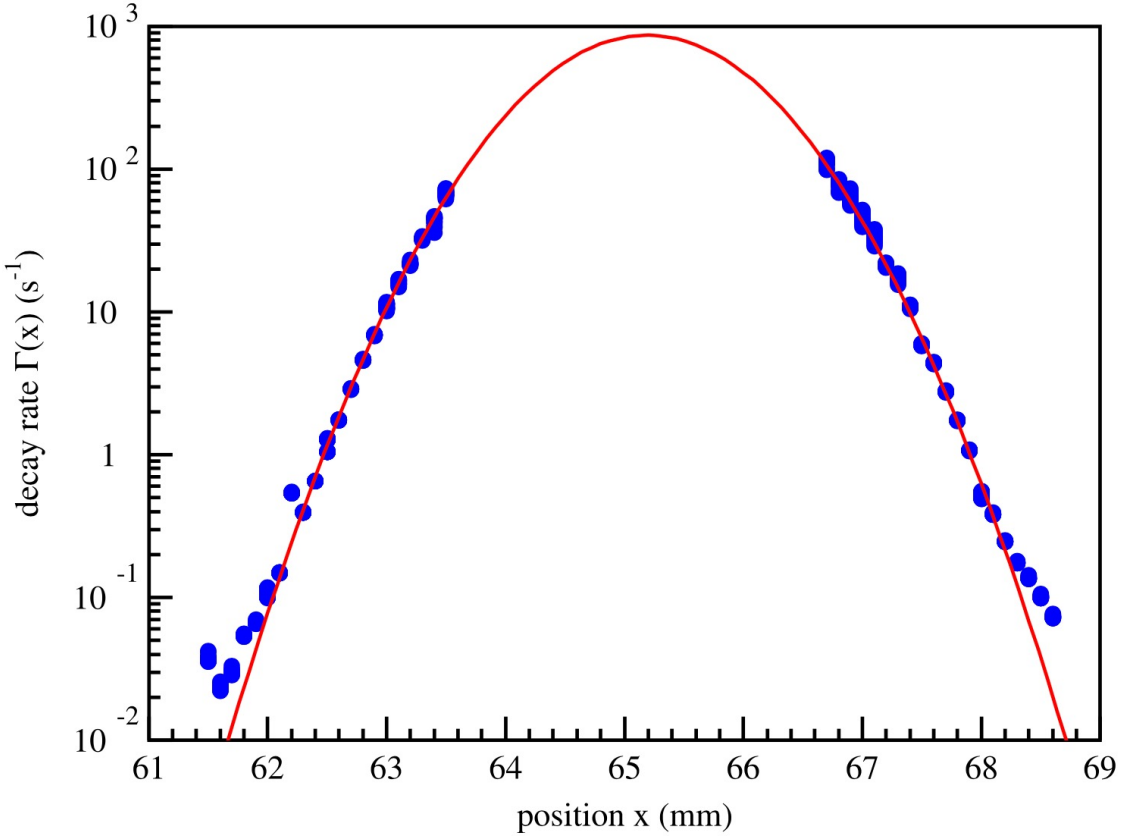
Estimation of electron beam profile by tagger counts

The photon intensity as a function of the elapsed time: $I(t) = I_0 \exp(-\Gamma t)$

The decay rate Γ giving the beam size σ_x

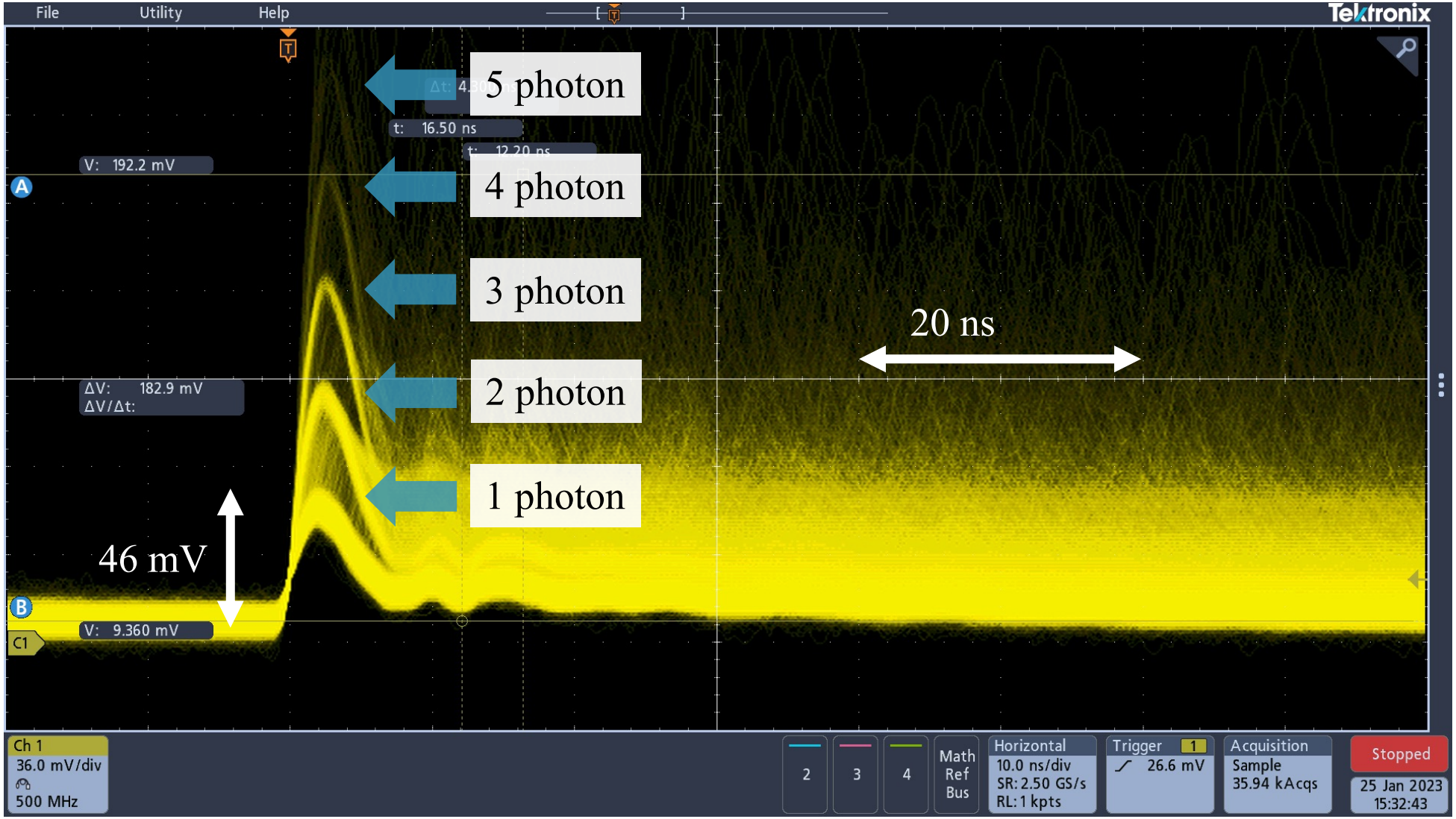
Detector: Tagger (for BM5)
Logic module: MPLM4X[5]
(contains FPGA, Xilinx Spartan-6)
- NIM-standard signals
- Scaling every 0.1 second

[4] Y. Obara *et al.*, NIM A 922 (2019) 108–113
[5] T. Ishikawa *et al.*, NIM A 811 (2016) 124;
Y. Matsumura, T. Ishikawa, NIMA 902 (2018) 103.



