The Simulation of Gas Avalanche in a Micro Pixel Chamber using Garfield++

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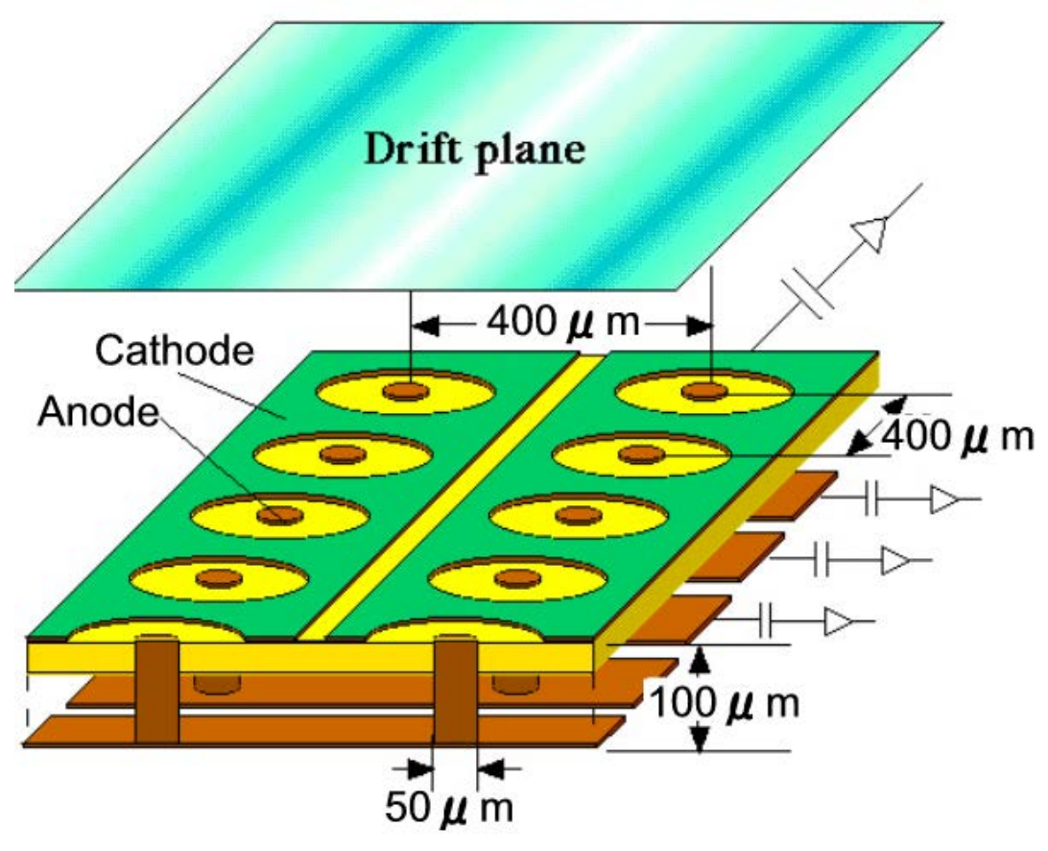
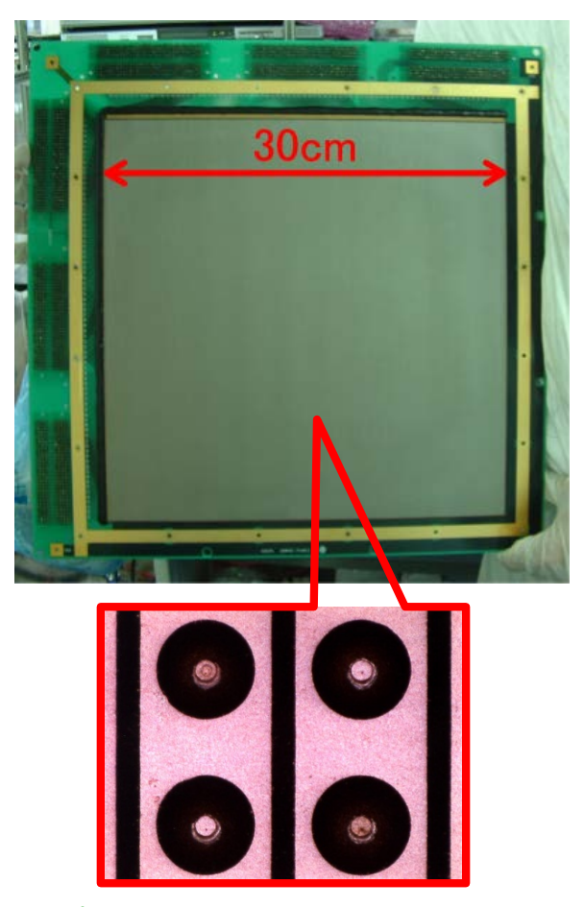
1. Micro Pixel Chamber (μ-PIC)

◆ Characteristics of μ-PIC[1]

- A gaseous 2D imaging detector with strip read out
- Cu electrodes and polyimide substrate
- Each pixel is placed with a pitch of 400 μm
- Large detection area 10×10 cm², and 30×30 cm²
- Based on the Print Circuit Board technology
- Maximum gas gain of ~15,000
- Fine position resolution (RMS ~120μm)
- Good gas gain uniformity (RMS ~5%) at the whole area
- Stable operation for >1000 hours with gas gain ~6,000



