次世代$\mu^+ \to e^+\gamma$崩壊探索のための光子ペアスペクトロメータの開発 ービームテストによるアクティブコンバーターの性能評価ー

Developing an experiment for a future search for $\mu^+ \to e^+\gamma$ - performance evaluation of the active converter through beam test -

榊原　澪

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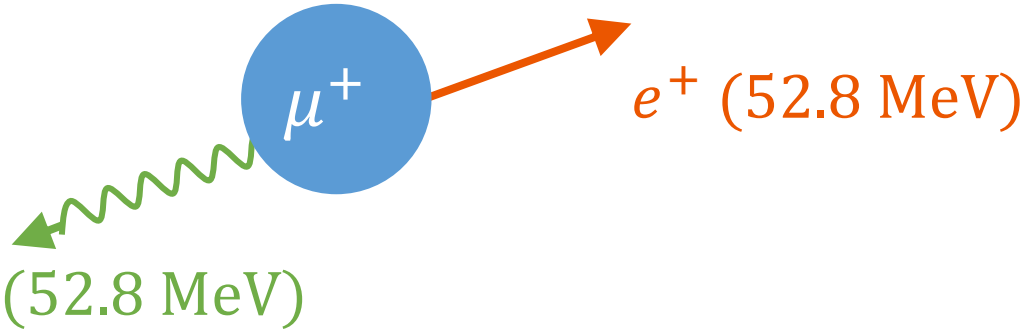
$\mu^+ \to e^+\gamma$ search

- Charged lepton flavor violation decay
  - $Br(\mu^+ \to e^+\gamma) \sim \mathcal{O}(10^{-53})$ …SM + ν oscillation
  - $Br(\mu^+ \to e^+\gamma) \sim \mathcal{O}(10^{-11} \sim 10^{-15})$…predicted in BSM (e.g. SUSY)

- Experiments
  - MEG experiment (2009-2013@PSI): $\mathrm{Br}(\mu^+ \to e^+\gamma) < 4.2\times10^{-13}(90\%\ \mathrm{C.L.})$
  - MEG II experiment (2021-) : ongoing with the target sensitivity 6×10^{-14}
  - Future $\mu^+ \to e^+\gamma$ experiment : planning with the target sensitivity of $\mathcal{O}(10^{-15})$



Future experiment of $\mu^+ \to e^+\gamma$ search

- **Motivation of search at $O(10^{-15})$ sensitivity**
  - Further search for $\mu^+ \to e^+\gamma$ (if it was not found in MEG II experiment)
  - Measurement of $\mu^+ \to e^+\gamma$ after discovery (branching ratio, angular distribution,…) for BSM model selection
- **Muon beam**

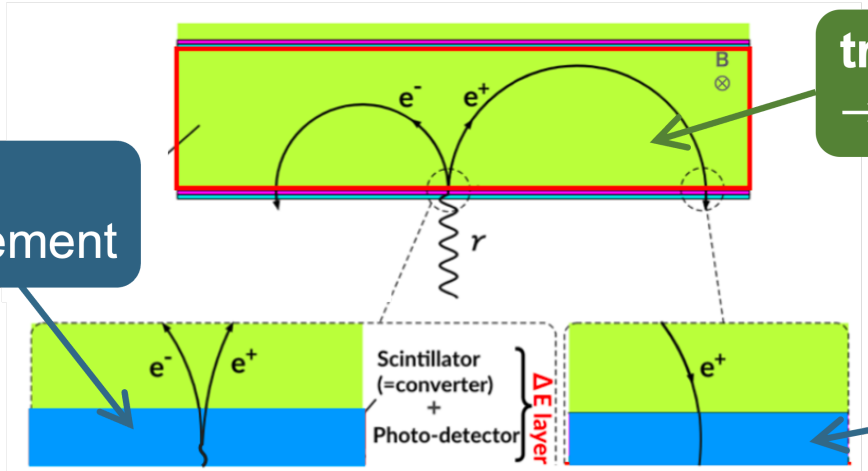
  the intensity of muon beam at PSI is planned to be increased to $\sim 10^{10}\ \mu^+/s$
  (High Intensity Muon Beam (HiMB), implemented in 2027-2028)
- **Detector**
  - R&D of new detectors with good resolutions & high rate capability is necessary
  - main background of $\mu^+ \to e^+\gamma$: accidental background

$$N_{acc} \propto R_\mu^2 \cdot \Delta E_\gamma^2 \cdot \Delta p_e \cdot \Delta\theta_{e\gamma}^2 \cdot \Delta t_{e\gamma} \cdot T$$

R_μ : muon stopping rate
$\Delta E_\gamma, \Delta p_e, \Delta\theta_{e\gamma}, \Delta t_{e\gamma}$: detector resolutions
T : measurement time

  $\to \gamma$ energy measurement resolution is important for background suppression
  - for γ measurement, pair spectrometer with active converter is under development

Pair spectrometer with active converter



problem with conventional pair-spectrometer

- low efficiency (compared to calorimeter) → want to increase thickness
- energy loss in converter → want to reduce thickness

→ solution : energy measurement by converter (active converter)

requirements for active converter

$\frac{\Delta E}{E} < 0.4\ \%$ at signal region ($E = 52.8\ \mathrm{MeV}$) & $\Delta t < 30\ \mathrm{ps}$ for pair spectrometer

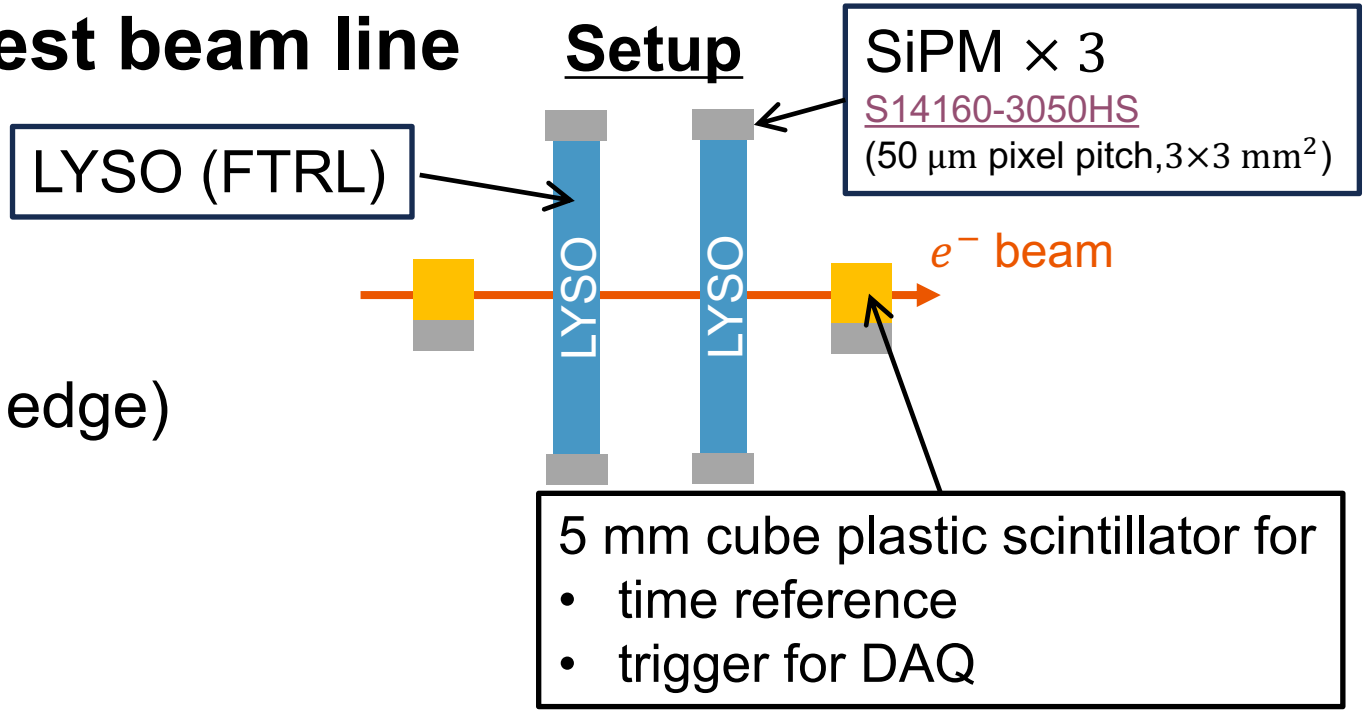
$N_{\mathrm{p.e.}} > 670$ p.e. (3mm thickness converter) & $\Delta t < 40\ \mathrm{ps}$ for 1 MIP

candidate material for active converter … LYSO

Beamtest of active converter

- **Electron beam at KEK PF-AR Test beam line**
  - Beam momentum ~ 3 GeV
  - Beam rate ~ 4.5 kHz
- **Active converter prototype**
  LYSO + SiPM readout (three on both edge)
- **Readout method**
  ① independent readout
    – Three readout channels /side
    – Timing is calculated from weighted average of channels
  ② series readout
    – Three SiPMs connected in series
    – One readout channel /side
    – reduced capacitance → faster response

Setup

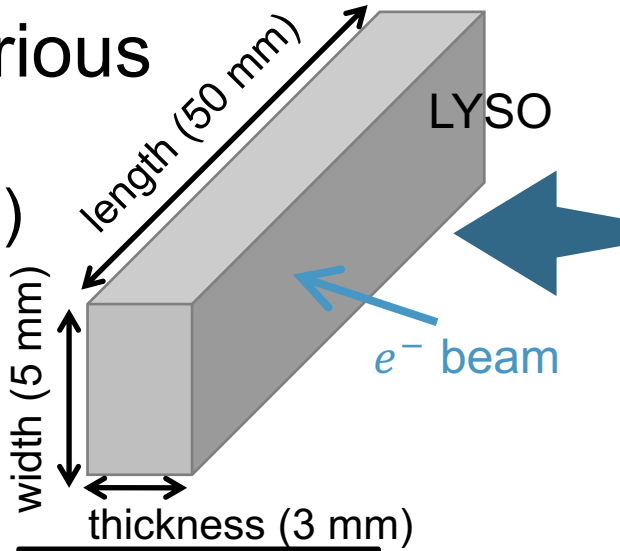


- preliminary analysis reported by R.Yokota (JPS 2024 spring,19aT1-9)
- more detailed analysis in this study

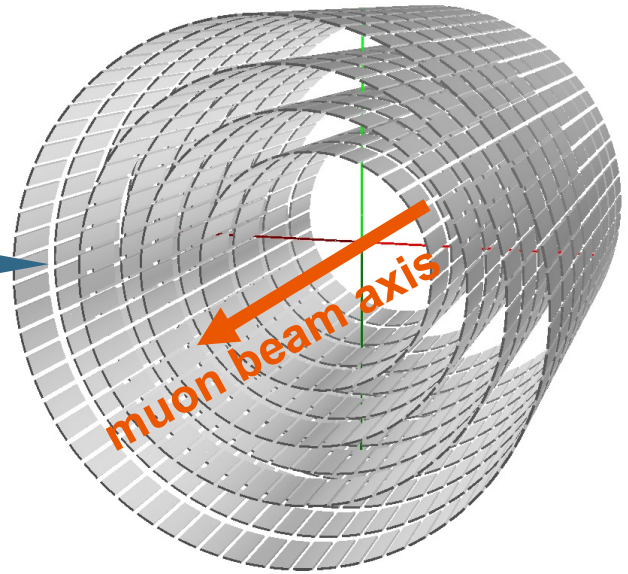
studied item on the beamtest

① Performance comparison with various
- LYSO size
- readout method (independent/series)
- SiPM pixel pitch

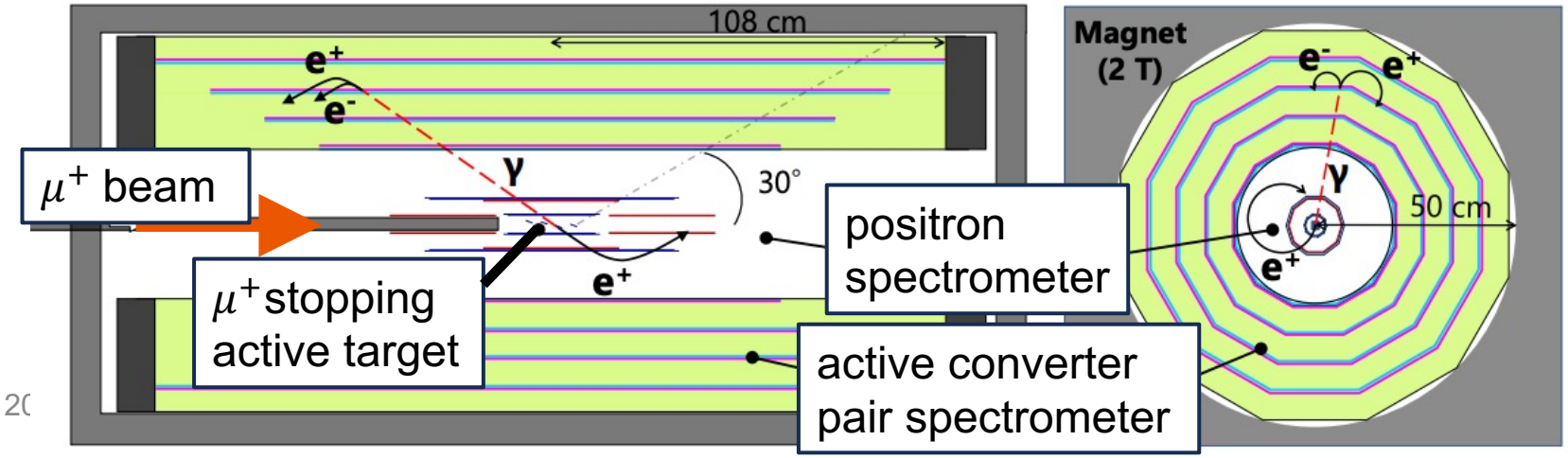
② Performance dependence on
- Beam injection position
- Beam injection angle



one segment (standard size)

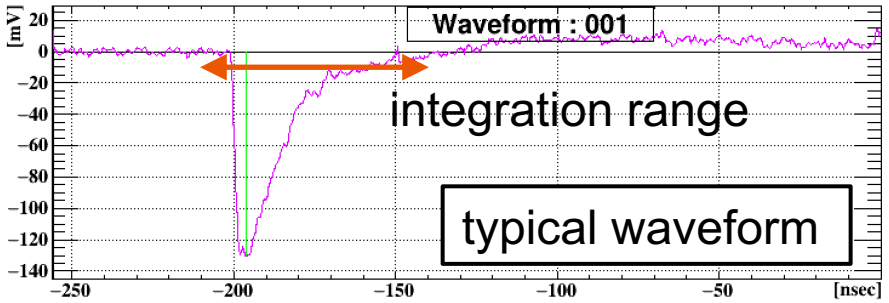


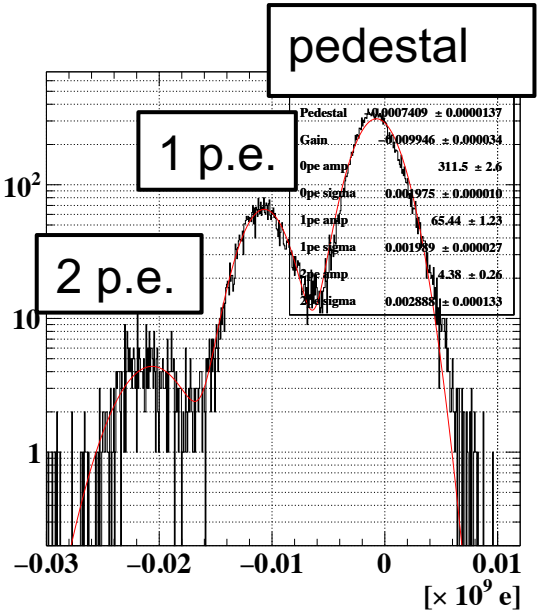
segmentation of converter in the future experiment



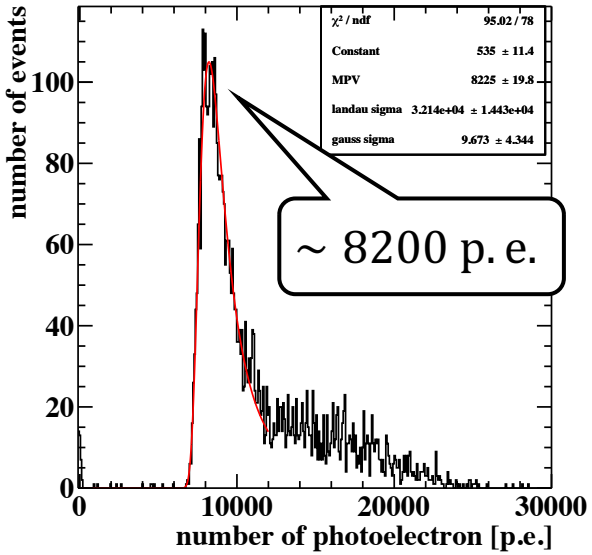
lightyield analysis

- 1 p.e. gain was calculated from dark count of MPPC
- Lightyield analysis was done with the low gain beam data
- Lightyield was far beyond the target (670 p.e.)

