Particle Tracking and Hadron Therapy Beam Monitoring with GEMPix – a Highly Pixelated Triple GEM Detector

Stuart P. George

Particle Tracking with Gempix - a Timepix Based Gas Detector

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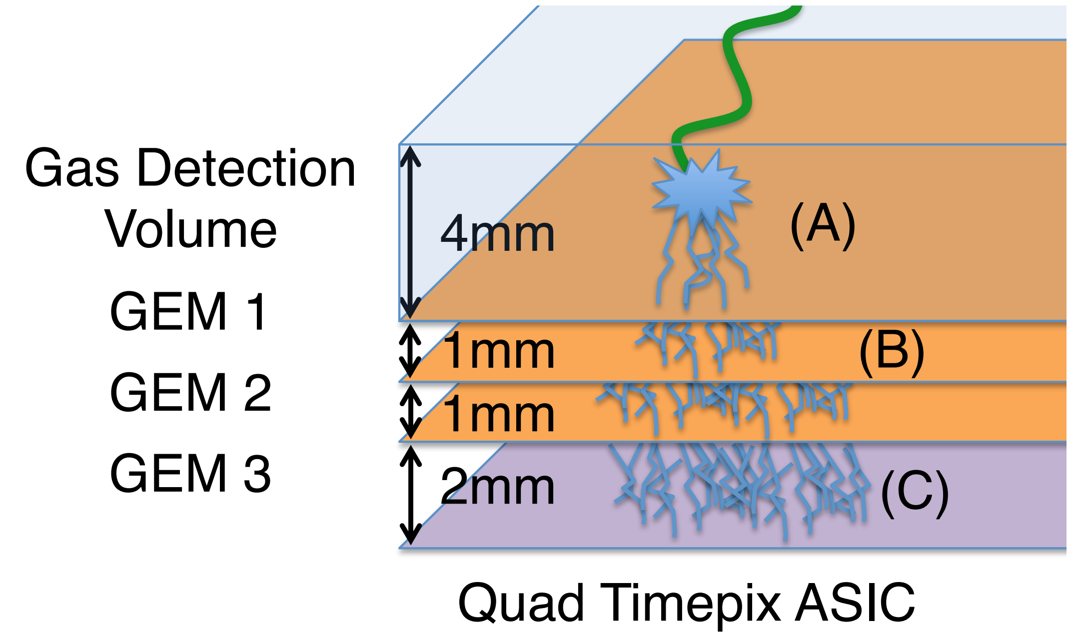
Thanks to, Eric Bosne, Erik Frojdh and John Idarraga and Fillippo Resnati

How does the Gempix Work?

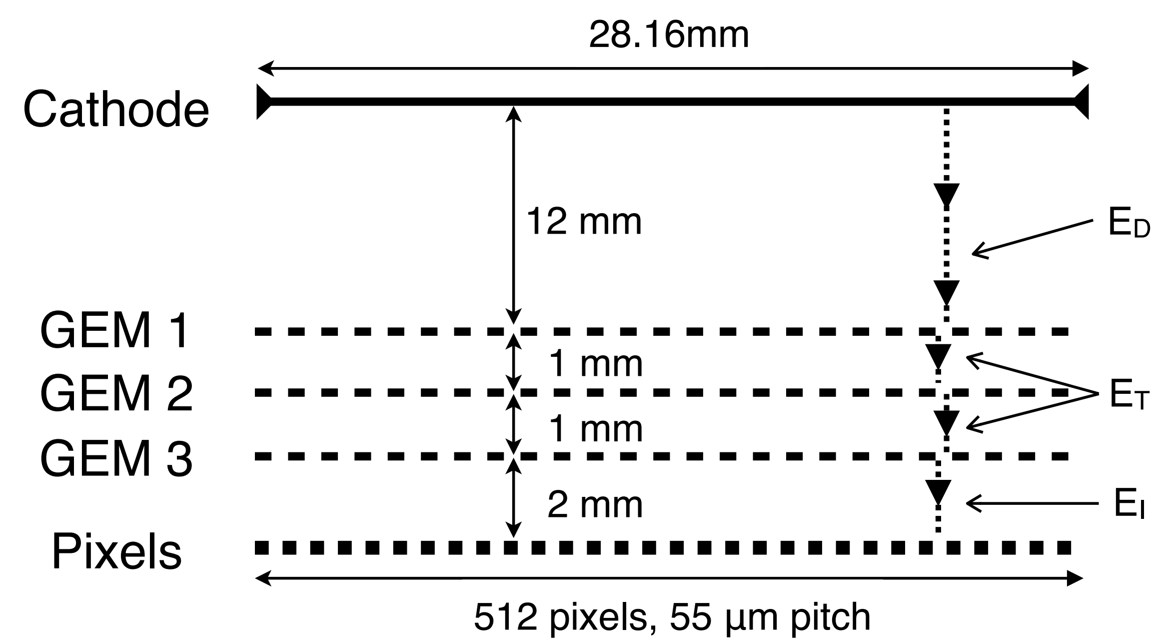
- Initial electrons created by an interaction are transported by electric fields to the GEM foils.

- Each GEM foil creates up to 40 output electrons for each electron in, three GEM foils give gains up to 10^5 (depending on the gas)

- These electrons are collected by the Timepix, ~1000 electrons is enough to trigger a pixel (high gain operation)



(A) Photon interaction, (B) Electron multiplication, (C) Detection/Readout



GEM Detectors

- A GEM consists of a large kapton sheet with both sides metallized

- A potential is placed across both sides and tiny holes etched in the detector

- Electrical fields can reach ~100 kV/cm inside the holes, allowing for a **localised** electron avalanche

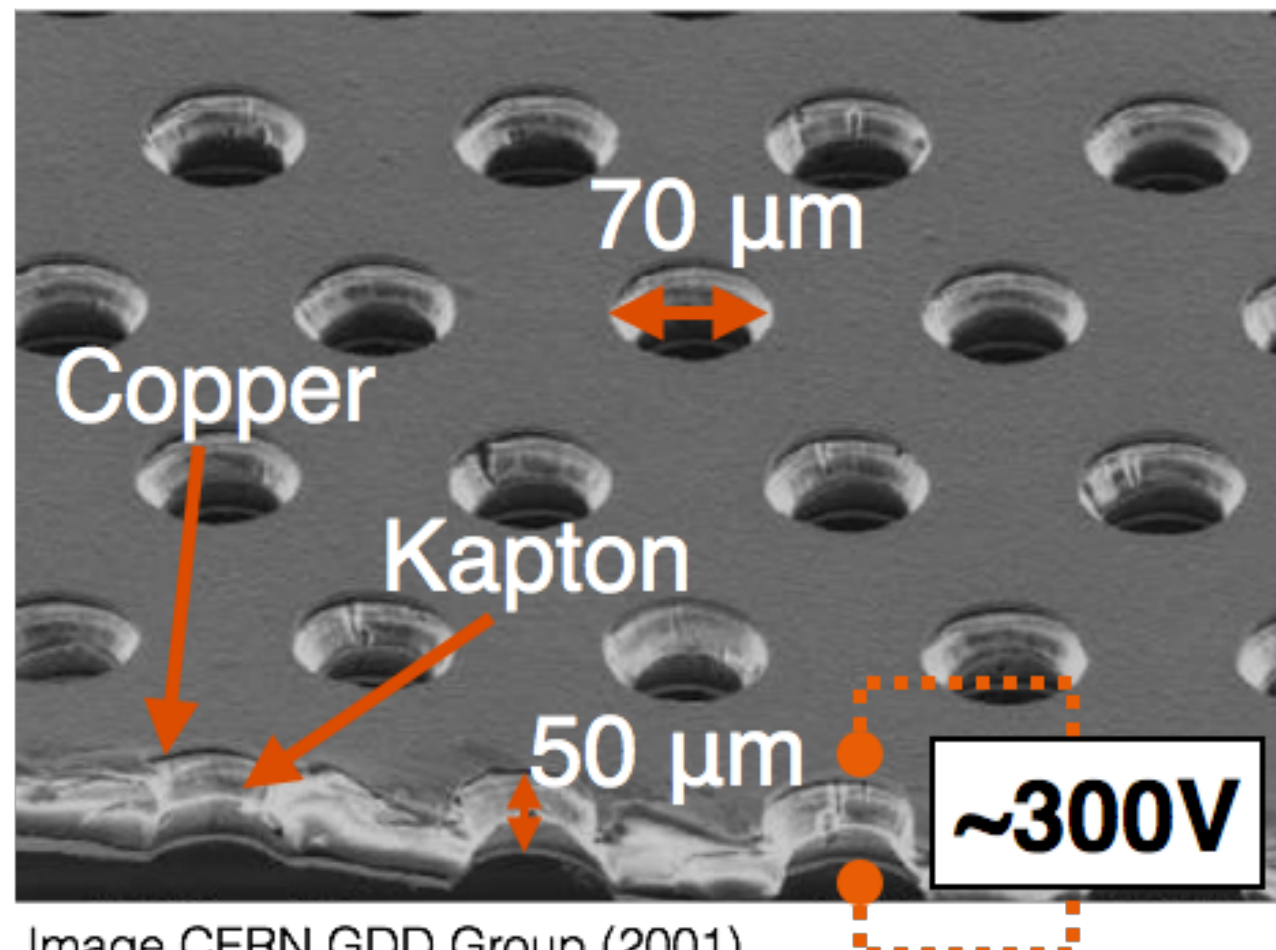


Image CERN GDD Group (2001)

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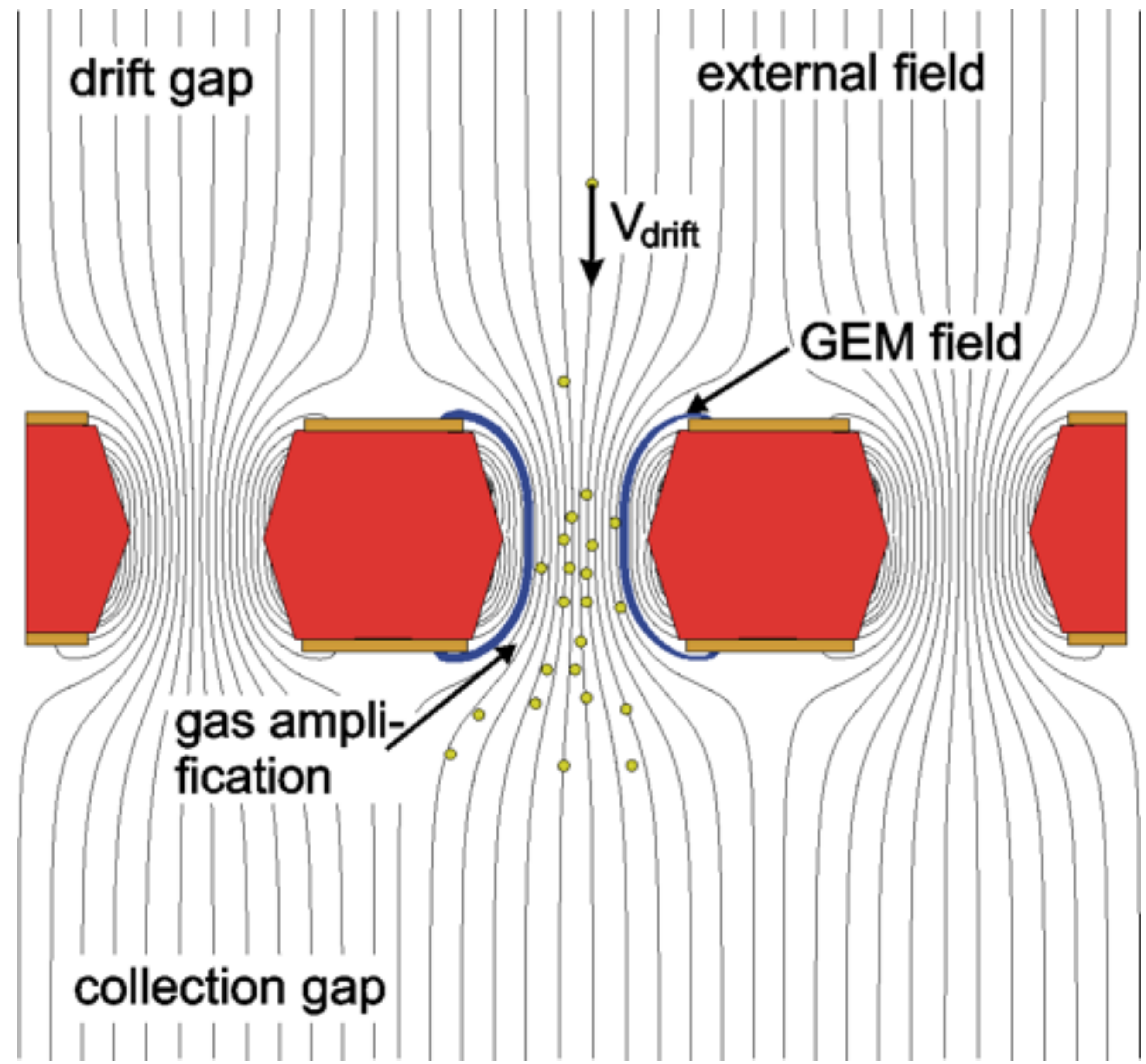
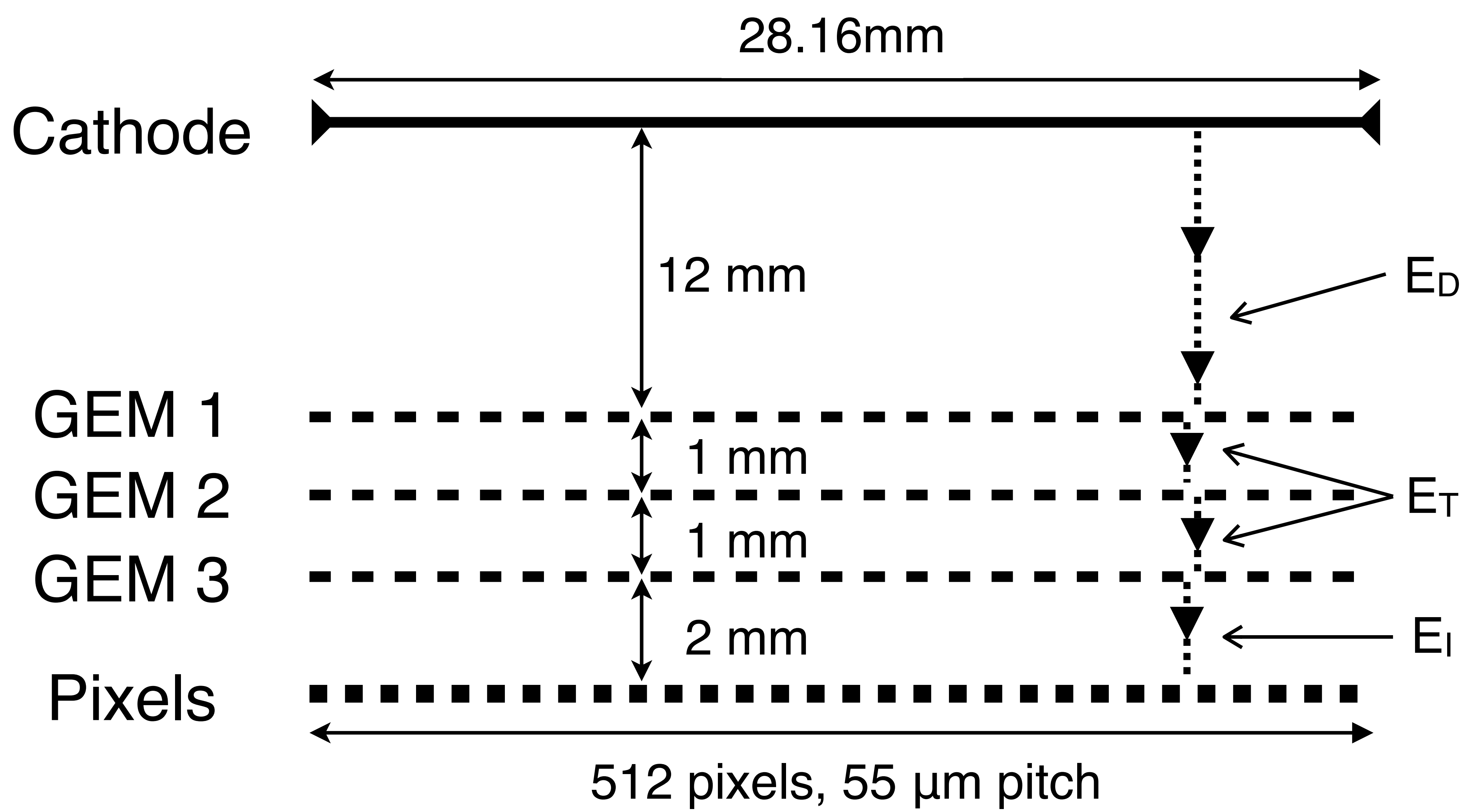
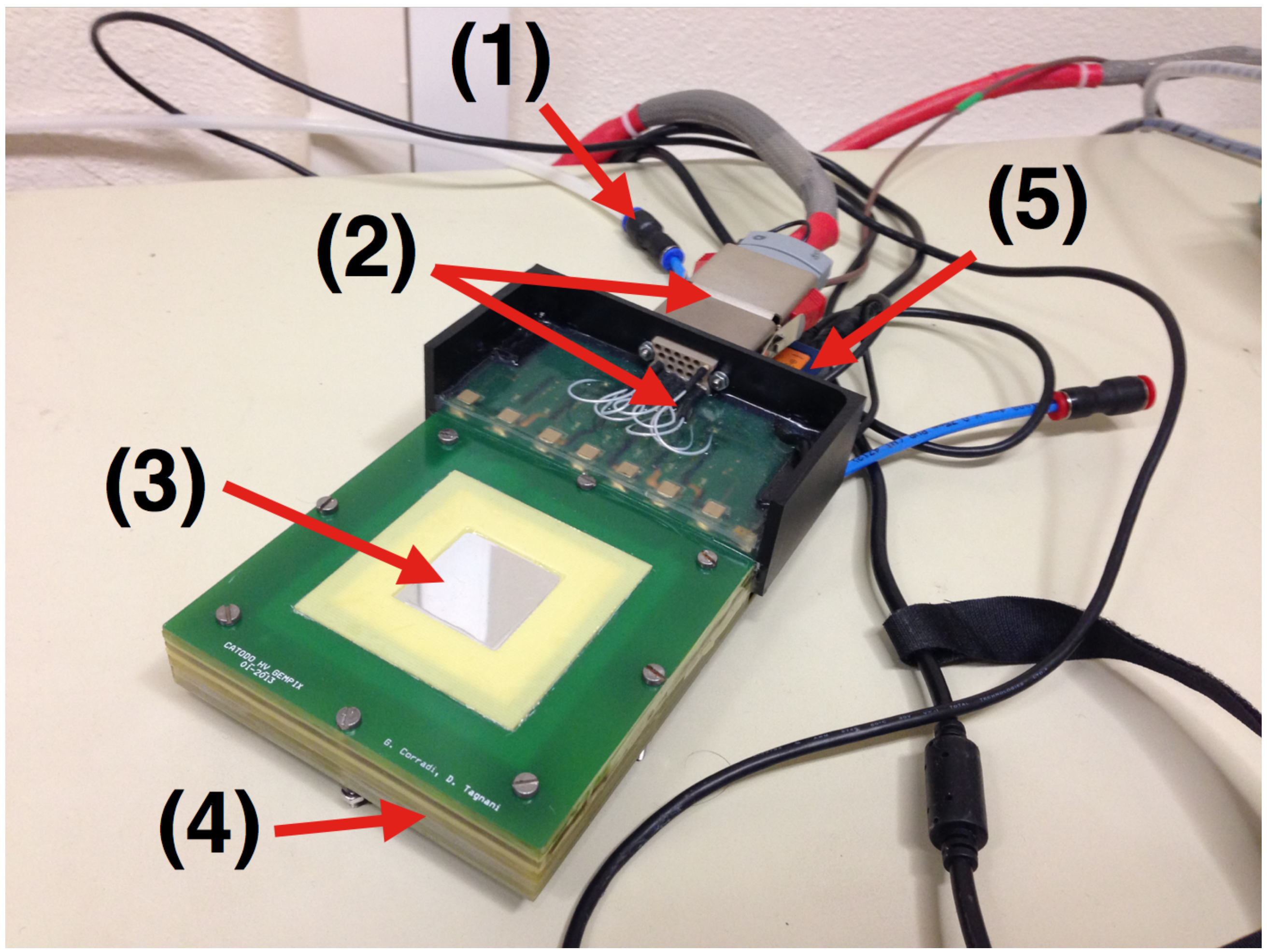


GEM Detectors



7 Independent electric fields - GEM 1,2,3 control the gas gain $E_{\mathbf{D}\text{rift}}$, $E_{\mathbf{T}\text{ransport}}$, and $E_{\mathbf{I}\text{nduction}}$ transport electrons through the detector

The Gempix - An Ultra Pixellated Gas Detector

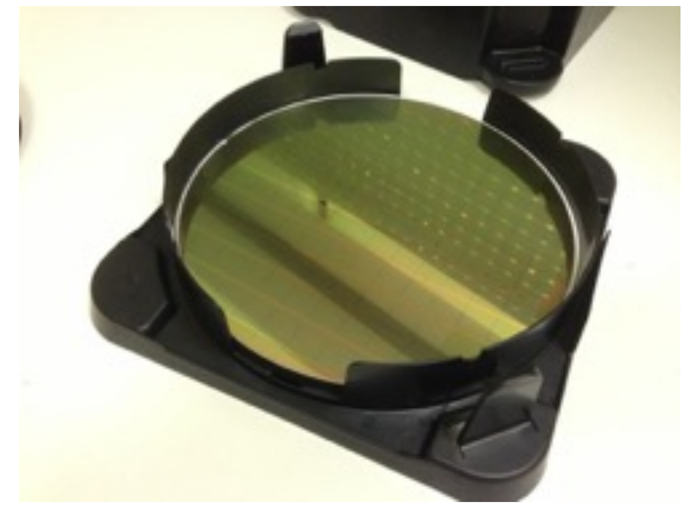


(1) Gas Supply
(2) High Voltage
(3) Entrance Window
(4) GEM Foils
(5) FITPix Readout

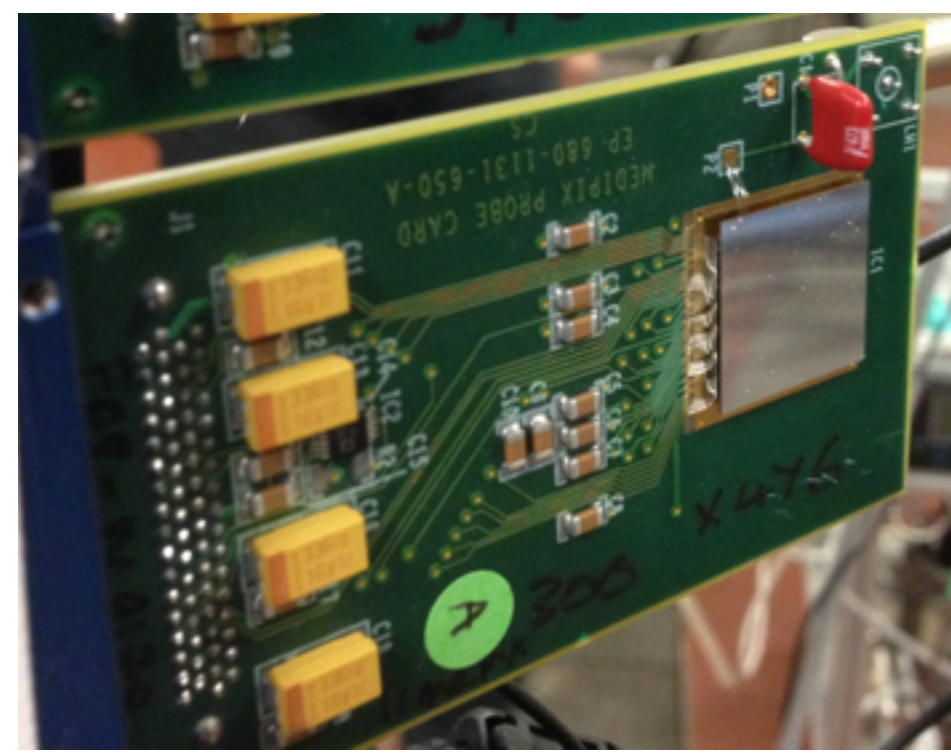
Sensitive area = 3 x 3 x 1.2 cm^3

The Timepix - a quick intro

- The timepix asic consists of 256 x 256 CMOS pixels each measuring 55 x 55 um.
- Each pixel can either measure charge deposited or do single particle counting.
- The detection threshold is about 1000 electrons, noise width about 100 electrons
- We use a quad configuration of 512x512 pixels for a total of 262144

