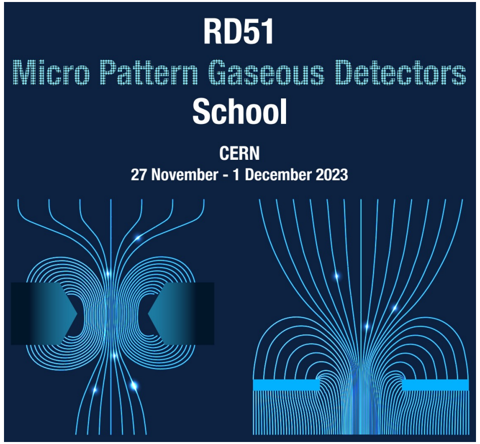
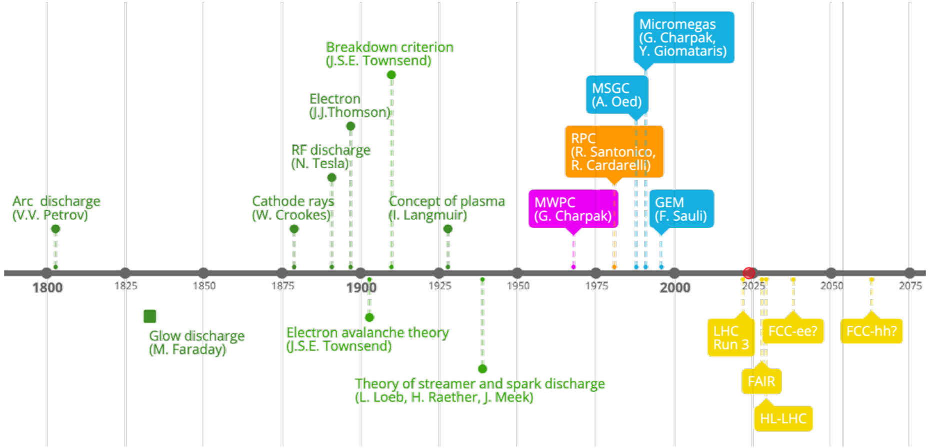
GASEOUS DETECTORS PHYSICS II

"BEYOND STABILITY POINT"



Piotr Gasik

Why studying gas discharges in MPGDs?



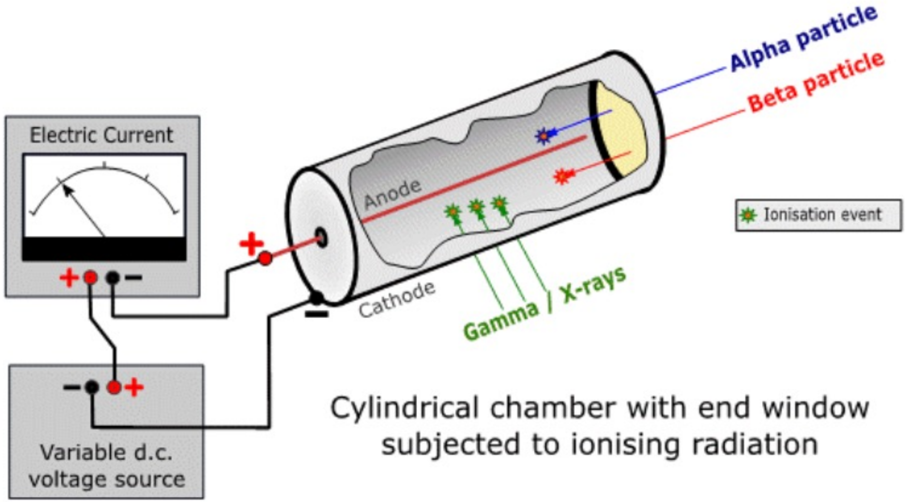
- Gas discharge physics is one of the best-known fields of modern physics
- >200 years since the discovery of the arc discharge by V.V. Petrov
- Still, the main limiting factor for the stable operation of gaseous detectors
- Understanding gas discharges helps to avoid their occurrence and mitigate their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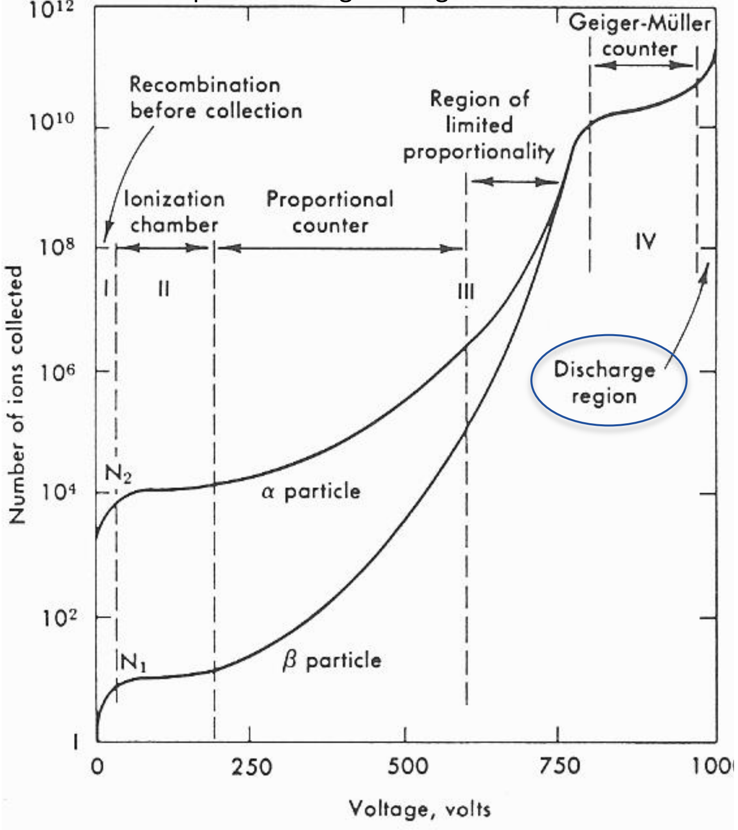
Operational regions of gaseous detectors

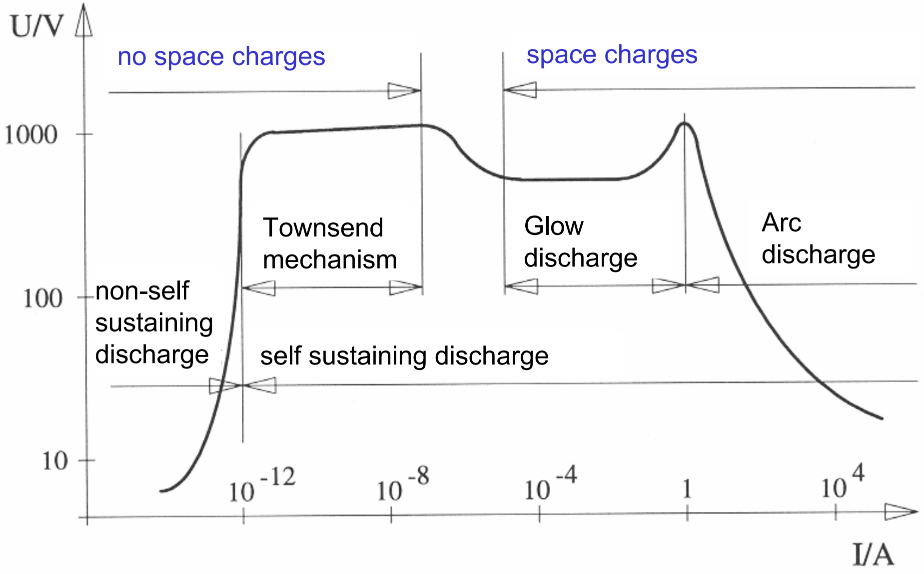


A.C. Melissinos, *„Experiments in modern physics“*, Academic Press (1966) NY

Volt-ampere characteristic curve in low pressure

Two discharge categories

- Non self-sustaining
- Self-sustaining

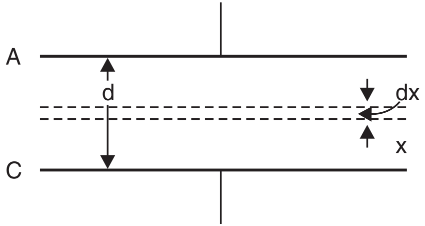


In the continuous discharge region, a steady discharge current flows. The applied voltage is so high (breakdown voltage V_S) that, once ionization takes place in the gas, there is a continuous discharge of electricity, so that the detector cannot be used for radiation detection.

Discharge/Breakdown/Spark – often used interchangeably!

Townsend mechanism

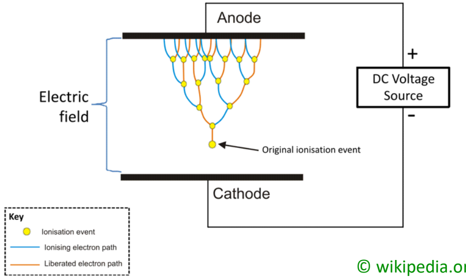
- Go back to the principles: Townsend **first** ionization coefficient α



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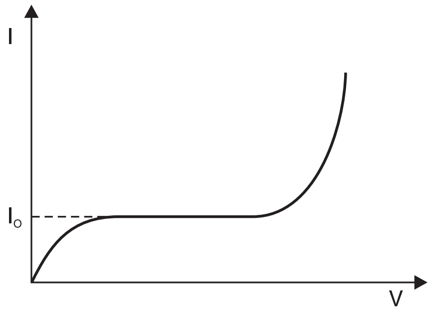
- $e^{\alpha d}$ – electron avalanche

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

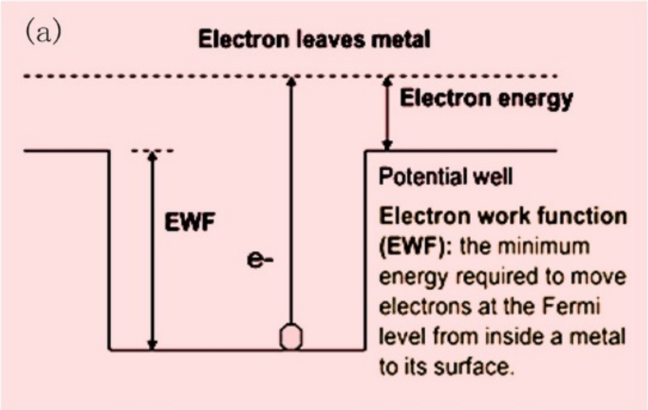


- Townsend **second** ionization coefficient β

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

Cathode processes

- Third Townsend coefficient: electrode surface ionization coefficient γ
- 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)

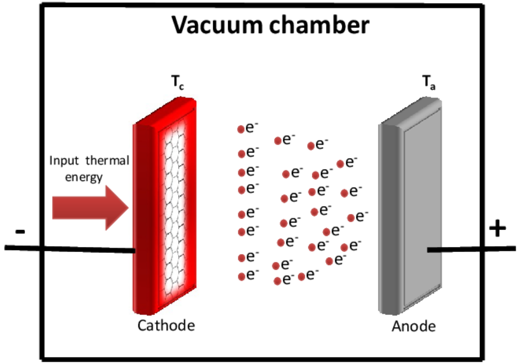
How to release an electron from the cathode?

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, λ_R – material-specific constant, A_0 – universal constant

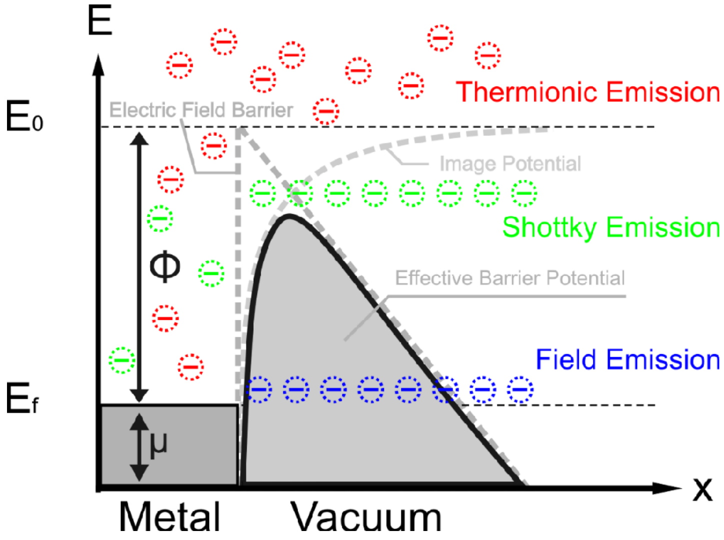
- **Current density increases with decrease in work function and increase in temperature.**



How to release an electron from the cathode?

Field electron emission

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

- Schottky effect (enhanced thermionic emission)
  - Wide range of temperature and electric fields
- Fowler-Nordheim tunneling
  - 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.

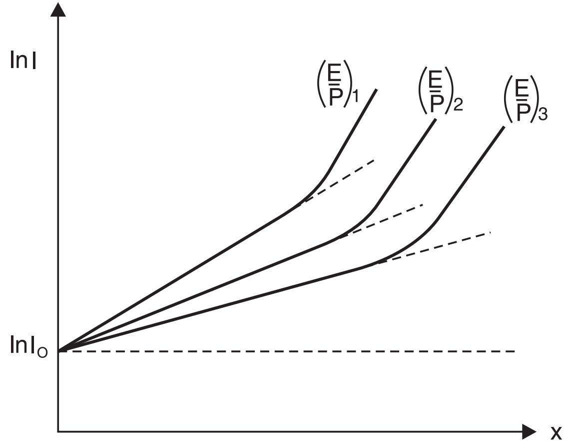
How to release an electron from the cathode?

Secondary emission

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

  (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 $\boldsymbol{\gamma}$

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



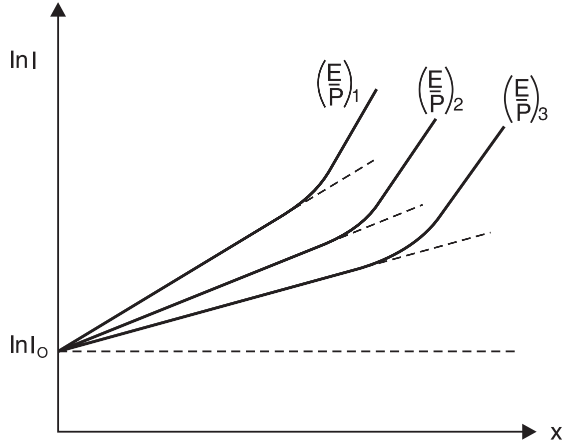
How to release an electron from the cathode?

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 $\boldsymbol{\gamma}$

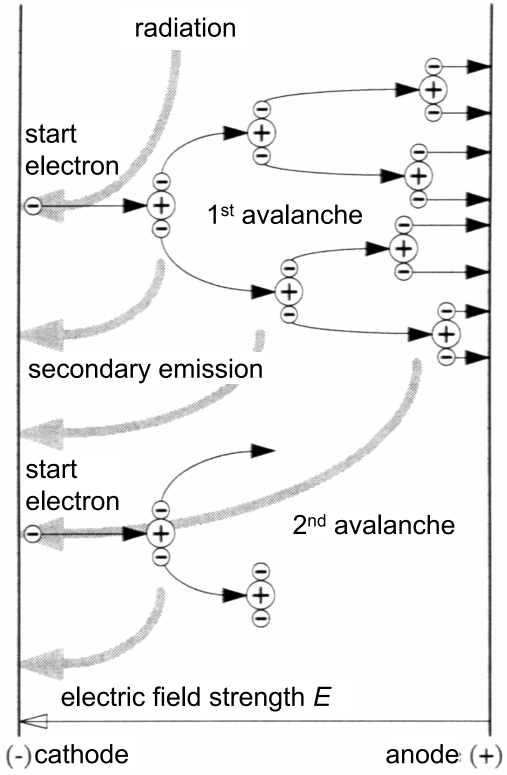
$$\gamma = \frac{\text{number of released free electrons from the electrode surface}}{\text{number of positive ions}}$$



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, $\gamma = \gamma_1 + \gamma_2 + \gamma_3 + \ldots$
- $\gamma = f(E/p$, electrode material, surface condition, gas)
- Townsend avalanche:

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

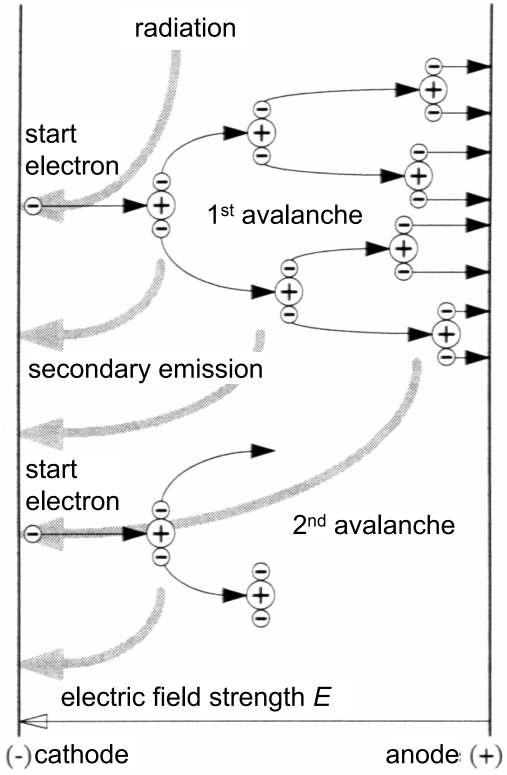


Townsend breakdown mechanism

- 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.

$$I = \frac{I_0 e^{\alpha d}}{1 - \gamma\left(e^{\alpha d} - 1\right)}$$

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

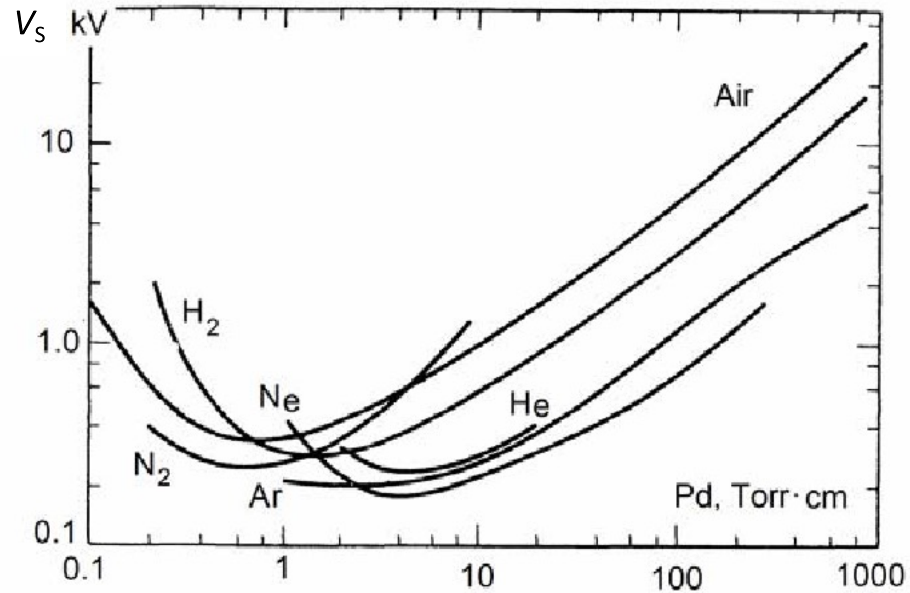


Paschen's law

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

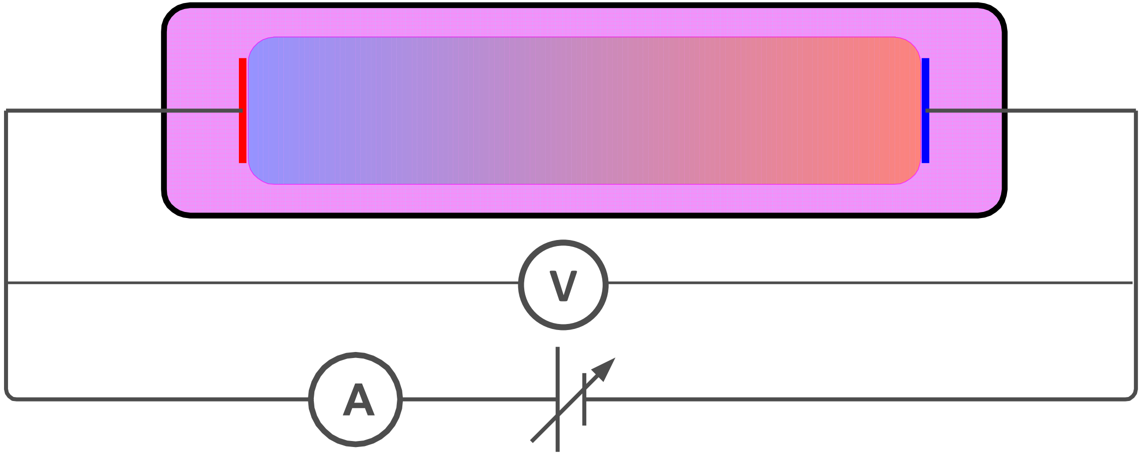
$$V_S = \frac{Bpd}{\ln(Apd) - \ln\left[\ln\left(1 + \frac{1}{\gamma_{se}}\right)\right]}$$