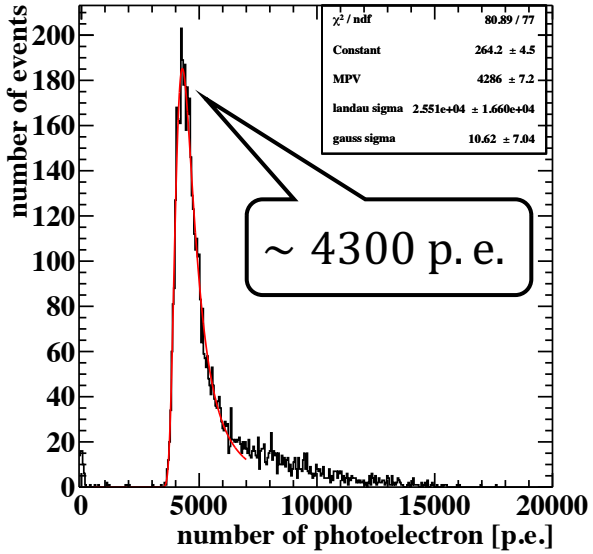




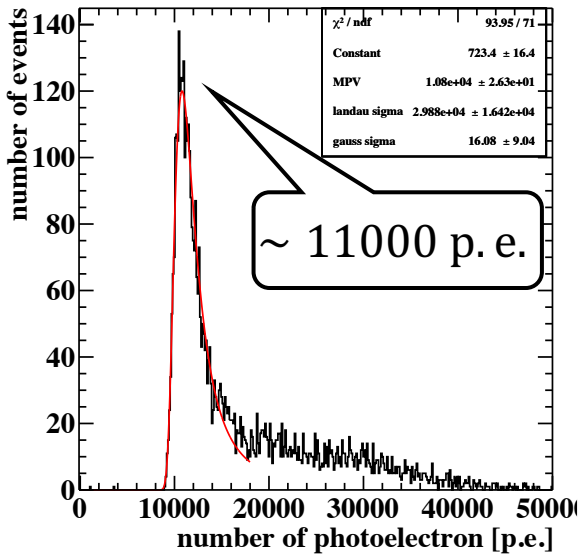
standard size
(3 mm×5 mm×50 mm)



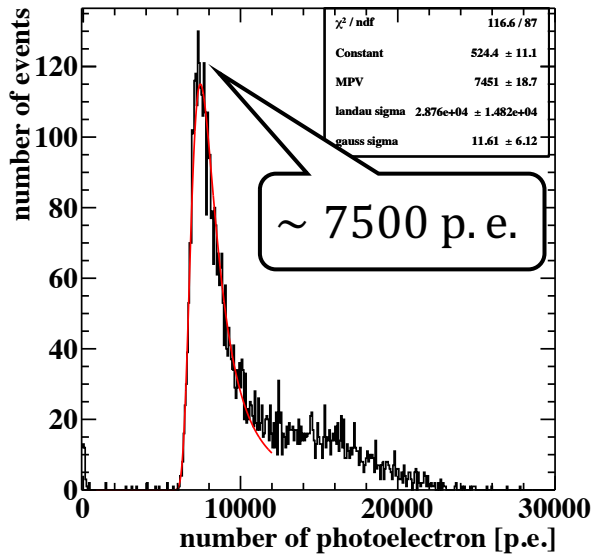
half thickness
(1.5 mm×5 mm×50 mm)



double width
(3 mm×10 mm×50 mm)



double length
(3 mm×5 mm×100 mm)



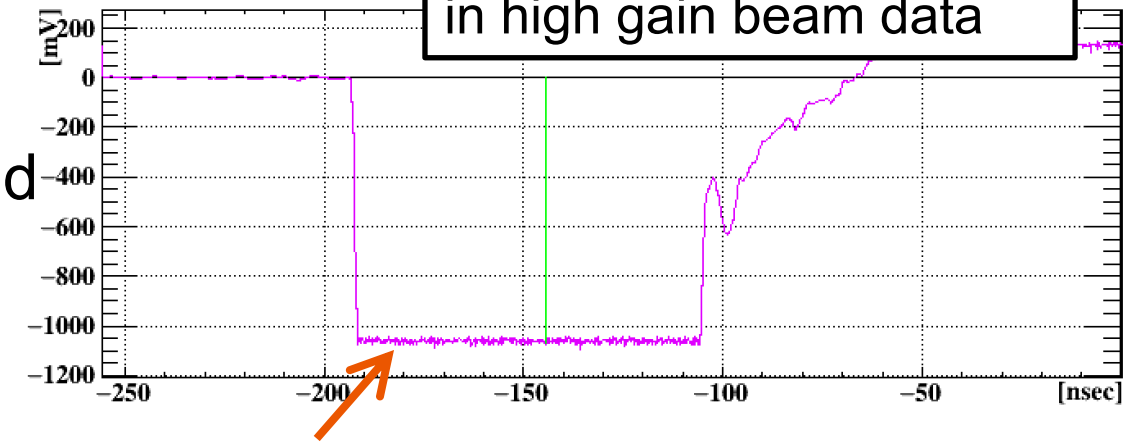
*in this analysis, gain of the electronics is assumed to have the nominal value

time resolution analysis method

- Operation in high gain (to focus on the early arrival photon)

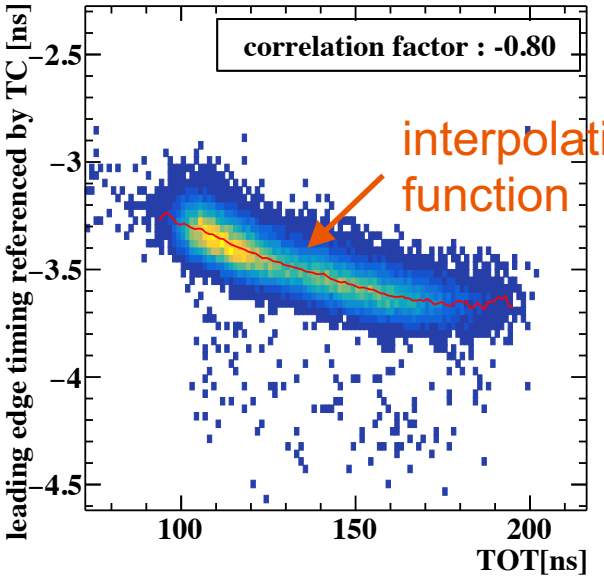
- Time pick-up : leading edge method
- Time walk correction : using time over threshold

typical waveform
in high gain beam data



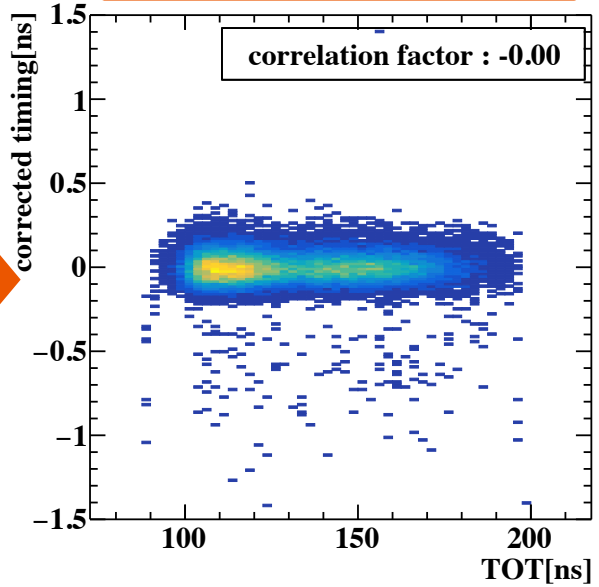
saturated waveform
due to the dynamic range of electronics

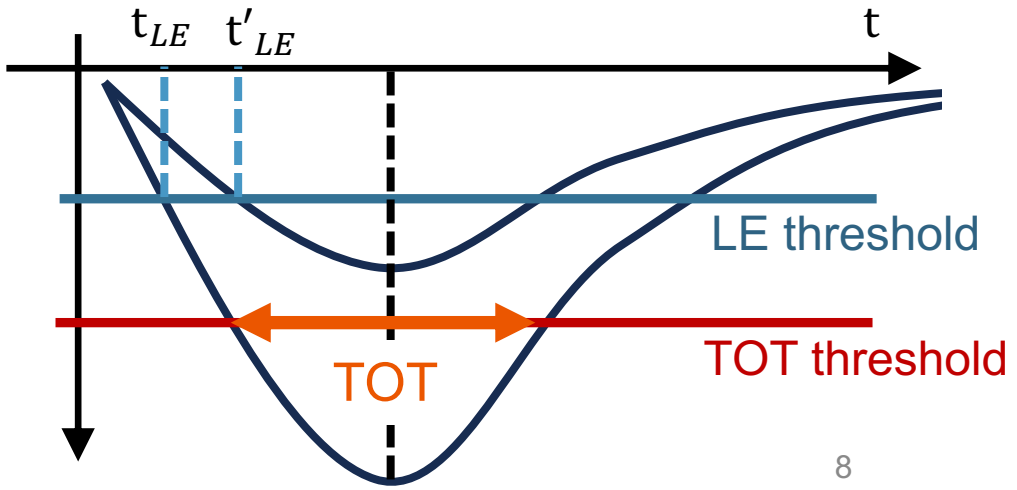
before correction



interpolation
function

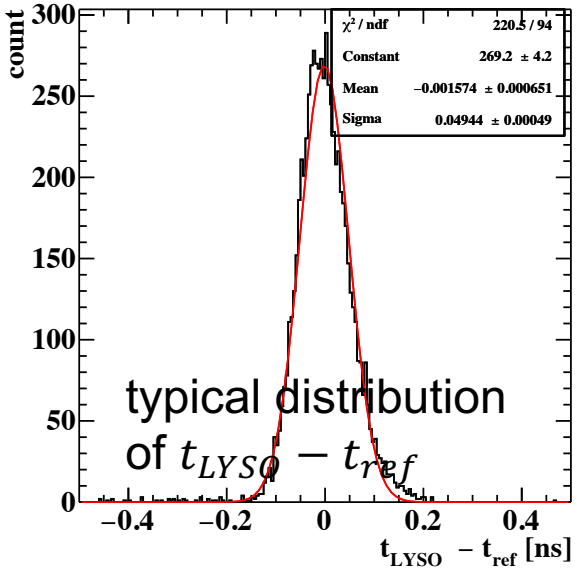
after correction



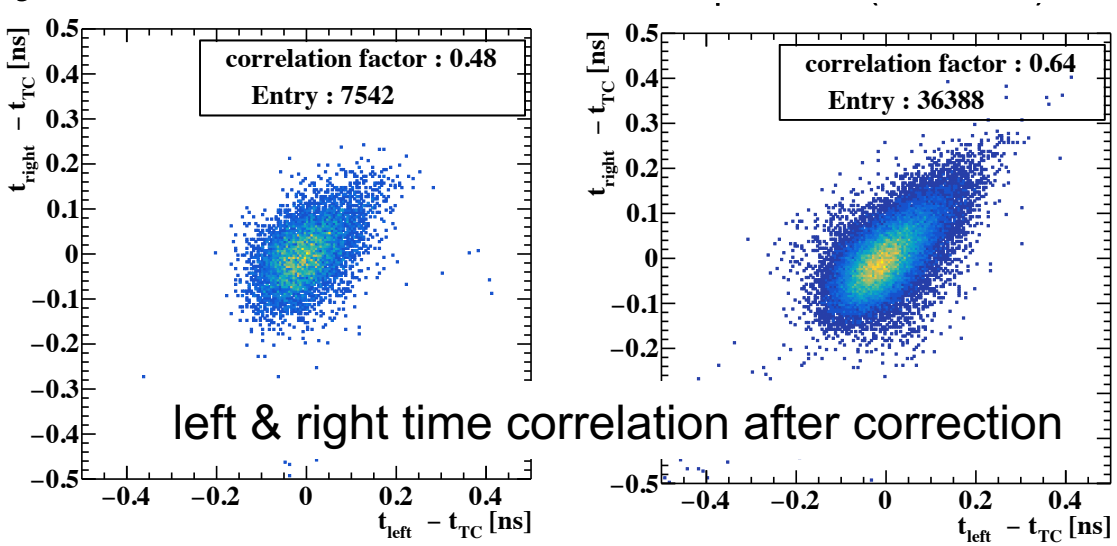


time resolution analysis result – LYSO size –

	Standard size (3 mm×5 mm×50 mm)	Half thickness (1.5 mm×5 mm×50 mm)	Double width (1.5 mm×5 mm×50 mm)	Double length (3 mm×5 mm×100 mm)
Independent readout	27.0 ps	36.1 ps	26.5 ps	30.4 ps
Series readout	29.4 ps	(no data taken)	27.6 ps	(no data taken)

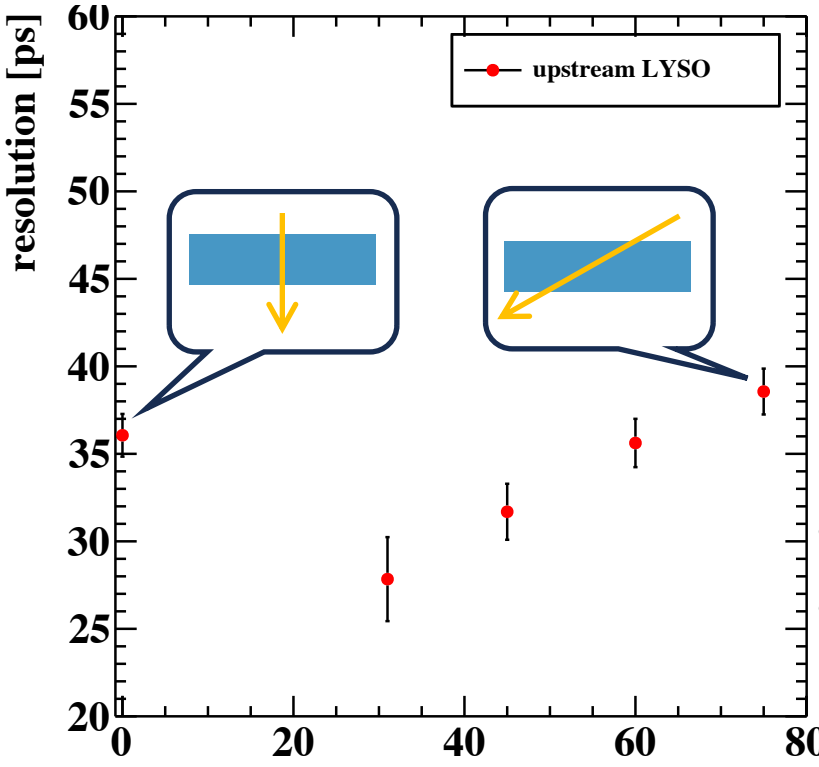


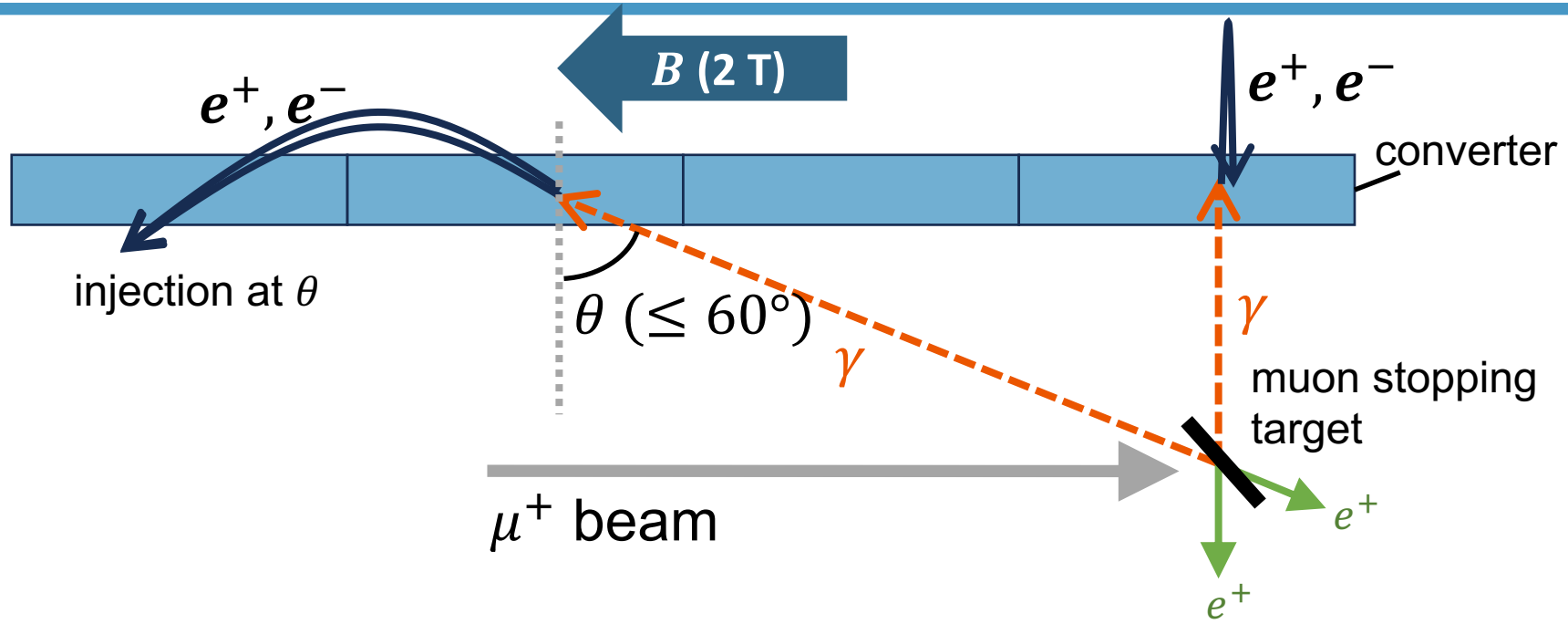
- Basically, LYSO size that had larger lightyield has better time resolution
- Independent readout has slightly better resolution by a few ps
  - This is due to the difference in the remaining time walk effect after correction
  - Correlation between timing of left channels and right channels → …stronger on series connection



time resolution analysis result – angle dependence –

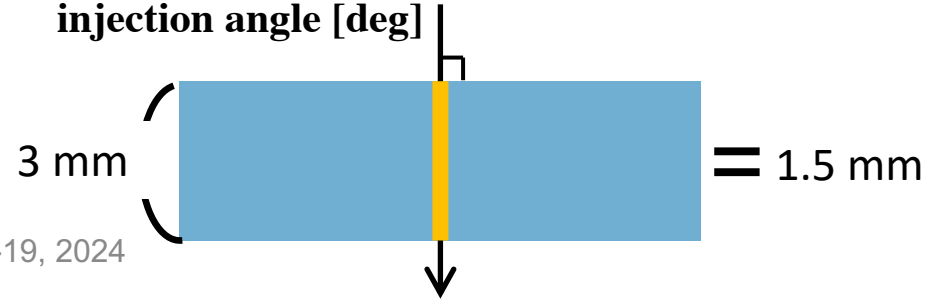
injection angle scan
(1.5 mm thickness LYSO)





- Injection angle will be steeper in the outer segments
- Steeper incident has longer effective thickness

➡ Outer converter should be thinner

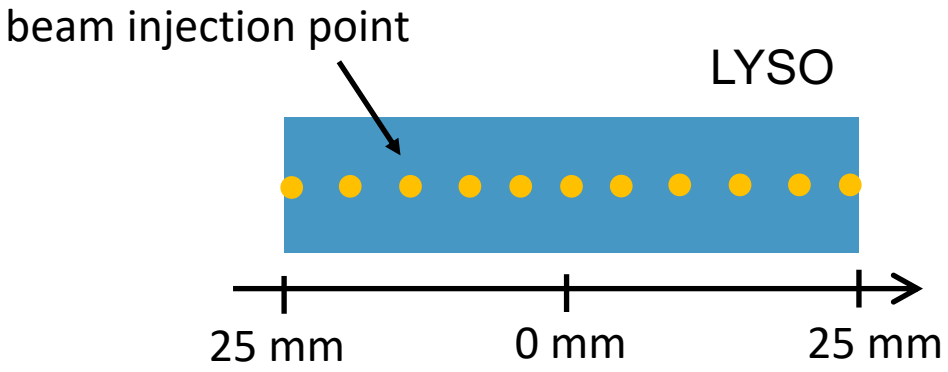


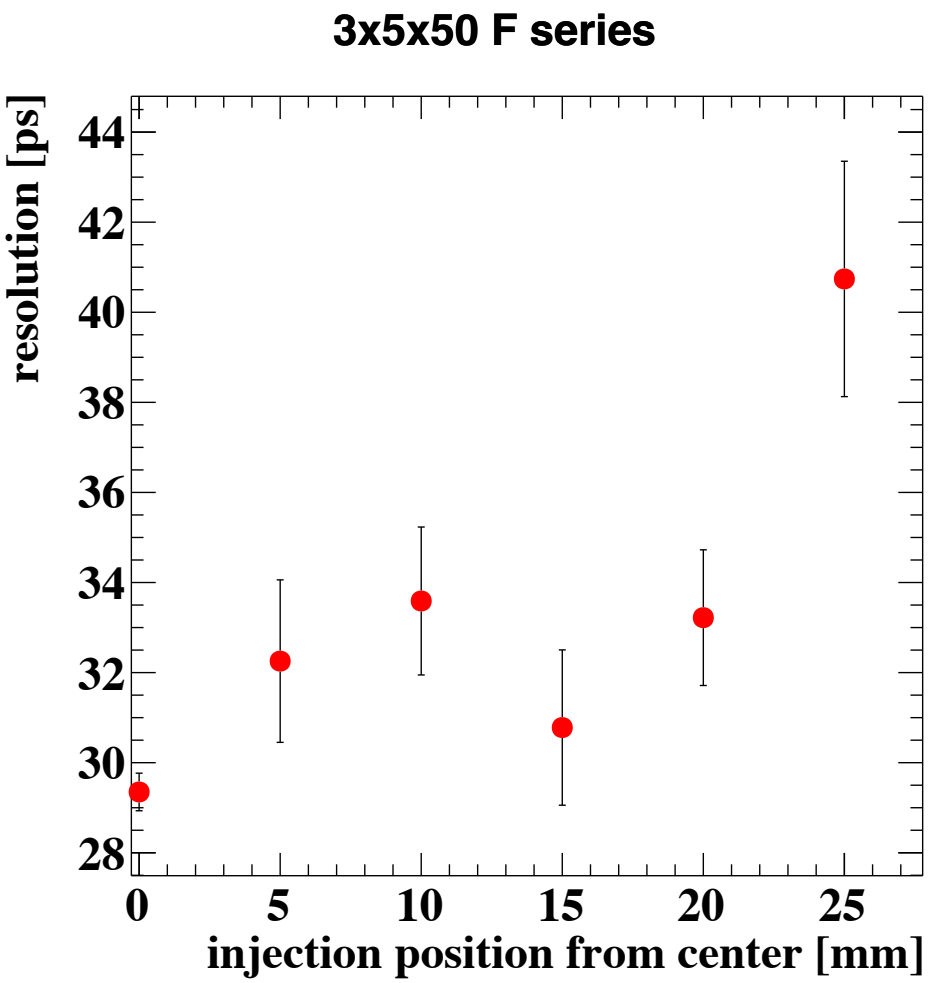
enough time resolution (35 ps) confirmed in this beamtest

