Characterization Study of GEM Detector for High Energy Experiment

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Contents

Detectors for High Energy Physics

Detecting and studying nuclear events is important as it provides invaluable insights into fundamental aspects of particle physics, nuclear structure, and interactions, contributing to our understanding of the universe's fundamental building blocks and the forces that govern their behaviour.

- **Gas filed detectors (e.g. Proportional counters, GEM, RPC etc.)**
- **Scintillation detectors (Plastic scintillator, NaI(Tl), CsI(Tl) etc.)**
- **Solid state detectors (Silicon tracker etc.)**

Gas Filled Detector

As ionizing radiation enters the gas between the electrodes, a finite number of ion pairs are formed. The behaviour of the resultant ion pairs is affected by the potential gradient of the gas's electric field and the fill gas's type and pressure.

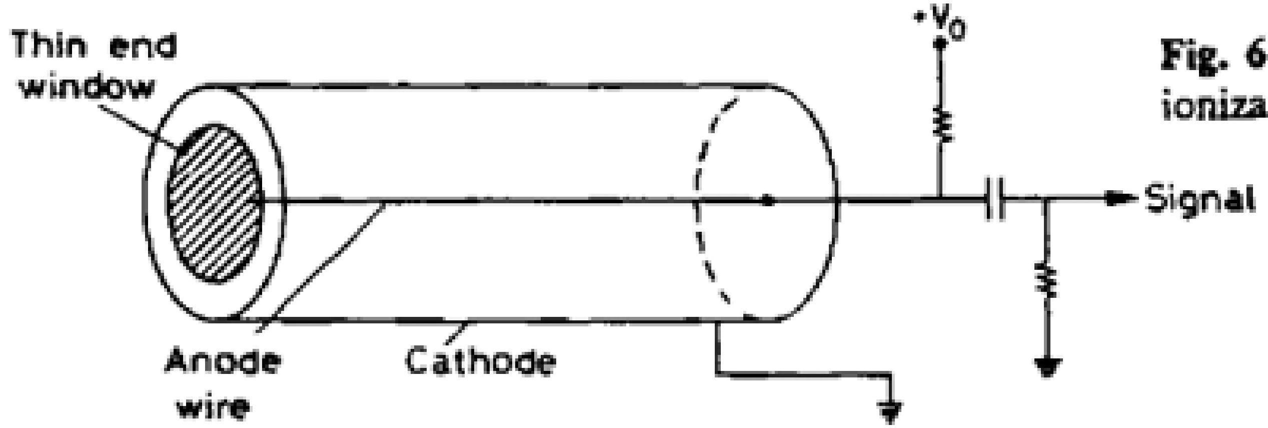
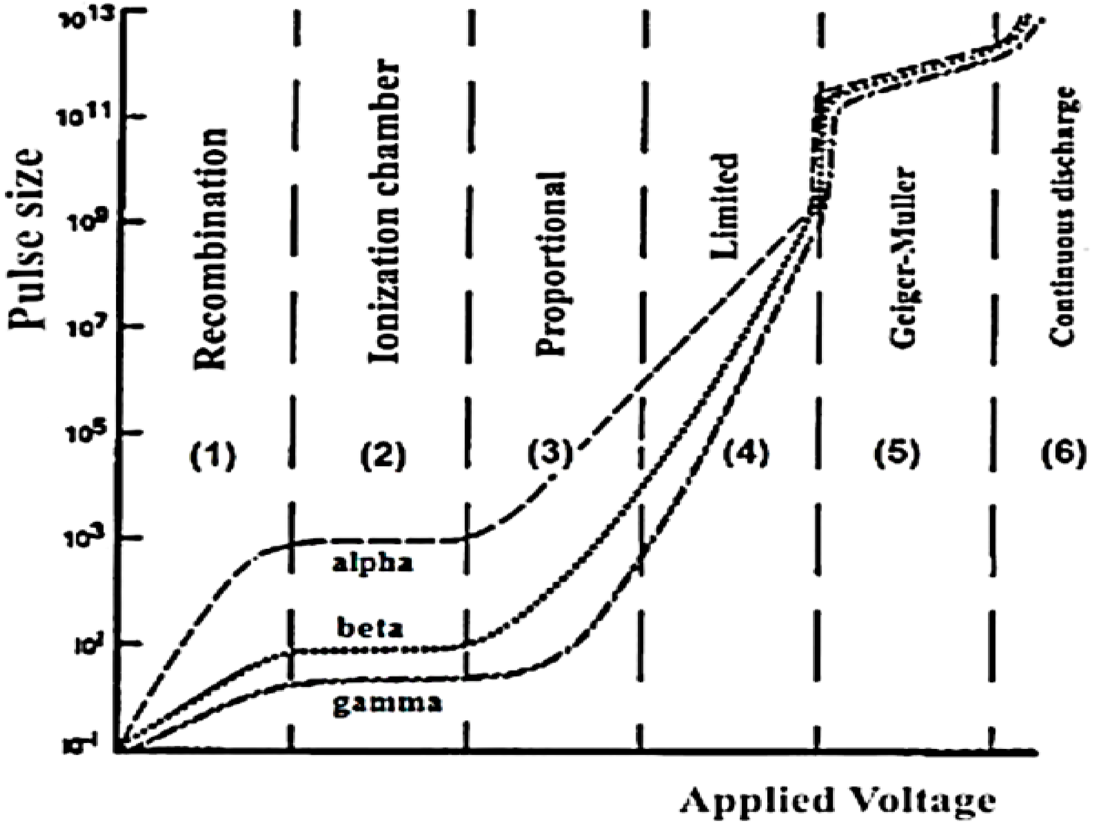


Fig. 6.1. Basic construction of a simple ionization detector

Ref : W.R. Leo, Techniques in Nuclear and particle physics, p : 129

General characteristic curve of gas-filled detector

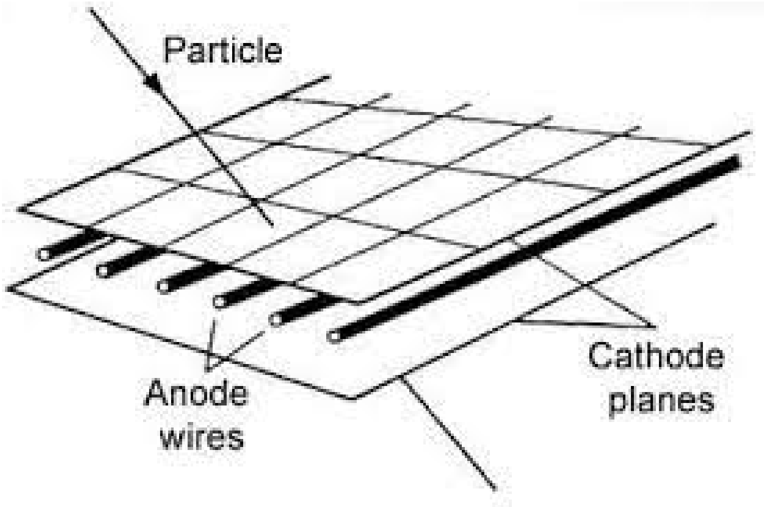
1) Recombination Region
2) Ionization Region
3) Proportional Region
4) Region of Limited Proportionality
5) Geiger Mueller region
6) Continuous Discharge



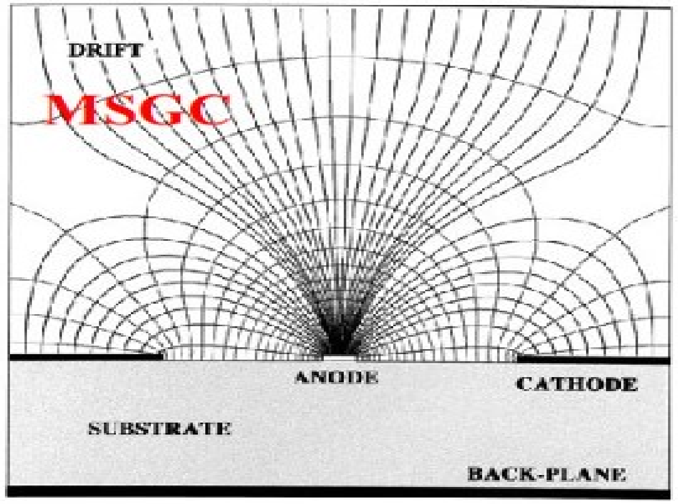
Why GEM !!!

Chronological development

MWPC



MSGC



Micro-Groove

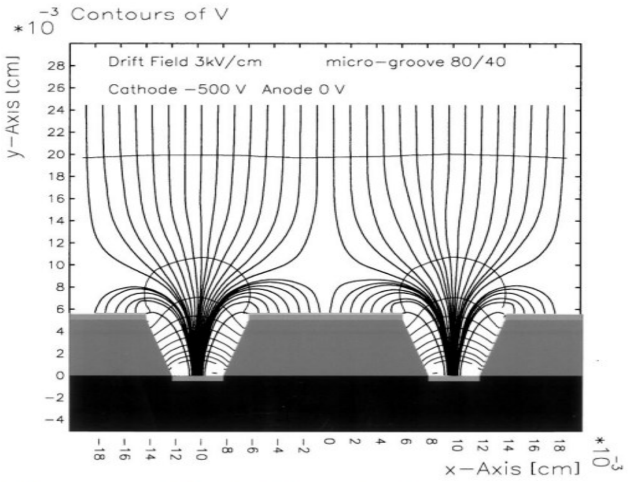
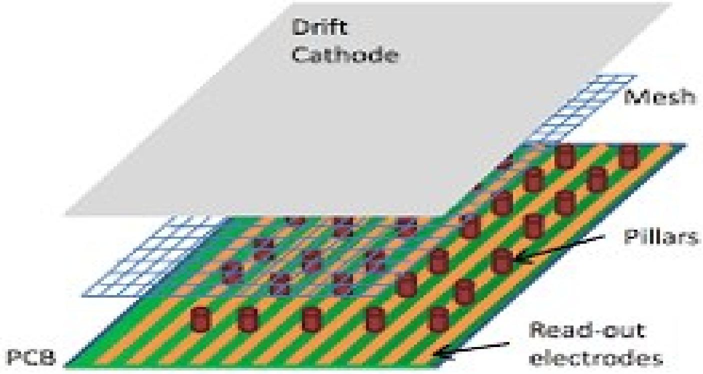


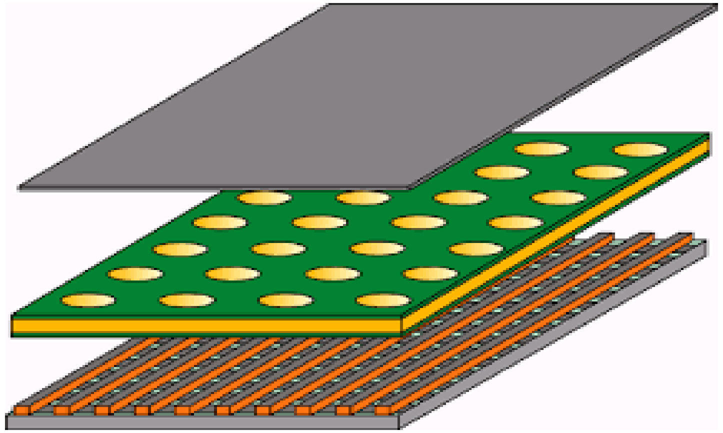
Fig. 2. Equipotential and drift lines (with zero diffusion) for the micro-groove detector.

Micro-Pin Array

Micromegas

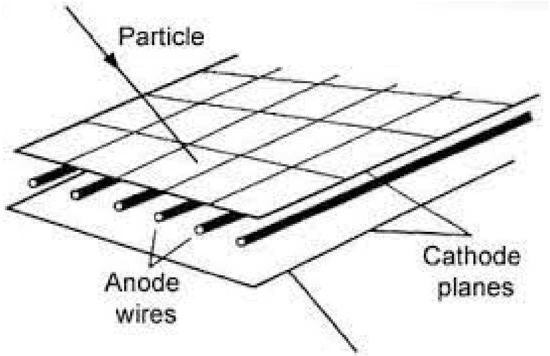


GEM



Chronological development

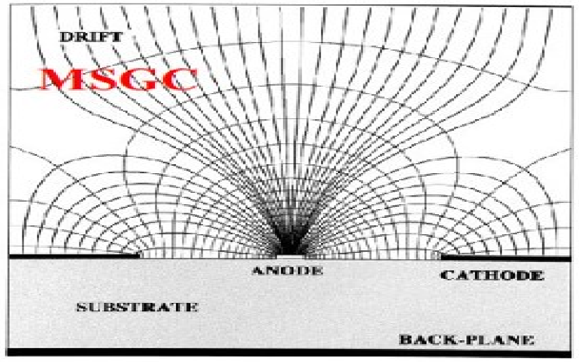
MWPC



- Gain decreases with increasing particles.
- Poor spatial resolution as anode wires are placed very closely

- Time resolution ~ 30 – 50 ns
- Position resolution ~ 250-500 µm
- Rate ~ 10^4 Hz/mm2

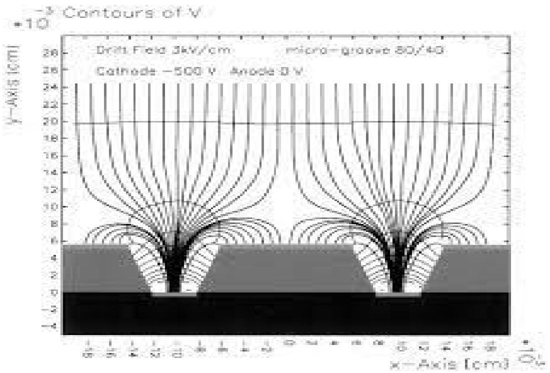
MSGC



- Rate ~ 10^6 Hz/mm2
- Spatial res. ~ 50-100 µm

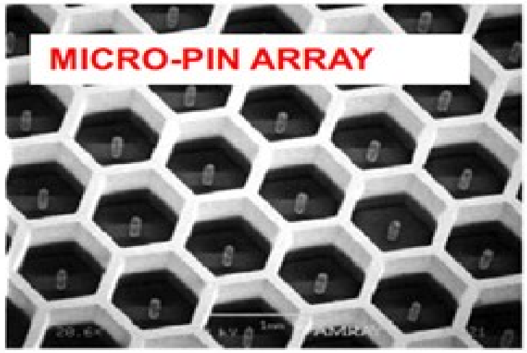
Micro-Groove

- Charging-up effect.
- Discharge effect



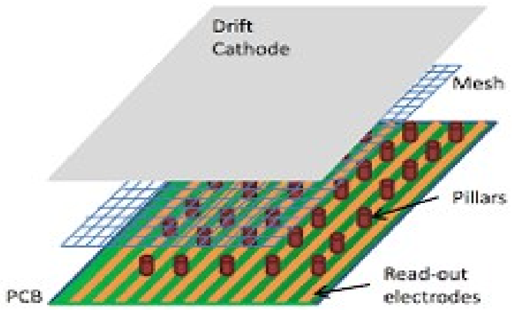
- 50 µm Kapton as dielectric substance with metal cladding
- 2D read-out possible

Micro-Pin Array



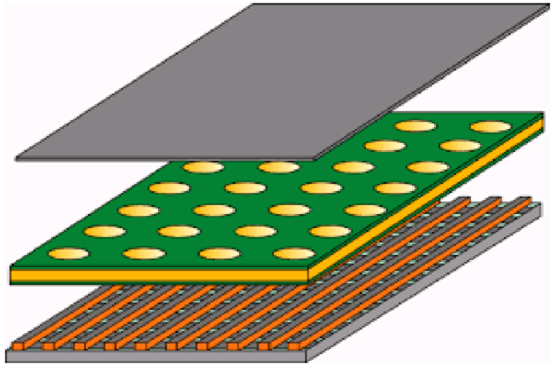
- Material budget is low
- Discharge prob. Is low

Micromegas

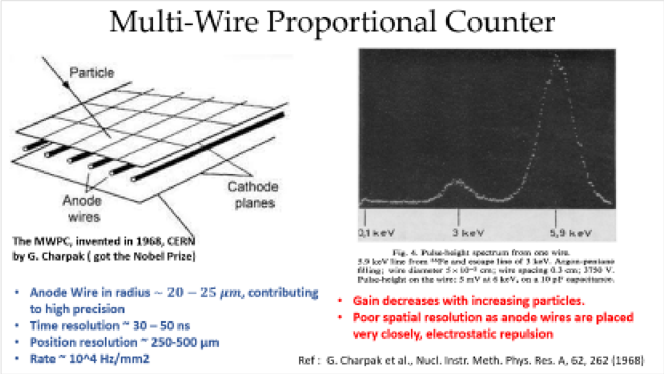


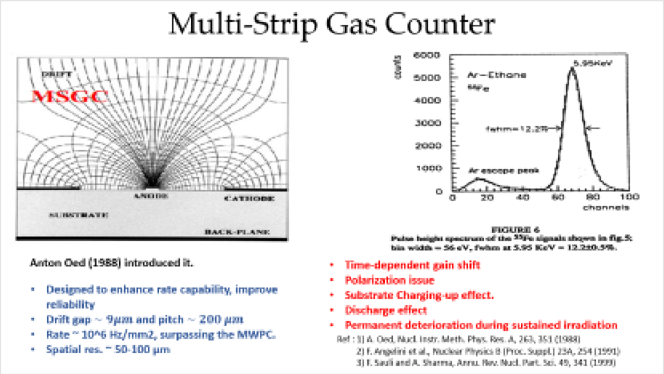
- Position res ~ 10-30 µm
- Time res ~ 1-5 ns
- Fast ion collection

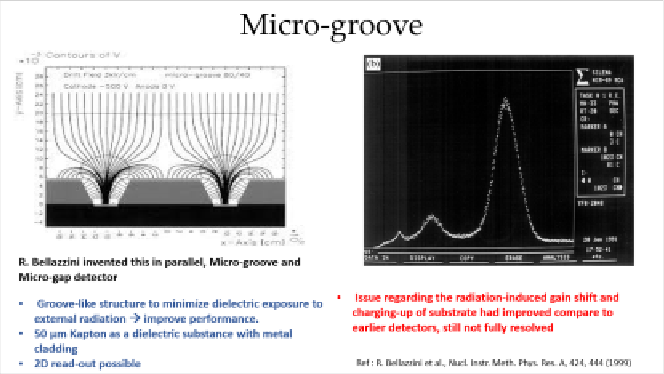
GEM

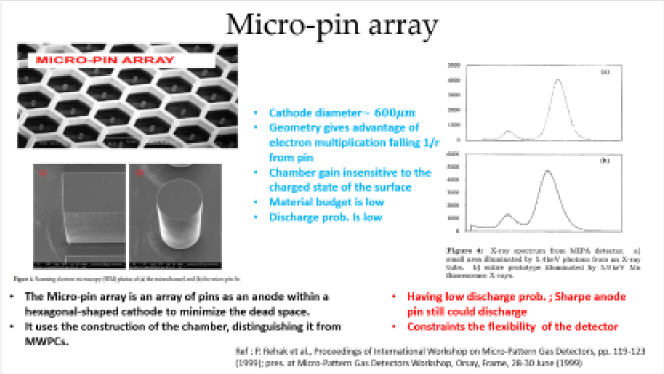


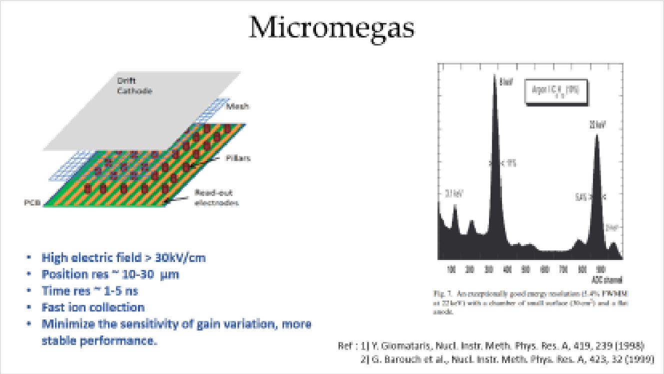
Let’s visit in little details



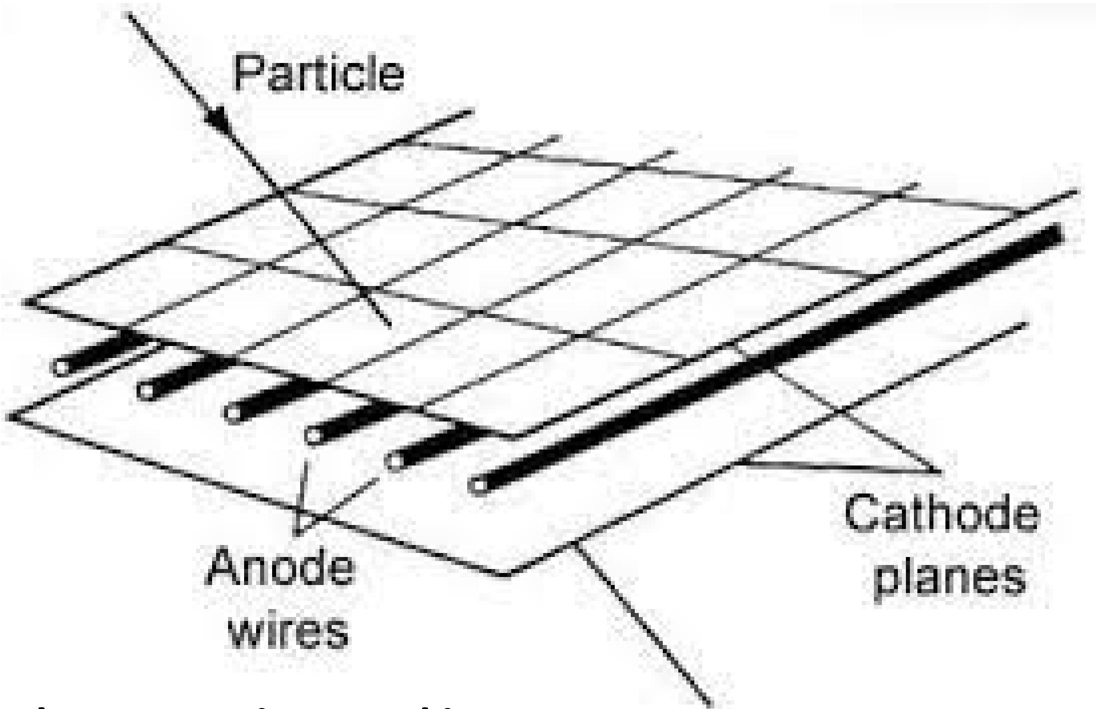








Multi-Wire Proportional Counter



The MWPC, invented in 1968, CERN by G. Charpak (got the Nobel Prize)