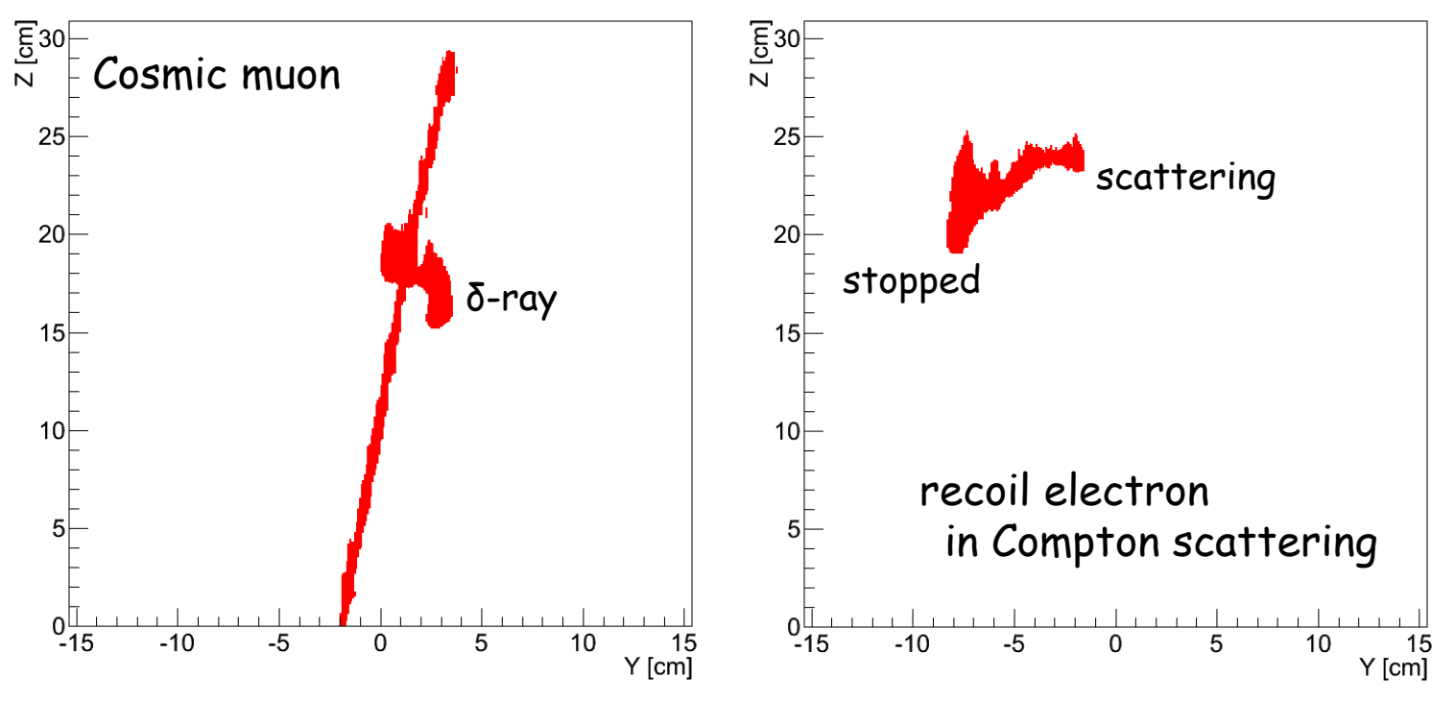


◆ Applications of μ-PIC are …

- Electron-Tracking Compton Camera
  in astronomy[2], Medical imaging[3]
- Neutron imaging[4]
- Direct dark matter search[5]
- X-ray crystallography[6]
- Gas photomultiplier[7]

◆ Time Projection Chamber with TOT

Recently, more precise tracks are required by some applications, we therefore developed a new data acquisition system for a Time Projection Chamber (TPC) using Time-Over-Threshold (TOT). By the TOT-TPC, we can already obtain the high resolution tracks, like the following figures.

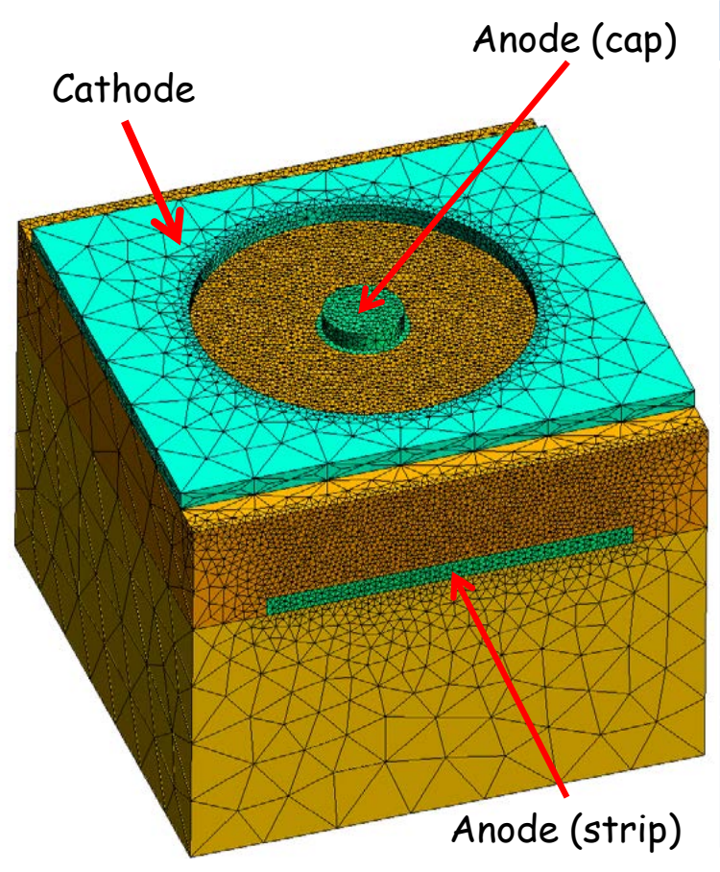


◆ Needs from Applications

A simulator, which is necessary for the accurate study of application detectors, requires the wave form, the uncertainty of gas gain, and the dependence on the anode voltage. For the purpose, we should simulate the avalanche in microscopic scale.

Let's simulate with Garfield++[8] !!