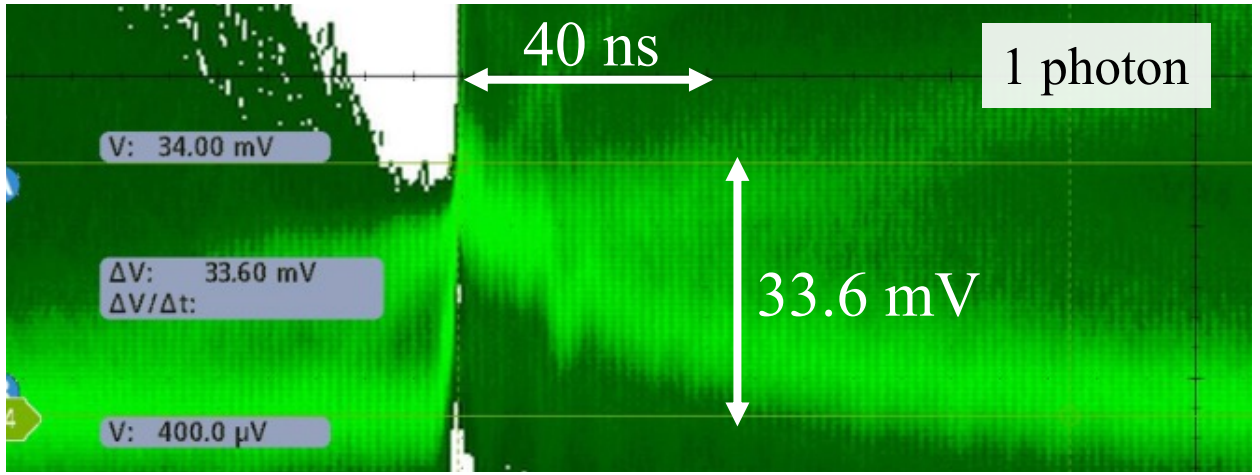
New system required for high-rate beam center measurements ➡ streaming TDC

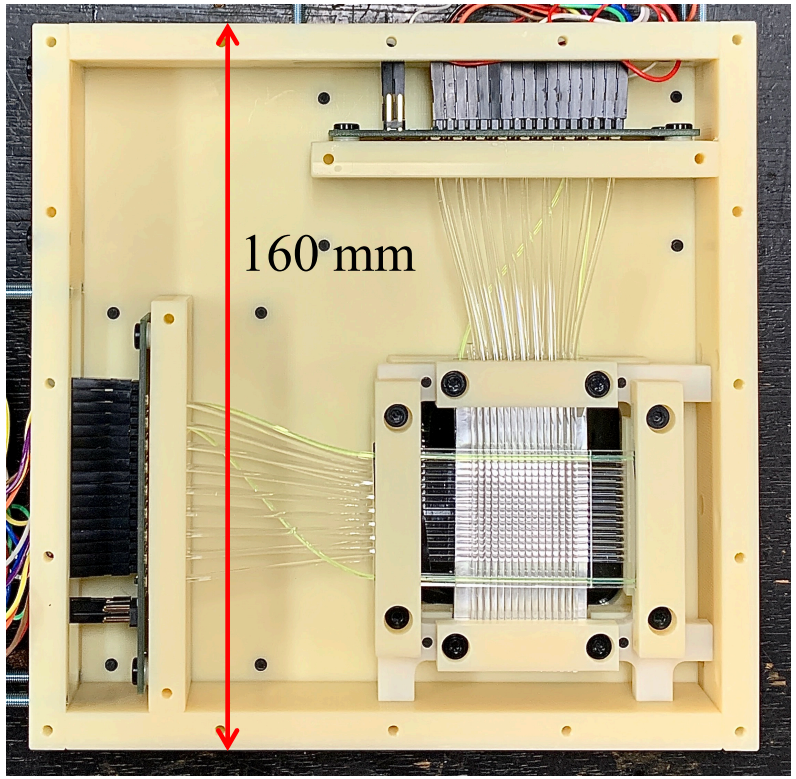
SiPM MPPC

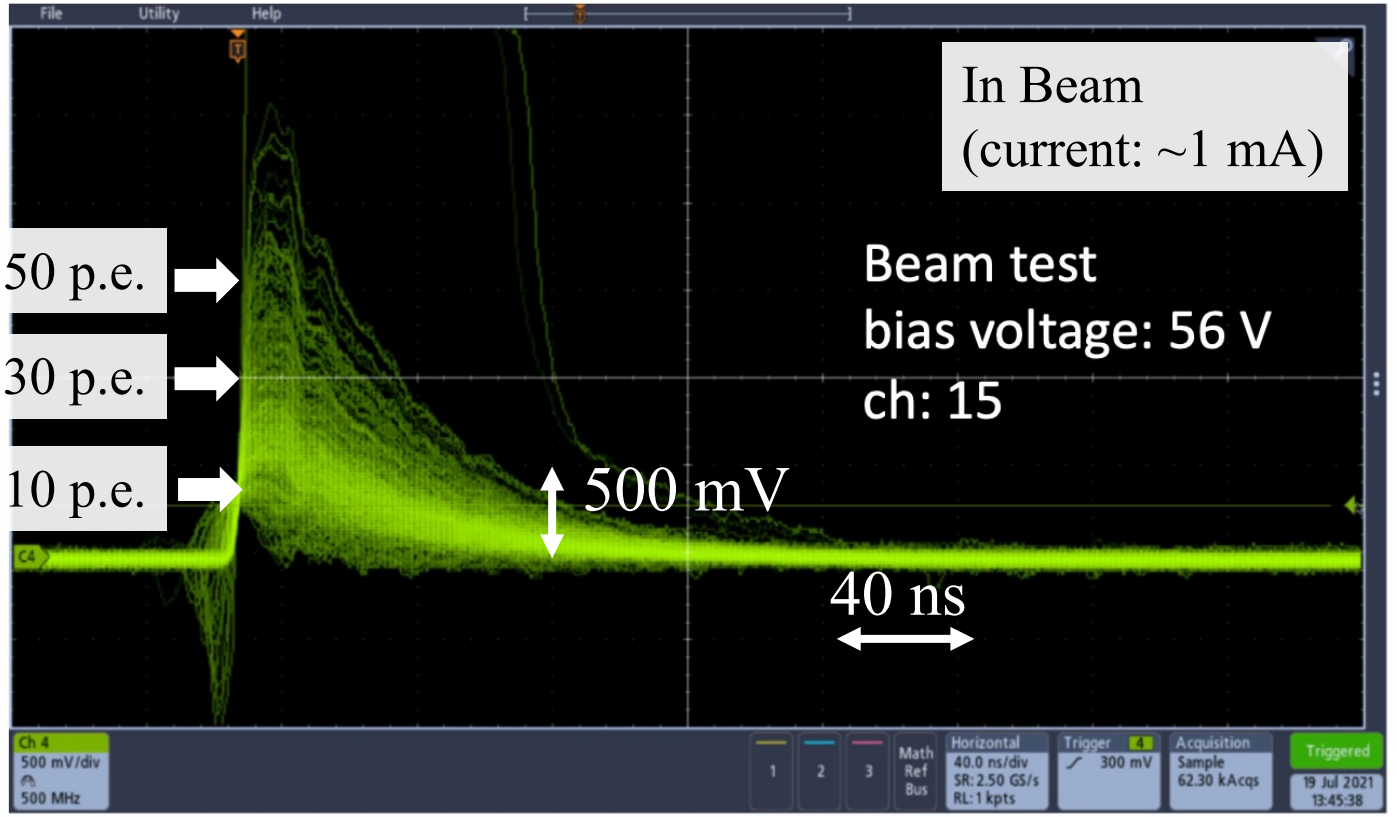

File
Utility
Help
Tektronix
5 photon
4 photon
3 photon
2 photon
1 photon
20 ns
46 mV
t: 16.50 ns
V: 192.2 mV
ΔV: 182.9 mV
ΔV/Δt:
V: 9.360 mV
C1
Ch 1
36.0 mV/div
500 MHz
2
3
4
Math
Ref
Bus
Horizontal
10.0 ns/div
SR: 2.50 GS/s
RL: 1 kpts
Trigger
26.6 mV
Acquisition
Sample
35.94 kAcqs
Stopped
25 Jan 2023
15:32:43

