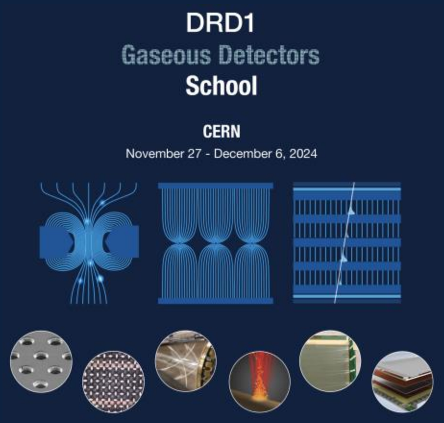
# GASEOUS DETECTORS PHYSICS II

# “BEYOND STABILITY POINT”




Piotr Gasik

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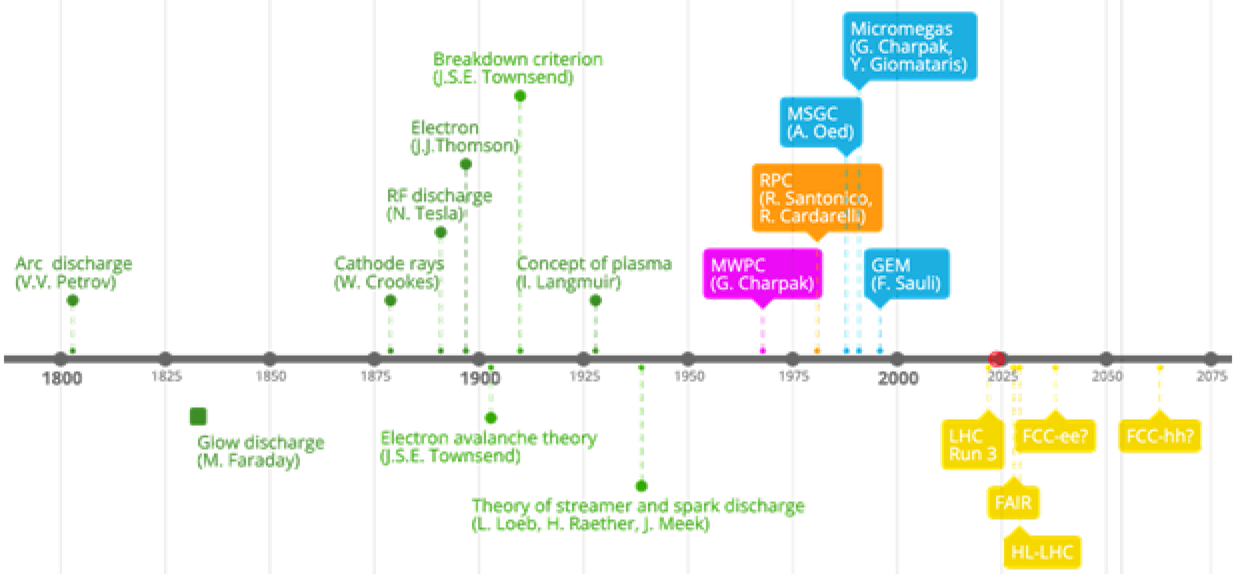
# Why studying gas discharges in gaseous detectors?



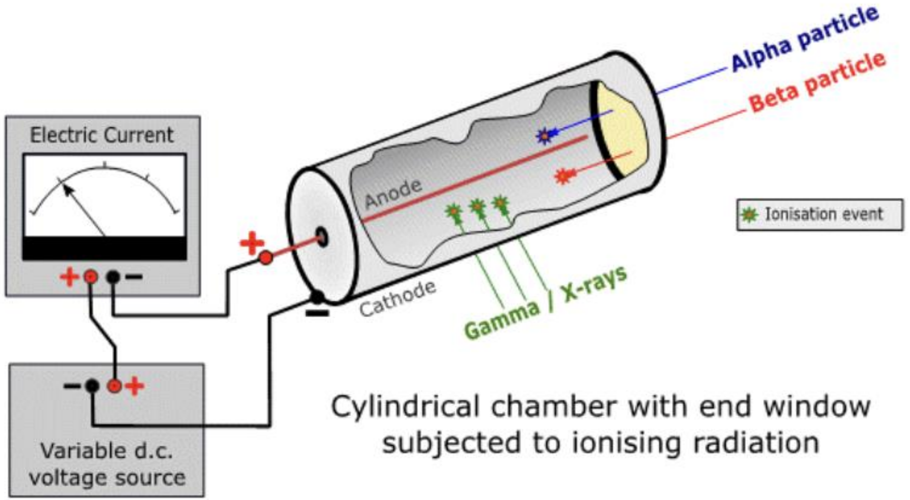

- Gas discharge physics is one of the best-known fields of modern physics
- >200 years since the discovery of the arc discharge by V.V. Petrov
- Still, the main limiting factor for the stable operation of gaseous detectors
- Understanding gas discharges helps to avoid their occurrence and mitigate their effects!

# GAS DISCHARGE PHYSICS

(brief overview of 200 years of research)

# Basics

- **Gas discharge** □ all phenomena of current going through gas

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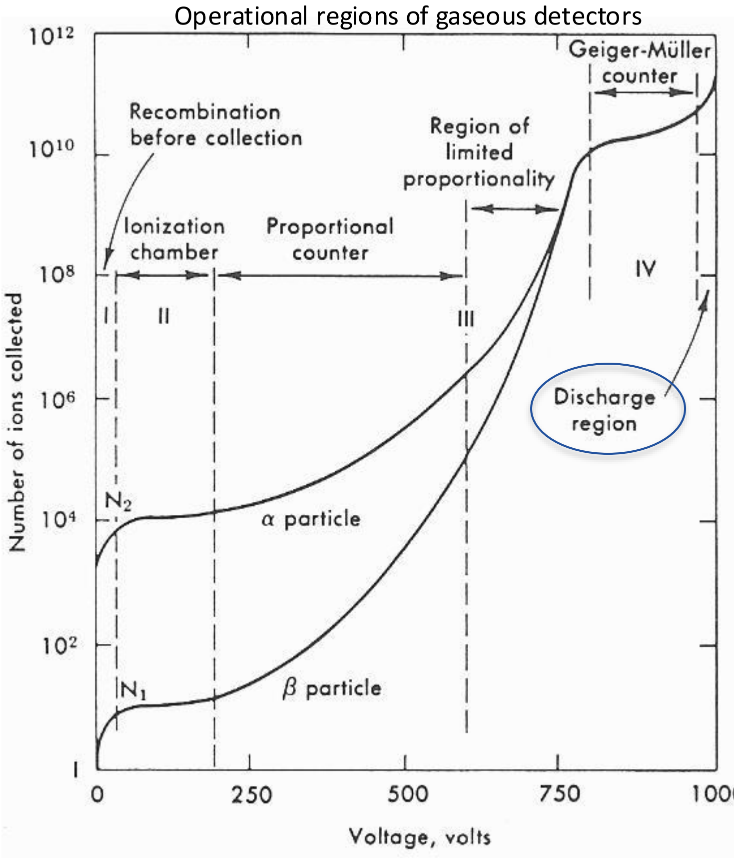


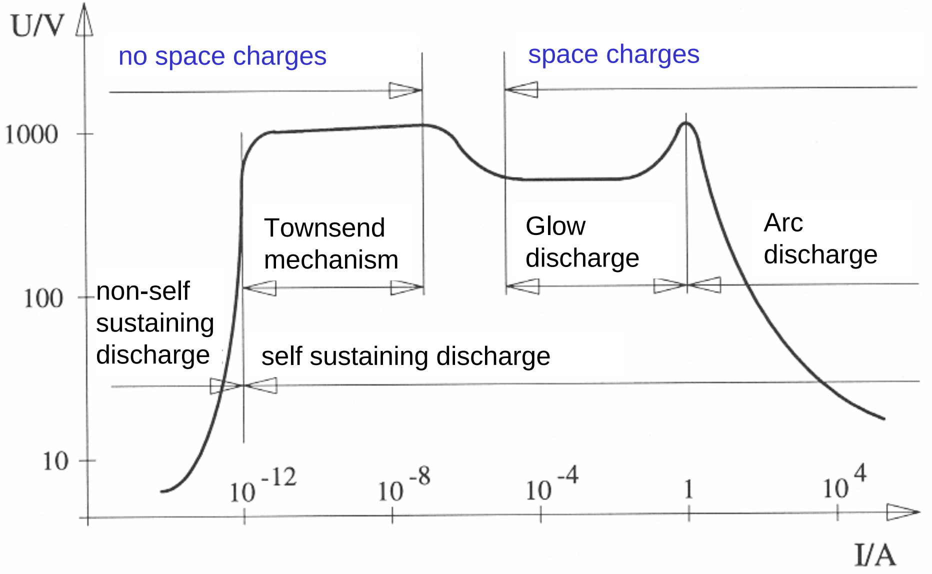

A.C. Melissinos, „*Experiments in modern physics*“, Academic Press (1966) NY

# Volt-ampere characteristic curve in low pressure

**Two discharge categories**

- Non self-sustaining
- Self-sustaining

In the continuous discharge region, a steady discharge current flows. The applied voltage is so high (breakdown voltage $V_S$) that, once ionization takes place in the gas, there is a continuous discharge of electricity, so that the detector cannot be used for radiation detection.

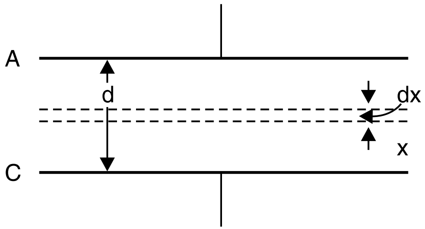




**Discharge/Breakdown/Spark** – often used interchangeably!

# Townsend mechanism

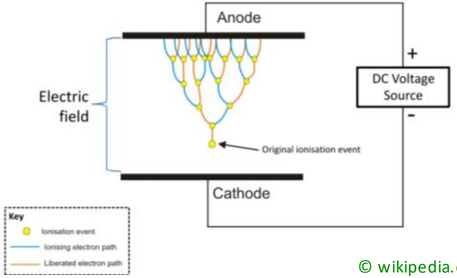
- Go back to the principles: Townsend **first** ionization coefficient α




- The number of electrons produced by an electron per unit length of path in the direction of field

$$N = N_0 e^{\alpha d}$$

$$I = I_0 e^{\alpha d}$$

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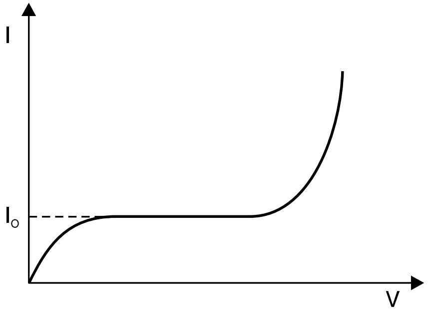
- $e^{\alpha d}$ – electron avalanche

(number of electrons produced by one electron travelling from cathode to anode)

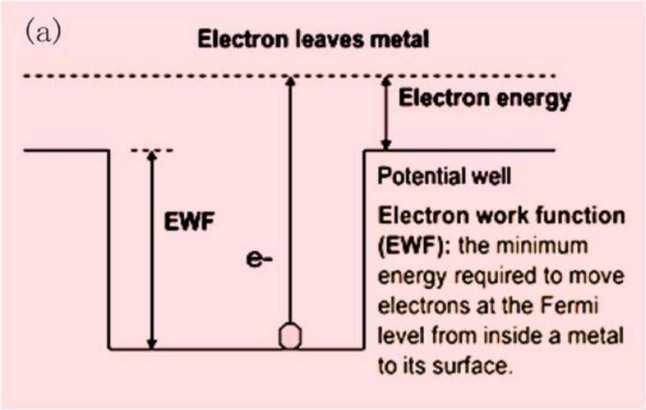



- Townsend **second** ionization coefficient β

ionization by positive ions, can be neglected (β ≈ 0)

# Cathode processes

- Third Townsend coefficient: electrode surface ionization coefficient $\gamma$
- Cathode plays an important role in gas discharges by supplying electrons for the initiation, sustenance and completion of a discharge
- Metal, under normal conditions: electrons are not allowed to leave the surface as they are tied together in the lattice
- Metal work function:
  - the energy required to knock out an electron from a Fermi level
  - characteristic of a given material.




Y. Luo et al. Sci Rep 11, 11565 (2021)

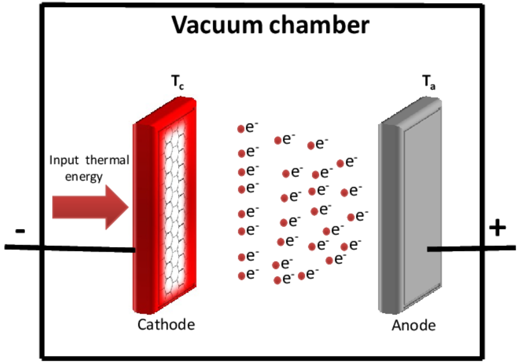
# How to release an electron from the cathode?

## Thermionic emission

- Electron thermal energy not sufficient to leave the surface at room temperature
- Above ~1500 K electrons will receive energy from the violent thermal lattice vibration, sufficient to cross the surface barrier and leave the metal
- Saturation current density: $J = A_G T^2 e^{-W/kT}$ with $A_G = \lambda_R A_0$ and $A_0 = \frac{4\pi m k^2 q_e}{h^3}$

*W* – work function, *T* – temperature, $\lambda_R$ – material-specific constant, $A_0$ – universal constant

- **Current density increases with decrease in work function and increase in temperature.**



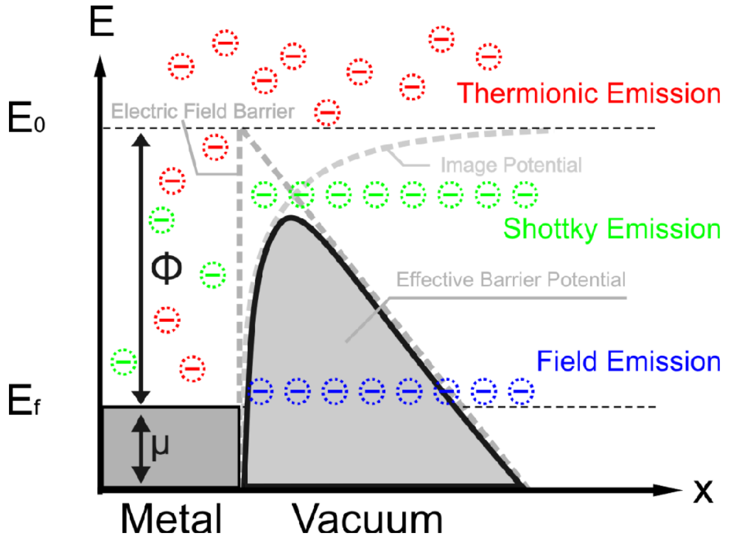
# How to release an electron from the cathode?

## Field enhanced thermionic emission - Schottky effect

- If a strong electric field *E* is applied between the electrodes, the effective work function of the cathode decreases by $\Delta W = \sqrt{q_e^3 E/(4\pi\varepsilon_0)}$

- Saturation current density: $J = A_G T^2 e^{-(W-\Delta W)/kT}$

- Wide range of temperature and electric fields




## Fowler-Nordheim tunnelling – field emission

- For the fields >$10^8$ V/m the cathode surface barrier becomes very thin and quantum tunneling of electrons occurs which leads to field emission even at room temperature.

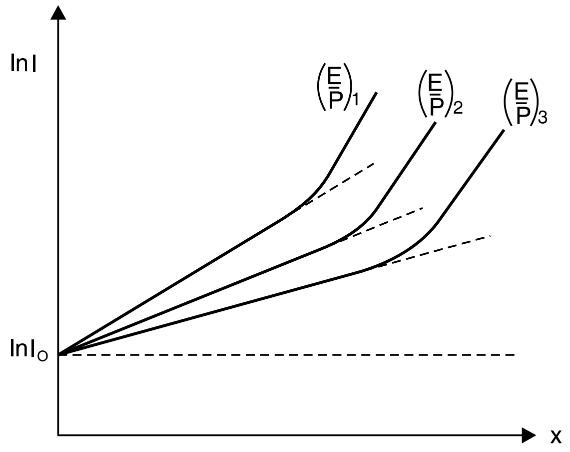
# How to release an electron from the cathode?

## Secondary emission

- Electron emission by a positive ion and excited atom bombardment
- Effective secondary emission by a positive ion with energy $E_{\text{ion}} \geq 2W$

  (one electron will neutralize the bombarding positive ion and the other electron will be released)
- The additional current due to the presence of positive ions
  - Electrode surface ionization coefficient $\boldsymbol{\gamma}$

$$\gamma = \frac{\text{number of released free electrons by positive ions}}{\text{number of positive ions arriving at the electrode surface}}$$



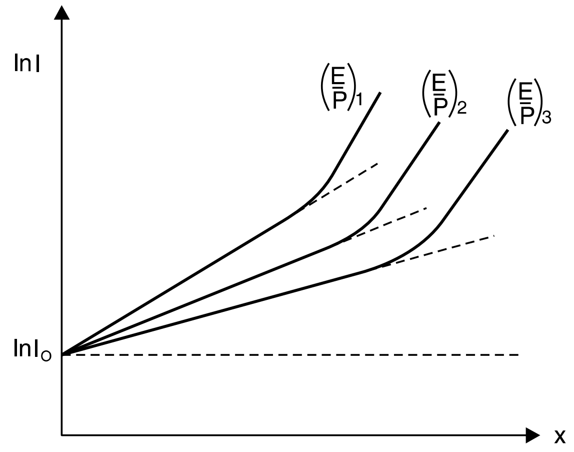
# How to release an electron from the cathode?

## Secondary emission

- Electron emission by a positive ion and excited atom bombardment
- Effective secondary emission by a positive ion with energy $E_{ion} \geq 2W$

  *(*one electron will neutralize the bombarding positive ion and the other electron will be released)
- The additional current due to the presence of positive ions and photons ($h\nu > W$)
  - Number of photons approximately proportional to number of positive ions at breakdown electric field strength
  - Common secondary emission coefficient $\boldsymbol{\gamma}$

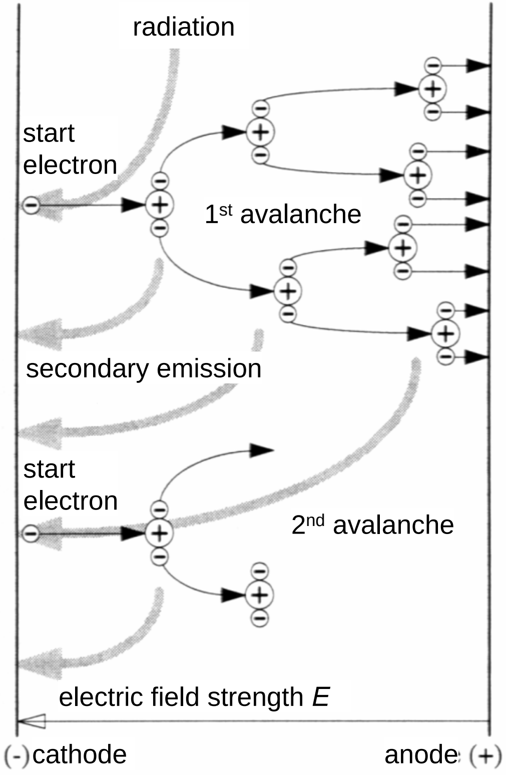
$$\gamma = \frac{\text{number of released free electrons from the electrode surface}}{\text{number of positive ions}}$$



# Townsend mechanism

- In practice positive ions, photons and metastable, all the three may participate in the process of ionization
- There may be more than one mechanism producing secondary ionization in the discharge gap, $g = g_1 + g_2 + g_3 + \ldots$
- $\gamma = f(E/p$, electrode material, surface condition, gas)
- Townsend avalanche:

$$N = \frac{N_0 e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \qquad I = \frac{I_0 e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)}$$



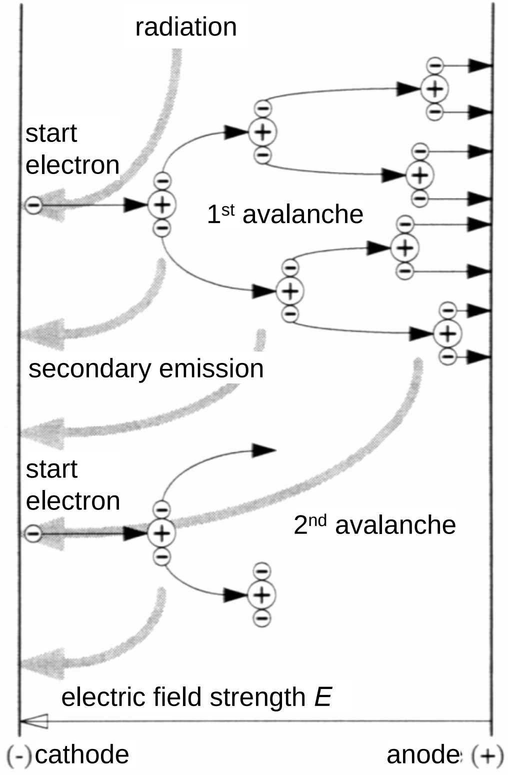
# Townsend breakdown mechanism

DRD1 Gaseous Detector Technologies

- Theoretically, the current become infinite when $\boldsymbol{\delta} = \boldsymbol{\gamma}(\mathbf{e}^{\alpha d} - \mathbf{1}) = \mathbf{1}$
- Practically:
  - limited by the resistance of the external circuit
  - limited partially by the voltage drop in the arc
- Townsend breakdown criterion
  - $\boldsymbol{\delta} < 1$ - current flow is not self-sustained.
  - $\boldsymbol{\delta} = 1$ - self-sustained discharge.
  - $\boldsymbol{\delta} > 1$ - ionization produced by successive avalanche is cumulative. Discharge grows more rapidly.

$$I = \frac{I_0 e^{ad}}{1 - g\left(e^{ad} - 1\right)}$$

- After gas breakdown the form of the discharge is related to the shape of the electrodes, geometric distance, pressure and external circuits.

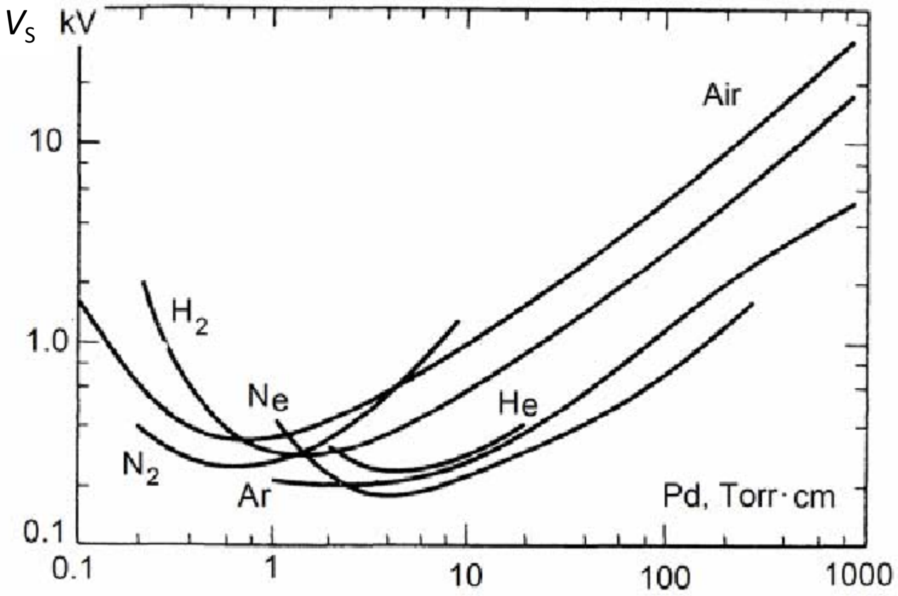


# Paschen's law

- Discovered empirically in 1889
- Analytic expression of gas breakdown potential in a uniform electric field.
- Derived from the 1st Townsend coefficient $\frac{\alpha}{P} = \mathrm{A}\exp\left(-\frac{\mathrm{B}}{E/P}\right)$ and breakdown criterion $\delta = \gamma\left(e^{ad} - 1\right) = 1$

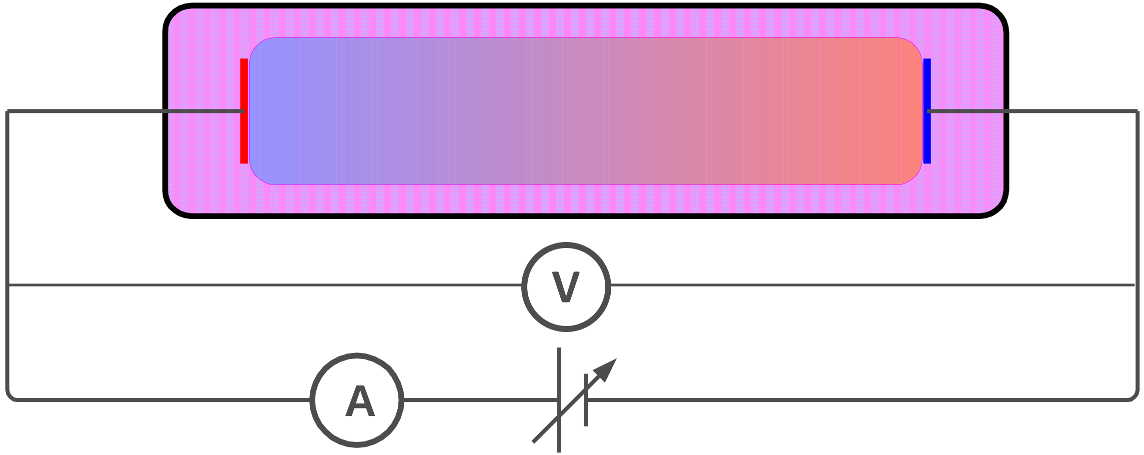
$$V_S = \frac{Bpd}{\ln(Apd) - \ln\left[\ln\left(1 + \frac{1}{\gamma_{se}}\right)\right]}$$

- If the type of gas and the cathode material are known, A, B, and γ are known constants, $V_s$ is only the function of the *Pd* product
- The equation loses accuracy for gaps $\mathcal{O}$(10 μm) at atmospheric pressure




*Y. P. Raizer, Gas Discharge Physics. Berlin, Germany: Springer, 1991*

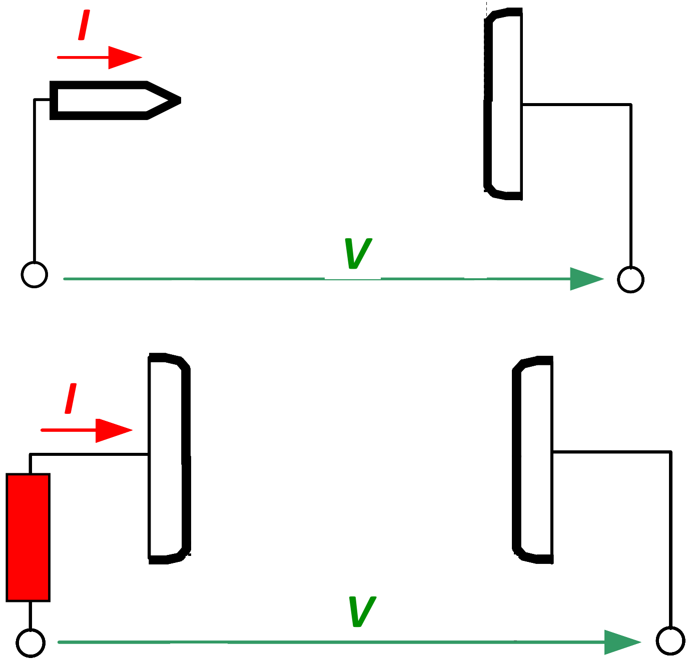
# Observation of discharges



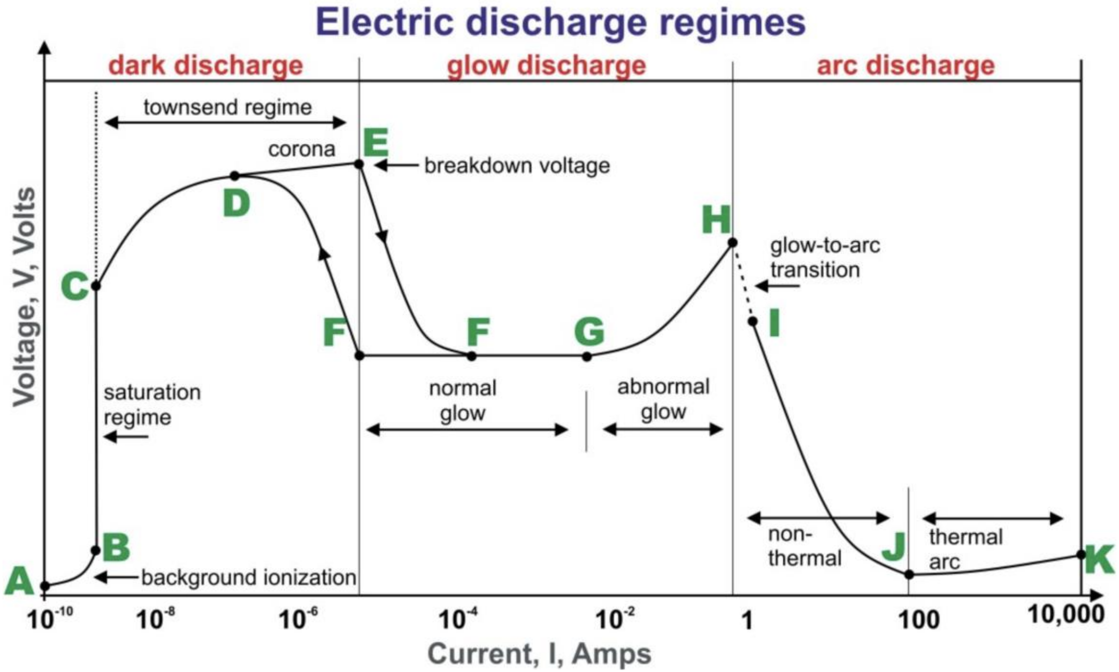

- Record current *I* and potential *V*, for different gas pressure *P* and temperature *T*
- Current reflects a discharge: charge separation
- Watch through the glass tube

# Different types of discharges

- Breakdown voltage $V_S$ reached
- Circuit **with current limitation:**
  - inhomogeneous field
  - homogeneous field with high series resistance
- Observed effects
  - pre-discharges, corona
  - visible glow



# Volt-ampere characteristic curve in low pressure

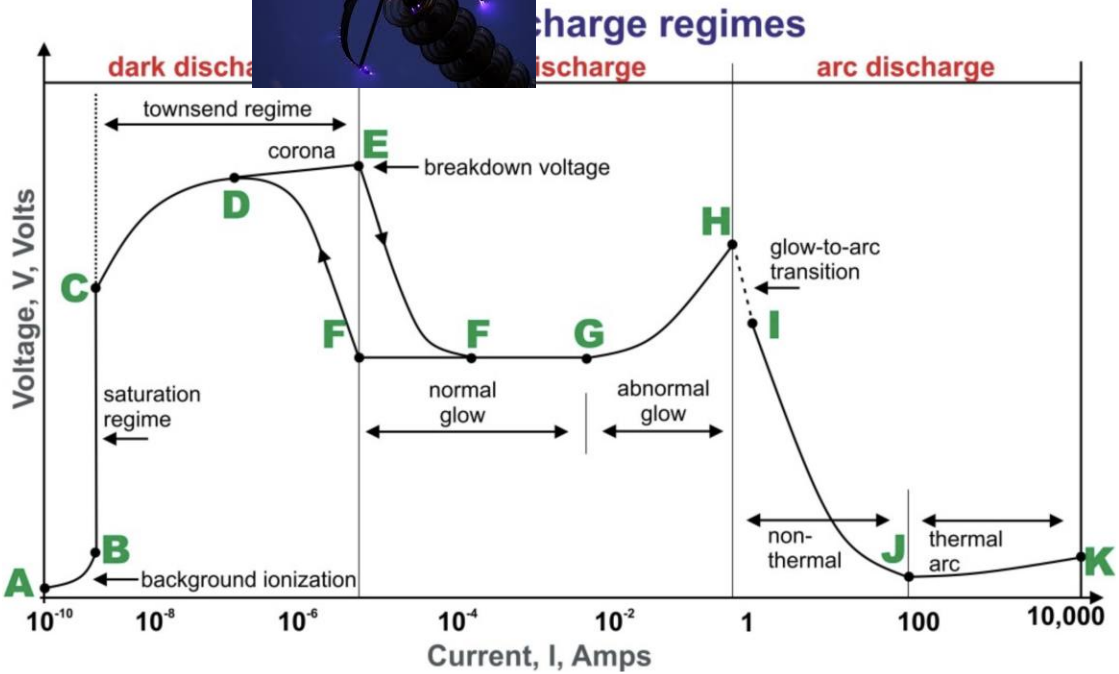



https://www.plasma-universe.com/electric-glow-discharge/

# Volt-ampere characteristic curve in low pressure



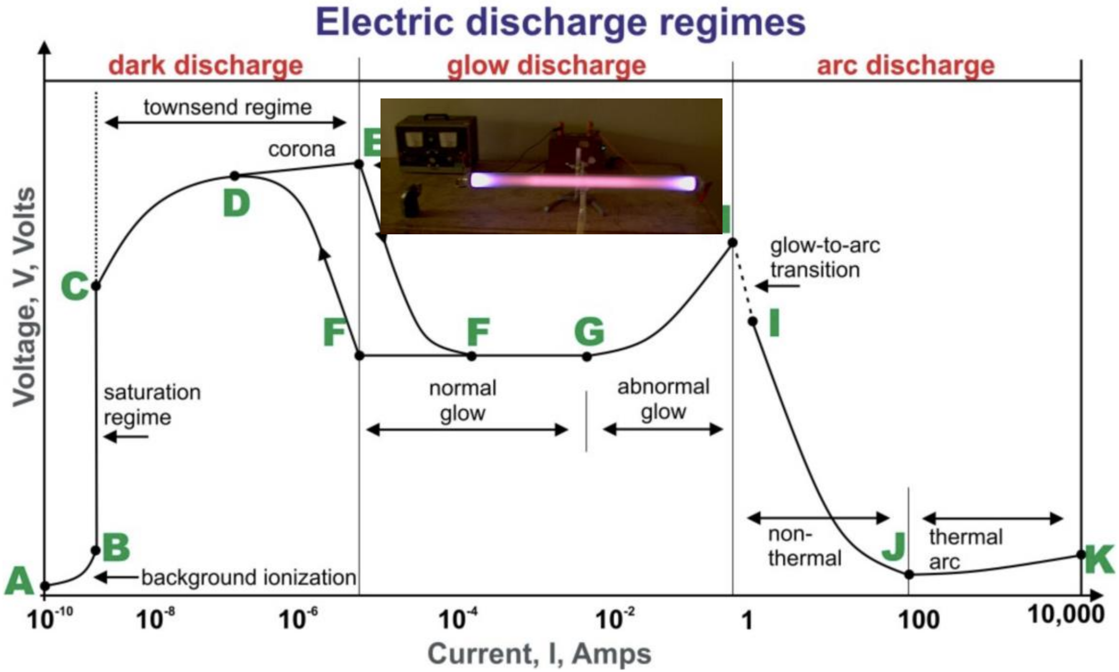
- In strongly non-uniform fields
  - around sharp points or wires
- A radiant corona around the critical region
  - indication of defects in the system
- Can be a special case of either glow or arc discharge
- "Single-electrode discharge"
- Possibly caused by secondary photo-processes in the gas near the wire