time resolution analysis result – position dependence –

Except the injection on the most edge,

LYSO achieved the goal resolution of 40 ps with all injection position

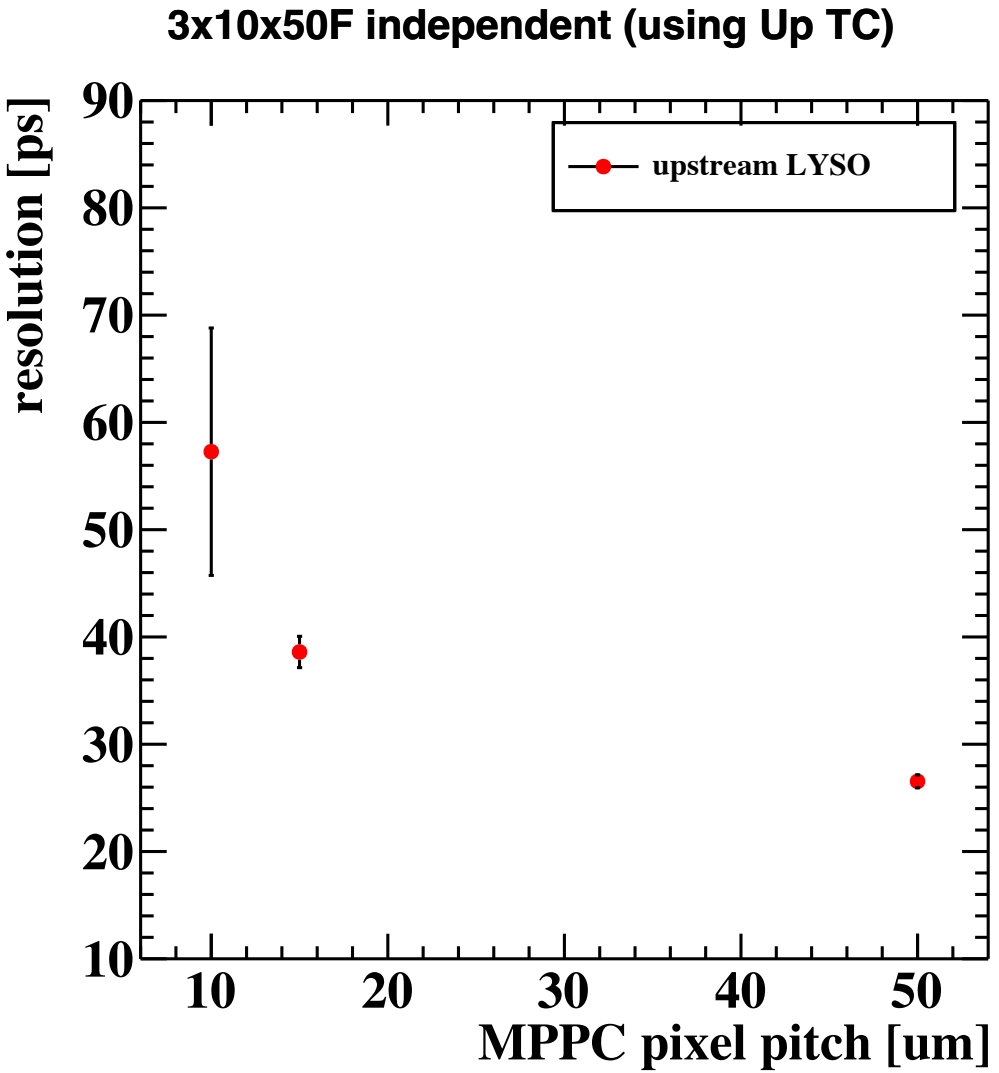




time resolution analysis result – pixel pitch comparison–

- Tested MPPCs with different pixel pitch
  - 10 μm (S14160-3010PS)
  - 15 μm (S14160-3015PS)
  - 50 μm (S14160-3050HS)

- 50 μm pixel pitch shows the best performance because of
  - high gain
  - high PDE



summary and prospect

summary

- Pair spectrometer with active converter is under R&D as a gamma detector for the future experiment for $\mu^+ \rightarrow e^+\gamma$ decay search.
- The beamtest result shows that requirement of energy and time resolution for a converter can be well achieved with LYSO.
- Active converter with 3 mm × 10 mm × 50 mm LYSO and 50 μm pixel pitch MPPC had the best performance in terms of energy & time resolution.

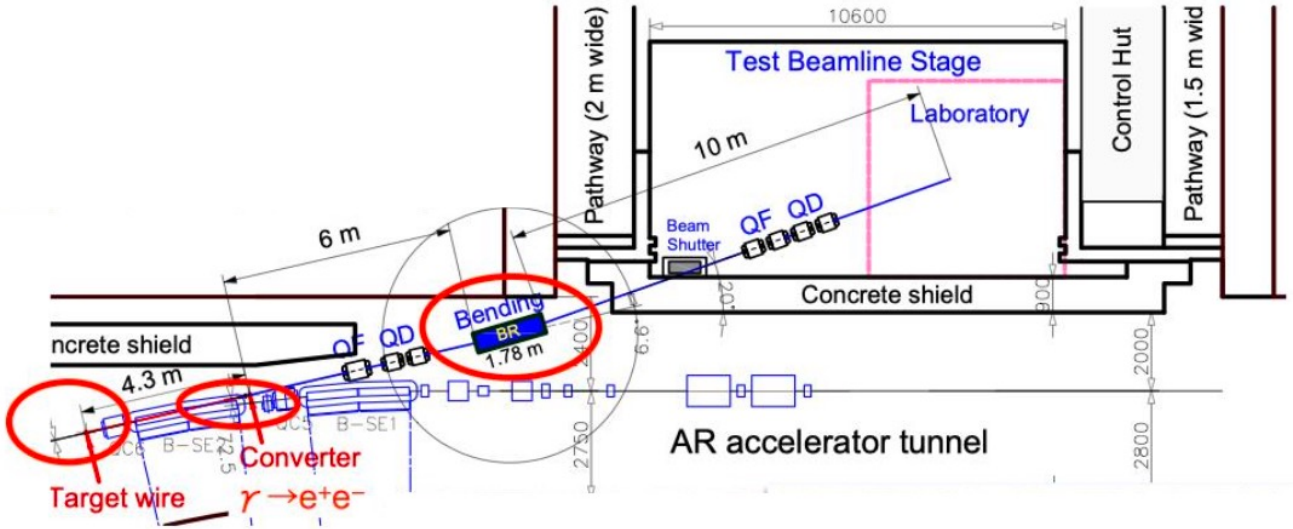
prospect

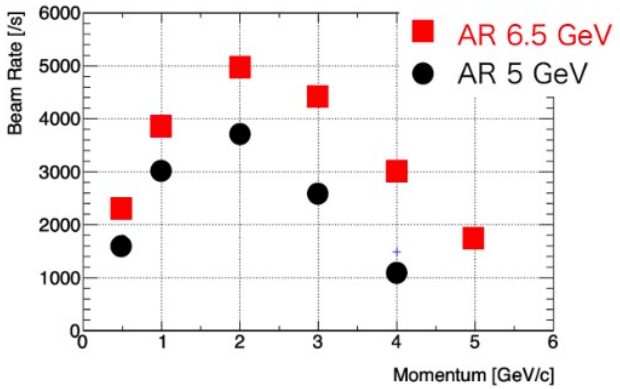
- Remaining time walk effect was seen even after the correction by TOT
  →improve correction by the charge information
- In the future experiment, timing and energy must be measured at the same time

➡ Beam test with high gain & low gain DAQ at the same time in Nov.-Dec. 2024

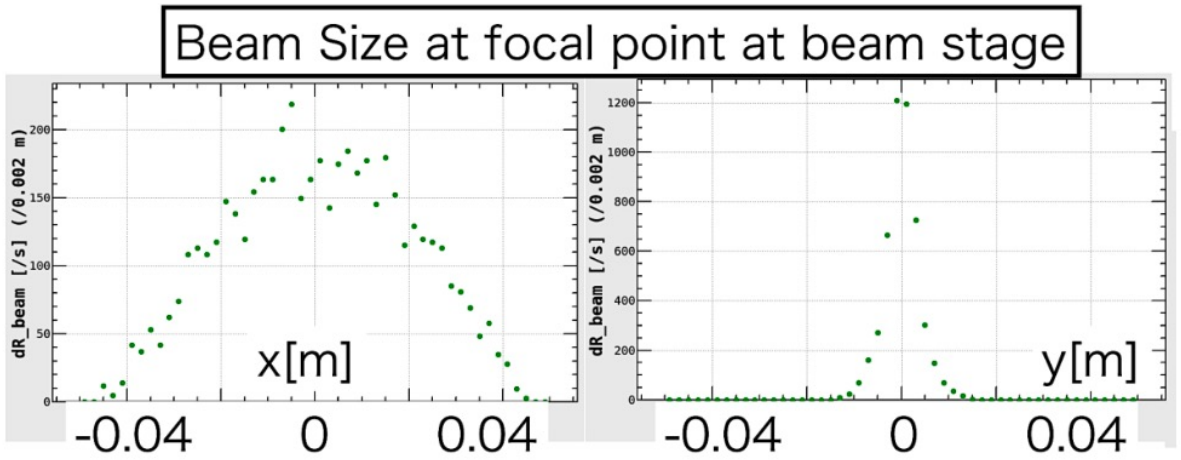
backup

KEK PF-AR test beam line





beam rate by momentum



requirements for the active converter

energy resolution

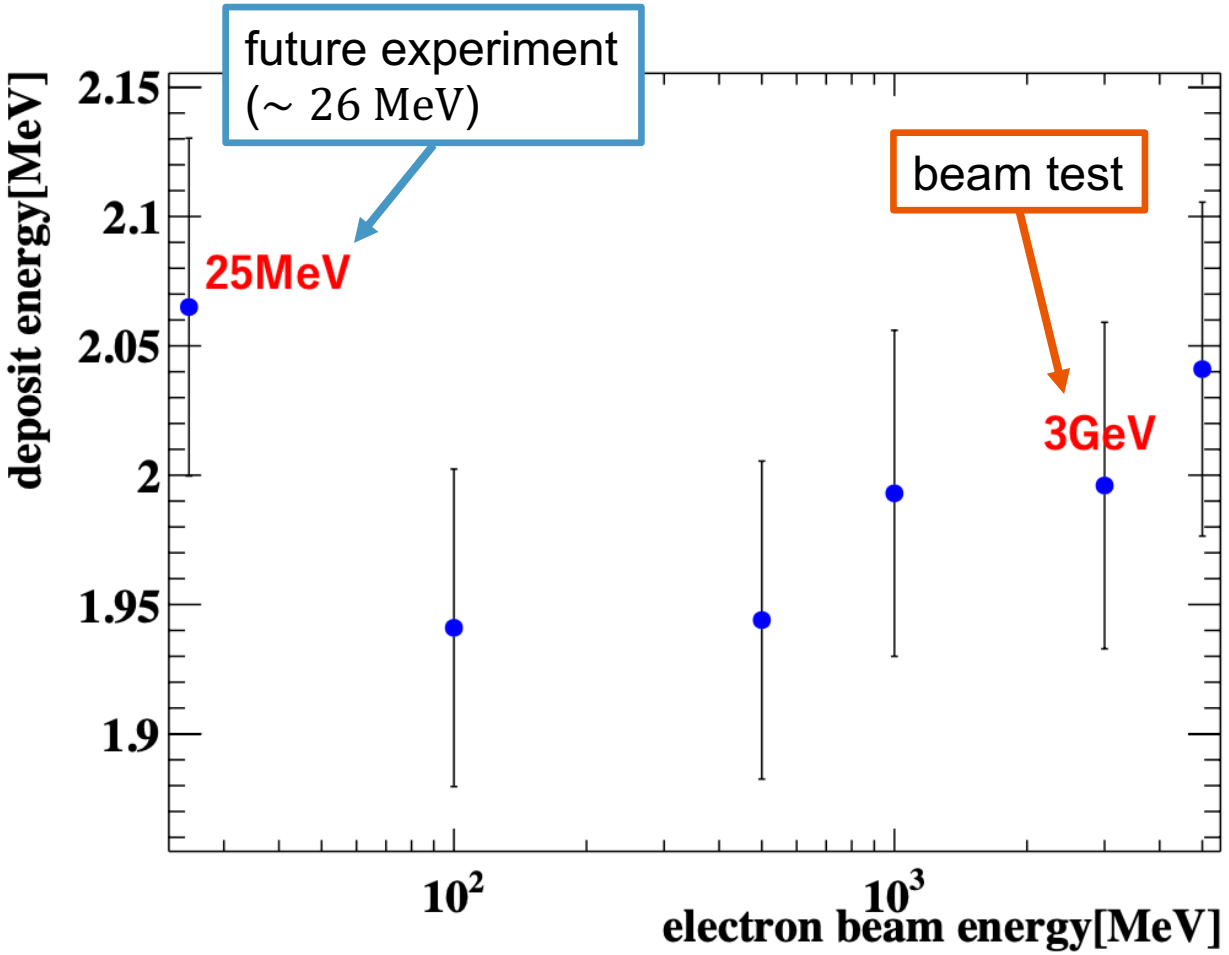
- $\frac{\Delta E}{E} \leq 0.4\ \%\ @E = 52.8\ \mathrm{MeV}$ for pair spectrometer
  $\rightarrow \Delta E \leq 211\ \mathrm{keV}$ for 2 MIP(e^+ & e^-)

- deposit energy of 2 MIP:
  $E' = 1.12\ \mathrm{MeV/mm} \times 3\ \mathrm{mm} \times 2 = 6.72\ \mathrm{MeV}$ (in 3 mm thickness LYSO)
  $\rightarrow \frac{\Delta E}{E'} = \frac{1}{\sqrt{N_{\mathrm{p.e.}}}} \leq \frac{211\ \mathrm{keV}}{7.72\ \mathrm{MeV}} = 2.73\ \%$
  $\rightarrow N_{\mathrm{p.e.}} \geq 1341$ for 2 MIP
  $\rightarrow N_{\mathrm{p.e.}} \geq 671$ for 1 MIP

time resolution

- $\Delta t = 30\ \mathrm{ps}$ for pair spectrometer $\rightarrow 30 \times \sqrt{2} = 42$ ps for 1 MIP

deposit energy by electron in different energy



(R.Yokota, 2023 thesis)

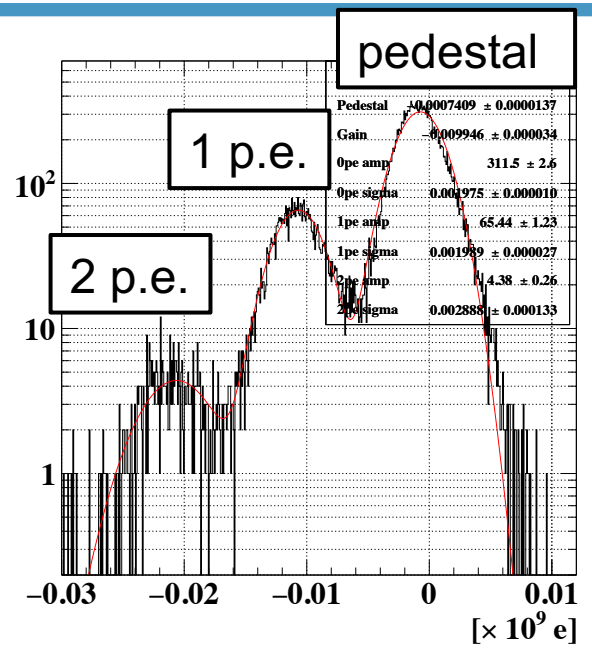
- deposit energy in LYSO was simulated with various electron beam energies
- deposit energy in LYSO of 3 GeV electron was almost identical to that of 25 GeV electron

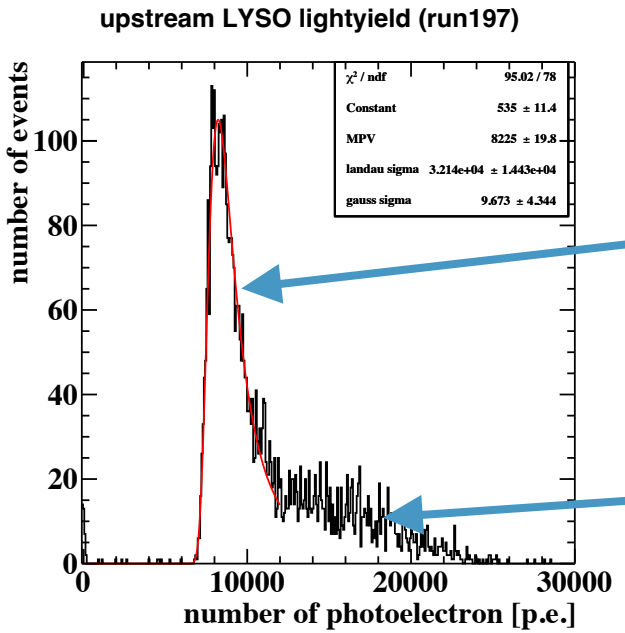
the resolution obtained in the beam test could be applied to the future experiment

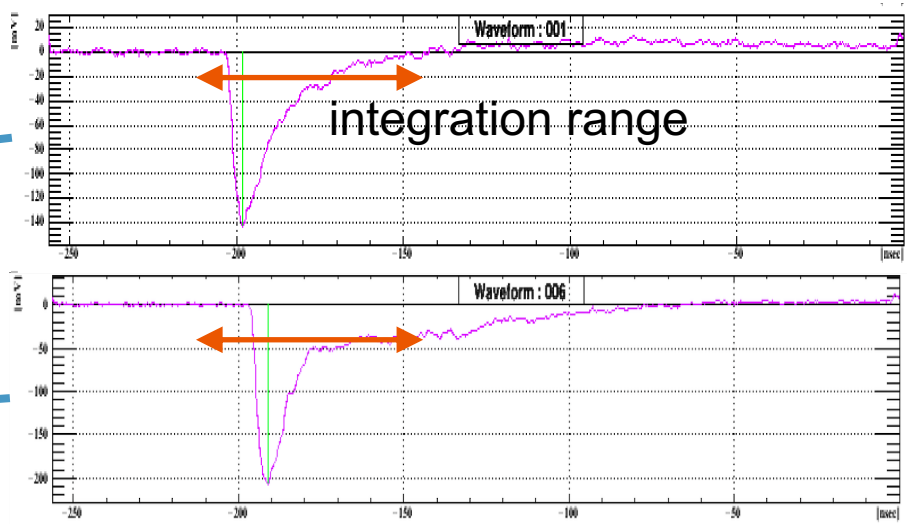
lightyield analysis method

1. estimate 1 p.e. gain with the dark count of MPPC
2. obtain charge from the low gain beam where full waveform is recorded
3. estimate the detected number of photoelectrons at LYSO by