- 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



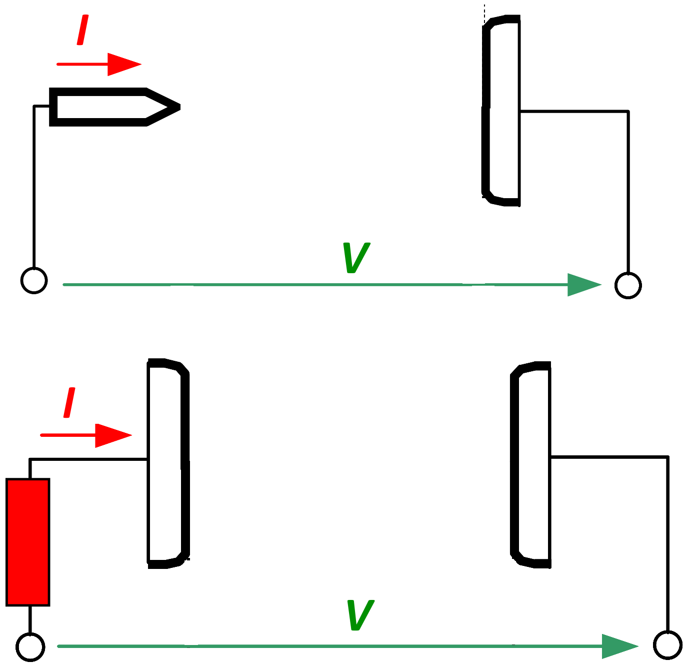
- Record current *I* and potential *V*, for different gas pressure *P* and temperature *T*
- Current reflects a discharge: charge separation
- Watch through the glass tube

Different types of discharges

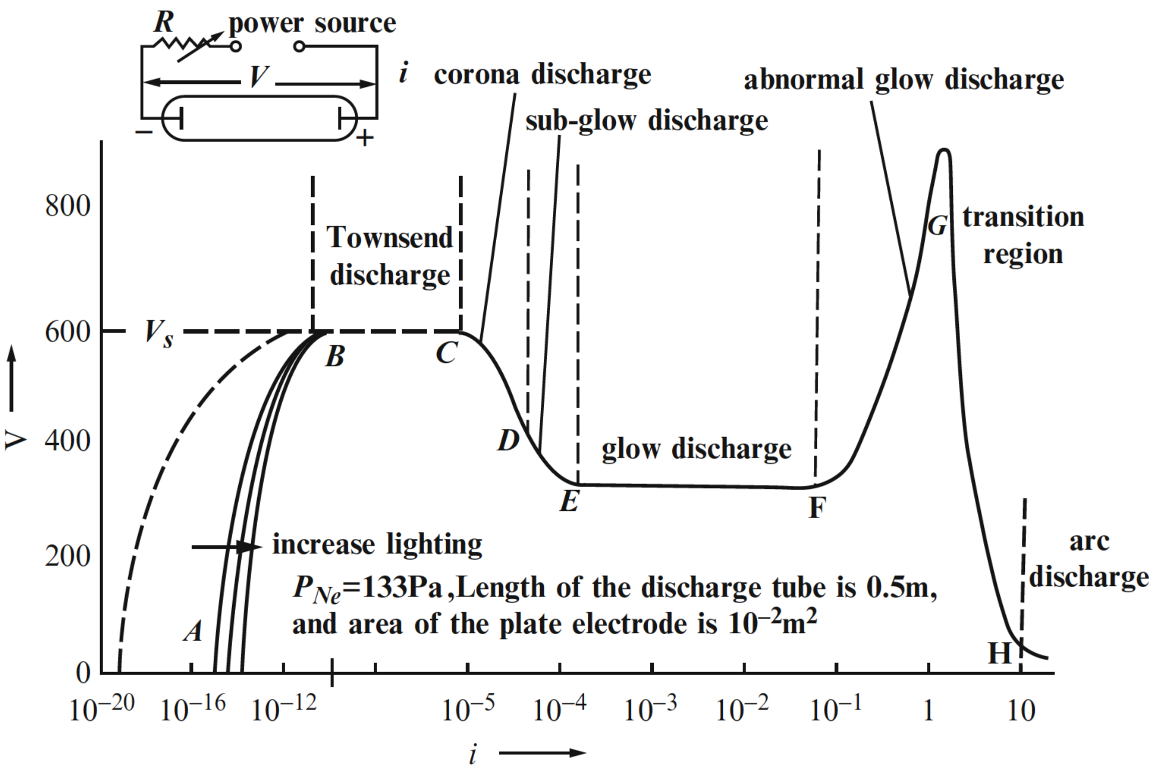
- Breakdown voltage V_S reached

- Circuit **with current limitation:**
  - inhomogeneous field
  - homogeneous field with high series resistance

- Observed effects
  - pre-discharges, corona
  - visible glow
  - partial discharge inception voltage



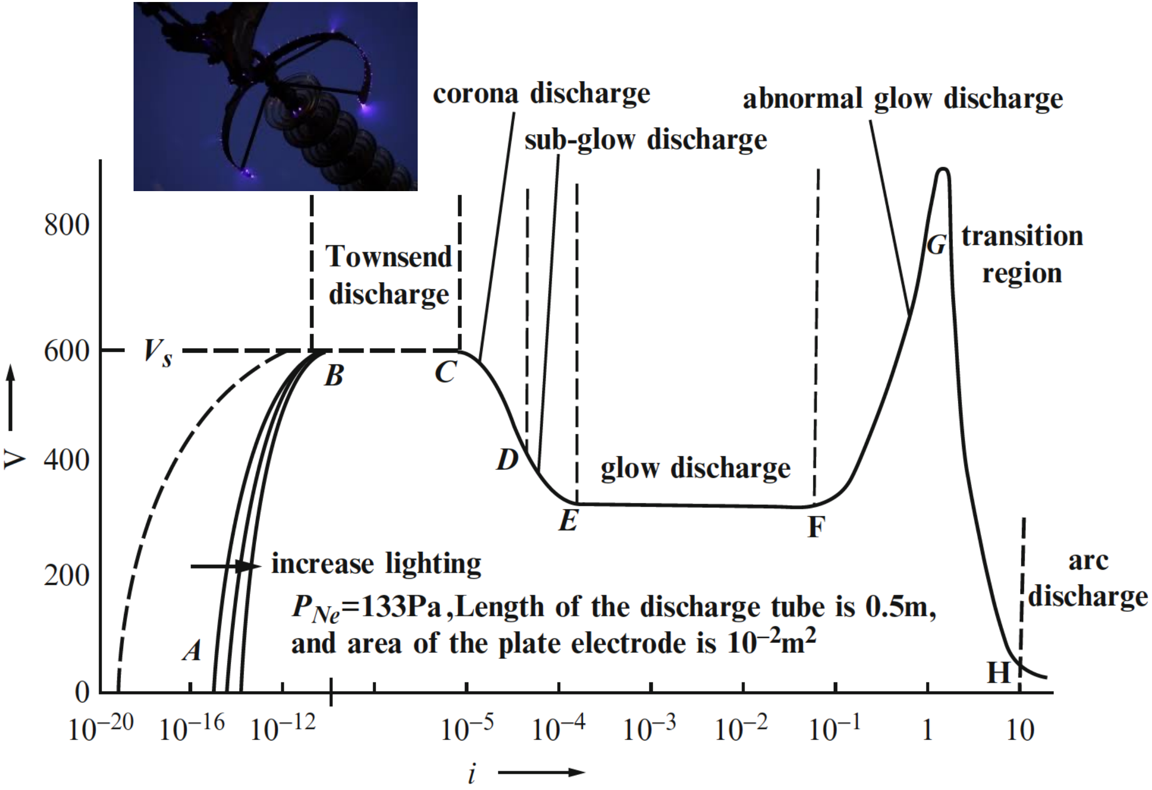
Volt-ampere characteristic curve in low pressure



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

Volt-ampere characteristic curve in low pressure

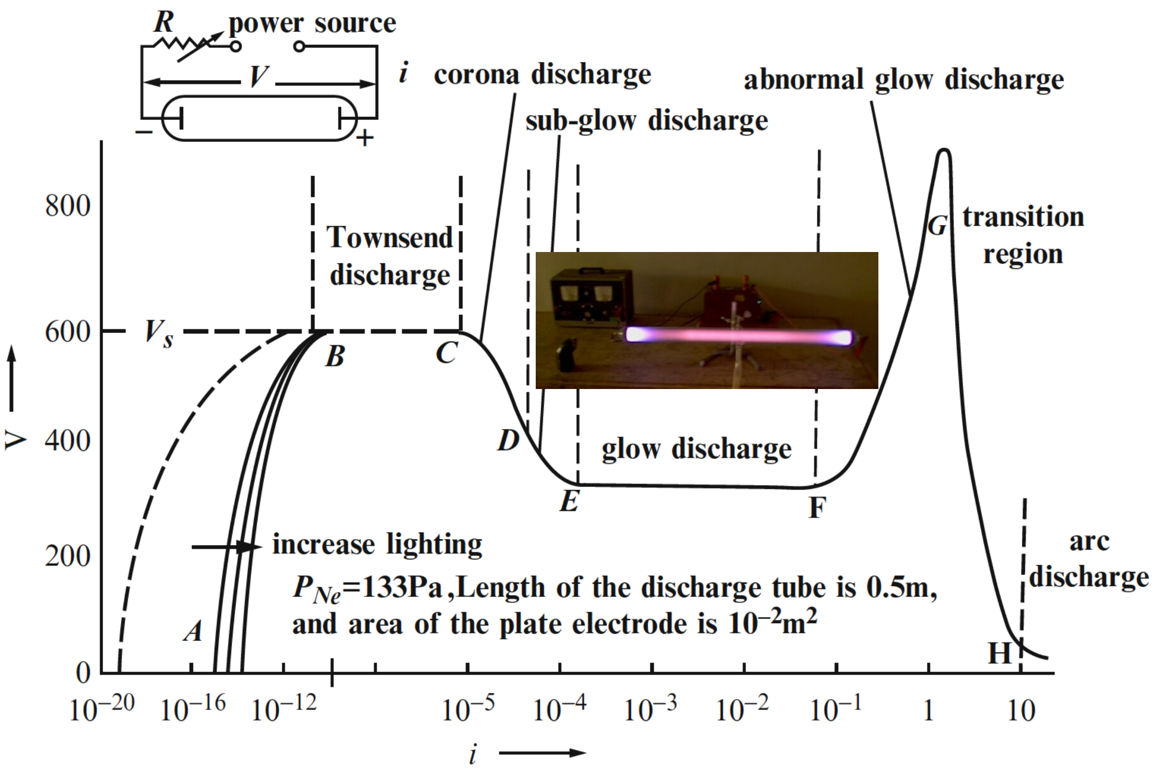
- In strongly non-uniform fields
  - around sharp points or wires
- A radiant corona around the critical region
  - indication of defects in the system
- Can be a special case of either glow or arc discharge
- “Single-electrode discharge”
- Possibly caused by secondary photo-processes in the gas near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



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

Volt-ampere characteristic curve in low pressure

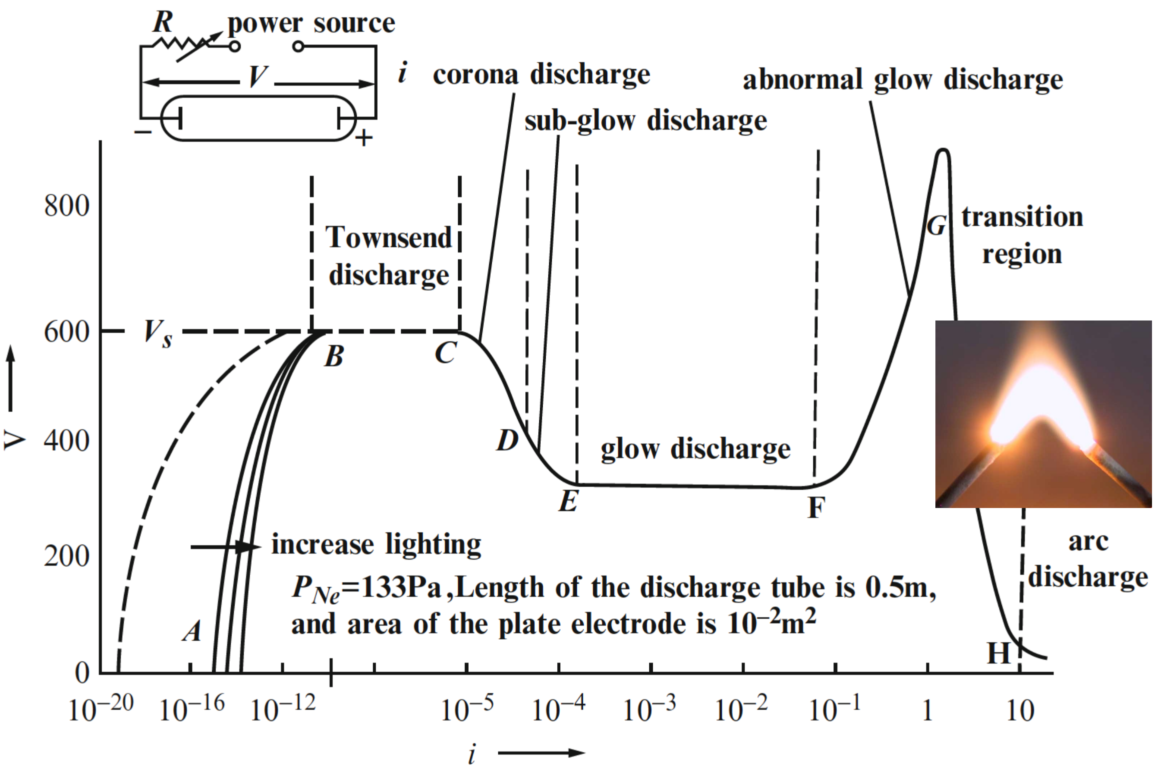
- Low pressure, current limited circuit
  - relatively low currents
  - radiant column between electrodes (neon light)
- Weakly ionised gas, mainly neutral: non-equilibrium plasma
  - $E_e >> E_{gas}$
  - T_e (10^4 K) >> T_{gas}
- Gas does not get hot
- Feedback: secondary emission from the cathode by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



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

Volt-ampere characteristic curve in low pressure

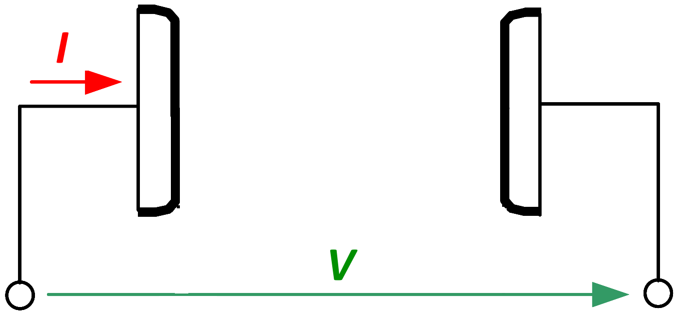
- Ambient pressure, no current limit
  - bright column between electrodes
  - high current
- Thermal equilibrium plasma
  - $T_e \sim T_{gas} > 10^4$ K
  - High ionisation
- Feedback: thermionic knock-out of electrons from the cathode



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

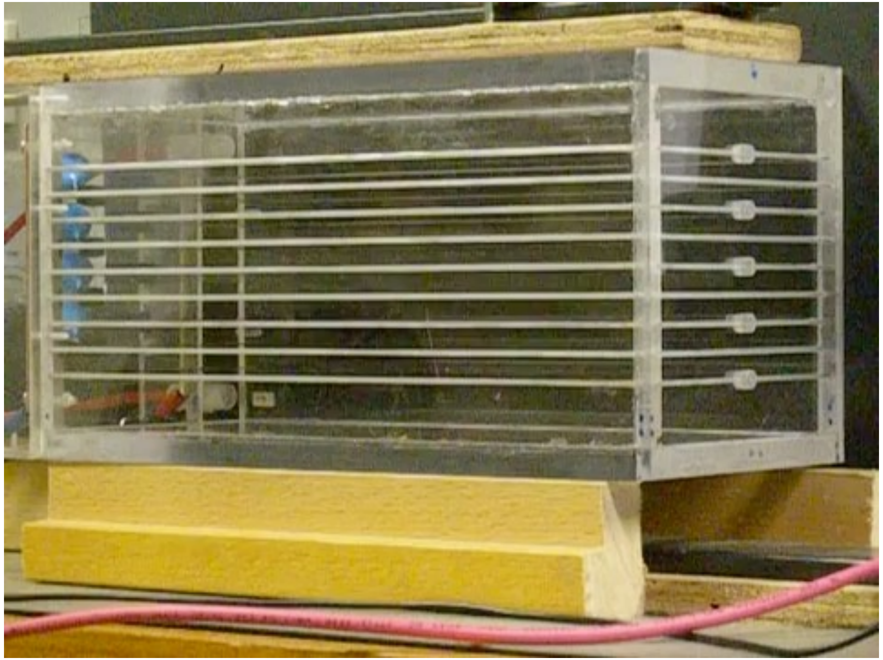
Full breakdown

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



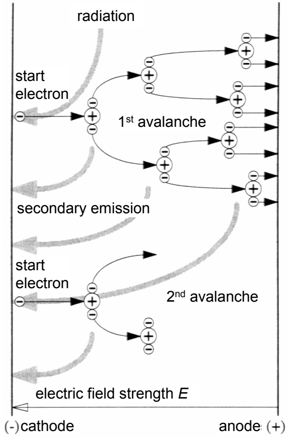
Spark discharge

- 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)

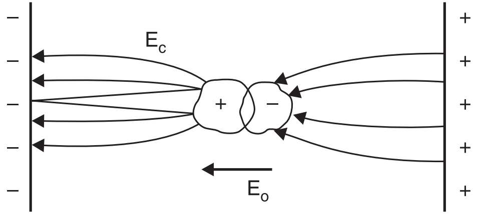


limitations of Townsend theory

- **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

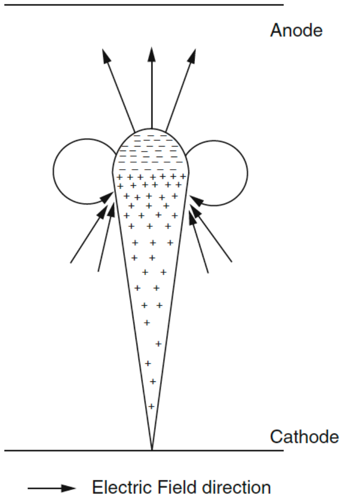


- **H. Raether, L.B. Loeb, J.B. Meek – streamer theory of spark discharge**
  - Improvement of the Townsend discharge theory (derived from the latter)
  - Electron impact ionization (determined by an α process of Townsend discharge),
  - Photoionization
  - Space-charge electric field effect caused by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

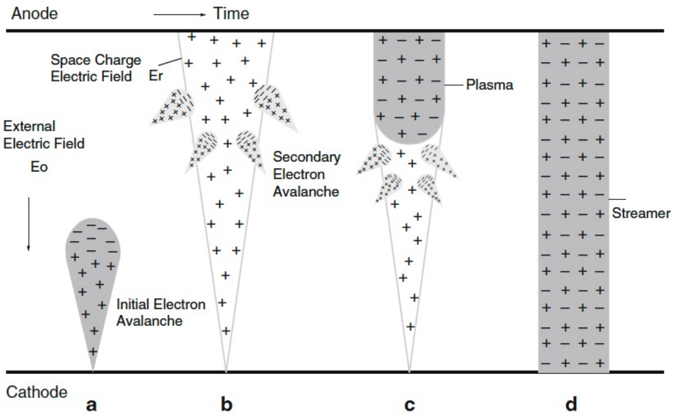
- **Raether criterion:** $Q_{max} = e^{\alpha d} > 10^8$ is the condition for streamer formation and self-sustained discharge (as in Townsend)

- **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 0.7×10^{12} cm^{-3} to ensure sufficient photoionisation)

Streamer theory

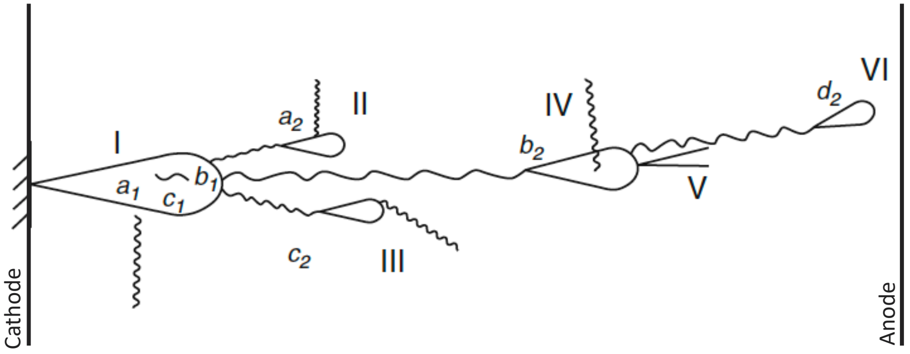
Following: D. Xiao, „Gas Discharge and Gas Insulation“, Springer 2016



- 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

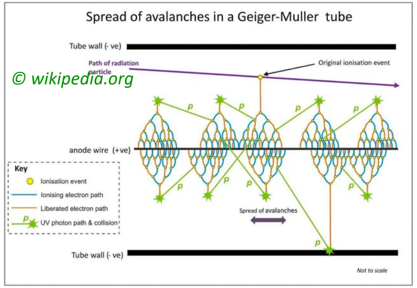


- Applied voltage > breakdown voltage (V_S) ⟶ **negative streamer formation**
- No need for the electron avalanche to go through the gap
- Ionization degree of the avalanche head part sufficient to form a streamer (photon emission)
- Streamer develops towards the anode (volume- and photoionization)
-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

GASEOUS DETECTORS DISCHARGES

Discharges in wire counters

- **Operation beyond proportional mode**



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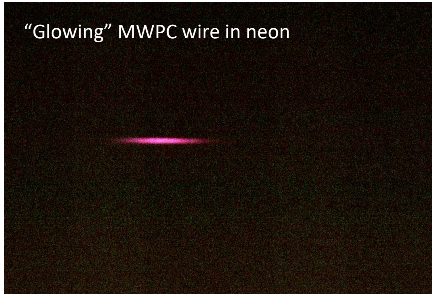
- **Geiger mode**
  - Poorly quenched gases, low pressures
  - Photon mediated avalanche propagated in both directions along the wire
  - Quenched with an external circuit (*R*) or space-charge effects (quenched gases)

- **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!