*https://www.plasma-universe.com/electric-glow-discharge/*

# Volt-ampere characteristic curve in low pressure

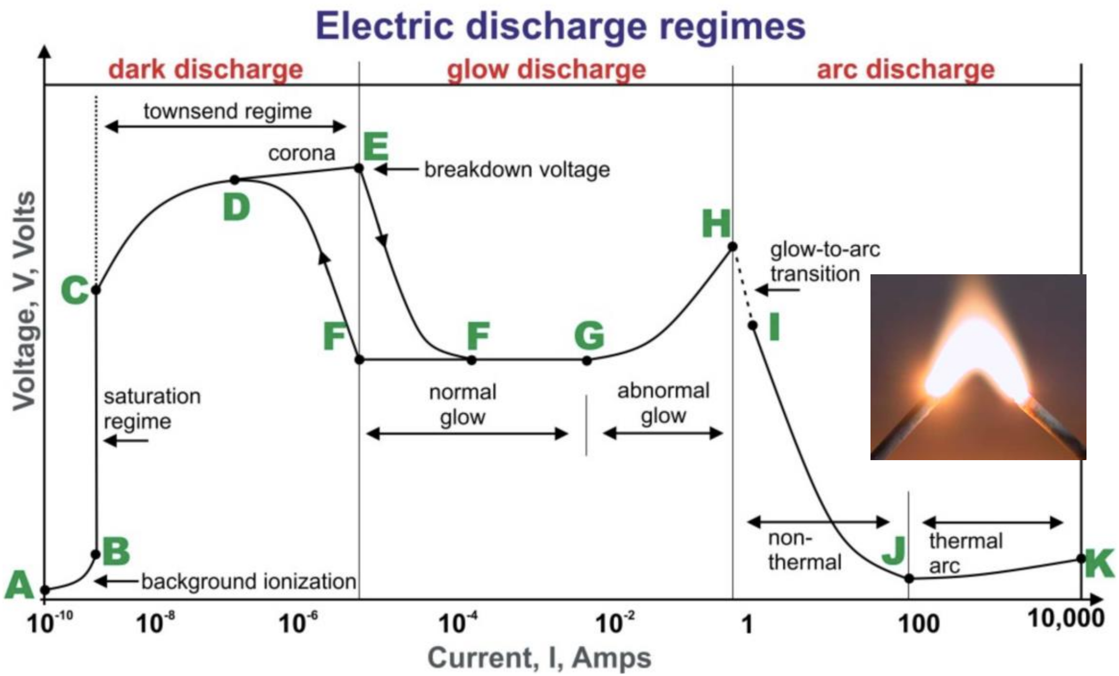
- Low pressure, current limited circuit:
  - relatively low currents
  - radiant column between electrodes (neon light)
- Weakly ionised gas, mainly neutral: non-equilibrium plasma
  - $E_e >> E_{gas}$
  - $T_e$ ($10^4$ K) $>> T_{gas}$
- Gas does not get hot
- Feedback: secondary emission from the cathode by ion bombardment




https://www.plasma-universe.com/electric-glow-discharge/

# Volt-ampere characteristic curve in low pressure

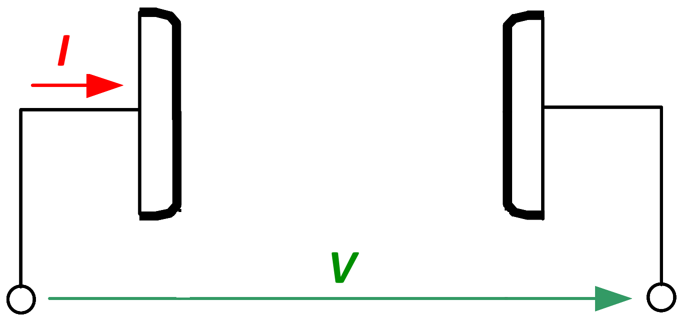
- Ambient pressure, no current limit
  - bright column between electrodes
  - high current
- Thermal equilibrium plasma
  - $T_e \sim T_{gas} > 10^4$ K
  - High ionisation
- Feedback: thermionic knock-out of electrons from the cathode




https://www.plasma-universe.com/electric-glow-discharge/

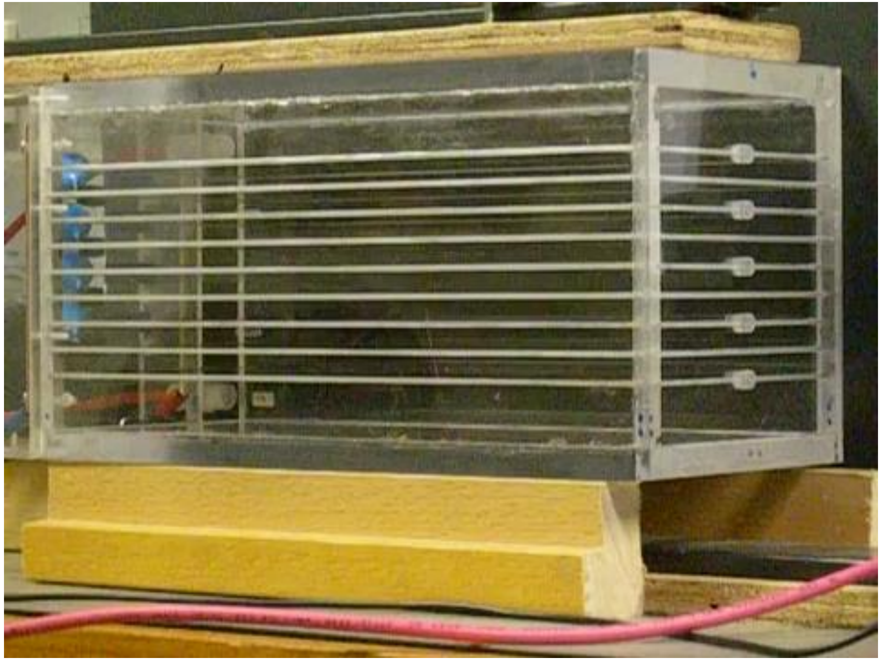
# Full breakdown

- Breakdown voltage $V_S$ reached
- Circuit **without current limitation:**
  - homogeneous field
  - low series resistance
- **Observed effects**
  - voltage collapse
  - complete breakdown



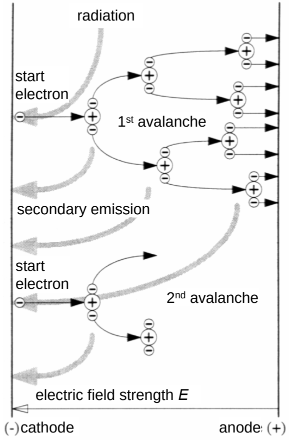
# Spark discharge

- A full breakdown of inter-electrode gap
- Strongly ionized plasma channel between electrodes
- Unstable electrical state (exhibits discontinuity, not uniform plasma)
- High light emission
- Temperature $\mathcal{O}(10^3\text{-}10^4$ K), high-pressure area formation and its movement – explosive phenomenon; noise due to thermal shock wave
- Non-continuous: duration $\mathcal{O}$(10-1000 ns)

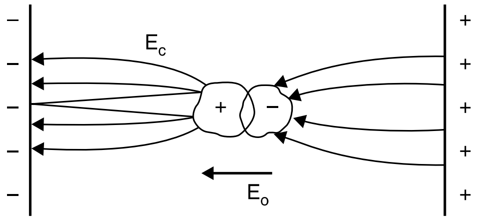


# limitations of Townsend theory

- **Townsend suggested secondary emission from the cathode as the main mechanism of a spark creation**
  - Discharge time-lag $\mathcal{O}$(100 ns) cannot be explained by the secondary emission which requires t ~ 50 µs
  - No correlation with cathode material
  - Avalanches not only start from the cathode - also anode or any other position between the electrodes

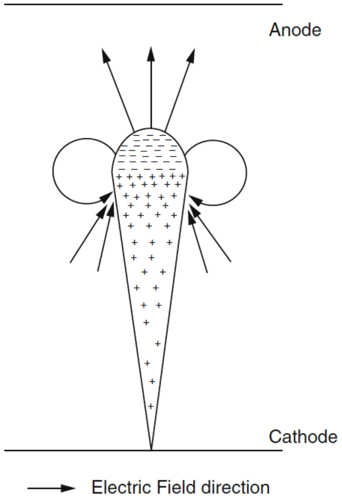



- **H. Raether, L.B. Loeb, J.B. Meek – streamer theory of spark discharge**
  - Improvement of the Townsend discharge theory (derived from the latter)
  - Electron impact ionization (determined by an α process of Townsend discharge),
  - Photoionization
  - Space-charge electric field effect caused by the avalanche
  - Breakdown caused by a single electron avalanche.



# Streamer theory

*Following: D. Xiao, „Gas Discharge and Gas Insulation“, Springer 2016*




- A single *e* starting at the cathode builds up an avalanche (ionization) that crosses the gap
- Electrons in the avalanche move very fast compared to the ions (regarded as stationary)
- The space-charge E-field will cause significant distortions which
  - strengthen the electric field of the head and tail parts of the electron avalanche
  - weaken electric field between the positive and negative charge regions

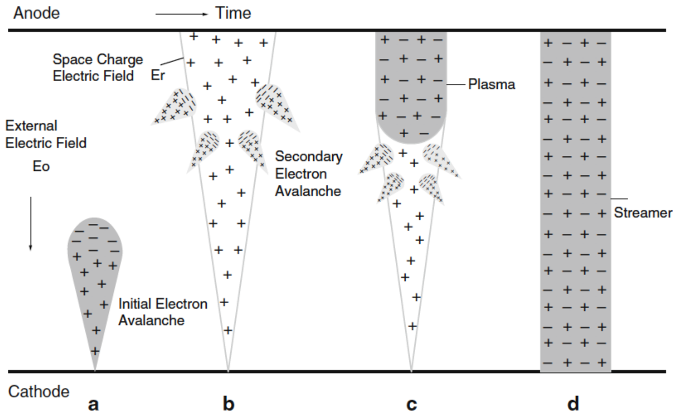
- **Raether criterion:** $Q_{max} = e^{\alpha d} > 10^8$ is the condition for streamer formation and self-sustained discharge (as in Townsend)

- **Meek criterion:** radial E-field intensity of the space-charge (head of the avalanche) is ~equal to the applied field;

(Supplemented by **Loeb condition** on the electron density in the avalanche of $0.7 \times 10^{12}$ cm$^{-3}$ to ensure sufficient photoionisation)

# Streamer theory

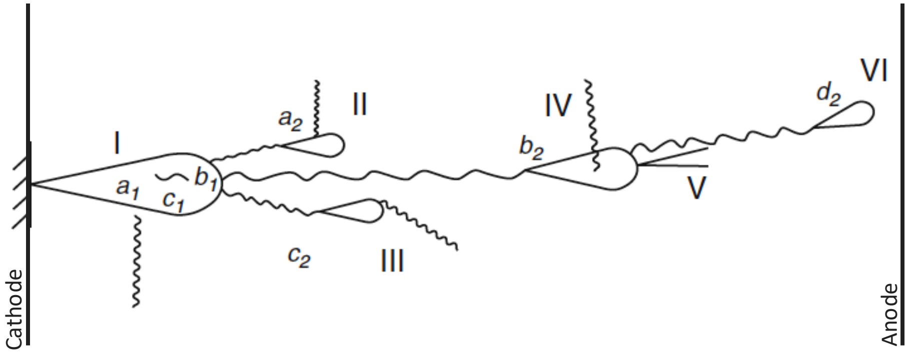
*Following: D. Xiao, „Gas Discharge and Gas Insulation“, Springer 2016*




- Applied voltage ~breakdown voltage ($V_S$) □ **positive streamer formation**
- The electron avalanche is through the whole space, E-field of the tail is greatly strengthened
- Photon radiation □ photoionization □ secondary electron avalanche (**b**)
- Electrons form negative ions □ creation of a plasma stream (**c**)
- Streamer has a good conductivity, strong electric field in front, process grows rapidly
- When streamer reaches the cathode, gap breakdown is completed (**d**)

# Streamer theory

*Following: D. Xiao, „Gas Discharge and Gas Insulation", Springer 2016*

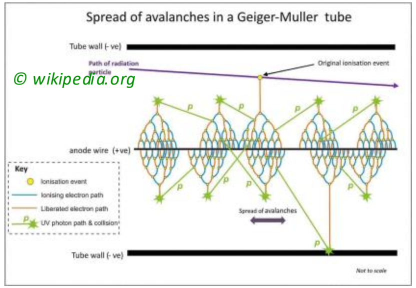



- Applied voltage > breakdown voltage ($V_S$) □ **negative streamer formation**
- No need for the electron avalanche to go through the gap
- Ionization degree of the avalanche head part sufficient to form a streamer (photon emission)
- Streamer develops towards the anode (volume- and photoionization)
- Expansion speed of of the streamer much larger than avalanche

# GASEOUS DETECTORS DISCHARGES

# Discharges in wire counters

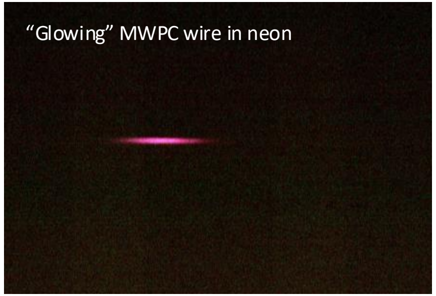
- **Operation beyond proportional mode**




*© wikipedia.org*

- **Geiger mode**
  - Poorly quenched gases, low pressures
  - Photon mediated avalanche propagated in both directions along the wire
  - Quenched with an external circuit (*R*) or space-charge effects (quenched gases)

- **Self-sustained discharges (glow/corona)**
  - Sustained discharge due to ion feedback mechanism (Townsend discharge)
  - He, Ne mixtures at atmospheric pressure (gain $10^4$-$10^5$) glows below sparking limits
  - Quality, cathode, quencher □ crucial!

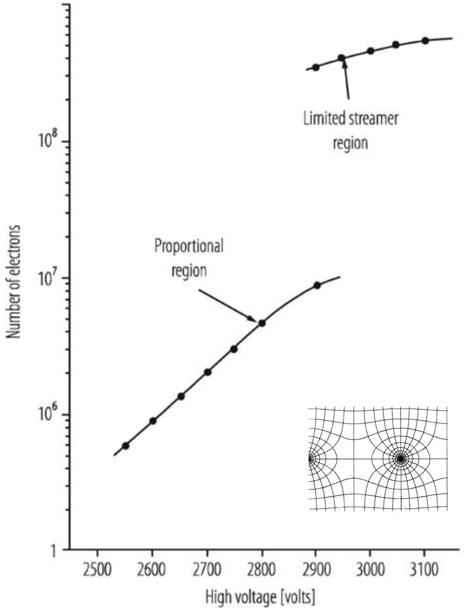



*© Courtesy of C. Garabatos*

# Discharges in wire counters

- **Operation beyond proportional mode**

- **Self-Quenched Streamer (SQS) mode**
  - Thick anode wires, hydrocarbon-rich mixtures
  - Streamer development, dumped before reaching the cathode
  - Radial fields, 1/*r* dependency allows to quench streamers



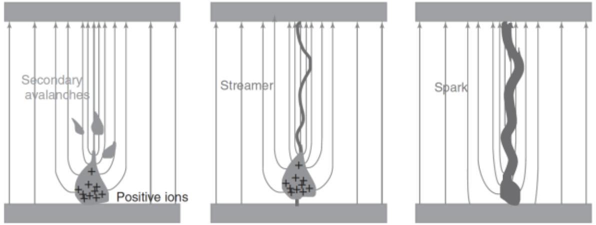

*M. Atac, A.V. Tollestrup, D. Potter, NIM 200 (1982) 345.*

- **Sparking limits**
  - When the critical charge ($\sim 10^8$) is reached – streamer mechanism
  - Enhanced by secondary emission from the high field regions in the cathode plane or Malter effect
  - Can be destructive, depending on the stored energy

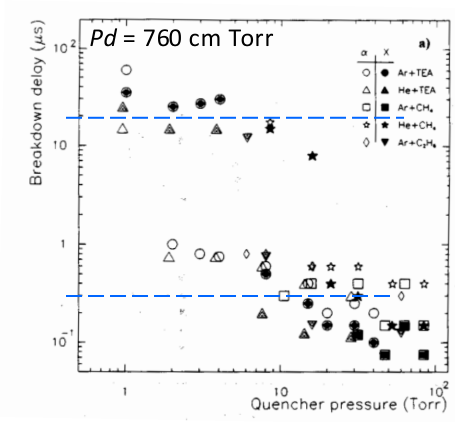
# Discharges in parallel-plate avalanche counters

DRD1 Gaseous Detector Technologies

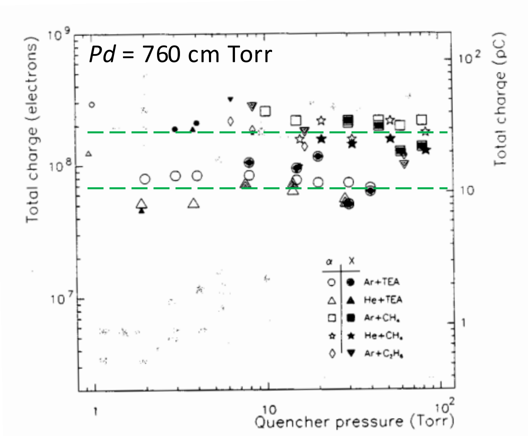
- Both Townsend (slow) and Streamer (fast) breakdown modes observed
- In uniform, parallel fields streamer develops until spark channel is created (no SQS, full breakdown)
- Transition depends on the gas composition (photon feedback)
- Critical charge for streamer/spark development ~$10^8$ (Raether limit?), but:
  - Differences up to factor of 5; quencher dependency (?) □ **no universal limit?**




*M. Abbrescia, P. Fonte, V. Peskov, Wiley-VCH Verlag GmbH & Co. KGaA, 2018*




*P. Fonte, V. Peskov, F. Sauli, NIM A 305 (1991) 91*




*P. Fonte, V. Peskov, F. Sauli, NIM A 305 (1991) 91*

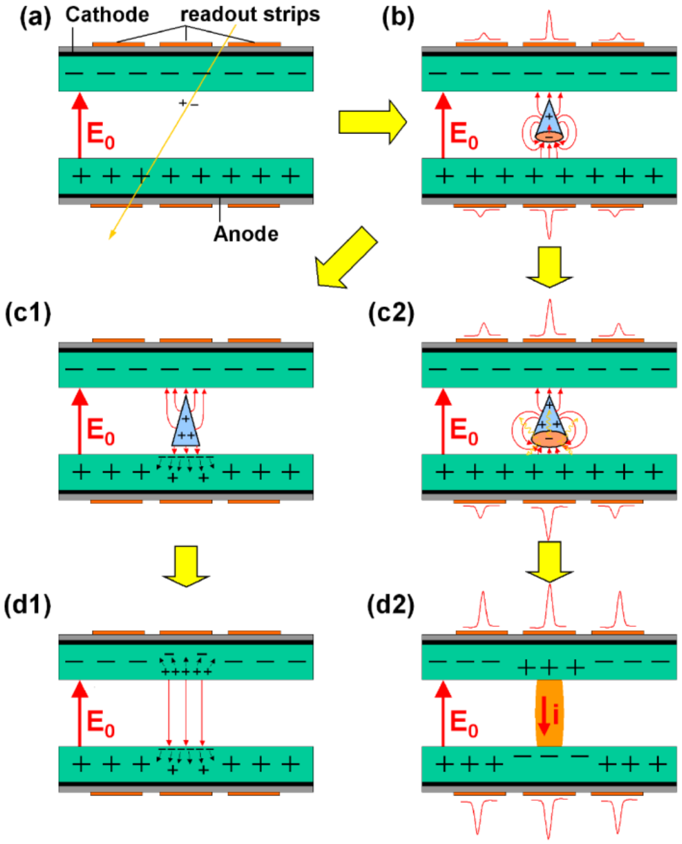
# Resistive plate chambers

See lecture by R. Santonico (link)

- Material with high volume resistivity
- Drop of the electric field around the initial avalanche
- Charge $Q_0$ that enters the resistive electrode:

$$Q(t) = Q_0 e^{-t/\tau} \quad \text{with} \quad \tau = \rho \varepsilon_0 \varepsilon_r$$

- With $\rho \approx 10^{10} - 10^{12}$ Ωcm, $\tau \approx 0.01 - 1$ s
- Remaining counter area remains sensitive to particles

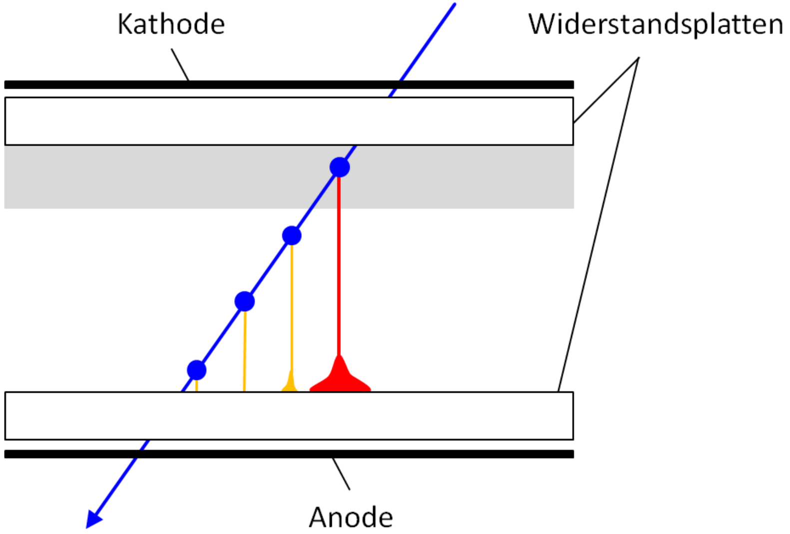


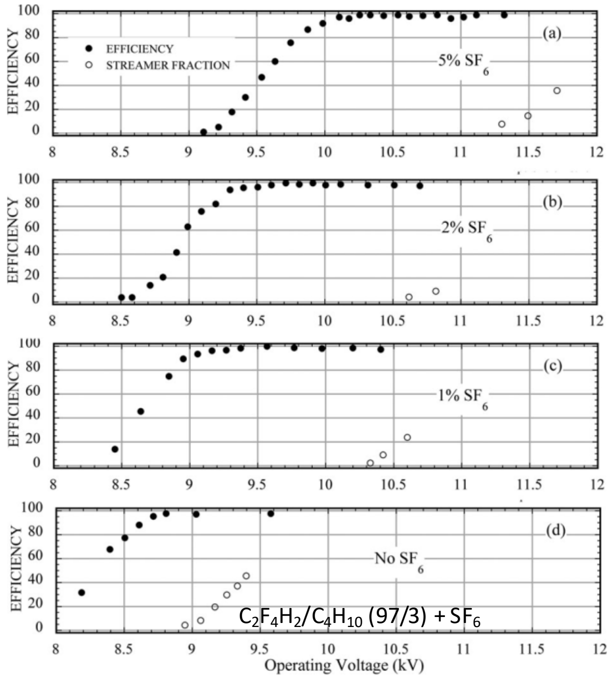

© Courtesy of I. Deppner, GSI

# RPC -- Streamer development by photon feedback

- The transition from a proportional avalanche to a streamer at $Q_{crit} \approx 10^8\ e$ ➞ discharge channel creation
- The released energy is strongly limited by the resistance of the plate!
- Reduce photon feedback and the avalanche growth with a properly quenched mixture (e.g. $C_2F_4H_2$, $SF_6$, …)

  ➞ reduce streamer probability



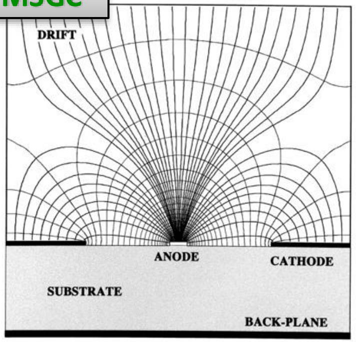




*P. Camarri et al, NIM A 414 (1998) 317*

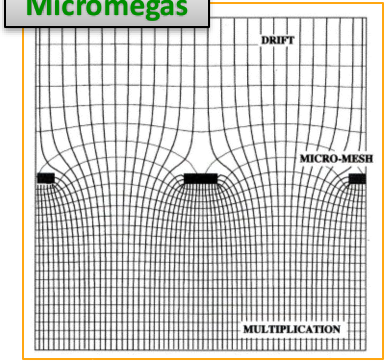
# Discharges in MPGDs

*Following: V. Peskov, „ Discharge phenomena in gaseous detectors “, RD51 Meeting, Munich 2018 (link)*

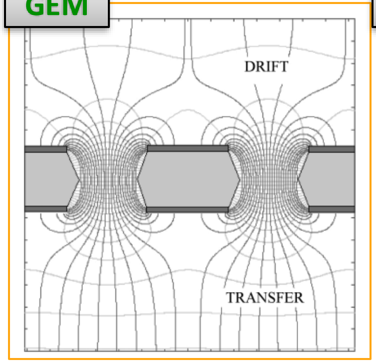
MSGC



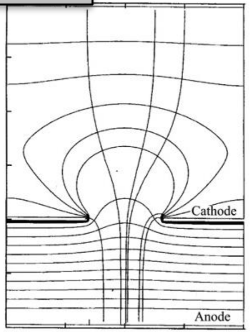

Micromegas



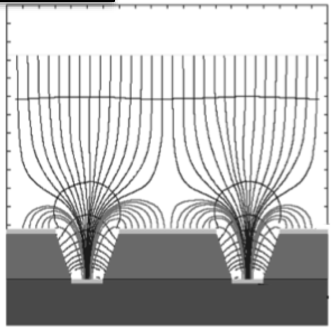

GEM



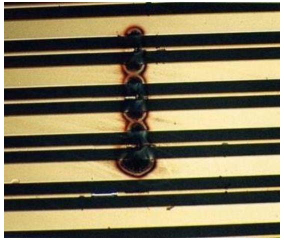

CAT



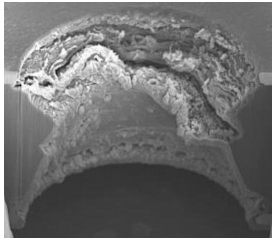

MGC

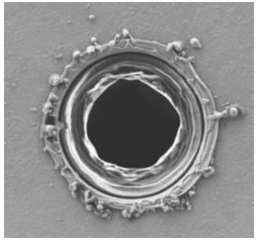


- In all these structures, there are regions with ~parallel field lines
- Streamers can develop by the same mechanism as in PPAC
- No quenching by field reduction, when streamers reaches the cathode □ full breakdown

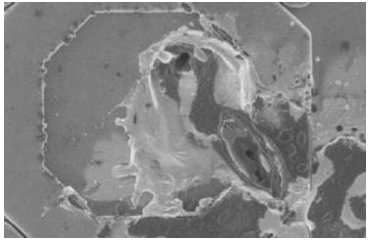


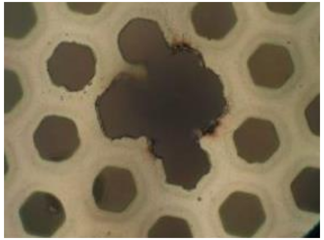
F.Sauli, IEEE NSS 2002



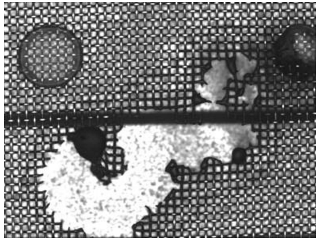


J. Merlin, “*Single-hole discharges in GEMs*”, RD51 Meeting, TUM 2018 (link)





*M. Chefdeville (NIKHEF), „The pixel readout of TPCs“, (link)*



*J.Galan, RD51 meeting (link)*

# Critical charge in MPGDs

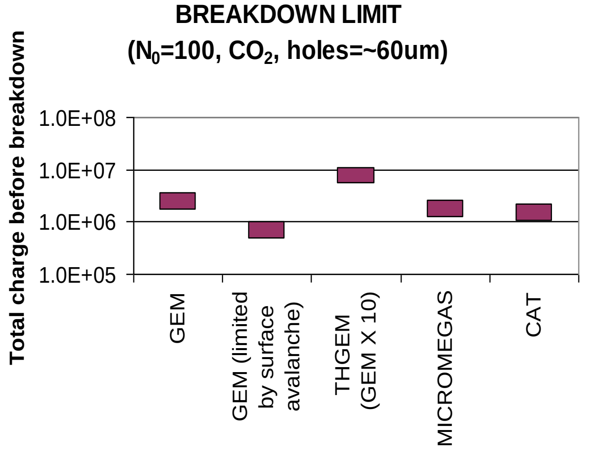
- In case of MPGDs we discuss mainly the (positive) streamer mechanism and a spark discharge
- Critical charge measurements in MPGDs point to a **limit of $10^6$-$10^7$ *e***, depending on the reference
- Different geometries, gases, source (x-ray, alphas)

$$G_{\mathrm{max}} = \frac{Q_{\mathrm{crit}}}{N_{\mathrm{primary}}}$$

*F. Sauli, Report at the RD51 collaboration meeting in Amsterdam, 2008*

| | DETECTOR | MAX GAIN | MAX CHARGE |
|---|---|---|---|
| i | MSGC | 2000 | 4 $10^7$ |
| ii | ADV PASS MSGC | 1000 | 2 $10^7$ |
| iii | MICROWELL | 2200 | 4.4 $10^7$ |
| iv | MICROMEGAS | 3000 | 6 $10^7$ |
| v | GEM | 2000 | 4 $10^7$ |

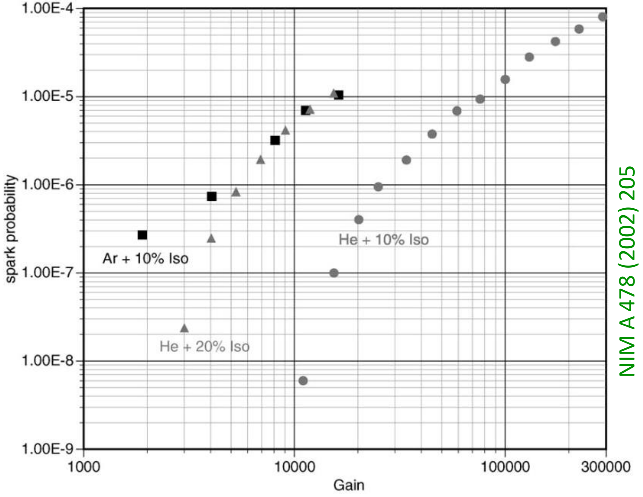
*P. Fonte, Simulations of discharge phenomena, RD51 meeting, Munich, 2018*



# MPGD Discharge probability

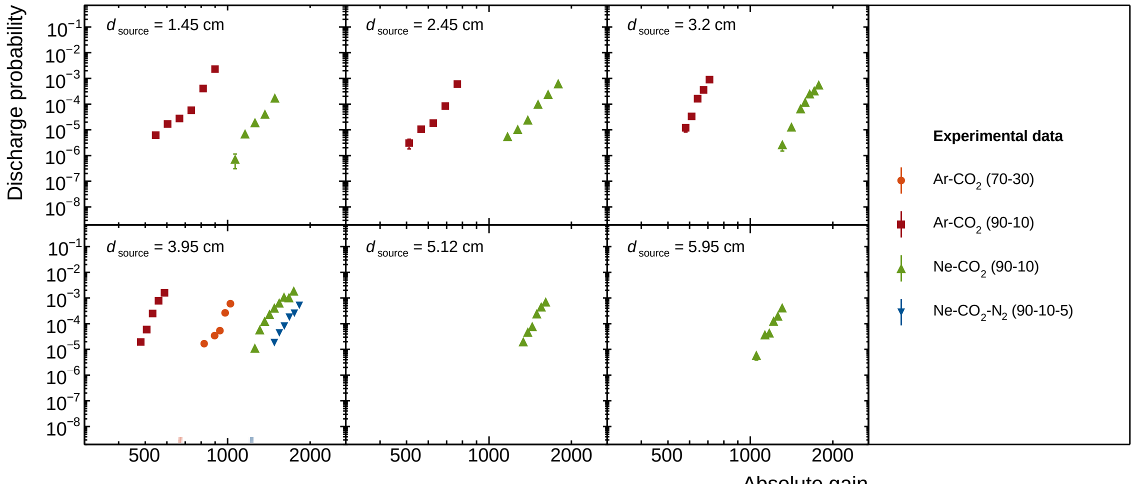
- Clear gas dependencies
- Abrupt drop of discharge rate for source distances larger than alpha range
- Clear correlation between discharge rate and ⟨$Z$⟩ of a gas mixture → primary charge density
  - Alpha range in Ne longer than in Argon
  - $W_i$ (Ar) < $W_i$ (Ne)

**MICROMEGAS**
**Hadron beam (10-15 GeV/*c* protons)**




NIM A 478 (2002) 205

**GEMs**
**Alpha particles**

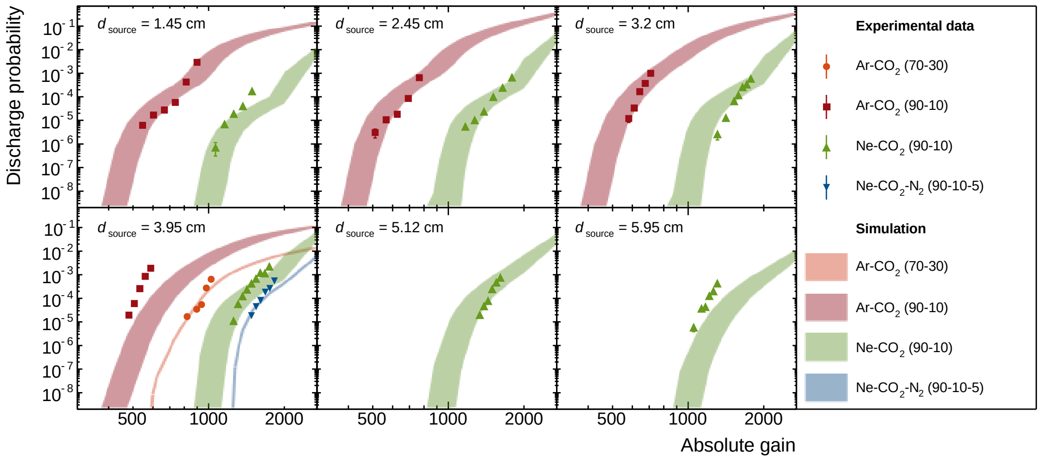



NIM A 870 (2017) 116

# Critical charge in different gases

- GEANT4 – based model describes data fairly well over several orders of magnitude
- Only primary ionization and basic gas properties taken into account ($D_L$, $D_T$, $v_d$)

| Gas | GEM $Q_{crit}$ [$\times 10^6$ $e$] |
|---|---|
| Ne-$CO_2$ (90-10) | 7.3 ± 0.9 |
| Ar-$CO_2$ (90-10) | 4.7 ± 0.6 |
| Ar-$CO_2$ (70-30) | – |



