Development of the thin TOF-PET scanner based on fast monolithic silicon pixel sensors

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on behalf of the TT-PET collaboration

TT-PET

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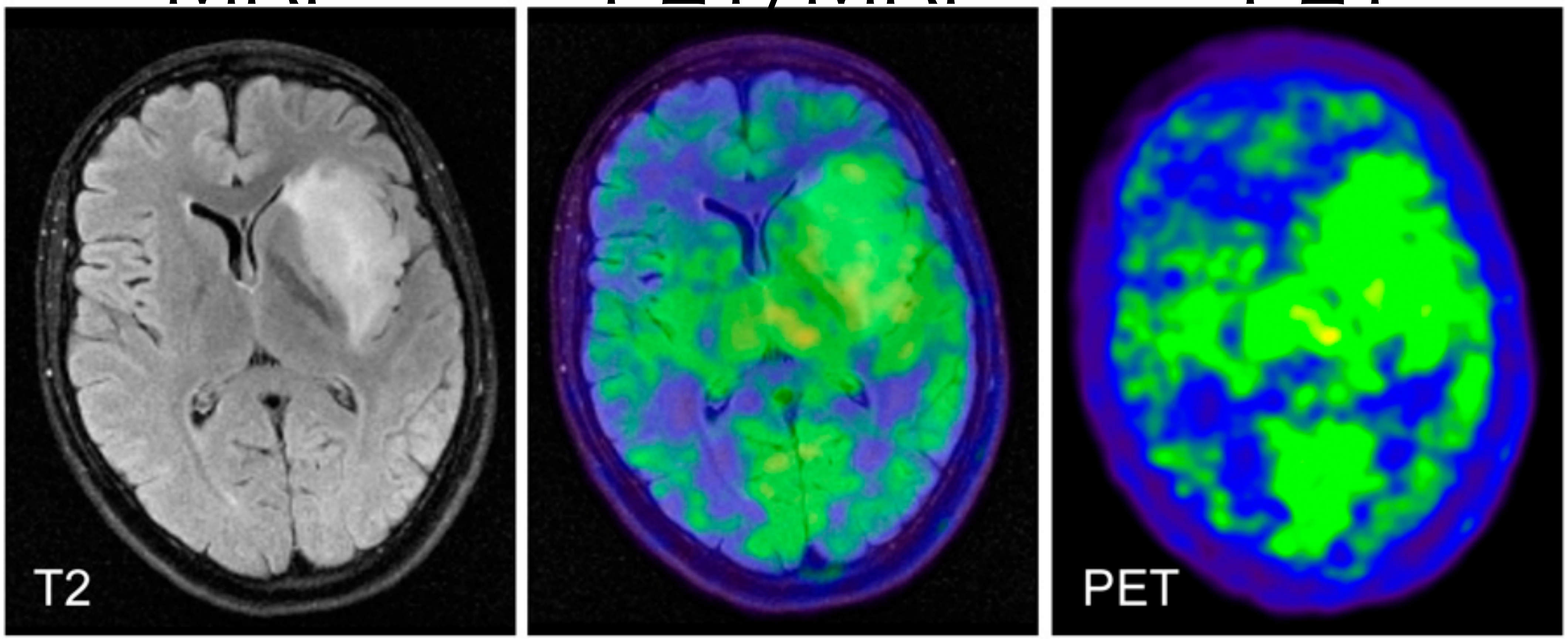
PET/MRI Imaging

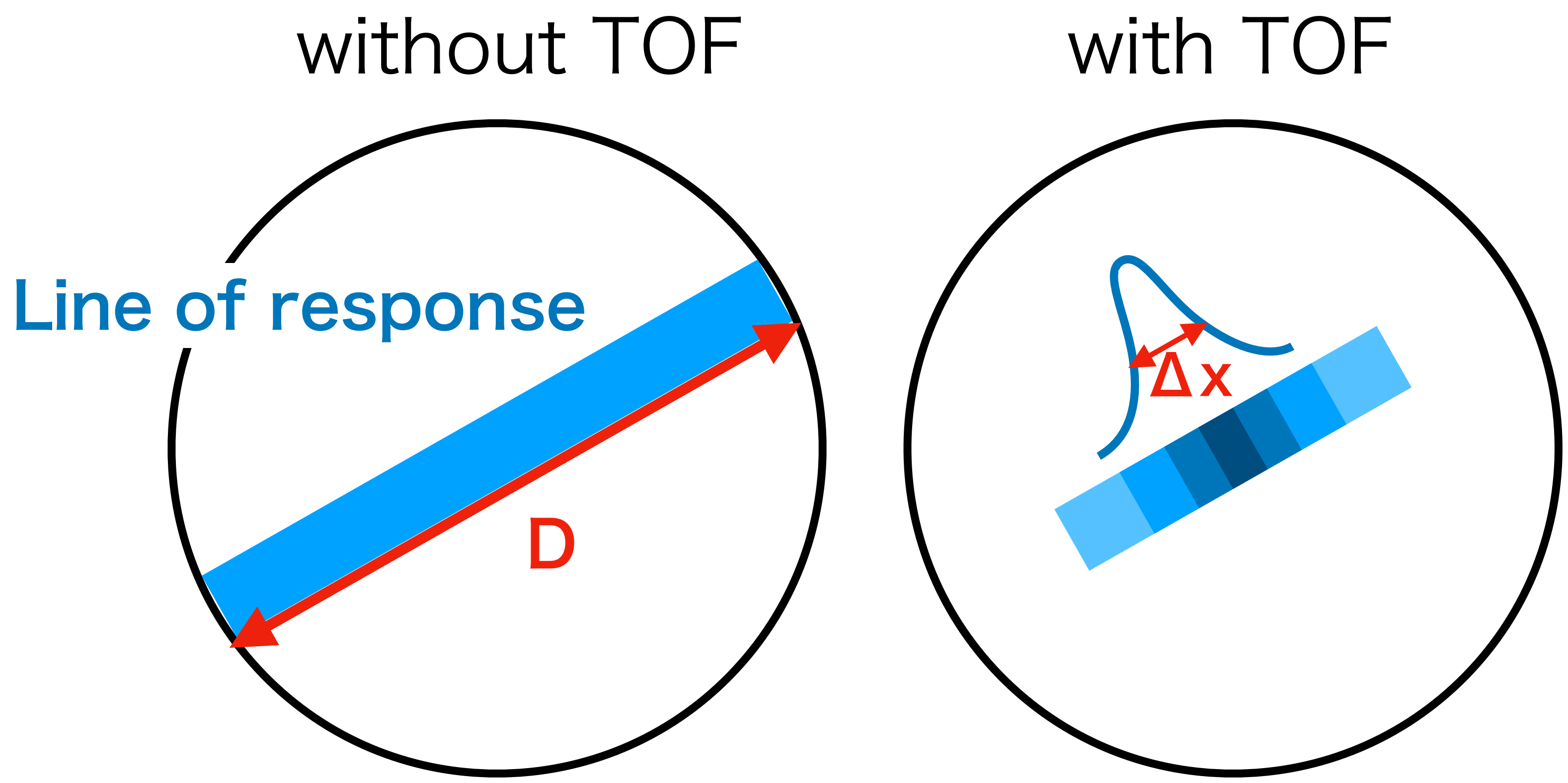
MRI PET/MRI PET



(10.2967/jnumed.110.074773)

- Positron Emission Tomography (PET)
  - Positrons from a radionuclide introduced in a body annihilate with the nearby tissue, emitting two back-to-back photons
  - The photons are detected in coincidence, tracking a <u>line of response (LOR)</u>
- Hybrid PET-MRI Imaging
  - Combining functional Image by PET and morphological image by MRI

