Glass Multi-gap RPCs for Non-Destructive Inspection

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Contents

1. Basic idea of gamma-ray detection with line-scan MRPC detectors

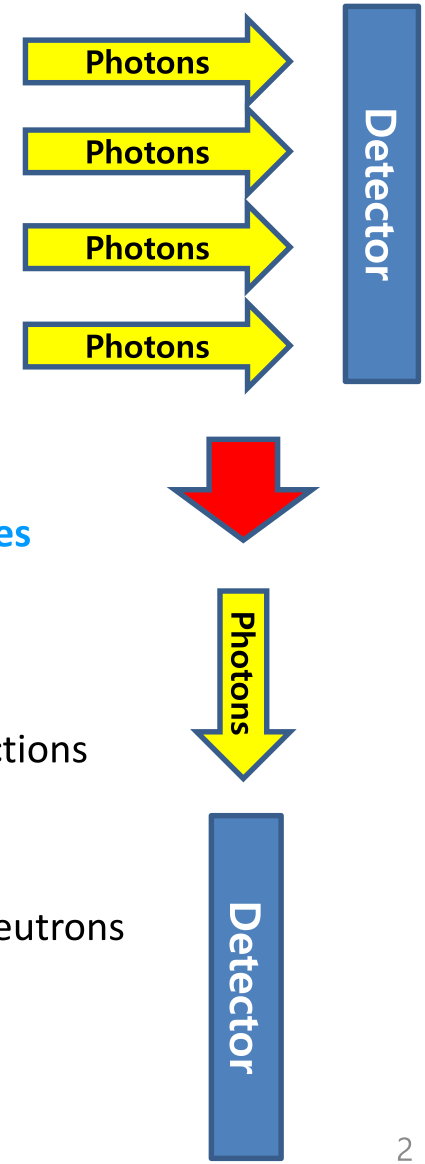
New idea: vertical-mode line-scan type glass MRPC detectors

Applications to Non destructive inspection with gamma rays (high-energy X rays)

Also potential application to measurements of secondary photons using
1) SPECT technology + 1D line scans for particle therapy
2) In-beam PET for particle therapy

GEANT4 simulations → we understand the RPC detector sensitivity to gammas via Compton scatterings is ~ independent to the incident angle, but …

***Line-scan detections are required* for better uniformity in 2D transmission images**



We propose narrow-area line-scan detections for photons

Let **photons emerge in the detector from the side** for line-scan detections
→ Dramatically increases the effective detect area participating the photon detections

- The realistic detection efficiency increases by a factors of ~ 10.
- Also mitigates the rate capability problem for glass RPCs.
- Why glass? → more sensitive to high-energy photons while less sensitive to neutrons

High efficiency for gamma rays → does not require a so high source activity

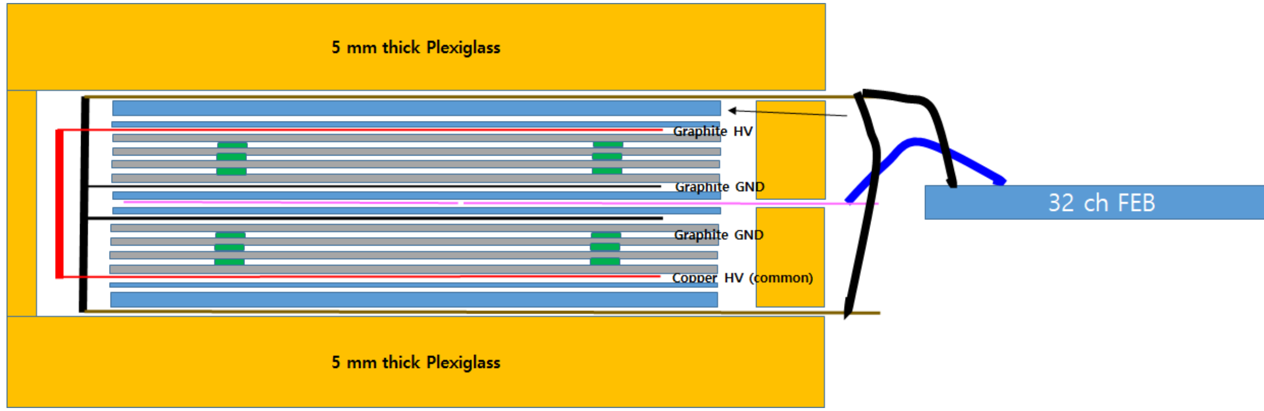
Constructed a MRPC composed of two triple gaps made of 0.55 mm thick glass plates + 0.53 mm thick spacers

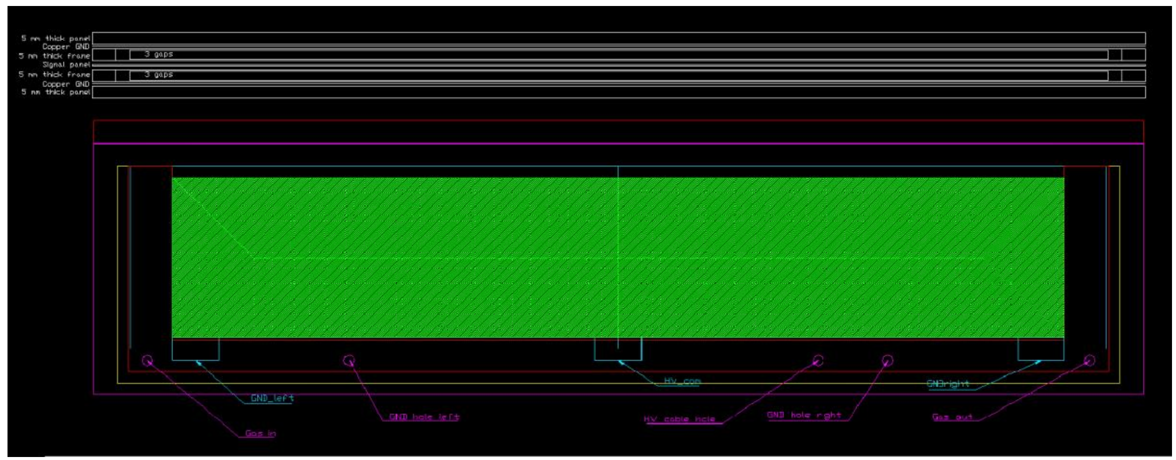
Detector dimension (active):
38.4 cm (length) x 7.0 cm (depth)
Thickness of the volume: 10 mm

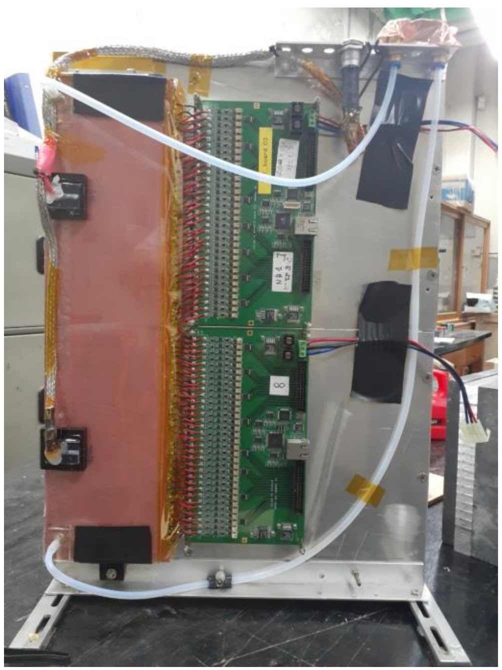
Number of spacers per gap: 24
Diameter of spacers: 8 mm

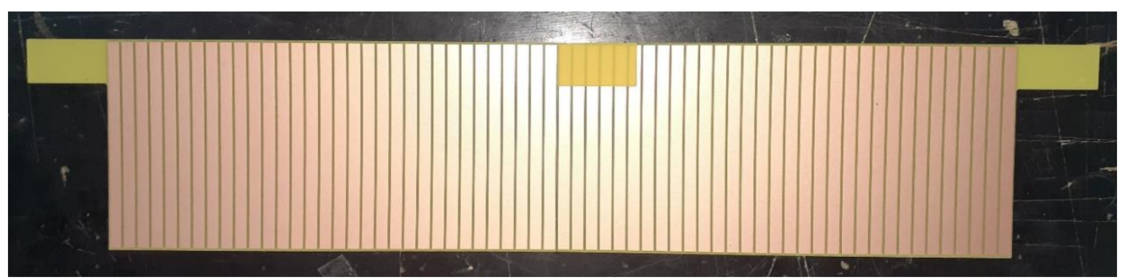
Sixty four 1D strips with
6- mm strip pitch

Expected position resolutions
> 2 mm along the scan direction
~ 2 mm in the vertical direction









Front-End Electronics (custom-made)

32 channels per a FEB
  Channel pitch: 6 mm

Current (voltage) sensitive mode
  Linear amplification up to maximum 10 pC inputs
  Gain of preamps: 200

Thresholds for input signals
  Minimum: 50 μV (~ 10 fC for MRPC signals)
  Maximum: 10 mV (~ 2 pC for MRPC signals)

Threshold control: Ethernet (intranet) connection

Output pulse type: LVDS (adjustable from 20 ns ~ 140 ns)

Data transferred via twist-pair cables and 34-pin connectors

In the present tests,
  Threshold: 400 ~ 800 μV
  LVDS width: ~ 60 ns

Trigger Electronics (custom made)

Time resolution of data: 1 ns
Both self-trigger and external-trigger modes are available.

1. **LVDS to LVTTL translator**: converts 128 pairs of LVDS input signals to LVTTL signals
   propagation delay = 2.6 ns
   part = SN75LVDT386 (Texas Instruments)

2. **LVTTL receiver**: buffers LVTTL gate signals
   propagation delay = 1.5 ns
   part = SN74LVC1G34 (Texas Instruments)

3. **Digital processor** (adjustable trigger window from 20 ns to 1270 ns)
   (1) Accepts LVDS inputs (minimum 10 ns) while the gate signal is high (either self or external trigger mode).
   (2) In the self trigger mode, the first channel of arrival (high) opens the trigger gate for all other channels (with a low or high state) and the timer value (provided by a local oscillator count) are recorded.
   (3) For each trigger, the data are transfered to a DRAM module
   (4) whenever the embeded DAQ PC requests data, the data are transferred from DRAM module to the DAQ PC.
   part = XC6SLX75-2FGG676C (Xilinx)

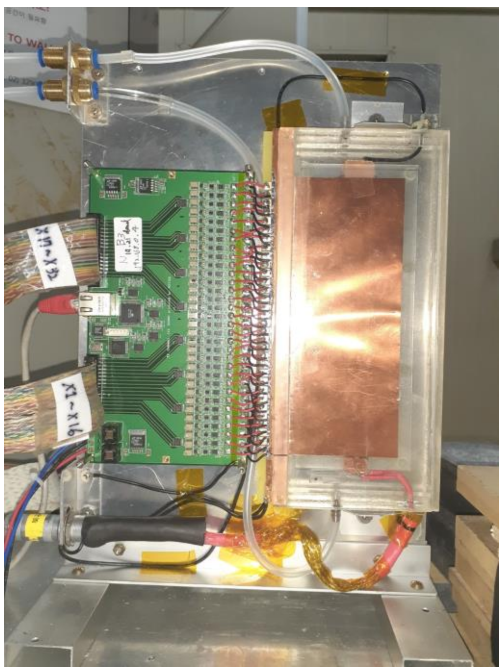
4. **4 Gbyte DRAM**: stores hit patterns and time data
   capacity = up to 128 M events
   part = M471B5173 (Samsung electronics)

5. **Embeded PC with gigabit TCP/IP link**: controls the digital processor and transfer the data from DRAM module
   OS = Linux, part = XC7Z020-1CLG484C (Xilinx, ARM cortex9 CPU embeded FPGA) and peripheral components

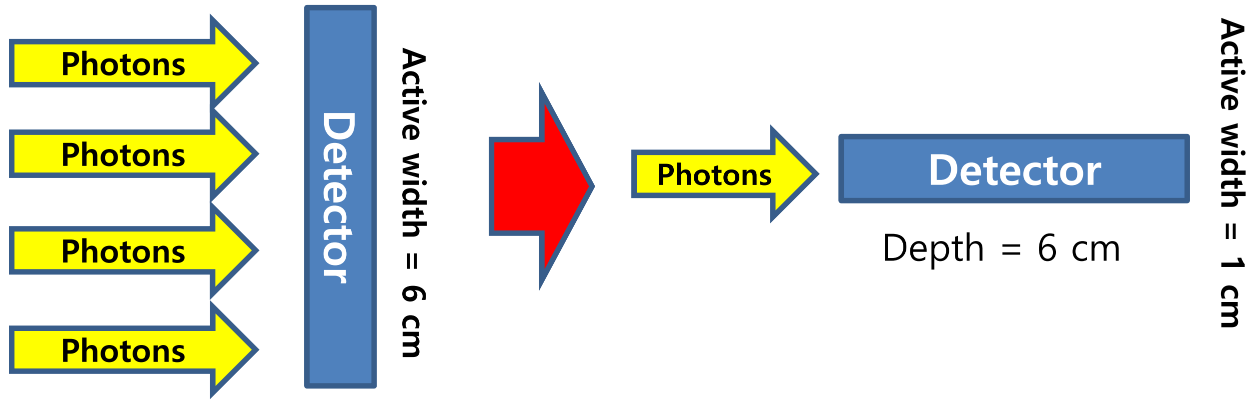
2. Simulations and tests for detection efficiencies