2. Geometry & Electric field



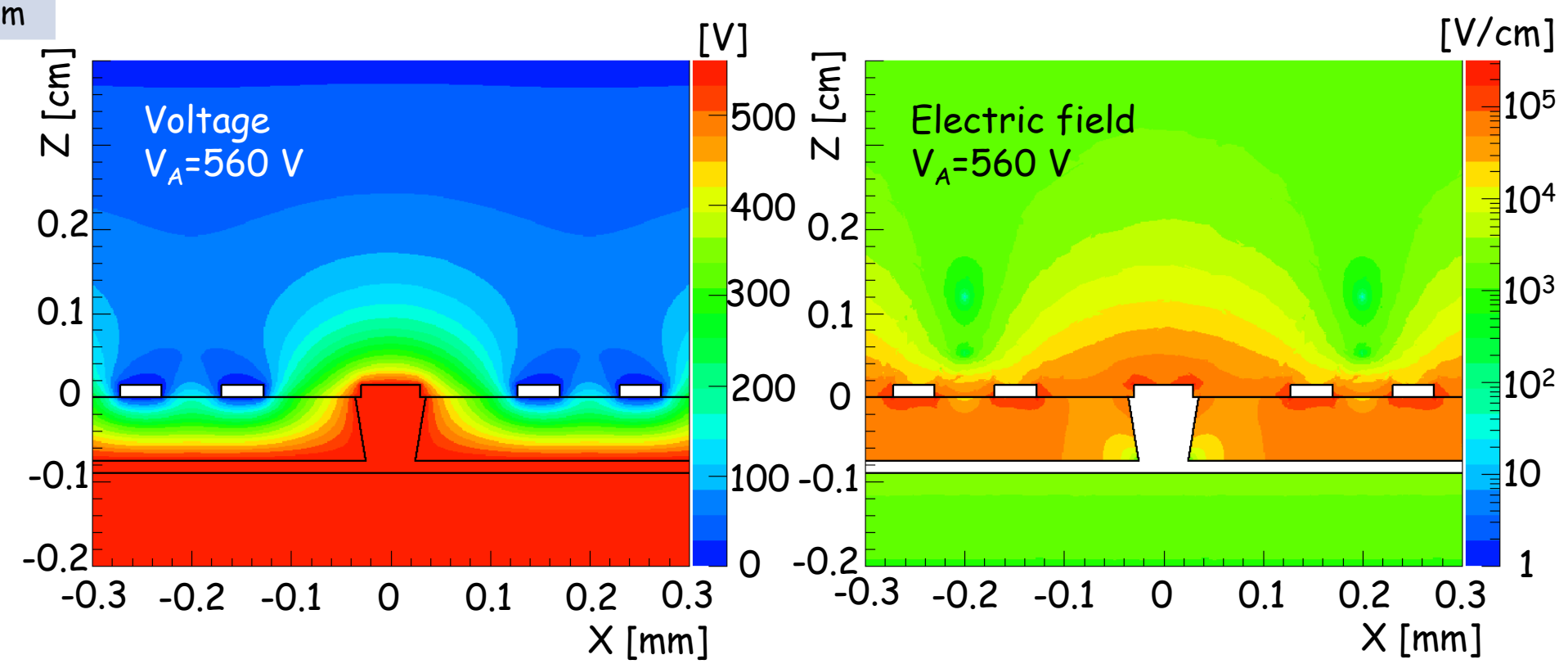
Parameter		Value
Anode	Pillar diameter	70 μm (upper) 50 μm (lower)
	cap	Diameter: 60 μm Height: 15 μm
	Strip	Width: 285 μm Thickness: 15 μm
Cathode	Opening	Diameter: 256 μm
	Strip	Width: 340 μm Thickness: 15μm
Substrate	Thickness	75 μm
	material	polyimide
gas	Electric Field	1 kV/cm
	material	Ar 90% + C_2H_6 10%, 1 atm

◆ Definition of Geometry

We defined the geometry of a pixel electrode as a unit cell in the area of 400×400 μm², and generated the three dimensional finite element mesh using Gmsh[9]. The gas area had the depth of 1.5 mm above the electrodes, and was filled by Ar 90% + Ethane 10% with the pressure of 1.0 atm. In the Garfield++, we placed this unit cell periodically. The initial electrons generated at random position in the area of 400×400 μm² at 1.0 mm above the electrodes.

◆ Calculation of Electric Field

For the calculation of the maps of electric field, voltage, and weighting field, we adopted Elmer[10]. The drift electric field was fixed at 1.0 kV/cm. The dielectric constants of gas, polyimide substrate, and copper electrode are 1, 3.5, and 10^{10}, respectively. To define these maps in Garfield++, we used ComponentElmer class[11].



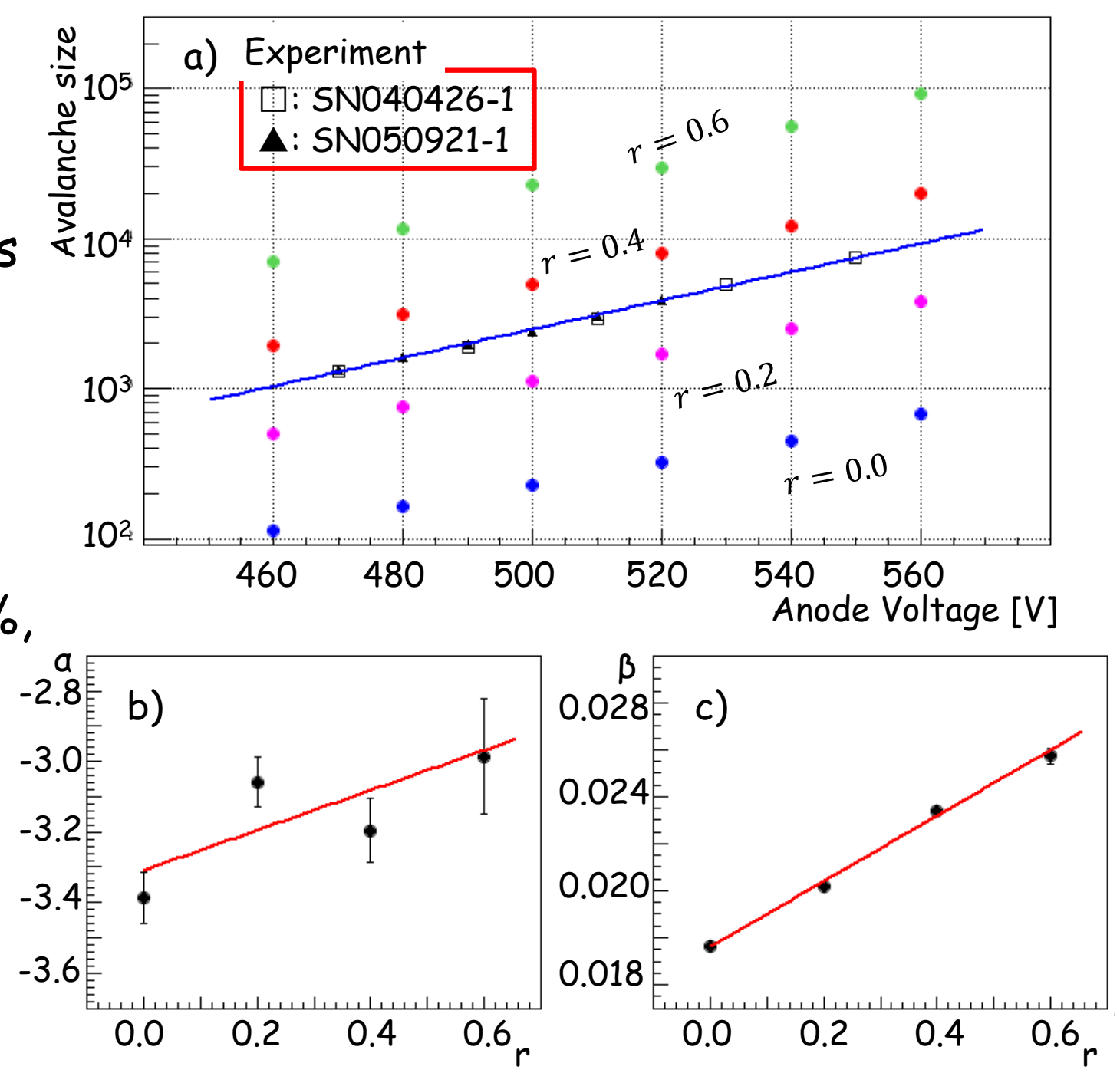
3. Avalanche in μ-PIC

◆ Avalanche Size

First, we simulated the avalanche size by counting the number of generated electrons in an avalanche using microscopic tracking. The obtained avalanche size was shown in the Figure a) with various anode voltage and Penning effect rate r. For comparison, the measured effective gas gain was also plotted in this figure (open squares and filled triangles). We fitted these plots with