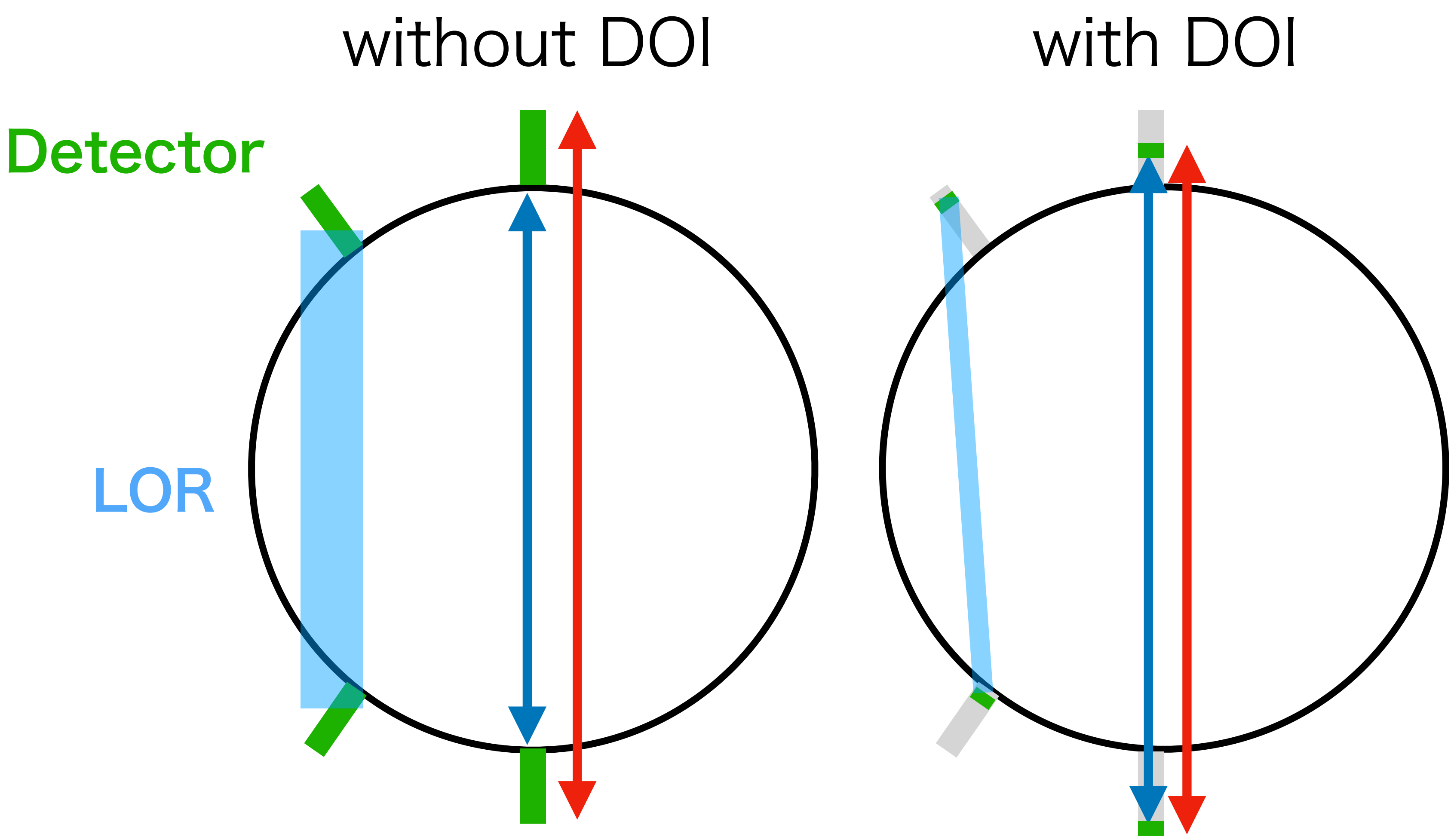
Time-of-Flight (TOF)



- TOF information improves the signal-to-noise ratio (SNR) of reconstructed images

$$\frac{\mathrm{SNR}_{TOF}}{\mathrm{SNR}_{CONVENTIONAL}} \sim \sqrt{\frac{D}{\Delta x}}$$

Depth-of-Interaction (DOI)



- Sensitivity for photon depth of interaction improves the spatial resolution across the whole view of the scanner
- It also reduces the uncertainty of TOF measurements

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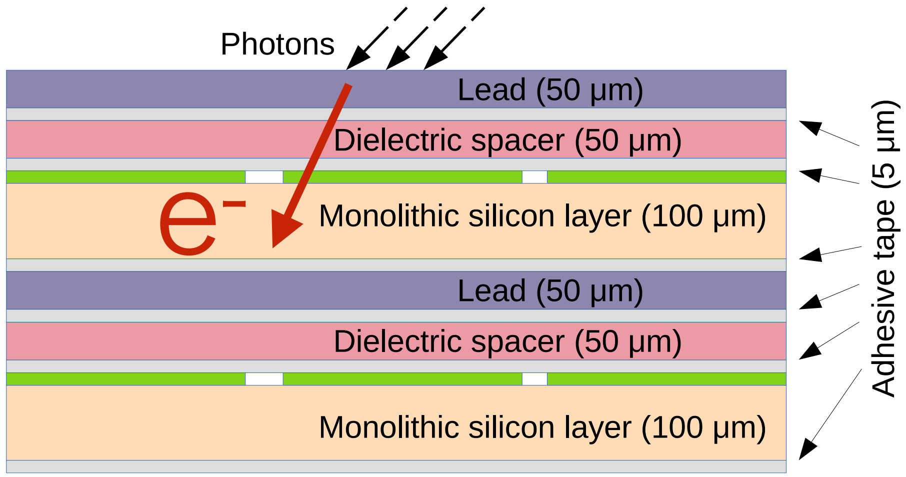
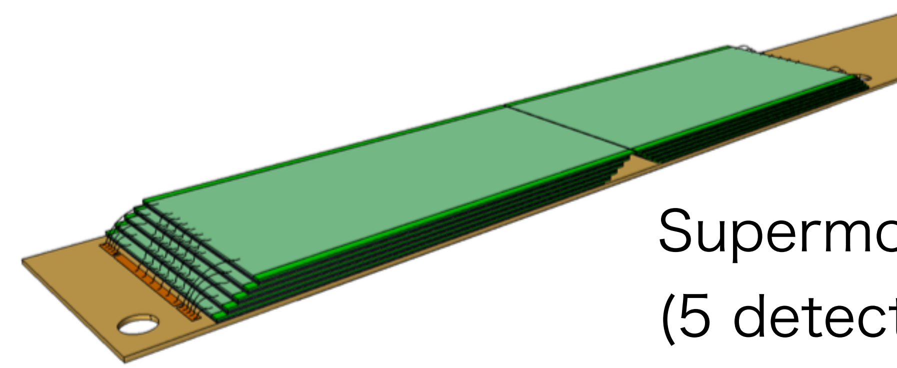
The TT-PET Scanner

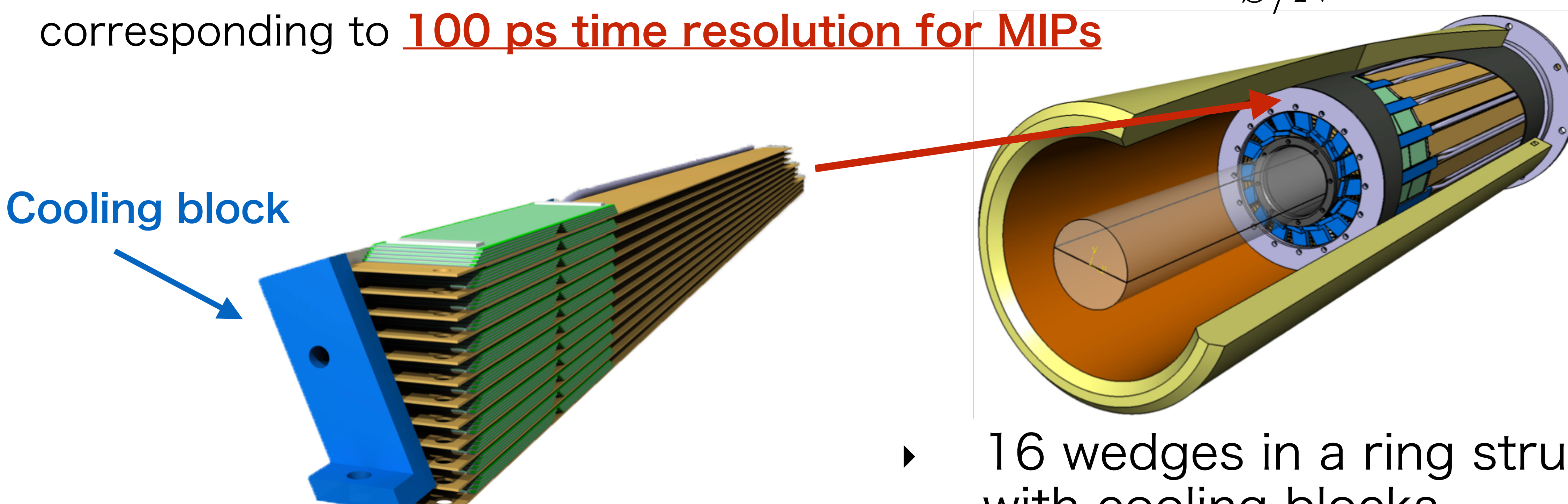




Supermodule
(5 detection layers)