NPE

July 2021 Beamtest@BM4
Prototype
Fiber: ϕ 1.5 mm (Kuraray SCSF-78)
MPPC: S1360-1350PE

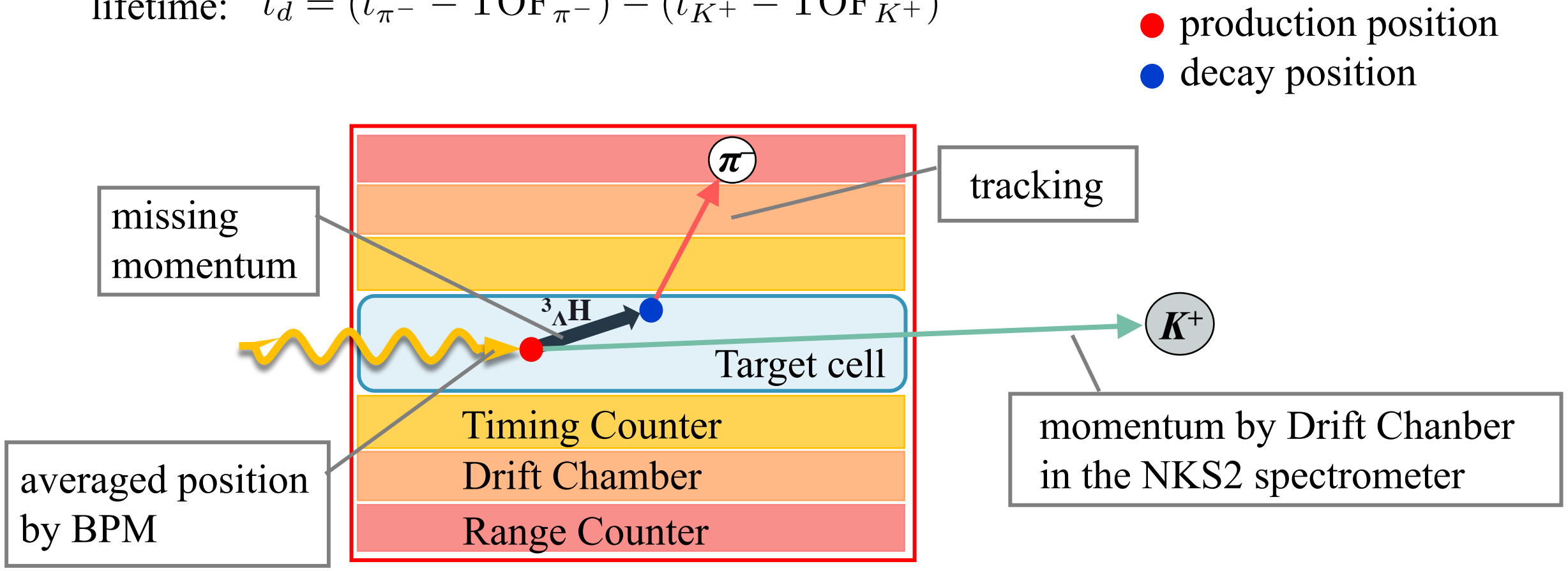




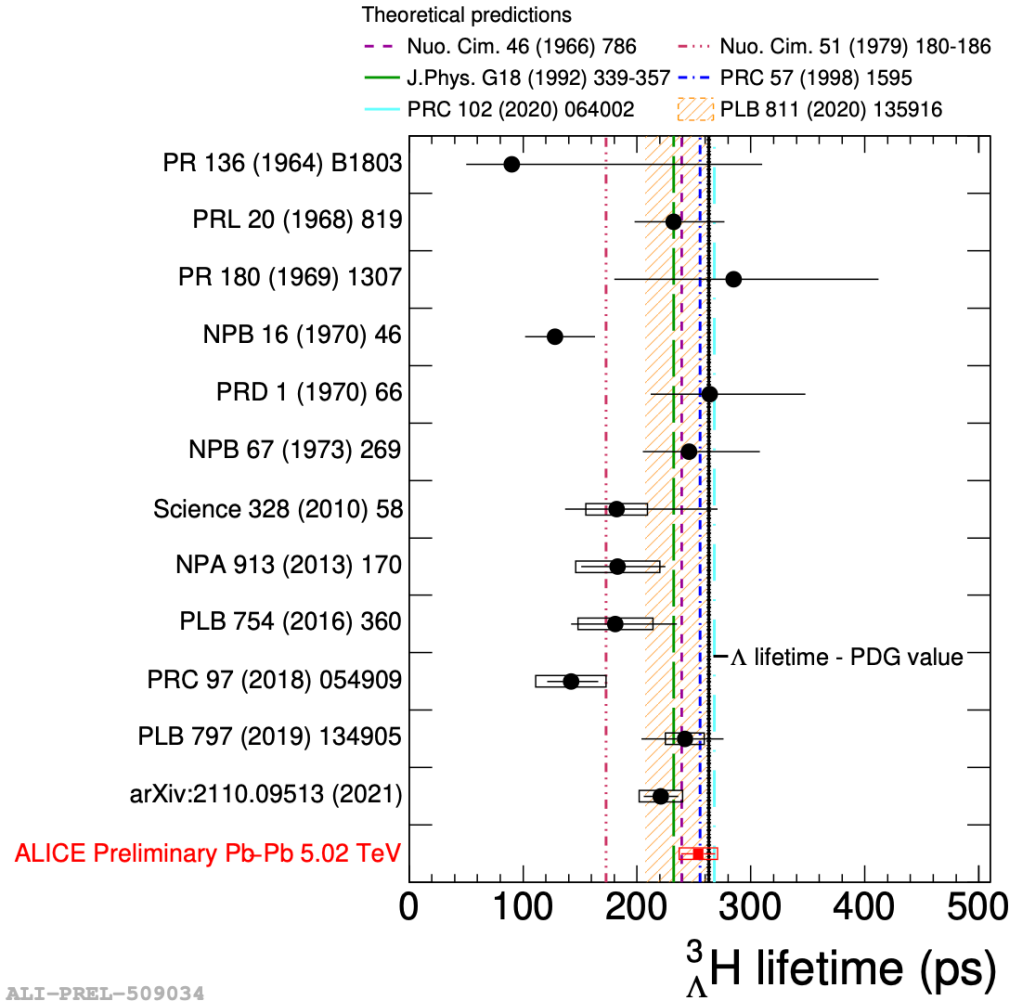


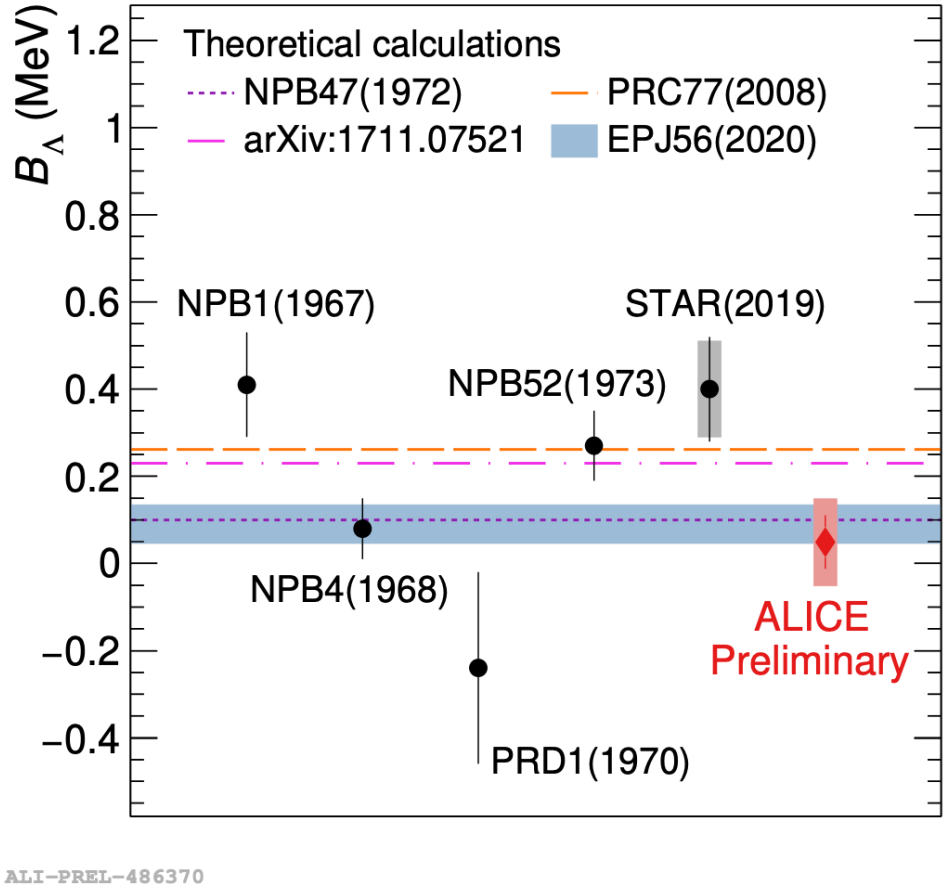
${}^{3}_{\Lambda}$H lifetime measurement at BM4 beamline

lifetime: $t_d = (t_{\pi^-} - \mathrm{TOF}_{\pi^-}) - (t_{K^+} - \mathrm{TOF}_{K^+})$



$^{3}_{\Lambda}$H lifetime measurement

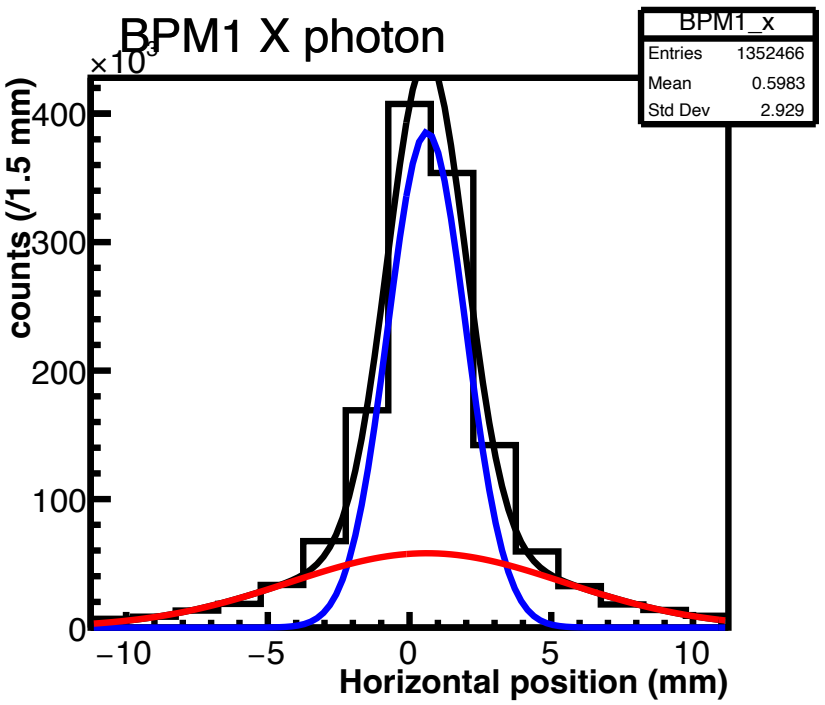