GEANT simulations
for line scan detections

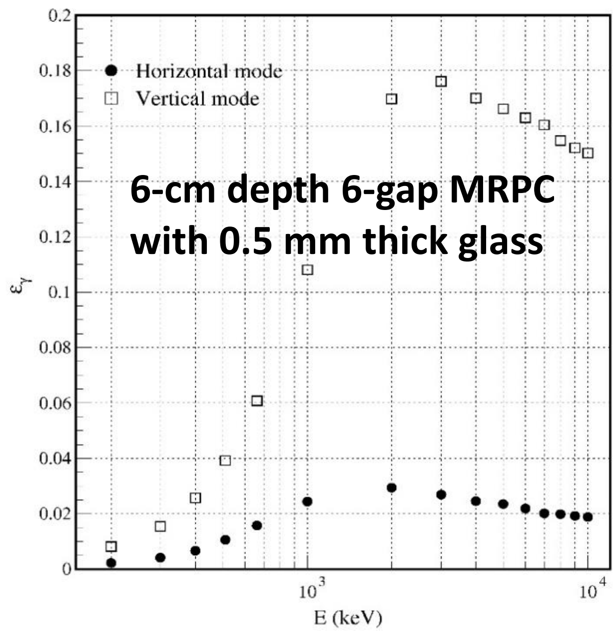
First 32 channel 6-gap MRPC
Active length and width =
19.2 cm / 6.0 cm

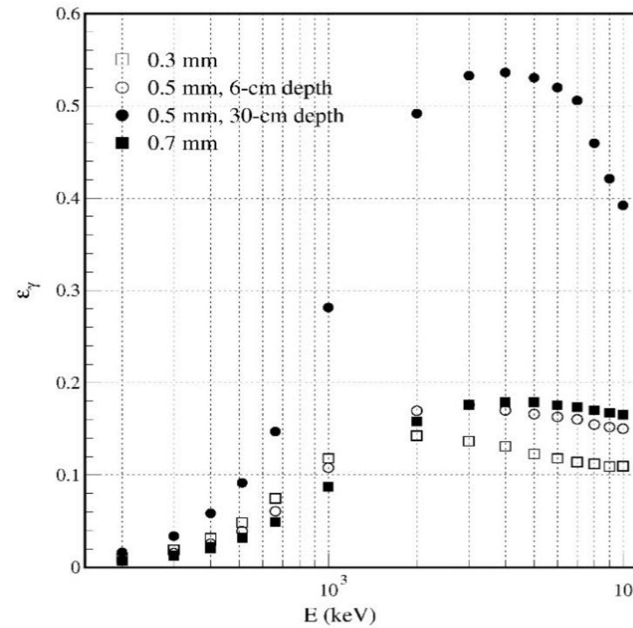


Horizontal mode / **Vertical mode**



For low energy gamma, thinner glass is better.

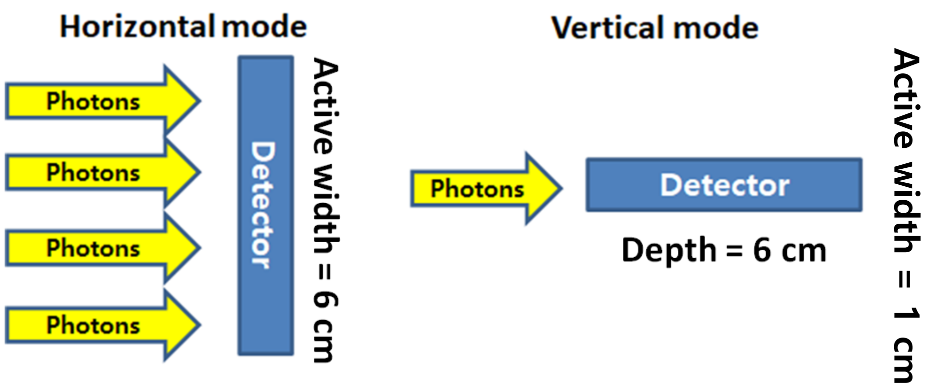


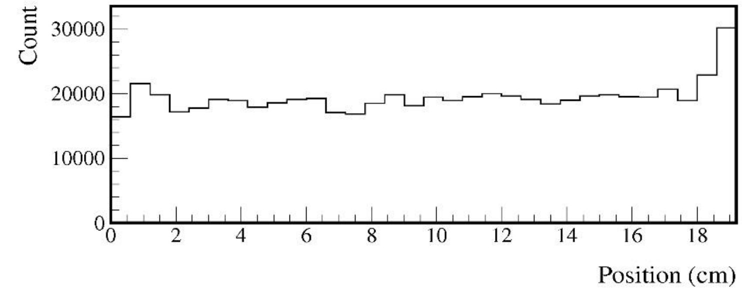


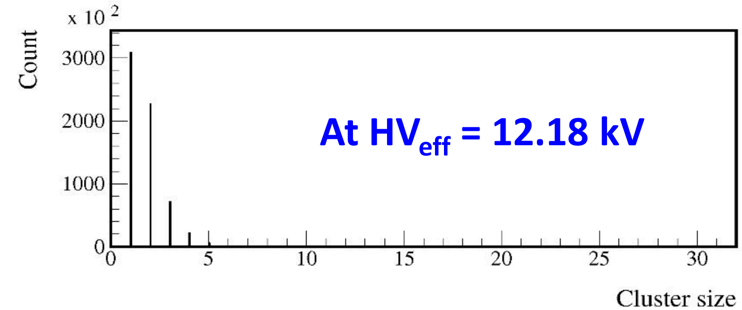
Efficiency test of a 32 channel 6-gap MRPC

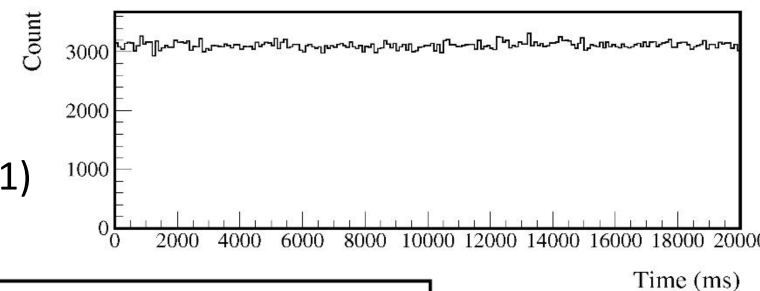
Gamma source: 4.74 GBq (127 mCi) ^{137}Cs

Gas mixture: 89.0% TFE + 10.0% iC_4H_{10} + 1.0% SF_6





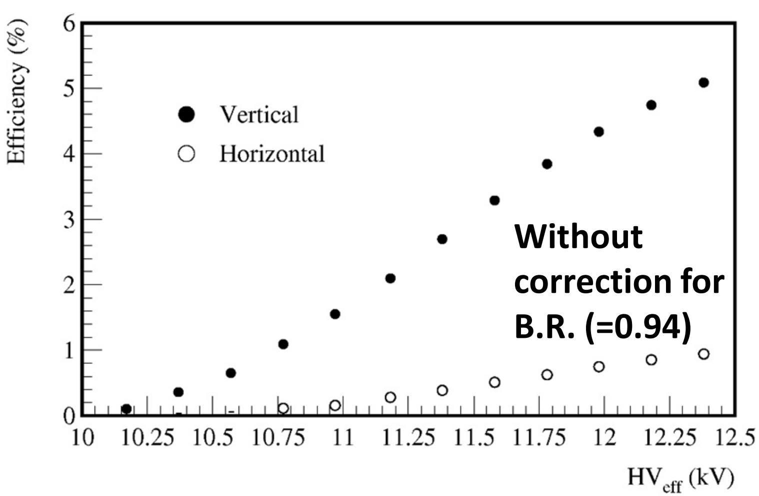


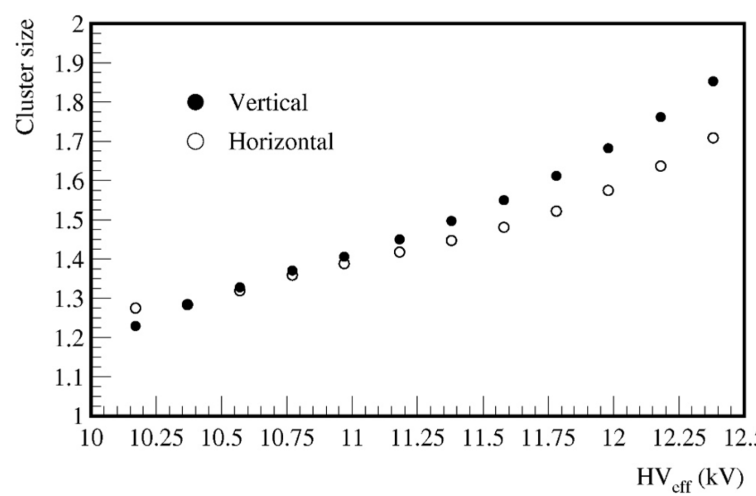


At HV_{eff} = 12.18 kV **Threshold = 400 μV**

Efficiency with a horizontal mode = 1.05% (1.5% by GEANT321)

with a vertical mode = 5.05% (6.2% by GEANT321)





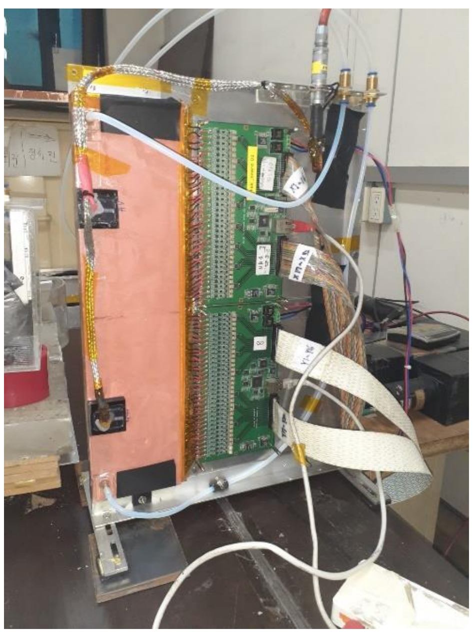
3. Gamma-transmission imaging using a 4.74 GBq ^{137}Cs source

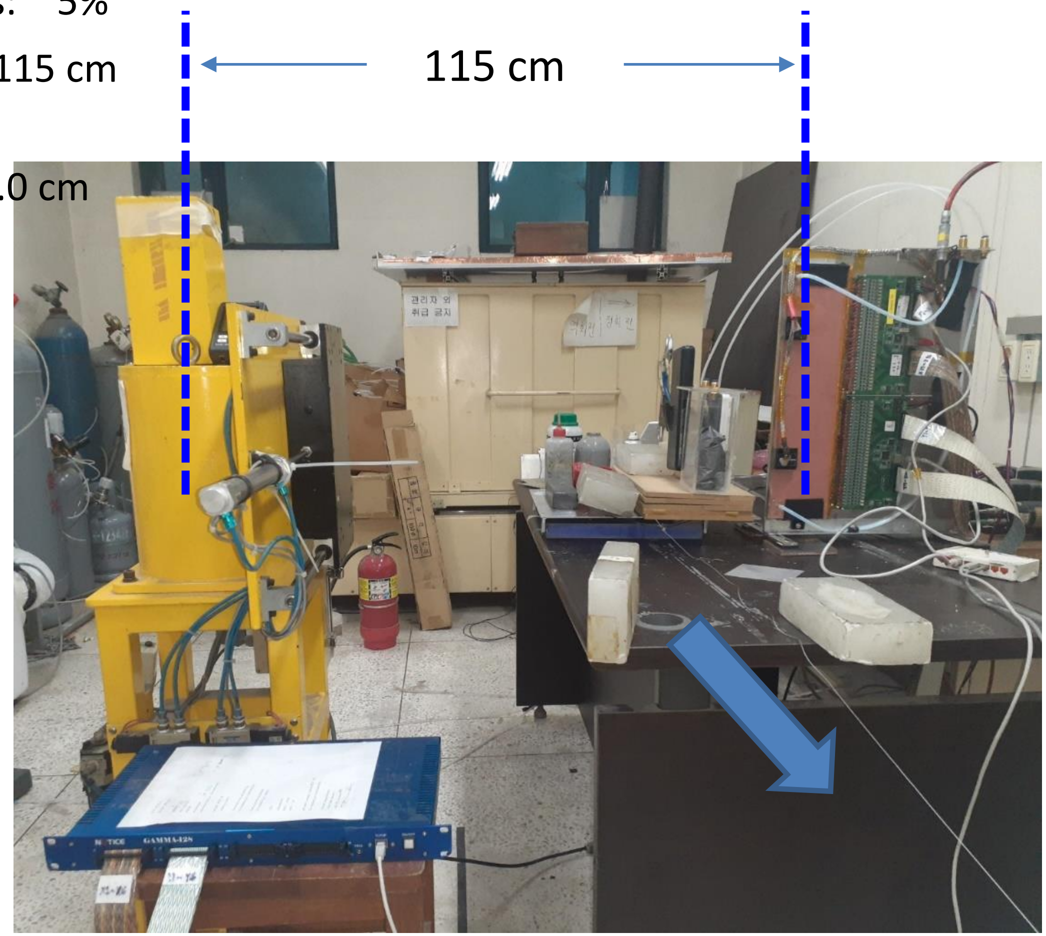
Constructed a 64-ch 6-gap RPC
  Active length and width = 38.4 cm / 7.0 cm

