Measurements of beam-induced photons for particle therapy

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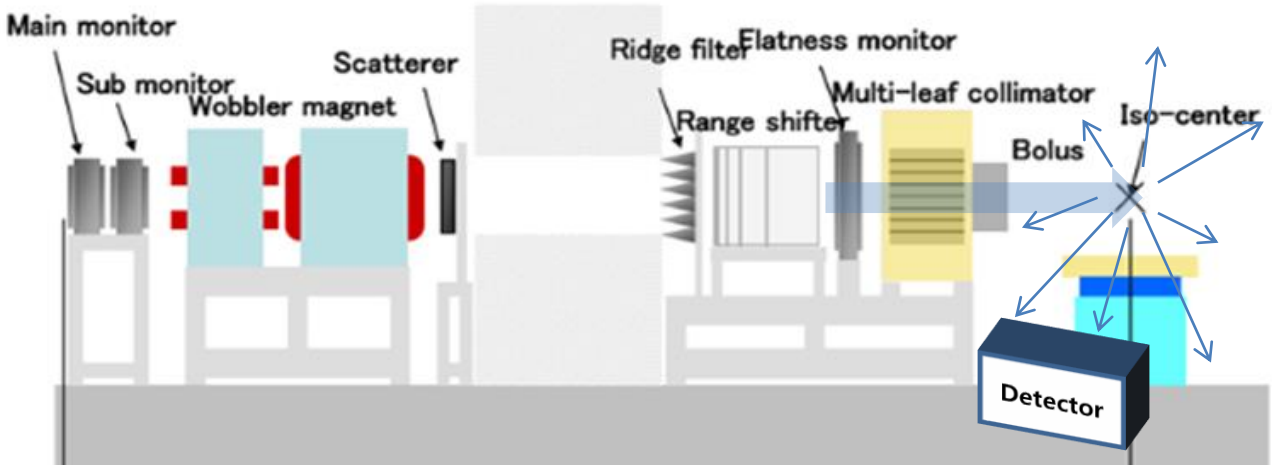
1. Motivation of R&Ds

On-line verification of beam activation in proton and carbon ion radiotherapies for quality assurance of hadron therapy treatments.

→ **Verification by measuring prompt gammas**

- In-beam PET (positron emission tomography)
- **Measuring single-photon emission using collimators**
- Compton camera

Fixed carbon beam line at HIMAC



Proton-beam Gantry at Samsung

2. Simulations for beam-induced secondary particles

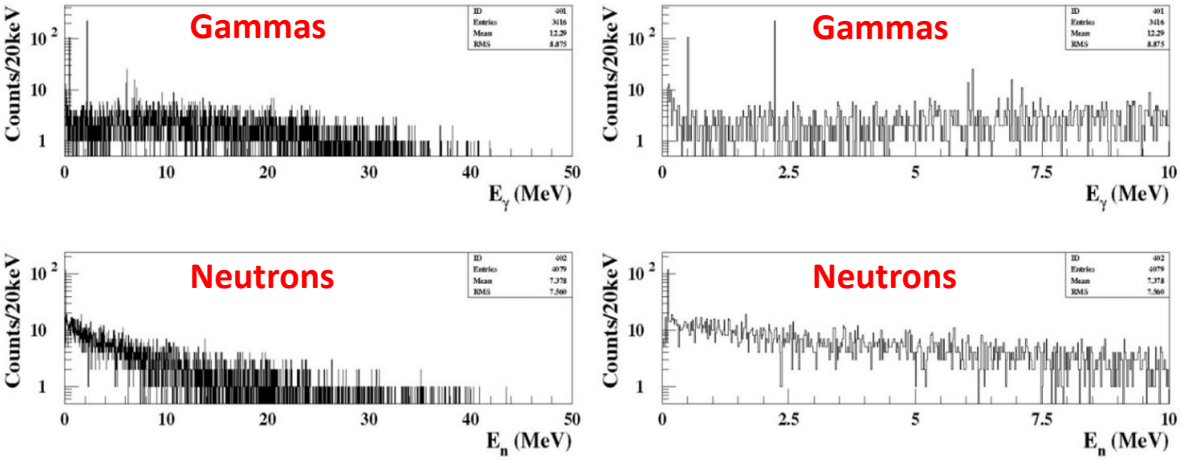
Using a GEANT4 program (2008 version), simulations for

- Prompt and delayed gammas of the excitation lines of nuclei, positron emission gammas, and bremsstrahlung occurred in a biological tissue
- Neutrons emitted from biological tissue
- Vertex positions, emission angles, energies of secondary particles

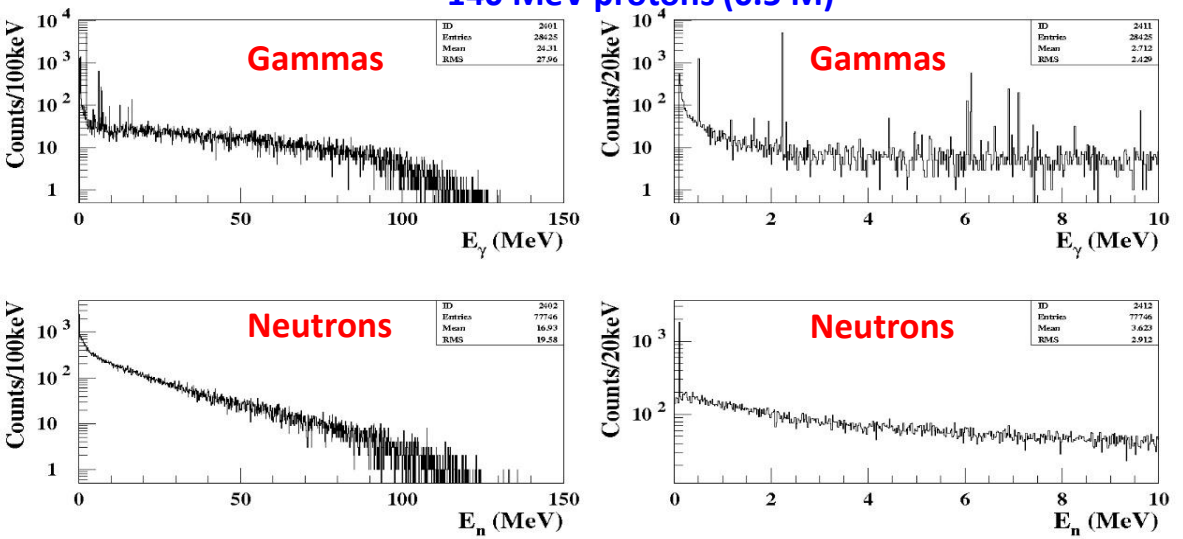
Gamma & neutrons per a proton

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}

44 MeV protons (0.5 M)



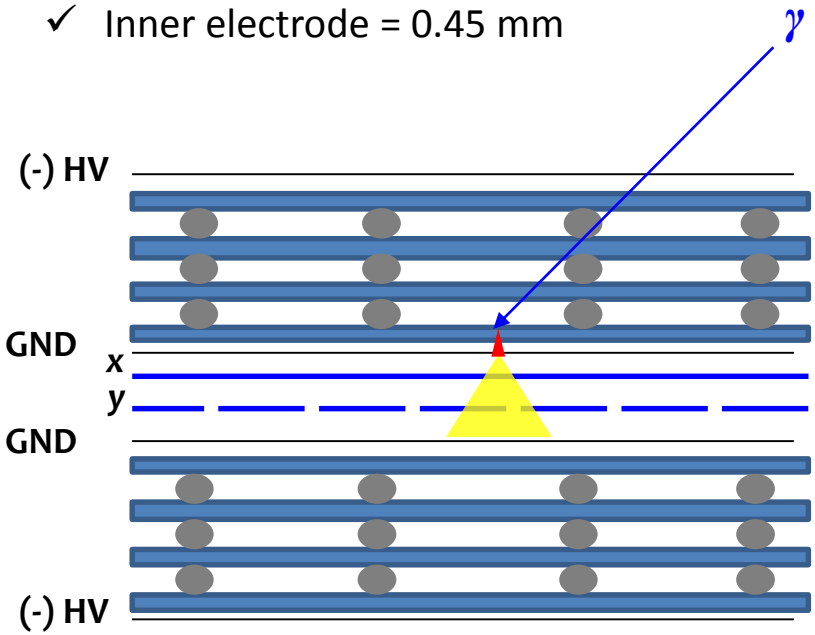
140 MeV protons (0.5 M)



3. MRPCs for gamma-ray measurements

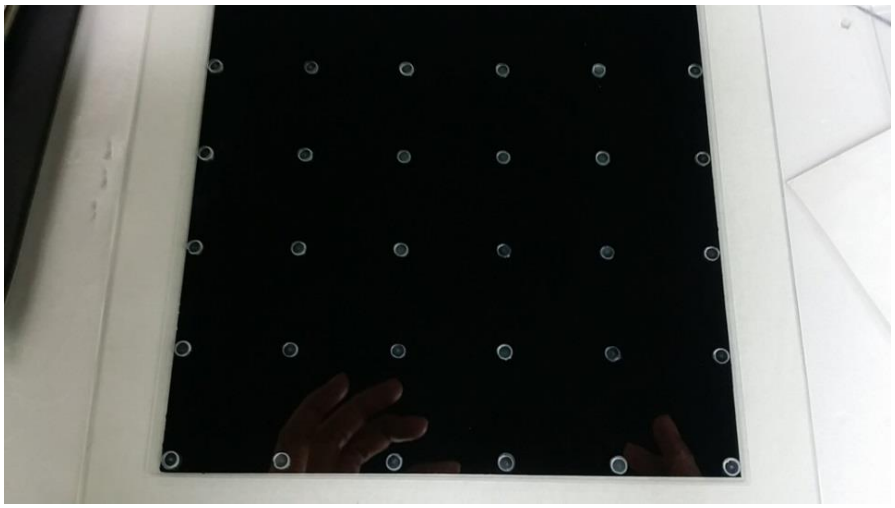
6-gap RPC

- Thickness of a single gap = 0.36mm
- Thickness/dia. of spacers = 0.35mm/4mm
- Active area = 16 x 16 cm^2
- Thicknesses of **glass**
  - ✓ Outer electrode = 1.10 mm
  - ✓ Inner electrode = 0.45 mm



4-gap MRPC

- Thickness of a single gap = 0.49mm
- Thickness/dia. of spacers = 0.48mm/10mm
- Active area = 16 x 16 cm^2
- Thicknesses of **glass** for all = 1.10 mm

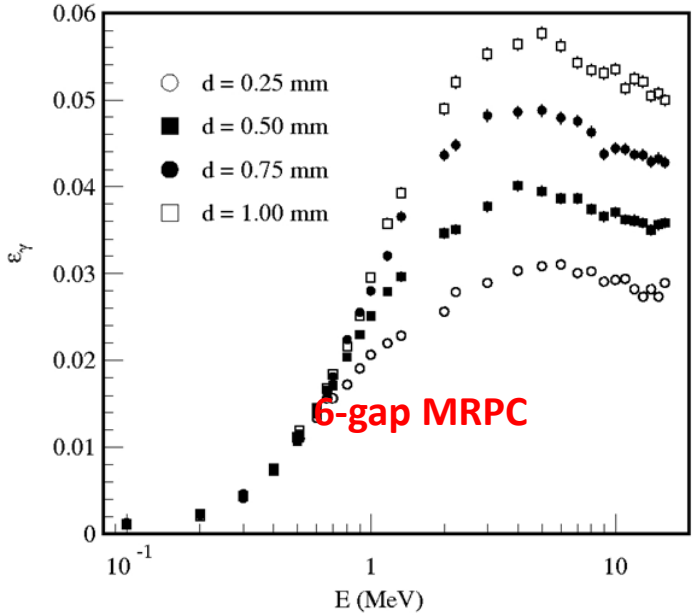


Estimation of Detector sensitivity (GEANT3)

8-glass six-gap MRPCs: Max. Q. E. via **Compton scatterings** = 0.058 at E_γ ~ 4 MeV for d = 1.25 mm

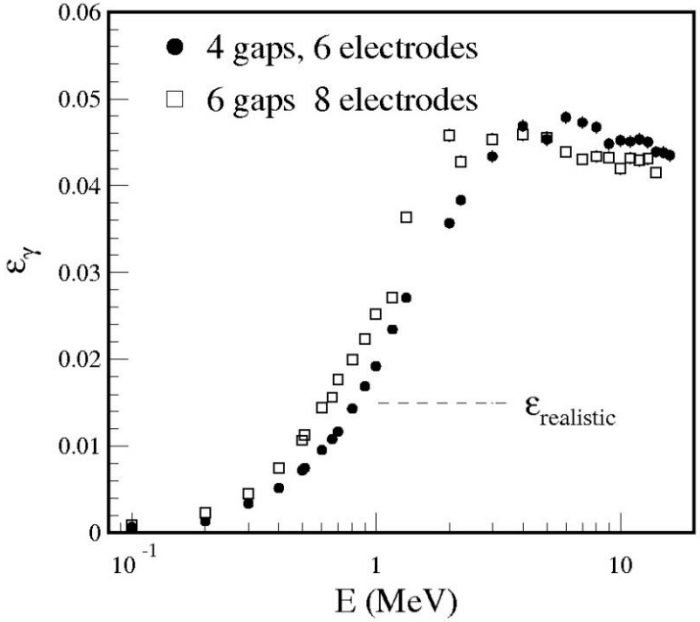
6-glass four-gap MRPCs with *d*=1.0 mm: Max. Q. E. for **Compton scatterings** = 0.048 at E_γ ~ 4 MeV

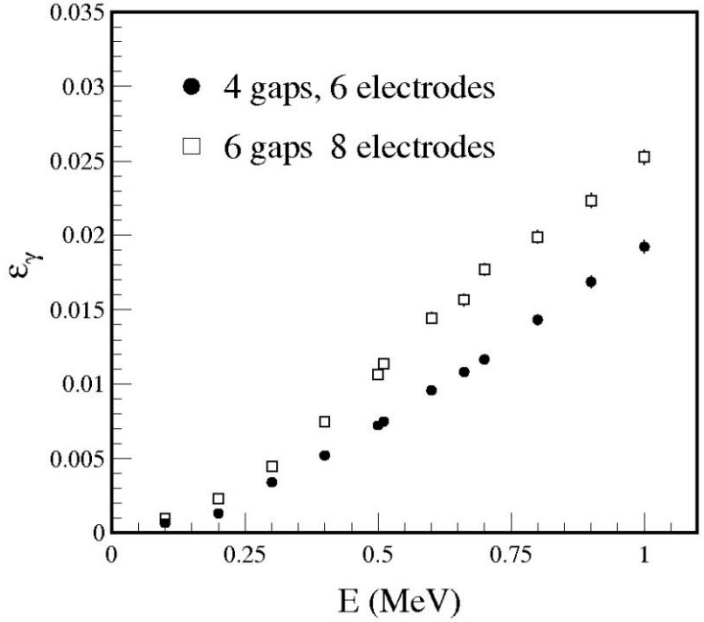
Realistic *x-y* matched sensitivity for E_γ > 1 MeV ~ 0.02



6-gap MRPC
Inner glass: 0.45 mm
Outer glass: 1.1 mm

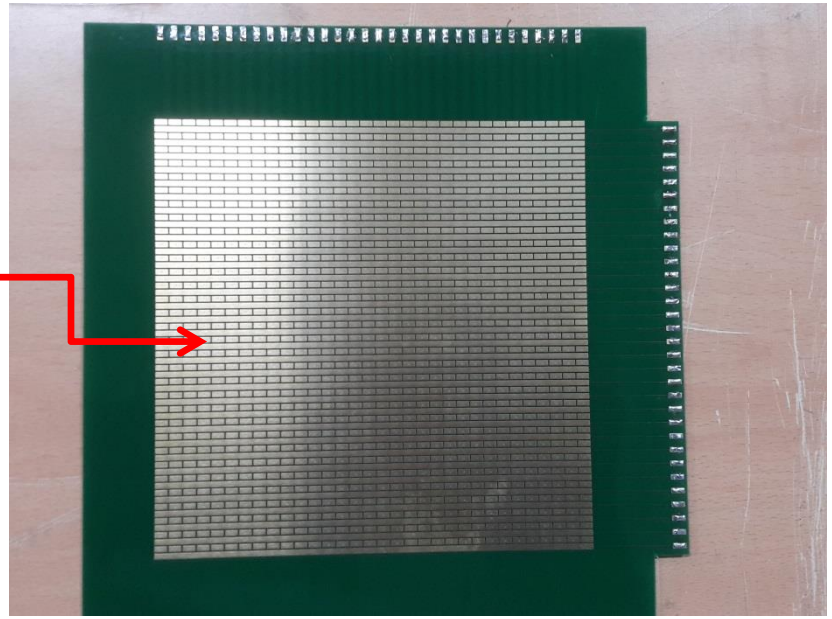
4-gap MRPC
1.1 mm for all glass

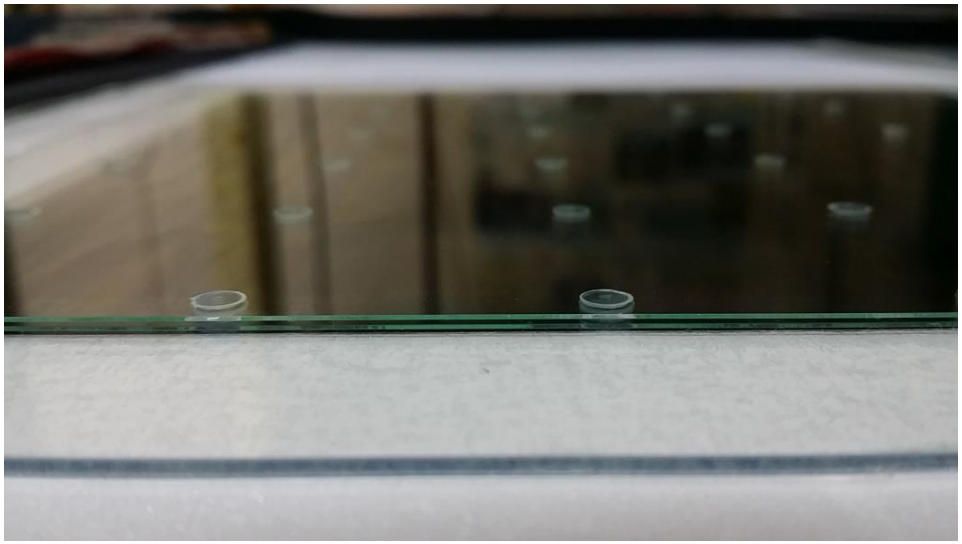


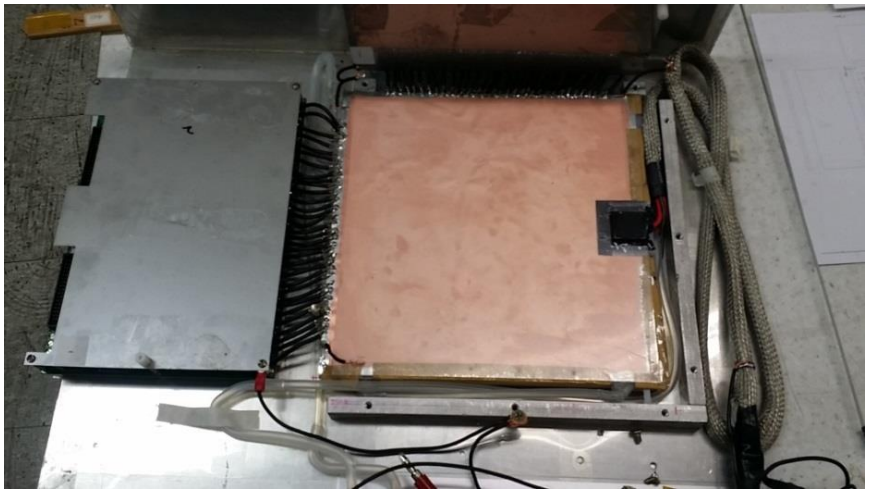


Readout strips

- **2-d strips for 2d imaging**
  - ✓ Orthogonal x strips and y pads (connected by 0.1 mm traces)
  - ✓ Short strips → neglecting impedance matching
  - ✓ Pitch = 5 mm (strip & pad width = 2.0 mm)
  - ✓ Position resolution ~ 2 mm