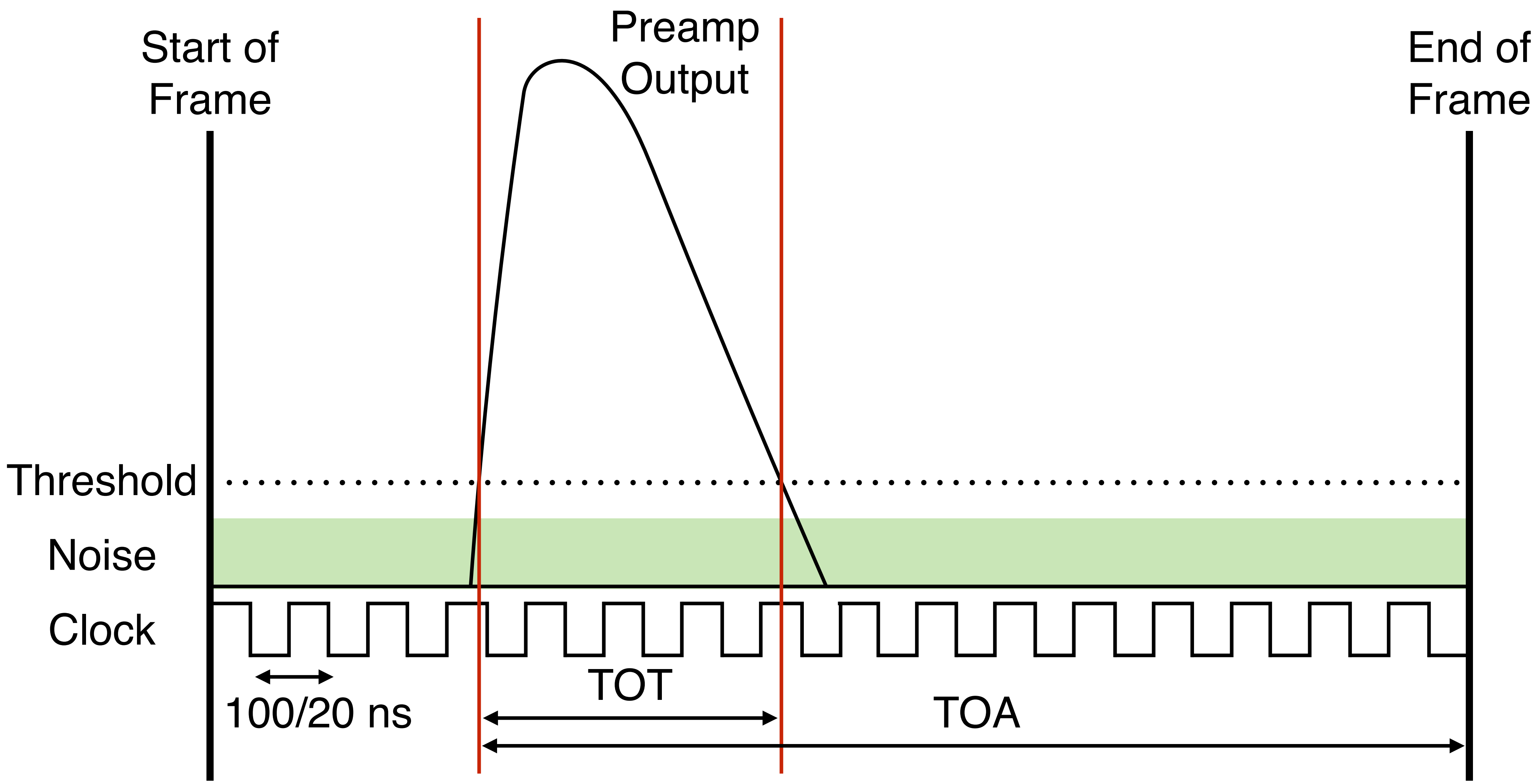


Timepix ASIC Wafer

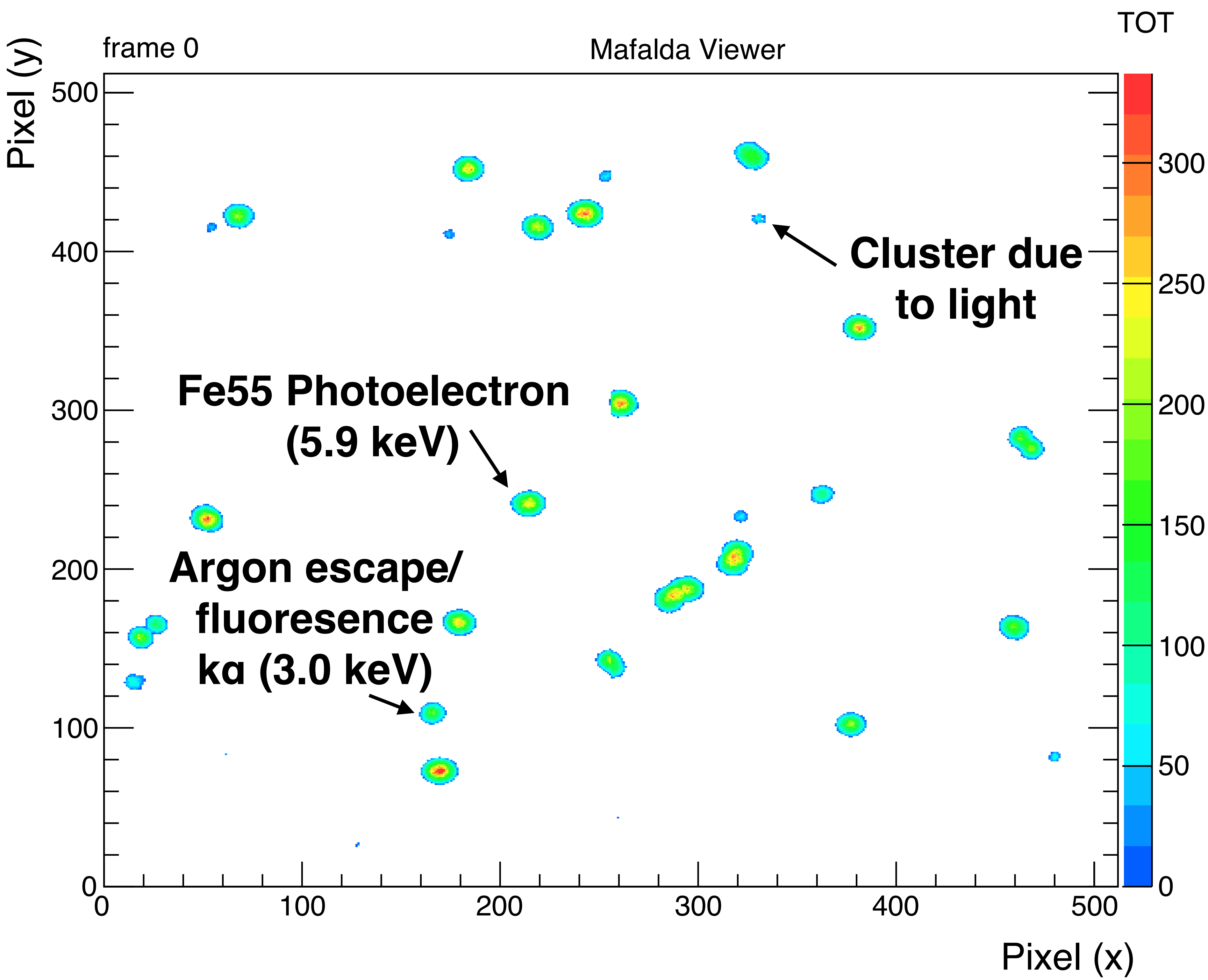


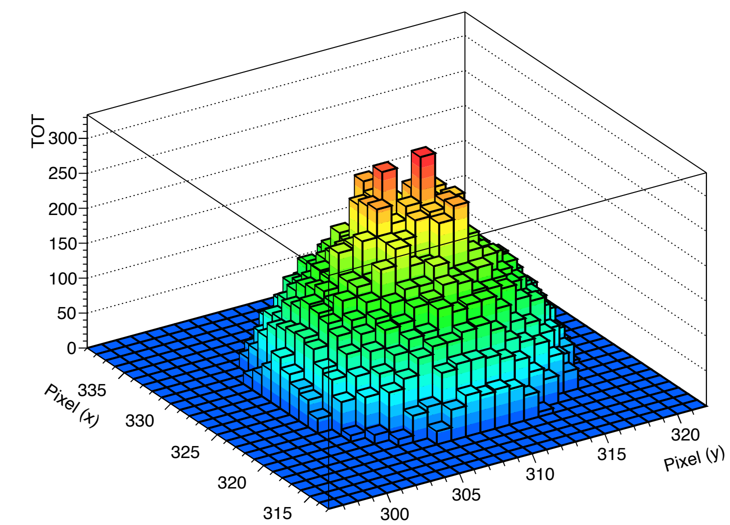
Timepix mounted on CERN probe card with Si sensor

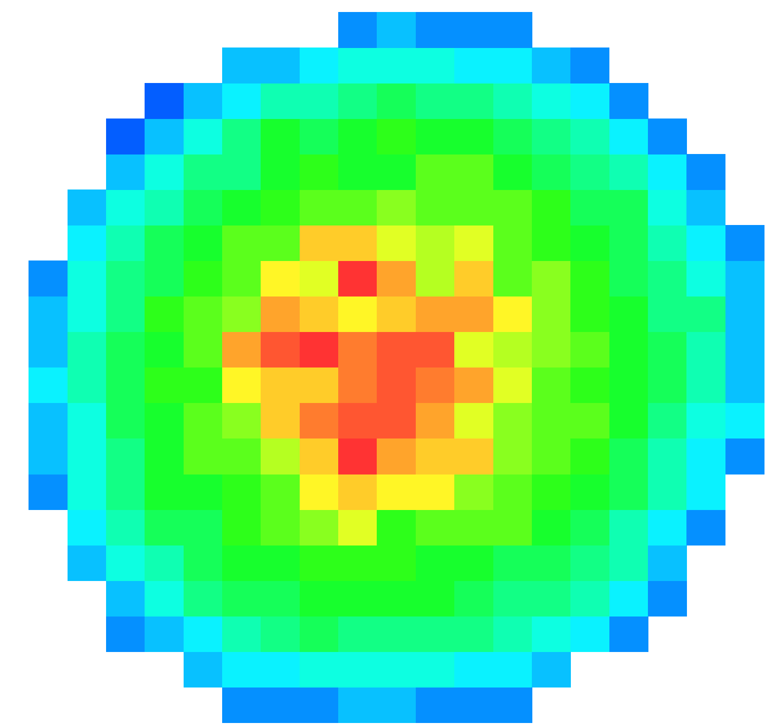
The Timepix Pixel



- Medipix (pulse counting)
- TOA (Time of arrival)
- TOT (Charge surrogate measurement as a Wilkinson ADC)
- TOA/TOT achieved with an on chip clock synchronised to all pixels (up to 100 Mhz, but 50 stable)





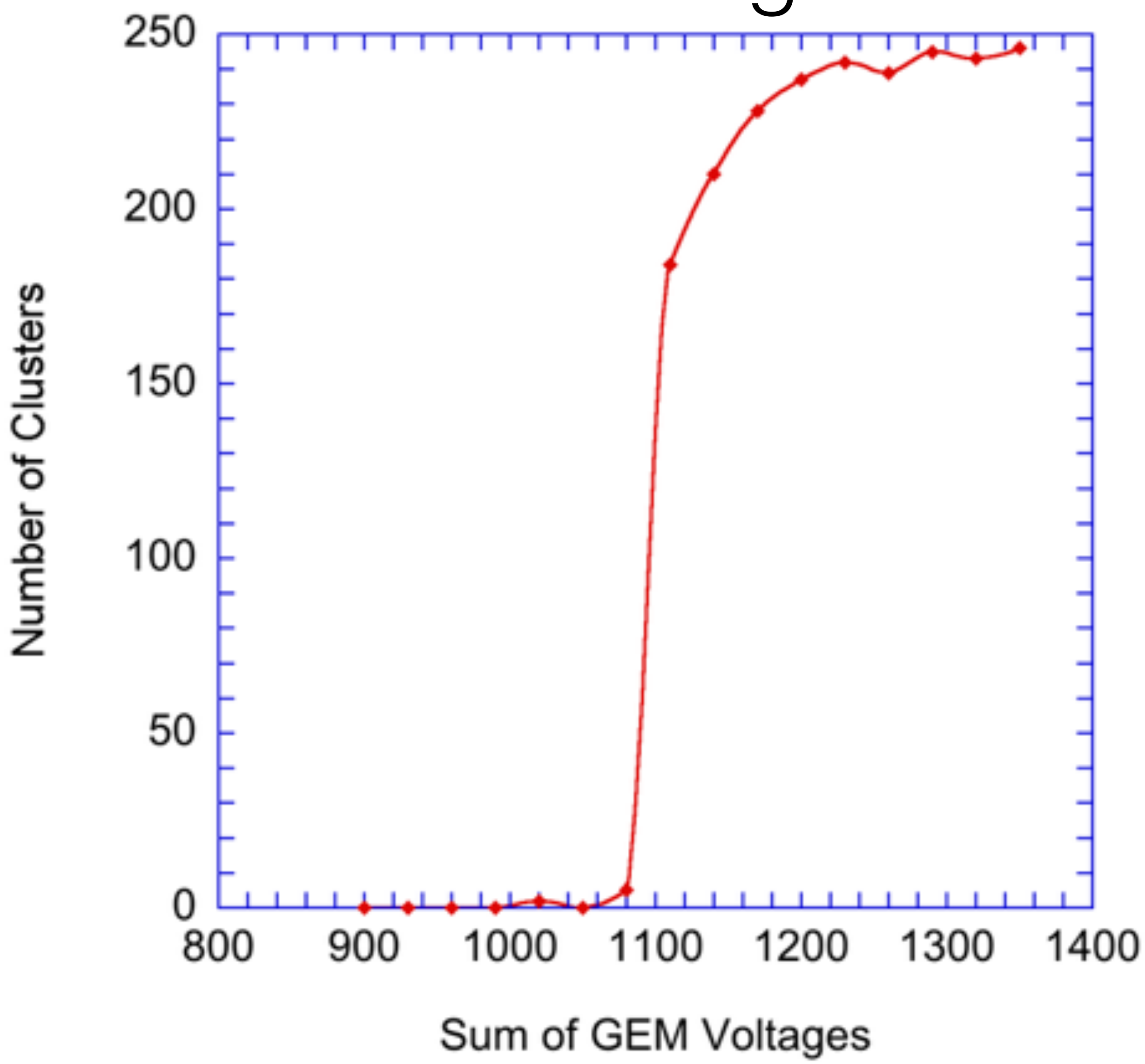


2.5×10^4 TOT
(9.6 Mhz)

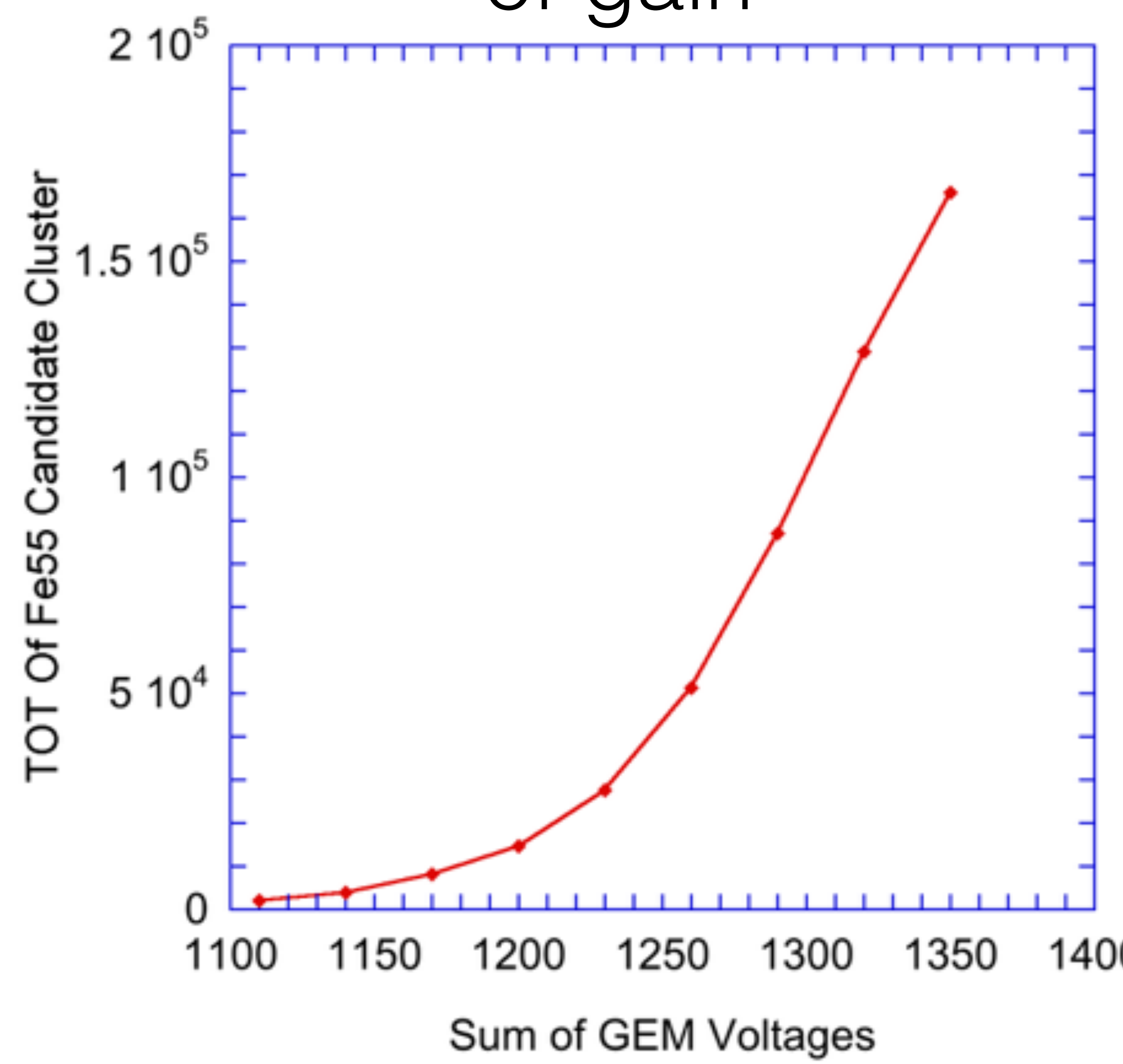
Gas Mix = Ar:CO_2CF_4 (45:15:40), Gain = 1350V = 2.10^4

Gain Scan with Fe55

Number of Clusters as a function of gain



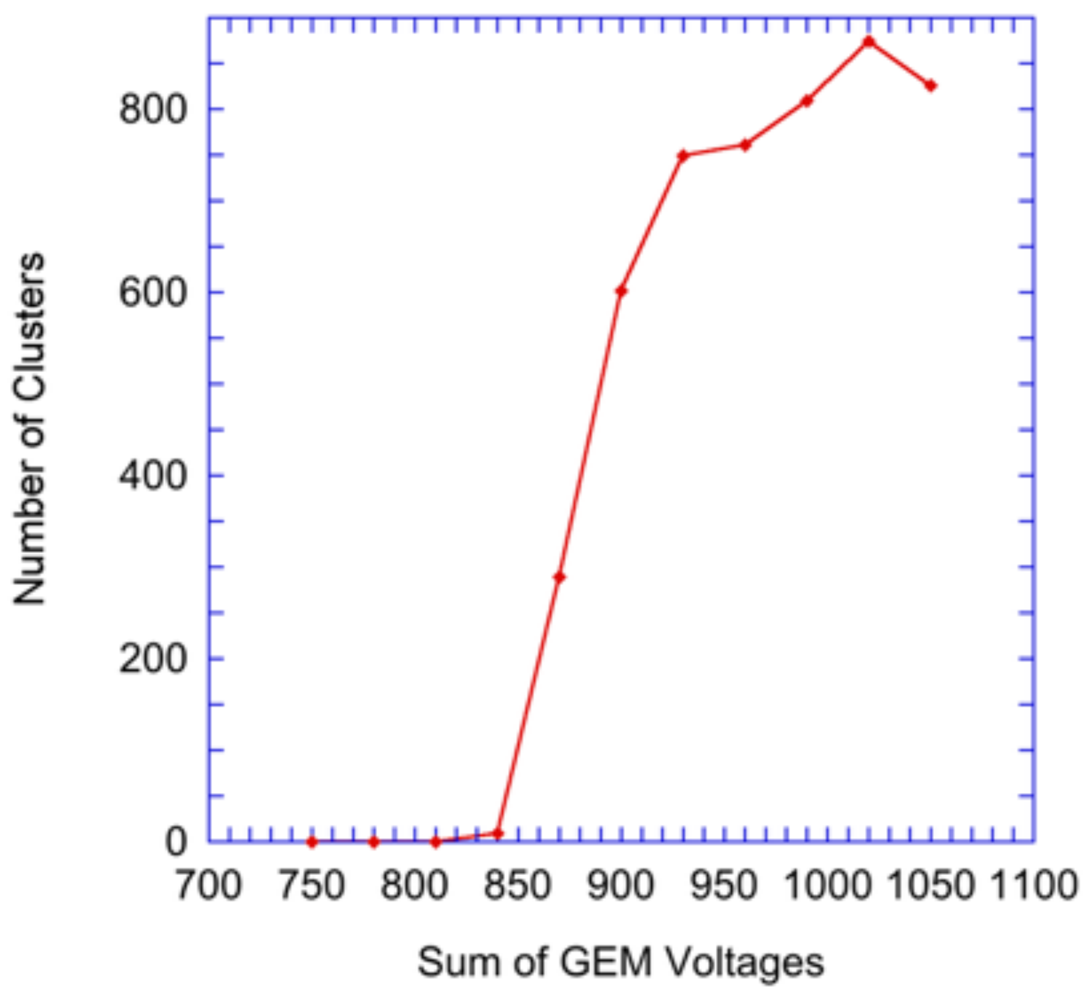
Cluster TOT as a function of gain



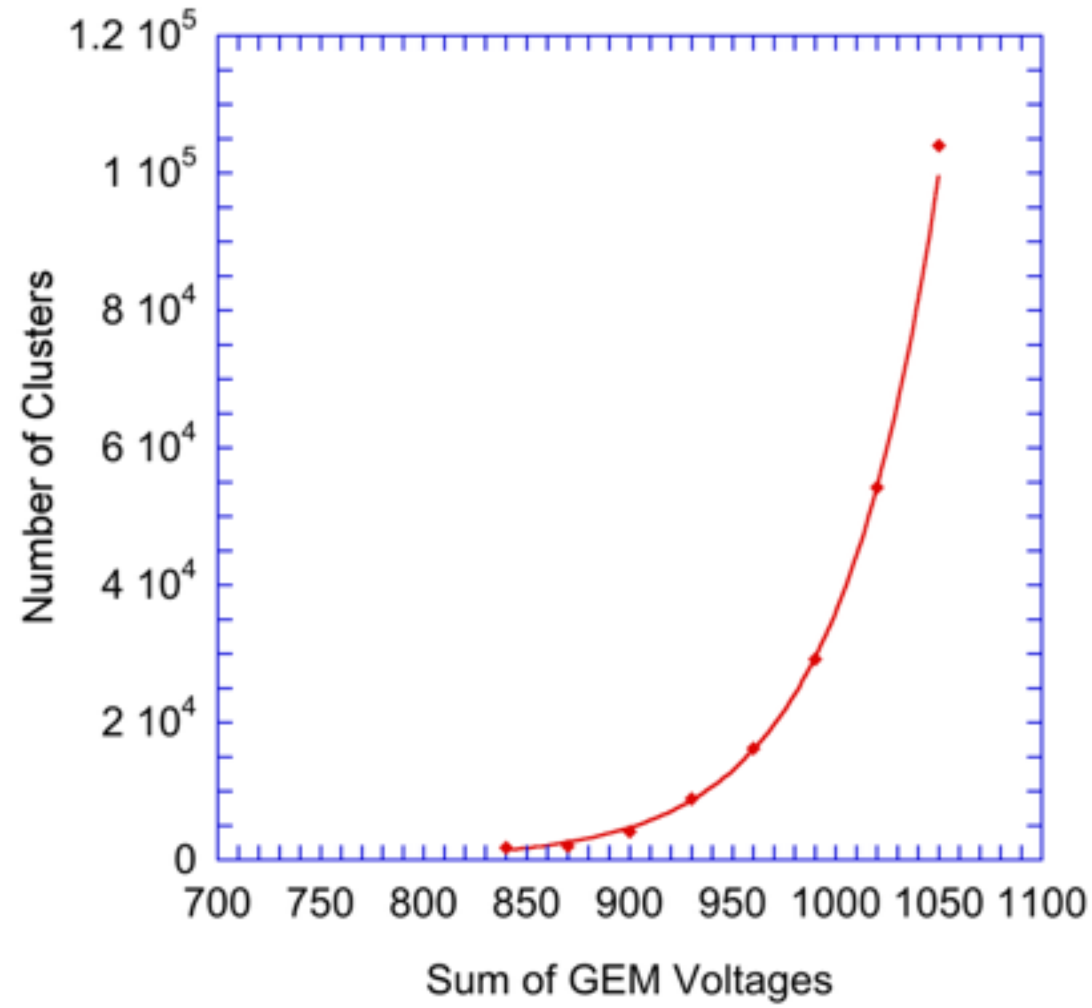
Working point at 1230 V

Alpha Particles (~6 MeV Am241)

Number of Clusters as a function of gain

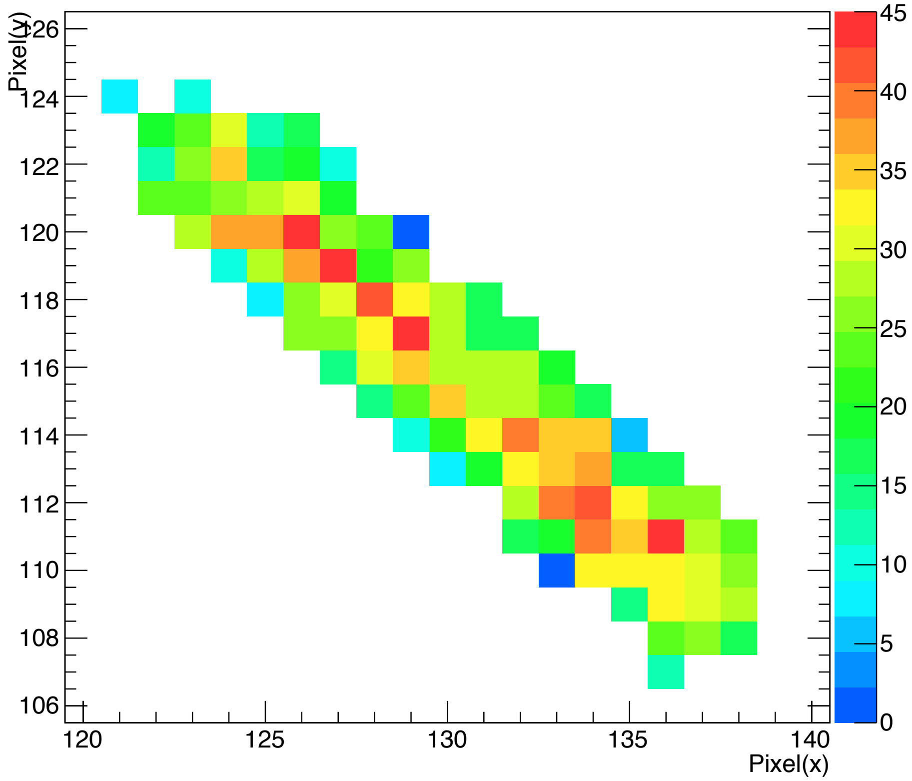


Cluster TOT as a function of gain



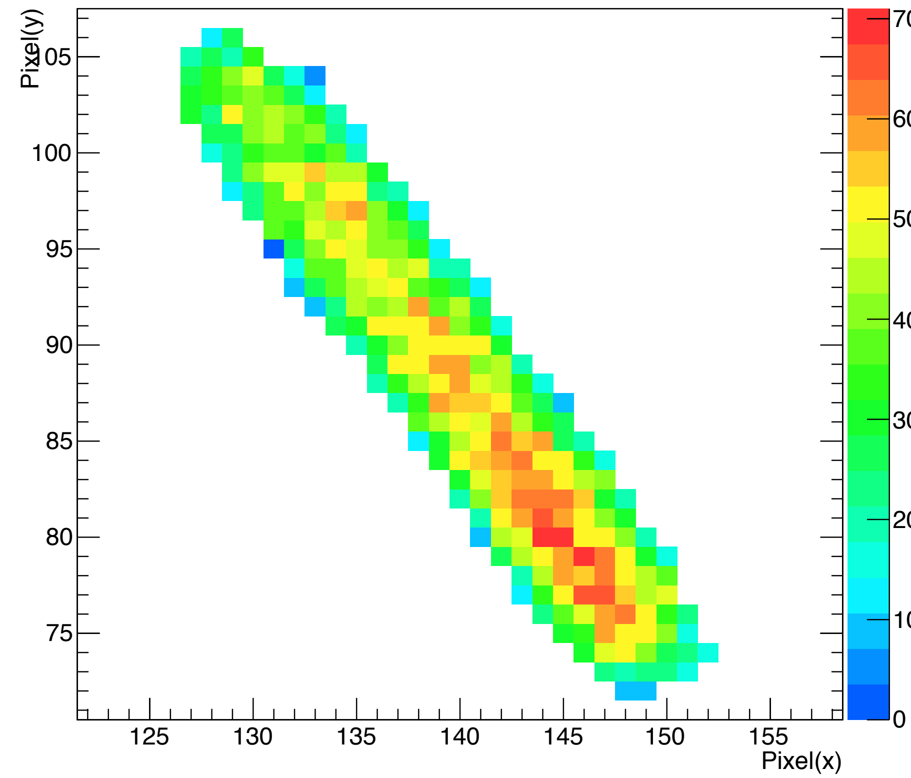
Working point at Gain ~950V, compare with 1230V for Fe55