$$F_r(x) = \exp(\alpha + \beta x)$$

at each r, and the dependences of the obtained α and β on r are shown in the Figures b) and c). In the case of Ar 90% + Ethane 10%, the Penning effect rate is 0.31 [12], we hence interpolated α and β under the assumption that the dependences of α and β are the linear functions of r. The calculated avalanche size using the interpolated α and β is represent the blue solid line in Figure a), and it is well consistent with the measured value.



◆ Single Electron Spectrum

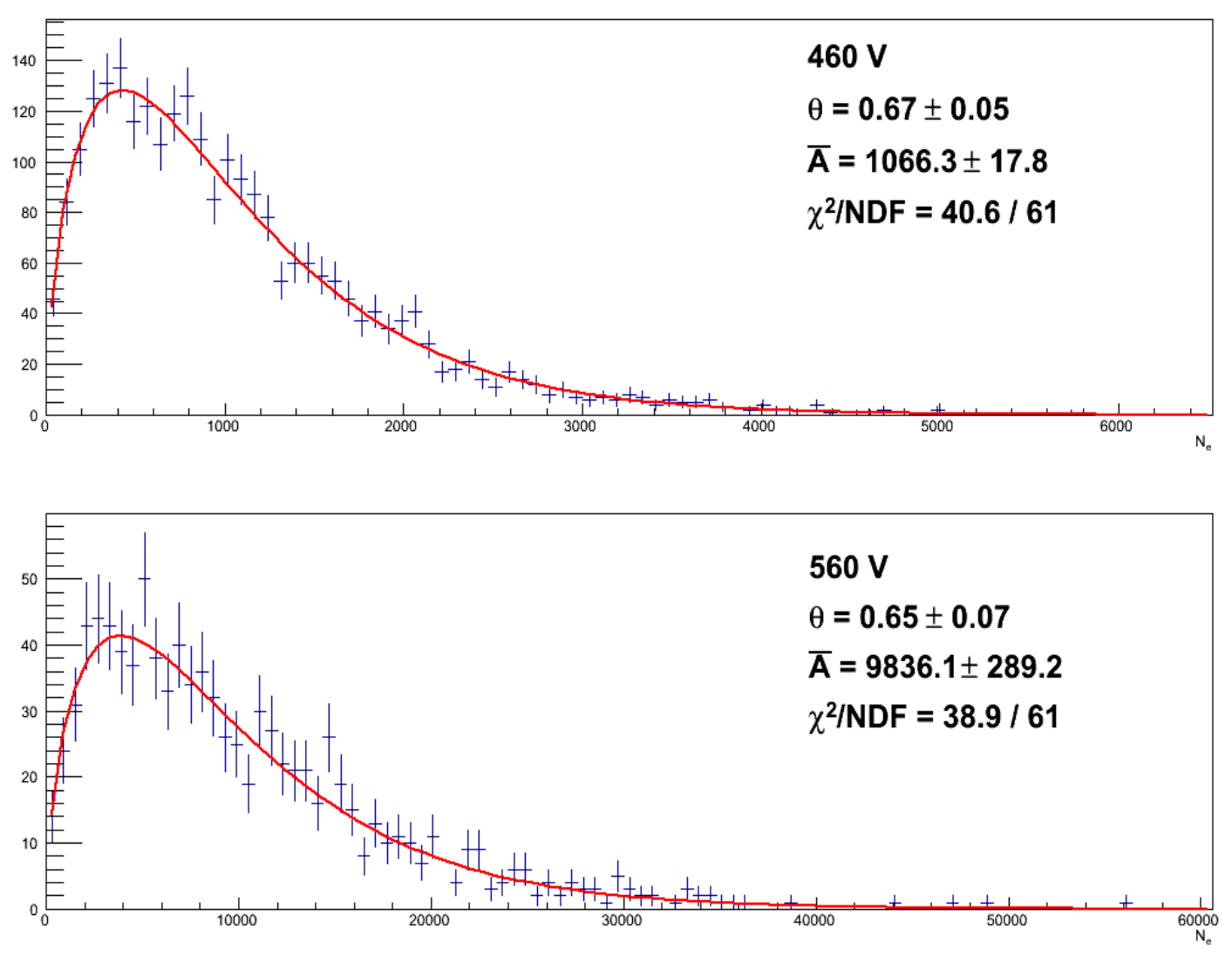
In the case of a proportional counter, the single electron spectrum, which represents the uncertainty of gas gain, is described by Polya distribution