32-ch front-end electronics manufactured with commercial preamp chips (voltage sensitive)

- ✓ Input impedance = 20 Ω
- ✓ Gain = 200 mV/mV
- ✓ Ethernet communication for FEBs
- ✓ LVDS output pulse width = 70 ns (fixed)
- ✓ RMS noise of board ~ 20 μV (~ 3 fC)
- ✓ Time resolution ~ 100 ps for 1 pC signals

Threshold = 1.5 mV for a 6-gap MRPC
= 0.5 mV for a 4-gap MRPC

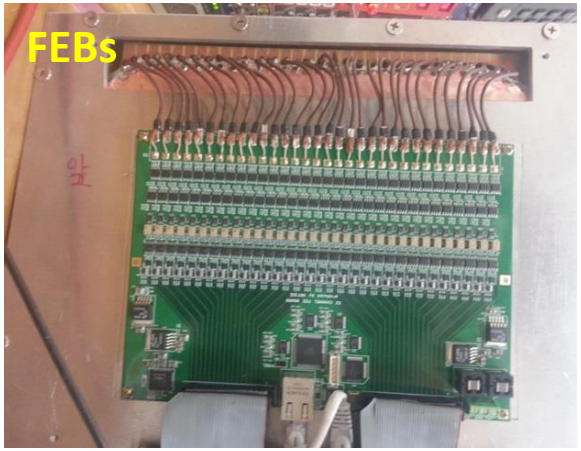
64-ch multi-hit TDC

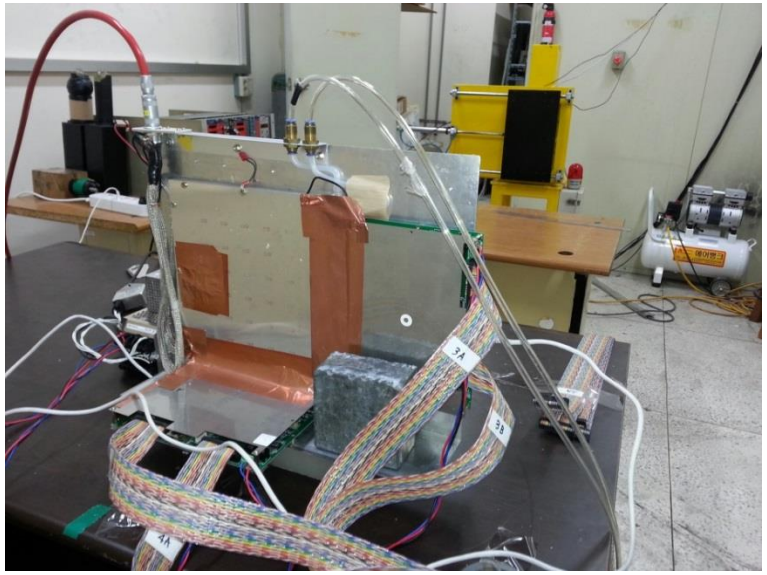
250 Hz clock triggers with a 65-μs gate width
→ Ratio for measurement in time = 0.01625

Gas: 90% TFE + 10% iC_4H_{10}

Typical HV: **~ 9.1 kV for 6-gap MRPC**
~ 7.0 kV for 4-gap MRPC

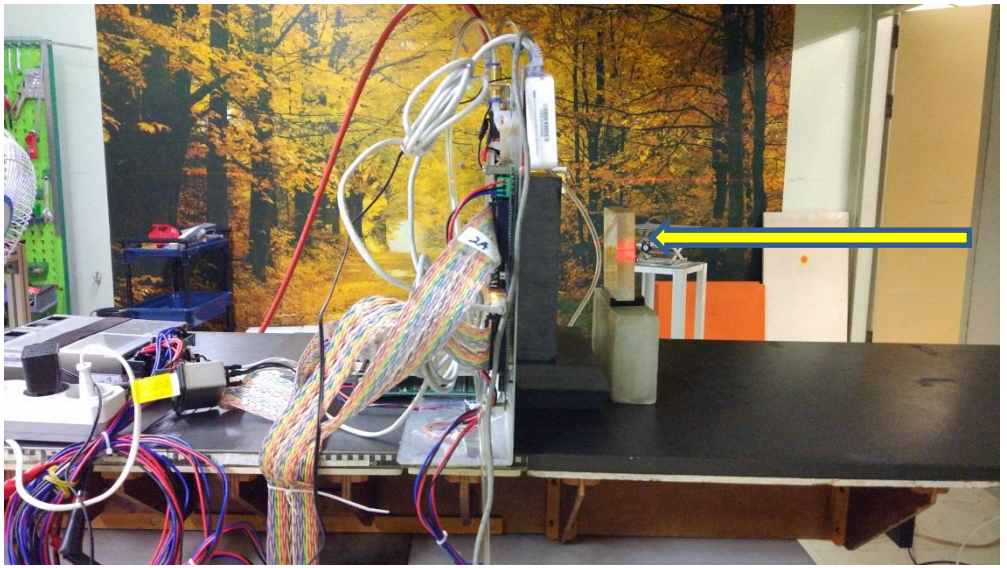
Typical strip multiplicity: 3 ~ 5

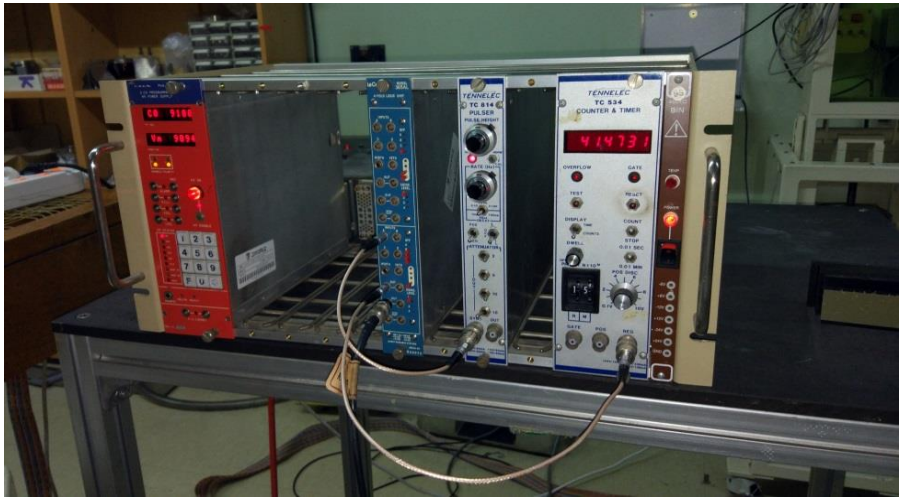


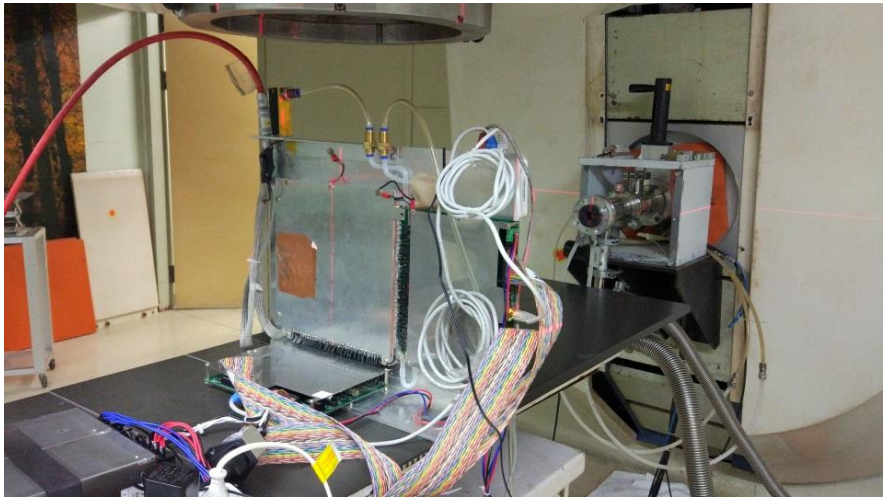


4. Beam test for a 6-gap MRPC at KIRAMS

- ✓ Use 20-mm thick PMMA as a phantom
- ✓ Installed detector 15 cm from the iso-center
- ✓ Continuous-wave proton beams
  Energy = 44 MeV
  Average beam current = 10 nA
  FWHM ~ 30 mm at 70 cm from the vacuum beam exit
- ✓ Collimators
  5-cm thick lead bricks
  4 mm holes with a 10x10 mm^2 2D pitch







Beam-off condition

Delayed-decay gammas with finite half life times and positrons annihilated 511-KeV gammas (^{11}C, ^{13}N, and ^{15}O)

Measured gammas for 400 s after an irradiation on 20mm thick acryl for 400 s by applying 250-Hz clock pulses

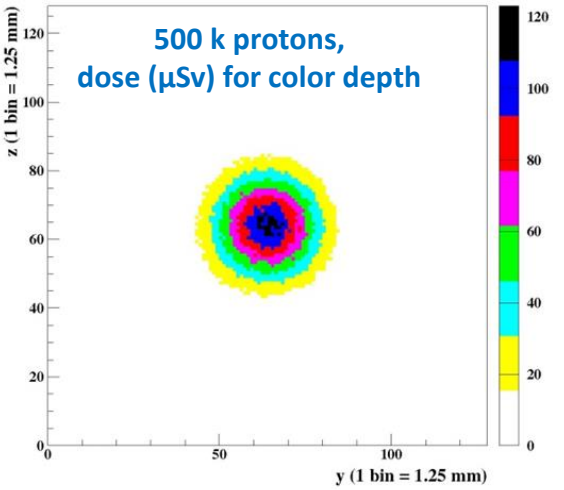
- ✓ TDC time window = 65 μs
  → DAQ efficiency ~ 1.6%
  → Actual measuring time = 6.5 s
- ✓ @HV_{eff} = 9.1/9.3 kV

Using **a single collimator layer**,
# of effective gamma hits = 7,850
→ Low statistics due to the low DAQ efficiency

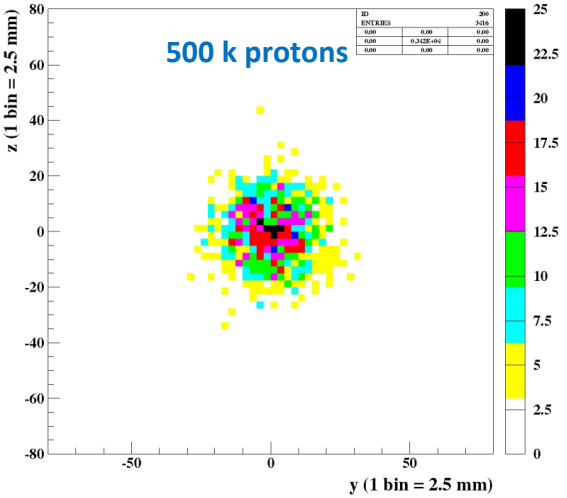
**** beam halo** image of secondary Gammas induced by neutrons passing through the collimator holes and by activating the detector.

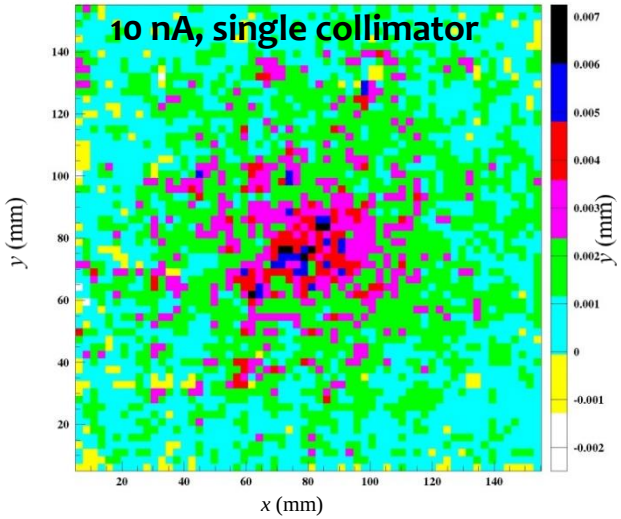
With double-layer collimators, # of effective gamma hits ~ 1,300

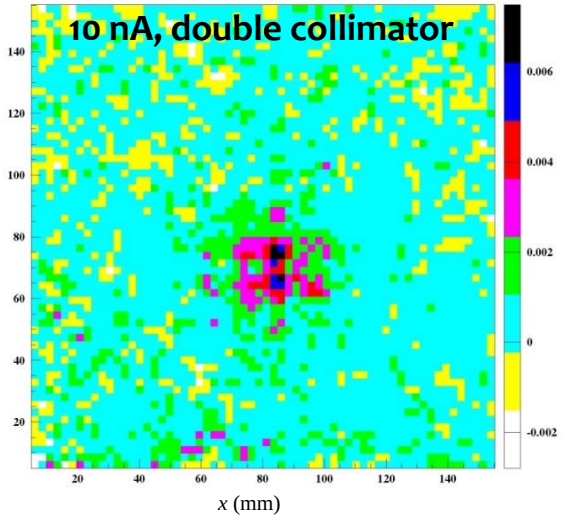
Simulated dose distribution in the horizontal plane



Simulated vertex distribution of γ on the horizontal plane







5. Beam test for a 4-gap MRPC at Samsung Proton Therapy Center

140 MeV 1 nA raster scan beam (medical cyclotron)

Raster-scan area = 5 cm x 5 cm

Image measured for 400 s

- ✓ TDC window = 65 μs
- ✓ Clock triger rate = 250 Hz

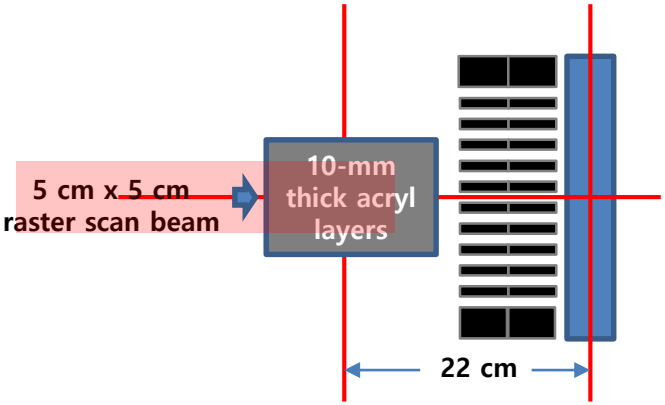
→ DAQ efficiency ~ 1.6%

→ Actual measuring time ~ 0.65 s

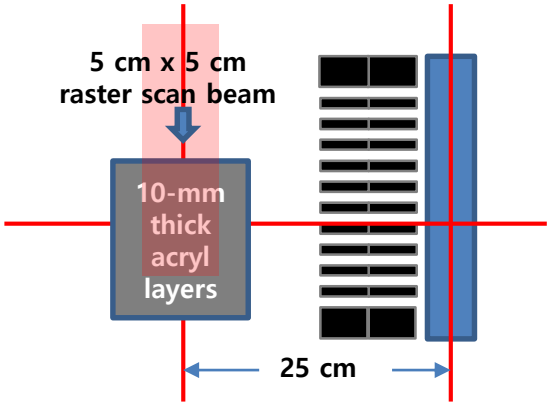
→ Even shorter because of low duty factor of the beam