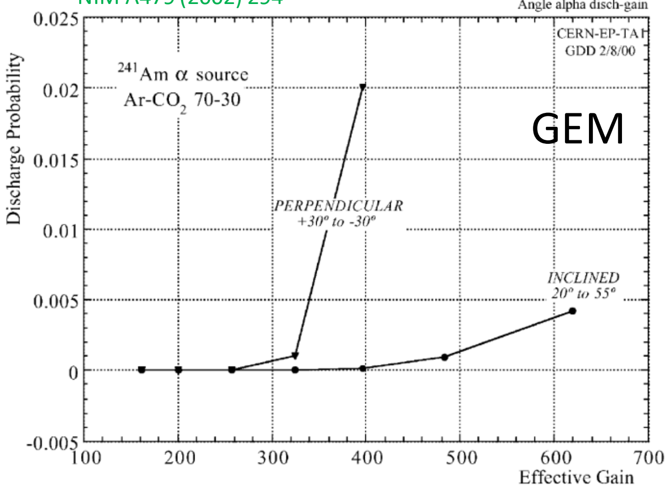

- **Primary charge density → driving factor for discharge formation**
- **Different $Q_{crit}$ for different gases → no universal limit.**
- See also studies by S. Procureur NIM A621 (2010) 177

$$G_{max} = \frac{Q_{crit}}{N_{primary}}$$

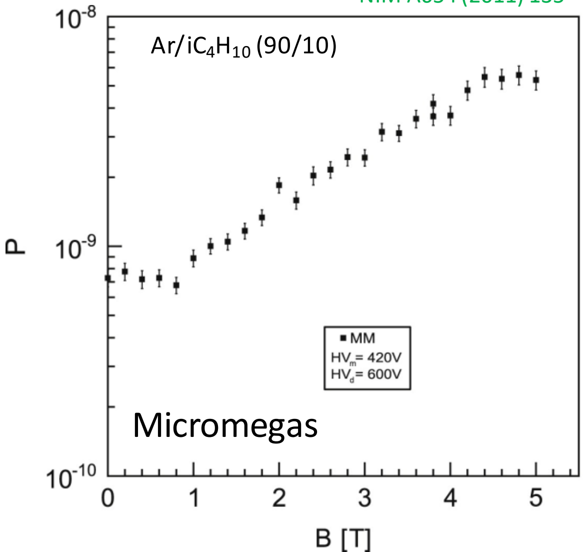
# Primary charge density

- Primary charge density is a more relevant parameter than the total number of electrons
- Source inclination studies – higher charge densities per hole for perpendicular tracks impinging a GEM
- B||E studies – reduced transverse diffusion – higher charge density arriving at GEM holes

NIM A479 (2002) 294



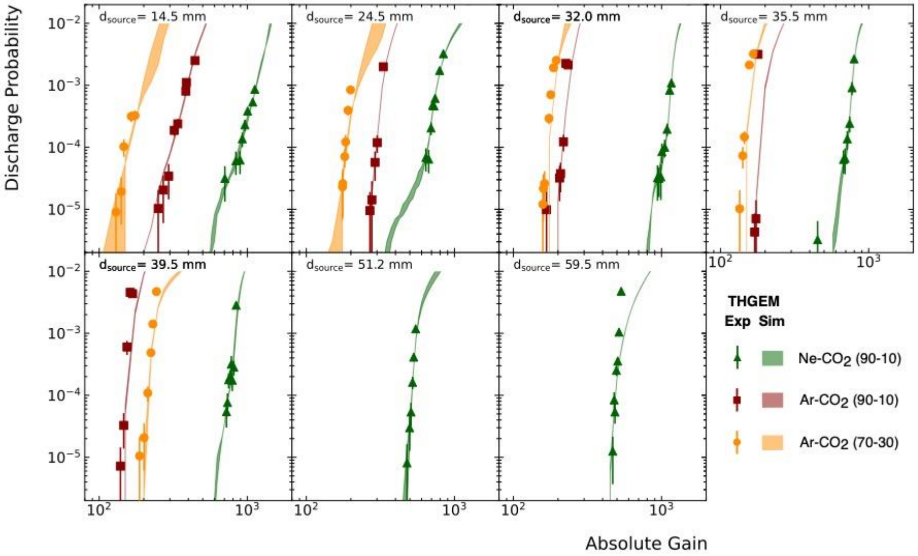

NIM A654 (2011) 135



# THGEM results

NIM A 1047 (2023) 167730

- THGEMs are large (robust, inexpensive) version of GEMs
  ➞ ~10× larger in each direction
- Discharge probability in THGEMs higher than in GEMs
  ➞ ~100× less holes, same electron collection




| Gas | THGEM $\langle Q_{crit} \rangle$ [$\times 10^6$ $e$] | GEM $Q_{crit}$ [$\times 10^6$ $e$] |
|---|---|---|
| Ne-$CO_2$ (90-10) | 7.1 ± 2.2 | 7.3 ± 0.9 |
| Ar-$CO_2$ (90-10) | 4.3 ± 1.5 | 4.7 ± 0.6 |
| Ar-$CO_2$ (70-30) | 2.5 ± 0.9 | – |

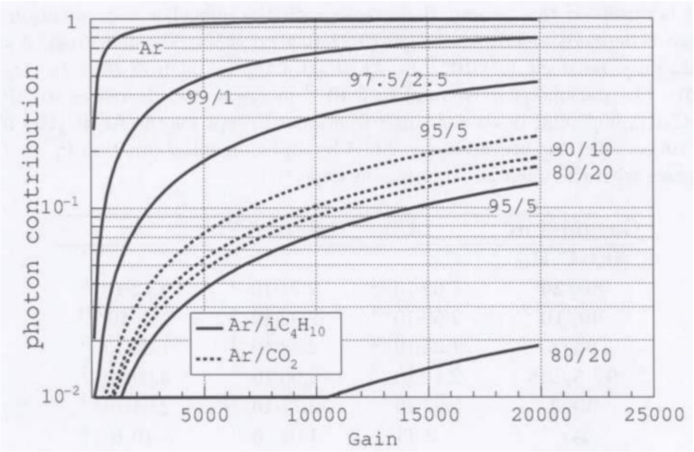
- Gas dependency observed again!
- $Q_{crit}$ for both structures agree with each other, in spite of geometrical differences
- The primary charge limits shall be considered per single holes, not normalized to the hole volume.

$$G_{max} = \frac{Q_{crit}}{N_{primary}}$$

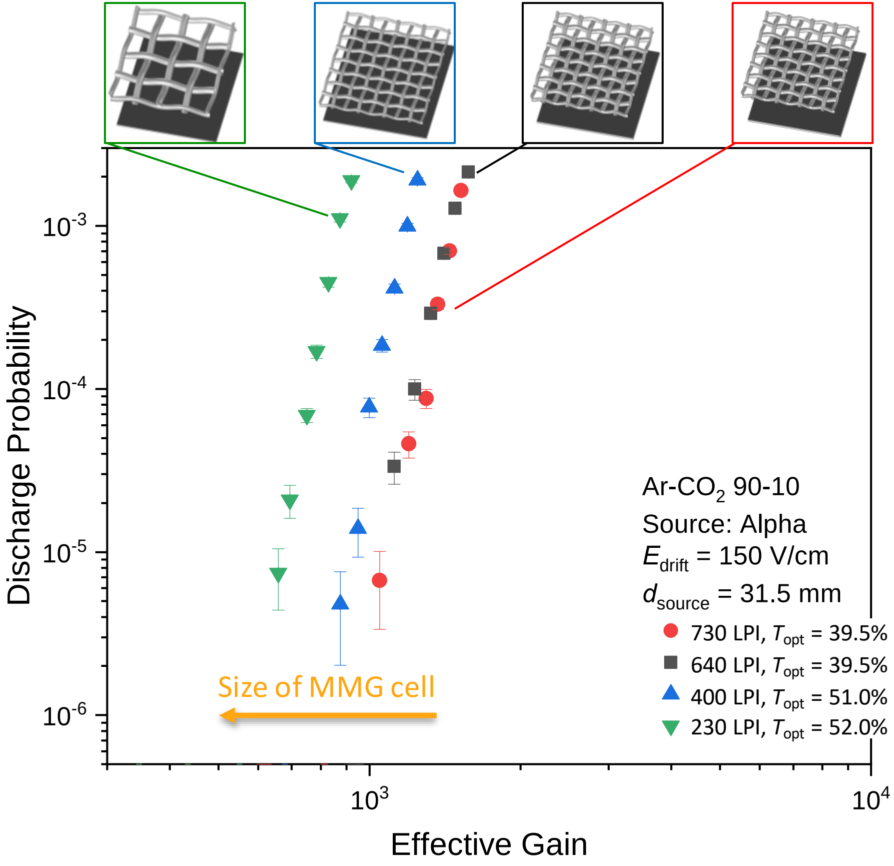
# Micromegas case

- Discharge rate scales with the mesh cell size
  ➞ mesh cell as an independent amplification structure

- Open geometries (e.g. Micromegas): UV photons feedback may lead to a Townsend discharge
  ➞ well-quenched gases preferable but watch out charge densities!




© M. Chefdeville, PhD Thesis (2009), IRFU/CEA




JINST 18 (2023) C06011

# Optimise gas in your gaseous detector

- **Light noble gases are preferable**
- Quencher content – **optimize primary charge density** and electron transport properties.
- Open geometries (e.g. Micromegas): UV photons feedback at high gains may lead to a Townsend discharge

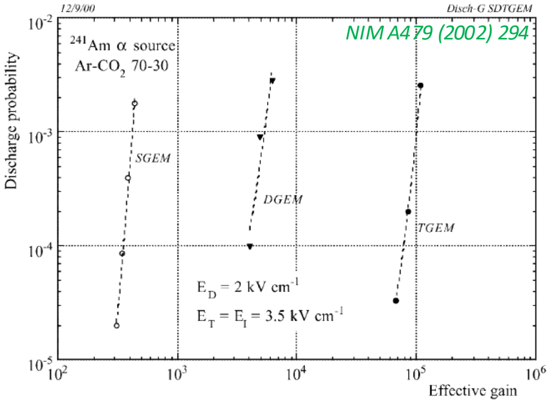
  → well-quenched gases preferable but watch out charge densities!
- **Reduce gain** as much as allowed by the signal-to-noise ratio requirements

  → trivial but most efficient method to minimize the discharge probability,

$$G_{\text{max}} = \frac{Q_{\text{crit}}}{N_{\text{primary}}}$$

# Build stacks – diffuse primary charge

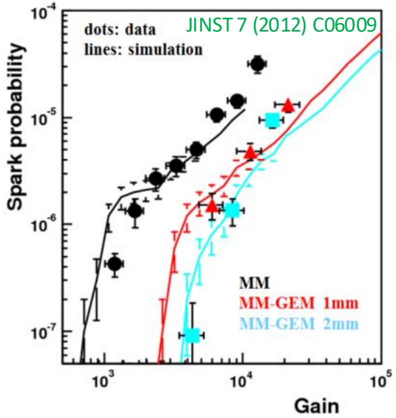
- **GEMs are easy to stack**
  - Pre-amplification stage – lower gain of single structures
  - Charge spread between independent holes – ***$Q_{crit}$* per hole stays the same!**
  - Small pitches preferable (more holes – more sharing)




- **GEM + MMG hybrids and multi-MMG stacks**

  NIM A 834 (2016) 149 and NIM A 976 (2020) 164282, NIM A 623 (2010) 94

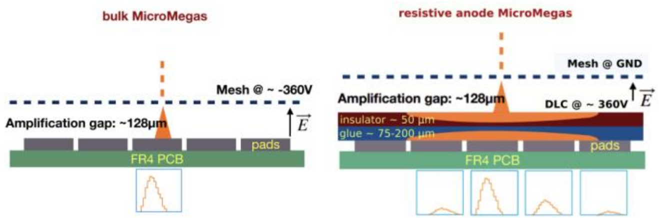
  - Clear influence of the pre-amplification stage on the stability of MMG
  - Lower charge densities reach (subsequent) MMG stages
  - Mesh cell as an independent amplification structure (see also JINST 18 (2023) C06011)




- **Optimized HV settings**
  - Lower gain towards the bottom of a stack to increase overall stability! NIM A 479 (2002) 294

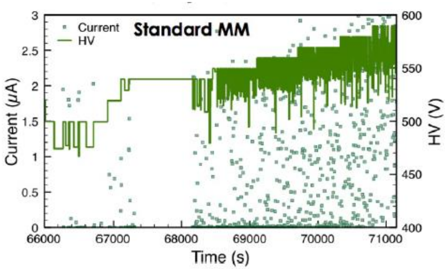
# Use resistive layers

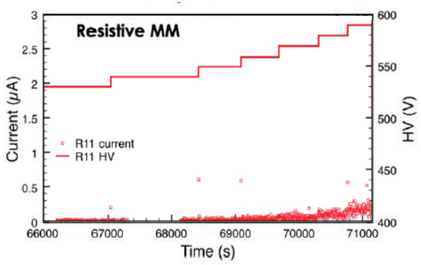
- Allow for charge sharing and create self-quenching mechanism
- Delay the charge evacuation and force local field reduction ➞ rate capabilities




**Resistive MICROMEGAS** (NIM A 629 (2011) 66, NIM A 1025 (2022) 166109)

- Reduces the charge released by MMG during spark formation.
- Provides spark protection to electronics

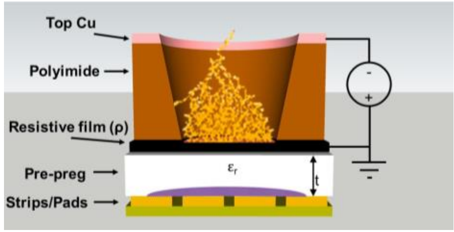


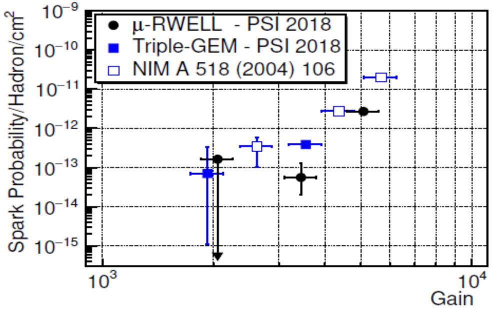




**New structures: µRWELL** (JINST 10 (2015) P02008)

- Single sided Gaseous Electron Multiplier (THGEM)
- Coupled to the readout anode through material of high bulk resistivity
- High rate capabilities restored by proper grounding of the DLC layers
- Single amplification stage

  --> material budget, simplicity, industrialization, costs!

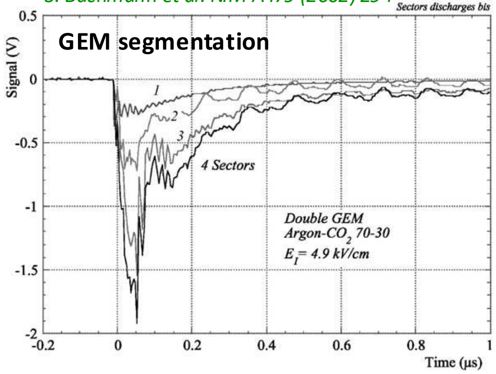


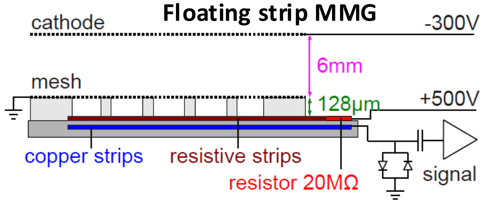



# MPGD design good practices

- Segmentation
  - Reduce area → capacitance
  - Reduce energy of a discharge
  - Minimize dead time

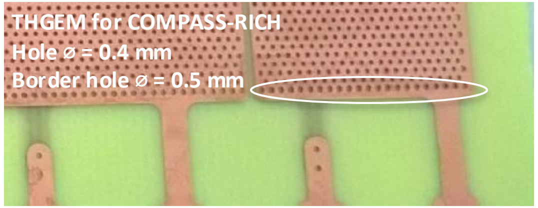
S. Bachmann et al. NIM A479 (2002) 294



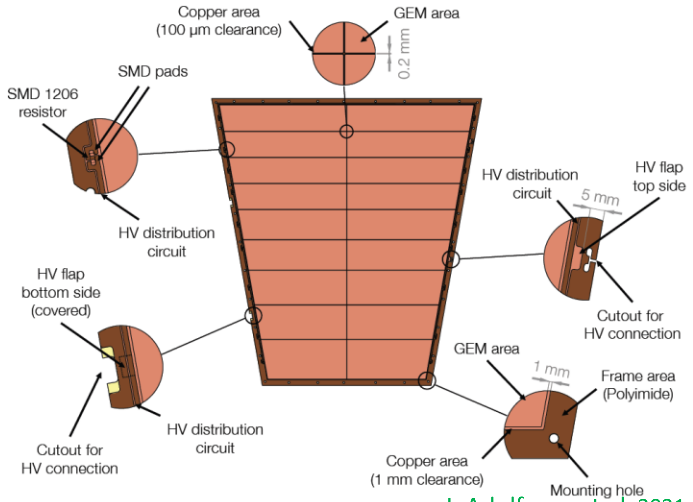




© J. Bortfeldt, Ph.D. Thesis, LMU, 2015.

- Careful detector design – avoid high fields!
  - Rounded corners
  - Electrode edge effects
  - Hole rim



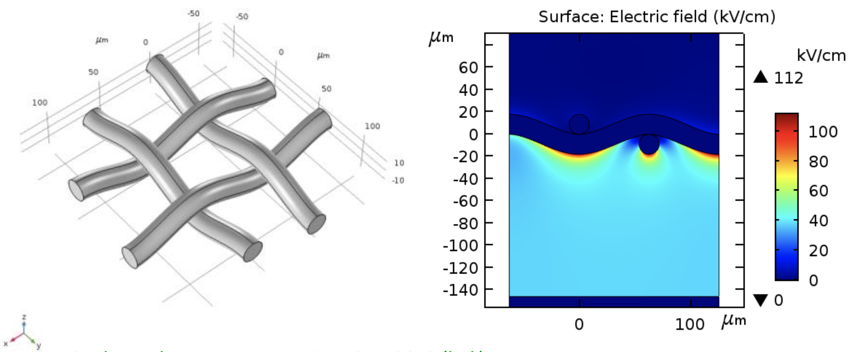

© S. Dalla Torre, F. Tessarotto (INFN)



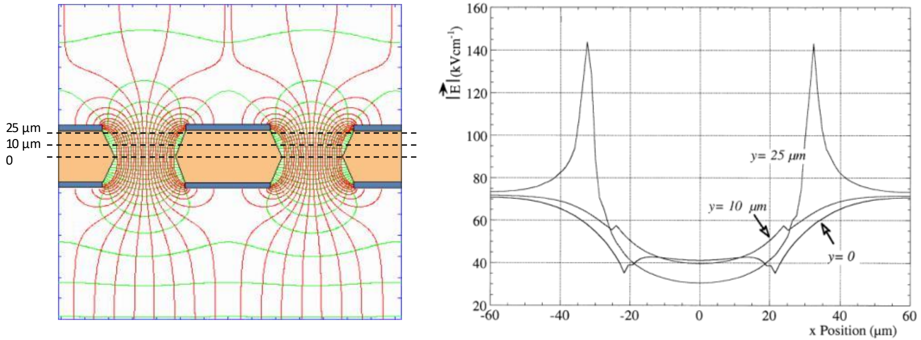

J. Adolfsson et al. 2021 JINST 16 P03022

# Further reduction of stability

- High fields, cathode material quality may further reduce stability of your detector



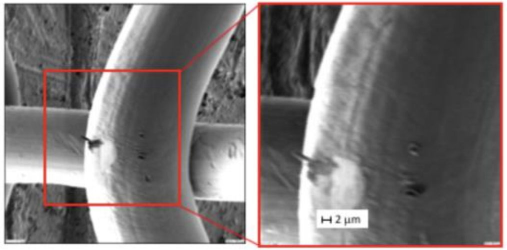

*D.S. Bhattacharya, RD51 Meeting, Sep. 2018 (link)*



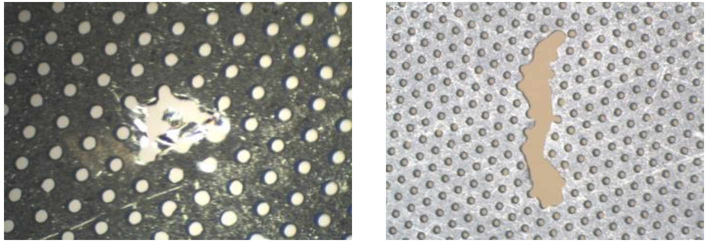

NIM A 438 (1999) 376

- High E-fields present in amplification regions (the curse of Micro-Patterns); can easily double/triple the average
- Detector QA of the highest importance: cannot analyze the entire surface □ HV tests @ Paschen limit

(for MPGDs see ALICE JINST 16 (2021) P03022, CMS NIM A 1034 (2022) 166716, ATLAS NIM A 1026 (2022) 166143)

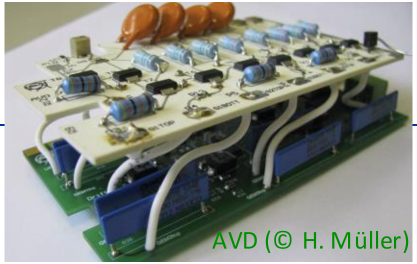


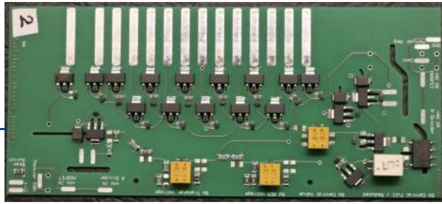

*D.S. Bhattacharya, RD51 Meeting, Sep. 2018 (link)*



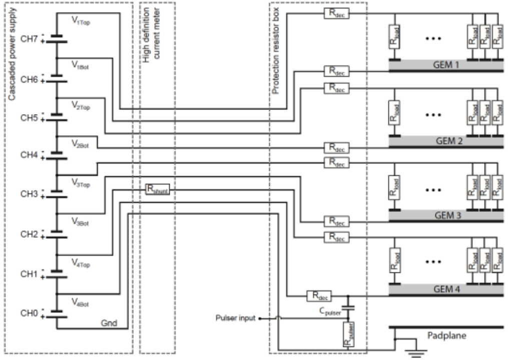
*© ALICE*

# HV scheme optimization


AVD (© H. Müller)


SVD (K. Flöthner, MSc thesis, Bonn 2020)
(J. Krauß, MSc thesis, Bonn 2024)

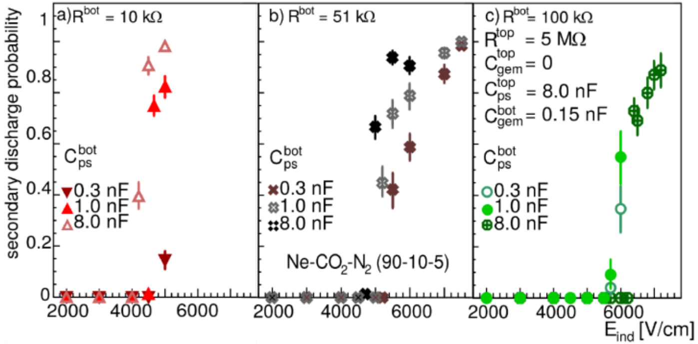
- HV system
  - Passive/active/stabilized voltage divider ➞ safest, reduced flexibility
  - Independent HV channels ➞ full flexibility, tripping times may cause fatal results
  - Cascaded power supply ➞ full flexibility, no overvoltage possible by design, costly



ALICE TPC HV Scheme

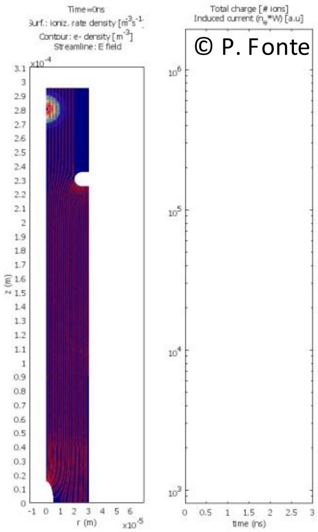
- HV scheme optimization □ use of protection resistors
  - Reduce currents
  - Quench secondary discharge development
  - Reduce and decouple parasitic capacitances parallel to MPGDs and transfer gaps in the MPGD stacks

    (RLC design rules, see e.g. JINST 14 (2019) P08024)

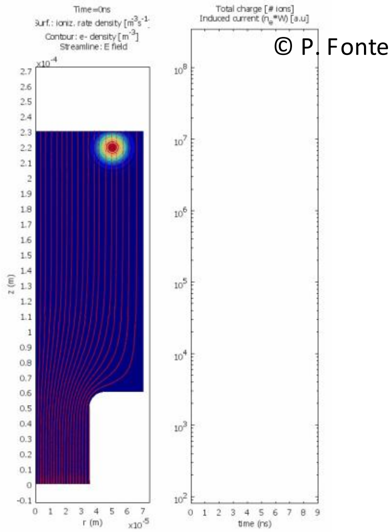


# New structures: MPGDs in SQS mode?

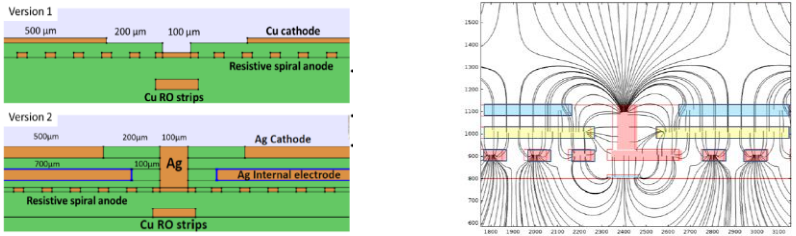
- Discharge probability could be reduced if a radial shape E-field is formed in the MPGD avalanche gap
- Both simulation and R&D effort. Still need for optimization, but ideas on the market!




Needle + InGrid

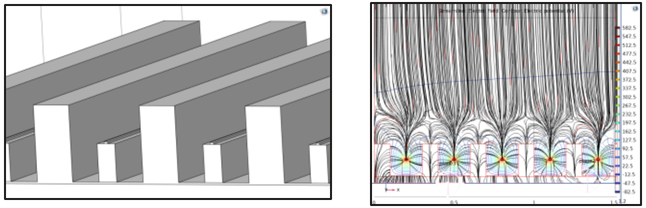



Cathodeless CAT




*V. Cairo et al, JINST 9 (2014) C11022*

*JINST* **18** (2023) C07009

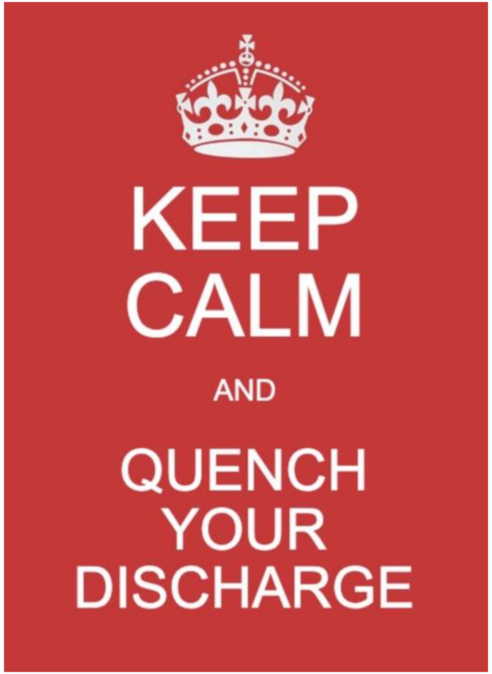
*RD51 Common Project: Spark-Less Amplification Microstructures, V. Peskov, PG (2020-2023)*

*P. Fonte, "Simulations of discharge phenomena", RD51 Meeting, TU Munich 2018 (link)*

# Summary

- **Gas discharge mechanisms in MPGDs well-understood**
- Fundamental gas limits for streamer/spark formation: $Q_{crit}$
- Avoid streamer development by lowering primary charge, charge sharing, avalanche quenching methods, and shaping of the electric field.
- Instabilities caused by defects/ageing/contamination can be avoided by good design practices and quality assurance/control methods

- **To do: more modelling work on discharge development, e.g.:**
  - Simulation of an avalanche process and its transition to a streamer (Garfield++)
  - Understand discharge probability and $Q_{crit}$ values obtained with different geometries
  - Simulation model describing secondary (propagated, delayed) discharges developing in the gaps between subsequent foils in a stack.



# BACKUP SLIDES

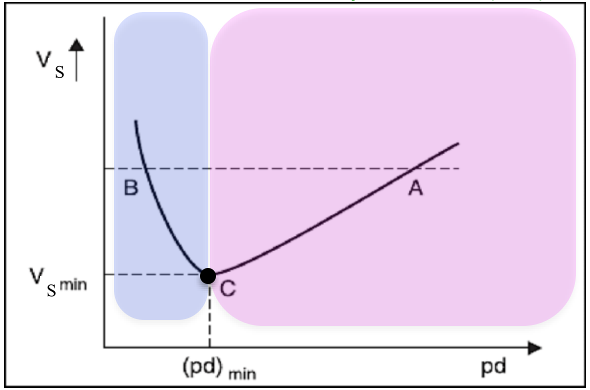
# Paschen's law

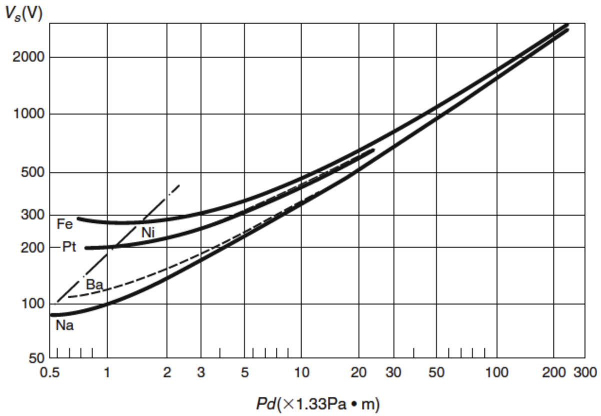
$$V_S = \frac{Bpd}{\ln(Apd) - \ln\left[\ln\left(1 + \frac{1}{\gamma_{se}}\right)\right]}$$

$$V_s = \frac{B(pd)}{C + \ln pd}, \quad \frac{E_s}{p} = \frac{B}{C + \ln pd}, \quad C = \ln \frac{A}{\ln(1/\gamma + 1)}$$

- There exists the minimal breakdown voltage for a discharge gap
- $V_{min}$ and $(Pd)_{min}$ – dependent on cathode material
- ***E/p* at the minimum** □ maximum ionization capability of electrons (Stoletov's point)
- Right from the minimum – $E_S/p$ decreases slowly, $V_S$ increases almost proportionally to *pd*. At increased *pd* electron can still produce ionizing collisions even at not very high *E/p*
- Left from the minimum – possibilities for collisions are very limited. Very high fields (and $\alpha/p$) are required for necessary amplification

M.K.Khalaf et al., WSN 55 (2016) 114



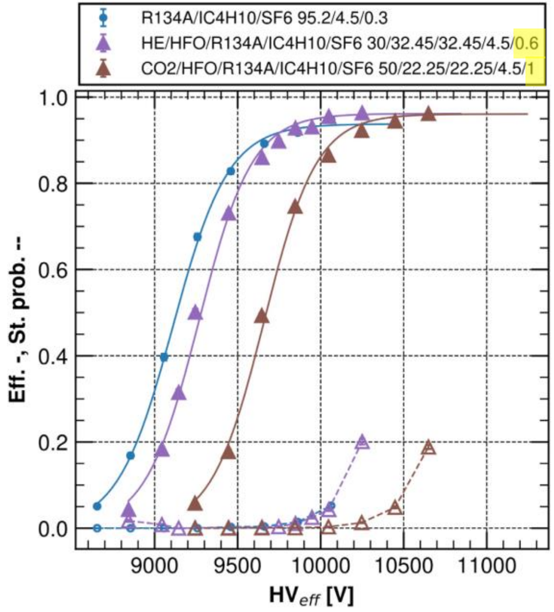



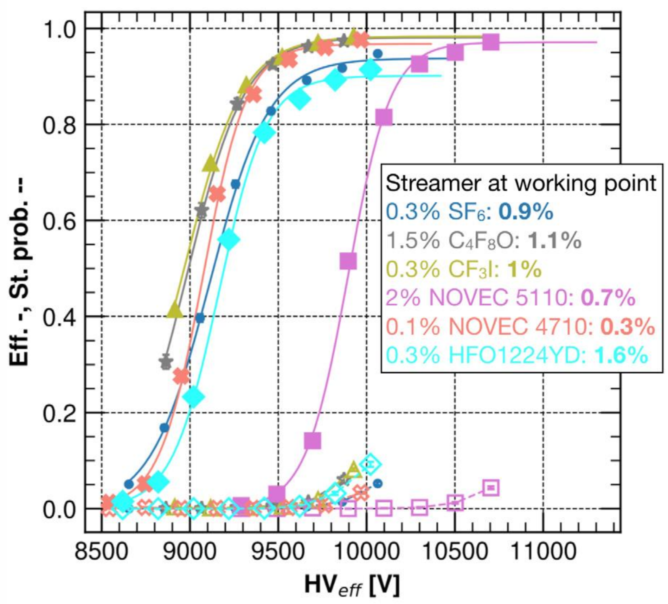

D. Xiao, „Gas Discharge and Gas Insulation", Springer 2016

# New RPC mixtures

See lecture by M. Abbrescia (link)

- $C_2F_4H_2$ and $SF_6$ → very high Global Warming Potential (GWP) of 1300 and 23800, resp.
- Finding a substitute requires compromises: working point, resolution, efficiency, currents, streamer probability
  - E.g. replacement of Tetrafluoroethane with HydroFluoroOlefyns (HFOs) increases working point. Adding $CO_2$ increases streamer probability and RPC currents