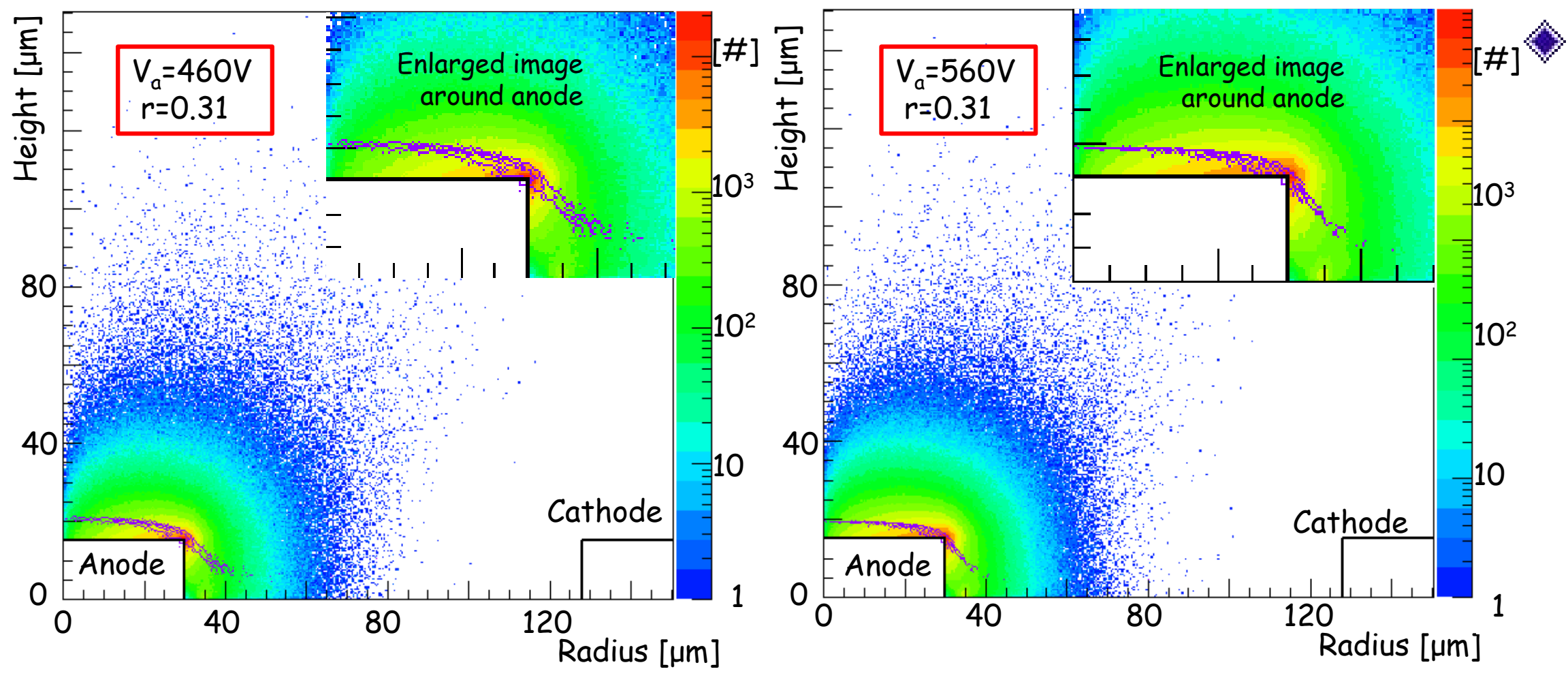
$$g(x) = \left(\frac{x(1+\theta)}{\bar{A}}\right)^{\theta} \exp\left(-\frac{x(1+\theta)}{\bar{A}}\right),$$

where $\bar{A}$ is the average of gas gain. The single electron spectrum of μ-PIC is shown in right figures, and it is fitted by $g(x)$. From these figures, it can be explained with Polya distribution, although the electric field map of μ-PIC is complicated in comparison with that of a proportional counter. The theoretical limit of energy resolution is obtained using Fano factor f and θ as follows:

$$\frac{\sigma_E}{E} = \sqrt{\frac{f+\frac{1}{1+\theta}}{\bar{N}}},$$

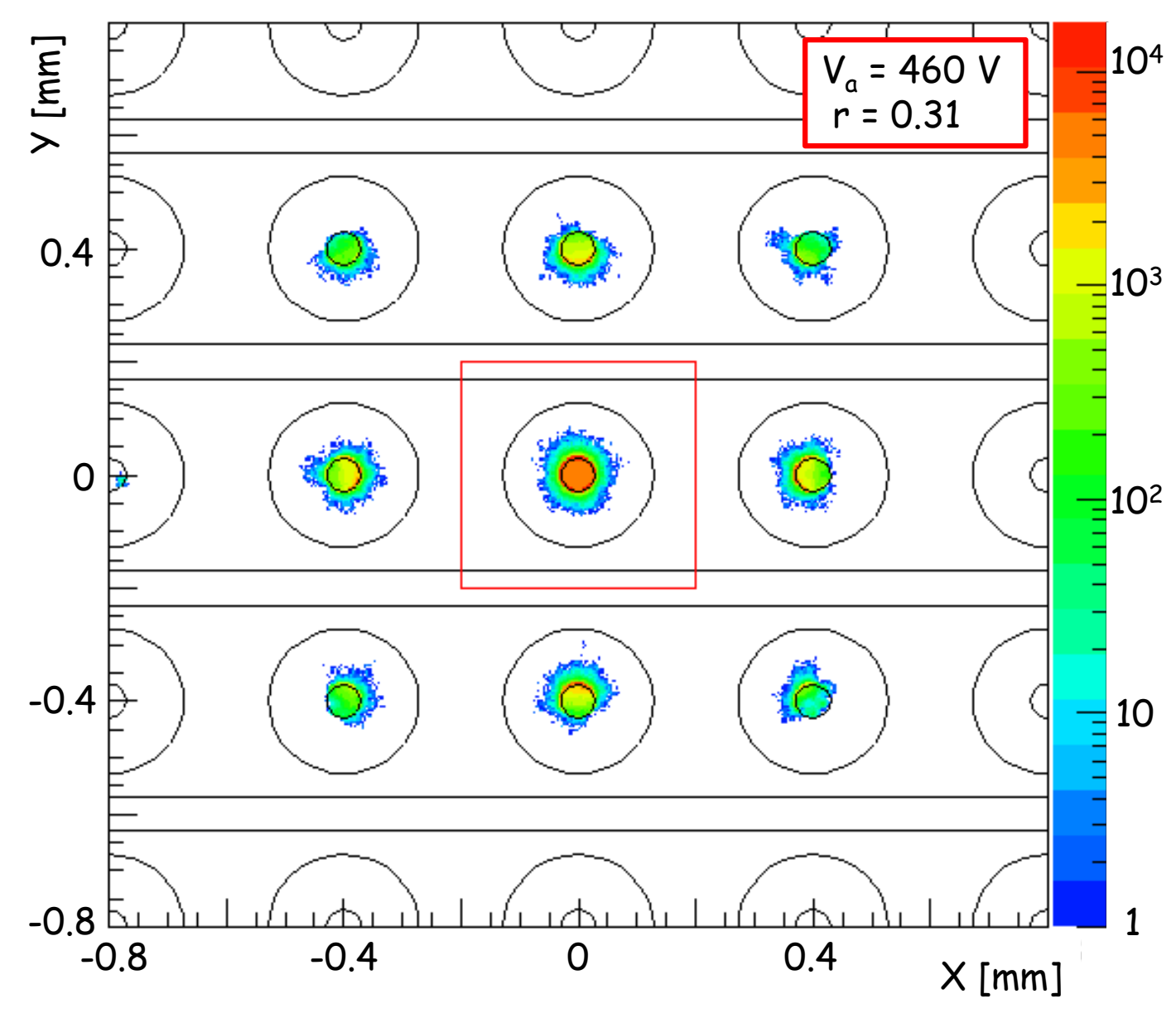
where $\bar{N}$ is the average number of seed electrons. θ of μ-PIC is approximately 0.65, which is independent on the anode voltage.