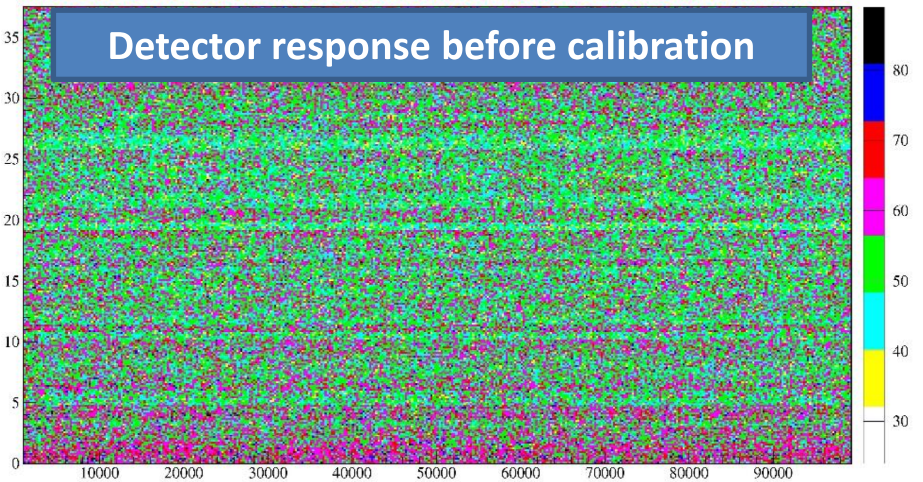
Gas mixture = 89.0% TFE + 10.0% iC_4H_{10} + 1.0% SF_6
  WP HV_{eff} = 12.1 kV
  Expected efficiency for 661.7 keV gammas: ~ 5%

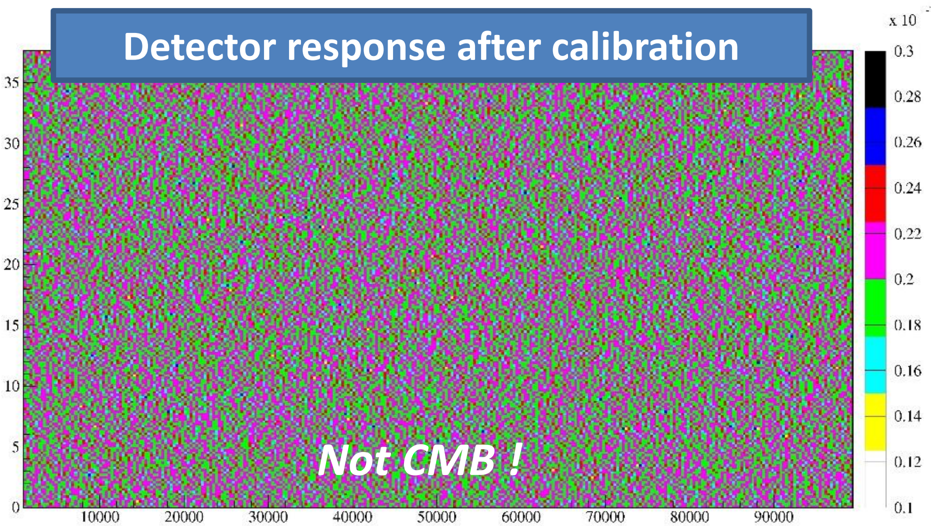
Distance of the scanner from the source = 115 cm
  Gamma particle rate ~ 1.3 kHz cm^{-2}

Scan area for moving objects: 38.4 cm x 64.0 cm
Scan time and speed: 100 s and 0.64cm/s



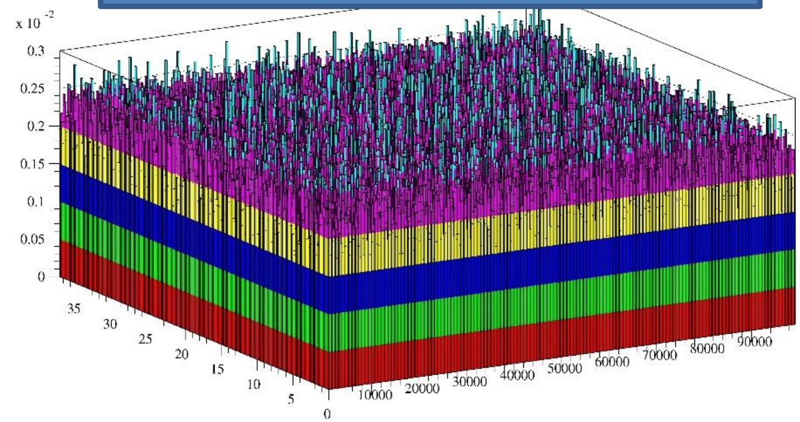




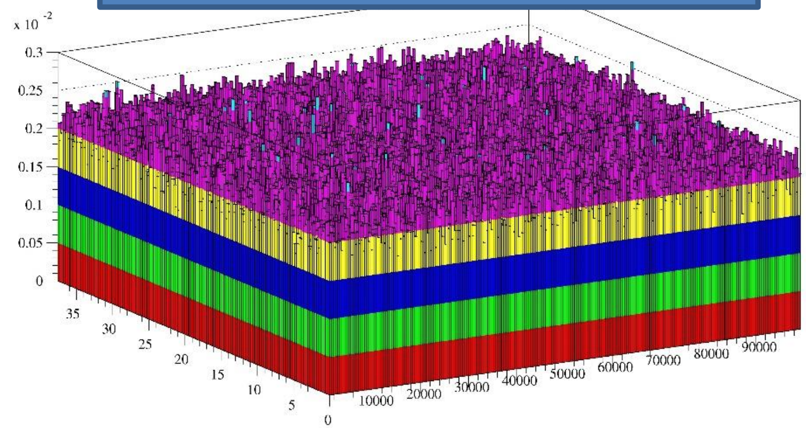


5.5 million ^{137}Cs Gammas (100 s)

1.5 mm pixel resolution (256 x 400)

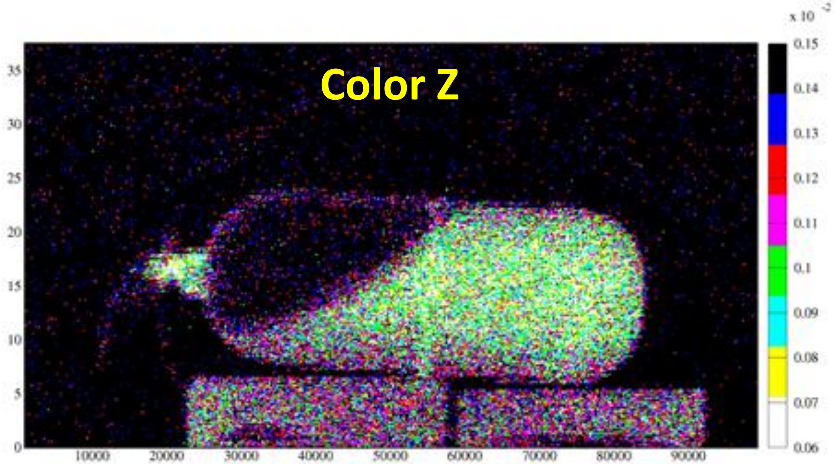


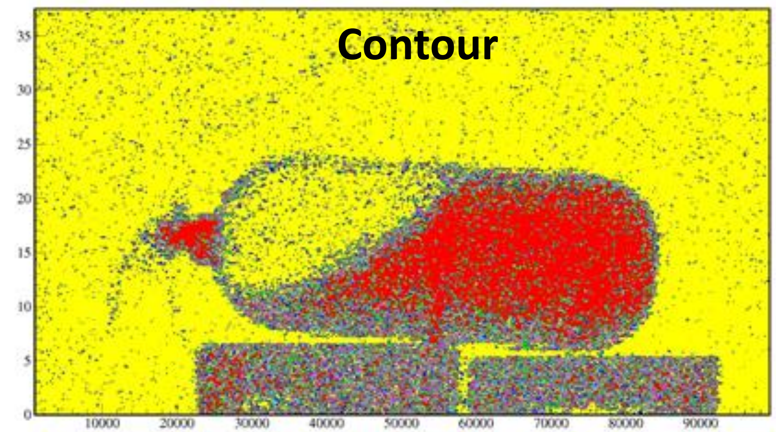
2.0 mm pixel resolution (192 x 300)



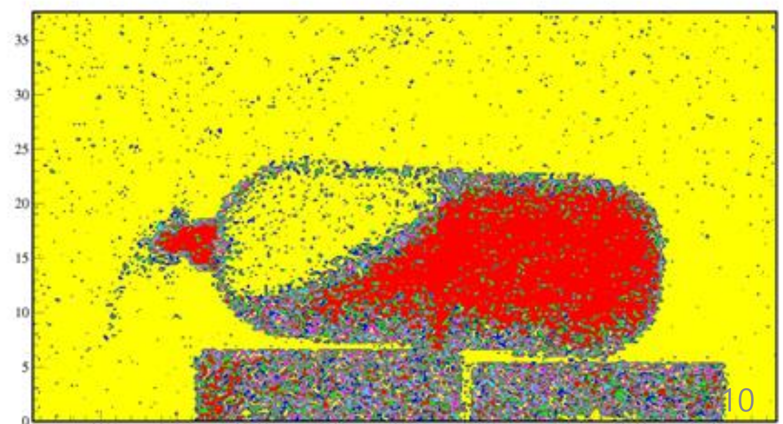
Fire extinguisher

1.5x1.5mm^2 pixel resolution, color depth ~ 60





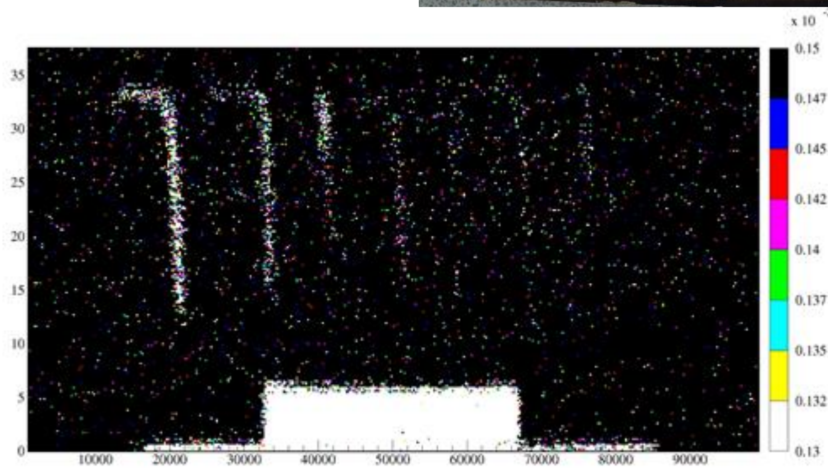
2.0x2.0mm^2 resolution, color depth ~ 100

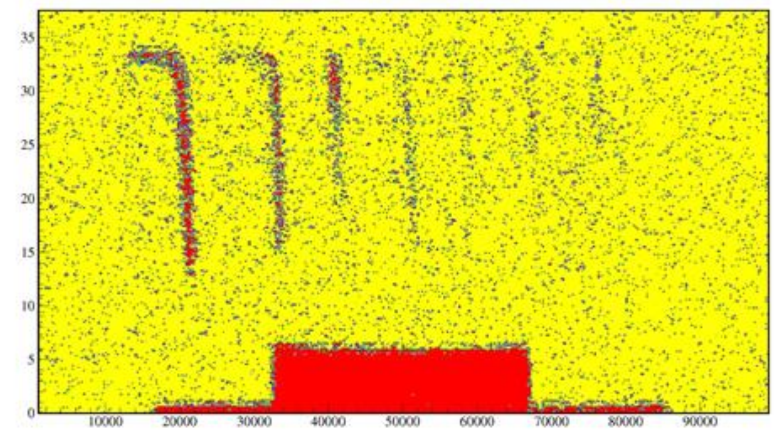


Wrenches, drill bits, drivers

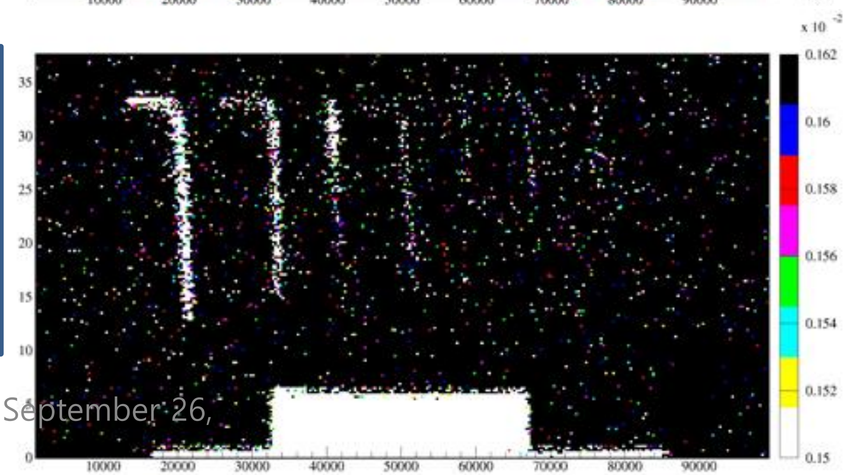
Barely identifies 3 mm thick steel drivers