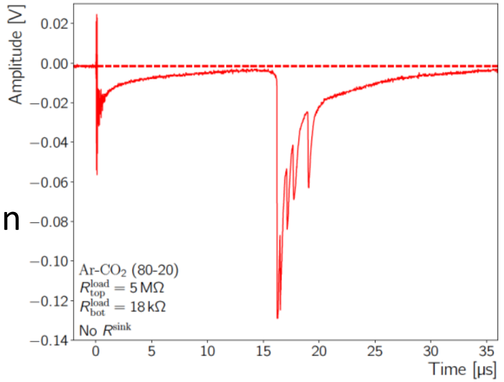



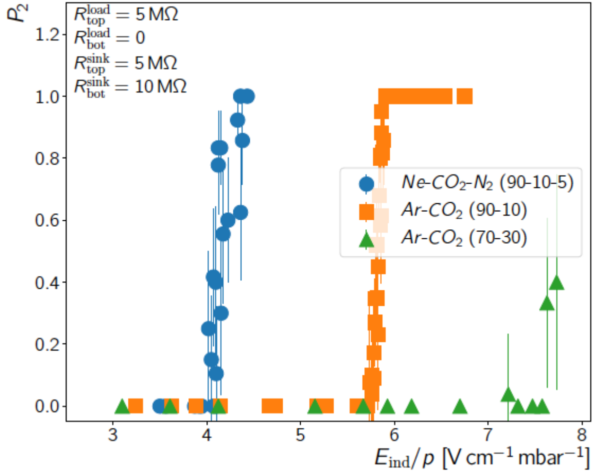

*R. Guida, B. Mandelli, G. Rigoletti, NIM A 1039 (2022) 167045*

# Secondary discharge formation*

Discharge in the transfer/induction gap appearing $\mathcal{O}$(1-10) μs after the primary spark

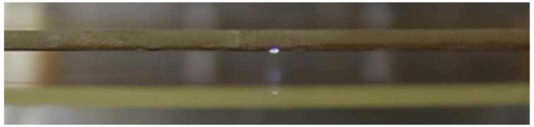
- Leading theory: heating of the cathode after the primary discharge
  - A. Deisting, et al. NIM A 937 (2019) 168
  - A. Utrobicic, et al. NIM A 940 (2019) 262
- Mitigation strategies established - quenching with external *R* elements, *C* reduction
  - L. Lautner, PG, et al. JINST 14 (2019) P08024
  - A. Deisting, C. Garabatos, PG, et al. NIM A 937 (2019) 168



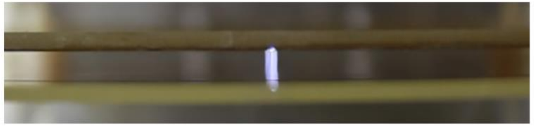



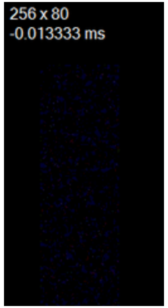

A. Deisting, et al. NIM A 937 (2019) 168

a) Primary discharge



b) Secondary discharge






A. Deisting, et al. NIM A 937 (2019) 168

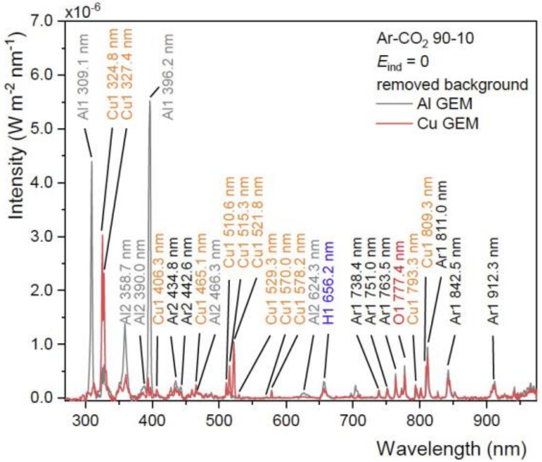
A. Utrobičić et al. MPGD 2019, La Rochelle

* See pioneering studies by *S. Bachmann et al. NIM A479 (2002) 294 & V.* Peskov, P.Fonte (2009) arXiv:0911.0463

# Discharge spectroscopy

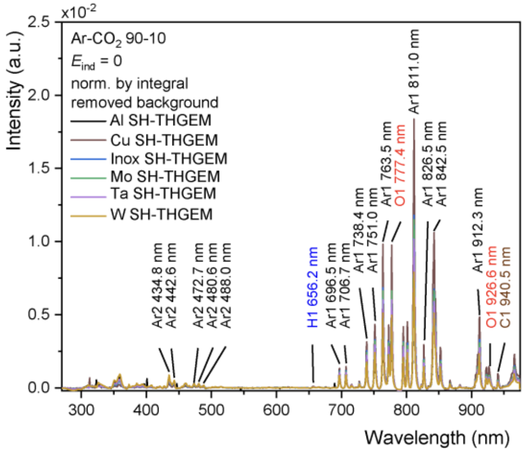
B. Ulukutlu et al., *NIM A 1019 (2021) 165829 + update*

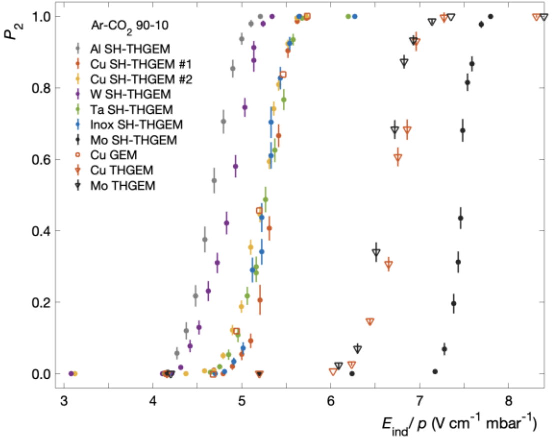
- Measuring emission spectra of the light emitted during primary discharges
- Cu and Al emission lines observed in GEM discharges
- vaporisation → presence of foil material in discharge plasma




- THGEMs with various electrodes → no emission lines corresponding to foil cladding
- No or strongly reduced material vaporisation from discharges in THGEM hole geometry → lower temperature reached?

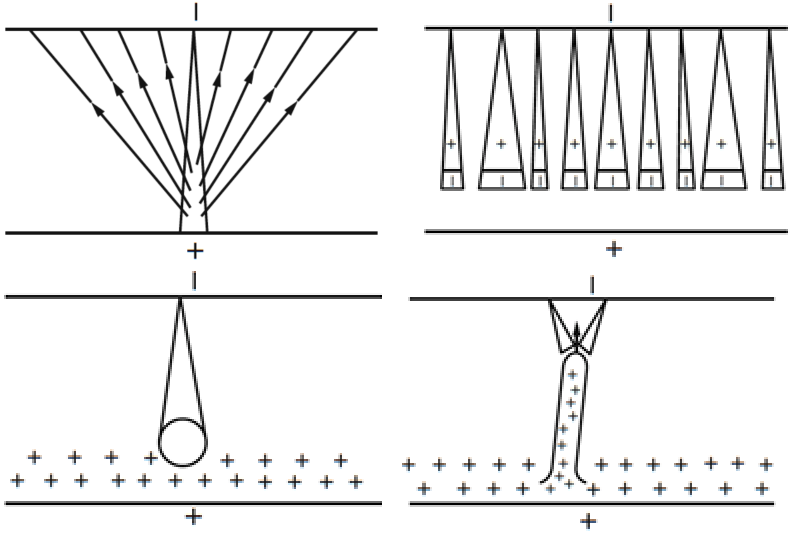
- Secondary discharges still prevalent in THGEMs
- No direct connection between material vaporisation and secondary discharge formation
- Influence of the cathode material properties or surface quality (Mo, polished Cu exceptionally stable)

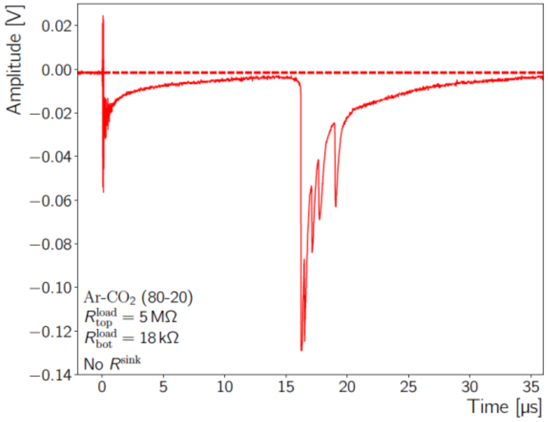


# Secondary discharge formation - hypothesis

- Transition between Townsend discharge and Streamer discharge?
  - Dependence on gas (α process) and cathode? (γ process - feeding)
  - Time lag $\mathcal{O}$(10 µs) with a rapid full gap breakdown





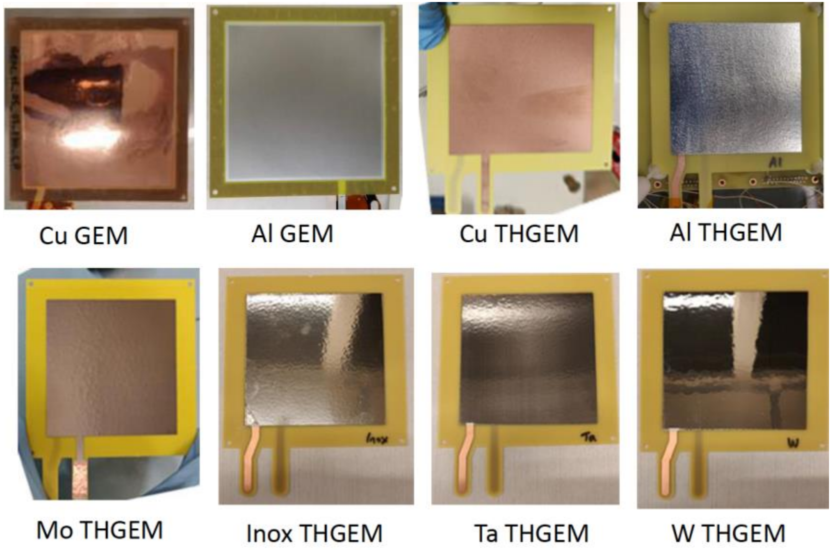

- Townsend mechanism initiated by electrons from a primary discharge;
- Secondary emission from the heated cathode;
- Space charge accumulation at the anode;
- Transition to a streamer.

# Study new electrode materials

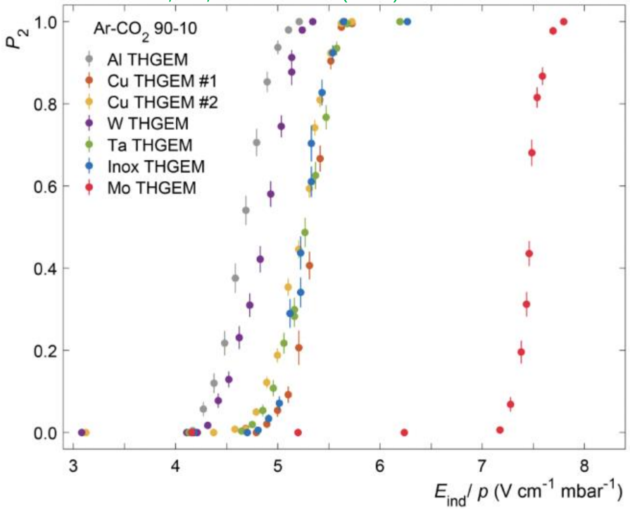


GSI, TU München

- Various coating materials used to study their influence on GEM performance
- Search for ultra-stable configuration for applications using extreme HV settings (e.g. single-photon detectors,)



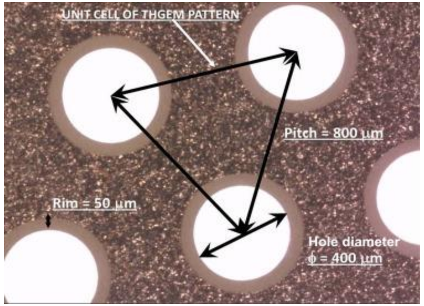

B. Ulukutlu, PG, et al. A 1019 (2021) 165829




- The preliminary results with the Molybdenum layers point to the surface quality as a possible driving factor for enhanced stability.
- Surface studies in preparation (profilometer at CERN, AFM in Pisa)

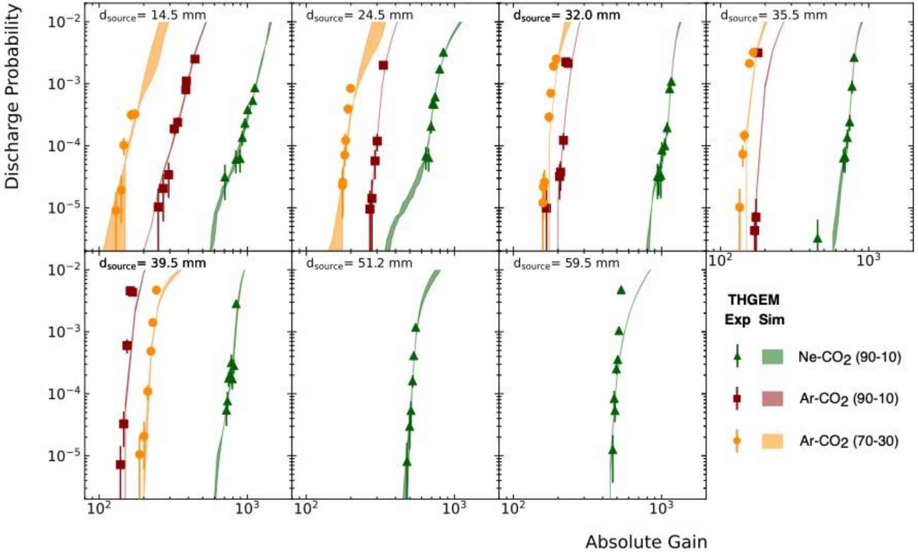
# THGEM results

- THGEMs are large (robust, inexpensive) version of GEMs
  → ~10× larger in each direction




- Gas dependency observed again!
- $Q_{crit}$ for both structures agree with each other, in spite of geometrical differences
- The primary charge limits shall be considered per single holes, not normalized to the hole volume.

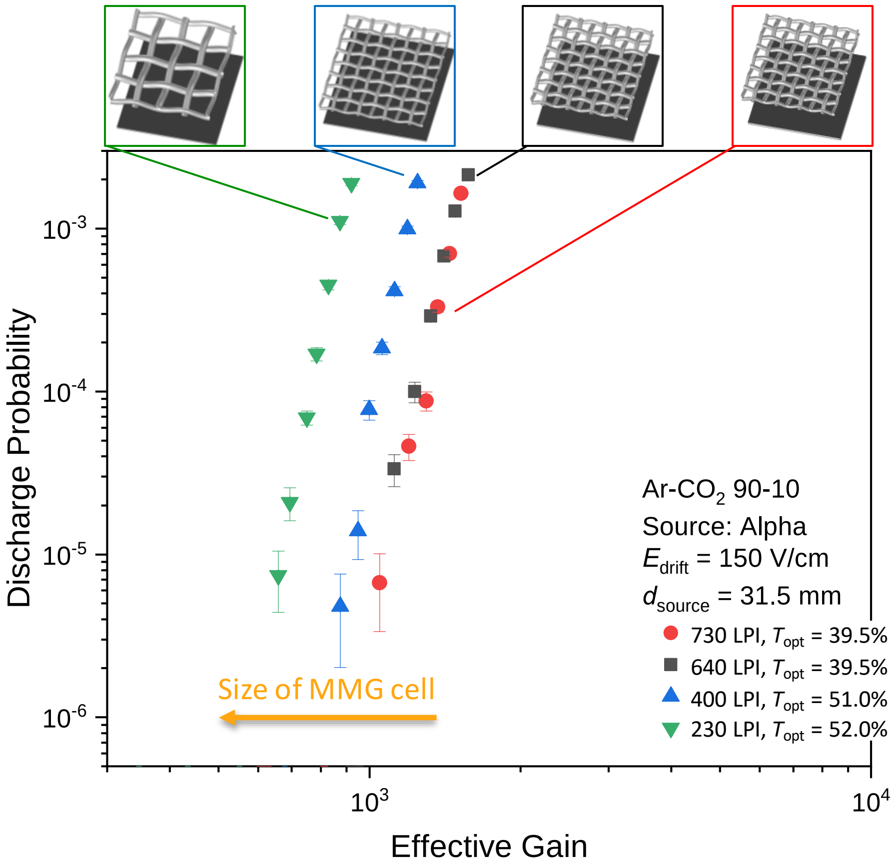
*NIM A 1047 (2023) 167730*




| Gas | THGEM $\langle Q_{crit} \rangle$ [$\times 10^6$ $e$] | GEM $Q_{crit}$ [$\times 10^6$ $e$] |
|---|---|---|
| Ne-$CO_2$ (90-10) | 7.1 ± 2.2 | 7.3 ± 0.9 |
| Ar-$CO_2$ (90-10) | 4.3 ± 1.5 | 4.7 ± 0.6 |
| Ar-$CO_2$ (70-30) | 2.5 ± 0.9 | – |

# Micromegas case

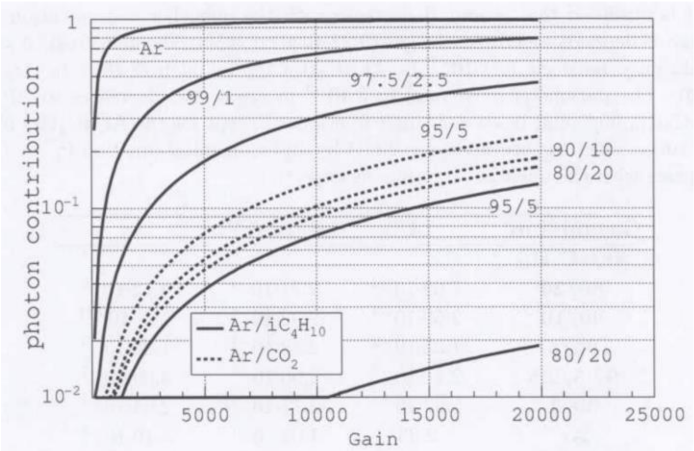
- Discharge rate scales with the mesh cell size (optical transparency)
- Mesh cell as an independent amplification structure



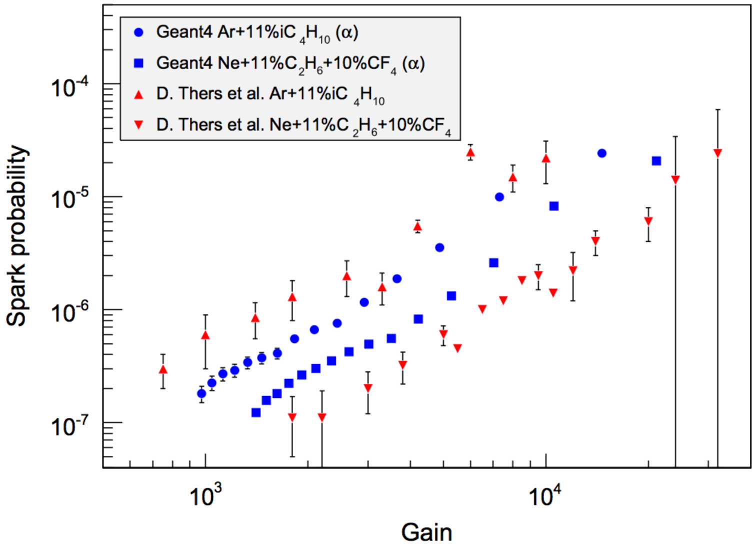

JINST 18 (2023) C06011

# Gas in MMG

- Open geometries (e.g. Micromegas): UV photons feedback may lead to a Townsend discharge
  → well-quenched gases preferable but watch out charge densities!
- Discharge curves in different gases cannot be explained with one $Q_{crit}$




*© M. Chefdeville, PhD Thesis (2009), IRFU/CEA*




*S. Procureur et al. NIM A621 (2010) 177*

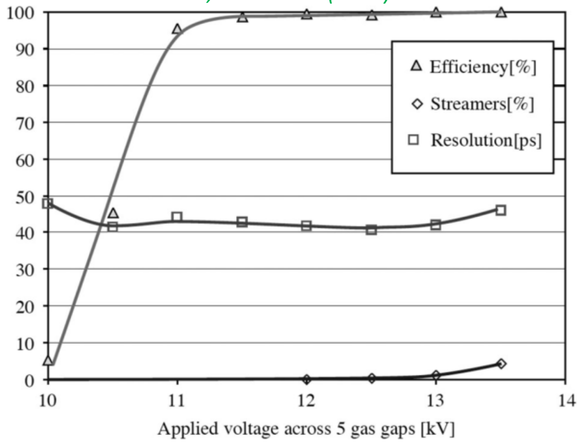
# Resistive layers – running horse of RPC technology

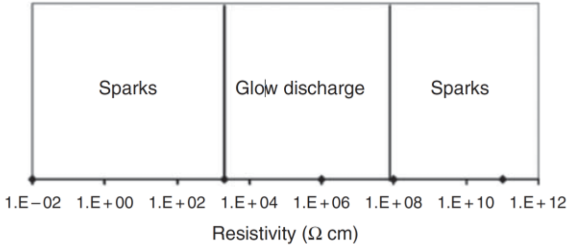
- Material with high-volume resistivity ➞ drop of the electric field around the initial avalanche ➞ remaining counter area remains sensitive to particles
- In normal operation:
  - the strong space charge created within the gas avalanche limits the avalanche's growth
  - quenching with molecular and electronegative gases

  ➞ **streamer probability reduced, but non-zero!**
- For high-rate capabilities, reducing $\rho$ can be beneficial
  - *See e.g. talks by M. Petris (Monday) and I. Deppner (Tuesday)*

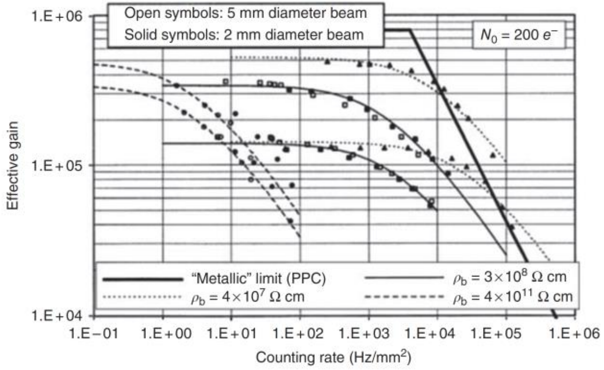
- With moderate-resistive materials, a glow discharge may develop!

*A.N. Akidinov et al., NIM A 533 (2004) 74*



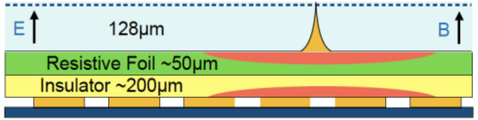

*T. Francke et al., NIM A 508 (2004) 83*




*P. Fonte et al., NIM A 431 (1999) 154*

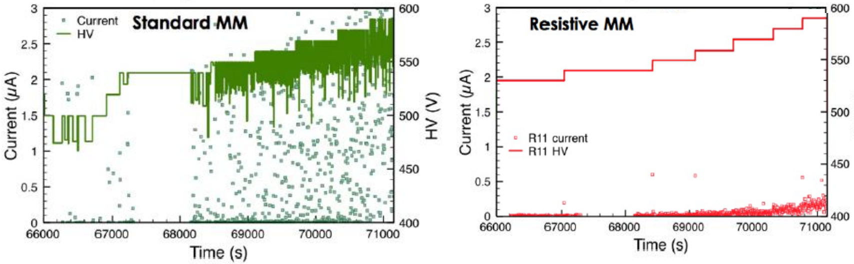
# Resistive MPGDs

- Allow for charge sharing and create self-quenching mechanism
- Delay the charge evacuation and force local field reduction ➞ rate capabilities



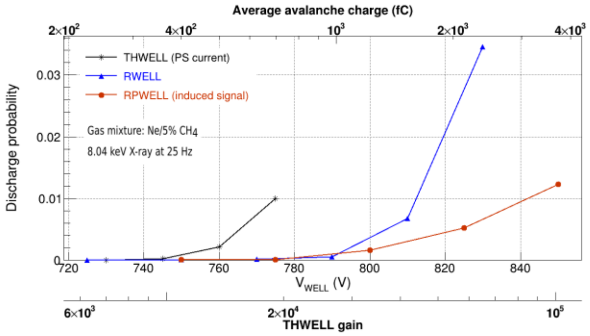

**Resistive MICROMEGAS** *(NIM A 629 (2011) 66, NIM A 1025 (2022) 166109)*

- Reduces the charge released by MMG during spark formation.
- Provides spark protection to electronics
- Standard solution for many MMG-based detectors
  (e.g. ATLAS NSW: Mod. Phys. Lett. A28 (2013) 1340020, NIM A 640 (2011) 110, T2K TPC Upgrade NIM A 957 (2020) 163286, …)




**Resistive WELL and Resistive Plate WELL** *(JINST 7 (2012) C05011, JINST 8 (2013) P11004)*

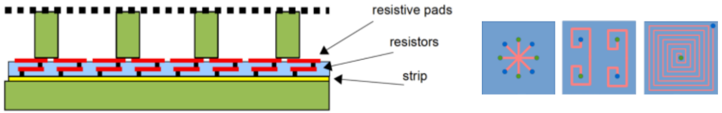
- Resistivity: 16 MΩ/□ (RWELL), $2 \cdot 10^{10}$ Ωcm (RPWELL)
- Stable operation at gains of up to a few $10^4$ (with gain drop corrections!)




*A. Jash et al., JINST 17 (2022) P11004*

**Embedded resistors** *(JINST 12 (2009) P12004, NIM A 824 (2016) 510)*

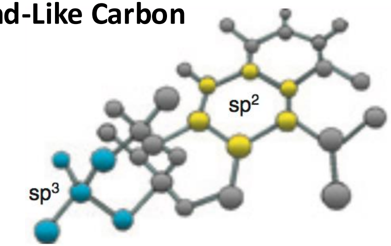
- Control of the resistance through R-pattern
- Tuned for minimal charge-up & spark suppression



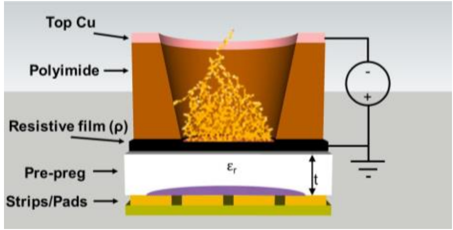
# New structures: micro-RWELL

*G. Bencivenni et al., JINST 10 (2015) P02008*

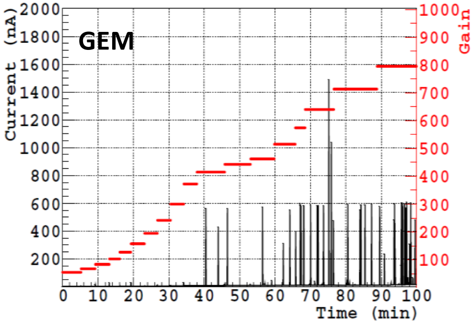
**Diamond-Like Carbon**

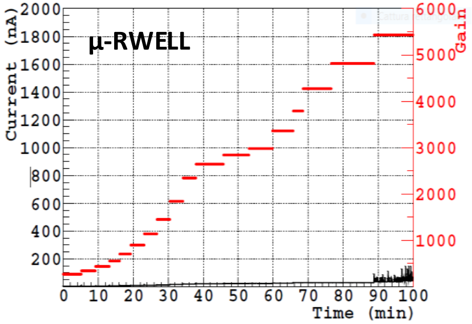



- Single-sided Gaseous Electron Multiplier (GEM) coupled to the readout anode through the material of high surface resistivity
- Single amplification stage ➞ material budget, simplicity, industrialization, costs!



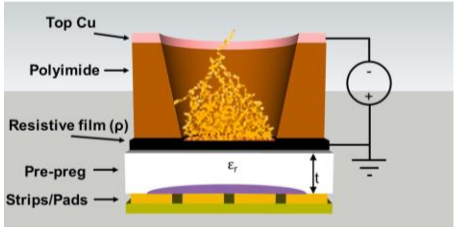

- Resistive layer ➞ suppression of the transition from streamer to spark, with a consequent reduction of the spark amplitude.
- Drawback ➞ the capability to stand high particle fluxes is reduced.



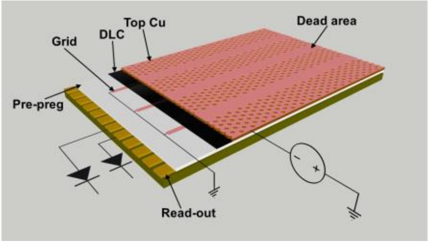



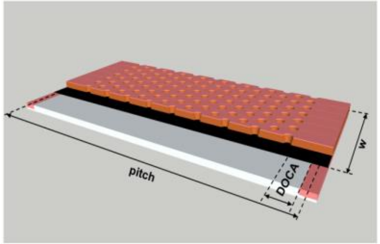
# New structures: micro-RWELL

*G. Bencivenni et al., JINST 14 (2019) P05014*

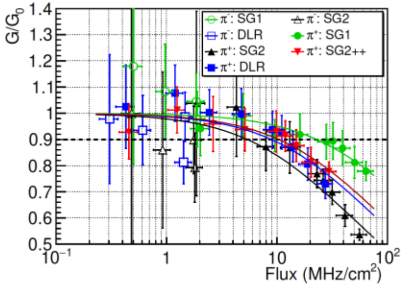


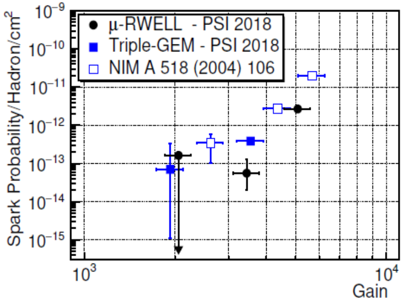

- Single-sided Gaseous Electron Multiplier (GEM) coupled to the readout anode through the material of high bulk resistivity
- Single amplification stage ➞ material budget, simplicity, industrialization, costs!




- High-rate capabilities restored by the proper grounding of the DLC layers ➞ improved charge evacuation
- Thorough optimisation, including surface discharge considerations ➞ concept of the distance-of-closest-approach crucial for stability!

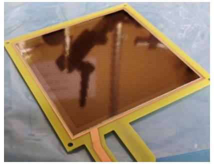


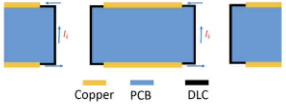




- Rate capabilities of up to 10 MHz/cm$^2$ demonstrated
- Discharge probability of a single micro-RWELL stage compatible with a triple GEM setup operated at stability-optimised HV settings

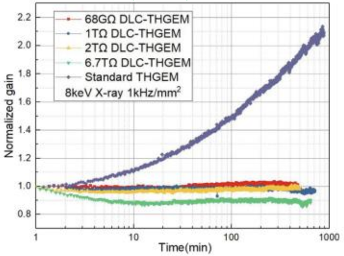
# New concepts with DLC layers

- **DLC (TH)GEMs, Micromegas, …**
  - clear discharge quenching mechanism observed
  - influence of resistive layers on discharge propagation → to be studied
  - coating of THGEM holes allows for minimising the charging-up effect!