870 V



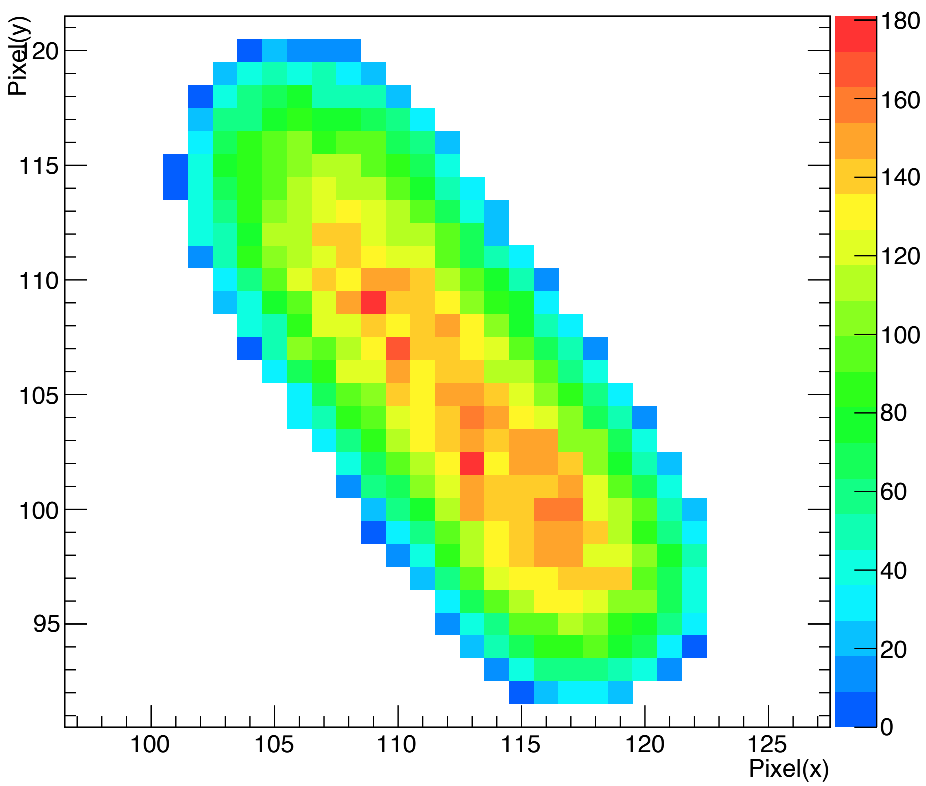
Length ~ 1 mm, vol ~70 px

930 V



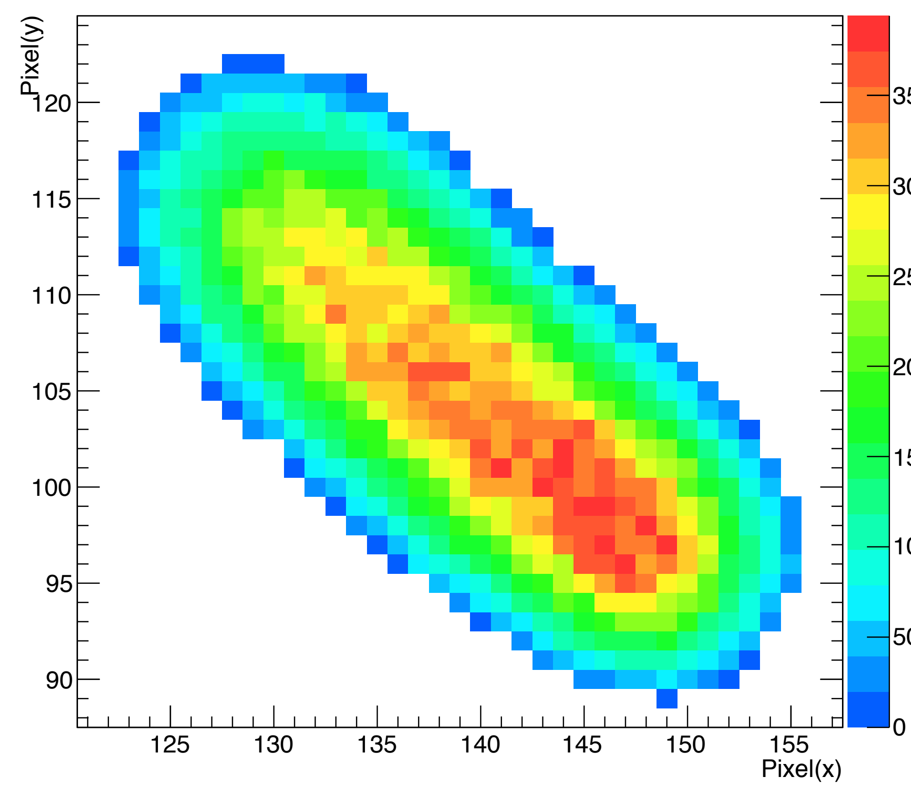
Length ~ 1.7 mm, vol ~200 px

990 V

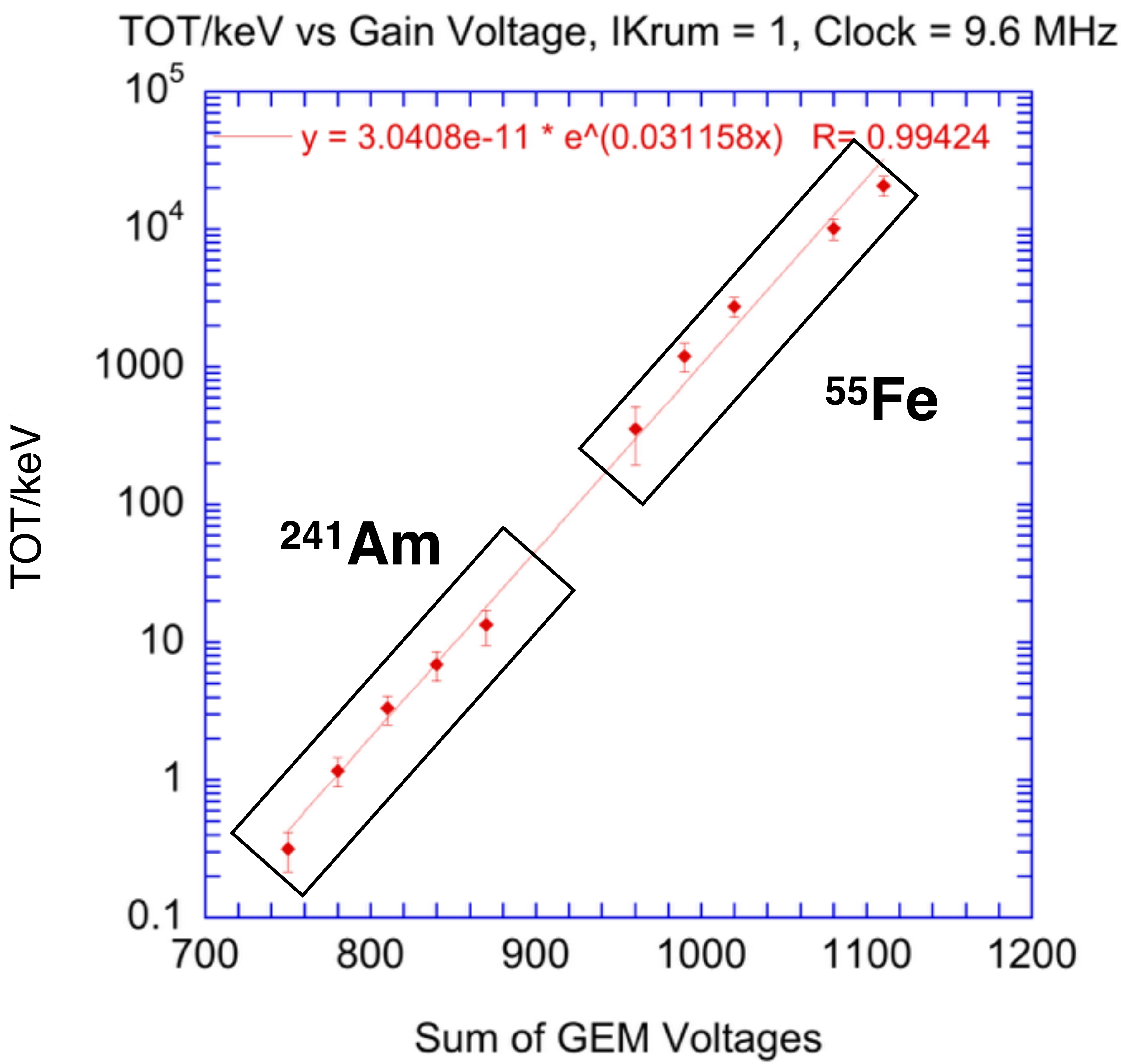


Length ~ 1.8 mm, vol ~350 px

1050 V

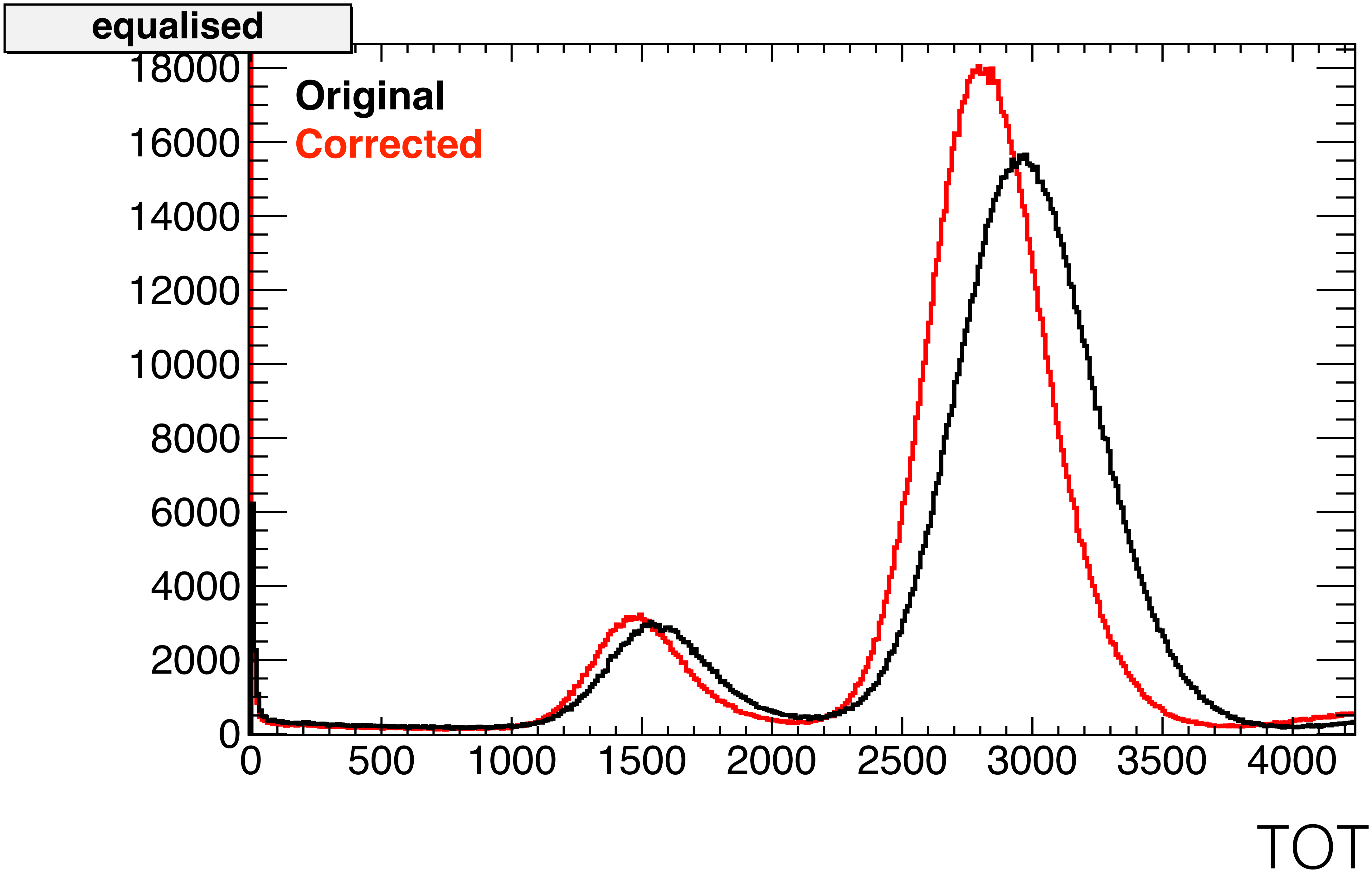


Length ~ 1.9 mm, vol ~600 px



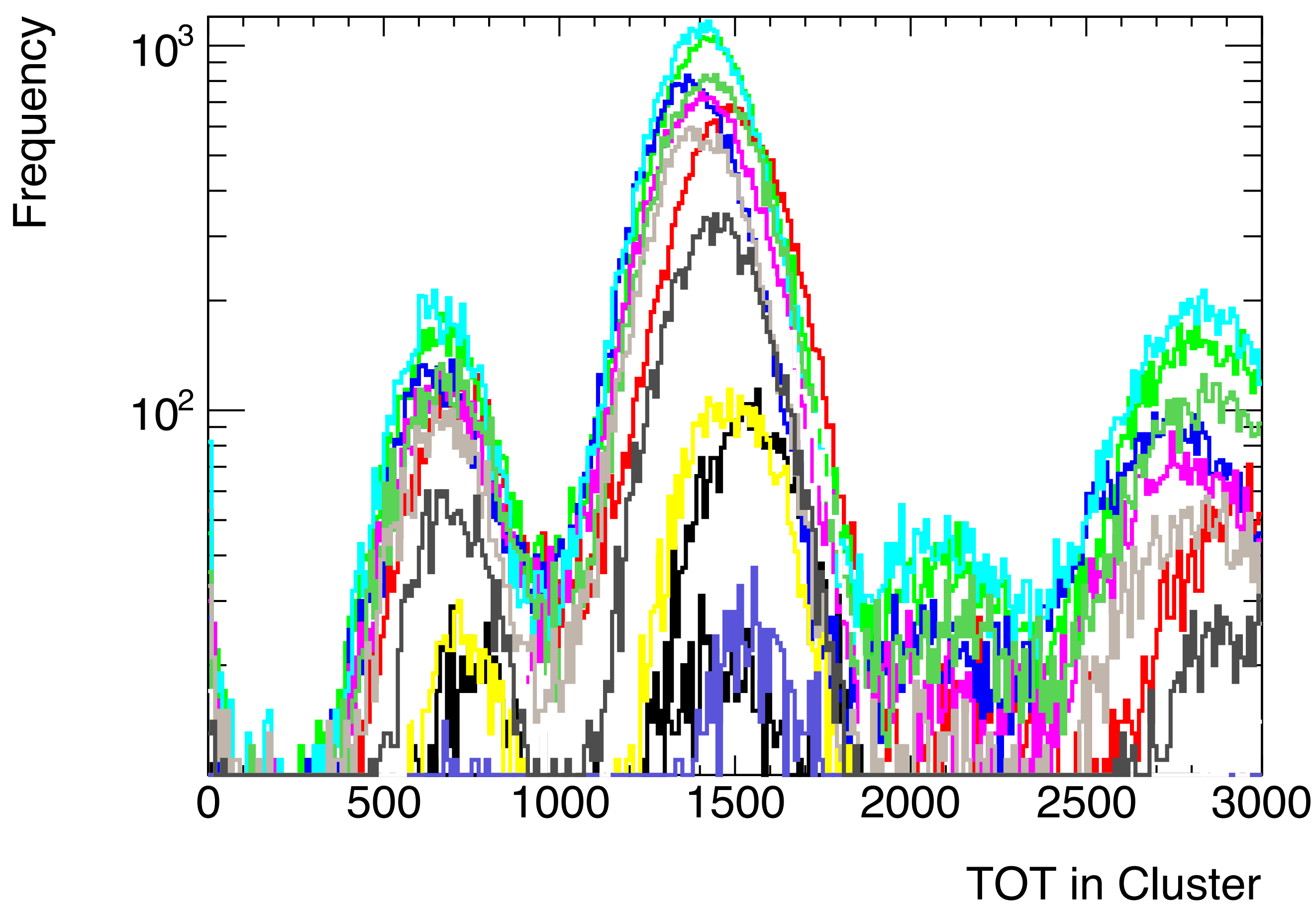
TOT/keV vs Gain Voltage, IKrum = 1, Clock = 9.6 MHz
y = 3.0408e-11 * e^(0.031158x) R= 0.99424
55Fe
241Am
TOT/keV
Sum of GEM Voltages

Spectra - ^{55}Fe (5.9 keV)

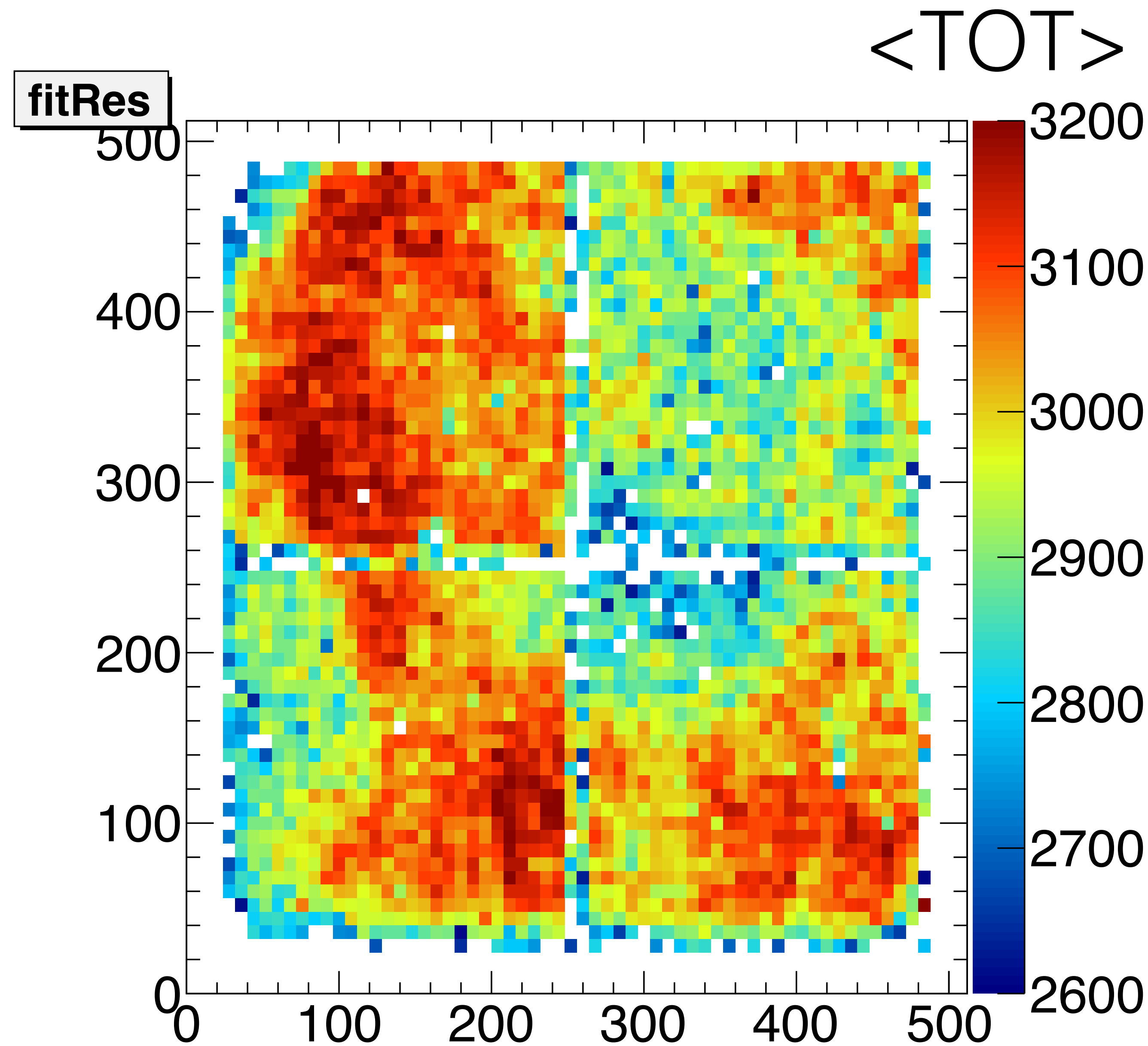


18.3% Energy Resolution on the corrected Fe Peak

Typical Frame - ^{55}Fe (5.9 keV)



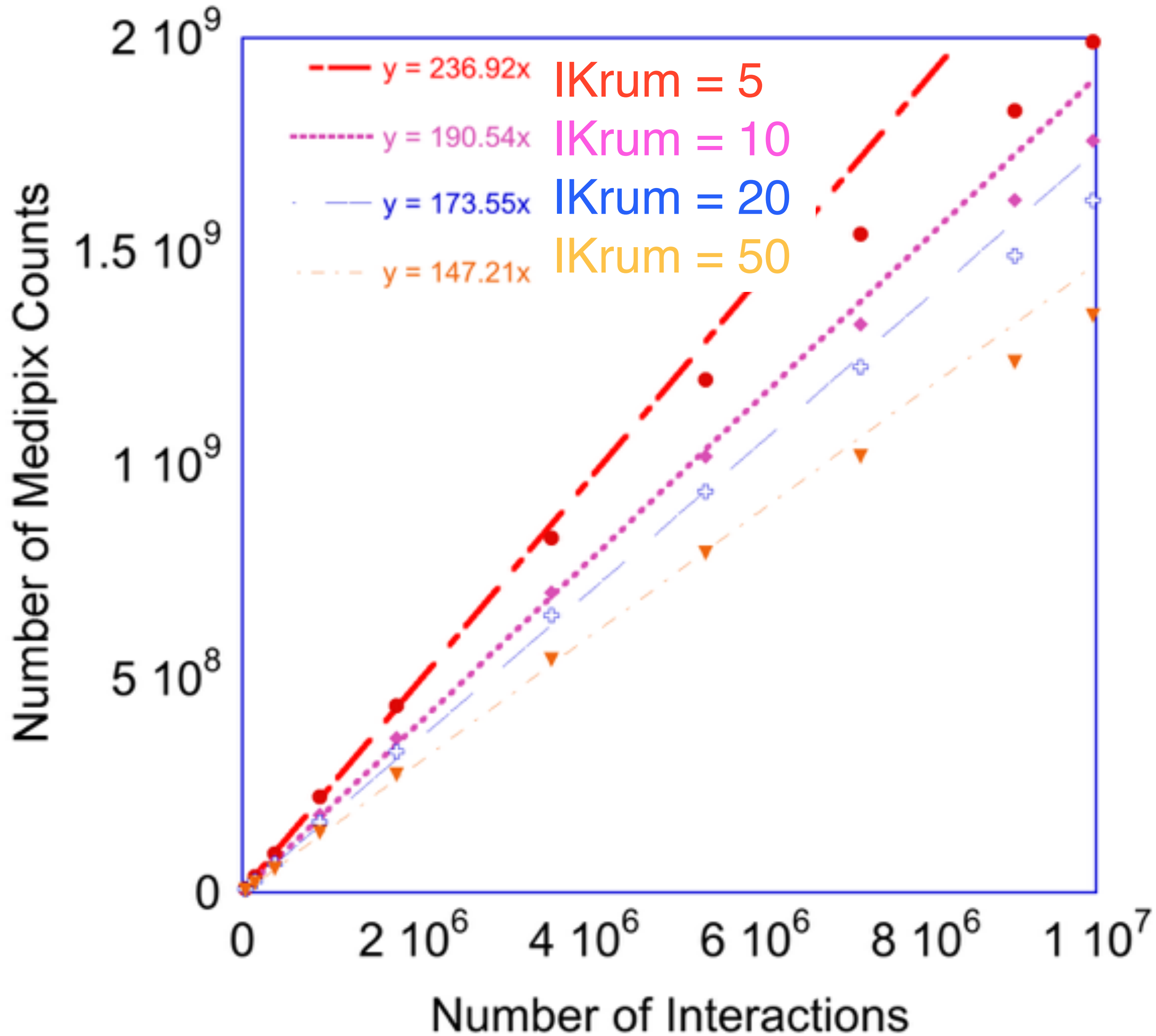
Response of 8x8 pixel regions



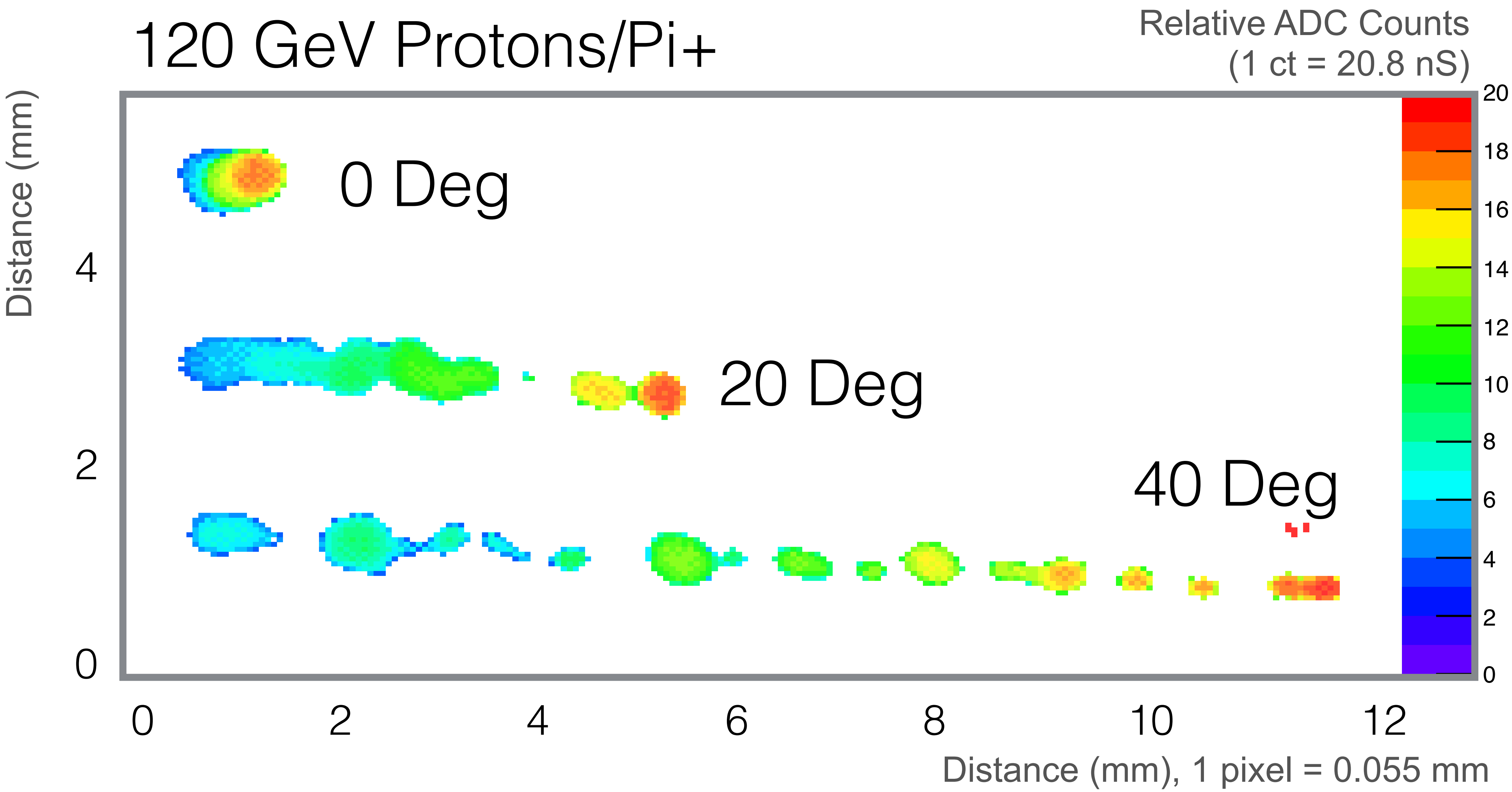
Mapped average response from gaussian fit

Maximum Count Rate (Xray tube, 40 kVp)

- Single interaction defined with clusterable data
- Maximum count rate ~10^7/s (10^6/cm^2/s)
- Some room for optimisation by changing asic settings (factor 2 variation)
- Possibly an effect of the relatively high gain needed to readout the Timepix?