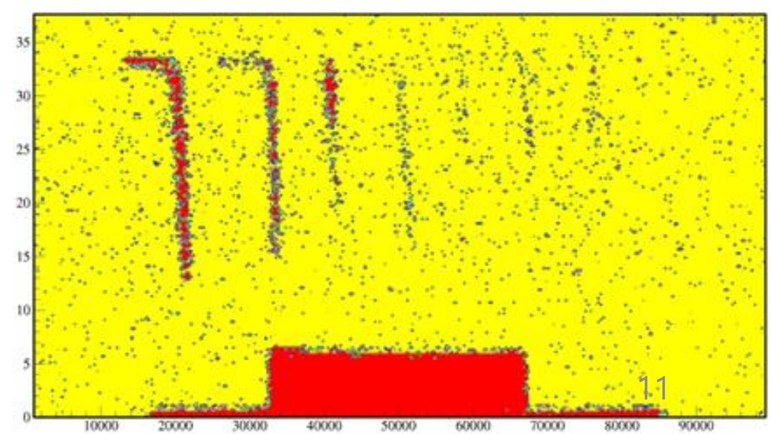
1.5x1.5mm^2 pixel resolution, color depth ~ 60





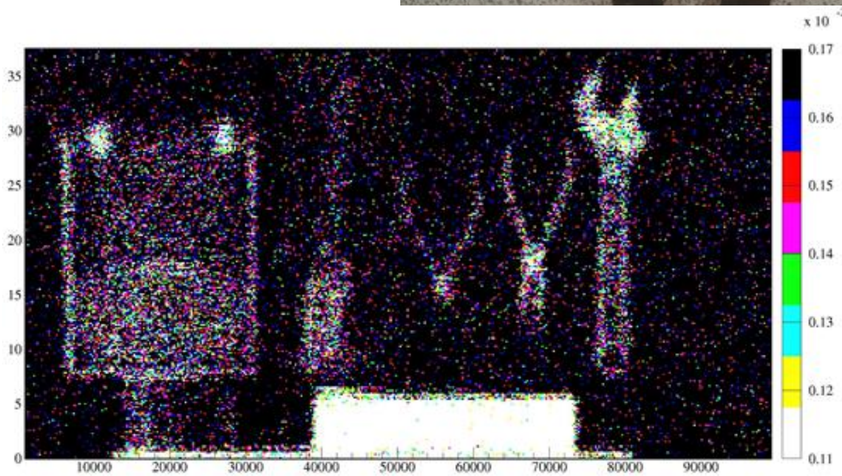
2.0x2.0mm^2 resolution, color depth ~ 100

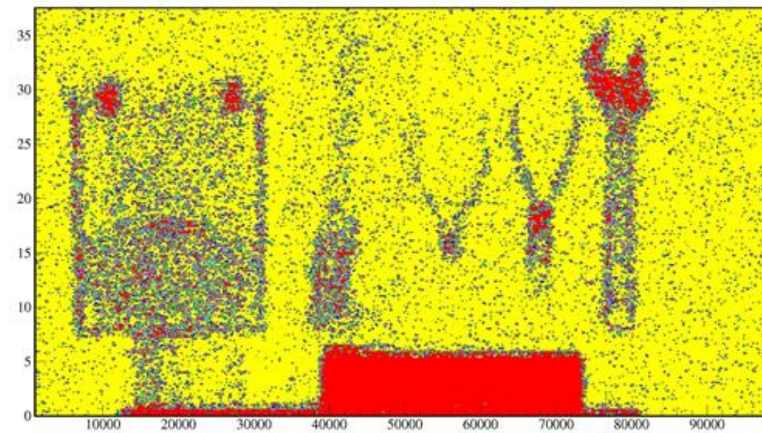




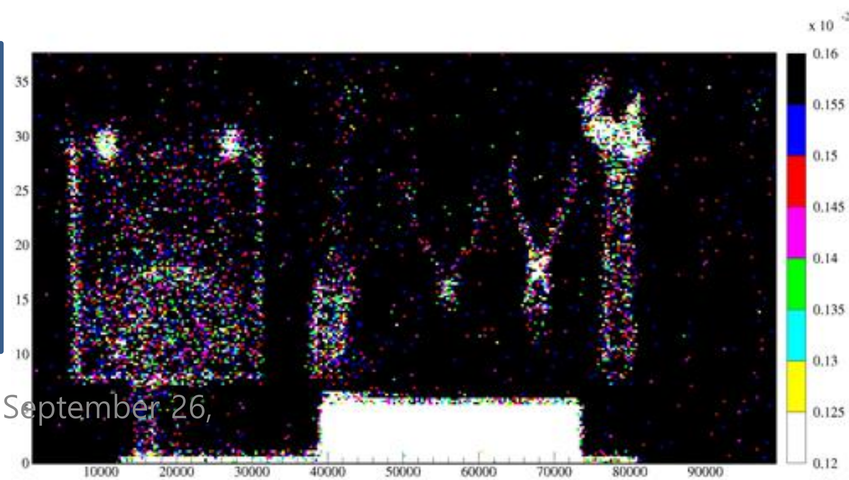
Spanner, cutter, calipers

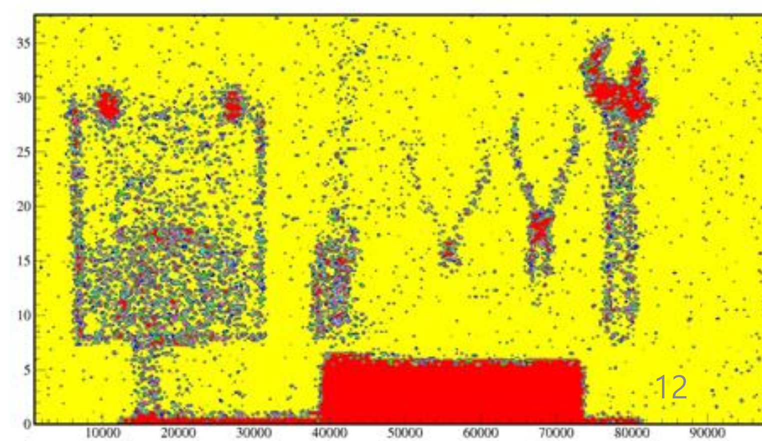
1.5x1.5mm^2 pixel resolution, color depth ~ 60





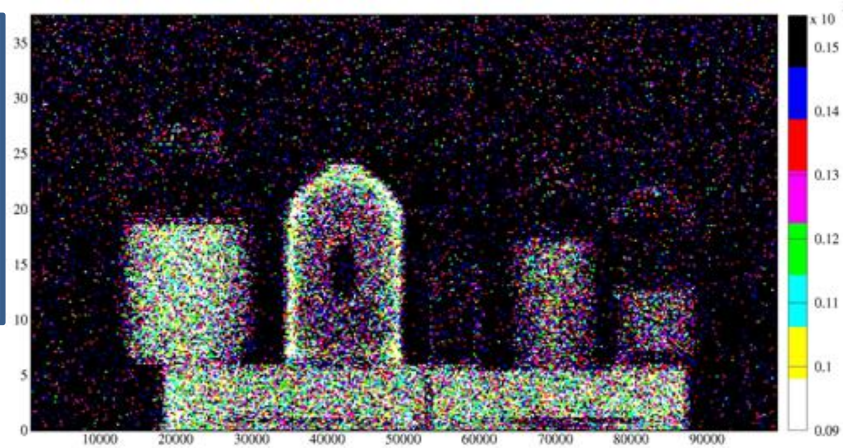
2.0x2.0mm^2 resolution, color depth ~ 100

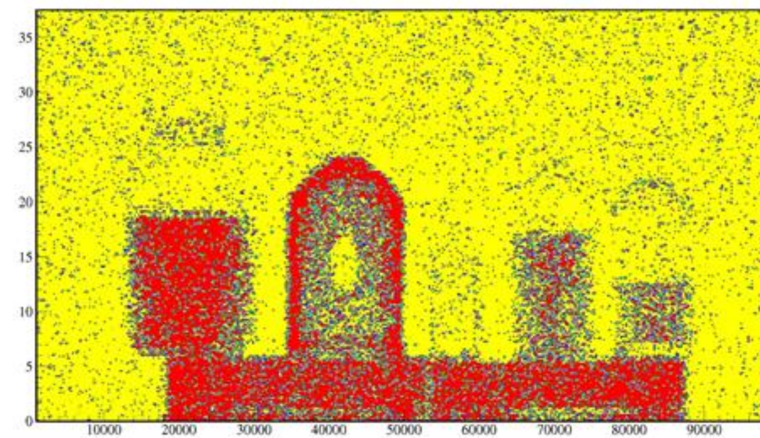




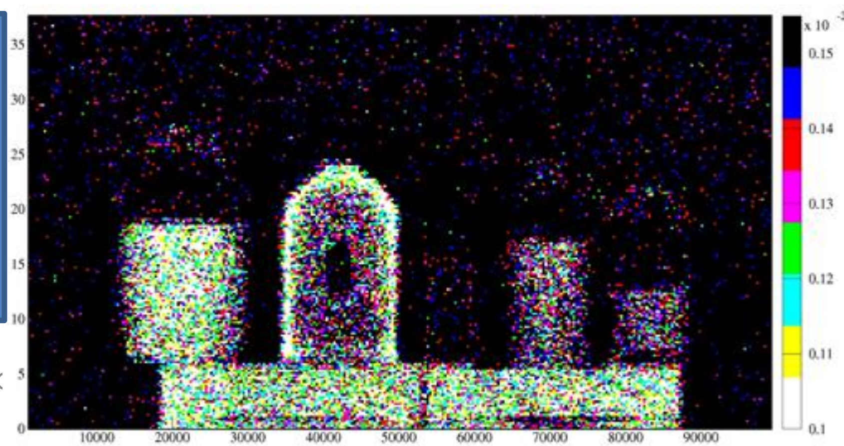
Bottles

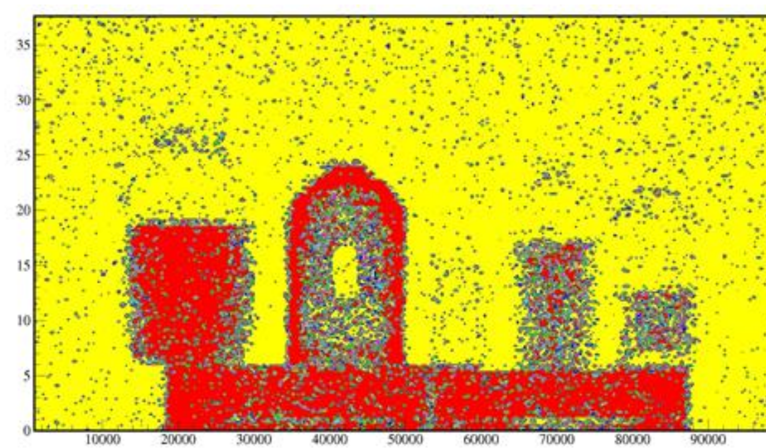
1.5x1.5mm^2 pixel resolution, color depth ~ 60





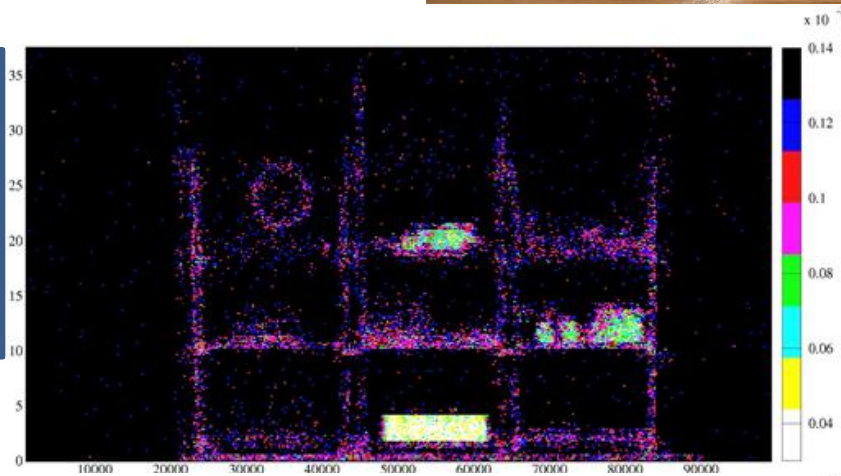
2.0x2.0mm^2 resolution, color depth ~ 100