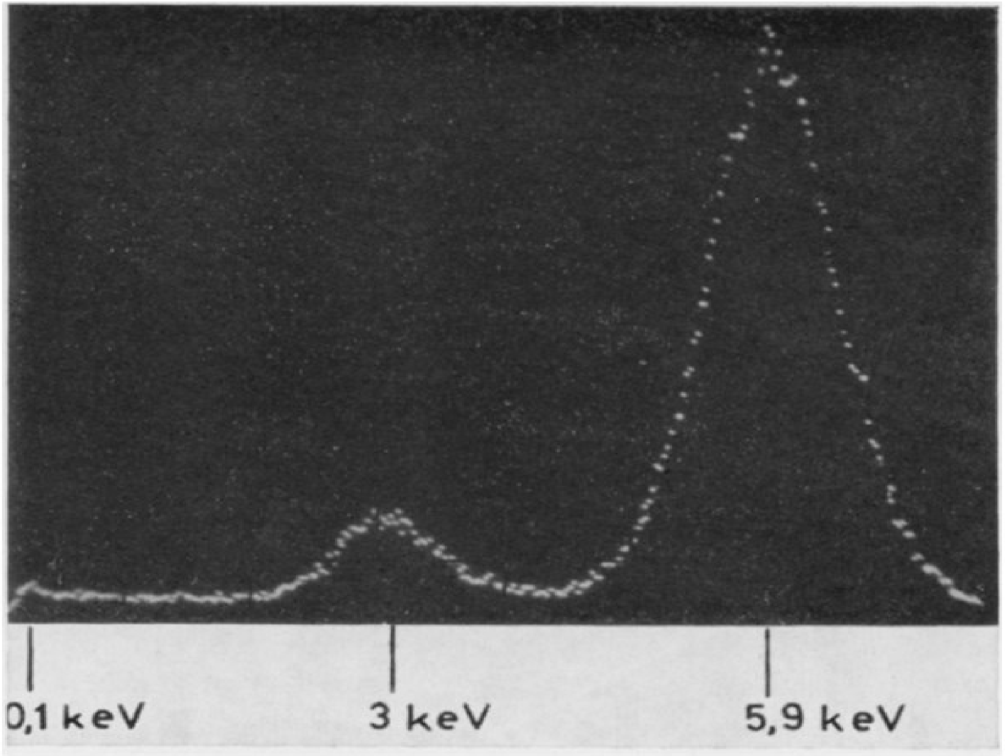


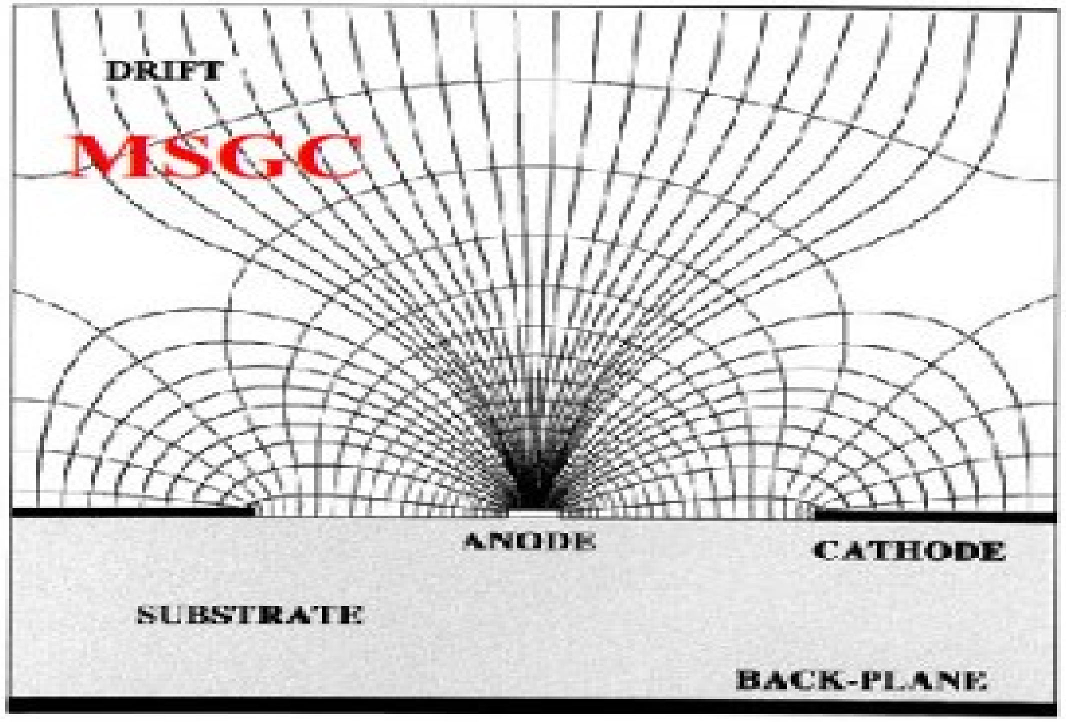
Fig. 4. Pulse-height spectrum from one wire.
5.9 keV line from ^{55}Fe and escape line of 3 keV. Argon-pentane filling; wire diameter 5×10^{-3} cm; wire spacing 0.3 cm; 3750 V. Pulse-height on the wire: 5 mV at 6 keV, on a 10 pF capacitance.

- Anode Wire in radius $\sim 20 - 25\ \mu m$, contributing to high precision
- Time resolution ~ 30 – 50 ns
- Position resolution ~ 250-500 µm
- Rate ~ 10^4 Hz/mm2

- **Gain decreases with increasing particles.**
- **Poor spatial resolution as anode wires are placed very closely, electrostatic repulsion**

Ref : G. Charpak et al., Nucl. Instr. Meth. Phys. Res. A, 62, 262 (1968)

Multi-Strip Gas Counter



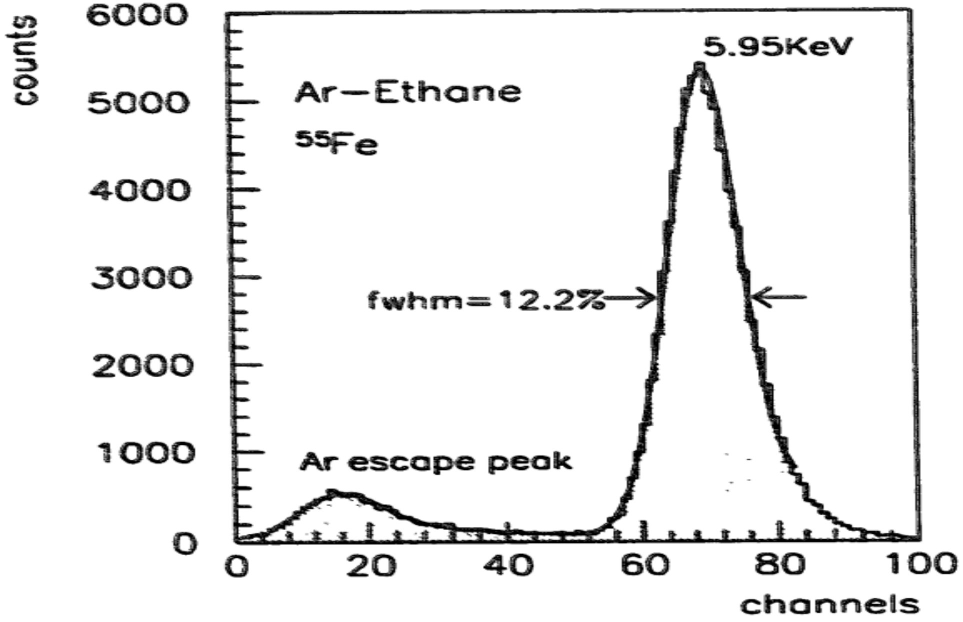


FIGURE 6
Pulse height spectrum of the ^{55}Fe signals shown in fig.5; bin width = 56 eV, fwhm at 5.95 KeV = 12.2±0.5%.

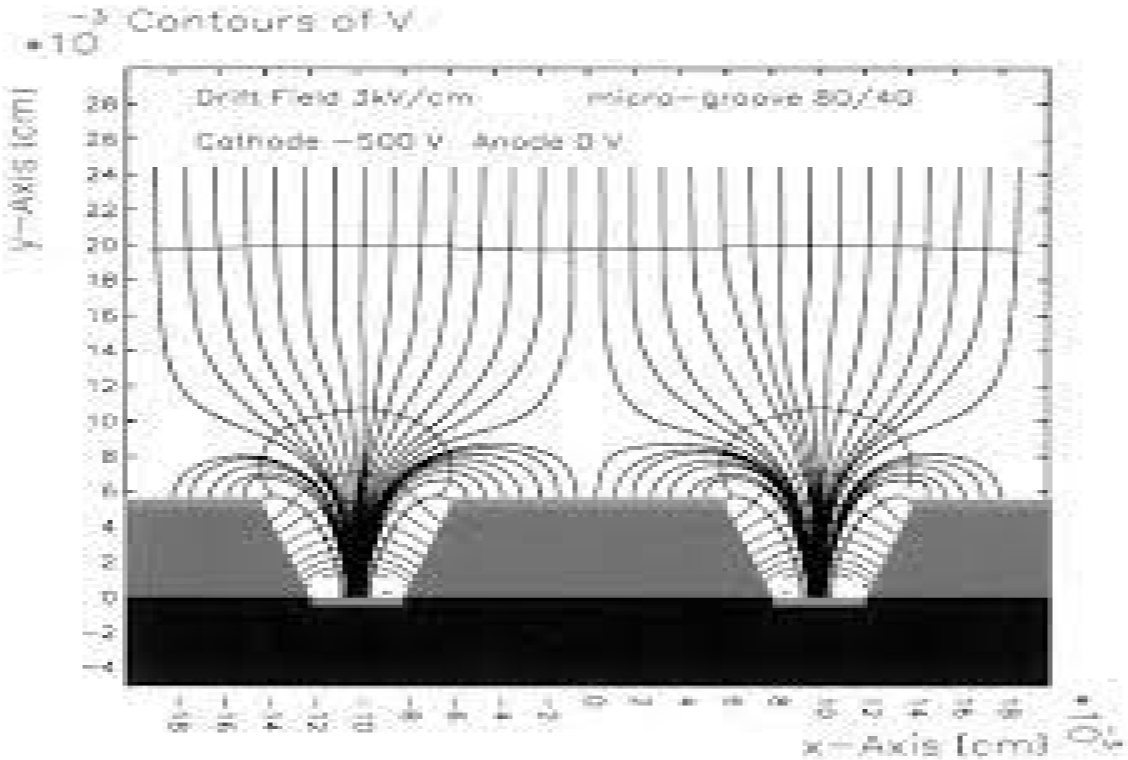
Anton Oed (1988) introduced it.

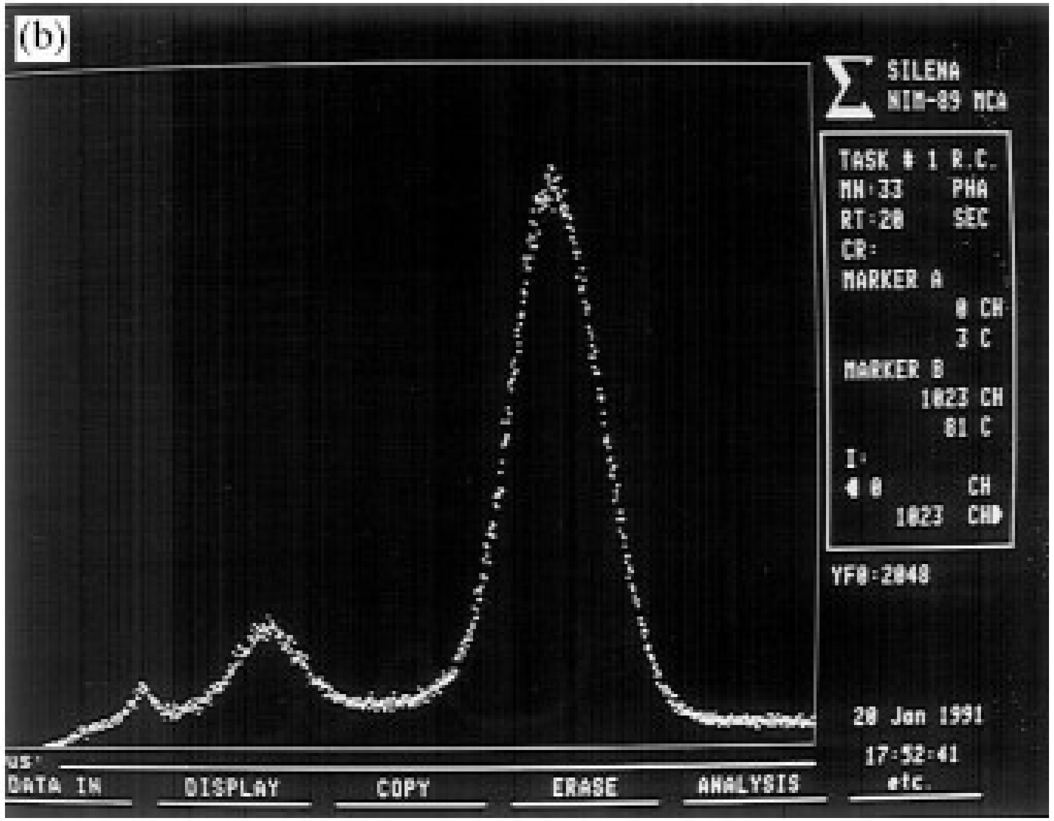
- **Designed to enhance rate capability, improve reliability**
- **Drift gap $\sim 9\mu m$ and pitch $\sim 200\ \mu m$**
- **Rate ~ 10^6 Hz/mm2, surpassing the MWPC.**
- **Spatial res. ~ 50-100 µm**

- **Time-dependent gain shift**
- **Polarization issue**
- **Substrate Charging-up effect.**
- **Discharge effect**
- **Permanent deterioration during sustained irradiation**

Ref : 1) A. Oed, Nucl. Instr. Meth. Phys. Res. A, 263, 351 (1988)
2) F. Angelini et al., Nuclear Physics B (Proc. Suppl.) 23A, 254 (1991)
3) F. Sauli and A. Sharma, Annu. Rev. Nucl. Part. Sci. 49, 341 (1999)

Micro-groove





R. Bellazzini invented this in parallel, Micro-groove and Micro-gap detector

- **Groove-like structure to minimize dielectric exposure to external radiation → improve performance.**
- **50 µm Kapton as a dielectric substance with metal cladding**
- **2D read-out possible**

- **Issue regarding the radiation-induced gain shift and charging-up of substrate had improved compare to earlier detectors, still not fully resolved**

Ref : R. Bellazzini et al., Nucl. Instr. Meth. Phys. Res. A, 424, 444 (1999)

Micro-pin array

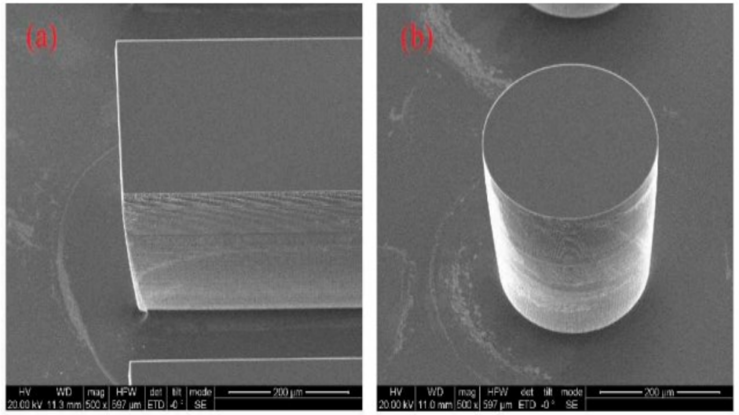


Figure 4. Scanning electron microscopy (SEM) photos of (a) the microchannel and (b) the micro pin fin.

- Cathode diameter~ $600\mu m$
- Geometry gives advantage of electron multiplication falling 1/r from pin
- Chamber gain insensitive to the charged state of the surface
- Material budget is low
- Discharge prob. Is low

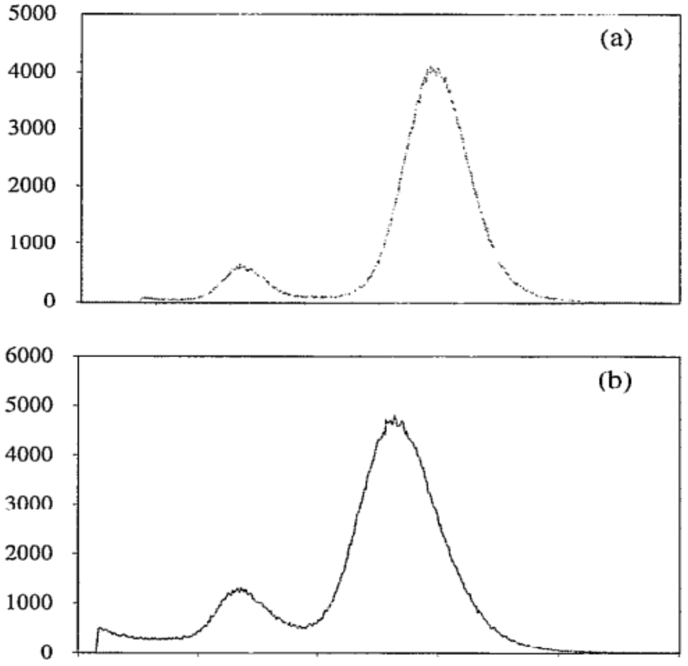


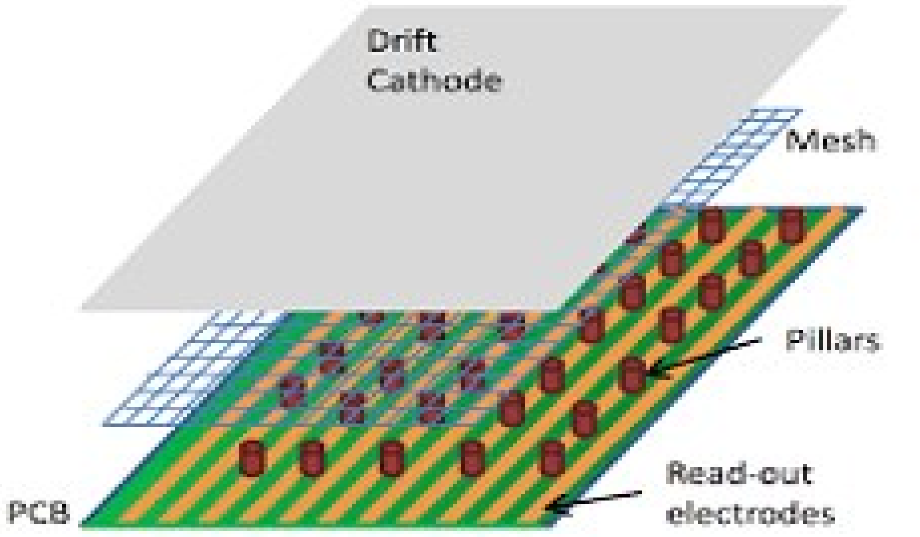
Figure 4: X-ray spectrum from MIPA detector. a) small area illuminated by 5.4 keV photons from an X-ray tube. b) entire prototype illuminated by 5.9 keV Mn fluorescence X-rays.

- **The Micro-pin array is an array of pins as an anode within a hexagonal-shaped cathode to minimize the dead space.**
- **It uses the construction of the chamber, distinguishing it from MWPCs.**

- **Having low discharge prob. ; Sharpe anode pin still could discharge**
- **Constraints the flexibility of the detector**

Ref : P. Rehak et al., Proceedings of International Workshop on Micro-Pattern Gas Detectors, pp. 119-123 (1999); pres. at Micro-Pattern Gas Detectors Workshop, Orsay, Frame, 28-30 June (1999)

Micromegas



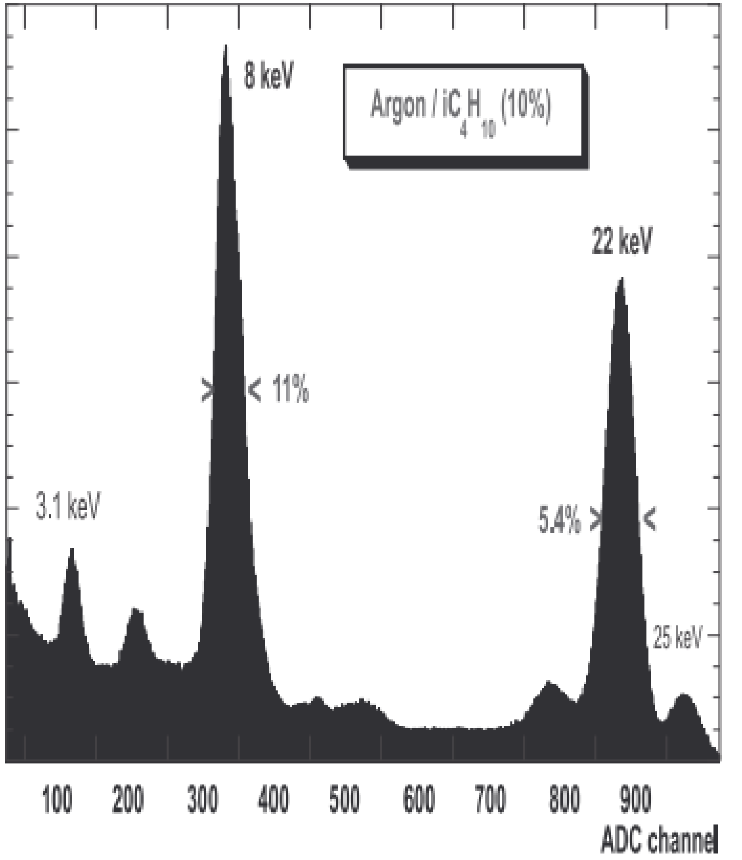


Fig. 7. An exceptionally good energy resolution (5.4% FWMM at 22 keV) with a chamber of small surface (30 cm^2) and a flat anode.

- **High electric field > 30kV/cm**
- **Position res ~ 10-30 μm**
- **Time res ~ 1-5 ns**
- **Fast ion collection**
- **Minimize the sensitivity of gain variation, more stable performance.**

Ref : 1) Y. Giomataris, Nucl. Instr. Meth. Phys. Res. A, 419, 239 (1998)
2) G. Barouch et al., Nucl. Instr. Meth. Phys. Res. A, 423, 32 (1999)

Why GEM !!!

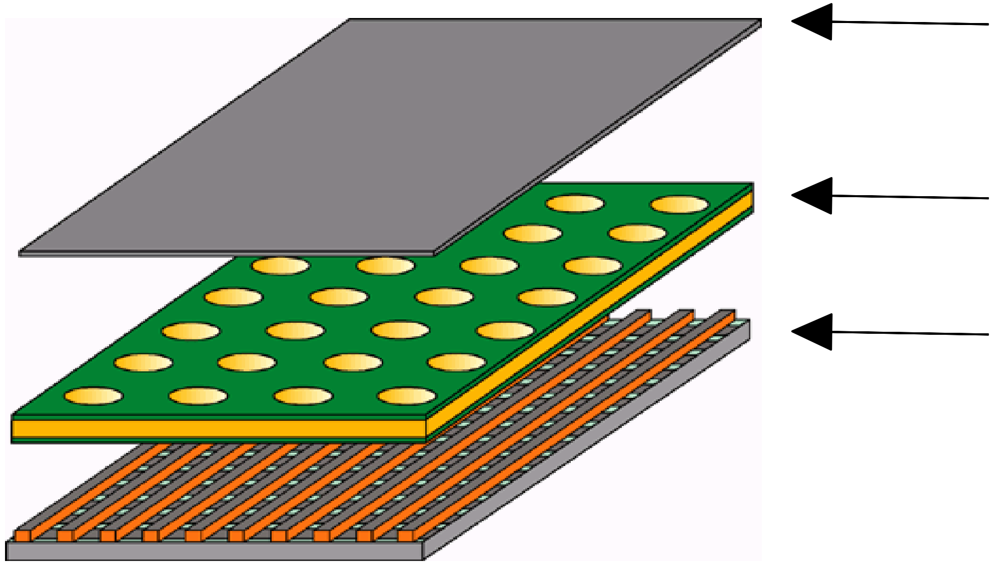
Ok ☺

Why GEM !!!