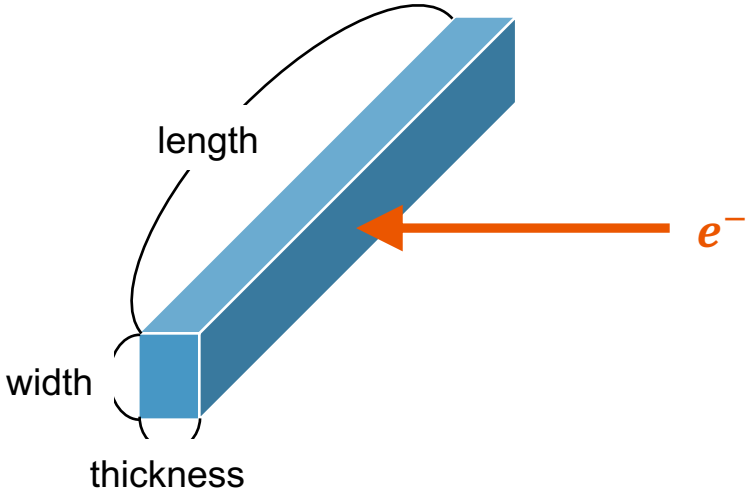
$$N_{p.e.} = \sum_{i=\text{MPPC channels}} \frac{(\text{ch } i \text{ charge})}{(\text{ch } i \text{ 1 p.e. gain})}$$

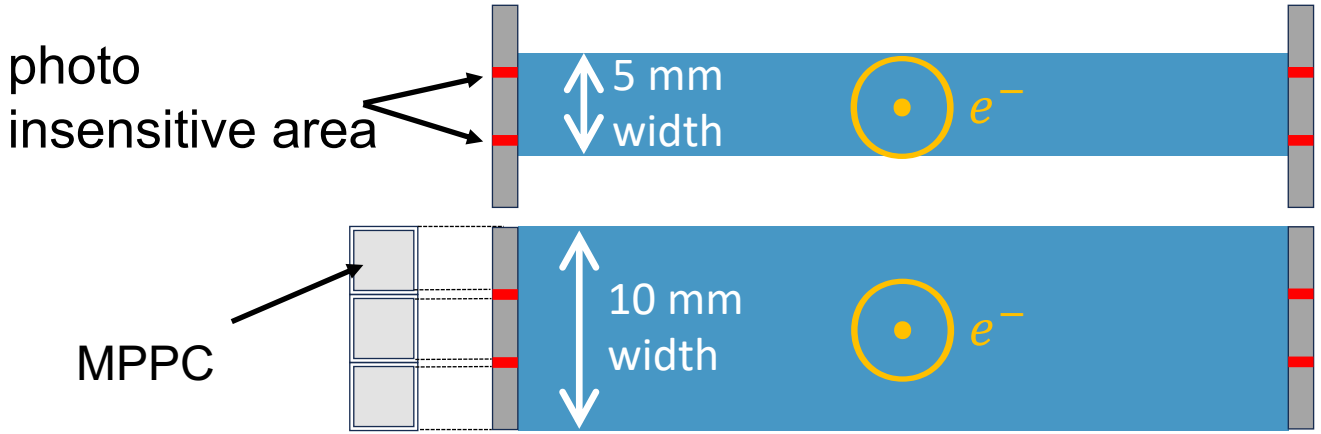






lightyield analysis result





LYSO size	Standard (3mm x 5mm x 50mm)	Half thickness	Double width	Double length
Lightyield [p.e.]	8344 ± 22	4345 ± 9	10900 ± 29	7564 ± 20

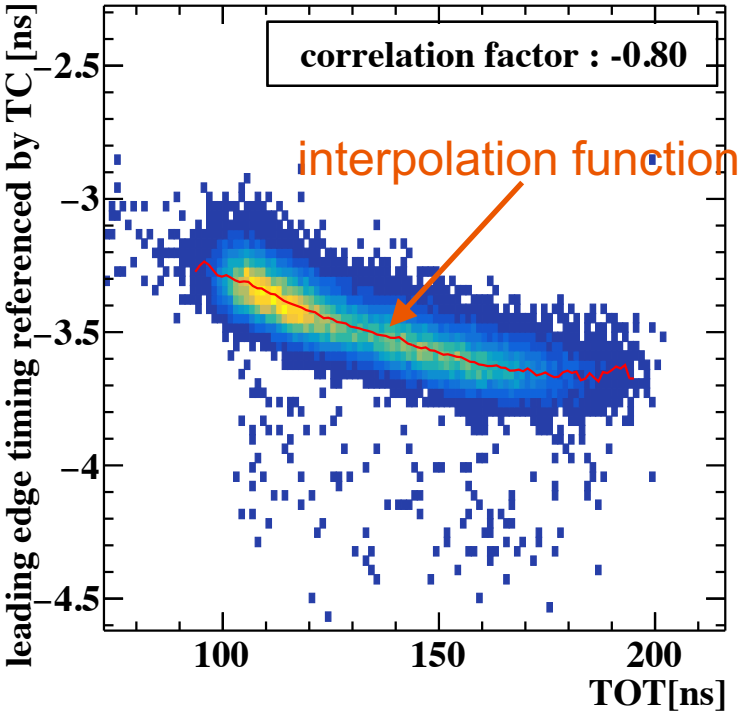
- thickness : lightyield decreases in proportion to the thickness
- width : wider LYSO have smaller ratio of photo-insensitive area
- length : longer LYSO is more susceptible to the attenuation of scintillation light

LYSO of all size achieved the goal of $N_{p.e.} > 670$

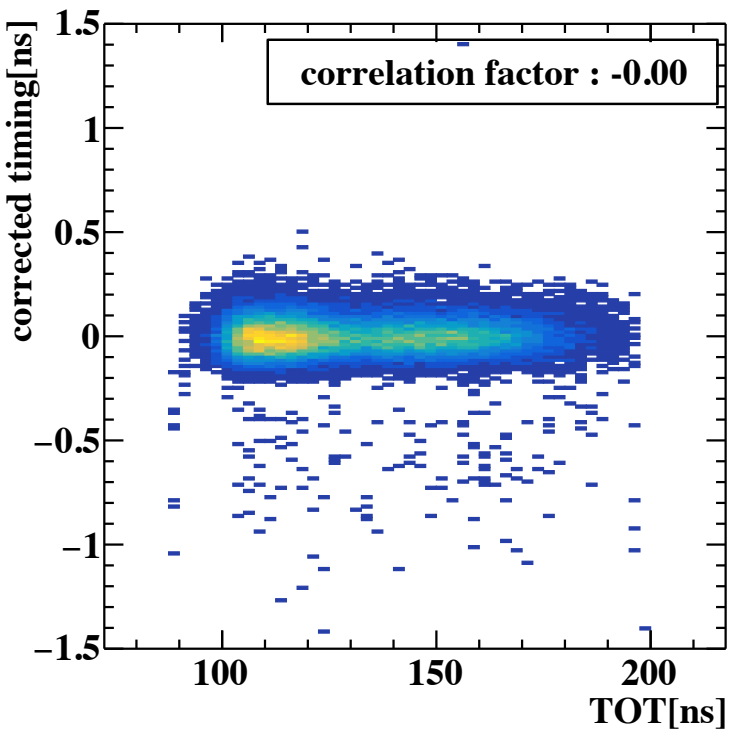
($N_{p.e.} > 168$ for half thickness)

time walk correction

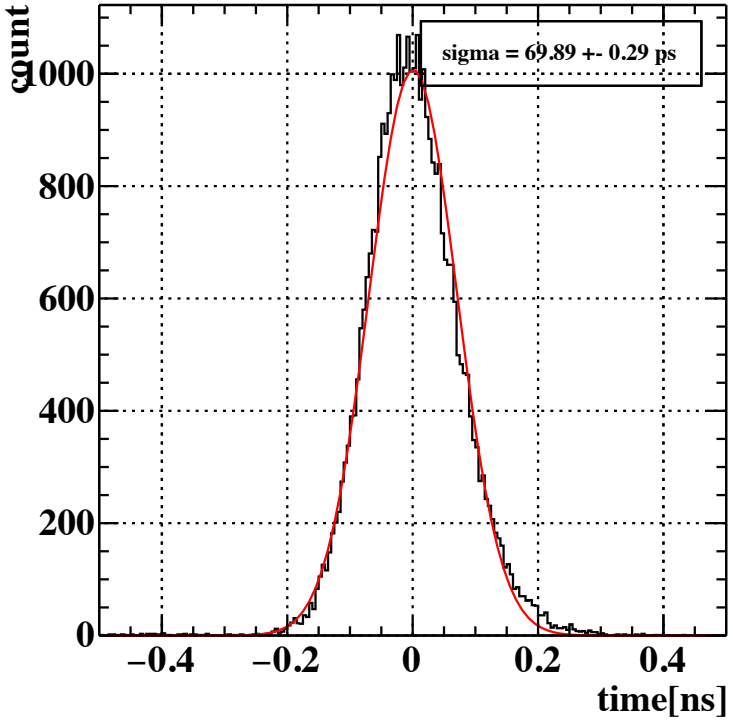
before time walk correction



after time walk correction



corrected time distribution



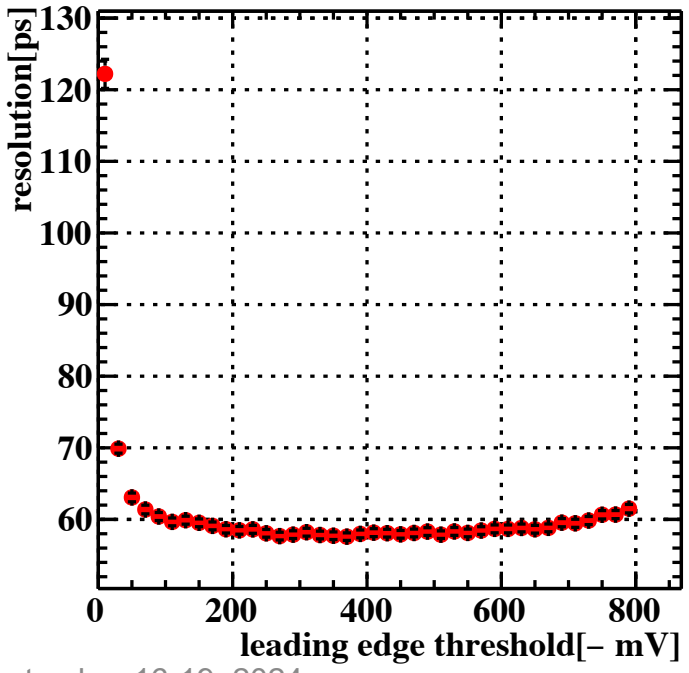
1. look at the correlation between $t_{LE} - t_{ref}$ and TOT, and get the interpolation function
2. subtract interpolation function from the datapoint
3. obtain resolution from a σ of a gaussian fit of corrected time

optimization of the thresholds

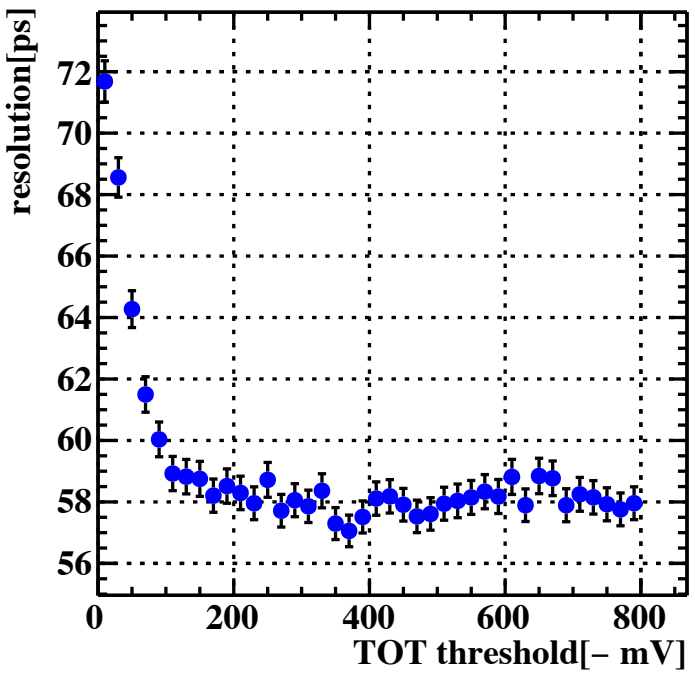
thresholds to be optimized:

1. leading edge threshold for each LYSO channel
2. TOT threshold for each LYSO channel
3. leading edge threshold for time reference counter

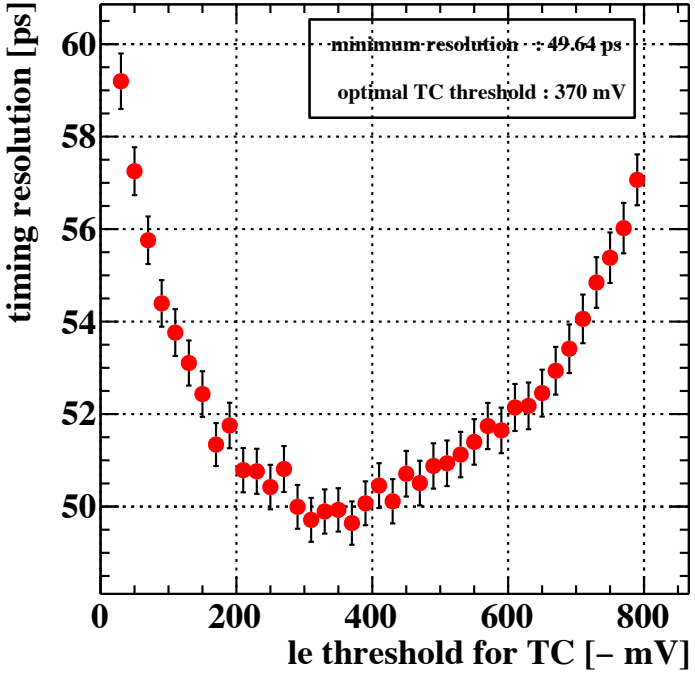
LE threshold scan



TOT threshold scan



LE threshold scan for reference TC

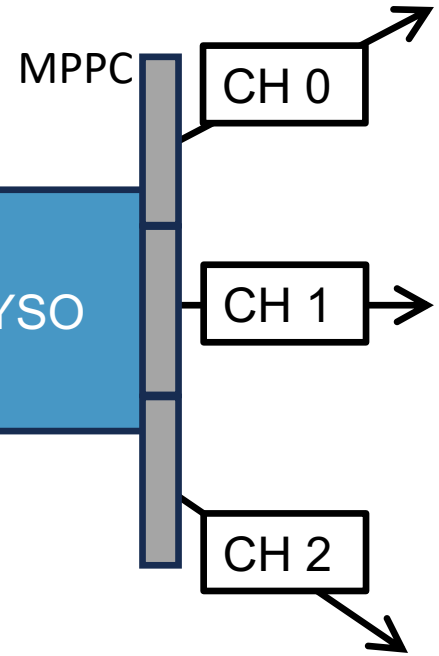


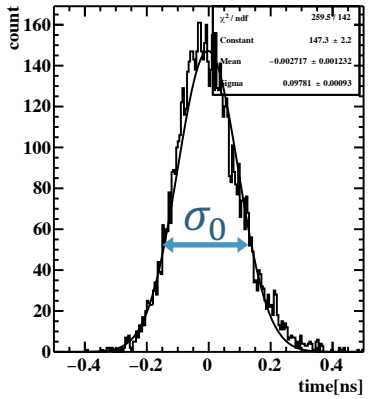
timing decision by multiple MPPC channels

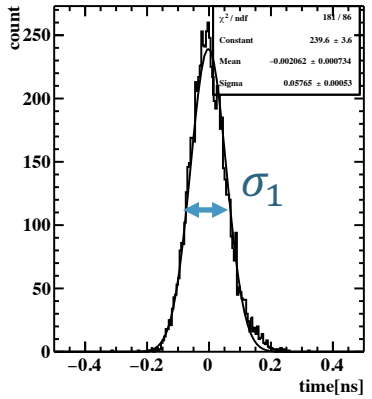
- asymmetry in lightyield in 3 channels(independent connection)
  →decide timing of LYSO by the weighted average of MPPC channels

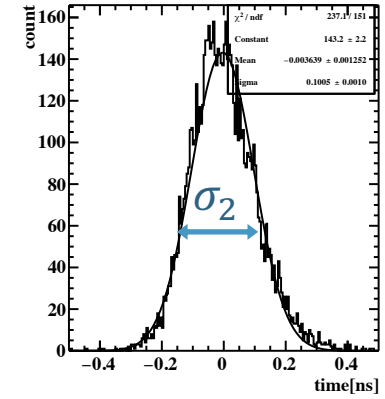
- weight $\propto 1/\sigma_i^2$
  (σ_i: time resolution of 1 MPPC channel)

$$t_{\mathrm{LYSO}} - t_{\mathrm{ref}} = \sum_{\mathrm{channels}} w_i (t_i - t_{\mathrm{ref}})$$









center MPPC channels (larger p.e.) are
weighted more than the edge MPPC channels (smaller p.e.)

estimation of contribution from reference counter

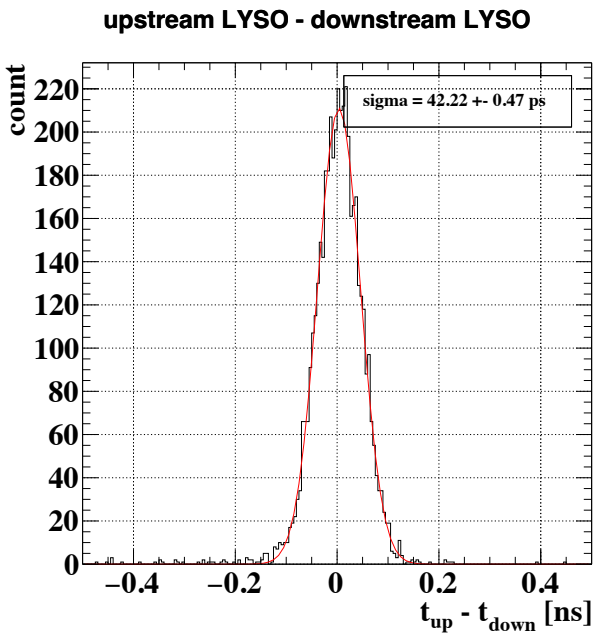
$$\sigma(t_{\mathrm{UpLYSO}} - t_{\mathrm{ref}}) = \sqrt{\sigma^2_{\mathrm{UpLYSO}} + \sigma^2_{\mathrm{ref}}}$$