Particle tracking (CERN SPS MIP's) - TOA Mode

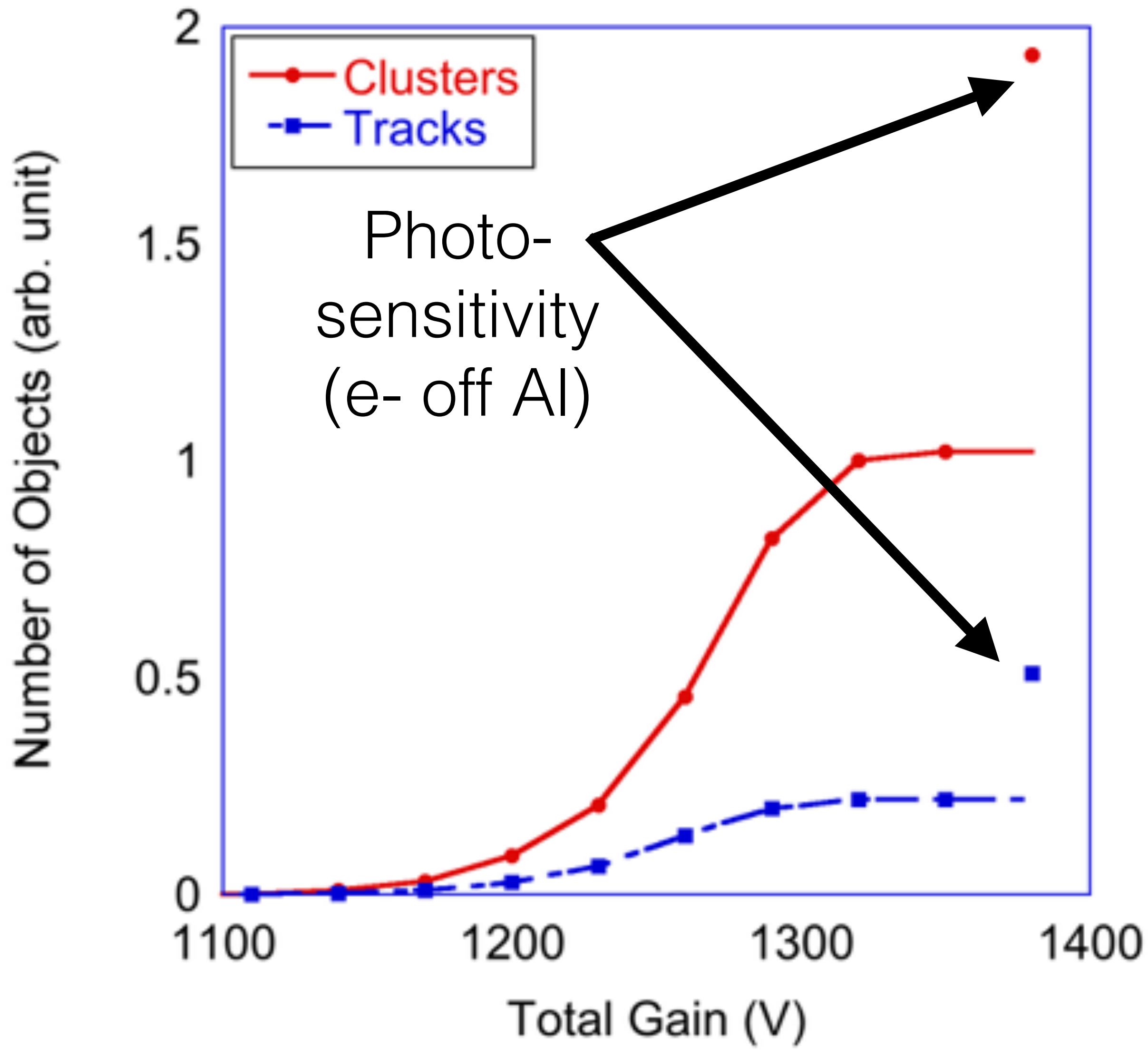


Total dT ~ 400 nS

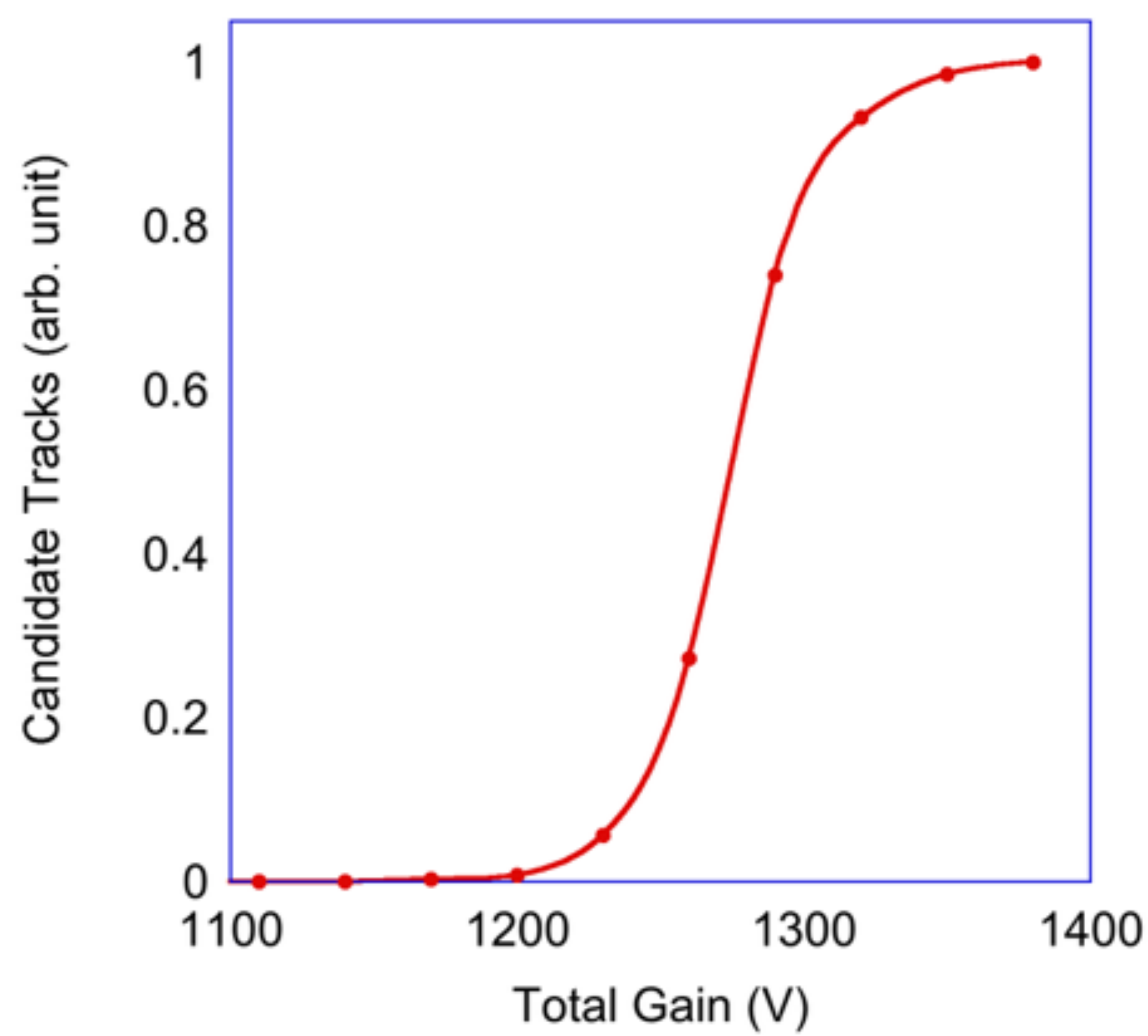
The main limitation of this mode is the maximum frame length, = 248 uS. This leads to a very large dead time

Effect of Chamber Gain

Everything

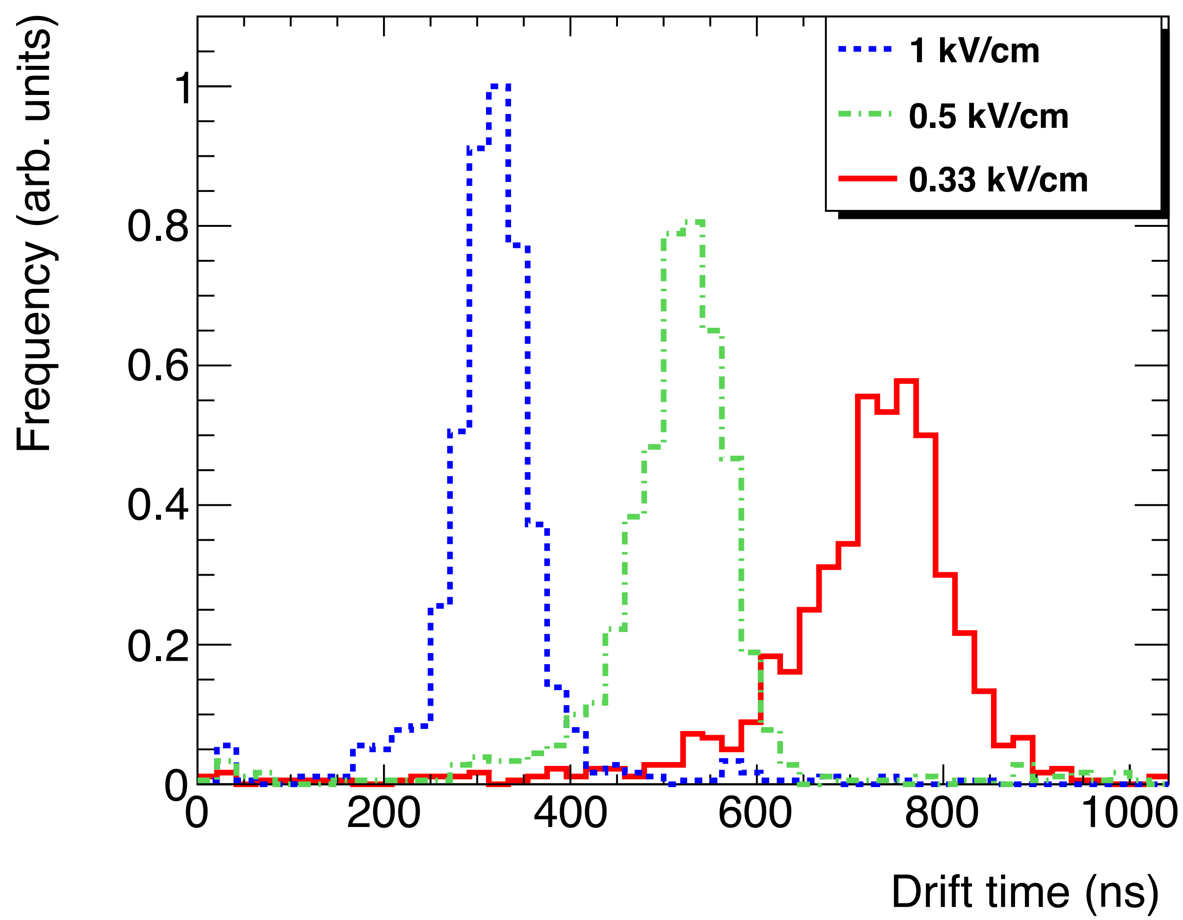


Candidate Tracks (>100px)

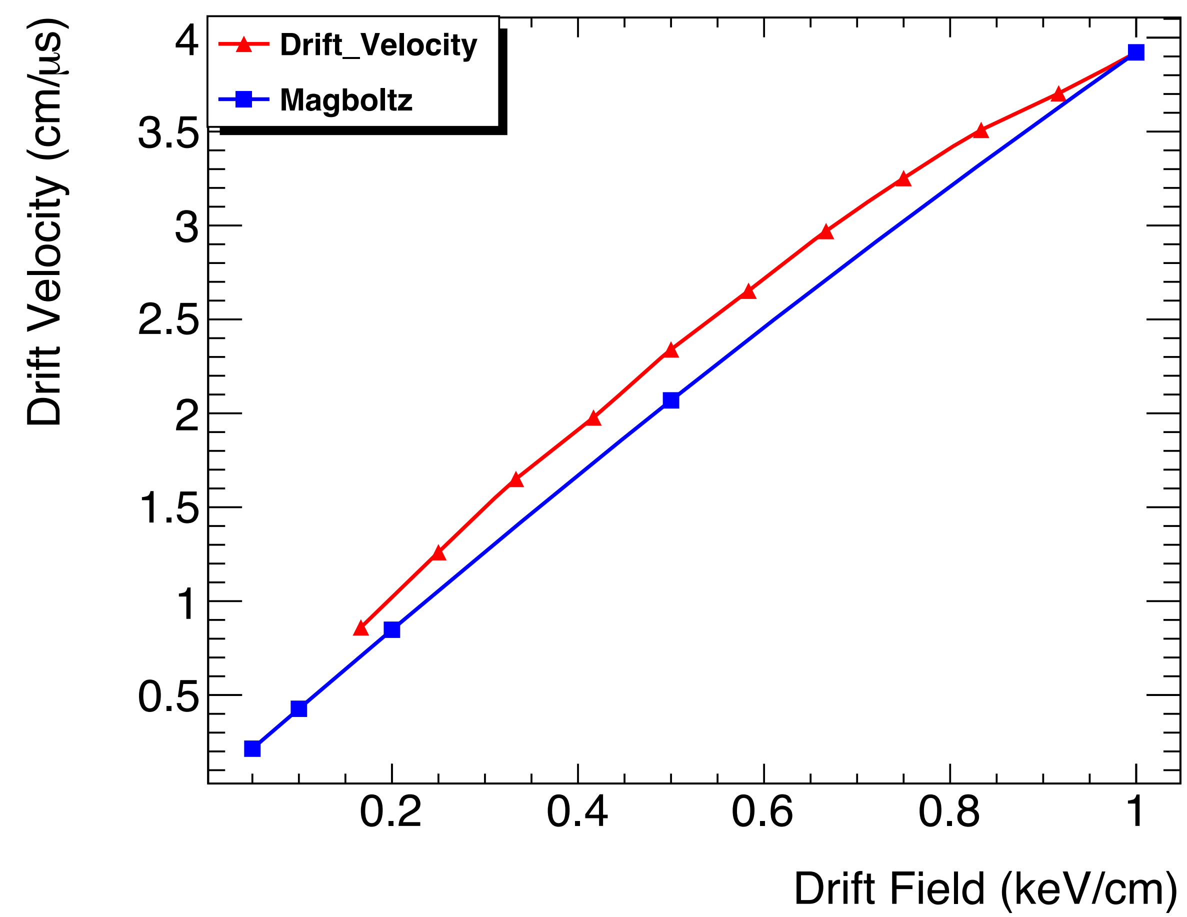


Measurement of Drift Velocity (vary drift field)

Track top/bottom delta times (morphological operator for time walk correction)

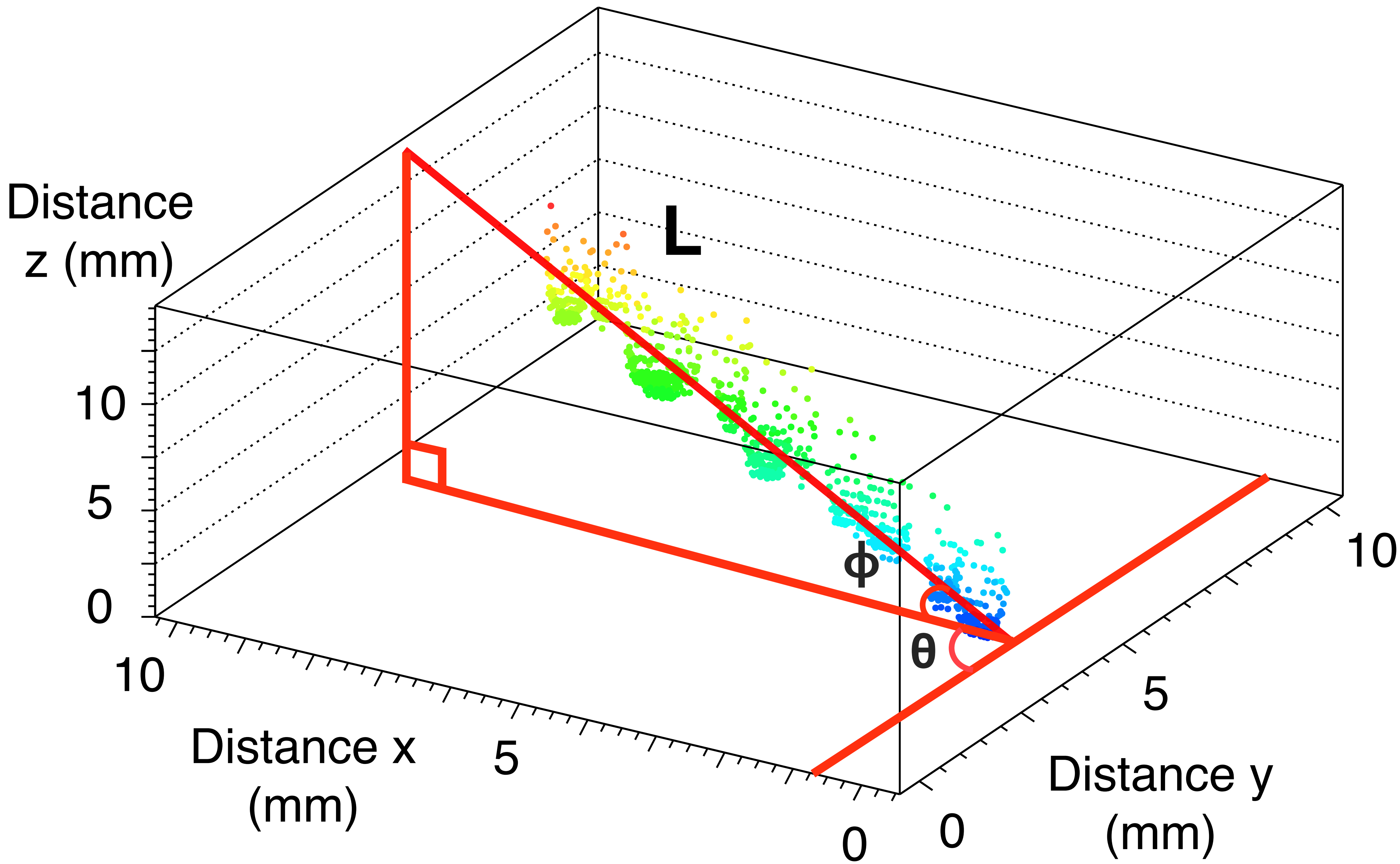


Drift Velocity (mean from gaussian fit of curves on left)

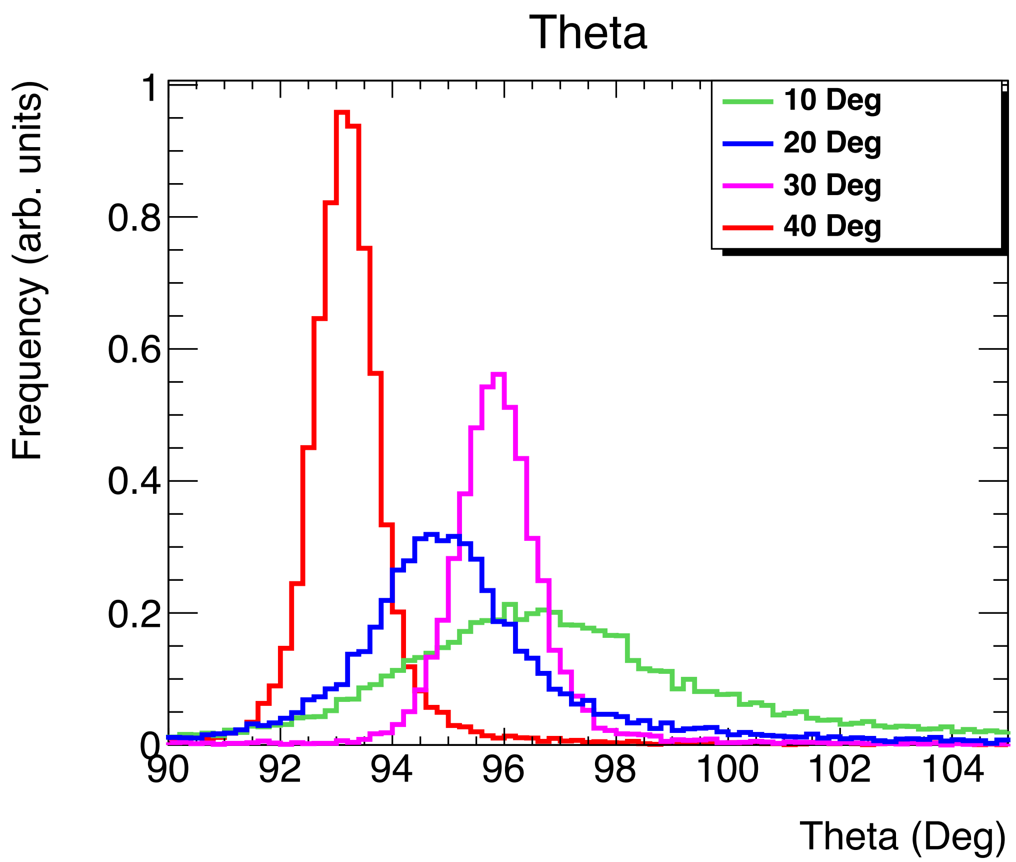


Track Reconstruction

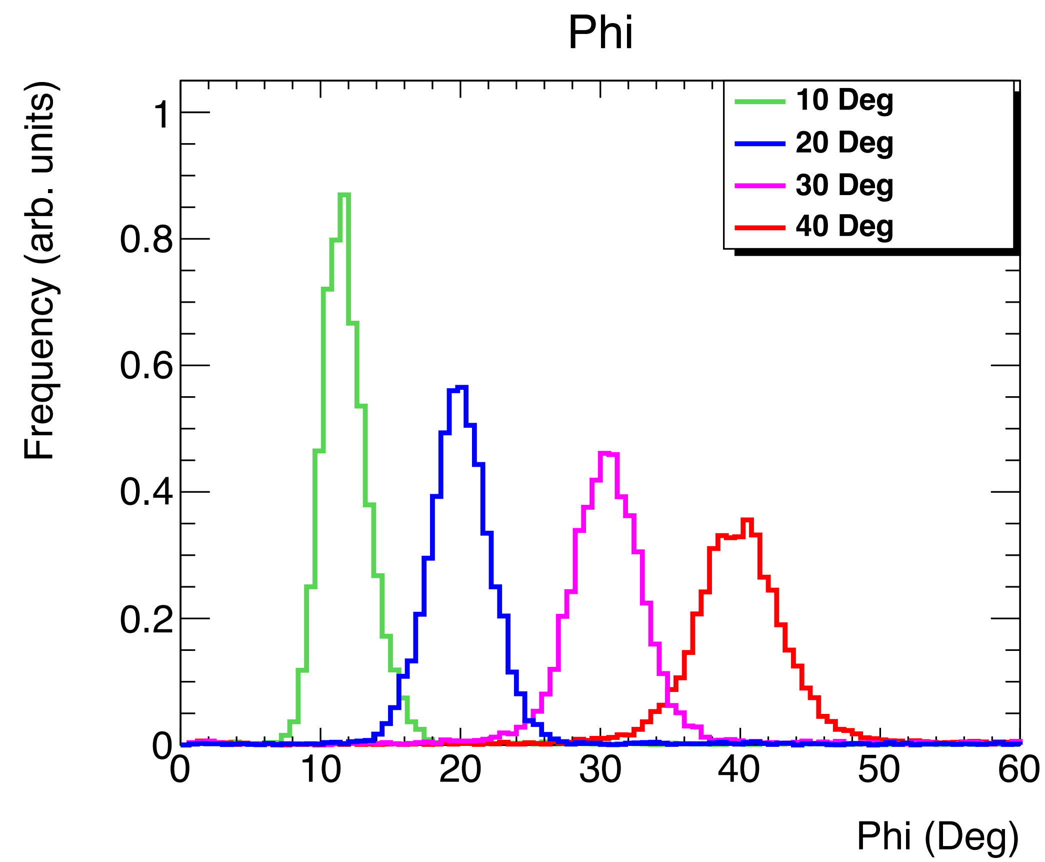
3D Least Squares Fit of 3 GeV MIP Track Incident at 30 Degrees



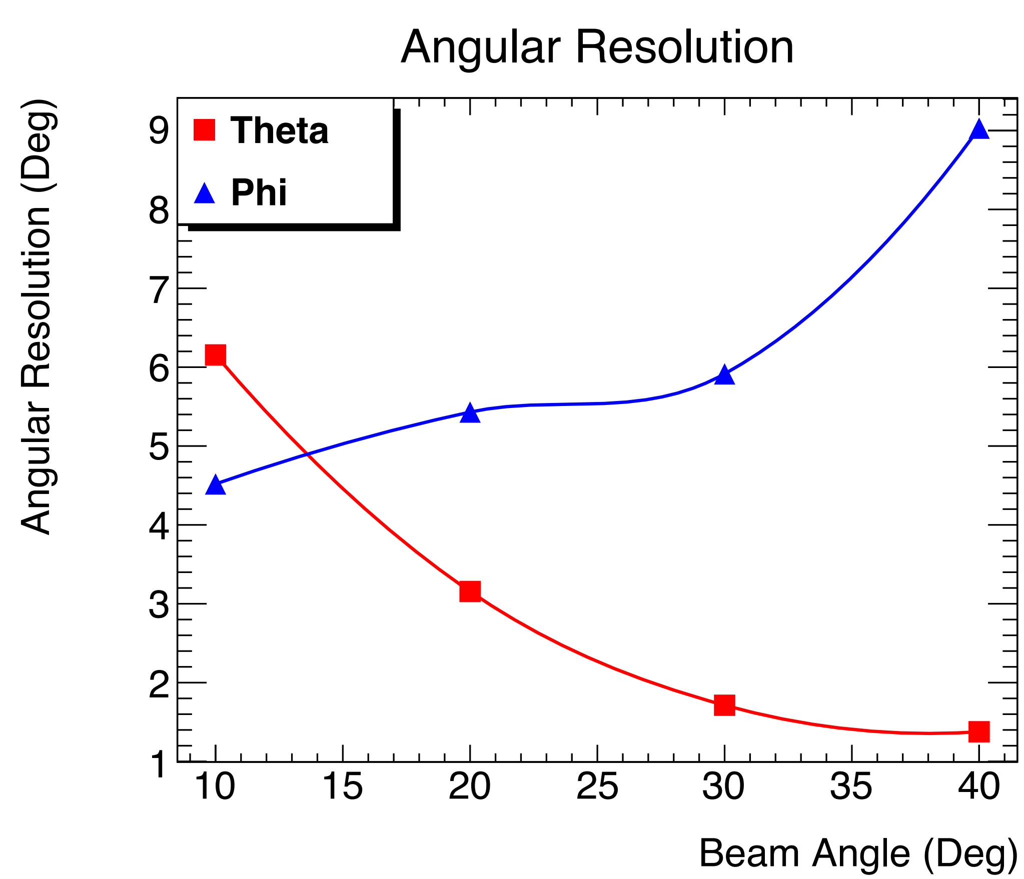
Illustrative (1/16 pixels drawn)