F. Mazzaschi, the ALICE collaboration, APBPS **16** 1-A149 (2023)

Beam profile: Photon event vs BG

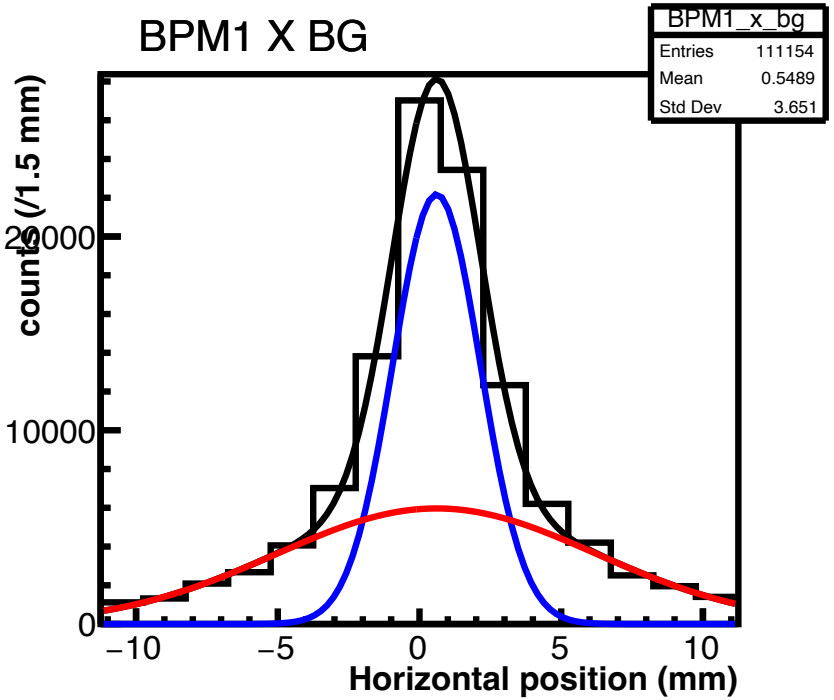
$[\ \overline{\text{VETO}}\ ] \otimes [\ x \text{ layer}\ ] \otimes [\ y \text{ layer}\ ] \otimes [\ \text{trig.}\ ]$



true / halo = 6.663

σ_x = 1.376 +/– 0.003 mm

$[\ \text{VETO}\ ] \otimes [\ x \text{ layer}\ ] \otimes [\ y \text{ layer}\ ] \otimes [\ \text{trig.}\ ]$