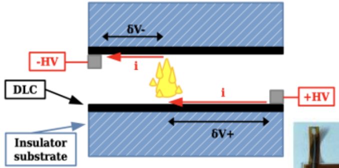


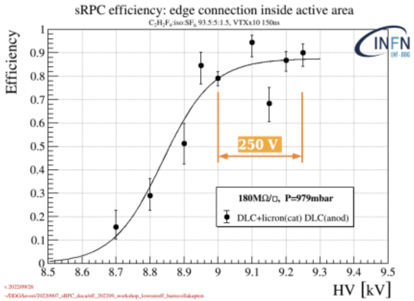



NIM A 958 (2020) 162759

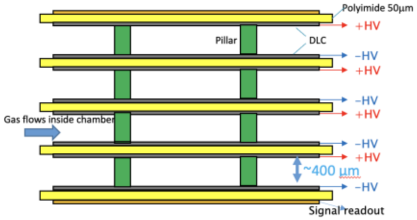


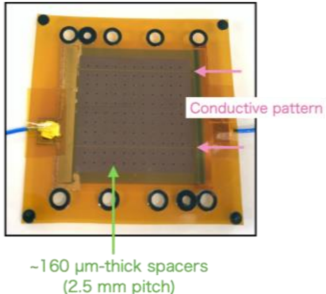

- **sRPC – Surface RPC** *(M. Giovannetti, MPGD2022)*
  - Single gap (2 mm) geometry
  - Baseline (low-rate) version: stable operation with ε ≈ 95% and $\Delta\tau \approx 1$ ns
  - High-rate version, with conductive grids, is being developed (ε ≈ 90% with 1 kHz/cm$^2$ X-rays, with some instabilities)



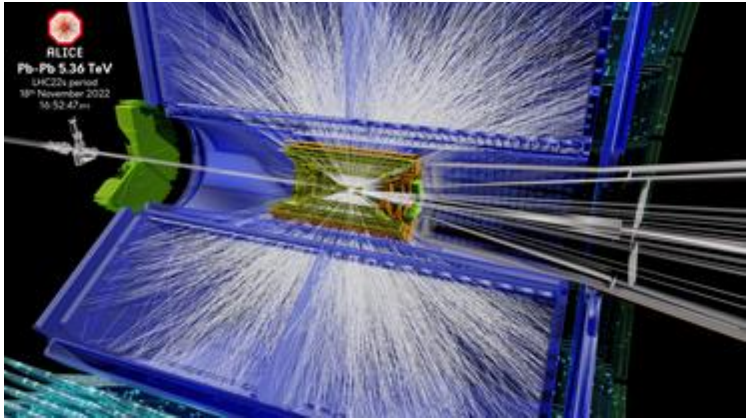




- **DLC-RPC for MEG II** *(J. Phys.: Conf. Ser. 2374 (2022) 012143, A. Ochi MPGD2022)*
  - Single- and multi-gap (~ 400 μm), ultra-low mass design (< 0.1% $X_0$)
  - 85% MIP efficiency achieved with multi-layers, $\Delta\tau \approx 170$ ps at 1-10 kHz/cm$^2$
  - 45-50% efficiency at 1 MHz/cm$^2$ !
  - New developments ongoing (HV feed lines)



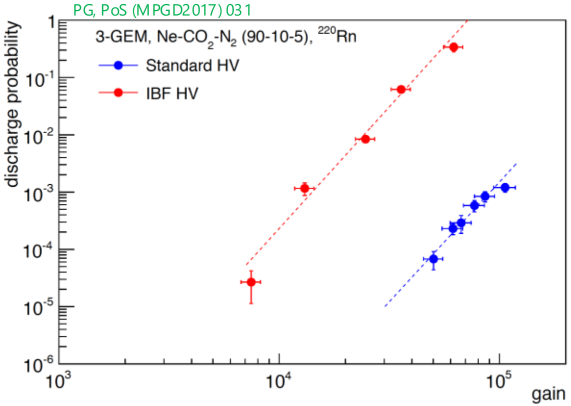



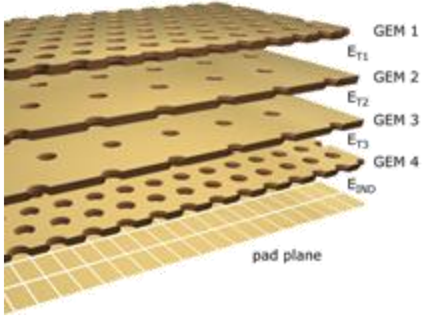
# Stability challenges of MPGD TPCs




**TPCs at high-rates (e.g. ALICE TPC @ 50 kHz Pb-Pb)**

- Direct rate of impinging particles $\mathcal{O}$(10 kHz/cm$^2$)
- Expected loads from the full drift, after amplification $\mathcal{O}$(10 nA/cm$^2$)
- Highly ionizing fragments
- Unprecedented challenges in terms of loads and performance (low IBF)



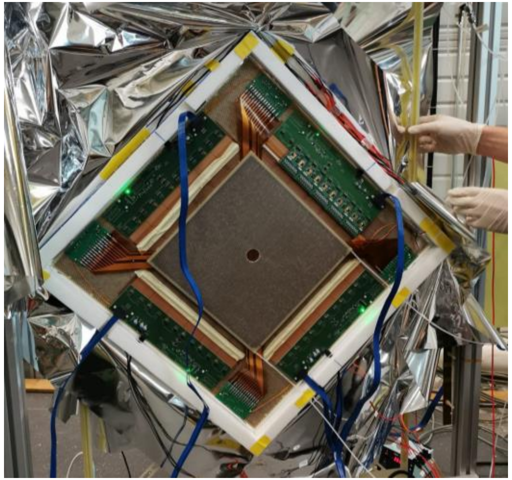




Baseline solution: 4-GEM stack

- Combination of standard (S) and large pitch (LP) GEMs
- Highly optimized HV configuration
- Result of intensive R&D
- Stability of a GEM stack operated in low-IBF mode can be restored by adding 4$^{th}$ GEM

# Few words on tracker rate capabilities

DRD1 Gaseous Detector Technologies



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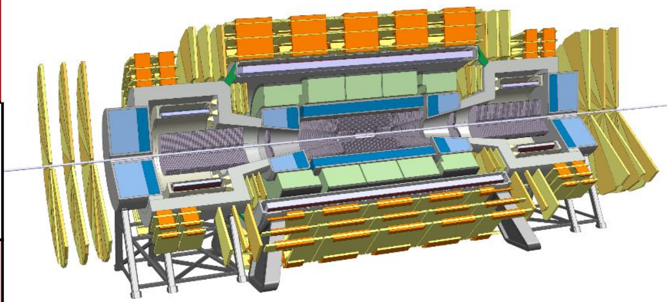
- **(Multi-MPGD) Trackers at moderate gains $\mathcal{O}(10^4)$**
- Short drift gap $\mathcal{O}$(mm), Ar-based mixtures, evacuation of primary electrons in $\mathcal{O}$(100 ns)
- No pile-up expected in a single GEM hole in $cm^2$ area for rates $\gg$ 1 MHz/$cm^2$
- Up to a few electrons/hole expected (MIP)

- **Troublemakers**
- Highly Ionizing fragments ($N_{prim,\alpha} = 10^4 \times N_{prim,MIP}$)
- High neutron doses (e.g. ~$10^{13}$ n.eq./$cm^2$/year in future CBM@FAIR GEMs)
- Charge densities in the bottom MPGD, after full amplification!
- Stability of the system relies on the **stability of a single amplification structure** (e.g. GEM)

# MPGD trackers at future colliders

| Experiment / Timescale | Application Domain | Gas Detector Technology | Total detector size / Single module size | Operation Characteristics / Performance |
|---|---|---|---|---|
| LHeC COLLIDER MUON SYSTEM at HL-LHC | Electron – Proton Collider Tracking/Triggering | RPC / MDT | Total area ~ 400 $m^2$<br>Single unit detect: 2-5 $m^2$ | **Max.rate**: 3 kHz/$cm^2$<br>**Time res.:** ~0.4 ns<br>**Rad. Hard.:** 0.3 C/$cm^2$<br>**Spatial res.:** 1mm (RPC)<br>80 µm (MDT single tube) |
| FCC-ee and/or CEPC IDEA PRESHOWER DETECTOR START: >2030 | Lepton Collider Tracking | µ-RWELL | Total area: **225 $m^2$**<br>Single unit detect: (0.5x0.5 $m^{2)}$ ~0.25 $m^2$ | **Max. rate:** 10 kHz/$cm^2$<br>**Spatial res.:** ~60-80 µm<br>**Time res.:** 5-7 ns<br>**Rad. Hard.:** <100 mC/$cm^2$ |
| FCC-ee and/or CEPC IDEA MUON SYSTEM START: >2030 | Lepton Collider Tracking/Triggering | µ-RWELL<br>RPC | Total area: **3000 $m^2$**<br>Single unit detect: ~0.25 $m^2$ | **Max. rate:** <1 kHz/$cm^2$<br>**Spatial res.:** ~150 µm<br>**Time res.:** 5-7 ns<br>**Rad. Hard.:** <10 mC/$cm^2$ |
| FCC-hh COLLIDER MUON SYSTEM START: > 2050 | Hadron Collider Tracking/Triggering | All HL-LHC technologies (MDT, RPC, MPGD, CSC) | Total area: **3000 $m^2$** | **Max. rate**: < **500 kHz/$cm^2$**<br>**Spatial res.:** <100 µm<br>**Time res.:** ~ 3 ns<br>**Rad. Hard.:** ~ C/$cm^2$ |
| MUON COLLIDER MUON SYSTEM START: > 2050 | Muon Collider | RPC or new generation fast Timing MPGD | Total area: ~ **3500$m^2$**<br>Single unit detect: 0.3-0.4$m^2$ | **Max.rate**: <**100 kHz/$cm^2$**<br>**Spatial res.:** ~100µm<br>**Time res.:** <10 ns<br>**Rad. Hard.:** < C/$cm^2$ |

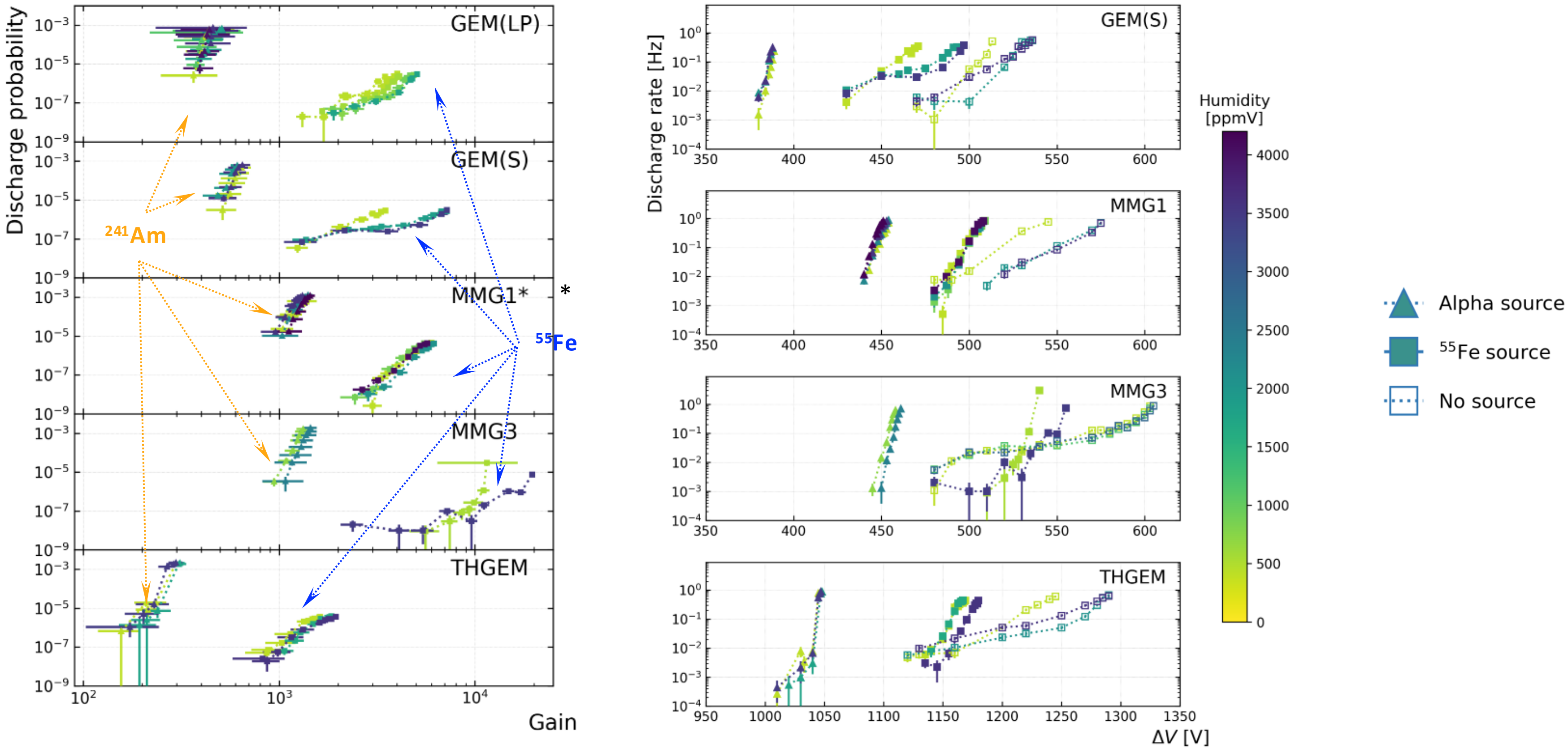


## Challenges

- High-rate capabilities, radiation hardness (ageing) and stability of large-area trackers
- Large areas, simple construction, industrialization → low cost
- Reliability and efficiency with suitable low GWP mixtures

# Global picture

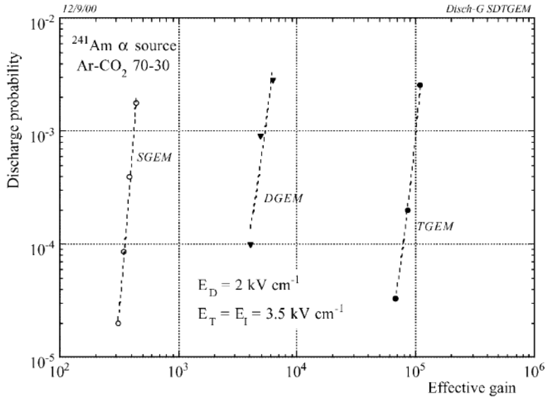
H. Fribert et al. JINST 18 (2023) C06015 + RD51 Coll. Meeting + Preliminary to be published

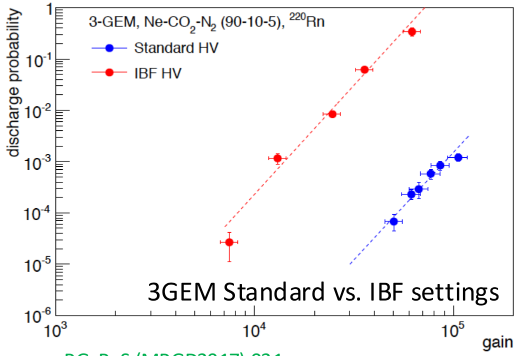



*Scaled gain – transparency < 100%

# GEM stacks

- GEMs are easy to stack
  - Build stacks, share charge between subsequent structures
  - Pre-amplification stage – lower gain of single structures
  - Charge spread between several independent holes – $Q_{crit}$ **per hole stays the same!**
- Optimized HV settings (lower amplification towards bottom of a stack)
  - Violated in case the stack optimized for low ion backflow (TPCs)
  - Adding further foils in the stack can improve its stability, e.g.:
    - 4GEM Readout for ALICE TPC (IBF optimized) - CERN-LHCC-2013-020, CERN-LHCC-2015-002
    - 5GEM RICH for eIC (stable operation at very high gains) - M. Blatnik et al., Trans. on Nucl. Sci. 62 (2015) 3256



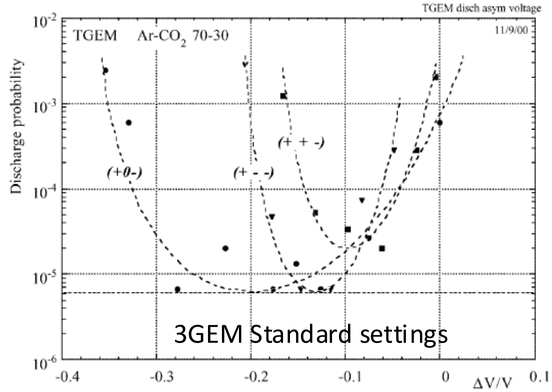

PG, PoS (MPGD2017) 031

Stability of a GEM stack operated in low-IBF mode can be restored by adding 4th GEM.

4GEM spark rates in $Ne\text{-}CO_2\text{-}N_2$ (90-10-5), G~2000:

- ~$10^{-10}$ 1/α
- $6.4\times10^{-12}$ 1/hadron

CERN-LHCC-2015-002



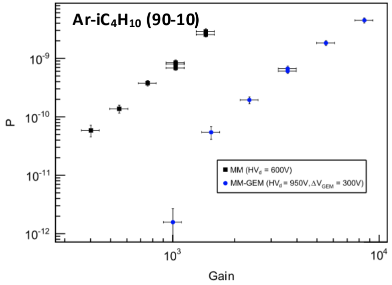

S. Bachmann *et al.*, NIM A 479 (2002) 294.

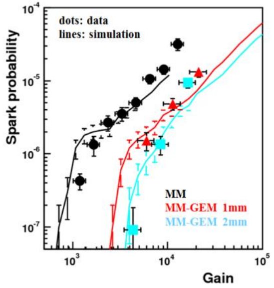
# Hybrid stacks (examples)

DRD1 Gaseous Detector Technologies

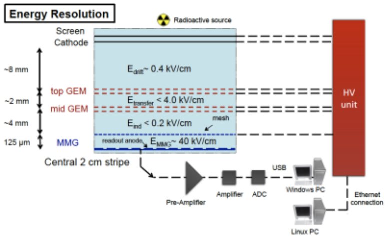
- GEM + MMG (e.g. B. Moreno et al, NIMA654(2011)135, S. Procureur et al. JINST 7 (2012) C06009)

> - Clear influence of the pre-amplification stage (GEM) on the stability of MMG
> - Lower charge densities reach MMG (cf. 1 and 2 mm gaps)
> - Confirmed with GEANT simulations




- 2GEM + MMG in low-IBF mode (e.g. E. Aiola et al. NIM A 834 (2016) 149)



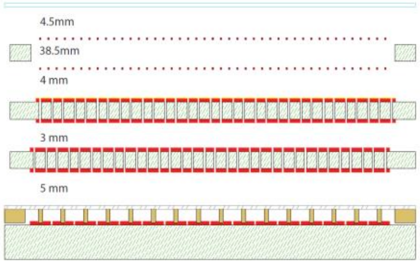

**Spark rates at G~2000**

$3 \times 10^{-7}$ 1/α in Ne-$CO_2$ (90-10)

$2 \times 10^{-8}$ 1/α in Ne-$CO_2$-$CH_4$ (82-9-9)

$3.5 \times 10^{-10}$ 1/(150 GeV $\pi$) in Ne-$CO_2$-$N_2$ (90-10-5)

- COMPASS hybrid THGEM + Micromegas (e.g. F. Tessarotto, RD51 Meeting, Munich 2018 link)



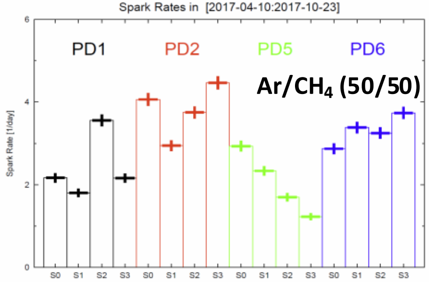

**Nominal G ~ 30000 with:**

THGEM1 gain × T1 ~20

THGEM2 gain × T2 ~15

MMG gain ~100

Moderate gains of single structures

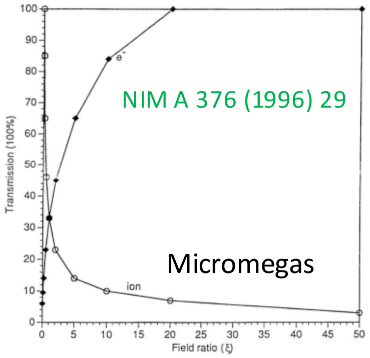


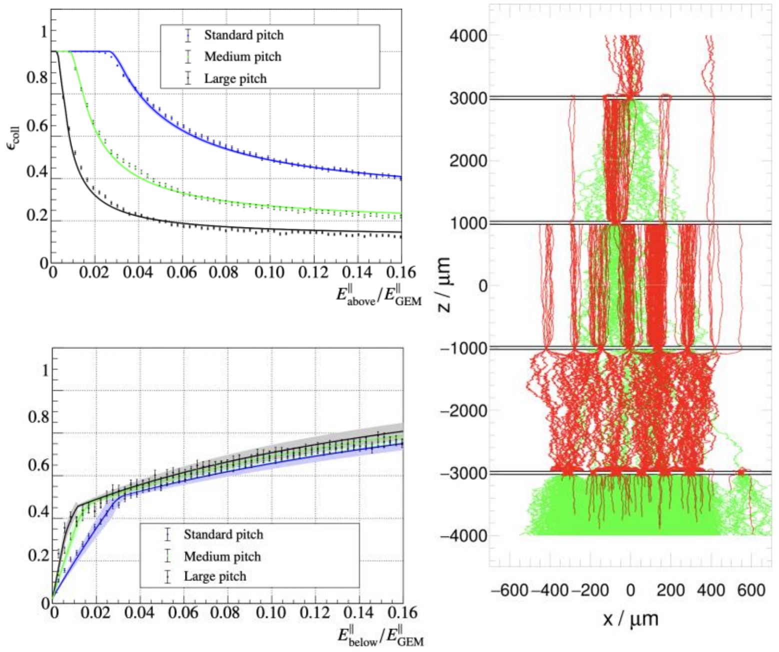

Moderate spark rate in all segments, constant in time

# Working point optimisation

- Not only discharge stability needs to be optimised. Working point for optimal performance in terms of:
  - Gain
  - Energy resolution
  - Ion-backflow capabilities
  - Long-term stability (charging-up)
  - Efficiency
  - Drift velocity, electron/ion mobility
  - Rate capability, time resolution

NIM A 376 (1996) 29

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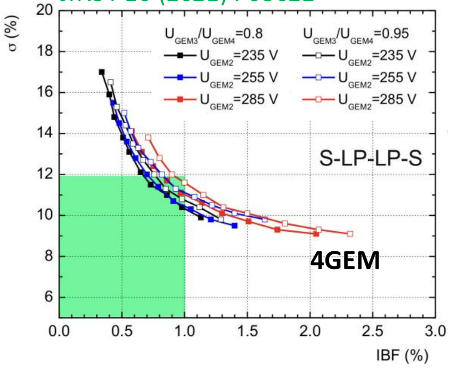
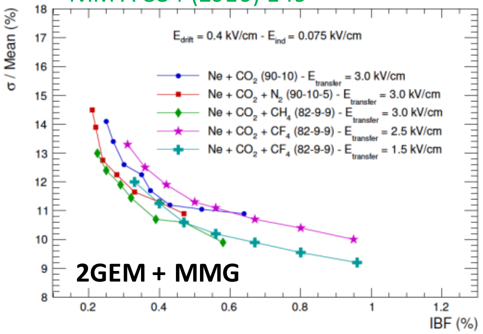
JINST 16 (2021) P03022




NIM A 834 (2016) 149

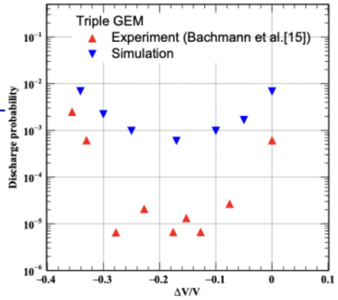


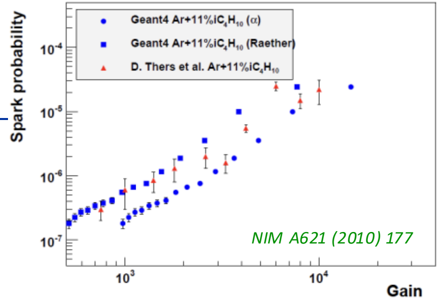
# SIMULATIONS

# What we can (Geant)

- Reproduce discharge curves obtained with different MPGDs
- Predict discharge rate with different sources and geometries
- Predict gas effects (more discharges with heavier gases)
- Evaluate discharge limits, incl. discharge dev. time
- Understand the effects related to charge density
  - Stacks (GEMs, GEM+MMG)
  - Magnetic field influence
  - Electric field influence
  - Emission angle, track length, drift lengths
  - Drift and diffusion

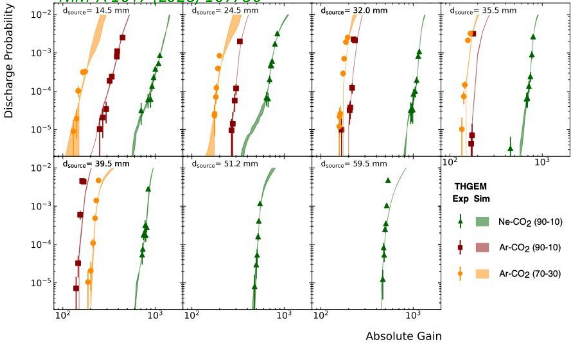
*JINST 16 (2021) P09001*



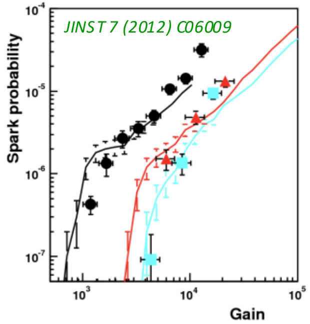




*NIM A621 (2010) 177*

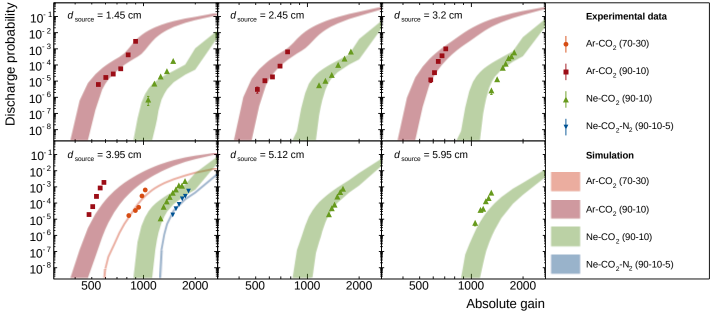
*NIM A 1047 (2023) 167730*

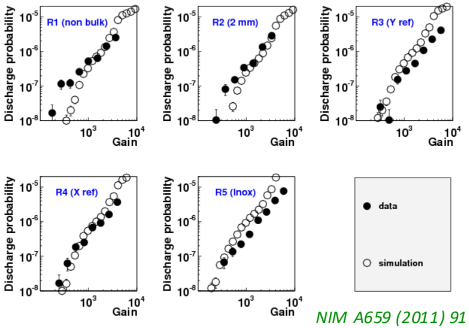



*JINST 7 (2012) C06009*




*NIM A 870 (2017) 116*



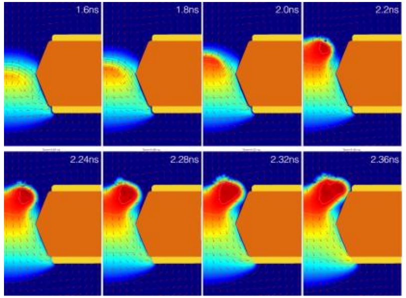

*NIM A659 (2011) 91*

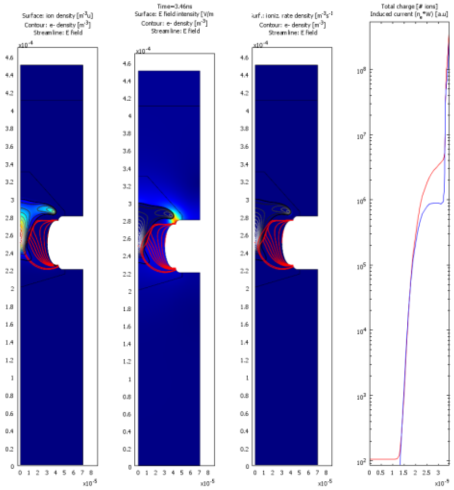
# What we can (FEM)

$$\begin{cases} \frac{\partial n_e}{\partial t} + \vec{\nabla}\cdot(\vec{W}_e n_e) = \alpha\left|\vec{W}_e\right| n_e + D_e \nabla^2 n_e \\ \frac{\partial n_{i+}}{\partial t} = \alpha\left|\vec{W}_e\right| n_e \\ \nabla^2 V = -\frac{e}{\varepsilon_0}(n_{i+} - n_e) \end{cases}$$

- We can simulate streamer formation using a simplified hydrodynamic model (no photoionization, diffusion-assisted streamers).

*IEEE (2015) 1*



*P. Fonte, MPGD Stability workshop, TUM 2018 (link)*

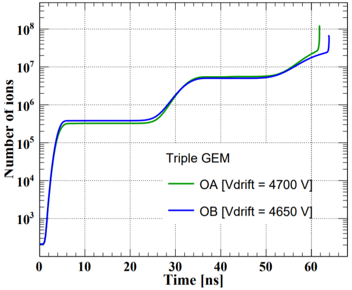
- The model:

*P. Fonte, TUM 2018*

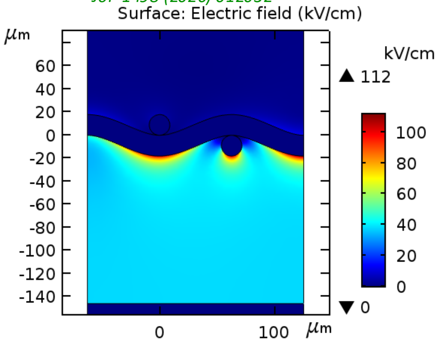
  - Seems to describe qualitatively fast breakdown in MPGDs
  - Gives correct breakdown limit for GEM
  - Seems to reproduce SQS in needles
  - Allows to simulate space charge effects, and their time development

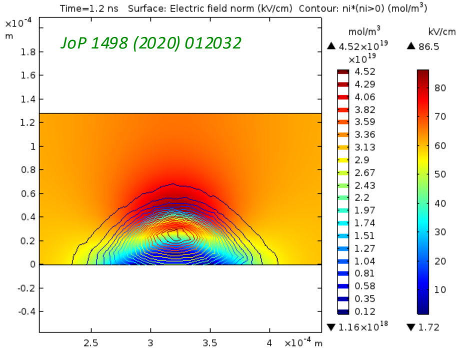
- We can optimize geometry, simulate hot spots, etc.

*P. Roy (link)*




*JoP 1498 (2020) 012032*



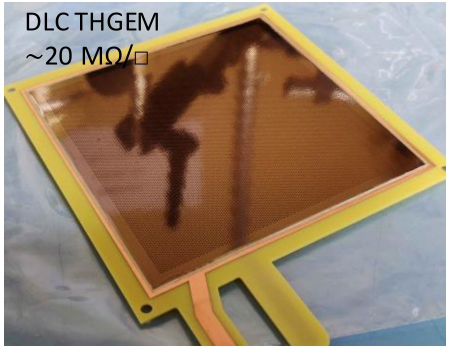



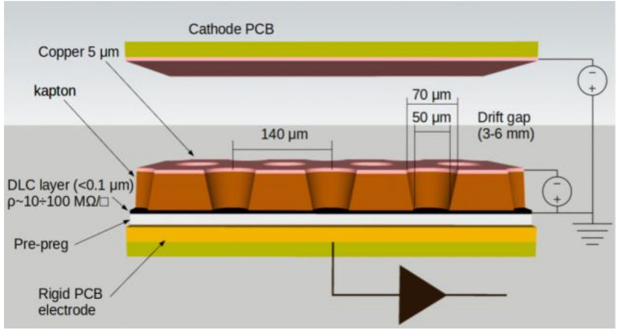

*JoP 1498 (2020) 012032*

# The effort needs to continue

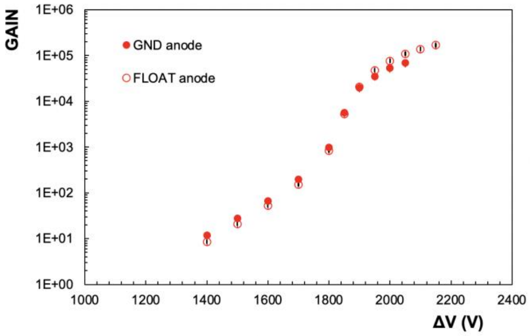
- Continue discharge simulations in new MPGD structures with currently available tools/models
- Update the tools/models ☺
- Discharge development with resistive layers

(more and more experimental data available, see e.g. JINST 17 P11004)



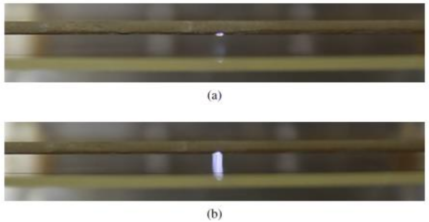




© DDG LAB Frascati INFN

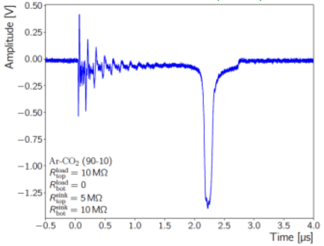


# What would be good to have/answer?

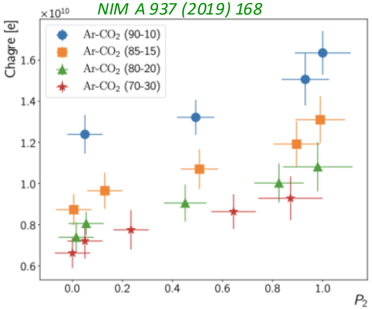
- Simulation model describing secondary (propagated, delayed) discharges developing in the gaps between subsequent foils in a stack.
  - Mechanism → still a topic of a debate.
  - Need to understand the entire process and, if possible, to eliminate the cause of these violent events completely.
  - Model development of a primary discharge in a GEM hole and its subsequent transition to a gap discharge, taking into account:
    - Space-charge densities
    - Drift and amplification of charges, ion bombardment
    - Heating of the electrodes …
    - … and thermionic emission from the latter.