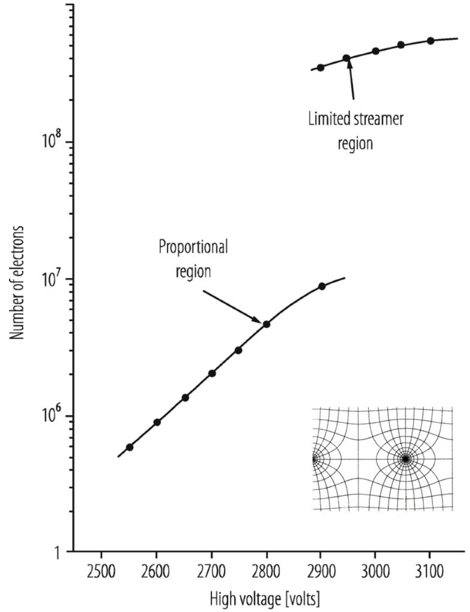


© Courtesy of C. Garabatos

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

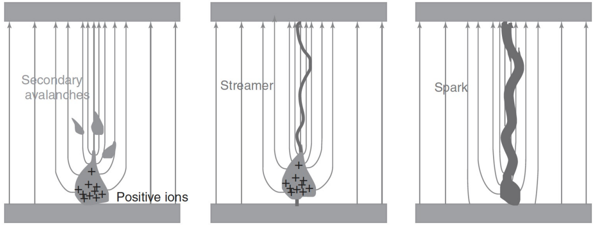


M. Atac, A.V. Tollestrup, D. Potter, NIM 200 (1982) 345.

- **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
  - Rather destructive

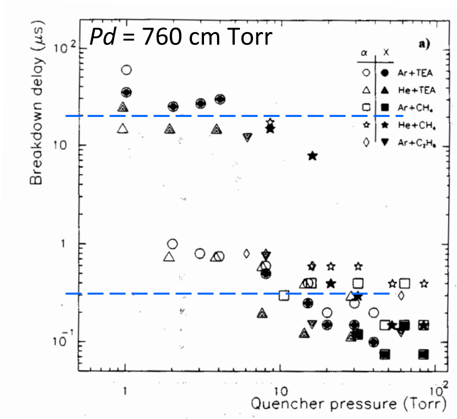
Discharges in parallel-plate avalanche counters

- Both Townsend (slow) and Streamer (fast) breakdown modes observed
- In uniform, parallel fields streamer develops until spark channel is created (no SQS, full breakdown)

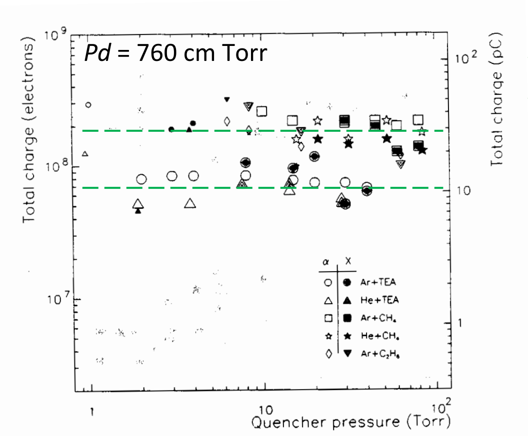


M. Abbrescia, P. Fonte, V. Peskov, Wiley-VCH Verlag GmbH & Co. KGaA, 2018

- 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?**



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



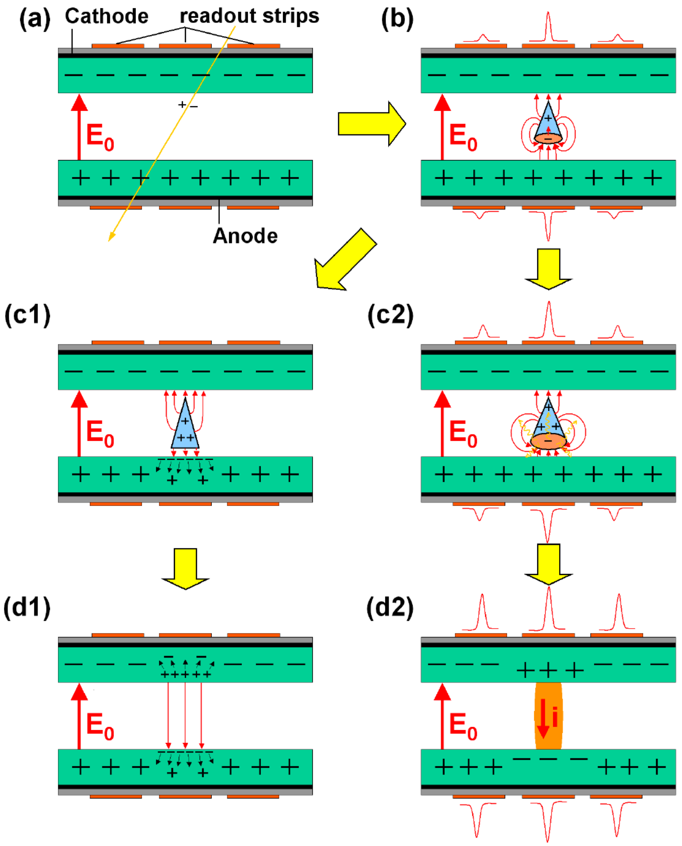
P. Fonte, V. Peskov, F. Sauli, NIM A 305 (1991) 91

Resistive plate chambers

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

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

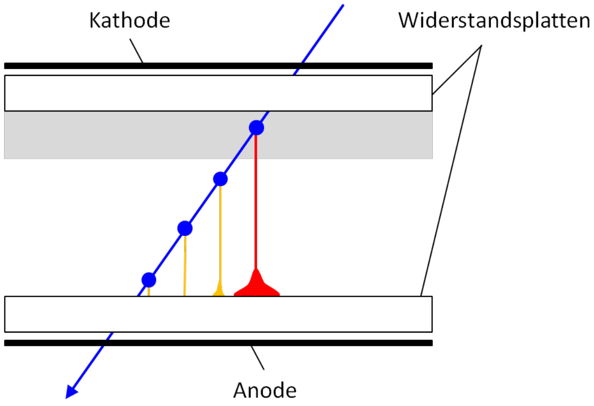
- With $\rho \approx 10^{10} - 10^{12}$ Ωcm, $\tau \approx 0.01 - 1$ s
- Remaining counter area is still sensitive to particles
- Streamer development by photon feedback → a discharge channel is created (spark). The released energy, however, is strongly limited by the resistance of the plate!



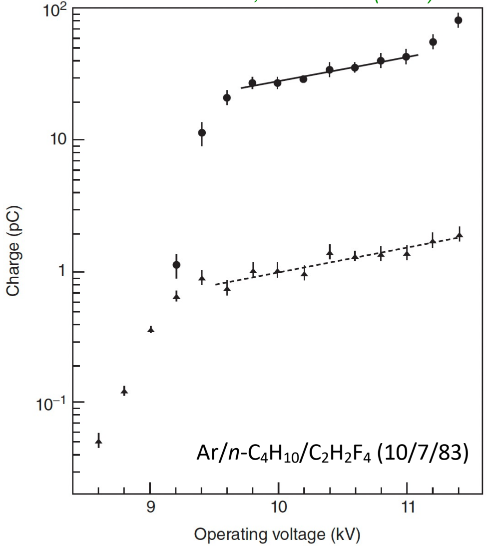
© Courtesy of I. Deppner, Uni HD

Resistive Plate Chambers

- The transition from a proportional avalanche to a streamer at $Q_{crit} \approx 10^8\, e$
- Material with high-volume resistivity ➞ drop of the electric field around the initial avalanche ➞ remaining counter area remains sensitive to particles
- Reduce photon feedback and the avalanche growth with a properly quenched mixture (e.g. $C_2F_4H_2$, SF_6, …) ➞ reduce streamer probability



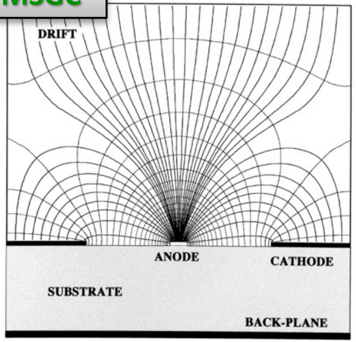
R. Cardarelli et al., NIM A 382 (1996) 470



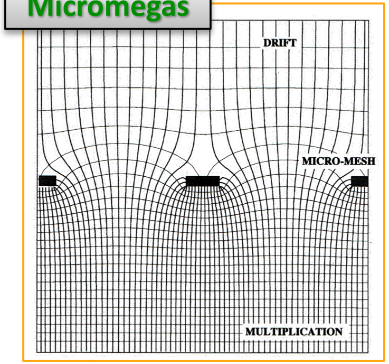
Discharges in MPGDs

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

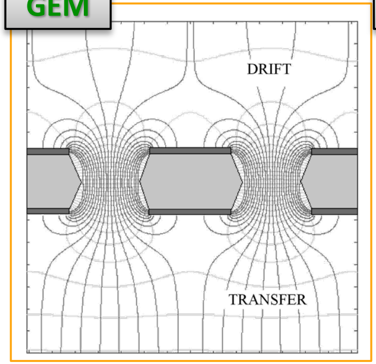
MSGC



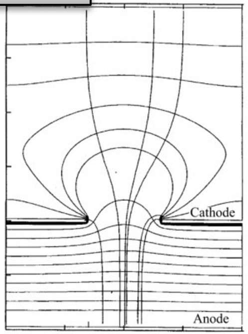
Micromegas



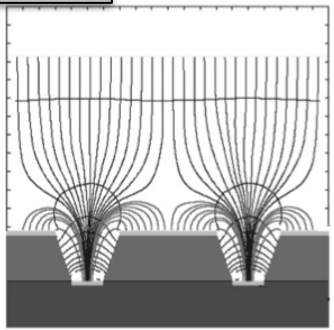
GEM



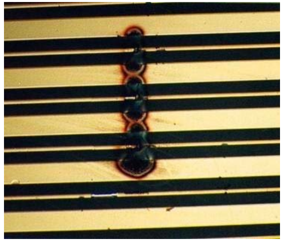
CAT



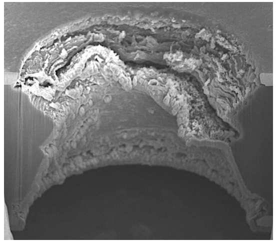
MGC

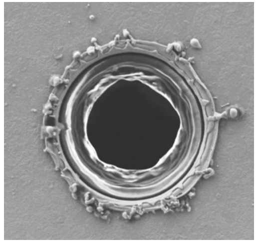


- In all these structures, there are regions with ~parallel field lines
- Streamers can develop by the same mechanism as in PPAC
- No quenching by field reduction, when streamers reaches the cathode → full breakdown

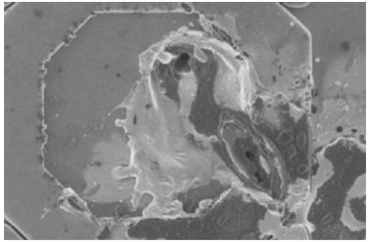


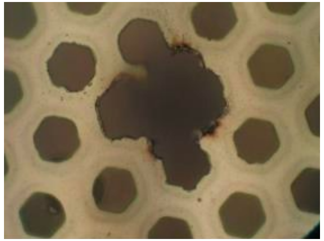
F.Sauli, IEEE NSS 2002



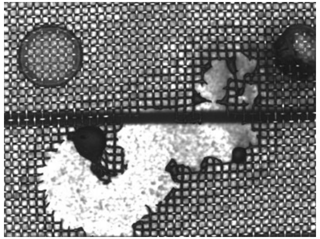


J. Merlin, *“Single-hole discharges in GEMs”*, RD51 Meeting, TUM 2018 (link)





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



J.Galan, RD51 meeting (link)

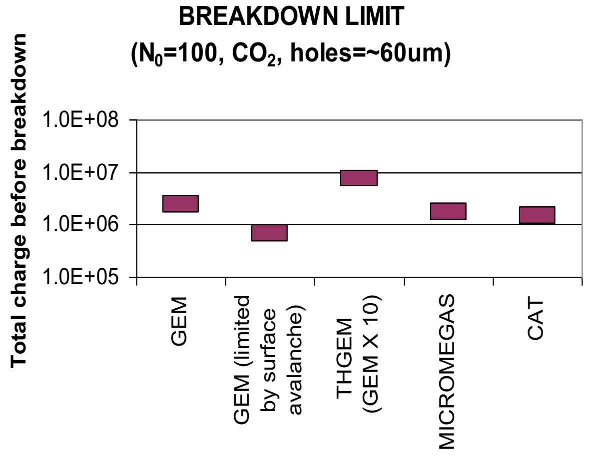
Critical charge in MPGDs

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

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	$4\ 10^7$

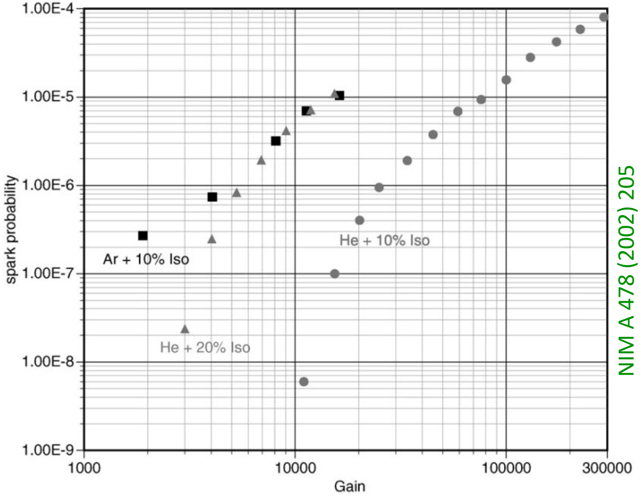
P. Fonte, Simulations of discharge phenomena, RD51 meeting, Munich, 2018



GEM Discharge probability

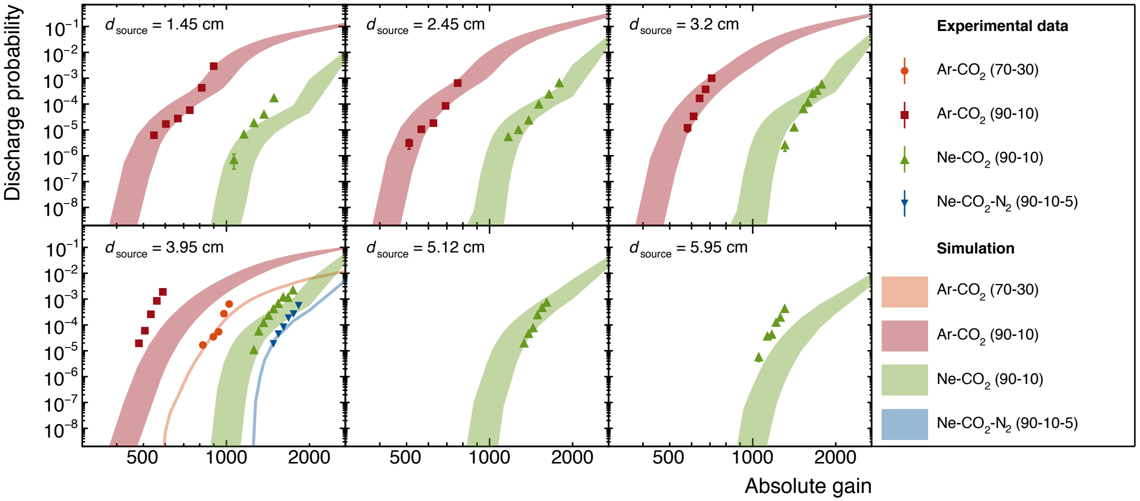
- Clear gas dependencies
- Discharge probability reduced for lighter gases ➞ charge density
- Clear correlation between discharge rate and ⟨Z⟩ of a gas mixture

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



NIM A 478 (2002) 205

GEMs
Alpha particles

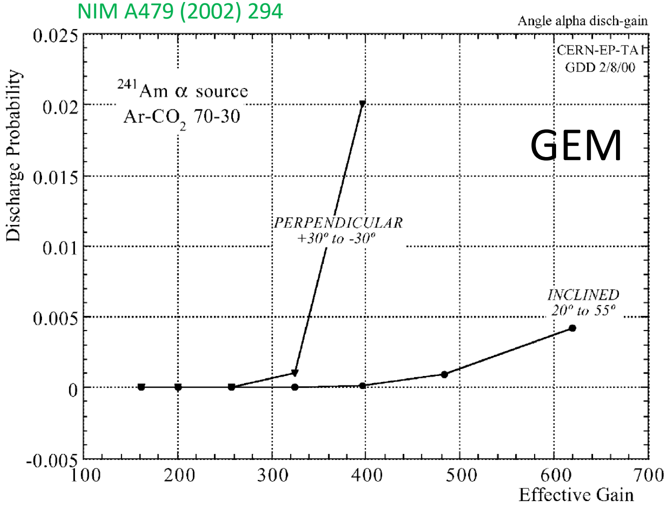


NIM A 870 (2017) 116

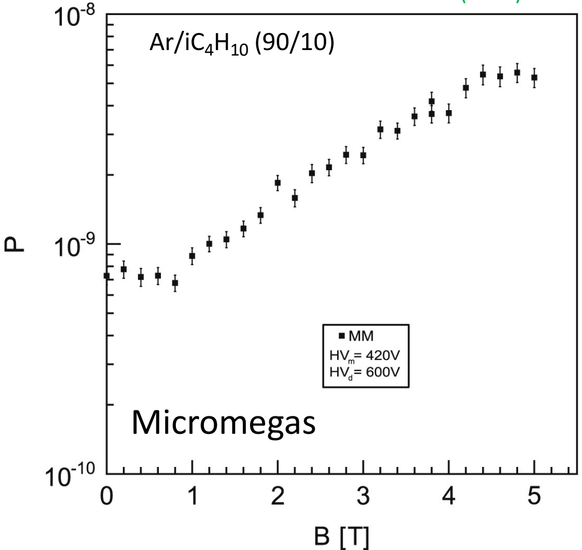
Charge density limit

- 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



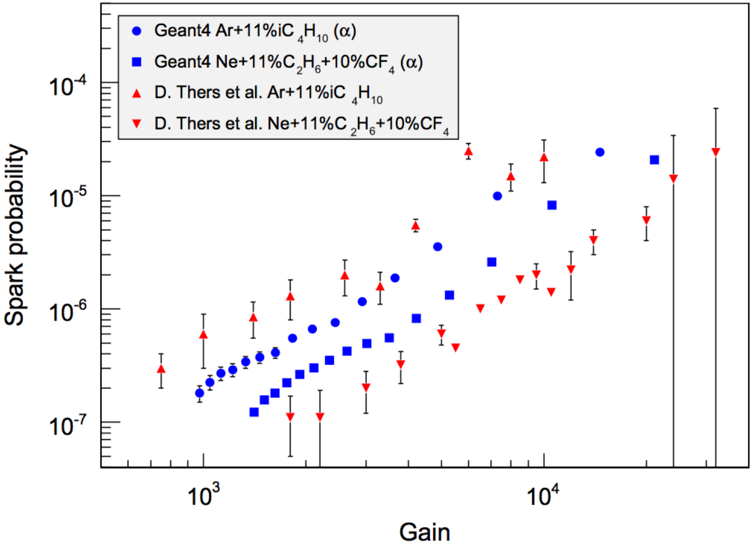
NIM A654 (2011) 135



Critical charge in different gases

- Simulations cannot describe Ne- and Ar- data using only W_i (effective ionization potential) weights
- Intrinsic properties of the working gas (transport, amplification, streamer development) could possibly explain the differences – more studies needed
- Model fits to GEM/THGEM data indicate different Q_{crit} values for different gas mitures

NIM A621 (2010) 177

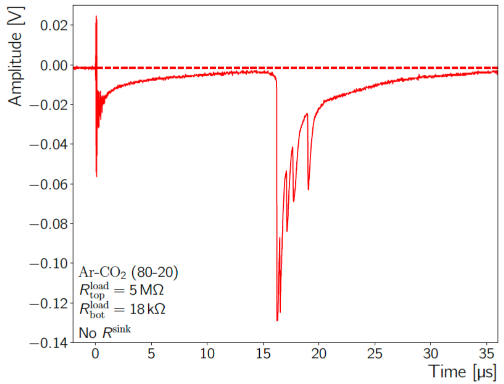


NIM A 1047 (2023) 167730

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	–

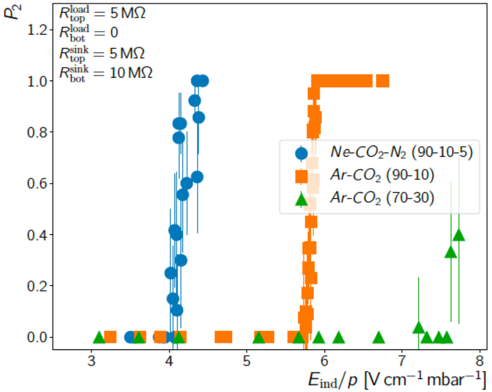
Secondary discharge formation*

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

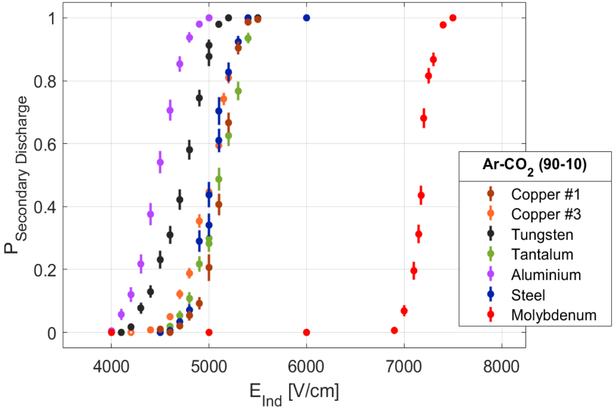


- Leading theory: heating of the cathode after the primary discharge
  - A. Deisting, et al. NIM A 937 (2019) 168
  - A. Utrobicic, et al. NIM A 940 (2019) 262
- Transition between Townsend discharge and Streamer discharge?
  - Dependence on gas (α process) and cathode? (γ process - feeding)
  - Time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