- We are developing silicon monolithic pixel sensors with **30 ps** time resolution for electrons
  - corresponding to **100 ps time resolution for MIPs**

$$\sigma_t \sim \frac{\text{rise time}}{S/N}$$

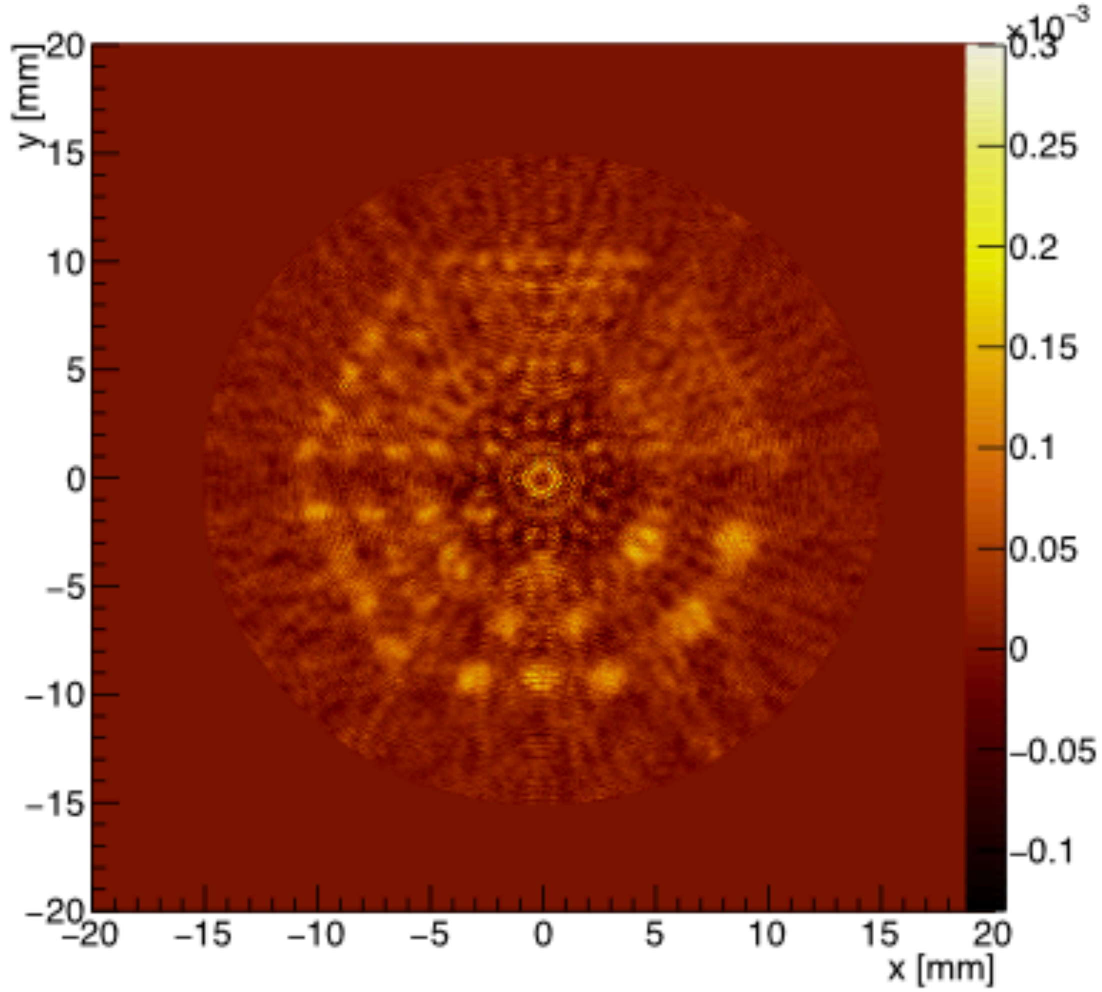


- 16 wedges in a ring structure with cooling blocks
- The scanner is meant to be inserted in small animal commercial MRI
- A wedge is composed of 60 layers (12 supermodules)

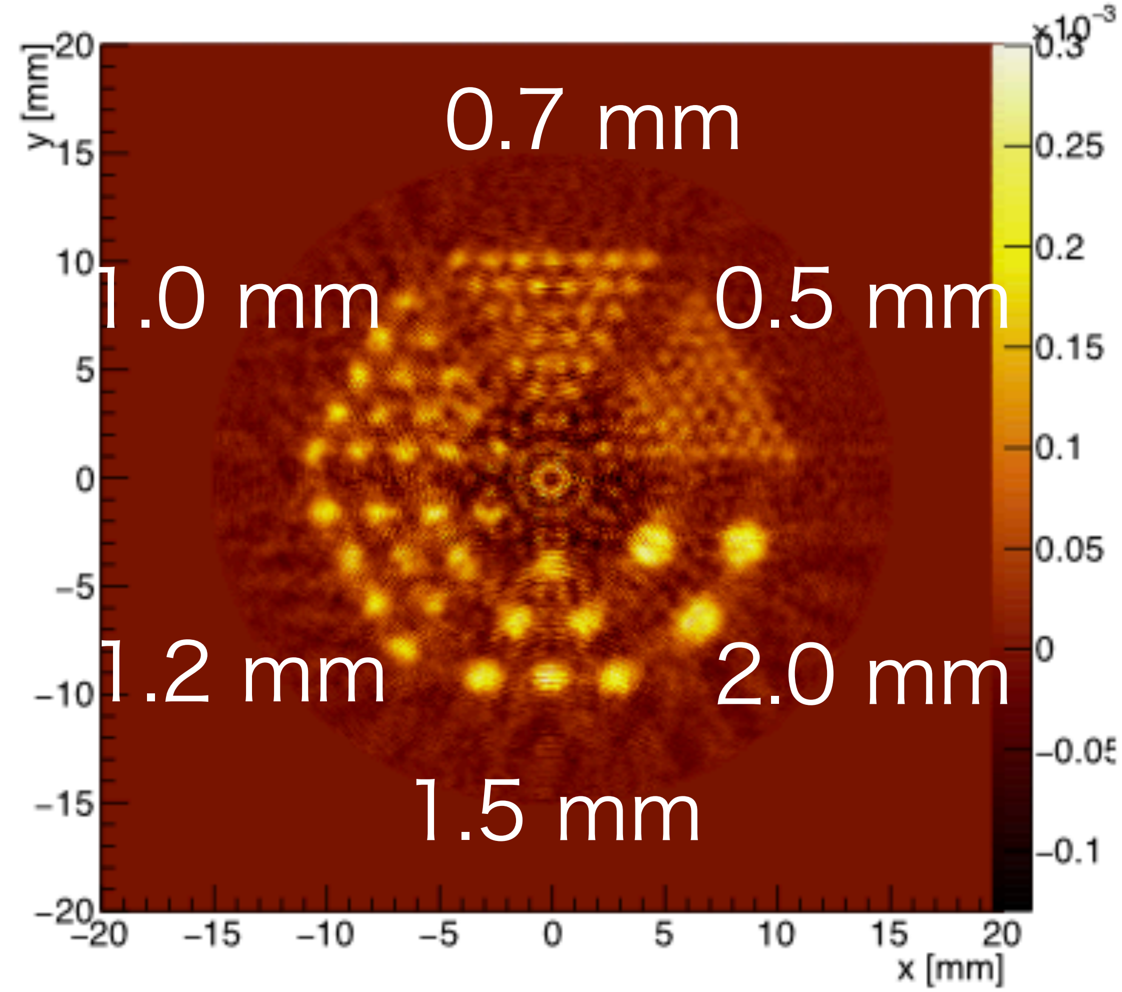
Expected Performance of the TT-PET Scanner

Detector simulation performed with Geant4 simulation shows excellent performance of the TT-PET scanner