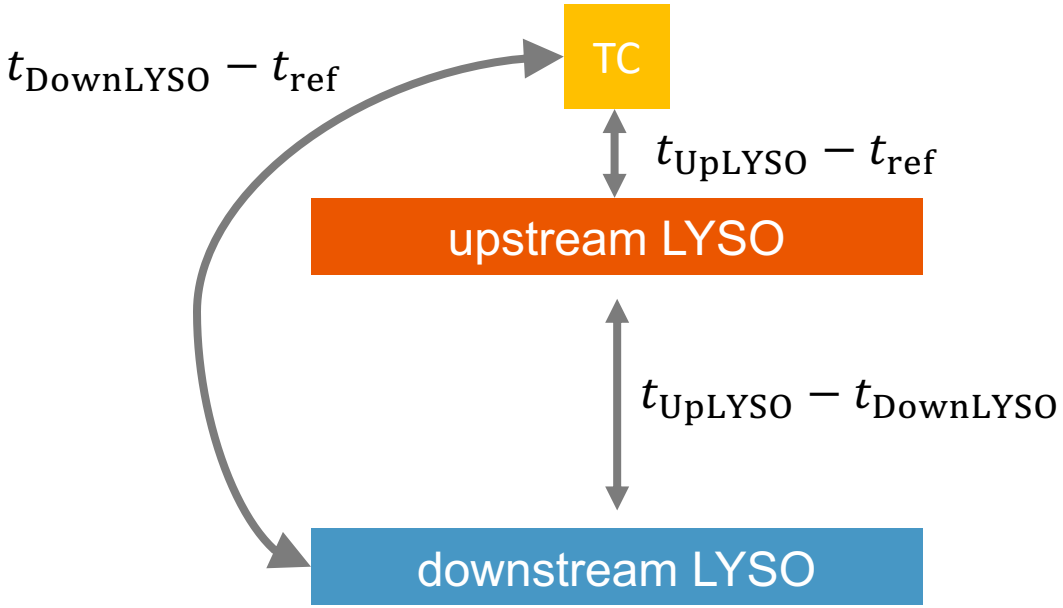
$$\sigma(t_{\mathrm{DownLYSO}} - t_{\mathrm{ref}}) = \sqrt{\sigma^2_{\mathrm{DownLYSO}} + \sigma^2_{\mathrm{ref}}}$$

$$\sigma(t_{\mathrm{UpLYSO}} - t_{\mathrm{DownLYSO}}) = \sqrt{\sigma^2_{\mathrm{UpLYSO}} + \sigma^2_{\mathrm{DownLYSO}}}$$

$$(t_{\mathrm{UpLYSO}} - t_{\mathrm{ref}}) - (t_{\mathrm{DownLYSO}} - t_{\mathrm{ref}})$$

able to calculate each σ_{UpLYSO}, $\sigma_{\mathrm{DownLYSO}}$ and σ_{ref}

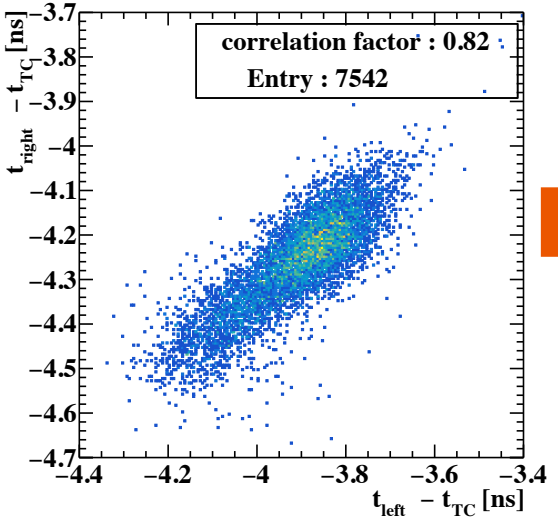




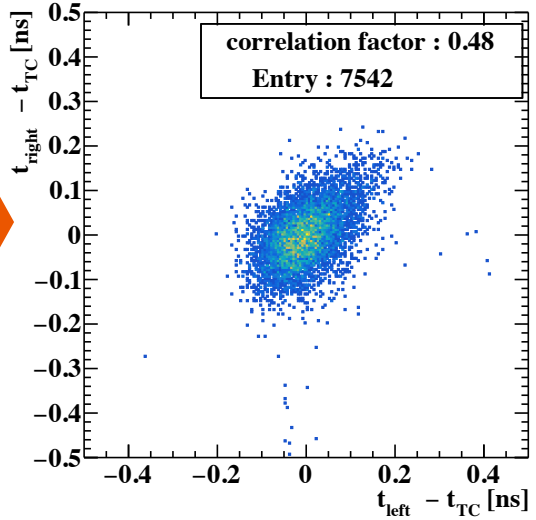
remaining time walk effect

independent connection

before correction

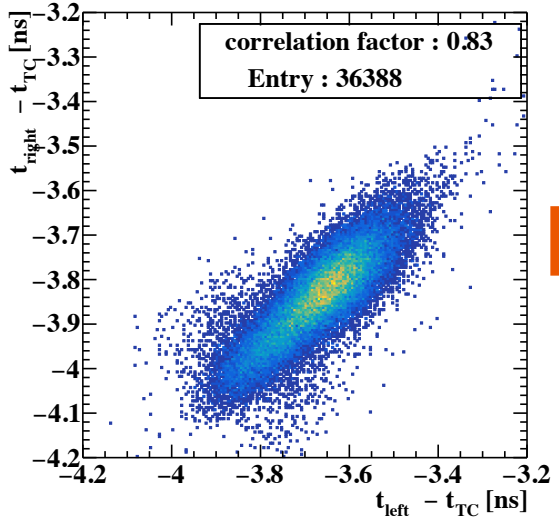


after correction

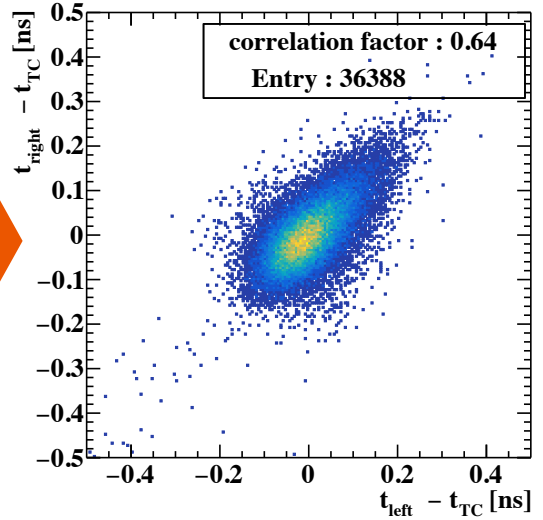


series connection

before correction

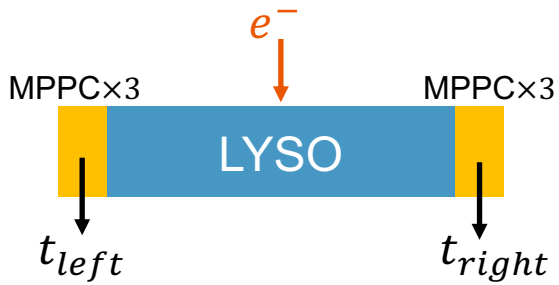


after correction



- if the time walk effect exists, t_{left} and t_{right} will correlate stronger

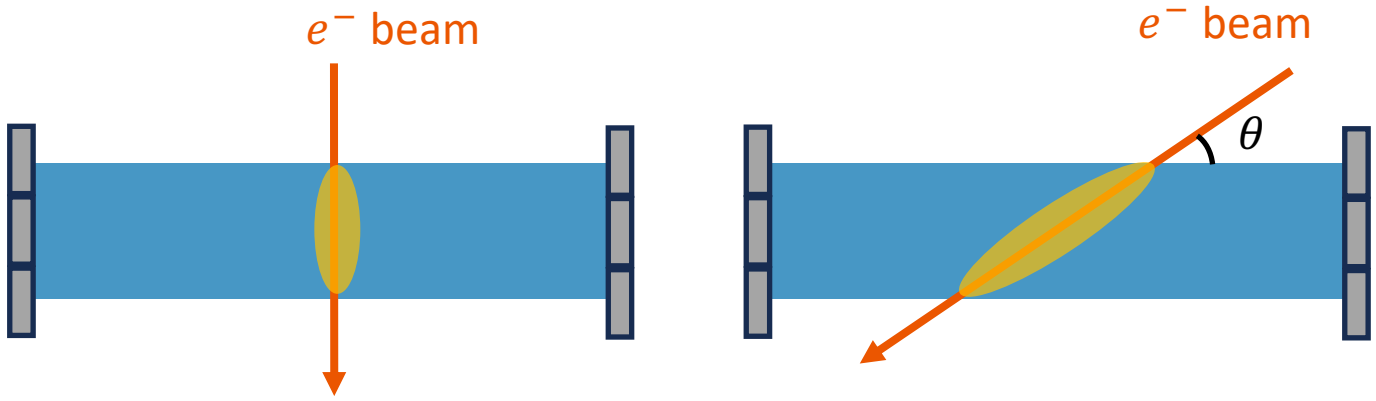
  larger lightyield → faster timing
  smaller lightyield → slower timing
  } in both sides

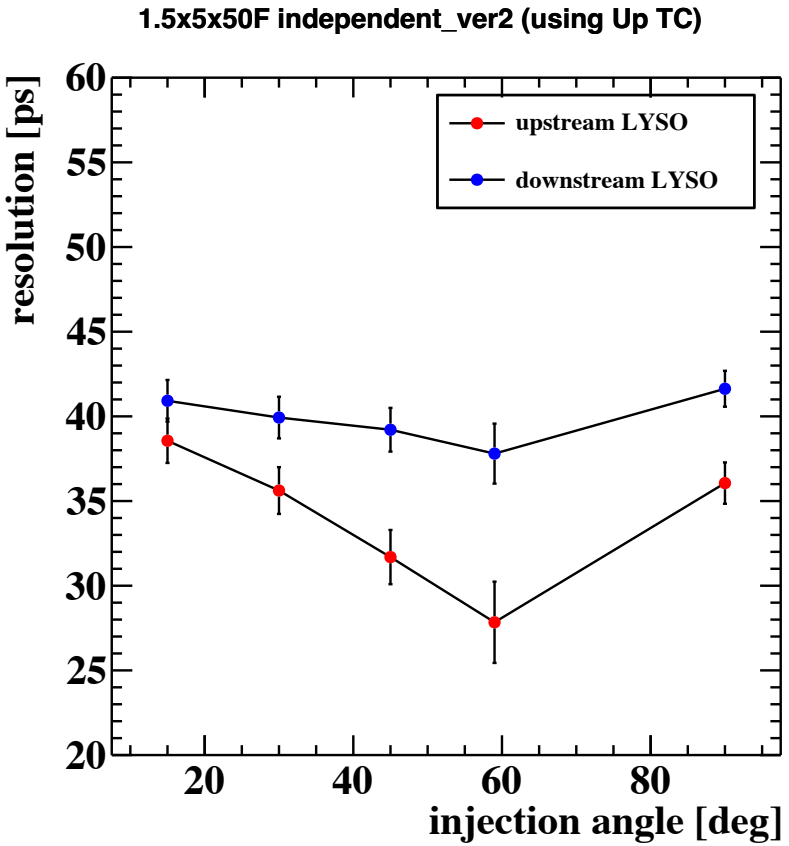


- series connection had stronger time walk effect left even after the correction by TOT

※$t_{left} - t_{TC}$ and $t_{right} - t_{TC}$ will have a small correlation even if there is no walk effect, because of t_{TC}

time resolution analysis result – angular dependence –

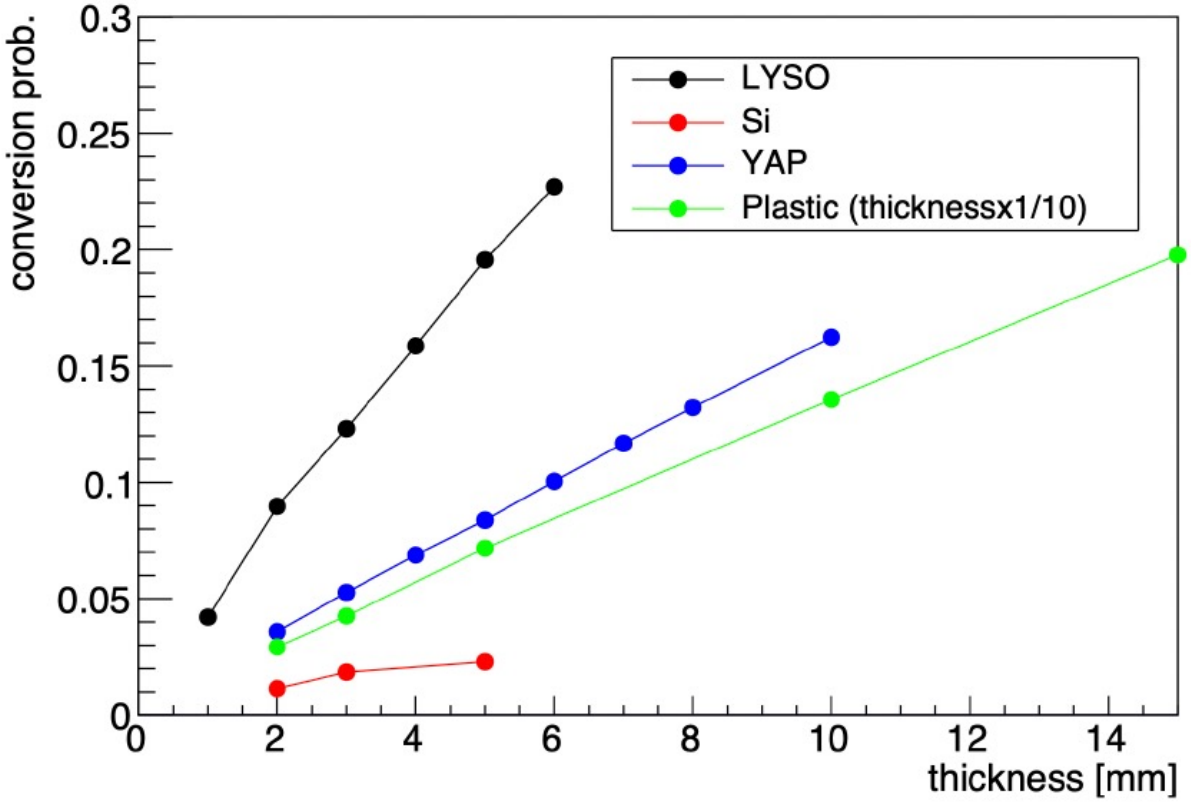




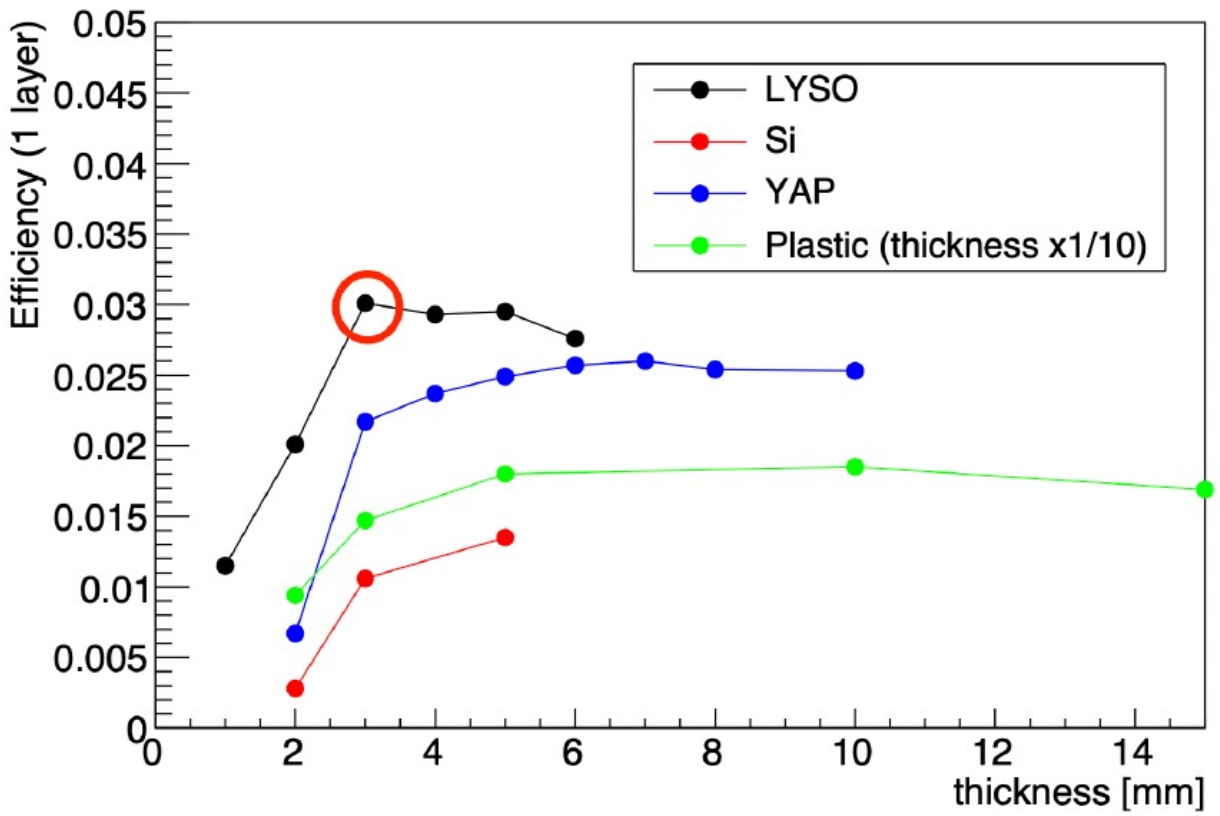
- steeper injection angle event has
  - more lightyield
    → improve time resolution
  - larger expansion in photon emission region
    → worsen time resolution