Ok ☺

but Why the long-term study on GEM !!!

Gas Electron Multiplier (GEM) detector



Drift plane

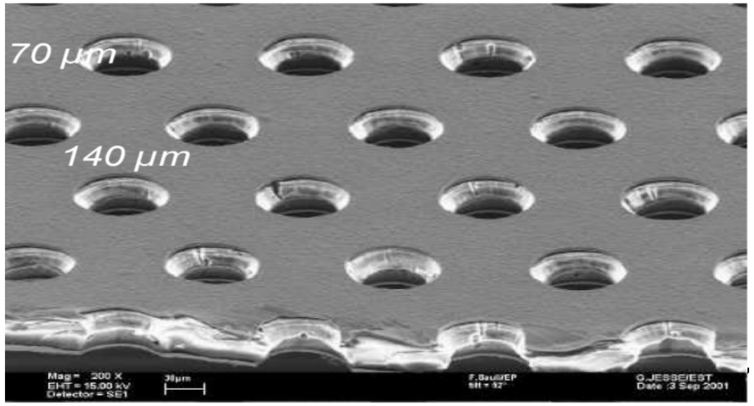
GEM foil

Readout

Schematic of a GEM detector

STANDARD GEM:

50 µm Kapton
5 µm Copper
70 µm holes at 140 µm pitch



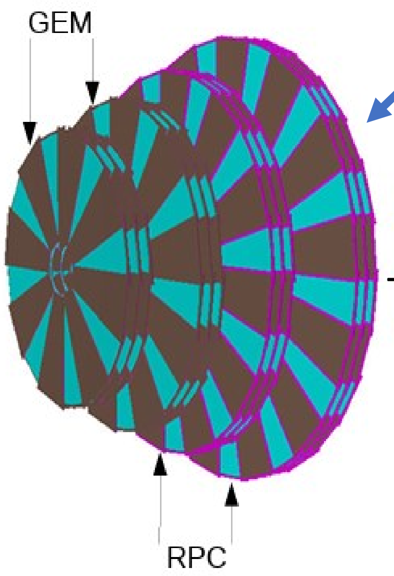


Fig : CBM MUCH with GEM+RPC layers

Simulated detector arrangement for MuCh detector sub-system.

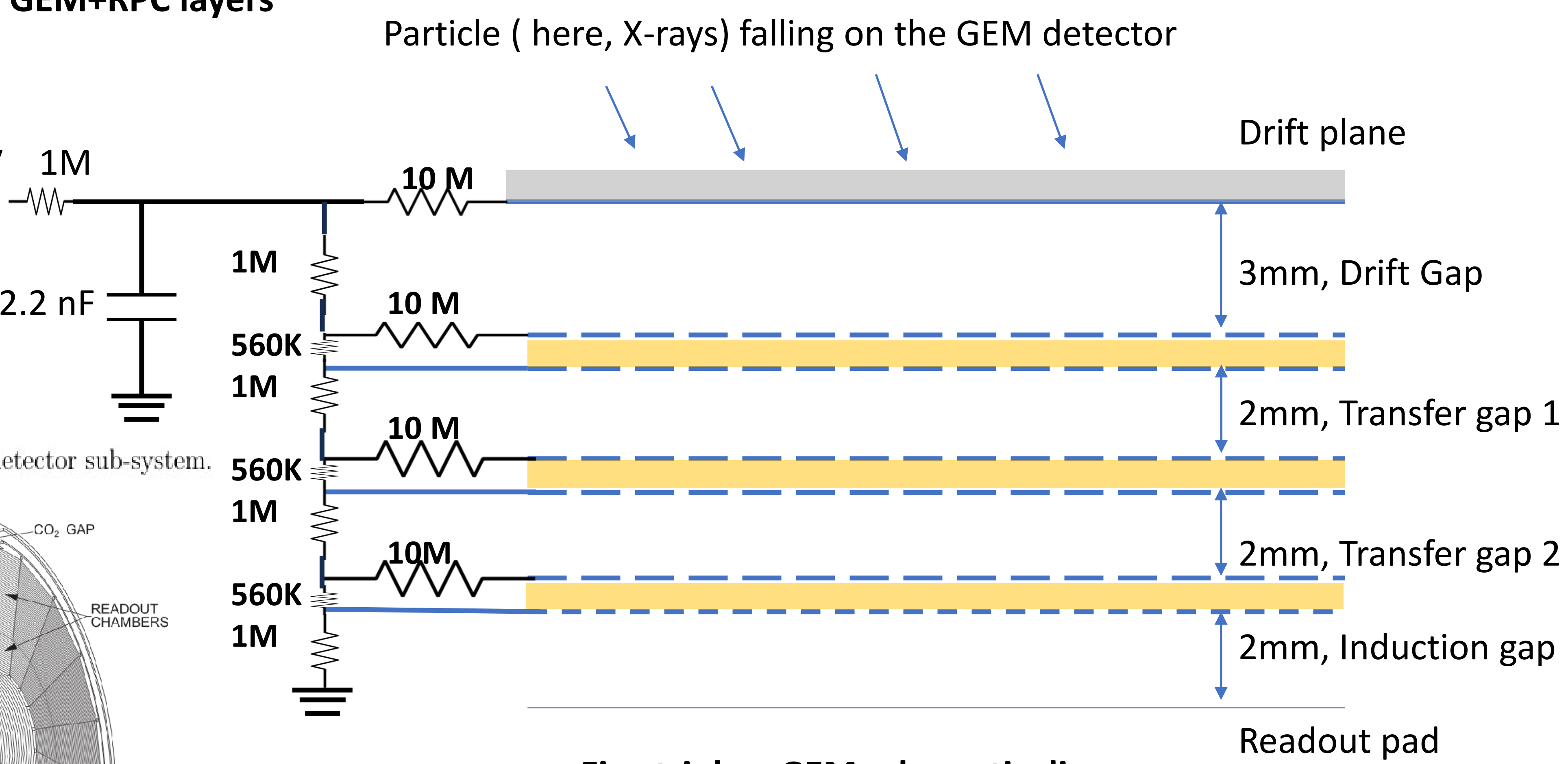


Fig : triple – GEM schematic diagram

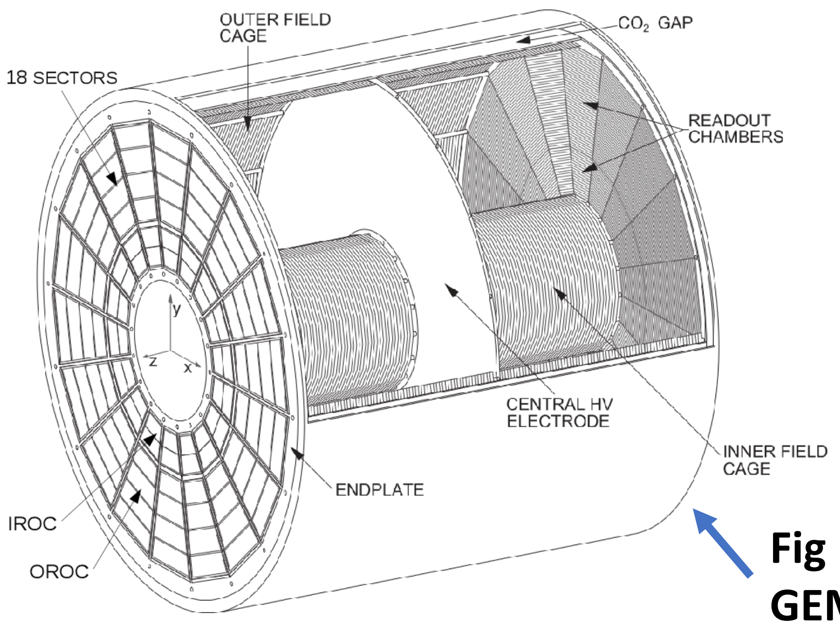
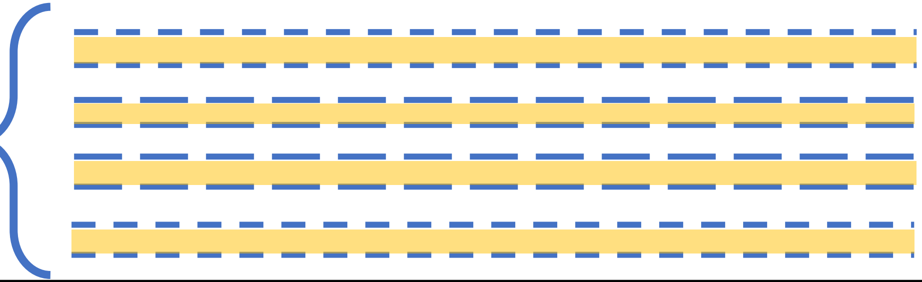


Fig : ALICE TPC with GEM upgradation



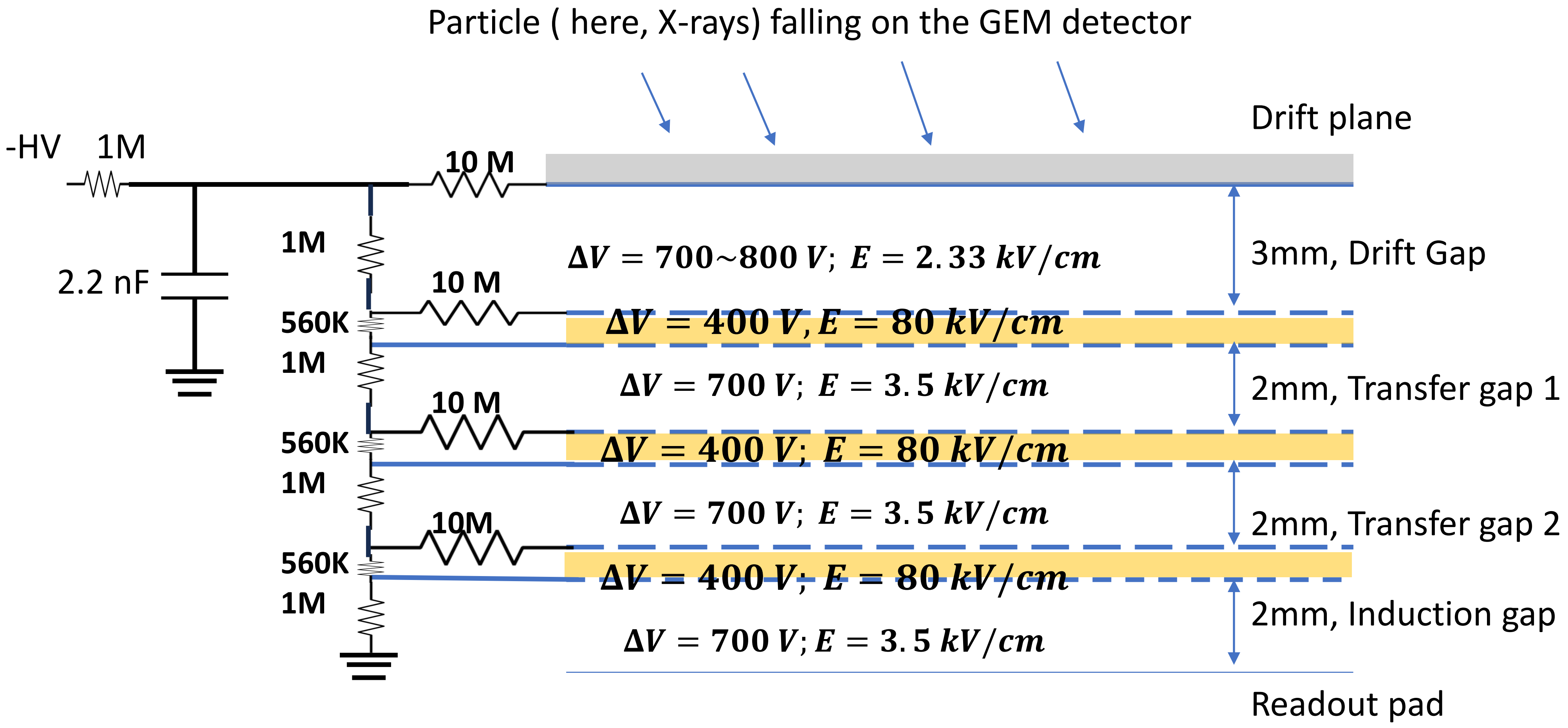
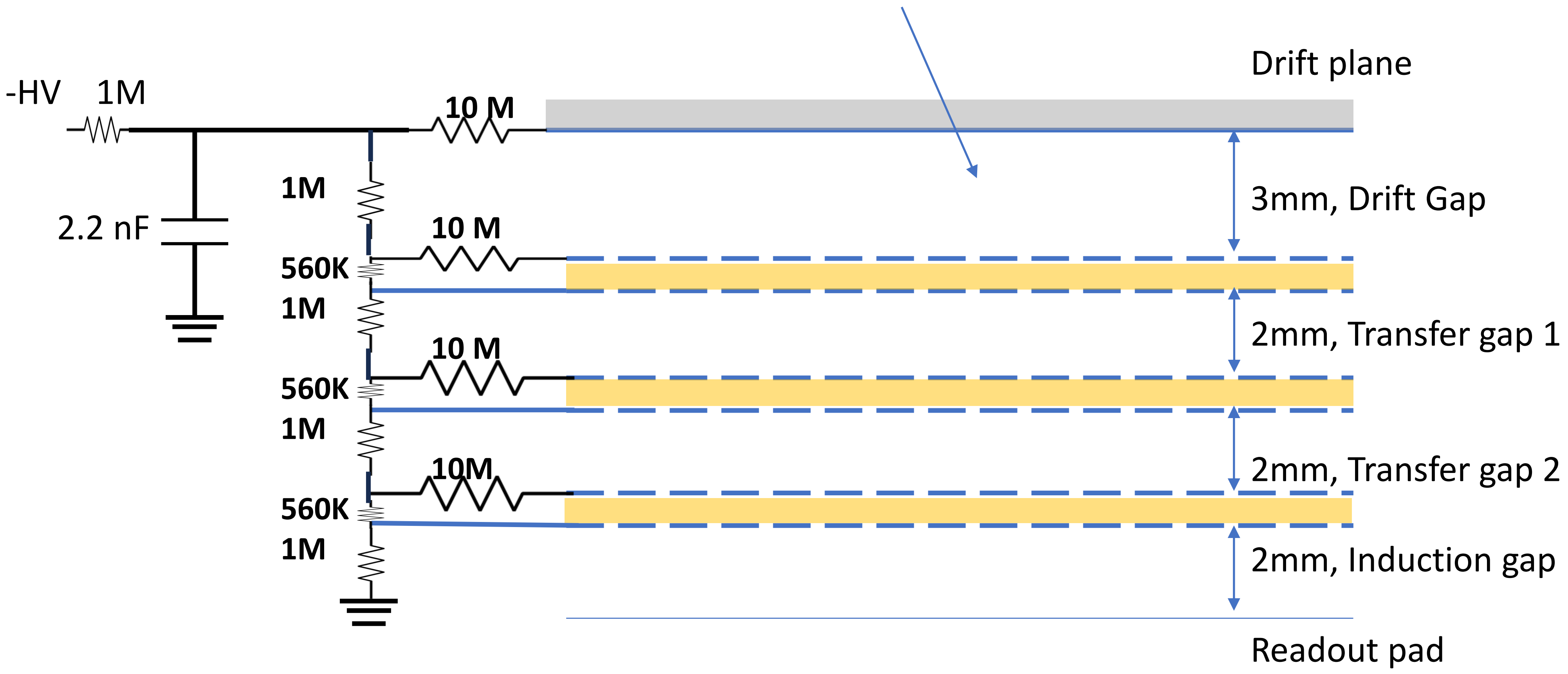


Fig : triple – GEM schematic diagram



-HV
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2.2 nF
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10 M
560K
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10 M
560K
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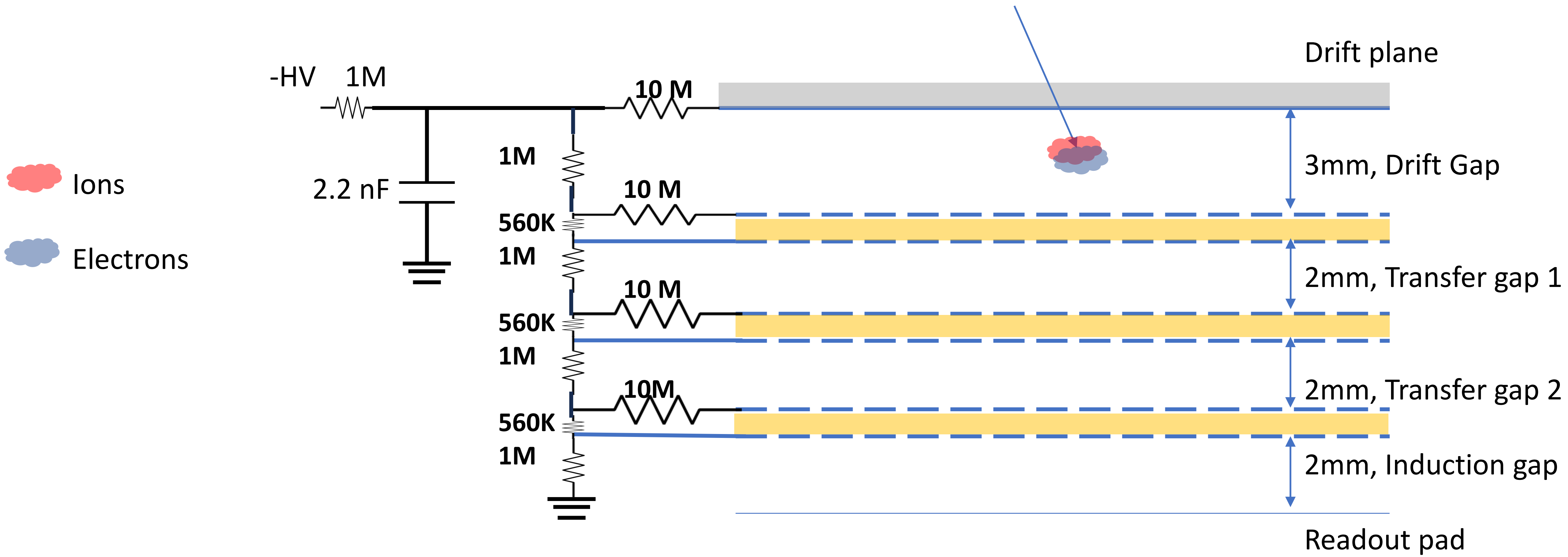
10M
560K
1M
Drift plane
3mm, Drift Gap
2mm, Transfer gap 1
2mm, Transfer gap 2
2mm, Induction gap
Readout pad



Ions
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Drift plane
3mm, Drift Gap
2mm, Transfer gap 1
2mm, Transfer gap 2
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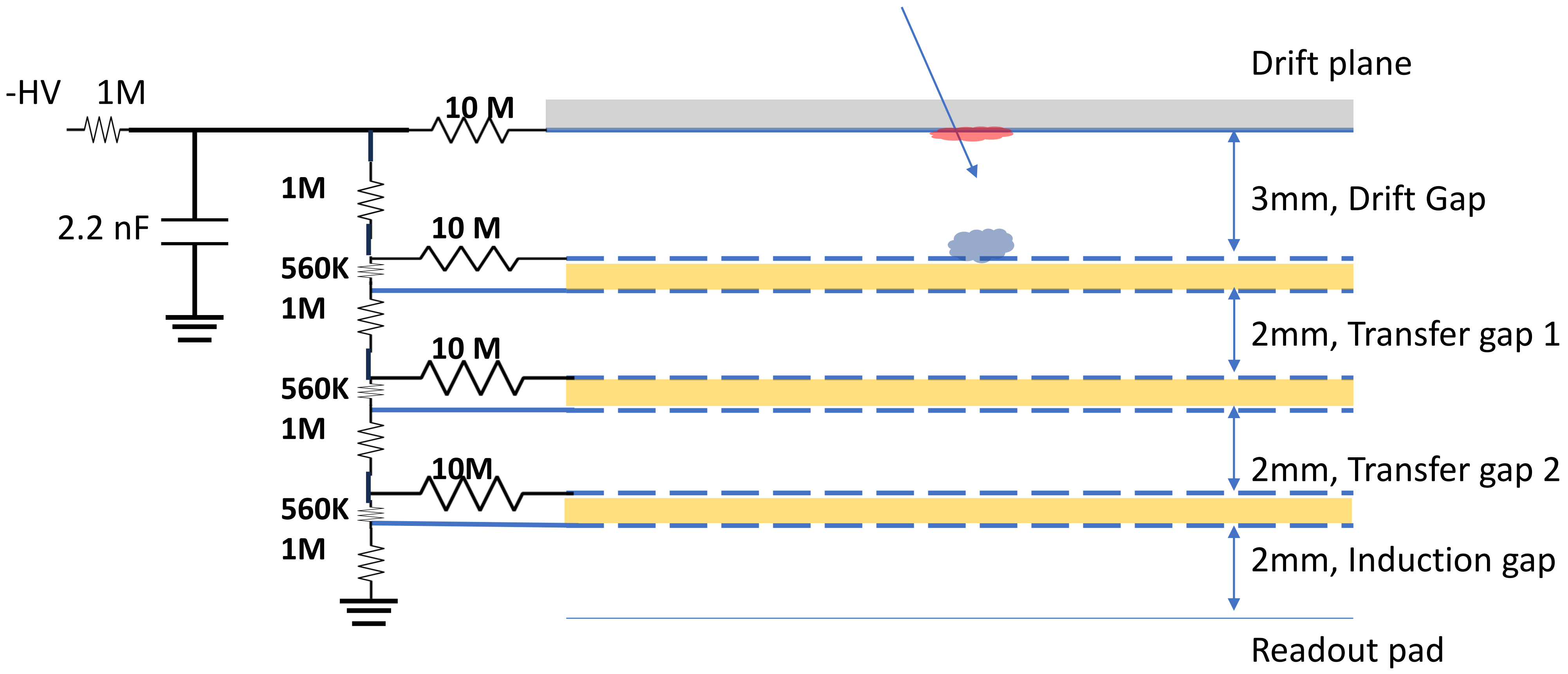
Readout pad



