Combined Optical and Electronic Readout for Event Reconstruction in a GEM-based TPC

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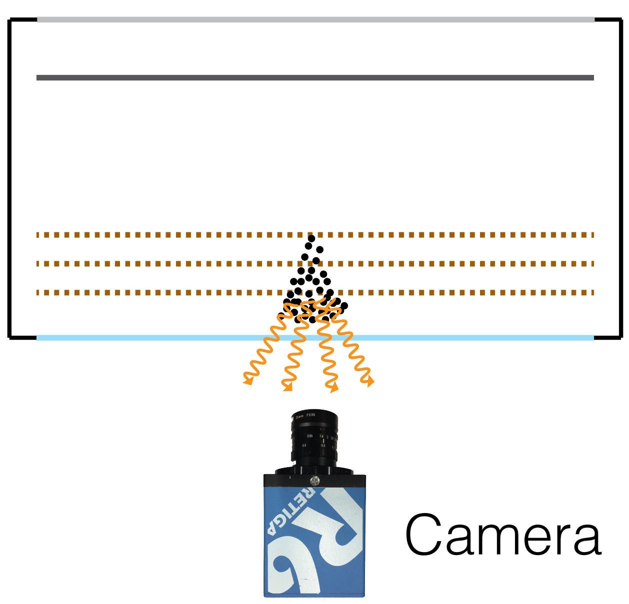
on behalf of the CERN GDD group

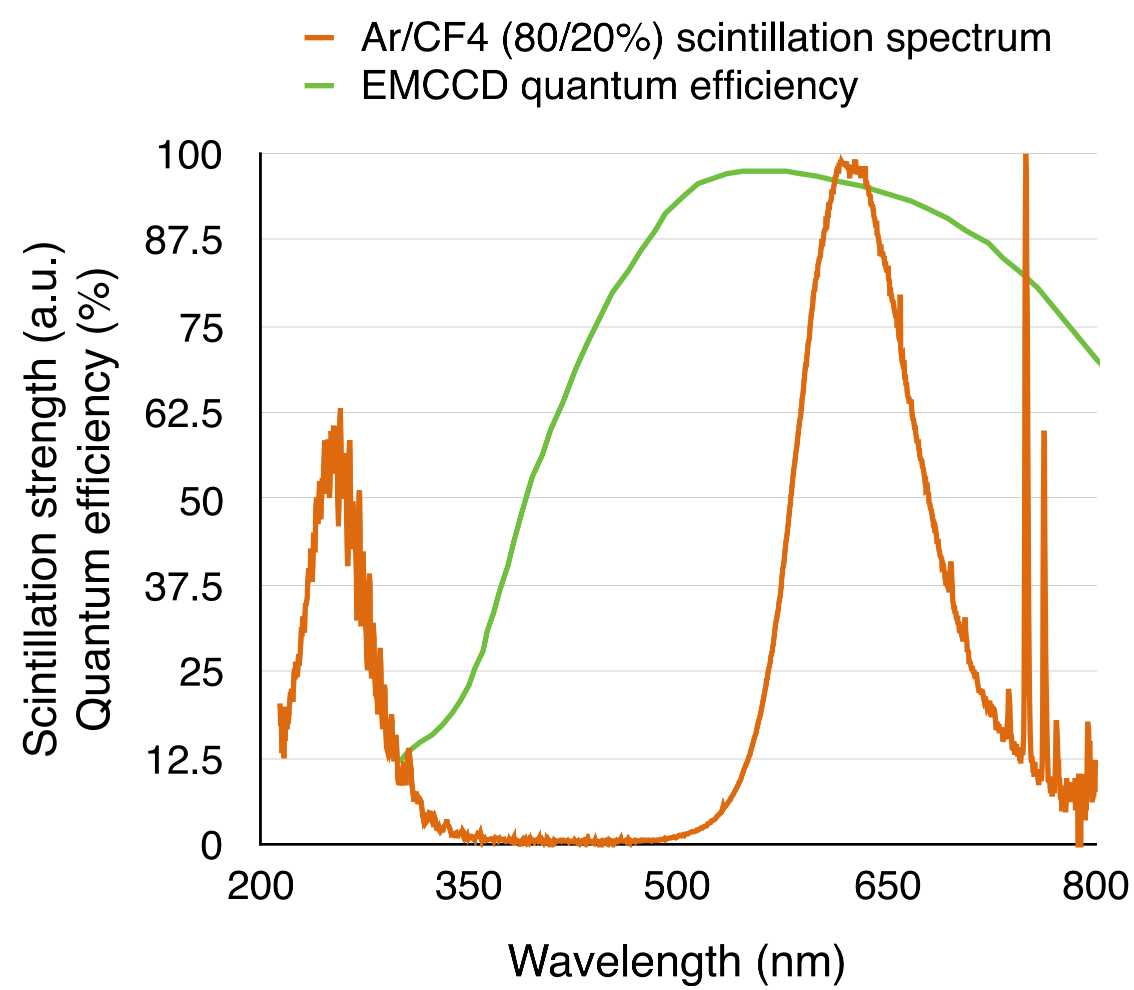
December 14, 2017 - RD51 Mini Week

Optical readout of MPGDs

Optical readout of MPGDs can provide high spatial resolution images without the need for extensive image reconstruction

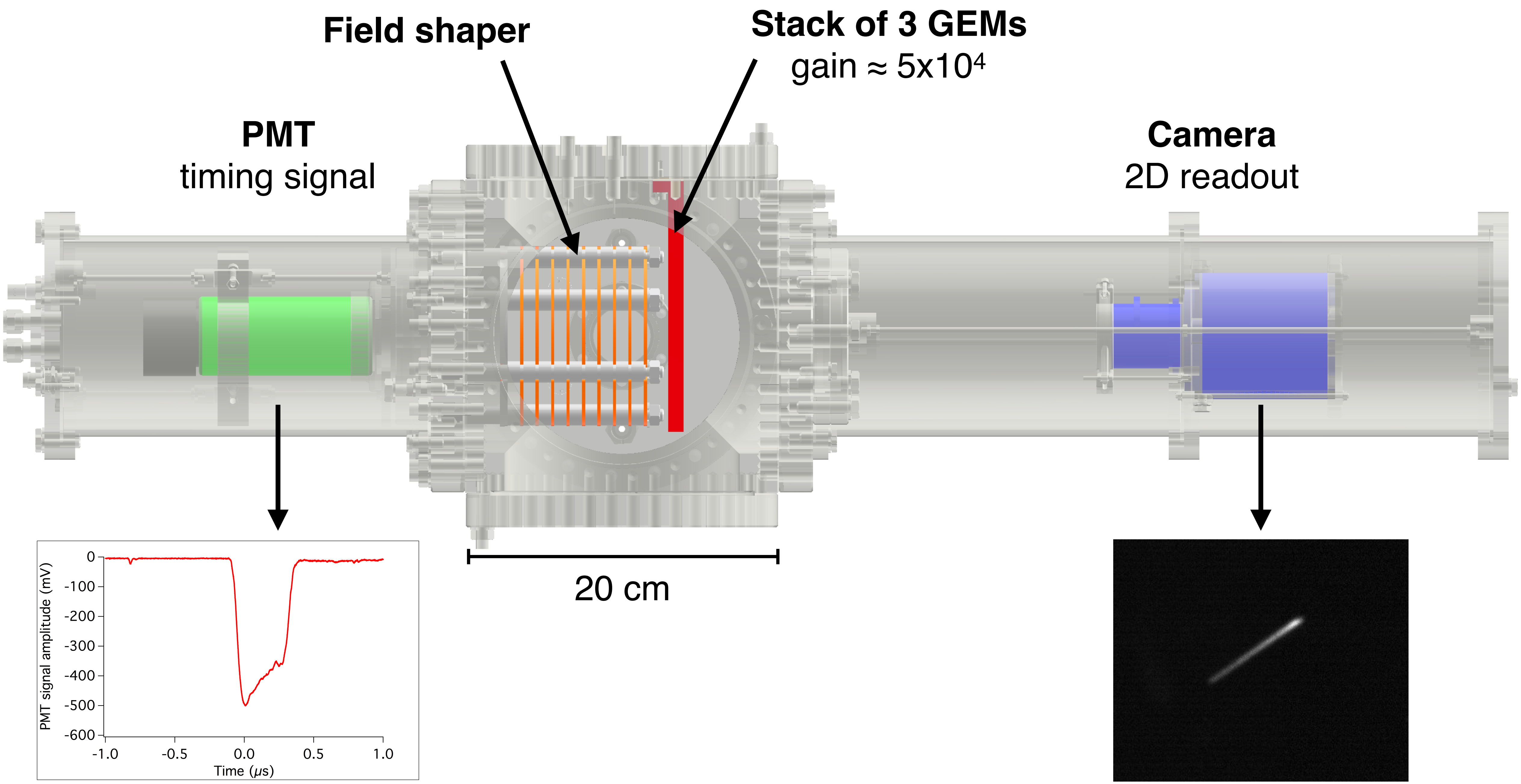
The secondary scintillation spectrum of gas mixtures containing CF_4 is well suited for readout with CCD, EMCCD or CMOS imaging sensors



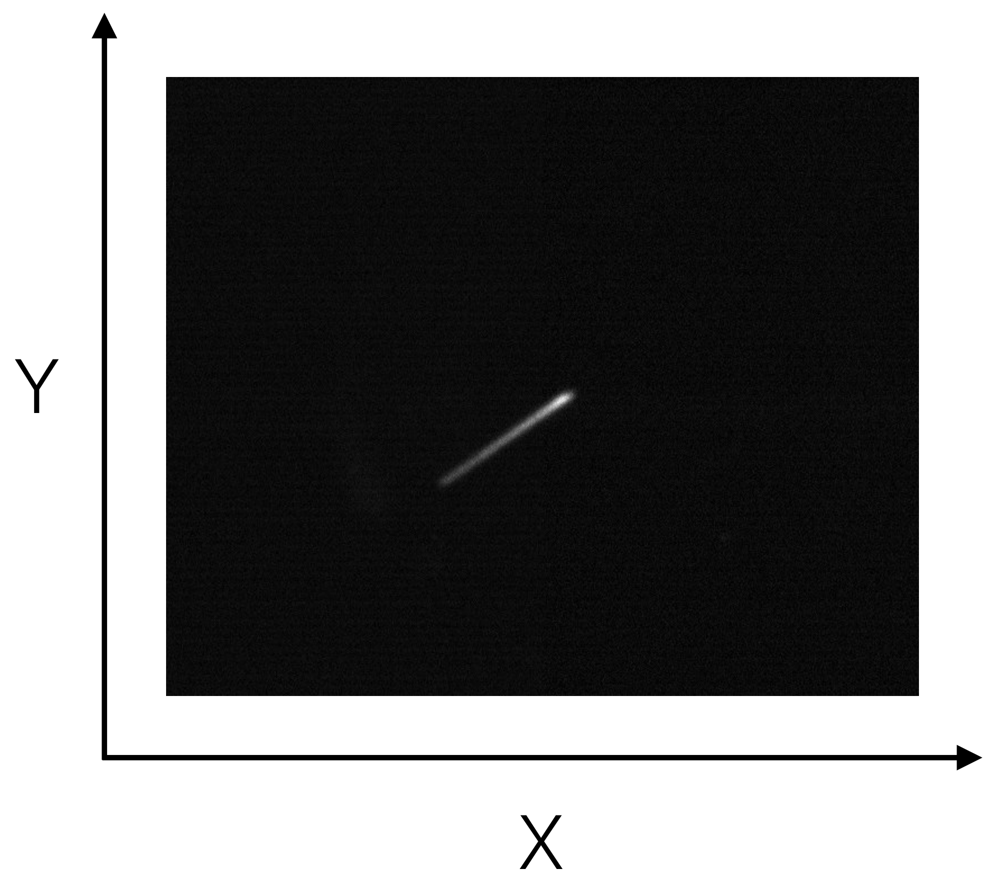


Optical readout

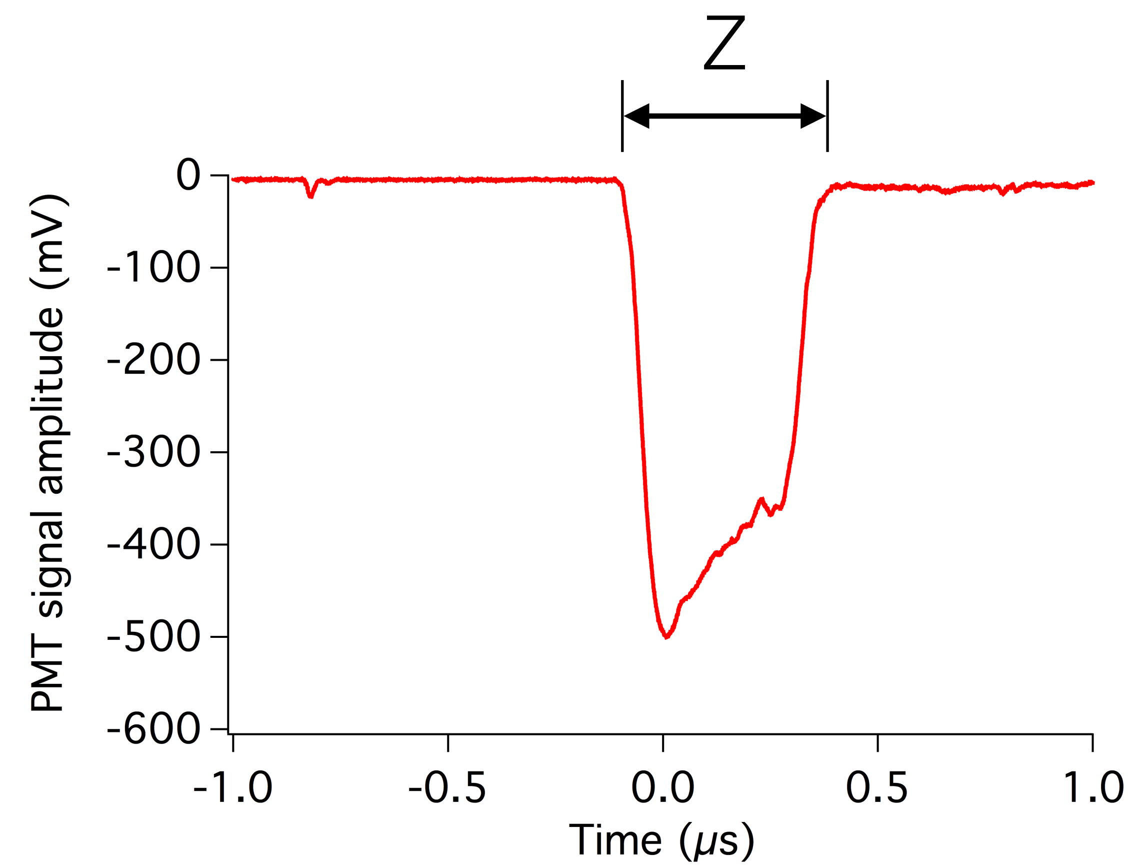
Optically read out TPC



X Y Z

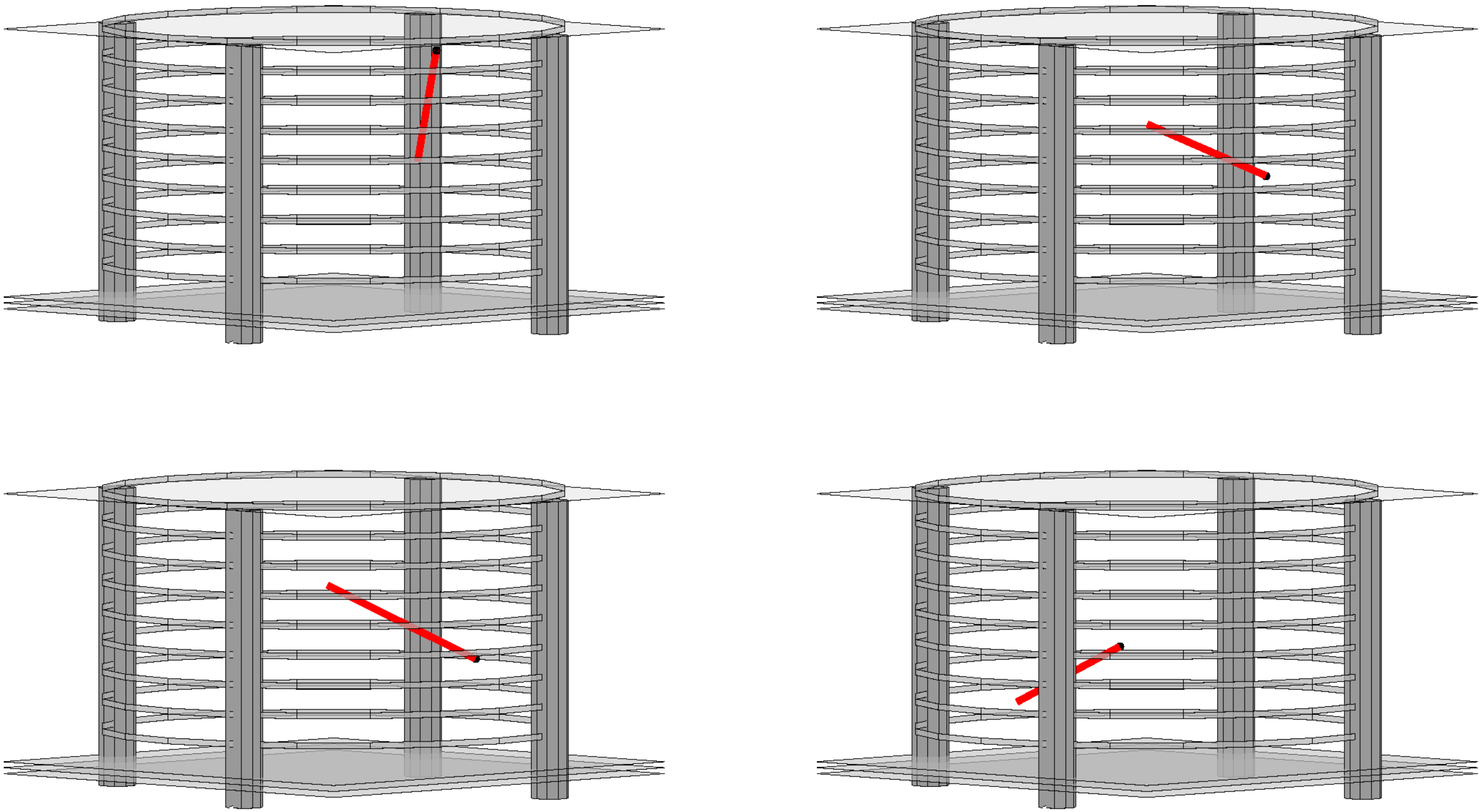


Camera image



PMT waveform

Reconstructed α tracks



Extension to intricate track geometries

3D reconstruction from images and Z-information obtained from PMT waveforms is limited to straight tracks

