# 젬 검출기의 원리와 특성

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# 학습 목표

- GEM 검출기의 동작 원리와 특성을 이해한다.

- 이를 위해 가스 검출기 이론을 넓고 얇게 소개한다.

★ GEM 포일, 검출기를 운영하는 실무적인 요령은 다루지 않음.
시간 관계상, GEM 응용 검출기도 다루지 않음.

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- Introduction to GEM detector

- Principles of gaseous detectors
  - Interaction of charged particles with matters
  - Drift and diffusion of charges in gas
  - Charge multiplication
  - Signal formation by induction

- Characteristics of GEM detector
  - Charge multiplication principle
  - Rate capability
  - Gain, gain uniformity and discharge Prob.
  - Suppression of positive ion backflow
  - Robustness to radiation
  - Resolutions
  - Gain shift due to charging up.

# Further readings

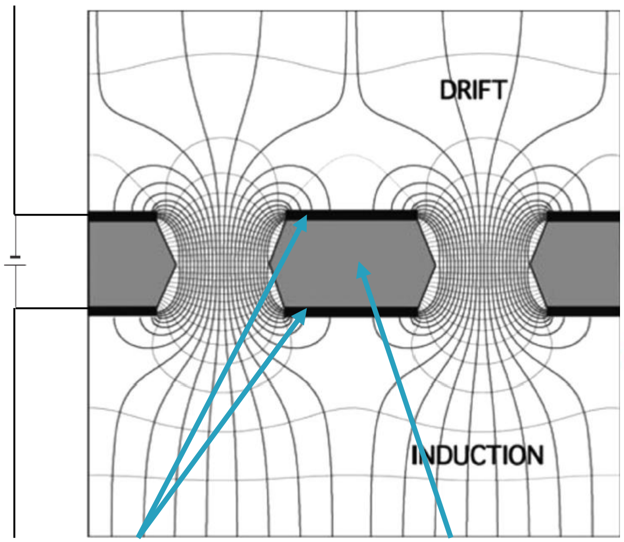
- Merlin, Jeremie Alexandre, CERN-THESIS-2016-041,
  https://cds.cern.ch/record/2155685
  : 젬 검출기 뿐 아니라 가스 검출기 전반에 대한 포괄적인 내용이 쉽고 친절하게 담겨 있음. 분량이 많아 보이나, 금방 읽을 수 있음.

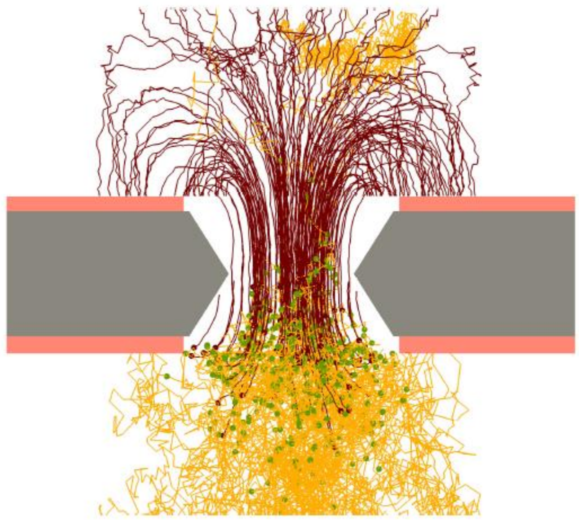
- Fabio Sauli, The gas electron multiplier (GEM): Operating principles and applications,
  https://doi.org/10.1016/j.nima.2015.07.060
  : 젬 검출기의 중요한 특정이 밀도 있게 담겨 있음.

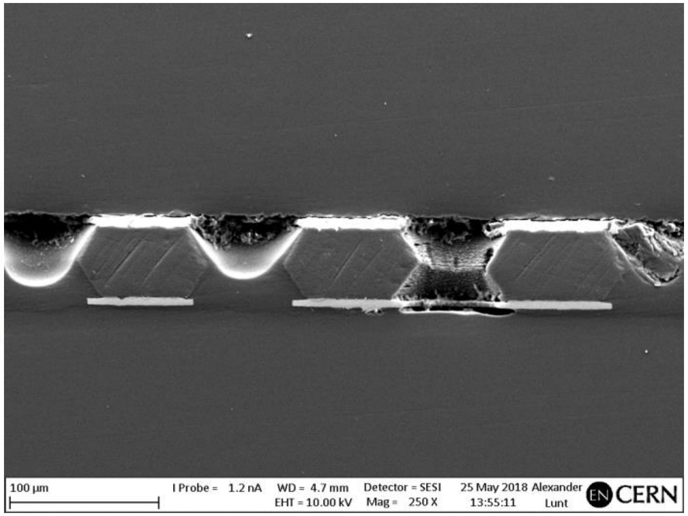
- CMS Collaboration, CMS-TDR-013,
  https://cds.cern.ch/record/2021453/?ln=en
  : R&D 과정이 자세하게 담겨 있음. 큰 시스템과 연동하는데 필요한 정보도 담겨 있음. 큰 프로젝트를 진행하는 관리적인 요소도 담겨 있음. 분량 압박.

- Fabio Sauli, Gaseous Radiation Detectors: Fundamentals and Applications,
  https://doi.org/10.1017/CBO9781107337701
  : 가스 검출기에 대한 아주 많은 정보가 담겨 있음. 분량 압박.

# 1 Introduction to GEM detector



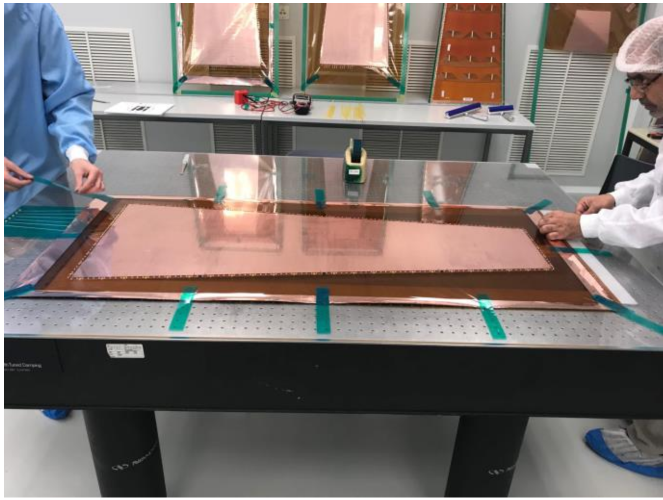



Cu    Polyimide( $\varepsilon_r = 3.4$ )

- Gaseous detector. Electron multiplication via GEM.

- Thickness of Cu: 5 $\mu m$, polyimide: 50 $\mu m$
  Usually, outer (inner) hole diameter: 70 (50) $\mu m$,
  pitch: 140 $\mu m$

- Electric field is squeezed into hole $\sim 15 kV\ cm^{-1}$
  Avalanche occurs in hole.



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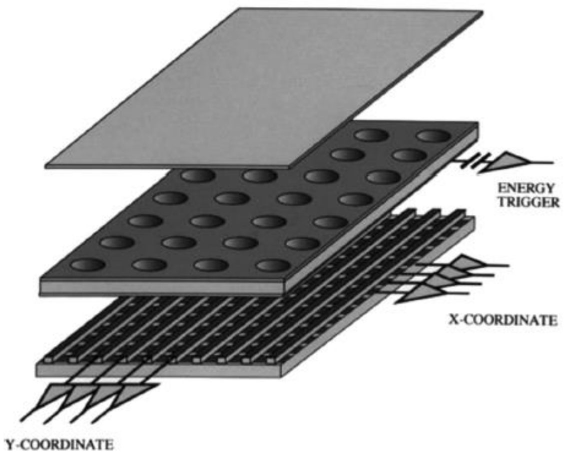
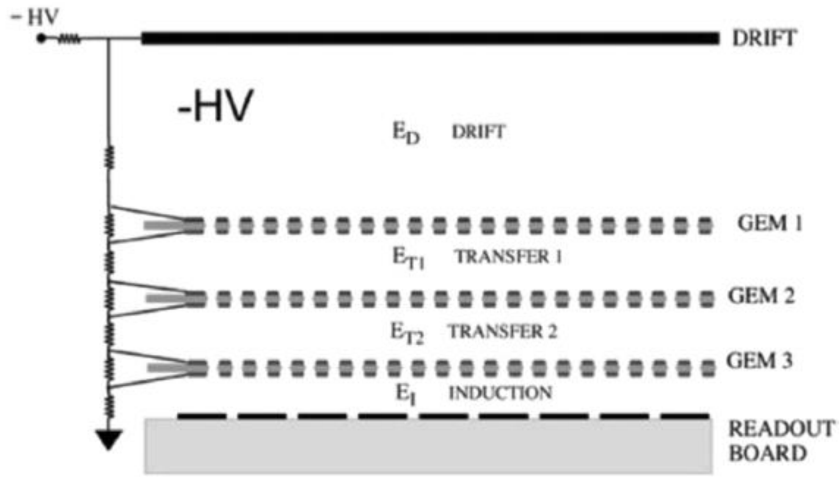
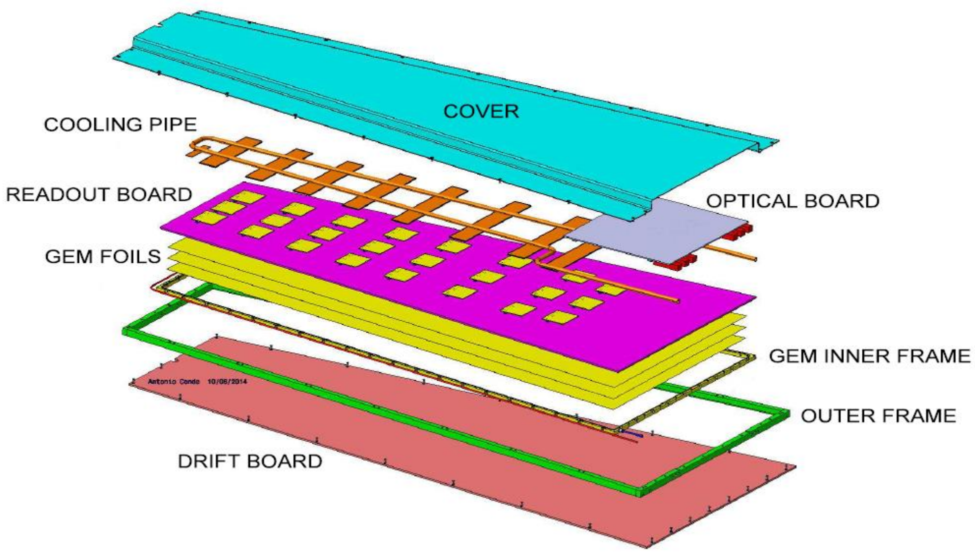
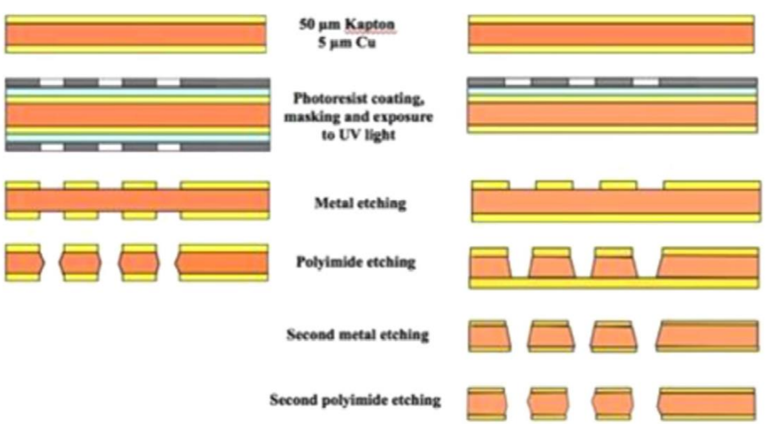