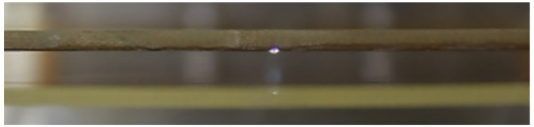
A. Deisting, et al. NIM A 937 (2019) 168



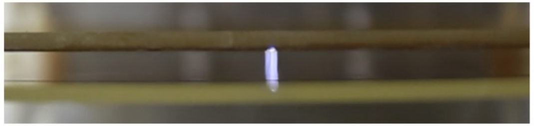
B. Ulukutlu, *RD51 Meeting, June 2020 (link)*



a) Primary discharge



b) Secondary discharge



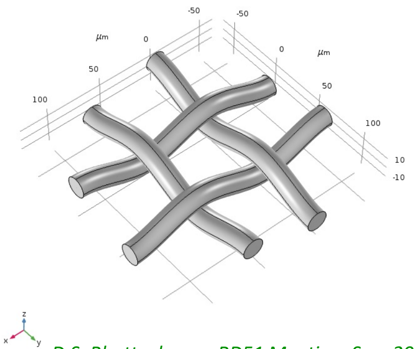
A. Deisting, et al. NIM A 937 (2019) 168

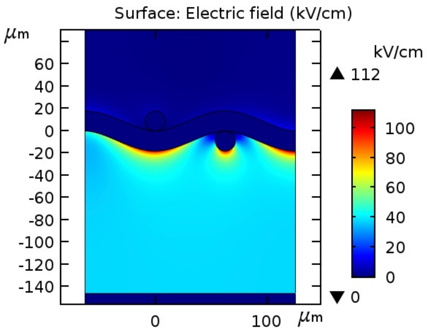
A. Utrobičić et al. MPGD 2019, La Rochelle

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

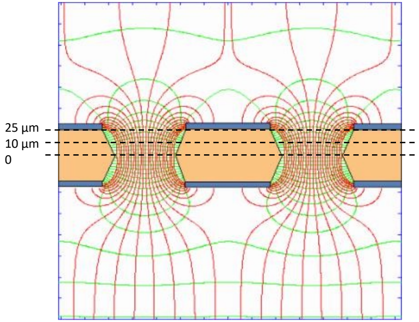
Further reduction of stability

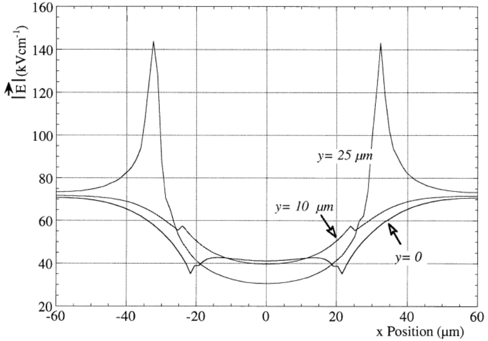
- High fields, cathode material quality may further reduce stability of your detector





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

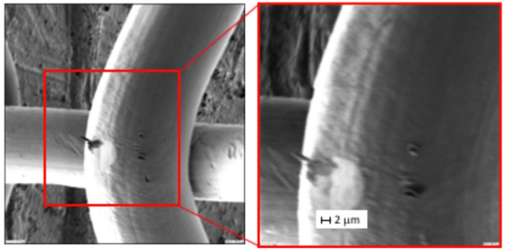




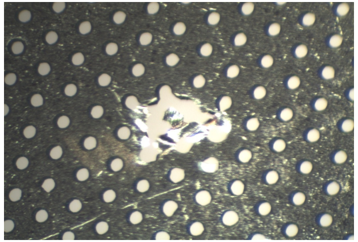
NIM A 438 (1999) 376

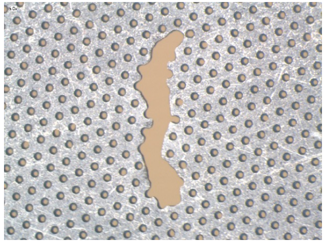
- High E-fields present in amplification regions (the curse of Micro-Patterns); can easily double/triple the average
- Detector QA of the highest importance: cannot analyze the entire surface → HV tests @ Paschen limit

(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)



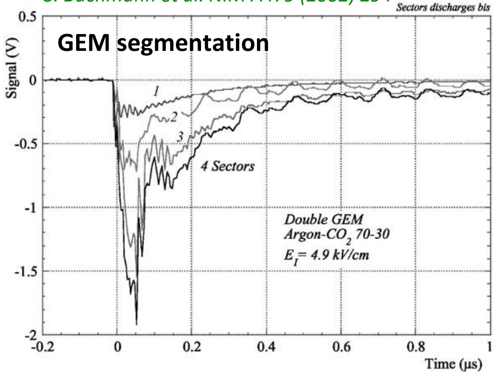


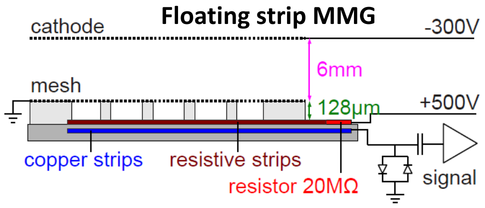
© ALICE

MPGD design good practices

- Segmentation
  - Reduce area → capacitance
  - Reduce energy of a discharge (also for secondary sparks)
  - Minimize dead time

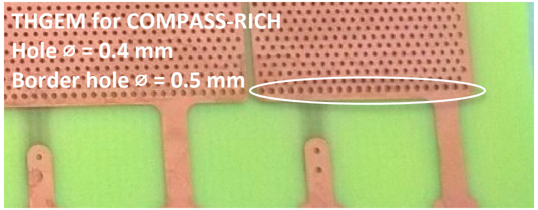
S. Bachmann et al. NIM A479 (2002) 294



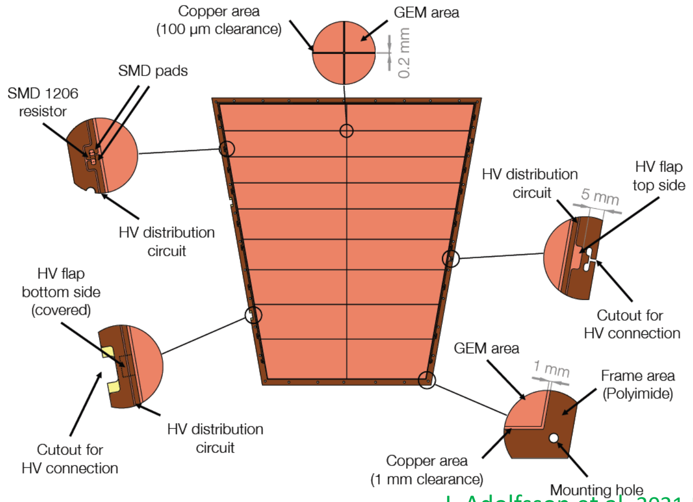


© J. Bortfeldt, Ph.D. Thesis, LMU, 2015.

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



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

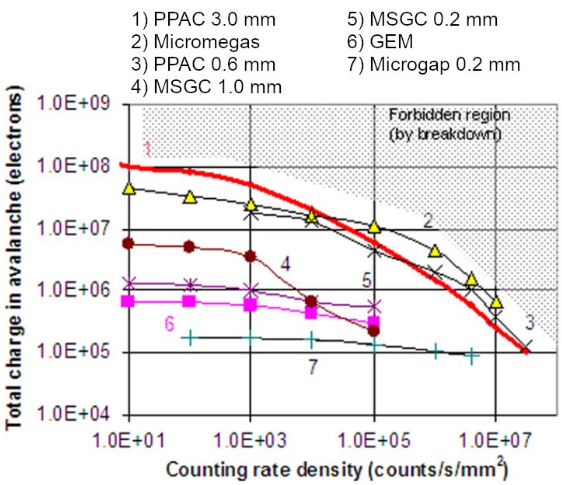


J. Adolfsson et al. 2021 JINST 16 P03022

Discharge limits, high rates

- Critical charge limits and max-gain rate dependency
- Overlap of avalanches may further reduce the stability of the detector
- Unlikely even at the highest rates and moderate gains

  (e.g. LHCb GEMs, COMPASS GEM and MMG, 0.5-1.0 MHz/cm^2)

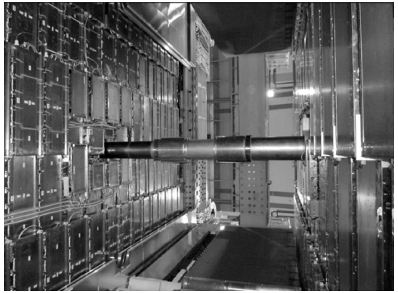


Plasma Sources Sci. Technol. ***19*** *(2010) 034021*

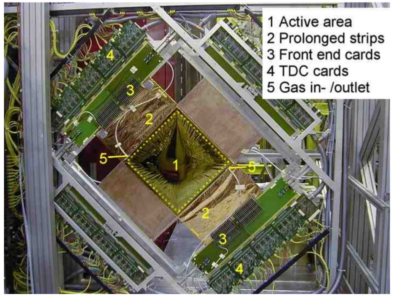
Troublemakers:

- Cathode excitation, electron jets, etc.
- Highly Ionizing fragments ($N_{prim,\alpha} = 10^4 \times N_{prim,MIP}$), high neutron doses
- Wide dynamic range operation (e.g. Active Target TPCs)
- Challenges wrt. loads and performance (e.g. low IBF)

The stability of your system relies on the fundamental stability limits of a single amplification structure.



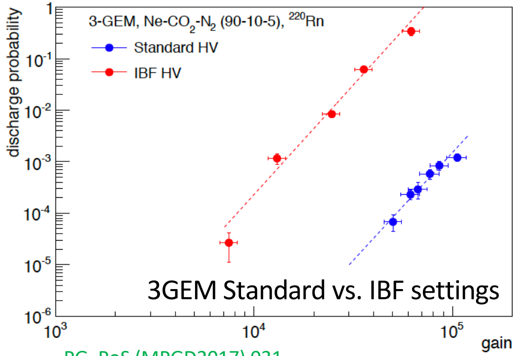
© LHCb GEM Tracker



©COMPASS MMG detector

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



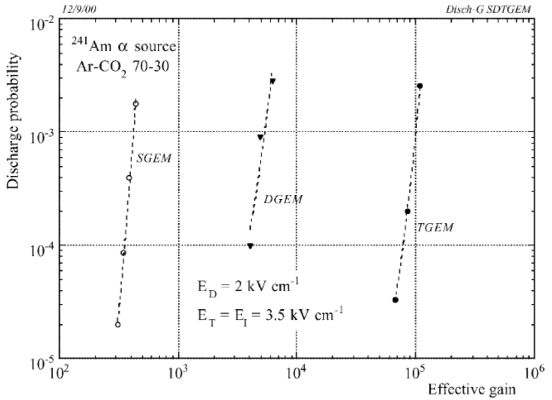
PG, PoS (MPGD2017) 031

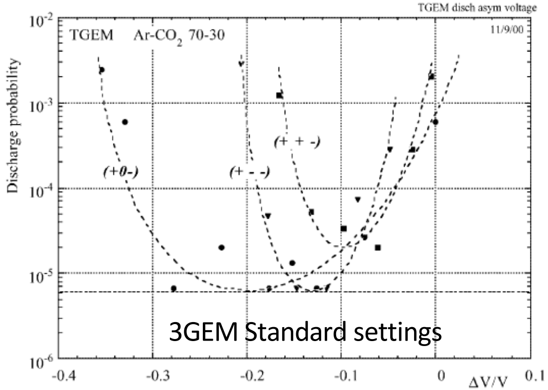
Stability of a GEM stack operated in low-IBF mode can be restored by adding 4th GEM.

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

- ~10^{-10} 1/α
- 6.4×10^{-12} 1/hadron

CERN-LHCC-2015-002



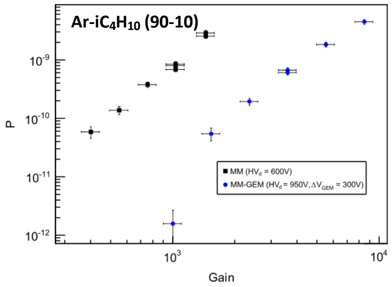


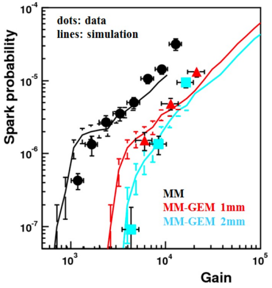
S. Bachmann *et al.*, NIM A 479 (2002) 294.

Hybrid stacks (examples)

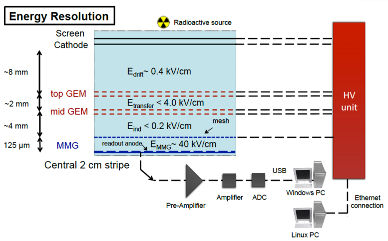
- GEM + MMG (e.g. B. Moreno et al, NIMA654(2011)135, S. Procureur et al. JINST 7 (2012) C06009)

  - 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)



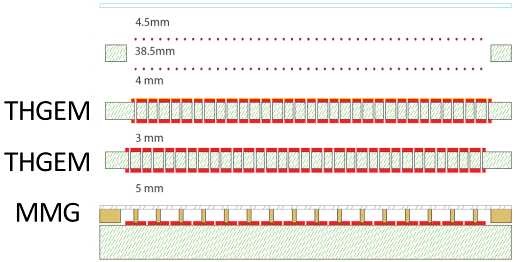
Spark rates at G~2000

3×10^{-7} 1/α in Ne-CO_2 (90-10)

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

3.5×10^{-10} 1/(150 GeV π) in Ne-CO_2-N_2 (90-10-5)

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



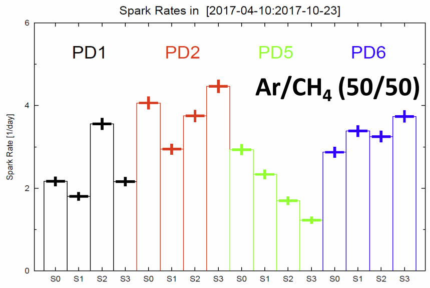
Nominal G ~ 30000 with:

THGEM1 gain × T1 ~20

THGEM2 gain × T2 ~15

MMG gain ~100

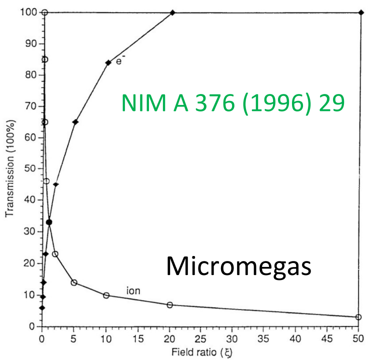
Moderate gains of single structures

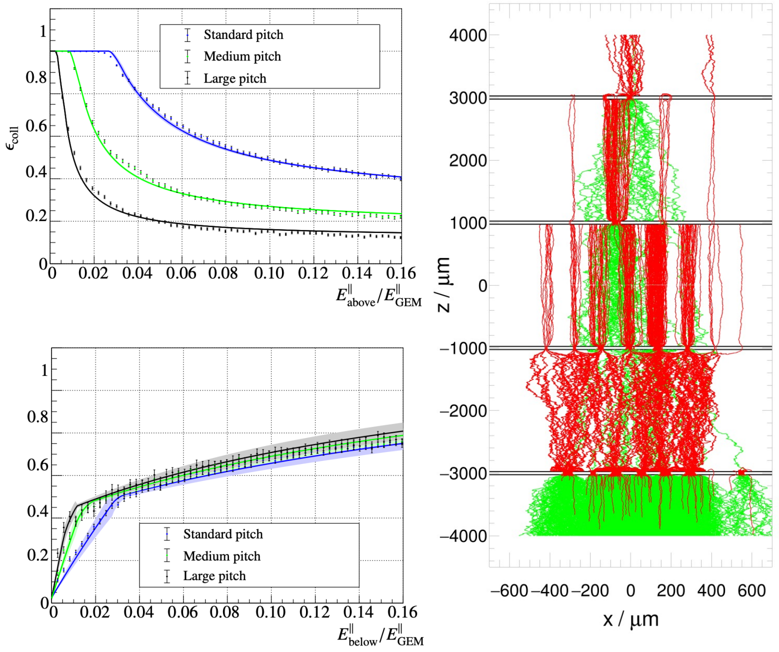


Moderate spark rate in all segments, constant in time

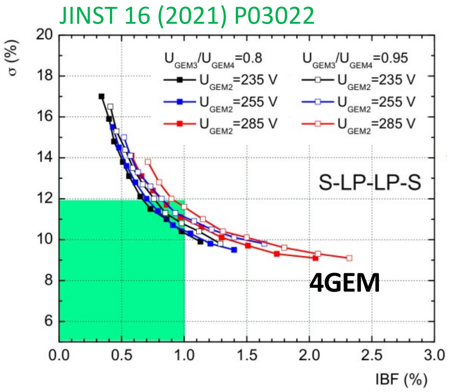
Working point optimisation

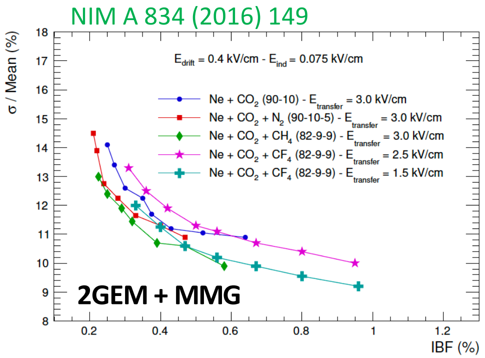
- Not only discharge stability needs to be optimised. Working point for optimal performance in terms of:
  - Gain
  - Energy resolution
  - Ion-backflow capabilities
  - Long-term stability (charging-up)
  - Efficiency
  - Drift velocity, electron/ion mobility
  - Rate capability, time resolution



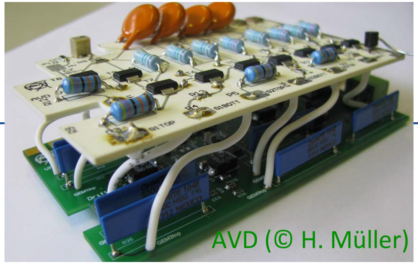


©V. Ratza, PhD Thesis, Bonn 2019

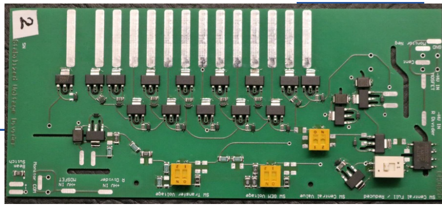




HV scheme optimization

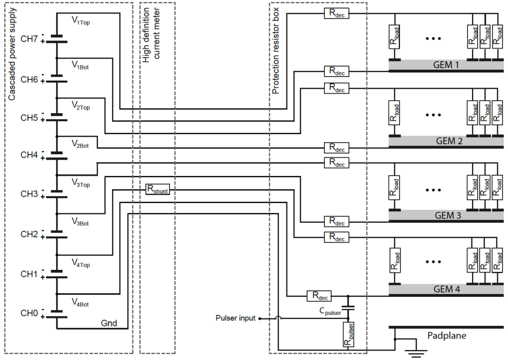


AVD (© H. Müller)



SVD (K. Flöthner, MSc thesis, Bonn 2020)

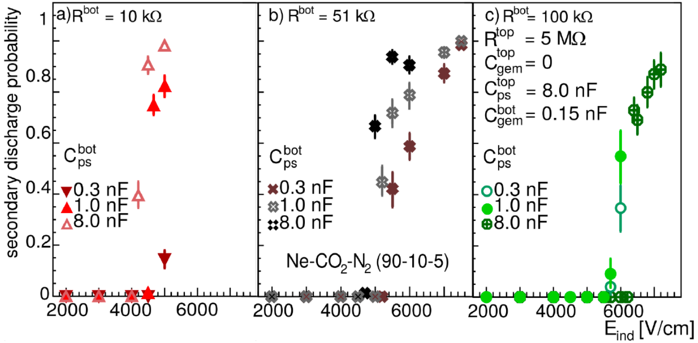
- HV system
  - Passive/active/stabilized voltage divider ➞ safest, reduced flexibility
  - Independent HV channels ➞ full flexibility, tripping times may cause fatal results
  - Cascaded power supply ➞ full flexibility, no overvoltage possible by design



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

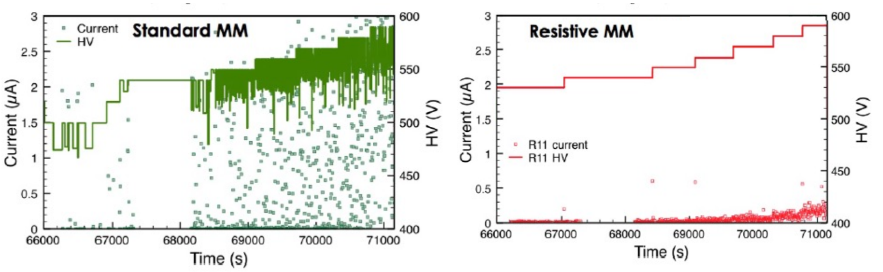
    (RLC design rules, see e.g. JINST 14 (2019) P08024)



Resistive MPGDs

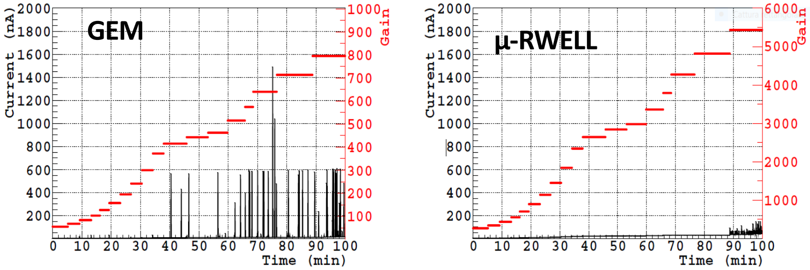
- Allow for charge sharing and create self-quenching mechanism
- Delay the charge evacuation and force local field reduction ➞ rate capabilities

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, …)

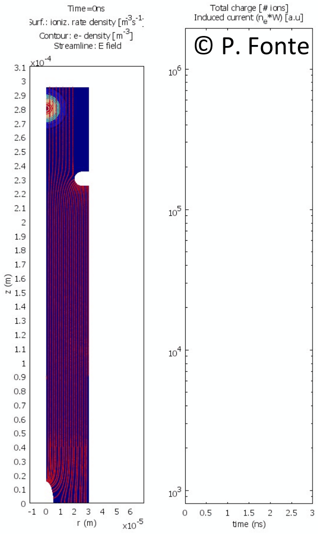
New structures: µRWELL



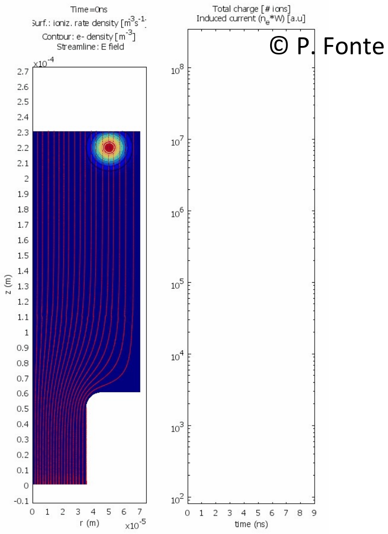
- Single-sided Gaseous Electron Multiplier (THGEM)
- Coupled to the readout anode through material of high bulk resistivity
- High rate capabilities restored by proper grounding of the DLC layers
- Single amplification stage --> material budget, simplicity, industrialization, costs!