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Drift plane
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2.2 nF
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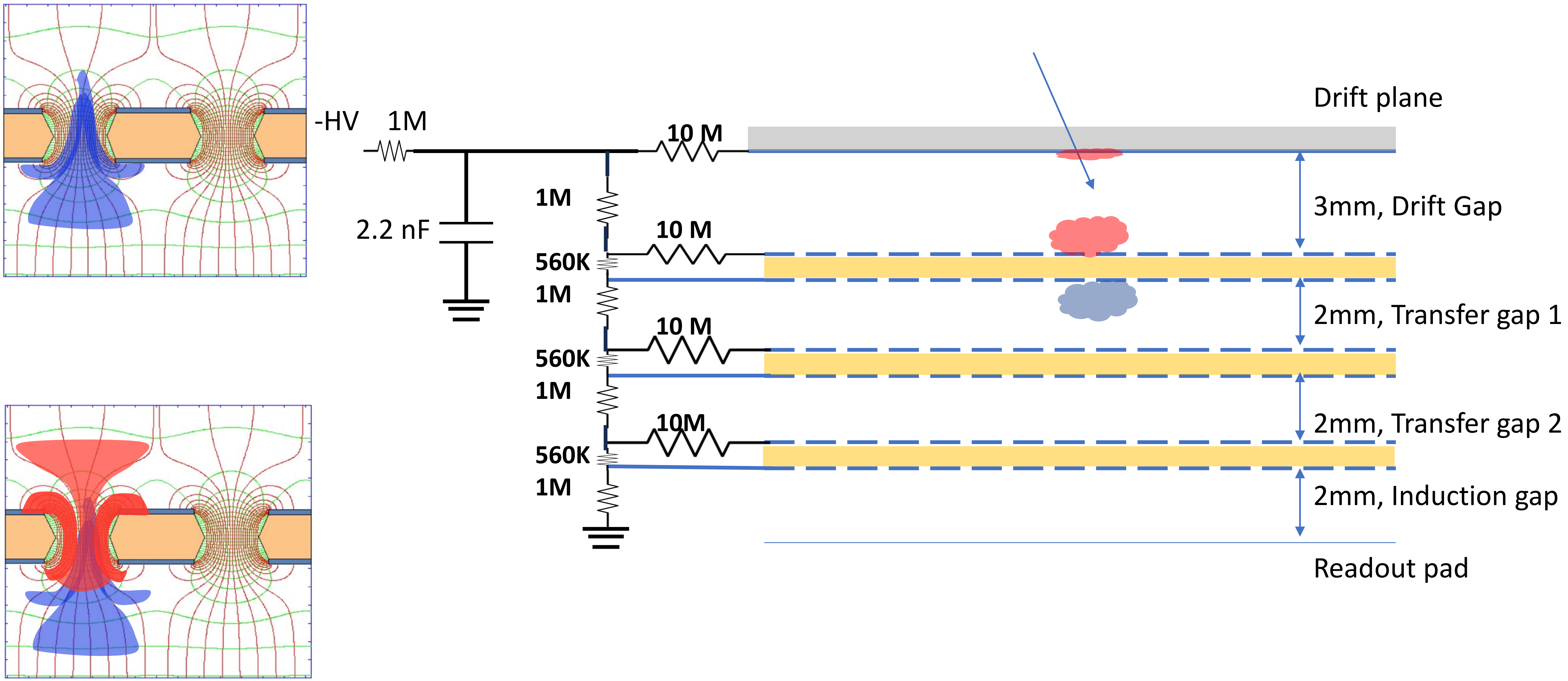
2mm, Transfer gap 2
560K
1M
2mm, Induction gap
Readout pad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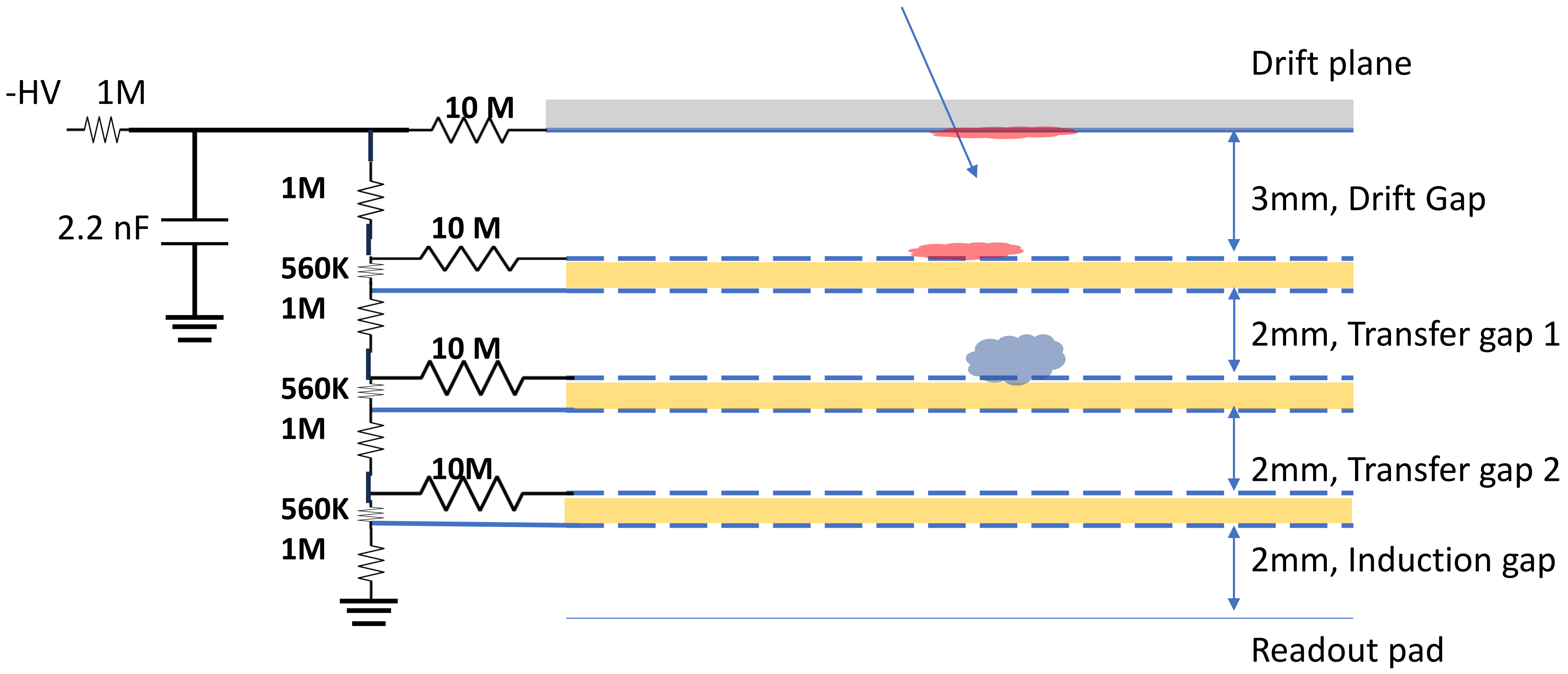
2mm, Induction gap
Readout pad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Drift plane
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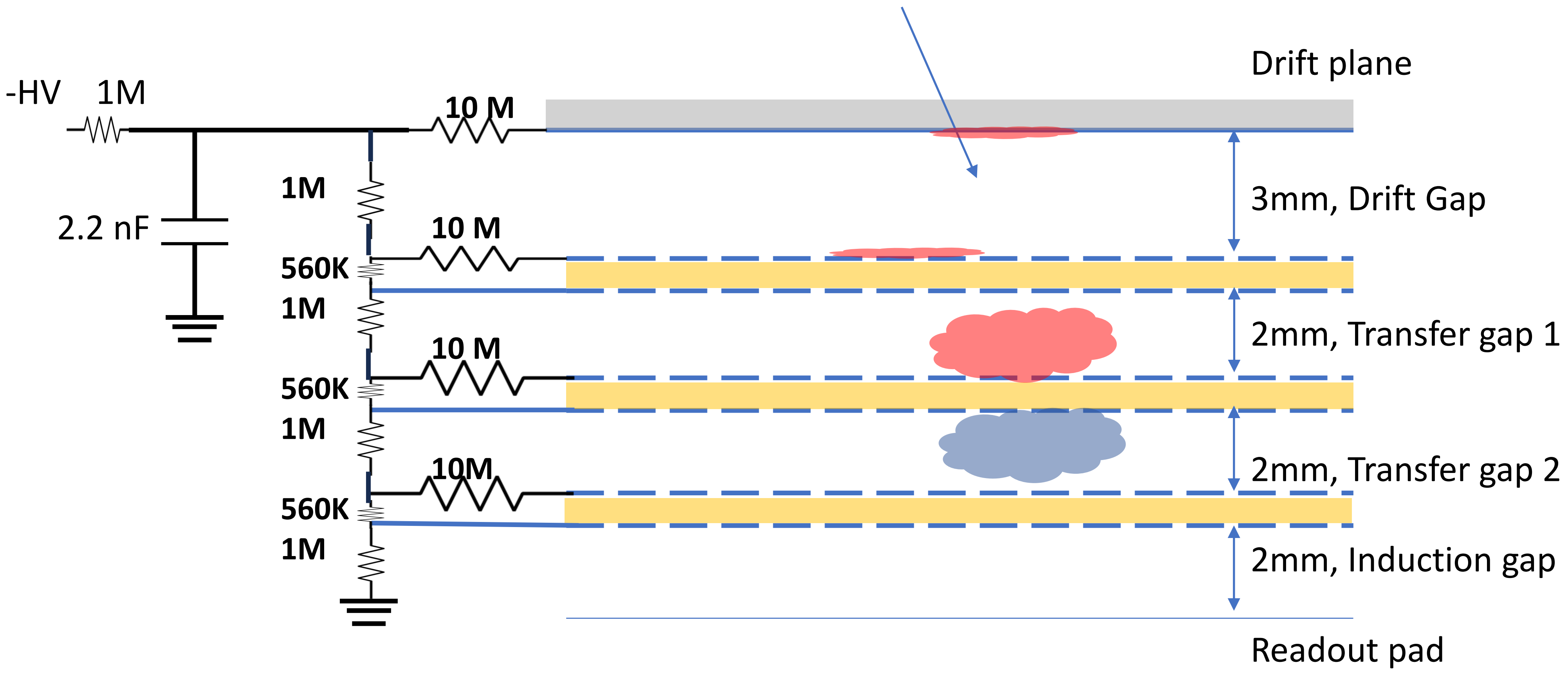
Readout pad



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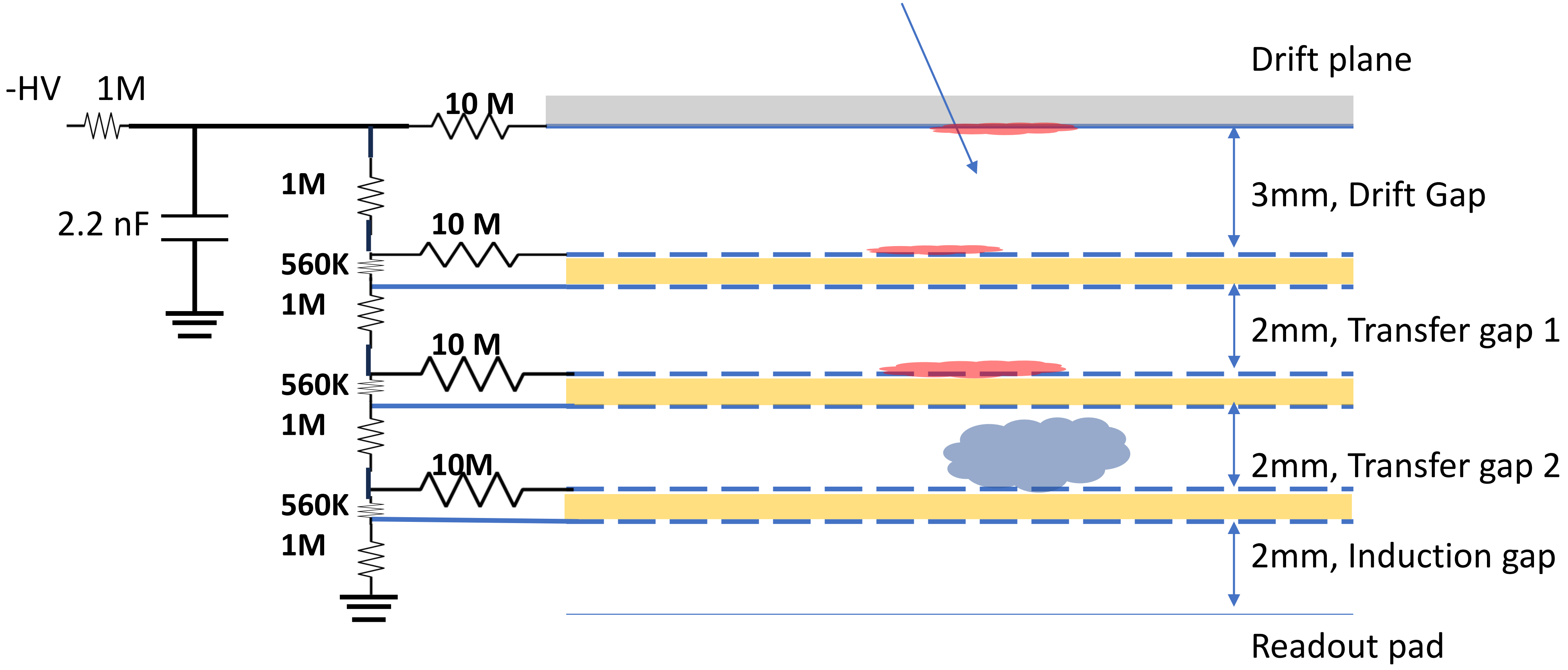
-HV
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2mm, Transfer gap 2
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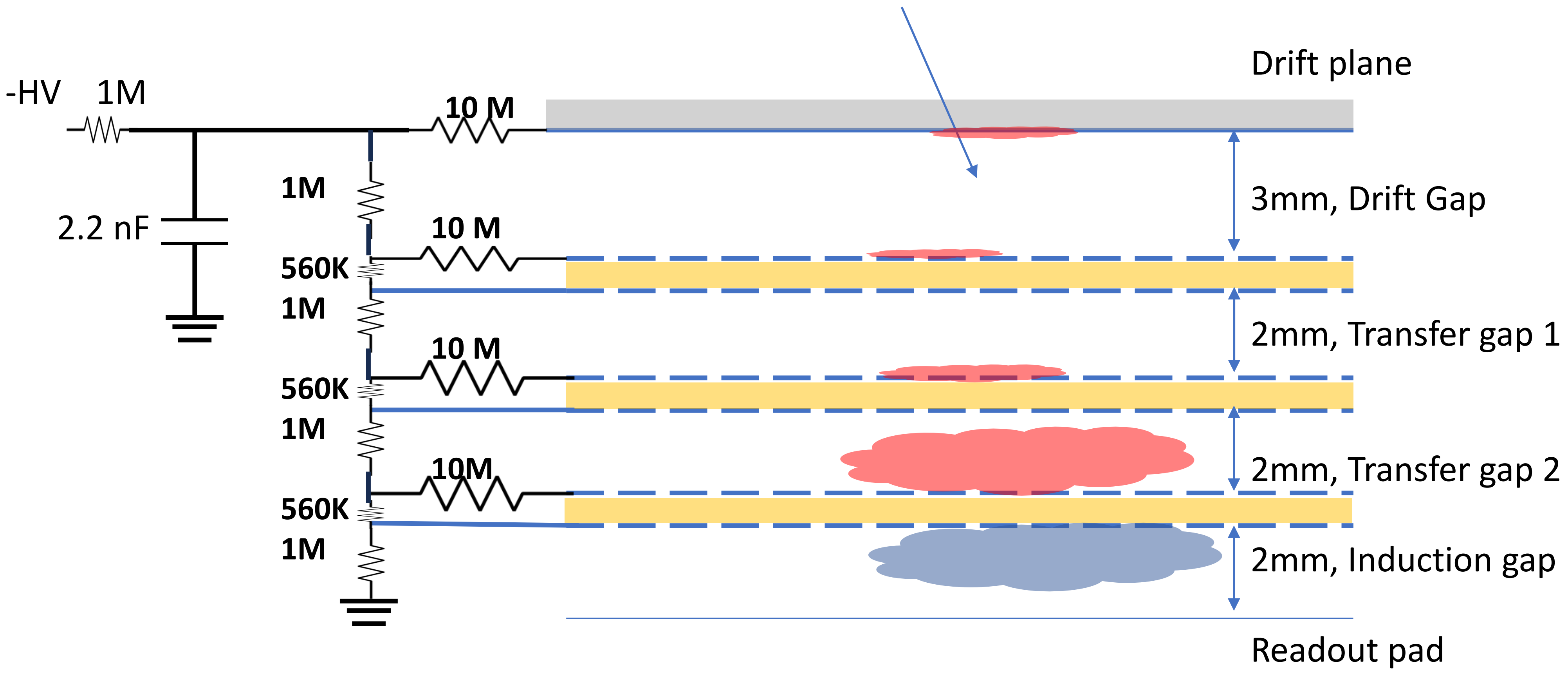
2mm, Induction gap
Readout pad



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Drift plane
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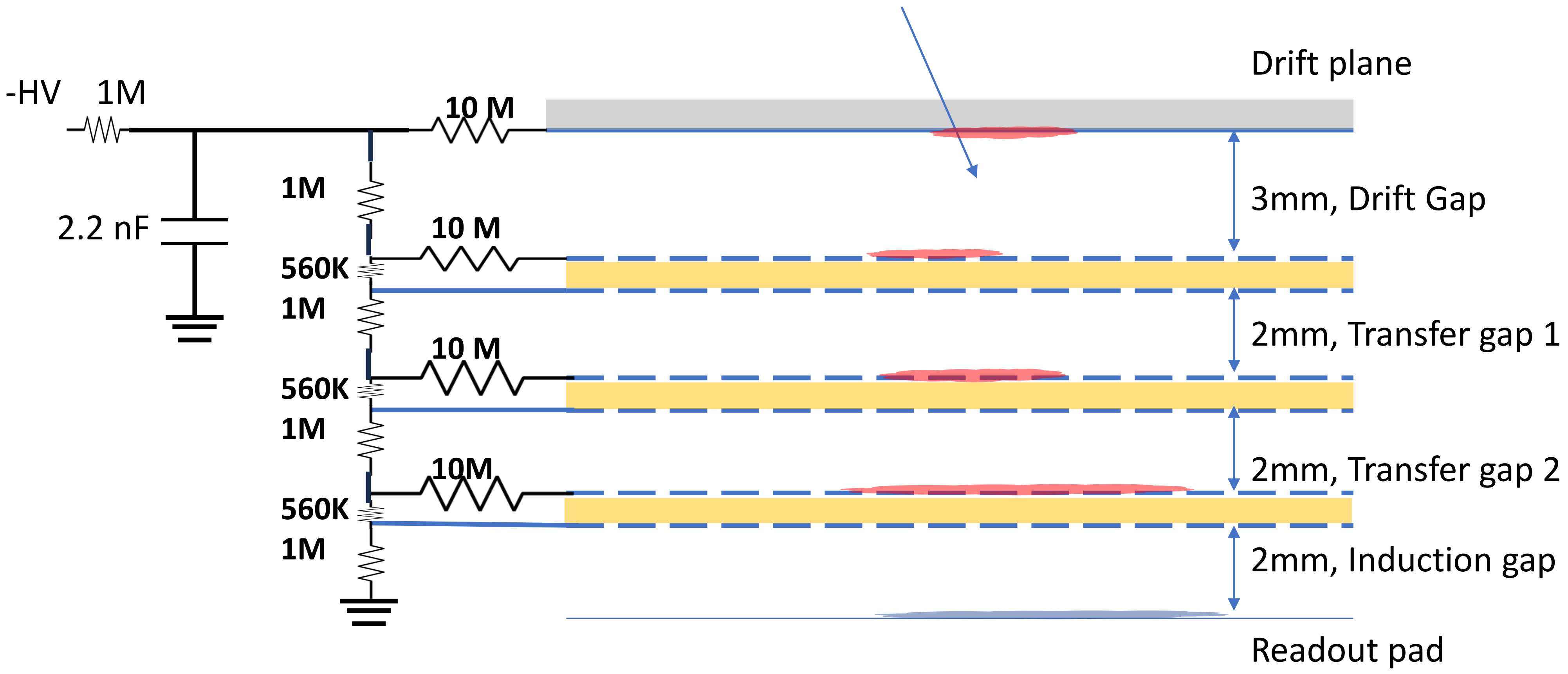
Readout pad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Drift plane
3mm, Drift Gap
2mm, Transfer gap 1
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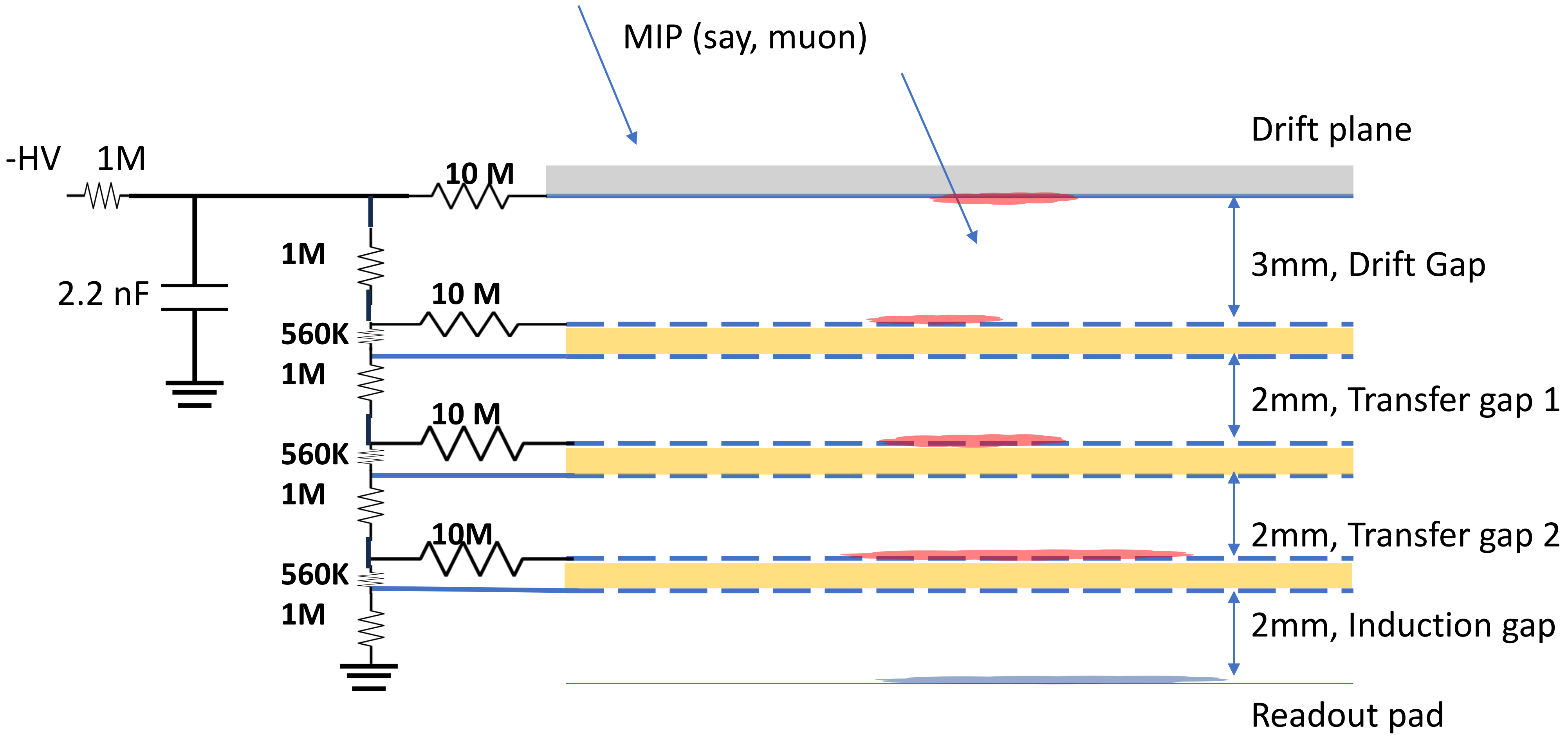
Readout pad