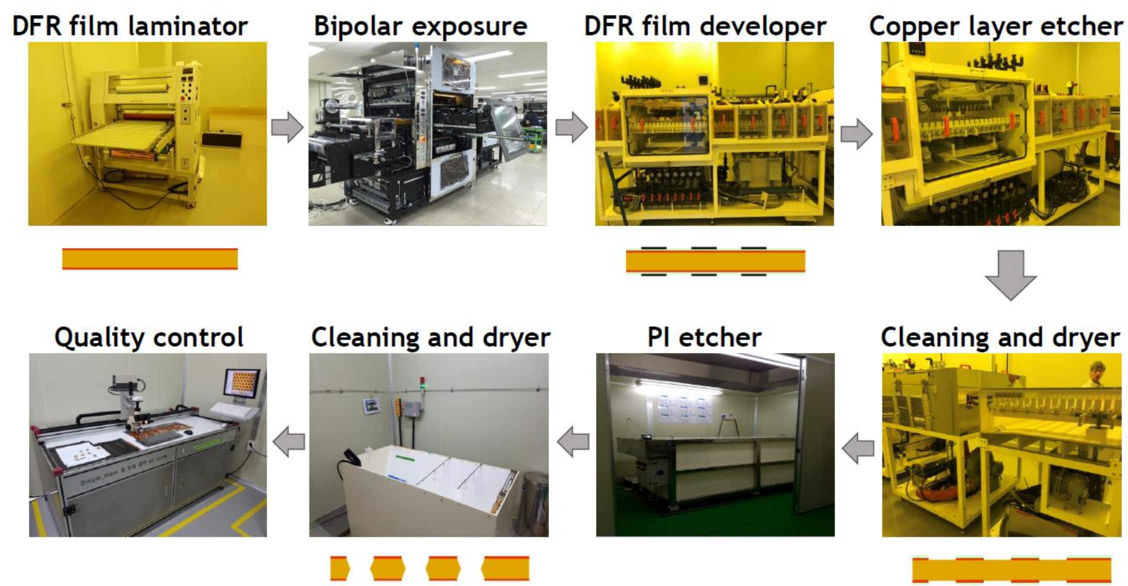




# 1 Introduction to GEM detector

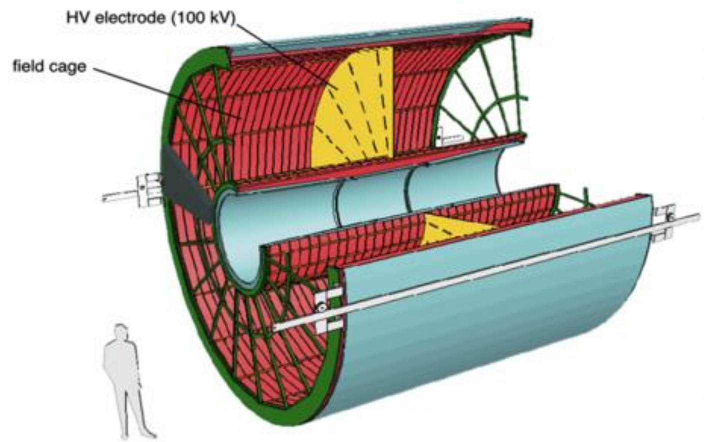
- Manufacturing GEM foils
  - Photolithography
  - KCMS main contribution towards CMS Phase-2 upgrade: supplying large size GEM foils.

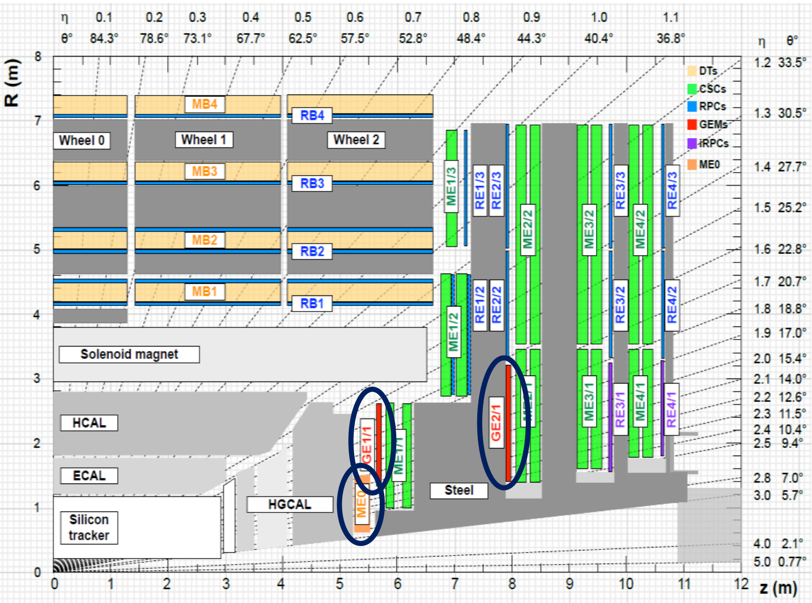


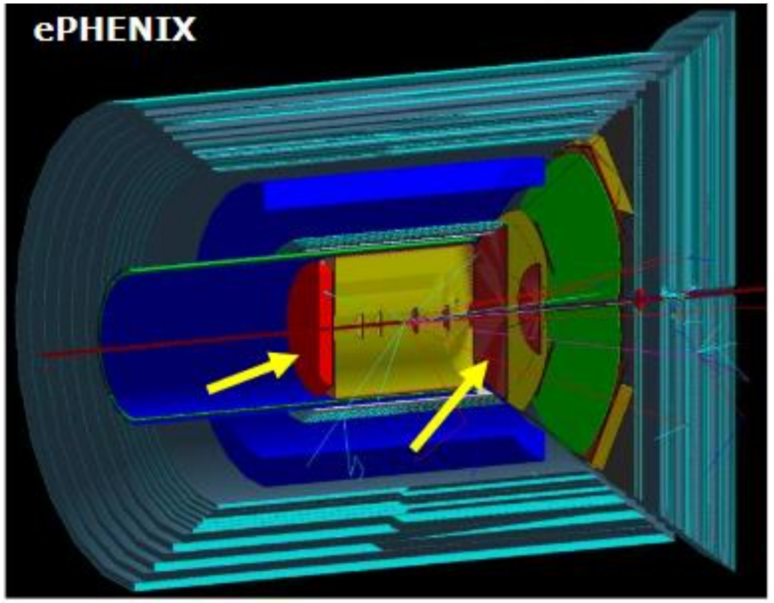



# 1 Introduction to GEM detector

- Tracker
- TPC
- Imaging



# 2 Principles – Interactions of charged ptl. with matters

- Charged ptl. penetrating matters lose energy via excitation, ionization, Bremsstrahlung, Chrenkov.
  - For ordinary gaseous detectors, the ionization is key process.
  - Electron by ionization → charge multiplication by avalanche → detectable signal via induction.
  - Photon from excitation usually too small to be detected.