◆ Avalanche Area

The left figures are maps of generated point of the secondary electrons at the anode voltage of 460 V and 560 V, respectively. The color indicates means the number density of secondary electrons, and the contour means the number density of the gravity center of each avalanche. The majority of avalanche is made in the limited area at the distance of 100 μm from anode electrode, and the center of gravity of avalanche are concentrated above anode electrode at the distance of approximately 5 μm. Because the avalanche points are almost not changed by the anode voltage, the signal waveform is insensitive to the anode voltage.

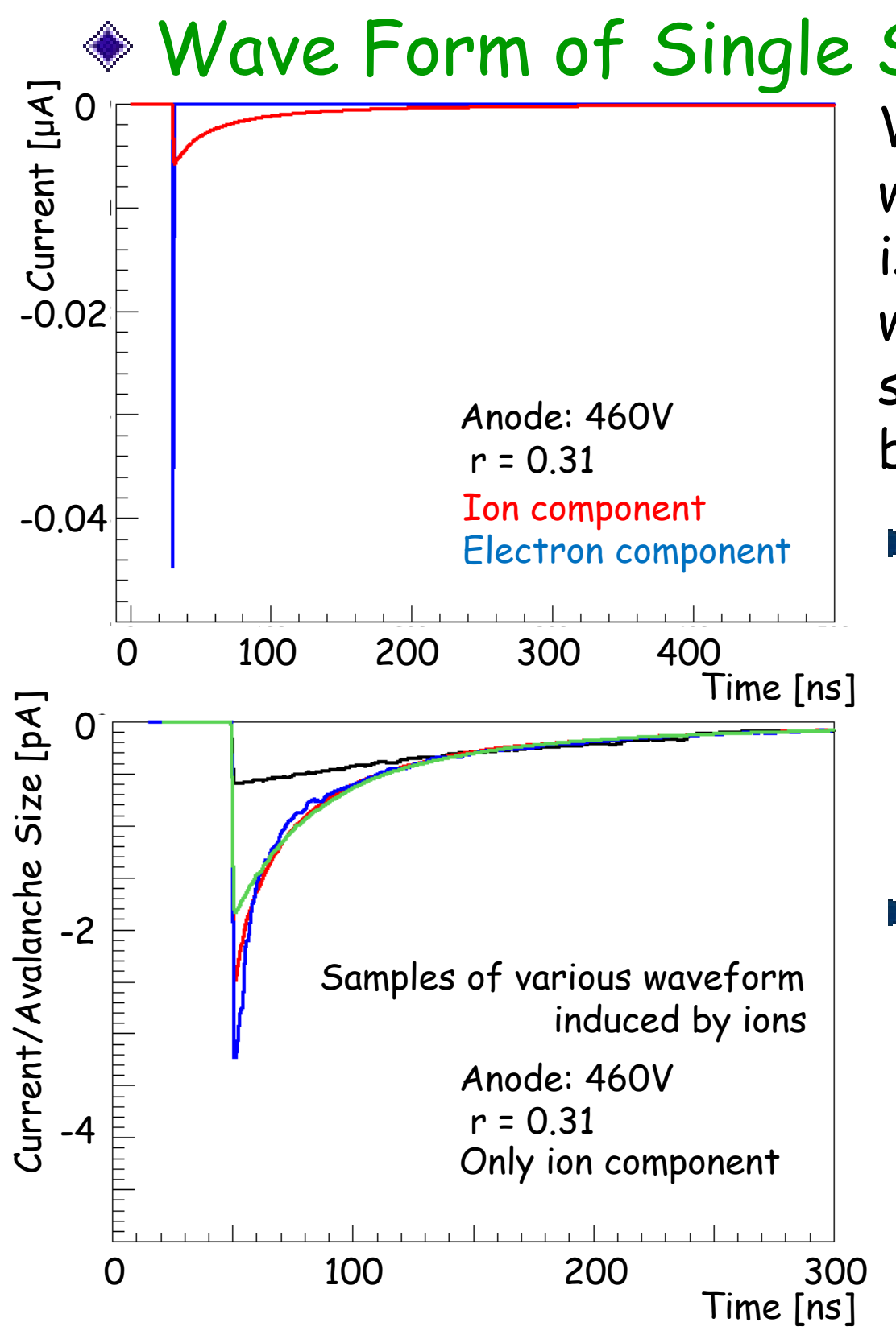


◆ Map of Termination Points

The left figure is the termination points map of all electron. The initial electrons were made at random position in the red box above the substrate at the distance of 1 mm. 2% of the electrons in avalanche are terminated on the substrate, and the electron collection efficiency of μ-PIC is 98%. This result is roughly consistent with the previous simulation result[13] which said that most of electrons reach to the anode electrode and the rest drift onto the substrate.