Arrival times of electronic signals in a certain spatial region can be combined with the 2D projection from the optical image to 3D track visualisations

Optical readout
High spatial resolution 2D projections

Electronic readout
Arrival times for depth information

Intuitive 2D projection from images and low number of electrically read out channels required for 3D reconstruction

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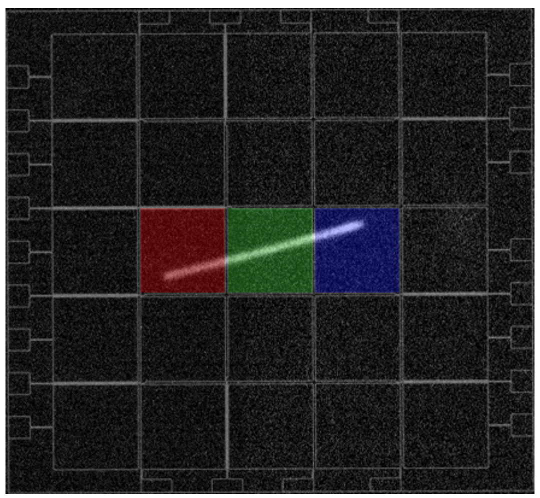
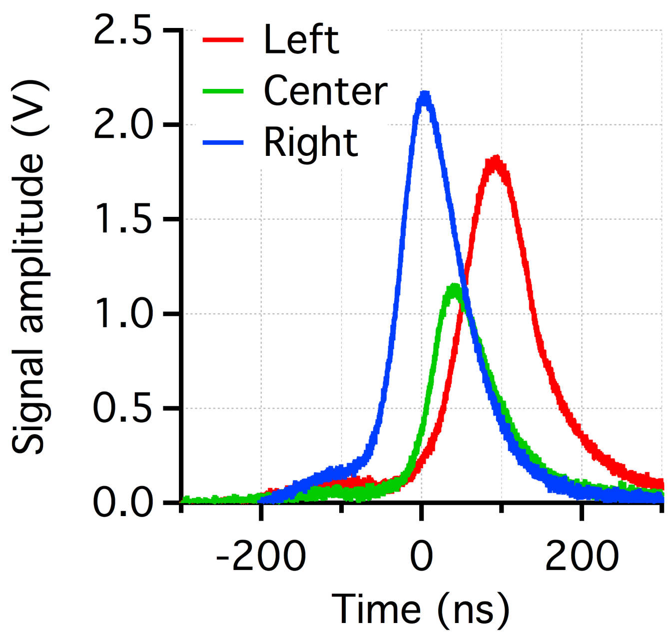
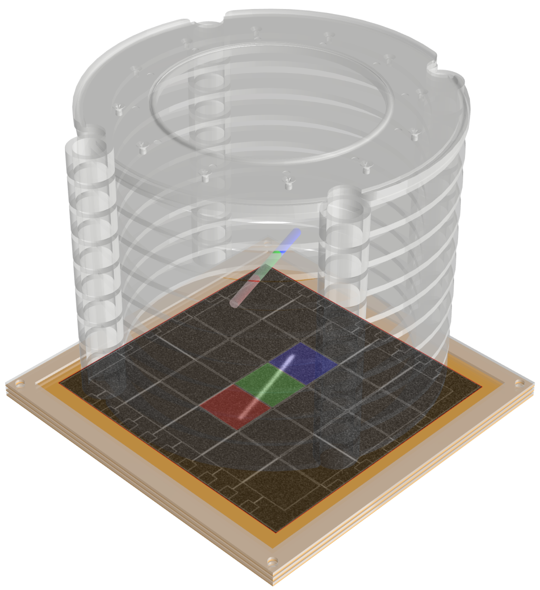
Optical and electronic readout



CCD image
X-Y information



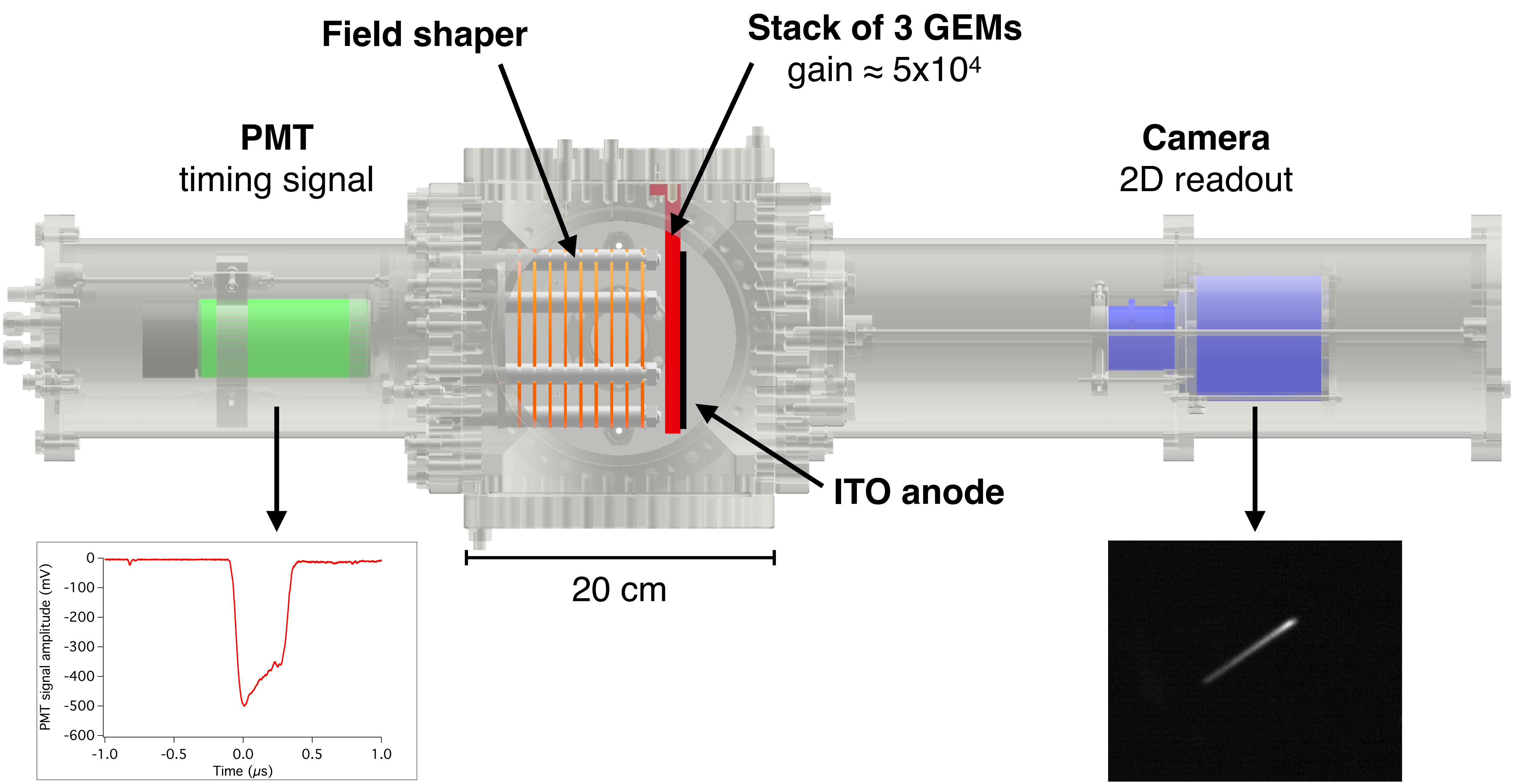
Electronic signals
Z information



Schematic visualisation
of 3D track

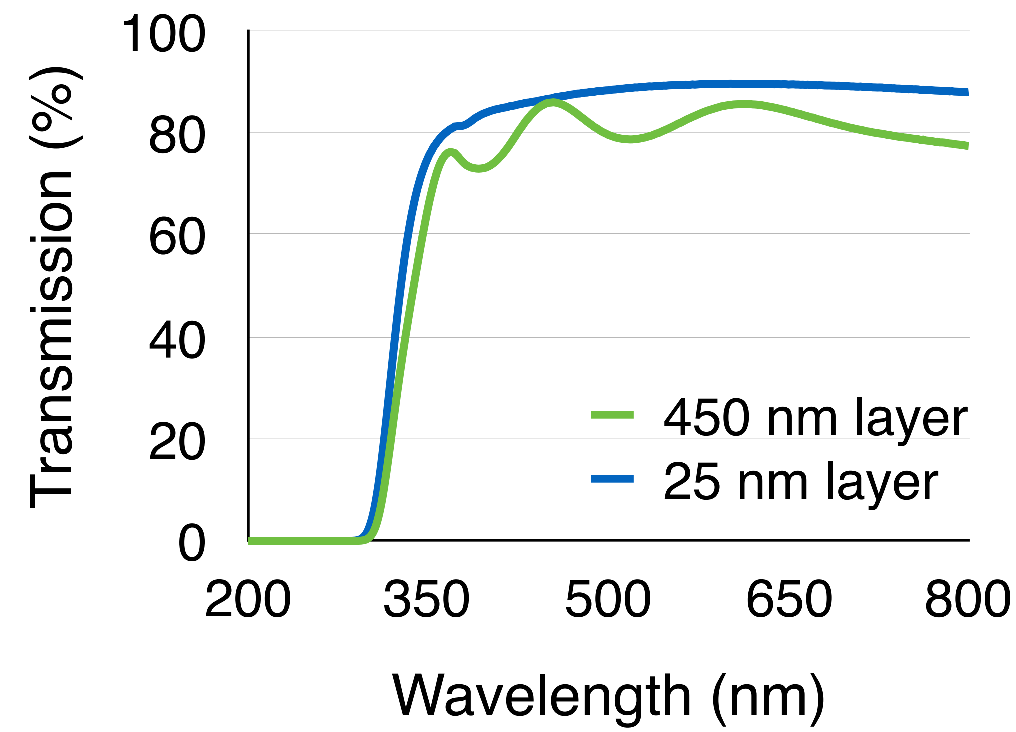
Arrival time of electronic signal at different locations along a track can be combined with optically read out image to 3D track reconstruction

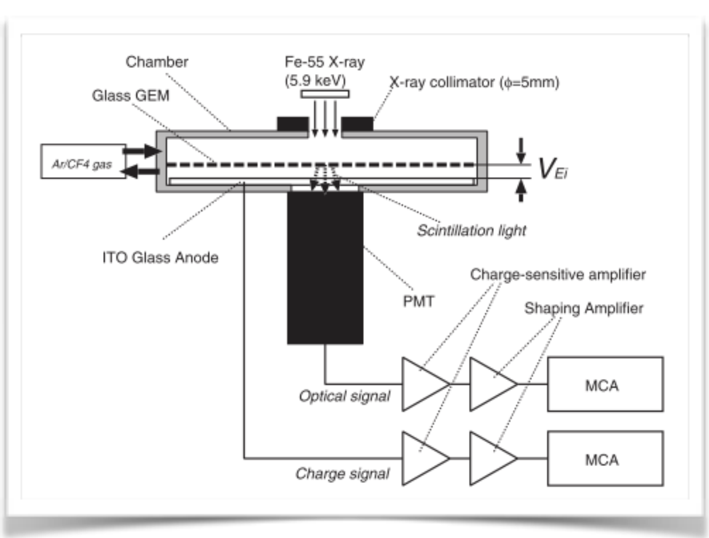
Optically read out TPC



Indium tin oxide (ITO)

- Optically transparent
- Electrically conductive
- Simple deposited of thin films by evaporation
- Can be etched in HCl
- Routinely used in LCD displays, touchscreen, solar cells, EMI shielding, …

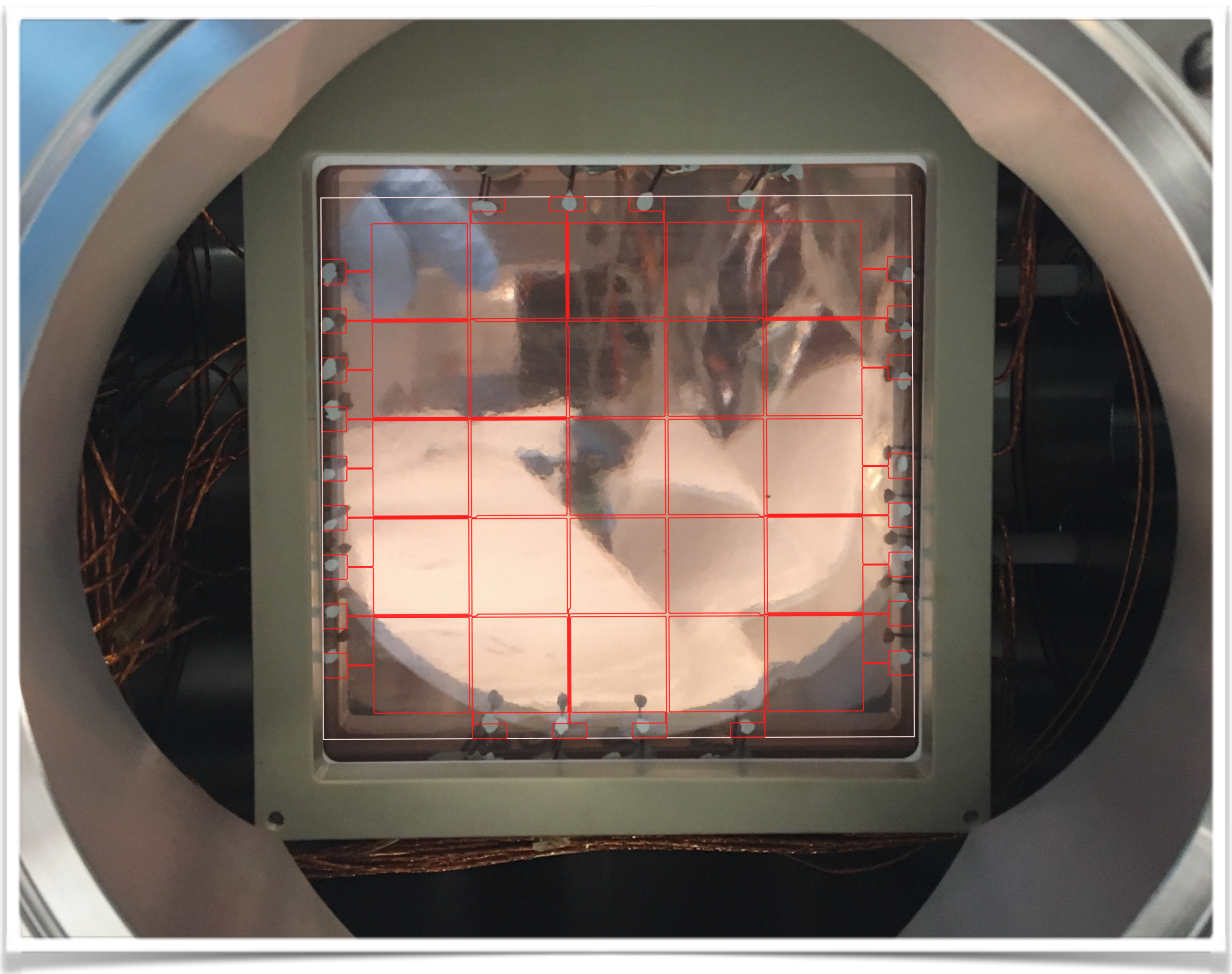




Used as transparent anode in optically read out detectors to collect energy spectra from charge signals

T. Fujiwara et al 2016 Jpn. J. Appl. Phys. **55** 106401

ITO pad anode



View into TPC as seen by camera
with ITO pattern shown in red overlay

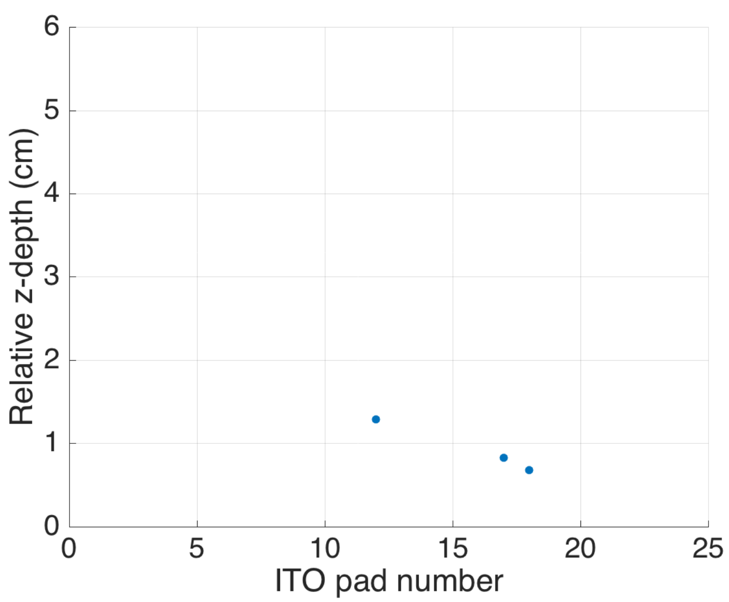
25 pads with 2x2 cm^2

25 nm ITO on glass

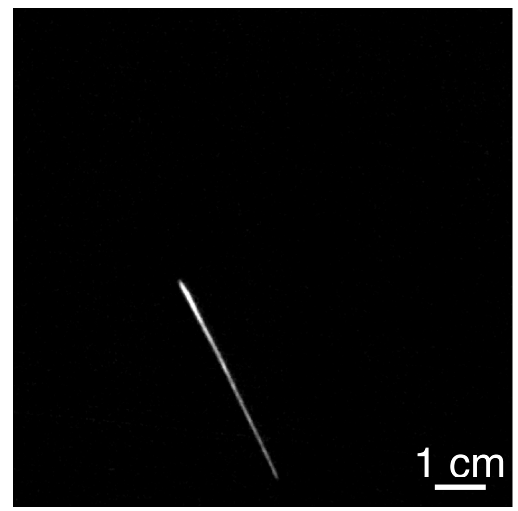
Structured by direct laser lithography and etching in HCl