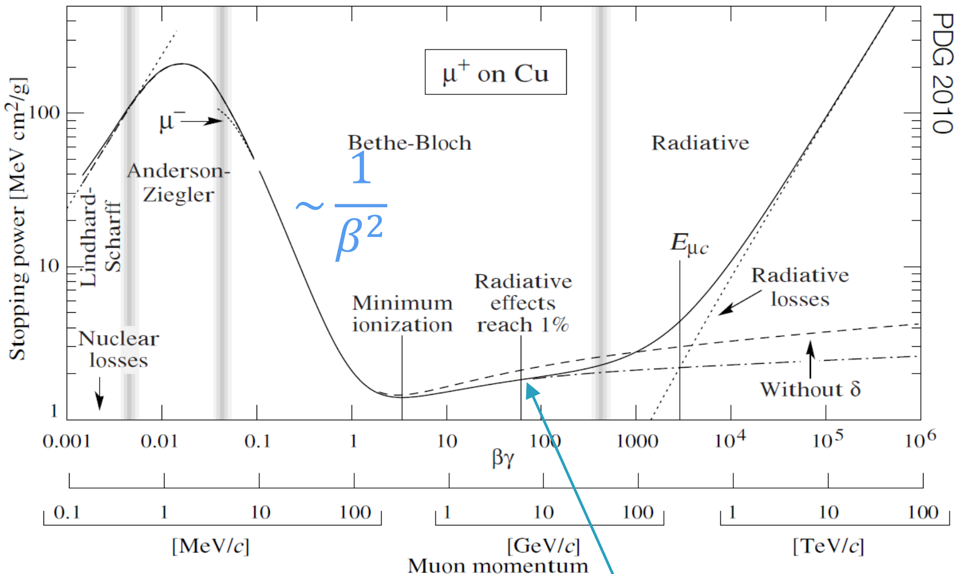
- Bethe-Bloch equation: energy loss processes due to multiple Coulomb interaction.

$$\frac{-dE}{dX} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z} \right]$$

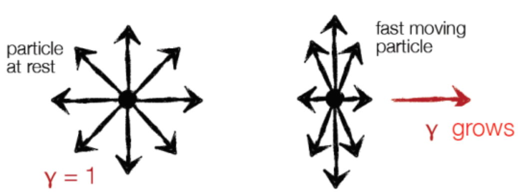
$$K = \frac{4 \pi e^4}{c^2 m_e} N_A = 0.31\, MeV\, cm^2/g$$

Stopping power

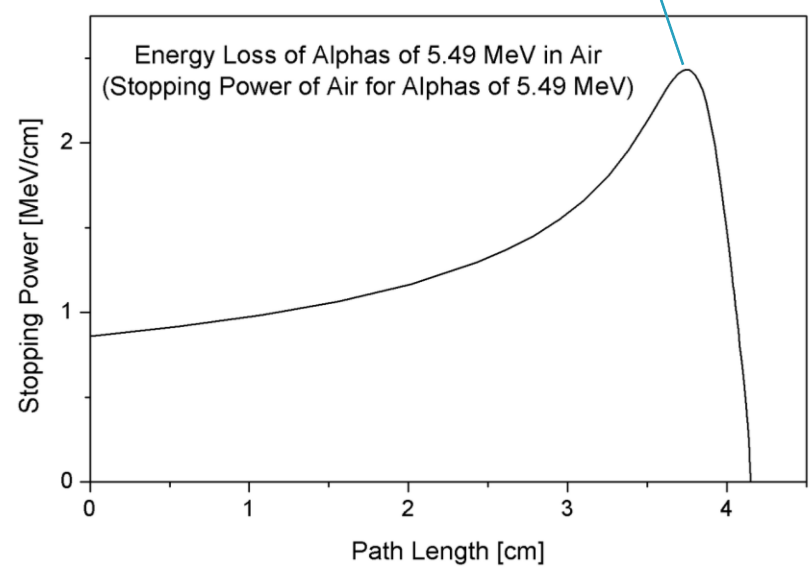
# 2 Principles – Interactions of charged ptl. with matters




Relativistic rise




Cancer therapy



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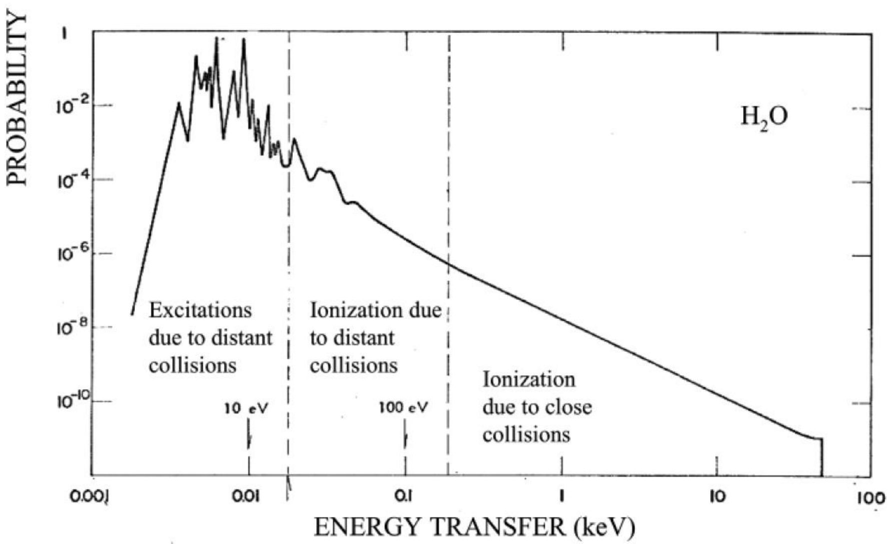
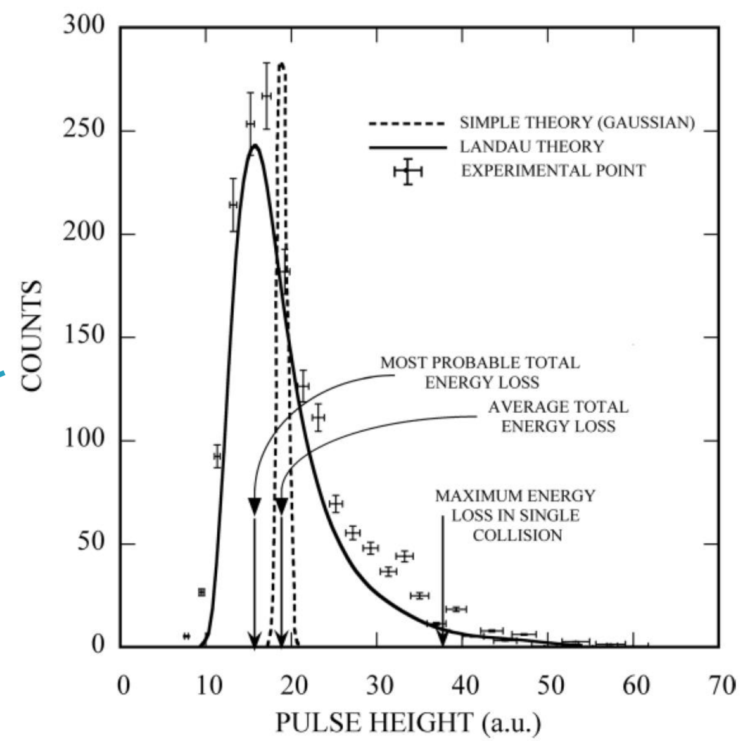



The energetic $\delta$-electron with low prob. but large ionization




For thin gaseous detector, energy deposit ~Landau distribution

# 2 Principles – Drift and diffusion of ions in gas

- Primary $e^-$ produced by ionization should be transported to avalanche region (=drift).
  - Diffusion occurs during drift.

- Drift and diffusion of ions can be described by simple formula

- Drift of ions in electric field.

$$\mu = \frac{w^+}{E}$$

| Gas | Ion | $\mu$ ($cm^2\ V^{-1}s^{-1}$) |
|---|---|---|
| $H_2$ | Self | 13.0 |
| He | Self | 10.2 |
| Ar | Self | 1.7 |
| Ar | $CH_4$ | 1.87 (Schultz *et al.*, 1977); 2.07 (Yamashita *et al.*, 1992) |
| Ar | $C_2H_6$ | 2.06 (Yamashita *et al.*, 1992) |
| Ar | $C_3H_8$ | 2.08 (Yamashita *et al.*, 1992) |
| Ar | i-$C_4H_{10}$ | 1.56 (Schultz *et al.*, 1977); 2.15 (Yamashita *et al.*, 1992) |
| Ar | $CO_2$ | 1.72 |
| Ar | $(OCH_3)_2CH_2$ | 1.51 |
| $CH_4$ | Self | 2.22 (Yamashita *et al.*, 1992) |
| $C_2H_6$ | Self | 1.23 (Yamashita *et al.*, 1992) |
| $C_3H_8$ | Self | 0.793 (Yamashita *et al.*, 1992) |
| i-$C_4H_{10}$ | Self | 0.612 (Yamashita *et al.*, 1992) |
| i-$C_4H_{10}$ | $(OCH_3)_2CH_2$ | 0.55 (Schultz *et al.*, 1977) |
| $(OCH_3)_2CH_2$ (Methylal) | Self | 0.26 (Schultz *et al.*, 1977) |
| $O_2$ | Self | 2.2 |
| $CO_2$ | Self | 1.09 |
| $H_2O$ | Self | 0.7 |
| $CF_4$ | Self | 0.96 (Yamashita *et al.*, 1992) |
| $CF_4$ | $CH_4$ | 1.06 (Yamashita *et al.*, 1992) |
| $CF_4$ | $C_2H_6$ | 1.04 (Yamashita *et al.*, 1992) |
| $CF_4$ | $C_3H_8$ | 1.04 (Yamashita *et al.*, 1992) |

# 2 Principles – Drift and diffusion of ions in gas

- Thermal diffusion ~ Gaussian distribution

$$\frac{\mathrm{d}N}{N} = \frac{1}{\sqrt{4\pi Dt}} \mathrm{e}^{-\frac{x^2}{4Dt}} \mathrm{d}x \qquad \sigma_x = \sqrt{2Dt}$$