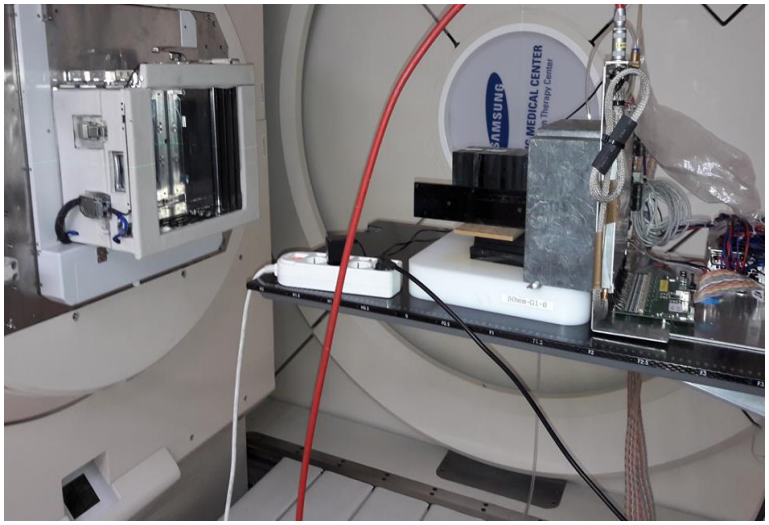
- ✓ HV_{eff} = 6.9 & 7.0 kV

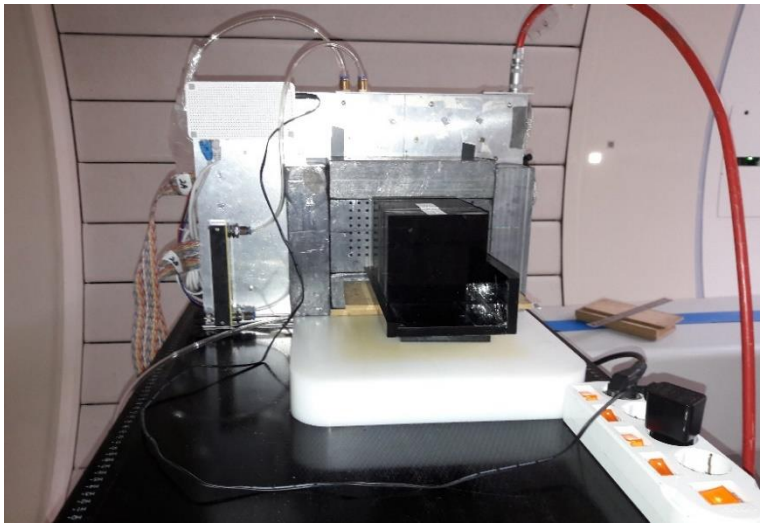
Case I:
For lateral distributions



Case II:
For depth distributions





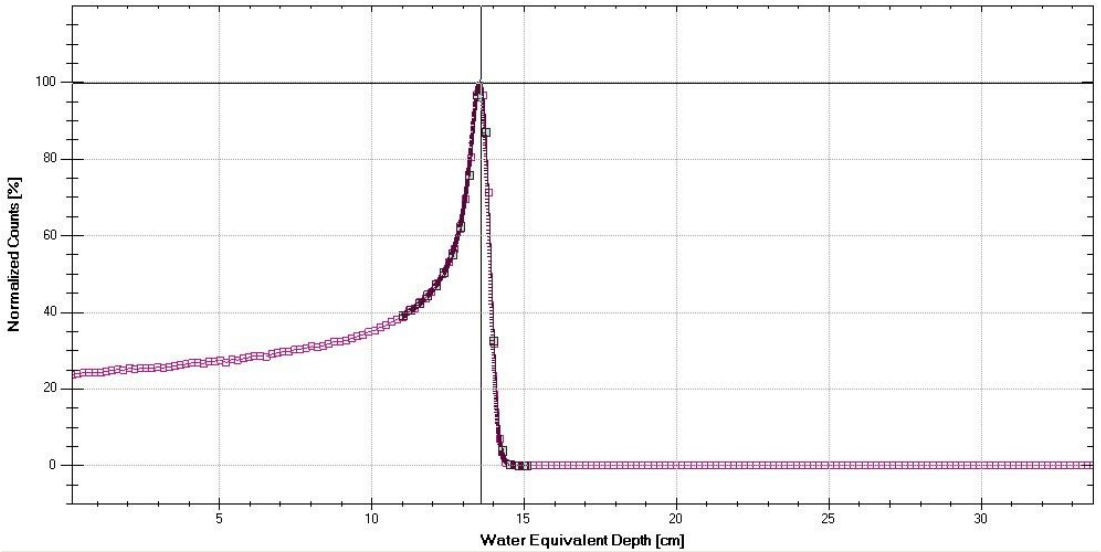


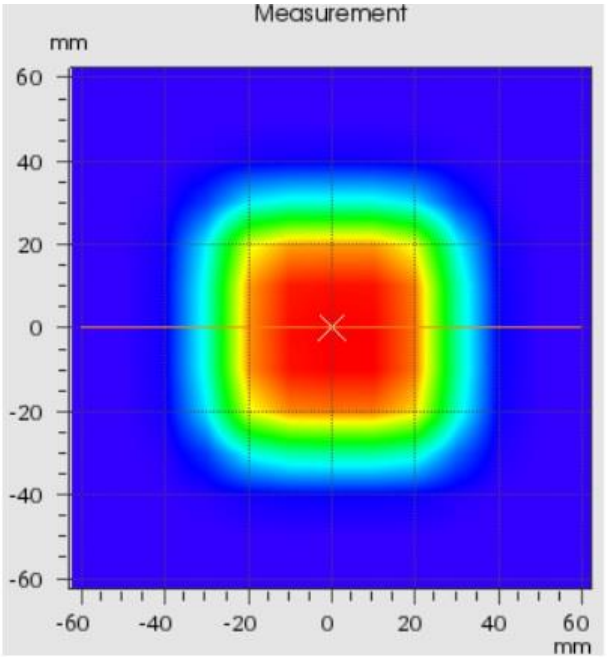
1-nA 140-MeV raster scan beam measured by an ionization chamber (Model PTW Octavius 729 XDR)

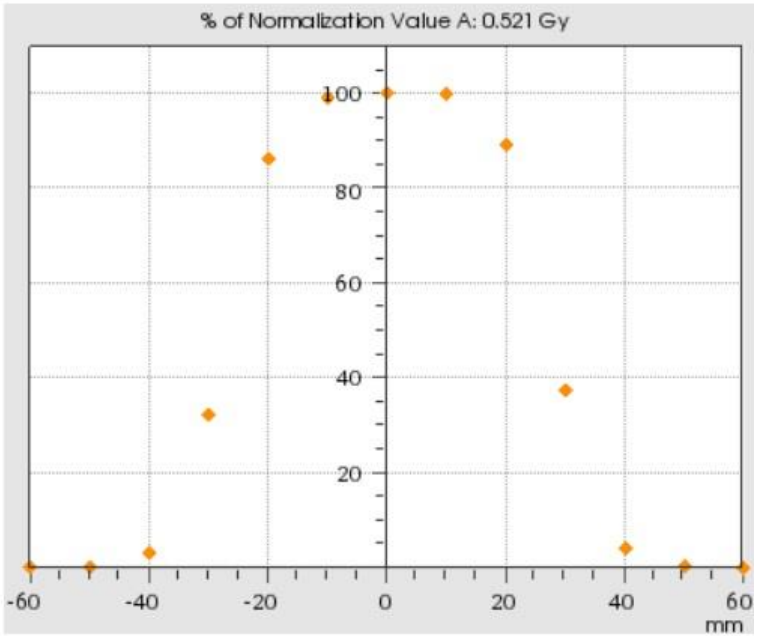
Scan area = 5 cm x 5 cm

Bragg peak position = 136 mm

The scale for the measured dose is set to 1/10 of the actual value.



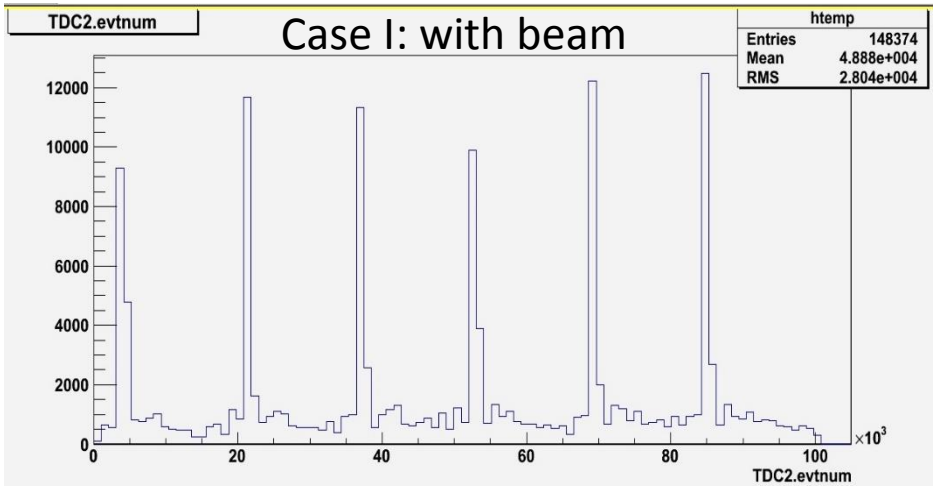


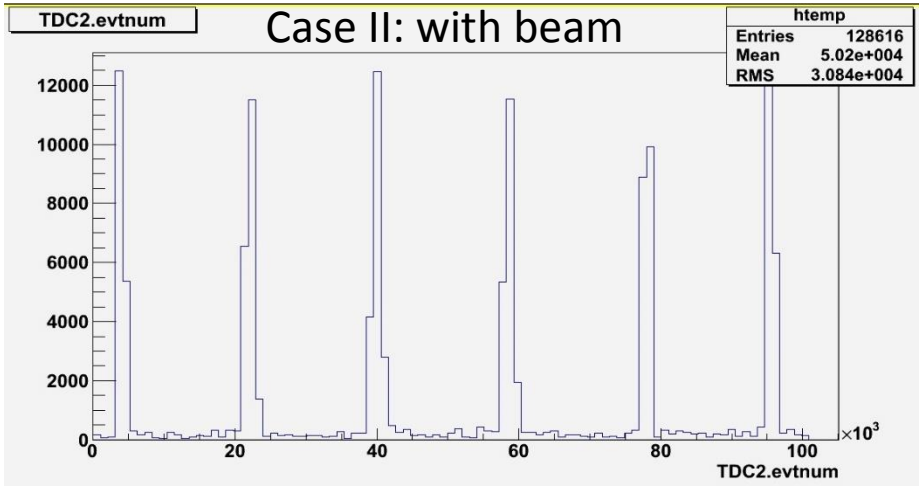


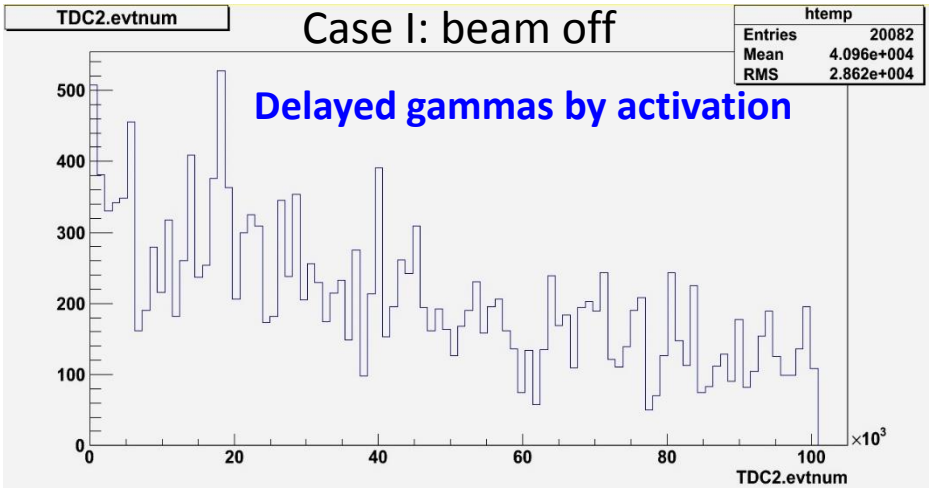
4-gap MRPC gamma (+neutron) hit data: Time profiles (TDC)

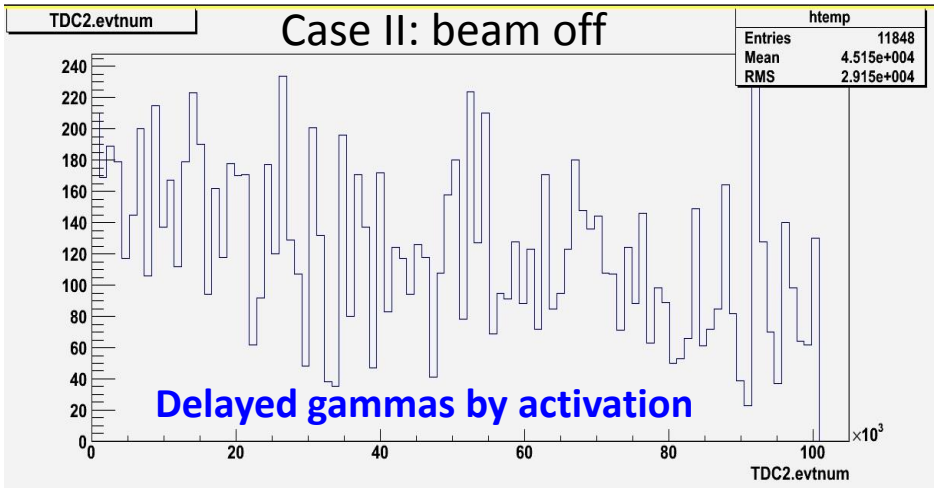
Duration of a raster scan = 6.6 s

6 raster scans in 400 s (actual irradiation time = 33.6 s → ~ 2 x 10^{11} protons → ~ 10^{10} photons)