Sheet resistance of 100 Ω/sq

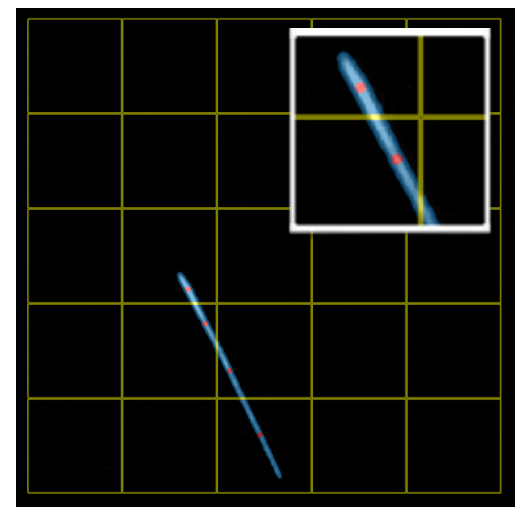
Alpha track reconstruction



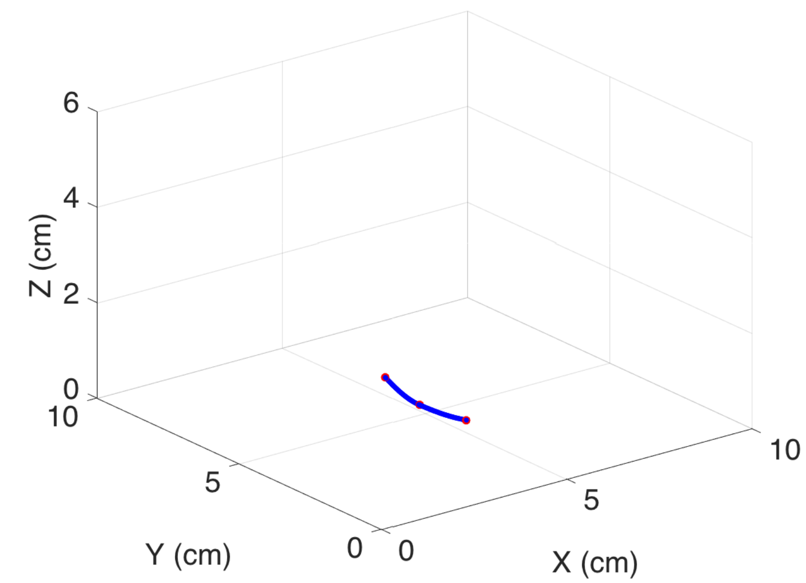
Depth information from pads



Raw image



Processed image with pad pattern overlay



3D reconstructed alpha track

Z-depth information is extracted from arrival times of electronic signals from ITO pads, image from camera is used to identify hit locations on pads (mean position of hit pixels in pad), 3D track points obtained from assigning depth information to each hit point, track from interpolation between points

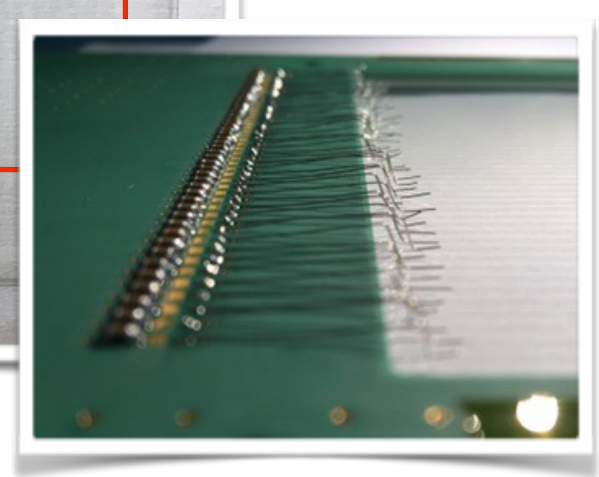
ITO strip anode

48 strips: 1.5 mm wide at 2 mm pitch

450 nm ITO on glass

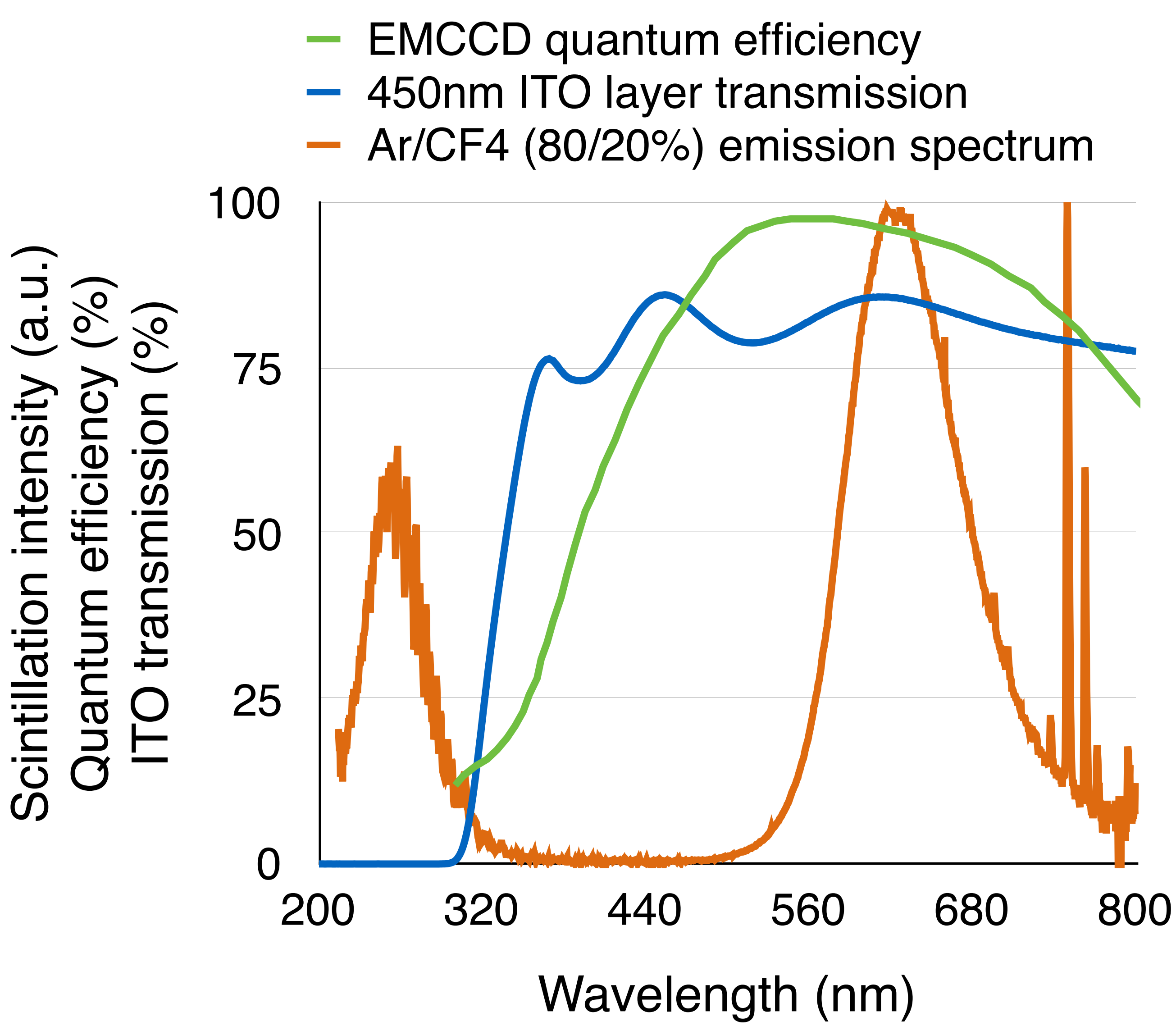
Structured by direct laser lithography and etching in 32% HCl

Sheet resistance of 4 Ω/sq results in resistance of ≈400 Ω across individual strips



Strips individually connected to APV25 channels by connection PCB with capacitive divider on each strip

ITO strip anode



Operated in TPC with Ar/CF_4 (80/20%) mixture at 1 bar

Optical readout with electron multiplying CCD camera

- >90% QE at 650 nm
- Externally triggered bulb mode operation

Electronic readout of individual strips of ITO anode by APV25 and RD51 Scalable Readout System (SRS)

- 27 time bins with 25 ns width
- Triggered by PMT scintillation signal

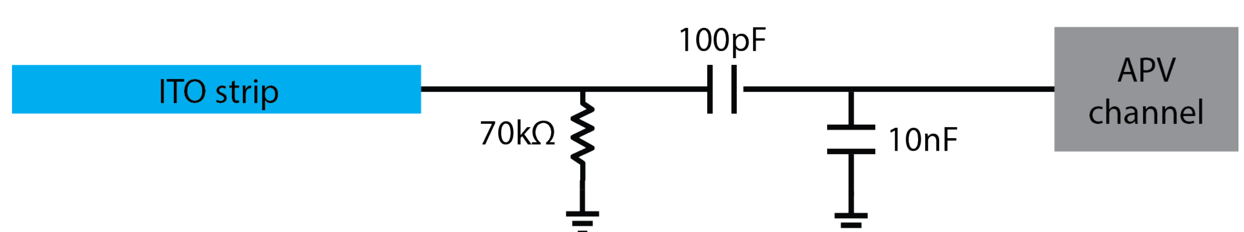
Signal attenuation

High gain
Sufficient secondary scintillation light for optical readout

Small electronic signal
Avoid saturation of electronic readout channels of APV25

Operating triple-GEM at gain of several 103, sufficiently strong secondary scintillation light to be recorded by camera is achieved

Employing capacitive voltage divider with attenuation factor of 100 and induction field of ≈2 kV/cm, saturation in APV channels is avoided



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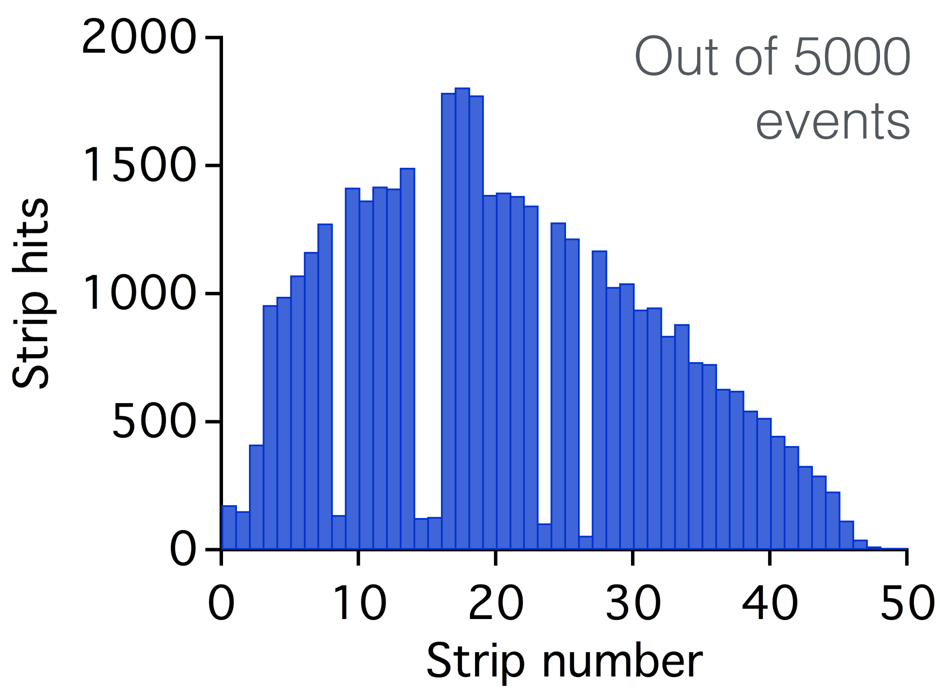
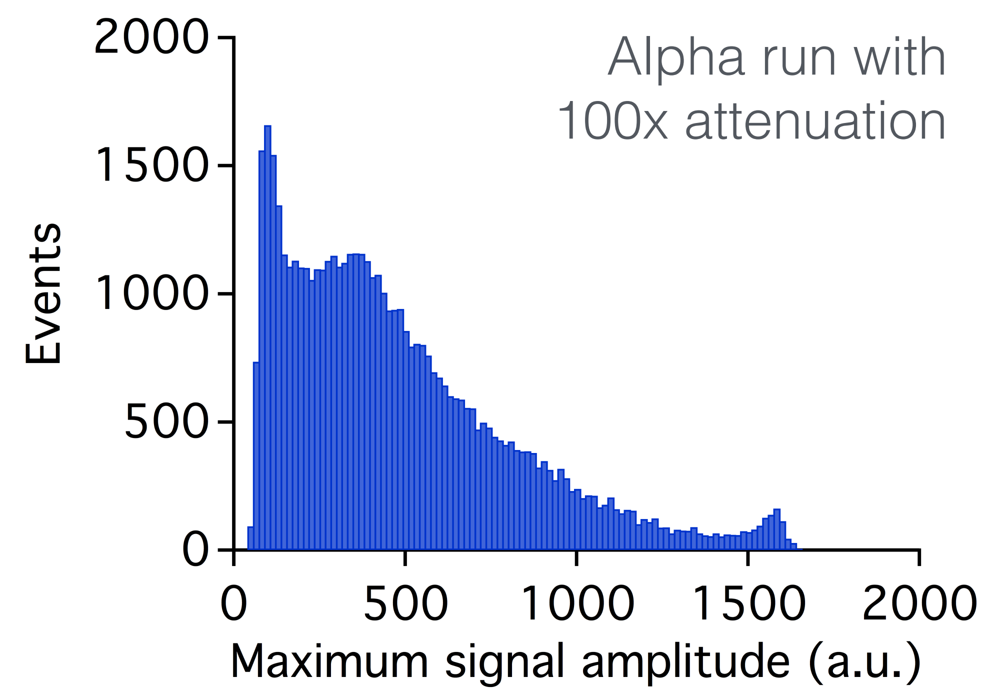
Electronic signals

Number of strip hits

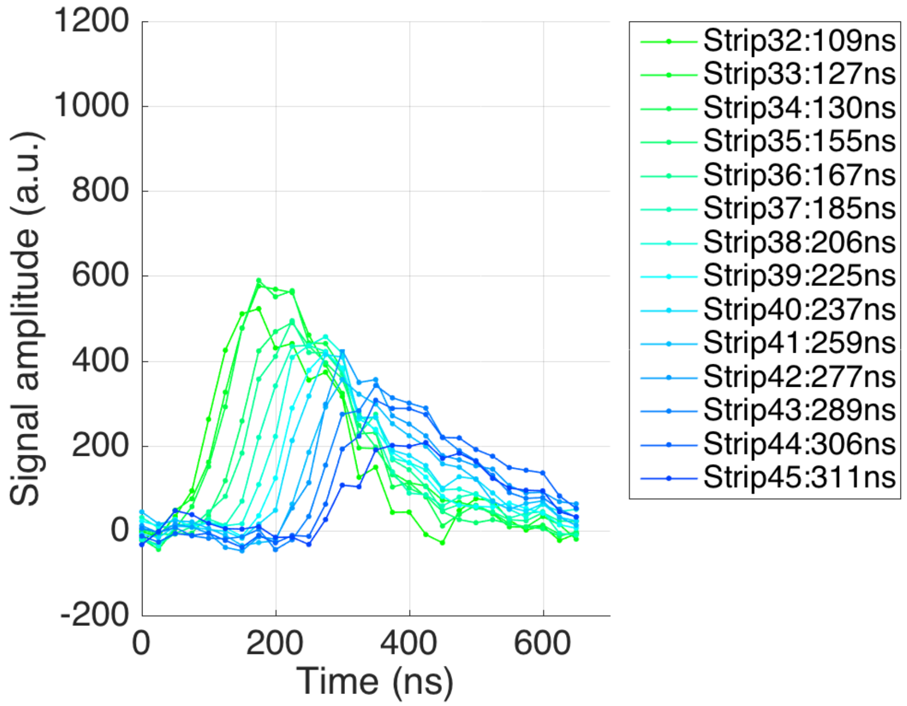


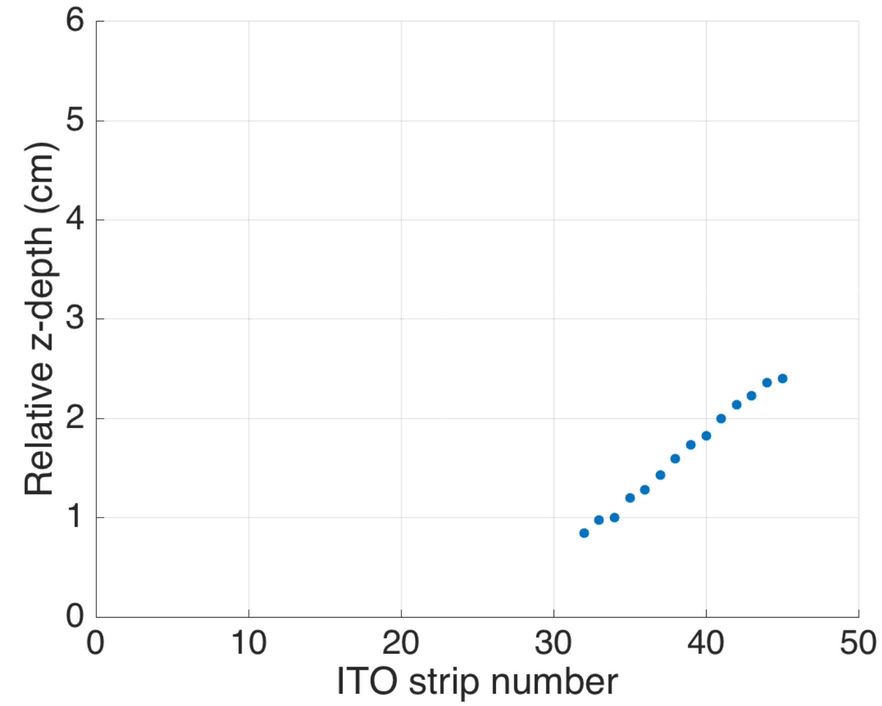
Maximum strip signal amplitude



Some dead strips due to connection of strips to APV via capacitive divider (shorts between channels), some saturation visible for alpha particles with 100x attenuation