- Nernst-Townsend relation

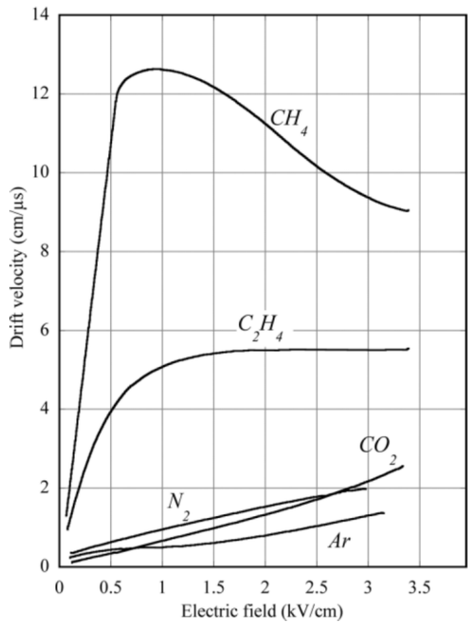
$$\frac{D}{\mu} = \frac{kT}{e}$$

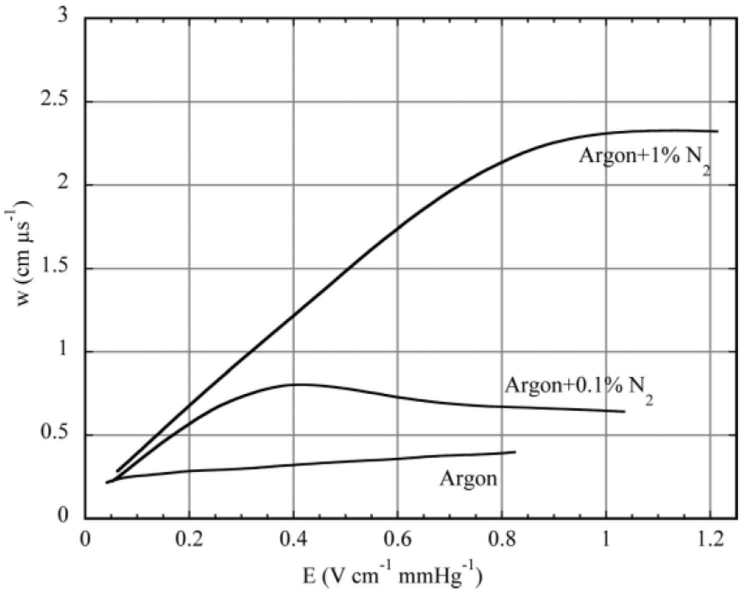
- Ions migrating over a length x under field E diffuses

$$\sigma_x = \sqrt{\frac{2kT}{e}\frac{x}{E}}$$

# 2 Principles – Drift and diffusion of electrons in gas

- Drift and diffusion of electron
  - Much more complicated… due to small mass, electron capture, ETC.



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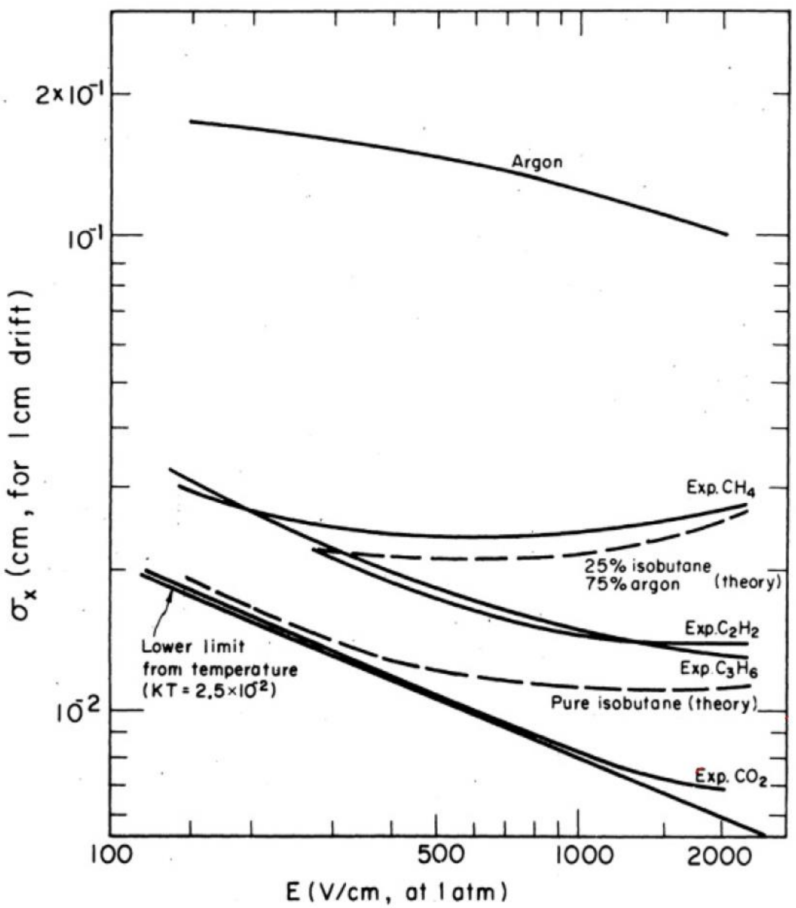
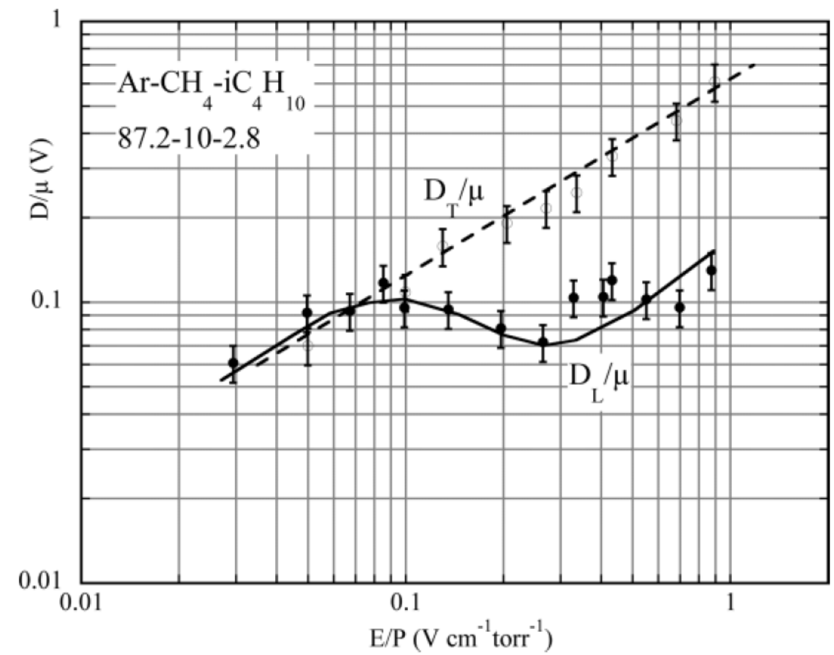



$D_T$: spatial resolution
$D_L$: time resolution

# 2 Principles – Drift and diffusion of electrons in gas

- Drift of electron in magnetic fields.

$$\vec{w} = \frac{e}{m}\frac{\tau}{1+\omega^2\tau^2}\left[\vec{E} + \omega\tau\frac{\vec{E}\times\vec{B}}{B} + \omega^2\tau^2\frac{\vec{B}\,(\vec{E}\bullet\vec{B})}{B^2}\right]$$

$\omega = EB/m$ is the Larmor frequency $\tau$ mean collisional time

- It's important to understand the effect of magnetic field. In many cases, detectors are installed inside magnetic field.

- Two limiting case

- $\vec{E}\perp\vec{B}$

$$\tan\,\theta_B = \omega\tau$$

$$w_B = \frac{E}{B}\frac{\omega\ \tau}{\sqrt{1+\omega^2\tau^2}}$$

- $\vec{E}//\vec{B}$

$$w_B = w_0$$

$$\sigma_L = \sigma_0$$

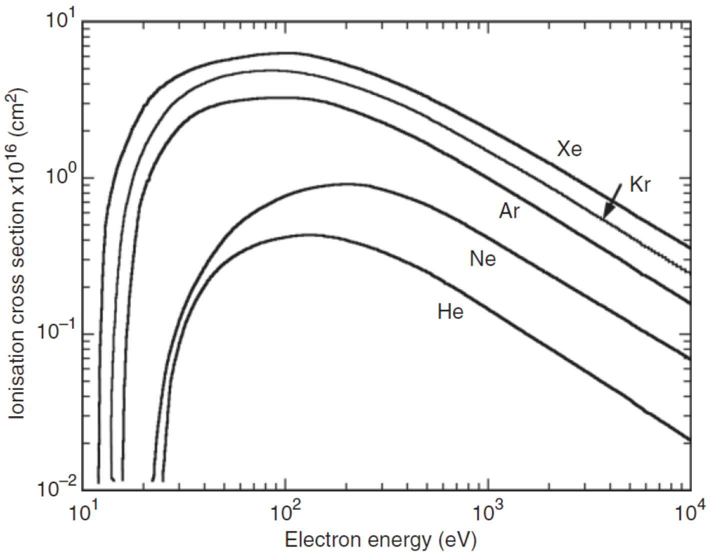
$$\sigma_T = \frac{\sigma_0}{\sqrt{1+\omega^2\tau^2}}$$

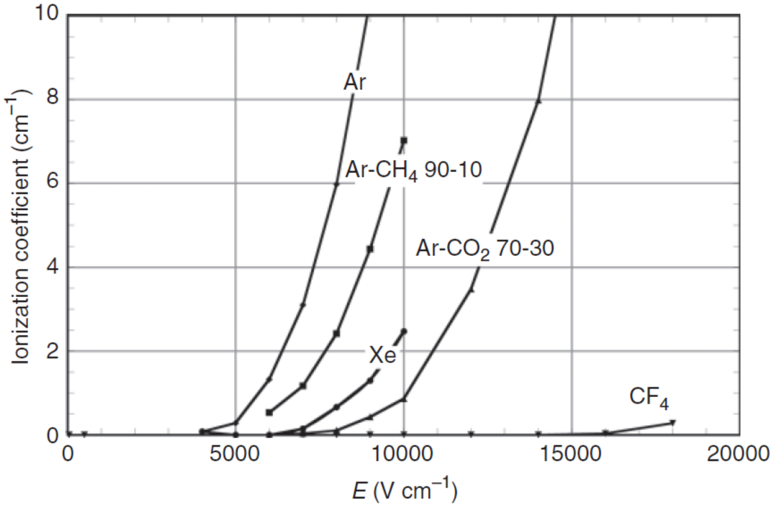
↓

Improve position resolution of TPC!!