Reconstruction without TOF



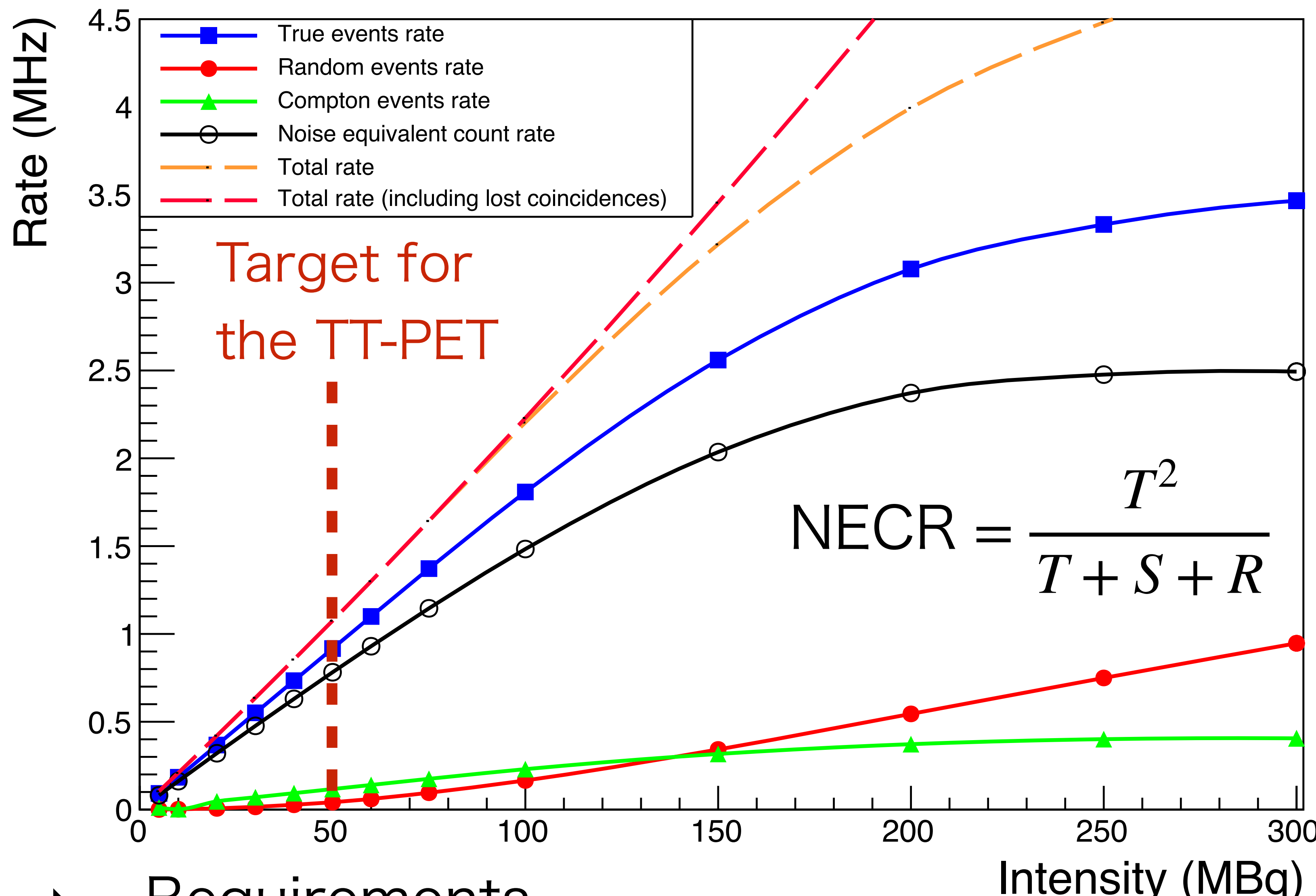
Reconstruction with TOF



- The very good spatial resolution (< 750 mm FWHM) does not degrade on the border of the scanner thanks to the depth of interaction measurement
- The SNR of the reconstructed image is improved thanks to the TOF measurement

arXiv: 1811.12381

Noise Equivalent Count Rate (NECR)



cylindrical source (radius: 1.6 mm, length: 50 mm) in a plastic phantom (radius: 12.5 mm, length: 50 mm)

$$\mathrm{NECR} = \frac{T^2}{T+S+R}$$

T: True

S: Compton Scattering

R: Random

$$\left(\mathrm{SNR} \propto \sqrt{\mathrm{NEC}}\right)$$

- Requirements
  - Coincidence window: 500 ps
  - The LOR intercepts the phantom
  - The energy deposits in the both pixels are larger than 20 keV
- High NECR (~ 900 kcps) for a 50 MBq source

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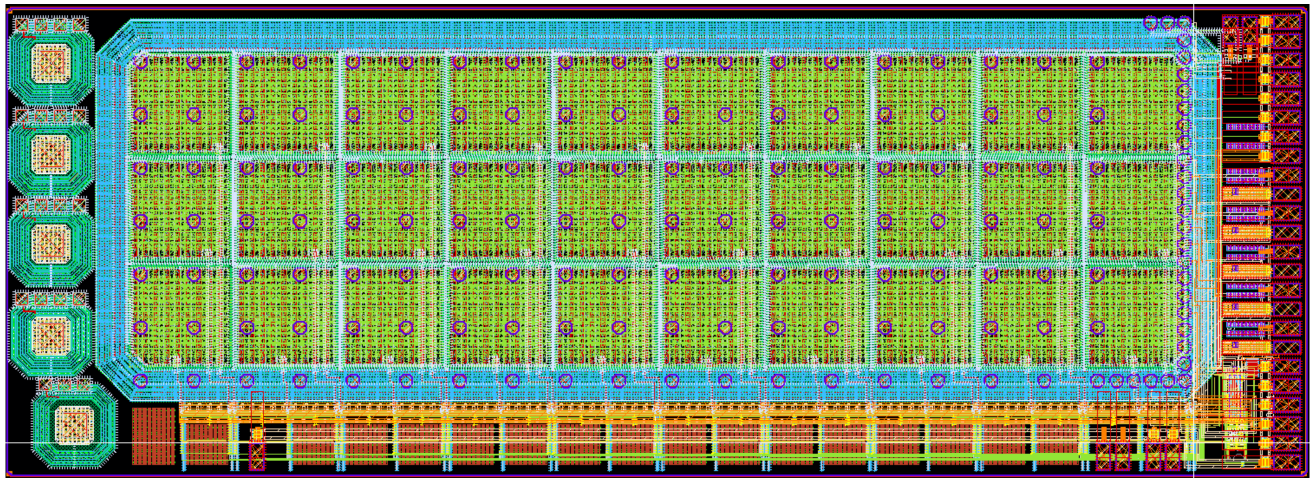
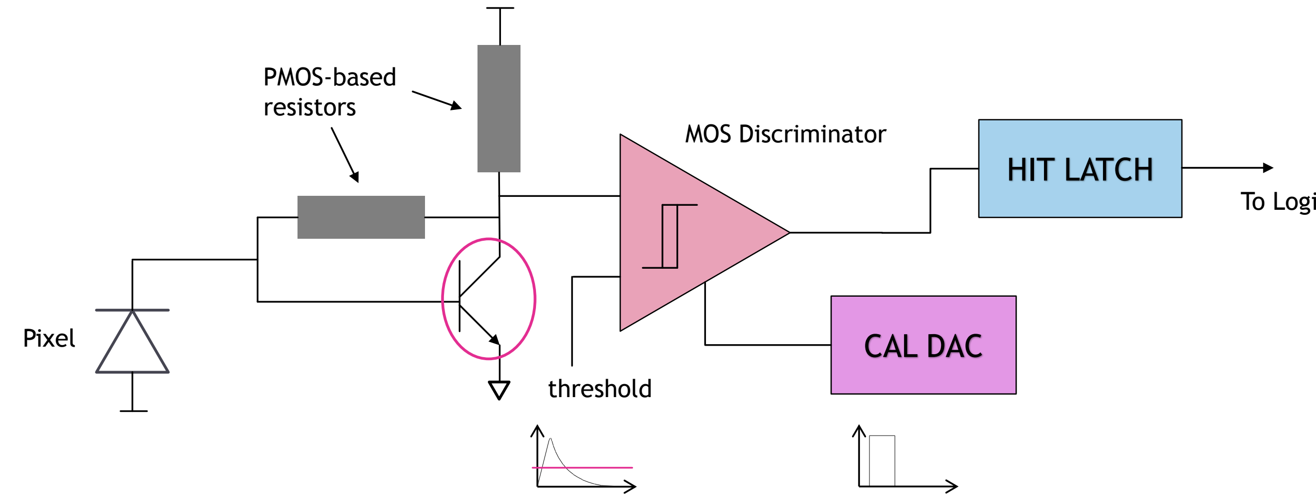
ASIC Demonstrator