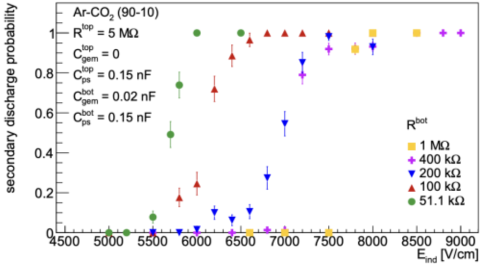

*NIM A 937 (2019) 168*



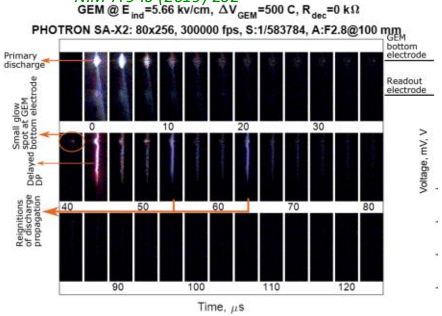

*NIM A 937 (2019) 168*



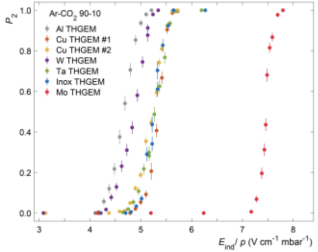

*JINST 14 (2019) P08024*




*NIM A 940 (2019) 262*




*NIM A 1019 (2021) 165829*



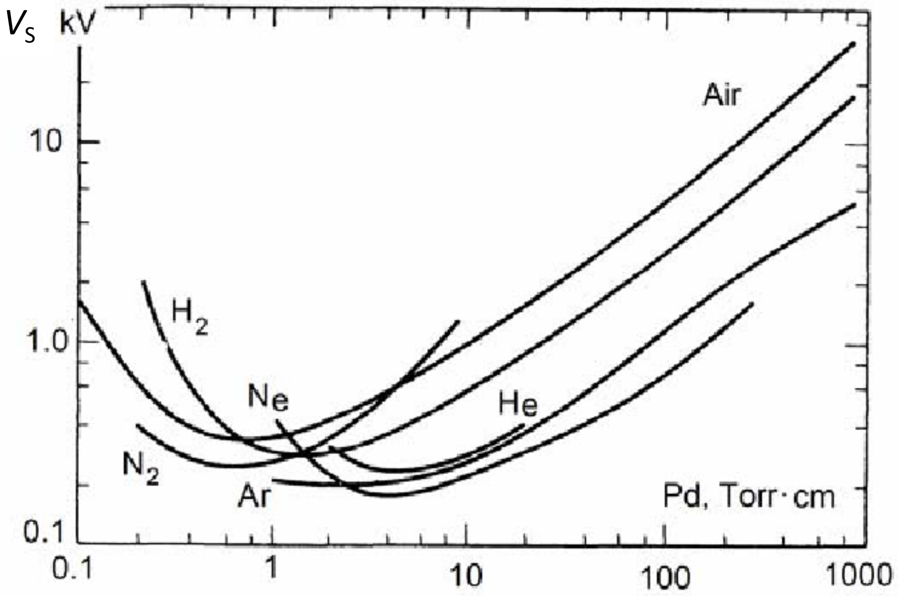
# PASHEN’S LAW

# Paschen's law

- Discovered empirically in 1889
- Analytic expression of gas breakdown potential in a uniform electric field.
- Derived from the 1st Townsend coefficient $\frac{\alpha}{P} = \mathrm{A}\exp\left(-\frac{\mathrm{B}}{E/P}\right)$ and breakdown criterion $\delta = \gamma\left(e^{ad} - 1\right) = 1$

$$V_S = \frac{Bpd}{\ln(Apd) - \ln\left[\ln\left(1 + \frac{1}{\gamma_{se}}\right)\right]}$$

- If the type of gas and the cathode material are known, A, B, and γ are known constants, $V_s$ is only the function of the *Pd* product
- The equation loses accuracy for gaps $\mathcal{O}$(10 μm) at atmospheric pressure




Y. P. Raizer, Gas Discharge Physics. Berlin, Germany: Springer, 1991

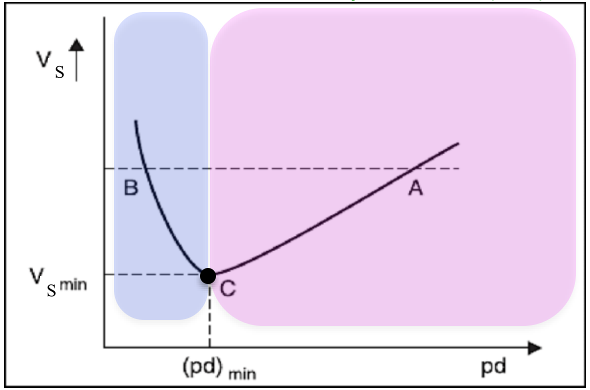
# Paschen's law

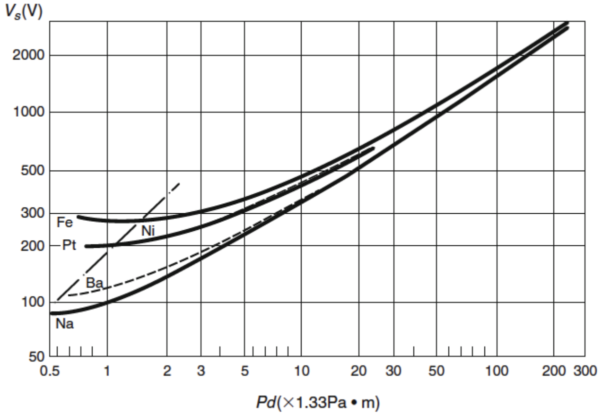
$$V_S = \frac{Bpd}{\ln(Apd) - \ln\left[\ln\left(1 + \frac{1}{\gamma_{se}}\right)\right]}$$

$$V_s = \frac{B(pd)}{C + \ln pd}, \quad \frac{E_s}{p} = \frac{B}{C + \ln pd}, \quad C = \ln \frac{A}{\ln(1/\gamma + 1)}$$

- There exists the minimal breakdown voltage for a discharge gap
- $V_{min}$ and $(Pd)_{min}$ – dependent on cathode material
- ***E/p* at the minimum (*B*)** □ maximum ionization capability of electrons (Stoletov's point)
- Right from the minimum – $E_S/p$ decreases slowly, $V_S$ increases almost proportionally to *pd*. At increased *pd* electron can still produce ionizing collisions even at not very high *E/p*
- Left from the minimum – possibilities for collisions are very limited. Very high fields (and $\alpha/p$) are required for necessary amplification

M.K.Khalaf et al., WSN 55 (2016) 114




D. Xiao, „Gas Discharge and Gas Insulation", Springer 2016

# MPGD LIMITS

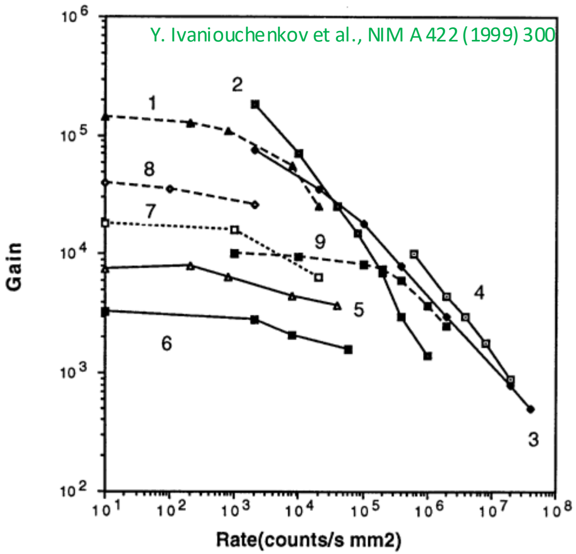
# High rates at high gains – limits!

**Rate-dependent reduction of maximum gain**

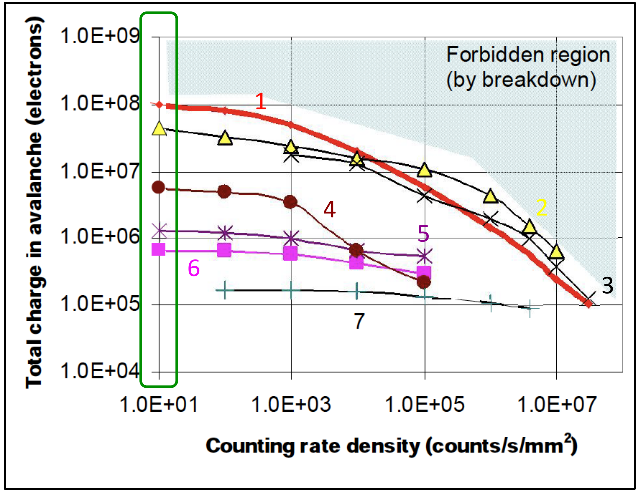
- Avalanches overlapping in time + statistical fluctuation of the avalanche size
- Non-zero probability of reaching $Q_{crit}$

**Also other, “cumulative” processes**

- Preparation activity
  - current spikes or current increase before breakdown
  - cathode excitation effect and electron jets
- Space charge effects
- See more: V.Peskov, P.Fonte (2009) arXiv:0911.0463




1) Thick wire MWPC
2) PPAC 3 mm
3) PPAC 0.6 mm
4) MMG
5) CAT
6) GEM
7-9) MWPCs space-charge limits




1) PPAC 3 mm
2) MMG
3) PPAC 0.6 mm
4) MSGC 1 mm
5) MSGC 0.2 mm
6) GEM
7) Microgap 0.2 mm

*P. Fonte, V. Peskov, Plasma Sources Science and Technology 19 (2010) 034021*

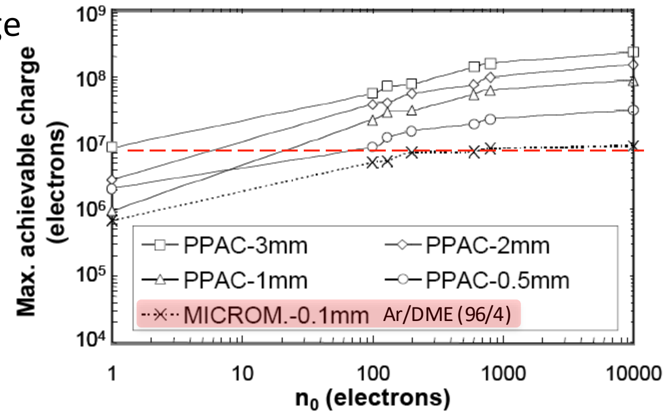
# Critical charge in MPGDs

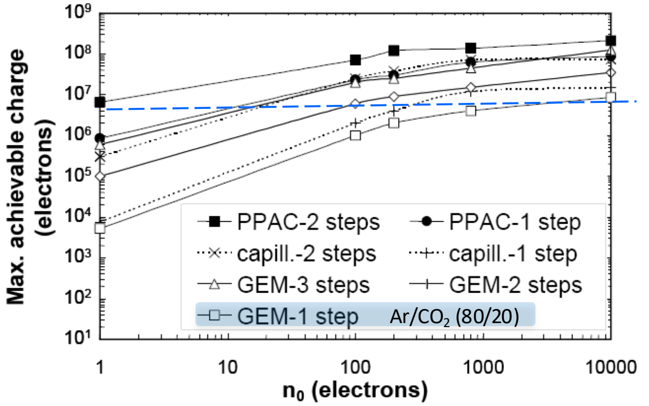
DRD1 Gaseous Detector Technologies

- In case of MPGDs we discuss mainly streamer mechanism of discharge development and a spark discharge
- Critical charge measurements in MPGDs point to a **limit of $10^6$-$10^7$ *e***

Is it one, universal limit?

- No gas dependency studied in details
- Clear dependency on the amplification gap □ **charge density?**
- Clear dependency on a number of primary electrons $n_0$



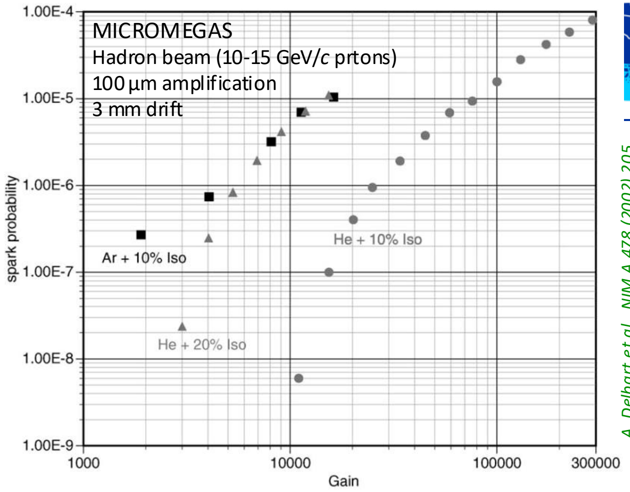




V. Peskov et al., IEEE Nucl. Sci. 48 (2001) 1070

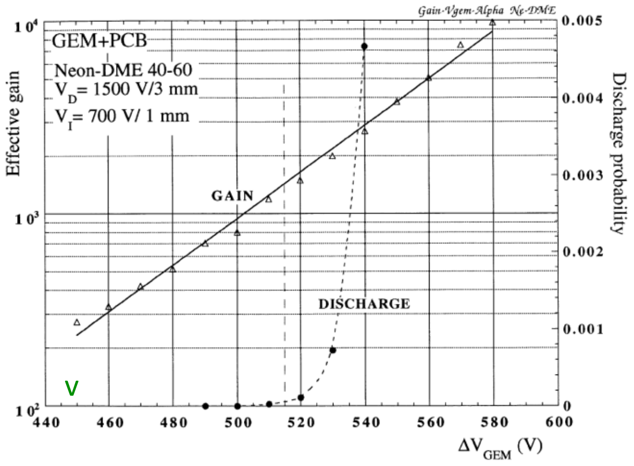
# Critical charge in MPGDs

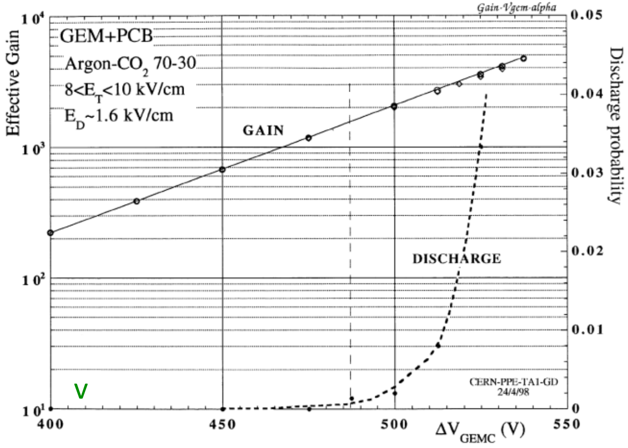


- Clear gas dependencies
- Discharge probability decreases for lighter gases
- Charge density effects
- Charge limits – different for different mixtures?




A. Delbart et al., NIM A 478 (2002) 205



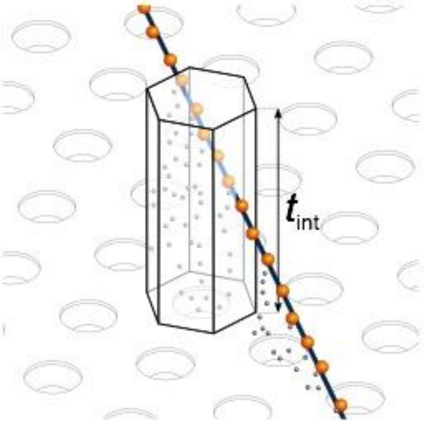




A. Bressan et al., NIM A 424 (1999) 321

# GEANT4 model

Developed by A. Mathis (TUM)

- Sorting into single GEM holes according to their arrival position
  - Honeycomb pattern around the GEM holes
  - Assume 100 % collection efficiency
  - Integrate over arrival time ($t_{int}$) above a given GEM hole



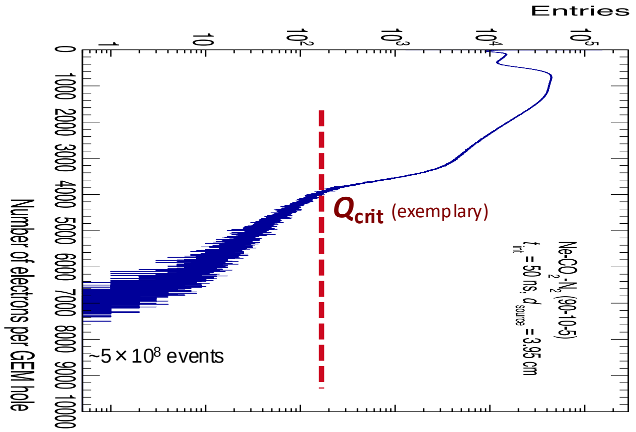

- Multiplication of the charges inside the GEM holes
  - Use absolute gain from the measurements
  - Count the electrons contained in single GEM holes

- Critical limit for charges $Q_{crit}$ in single GEM hole
  - When exceeded → discharge (a'la *Raether* limit)

- Count such large primary ionisation clusters and normalize to the number of all α-particles
  - **Discharge probability**

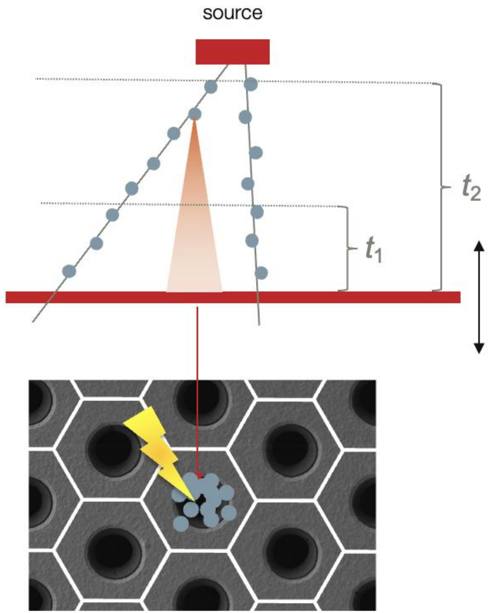
- Cut on a discharge pile-up (one alpha – max one discharge)

- Not known: $Q_{crit}$ & $t_{int}$ → parameter scan + $\chi^2$ minimization



# Model

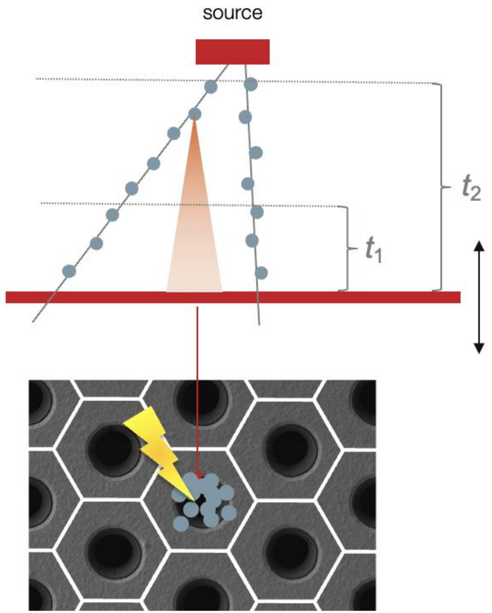
*PG et al. NIM A 870 (2017) 116*




- Realistic model of the detector
- Simulation of the energy deposit of alpha particles in the active detector medium (GEANT4)
- Conversion of energy deposit into ionization electrons $n_{ele} = E_{dep}/W_i$
- Drift of the electrons towards the GEM plane taking into account transverse and longitudinal diffusion and the electron drift velocity
  - Smearing with Gaussian distribution
  - Repeated for many different $d_{source}$
- Collection the charges according to their arrival position + multiplication

# Model

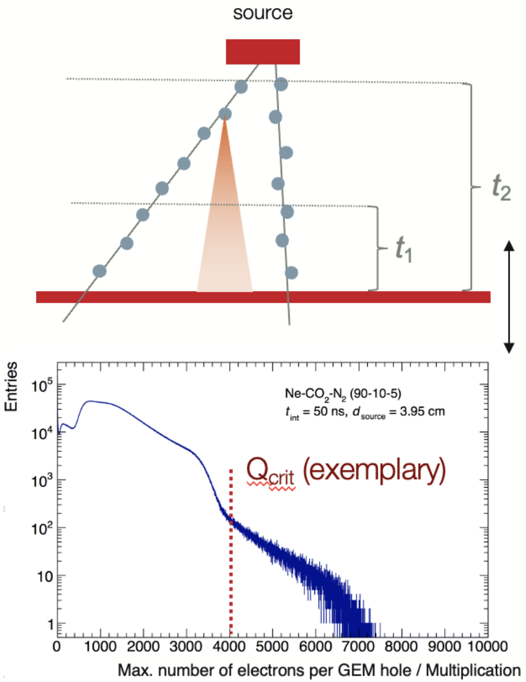
*PG et al. NIM A 870 (2017) 116*




- Collection the charges according to their arrival position
  - Honeycomb pattern around the GEM holes
  - Assume 100 % collection efficiency
- Multiplication of the charges inside the GEM holes
  - Count the electrons contained in single GEM holes
- Critical limit for charges $Q_{crit}$ in single GEM hole
  - When exceeded → discharge (à la Raether limit)
- Count such large primary ionization clusters and normalize to the number of all α-particles
  - Discharge probability
- Not known: $Q_{crit}$ & the time it takes to develop a discharge $t_{int}$
  - Parameter scan + $\chi^2$ minimization

# Model

*PG et al. NIM A 870 (2017) 116*



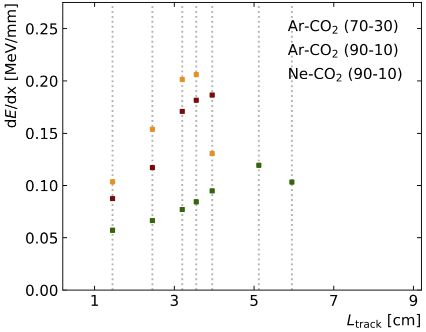

- Collection the charges according to their arrival position
  - Honeycomb pattern around the GEM holes
  - Assume 100 % collection efficiency
- Multiplication of the charges inside the GEM holes
  - Count the electrons contained in single GEM holes
- Critical limit for charges $Q_{crit}$ in single GEM hole
  - When exceeded → discharge (à la Raether limit)
- Count such large primary ionization clusters and normalize to the number of all α-particles
  - Discharge probability
- Not known: $Q_{crit}$ & the time it takes to develop a discharge $t_{int}$
  - Parameter scan + $\chi^2$ minimization

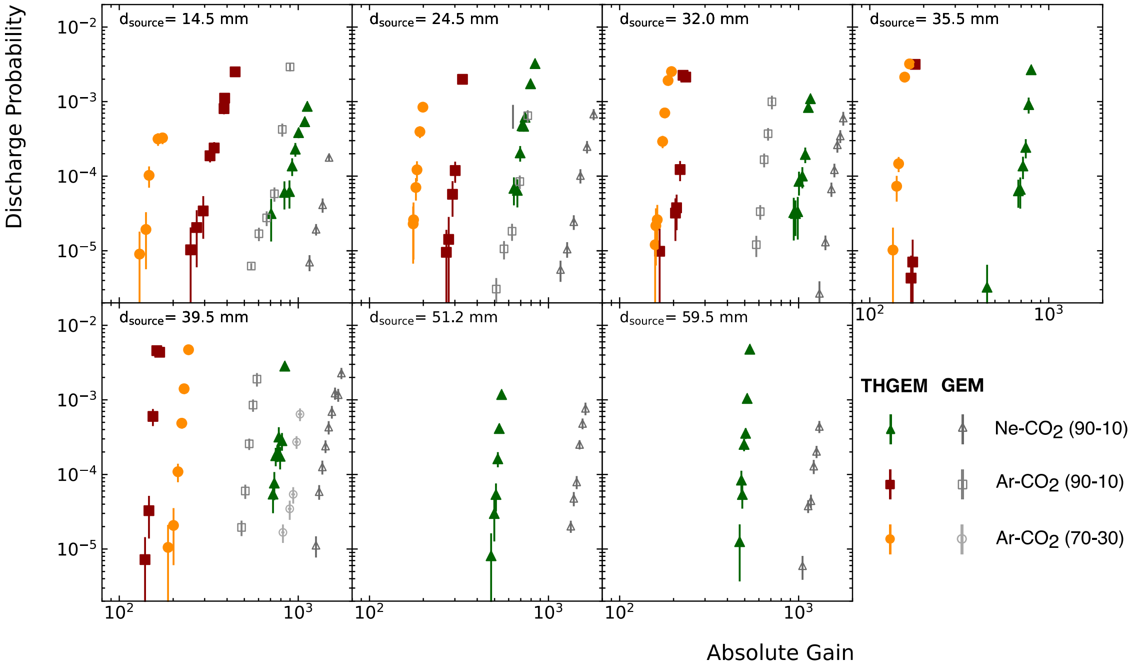
# Discharge probability

## Quencher content dependence

- Larger $CO_2$ content does not increase stability
- Again, range and gas properties
- Inversion at 39.5!

| Gas | $v_{drift}$ [cm µs$^{-1}$] | $D_L$ [$\sqrt{cm}$] | $D_T$ [$\sqrt{cm}$] | $W_i$ [eV] |
|---|---|---|---|---|
| Ar-$CO_2$ (70-30) | 0.932 | 0.0138 | 0.0145 | 30.2 |
| Ar-$CO_2$ (90-10) | 3.25 | 0.0244 | 0.0268 | 28.8 |
| Ne-$CO_2$ (90-10) | 2.66 | 0.0219 | 0.0223 | 38.1 |

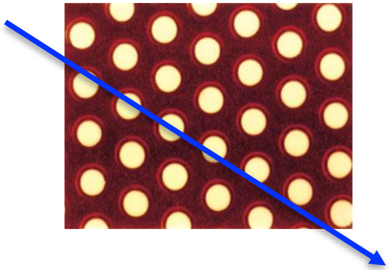


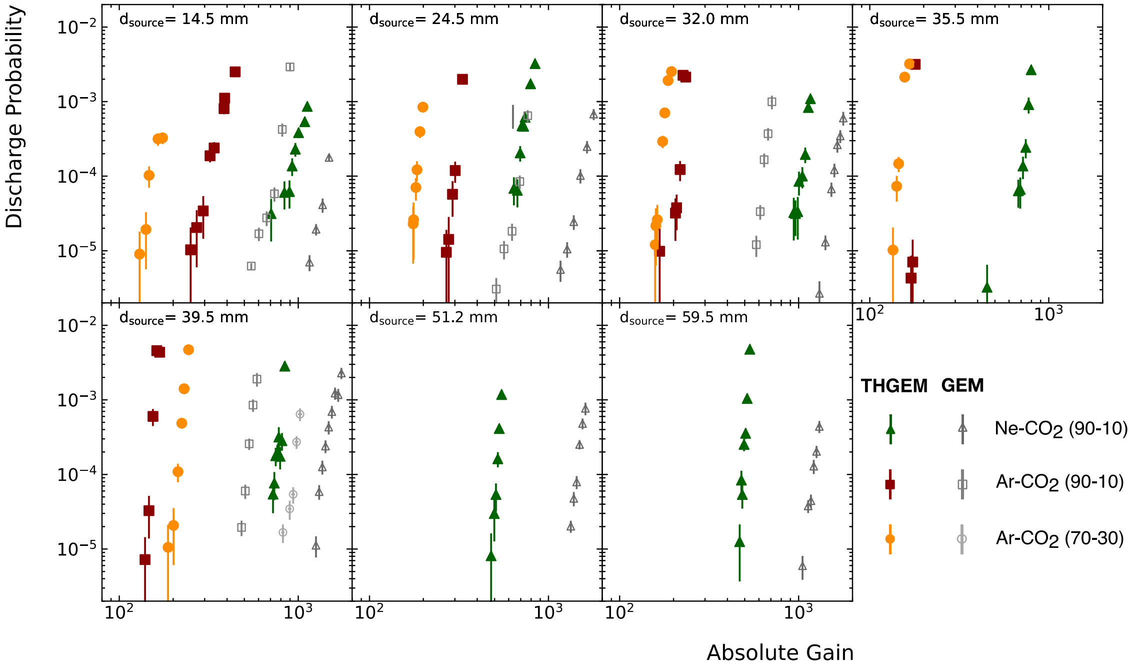



# Discharge probability

GEM vs. THGEM

- THGEMs less stable than GEMs
- For the same discharge probability: abs. gain factor 2-5 different
- Collection eff: 100%
- Primary electrons shared by lower no. holes in THGEMs
- ~Linear scaling with the (TH)GEM pitch

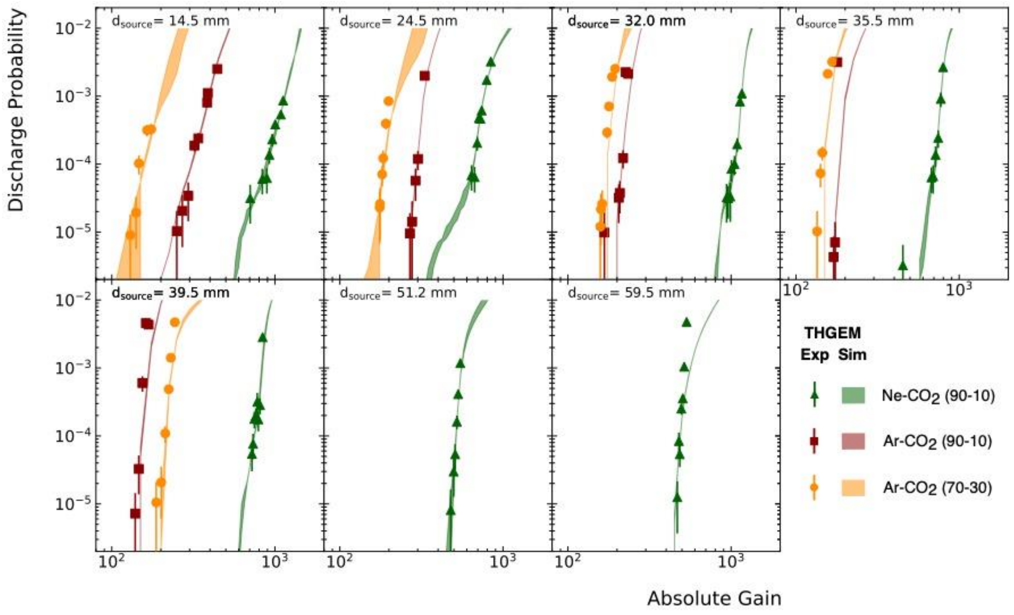





- Perform simulations to account for all orientations, emission angles, track lengths, etc.

# Simulation fits

- Simulated discharge curves obtained for a given parameter pair ($Q_{crit}$, $t_{int}$) are fitted to the data by means of $\chi^2$ minimization for each gas and $d_{source}$




**Interpretation of $t_{int}$ not straightforward**

- Defines charge collection into the holes taking into account
  primary charge density and transport properties
- It is $d_{source}$-dependent, cannot be interpreted as a discharge development time
- The order of magnitude resembles transition to streamer time
- Larger values for THGEMs may be related to the size?

| Gas | THGEM $\langle Q_{crit} \rangle$ [$\times 10^6\ e$] | THGEM $t_{int}$ [ns] | GEM $Q_{crit}$ [$\times 10^6\ e$] | GEM $t_{int}$ [ns] |
|---|---|---|---|---|
| Ne-$CO_2$ (90-10) | 7.1 ± 2.2 | 30–210 | 7.3 ± 0.9 | 20–90 |
| Ar-$CO_2$ (90-10) | 4.3 ± 1.5 | 20–110 | 4.7 ± 0.6 | 15–50 |
| Ar-$CO_2$ (70-30) | 2.5 ± 0.9 | 40–310 | – | – |

# Streamer development in a (TH)GEM hole

| Gas | THGEM $\langle Q_{crit} \rangle$ [$\times 10^6$ $e$] | THGEM $t_{int}$ [ns] | GEM $Q_{crit}$ [$\times 10^6$ $e$] | GEM $t_{int}$ [ns] |
|---|---|---|---|---|
| Ne-$CO_2$ (90-10) | 7.1 ± 2.2 | 30–210 | 7.3 ± 0.9 | 20–90 |
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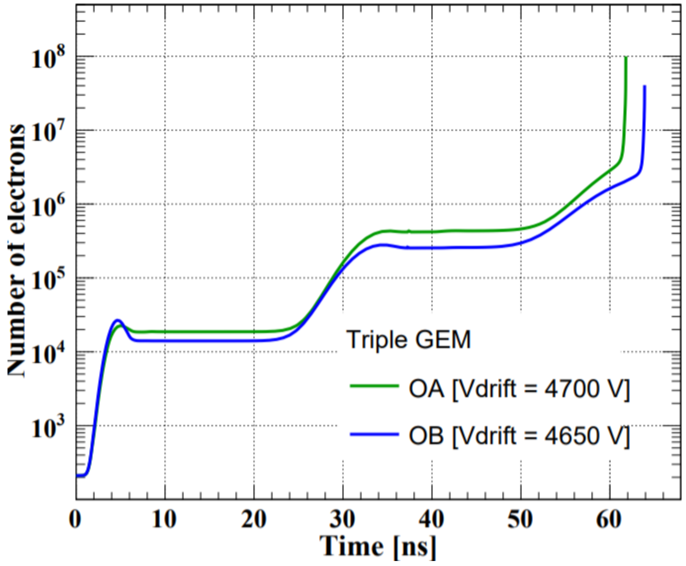
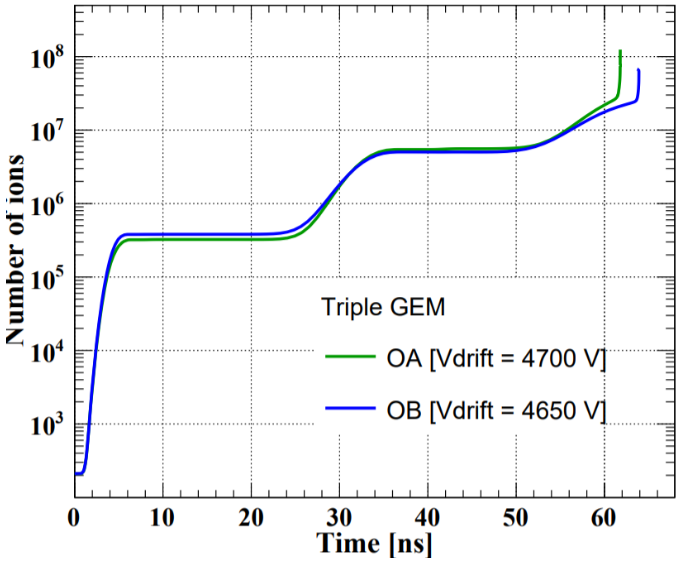
| Ar-$CO_2$ (70-30) | 2.5 ± 0.9 | 40–310 | – | – |

- Timescale of streamer development ~1 ns
- $t_{int}$ >> 1 ns points to ions building up space charge which leads to streamer formation
- Compatible with the results presented in recent studies by P. Roy (Saha Institute of Nuclear Physics) - Link



# Streamer development in a (TH)GEM hole

| Gas | THGEM | | GEM | |
|---|---|---|---|---|
| | $\langle Q_{crit} \rangle$ [$\times 10^6\ e$] | $t_{int}$ [ns] | $Q_{crit}$ [$\times 10^6\ e$] | $t_{int}$ [ns] |
| Ne-$CO_2$ (90-10) | 7.1 ± 2.2 | 30–210 | 7.3 ± 0.9 | 20–90 |
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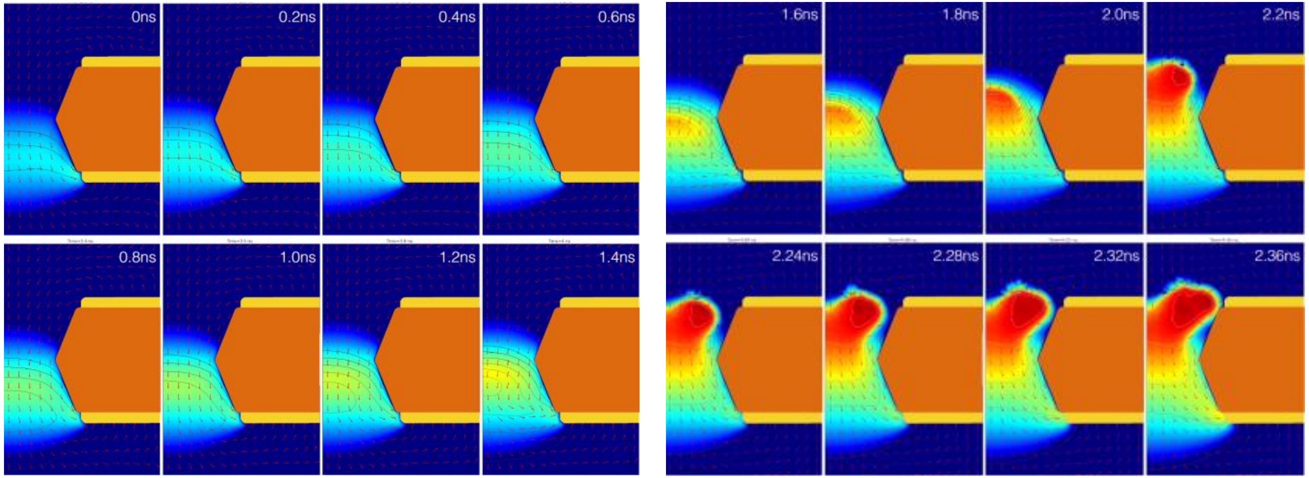
| Ar-$CO_2$ (70-30) | 2.5 ± 0.9 | 40–310 | – | – |

- Timescale of streamer development ~1 ns
- $t_{int}$ >> 1 ns points to ions building up space charge which leads to streamer formation
- Compatible with the results presented in S. Franchino et al., IEEE (2015) 1