Future: 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!

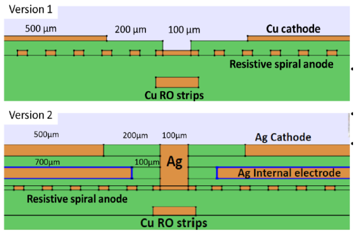


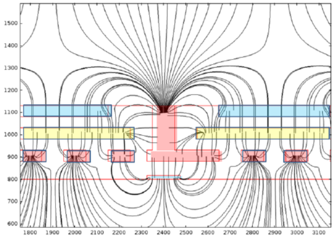
Needle + InGrid



Cathodeless CAT

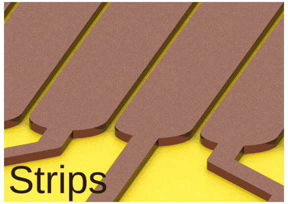
P. Fonte, "Simulations of discharge phenomena", RD51 Meeting, TU Munich 2018 (link)

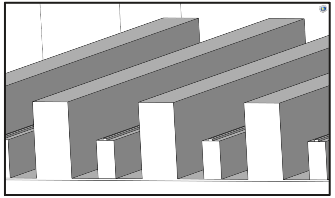


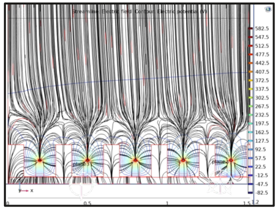


V. Cairo et al, JINST 9 (2014) C11022

JINST **18** (2023) C07009







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

Thank you!

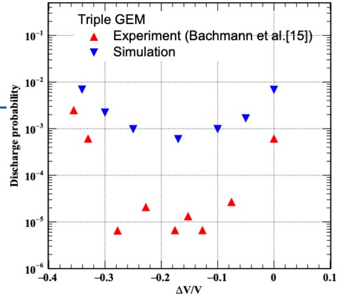
BACKUP SLIDES

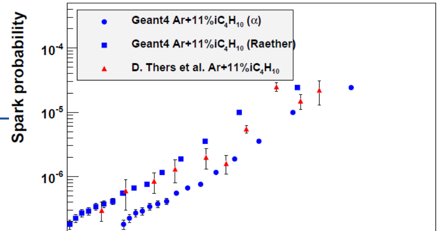
SIMULATIONS

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

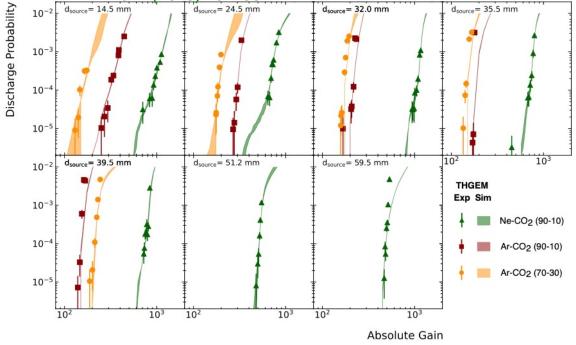
JINST 16 (2021) P09001



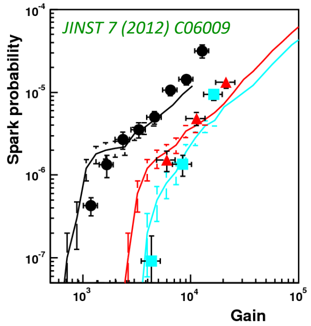


NIM A621 (2010) 177

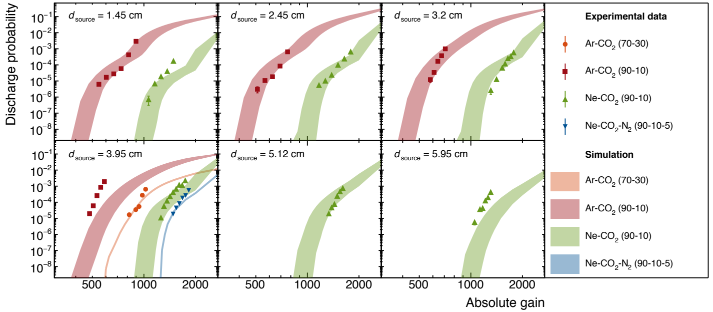
NIM A 1047 (2023) 167730

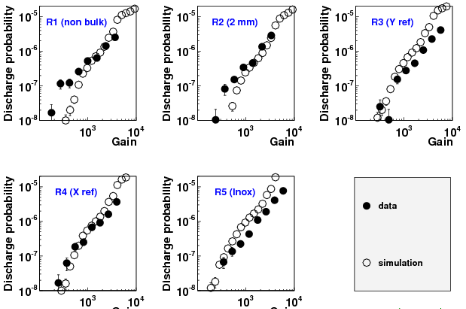


JINST 7 (2012) C06009



NIM A 870 (2017) 116

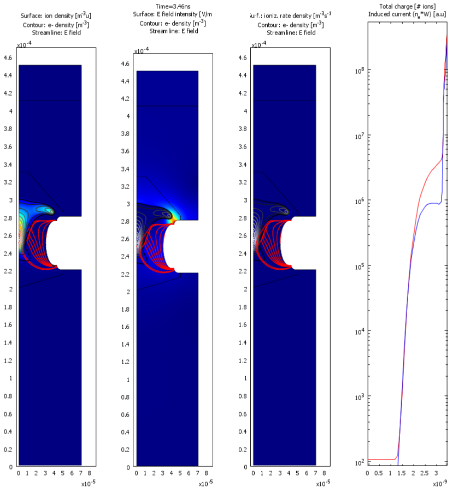




NIM A659 (2011) 91

What we can (FEM)

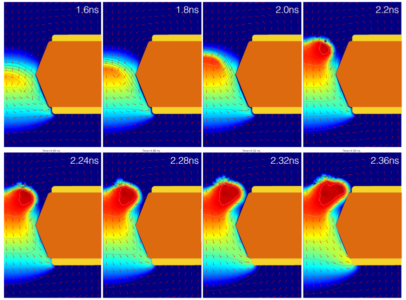
$$\begin{cases} \frac{\partial n_e}{\partial t} + \vec{\nabla}\cdot(\vec{W}_e n_e) = \alpha\left|\vec{W}_e\right| n_e + D_e \nabla^2 n_e \\ \frac{\partial n_{i+}}{\partial t} = \alpha\left|\vec{W}_e\right| n_e \\ \nabla^2 V = -\frac{e}{\varepsilon_0}(n_{i+} - n_e) \end{cases}$$



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

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

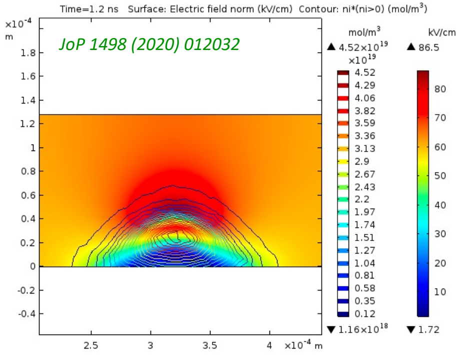
IEEE (2015) 1



- The model:

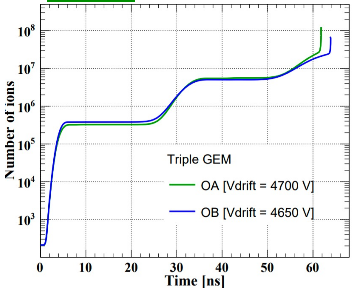
P. Fonte, TUM 2018

  - 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

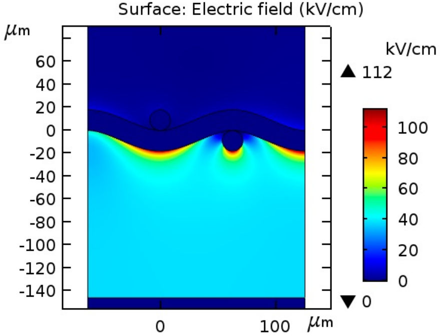


- We can optimize geometry, simulate hot spots, etc.

P. Roy (link)



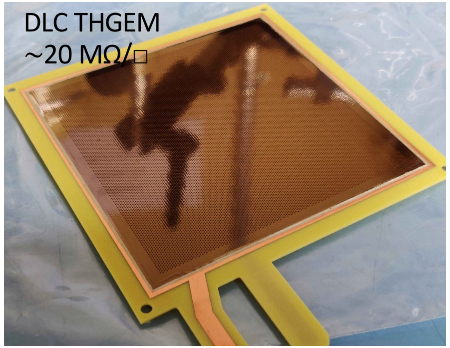
JoP 1498 (2020) 012032

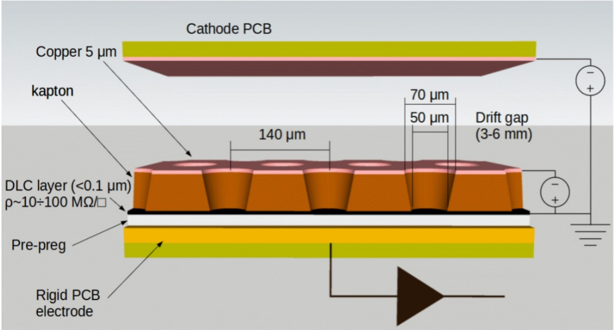


The effort needs to continue

- 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)





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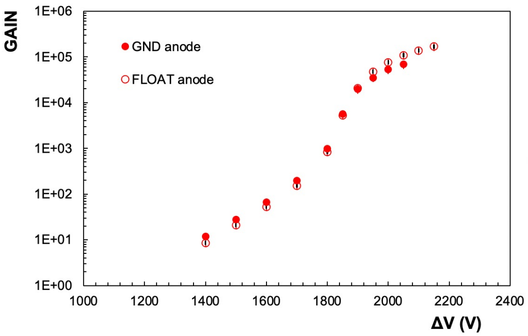
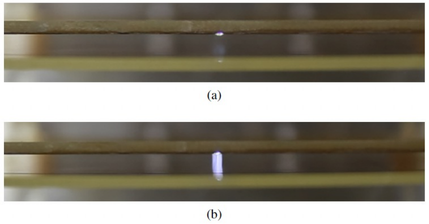
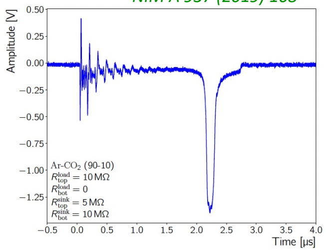


What would be good to have/answer?

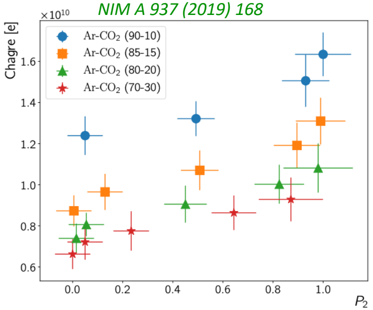
- Simulation model describing secondary (propagated, delayed) discharges developing in the gaps between subsequent foils in a stack.
  - Mechanism → still a topic of a debate.
  - Need to understand the entire process and, if possible, to eliminate the cause of these violent events completely.
  - Model 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.



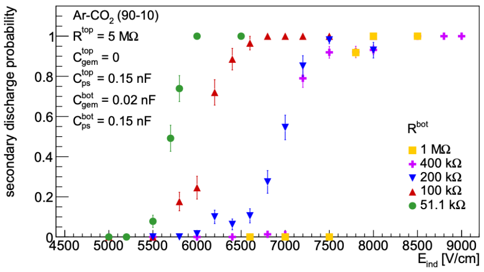
NIM A 937 (2019) 168



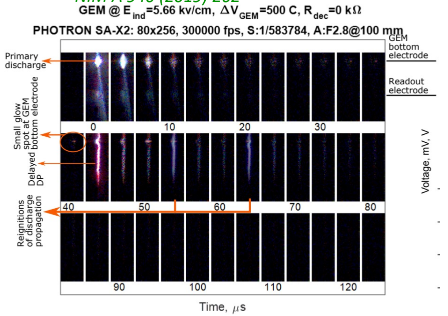
NIM A 937 (2019) 168



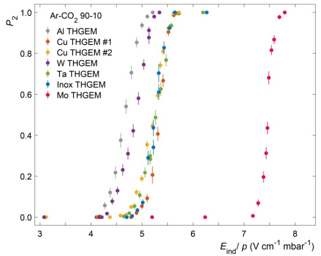
JINST 14 (2019) P08024



NIM A 940 (2019) 262



NIM A 1019 (2021) 165829



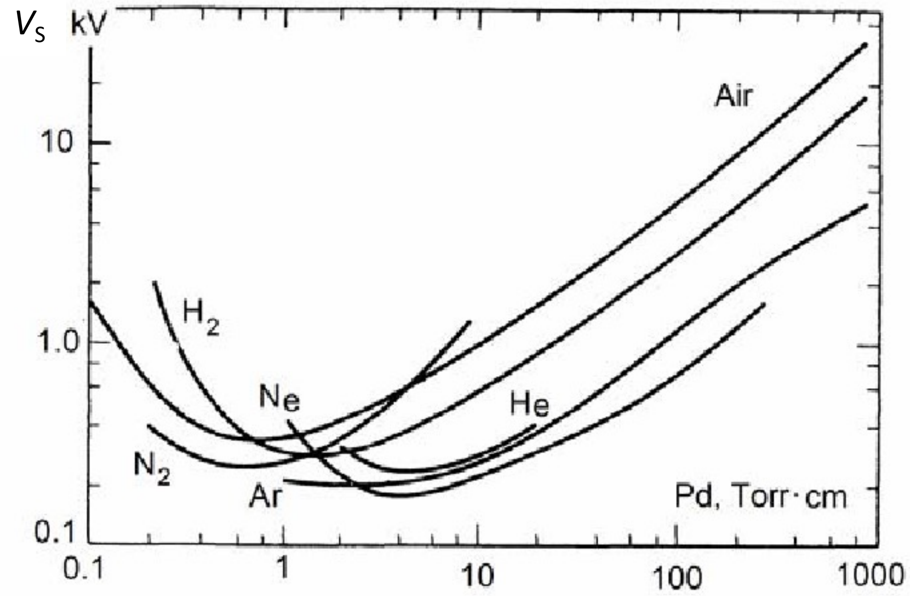
PASHEN’S LAW

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

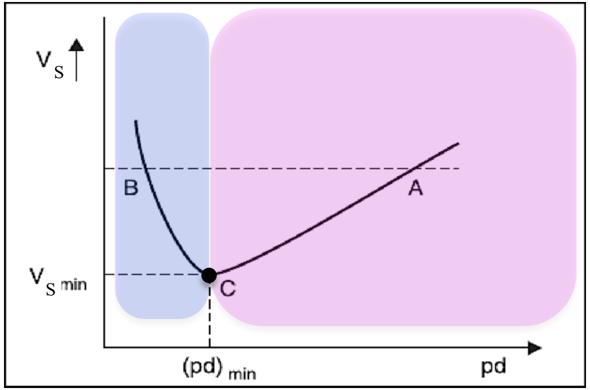


Y. P. Raizer, Gas Discharge Physics. Berlin, Germany: Springer, 1991

Paschen's law

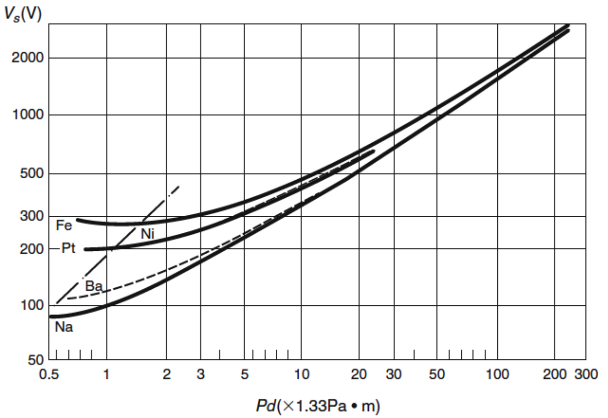
$$V_S = \frac{Bpd}{\ln(Apd) - \ln\left[\ln\left(1 + \frac{1}{\gamma_{se}}\right)\right]}$$

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



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

- 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 α/p) are required for necessary amplification



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

MPGD LIMITS

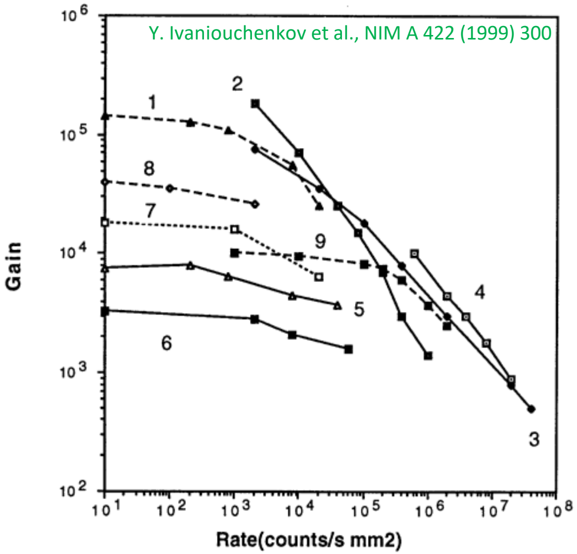
High rates at high gains – limits!

Rate-dependent reduction of maximum gain

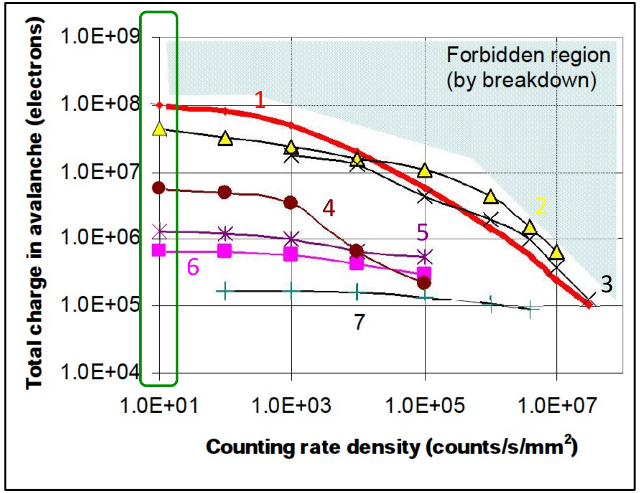
- Avalanches overlapping in time + statistical fluctuation of the avalanche size
- Non-zero probability of reaching Q_{crit}

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

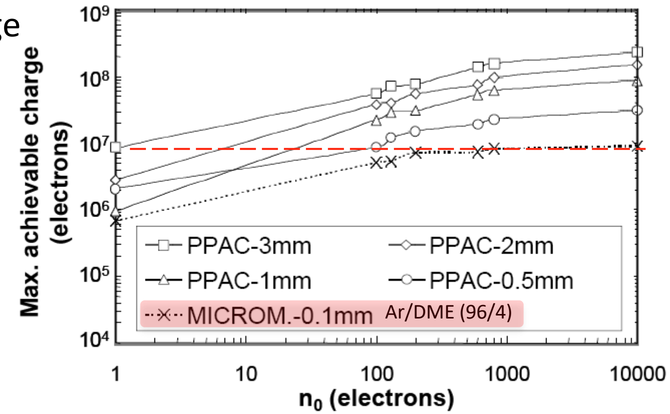


1) PPAC 3 mm
2) MMG
3) PPAC 0.6 mm
4) MSGC 1 mm
5) MSGC 0.2 mm
6) GEM
7) Microgap 0.2 mm

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

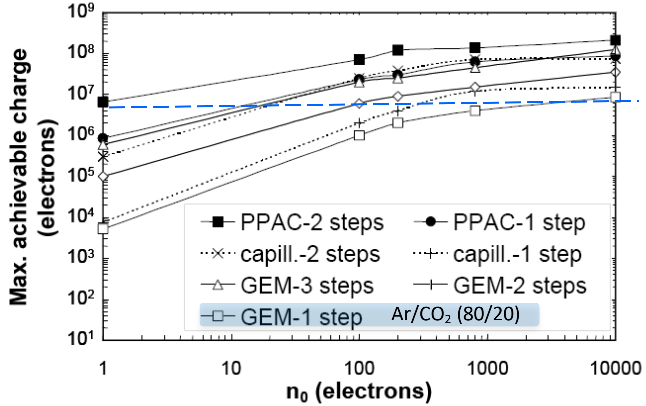
Critical charge in MPGDs

- 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?