MIP (say, muon)
-HV
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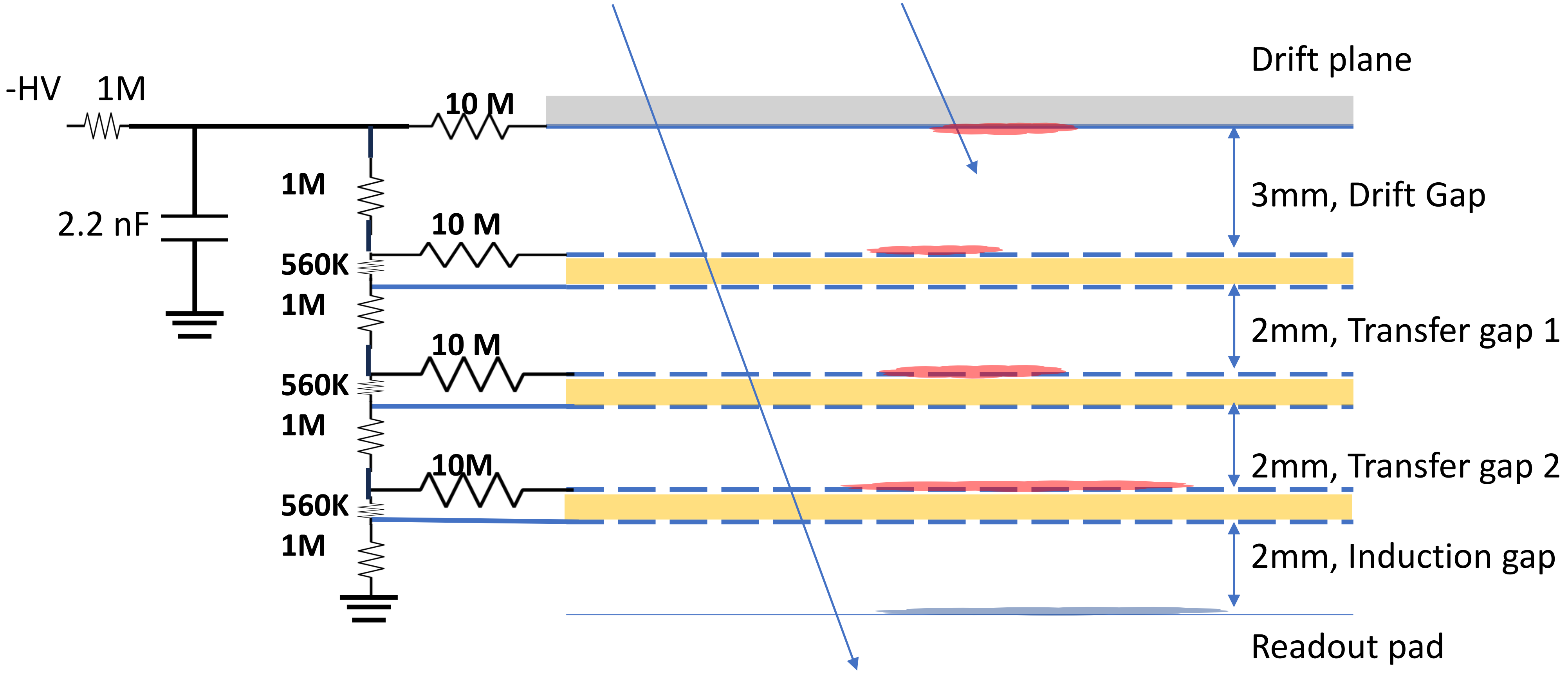
10 M
Drift plane
2.2 nF
1M
10 M
3mm, Drift Gap
560K
1M
10 M
2mm, Transfer gap 1
560K
1M
10M
2mm, Transfer gap 2
560K
1M
2mm, Induction gap
Readout pad



-HV
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2.2 nF
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560K
1M
Drift plane
3mm, Drift Gap
2mm, Transfer gap 1
2mm, Transfer gap 2
2mm, Induction gap
Readout pad

Features of the GEM detector

- Radiation hard detector
- Flexible geometry
- High gain (~ 10^4)
- High particle rate handling capabilities
- Good position resolution (~ 1 μm)
- Good time resolution (~ 10 ns)
- Good energy resolution
- Stable for long-term operation
- Features a low material budget

Application

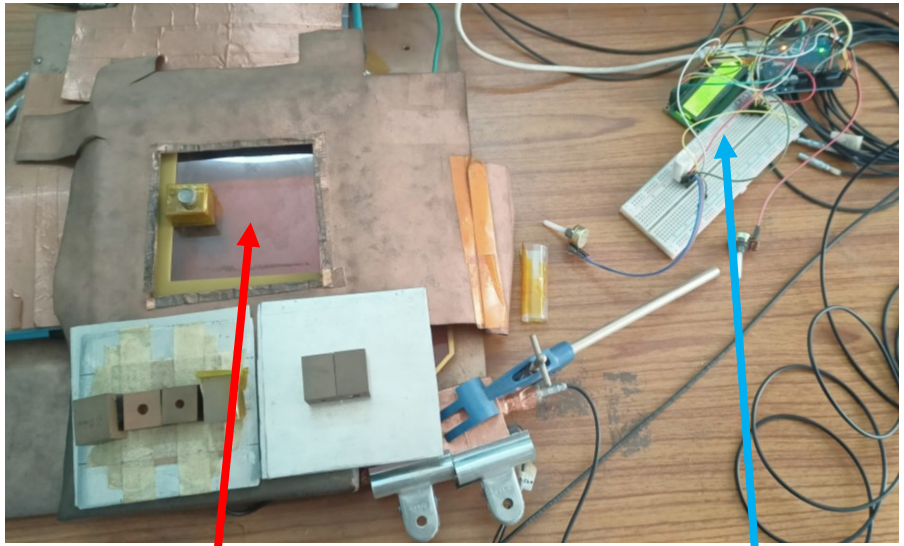
Experiment	Purpose (& requirement)	Dimension	Gas gap configuration	Gas mixture
HERA-B [34, 35, 36]	Pre-amplifying stage of MSGC (Reduce the discharge probability of MSGC)	25 cm × 25 cm	Drift gap: 3 mm Gap between GEM and MSGC: 2.8 mm	Ar based gas mixtures
COMPASS [38, 39, 40]	Tracking [Rate ($\sim$ 25 kHz/mm^2) handling with good resolution]	31 cm × 31 cm	Drift gap: 3 mm Transfer gaps: 2 mm Induction gap: 2 mm	Ar/CO_2 (70/30)
LHCb [42, 43]	Trigger [Rate ($\sim$ 500 kHz/cm^2) handling with high efficiency]	20 cm × 24 cm	Drift gap: 3 mm Transfer gap 1: 1 mm Transfer gap 2 : 2 mm Induction gap: 1 mm	$Ar/CO_2/CF_4$ (45/15/40)
TOTEM [45, 46]	Trigger & tracking (-)	Semi-cylindrical with radial extension from 4.25 cm to 14.45 cm	Drift gap: 3 mm Transfer gaps: 2 mm Transfer gap 2 : 2 mm Induction gap: 1 mm	Ar/CO_2 (70/30)
CMS [48, 49]	Tracking (Cope up with the upgradation of LHC to HL-LHC)	Trapezoidal modules 99 cm (height) × 45.5 cm (width at the wider side) 190 cm (height) × 120 cm (width at the wider side)	Drift gap: 3 mm Transfer gap 1: 1 mm Transfer gap 2 : 2 mm Induction gap: 1 mm	Ar/CO_2 (70/30)
ALICE [51, 52]	Readout of TPC (Reduce the ion back flow below)	Trapezoidal modules 49.7 cm (height) × 46.7 cm (width)	Quadrupole GEM Drift, transfer and induction gaps: 2 mm	$Ne/CO_2/N_2$ (90/10/5)

Table : Summary of the application of the GEM detector in HEP experiments.

- Triple GEM trackers, like used in the COMPASS experiment, are harnessed for Proton Range Radiography (PRR) in hadron therapy that involves correlating measured positions with energy loss profiles, revealing density distribution within the target.
- Anticipated use of triple GEM chambers in muon chambers for upcoming High-Energy Physics (HEP) experiments, including CBM at FAIR
- This application aims to enhance muon tracking capabilities, addressing objectives related to Compressed Baryonic Matter (CBM) studies.

Ref : Sayak Chatterjee, Performance Studies of Gas Electron Multiplier Detector for the Muon Chamber of High Rate CBM Experiment at FAIR, Ph.D. Thesis, University of Calcutta, 2023

Setup at Bose Institute



GEM Detector

Single Mask,
10 cm X 10 cm

Data-logger

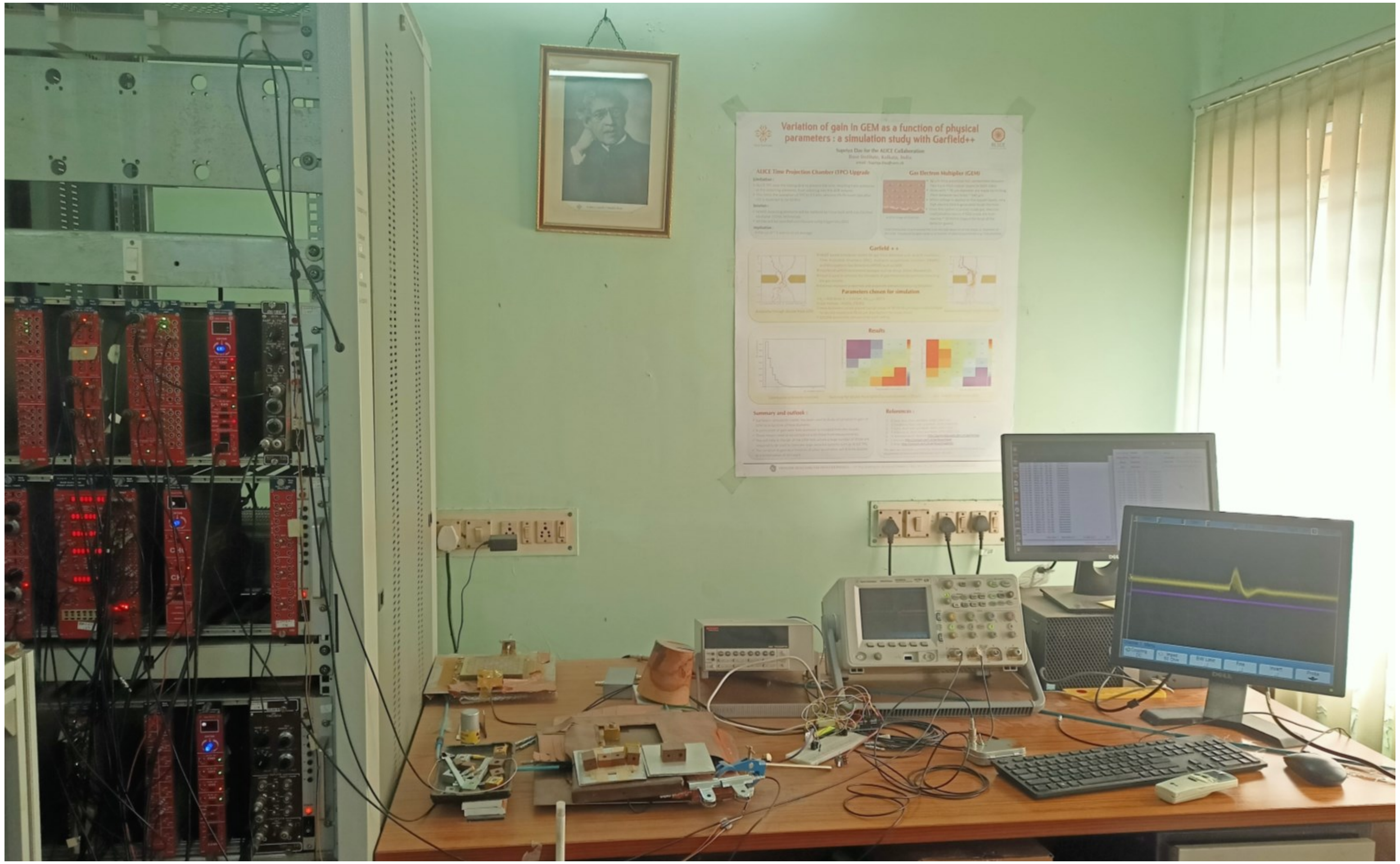
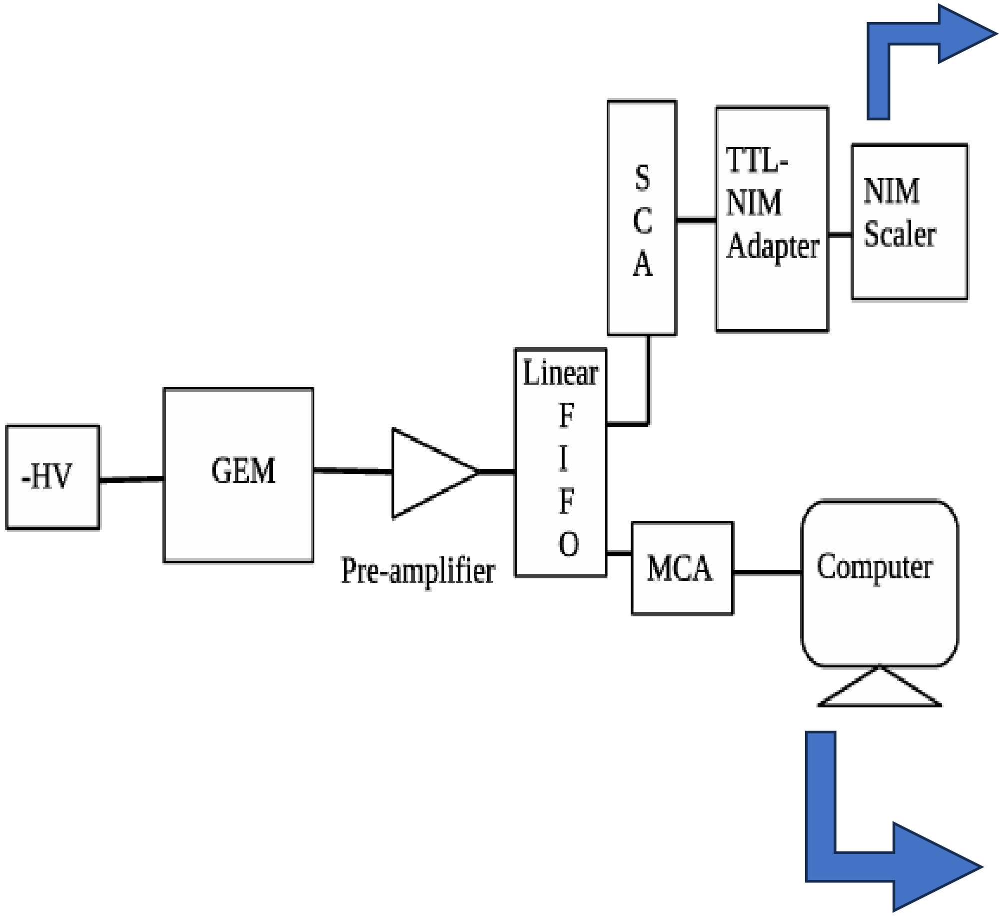
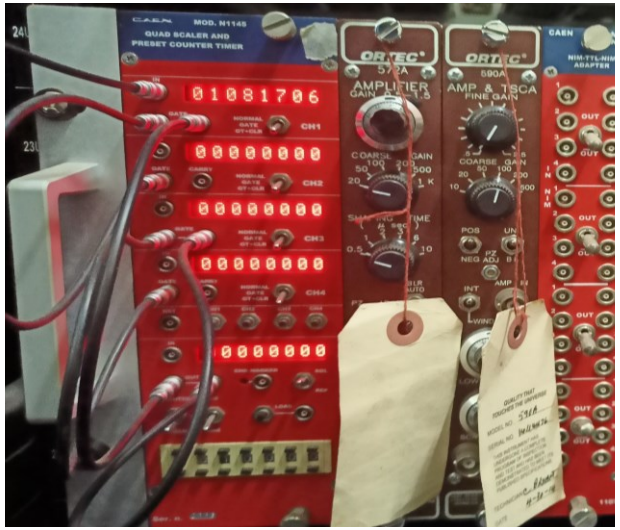
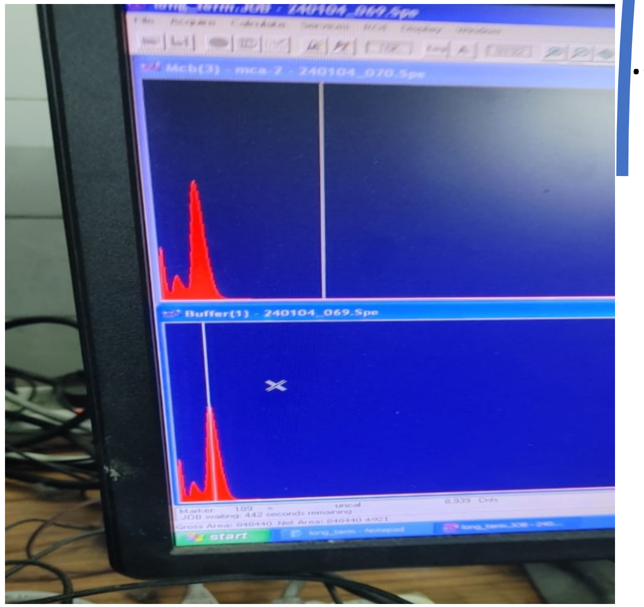


Fig : The whole GEM Detector Setup at BOSE Institute

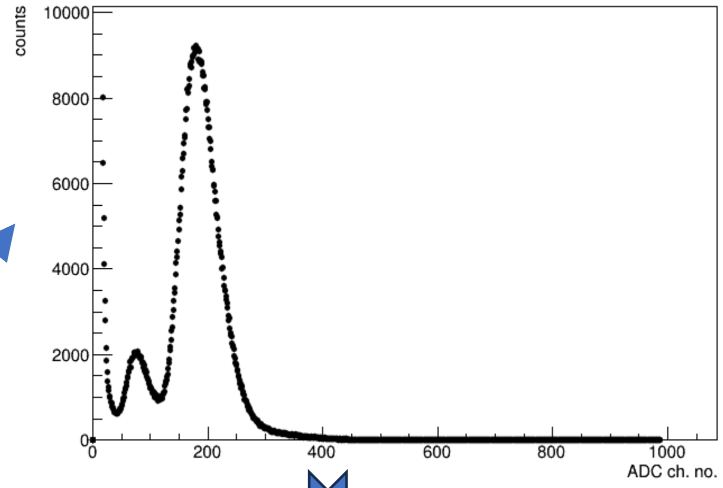
Data Collection



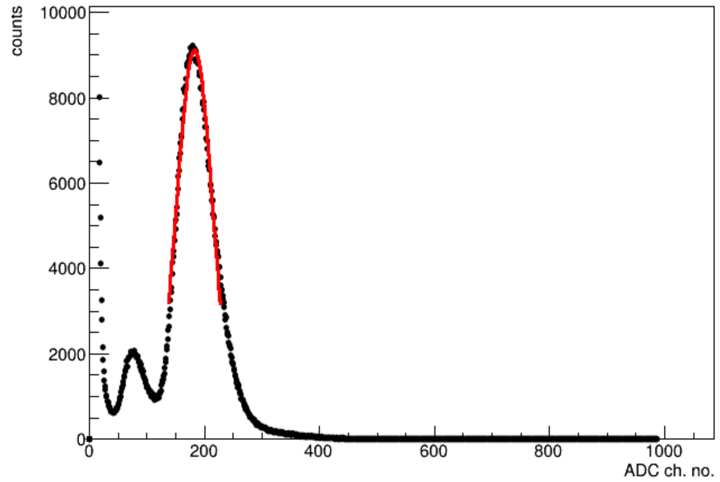




.Spe file

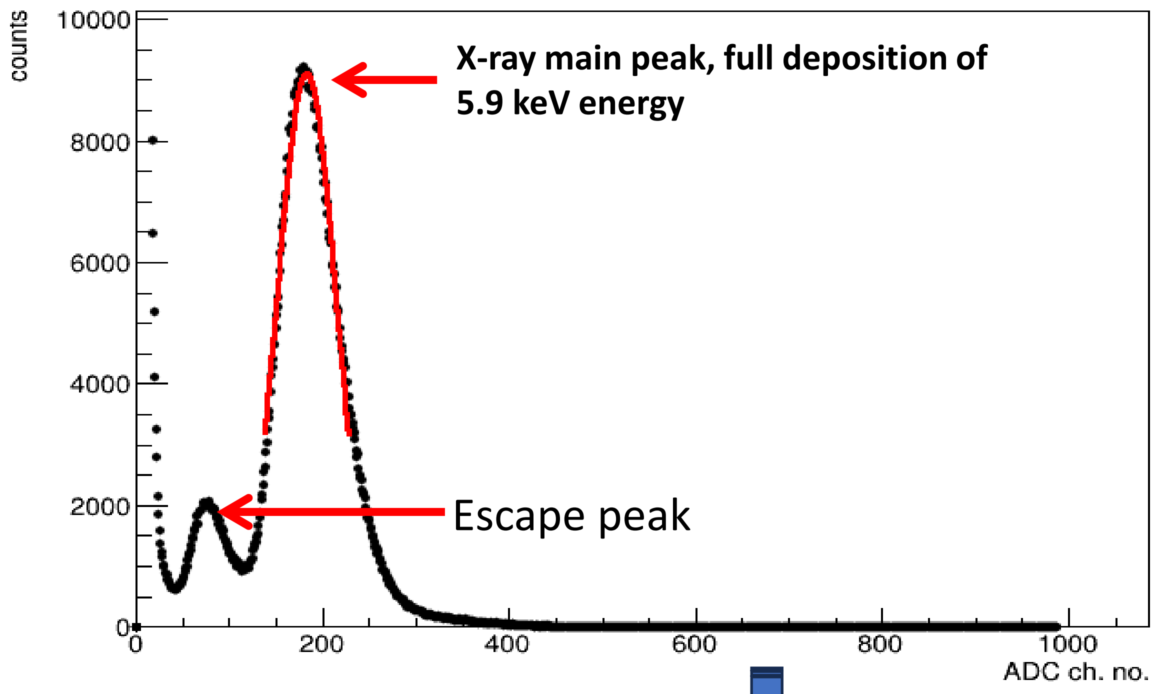


Fit with Gaussian for peak and sigma.



Results

Analysis Details



Sigma → energy resolution

$$\textbf{energy resolution} = \frac{\textbf{sigma} \times 2.355}{\textbf{mean}} \times \ 100\ \%$$

Mean → Peak of the Spectrum

$$Pulse\ height\ (in\ V) = MCA\ channel\ no. \times 0.0014 + 0.1428$$

$$gain = \frac{Output\ charge}{Input\ charge} = \frac{\left(\frac{(Pulse\ height)}{2\ mV}\right) fC}{No.of\ primary\ electron \times\ eC}$$

The number of the primary electrons in the gas mixture is calculated in the following way: Number of primary electrons,

$$N_0 = E_\gamma \left(\frac{\%Ar}{W_{Ar}} + \frac{\%CO_2}{W_{CO_2}}\right)$$

Where E_γ is the energy of the photon (5.9 keV X-ray Fe^{55} $sorce$), for the combination of Ar/CO_2 : 70/30, $N_0 \sim 212$

Analysis Details

Also, the ambient Temperature(K), Pressures(atm), and Relative Humidity(%) have been logged using a data logger.