4-gap MRPC data with beam-on

Case I: For lateral distributions

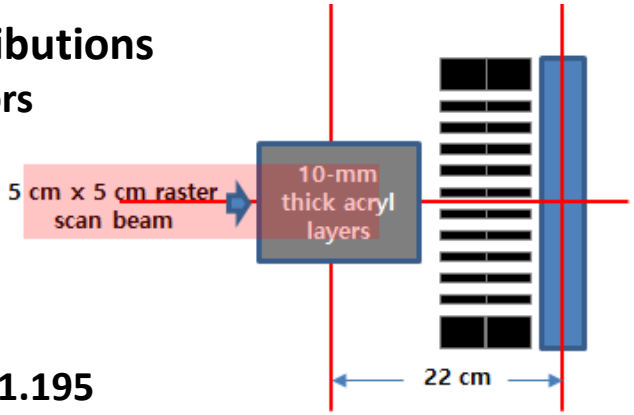
Using two-layer collimators

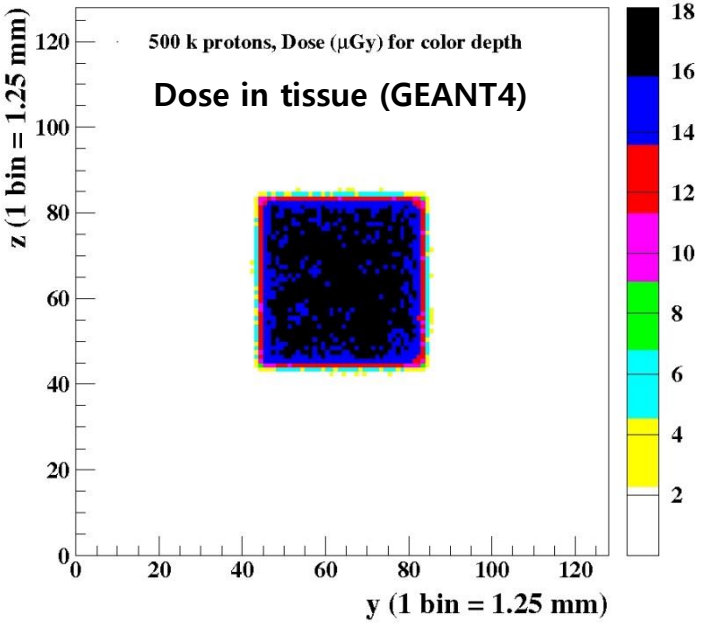
Image obtained with

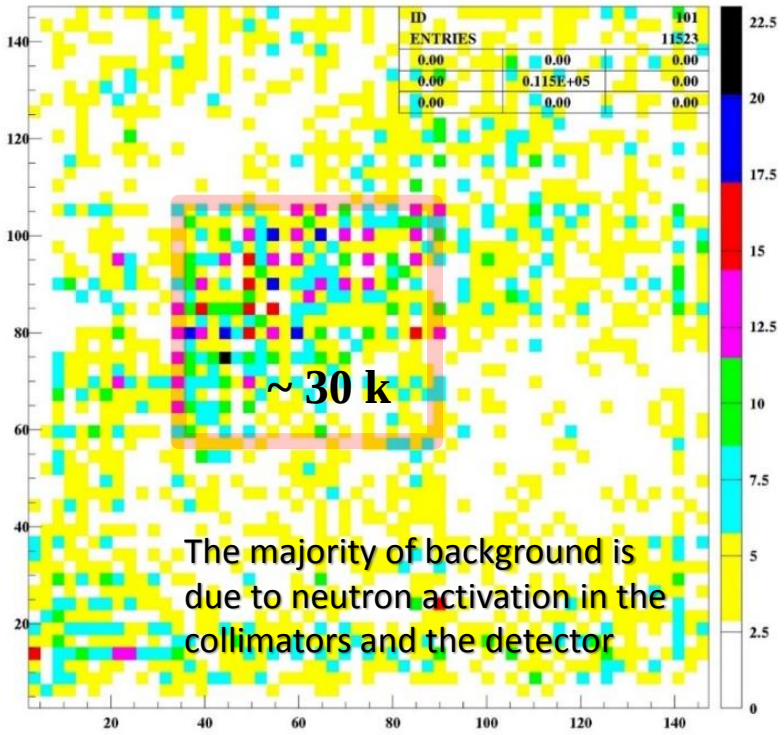
$C_{s,x}$ *and* $C_{s,y} < 8$

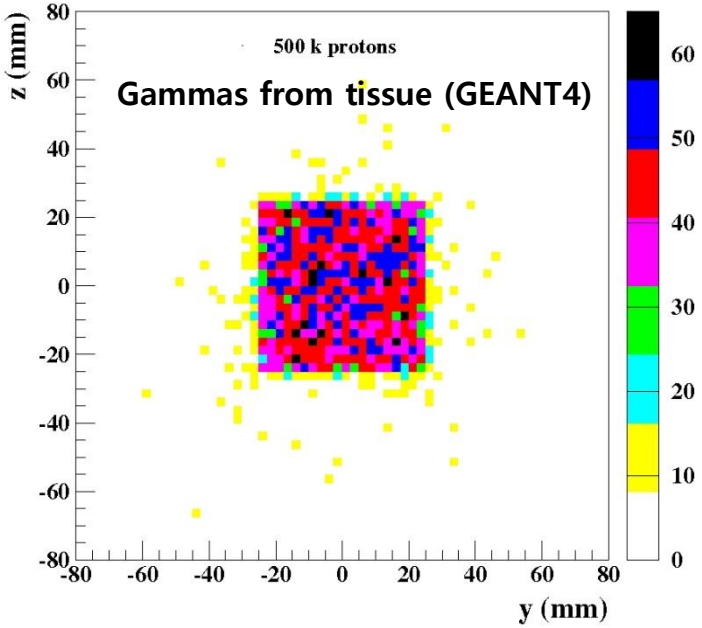
HV = 6.9 kV with beam

Specific gravity of acryl = 1.195









4-gap MRPC data with beam-on

Case II: For depth distributions

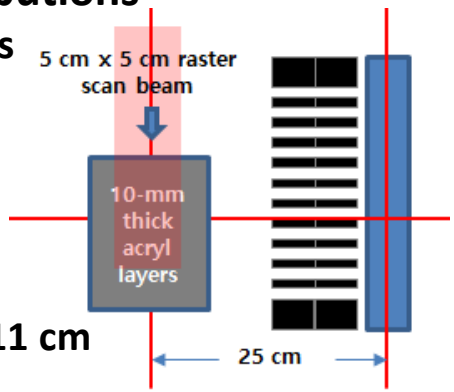
Using two-layer collimators

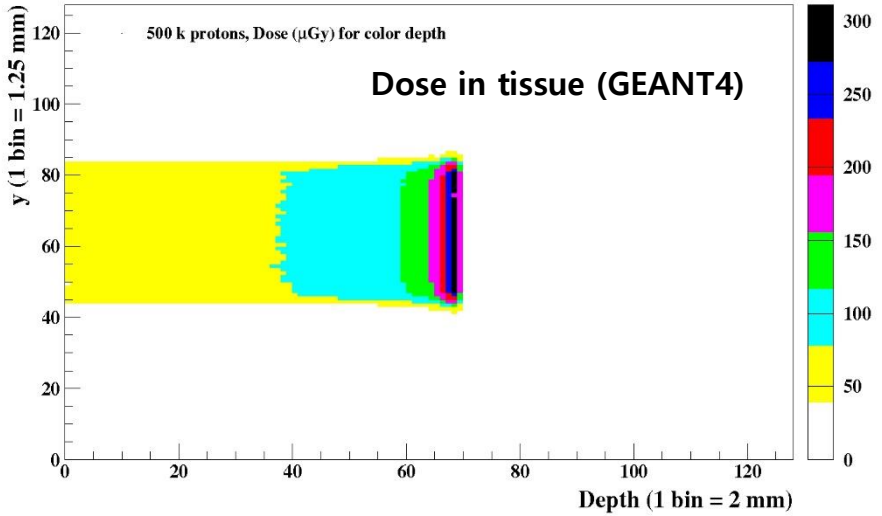
Image obtained

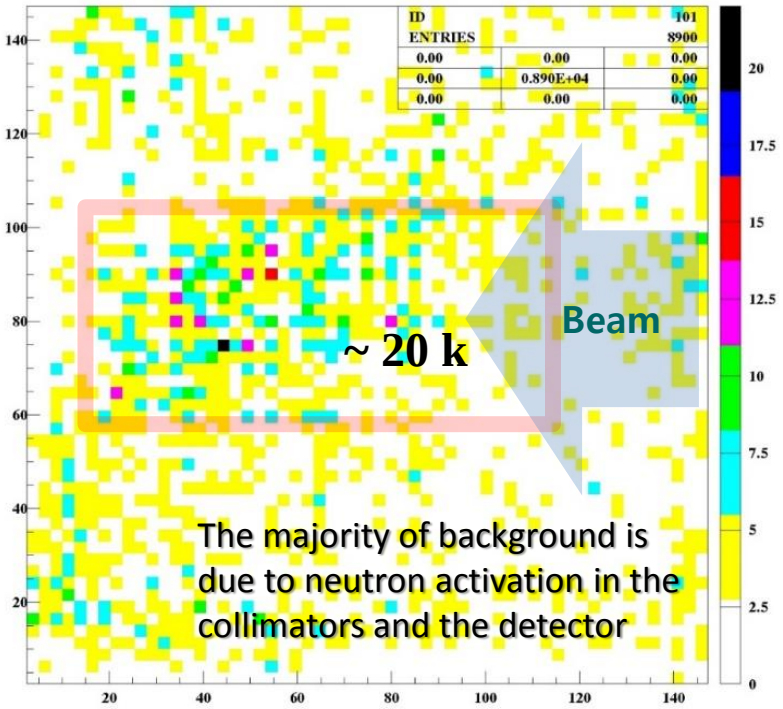
with $C_{s,x}$ and $C_{s,y}$ < 8

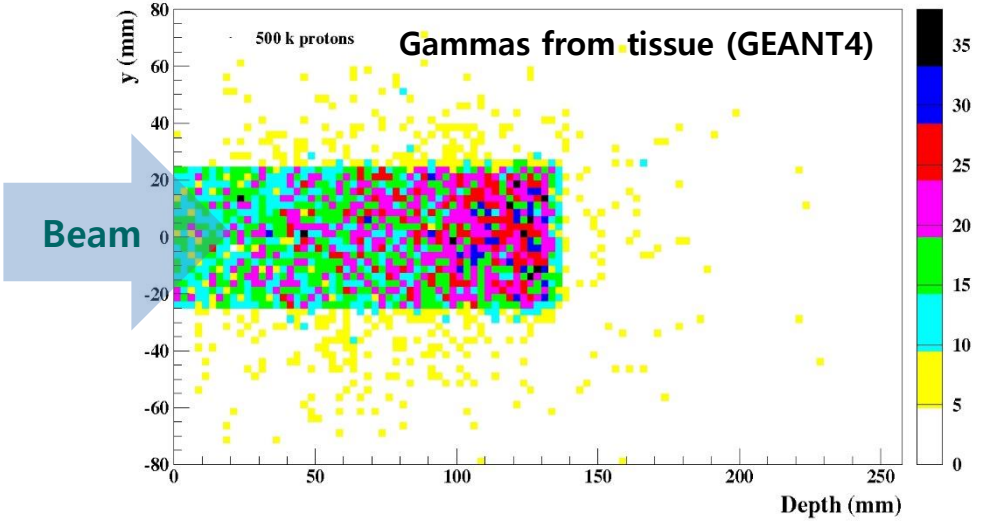
HV = 6.9 kV with beam

Expected depth in acryl = 11 cm







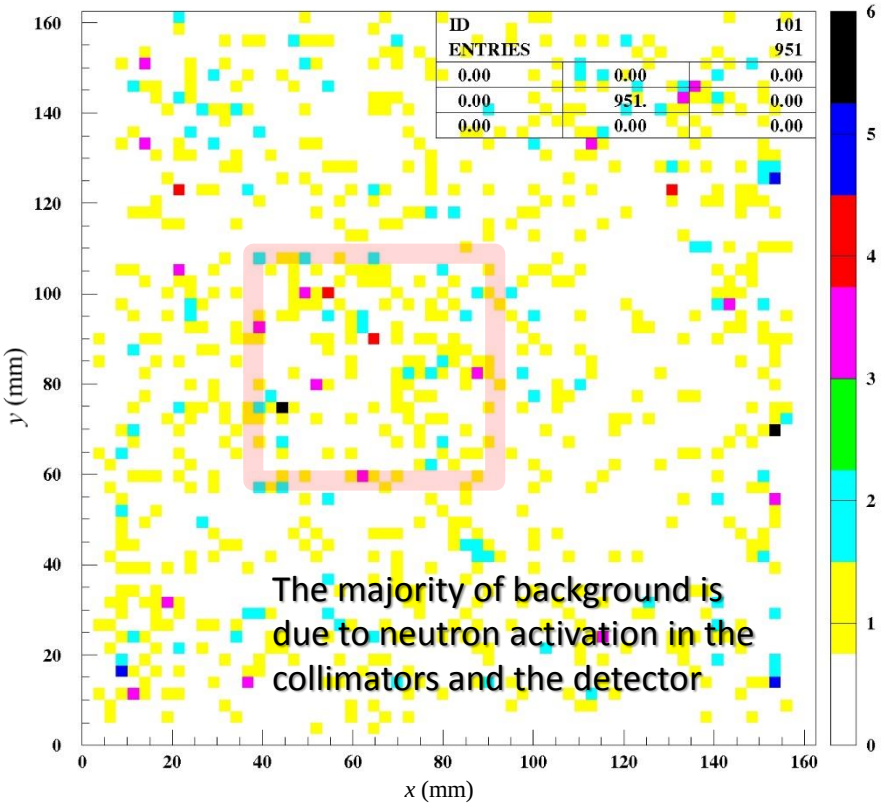


4-gap MRPC data (beam-off) using two-layer collimators

Case I: For lateral distributions

Image obtained with $C_{s,x}$ and $C_{s,y}$ < 8

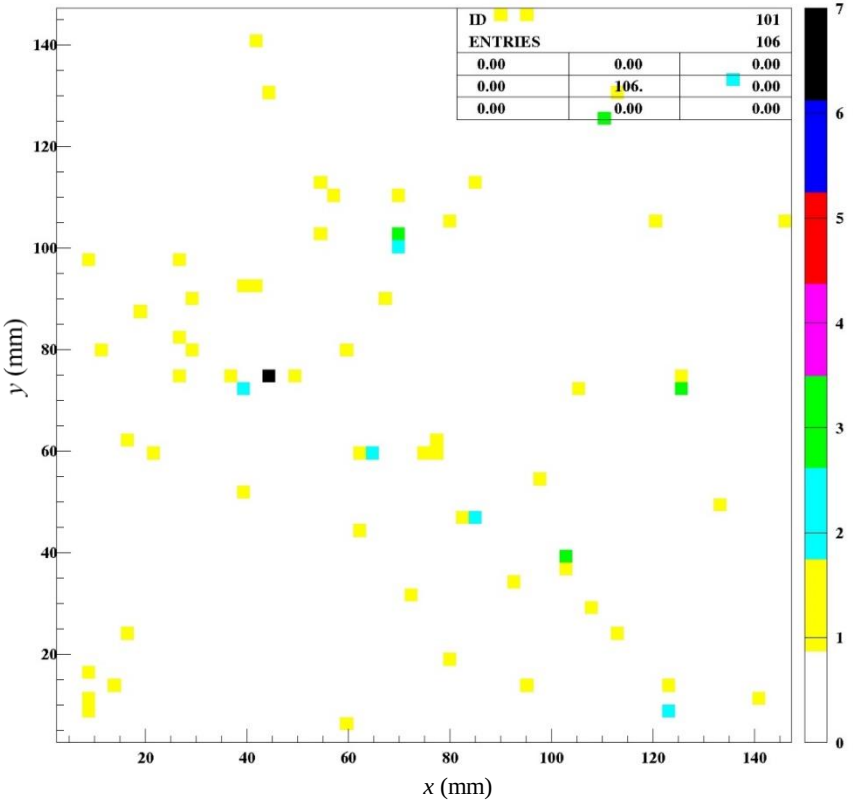
HV = 6.9 kV, beam off



Detector noise distribution

Image obtained with $C_{s,x}$ and $C_{s,y}$ < 8

HV = 6.9 kV



6. Conclusions and Milestones

Conclusions: Have examined and proven the basic technology of MRPCs for proton-beam verifications

- Simulations for prompt gammas to utilize all spectral lines of the beam driven excitations
- Confirmed the detector sensitivities and the resolution for the 2D gamma images
- Confirmed the imaging method for the radio active area induced by proton beams
  - ✓ 6-gap MRPC using 10-nA 44-MeV protons at KIRAMS **(beam-off condition)**
  - ✓ 4-gap MRPC using 1-nA 140-MeV protons at Samsung Proton Therapy Center **(beam-on condition)**
- **To be solved: Low statistics → should improve the high DAQ dead time (low DAQ efficiency in time)**
- **To be solved: Neutron background problem → needs better neutron shielding for detectors**
- **To be solved: Optimization of collimators (layer out, thickness, and neutron shielding)**
- **Gas mixture (aging with Freon-base gas → other option: Ar + iC_4H_{10})**

Milestones: To enhance the statistics of data, need a **dedicated trigger/data-transfer electronics**

- ✓ **No DAQ dead time → the statistics will be 60 times larger!**
- ✓ Latching of all LVDS detector signals in a FPGA memory
- ✓ Ethernet (or USB3) data transfer to DAQ PC

For a typical proton beam of energy ~ 140 MeV with the typical 6 raster scans

→ Expected statistics ~ 200 k gammas with beam-on

~ 10 ~ 20 k gammas even for the beam-off condition

*When using collimators, **MRPCs are the best for range-verification** for particle therapy.*

BACKUPS

In-beam PET

Coincident measurement of 511-keV gammas emitted from only β decays of ^{11}C, ^{13}N, ^{15}O

- Excellent resolution < 2 mm (Converged vertex images)
- Small field sizes
- Expensive

Collimation for single γ

Measurement of prompt gammas emitted from all excitation lines (> 0.5 MeV)

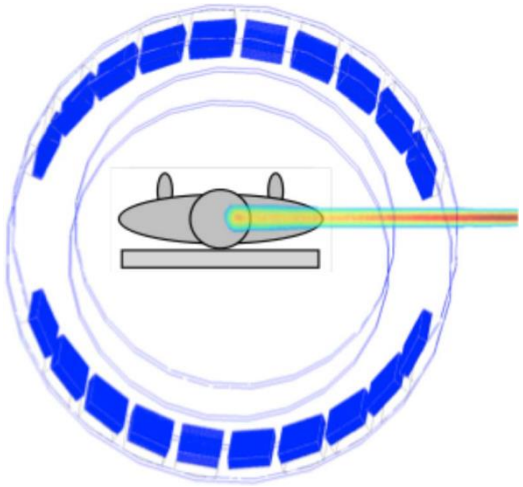
- Resolution < 5 mm
- Very low tagging efficiency for 2D imaging
- Large field sizes
- Cheep

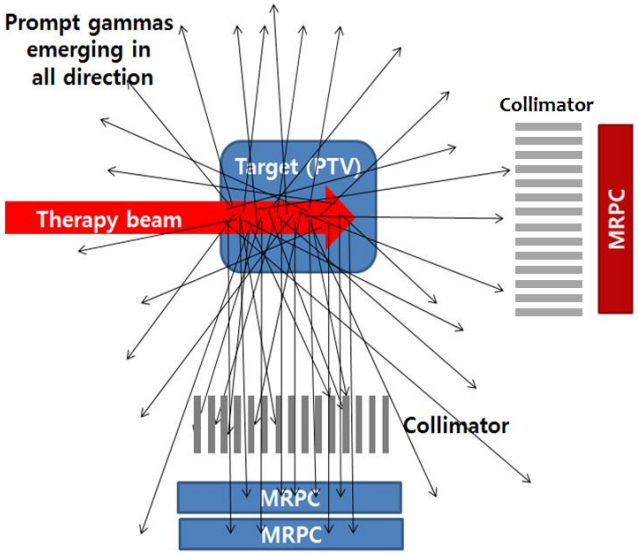
Compton camera

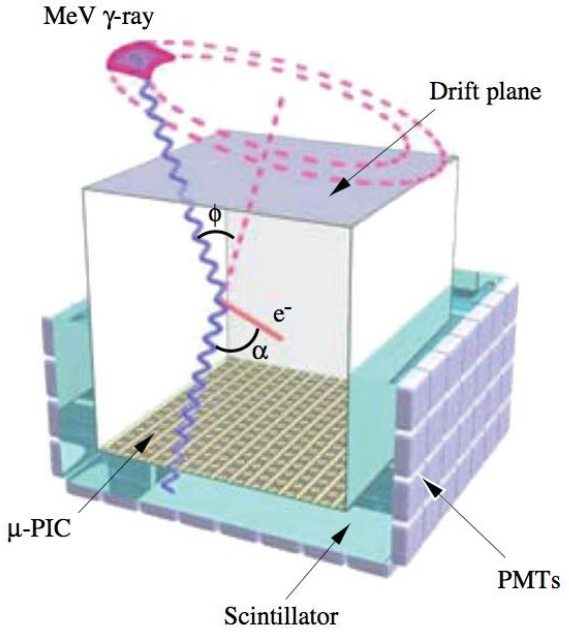
Tracking all gamma rays

→ Best efficiencies

- Difficult tomographic process
- Poor position resolution (diverged vertex images)
- Small field size
- Expensive



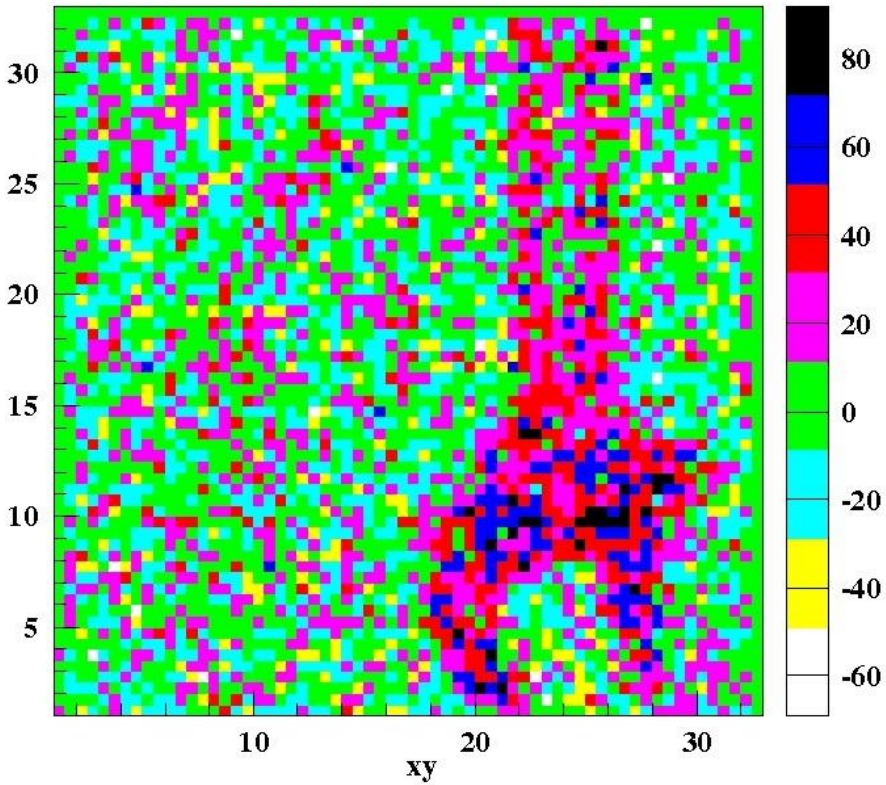




64 x 64 pixels 2D image obtained by x(mean)-y(mean) matched data points
# of gamma hits per pixel ~ 170
Resolution ~ 2 mm

Spanner: stainless, 0.6 mm ~ 1.2 cm
Scissors: stainless, ~ 0.8 mm
Coins: brass, 1.0 ~ 2.0 mm

Half attenuation length of stainless for ^{137}Cs 661.7 keV gammas ~ 6 cm



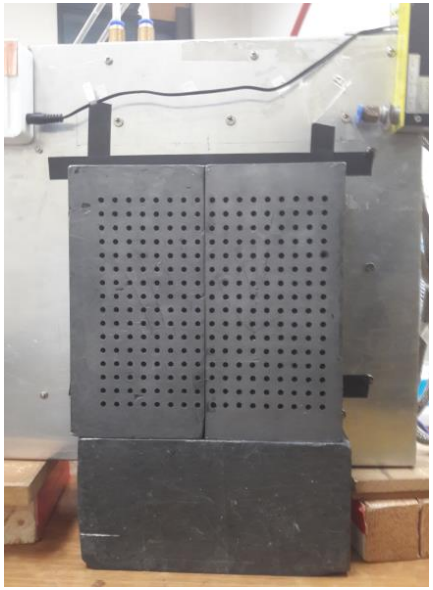
Expected particle rates on the collimator (for ten minutes after beam off)

Beam energy of proton	γ signal rate on collimators
44 MeV	~ 2 kHz cm^{-2}
100 MeV	~ 12 kHz cm^{-2}
190 MeV	~ 25 kHz cm^{-2}

Expected detection rate (beam off condition)

Mean Q.E. for gammas at 8-stacked glass MRPC (6 gaps) ~ 0.02
Collimator efficiency ~ 0.02 (single) / 0.005 (double)

Beam energy of proton	γ detection rate on the detector
44 MeV	~ 0.8 Hz cm^{-2} / ~ 0.2 Hz cm^{-2}
100 MeV	~ 5 Hz cm^{-2} / ~ 1.2 Hz cm^{-2}
190 MeV	~ 10 Hz cm^{-2} / ~ 2.5 Hz cm^{-2}



With a 44 MeV proton beam,
the actual rate (400 s after beam off)
= 4.7 Hz cm^{-2} (single collimator)
~ 0.7 Hz cm^{-2} (double collimator)

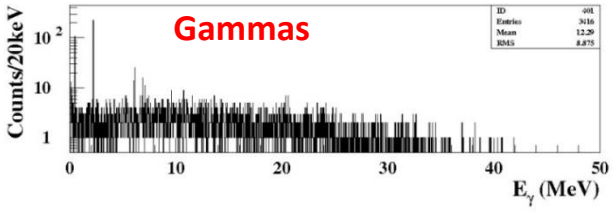
→ Larger than the expected rate by GEANT4
✓ Collimator efficiency might be underestimated.
✓ Neutron driven gamma backgrounds in the detector.