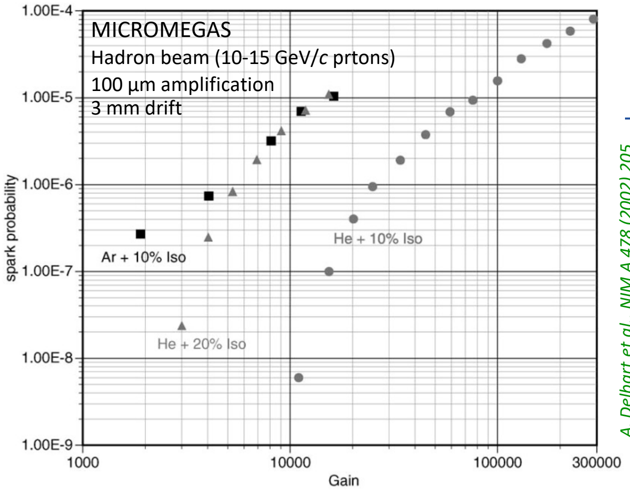
- No gas dependency studied in details
- Clear dependency on the amplification gap → **charge density?**
- Clear dependency on a number of primary electrons n_0



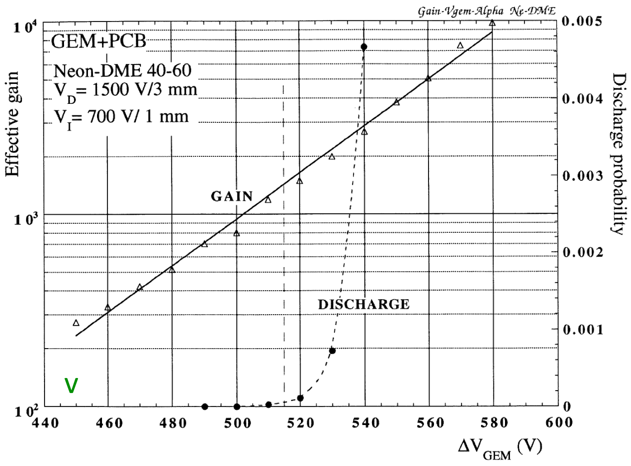
V. Peskov et al., IEEE Nucl. Sci. 48 (2001) 1070

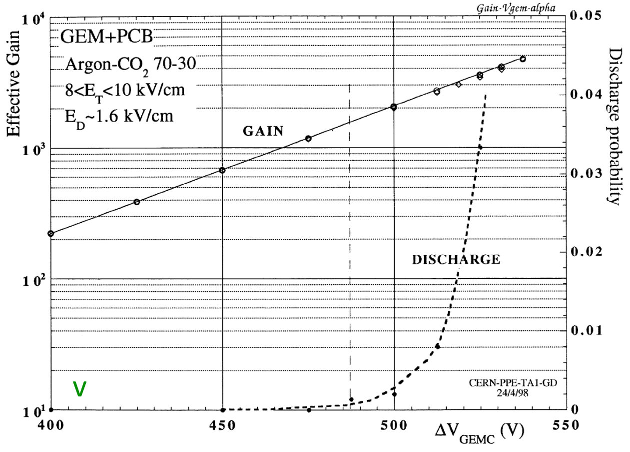
Critical charge in MPGDs

- 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



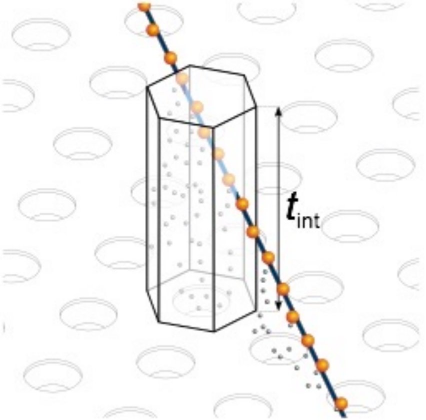


A. Bressan et al., NIM A 424 (1999) 321

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



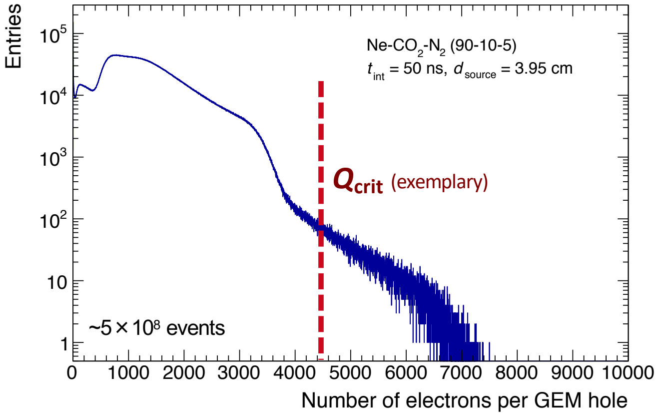
- Multiplication of the charges inside the GEM holes
  - Use absolute gain from the measurements
  - Count the electrons contained in single GEM holes

- 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**

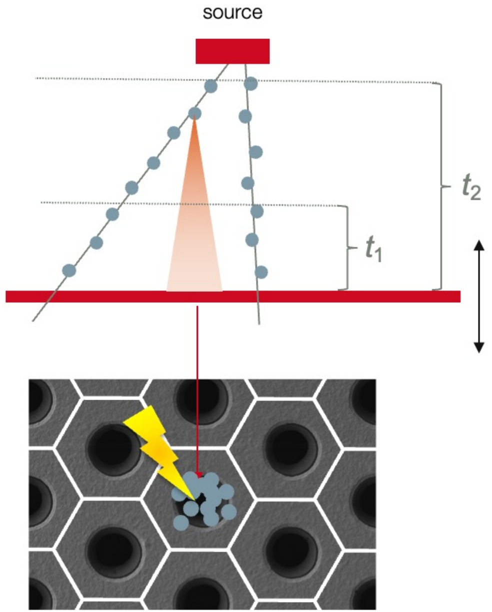
- Cut on a discharge pile-up (one alpha – max one discharge)

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



Model

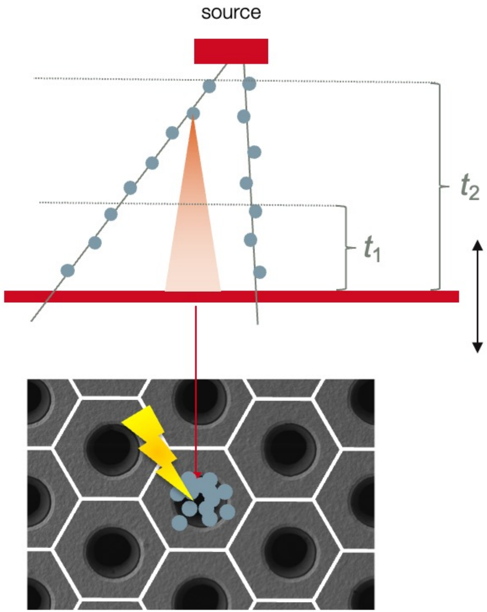
PG et al. NIM A 870 (2017) 116



- 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

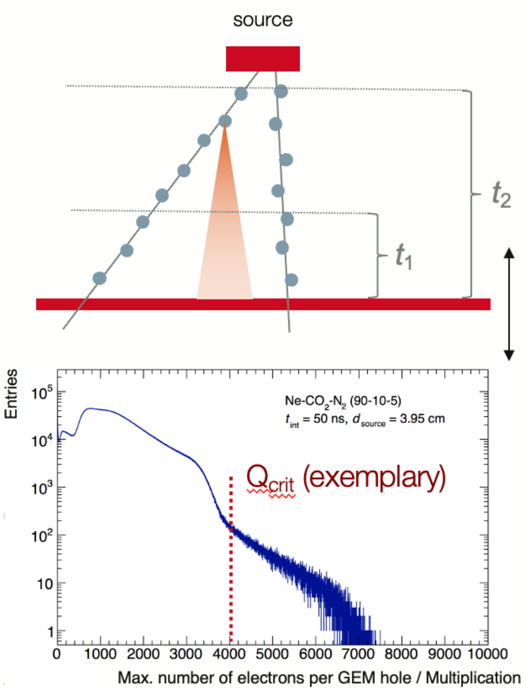
PG et al. NIM A 870 (2017) 116



- 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 + χ^2 minimization

Model

PG et al. NIM A 870 (2017) 116



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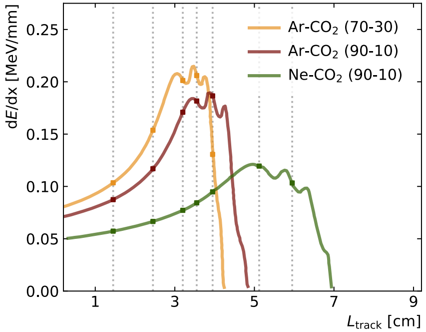
  - Count the electrons contained in single GEM holes
- Critical limit for charges Q_{crit} in single GEM hole
  - When exceeded → discharge (à la Raether limit)
- Count such large primary ionization clusters and normalize to the number of all α-particles
  - Discharge probability
- Not known: Q_{crit}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

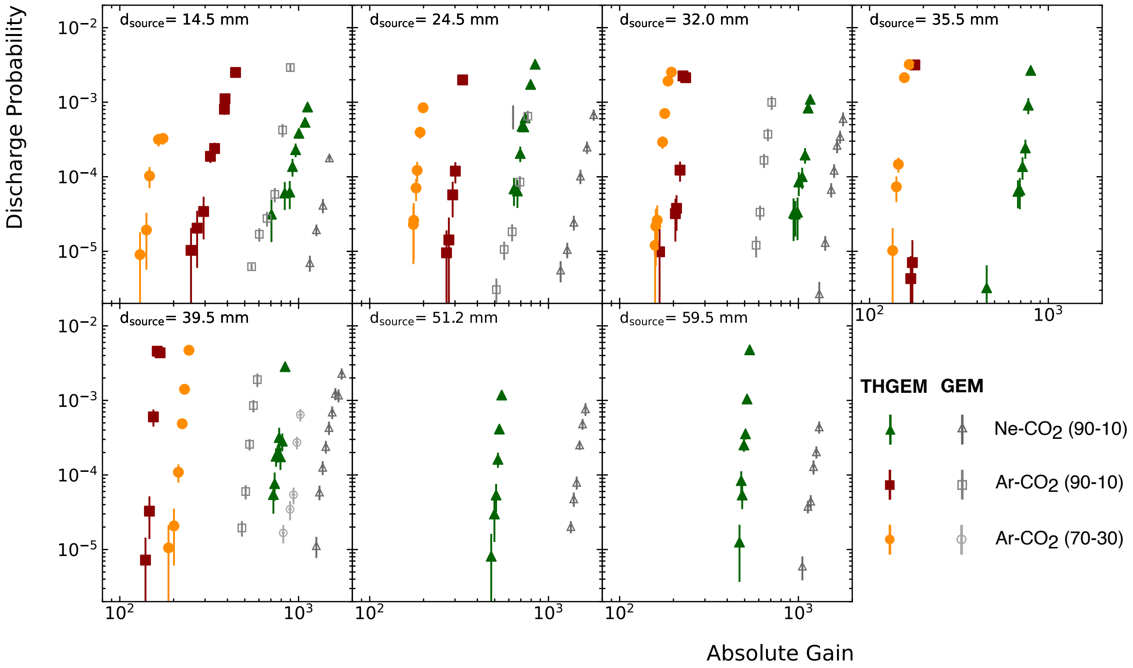
Discharge probability

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

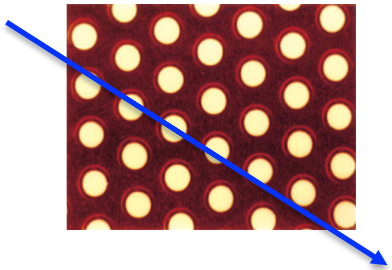


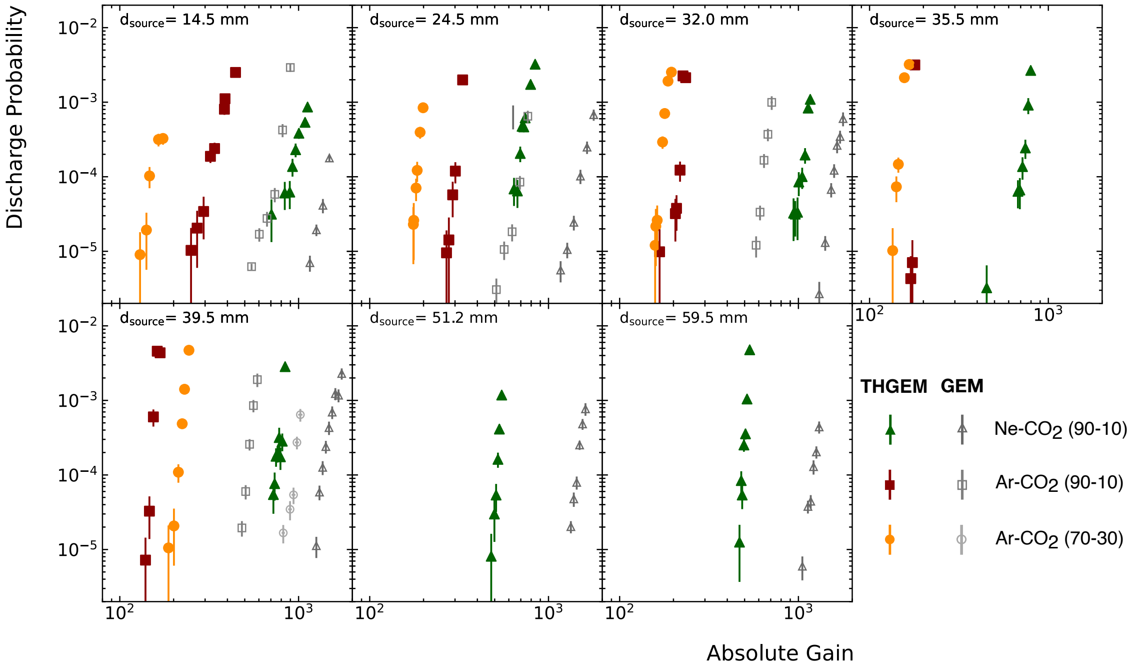


Discharge probability

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





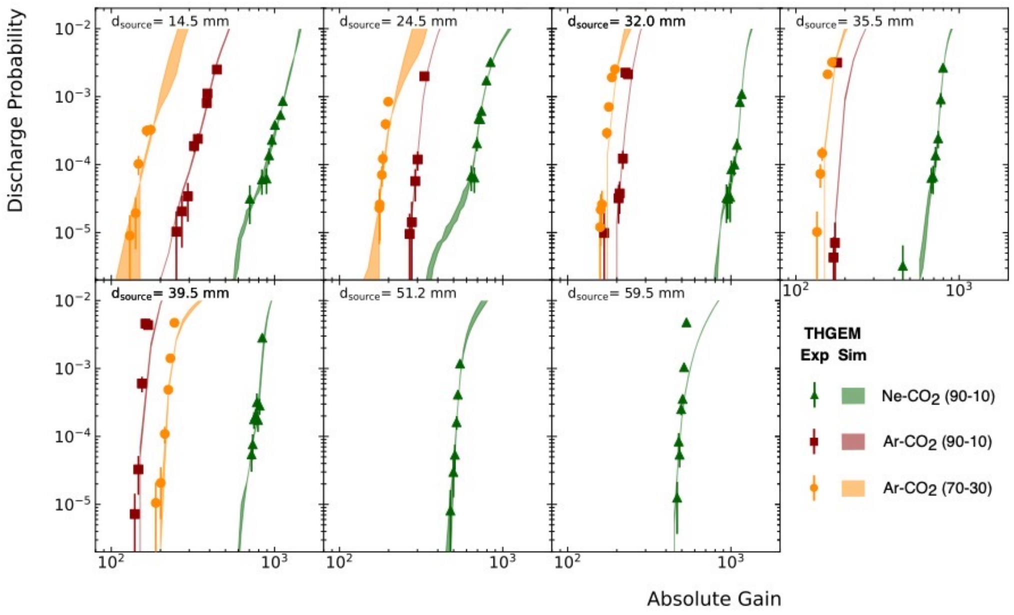
- Perform simulations to account for all orientations, emission angles, track lengths, etc.

Simulation fits

- Simulated discharge curves obtained for a given parameter pair (Q_{crit}, t_{int}) are fitted to the data by means of χ^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?

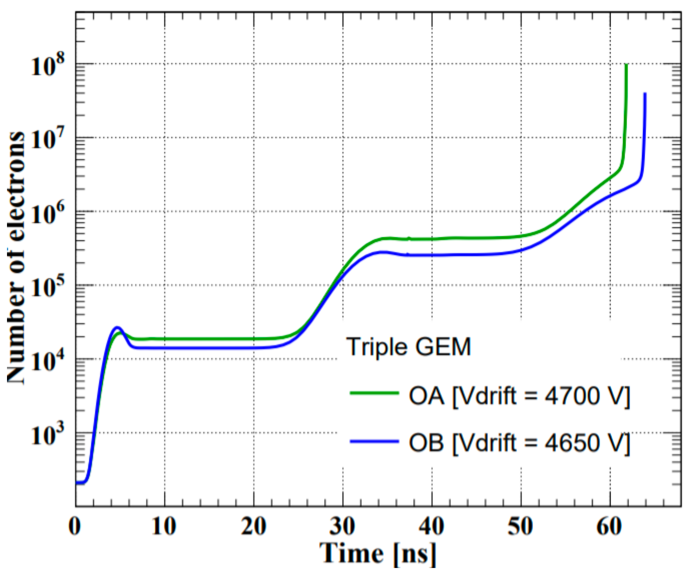


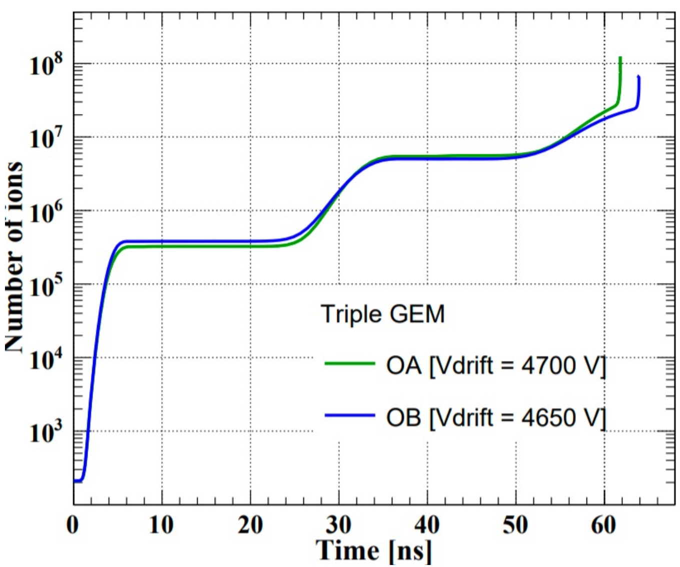
Gas	THGEM		GEM	
	$\langle Q_{crit} \rangle$ [$\times 10^6\, e$]	t_{int} [ns]	Q_{crit} [$\times 10^6\, e$]	t_{int} [ns]
Ne-CO_2 (90-10)	7.1 ± 2.2	30–210	7.3 ± 0.9	20–90
Ar-CO_2 (90-10)	4.3 ± 1.5	20–110	4.7 ± 0.6	15–50
Ar-CO_2 (70-30)	2.5 ± 0.9	40–310	–	–

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
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	–	–

- 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]
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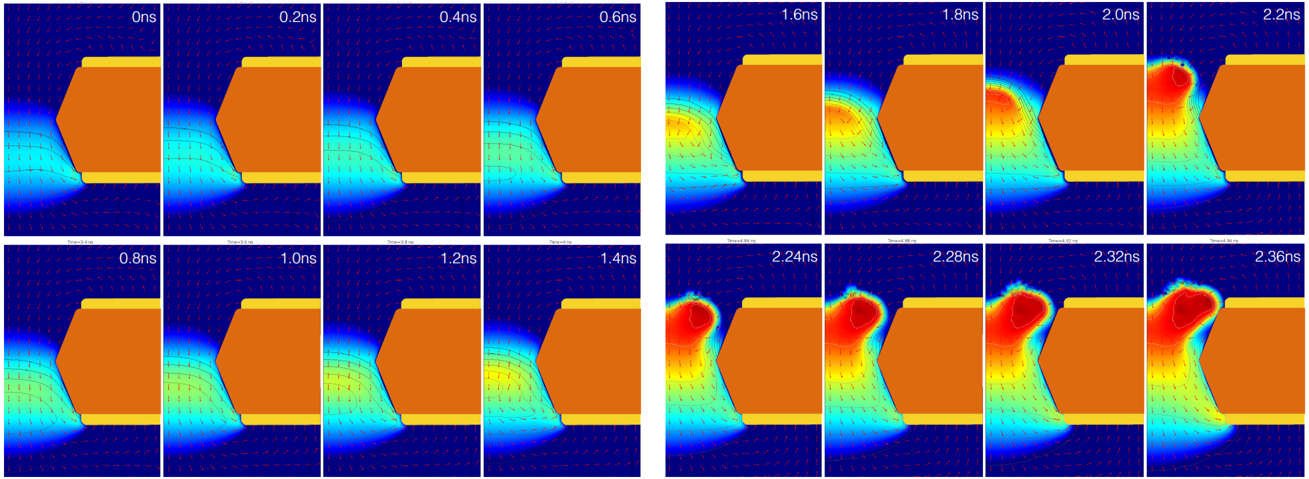
Ar-CO_2 (90-10)	4.3 ± 1.5	20–110	4.7 ± 0.6	15–50
Ar-CO_2 (70-30)	2.5 ± 0.9	40–310	–	–