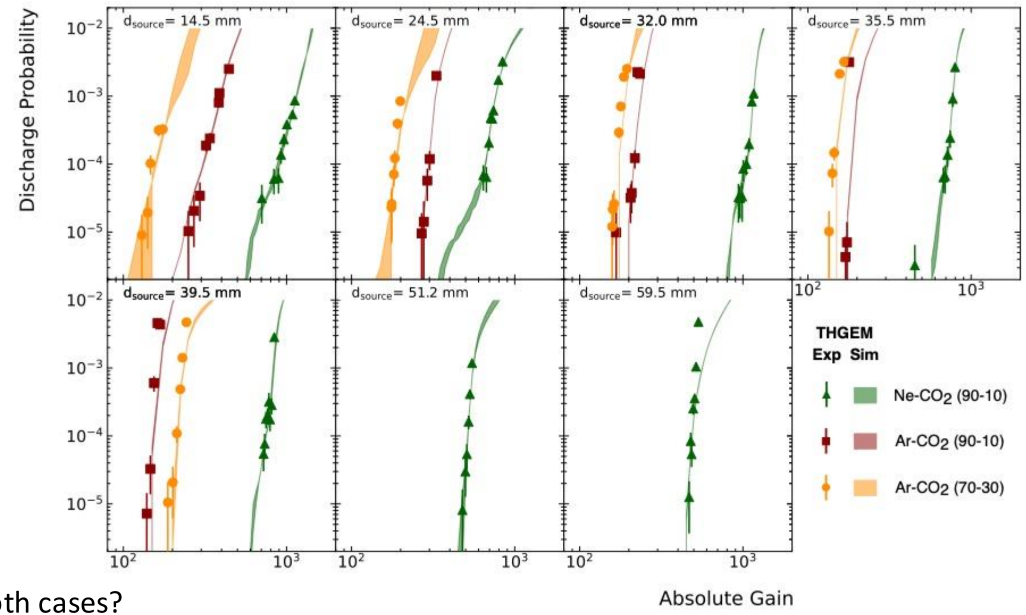



© S. Franchino, **IEEE (2015) 1,** arXiv:1512.04968

# Simulation fits

*PG, L. Lautner et al.* arXiv:2204.02853v1

- Simulated discharge curves obtained for a given parameter pair ($Q_{crit}$, $t_{int}$) are fitted to the data by means of $\chi^2$ minimization for each gas and $d_{source}$



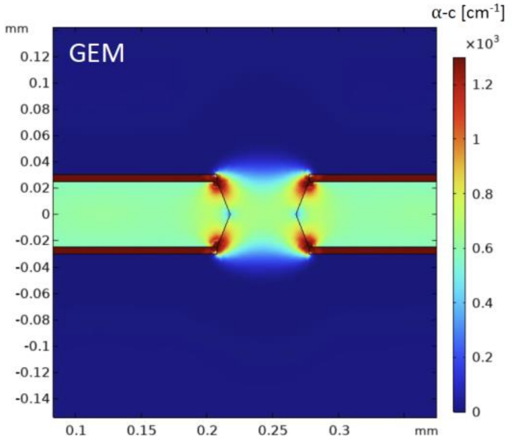

**$Q_{crit}$ extracted individually for each distance and averaged using a weighted mean method**

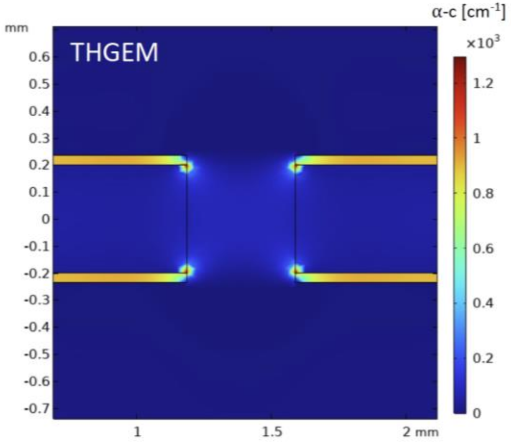
- Gas dependency observed again!
- $Q_{crit}$ for both structures agree with each other, in spite of geometrical differences!
- Effective volume of streamer formation is similar in both cases?
- The primary charge limits shall be considered per single holes, not normalized to the hole volume.

| Gas | THGEM | | GEM | |
|---|---|---|---|---|
| | $\langle Q_{crit} \rangle$ [$\times 10^6$ $e$] | $t_{int}$ [ns] | $Q_{crit}$ [$\times 10^6$ $e$] | $t_{int}$ [ns] |
| $Ne$-$CO_2$ (90-10) | 7.1 ± 2.2 | 30–210 | 7.3 ± 0.9 | 20–90 |
| $Ar$-$CO_2$ (90-10) | 4.3 ± 1.5 | 20–110 | 4.7 ± 0.6 | 15–50 |
| $Ar$-$CO_2$ (70-30) | 2.5 ± 0.9 | 40–310 | – | – |

# Townsend maps

- $Q_{crit}$ for both structures agree with each other, in spite of geometrical differences!
- Townsend coefficient maps for a GEM and a THGEM geometry (Comsol® electric field simulation convoluted with Townsend coefficients)
- The "effective volume" of a streamer creation in a THGEM may be comparable to the size of a GEM hole
- **Detailed simulations of streamer formation are necessary! Also to understand gas dependency of $Q_{crit}$**



# PRESSURE?

# High-pressure operation

- Not much data available for MPGD
- If anything --> HP Xe, Ar, DP TPC, etc.
- MPGD in $H_2$ – max at 1 Atm
- Intensive R&D necessary to fulfill requirements of the new 10bar $H_2$ TPC
- Approximate number density (*N* – controlled by *P* adjustement) and reduced electric field (*E/N*) scaling:

| magnitude | scaling $(n = N/N_0)$ |
|---|---|
| electron, ion drift velocity $v_d$ | $v_d(E/n)$ |
| electron, ion diffusion coefficients $D^*_{L,T}$ | $\frac{1}{\sqrt{n}} D^*_{L,T}(E/n)$ |
| attachment coefficient $\eta$ | $n \cdot \eta(E/n)\ ^{*a}$ |
| Light transparency $\mathcal{T}$ | $\exp(-n\Pi_a L^*)$ |
| scintillation probability $P_{scin}$ | $\frac{1}{1+n\tau k}$ |
| particle range $R$ | $R/n$ |
| Fano factor $F_e$, $W_I$, $W_{ex}$ | $\sim$ constant |
| charge multiplication coefficient $\alpha$ | $n \cdot \alpha(E/n)\ ^{*b}$ |
| secondary scintillation coefficient $Y$ | $n \cdot Y(E/n)\ ^{*b}$ |

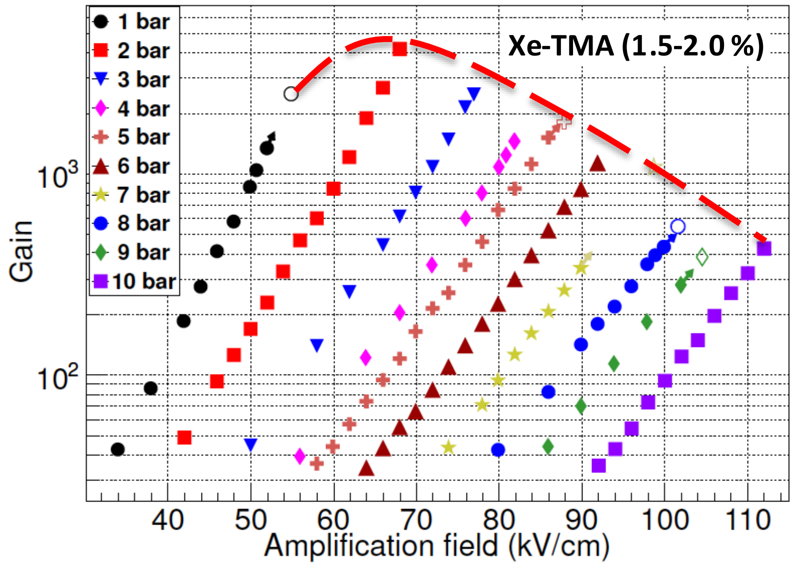
D. Gonzalez-Diaz et al., NIM A 878 (2018) 200

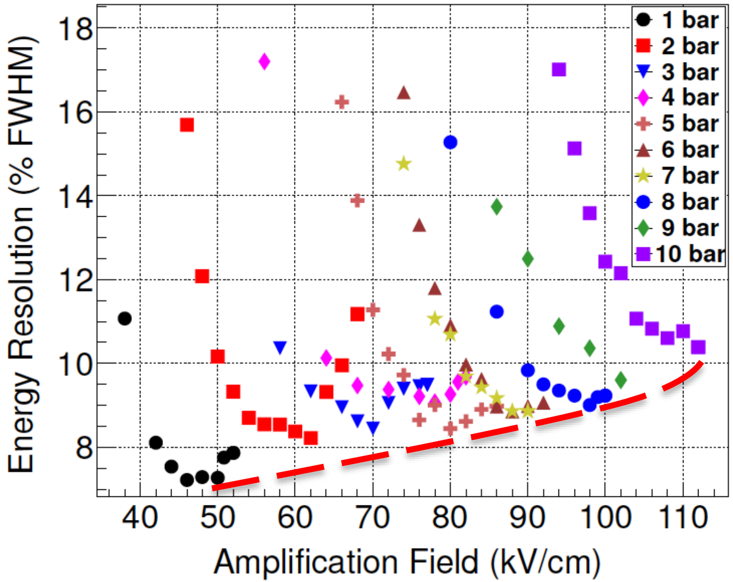
- High voltage in drift region (pressure dependence of $v_d$, $D_L$, $\eta$) – insulation (see e.g. B. Rebel at al. JINST 9 (2014) T08004)

# MPGDs in high-pressure (MMG TPC)

- Double voltage for multiplication at ×10 pressure increase (no major insulation issues)
- Maximum achievable gain drops with pressure
- Energy resolution suffers at high *P* from the *E/P* reduction and the associated increase of the avalanche fluctuations

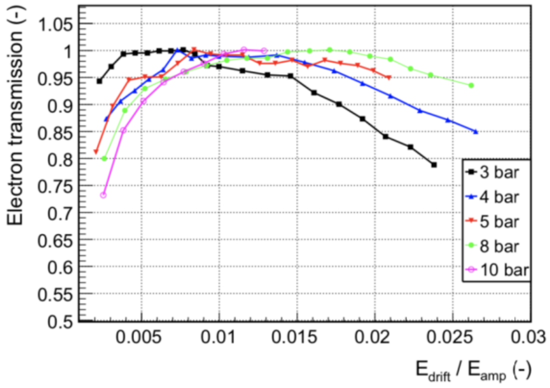
S. Cebrián et al. JINST 10 (2015) E07001 *"**Micromegas-TPC** operation at high pressure in xenon-trimethylamine mixtures"*

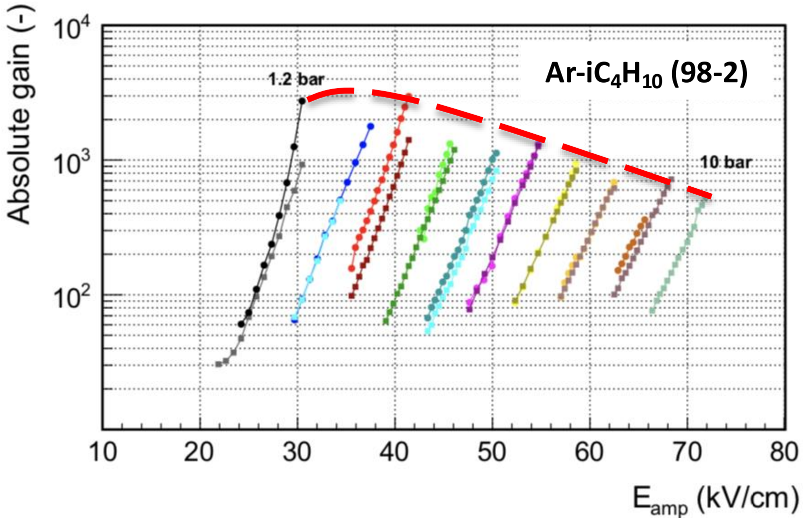


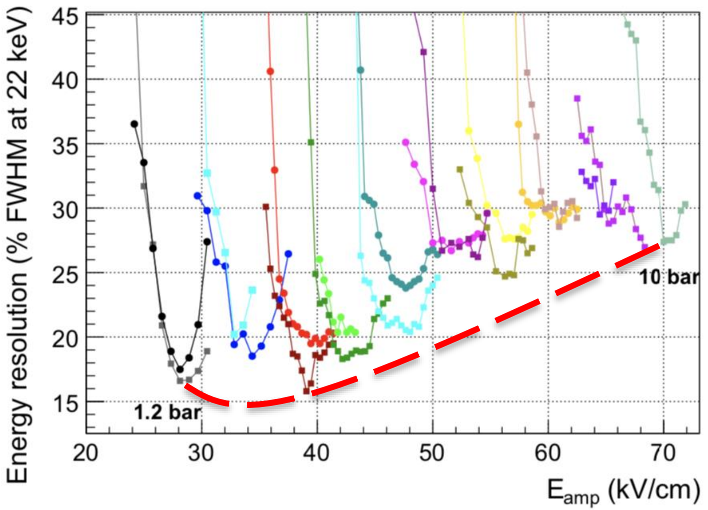



# MPGDs in high-pressure (MMG TPC)

- Similar results in Ar-$iC_4H_{10}$ (98-2) obtained by TREX-DM collaboration
- F.J. Iguaz et al. Eur. Phys. J. C (2016) 76:529
- TREX-DM, 20×20 cm$^2$, 128 µm gap, bulk MMG
- Note electron transmission dependency on the *P*
  - Loss of electrons due to attachement and optical transparency
  - Influence of the ballistic deficit for lower $v_d$ and $D_L$
- Also: activity of the natural chains and some common radioactive isotopes in components and materials intended used at the TREX



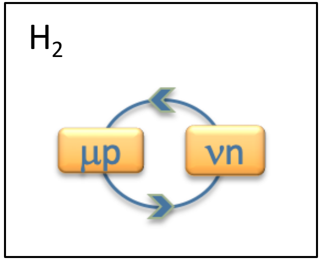



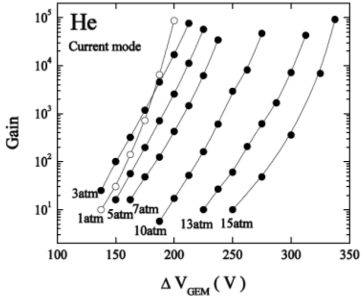



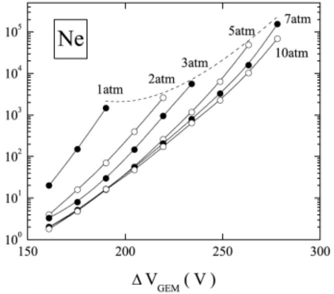
# MPGDs in high-pressure (GEMs)

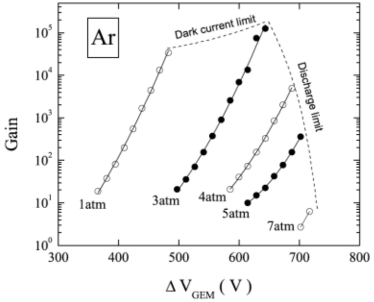
DRD1 Gaseous Detector Technologies

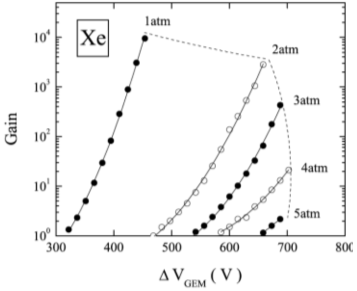
- Pioneering studies of GEM gain in noble gases at 1-15 atm (plots below)
  - A. Bondar et al. NIM A 481 (2002) 200
  - A. Bondar et al. NIM A 493 (2002) 8
- Maximum achievable gain drops abruptly in heavy noble gases
- Light gases (He, Ne) stable; also weaker gain dependency on *P*
  - Associative ionization as the dominant avalanche mechanism in HP He and Ne; $He + He^* \rightarrow He^+_2 + e^-$

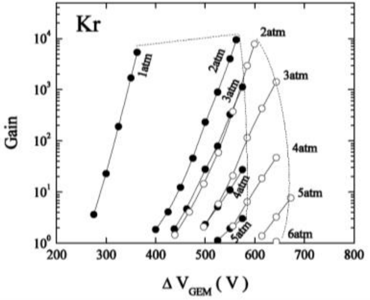


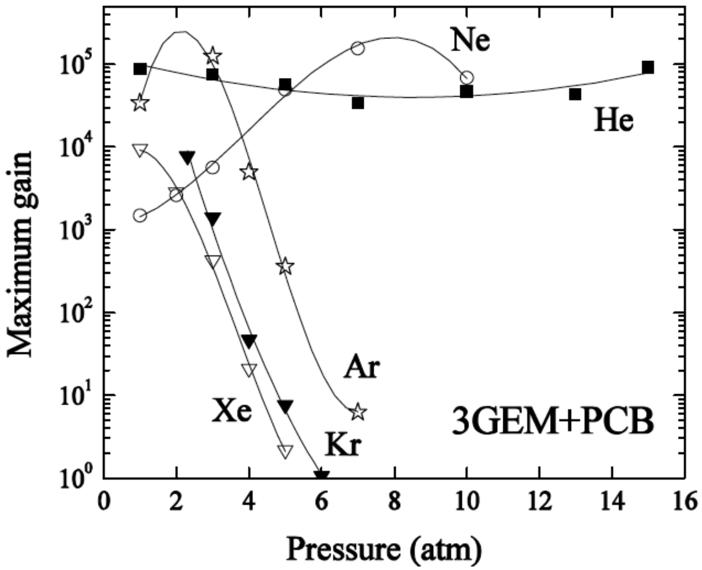



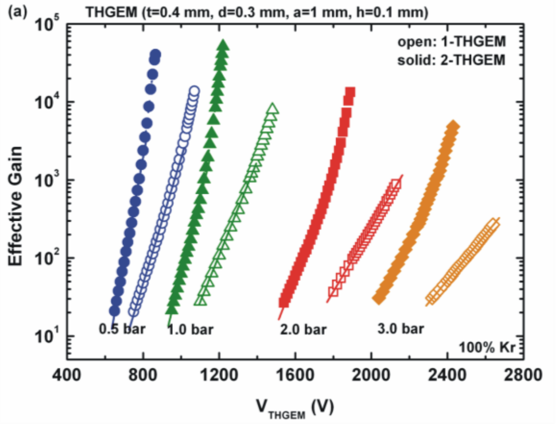



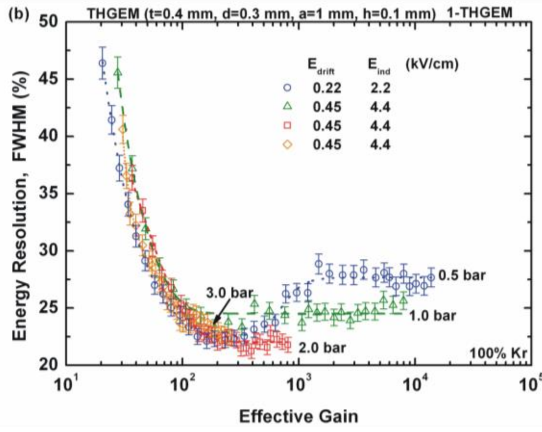

- See also "Gas gain and signal length measurements with a triple-GEM at different pressures of Ar-, Kr- and Xe-based gas mixtures", A. Orthen et al. NIM A 512 (2003) 476

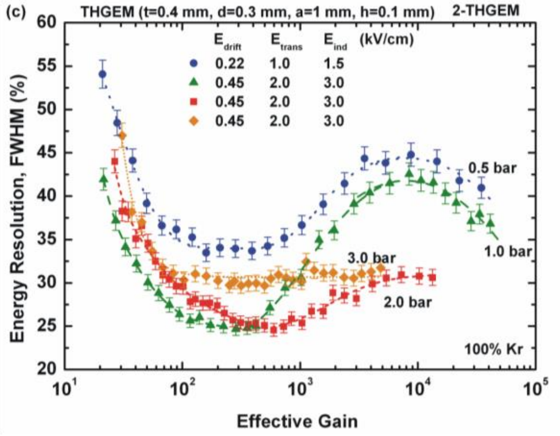
# MPGDs in high-pressure (THGEMs)

- THGEM in high-pressure Kr
- J.M. Maia et al., JINST 4 (2009) P10006
- Single and double THGEM
- Same max-gain dependency on *P* as with other MPGDs
  - Non-exponential dependency for *G* > 1000 due to photon feedback?
- Energy resolution improves with *P* in 2-THGEM system?
  - Deterioration of energy resolution for *G* > 1000




| Active area (mm×mm) | 14×13 |
|---|---|
| Thickness *t* (mm) | 0.4 |
| Hole diameter *d*(mm) | 0.3 |
| Pitch *a*(mm) | 1.0 |
| Rim *h*(mm) | 0.1 |
| Hole density ($mm^{-2}$) | 1.149 |
| Metal area (%) | 77.3 |
| Optical transparency (%) | 8.1 |

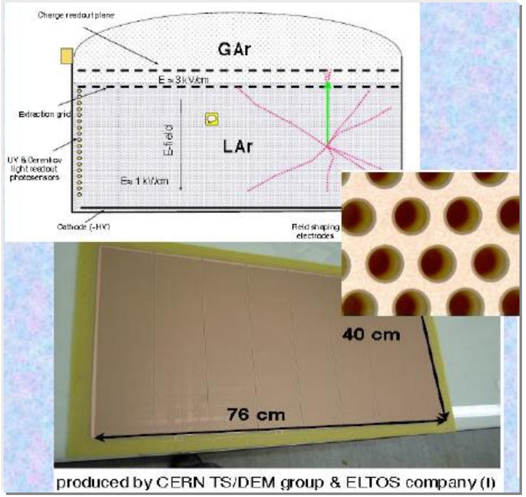


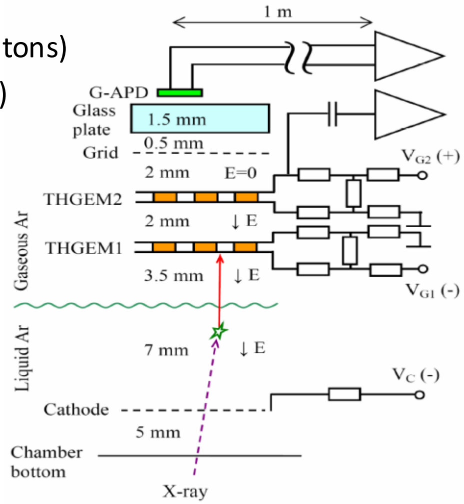
# Gain limits in noble gases

from: A. Breskin (WIS), IWAD Kolkata, 28.10.2014 (link)

- E.g. LEM (THGEM) for ArDM & GLACIER 100kton LAr neutrino observatory
- A. Rubbia et al. JINST 8 (2013) P04012
- Detection of WIMP-induced ionization electrons in LAr for dark-matter search
- Problem: gain <100 in pure Ar, due to photon feedback!
  - easier situation in Xe, because of lower photon energy (smaller feedback)
  - More on max THGEM/GEM gain in Ar: A. Bondar et al. JINST 8 (2008) P02008

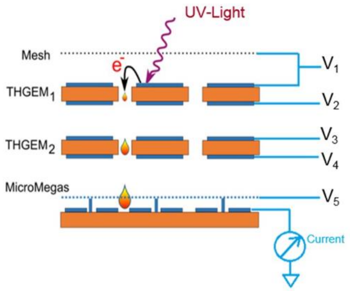



- Possible solutions:
  - Use cascaded THGEMs (to mask final-avalanche photons)
  - THGEM at low gain + Optical readout (SiPM, LAAPDs)
  - But now we enter the double-phase TPC region…
  - Unless…scintillation in $H_2$

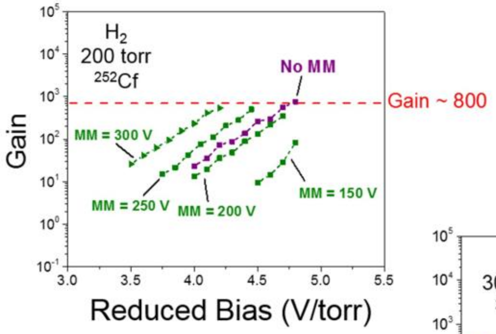


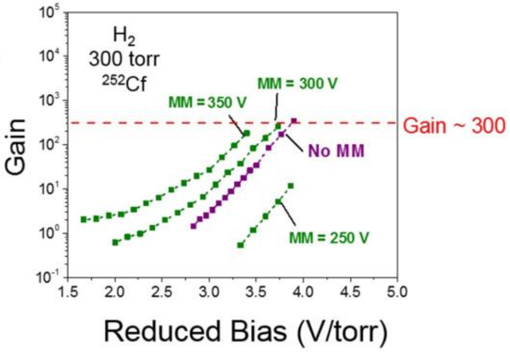

Two-phase Ar detector with THGEM/gAPD optical readout in the NIR
- Bondar, Buzulutskov JINST 2010
- Buzulutskov 2012 JINST 7 C02025

# Low-pressure $H_2$ (THGEM+MMG)



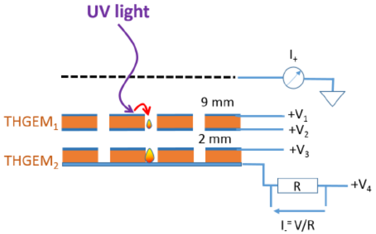

- **AT-TPC Collaboration** basic performance evaluation studies in low-pressure He and $H_2$
- M. Cortesi et al., EPJ Web of Conf. 174 (2018) 01007
- 2-THGEM + MMG for stable operation, due to (direct citation):
  - *the extended dimension of the THGEM holes, typically several times larger than the electron mean-free path even at low pressure;*
  - *the confinement of the avalanche within the holes, resulting in smaller photon-mediated secondary effects*
  - *the quenching effect of small amounts of impurities from natural outgassing of detector components - e.g. N2 acts as wavelength shifter suppressing UV-photons emitted during the avalanche.*



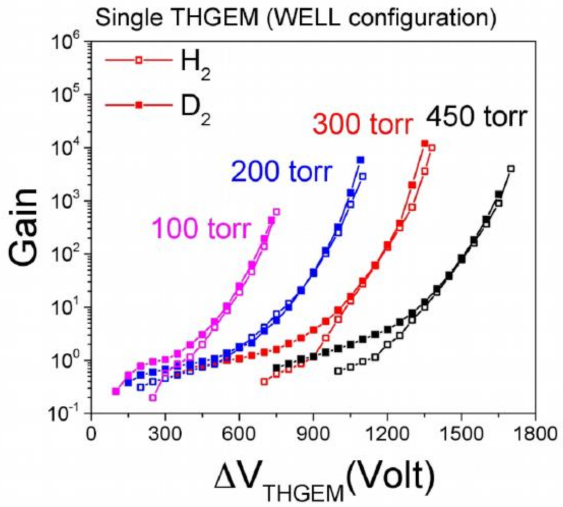



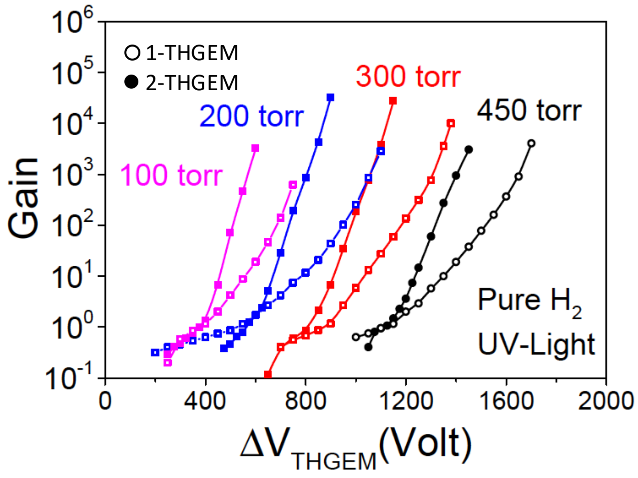

- For low MMG voltage – loss of electron collection efficiency and thus effective gain of the structure
- High x-section for radiation less processes in $H_2$ (excitation of vibrational and rotational levels)
- Higher electric fields necessary for a substantial gas avalanche multiplication (resulting in e.g. field emission)
- Higher voltages → higher discharge probability → lower max. achievable gain. Need R&D in HP $H_2$

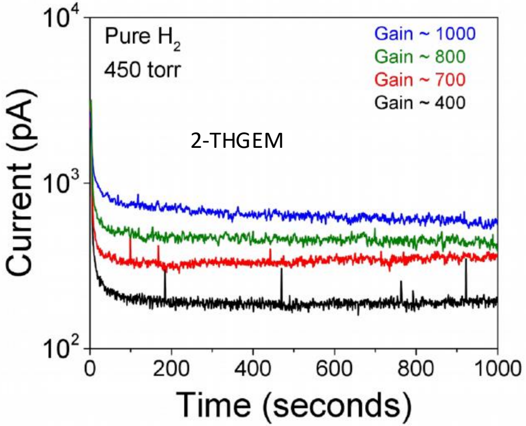
# Low-pressure $H_2$ (WELL, THGEM and 2-THGEM)




- Single THGEM (WELL) at low *P* – photon mediated secondary effects become relevant (lower maximum gain)
- Double THGEM structure (charge/gain sharing) – improves stability
- Instabilities at high pressures due to high absolute voltage
-



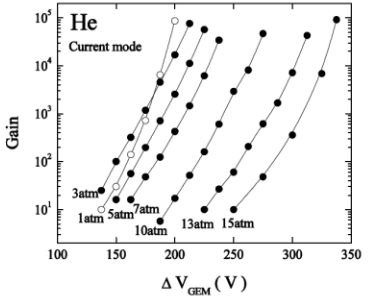



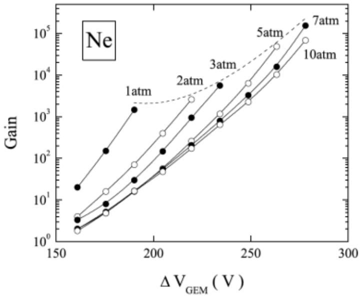



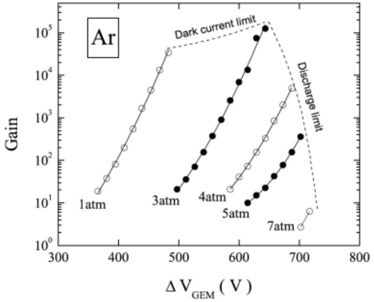
# GEMs in high-pressure

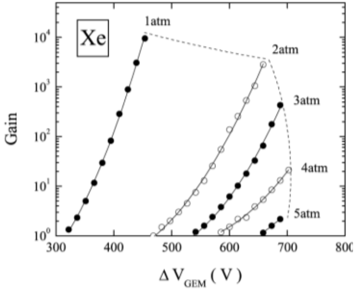


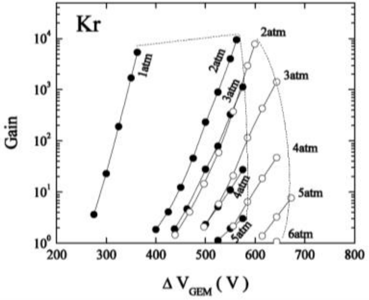
- Pioneering studies of GEM gain in noble gases at 1-15 atm (plots below)
  - A. Bondar et al. NIM A 481 (2002) 200
  - A. Bondar et al. NIM A 493 (2002) 8
- Maximum achievable gain drops abruptly in heavy noble gases □ increased HV, reduced stability
- Light gases (He, Ne) stable; also weaker gain dependency on *P*
  - Associative ionization as the dominant avalanche mechanism in HP He and Ne; $He + He^{*} \rightarrow He^{+}_{2} + e^{-}$

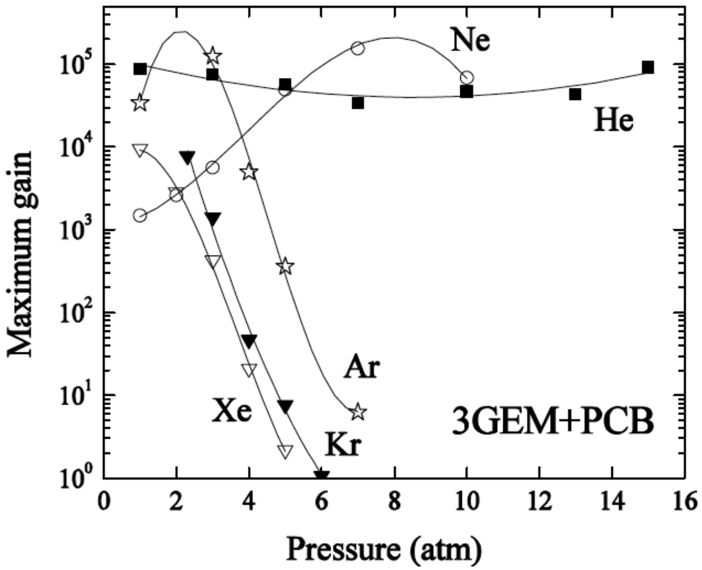


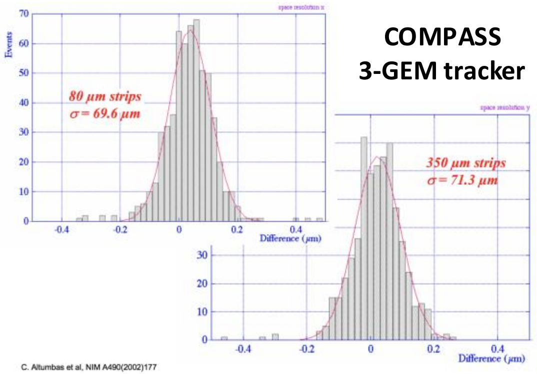




- See also "Gas gain and signal length measurements with a triple-GEM at different pressures of Ar-, Kr- and Xe-based gas mixtures", A. Orthen et al. NIM A 512 (2003) 476

# R LAYERS

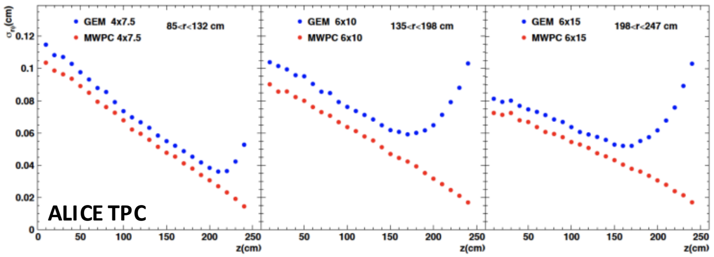
# Resistive layers – charge spread




COMPASS
3-GEM tracker

- Spatial resolution
  - Limited by the pad size ($\sigma \approx W/\sqrt{12}$)
  - Charge distribution narrow (influence of drift distance -> tr. diffusion)

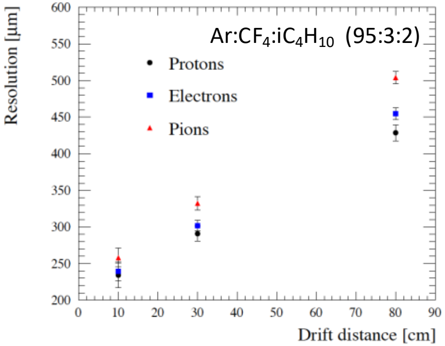
1) Decrease the pad/strip size
  - Single electron efficiency
  - Increase number of readout channels

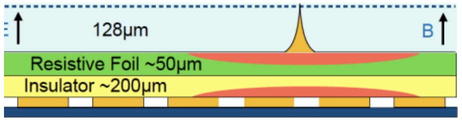



CERN-LHCC-2013-020, 2013, https://cds.cern.ch/record/1622286

2) Spread charge over several pads – resistive anode
  + Reduce number of channels
  + Protect electronics (see prev. slides)
  - Limited track separation

- ATLAS NSW
  - J. Wotschack, Mod. Phys. Lett. A28 (2013) 1340020
  - T. Alexopoulos et al., NIM A 640 (2011) 110
- T2K TPC Upgrade
  - D. Attié et al. arXiv:1907.07060v2



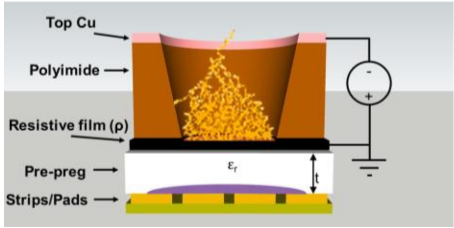

$\rho(r,t) = RC/2t \exp(-r\uparrow 2\ RC/4t)$

$\rho(r,t)$: the surface charge density
R: the surface resistivity of the resistive layer
C: the capacitance per unit area.