Theta
10 Deg
20 Deg
30 Deg
40 Deg
Frequency (arb. units)
0
0.2
0.4
0.6
0.8
1
90
92
94
96
98
100
102
104
Theta (Deg)

(a)

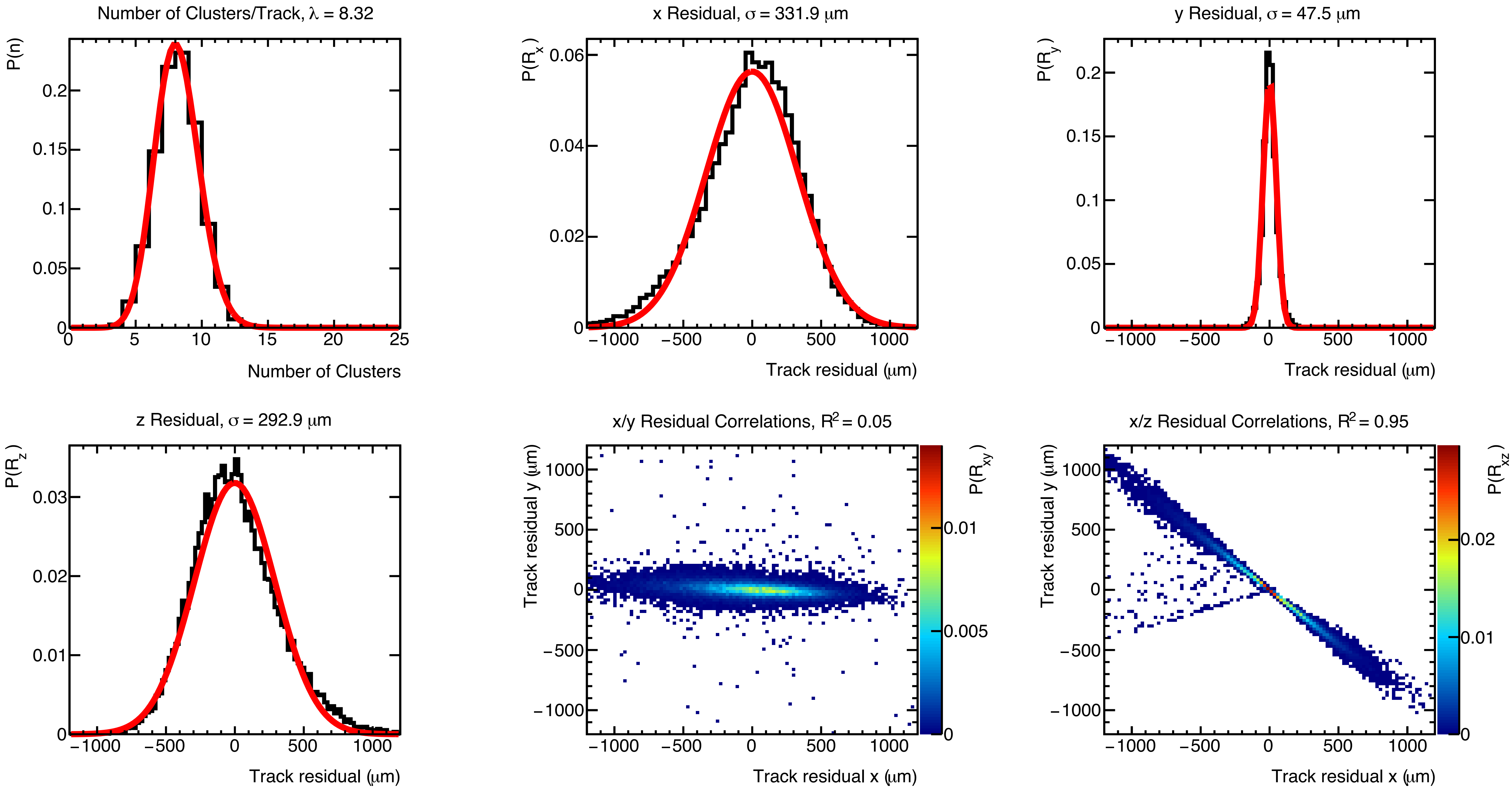

Phi
10 Deg
20 Deg
30 Deg
40 Deg
Frequency (arb. units)
0
0.2
0.4
0.6
0.8
1
0
10
20
30
40
50
60
Phi (Deg)

(b)


Angular Resolution
Theta
Phi
Angular Resolution (Deg)
1
2
3
4
5
6
7
8
9
10
15
20
25
30
35
40
Beam Angle (Deg)

(c)

Spatial Resolution

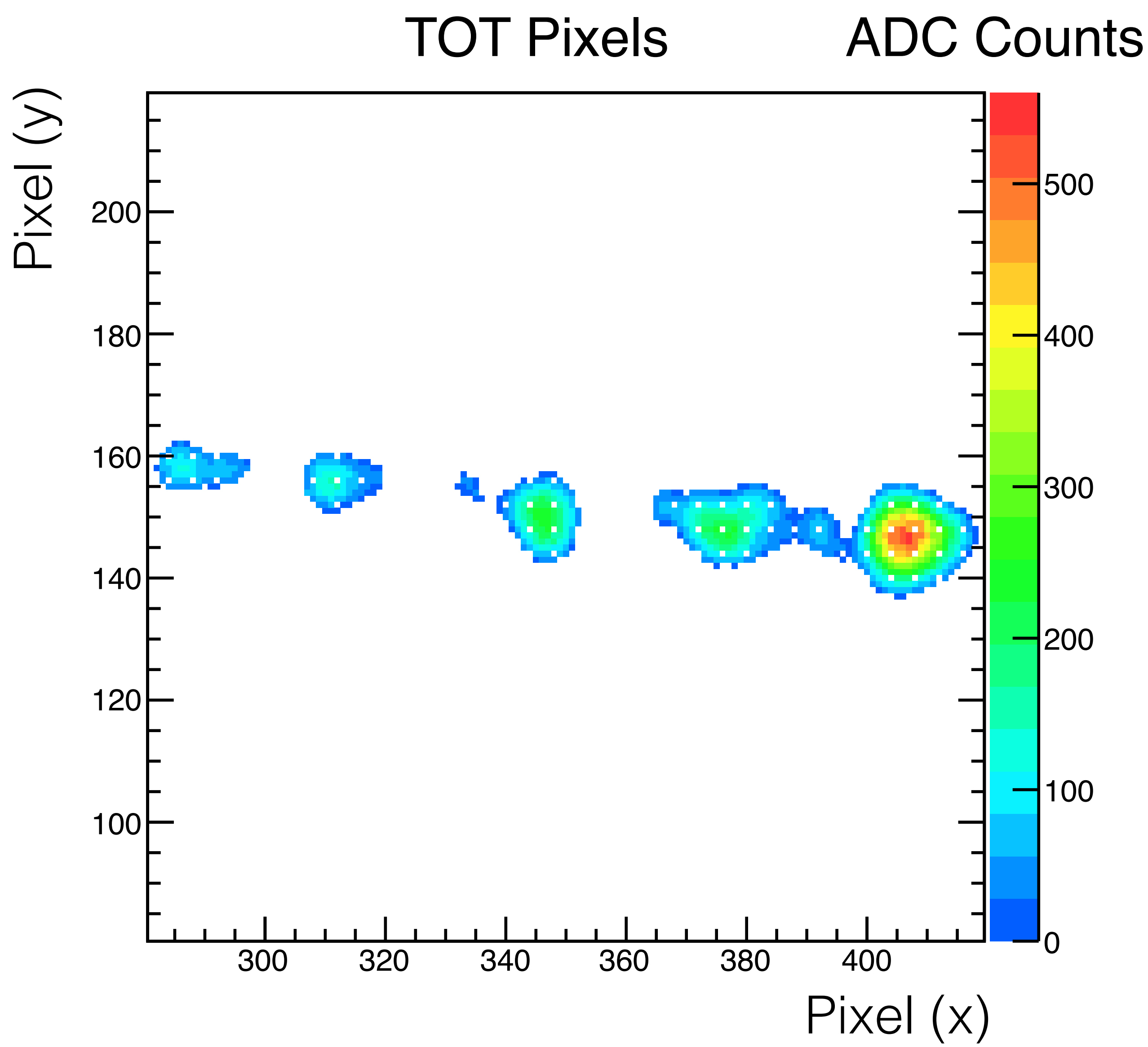


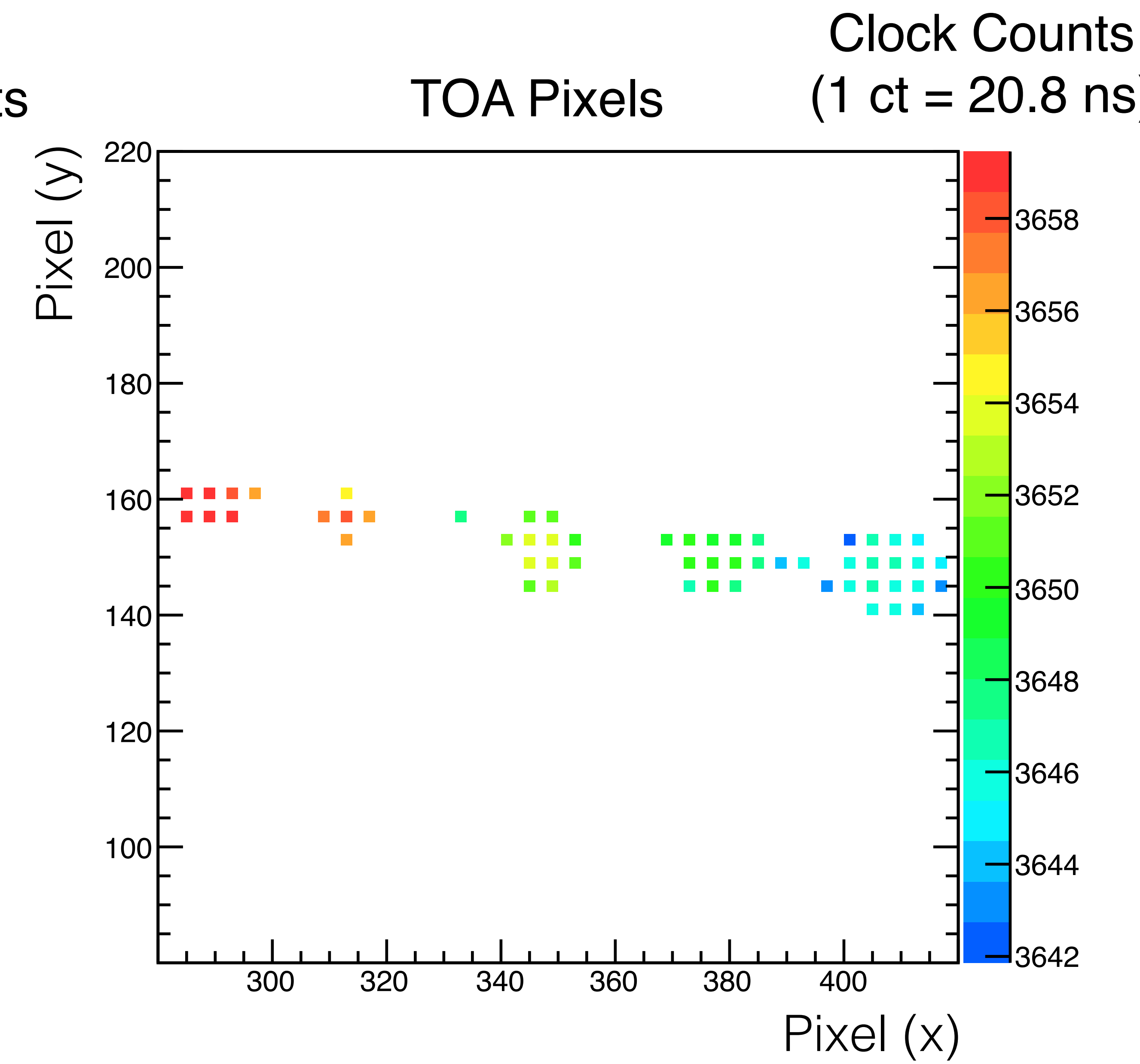
$R = 170\,\mu\mathrm{m}$

$R_{px} = 17\,\mu\mathrm{m}$

(mostly because the time resolution is poorer than the spatial resolution)

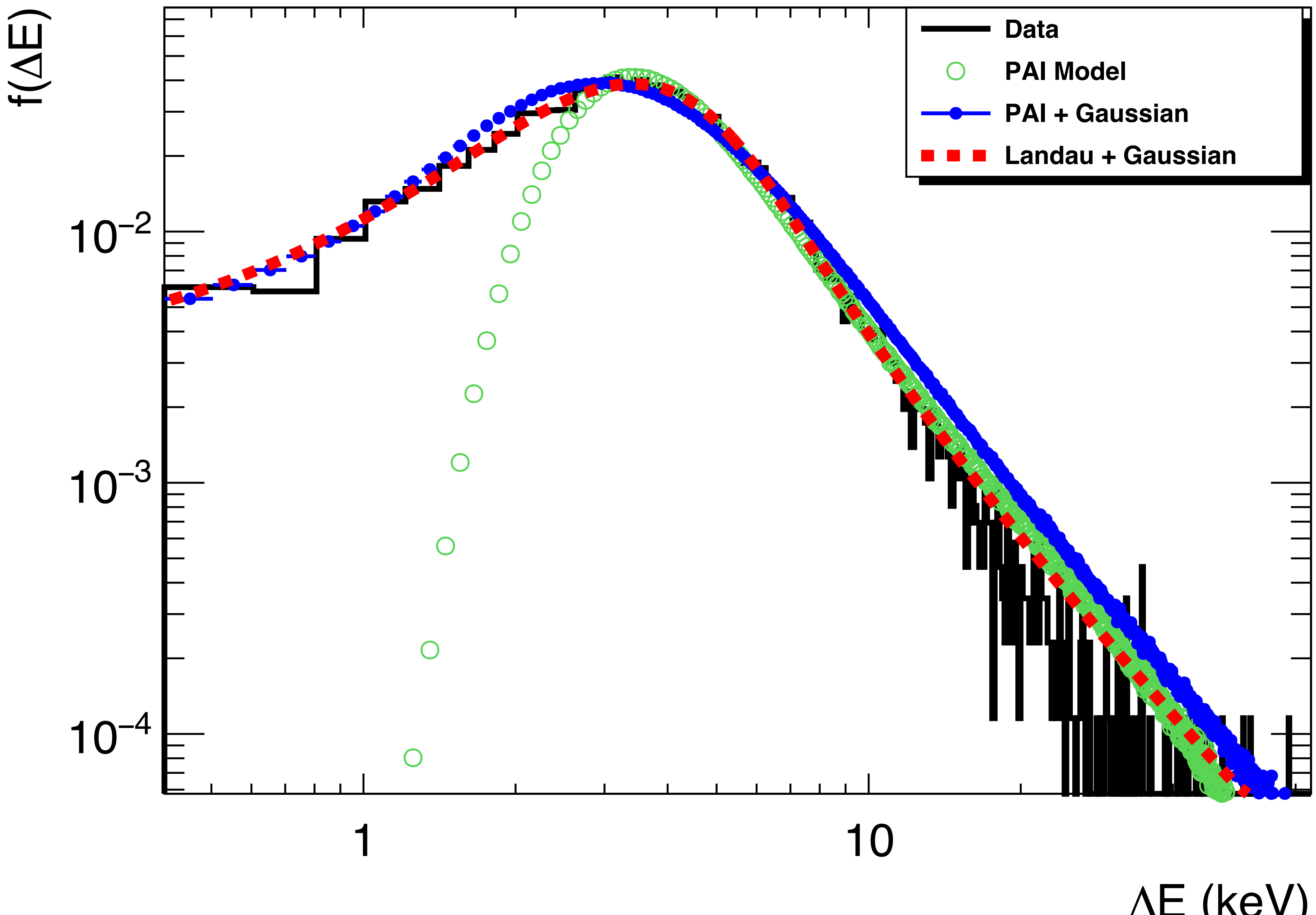
Mixed Mode Operation





Note, TOA pixels are doubled in lateral size for visual effect

Gempix Energy Deposition Spectrum

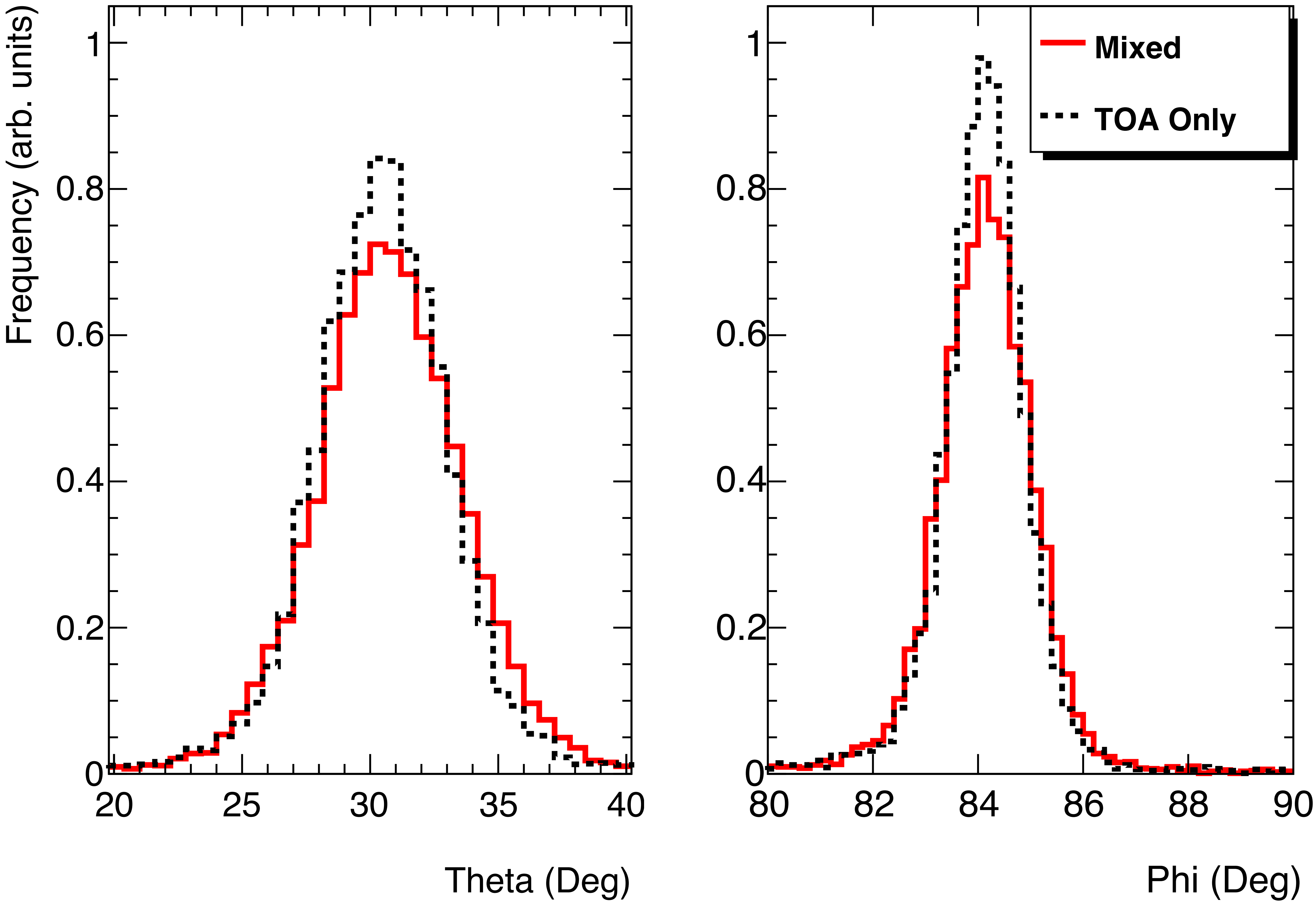


PAI -> Geant4 PAI model, range cut = 0.1 mm, mono energetic 3 GeV 2/3 proton, 1/3 pi+ pencil beam on 24 mm $ArCO_2CF_4$

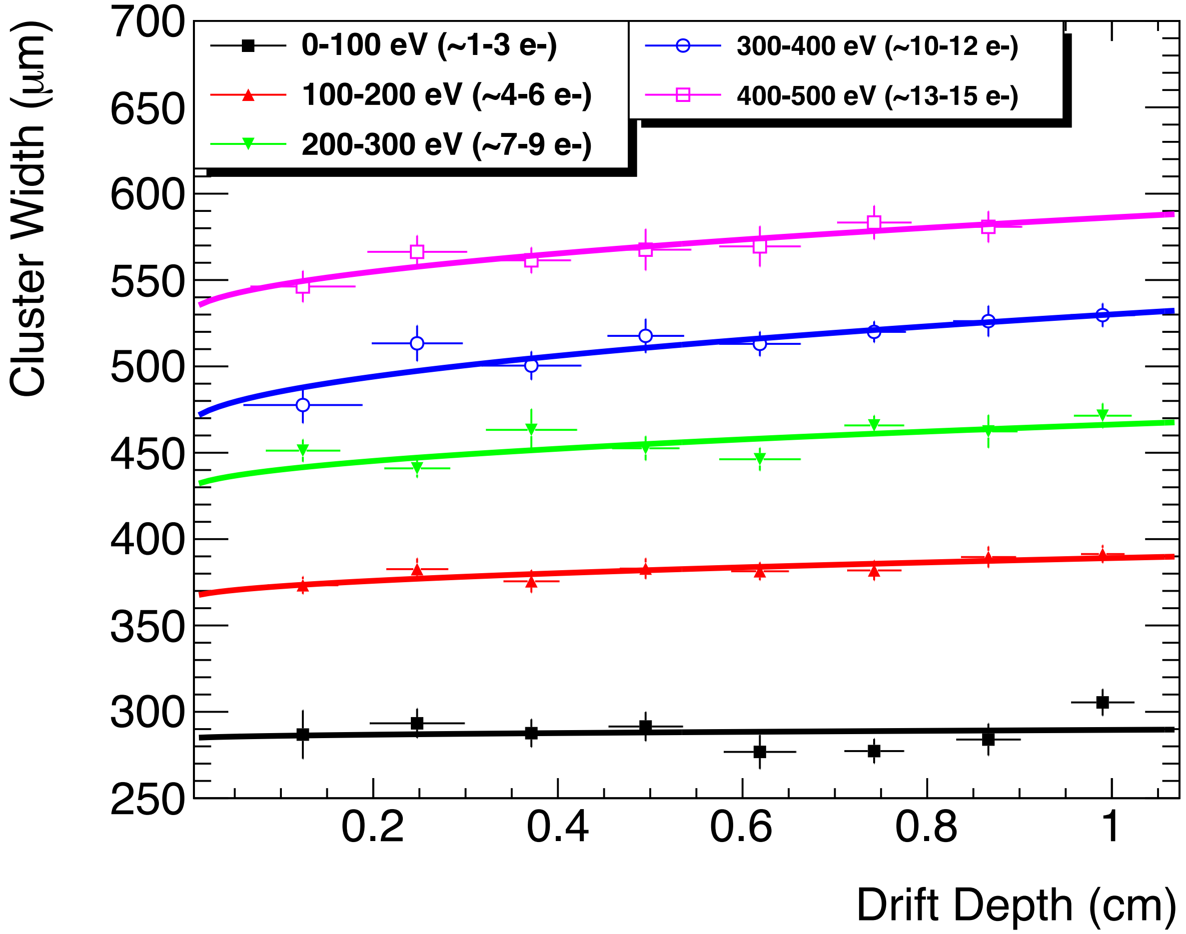
Gaussian + PAI -> Smearing following: $\sigma = A\sqrt{\Delta E(\mathrm{keV})}$

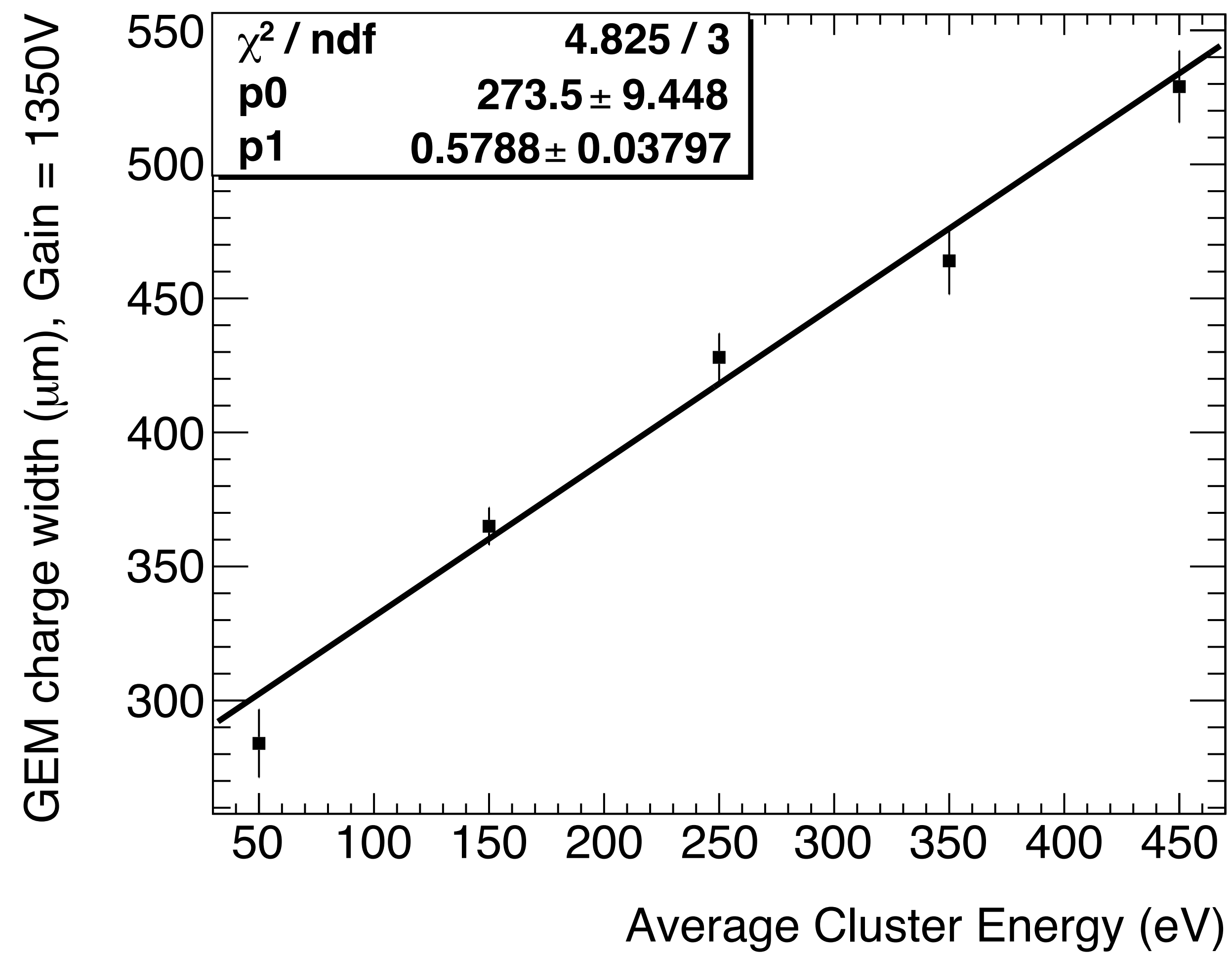
[1] J. Apostolakis et al, *"An implementation of ionisation energy loss in very thin absorbers for the GEANT4 simulation package"*, NIM A, Volume 453, Issue 3, 21 October 2000, Pages 597–605