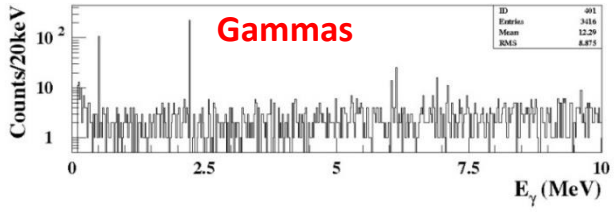
2. Simulations for beam-induced secondary particles

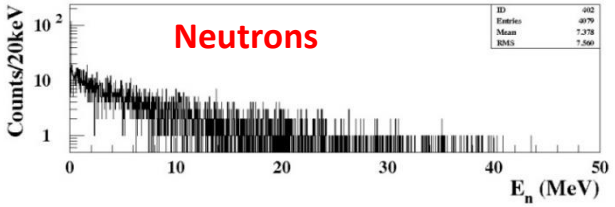
Using a GEANT4 program (2008 version), simulations for

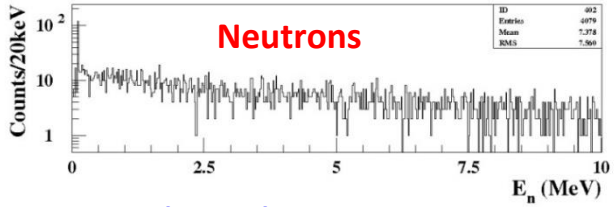
- Prompt and delayed gammas of the excitation lines of nuclei and Bremsstrahlung occurred in a biological tissue
- Neutrons emitted from biological tissue
- Vertex positions, emission angles, energies

44 MeV protons (0.5 M)

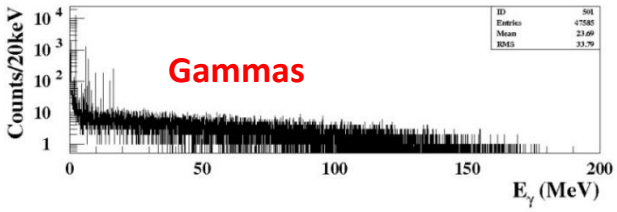


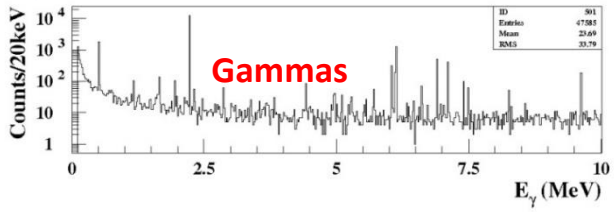


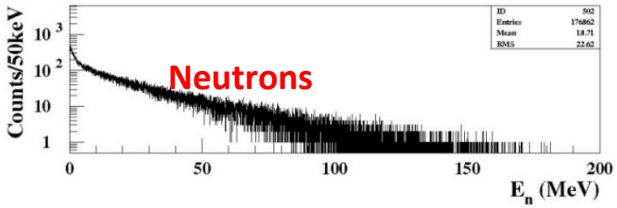


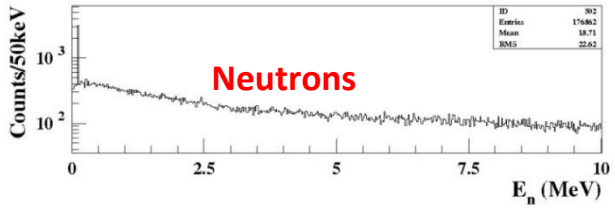


190 MeV protons (0.5 M)



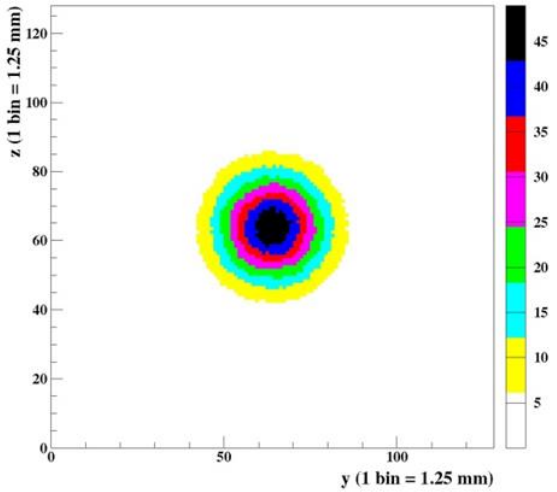




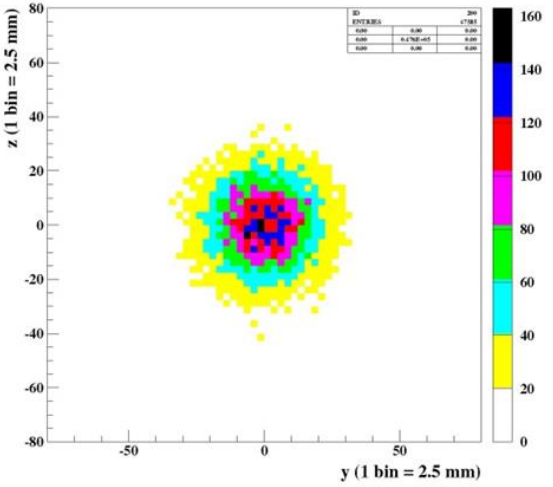


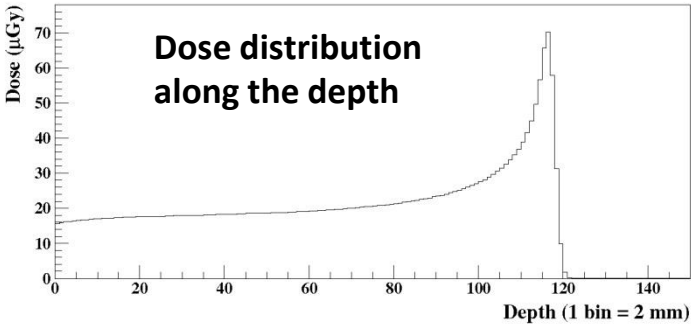
GEANT4 simulation for 190 MeV protons
FWHM = 3 cm
Phantom size (biological tissue) = 30 cm x 16 cm x 16 cm

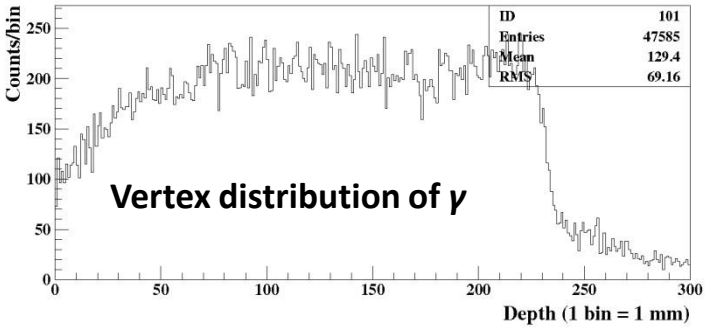
Dose distribution in the horizontal plane

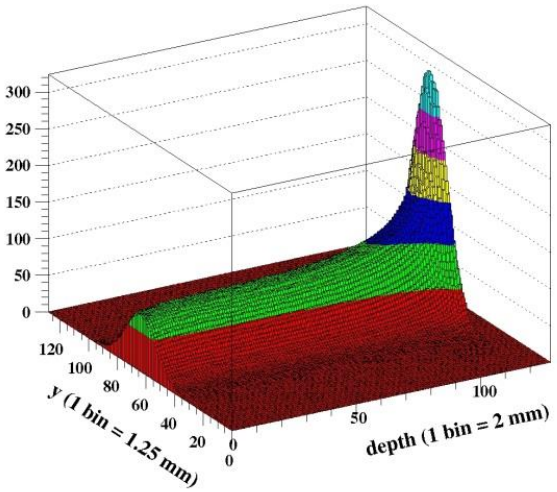


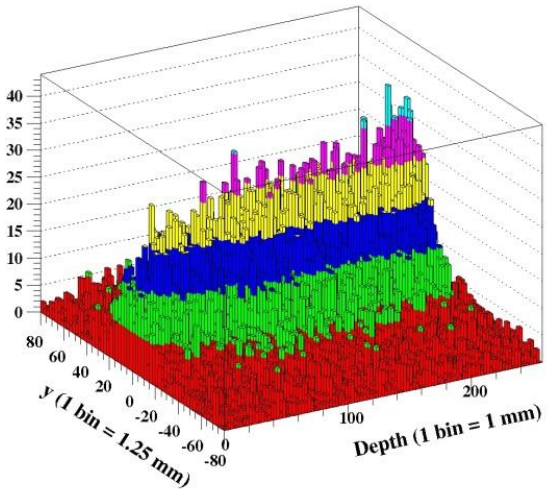
Vertex distribution of γ on the horizontal plane



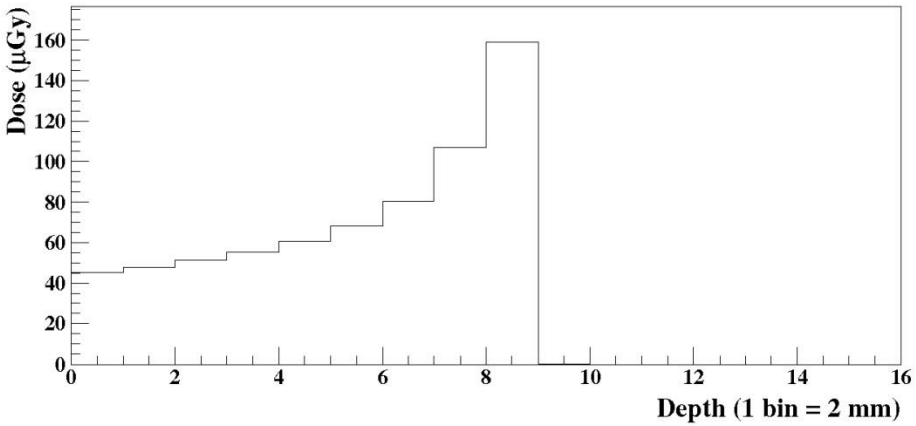




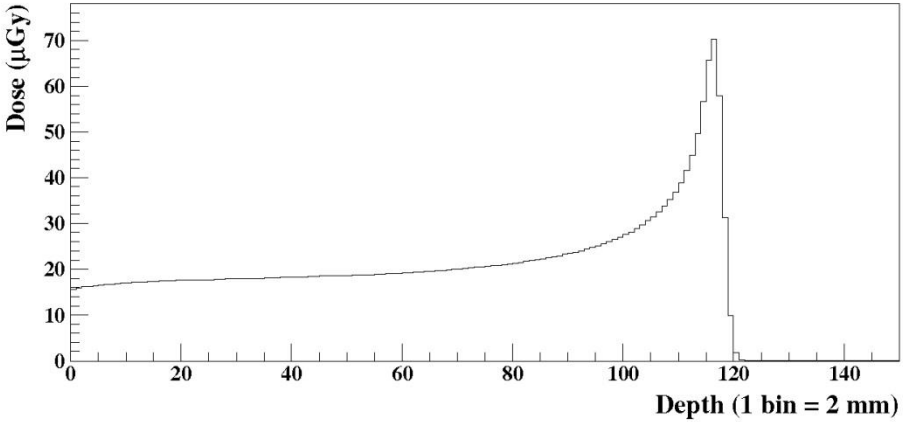




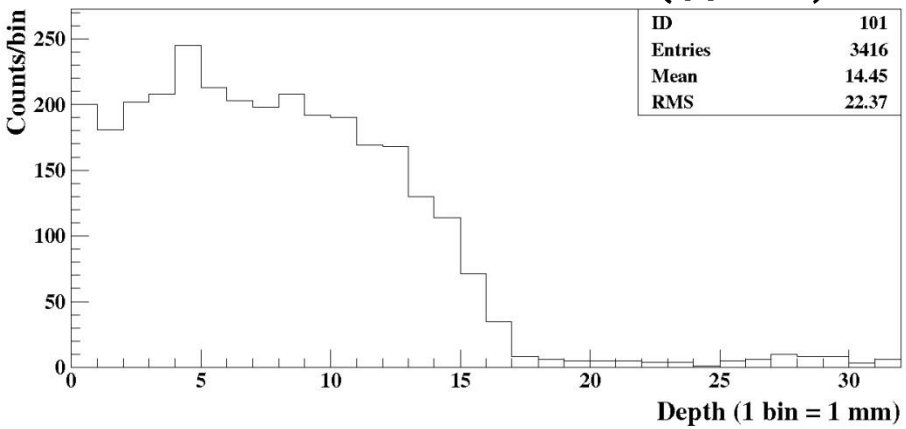
Dose distribution along the depth (44 MeV)



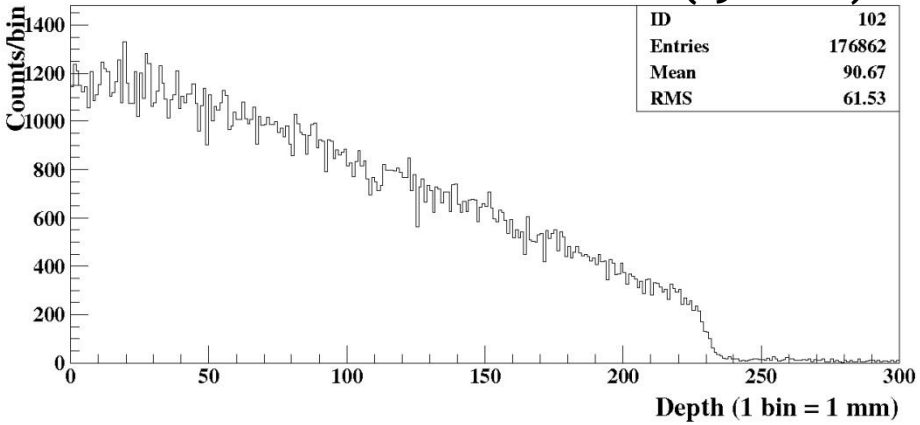
Dose distribution along the depth (190 MeV)

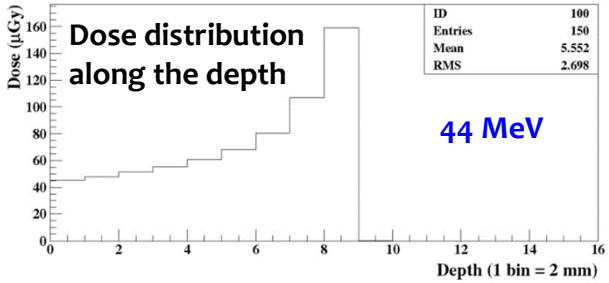


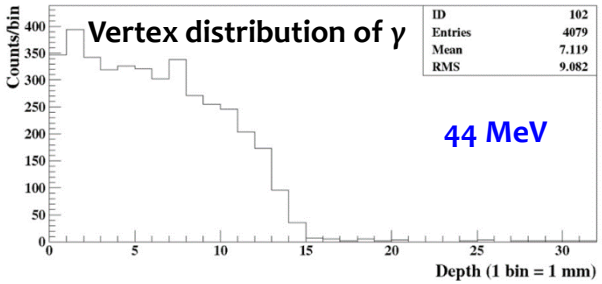
Vertex distribution of neutrons (44 MeV)

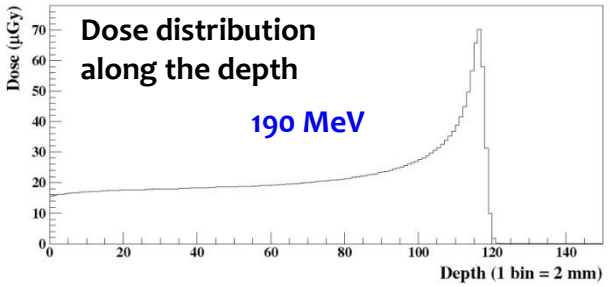


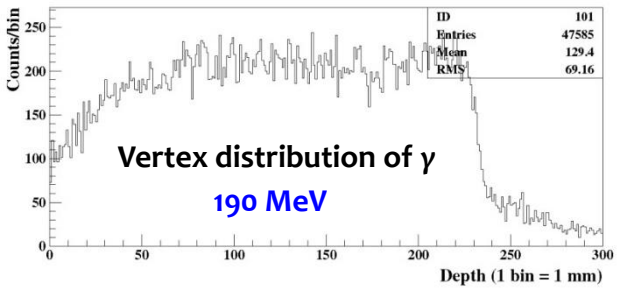
Vertex distribution of neutrons (190 MeV)

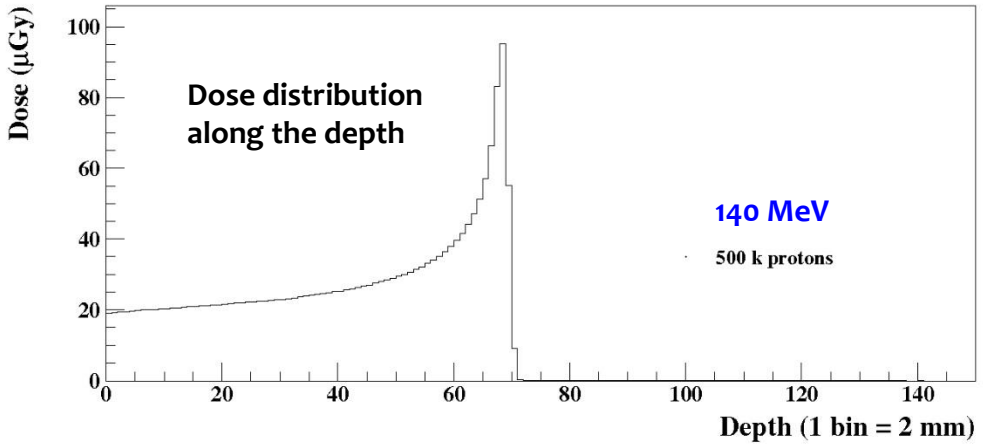


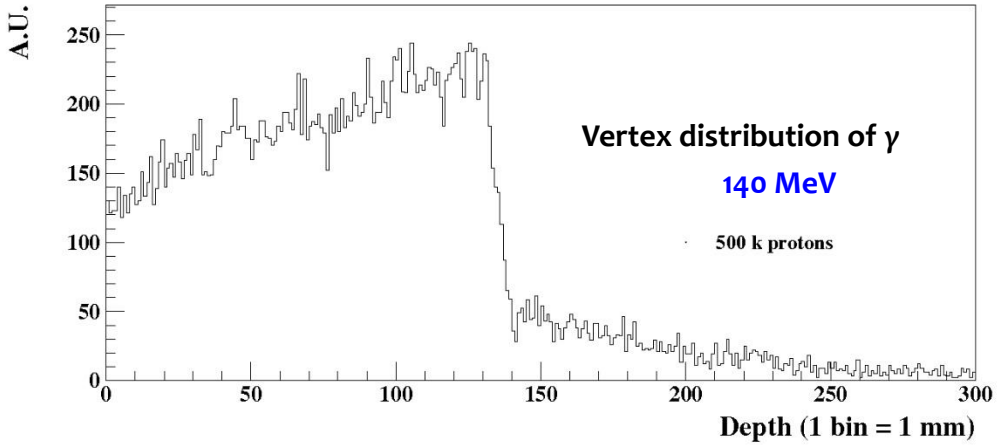

Dose distribution
along the depth
44 MeV
ID 100
Entries 150
Mean 5.552
RMS 2.698
Dose (μGy)
Depth (1 bin = 2 mm)