LYSO achieved the goal resolution of 42 ps with all injection angle

comparison between material & thickness



(a) 異なる材質ごとの厚みに対するコンバージョン確率

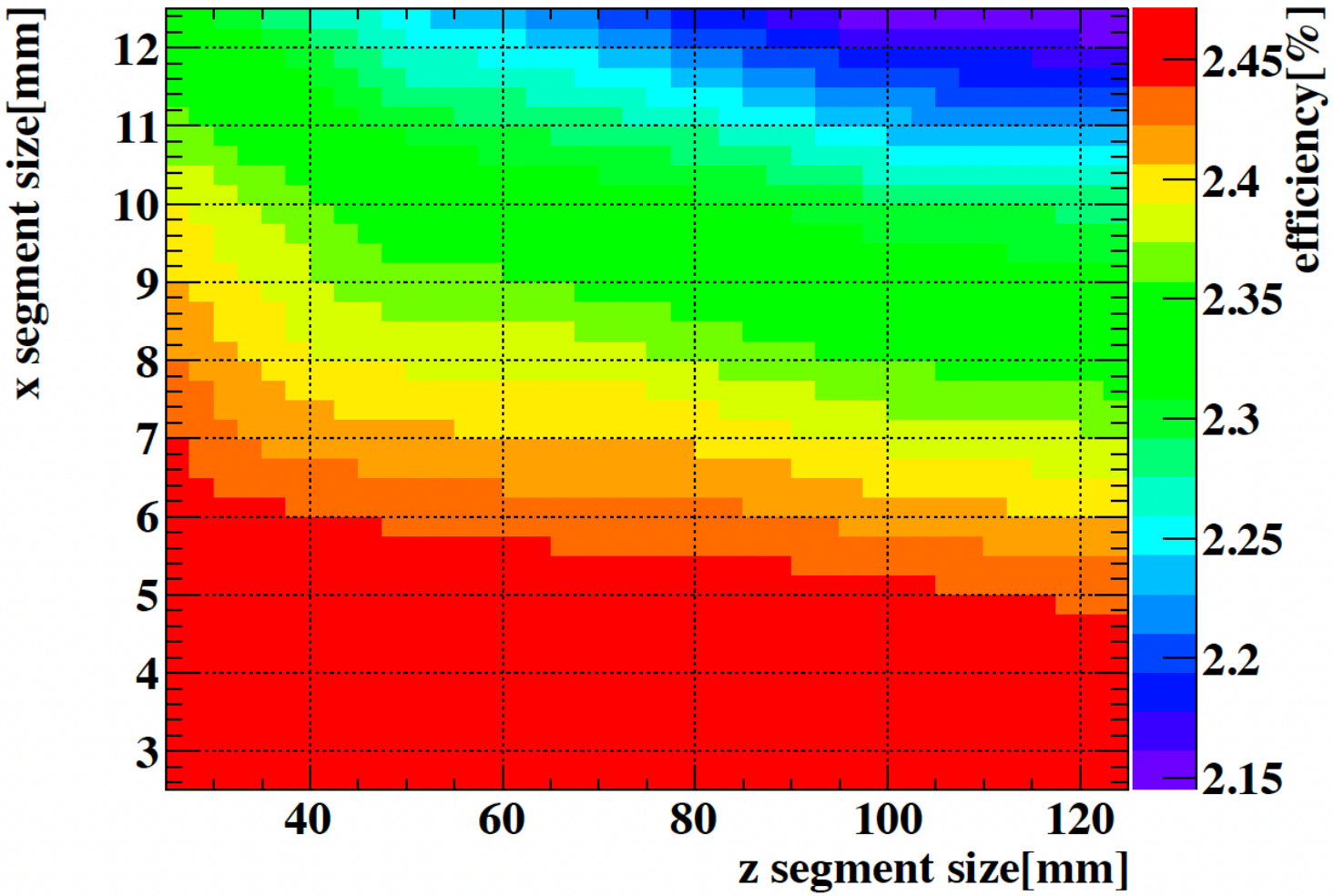


(b) 異なる材質ごとの厚みに対する検出効率

- conversion probability
- energy loss due to the bremsstrahlung

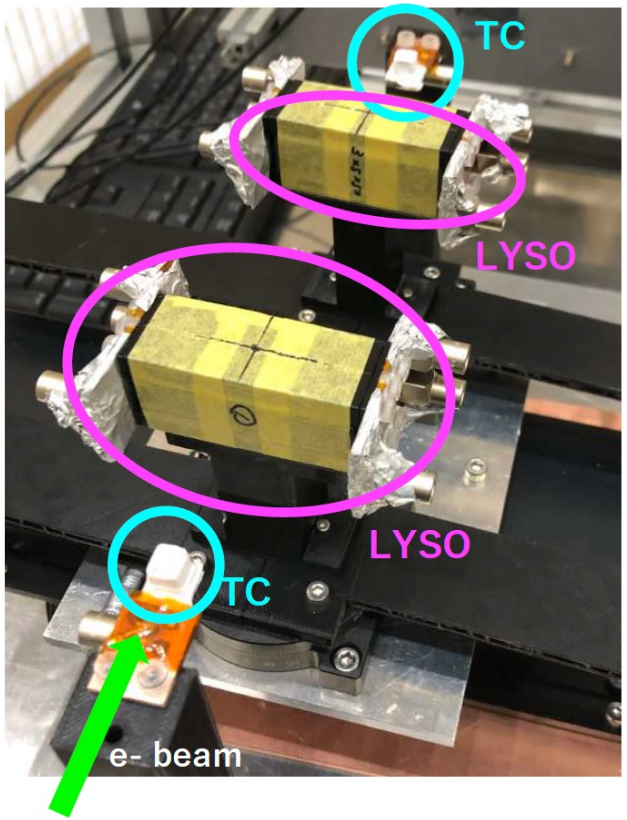
} increase with thickness

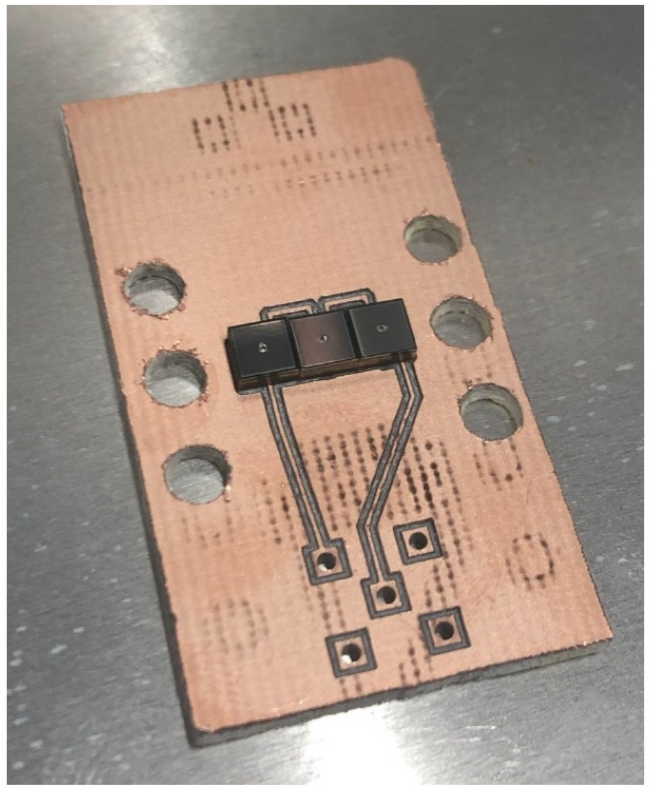
→ best balance at 3 mm thickness

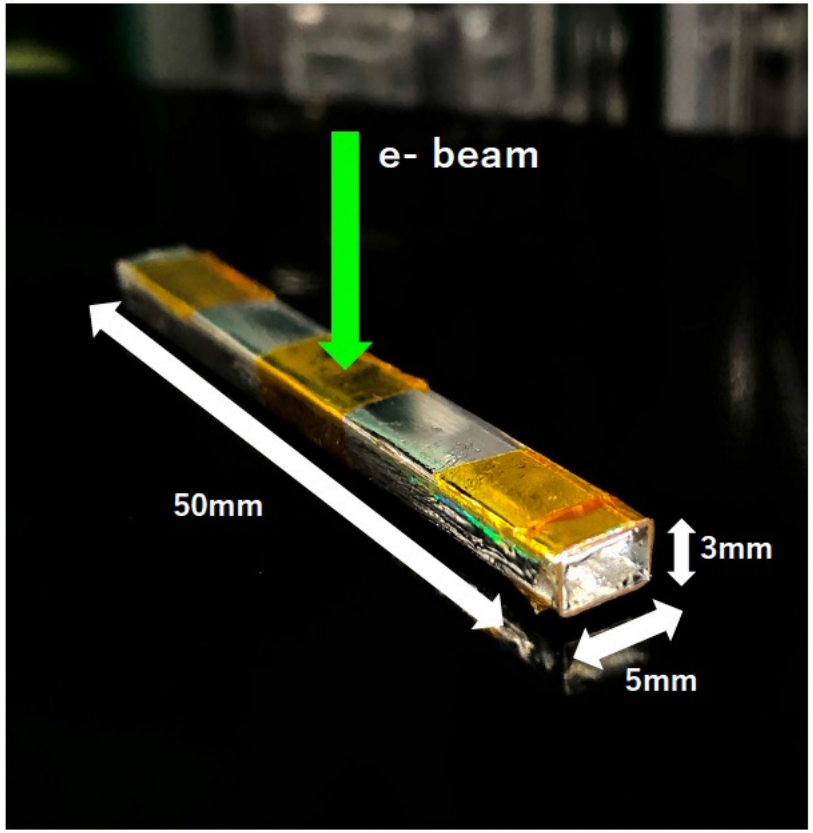


efficiency in 3 mm thickness LYSO

pictures





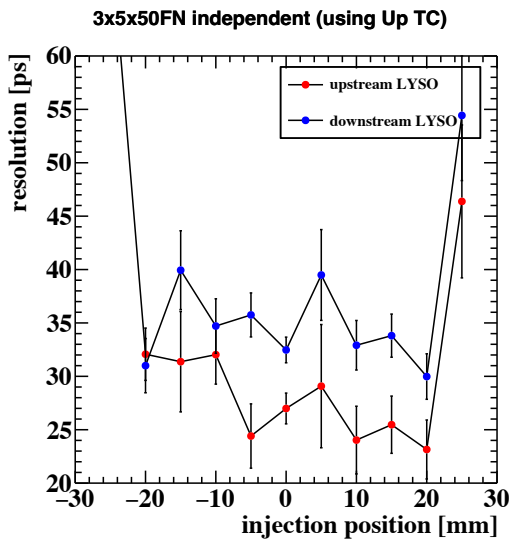


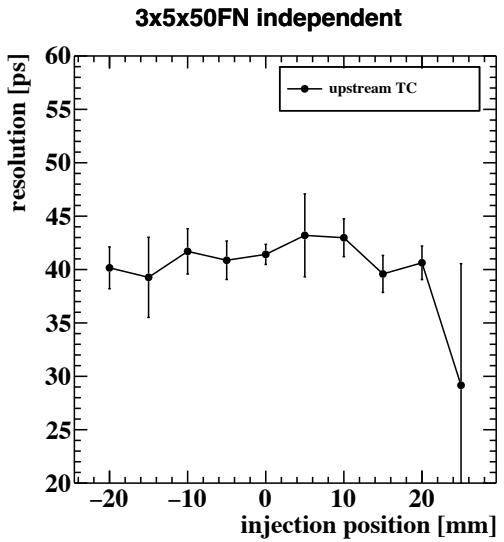
ピクセルサイズ	小 ◀——▶ 大
増倍率	
検出効率	
ダイナミックレンジ	
高速応答性	

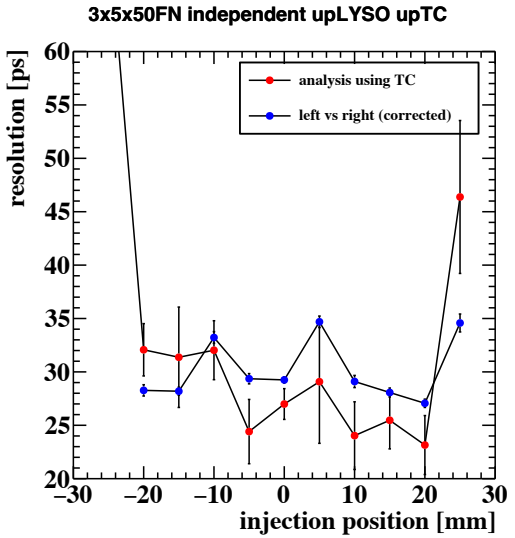
JTC's Scintillation Product Information

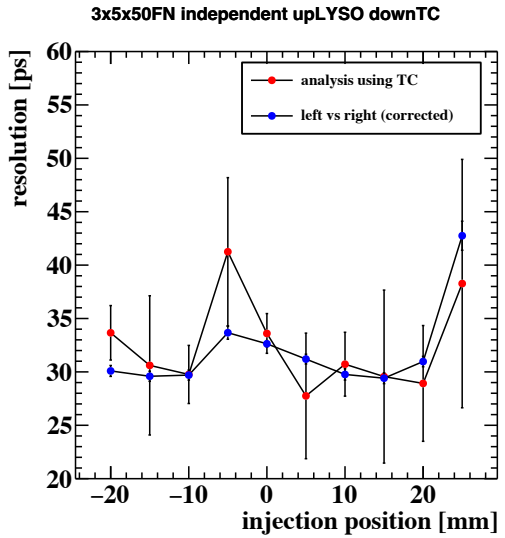
Properties	Ce:FTRL	Ce:LYSO	YSO
Coincident Time Resolution(ps) 2mm cube	96	125	
LO (Ph/MeV)	30000±10%	36000±10%	27000
Decay Time (ns)	31	40	70
Energy Resolution	8-10%	8-10%	11%
Hygroscopic	No	No	No
Wavelength of Max Emission (nm)	420	420	420
Refractive Index	1.81	1.81	1.8
Density (g/cm3)	7.2	7.2	4.5

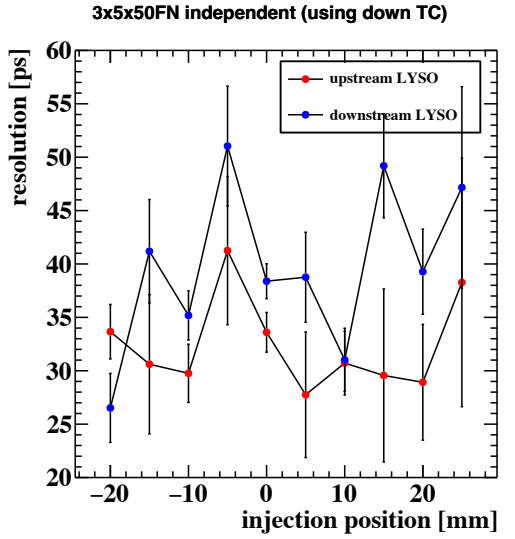
3 x 5 x 50 F&N (independent) position scan