Angular Reconstruction - Mixed vs TOA



Avalanche Statistics





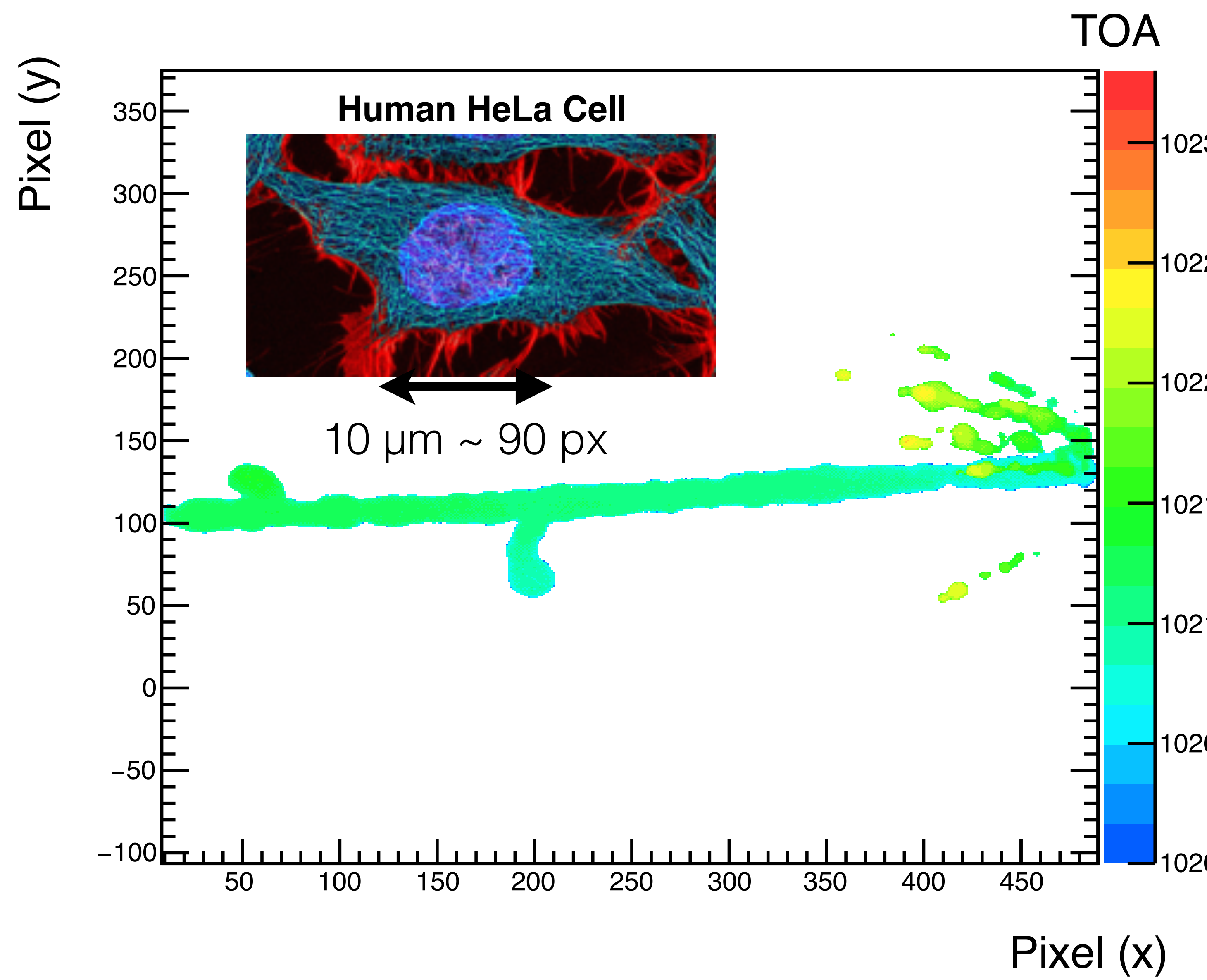
Fit with $y = a + \sqrt{bx}$

B factors not constant - threshold effects?

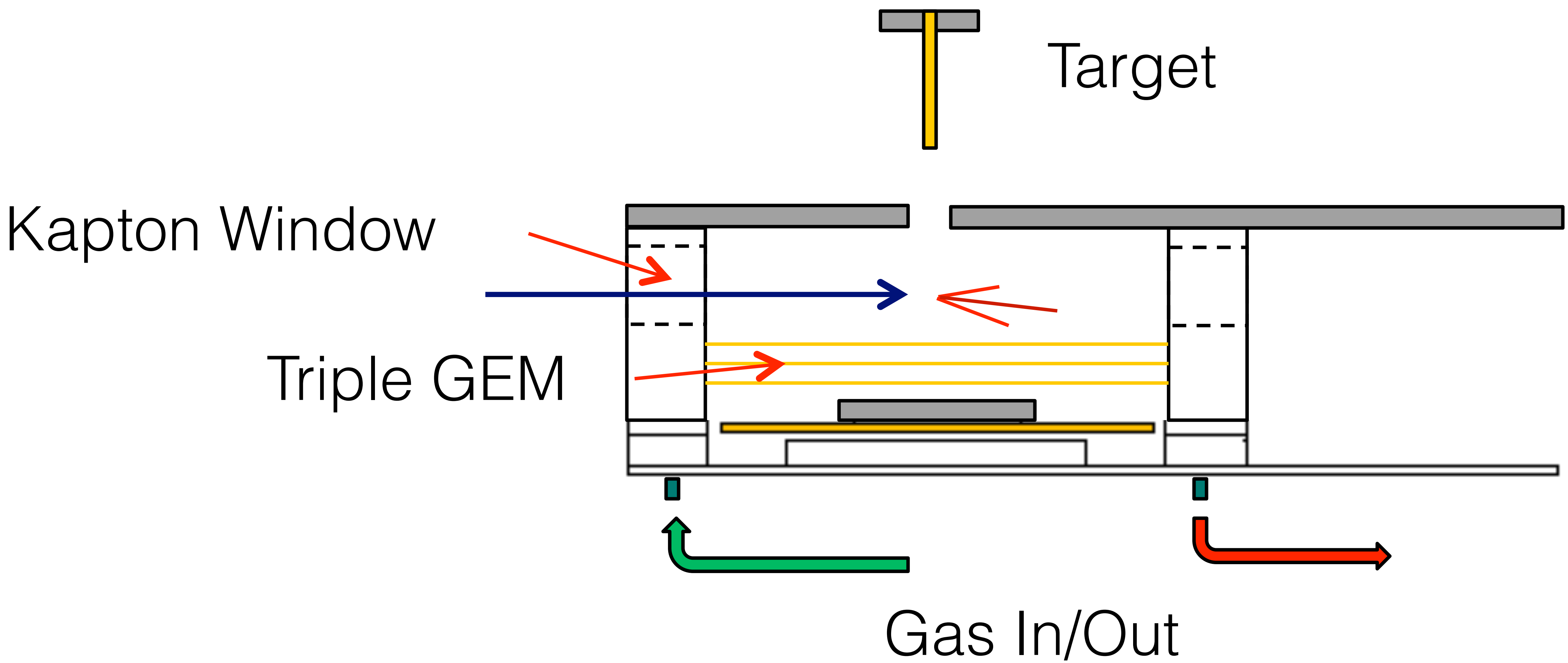
Plot of intercept parameter from left (charge cloud width 'just' from GEM structure)

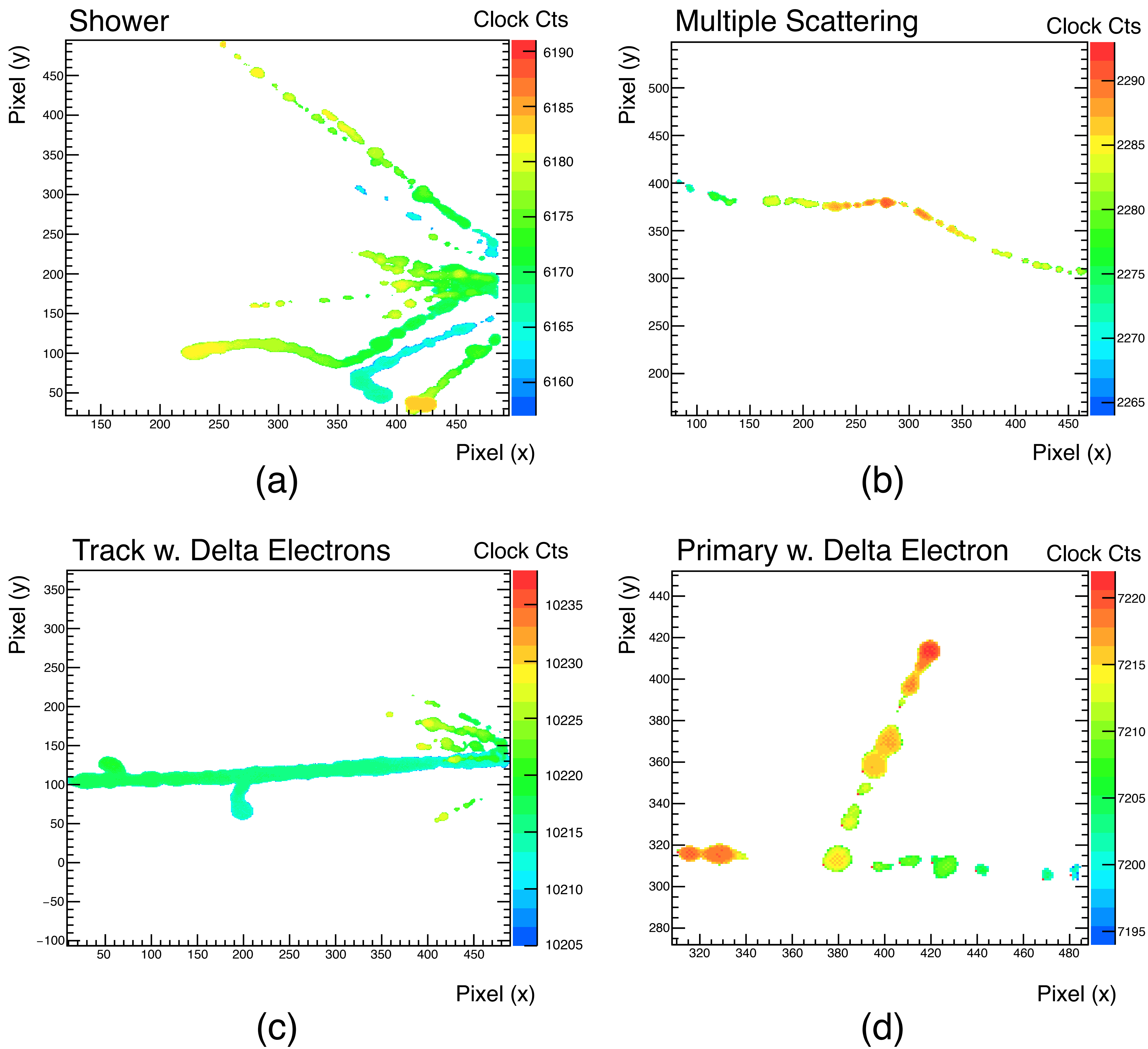
An Application - Microdosimetery

- The study of radiation interactions at the scale of cellular structure
- The number of atoms in a 5 mm path in gas is about the same as in a cellular nucleus
- Typical instrumentation is a single low pressure gas volume or silicon volume
- Gas pixel detectors offer the ability to examine each track individually



Towards Microdosimitery

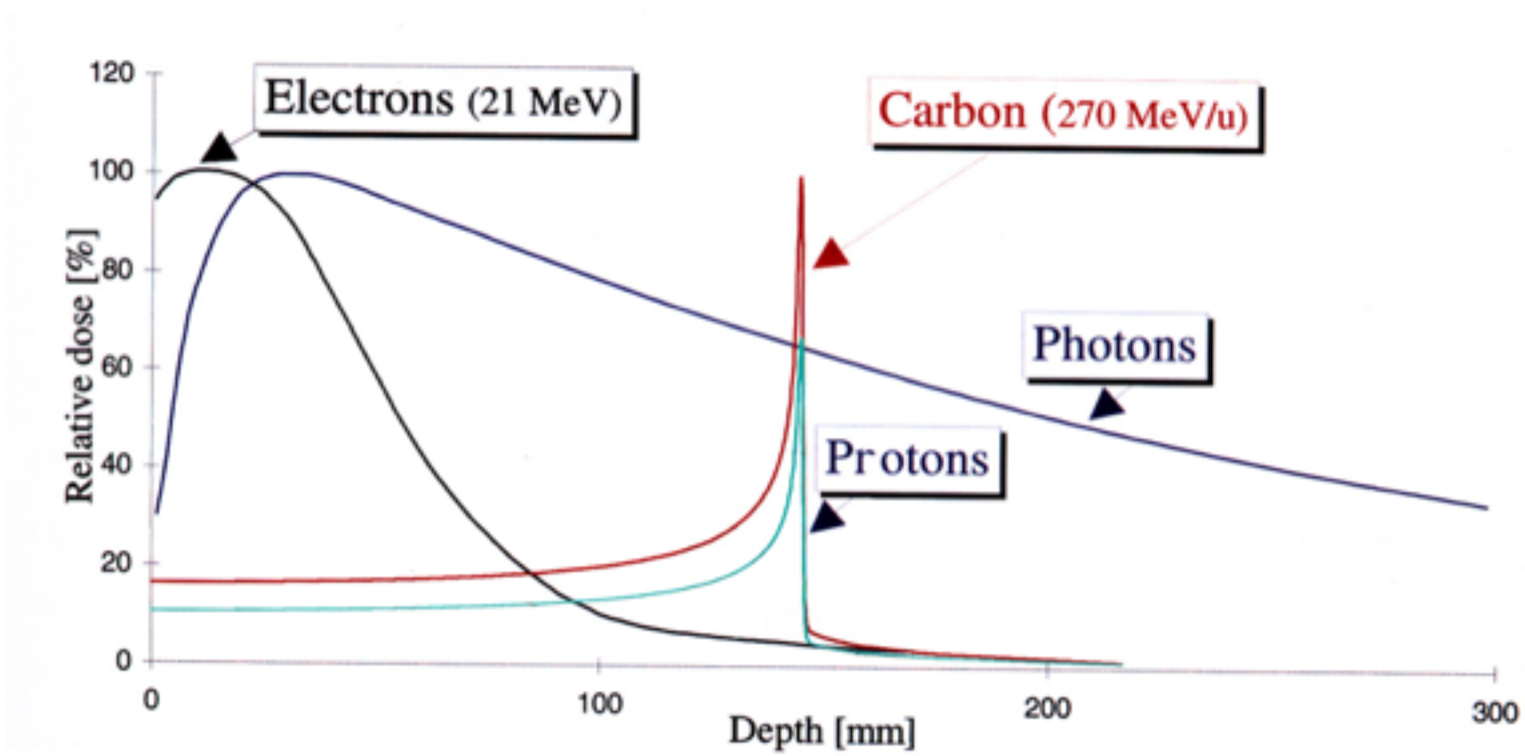




Shower
Clock Cts
Pixel (y)
Pixel (x)
(a)
Multiple Scattering
Clock Cts
Pixel (y)
Pixel (x)
(b)
Track w. Delta Electrons
Clock Cts
Pixel (y)
Pixel (x)
(c)
Primary w. Delta Electron
Clock Cts
Pixel (y)
Pixel (x)
(d)

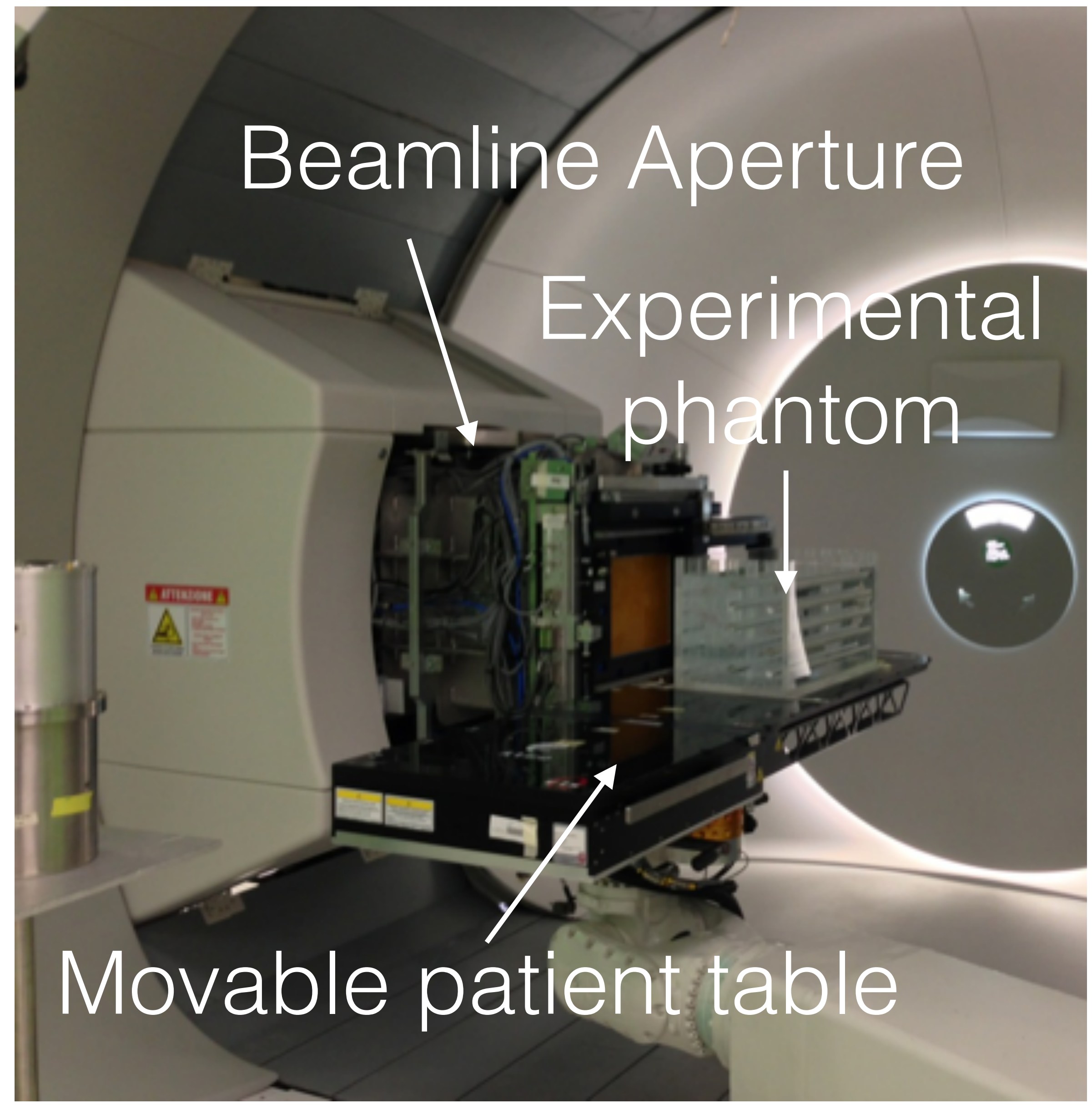
Hadron Therapy

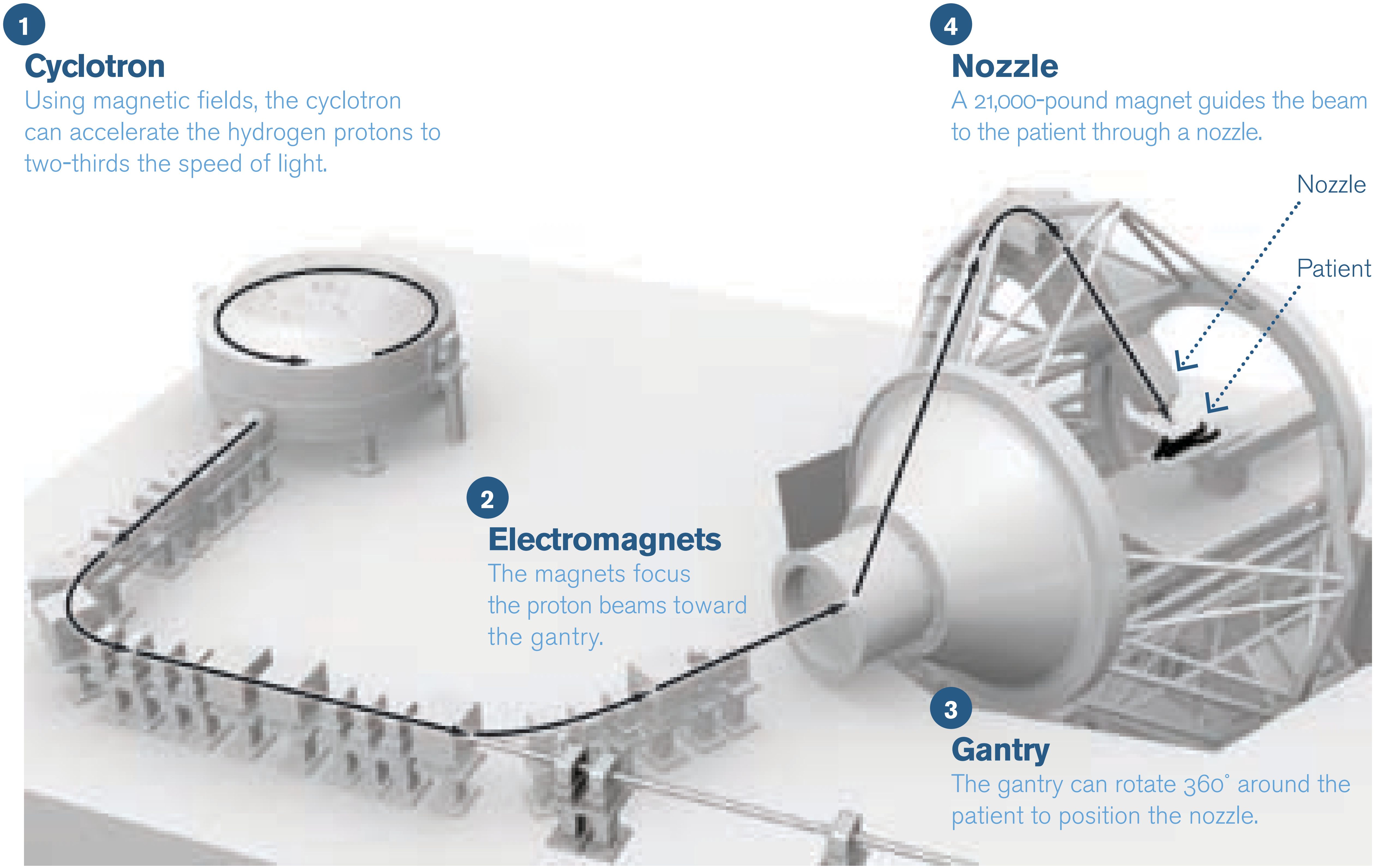
- Hadron therapy uses beams of Protons and Carbon ions to treat cancer
- Exploits the energy deposition properties of charged hadrons (Bragg peak)



Hadron Therapy

- ~30 centers world wide (Majority in USA, then Japan)
- ~150 million for one centre (~2k patients/yr)
- Economics arguments often produce numbers such as 1 centre per ~20 million people - though cost benefit is contentious
- **Limited QA tools compared to photon therapy**





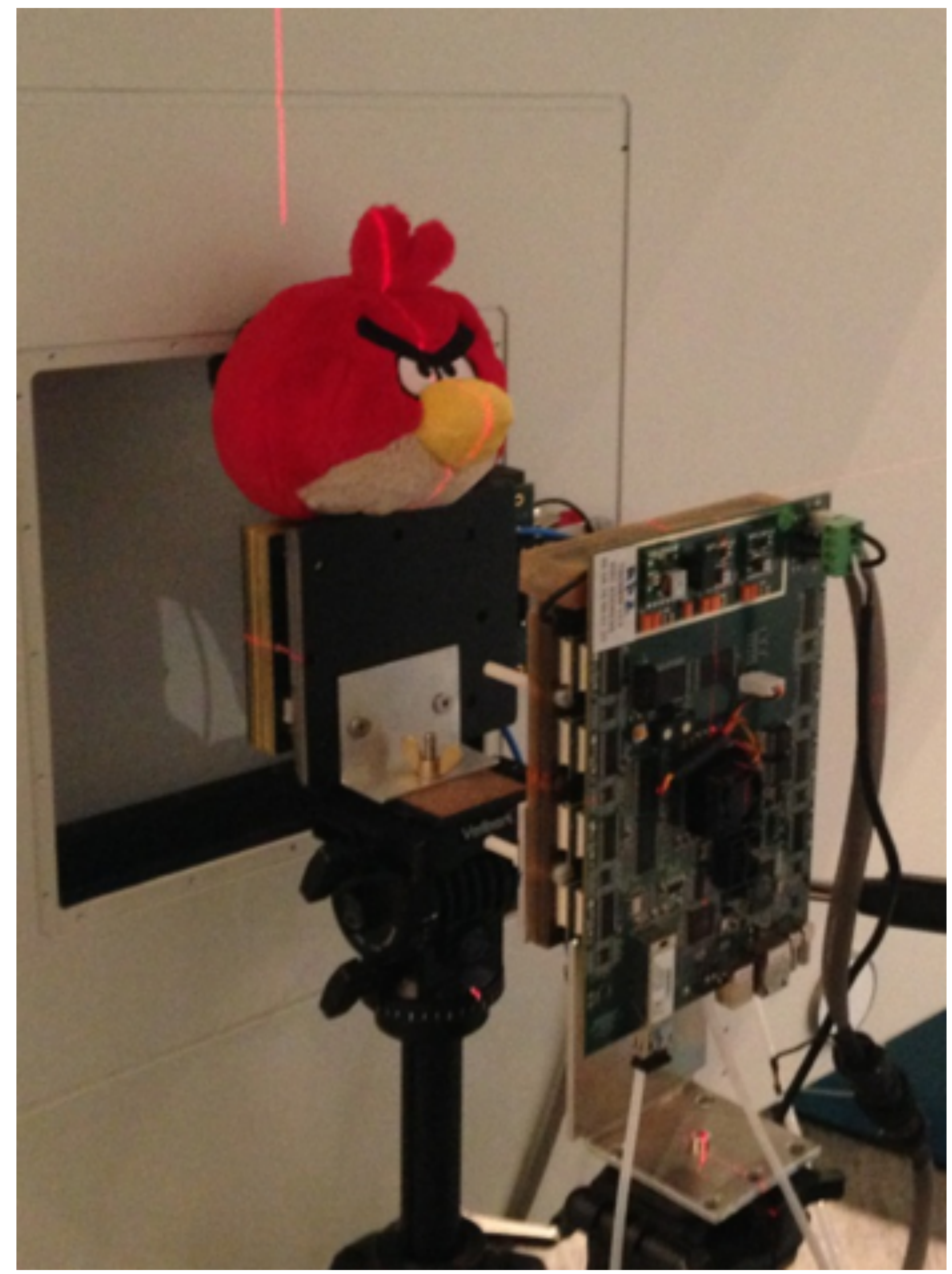
Credit New York Times

Beam Monitoring Measurements for Hadron Therapy

- Proton beams at CNAO (National Centre of Oncological Hadrontherapy) in Pavia, Italy