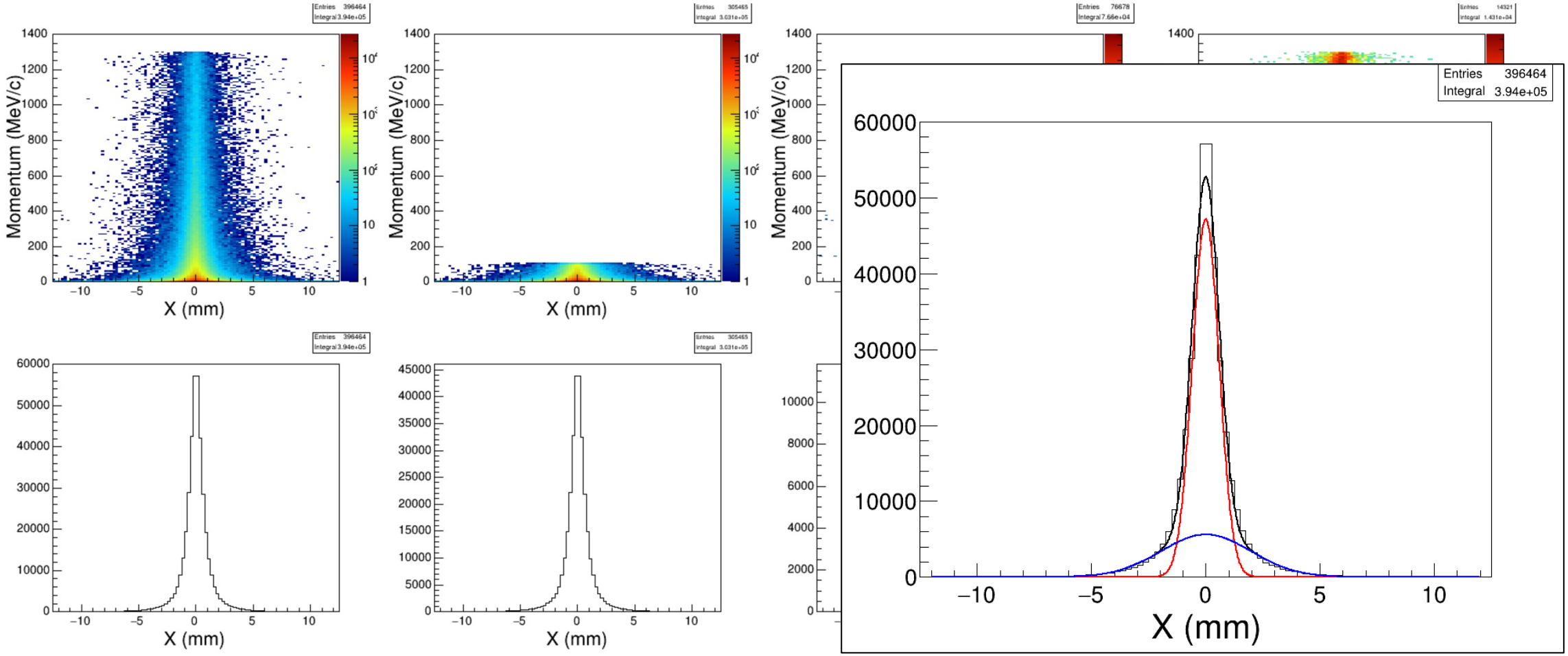


true / halo = 3.716

σ_x = 1.543 +/– 0.014 mm

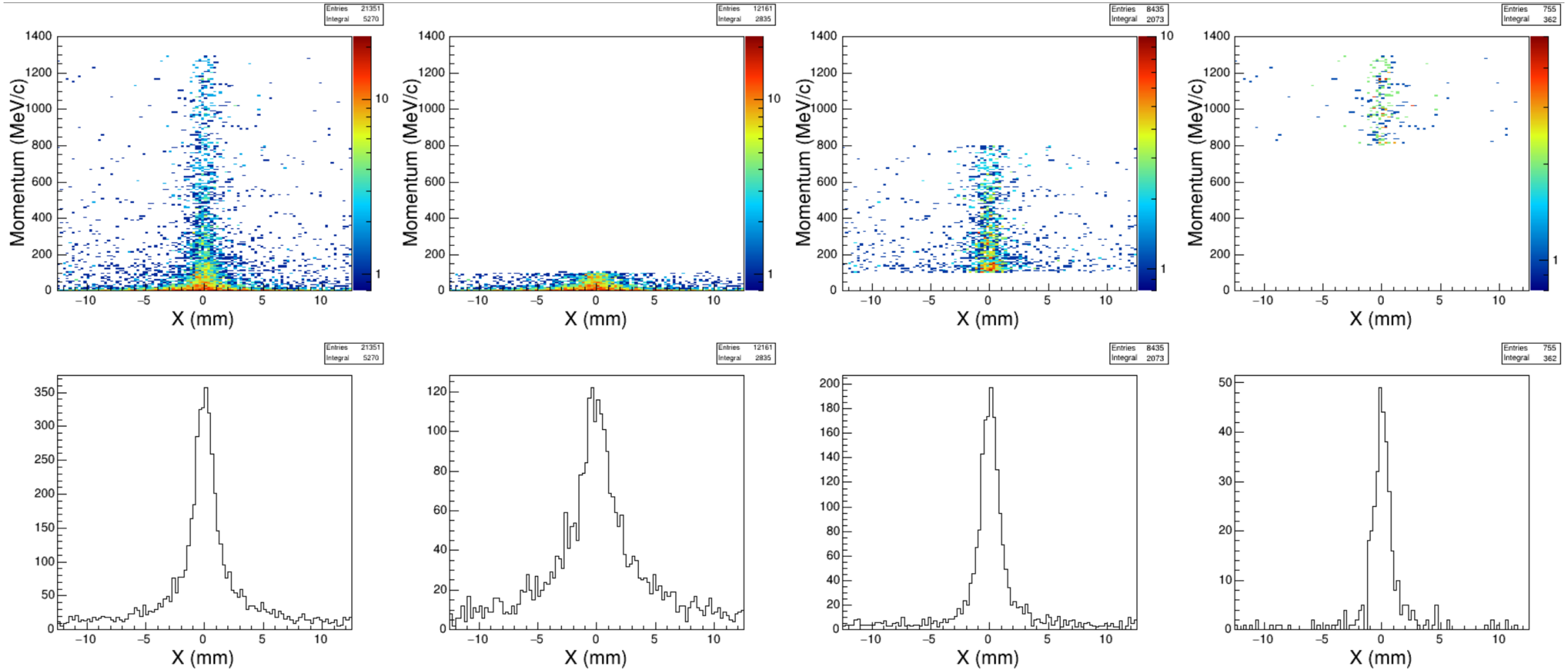
GEANT4 Simulation

Gamma rays distribution(z ~3 m)



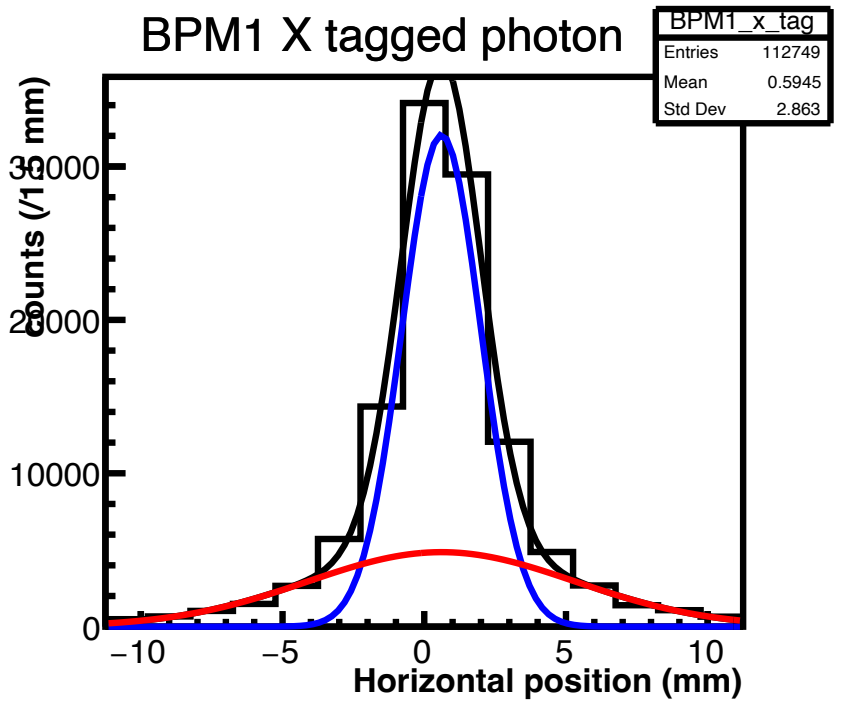
GEANT4 Simulation

e^+/e^- distribution (z ~3 m)