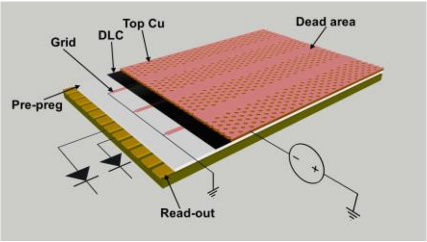
© D. Attié et al. arXiv:1907.07060v2

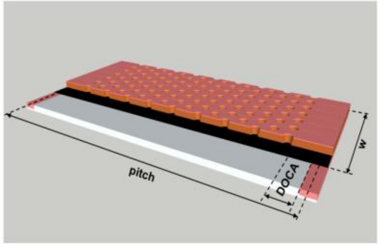
# New structures: micro-RWELL

*G. Bencivenni et al., JINST 14 (2019) P05014*

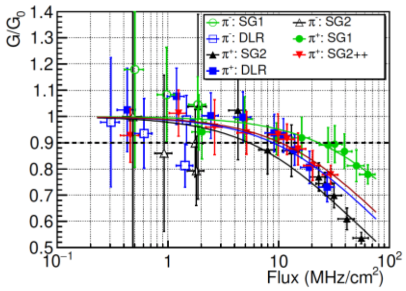


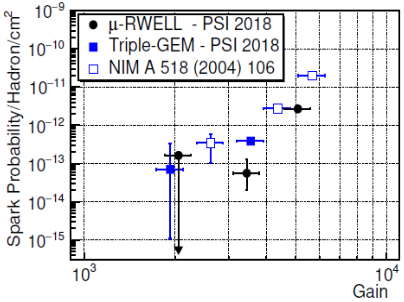

- Single-sided Gaseous Electron Multiplier (GEM) coupled to the readout anode through the material of high bulk resistivity
- Single amplification stage ➞ material budget, simplicity, industrialization, costs!




- High-rate capabilities restored by the proper grounding of the DLC layers ➞ improved charge evacuation
- Thorough optimisation, including surface discharge considerations ➞ concept of the distance-of-closest-approach crucial for stability!



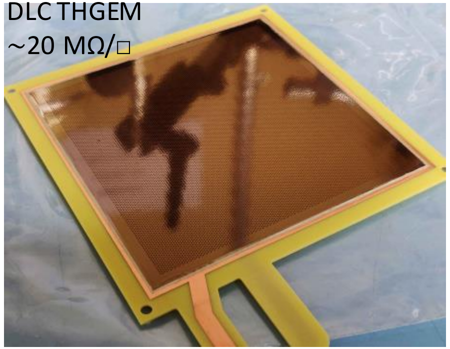



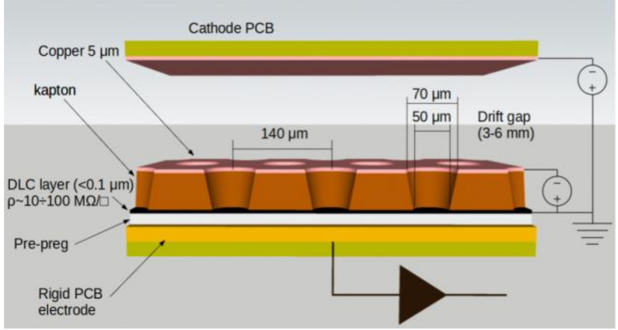

- Rate capabilities of up to 10 MHz/cm$^2$ demonstrated
- Discharge probability of a single micro-RWELL stage compatible with a triple GEM setup operated at stability-optimised HV settings

# Resistive layers studied at GSI

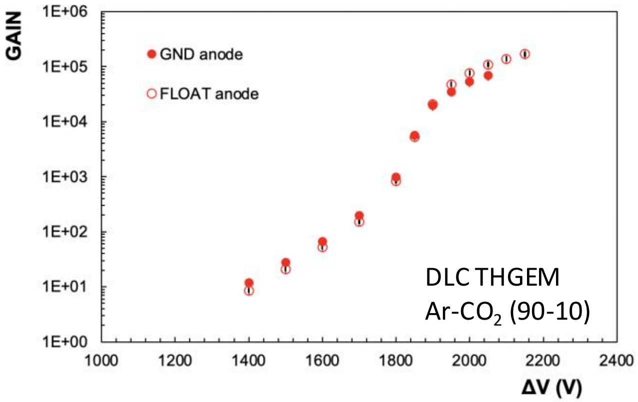
- Goal: characterise primary and secondary discharge stability of resistive **DLC (TH)GEMs** and **micro-RWELL** (GEM-based RWELL structure)
- Attractive option for future upgrades of, e.g. CBM MuCh system
- **DLC THGEM**: clear quenching mechanism observed, no discharges recorded at the gains where 100% probability is expected from standard THGEM studies
- Gain saturation not observed, though!

DLC THGEM
~20 MΩ/□






© DDG LAB Frascati INFN



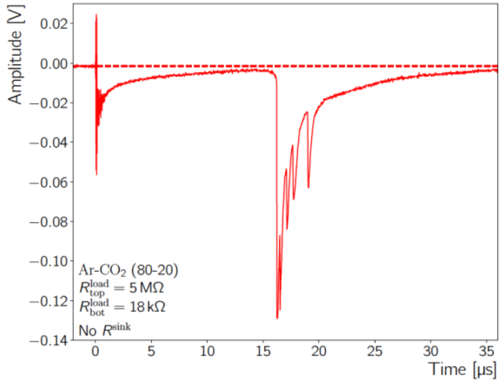

DLC THGEM
Ar-$CO_2$ (90-10)

# SECONDARY DISCHARGES

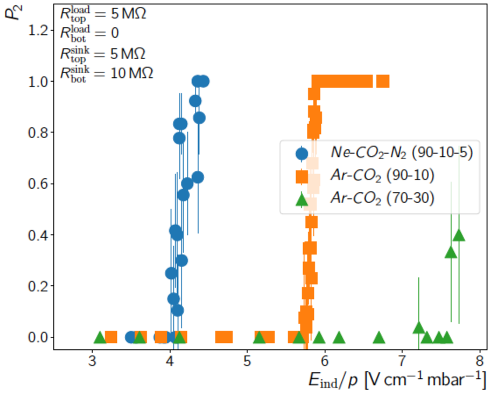
# Secondary discharge formation*

Discharge in the transfer/induction gap appearing $\mathcal{O}$(1-10) μs after the primary spark

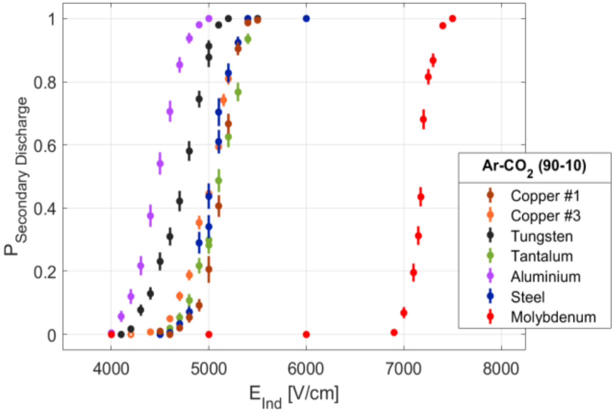
- Leading theory: heating of the cathode after the primary discharge
  - A. Deisting, et al. NIM A 937 (2019) 168
  - A. Utrobicic, et al. NIM A 940 (2019) 262
- Transition between Townsend discharge and Streamer discharge?
  - Dependence on gas (α process) and cathode? (γ process - feeding)
  - Time lag $\mathcal{O}$(10 μs) with a rapid full gap breakdown



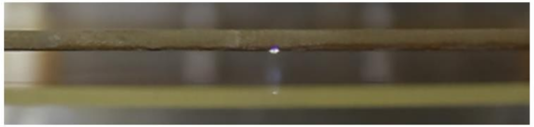

A. Deisting, et al. NIM A 937 (2019) 168



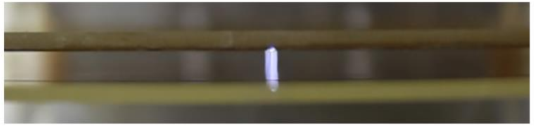

B. Ulukutlu, *RD51 Meeting, June 2020 (link)*



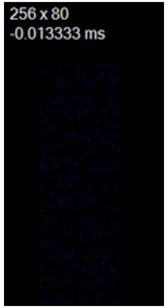

a) Primary discharge



b) Secondary discharge



A. Deisting, et al. NIM A 937 (2019) 168




A. Utrobičić et al. MPGD 2019, La Rochelle

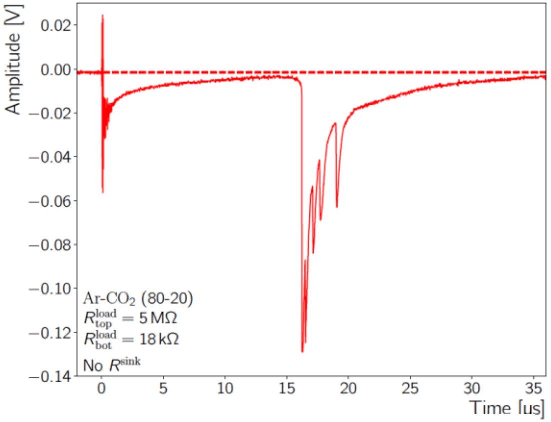
* See pioneering studies by *S. Bachmann et al. NIM A479 (2002) 294* & V. Peskov, P.Fonte (2009) arXiv:0911.0463

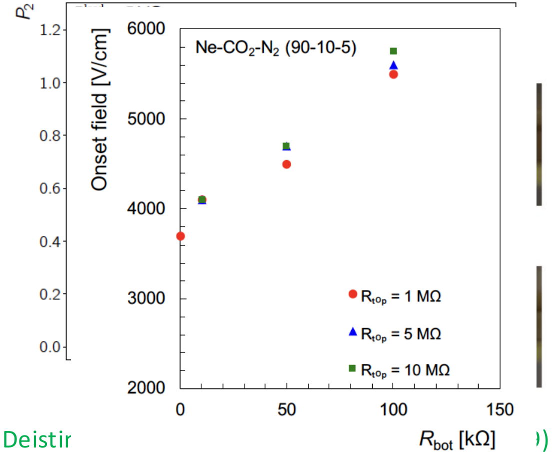
# Secondary discharges in GEMs*

Discharge in a transfer/induction gap

- Full gap voltage breakdown – can be associated with a spark development
- Appears $\mathcal{O}$(μs) after the primary spark
- Develops at the gap fields below the amplification region
- Precursor current can be measured in between two discharges

  ➞ Secondary emission and streamer development in the gap?
- Leading theory: heating of the cathode after the primary discharge
  - A. Deisting C. Garabatos, PG, et al. NIM A 937 (2019) 168
  - A. Utrobicic, et al. NIM A 940 (2019) 262
- Mitigation strategies established
  - L. Lautner, PG, et al. JINST 14 (2019) P08024
  - A. Deisting, C. Garabatos, PG, et al. NIM A 937 (2019) 168



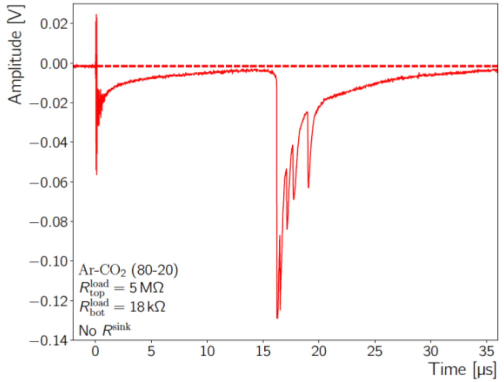




A. Deistir ... ) 168

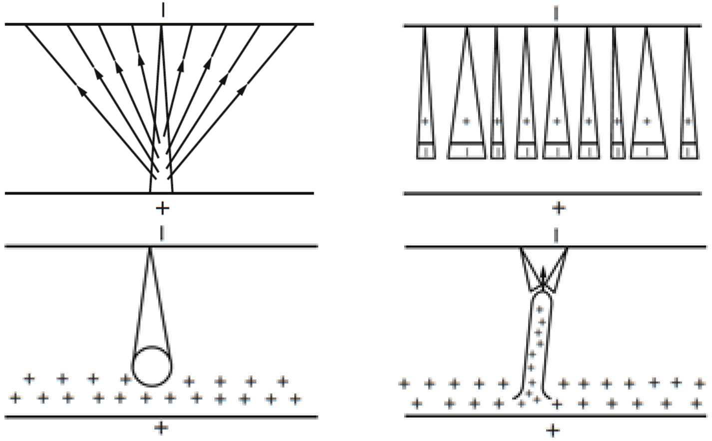
* See pioneering studies by *S. Bachmann et al. NIM A479 (2002) 294 & V.* Peskov, P.Fonte (2009) arXiv:0911.0463

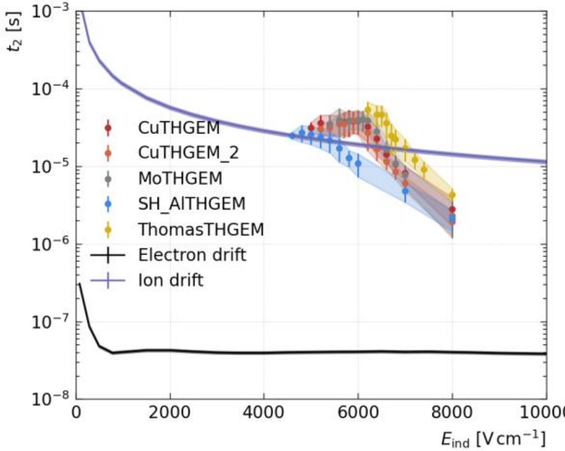
# Secondary discharge formation

Discharge in the transfer/induction gap appearing $\mathcal{O}$(1-10) µs after the primary spark




- Leading theory: heating of the cathode after the primary discharge
  - A. Deisting, et al. NIM A 937 (2019) 168
  - A. Utrobicic, et al. NIM A 940 (2019) 262
- Transition between Townsend discharge and Streamer discharge?
  - Townsend mechanism initiated by electrons from a primary discharge;
  - Secondary emission from the heated cathode;
  - Space charge accumulation at the anode;
  - Transition to a streamer.

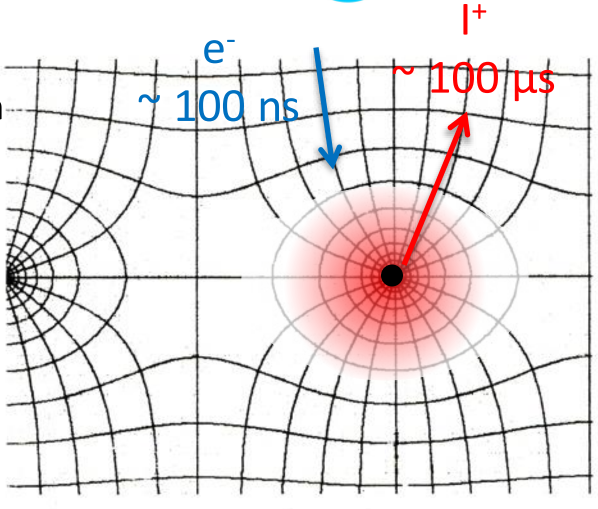




# STACKS

# Limitations of wire readout

1) **Relatively long time to evacuate ions from the amplification region**
   - Fast gain drop at high fluxes: (>10 kHz/cm²)
   - Space charge accumulation, distortion of E field.
   - Screening effect for next event

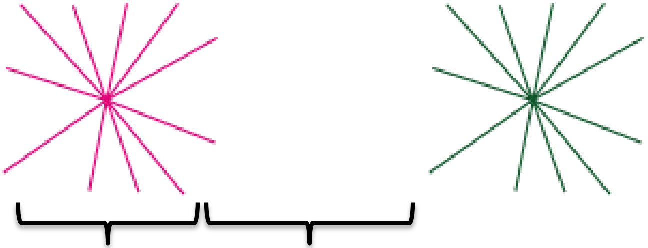





2) **Limited multi-track separation** (~100 µm)
   - Minimum wire distance ~1mm
     (mechanical instabilities due to electrostatic repulsion)

3) **E×B effects** (Lorentz angle) around wires degrades *x-y* resolution

4) **MWPC with Gating Grid**
   - Introduces dead time (e.g. 200 µs in ALICE)
   - Continuous operation not possible
   - Reduces maximum readout rates to $\mathcal{O}$(1 kHz)
   - IBF = 10-20% without GG




5) **Ageing - note gas and material dependency, also in MPGDs**
   - Formation of solid deposits
   - Gain drops and instabilities

# Build stacks!

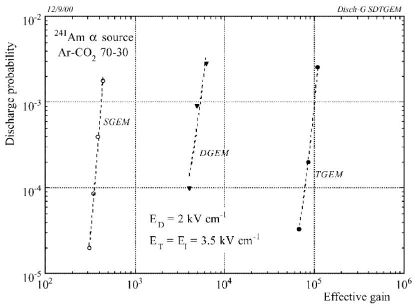
- **GEMs are easy to stack**
  - Pre-amplification stage – lower gain of single structures
  - Charge spread between independent holes – ***$Q_{crit}$*** **per hole stays the same!**
  - Small pitches preferable (watch out quality!)

- **GEM + MMG hybrids and multi-MMG stacks**

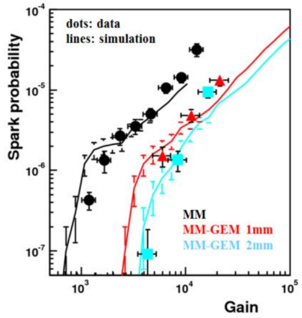
  NIM A 834 (2016) 149 and NIM A 976 (2020) 164282, NIM A 623 (2010) 94
  - Clear influence of the pre-amplification stage on the stability of MMG
  - Lower charge densities reach (subsequent) MMG stages
  - Mesh cell as an independent amplification structure (see also JINST 18 (2023) C06011)

- **Optimized HV settings** (lower amplification towards bottom of a stack)
  - Violated in case the stack optimized for low ion backflow (TPCs)
  - Adding further foils in the stack can improve its stability, → 4GEM Readout for ALICE TPC (IBF optimized)
  - Optimize the electric field above/below the MPGD (diffusion, focusing, extraction/collection)

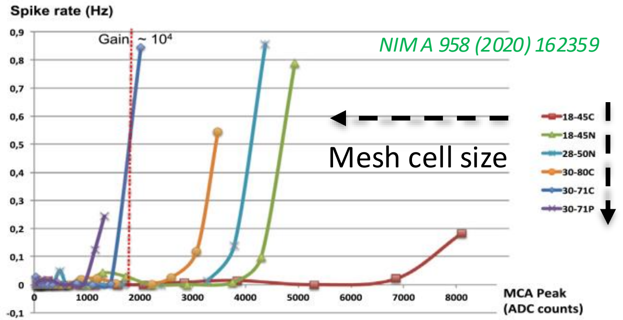
*NIM A479 (2002) 294*

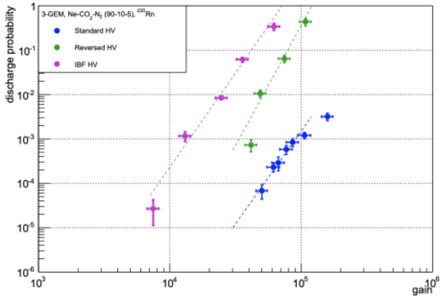



*JINST 7 (2012) C06009*




*NIM A 958 (2020) 162359*

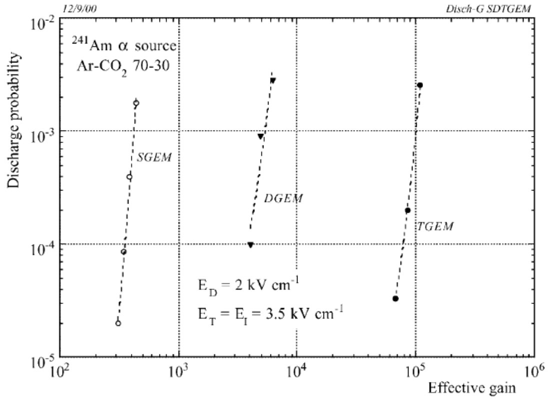


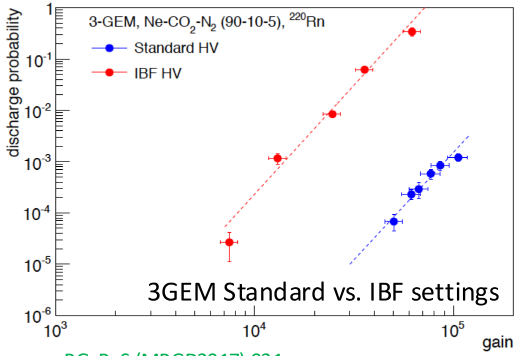




*ALICE TPC Upgrade TDR Addendum, CERN-LHCC-2015-002*

# GEM stacks

- GEMs are easy to stack
  - Build stacks, share charge between subsequent structures
  - Pre-amplification stage – lower gain of single structures
  - Charge spread between several independent holes – **$Q_{crit}$ per hole stays the same!**
- Optimized HV settings (lower amplification towards bottom of a stack)
  - Violated in case the stack optimized for low ion backflow (TPCs)
  - Adding further foils in the stack can improve its stability, e.g.:
    - 4GEM Readout for ALICE TPC (IBF optimized) - CERN-LHCC-2013-020, CERN-LHCC-2015-002
    - 5GEM RICH for eIC (stable operation at very high gains) - M. Blatnik et al., Trans. on Nucl. Sci. 62 (2015) 3256



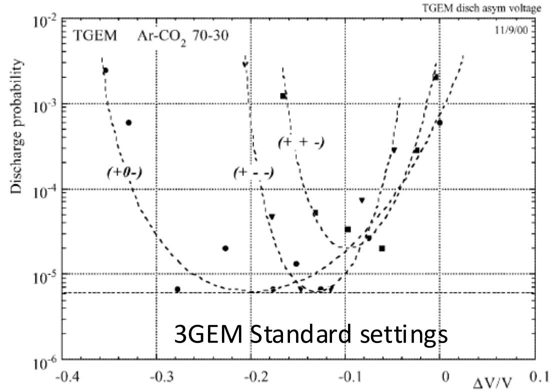

PG, PoS (MPGD2017) 031

Stability of a GEM stack operated in low-IBF mode can be restored by adding 4th GEM.

4GEM spark rates in $Ne\text{-}CO_2\text{-}N_2$ (90-10-5), G~2000:

- ~$10^{-10}$ 1/α
- $6.4\times10^{-12}$ 1/hadron

CERN-LHCC-2015-002

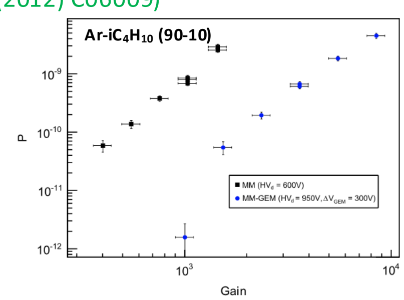


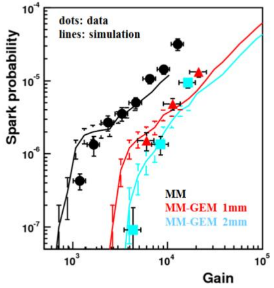

S. Bachmann *et al.*, NIM A 479 (2002) 294.

# Hybrid stacks (examples)

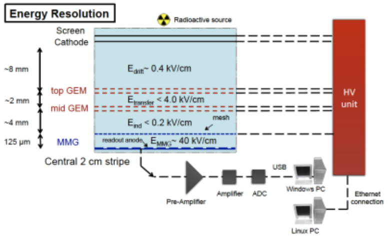
- GEM + MMG (e.g. B. Moreno et al, NIMA654(2011)135, S. Procureur et al. JINST 7 (2012) C06009)

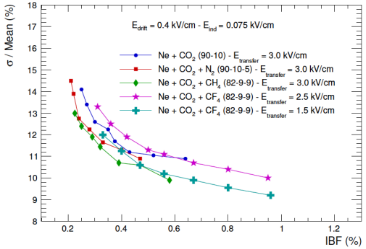
> - Clear influence of the pre-amplification stage (GEM) on the stability of MMG
> - Lower charge densities reach MMG (cf. 1 and 2 mm gaps)
> - Confirmed with GEANT simulations




- 2GEM + MMG in low-IBF mode (e.g. E. Aiola et al. NIM A 834 (2016) 149)



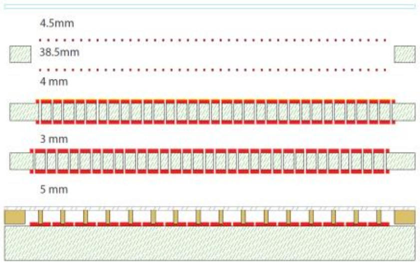

> **Spark rates at G~2000**
>
> $3\times10^{-7}$ 1/α in Ne-$CO_2$ (90-10)
>
> $2\times10^{8}$ 1/α in Ne-$CO_2$-$CH_4$ (82-9-9)
>
> $3.5\times10^{-10}$ 1/(150 GeV $\pi$) in Ne-$CO_2$-$N_2$ (90-10-5)

- COMPASS hybrid THGEM + Micromegas (e.g. F. Tessarotto, RD51 Meeting, Munich 2018 link)

THGEM

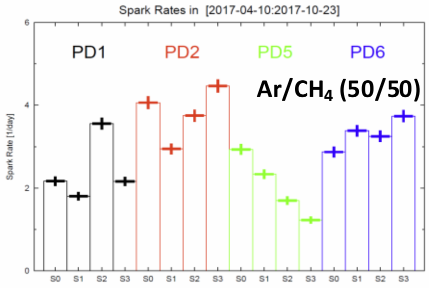
THGEM

MMG




> **Nominal G ~ 30000 with:**
>
> THGEM1 gain × T1 ~20
>
> THGEM2 gain × T2 ~15
>
> MMG gain ~100

Moderate gains of single structures

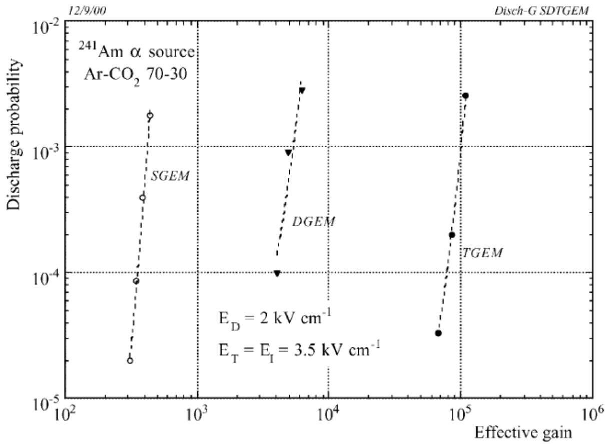


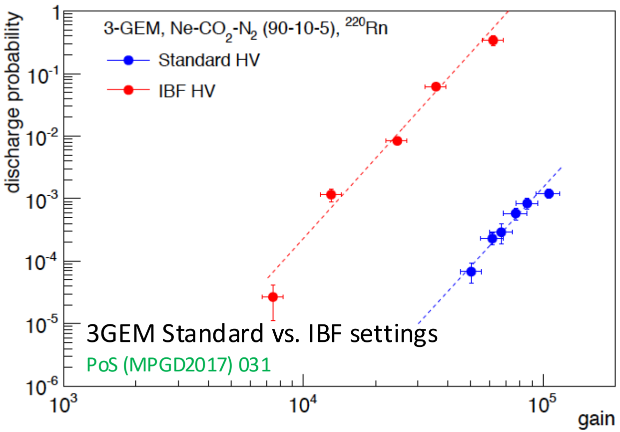

Moderate spark rate in all segments, constant in time

# Build stacks!

- GEMs are easy to stack
  - Build stacks, share charge between subsequent structures
  - Pre-amplification stage – lower gain of single structures
  - Charge spread between several independent holes – **$Q_{crit}$ per hole stays the same!**
- Optimized HV settings (lower amplification towards bottom of a stack)
  - Violated in case the stack optimized for low ion backflow (TPCs)
  - Adding further foils in the stack can improve its stability,

    → e.g. 4GEM Readout for ALICE TPC (IBF optimized)




3GEM Standard vs. IBF settings

PoS (MPGD2017) 031

Stability of a GEM stack operated in low-IBF mode can be restored by adding 4th GEM.

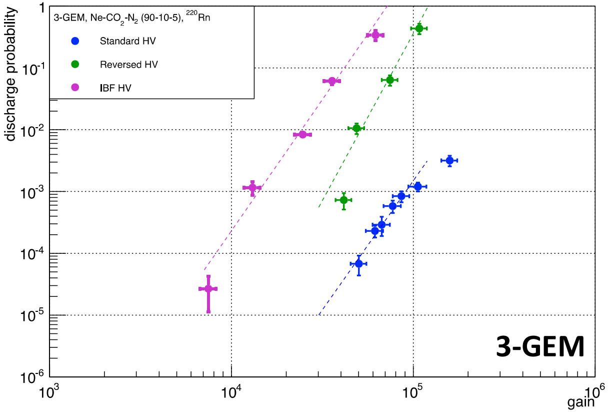
4GEM spark rates in $Ne-CO_2-N_2$ (90-10-5), G~2000:

- ~$10^{-10}$ 1/α
- $6.4\times10^{-12}$ 1/hadron

CERN-LHCC-2015-002

# DISCHARGE STUDIES

- Influence of HV settings




- Different HV settings have been tested with a 3-GEM configuration
- "<u>Standard</u>" → "<u>IBF</u>"
  - Standard – optimized for stability (COMPASS)
  - IBF → optimized for IBF
- Significant drop of stability while using IBF settings with a typical 3-GEM configuration

- **4-GEM configuration,** optimized for energy resolution and IBF is also stable against electrical discharges

| | S-S-S 'standard' HV G = 2000 | S-S-S-S *IB* = 2.0% G = 2000 | *IB* = 0.34% G = 1600 | S-LP-LP-S *IB* = 0.34% G = 3000 | *IB* = 0.34% G = 5000 | *IB* = 0.63% G = 2000 |
|---|---|---|---|---|---|---|
| $^{220}$Rn<br>$E_\alpha$ = 6.4 MeV<br>rate = 0.2 Hz | $\sim 10^{-10}$ | | | $< 2\times10^{-6}$ | $< 7.6\times10^{-7}$ | |
| $^{241}$Am<br>$E_\alpha$ = 5.5 MeV<br>rate = 11 kHz | | | | | | $< 1.5\times10^{-10}$ |
| $^{239}$Pu+$^{241}$Am+$^{244}$Cm<br>$E_\alpha$ = 5.2+5.5+5.8 MeV<br>rate = 600 Hz | | $< 2.7\times10^{-9}$ | $< 2.3\times10^{-9}$ | $(3.1\pm0.8)\times10^{-8}$ | | $< 3.1\times10^{-9}$ |
| $^{90}$Sr<br>$E_\beta$ < 2.3 MeV<br>rate = 60 kHz | | | | | $< 3\times10^{-12}$ | |

# Hybrid stacks (example)

GEM + MMG (e.g. B. Moreno et al, NIMA654(2011)135, S. Procureur et al. JINST 7 (2012) C06009)

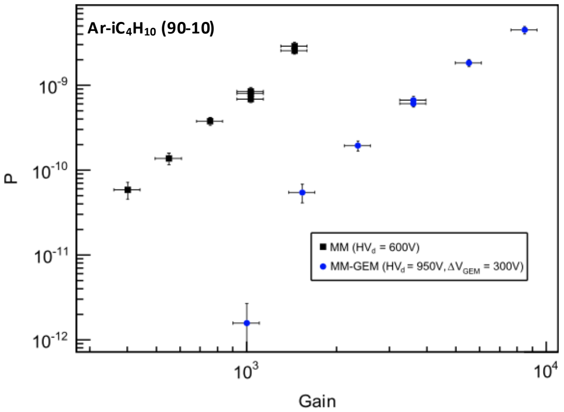
- Clear influence of the pre-amplification stage (GEM) on the stability of MMG
- Lower charge densities reach MMG (cf. 1 and 2 mm gaps)
- Confirmed with GEANT simulations
- GEM+MMG characterized by good ion backflow performance

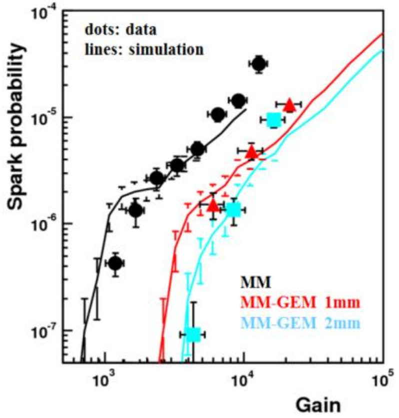
  (e.g. E. Aiola et al. NIM A 834 (2016) 149)
- Considered for future CEPC TPC (China) or HYDRA TPC at R3B (GSI)

  H. Qi, Joint Workshop of CEPC , April, 15, 2021

- **Room for optimization ➞ Micromegas mesh geometry**

  **(small cells for low charge densities in single cells)**



# Electric field above GEM

- Clear influence of a field **above** the GEM on its stability
- Correlation with drift parameters: diffusion → charge density → discharge probability
- Increase for $E$ < 400 V/cm not related to gain
- Drop for $E$ > 400 V/cm not related to the collection efficiency