- 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

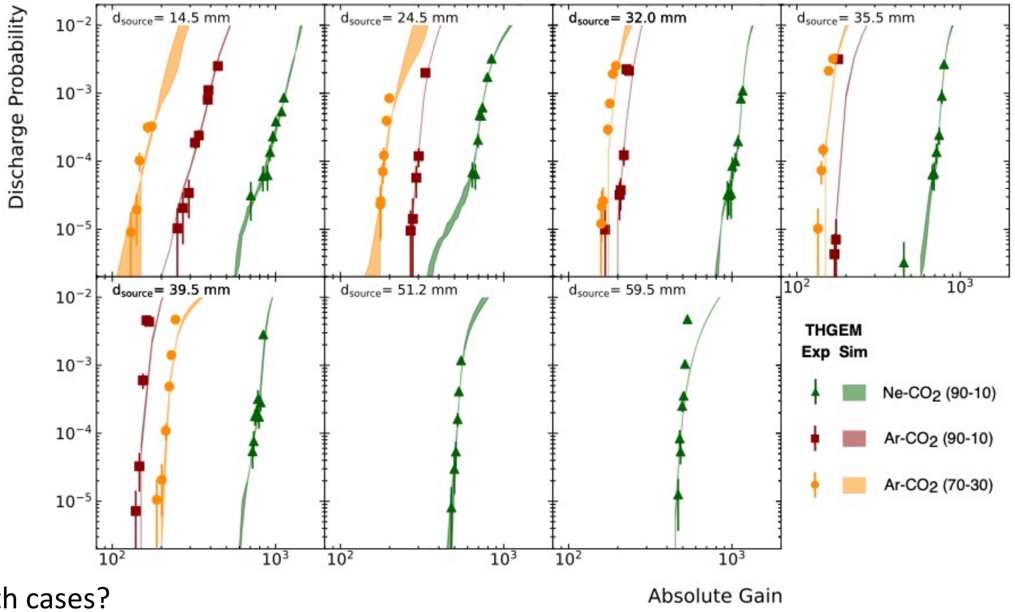
Simulation fits

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 χ^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 $\langle Q_{crit} \rangle$ [$\times 10^6$ e]	THGEM t_{int} [ns]	GEM Q_{crit} [$\times 10^6$ e]	GEM t_{int} [ns]
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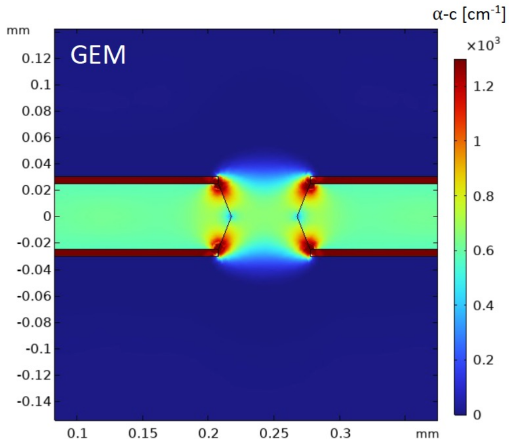
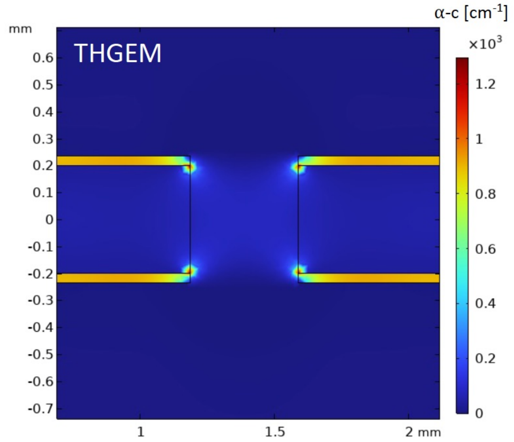
Townsend maps

- 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 η	$n \cdot \eta(E/n)\ ^{*a}$
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 α	$n \cdot \alpha(E/n)\ ^{*b}$
secondary scintillation coefficient Y	$n \cdot Y(E/n)\ ^{*b}$

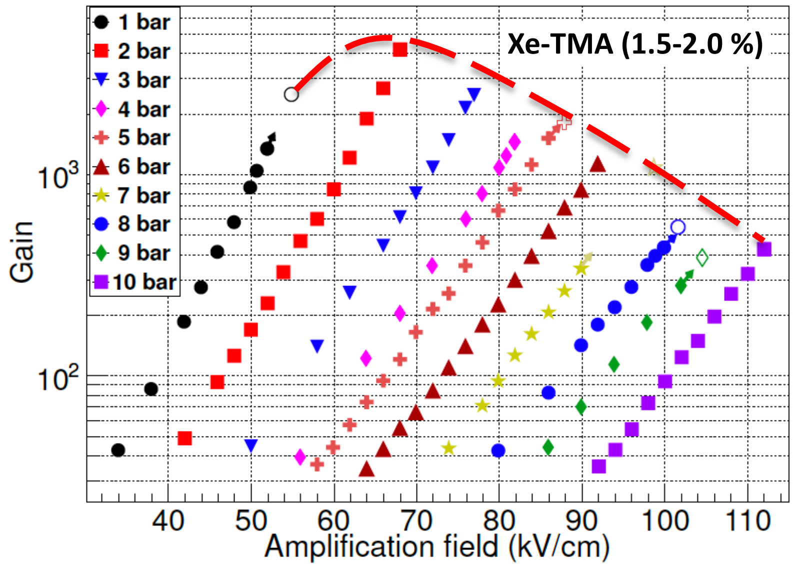
D. Gonzalez-Diaz et al., NIM A 878 (2018) 200

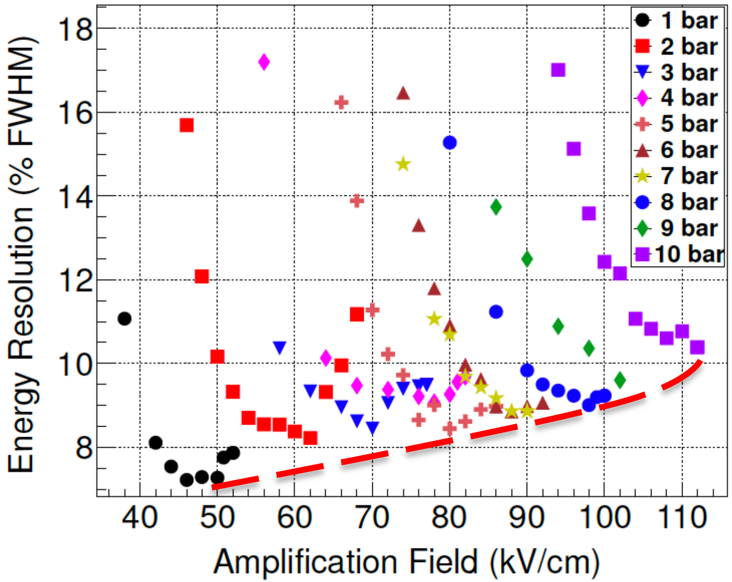
- High voltage in drift region (pressure dependence of v_d, D_L, η) – insulation (see e.g. B. Rebel at al. JINST 9 (2014) T08004)

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

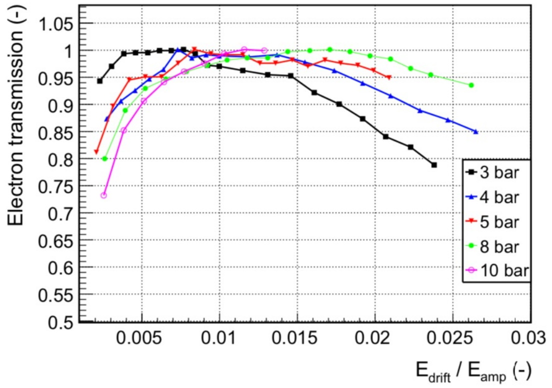
S. Cebrián et al. JINST 10 (2015) E07001 *"**Micromegas-TPC** operation at high pressure in xenon-trimethylamine mixtures"*

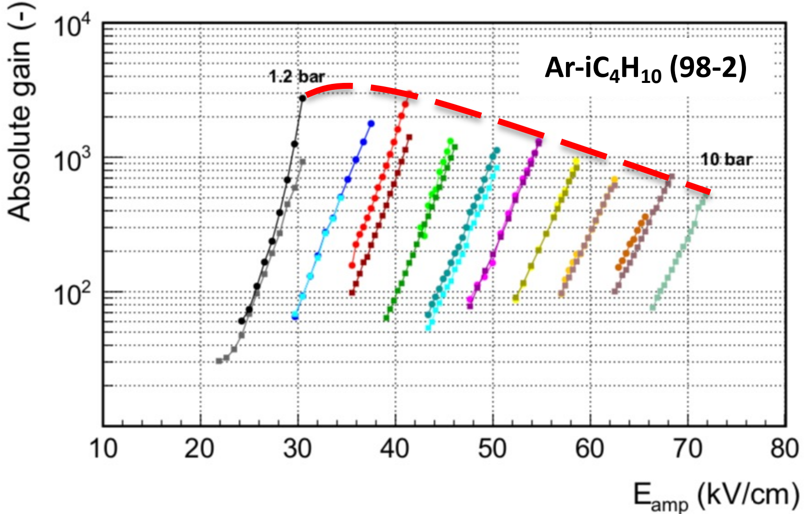


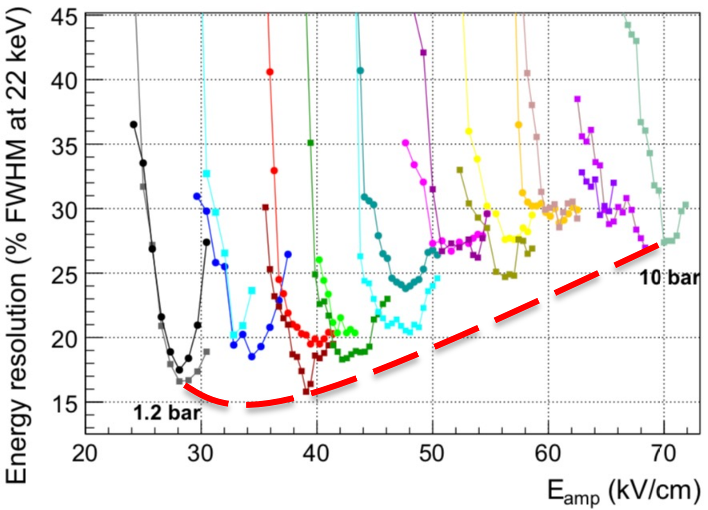


MPGDs in high-pressure (MMG TPC)

- 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

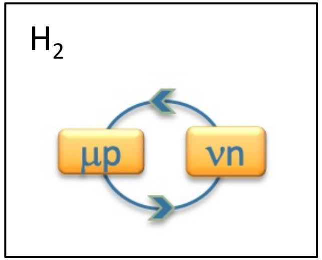


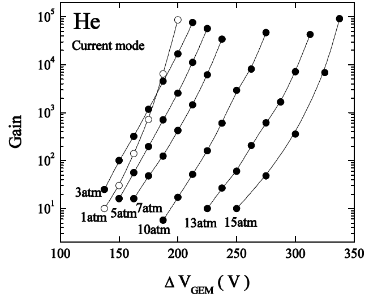


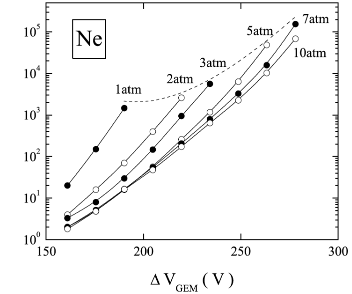


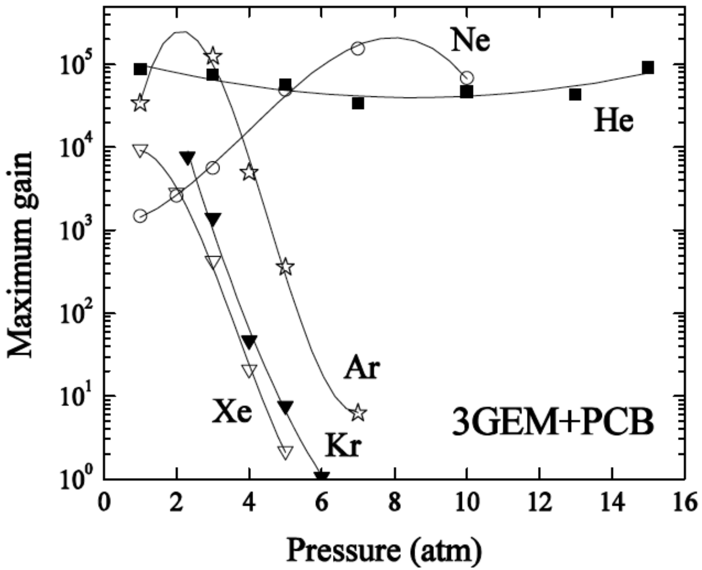
MPGDs in high-pressure (GEMs)

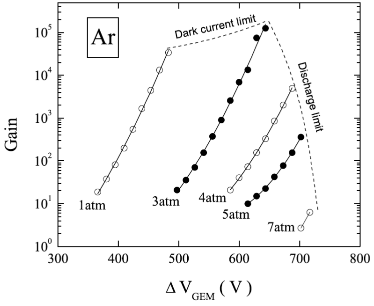
- Pioneering studies of GEM gain in noble gases at 1-15 atm (plots below)
  - A. Bondar et al. NIM A 481 (2002) 200
  - A. Bondar et al. NIM A 493 (2002) 8
- Maximum achievable gain drops abruptly in heavy noble gases
- Light gases (He, Ne) stable; also weaker gain dependency on *P*
  - Associative ionization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

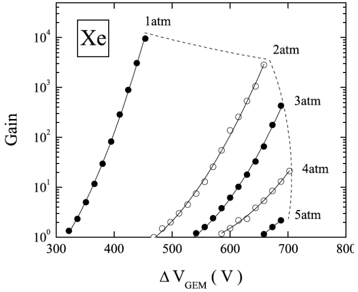


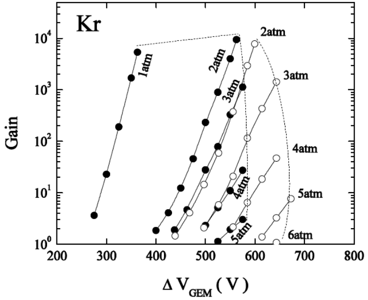








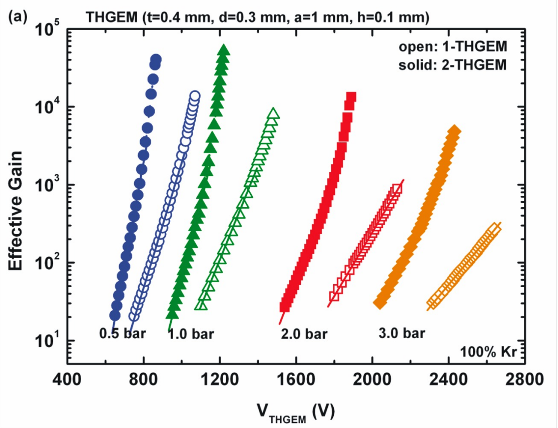




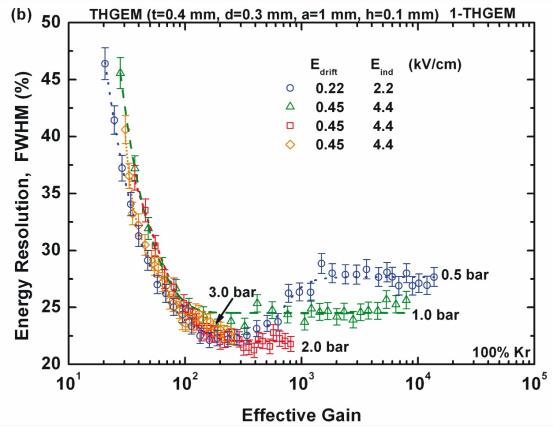
- See also "Gas gain and signal length measurements with a triple-GEM at different pressures of Ar-, Kr- and Xe-based gas mixtures", A. Orthen et al. NIM A 512 (2003) 476

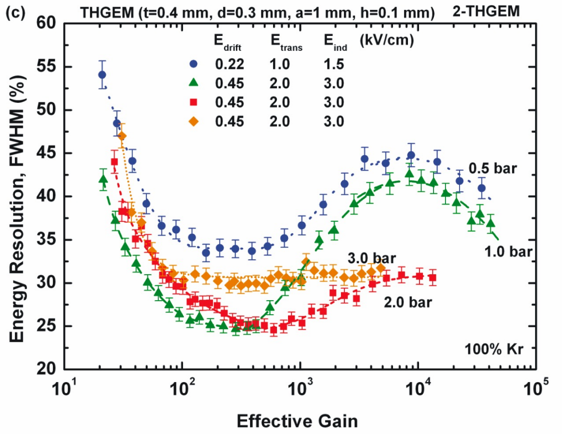
MPGDs in high-pressure (THGEMs)

- 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

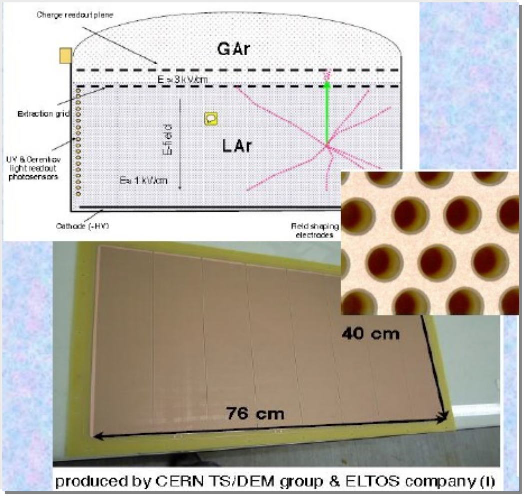




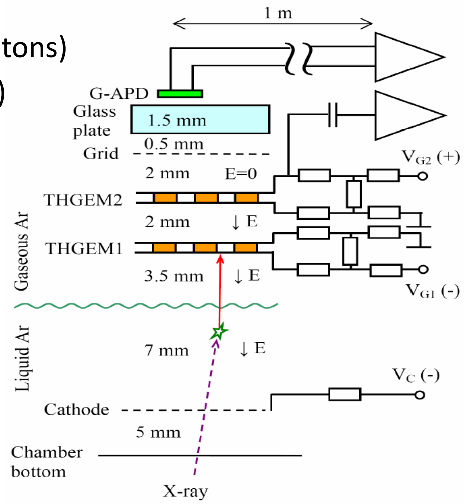
Gain limits in noble gases

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

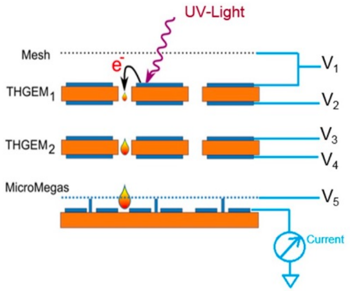


- Possible solutions:
  - Use cascaded THGEMs (to mask final-avalanche photons)
  - THGEM at low gain + Optical readout (SiPM, LAAPDs)
  - But now we enter the double-phase TPC region…
  - Unless…scintillation in H_2

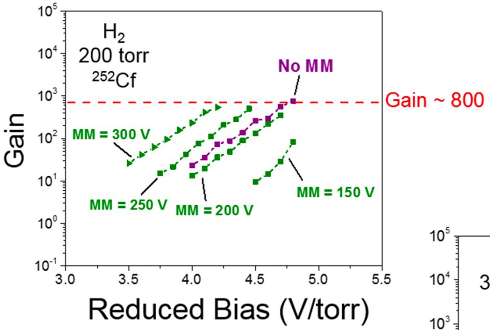


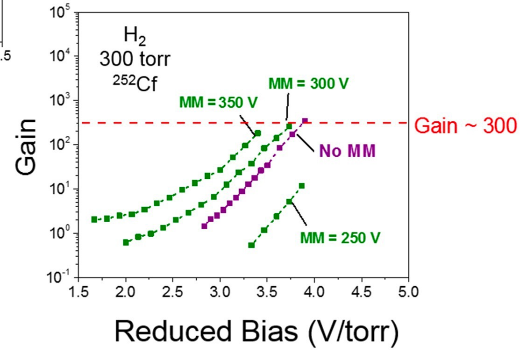
Two-phase Ar detector with THGEM/gAPD optical readout in the NIR
- Bondar, Buzulutskov JINST 2010
- Buzulutskov 2012 JINST 7 C02025

Low-pressure H_2 (THGEM+MMG)