# 2 Principles – Charge multiplication

- Electrons in strong electric field can be multiplied by ionization.
- $\alpha = \lambda^{-1}$: first Townsend coefficient, number of ion pair produced per unit length of drift.
  $\alpha = N\sigma$, $N$: number of molecules per unit volume.
  $\Rightarrow$ That's why gain of gas detectors depend on P/T.
- $dn = n\alpha dx$
  $n = n_0 e^{\alpha x}$
  $M = e^{\int_{x_1}^{x_2} \alpha(x) dx}$



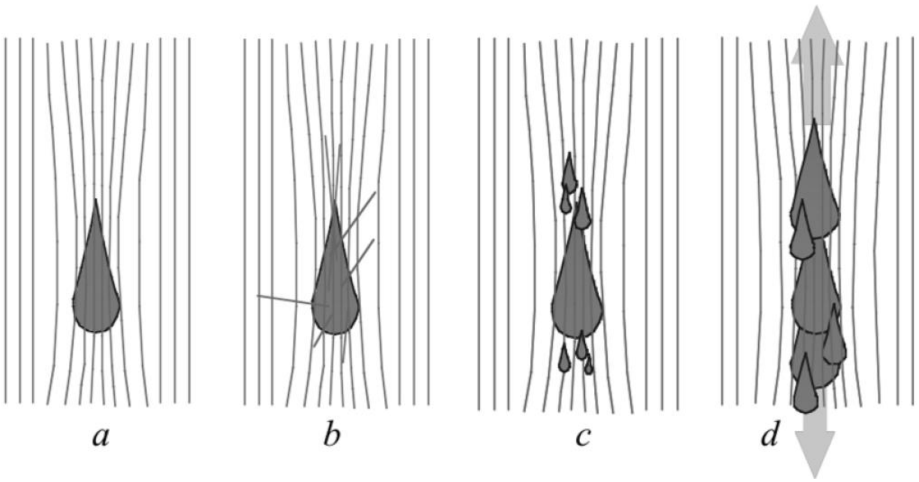



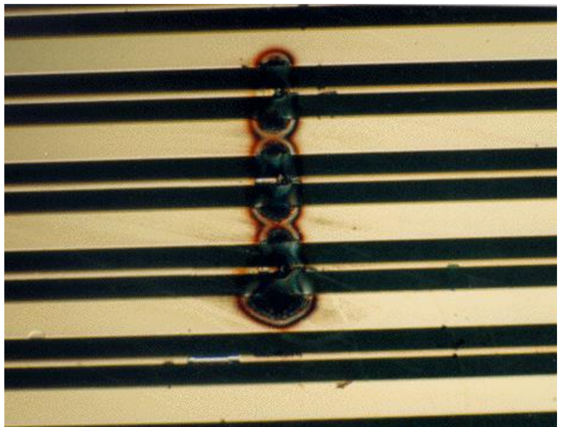
# 2 Principles – Charge multiplication

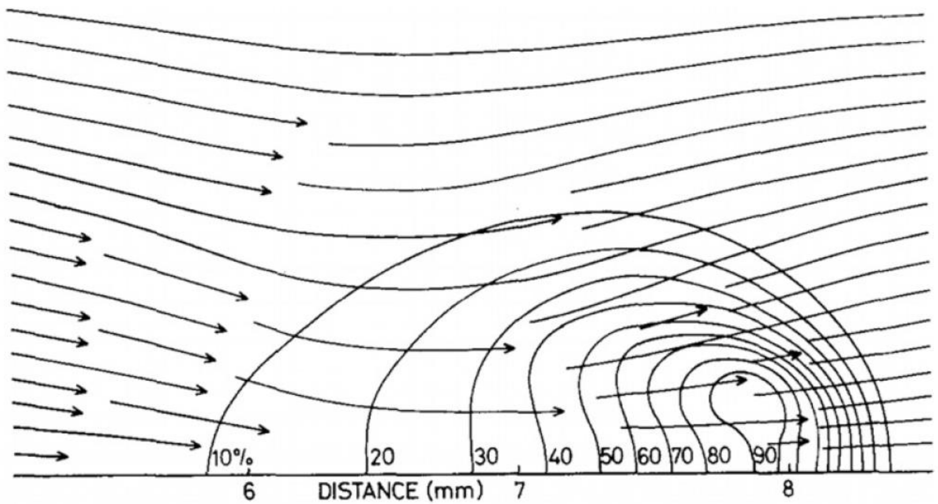
- Streamer formation
  - Field distortion by space charge and secondary avalanche by UV

- Raether's limit: $\alpha x < 20$, gain~$10^8$
  However due to statistical fluctuation, usual maximum gain $< 10^6$.

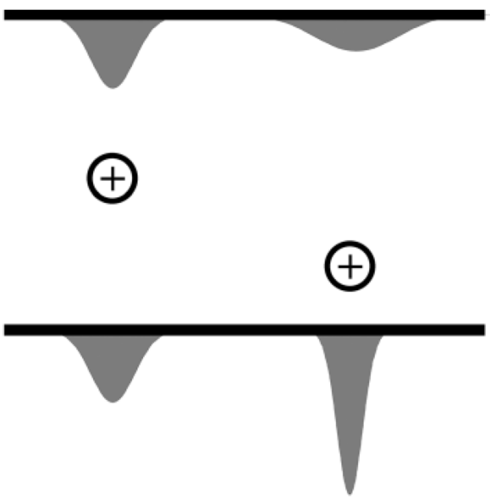
- Suppressing secondary avalanche by UV.
  - Necessity of quenching gas



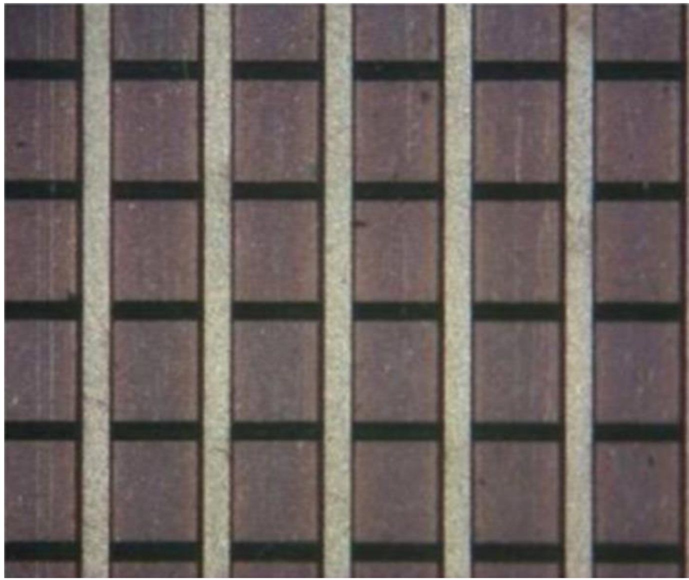





# 2 Principles – Signal formation by induction

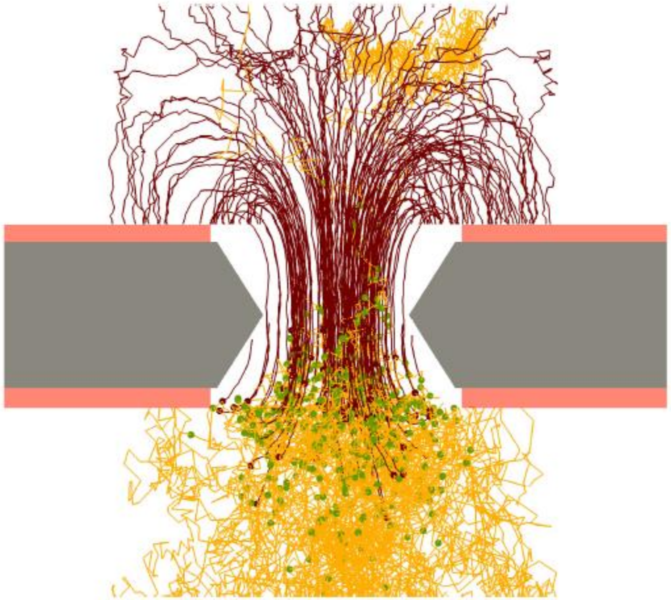


- Signal is induced by the motion of charges.
- Common misunderstanding: when charges touch readout strip, current is formed.
  Wrong!! touching readout strip means the end of signal!!
- Shockley–Ramo theorem: $i = q\overrightarrow{E_i} \cdot \vec{v}$
  $\overrightarrow{E_i}$: the electric field at the charge's instantaneous position,
  under the following conditions: charge removed,
  given electrode raised to unit potential,
  and all other conductors grounded.
  $\vec{v}$: drift velocity of charges
  q: charges