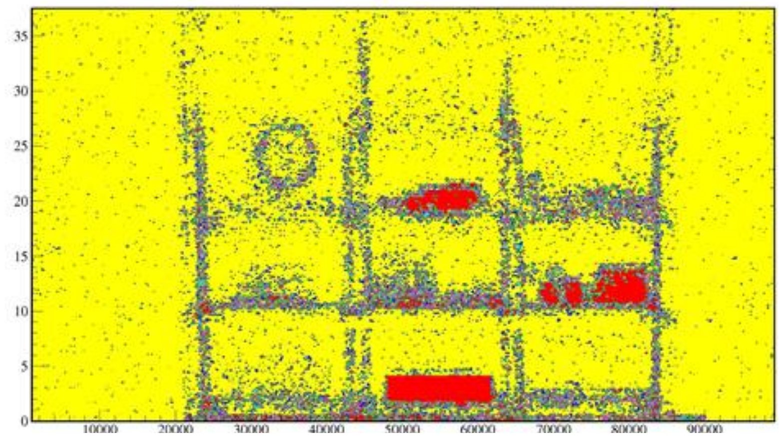




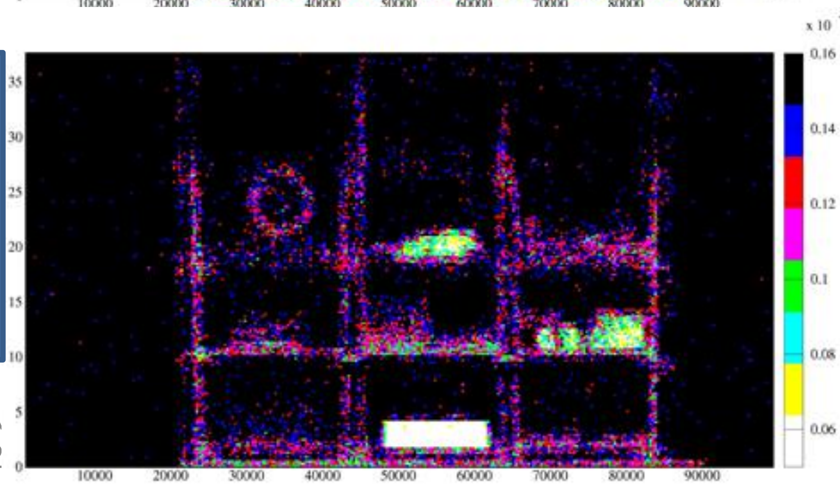
Materials in a shelve

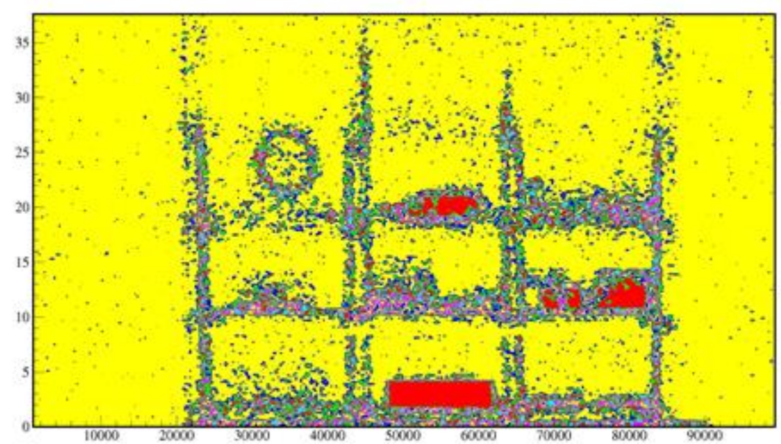
1.5x1.5mm^2 pixel resolution, color depth ~ 60





2.0x2.0mm^2 resolution, color depth ~ 100



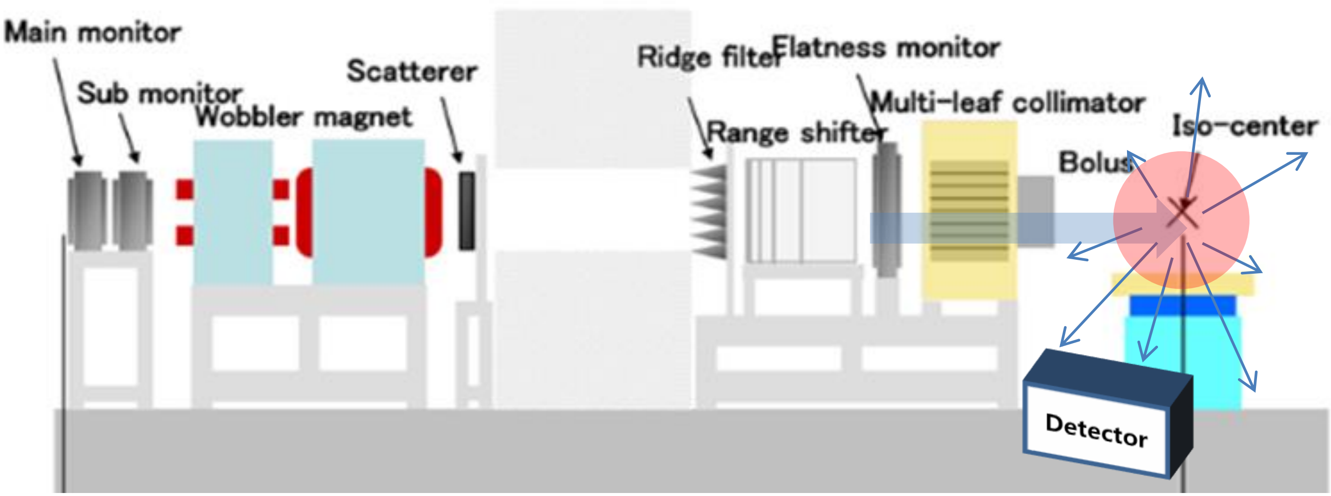


4. Potential application to on-line verification of beams in hadron therapy.

→ **Verification of therapy beams (protons and heavy ions) by measuring secondary photons emitted from planned treatment volumes (PTVs)**

- Single-photon emission tomography using collimators by measuring **all prompt gammas**
- In-beam PET (positron emission tomography) by measuring positron decays

Fixed carbon beam line at HIMAC



Proton-beam Gantry at Samsung

Simulations for beam-induced secondary particles

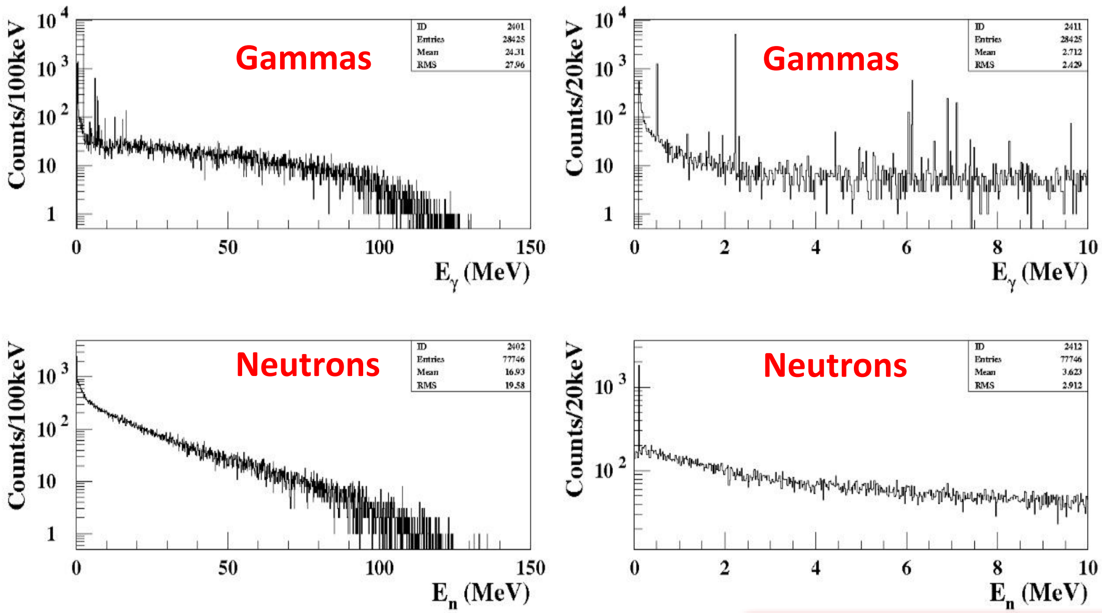
Using a GEANT4 program, simulations (presented at RPC2018) for

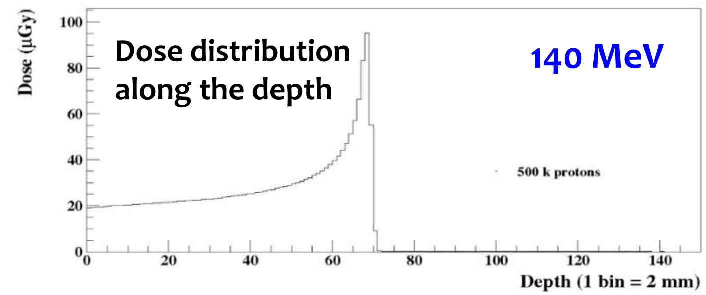
- Prompt and delayed gammas of the excitation lines of nuclei, positron-emission gammas (511 keV), and bremsstrahlung occurred in biological tissues
- Neutrons emitted from biological tissues
- Vertex positions, emission angles, energies of secondary particles

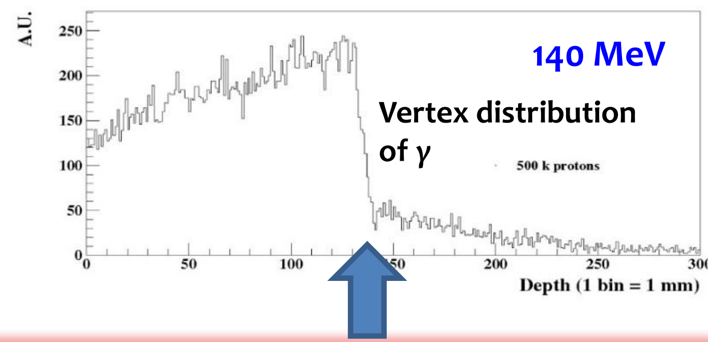
Gamma & neutrons per a proton

Beam energy of proton	γ per proton	n per proton
44 MeV	6.832×10^{-3}	8.158×10^{-3}
140 MeV	5.670×10^{-2}	1.605×10^{-1}
190 MeV	9.157×10^{-2}	3.537×10^{-1}

140 MeV protons (0.5 M)







What is the mission?: verifying distal edges of therapy beams

Line scan detector (SPECT)

Glass MRPCs are adequate for measuring high-energy prompt gammas (> 1 MeV)

When applied to therapeutic-beam verification via measuring secondary gammas,
The scanner can be used for both cases

- **During the therapy (yes)**
- **Right after the therapy (statistics?)**

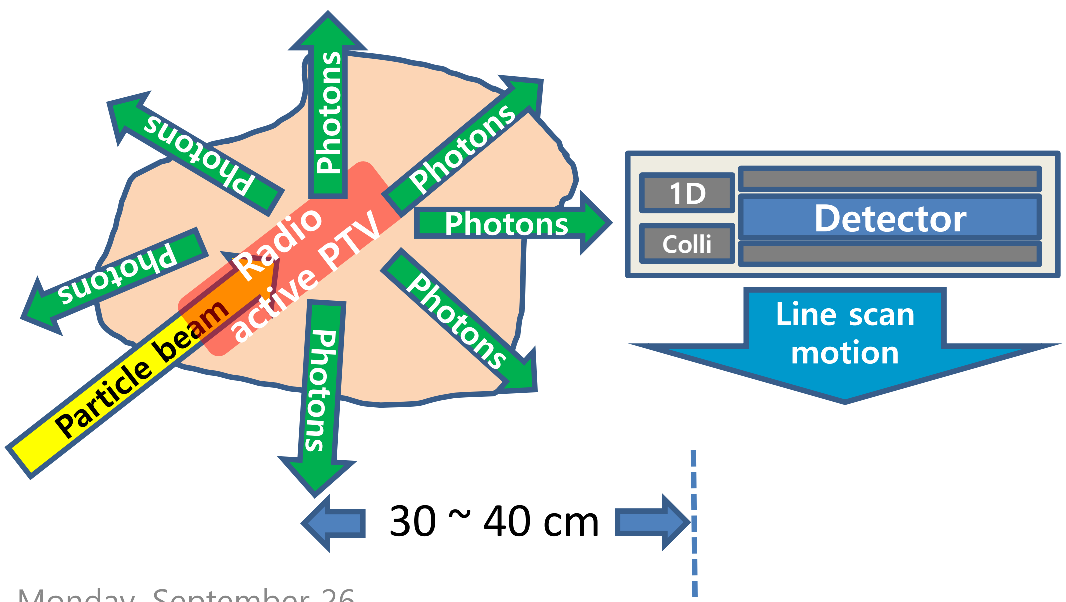
Expecting a serious neutron activation background

→ The line scan detection can minimize the detector surface facing the fast neutrons emitted from planned treatment volumes (PTVs).