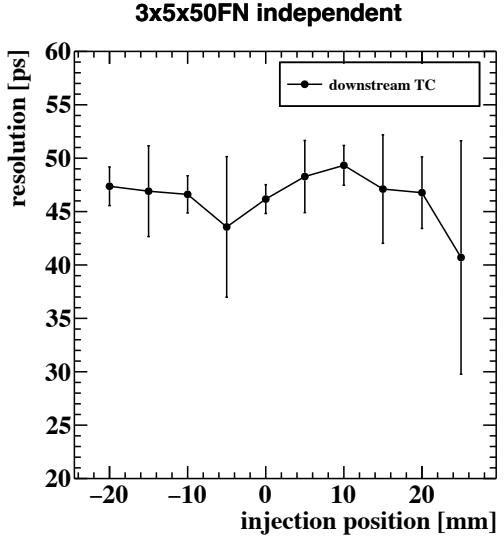


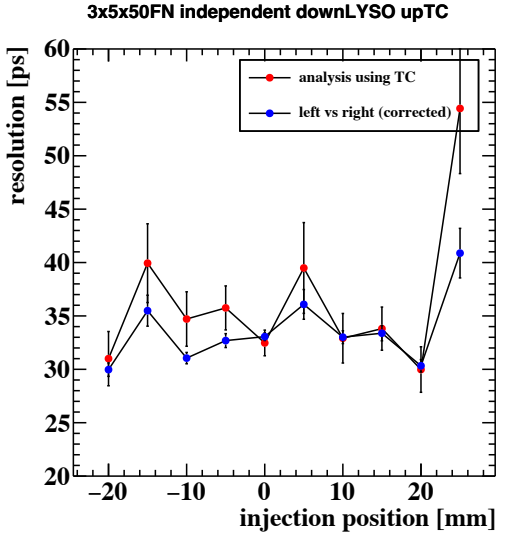


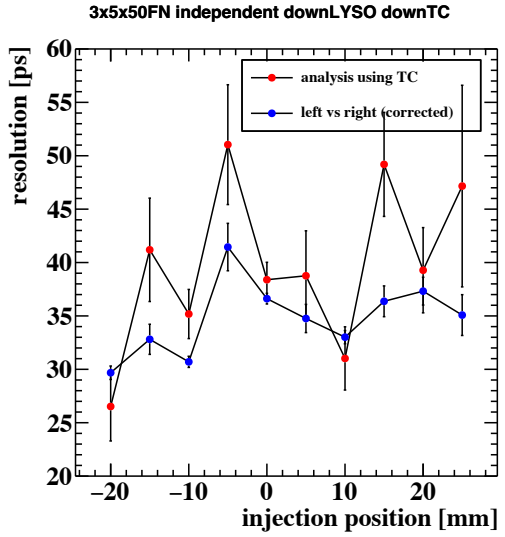




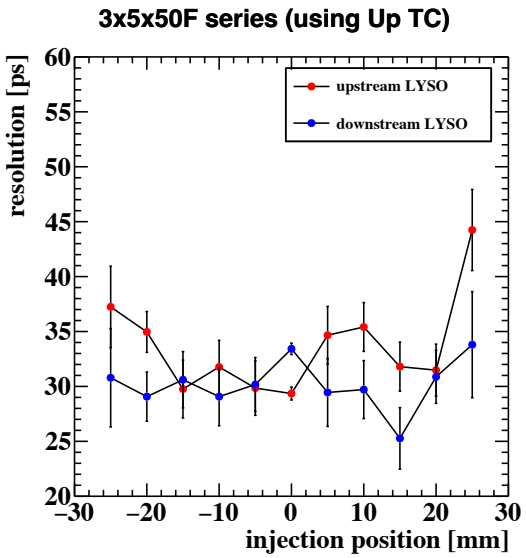


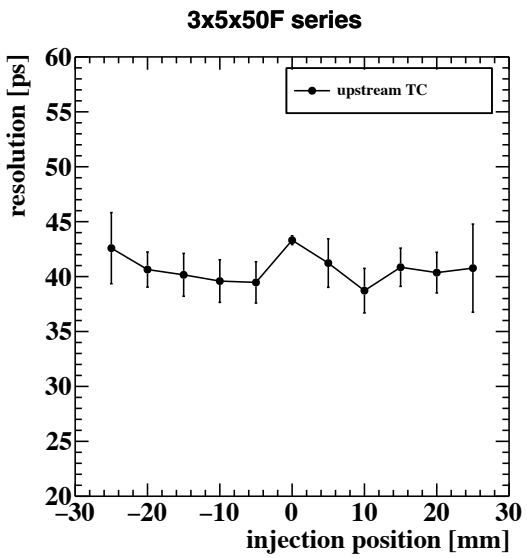


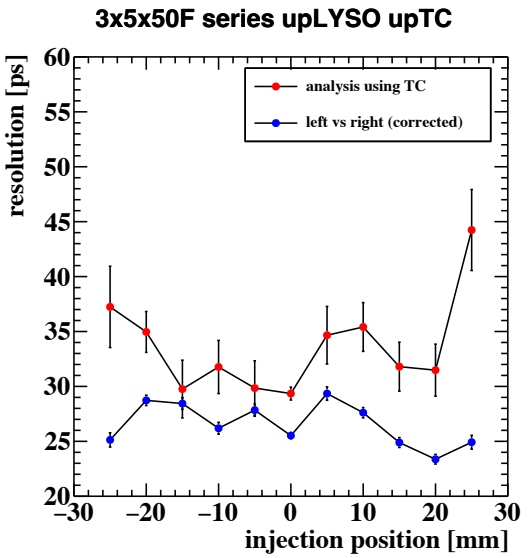


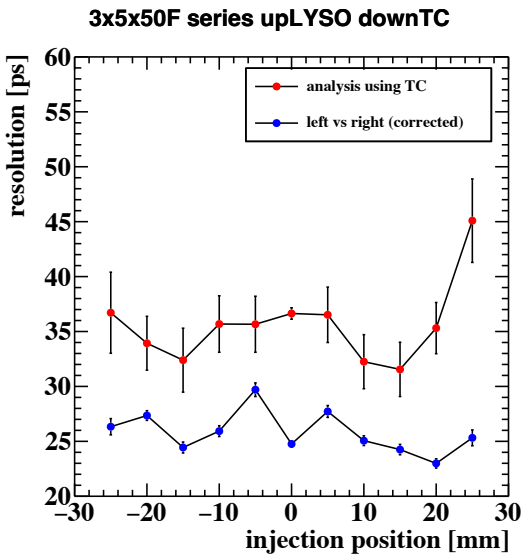


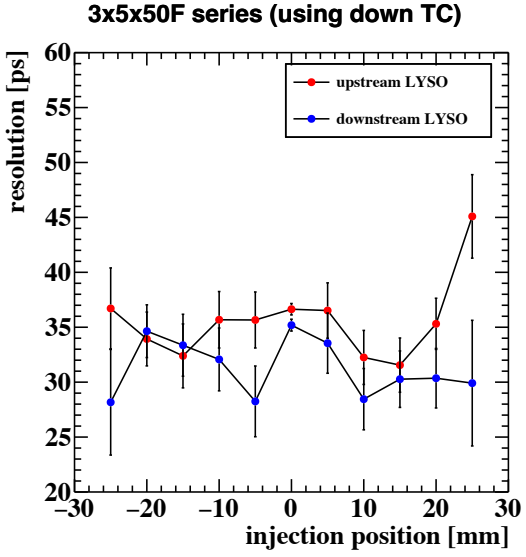
3 x 5 x 50 F (series) position scan

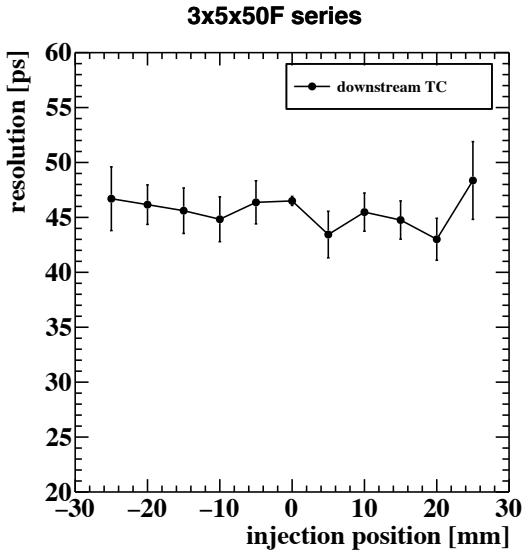


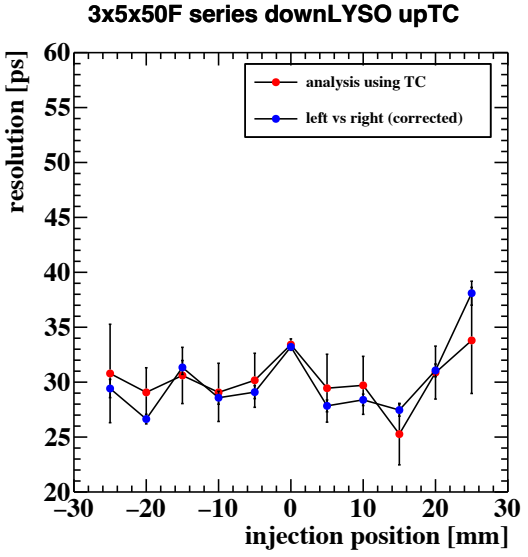


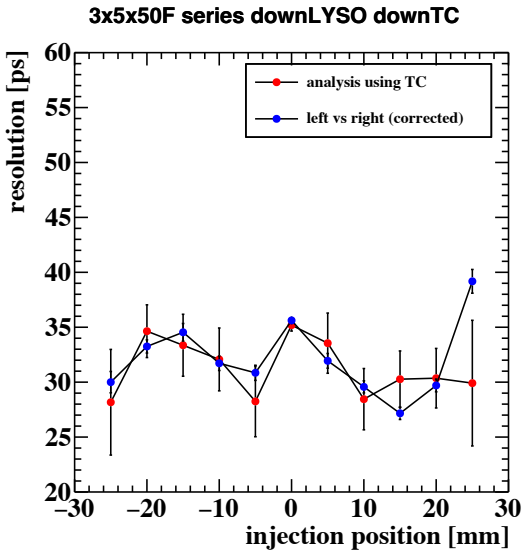




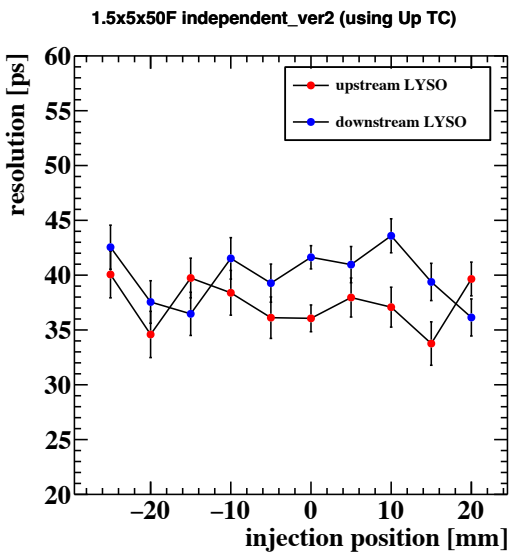


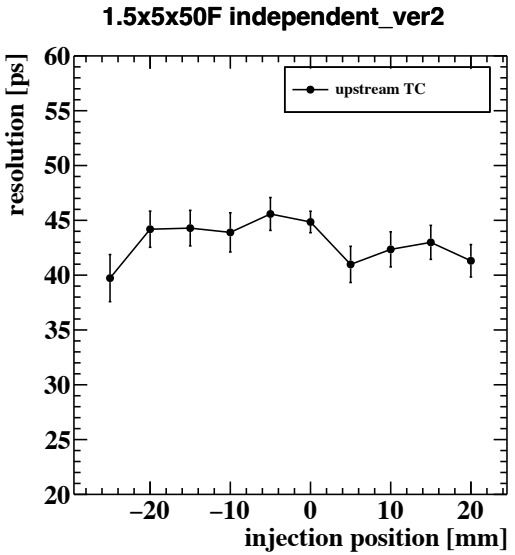


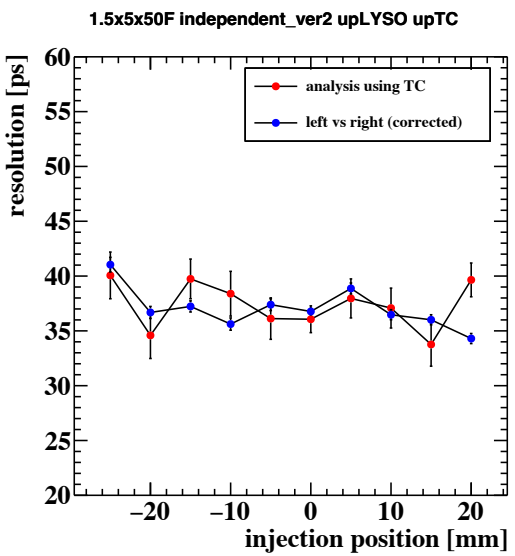


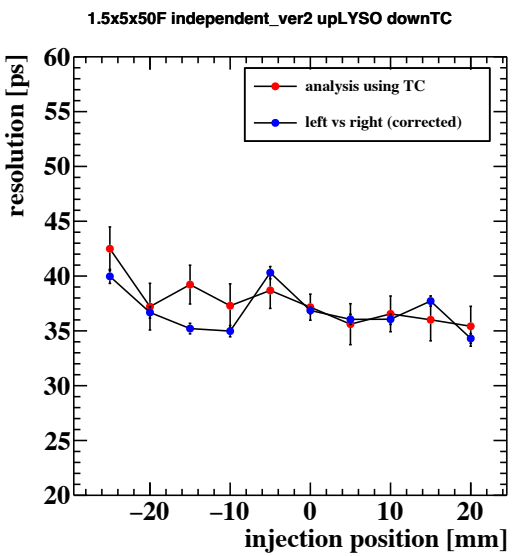


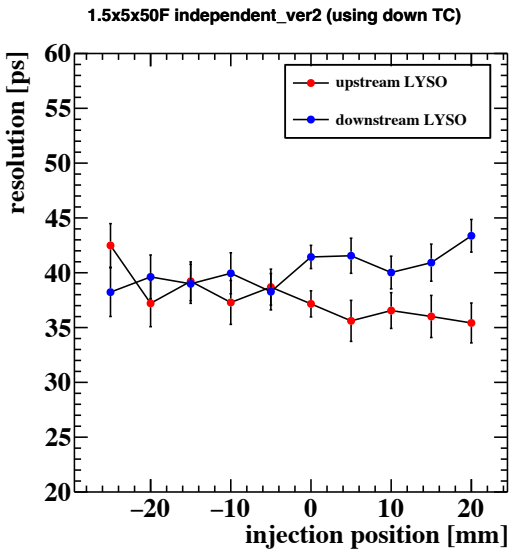
1.5 x 5 x 50 (independent) position scan