# 3 Characteristic of GEM – Charge multiplication principle

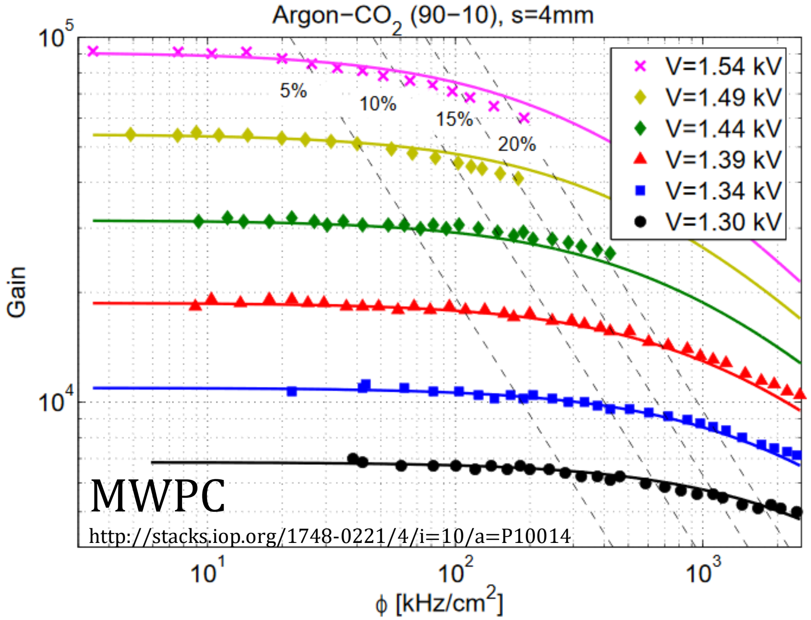
- Charge multiplication in micro holes.
  - Each micro holes work as "independent proportional counter" screened from each others.

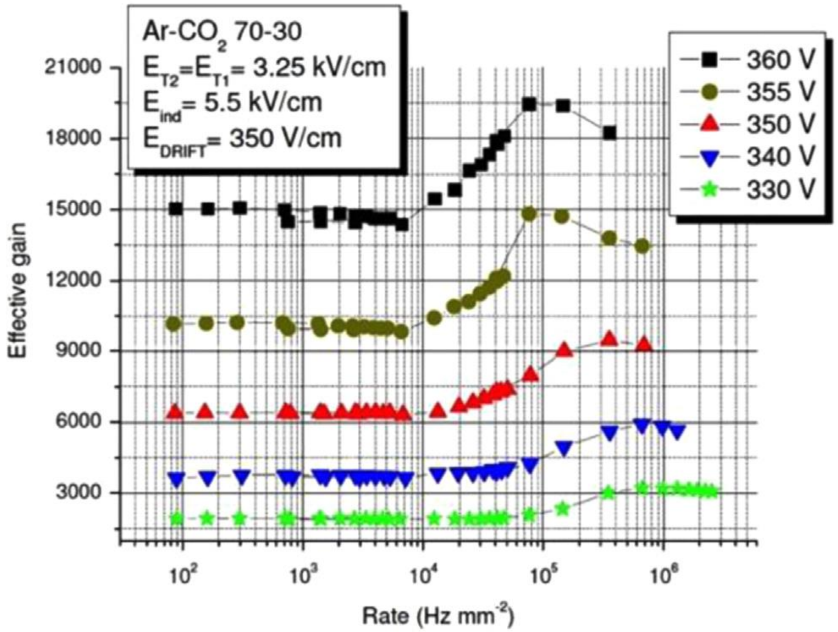


Garfield / Magboltz simulation
Dark brown: ion, light brown: $e^{-}$
Dot where ionization occurs

# 3 Characteristic of GEM – Rate capability

- 10-100 times better rate capability than MWPC.
  - Reason of gain drop of MWPC at high flux: space charge due to slow ions.
  - High density of micro holes, GEM detectors have very high rate capability.



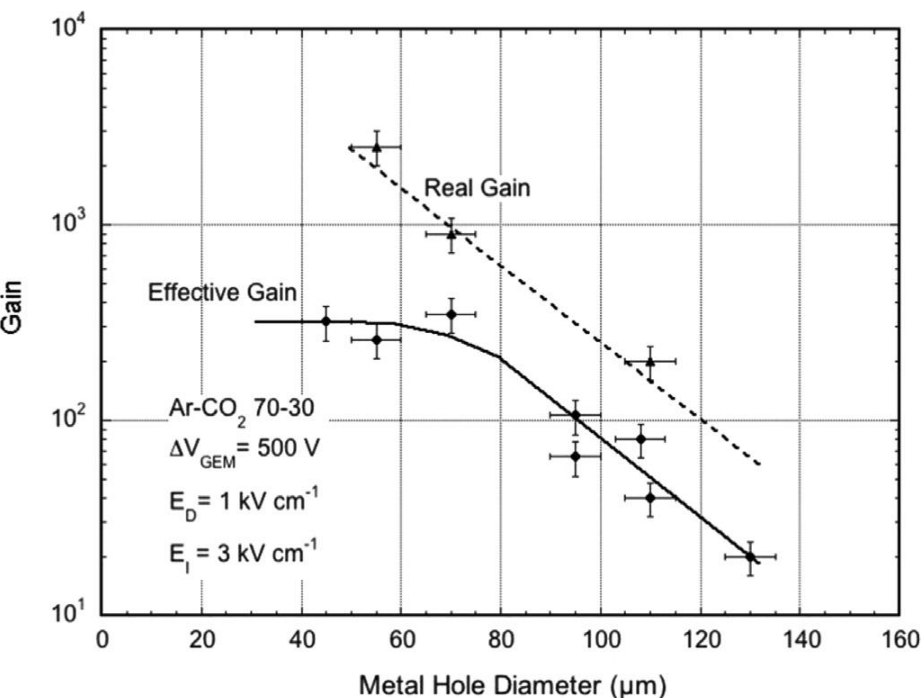



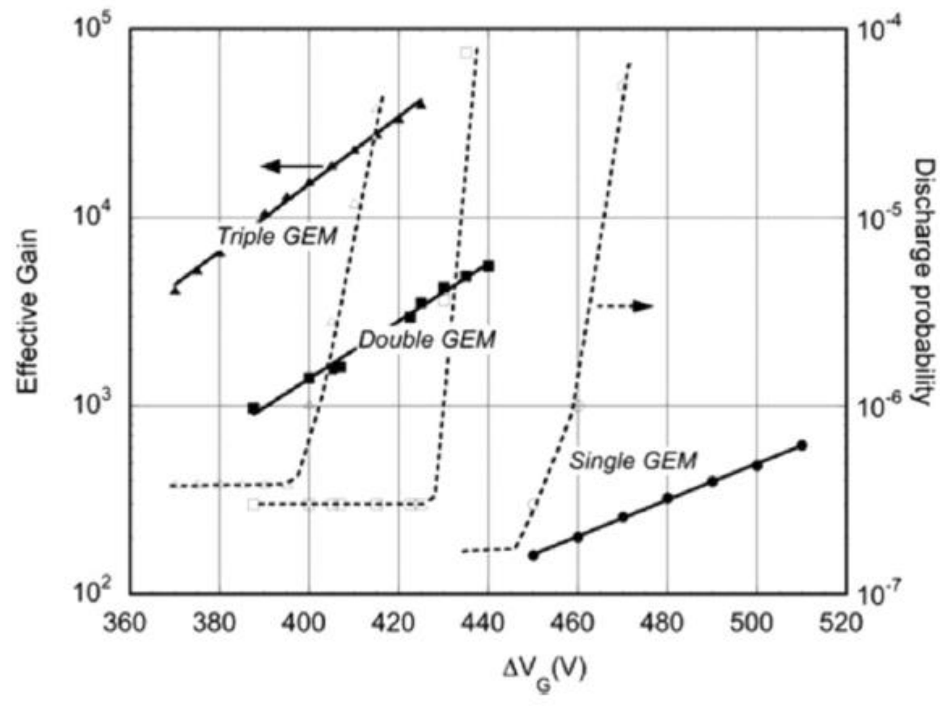
# 3 Characteristic of GEM – Gain and discharge

- Effective gain = collection Effi.× “real gas gain”×extraction Effi.

 - Collection Effi. and extraction Effi. are function of hole geometry, and field strength

- Thanks to step-by-step multiplication, high gain is achievable  wo/ discharge.



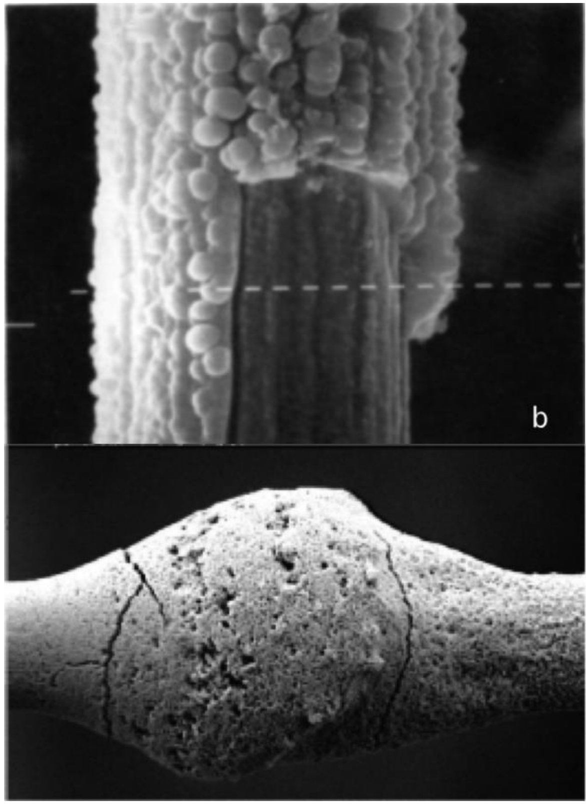



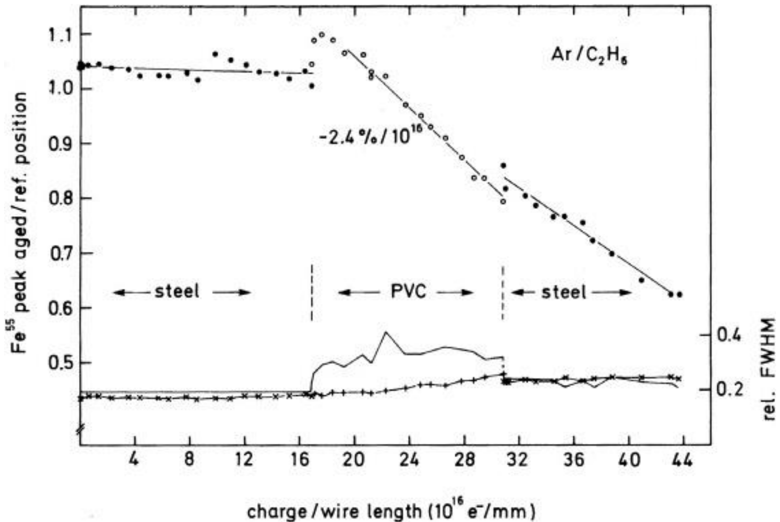
# 3 Characteristic of GEM – Robustness to radiation