1-cm pitch 1D collimator

2-cm thick lead bricks + 1-cm pitch collimators made of twenty 5mm x 5mm x 100mm tungsten bars

Line scan detector with 1D collimators



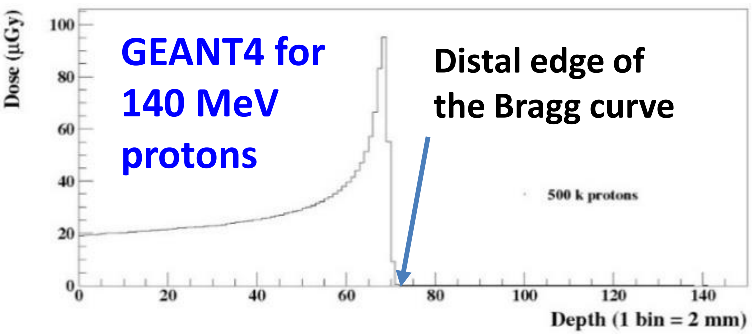
First, measured photon images of a 4.74 GBq Cs-137 point source → intrinsic resolution of images

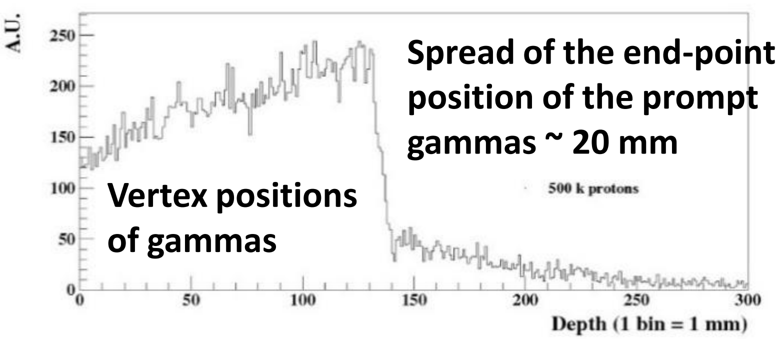
HV_{WP} = 11.4 kV with 89.0% TFE + 10.0% iC_4H_{10} + 1.0% SF_6

The scan image of a point gamma source will be more or less blur because of

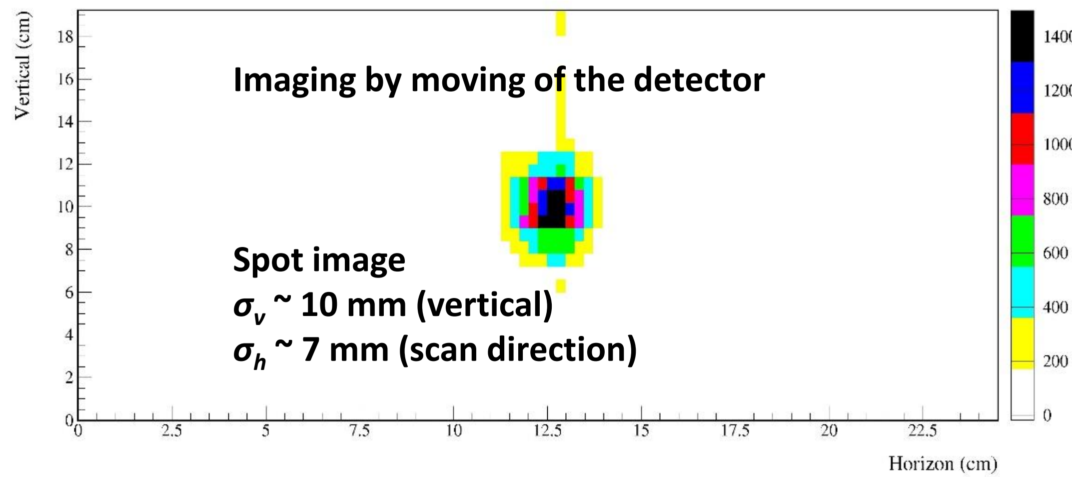
Blurring effect in both directions due to **small-angle Compton scatterings in the lead collimator**

But, a better resolution of the photon images may NOT be so necessary because





2D scan image of a spot beam of 661.7-keV gammas passing through a 1D collimator
The scanning done 30 cm from a Cs-137 point source

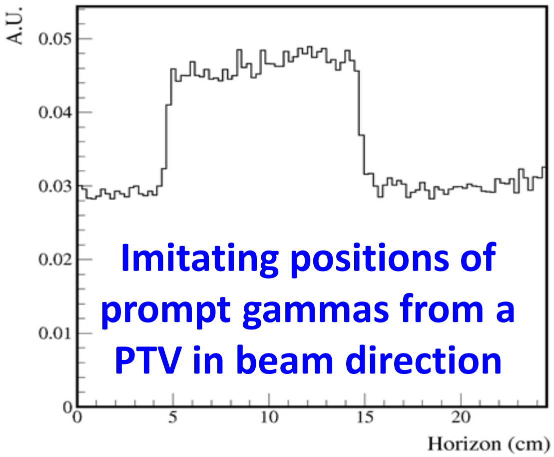


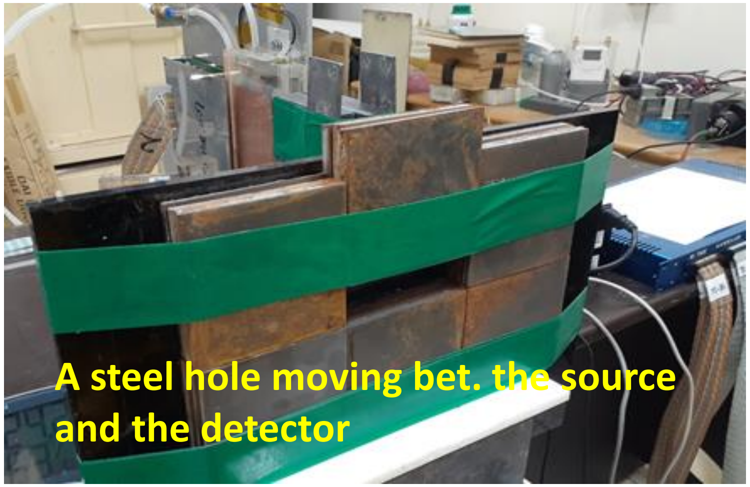
More realistic tests:

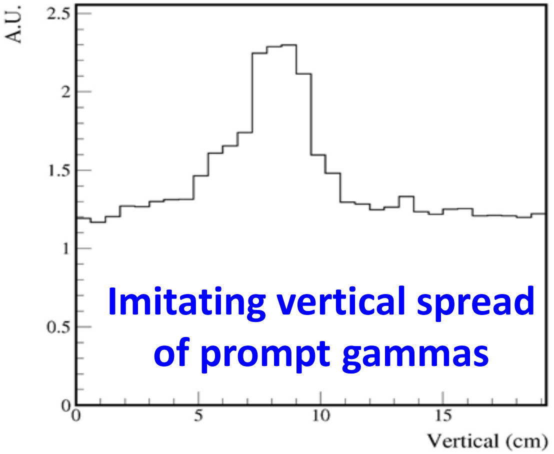
2D images of 661.7-keV gammas passing through a 4-cm thick 3.5 cm x 10 cm steel hole (100 s)
Installed the 1D collimator **73 cm** from the Cs-137 point source.
4 cm thick steel plate allows ~ an half of the gammas passing through

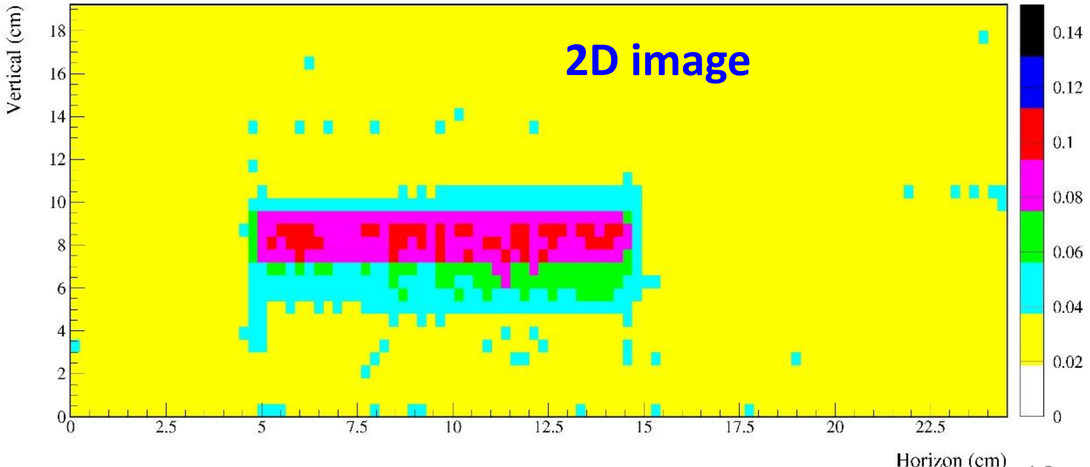
→ Tried to *imitate*

1) prompt gamma images showing the range of the therapy beam in PTVs
2) Flat neutron activation background in the images.









5. Conclusions

Non destructive inspection with a line-scan method

- Efficiencies for 661.7-keV gamma rays

GEANT simulations → 6% in 6-cm and 15% in 30-cm deep vertical-mode detectors, respectively.

Measurement using a 4.74 GBq Cs-137 source

→ The scan images obtained with ~ 5% efficiency @HV=12.1 kV in a 7-cm deep vertical mode detector.

→ The detector response is fairly stable and consistently uniform after a proper calibration.

- The data statistics were a bit poor due to the low activity of the Cs-137 source (4.74 GBq).

  Nevertheless, we have confirmed the detector performance guaranteeing quality measurements.

  → The position resolutions in the vertical ~ 2 mm and in the scanning direction ~ 2 mm or better.

  → A 3-mm thick steel driver was barely identified with a 100 color depth.

  The proper color depth should be at least ~ 500.

SPECT technology + 1D line scans for verification of therapy beams

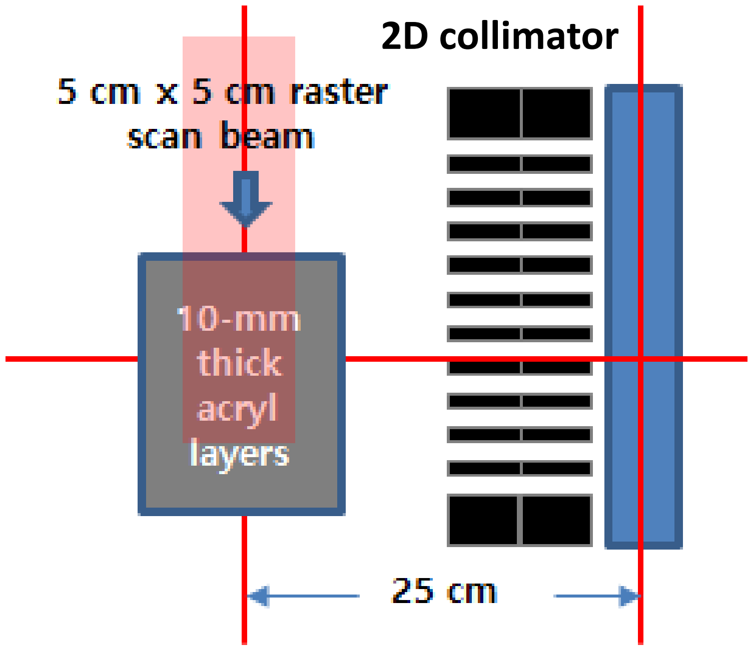
- Obtained proper 2D line-scan images of 661.7-keV gammas from a Cs-137 source.

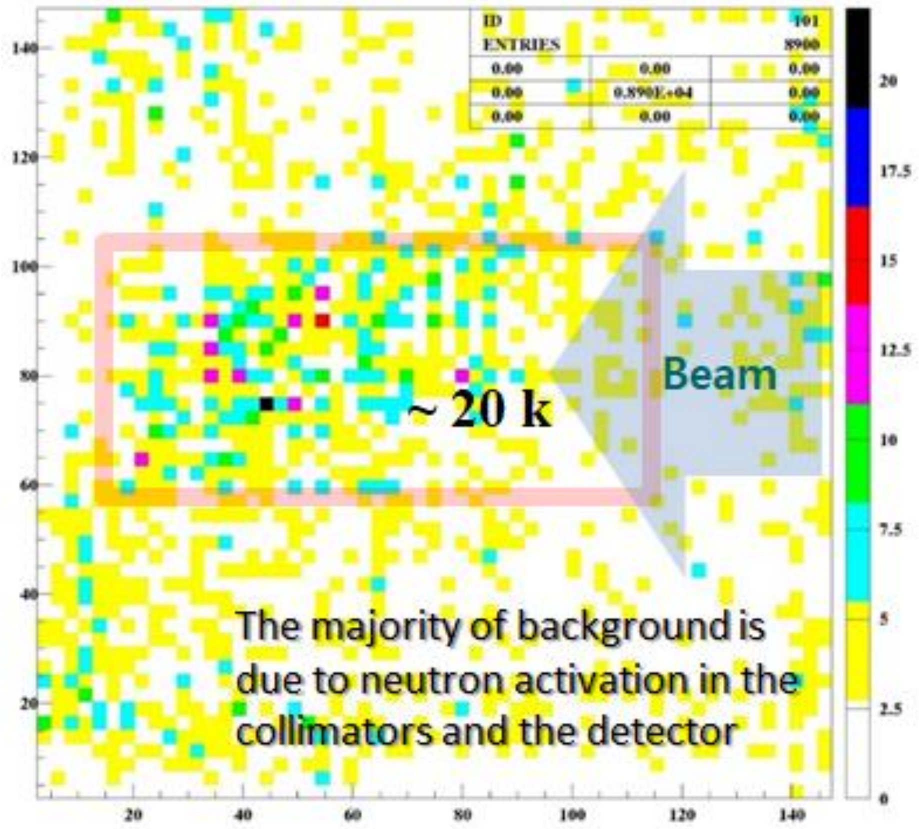
→ The determination of distal edges of beams can be done with a few mm accuracy.