- **The gain can depend on this ratio of temp. and pressure(T/p) as,**

$$gain\left(\frac{T}{p}\right) = A\exp\left(B * \frac{T}{p}\right)$$

- **Also, the energy resolution can depend on the same as,**

$$energy\ resolution\left(\frac{T}{p}\right) = A'\exp\left(B' * \frac{T}{p}\right)$$

- **Then, we get normalised gain as,**

$$gain_{normalised} = \frac{gain_{measured}}{A\exp\left(B * \frac{T}{p}\right)}$$

- **And, normalised energy resolution as,**

$$enrgy\ resolution_{normalised} = \frac{energy\ resolution_{measured}}{A'\exp\left(B' * \frac{T}{p}\right)}$$

- **This normalised gain and energy-resolution can also be seen as a function of accumulated charge per unit area,**

$$\int \left(\frac{dq}{dA}\right) dt = \int ((r \times \mathrm{n} \times \mathrm{e} \times \mathrm{G} \times \mathrm{dt})/\mathrm{dA})$$

where e : electronic charge; n: no. of primary electron; G: Gain; r: rate of incident particle

Analysis Details

In this way, I analysed the observations from Jan 18, 2023, to Oct 08, 2023

Among them, one of the longest continuous running of the GEM detector was observed from Sep 18, 2023, to Oct 08, 2023. So, we further study that particular data set.

For this time Ar/CO_2 :: 70 / 30, Applied voltage : 4500 V for $\sim 25\ hrs$ then 4600 V for the rest of time.

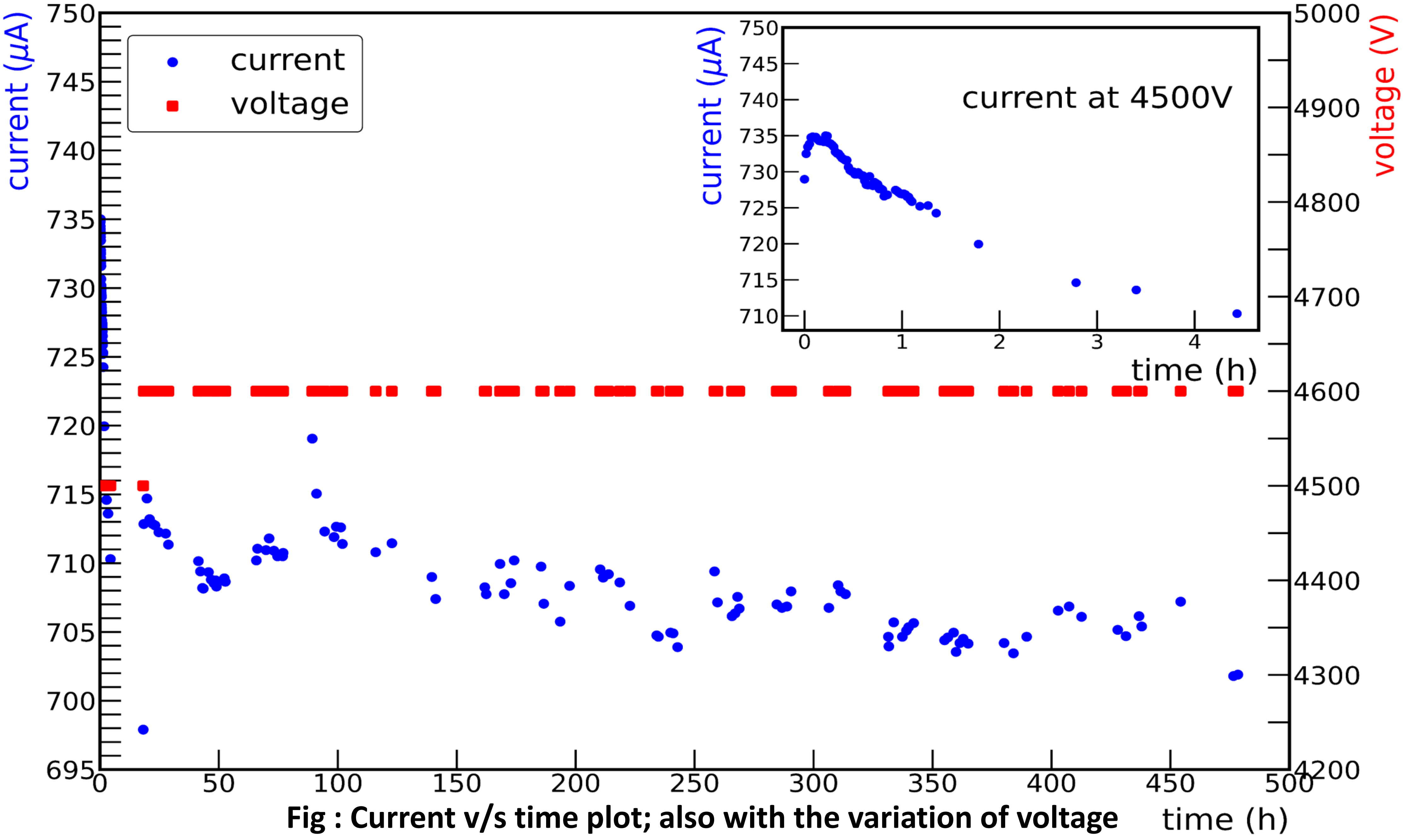


Fig : Current v/s time plot; also with the variation of voltage

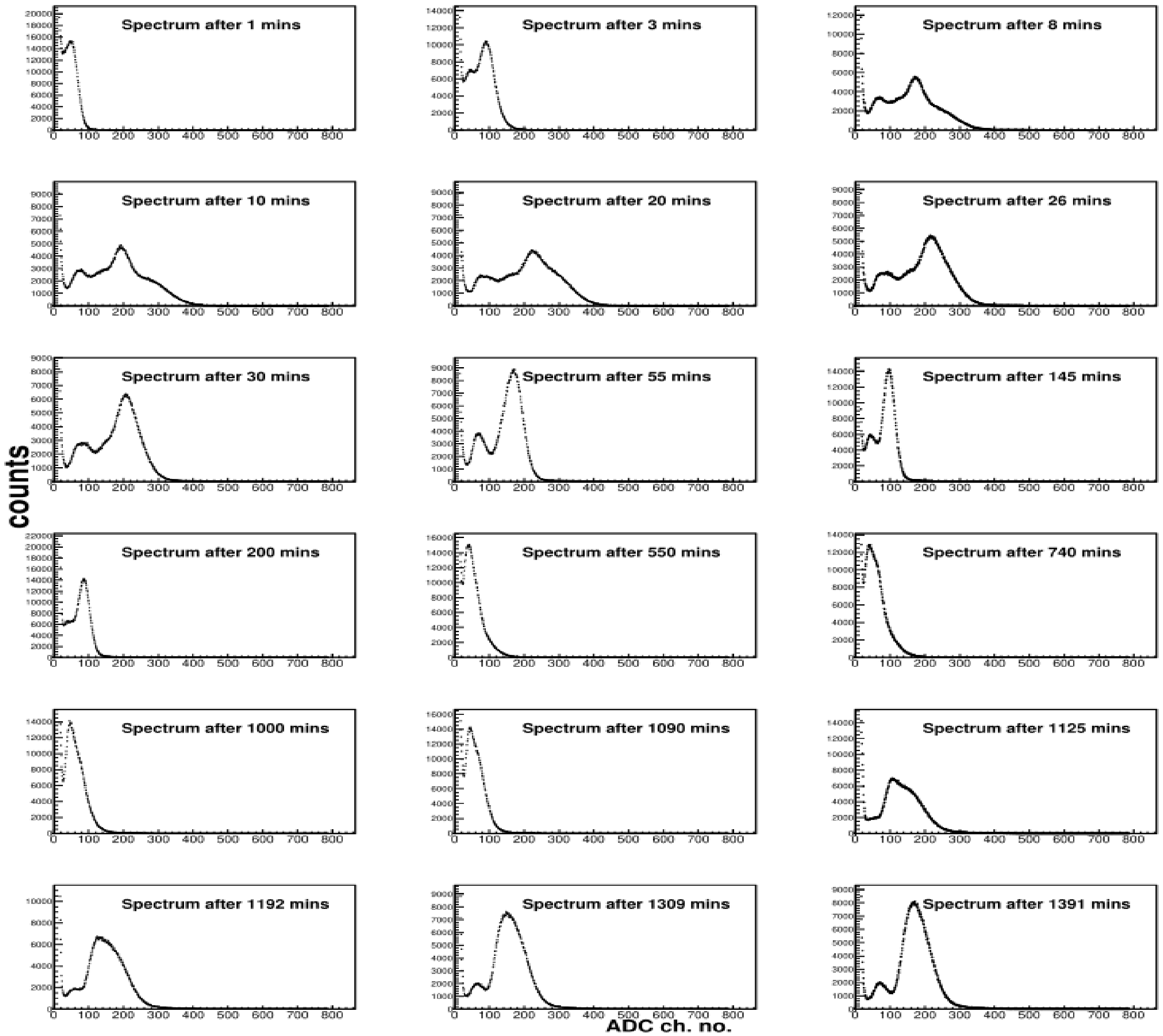


Fig : Different spectrum for the first few minutes when the current is continuously decreasing

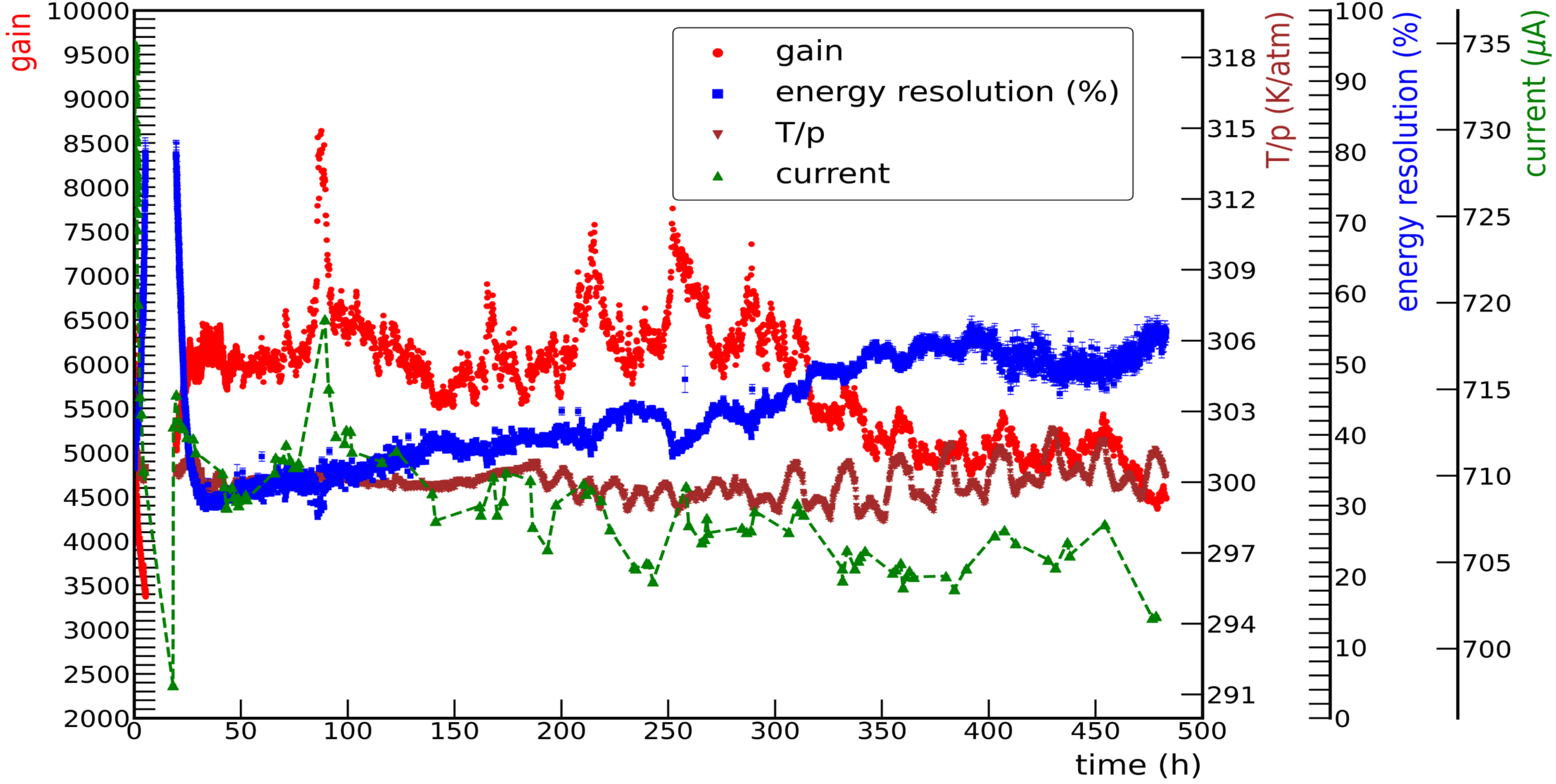


Fig : gain v/s time plot; also with the variation of energy resolution and T/p.

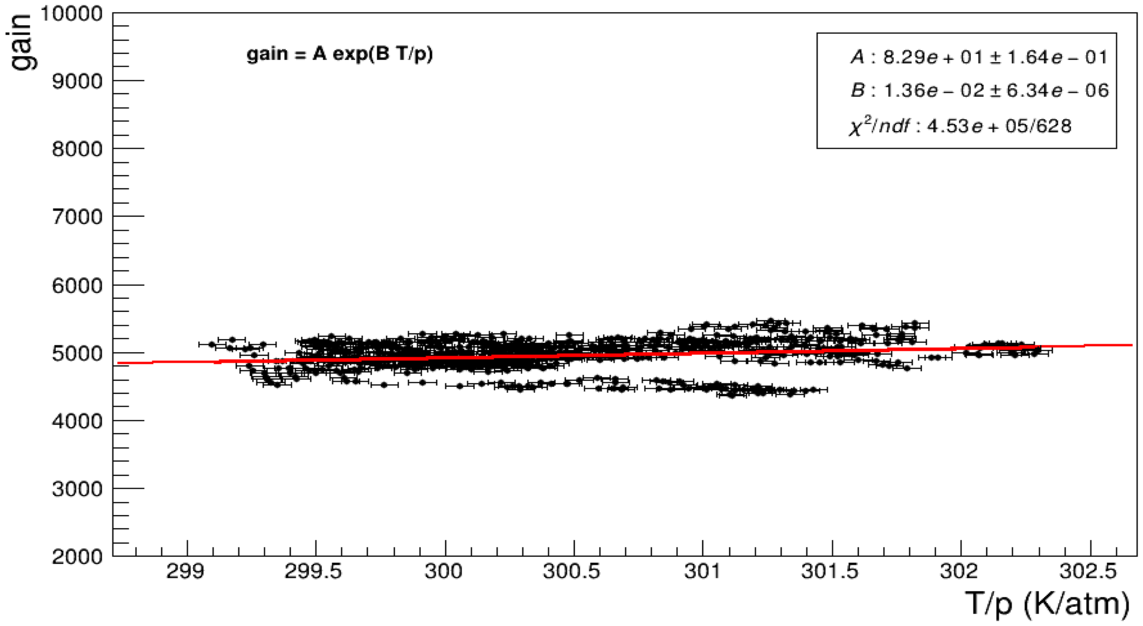


Fig : gain v/s (T/p) fitting plot with function A*exp(B*T/p)

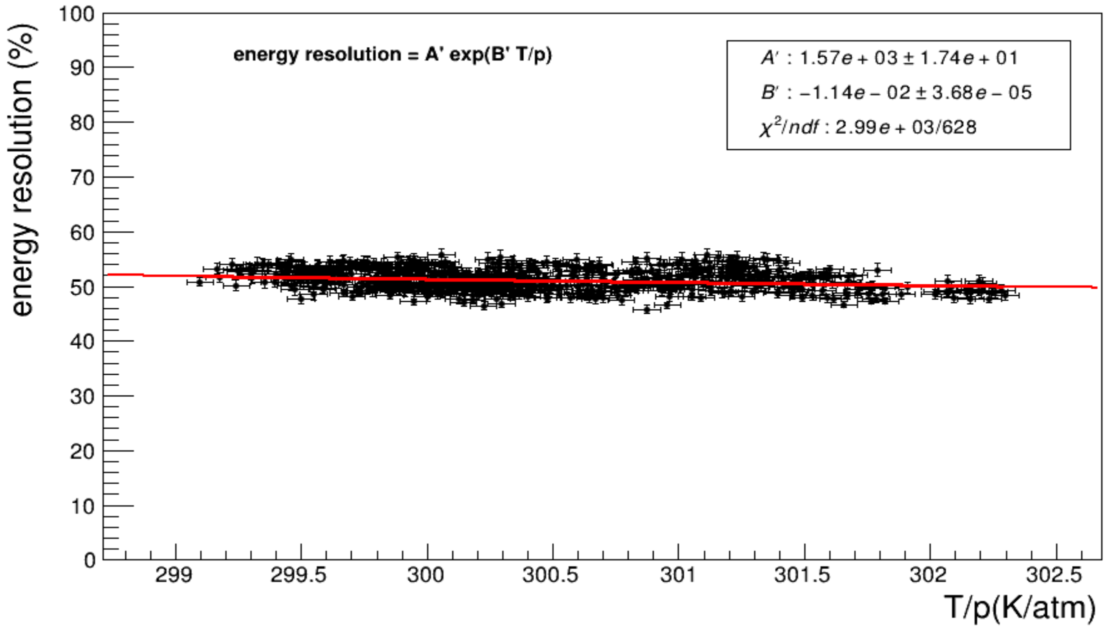


Fig : E.res v/s (T/p) fitting plot with function A'*exp(B'*T/p)