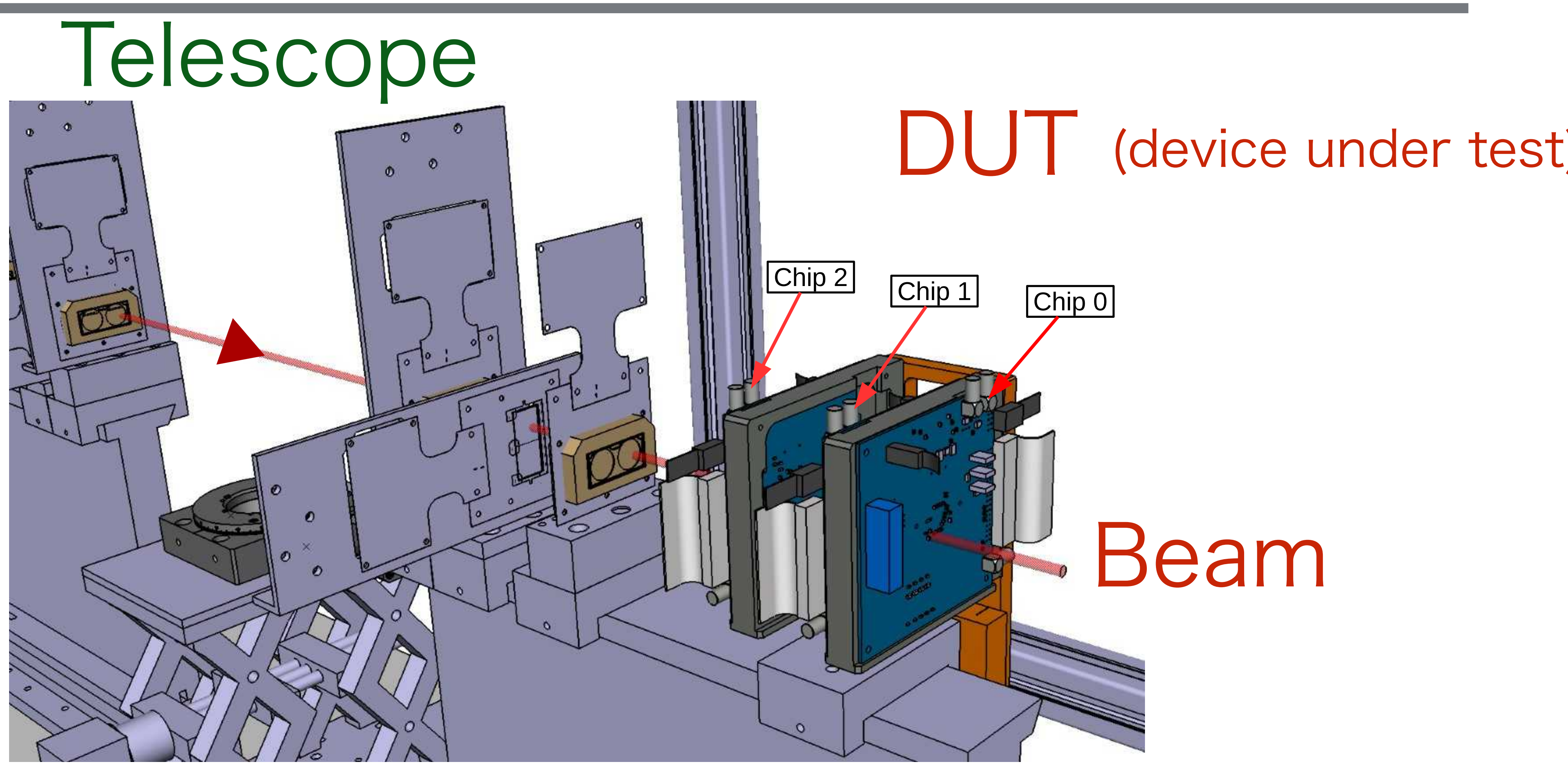




- ASIC demonstrator in 130 nm IHP SiGe-HBT technology (β = 900, f_T = 250 GHz)
  - 30 pixels, size: 500 × 500 μm^2
  - Amplifier, discriminator, 50 ps binning TDC, logic and serializers
    - ✦ The output of the discriminator is sent to a fast-OR chain, which preserves TOT and TOA
  - Thinned to 100 μm, backplane metallized
  - 1500 Ω*cm resistivity (full depletion voltage: ~ 45 V)
    - ✦ Confirmed by laser TCT measurement

arXiv: 1811.10246

Testbeam Measurement



- Testbeam facility at CERN SPS (MIPs)
  - Tracking telescope, providing external trigger
  - 3 chips were readout by a system developed by the DPNC (particle physics department at University of Geneva) with custom FPGA firmware
  - Applied 180 V to the pixels

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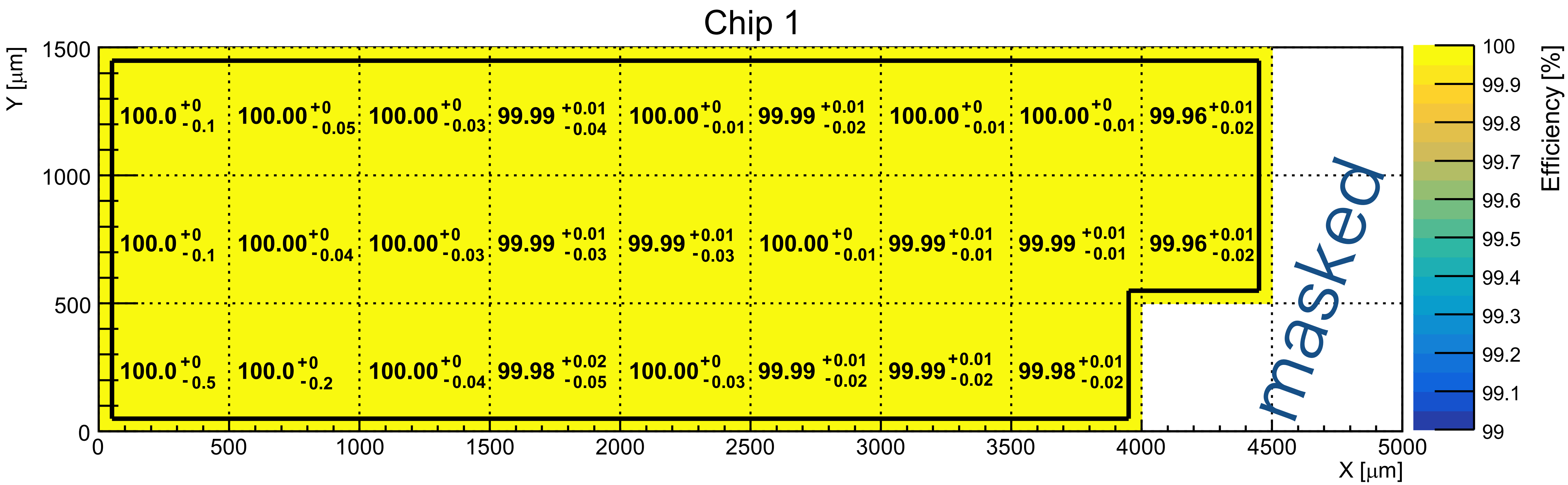
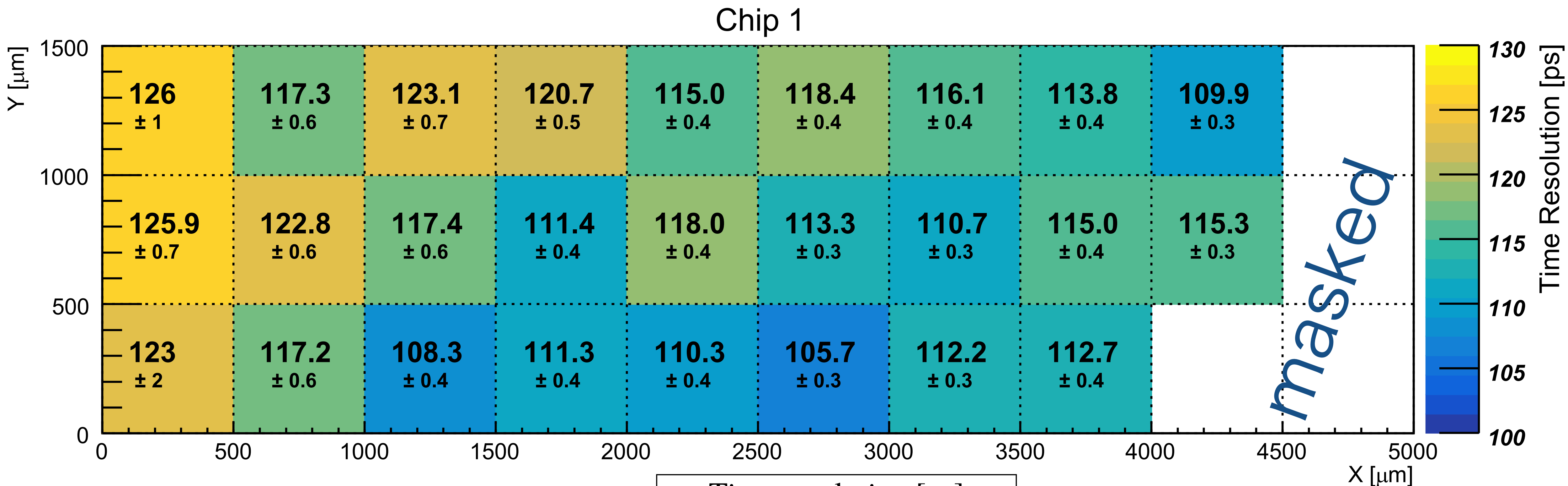
Efficiency Map