Electronic readout



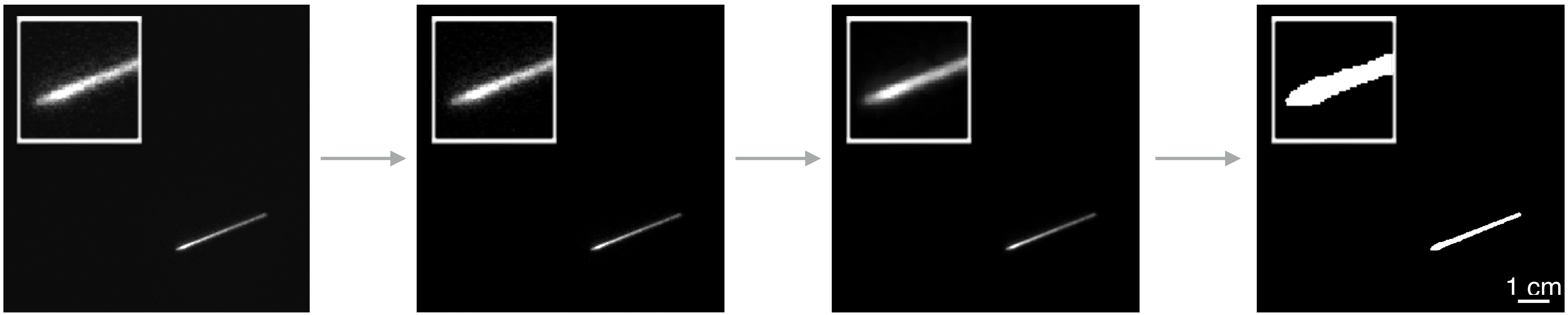


Waveforms from ITO anode strips acquired by APV25

Relative depth information from strips with 8 cm/μs drift velocity (300 V/cm drift field)

Arrival time determined by 30% constant fraction discrimination on rising edge
Differences in arrival time of electronic signals at different strips can be converted to relative z-information by multiplying arrival time differences by drift velocity

Optical readout



Raw image (512x512 px)

Background image subtracted

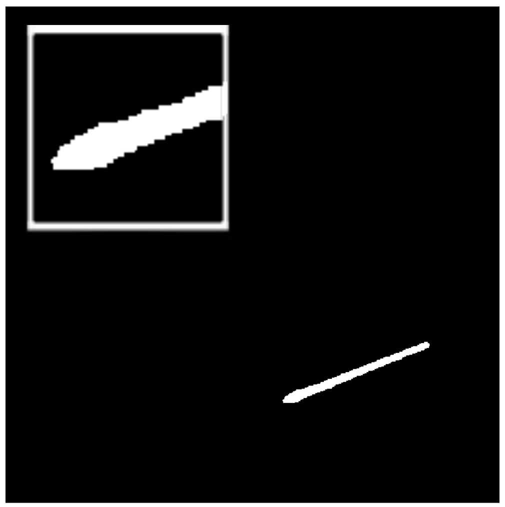
Median filtered image (4x4)

Binary image with threshold at 5000

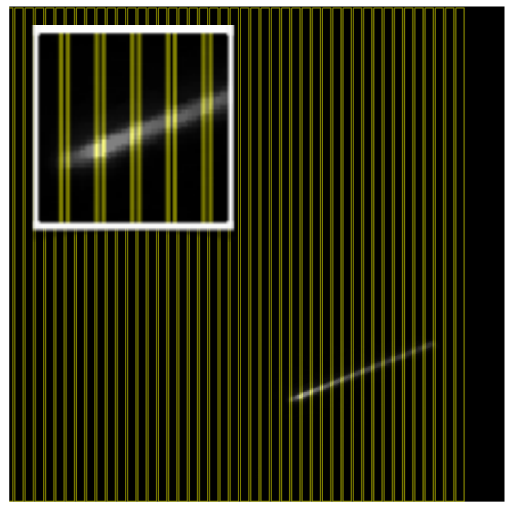
An averaged background image is subtracted from images acquired by the camera
The resulting image is median filtered to remove hot pixels and converted to a binary image

The shown images represent a 10x10 cm^2 area and are displayed with a range of 0-40000 in pixel value intensity

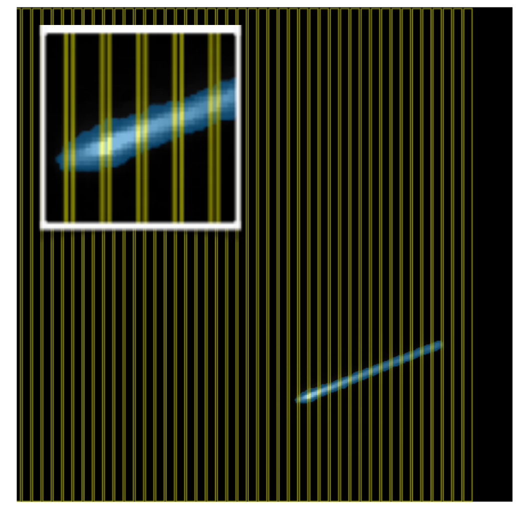
Optical readout



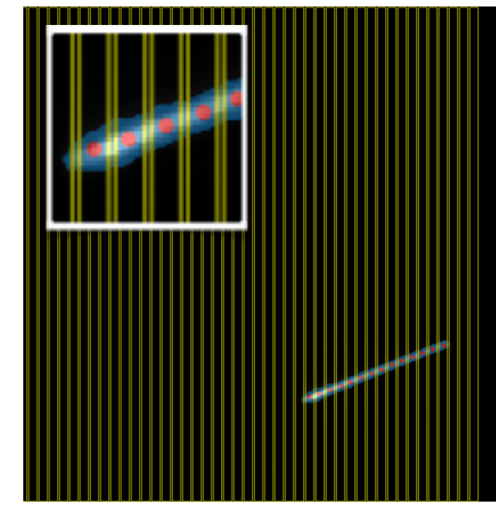
Using binary image as mask



Overlaying anode strip pattern



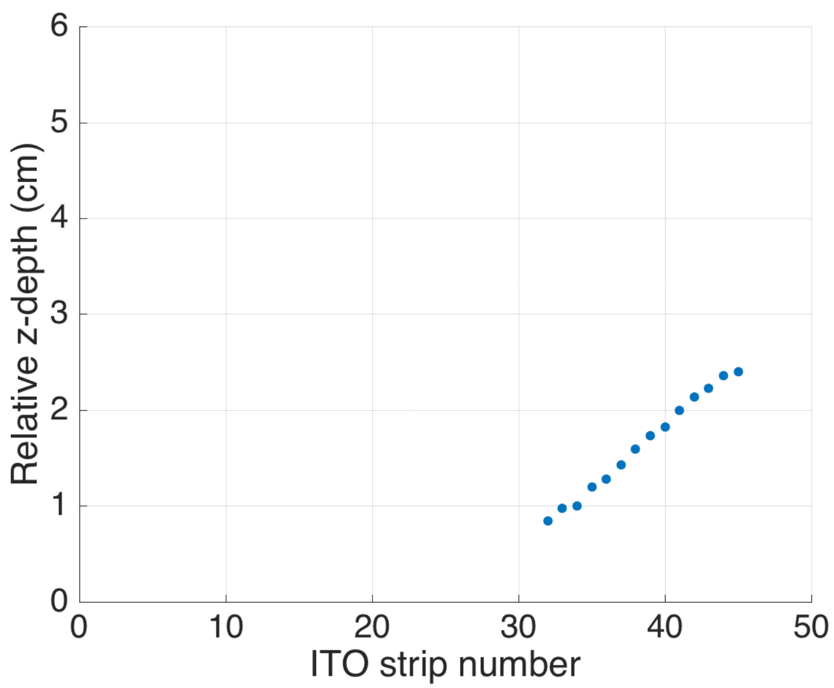
Identifying hit pixels within strips

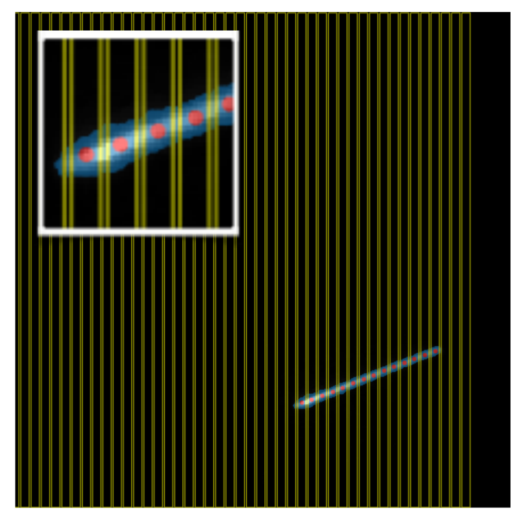


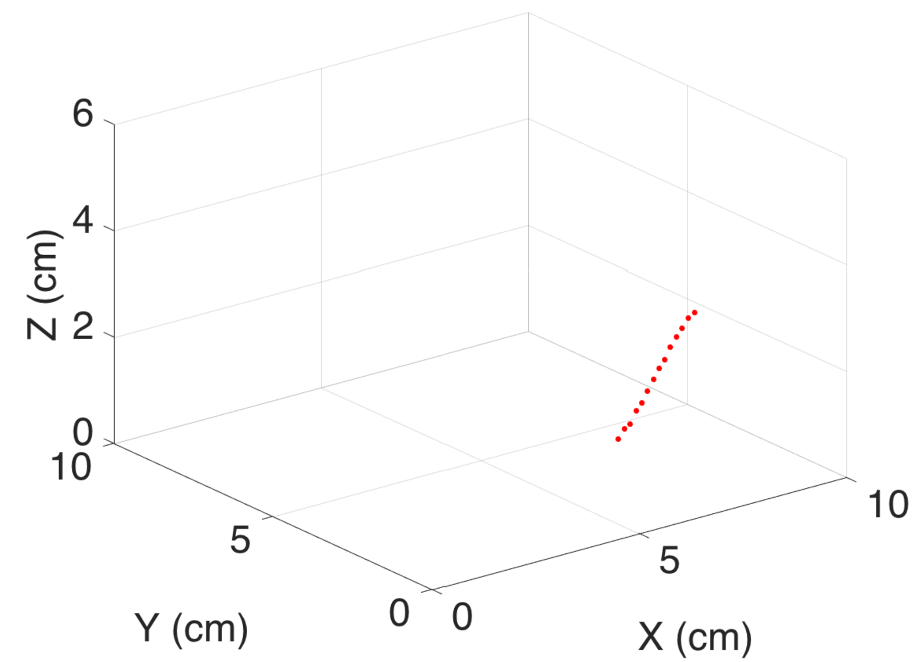
Determining mean positions of strip hits

Hit points on each anode strip are determined from averaging all hit pixels identified by the binary image within a certain strip

Combining information



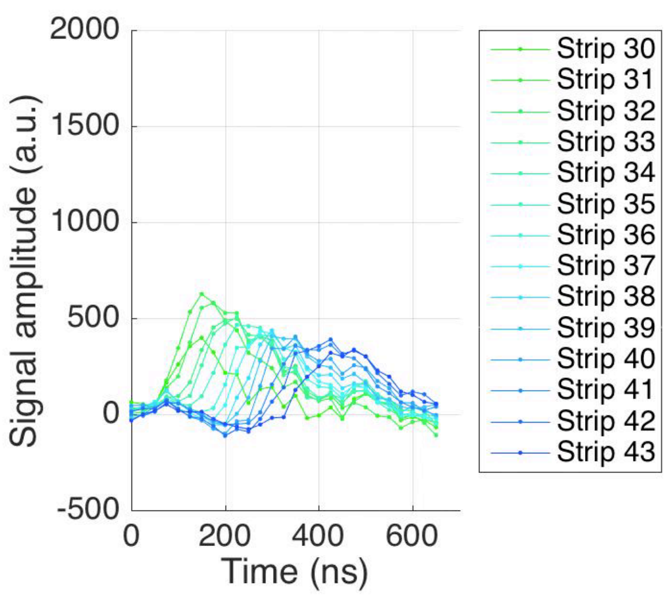




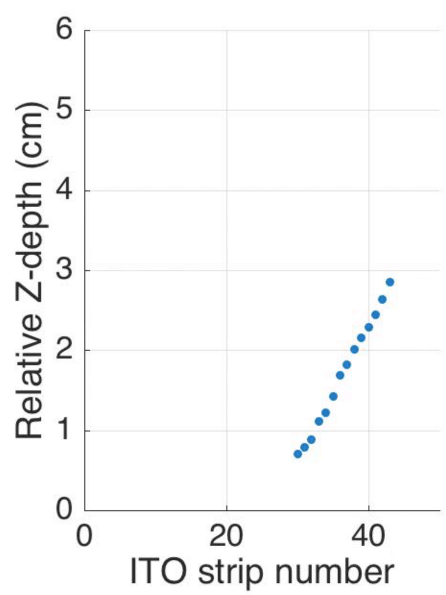
Relative depth information for each hit strip from electronic readout is combined with 2D positions of strip hits from optical readout to 3D track points

Alpha tracks

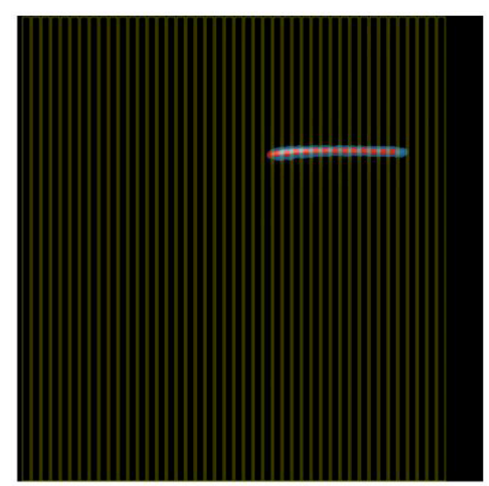
ITO strip signals



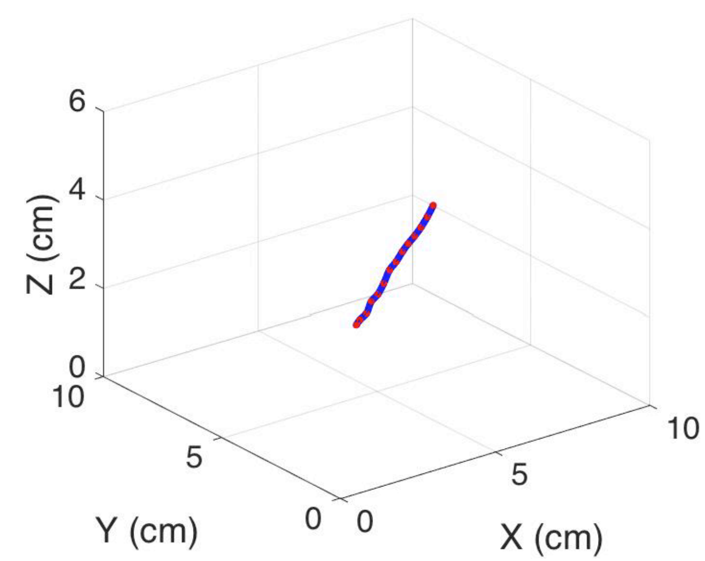
Depth information



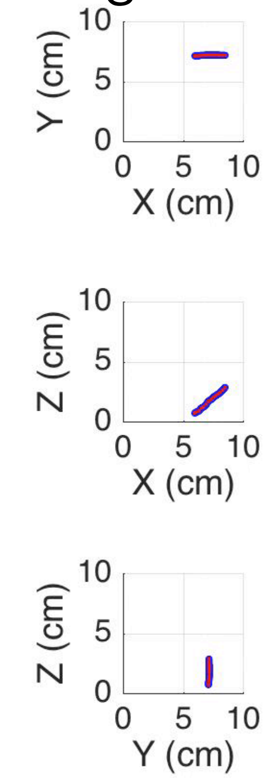
Camera image



3D track visualisation



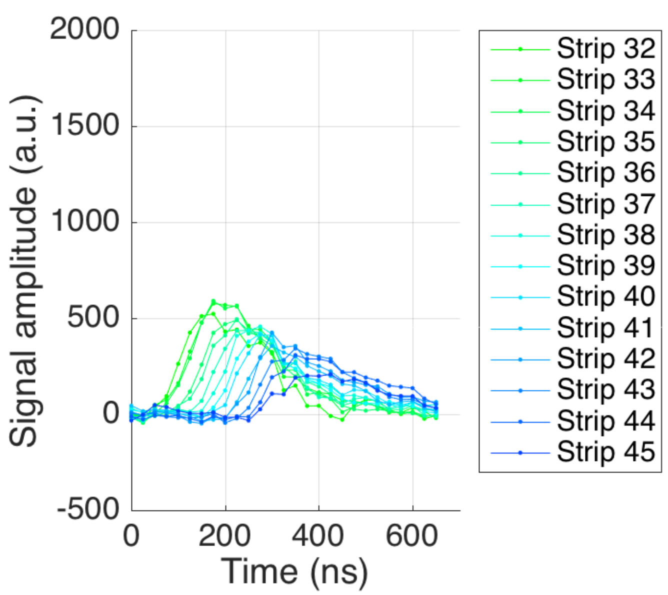
Projections



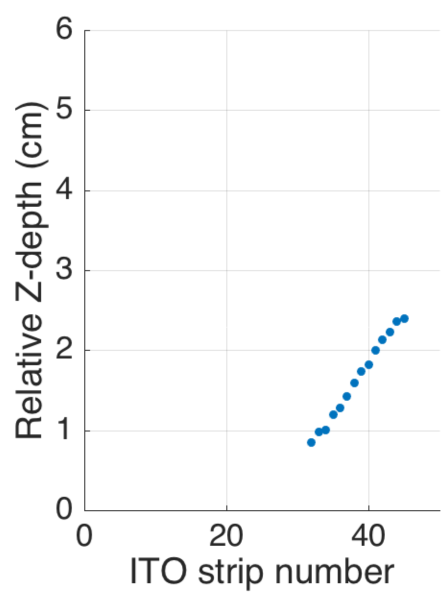
^{220}Rn flushed into gas, 300 V/cm drift field, GEMs operated at 380V, 1.8 kV/cm induction field, 100x signal attenuation, recorded event rate ≈1.5 Hz, recorded with EMCCD camera with EM gain of 1000x