Beam profile: tagged vs untagged photon

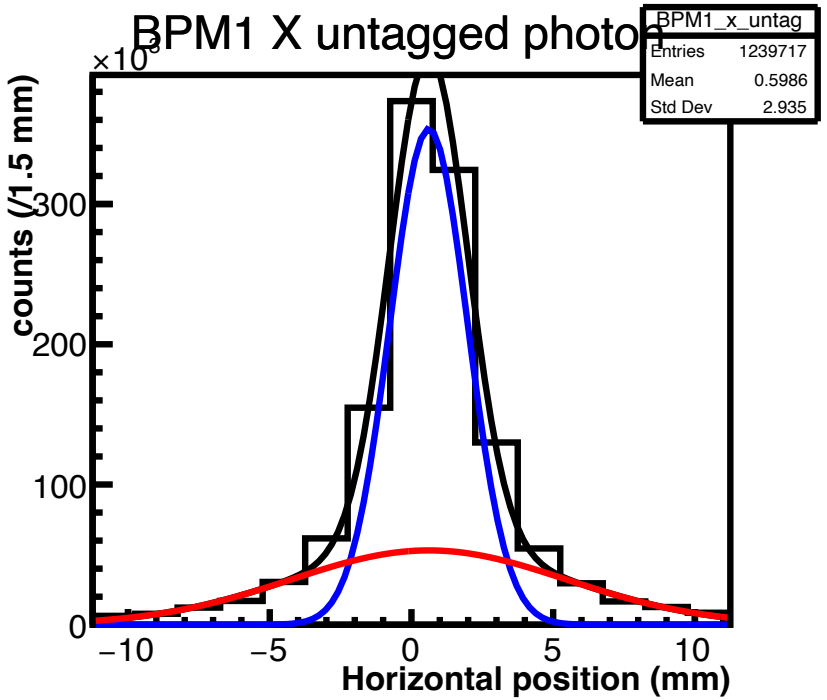
[Photon event] ⊗ [TagB]



true / halo = 6.596

σ_x = 1.393 +/– 0.010 mm

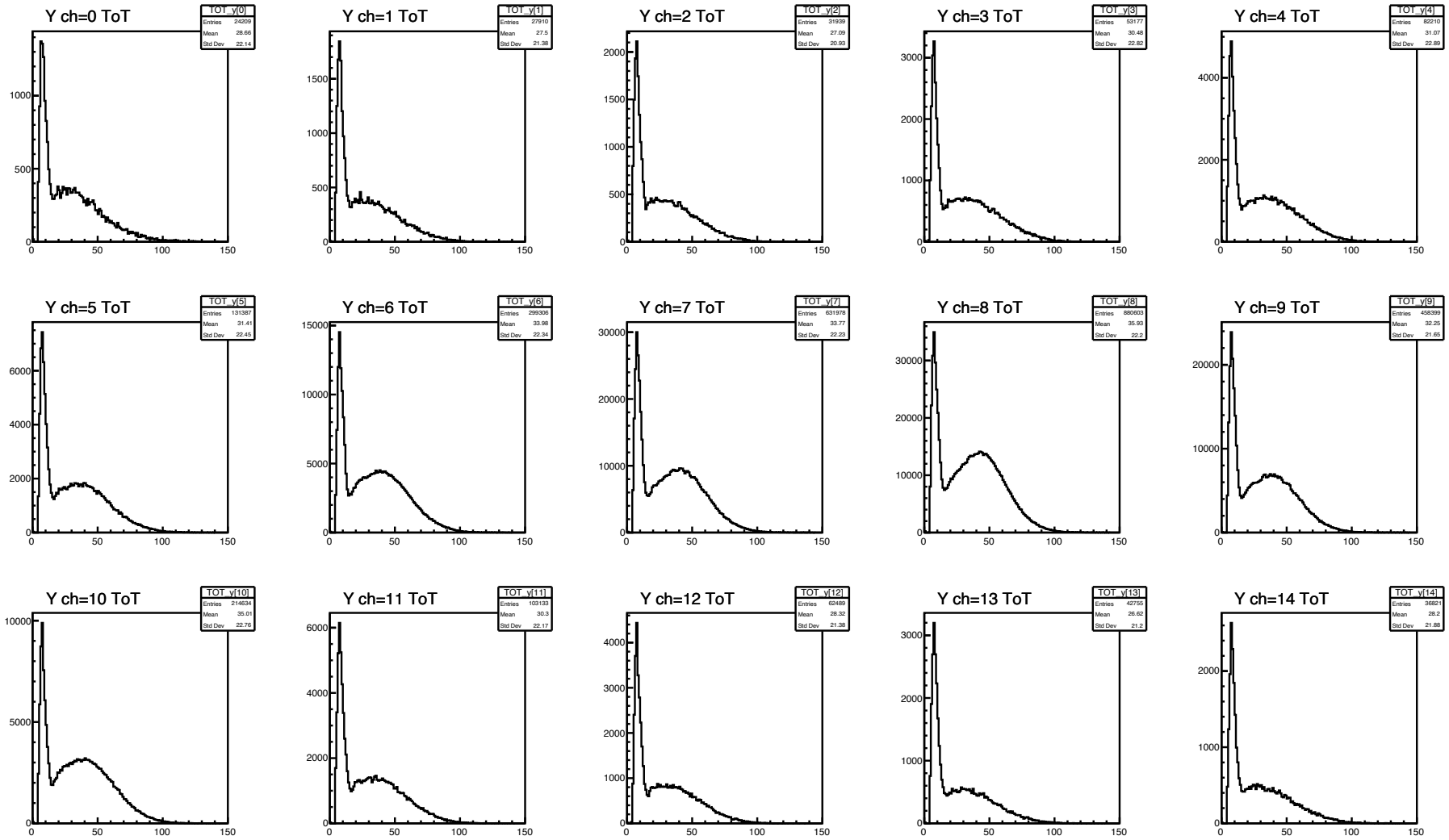
[Photon event]