- Greater than **99.9% efficiency** was observed for the 26 pixels that were readout
  - 4 pixels were masked on hardware due to noise induced from signal-ended clock line
  - The region defined by the continuous lines shows the area used for efficiency calculation

Time Resolution



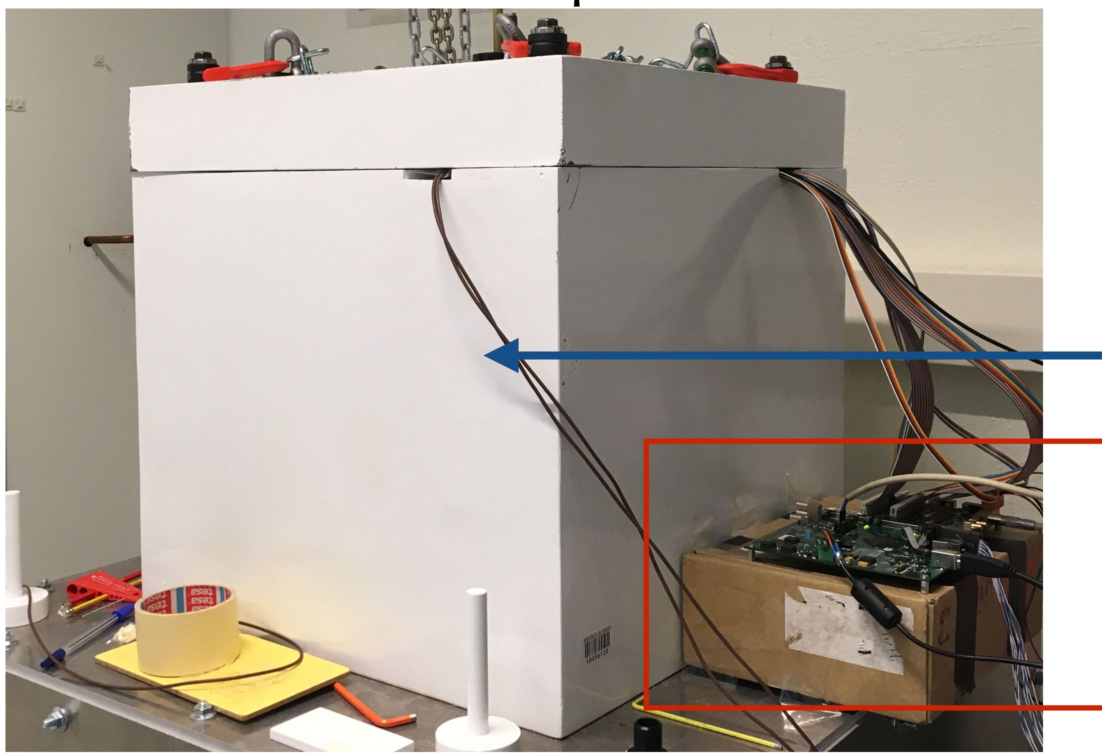
	Time resolution [ps]	
	low-power	high-power
$\sigma_{t,\ chip\ 0}$	**127.3 ± 0.2**	**111.3 ± 0.1**
$\sigma_{t,\ chip\ 1}$	**134.2 ± 0.2**	**116.7 ± 0.1**
$\sigma_{t,\ chip\ 2}$	**127.2 ± 0.2**	**111.2 ± 0.1**

- **110 ps RMS** was measured at 375 μW/channel power consumption
- **130 ps RMS** was measured at 160 μW/channel power consumption
  - Pixel area: 500 × 500 μm^2, 750 fF capacitance

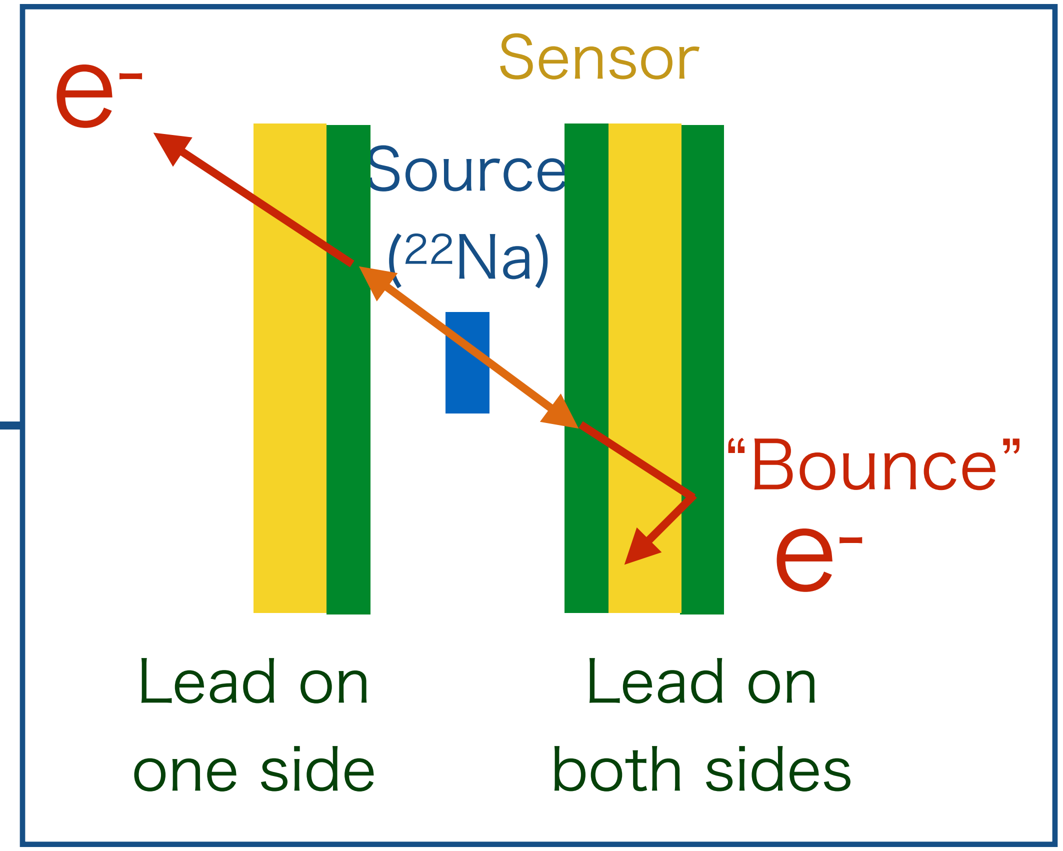
Best time resolution ever for silicon monolithic pixel sensor!