Alpha tracks

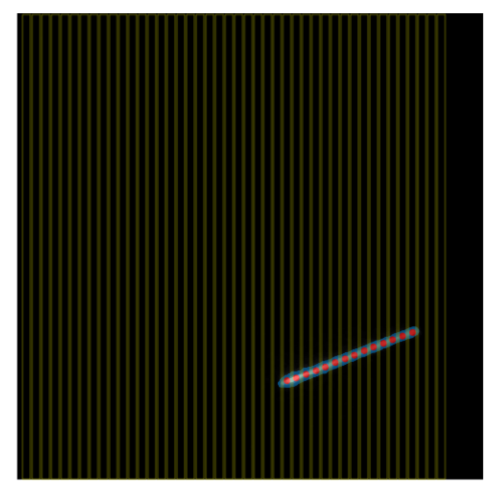
ITO strip signals



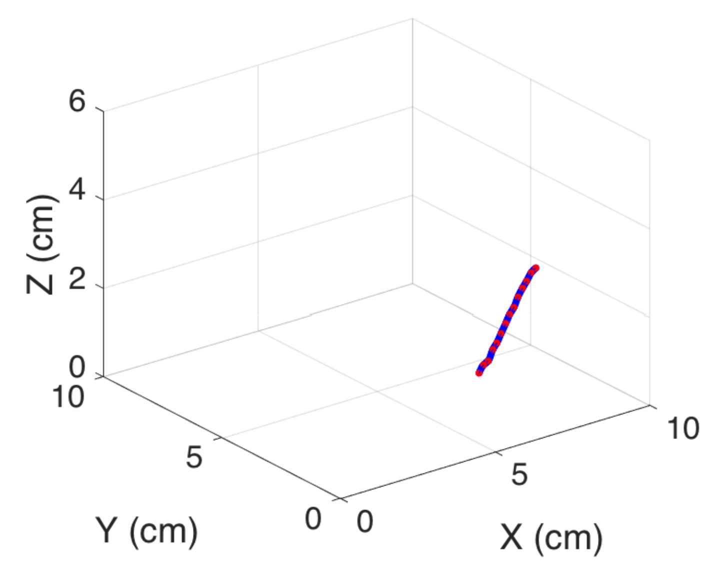
Depth information



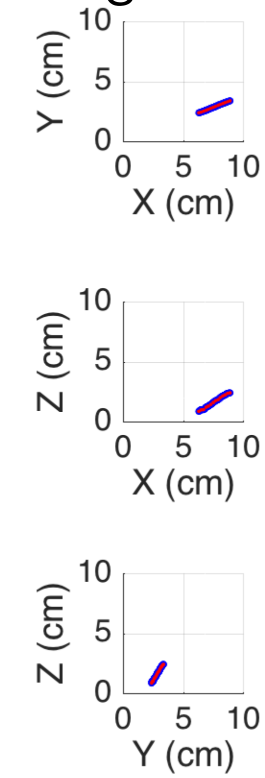
Camera image



3D track visualisation

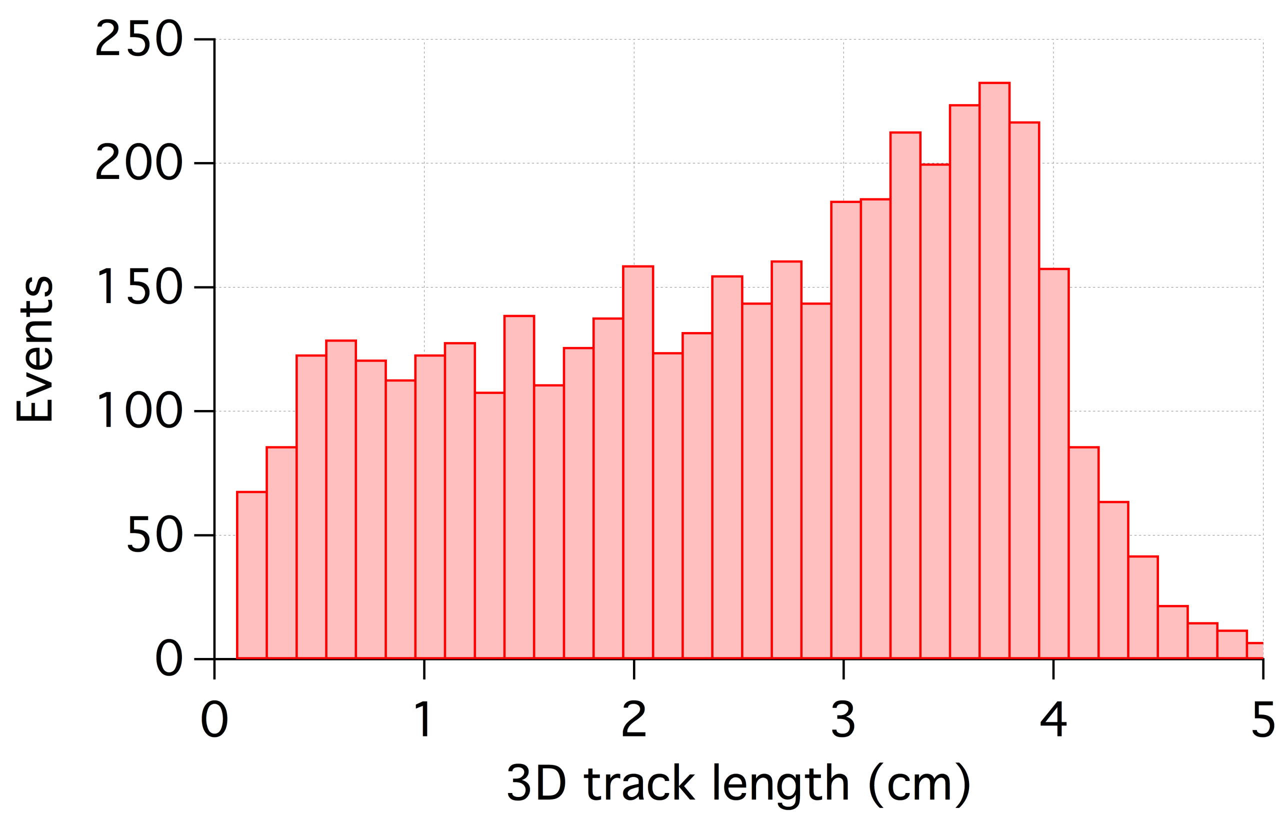


Projections



^{220}Rn flushed into gas, 300 V/cm drift field, GEMs operated at 380V, 1.8 kV/cm induction field, 100x signal attenuation, recorded event rate ≈1.5 Hz, recorded with EMCCD camera with EM gain of 1000x

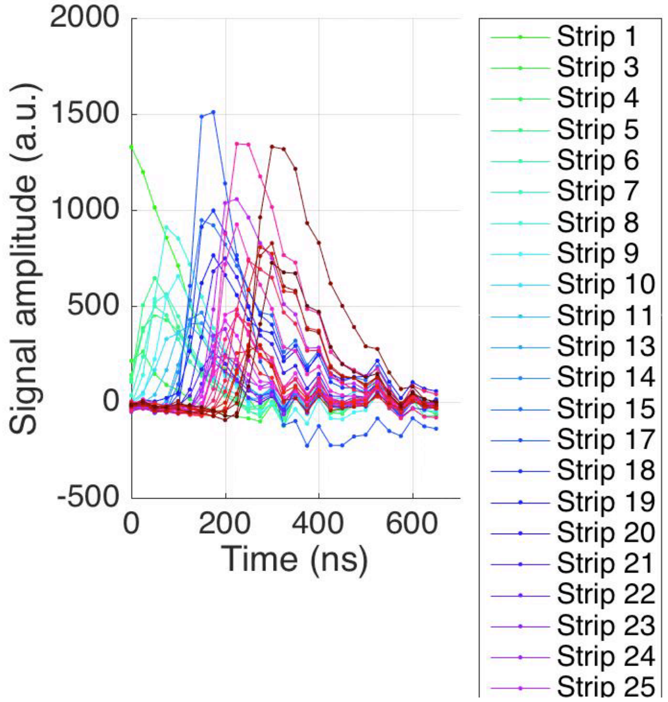
Track length distribution



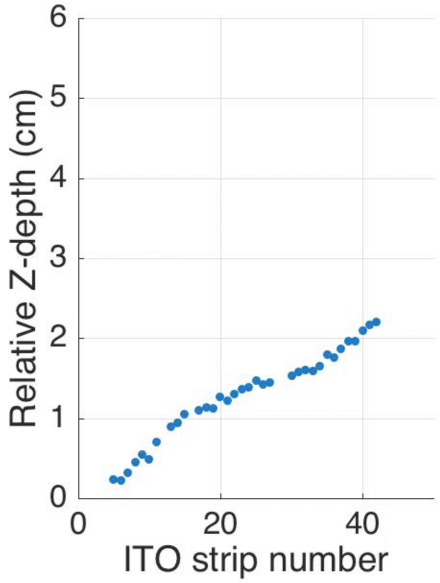
Distribution of track lengths from 3D reconstruction of 6.4 MeV alpha particle tracks shows a shoulder attributed to partially contained tracks and a peak at fully contained tracks

Cosmic events

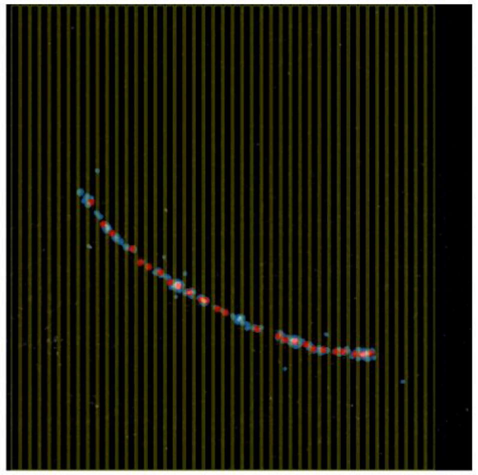
ITO strip signals



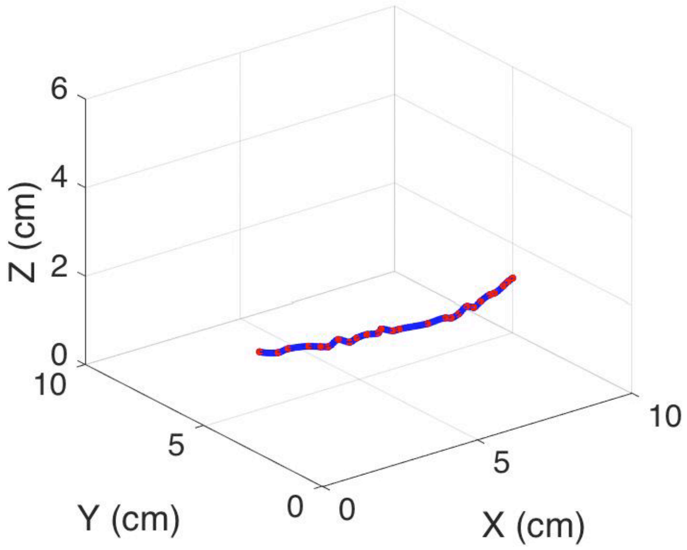
Depth information



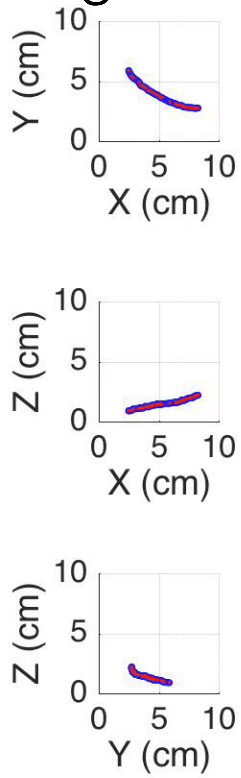
Camera image



3D track visualisation



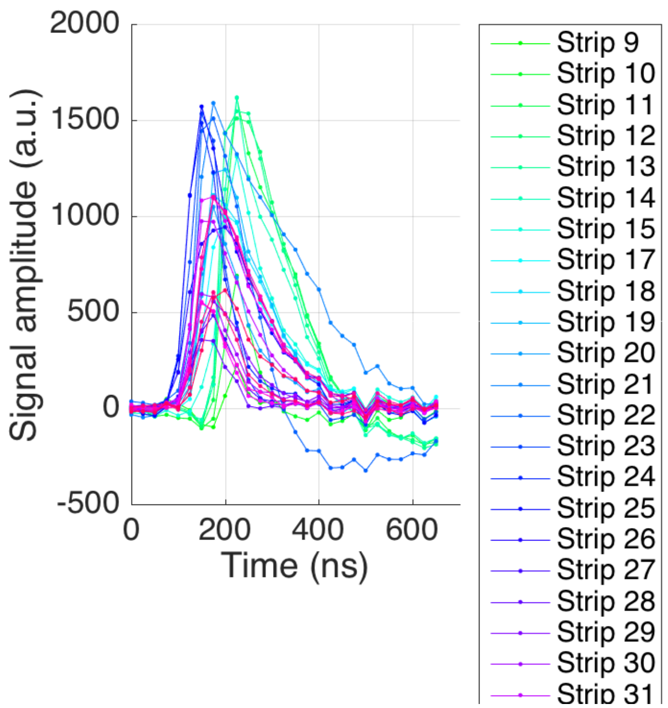
Projections



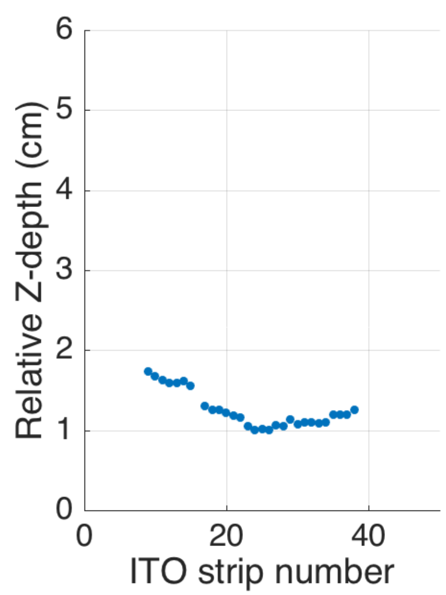
300 V/cm drift field, GEMs operated at 400V, 0.65 kV/cm induction field, no signal attenuation, recorded event rate ≈1 Hz, recorded with EMCCD camera with EM gain of 1200x and 5x signal amplification

Cosmic events

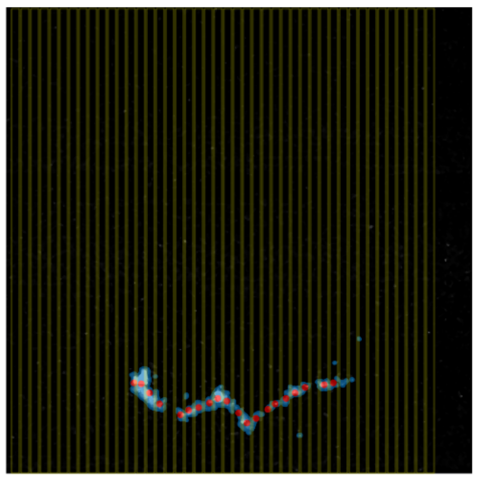
ITO strip signals



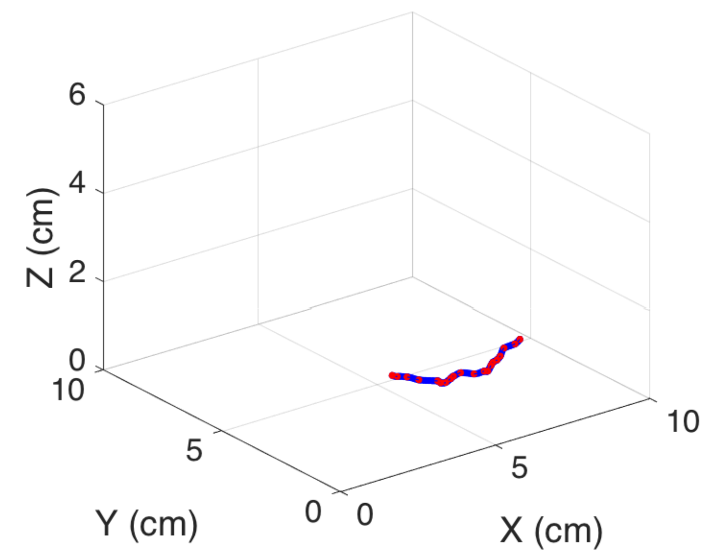
Depth information



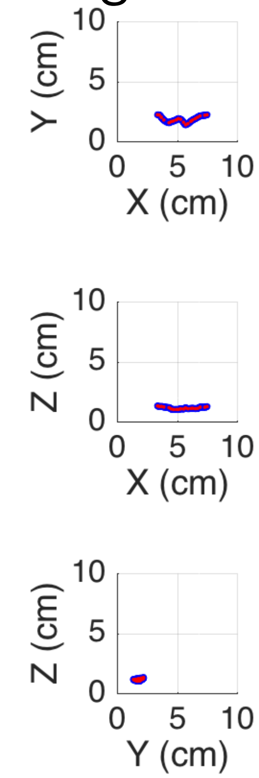
Camera image



3D track visualisation



Projections



300 V/cm drift field, GEMs operated at 400V, 0.65 kV/cm induction field, no signal attenuation, recorded event rate ≈1 Hz, recorded with EMCCD camera with EM gain of 1200x and 5x signal amplification