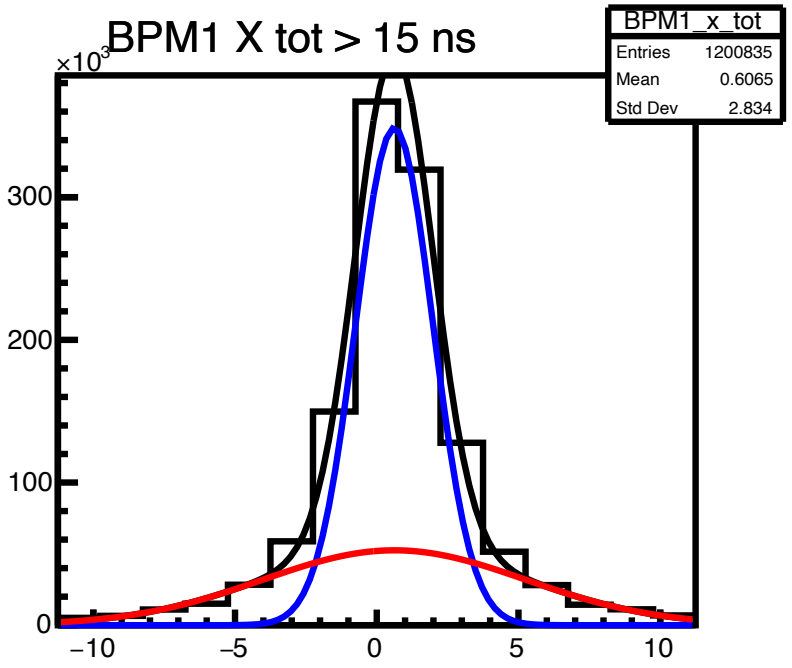
true / halo = 6.667

σ_x = 1.374 +/– 0.003 mm

Beam profile: ToT cut

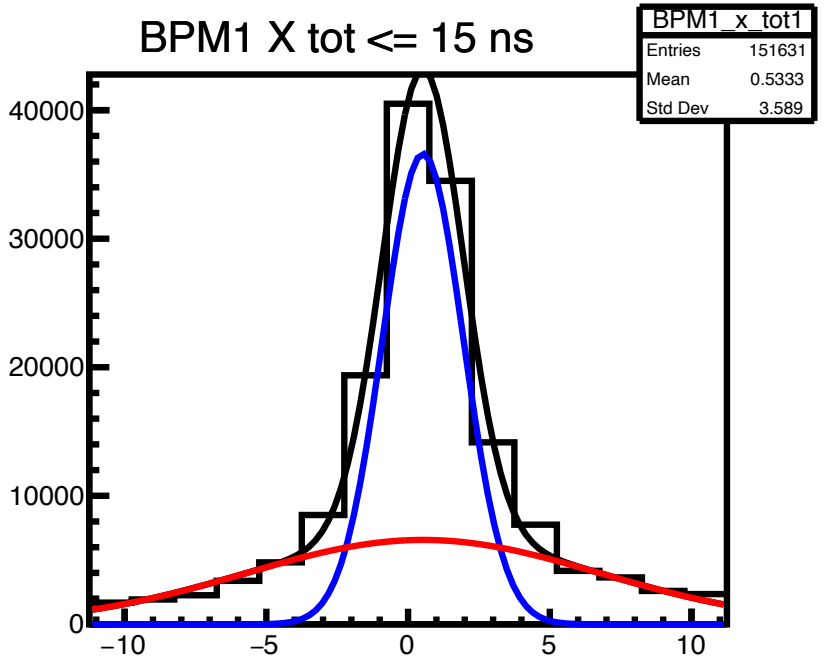


Beam profile: ToT cut



true / halo = 6.634

σ_x = 1.365 +/– 0.003 mm

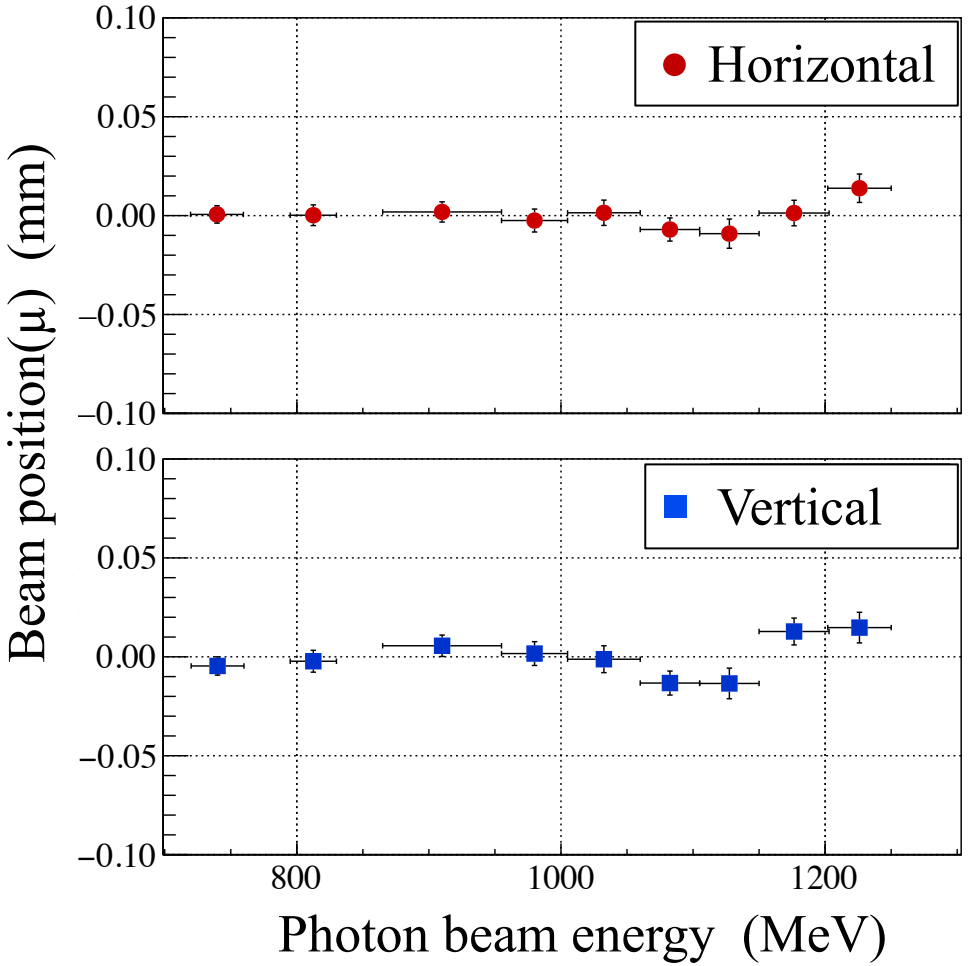


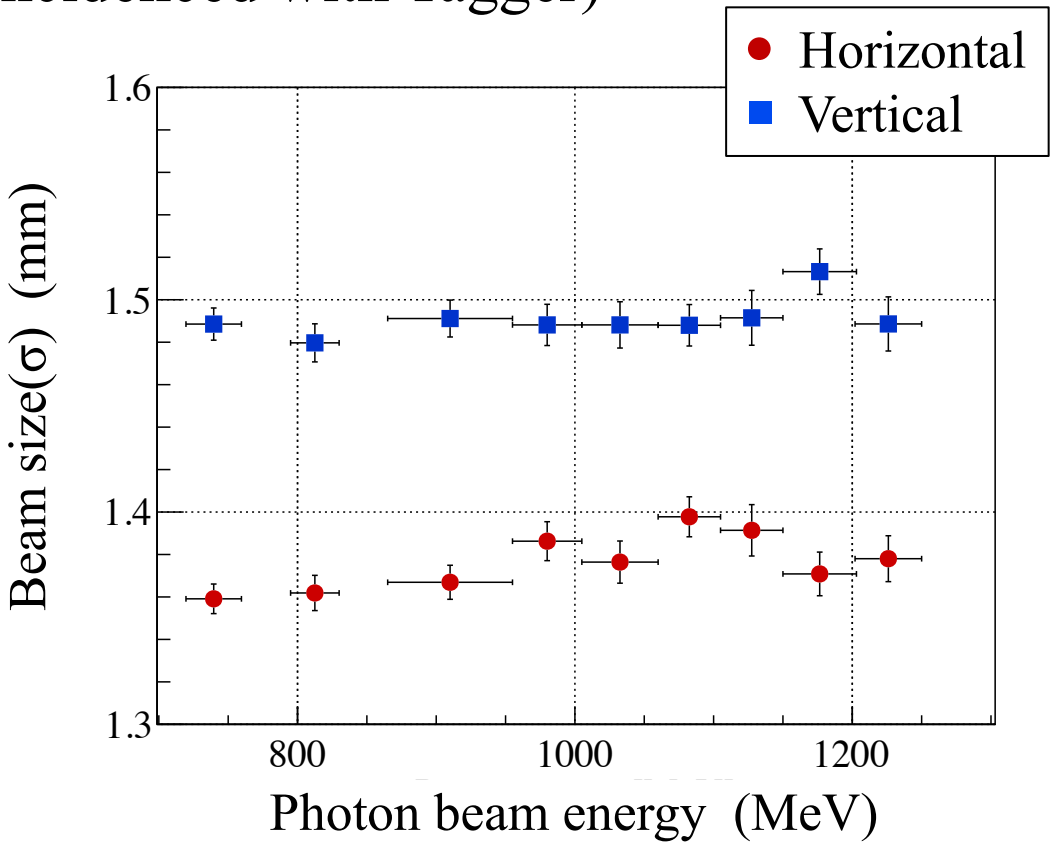
true / halo = 5.574

σ_x = 1.427 +/– 0.009 mm