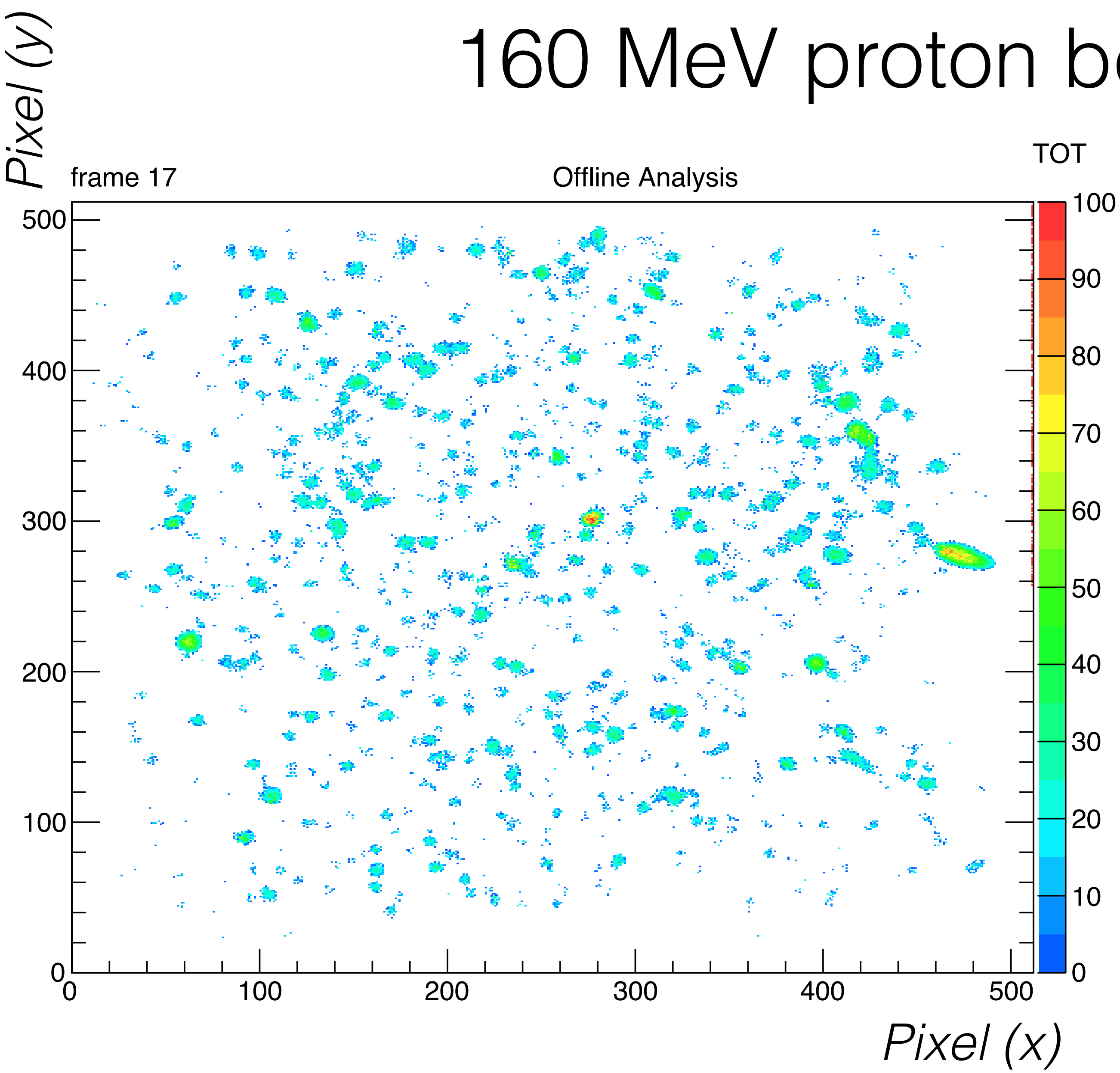
- Started treatment in 2011

- Proton fluences $\sim 10^{10}/\mathrm{cm}^2\mathrm{s}$

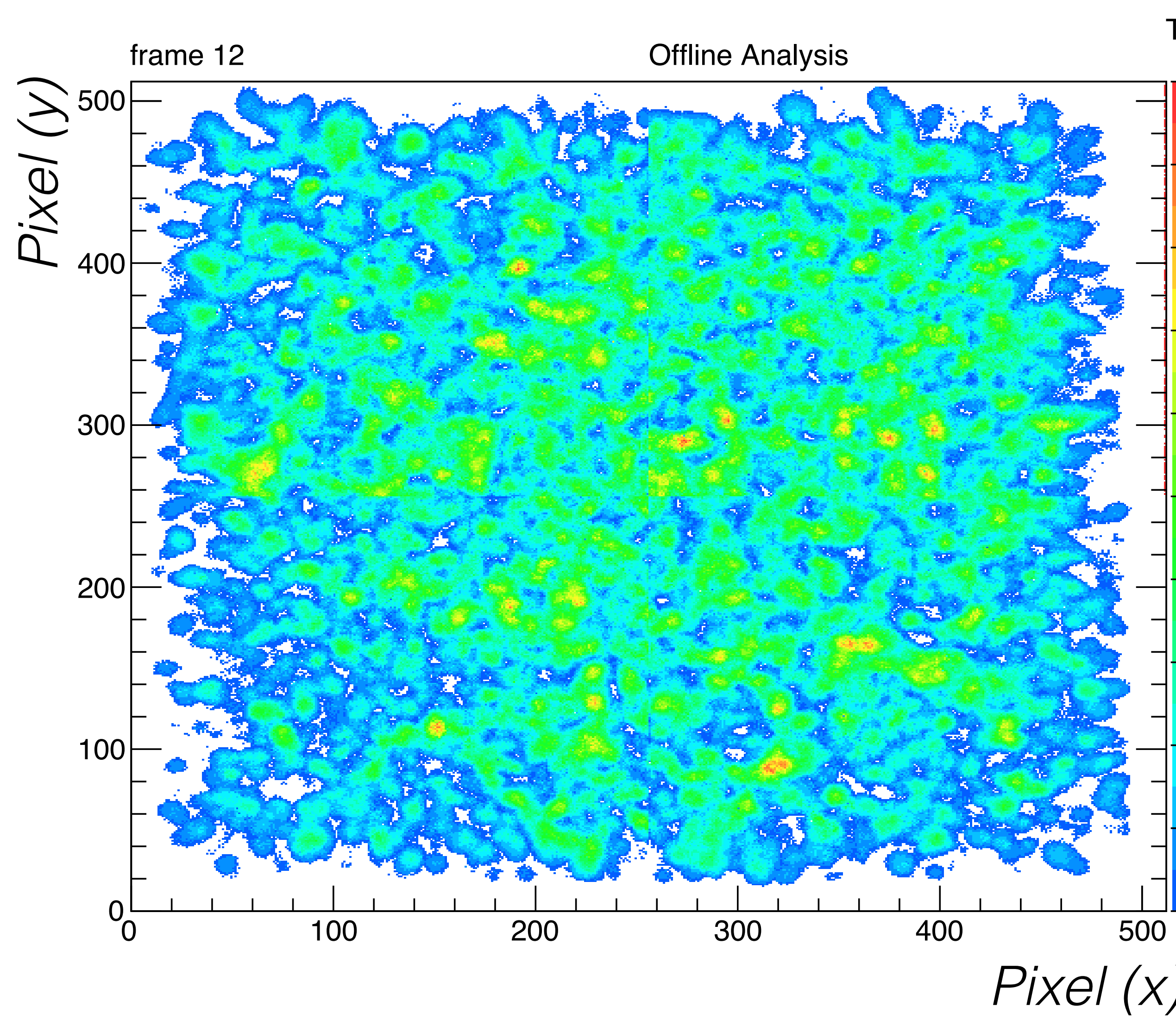


Proton Beam at Different Gains

160 MeV proton beam, flux~10^{10}/cm^{2}s

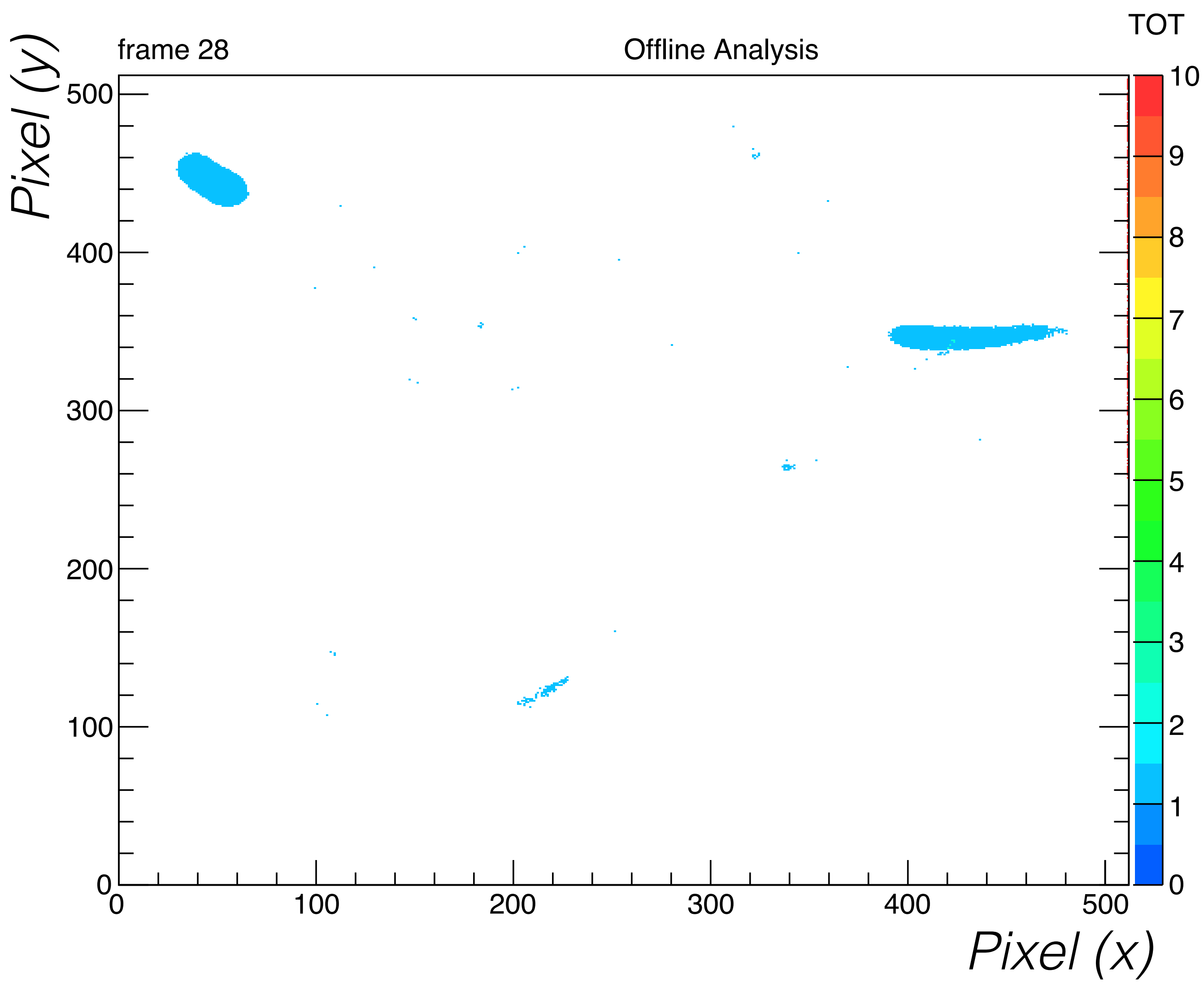


Gain 930 - 0.001s frame

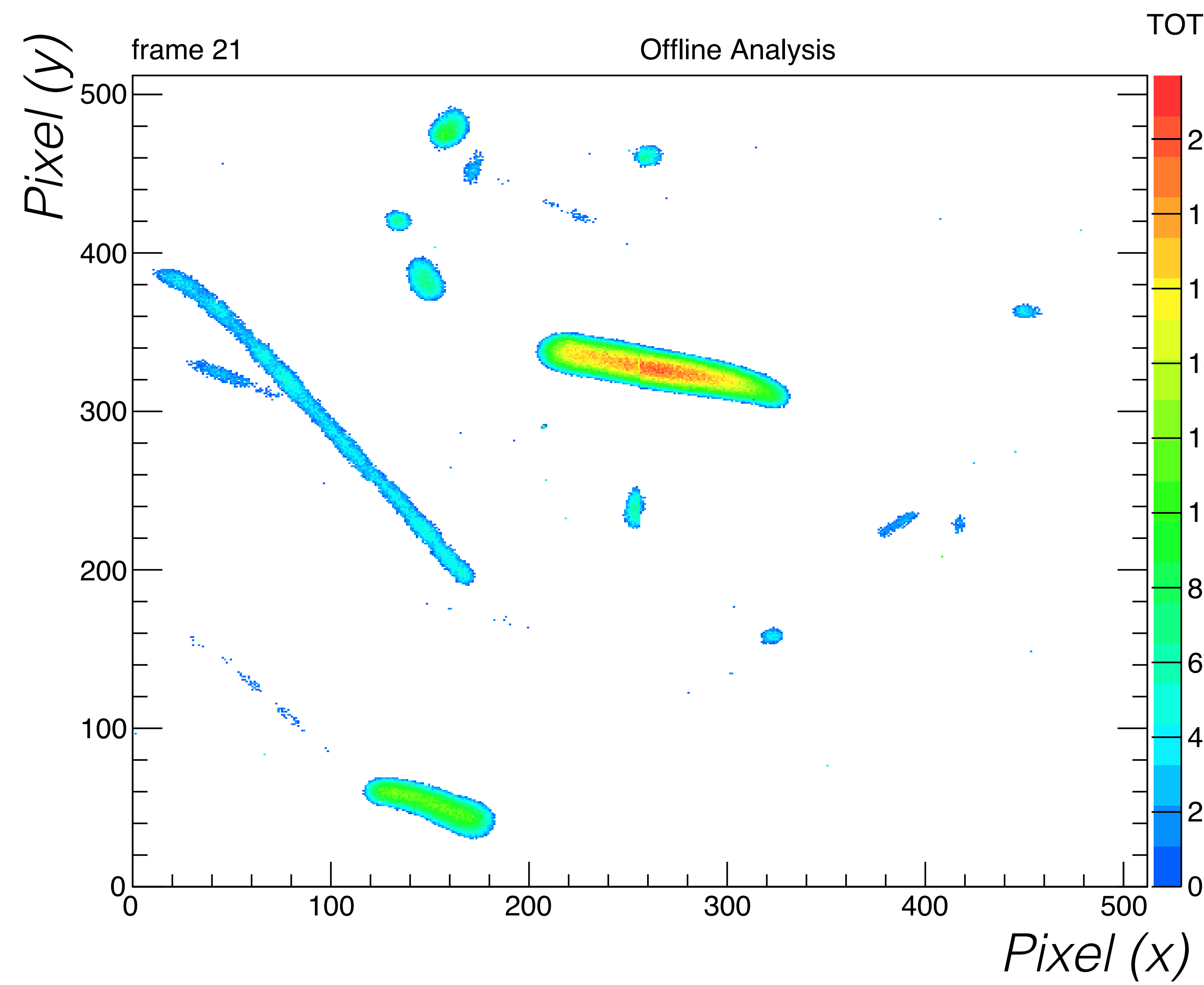


Gain 990 - 0.001s frame

Proton Beam at Different Gains



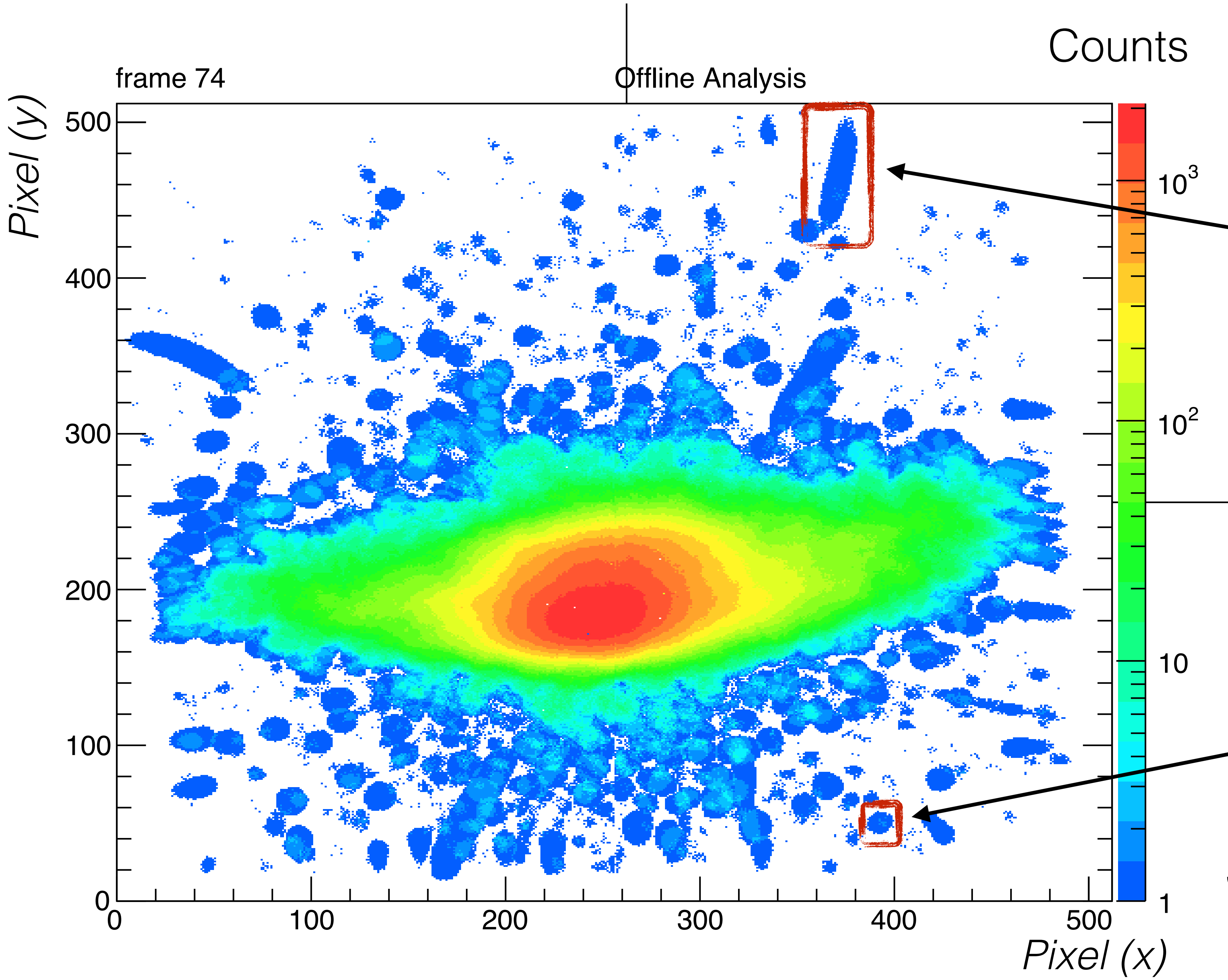
Gain 900 - 0.001s frame

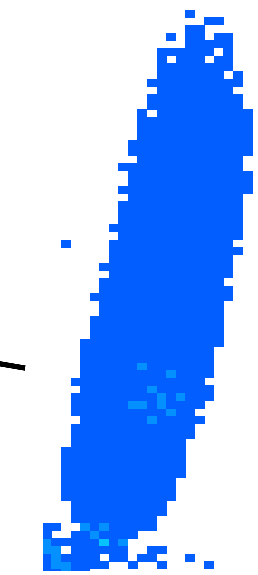


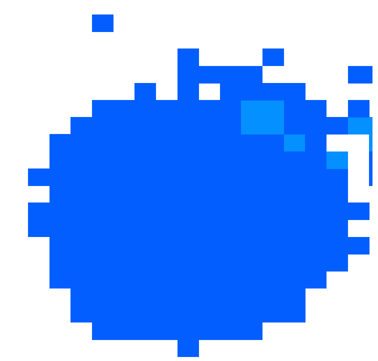
Gain 870 - 1s frame

The gain can be used to set a minimum ‘threshold’ on the per particle dE/dx - measurements of unusual events