Vertex distribution of γ
44 MeV
ID 102
Entries 4079
Mean 7.119
RMS 9.082
Counts/bin
Depth (1 bin = 1 mm)

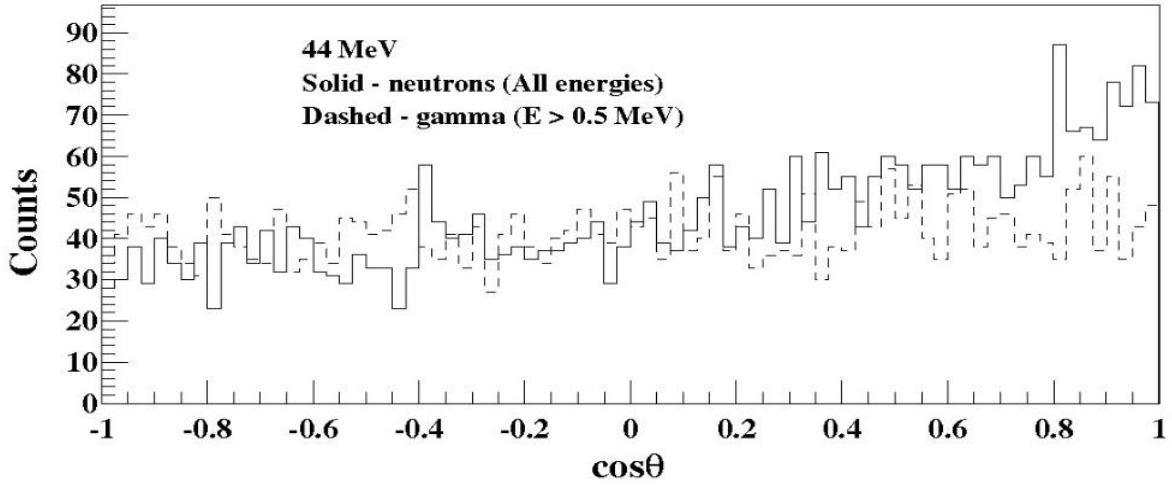

Dose distribution
along the depth
190 MeV
Dose (μGy)
Depth (1 bin = 2 mm)

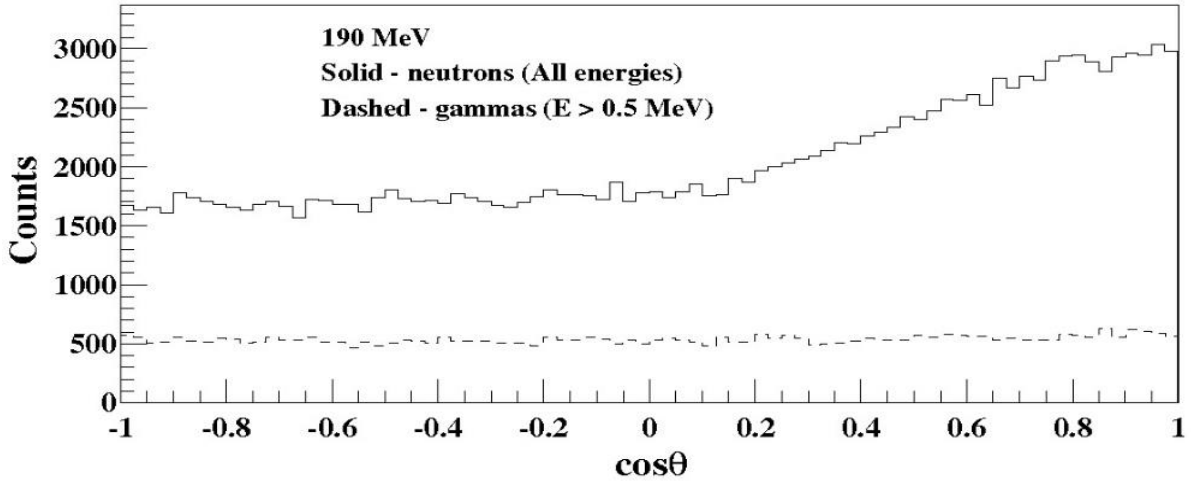

Vertex distribution of γ
190 MeV
ID 101
Entries 47585
Mean 129.4
RMS 69.16
Counts/bin
Depth (1 bin = 1 mm)

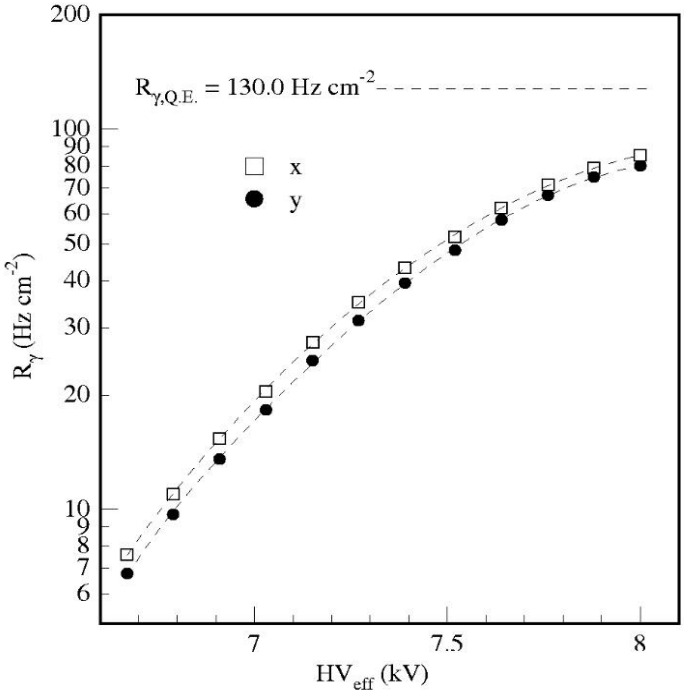

Dose distribution
along the depth
140 MeV
500 k protons
Dose (μGy)
Depth (1 bin = 2 mm)

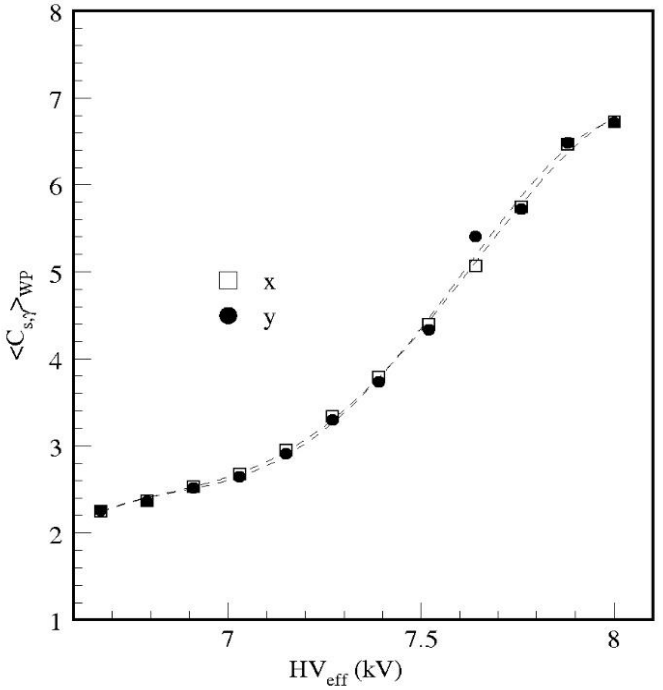

Vertex distribution of γ
140 MeV
500 k protons
A.U.
Depth (1 bin = 1 mm)

GEANT4: spatial and angle distributions

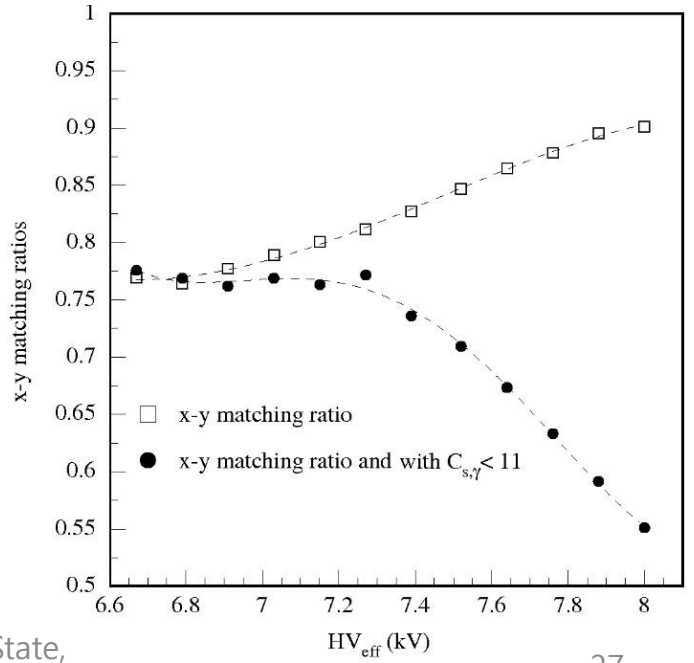






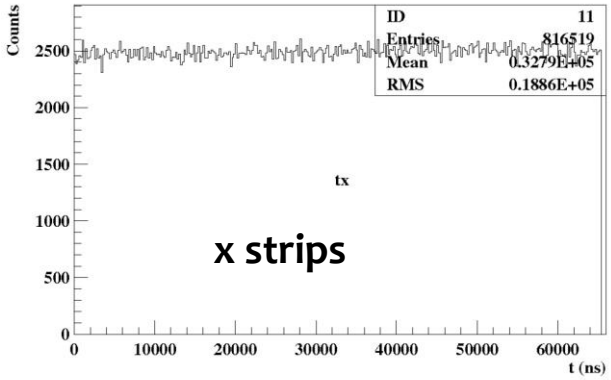


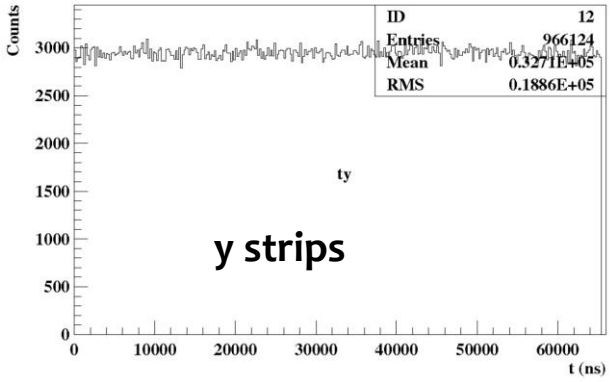
Test of 4-gap MRPC at 2.3 m from 5.0 GBq ^{137}Cs source (661.7 keV)