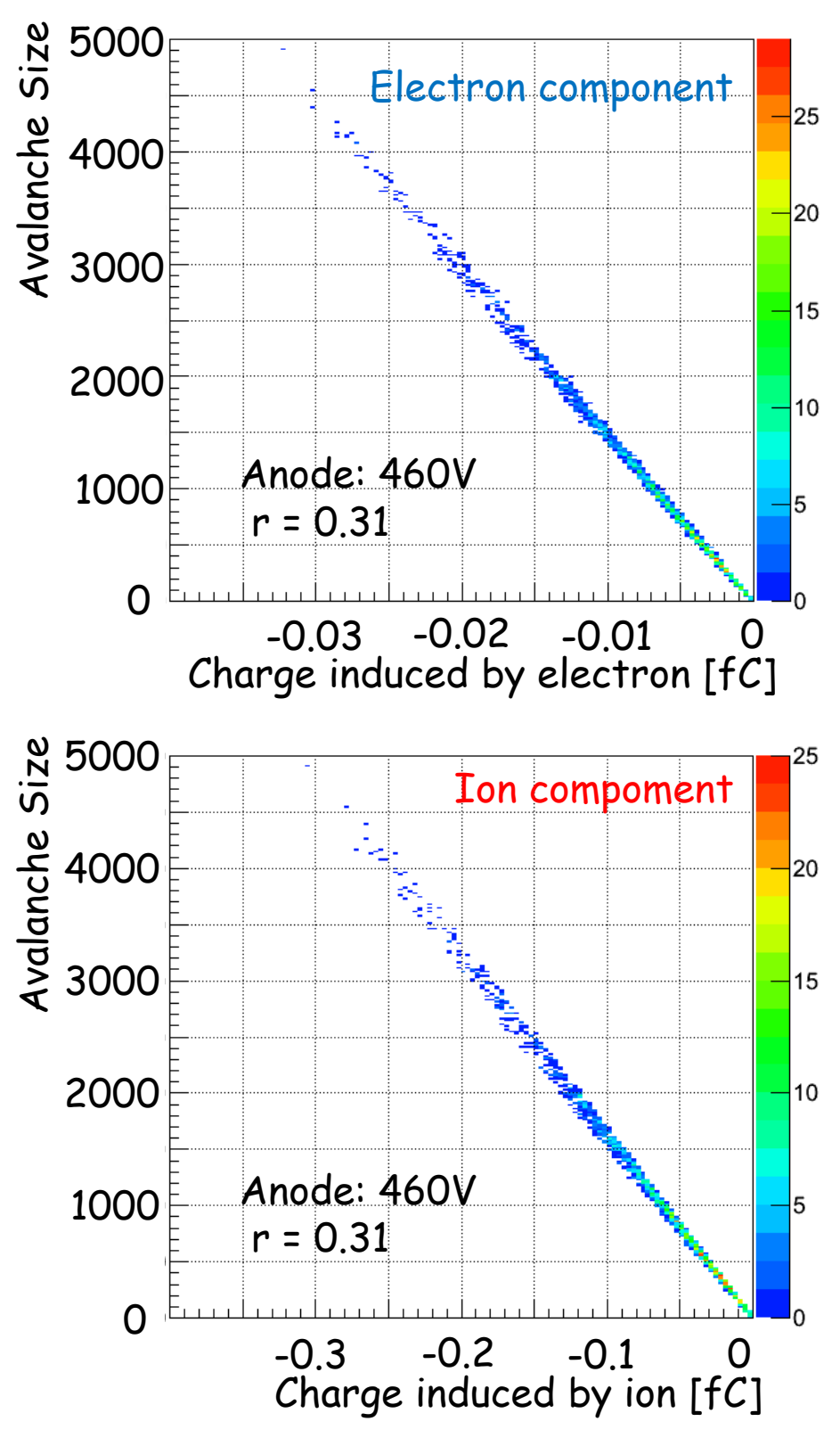
4. Signals of μ-PIC

◆ Wave Form of Single Seed Electron



We simulated the induced current using the weighting field of anode electrode. The left figure is a sample of single electron signal. The signal waveform consists of two components. One is sharp spike induced by electrons, and the other induced by ions has slow decay time.

- Electron component
  - The charge induced by electron is proportional to the avalanche size.
  - The pulse width of electron component is approximately 1 ns.
- Ion component
  - The charge induced by ion is proportional to the avalanche size, and it is approximately 9 times larger than the charge of electron component.
  - As like the left figure, the ion component takes various pulse shape, which depends on the ion transportation paths.

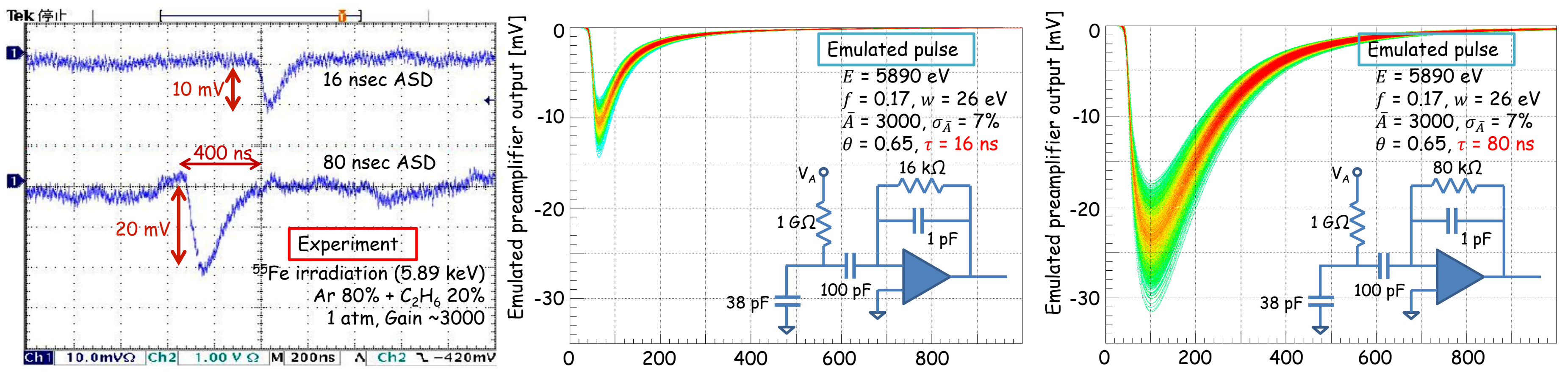


◆ Emulation of X-ray Irradiation

In order to emulate the signal output of u-PIC, we simulated 2000 single electron signals as the wave form templates. Using this template, we calculated with the processes as follows:

1. Create seed electron with a Gaussian having mean of $\frac{E}{w}$ and sigma of $\sqrt{fE/w}$, where E, f, and w are the deposit energy, Fano factor, and w value of gas, respectively.
2. Define the uncertainty of arrival time using the longitudinal diffusion for each seed electron.
3. Because a μ-PIC has the fluctuation in the gain uniformity, define the average avalanche size $\bar{A}$ with a Gaussian having the sigma of $\sigma_{\bar{A}}$, for each pixel.
4. Obtain the avalanche size A using a Polya distribution with mean of $\bar{A}$ and θ of 0.65 for each seed electron.
5. Select a wave form from 2000 signal templates, and multiplied by A.
6. Obtain an output signal of u-PIC with summing the single electron signal for all seed electron.
7. Emulate the readout circuit, and compare with experimental data.

As a readout, we use an amplifier-shaper-discriminator (ASD) chip having a time constant of 16 ns[14], which was designed for the Thin Gap Chamber in ATLAS, or a redesigned ASD having a time constant 80 ns[15]. By the measurement with X-ray irradiation of ^{55}Fe, the pulse height obtained by 80 ns ASD is about two times higher than that of 16 ns ASD. We tried to confirm this pulse height difference. The emulated signal pulses are shown in below. At the gas gain of 3000, the emulated pulse heights of 16 ns preamplifier and 80 ns preamplifier are 11 mV and 23 mV, respectively. The ratio of pulse height is approximately 2.2, which is well consistent with the measurement.