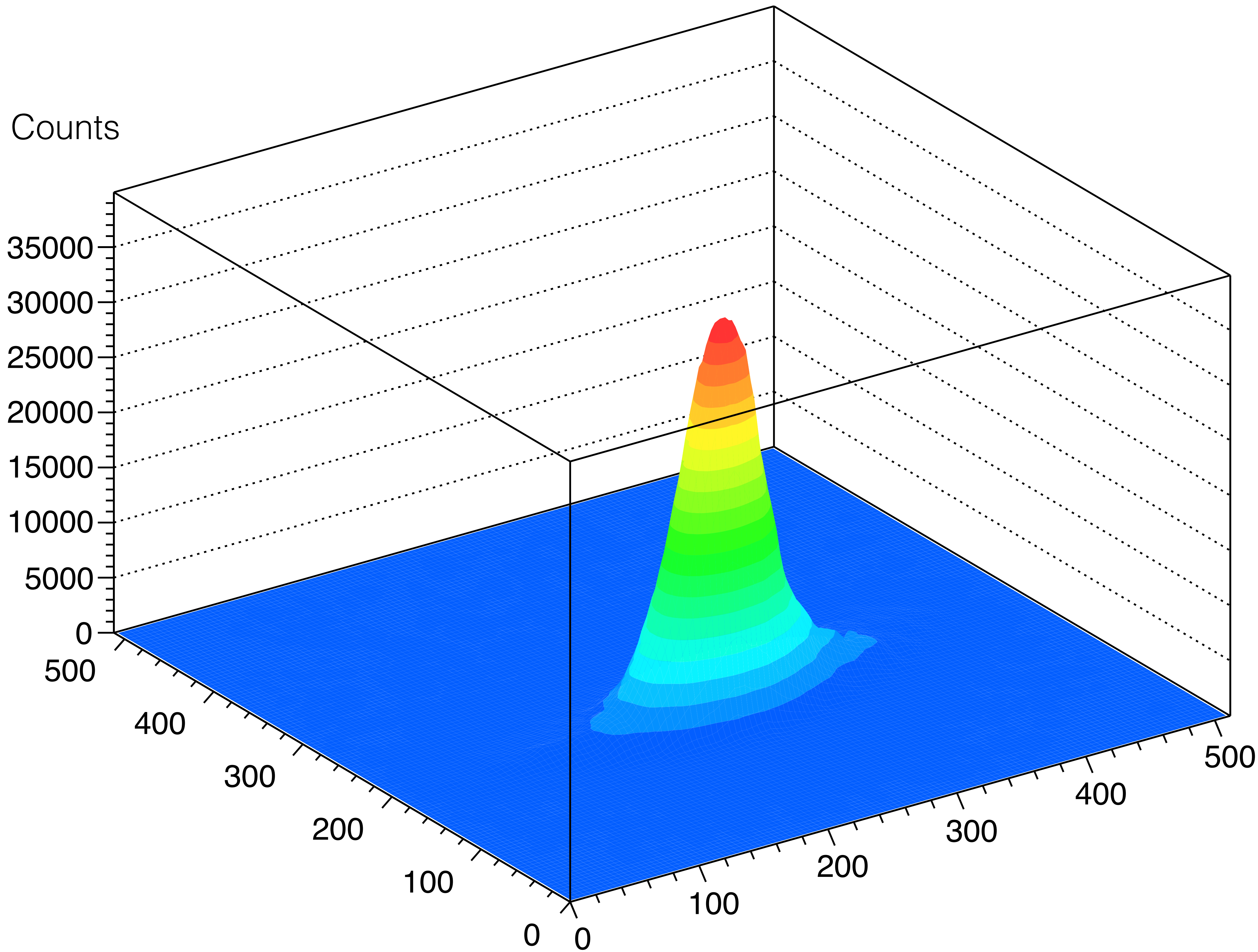
Gempix as a Beam Monitor



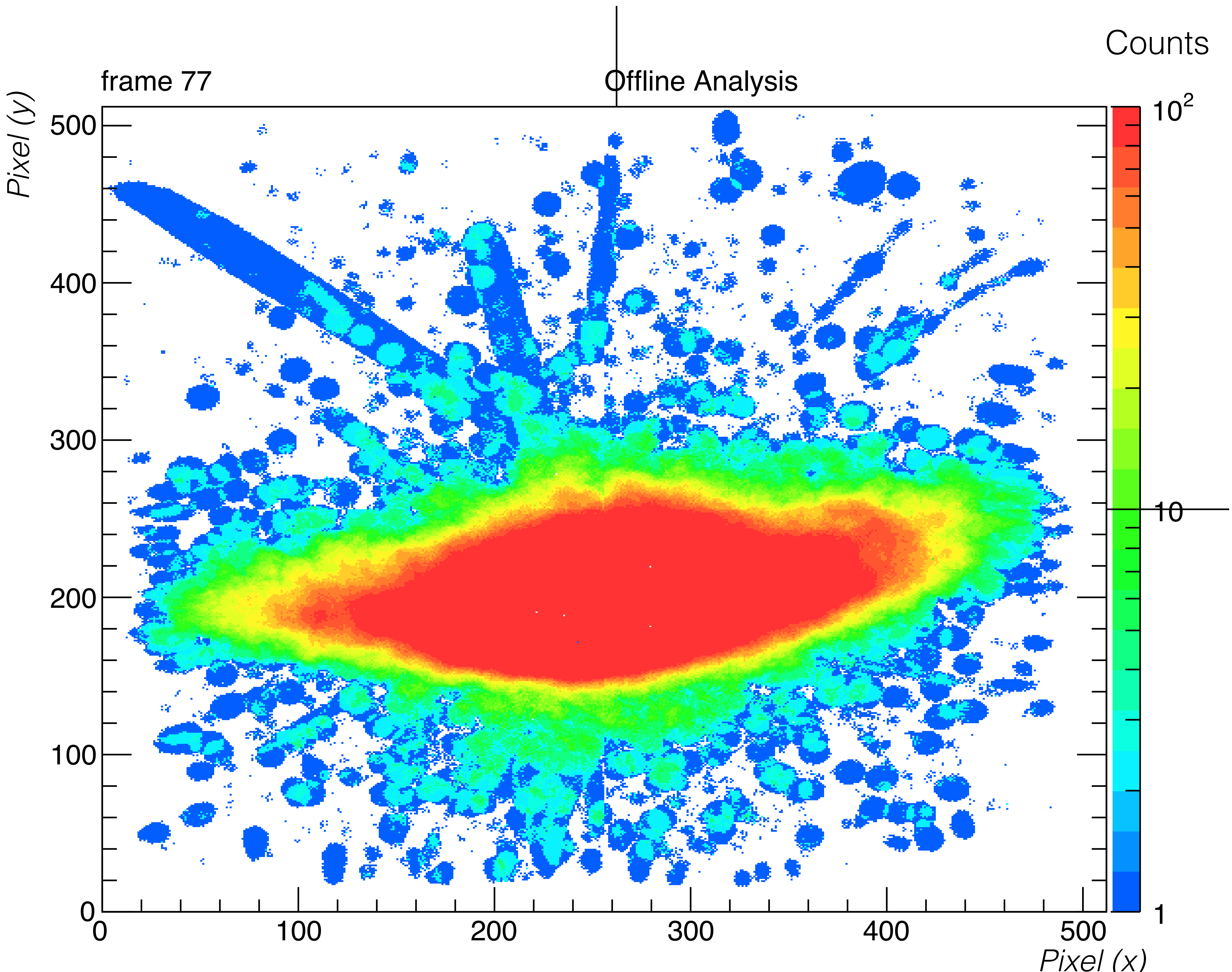




480 MeV/A carbon ions, 0.01s frame, **ASIC in particle counting (medipix) mode**, IKrum = 5



Overall beam shape



Halo, down to single particle resolution

Spot Scan …

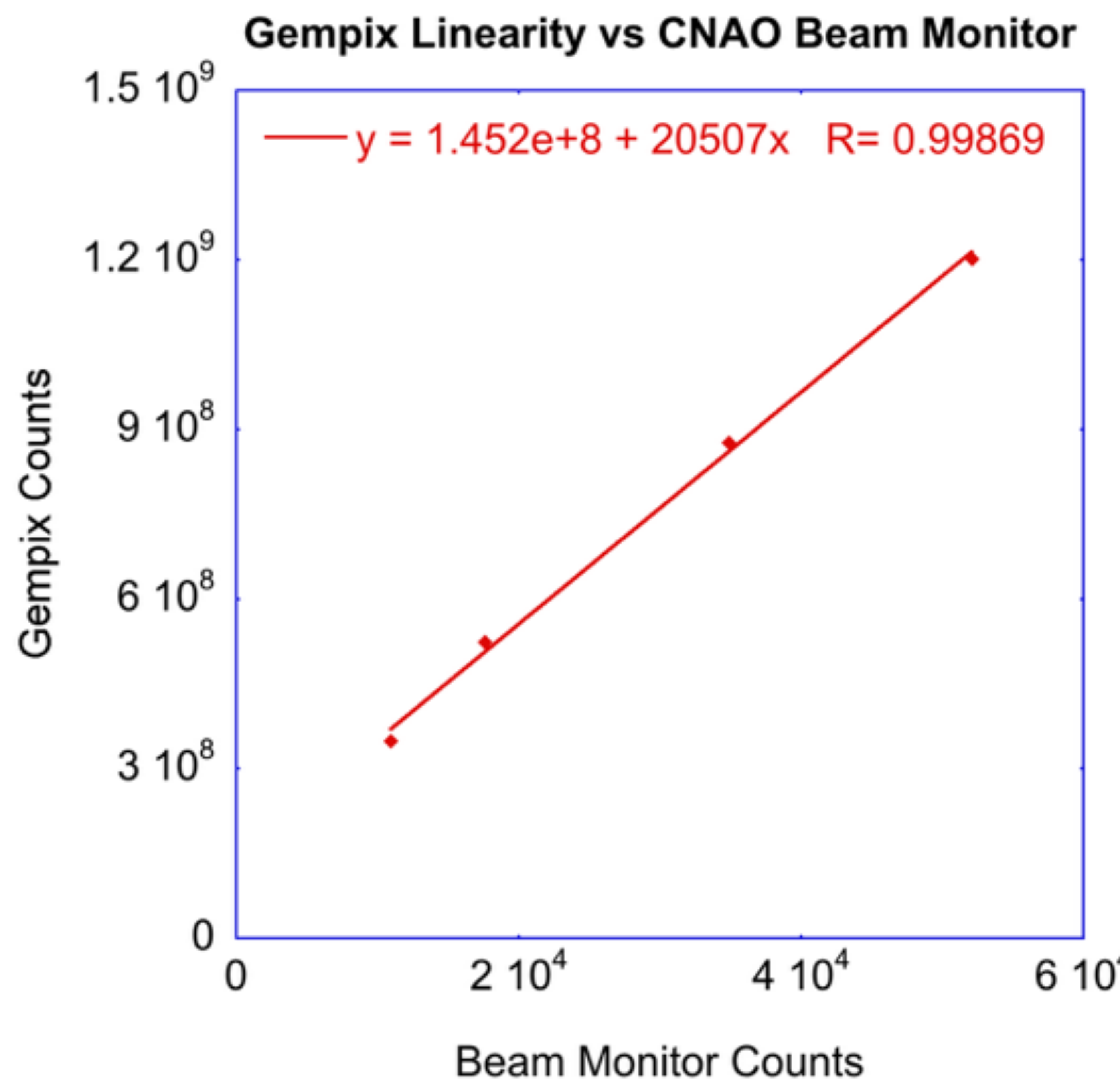
Detector Linearity

90s measurement, 1s spill, spill every 5 seconds

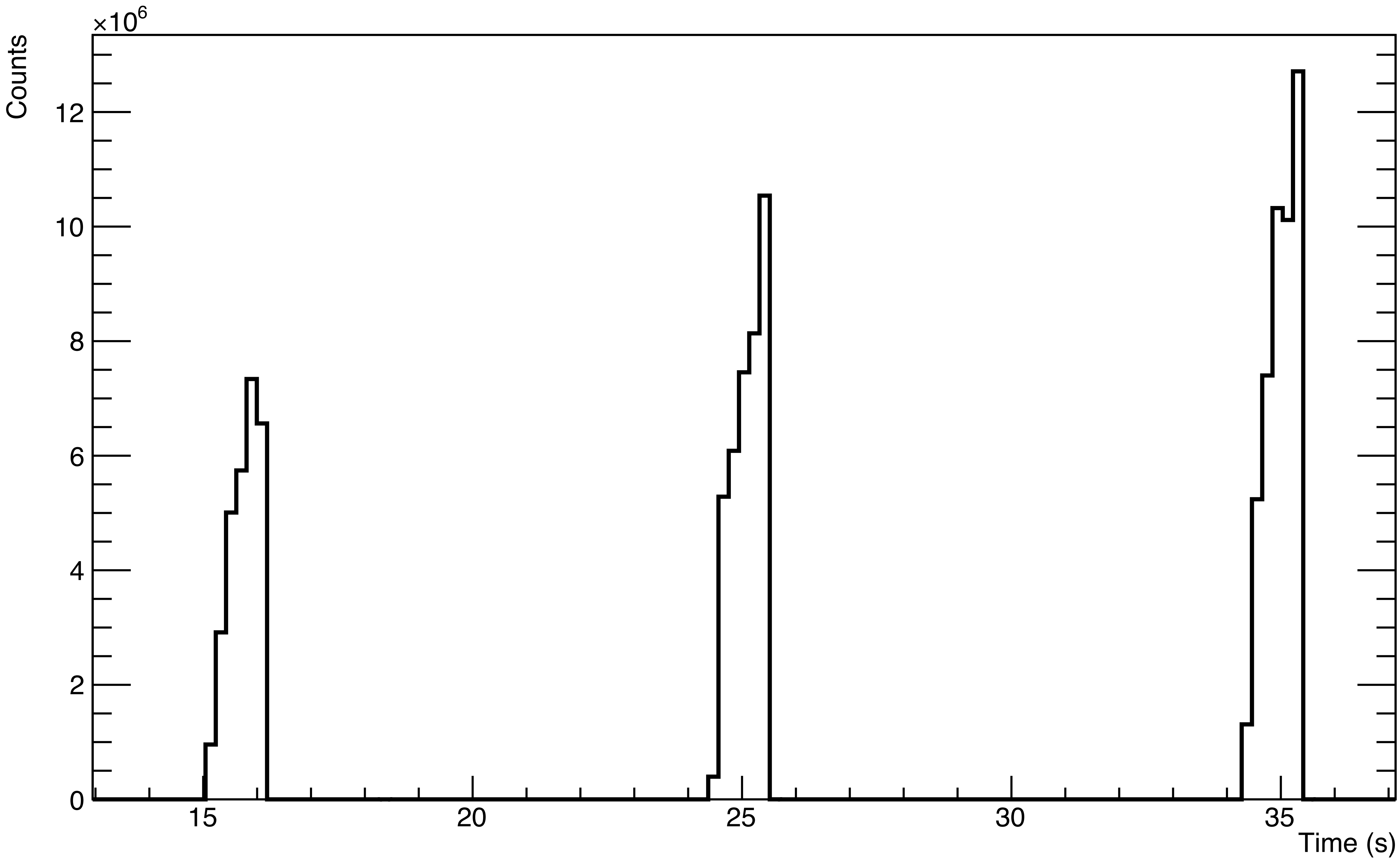
Counts are the integral over the total 90s period

Number of ions is the counts/average carbon cluster size (~130 pixels)

(Dead time is significant however ~1/10)

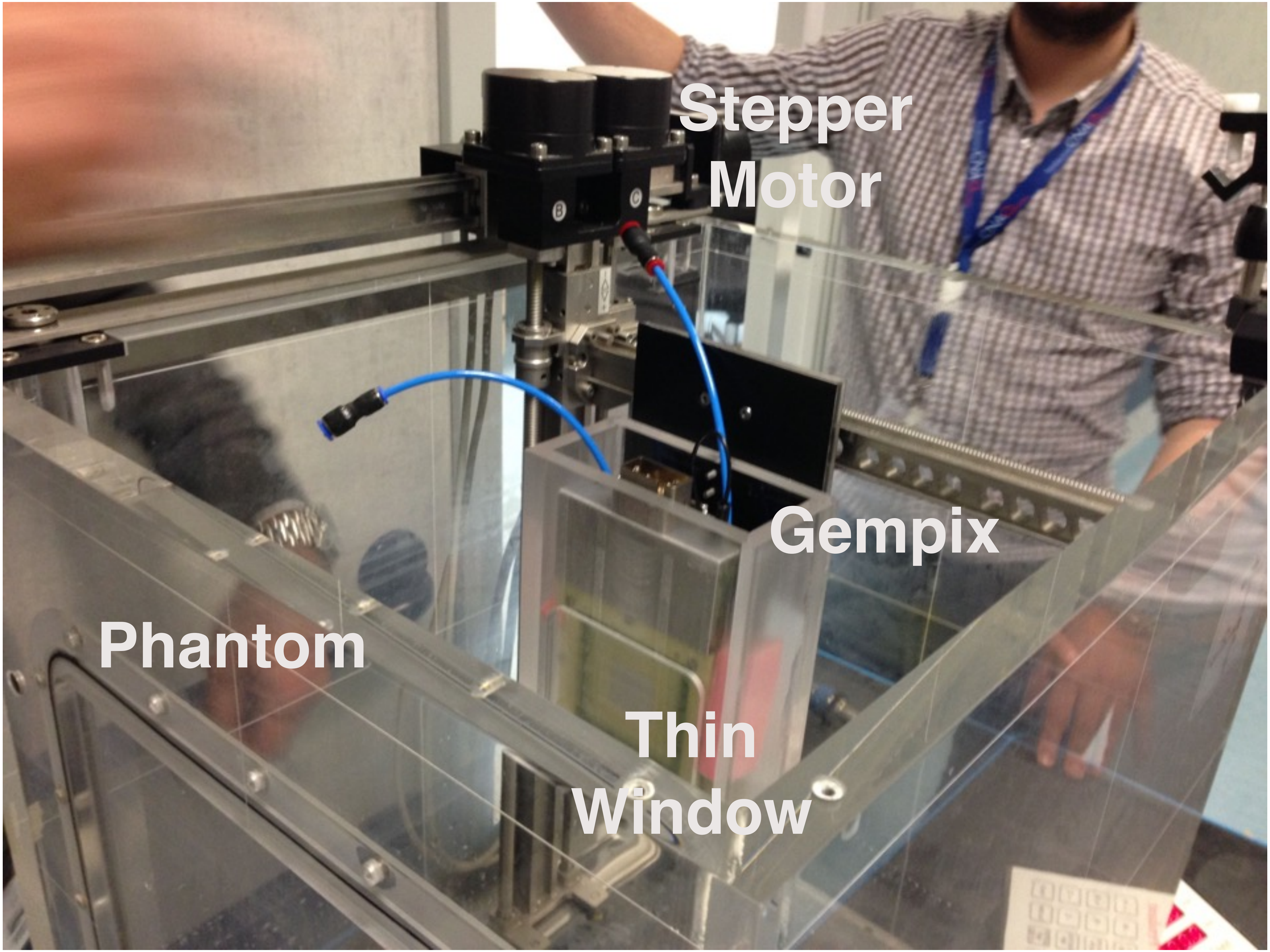


Time Profile of Particle Spill

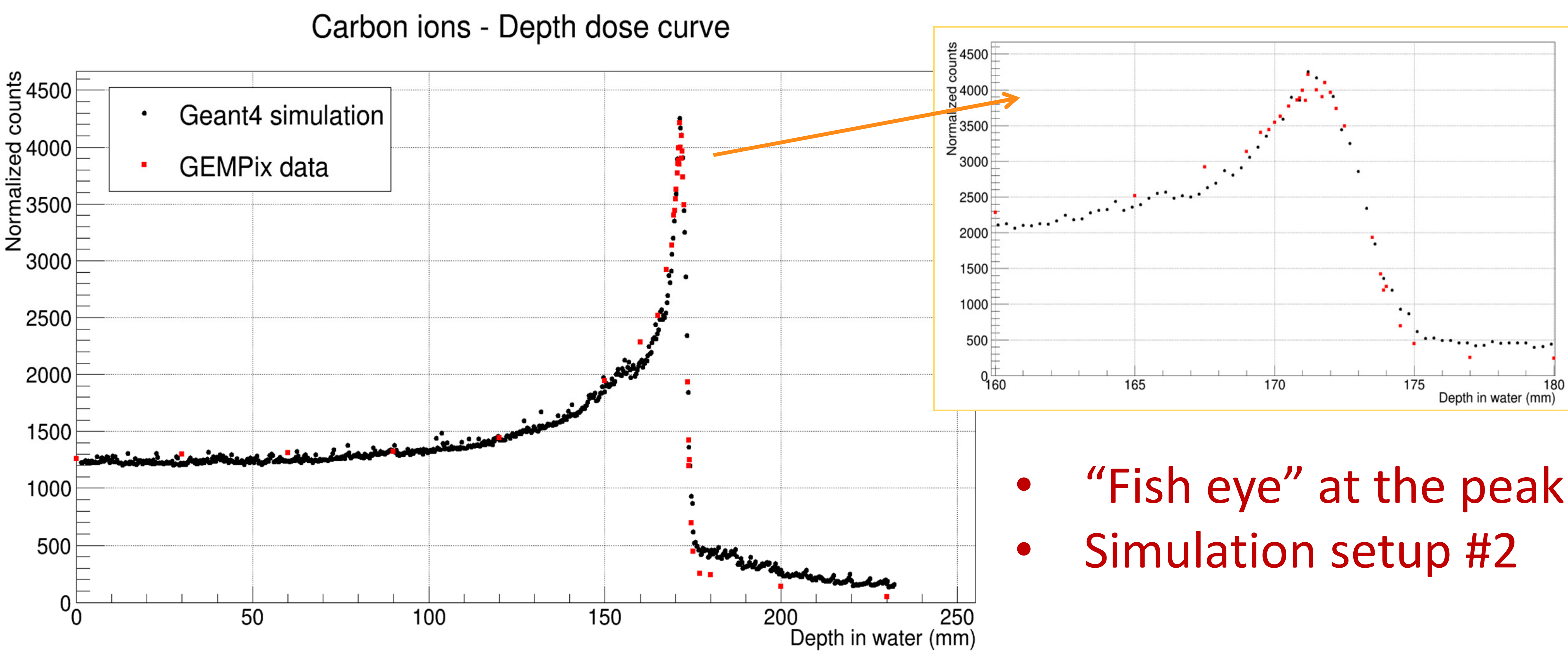


Energy Deposition Measurements for Hadron Therapy

- 480 MeV/A Carbon Ion Beam at CNAO
- 23 different depths throughout water phantom
- Each position given spot 10^7 carbon ion treatment


Stepper Motor
Gempix
Phantom
Thin Window

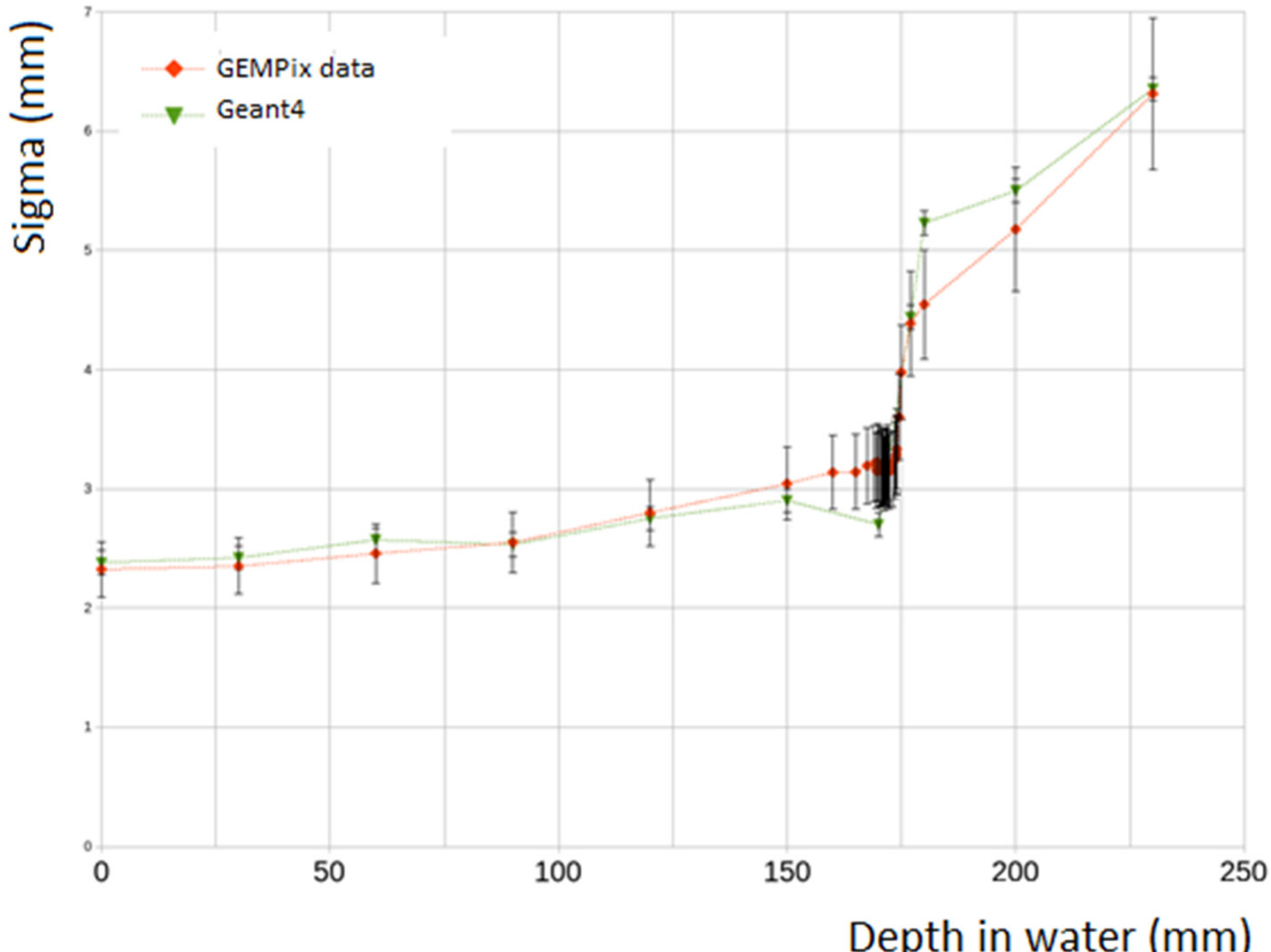
Results at CNAO



- “Fish eye” at the peak
- Simulation setup #2

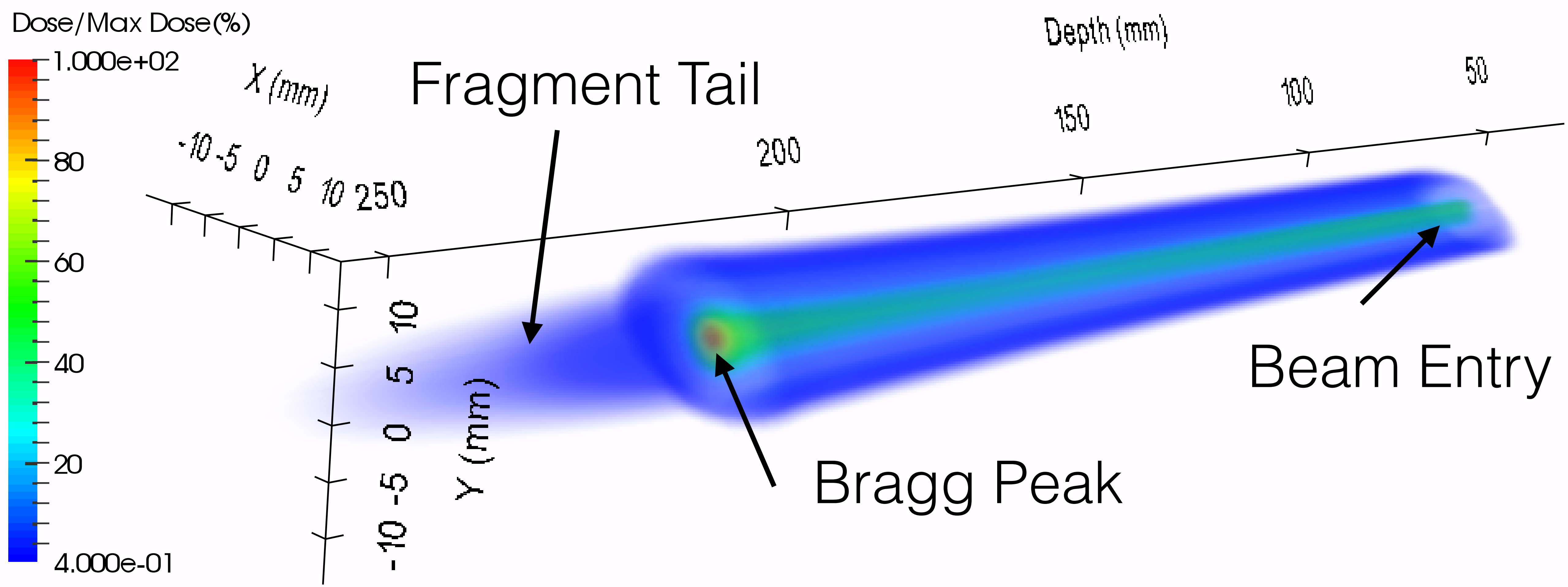
Simulation/figure by A. Tamborini
Systematic underdose in fragment tail needs to be explained

Beam spot lateral dimensions as a function of depth in water



Simulation/figure by A. Tamborini

3D Beam Reconstruction



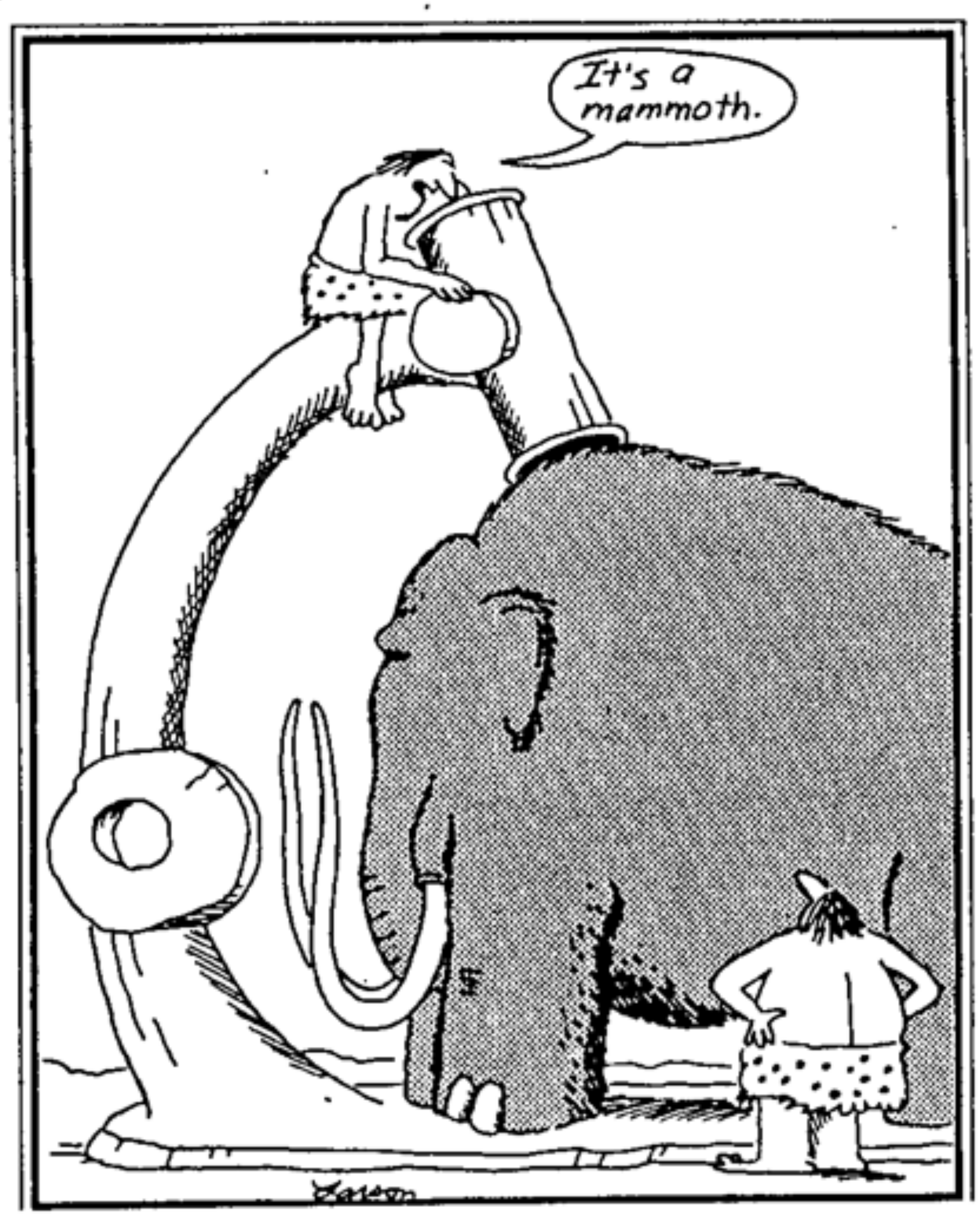
Future Thoughts

- A GEMPix based on the new Timepix3 ASIC will solve many of the dead time issues in tracking.

- GEMPix as a microdosimeter is mainly advantageous over normal TEPC’s because it measures track by track. Possibility to operate at low pressure as a **nano-dosimeter**

- Work is underway to perform the CNAO measurements much faster using better integration with the CNAO beam delivery system. In this application it may be useful for realistic QA.

Thanks for your attention



Early microscope