→ The detector operation is quite stable and the data are uniform in time. → quality measurement

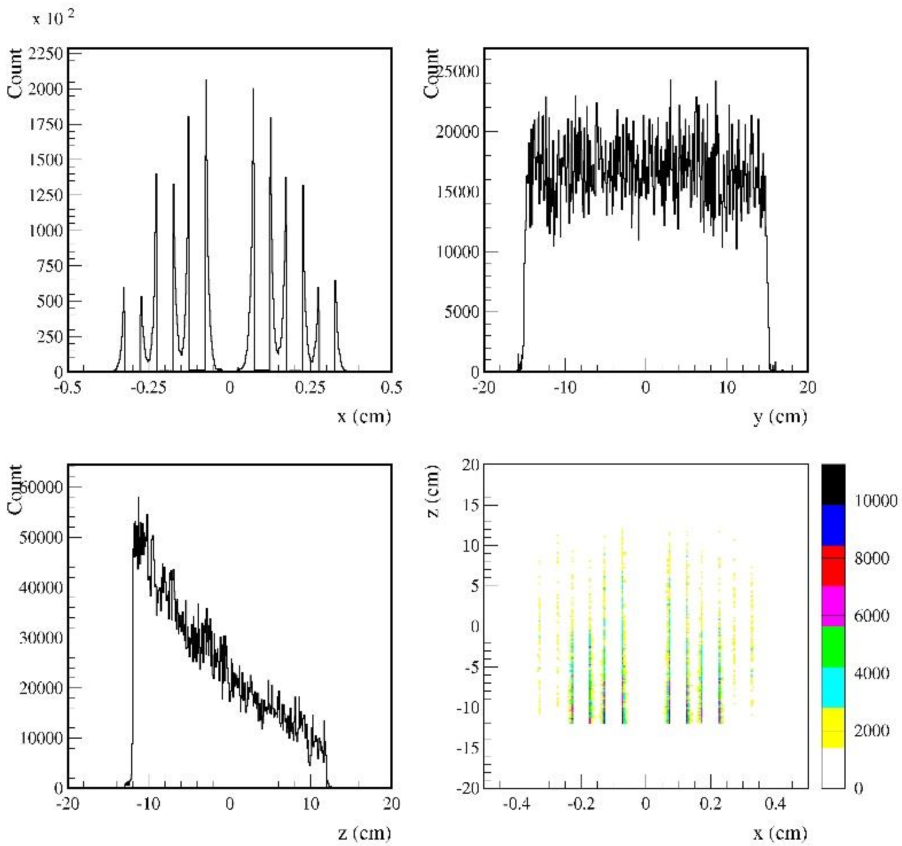
<u>BACK UPS</u>

In 2017, prompt-gamma images measured for a 140 MeV raster scan proton beam provided by Samsung Cancer Center (Seoul) (K. S. Lee, RPC2018)

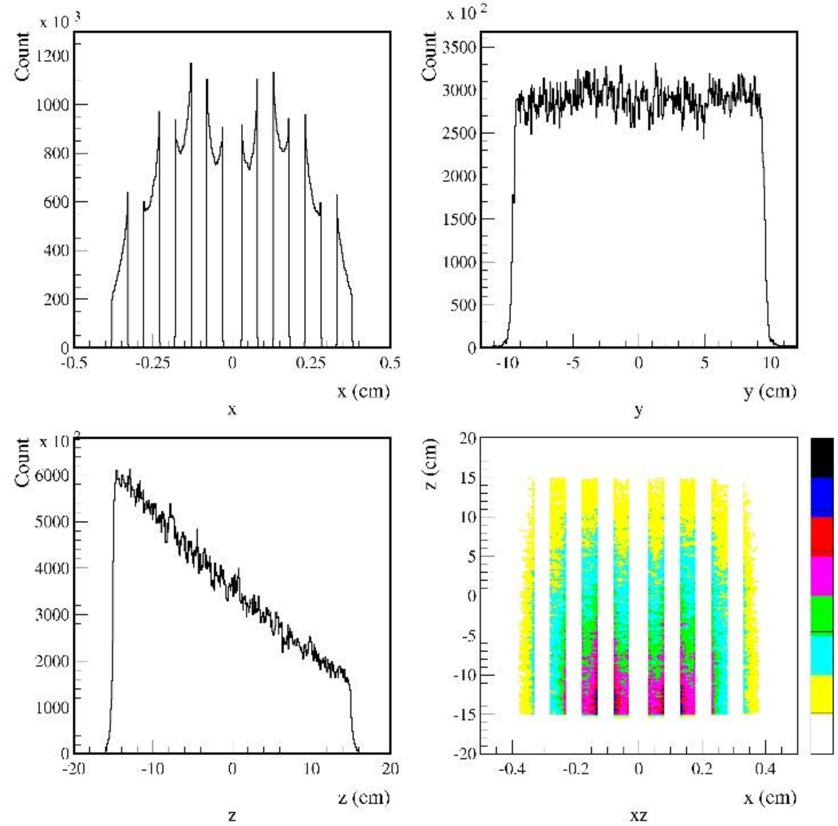




Positions of 661.7-keV gammas interacting in a 30-cm depth 6-gap glass RPC and ejecting a Compton electron



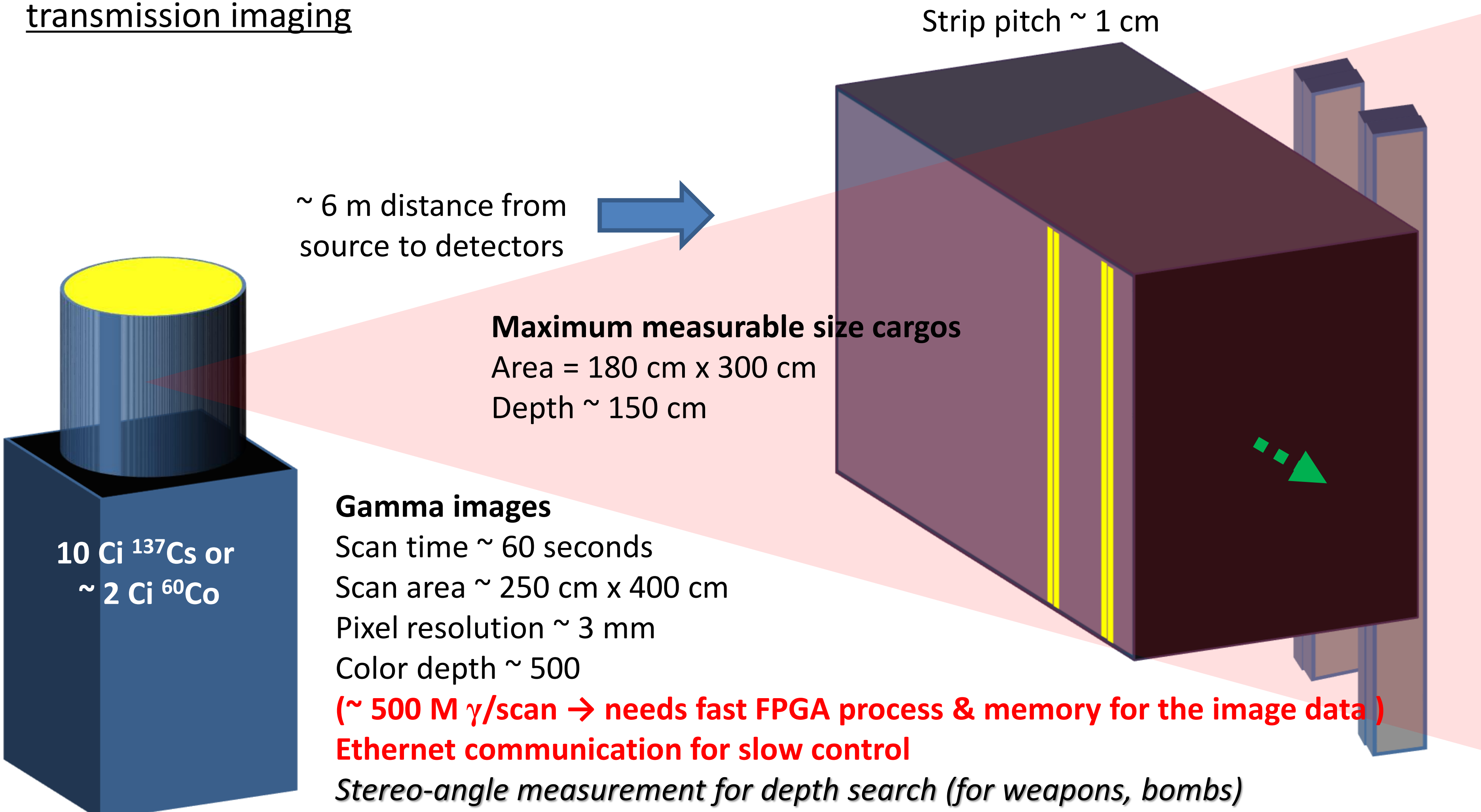
Positions of 3-MeV gammas interacting in a 30-cm depth 6-gap glass RPC and ejecting a Compton electron



An idea of application for a real-sized small gamma-scan system in airports

<u>Wish to use list mode scan data for gamma transmission imaging</u>

Two pairs of 2.7-m-long line detectors with a stereo angle
4 x 320 = 1280 channels
Detector depth ~ 20 cm
Strip pitch ~ 1 cm



~ 6 m distance from source to detectors

Maximum measurable size cargos
Area = 180 cm x 300 cm
Depth ~ 150 cm

Gamma images
Scan time ~ 60 seconds
Scan area ~ 250 cm x 400 cm
Pixel resolution ~ 3 mm
Color depth ~ 500
(~ 500 M γ/scan → needs fast FPGA process & memory for the image data)
Ethernet communication for slow control
Stereo-angle measurement for depth search (for weapons, bombs)

Images of 3.5 cm x 10 cm steel hole

Repeated the same measurements many times

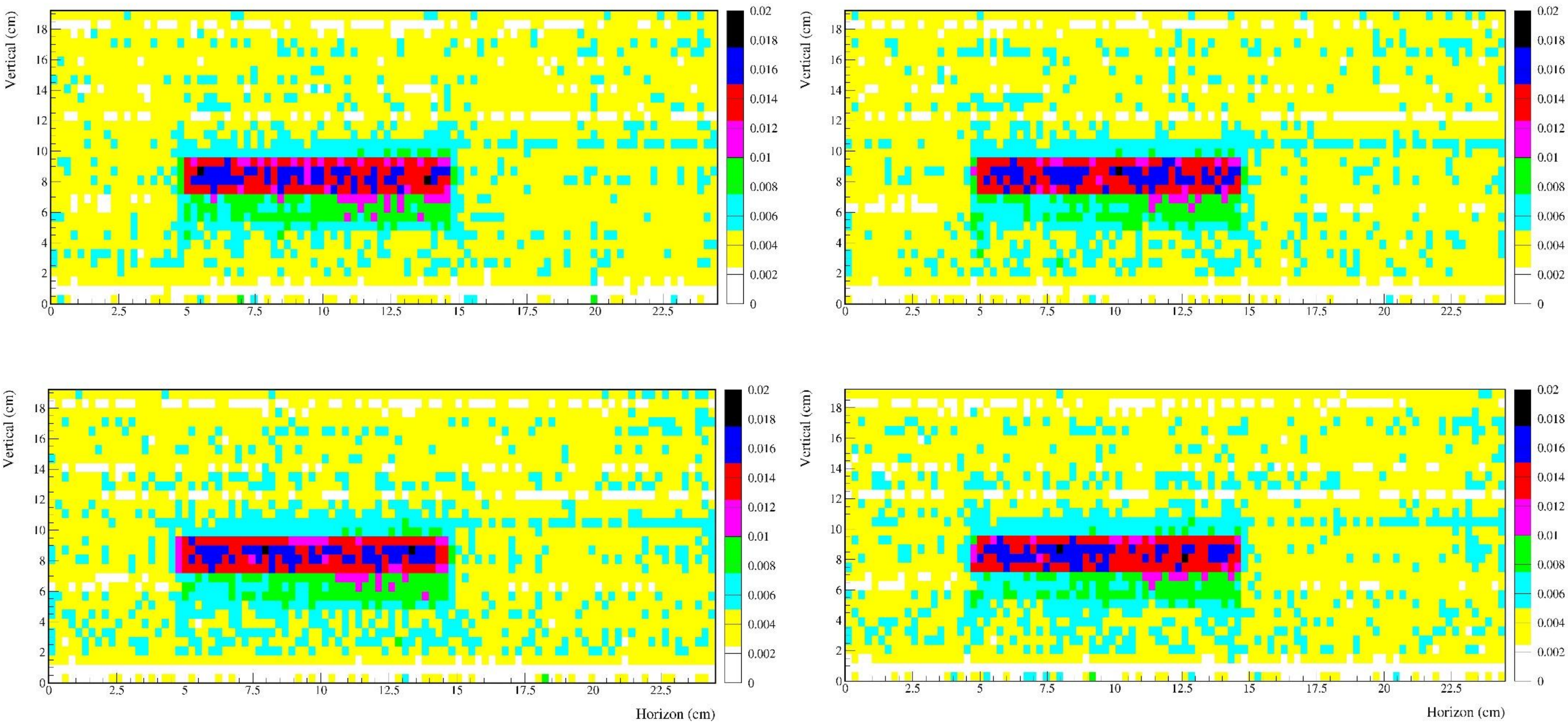
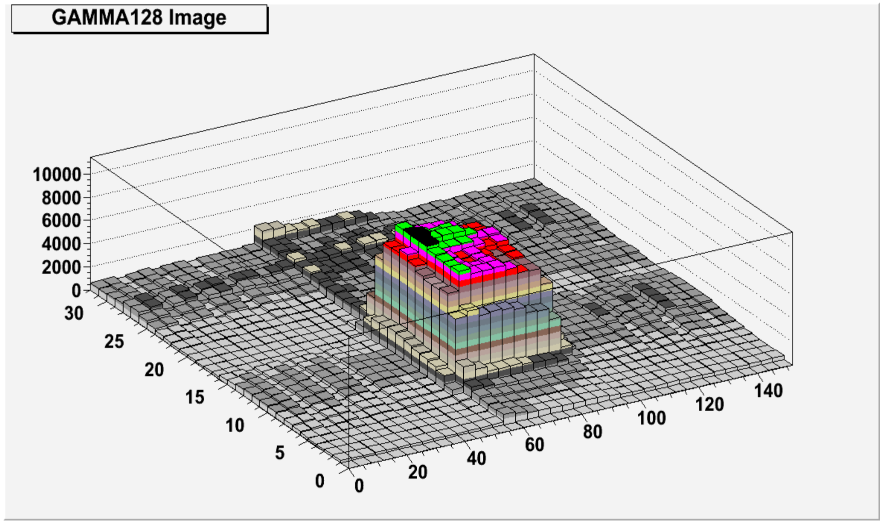
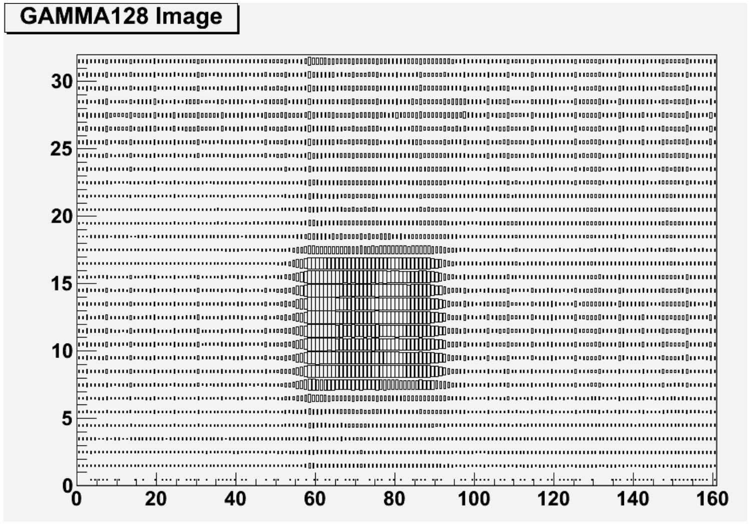