◆ Time over Threshold

Finally, we simulated the TOT distribution depending on the deposit energy using the hit pixel number of the TOT-track images. The TOT distribution of electrons in the experimental data has two components. One is the component of fully contained events, and another is the component of escape events. At the energy of 40 keV and 100 keV, the typical TOT hits for fully contained electrons are about 500 pixels and 1500 pixels, respectively.

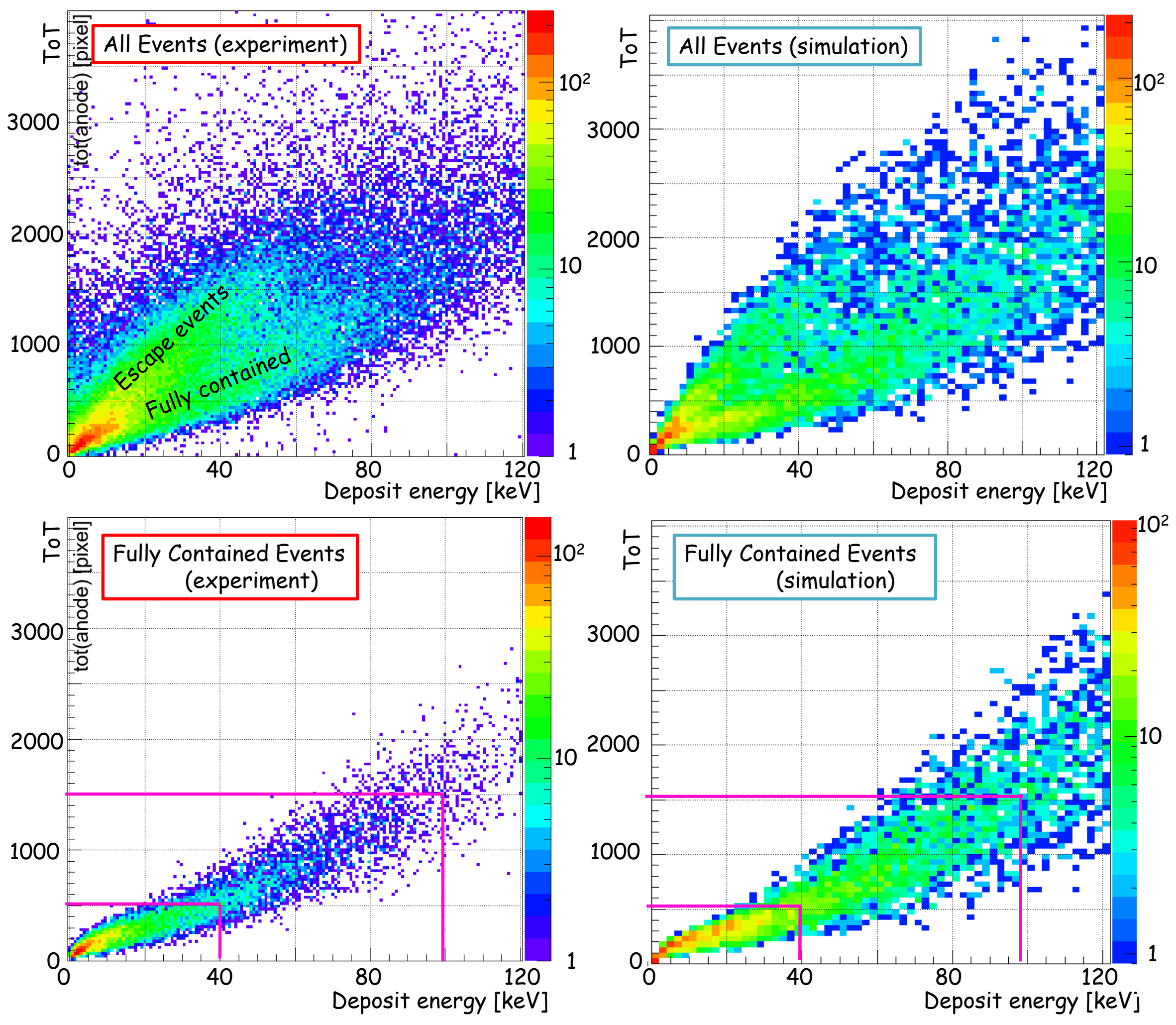
For the purpose of emulating the TOT-tracks, we made a simulator of μ-PIC TPC using Geant4[16]. By this simulator, we obtained the energy deposit of electrons, calculated signals at each pixel, emulated digital pulses, and compared with the experimental TOT tracks. The emulated TOT distribution also has two components, and the number of emulated TOT hits is nearly equal to that of experimental data at each energy. Therefore, we can say that this emulator well describes the TOT distribution, and we will be able to realize a precise simulator for μ-PIC application.

Experiment setup

TPC Size:	7.5×7.5×14 cm³
Gas:	Ar 90% + C_2H_6 10%, 1.5 atm
Gas gain:	24000 (μ-PIC + GEM)
Readout:	ASD (τ = 80 ns)
Threshold:	-15 mV
Source:	^{137}Cs irradiation
Drift field:	170 V/cm
Induction:	1.1 kV/cm

Simulation parameters

TPC Size:	10×10×14 cm³
Gas:	Ar 90% + C_2H_6 10%, 1.5 atm
w value:	26 eV
Fano factor:	0.17
Gas gain:	24000 (θ = 0.65)
Readout:	ASD (τ = 80 ns)
Threshold:	-15 mV
Electron energy:	< 200 keV
Drift velocity:	3.2 cm/μs
Diffusion:	450 μm/√cm for transverse 350 μm/√cm for longitudinal



5. Summary

- We defined the three dimensional finite element mesh using Gmsh, and calculated the map of voltage, electric field, and weighting field with Elmer.
- Using Garfield++, we simulated the avalanche in μ-PIC.
- The simulated avalanche size is well consistent with the measured gas gain.
- The single electron spectrum of μ-PIC is described by a Polya distribution.
- The electron collection efficiency is roughly consistent with the previous simulation result.
- We also obtain the wave form of single electron incident.
- The pulse height dependence on the time constant of preamplifier is well explained.
- With Geant4 and ASD emulator, we can roughly explain the TOT hits distribution.
- By these results, the simulation for the applications will be improved. Moreover, the Garfield++ simulation will make the μ-PIC development more easily.

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