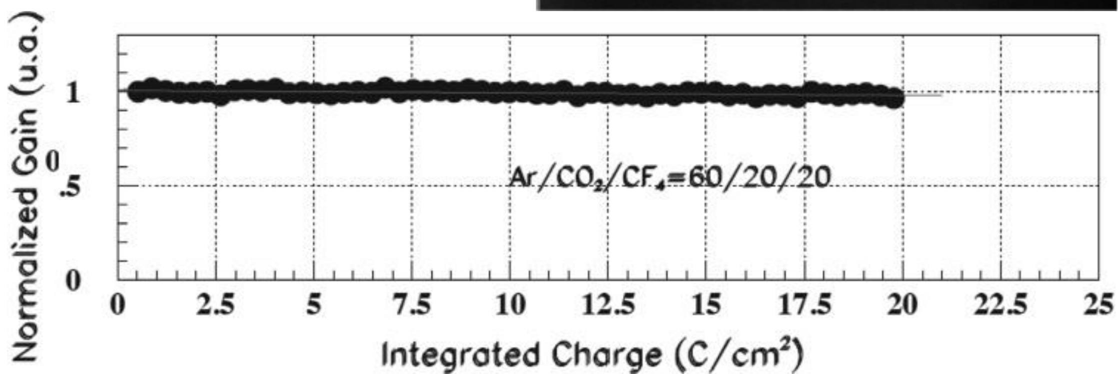
- Classical aging.
  - Quenching gas can form insulating polymer on electrode wire.
  - Charge collection hindered, space charge accumulate, field distorted, dark current increases and discharge occurs.

- GEM is very strong to radiation.

- **Be very careful with outgassing and leak!!**



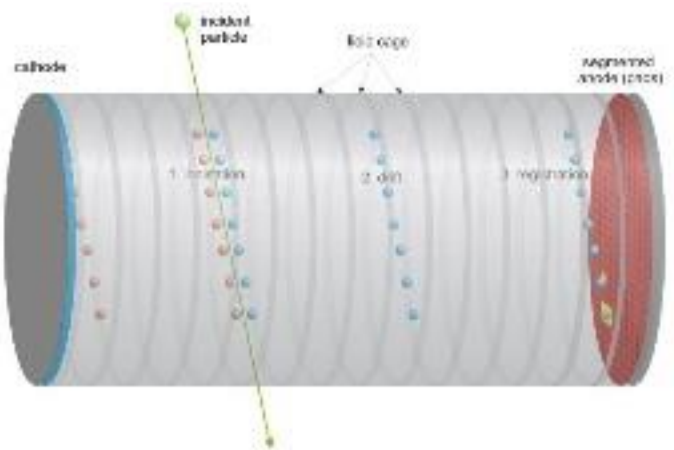
# 3 Characteristic of GEM – Suppression of ions backflow

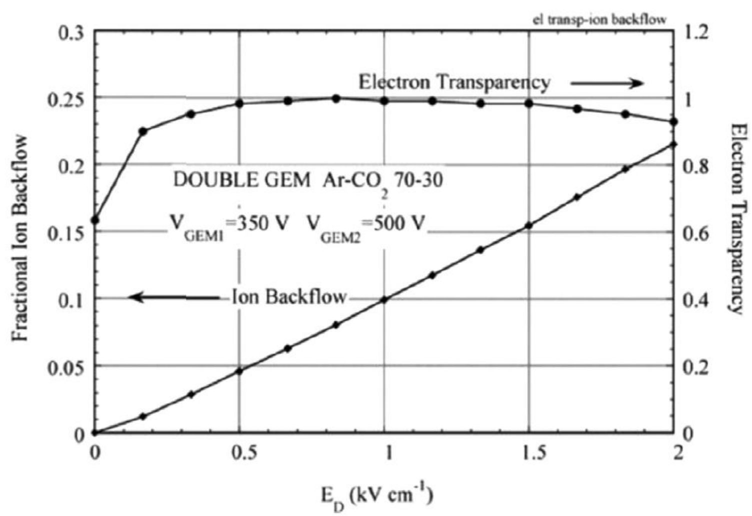
- GEM foil works as screen of ions; Suppression of positive ions backflow.

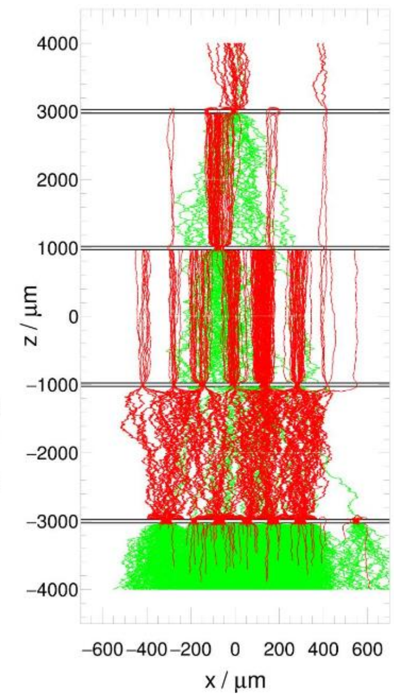
- Space charge due to ion distorts field line for drift. Long time is needed to extract slow ions from drift region.

 ⇒ Reason of extremely low rate capability of TPC.

 ⇒ Good property for TPC.



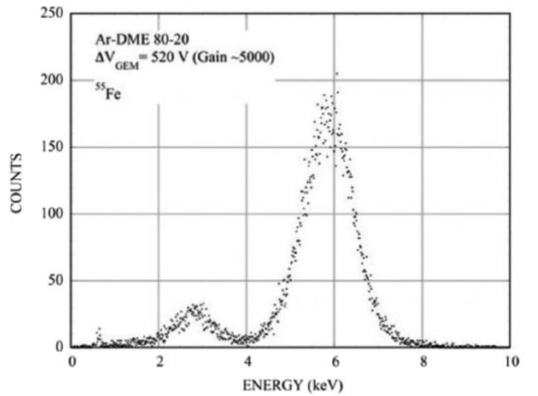


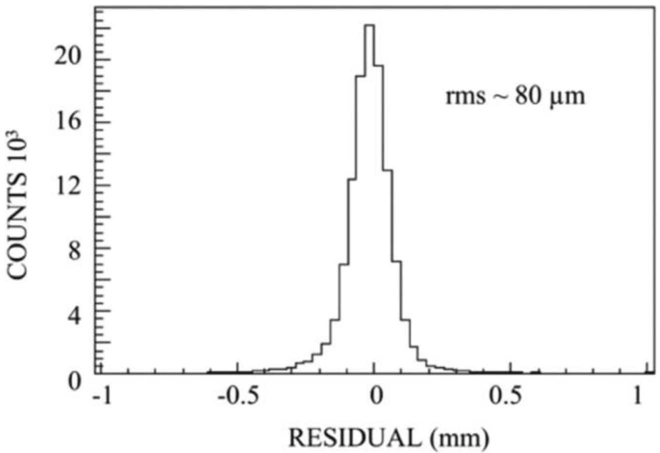



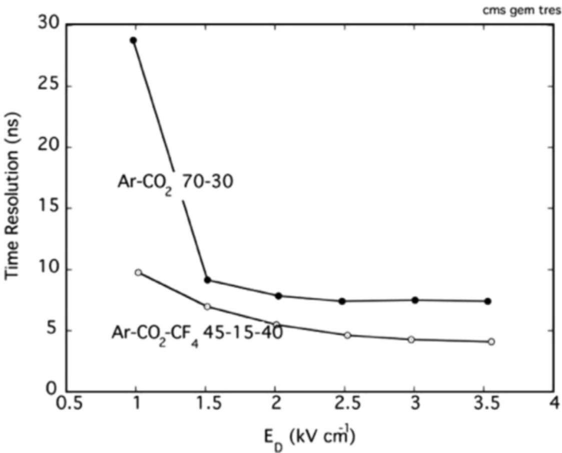

J. Ottnad,
RD51 meeting, 2018.05.12

# 3 Characteristic of GEM – Resolutions

- Energy resolution~17% comparable to proportional counter.
- Time resolution~7ns $Ar: CO_2 = 70\%: 30\%$
  ~4.5ns $Ar: CO_2: CF_4 = 45\%: 15\%: 40\%$
- Spatial resolution: 70-80 $\mu m$.
- Multitrack resolution~$O(100\mu m)$.