Next steps

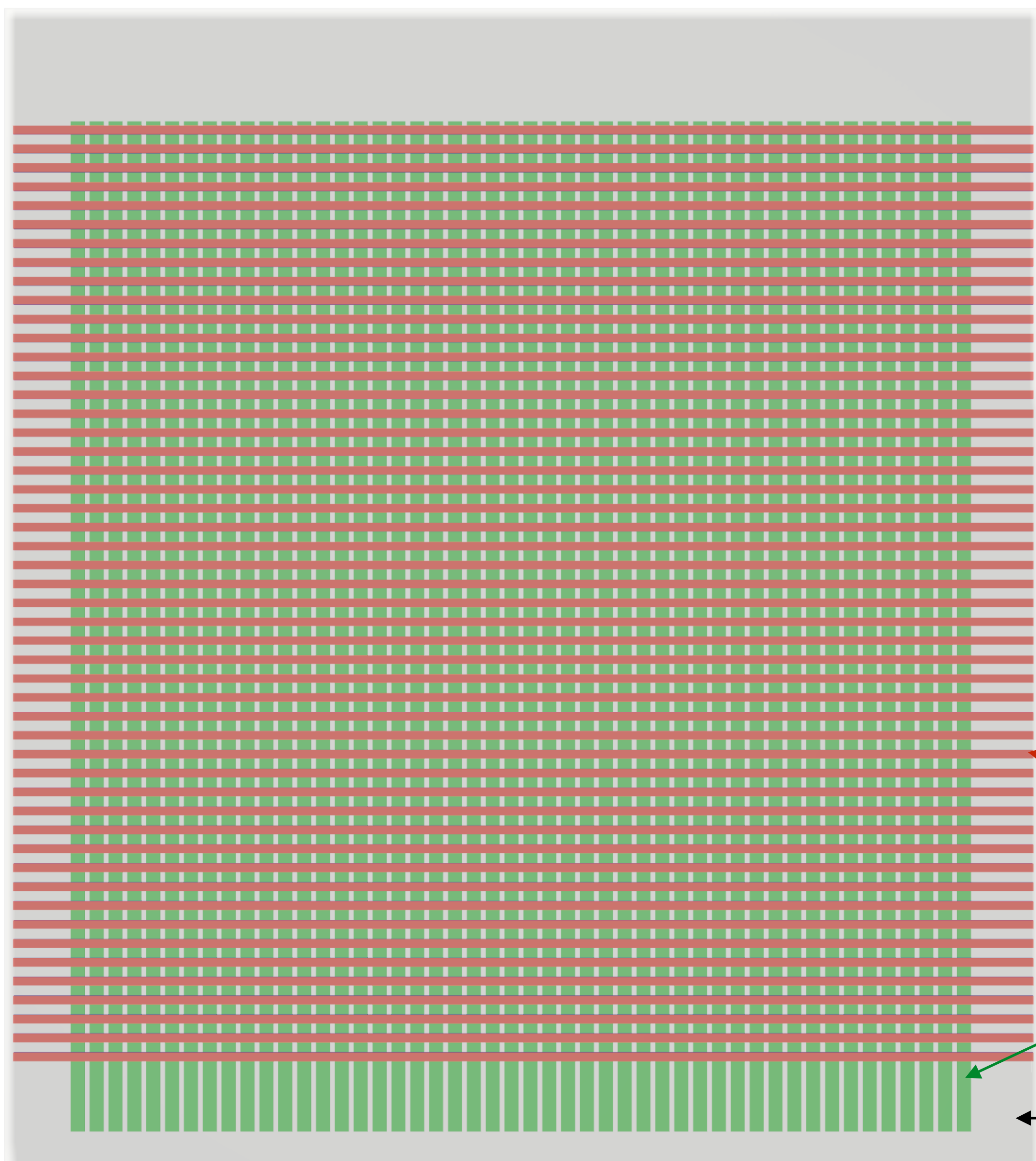
2D strip anode

- Reduced ambiguity for complex track geometries
- Alternatively, combination of ITO anode and wires

VMM3 readout

- Instead of APV25 readout
- Higher dynamic range possibly allows operation without electronic signal attenuation
- Finer time sampling improves Z-coordinate resolution

2D ITO strip anode



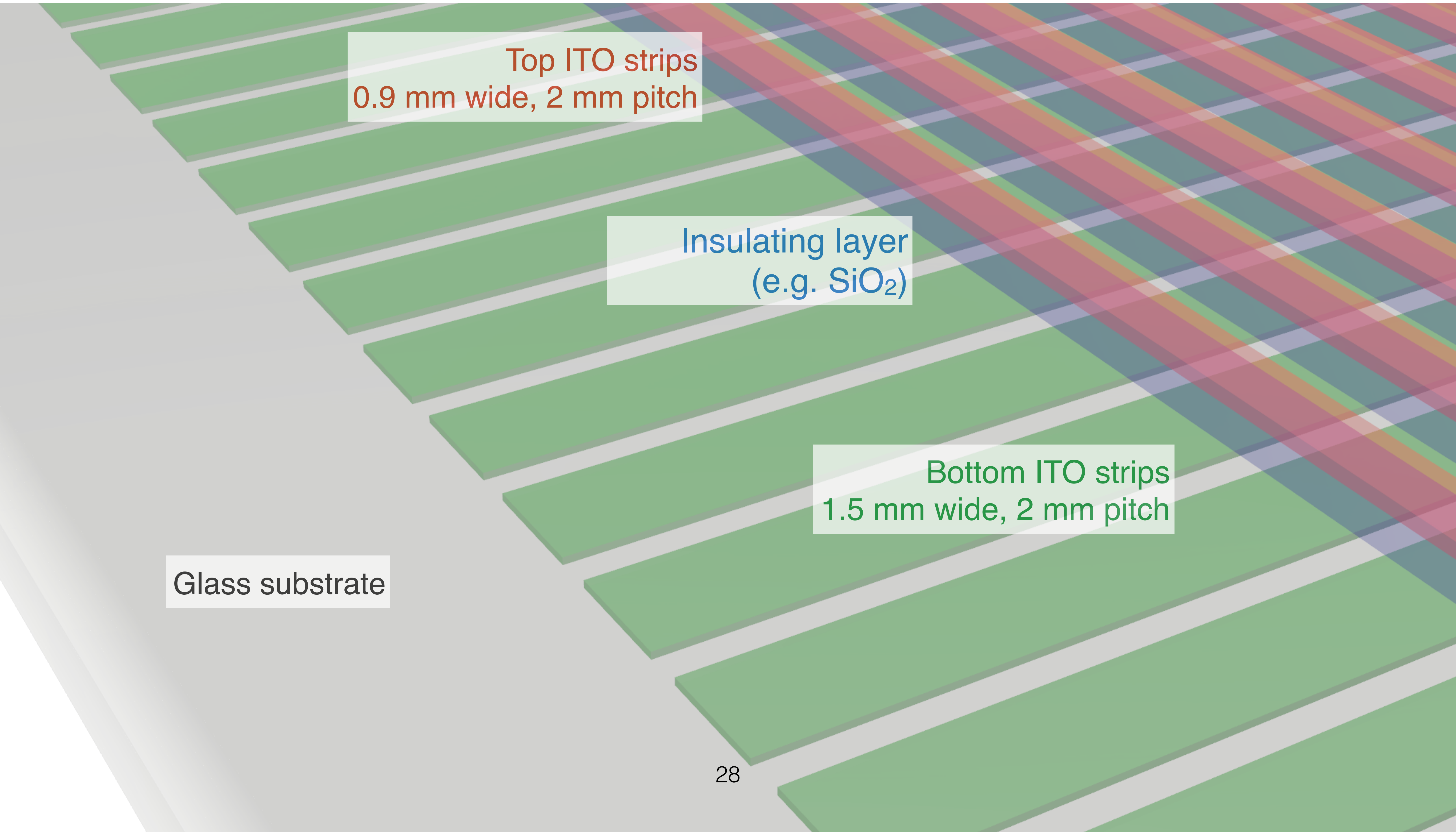
2D strips made of ITO deposited on glass substrate with insulating layer between them

Top strips
0.9mm wide, 2mm pitch

Bottom strips
1.5mm wide, 2mm pitch

Glass substrate

2D ITO strip anode

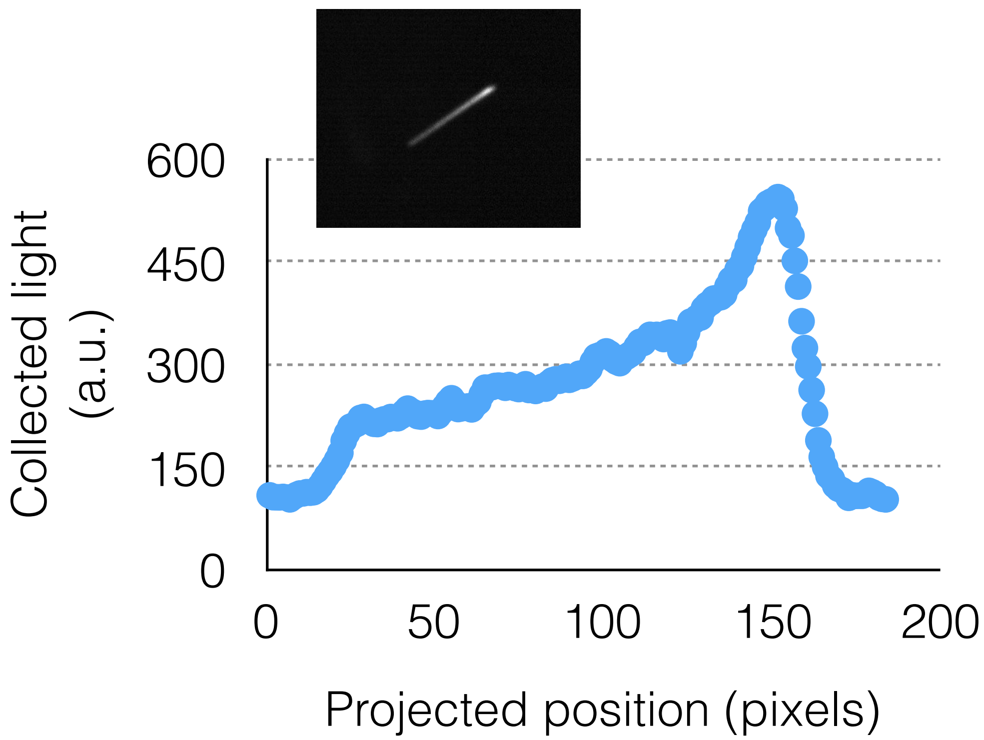


Summary

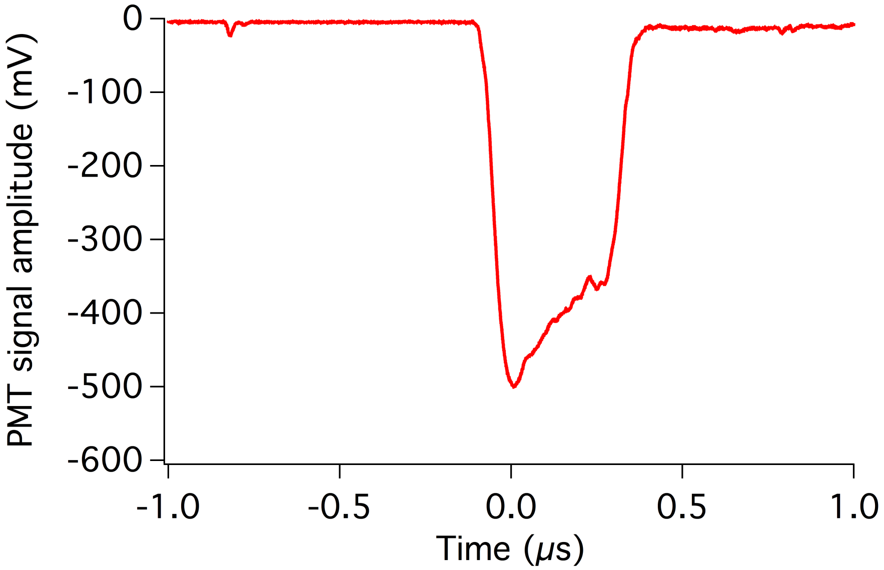
- 3D reconstruction capabilities of optically read out GEM-based TPC extended beyond straight tracks by combination of optical and electronic readout
- Fabrication of structured ITO anodes by photolithographic methods
- Low number of electronic readout channels required and high spatial resolution projection obtained from optical readout
- Reconstruction of curved events demonstrated
- Applicability to intricate track geometries limited by 1D strips and signal attenuation required due to limited dynamic range of APV25
- 2D ITO anode and other readout electronics could overcome these limitations