Measured photon beam profile

- Beam energy dependence (events coincidenced with Tagger)

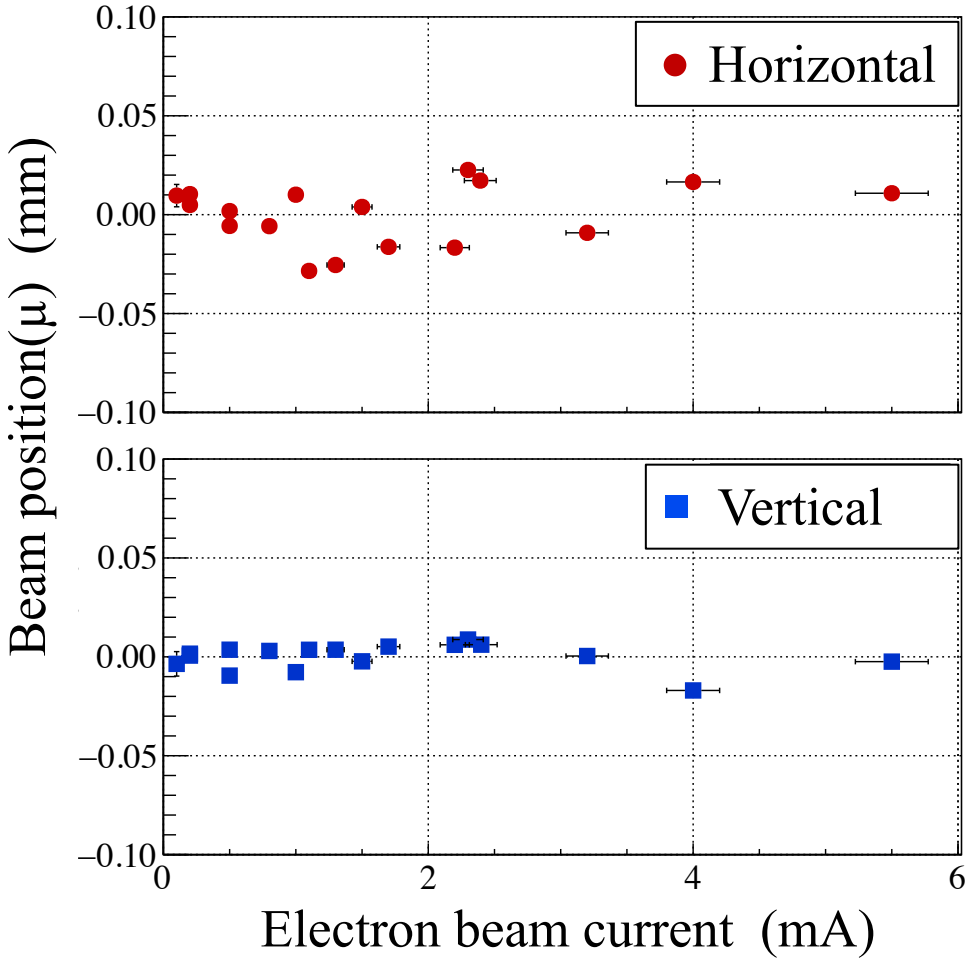


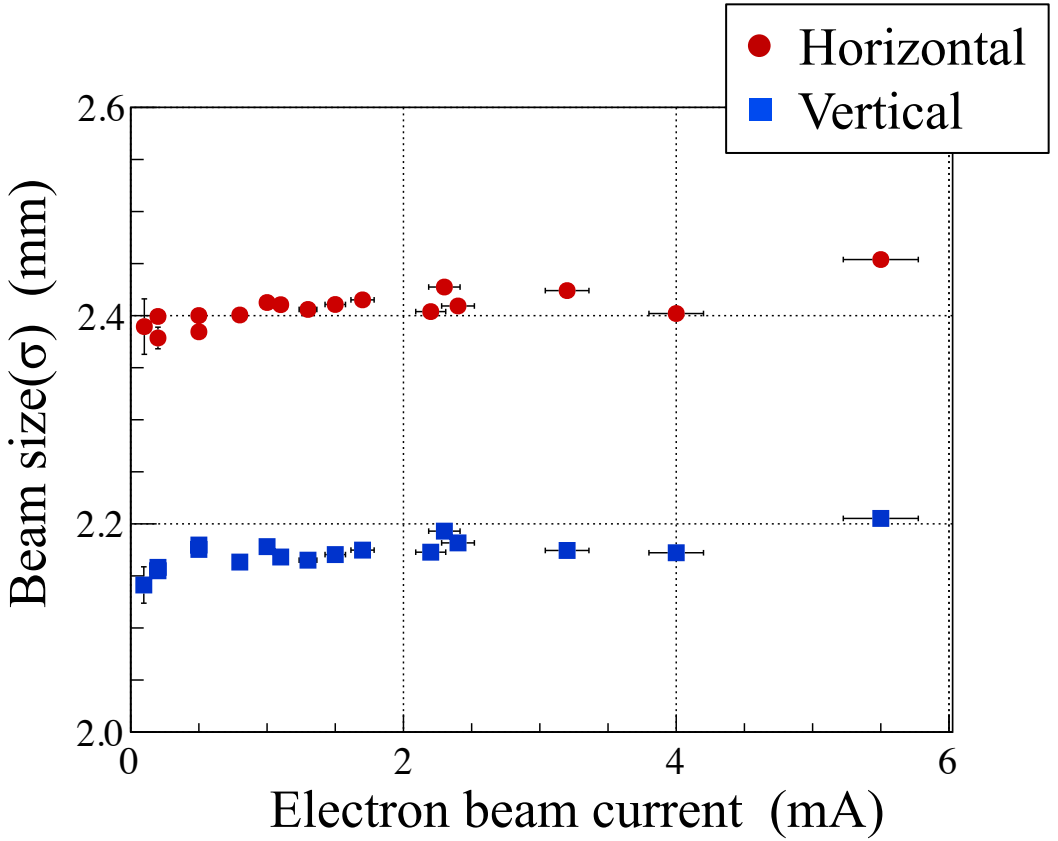


→ small energy dependence

Measured photon beam profile

- Beam intensity dependence





→ Position: No energy dependence
Size: Increasing with beam current