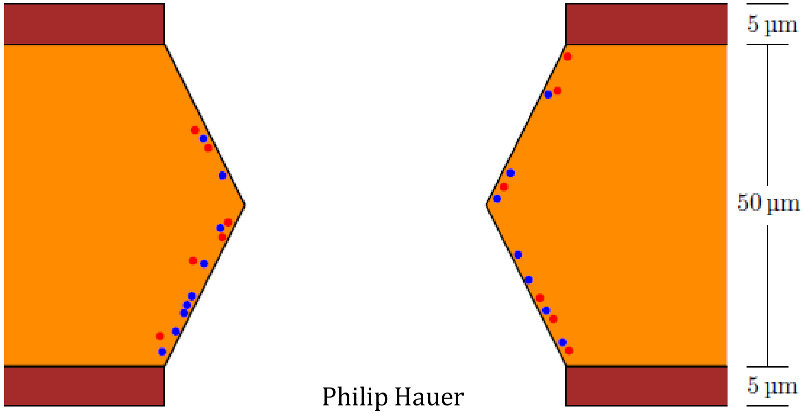



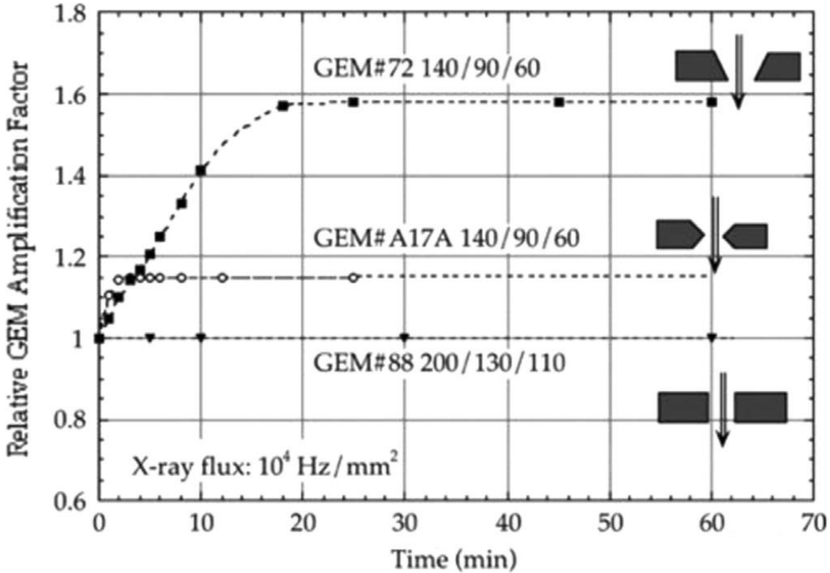
# 3 Characteristic of GEM – Disadvantages

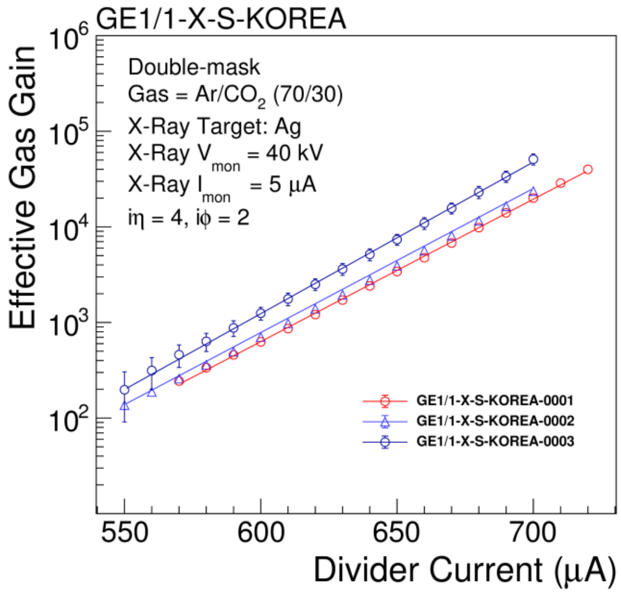
- Gain shift due to charging up.
  - Charges stick to PI layer distort fields and shift gain.
  - Hole geometry is key factor.
  - Combined with "the natural gain shift" of gaseous detector, gain shift of GEM detector is significant.

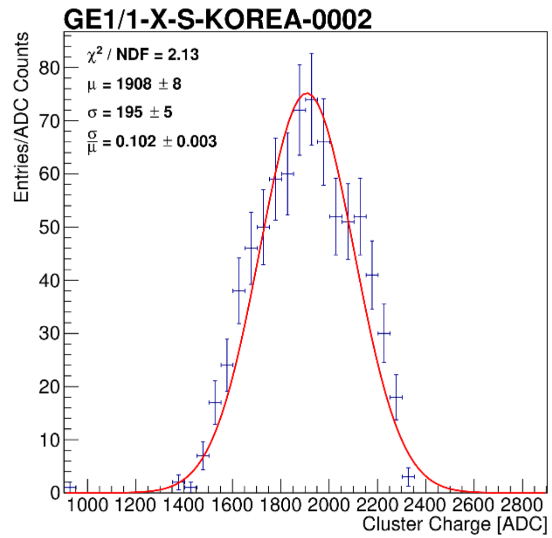
- High material budget.
  - Due to multiple Cu layers
  - R&D ongoing to produce GEM foil with Al or thin Cr instead of Cu.

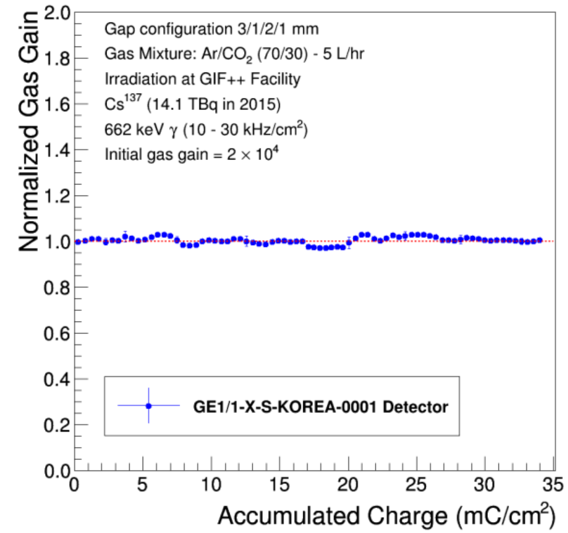


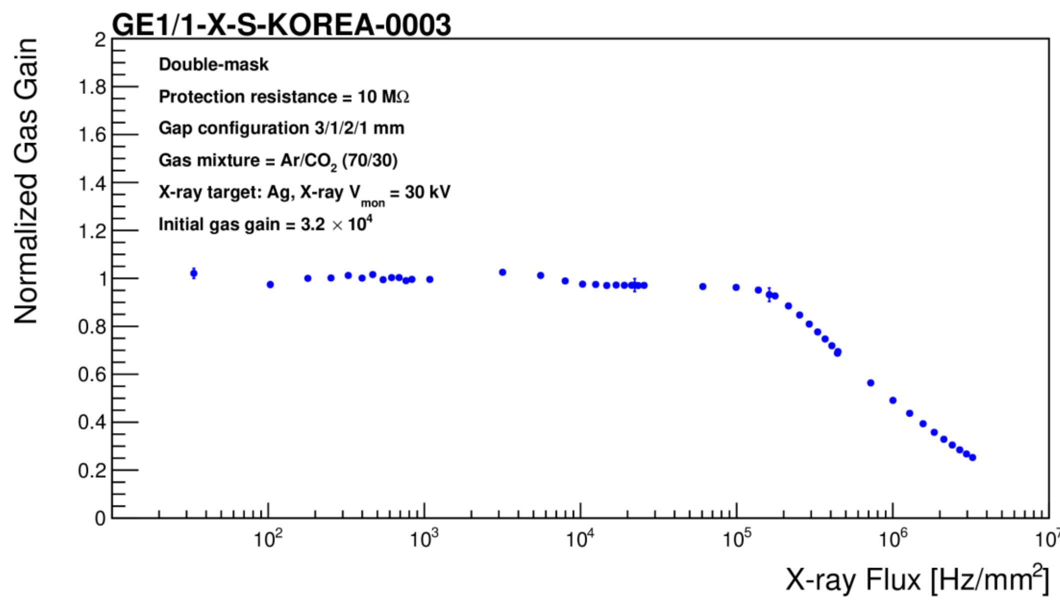

Philip Hauer
RD51 meeting, 2018.05.12




GE1/1-X-S-KOREA
Double-mask
Gas = Ar/CO2 (70/30)
X-Ray Target: Ag
X-Ray Vmon = 40 kV
X-Ray Imon = 5 μA
iη = 4, iϕ = 2
GE1/1-X-S-KOREA-0001
GE1/1-X-S-KOREA-0002
GE1/1-X-S-KOREA-0003
Effective Gas Gain
Divider Current (μA)


GE1/1-X-S-KOREA-0002
χ2 / NDF = 2.13
μ = 1908 ± 8
σ = 195 ± 5
σ/μ = 0.102 ± 0.003
Entries/ADC Counts
Cluster Charge [ADC]


Gap configuration 3/1/2/1 mm
Gas Mixture: Ar/CO2 (70/30) - 5 L/hr
Irradiation at GIF++ Facility
Cs137 (14.1 TBq in 2015)
662 keV γ (10 - 30 kHz/cm2)
Initial gas gain = 2 × 104
GE1/1-X-S-KOREA-0001 Detector
Normalized Gas Gain
Accumulated Charge (mC/cm2)


GE1/1-X-S-KOREA-0003
Double-mask
Protection resistance = 10 MΩ
Gap configuration 3/1/2/1 mm
Gas mixture = Ar/CO2 (70/30)
X-ray target: Ag, X-ray Vmon = 30 kV
Initial gas gain = 3.2 × 104
Normalized Gas Gain
X-ray Flux [Hz/mm2]