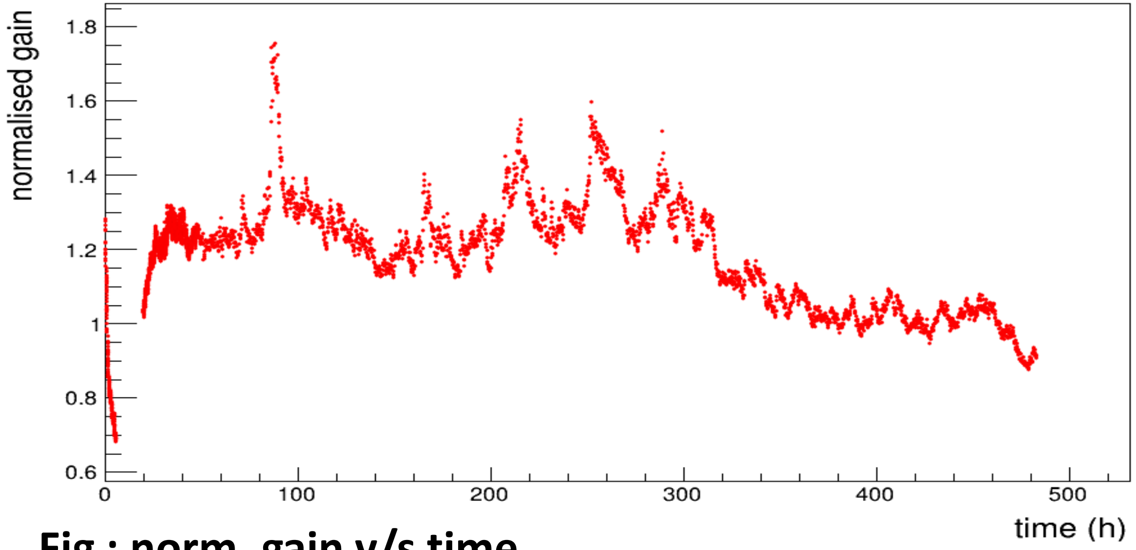


Fig : norm. gain v/s time

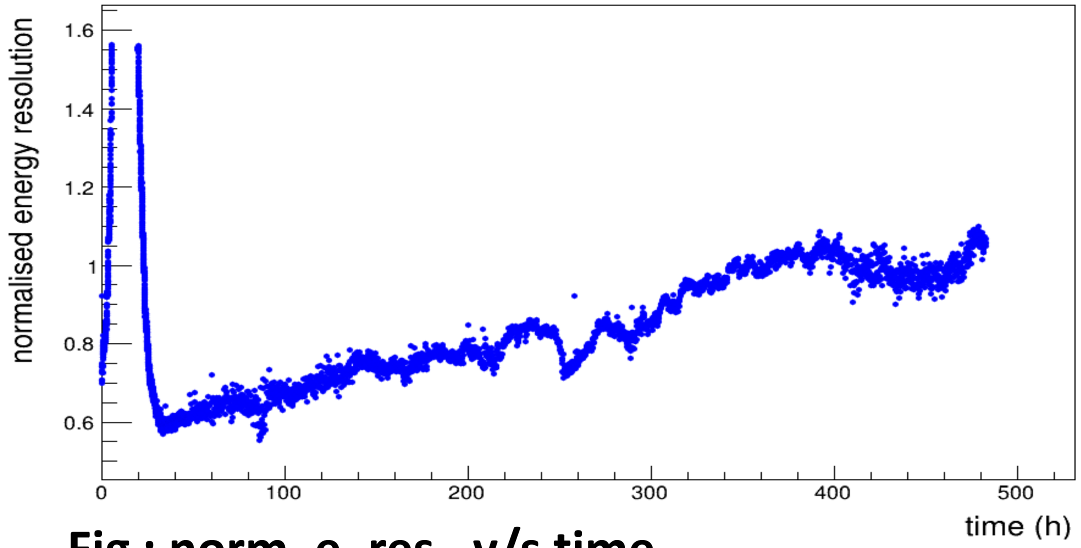


Fig : norm. e. res. v/s time

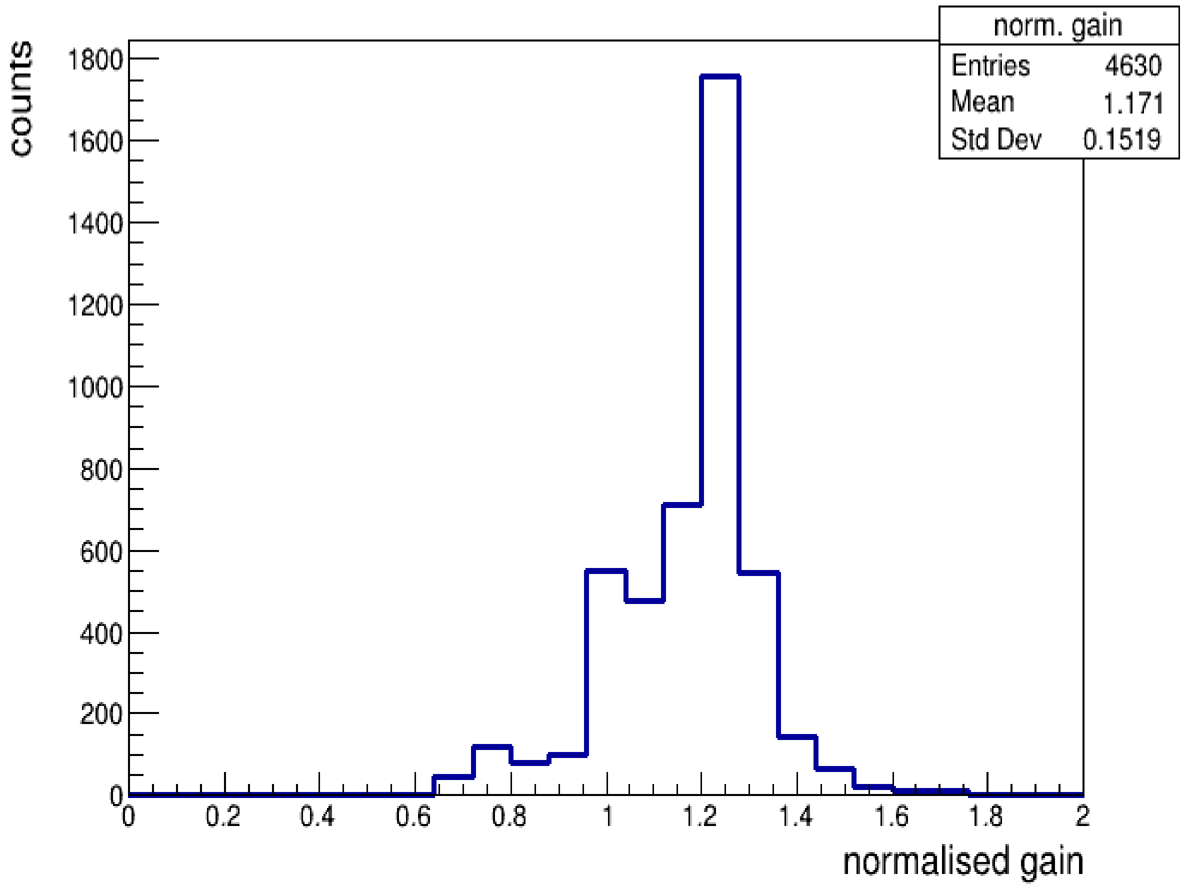


Fig : norm. gain distribution

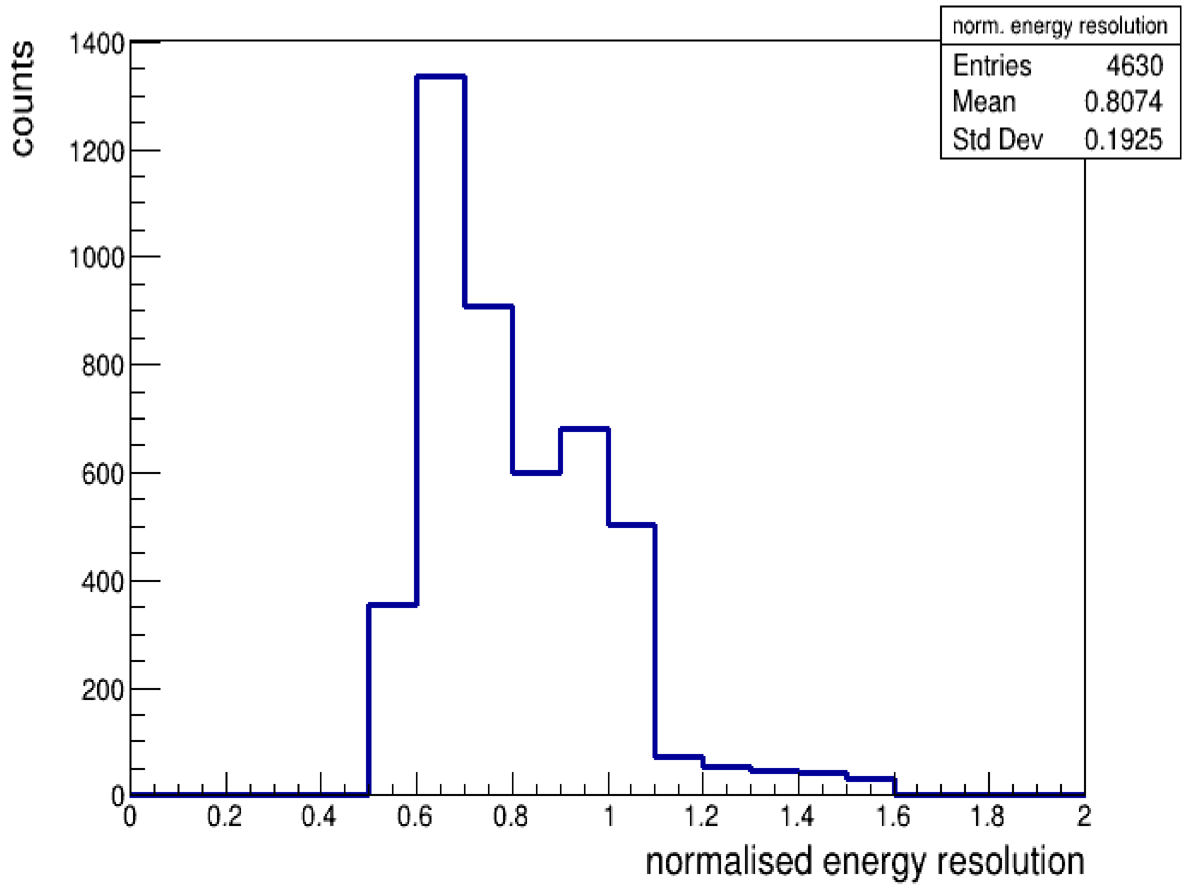


Fig : norm. energy resolution distribution

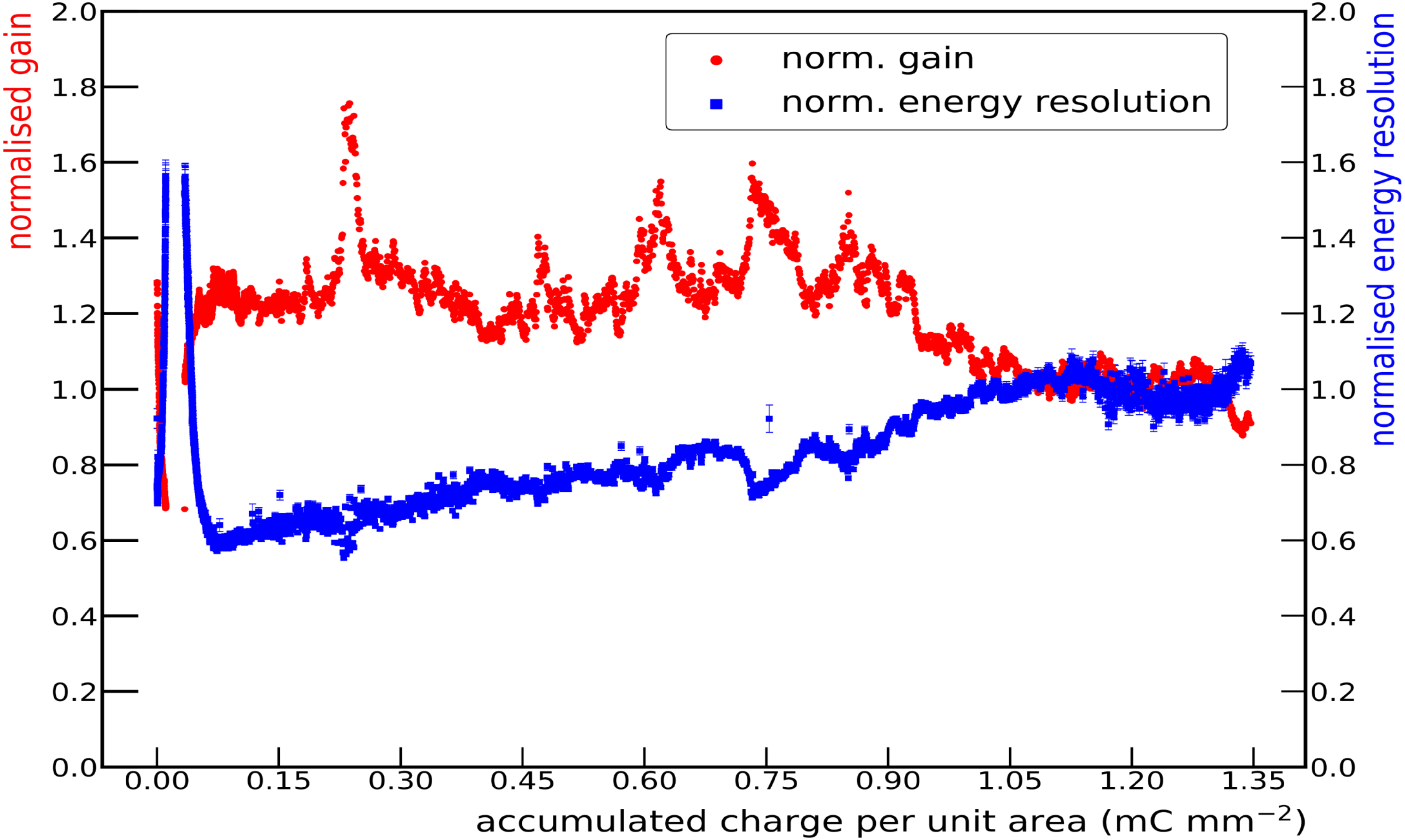


Fig : norm. gain and norm. energy resolution v/s accumulated charge per unit area

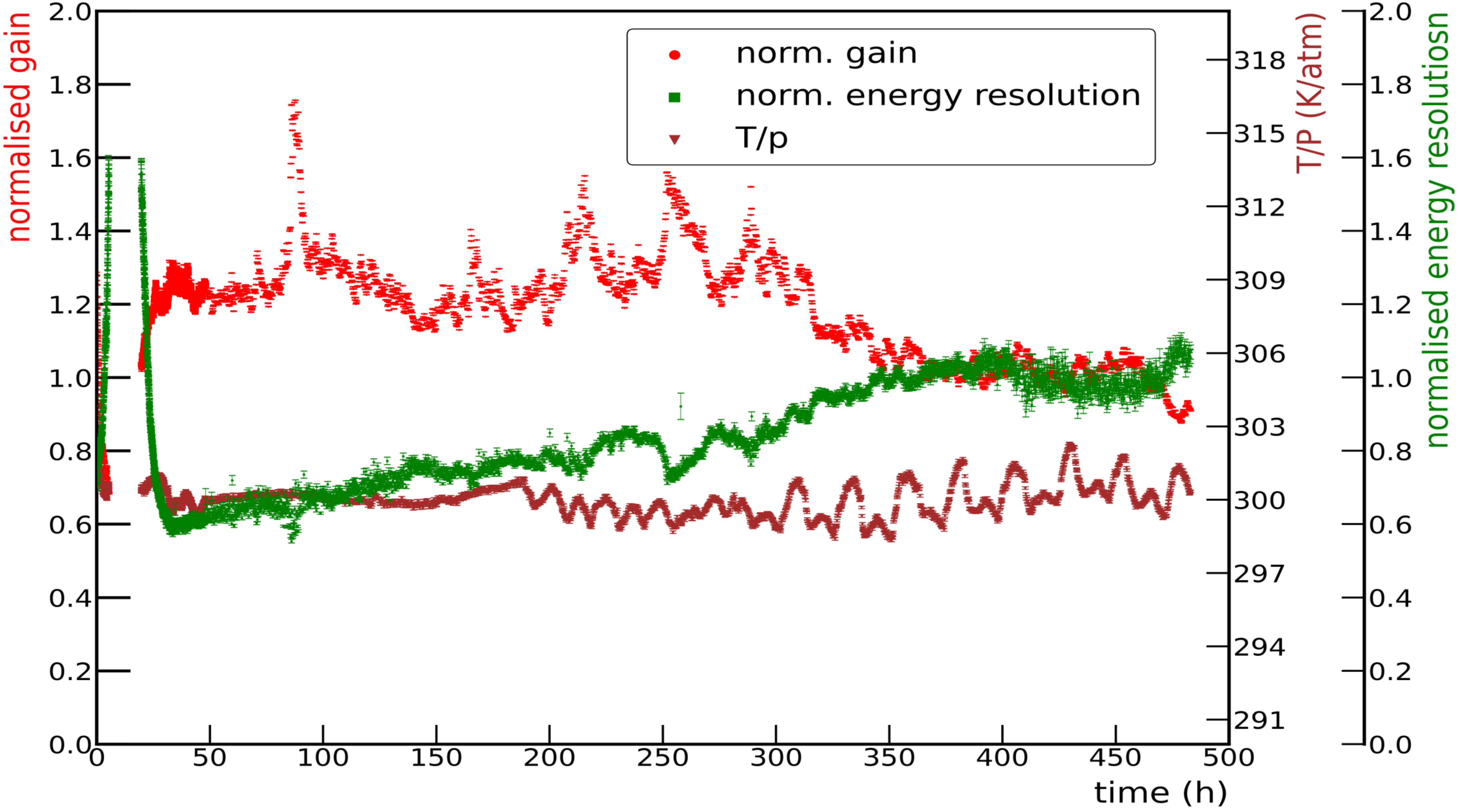


Fig : Normalised gain v/s time plot; also with the variation of normalised energy resolution and T/p.

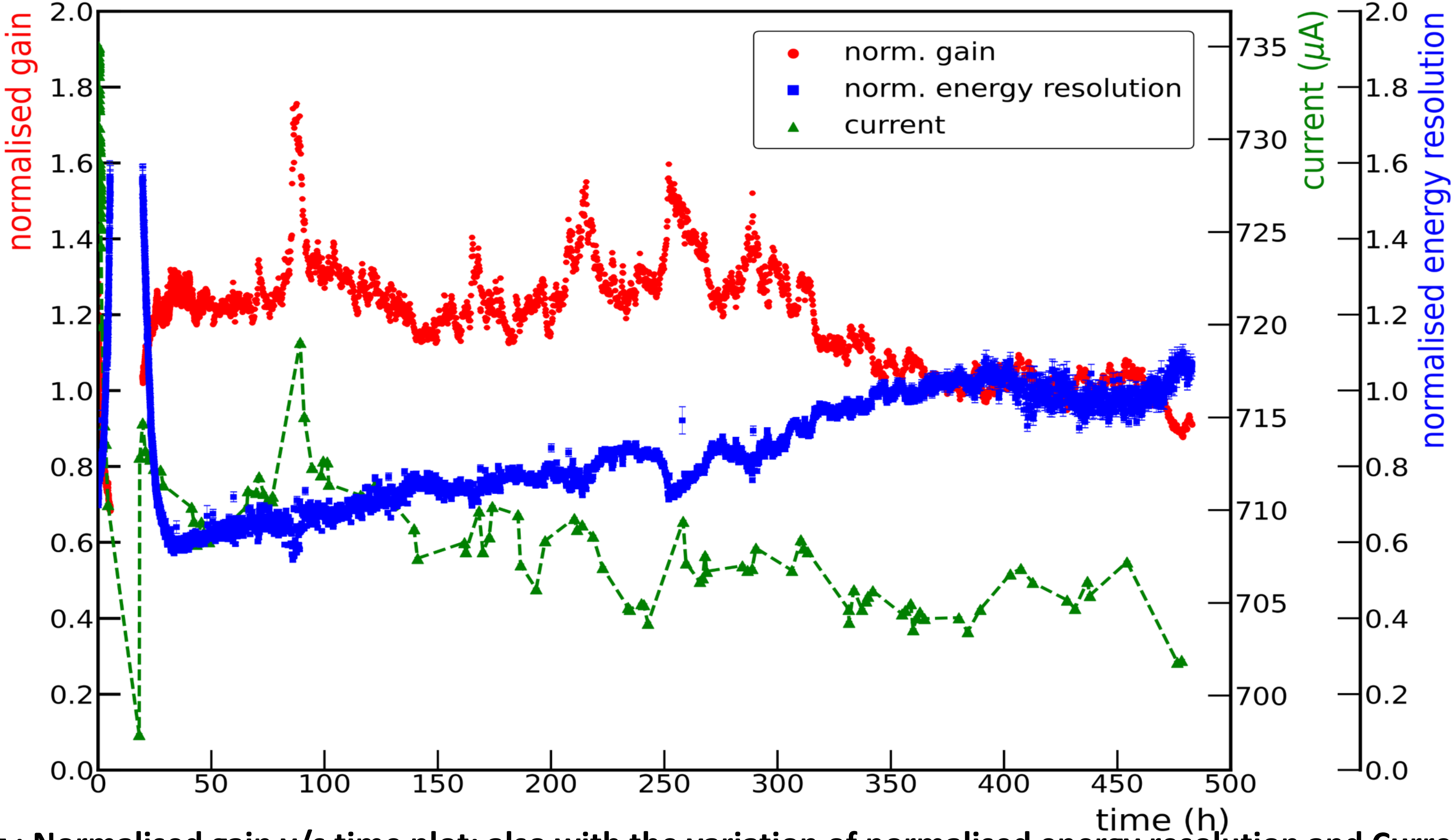


Fig : Normalised gain v/s time plot; also with the variation of normalised energy resolution and Current.