^{22}Na Measurement

Lead box for radiation protection



Readout system



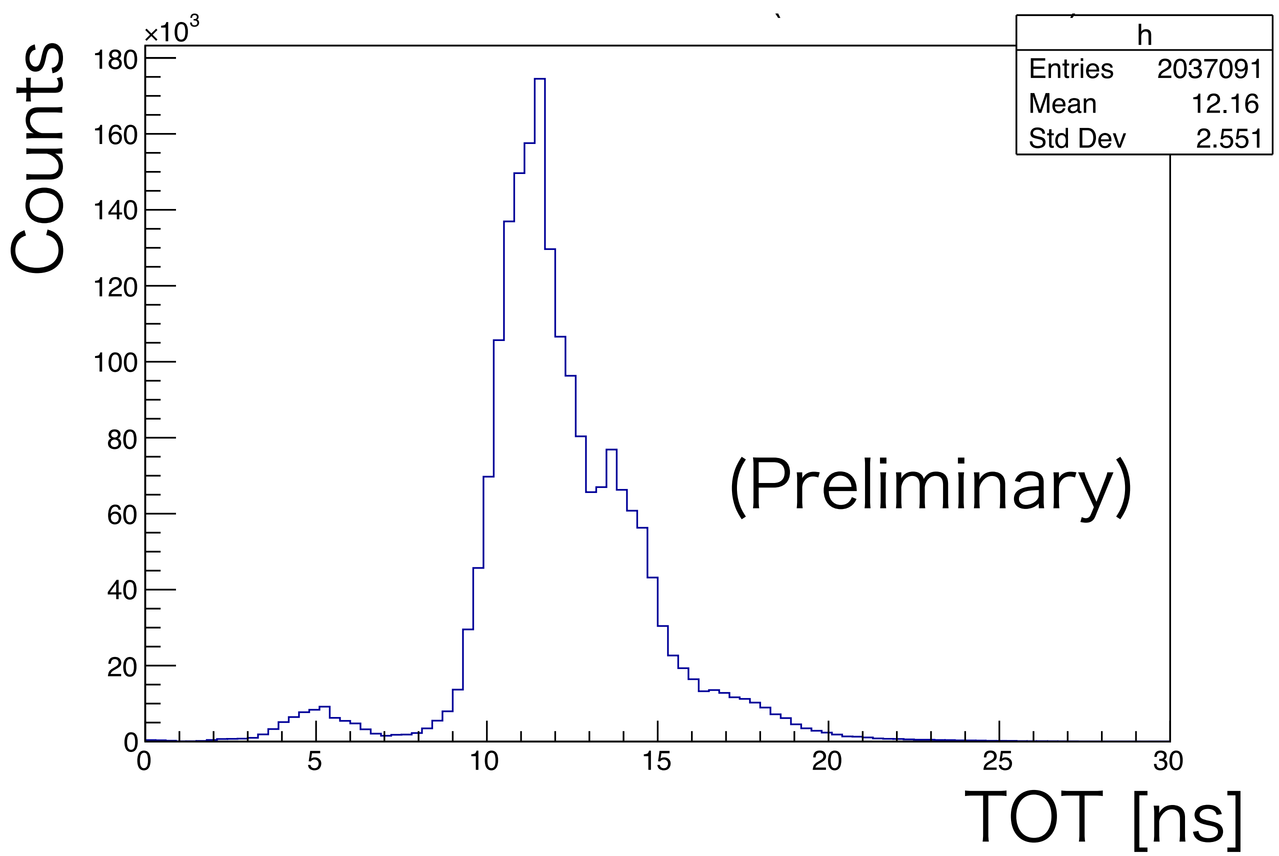
- 30 ps time resolution with electrons from 511 keV photons can be achieved thanks to the larger signal w.r.t. MIPs

$$\sigma_t \sim \frac{\text{rise time}}{S/N}$$

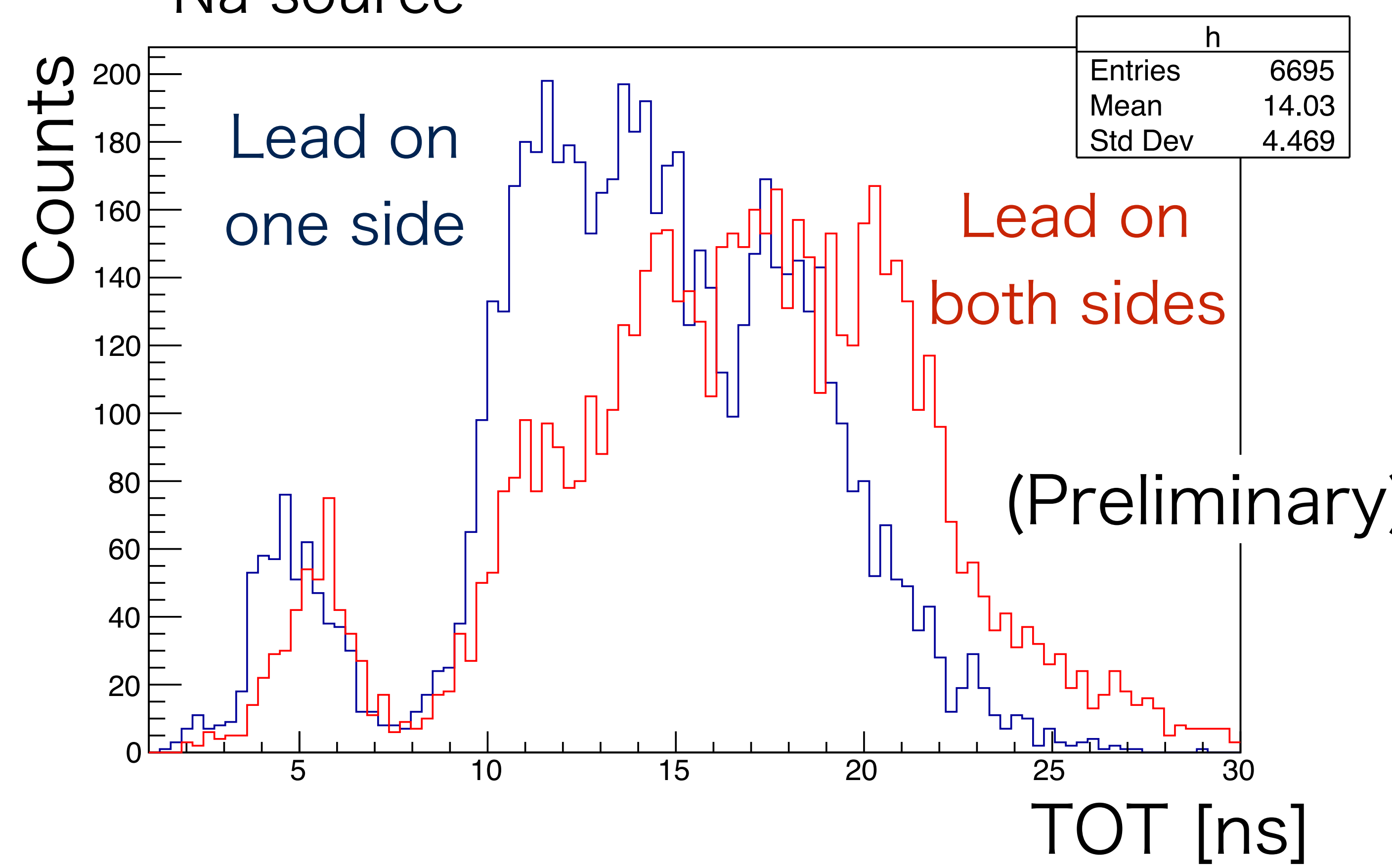
- Measurement with ^{22}Na source
  - Two boards, one with lead on one side and one with lead on both sides
  - Larger signal is expected by <u>electrons bouncing</u> back from lead

Preliminary Results

Testbeam with MIPs



^{22}Na source



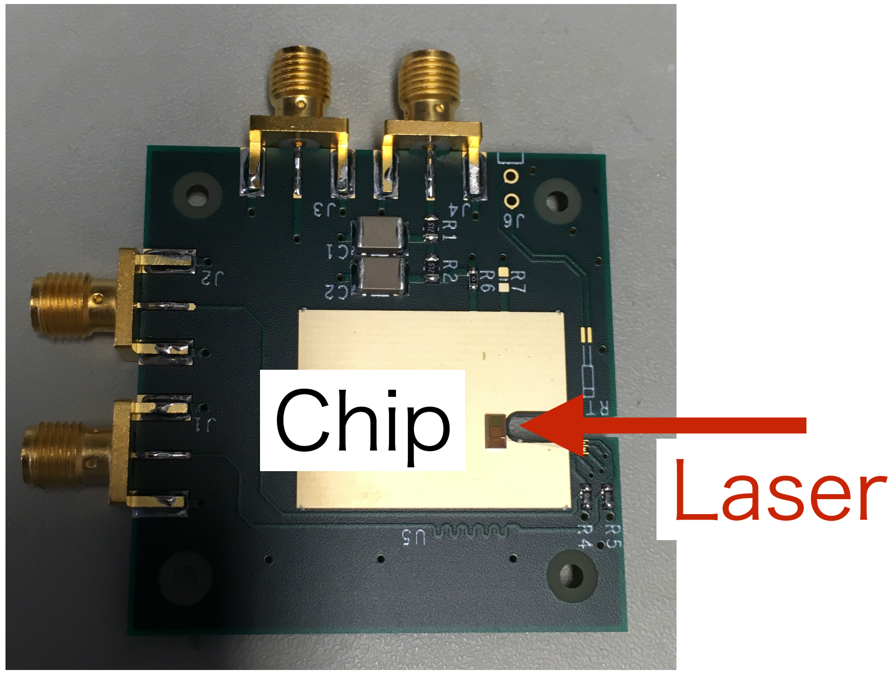
- <u>Larger TOT (Time over threshold) values are observed with lead on both sides</u>
- Measurement for time resolution and efficiency is being done