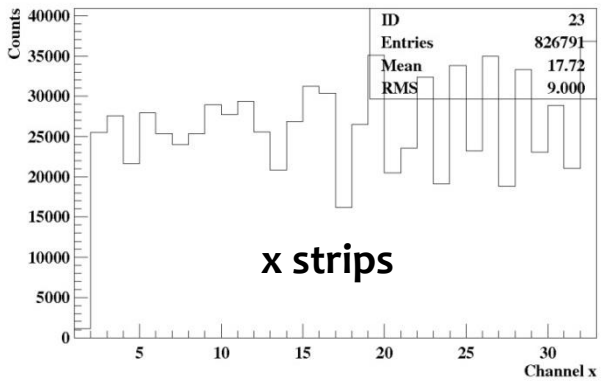
Responses to ^{137}Cs gammas

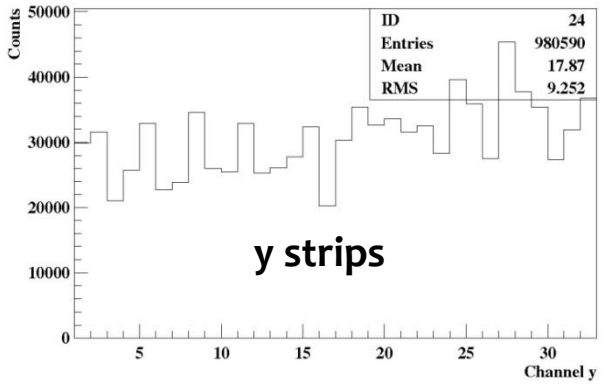
Time profiles



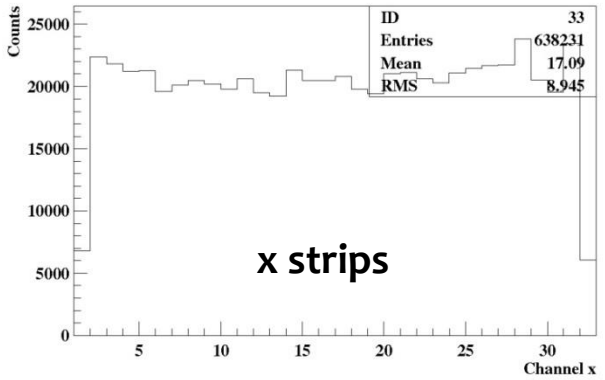


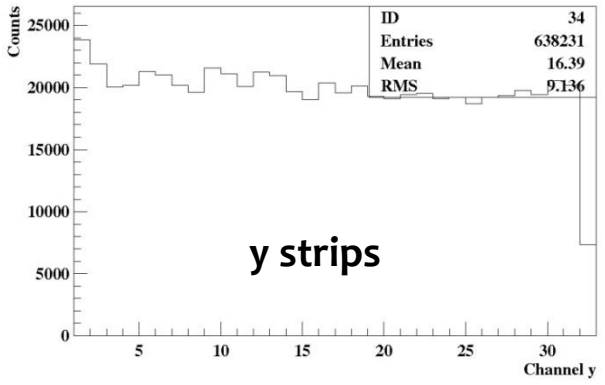
Channel distribution





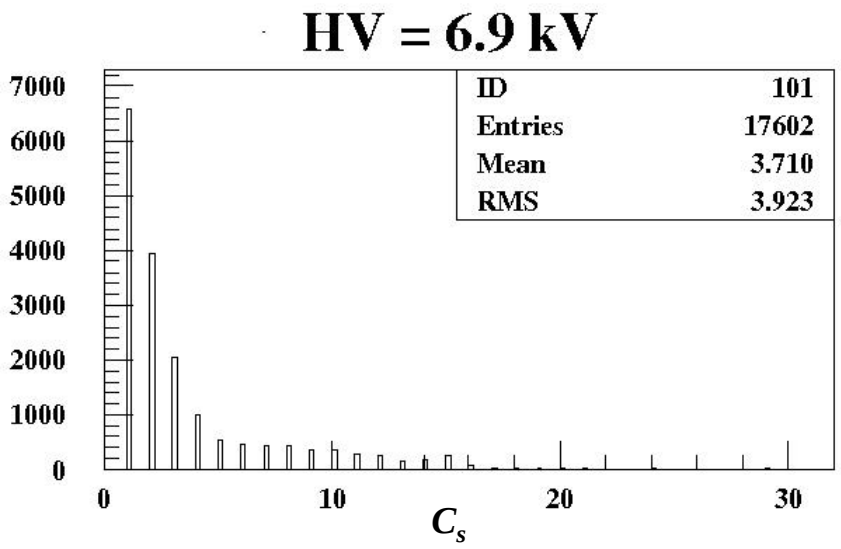
Channel distribution x-y matched

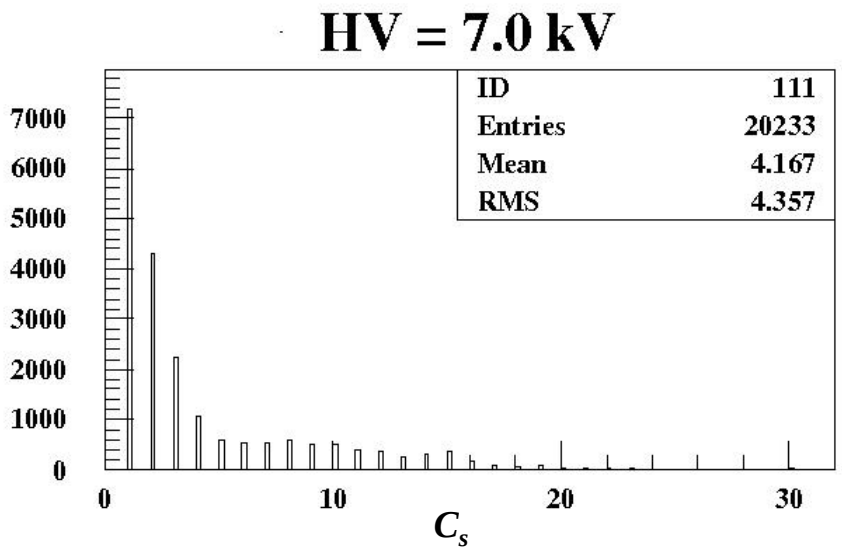


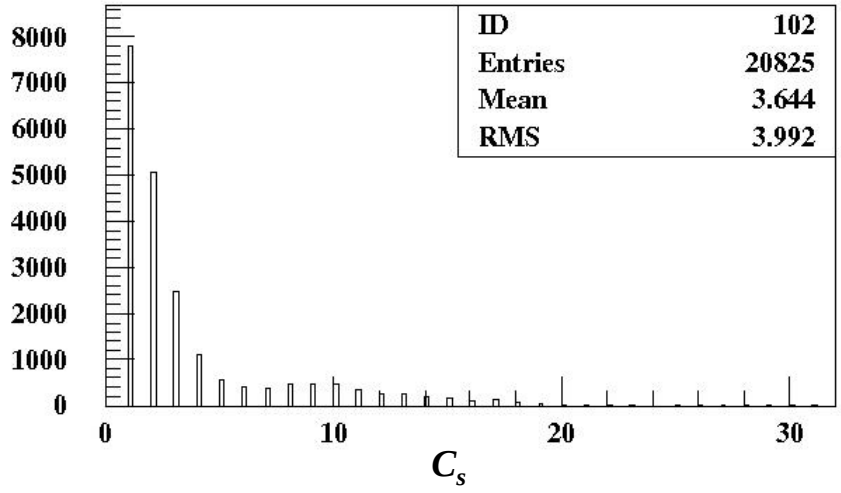


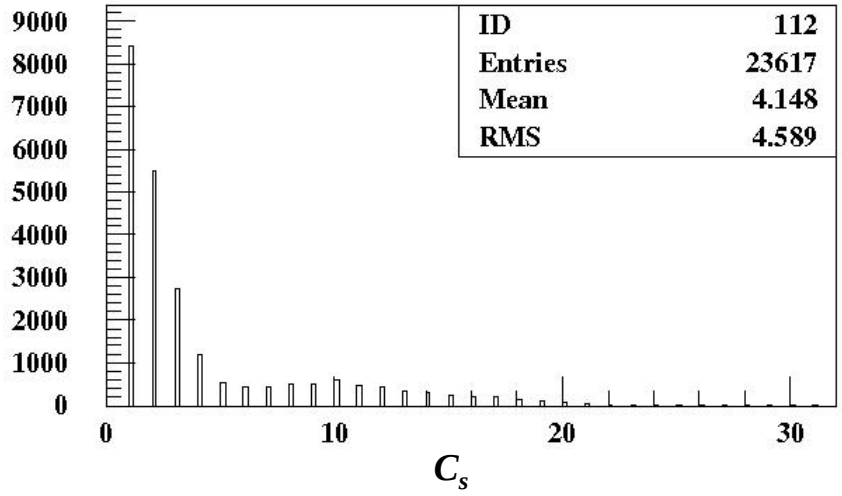
4-gap MRPC data with 140 MeV beam

Cluster size distribution for Case I



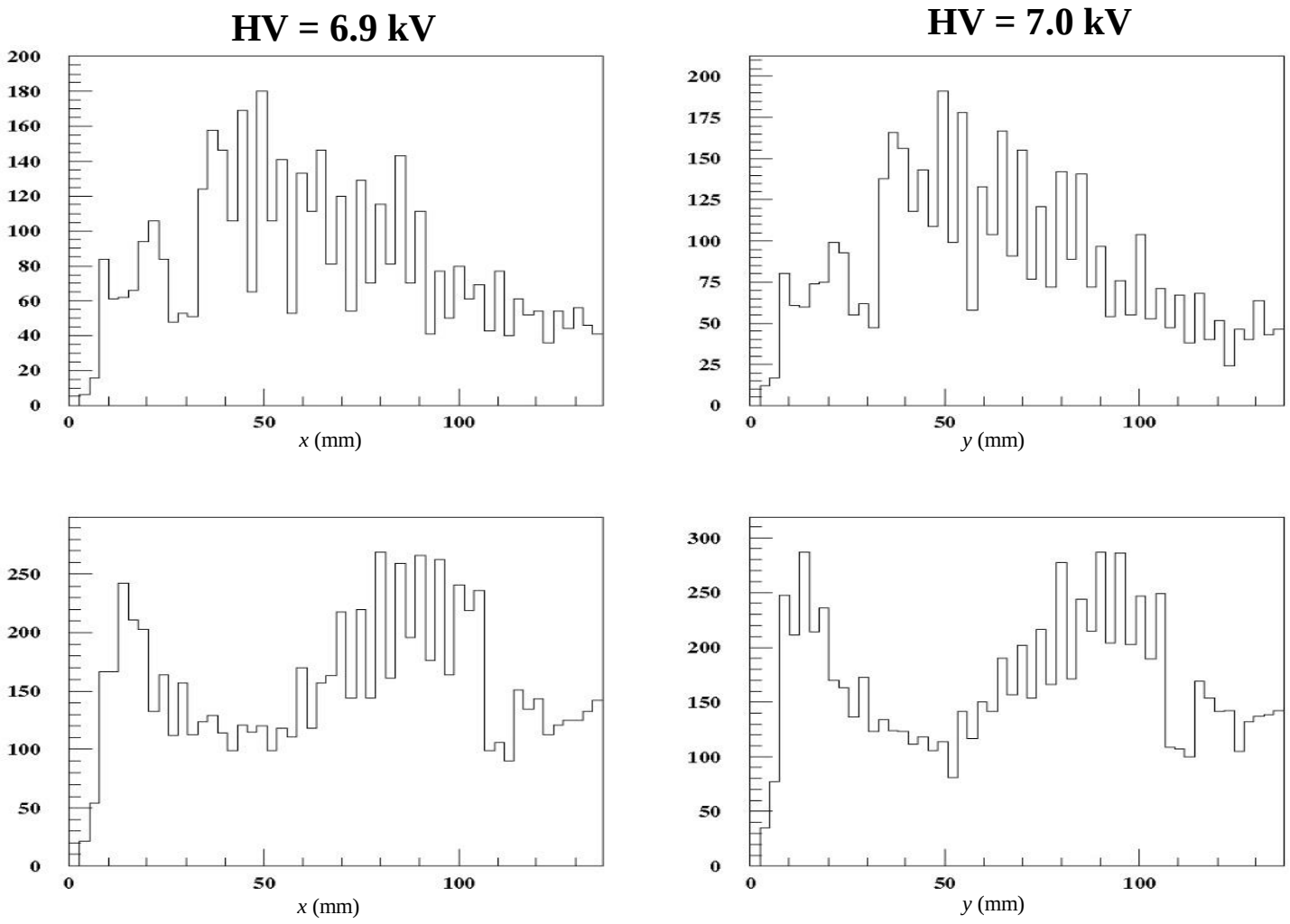




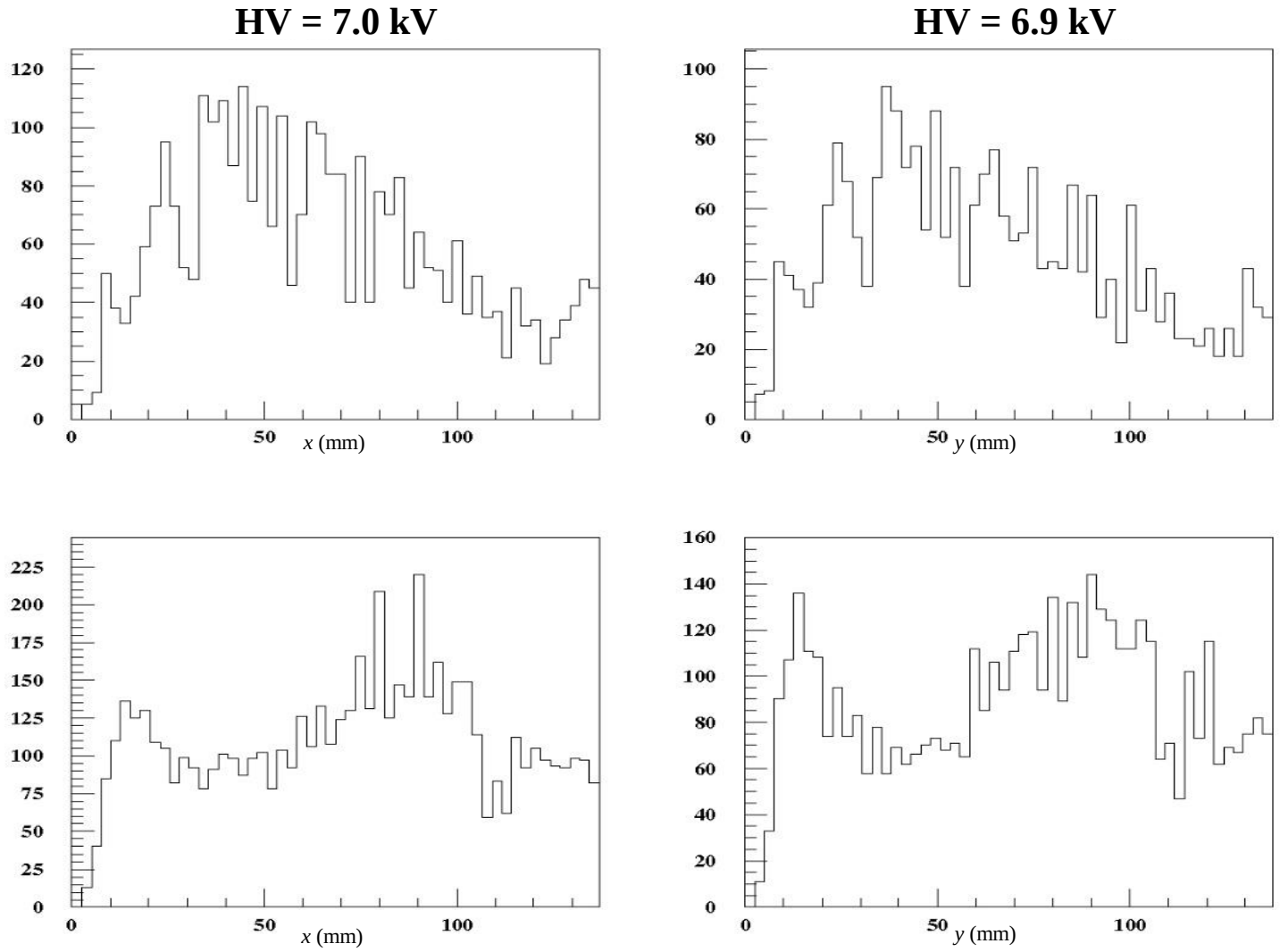


4-gap MRPC data

Case I: For lateral distributions in PMMA



Case II: For depth distributions in PMMA



2D response function for calibration (440 k γ) + random number generations of 500 times to smooth the response function image

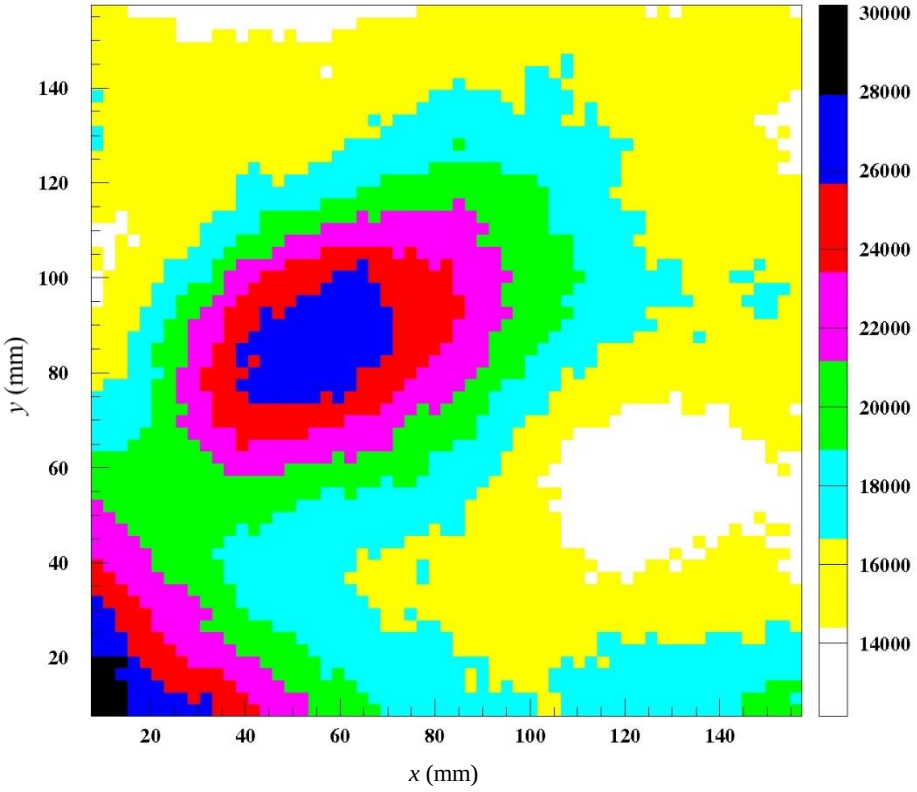
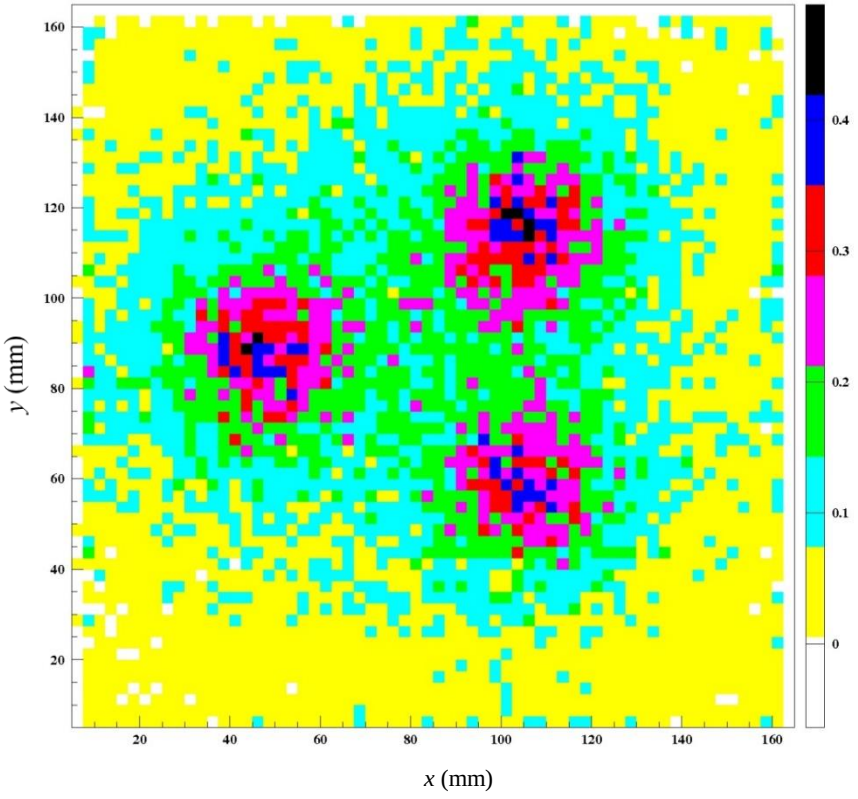
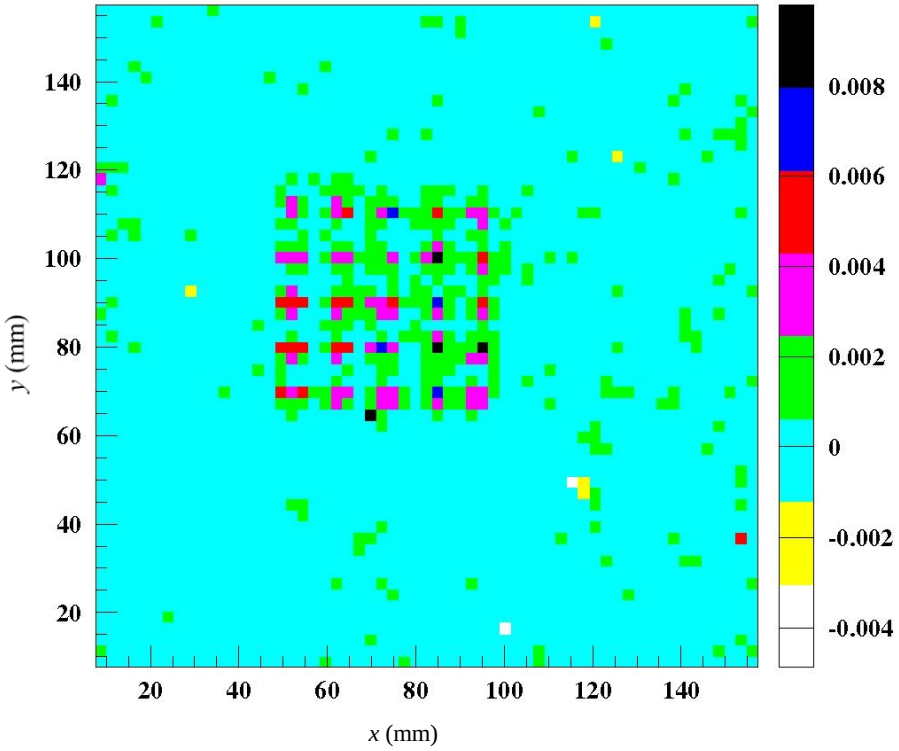


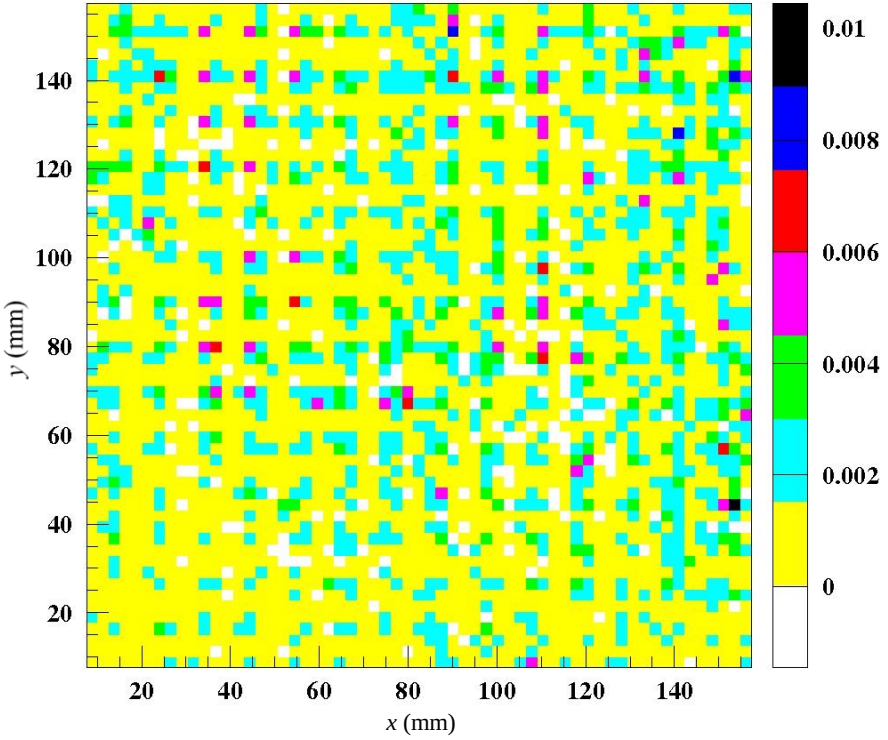
Image of three of ~ 3 μCi ^{60}Co



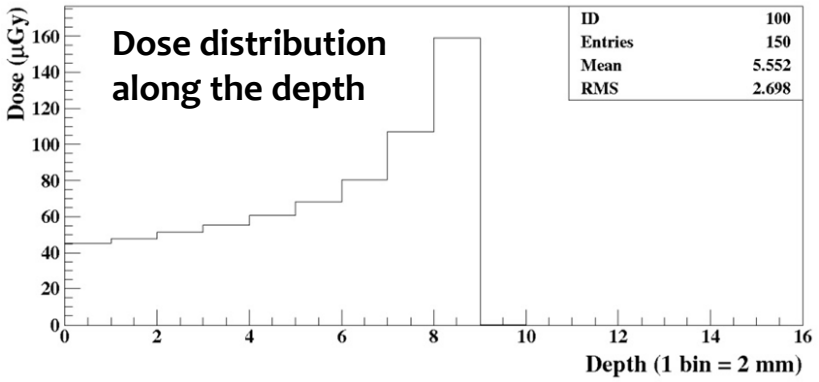
Flood images through 4 cm x 4 cm window

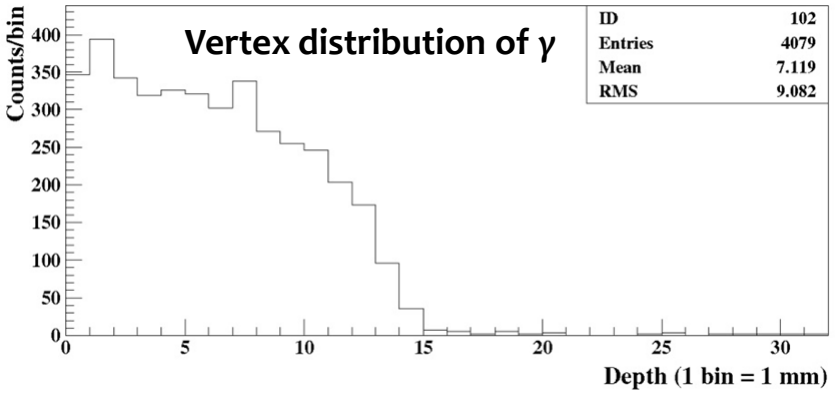


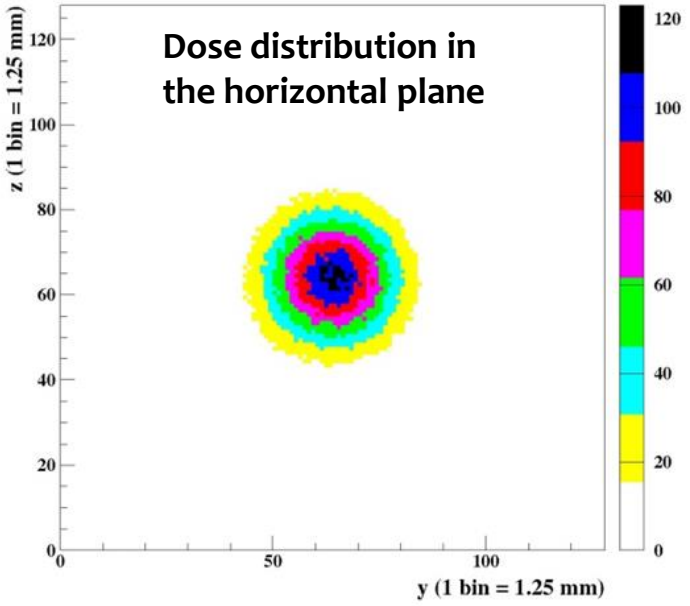
Flood images (all)