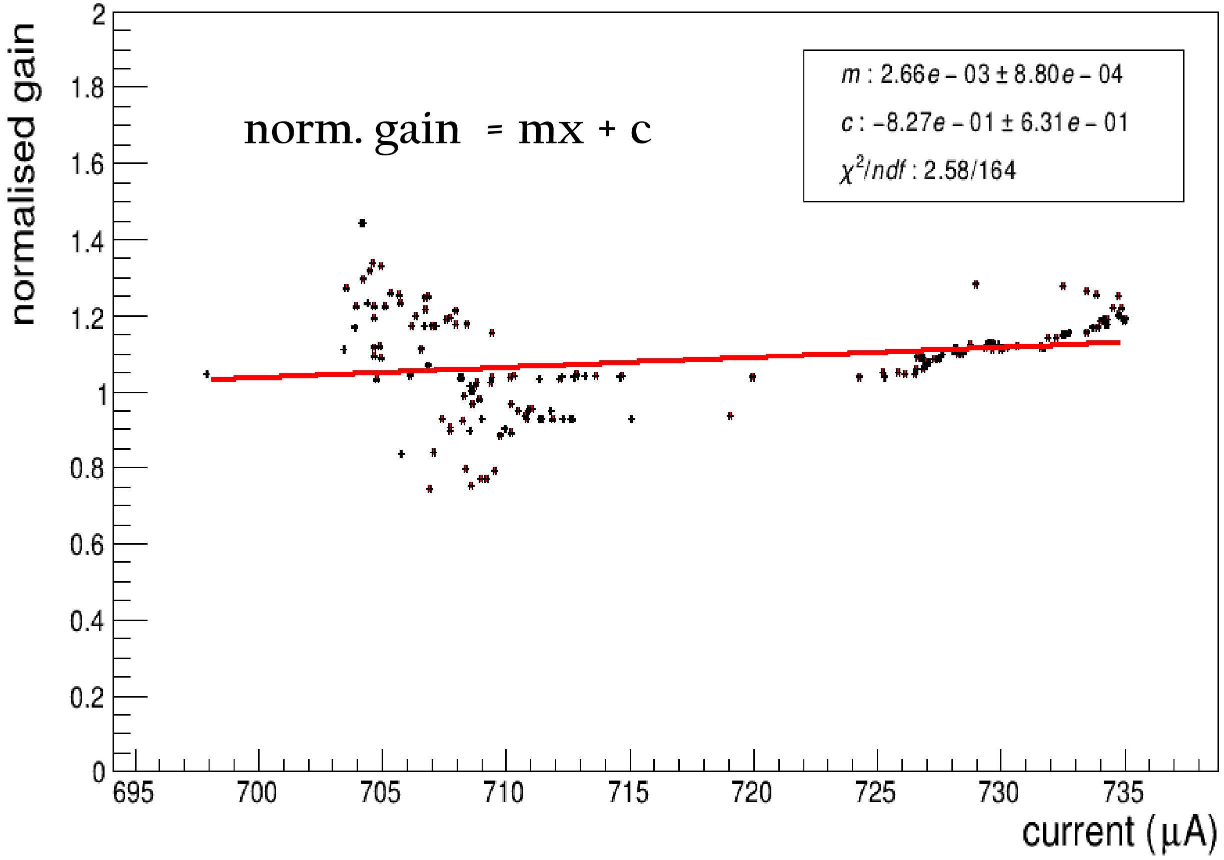


Fig : Correlation plot between normalised gain and current

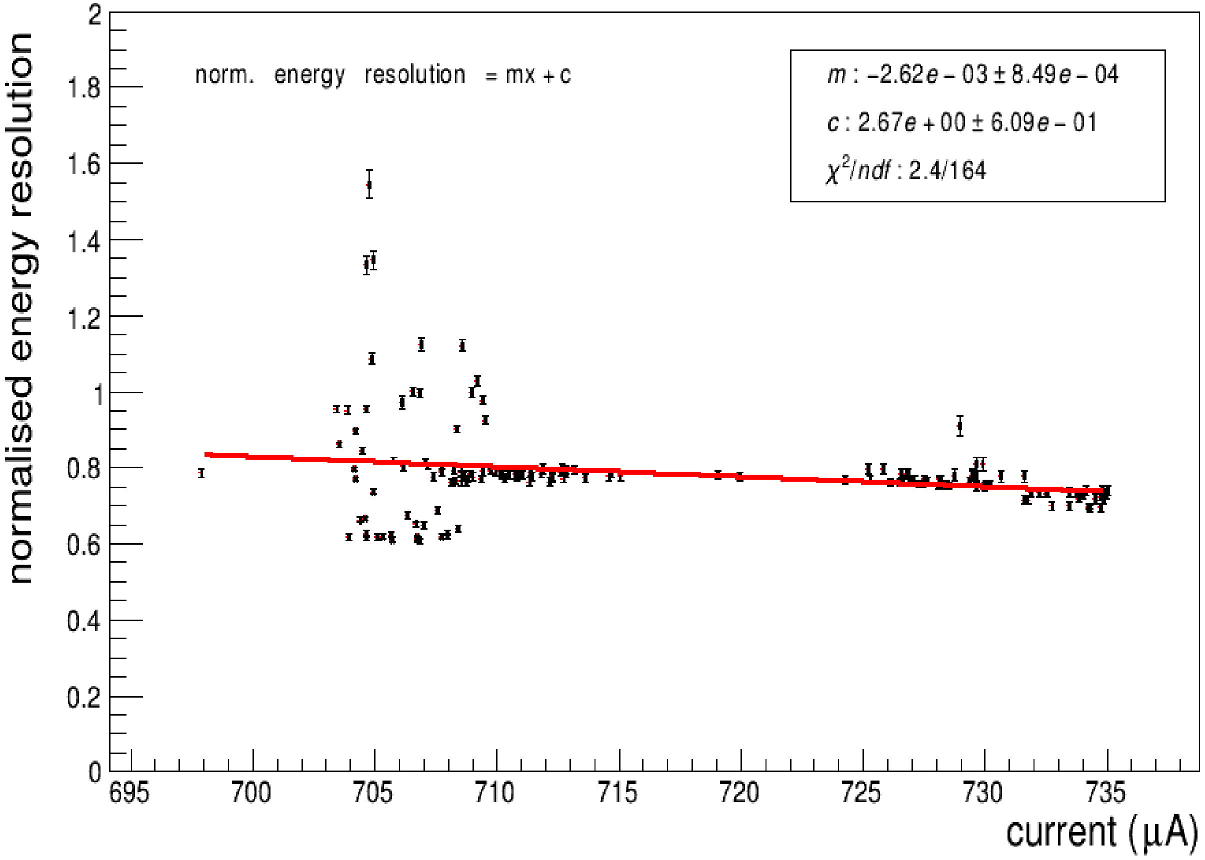
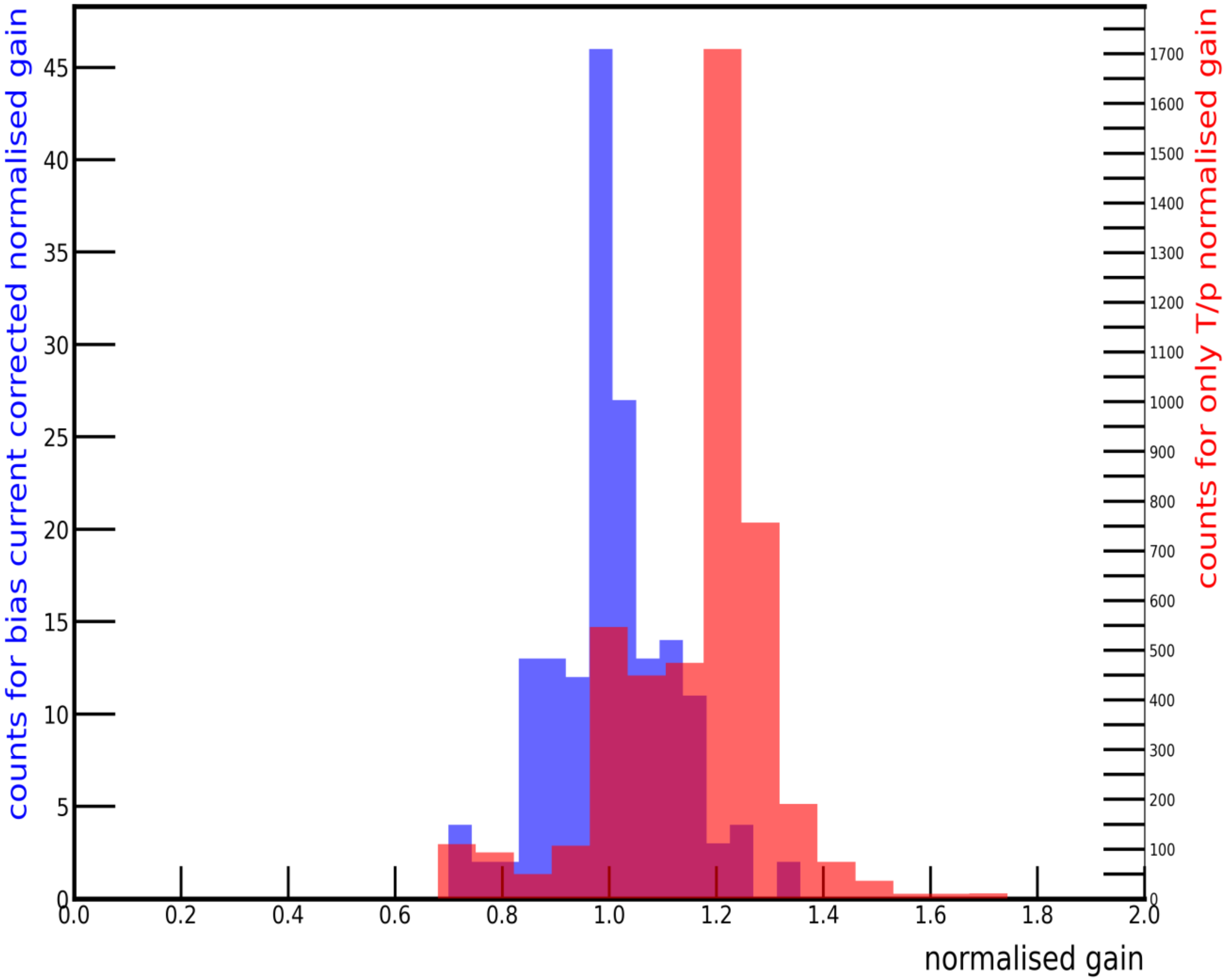
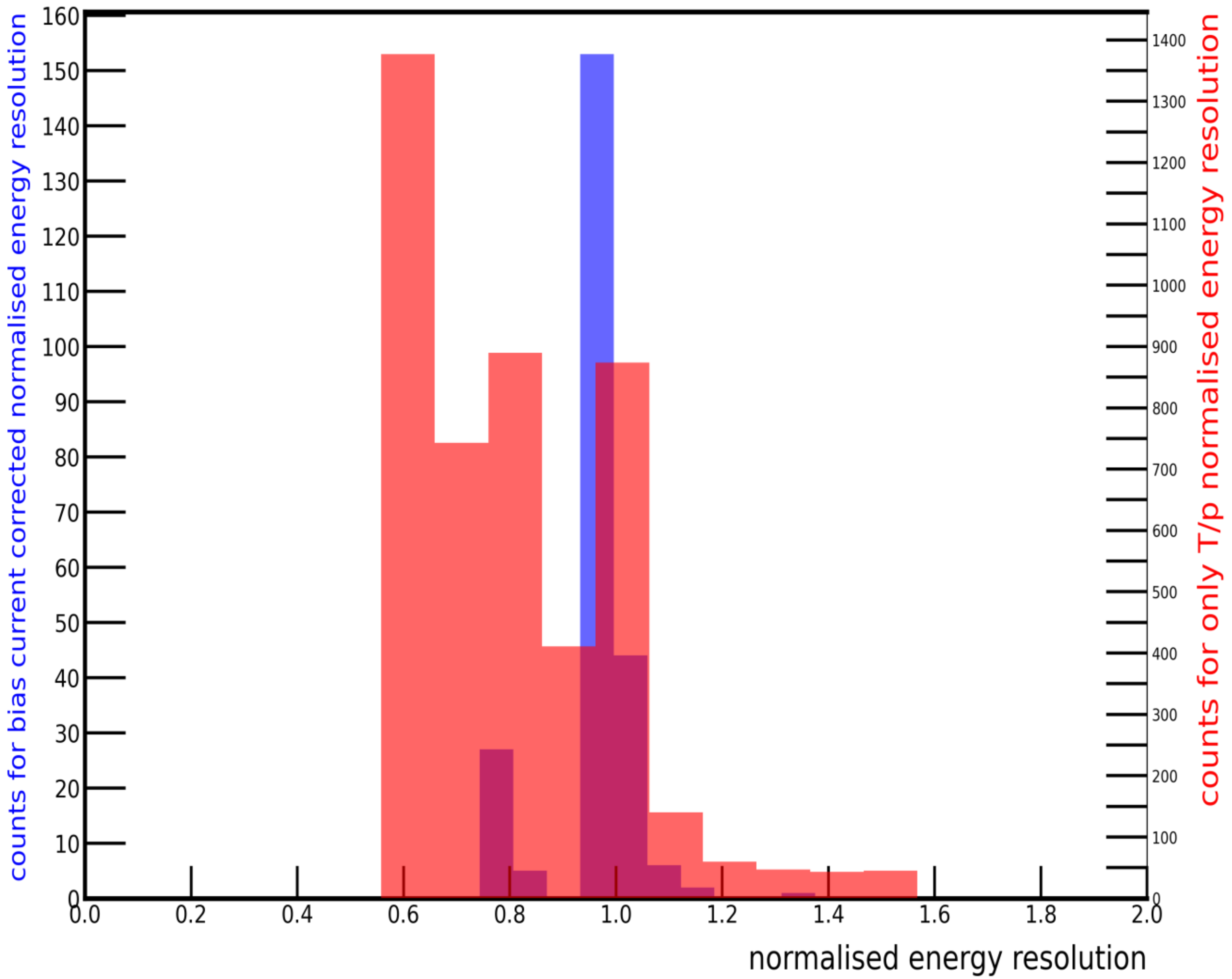


Fig : Correlation plot between normalised gain and current





Before current correction : mean = 1.161

After current correction: mean = 1.004

Before current correction : mean = 0.814

After current correction: mean = 0.961

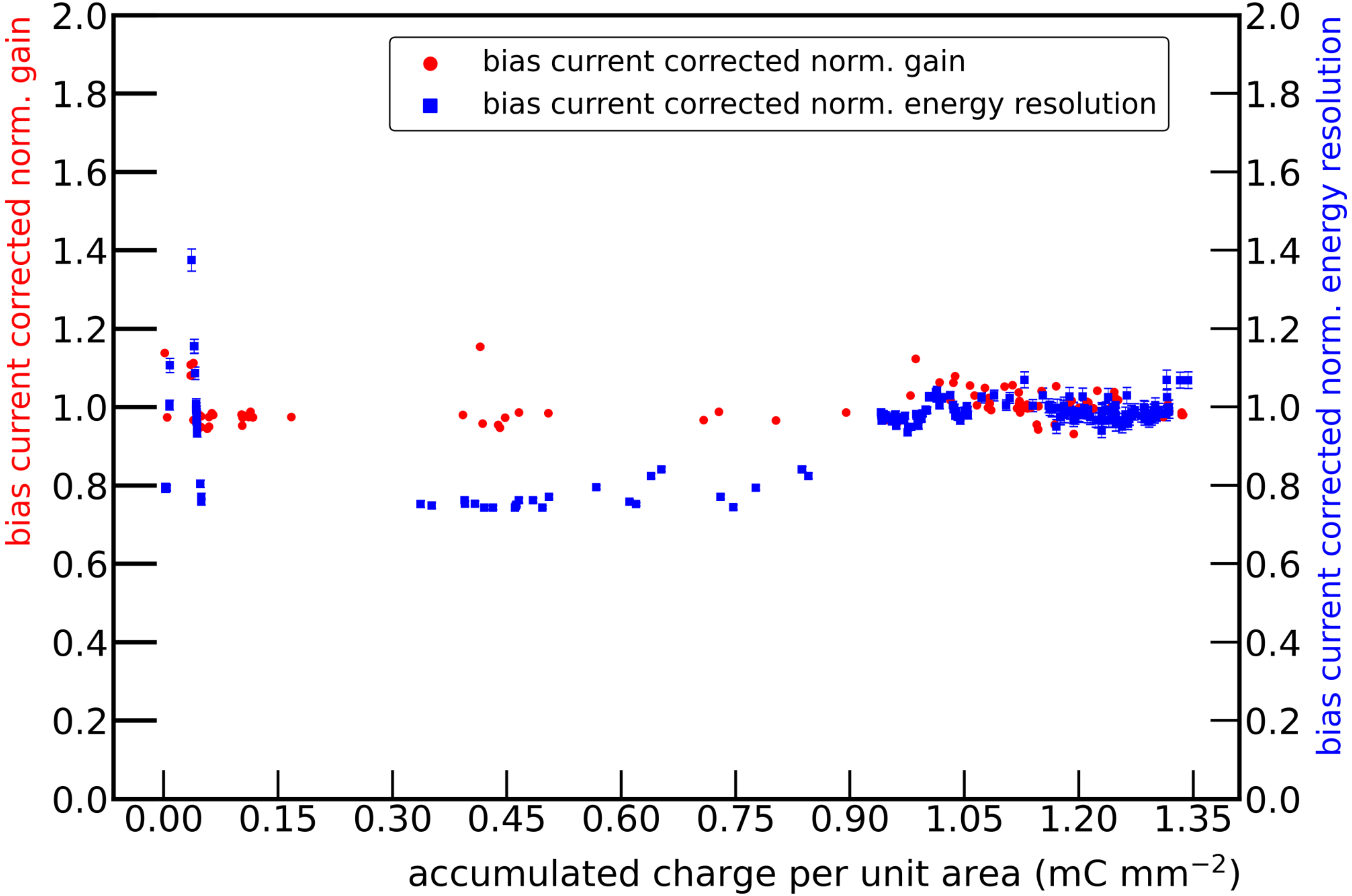


Fig : bias current corrected norm. gain and norm. energy resolution v/s accumulated charge per unit area

Investigation of the stability in the performance of triple GEM detectors for High Energy Physics experiments

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Abstract

Gas Electron Multiplier (GEM) is one of the mostly used gaseous detectors in the High Energy Physics (HEP) experiments. GEMs are widely used as tracking devices due to their high-rate handling capability and good position resolution.

An initiative is taken to study the stability in performance of the GEM chamber prototypes in the laboratory using external radiation for different Argon based gas mixtures. The effect of ambient parameters on the gain and energy resolution are studied. Very recently some behavioural changes in the performance of a SM GEM chamber is observed. The details of the experimental setup, methodology and results are reported here.

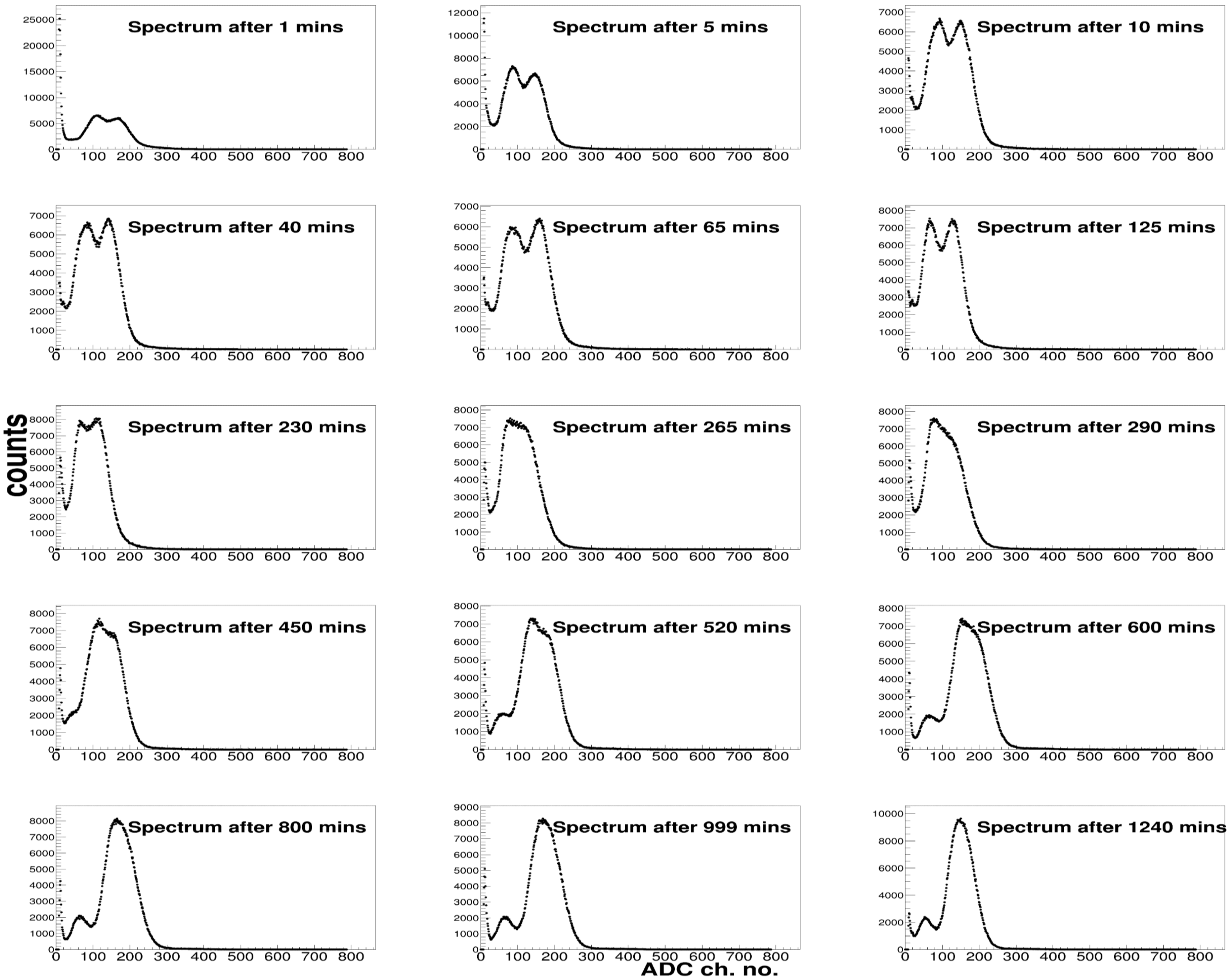
Keyword: Gas Electron Multiplier; GEM; Stability; Gain; Energy Resolution

Summary of the Observation

- The current is decreasing in first few hours(~ 5 hrs) rapidly
- Due to the decrease in current, the first few spectrums are not also good
- The current decreased $\sim 25\ \mu A$ and voltage decreases $\sim 14\ V$, due to this gain decreased by $\sim$5000, so the energy resolution is also very bad
- When the gain becomes stable and high enough, energy resolution increases gradually

Future Research

- A systematic investigation has to be done to understand the probable reasons behind the observed variation in divider current and also to find its possible remedies.
- Sometimes, double-peak is noticed in other observations, needed to find the reason.
- Stability study of triple GEM detector for long-term operation.
- Study on uniformity of characteristics over the surface of the GEM detector.
- Test the detector in the CBM, or other experiment beam line.



Spectrum after 1 mins
Spectrum after 5 mins
Spectrum after 10 mins
Spectrum after 40 mins
Spectrum after 65 mins
Spectrum after 125 mins
Spectrum after 230 mins
Spectrum after 265 mins
Spectrum after 290 mins
Spectrum after 450 mins
Spectrum after 520 mins
Spectrum after 600 mins
Spectrum after 800 mins
Spectrum after 999 mins
Spectrum after 1240 mins
counts
ADC ch. no.

Acknowledgement

- I thank everyone who helped me in this project through to completion. I want to express my sincere gratitude to my advisor, **Dr. Saikat Biswas**, whose mentorship and trust in my abilities provided me with the encouragement and confidence to undertake and complete this project. His insights and direction were instrumental in shaping the project's success.

- I am also deeply thankful **to Mr. Subir Mandal, Dr. Somen Gope, Dr. Anjali Sharma, Dr. Arindam Sen, and Dr. Sayak Chatterjee** for their invaluable support, guidance, and unwavering assistance throughout the duration of my project. Their expertise and willingness to share knowledge significantly contributed to the successful completion of this endeavour.

- I would also like to thank the **administrators of Bose Institute** for this opportunity, and Thanks to **everyone** for making my internship full of happiness.

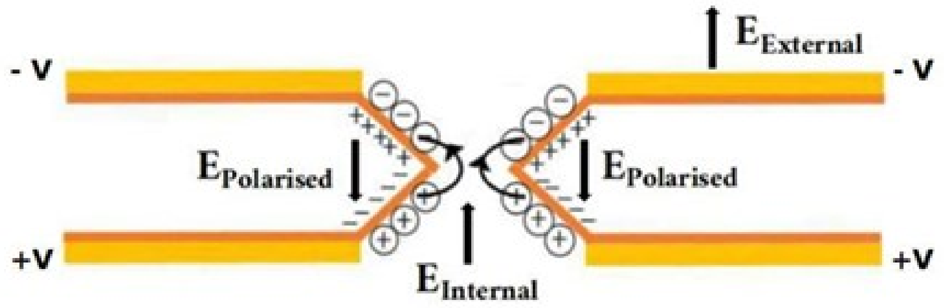
-- Sayan Dhani

Comments, Questions?

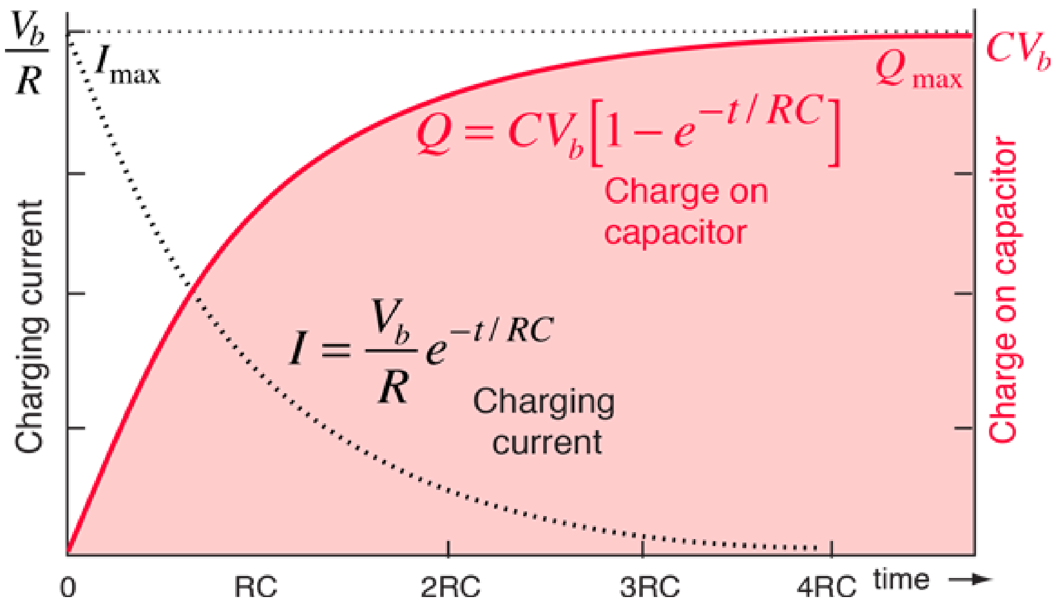
Thank you !!

Back-up

Charging-up Effect



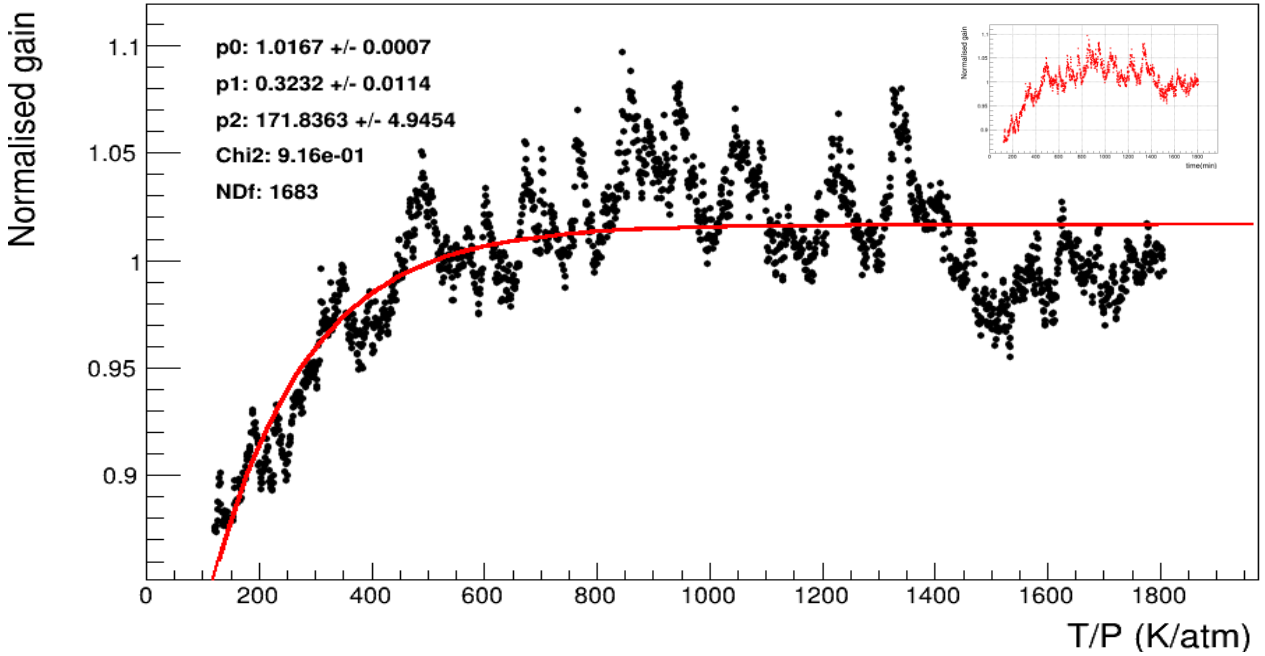
Due to high $\vec{E}$ inside the GEM hole → Ionization happens → Dielectric polarisation of the Kapton → locally produced charges absorb → High resistive Kapton accumulate charges → Change the electric field dynamically → Proper conditioning need time



The gain distribution over time is very similar to the charging-up curve of the capacitors, given by , $Q = CV_b\left(1 - e^{-\frac{t}{RC}}\right)$

So, fit the norm. gain v/s time distribution with the following,

$\boldsymbol{gain = p_0\left(1 - p_1^{\left(\frac{t}{p_2}\right)}\right)}$, t = time, charging-up time = p_2



Back-up