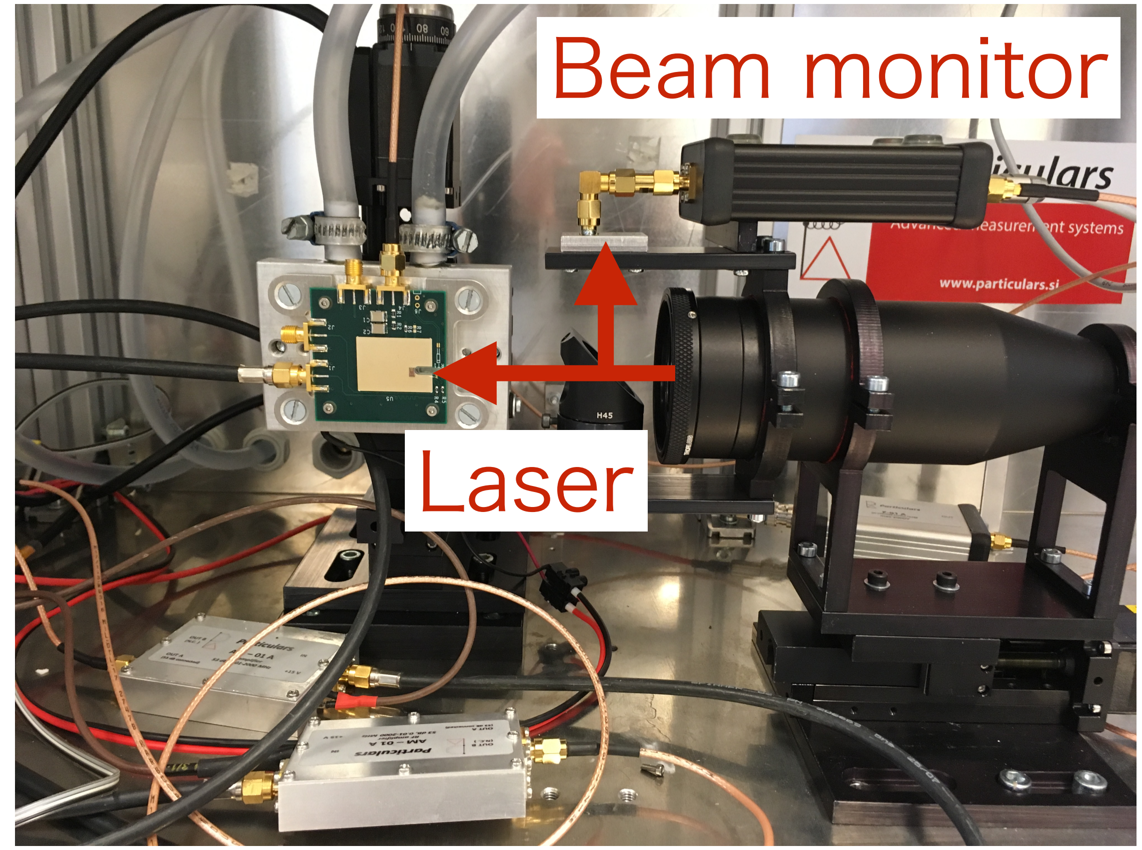
Conclusions

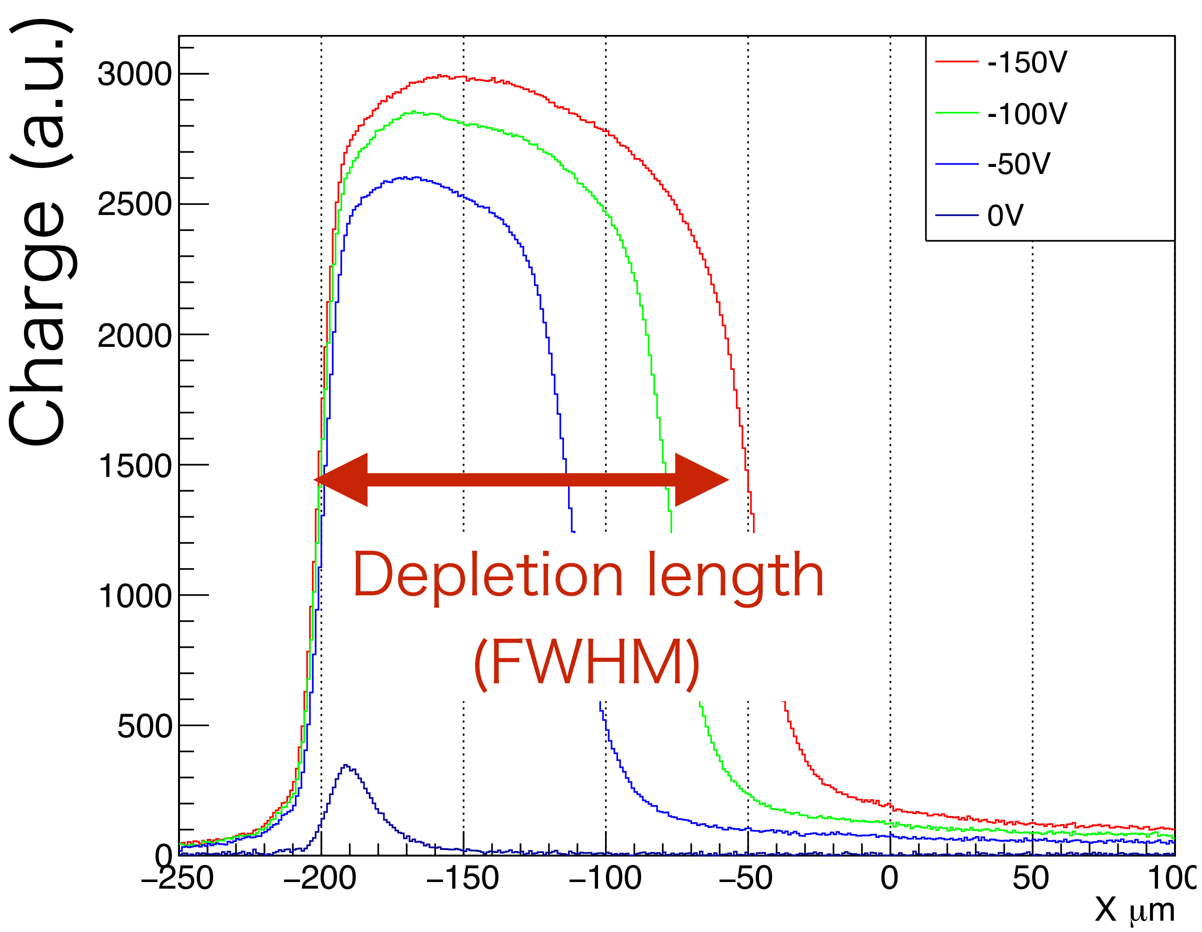
- **The TT-PET scanner**, which aims at the construction of a small animal TOF-PET scanner, was designed to exploit **Time-of-Flight (TOF)** and **Depth-of-Interaction (DOI)** of a multi-layer silicon structure
- Excellent performance of the TT-PET scanner was expected by Geant4 simulation and image reconstruction
- ASIC demonstrator with silicon monolithic pixels was fabricated in **IHP SiGe-HBT technology**
- **More than 99.9% efficiency** and **110 ps at 375 μW/channel power consumption** were measured at CERN SPS testbeam facility
- Measurement with ^{22}Na source is on-going to prove the ~30 ps time resolution with 511 keV electrons

Backups

Laser Edge-TCT Measurement







- Laser edge-TCT measurement at DPNC
  - Depletion lengths correspond to <u>1500 Ω*cm resistivity</u>