Backup

Orientation by Bragg curve

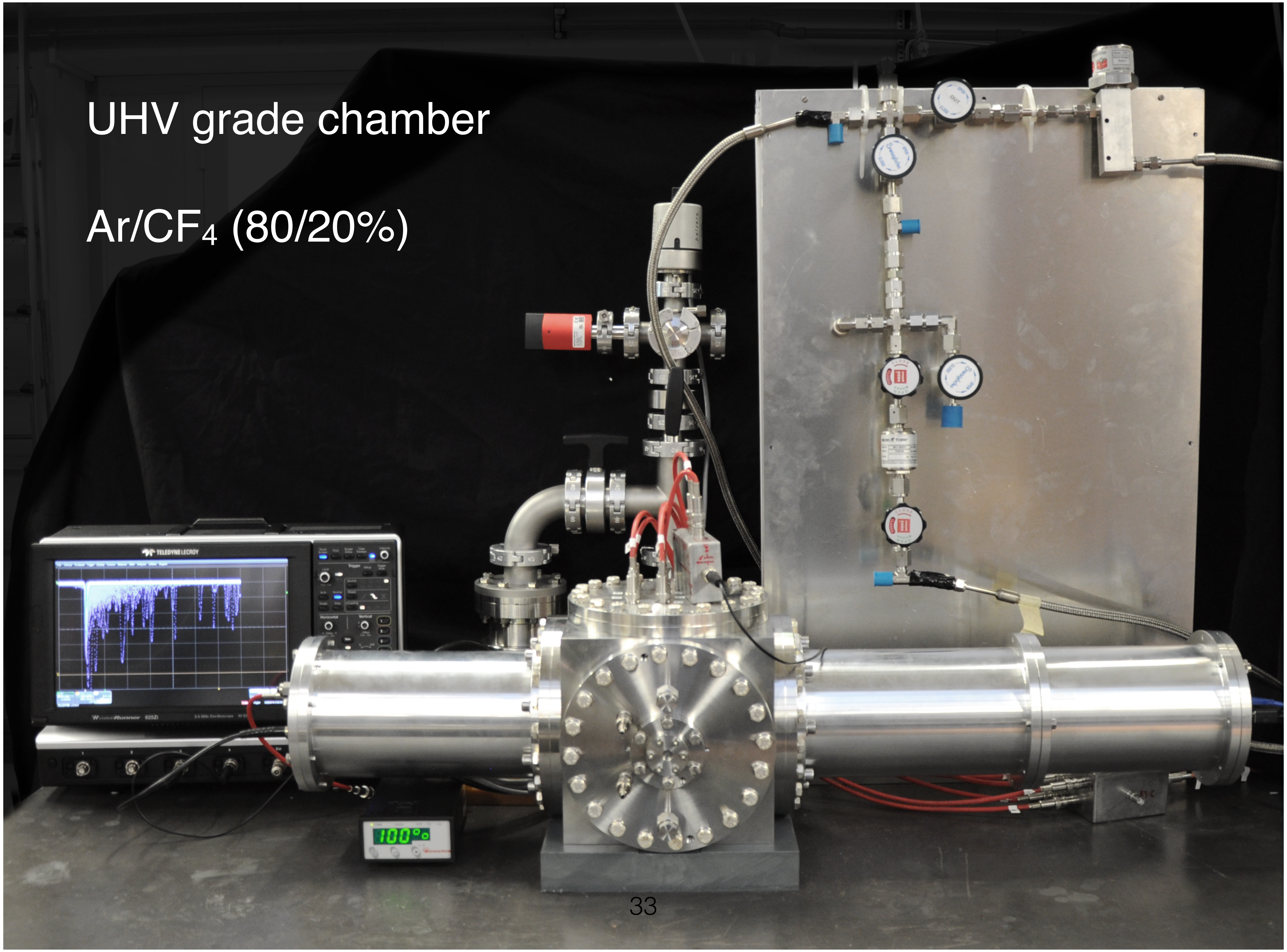


Intensity profile from CCD image



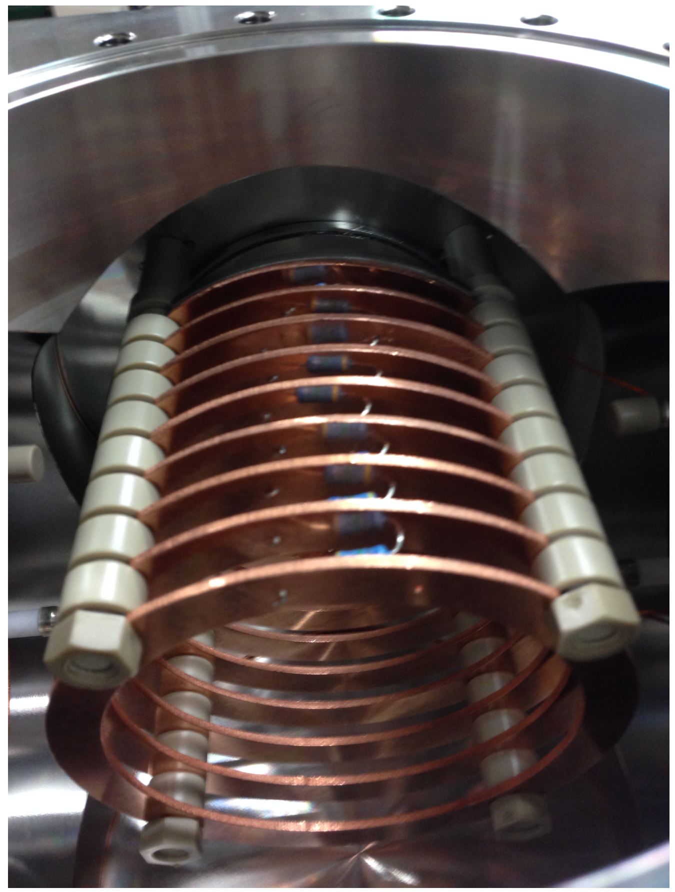
PMT waveform

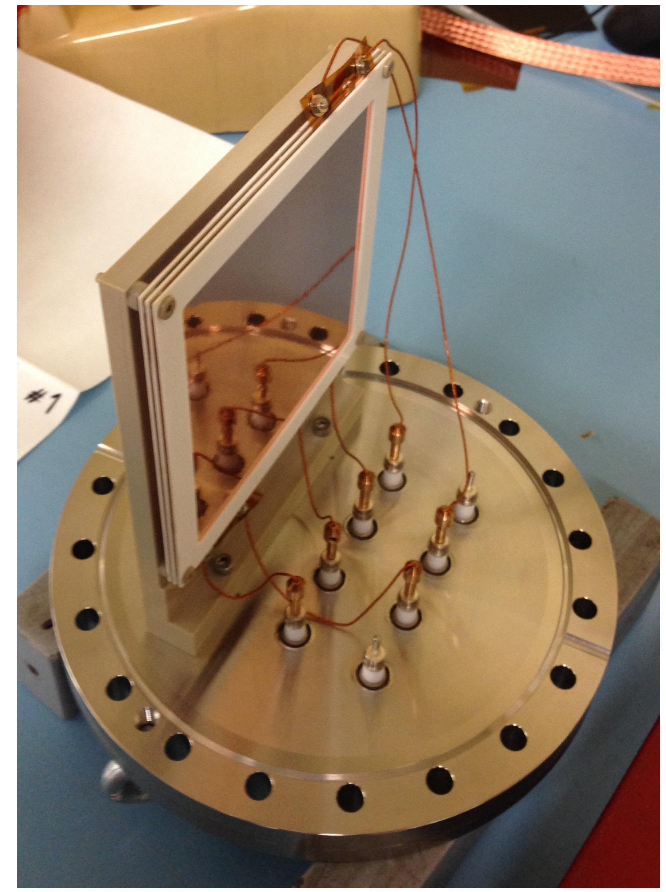
Bragg peak earlier in time ⇒ Track oriented towards GEMs



UHV grade chamber

Ar/CF_4 (80/20%)





Field shaper

⌀ 10 cm, length 10 cm

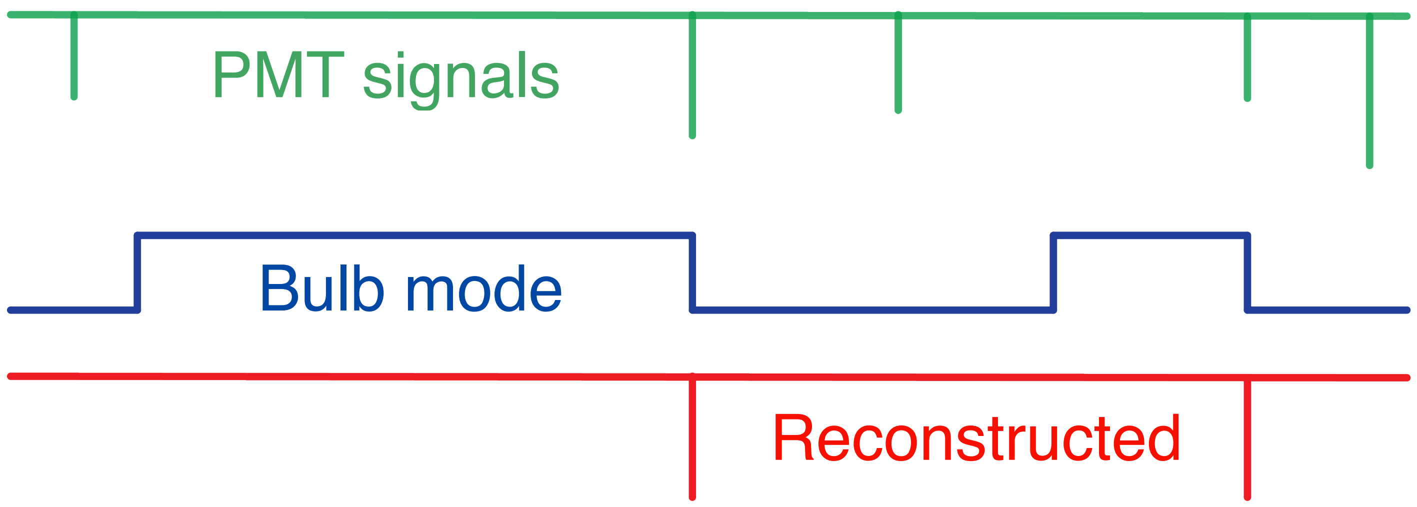
Cu rings, PEEK rods

Triple GEM

10 x 10 cm^2

70 μm holes, 140 μm

Bulb mode exposure and triggering

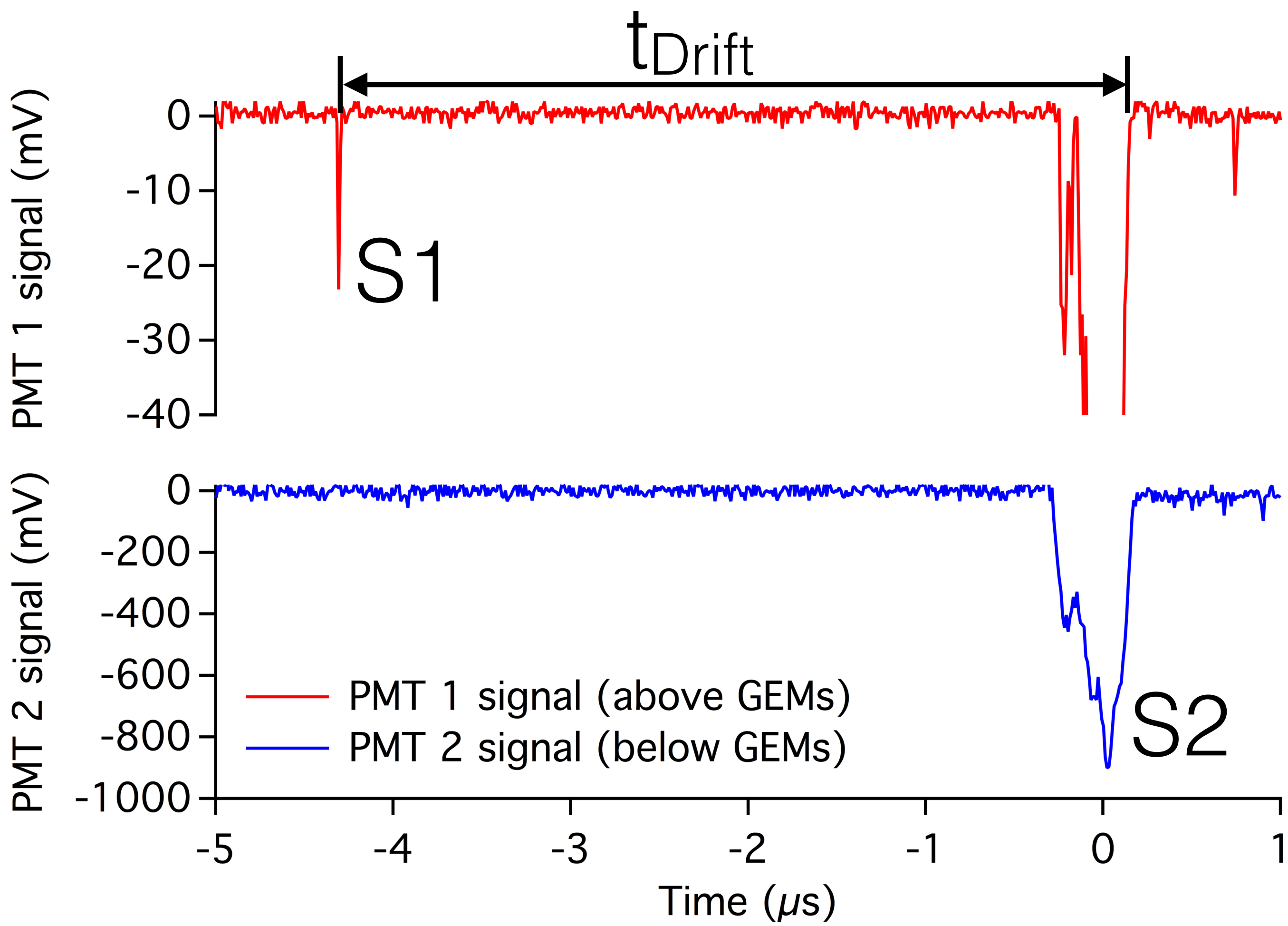


- Bulb mode exposure of camera stopped by trigger from PMT when system not busy
- Image from camera and waveform from PMT read out and stored
- Possible online event display
- Limited by frame rate of camera and readout of devices

$^{220}Rn \rightarrow {}^{216}Po \rightarrow {}^{212}Pb$

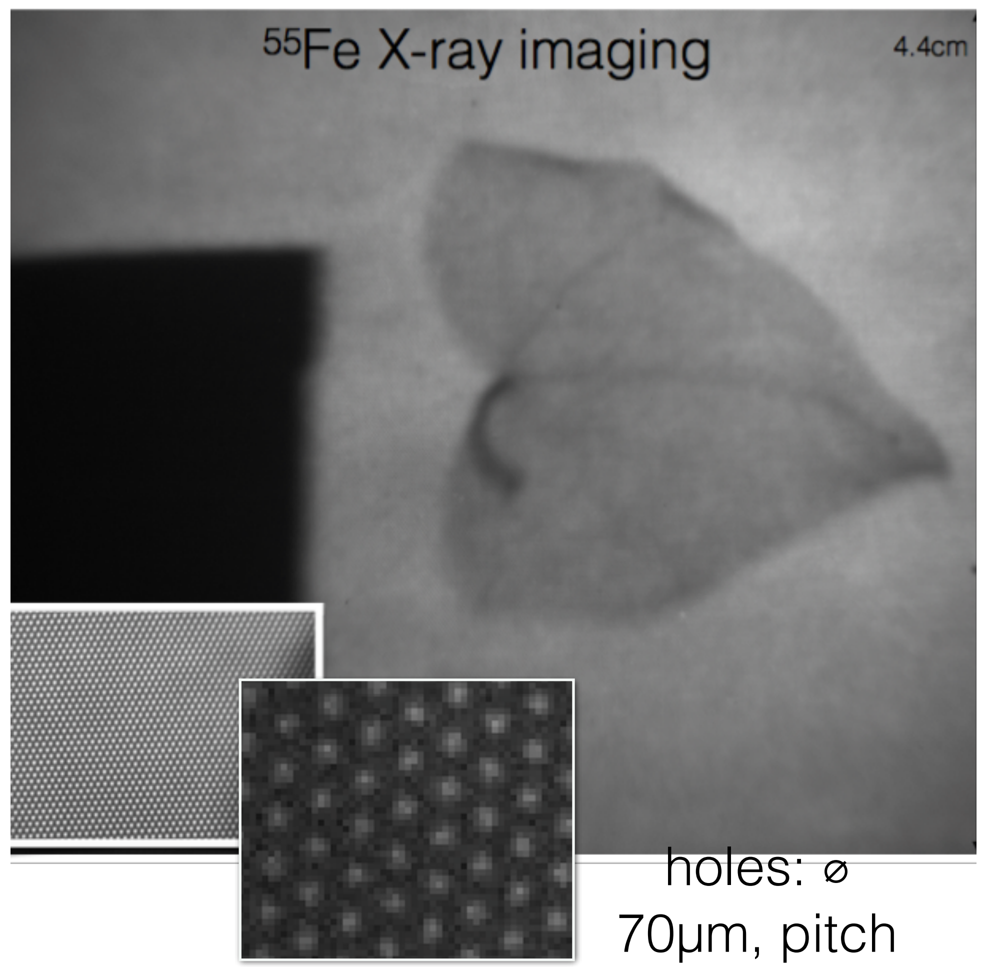
- Ar/CF_4 (80/20%) flushed through Th cartridge
- α-decays in chamber from Rn and Po
- 6.4 MeV α-tracks from Rn are ≈ 4.5 cm long at 1 bar
- α-decay of Po with half life λ = 140 ms

α signal



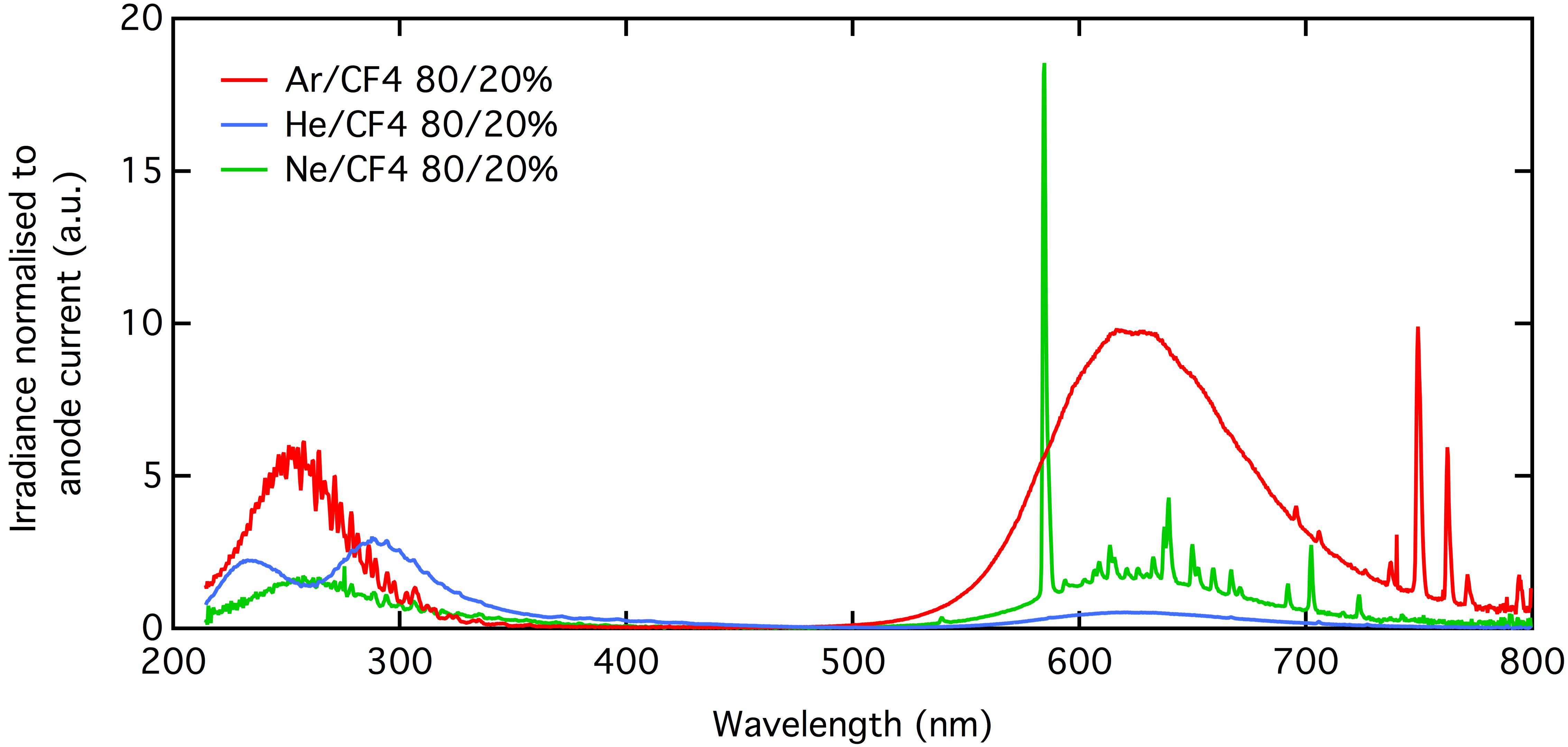
Primary (S1) and secondary (S2) scintillation of α-tracks