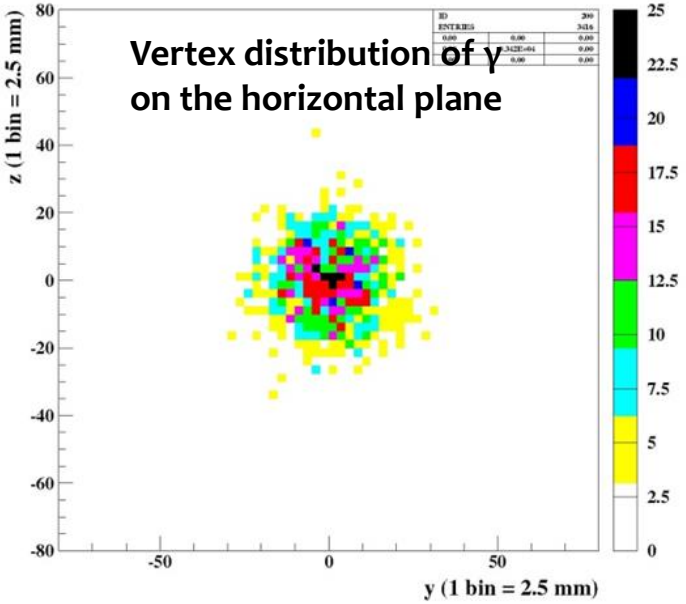


GEANT4 simulation for 44 MeV protons (FWHM = 3 cm) for KIRAMS test
Phantom size (biological tissue) = 3 cm x 16 cm x 16 cm





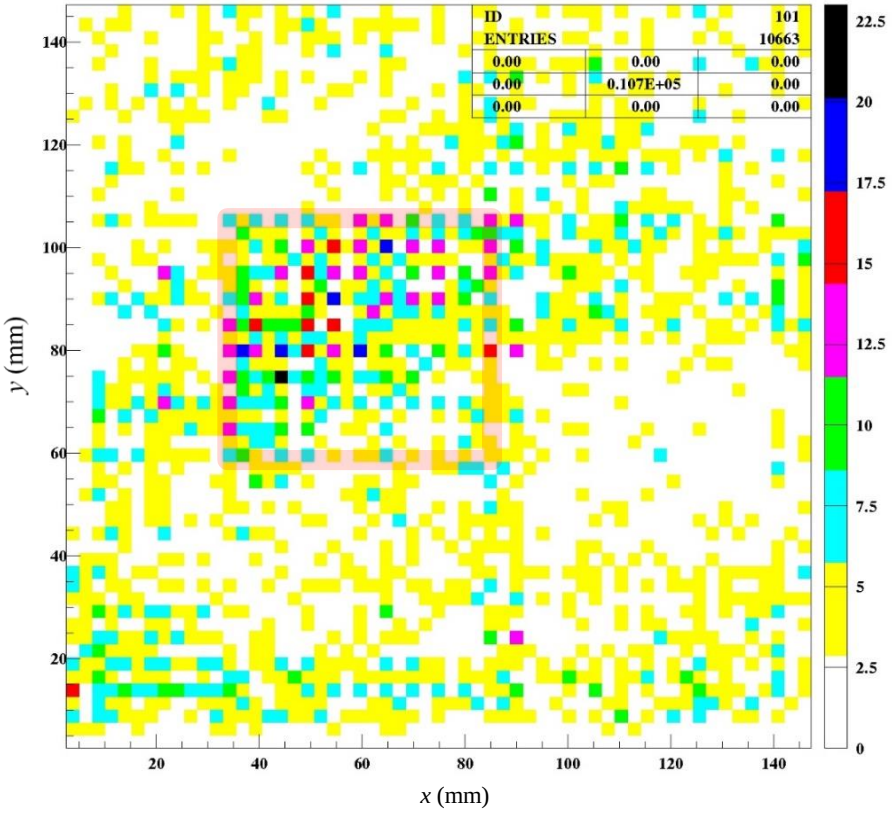




Case I: For lateral distributions

Image obtained with $C_{s,x}$ *and* $C_{s,y}$ < 6

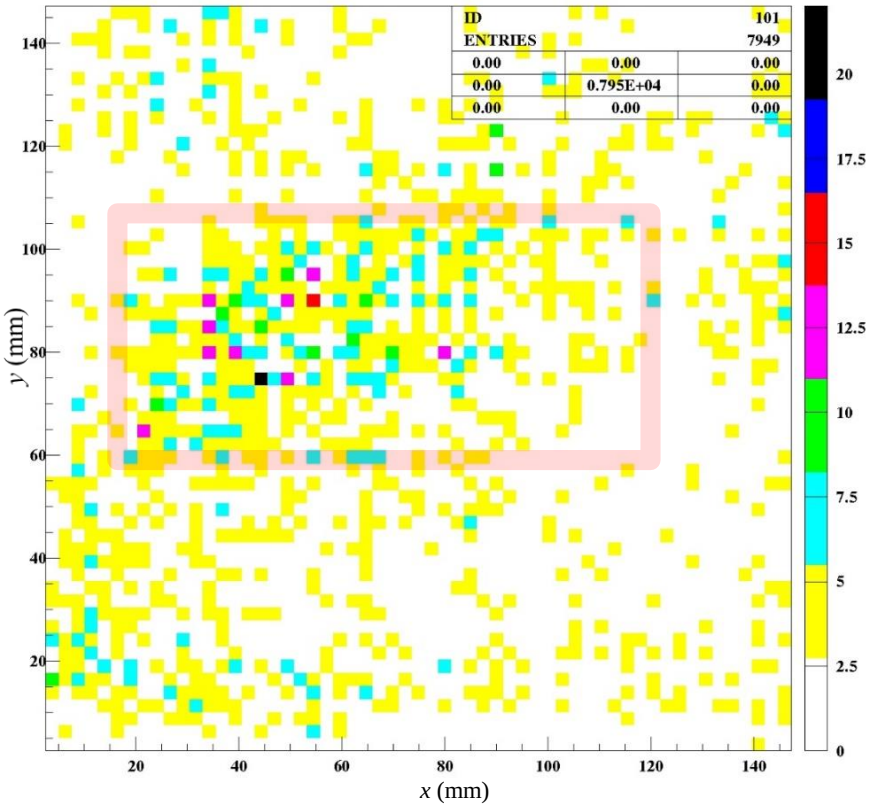
HV = 6.9 kV with beam



Case II: For depth distributions

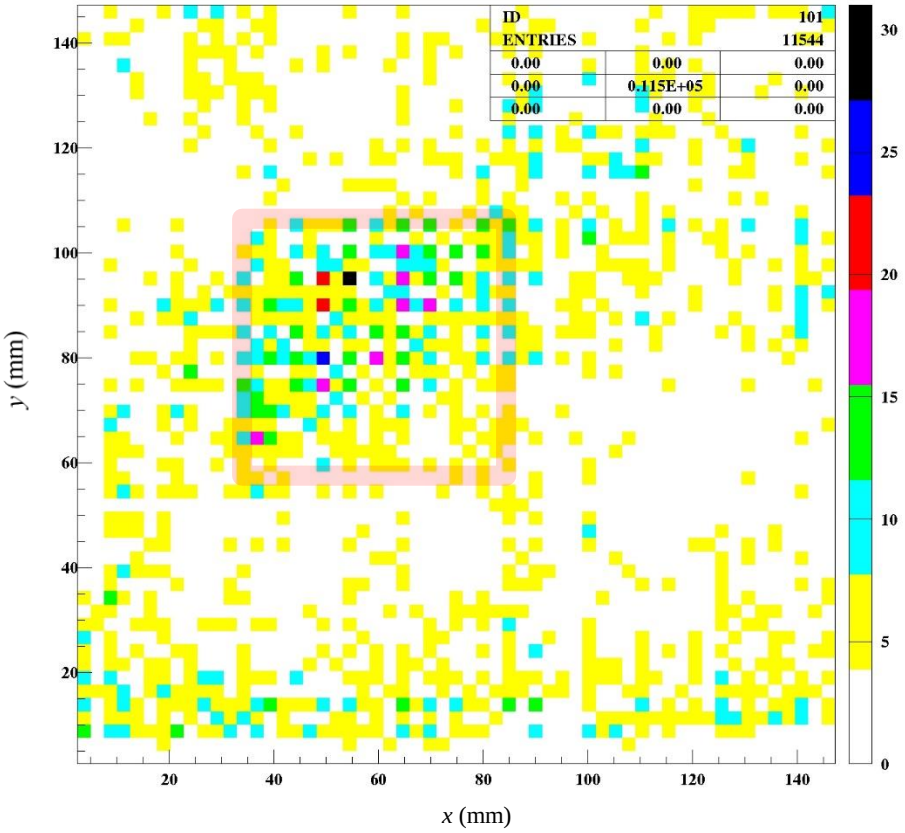
Image obtained with $C_{s,x}$ *and* $C_{s,y}$ < 6

HV = 6.9 kV with beam



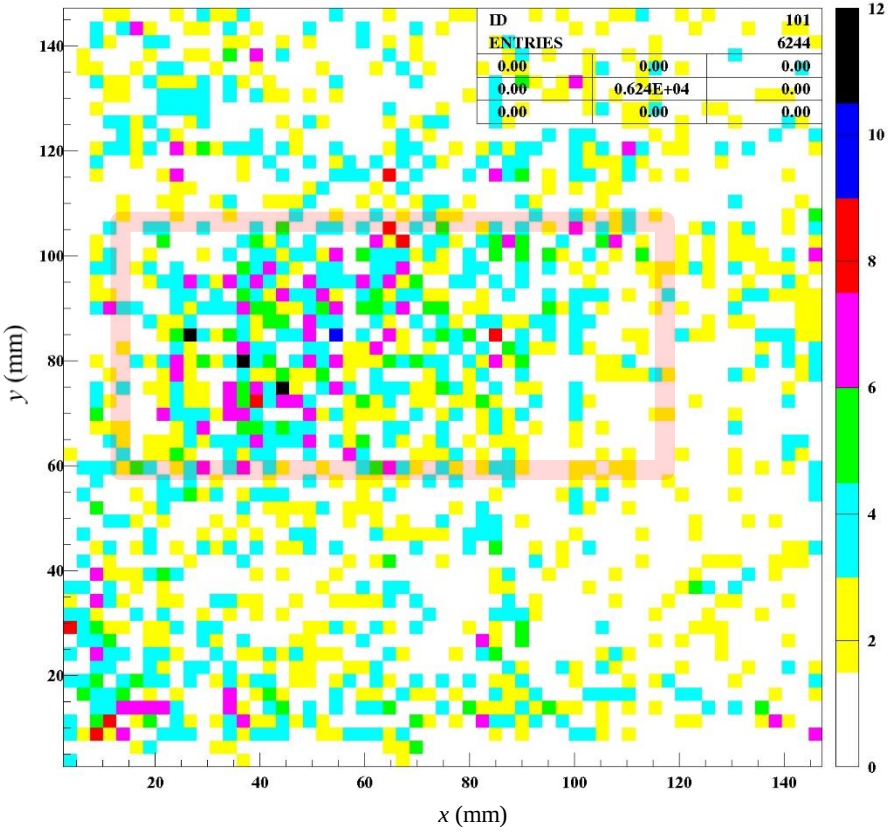
Case I: For lateral distributions

Image obtained with $C_{s,x}$ *and* $C_{s,y}$ < 6
HV = 7.0 kV with beam



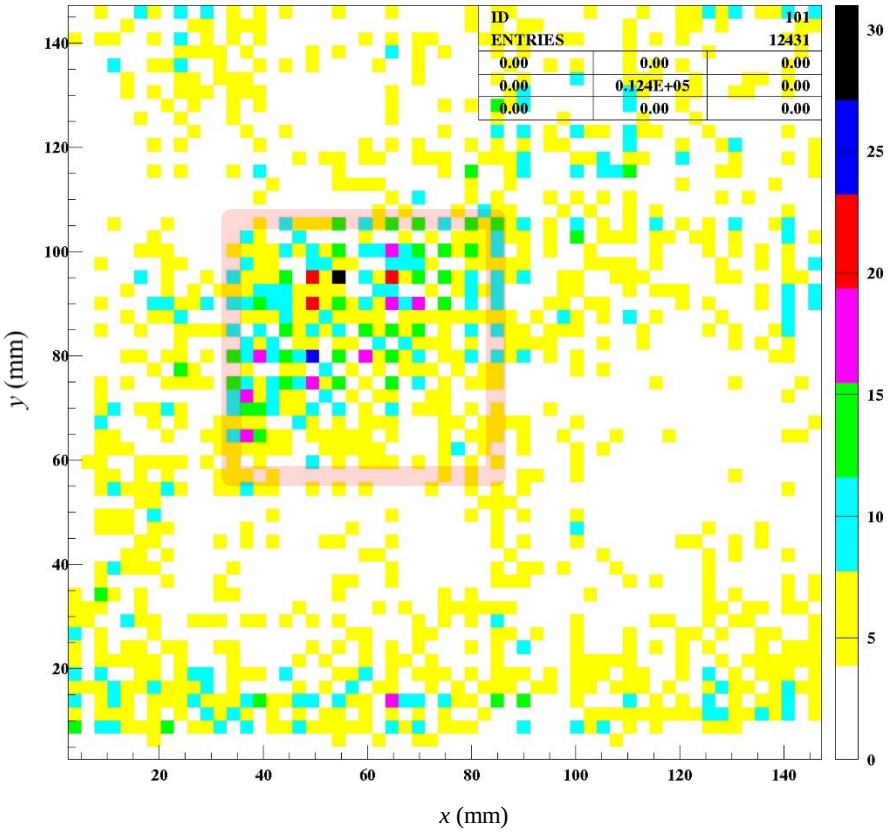
Case II: For depth distributions

Image obtained with $C_{s,x}$ *and* $C_{s,y}$ < 6
HV = 7.0 kV with beam



Case I: For lateral distributions

Image obtained with $C_{s,x}$ *and* $C_{s,y}$ < 8
HV = 7.0 kV with beam



Case II: For depth distributions

Image obtained with $C_{s,x}$ *and* $C_{s,y}$ < 8
HV = 7.0 kV with beam

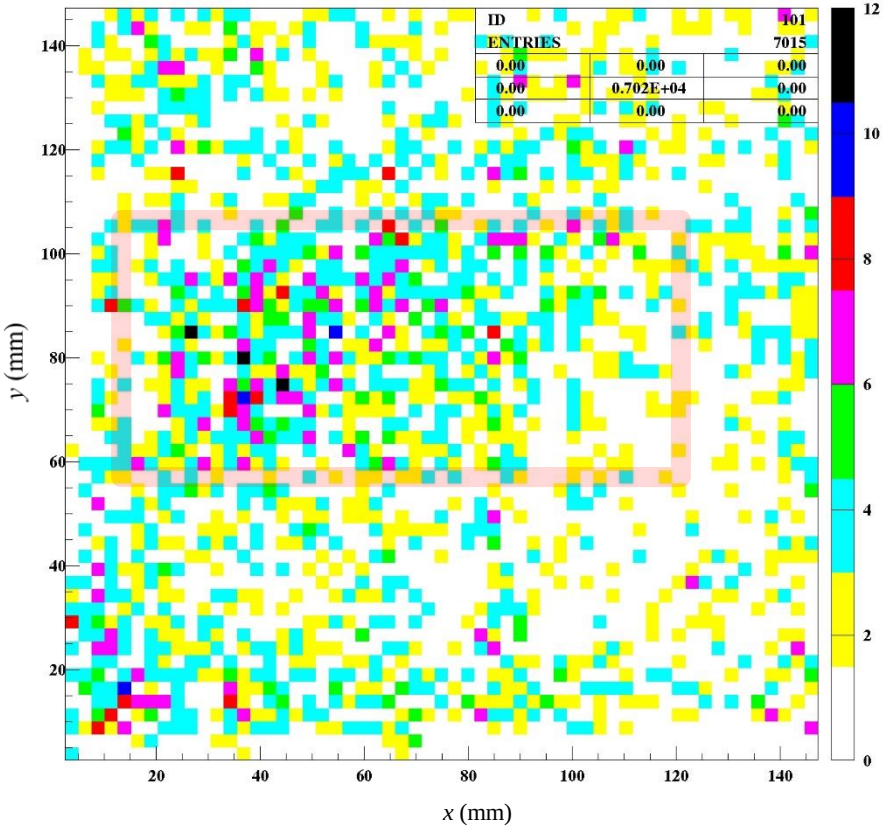


Image of 661.7 keV gammas @42 cm from a 5 GBq ^{137}Cs source