Image of 661.7 keV gammas passing through 6 cm x 6 cm lead hole (thickness of the lead = 5 cm).

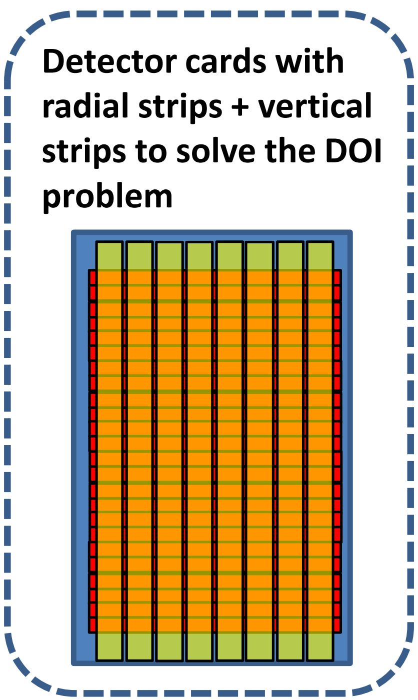


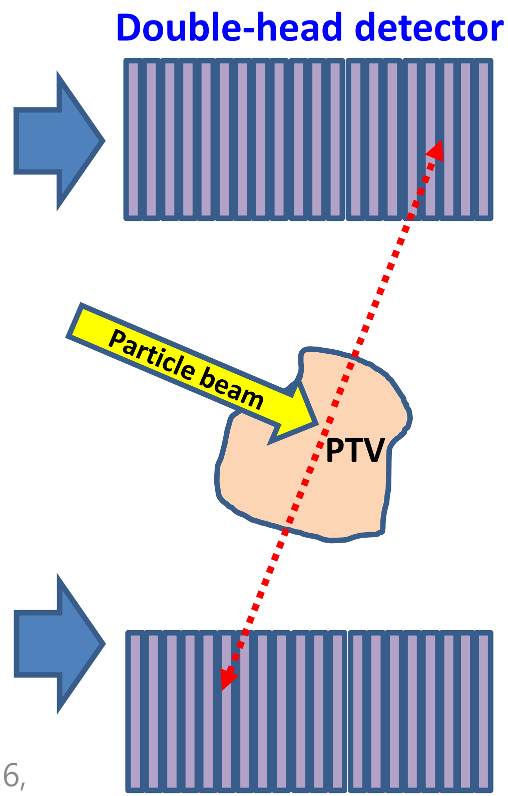


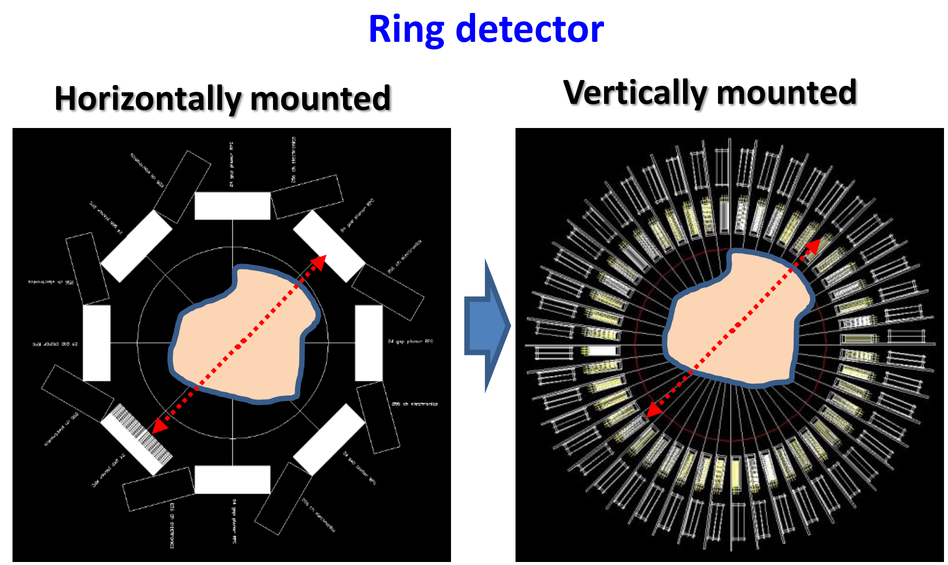
In-beam PET system (potential future work)

Measuring positron decayed 511 keV gamma pairs (for LORs) from C11, N13, O15 formed in the PTV by proton beams (or C12)

- Should be measured during the therapy due to poor statistics for positron decays when the beam irradiation OFF. Moreover, the longest $t_{1/2}$ is at best 20 mins.
- GEANT4 -> Single detector sensitivity for 511-keV gammas is around 10 %
- **Occupancy of the sensitive detector material (glass)** in the detection volume can be dramatically increasing using the vertically mounting mode → Makes the geometrical efficiency higher







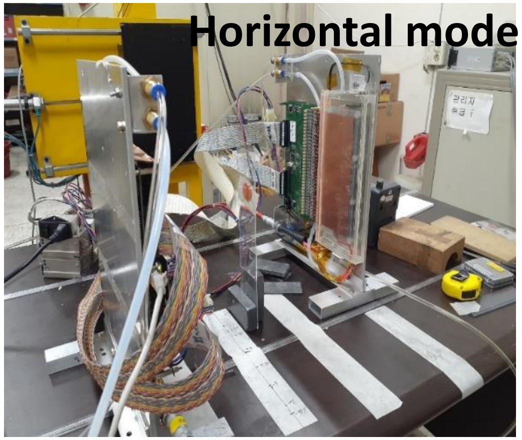
In-beam PET system (potential future work)

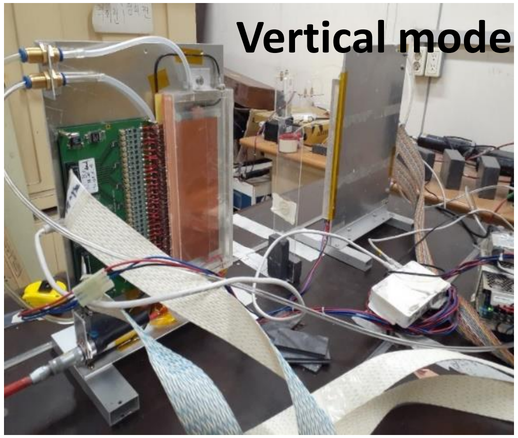
Measuring positron decayed 511 keV gamma pairs (for LORs)
from C11, N13, O15 formed in the PTV by proton beams (or C12)

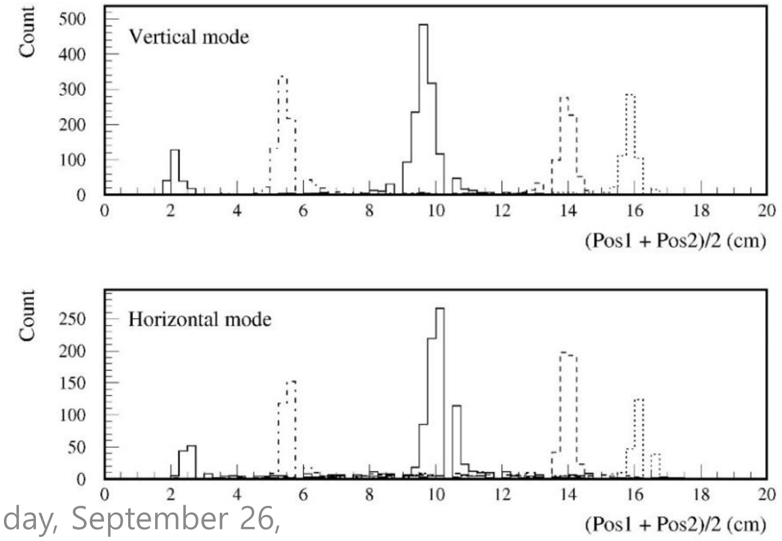
Coincidence measurement for two positron decayed 511-keV gammas from 3 μCi ^{22}Na. 40 cm distance between two detectors

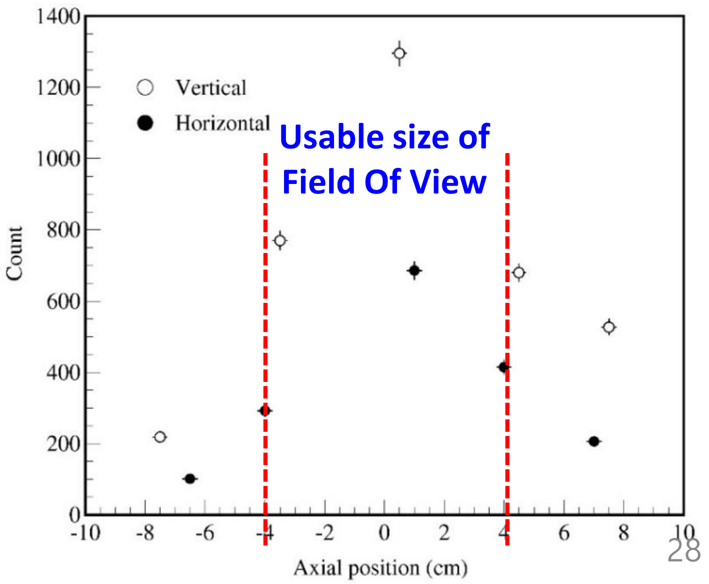
1D LORs reconstructed.
Gate window = 200 ns
1D resolution at decay vertices: < 3 mm

The sensitivity of measuring two 511 keV gammas should be same for both cases, but the vertical mode was measured with higher sensitivity because of 1.274 MeV contamination.









New idea of the vertical mode 6-gap RPCs for particle therapy

Potential applications in particle therapy (both to protons and heavy ions)

(1) SPECT technology + 1D line scans

- Obtained proper line-scan images of the 661.7-keV gammas using a Cs-137 source.
  → The determination of distal edges of proton breams can be done with a few mm accuracy.
  → The ranges of the proton beams can be properly verified using 2-dimensional gamma images.
- GEANT simulation → Efficiency > 15% for the gammas with energies > 1 MeV

(2) In-beam PET for particle therapy

- Measured 1D LORs using the Na-22 source → 2 ~ 3 mm resolution
- But, the priority for the future R&D is more or less low because
  - ✓ Building a realistic in-beam PET system is too difficult to be achieved in a level of a basic R&D.
  - ✓ **~ 10% efficiency for 511 keV gammas predicted by GEANT is still too low.**

    (But, do we need a high efficiency for an in-beam-PET system? → Open question)