Imaging



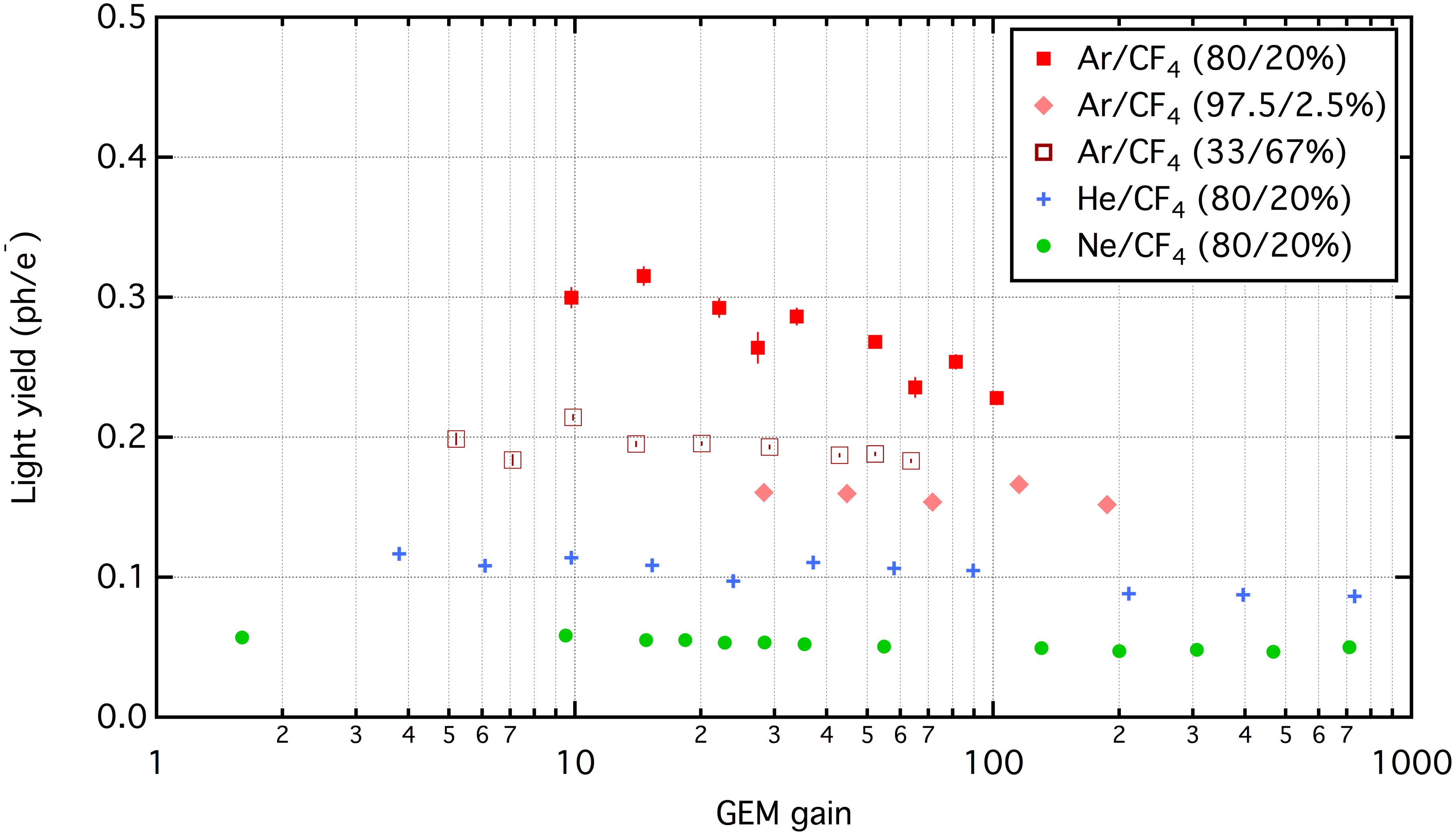
holes: ⌀ 70µm, pitch 140µm

Scintillation spectra



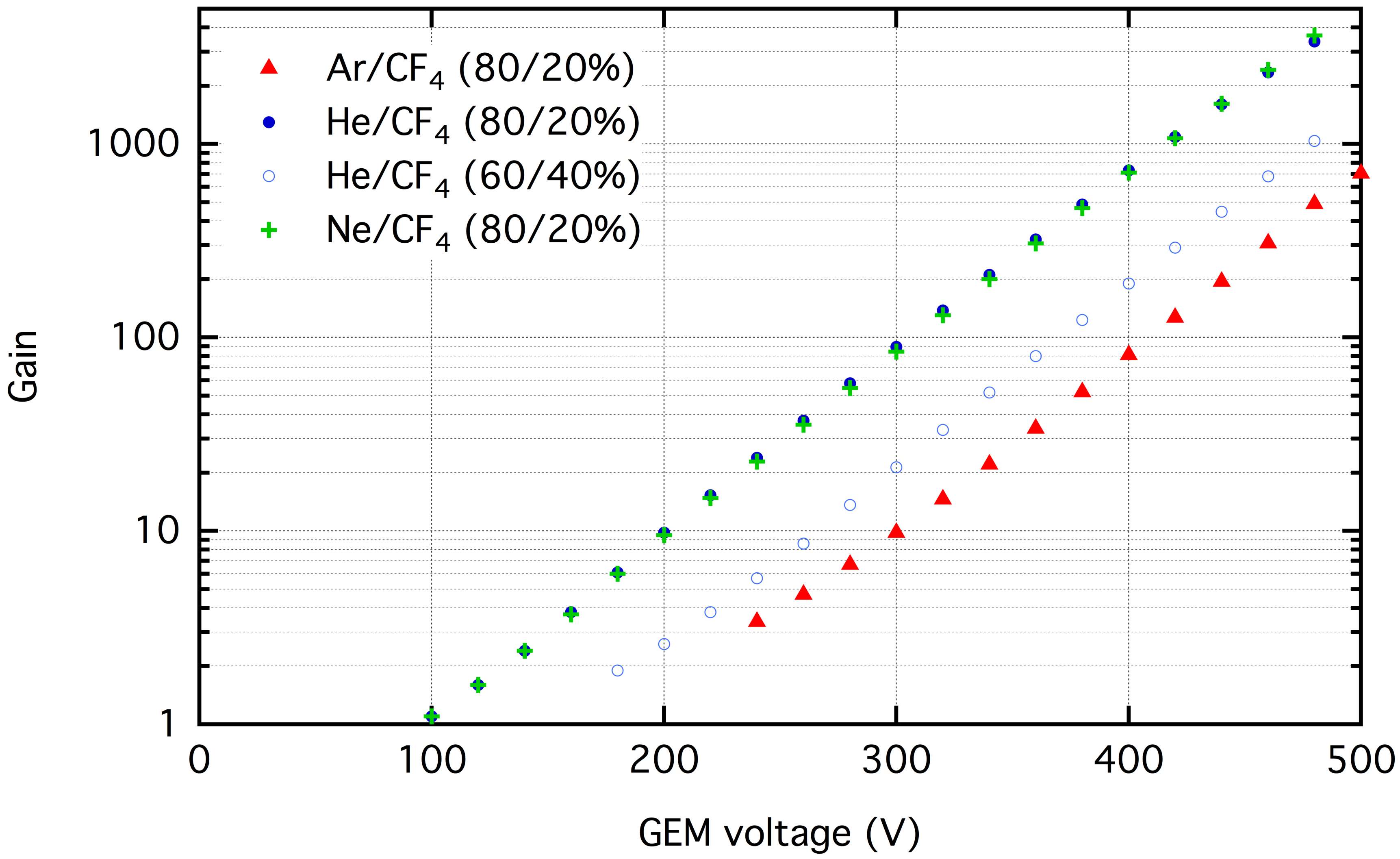
Secondary scintillation spectra of triple GEM under X-ray irradiation, normalised to anode (GEM3 bottom) current

Light yield



Light yield (photons / secondary electrons) for 200-800nm range
Up to 0.3 photons / electron for Ar/CF_4 80/20%

Single GEM gain



Light yield of He or Ne based mixtures is lower but higher gains are reached with the same voltage drops compared to Ar based mixtures

Camera options

QImaging Retiga R6	Hamamatsu ORCA-Flash4.0 V3	Hamamatsu ImagEM X2
		
6MP **CCD camera**	4MP **CMOS camera**	0.25MP **EM-CCD camera**
4.54x4.54μm^2 pixels 5.7e- read noise 20Hz frame rate	6.5x6.5μm^2 pixels 1.6e- read noise 100Hz frame rate	16x16μm^2 pixels EM gain up to 1200x 1e- read noise (max.) 70Hz frame rate

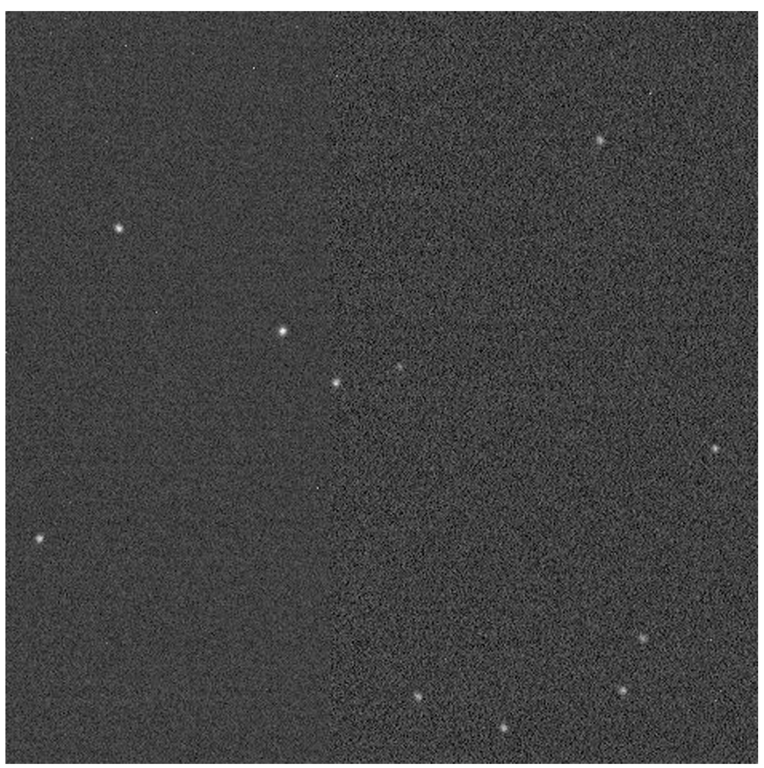
SNR for ^{55}Fe events

QImaging
Retiga R6

Hamamatsu
ORCA-Flash4.0 V3

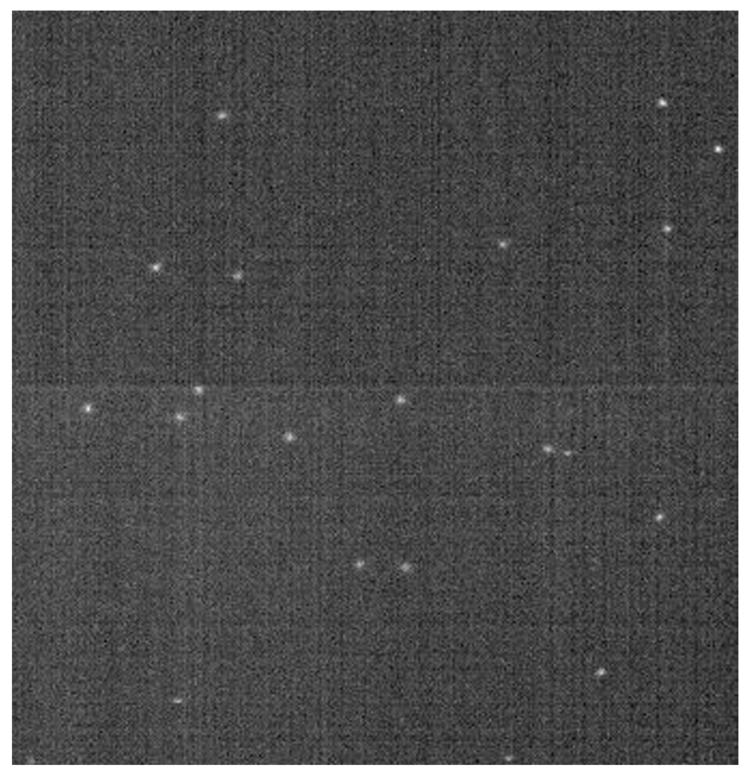
Hamamatsu
ImagEM X2

(a)



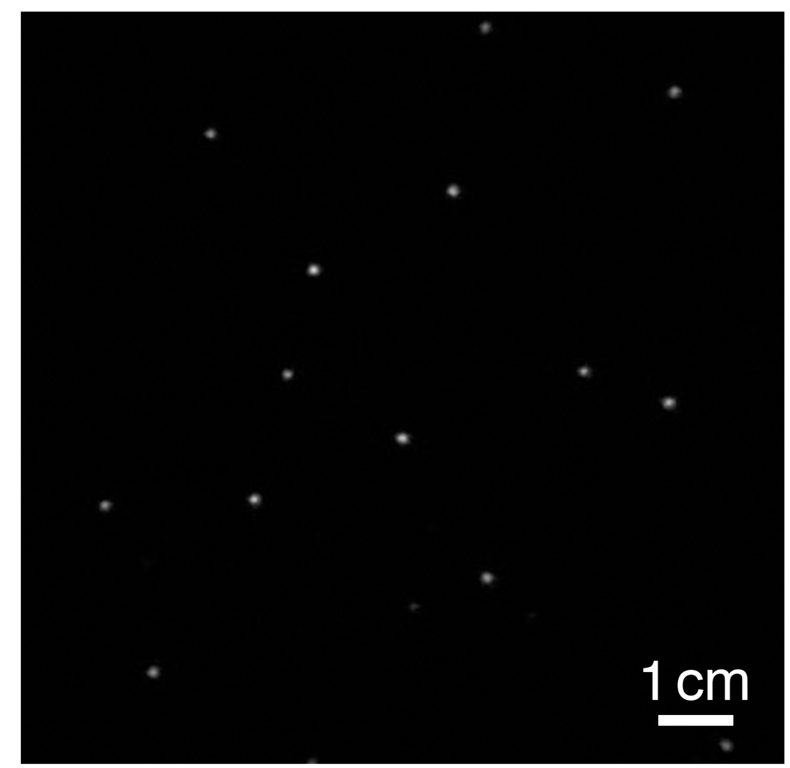
SNR = 14

(b)



SNR = 12

(c)

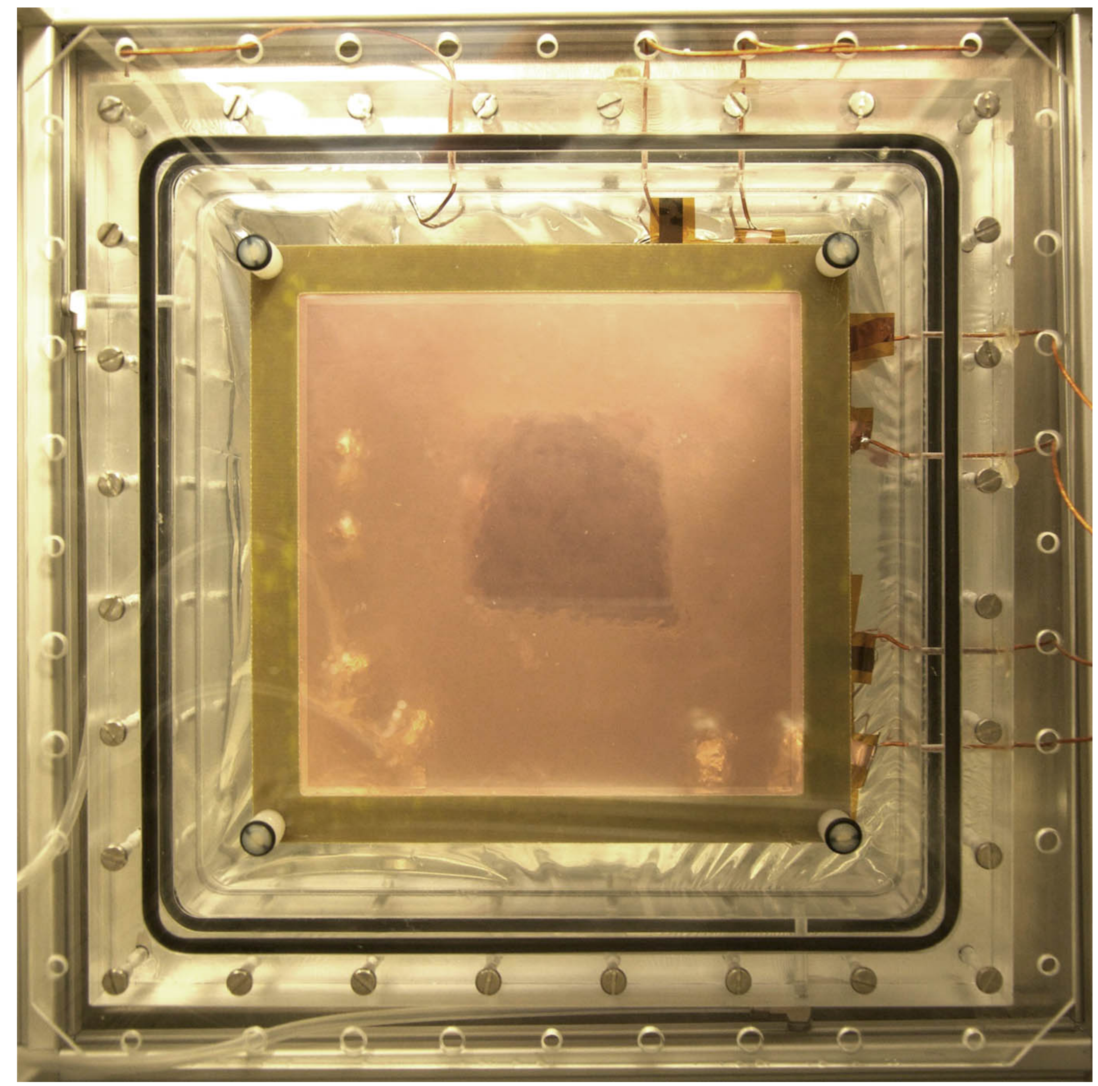


SNR = 600

Optical readout of GEMs

25mm **lens**
aperture: f/0.95

17mm **lens**
aperture: f/0.95



10x10cm^2 **triple-GEM** in
transparent gas volume