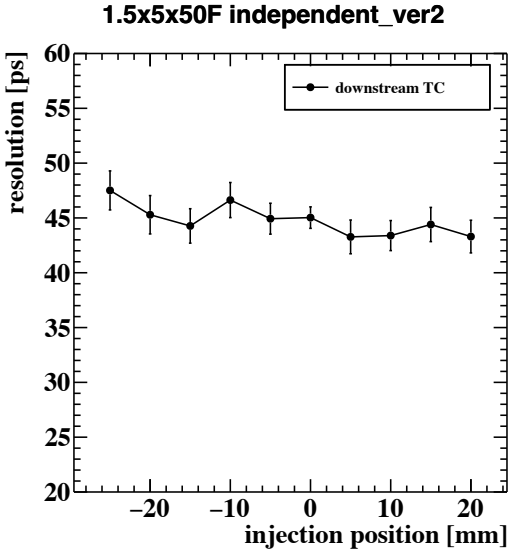


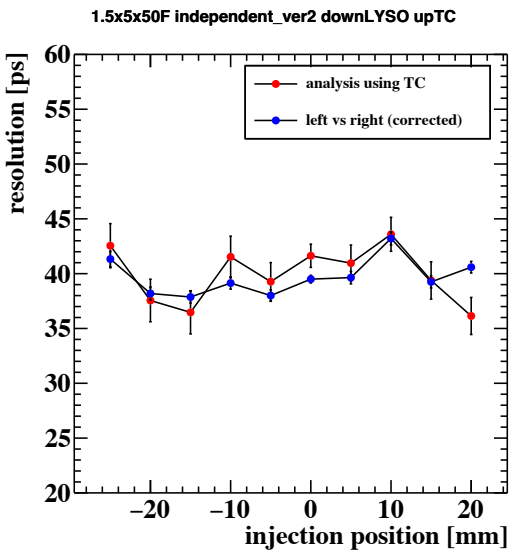


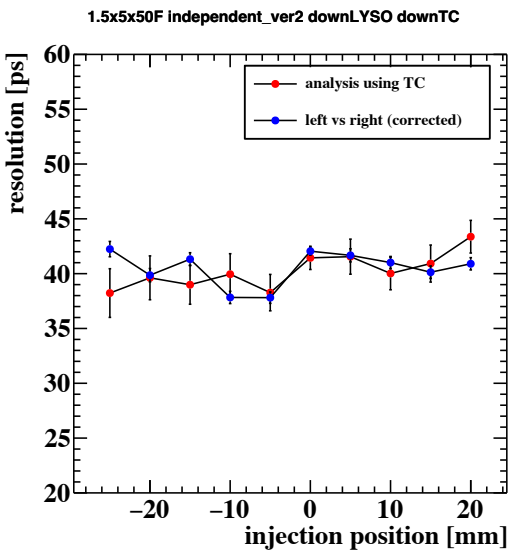




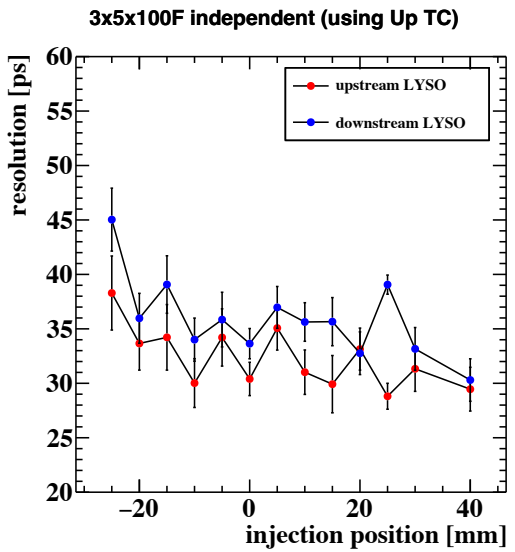


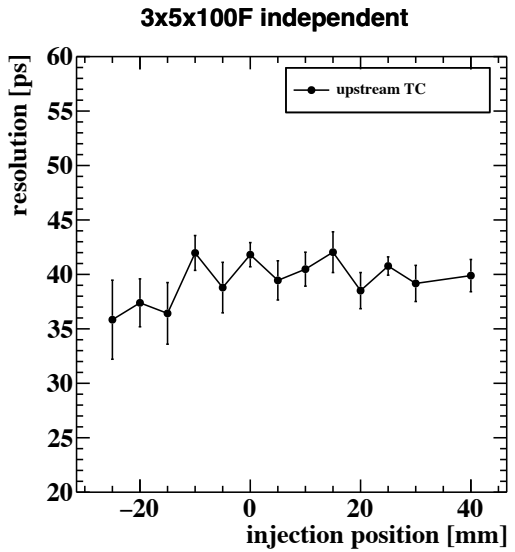


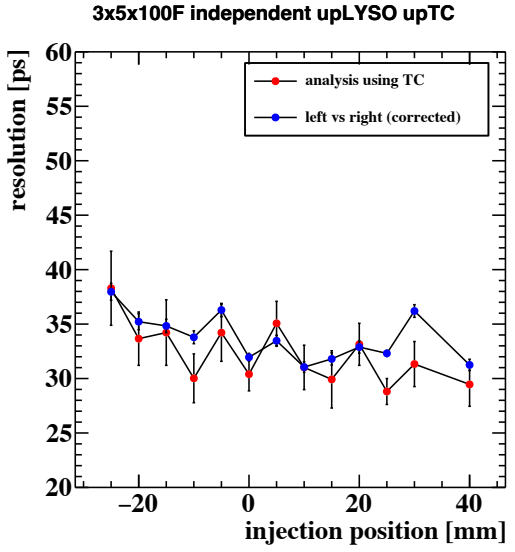


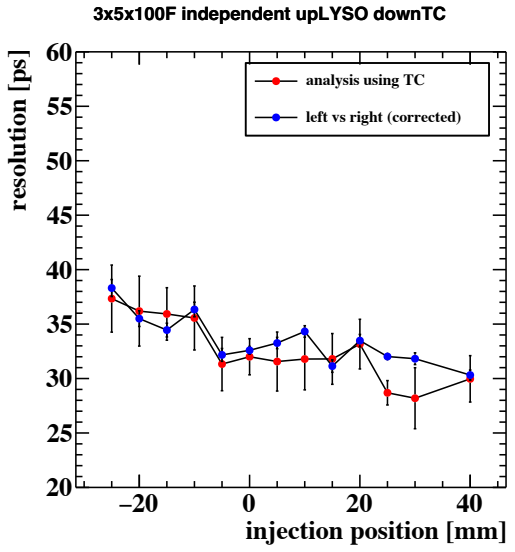


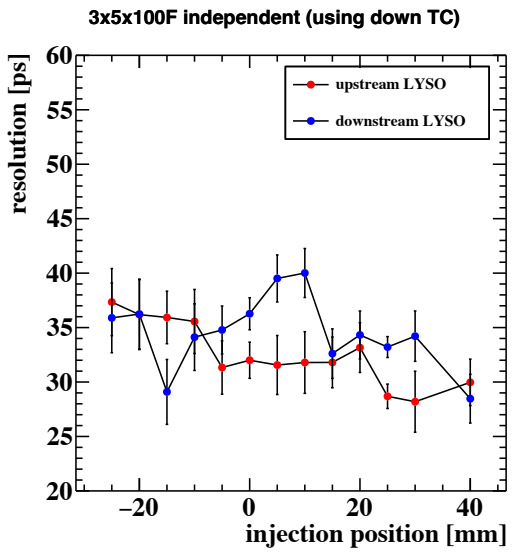
3 x 5 x 100 (independent) position scan

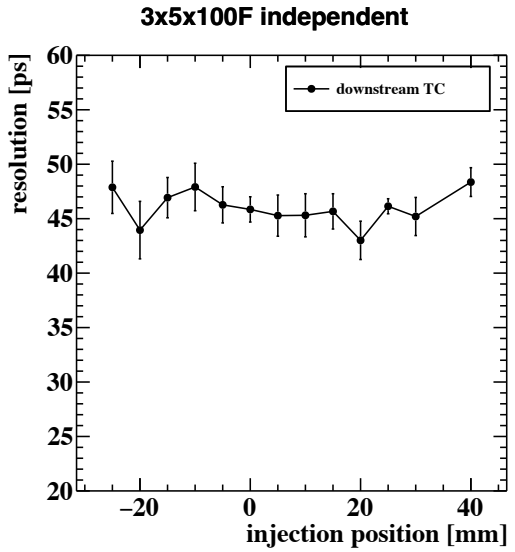


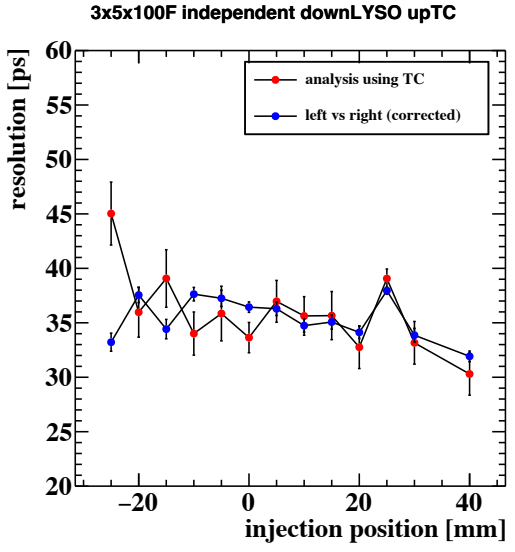


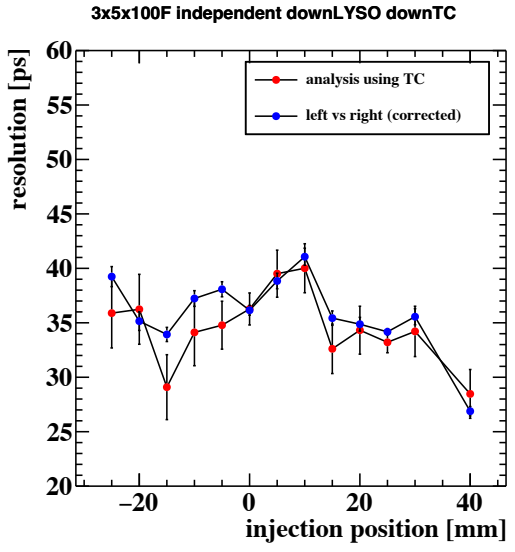




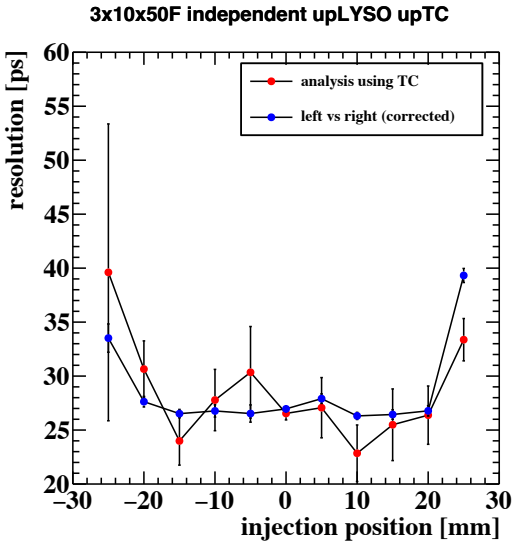


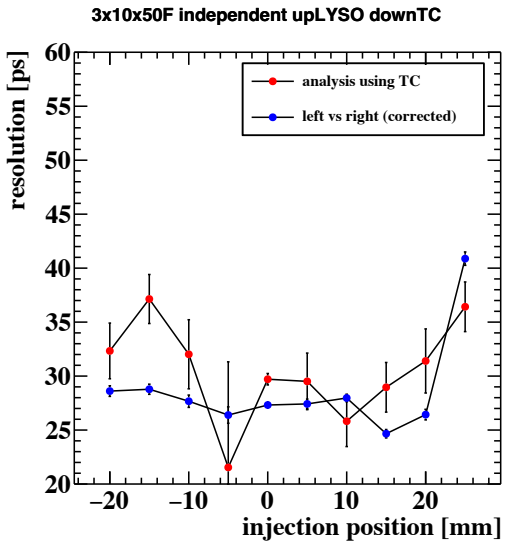


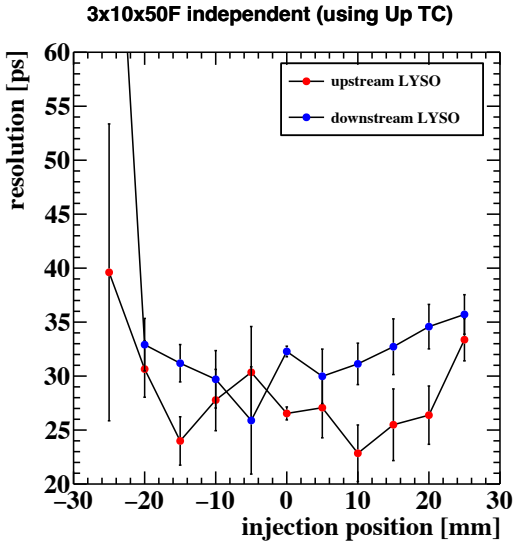


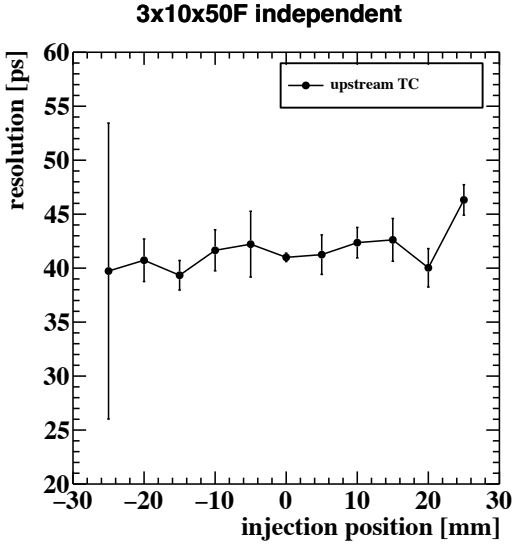


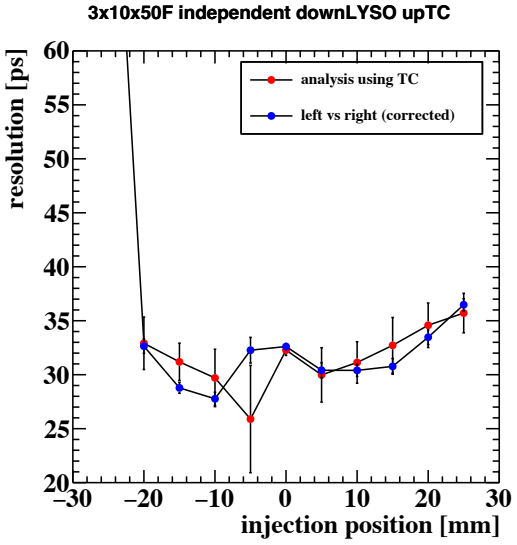
3 x 10 x 50 (independent) position scan

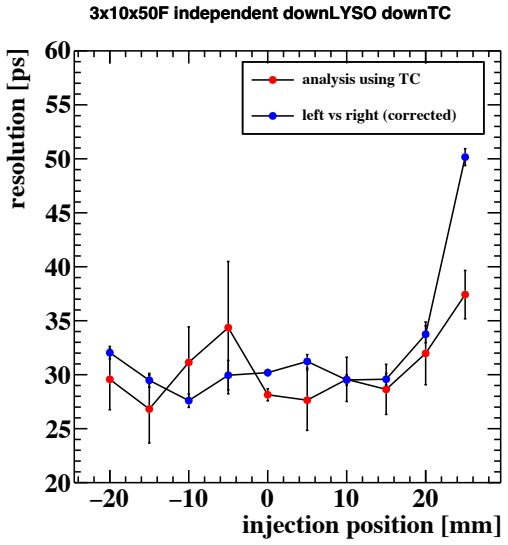


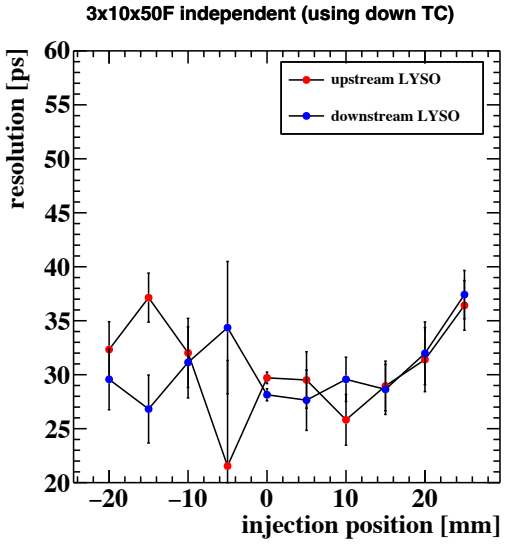


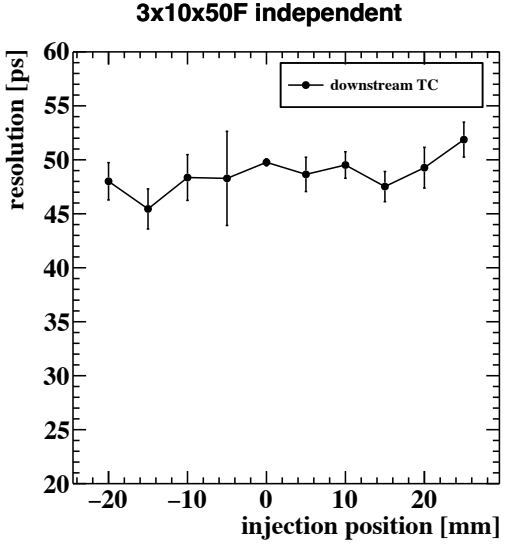




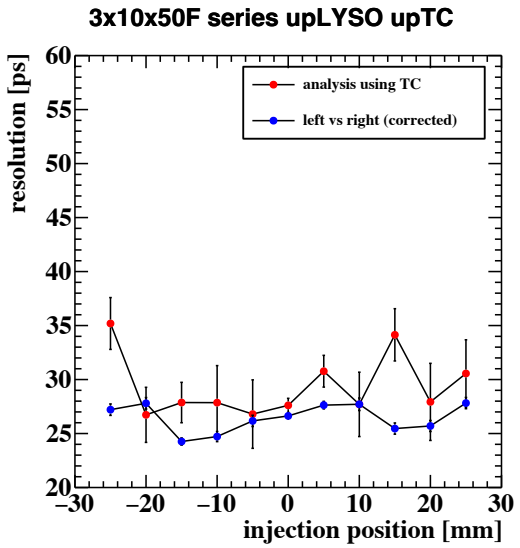


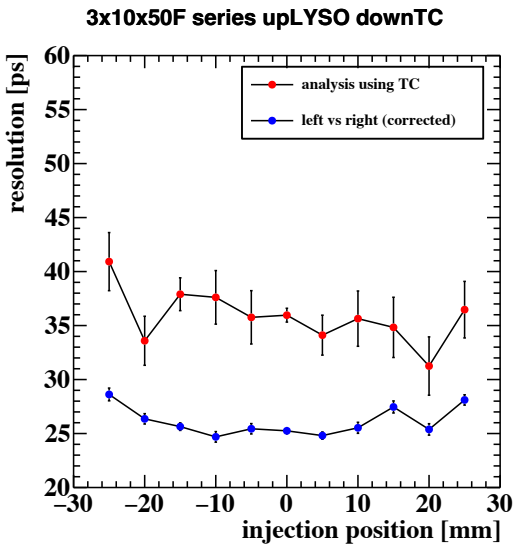


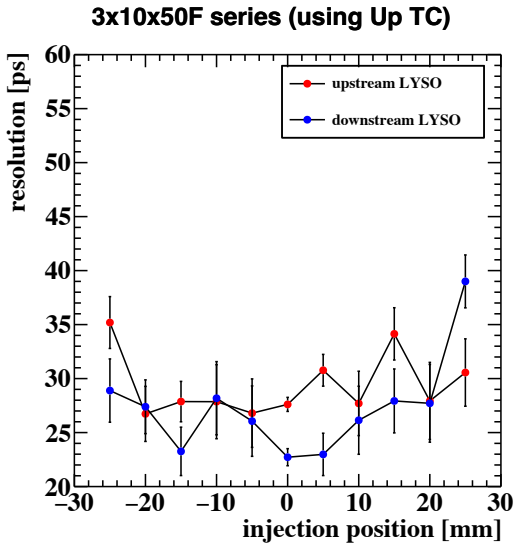


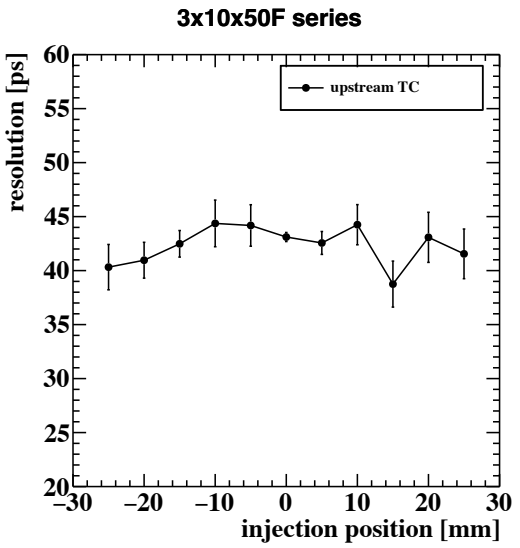


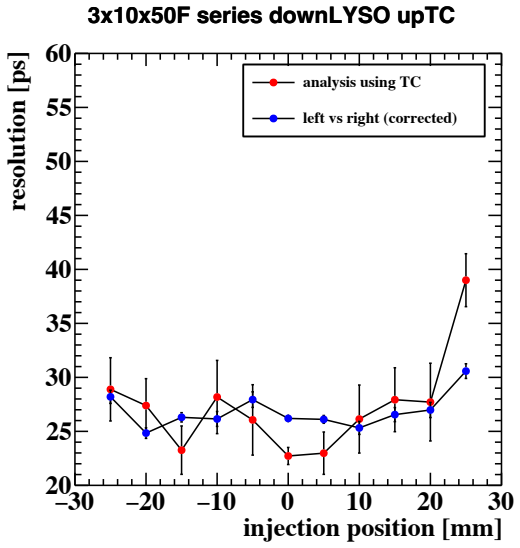
3 x 10 x 50 (series) position scan

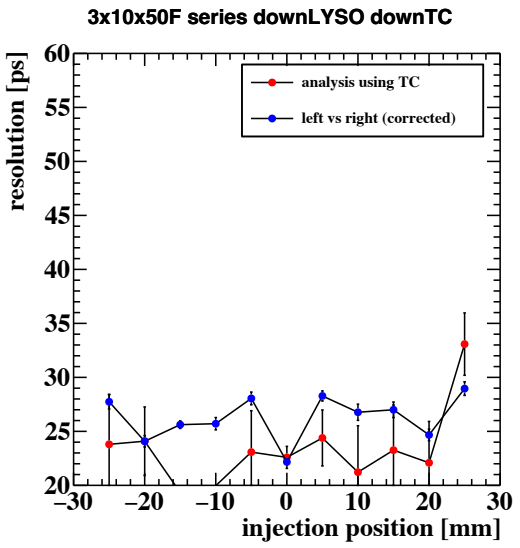


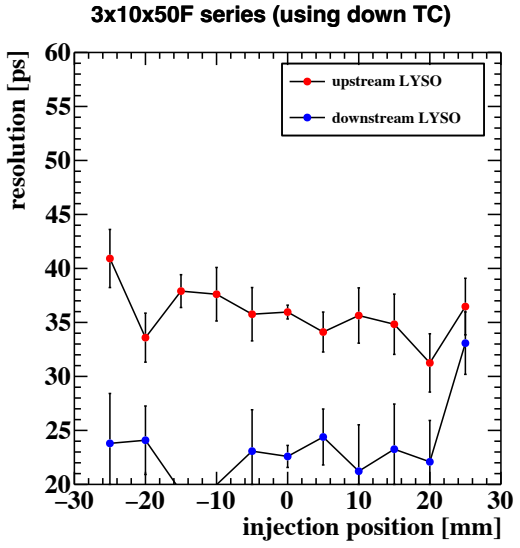


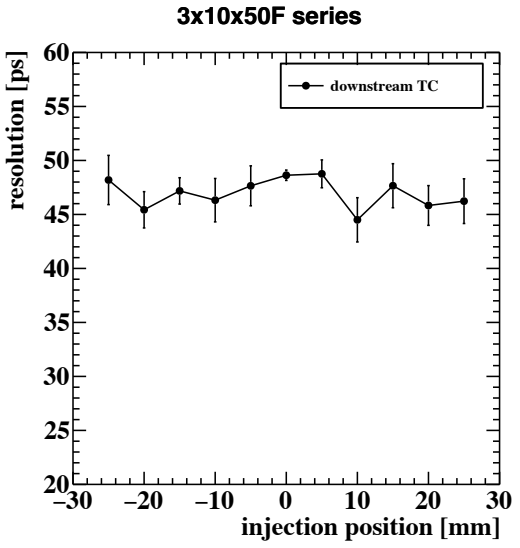




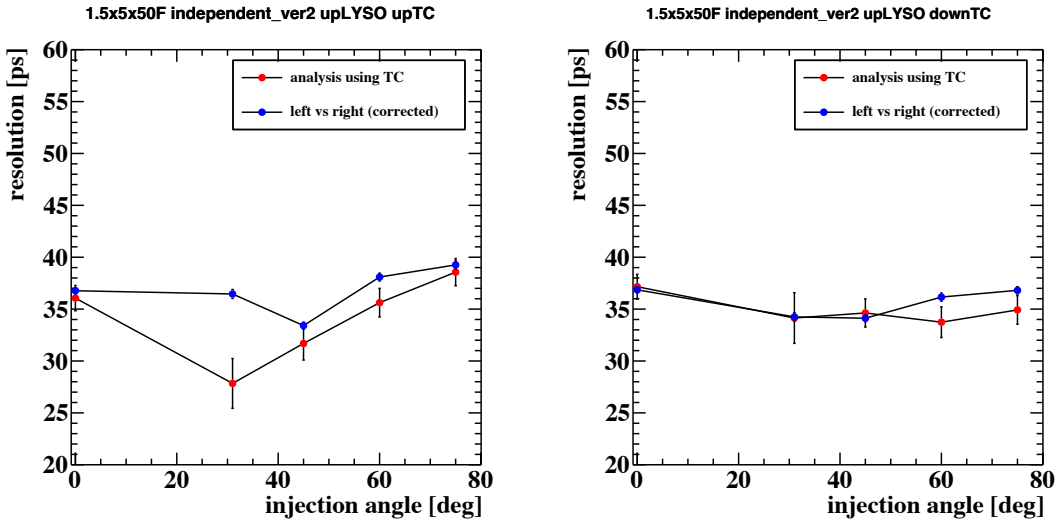


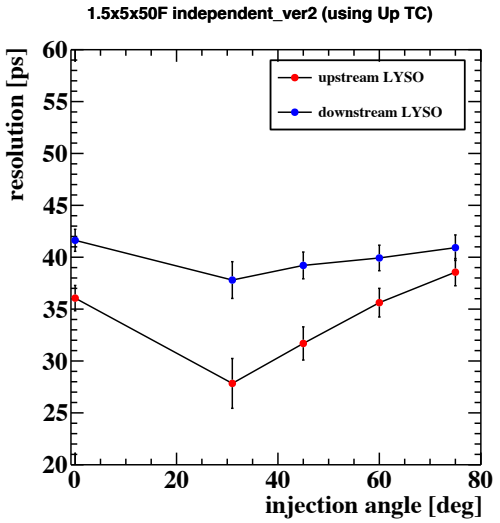


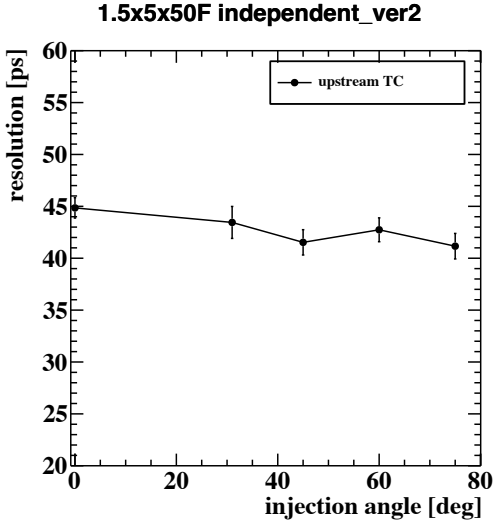


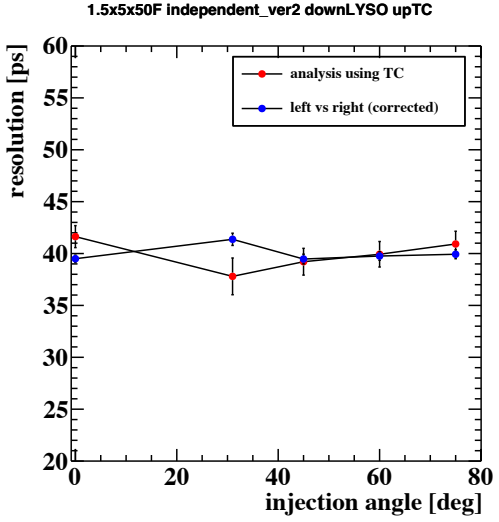


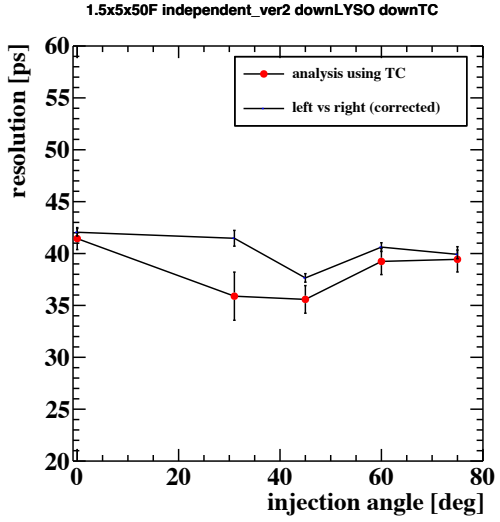
1.5 x 5 x 50 angle scan

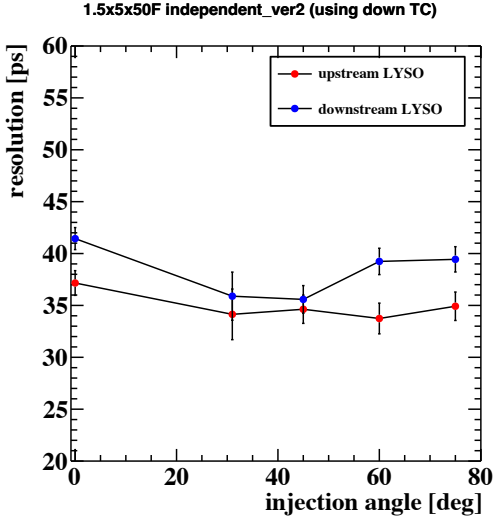


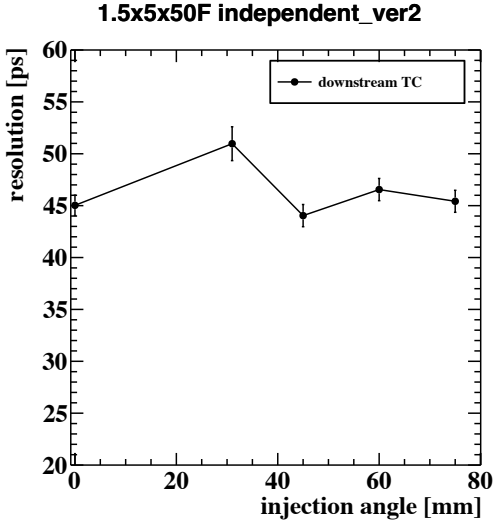












3 x 10 x 50 angle scan