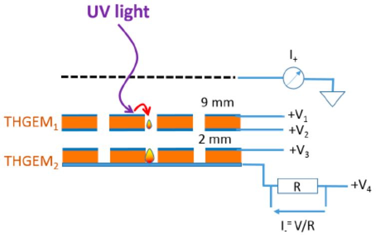
- **AT-TPC Collaboration** basic performance evaluation studies in low-pressure He and H_2
- M. Cortesi et al., EPJ Web of Conf. 174 (2018) 01007
- 2-THGEM + MMG for stable operation, due to (direct citation):
  - *the extended dimension of the THGEM holes, typically several times larger than the electron 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.*



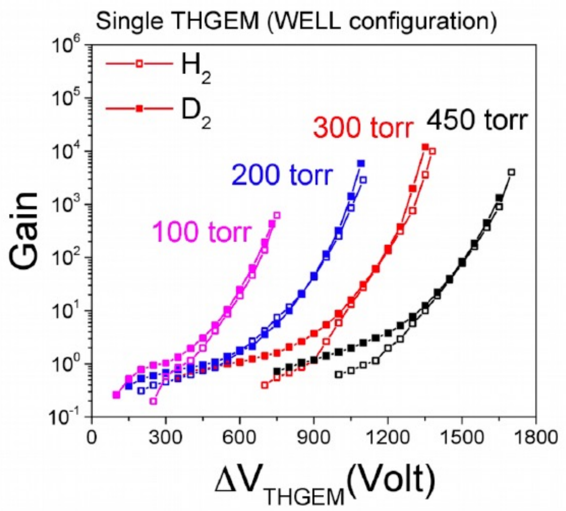


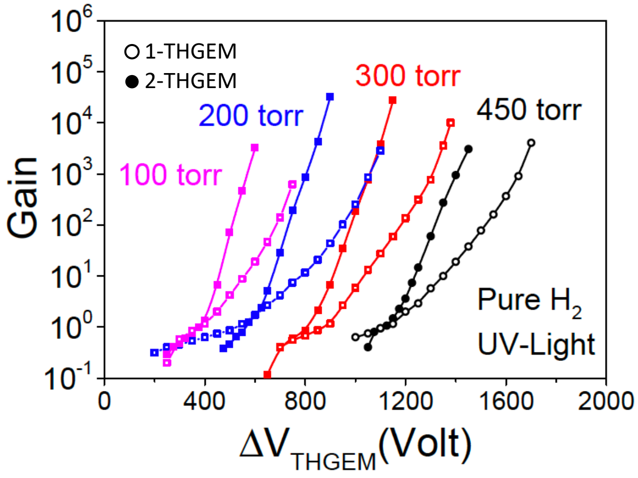
- For low MMG voltage – loss of electron collection efficiency and thus effective gain of the structure
- High x-section for radiation less processes in H_2 (excitation of vibrational and rotational levels)
- Higher electric fields necessary for a substantial gas avalanche multiplication (resulting in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

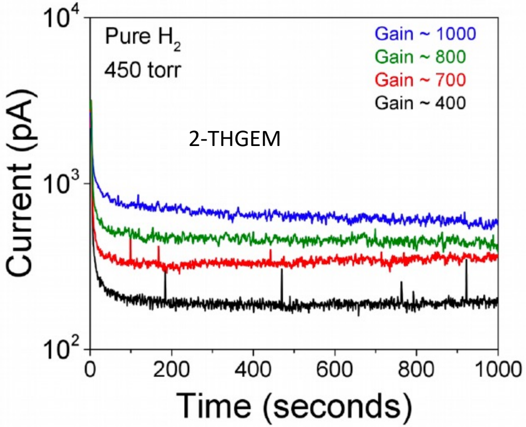
Low-pressure H_2 (WELL, THGEM and 2-THGEM)



- 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
-

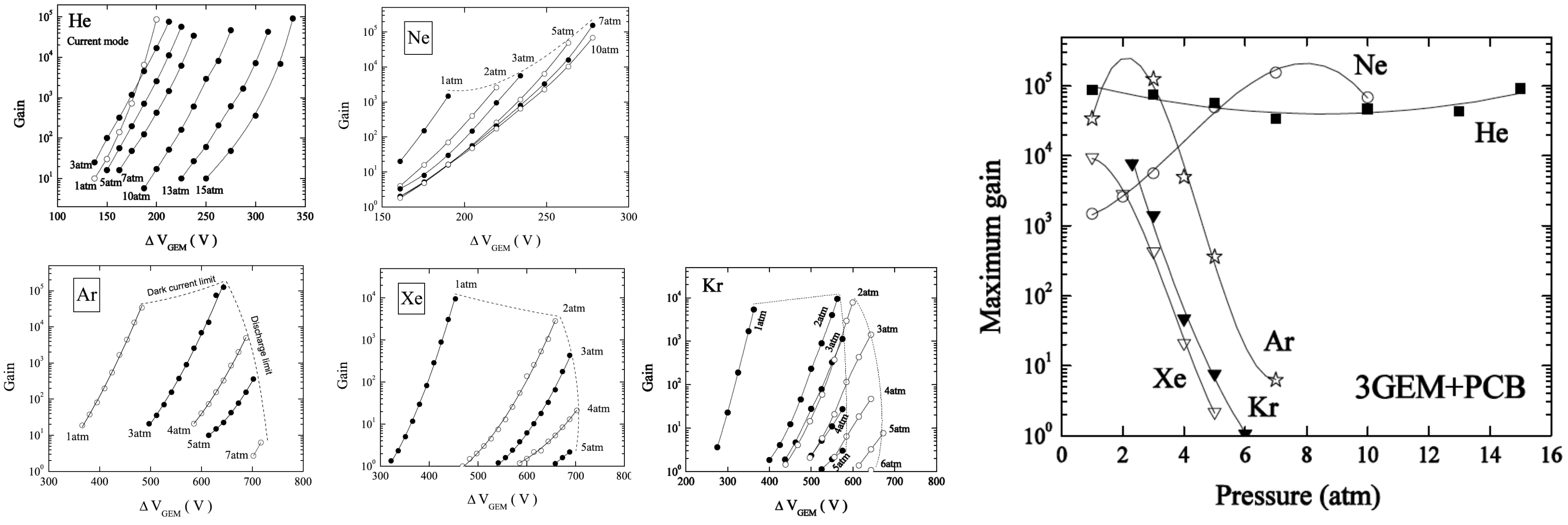






GEMs in high-pressure

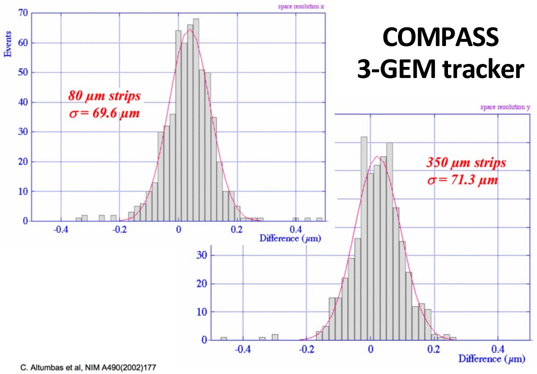
- Pioneering studies of GEM gain in noble gases at 1-15 atm (plots below)
  - A. Bondar et al. NIM A 481 (2002) 200
  - A. Bondar et al. NIM A 493 (2002) 8
- Maximum achievable gain drops abruptly in heavy noble gases → increased HV, reduced stability
- Light gases (He, Ne) stable; also weaker gain dependency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

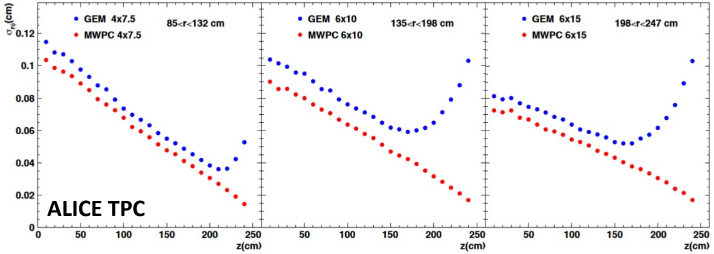
R LAYERS

Resistive layers – charge spread



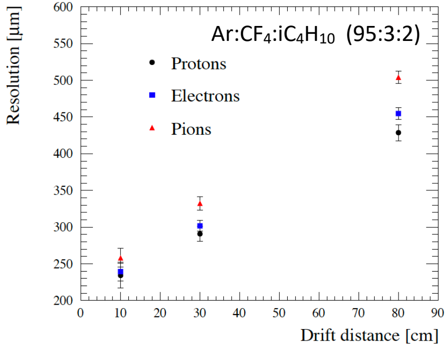
- Spatial resolution
  - Limited by the pad size ($\sigma \approx W/\sqrt{12}$)
  - Charge distribution narrow (influence of drift distance -> tr. diffusion)

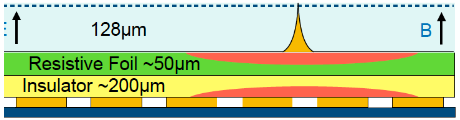
1) Decrease the pad/strip size
  - Single electron efficiency
  - Increase number of readout channels



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





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

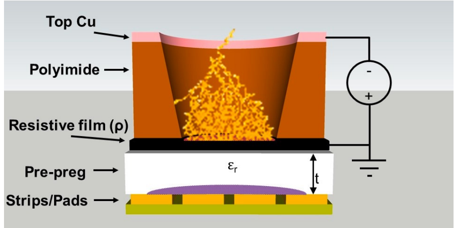
$\rho(r,t)$: the surface charge density
R: the surface resistivity of the resistive layer
C: the capacitance per unit area.

© D. Attié et al. arXiv:1907.07060v2

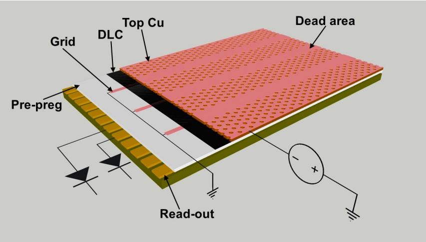
New structures: micro-RWELL

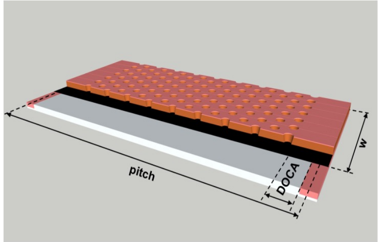
G. Bencivenni et al., JINST 14 (2019) P05014

- 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!

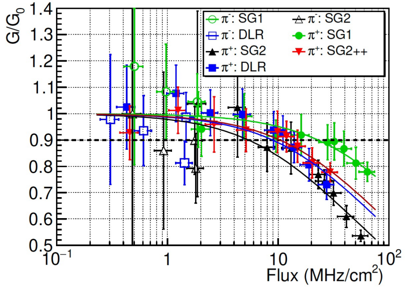


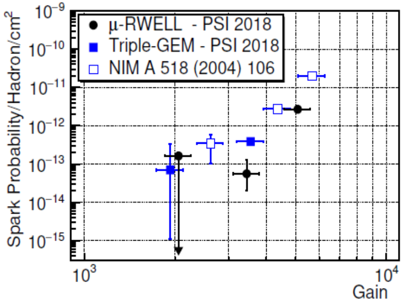
- High-rate capabilities restored by the proper grounding of the DLC layers → improved charge evacuation
- Thorough optimisation, including surface discharge considerations → concept of the distance-of-closest-approach crucial for stability!





- Rate capabilities of up to 10 MHz/cm² demonstrated
- Discharge probability of a single micro-RWELL stage compatible with a triple GEM setup operated at stability-optimised HV settings

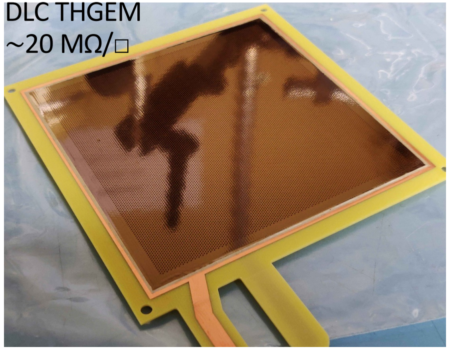


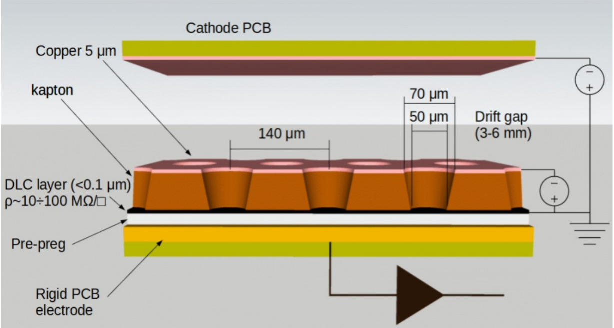


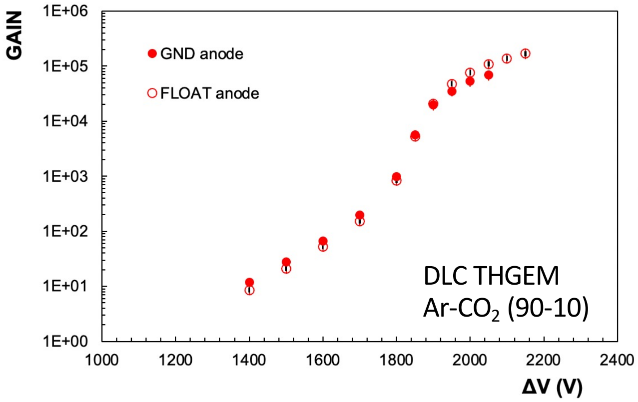
Resistive layers studied at GSI

- 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/□





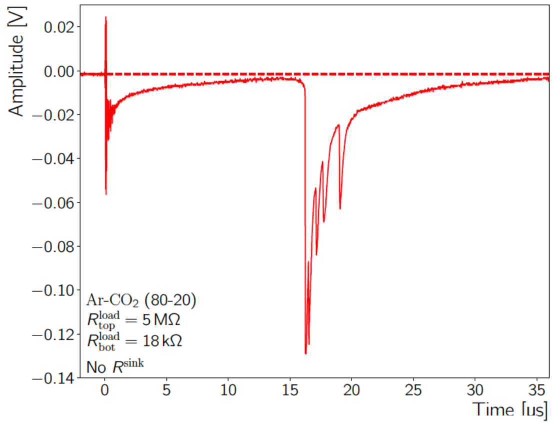


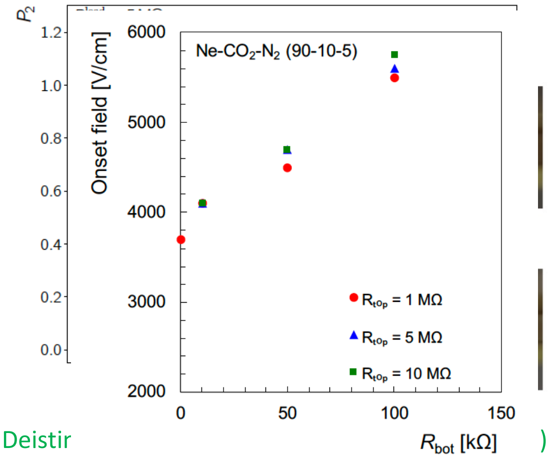
SECONDARY DISCHARGES

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





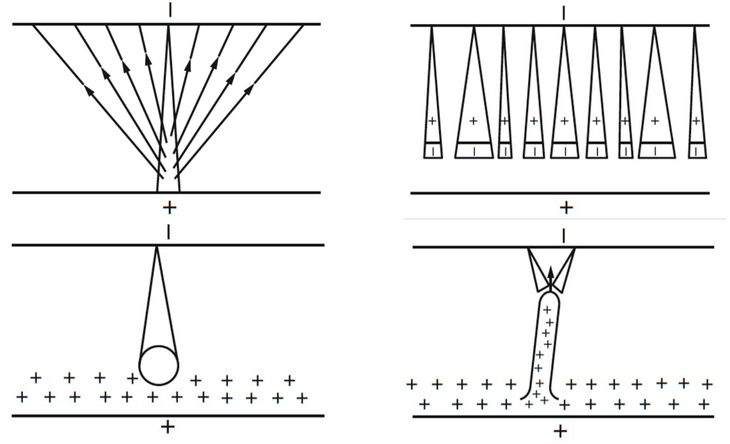
A. Deistir) 168

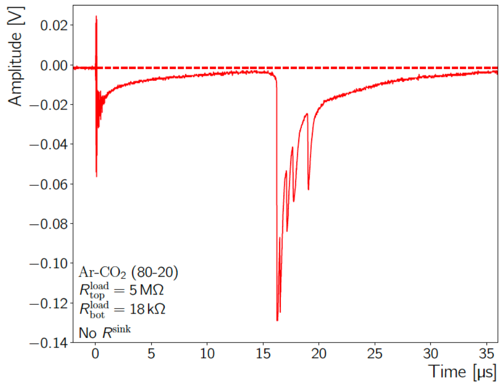
* See pioneering studies by *S. Bachmann et al. NIM A479 (2002) 294 & V.* Peskov, P.Fonte (2009) arXiv:0911.0463

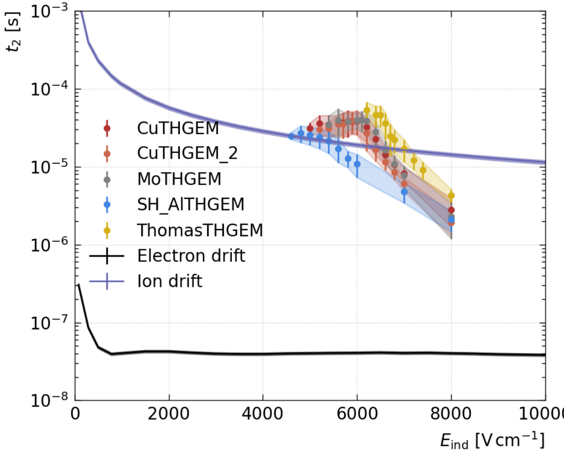
Secondary discharge formation

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

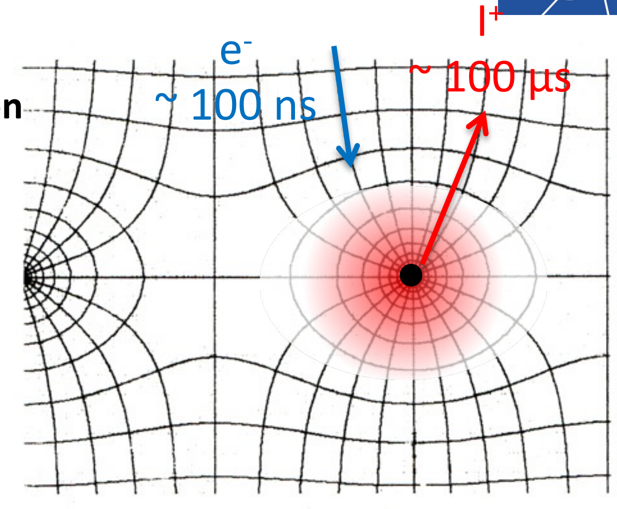
1) **Relatively long time to evacuate ions from the amplification region**
   - Fast gain drop at high fluxes: (>10 kHz/cm^2)
   - Space charge accumulation, distortion of E field.
   - Screening effect for next event

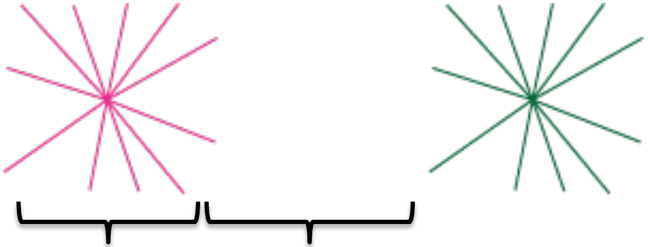
2) **Limited multi-track separation** (~100 µm)
   - Minimum wire distance ~1mm
     (mechanical instabilities due to electrostatic repulsion)

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





Drift time in TPC. Gated grid open

Gated wire grid must stay closed, no event readout

Build stacks!

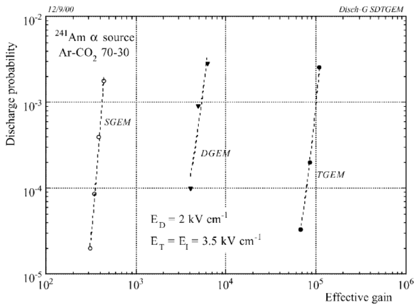
- **GEMs are easy to stack**
  - Pre-amplification stage – lower gain of single structures
  - Charge spread between independent holes – $\boldsymbol{Q_{crit}}$ **per hole stays the same!**
  - Small pitches preferable (watch out quality!)

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

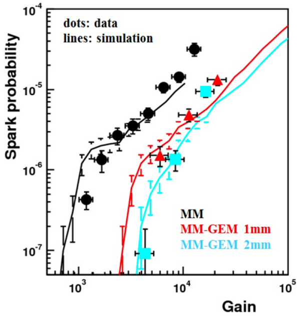
  NIM A 834 (2016) 149 and NIM A 976 (2020) 164282, NIM A 623 (2010) 94
  - Clear influence of the pre-amplification stage on the stability of MMG
  - Lower charge densities reach (subsequent) MMG stages
  - Mesh cell as an independent amplification structure (see also JINST 18 (2023) C06011)

- **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)

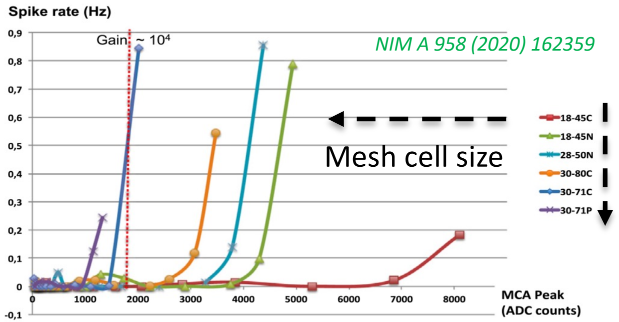
NIM A479 (2002) 294

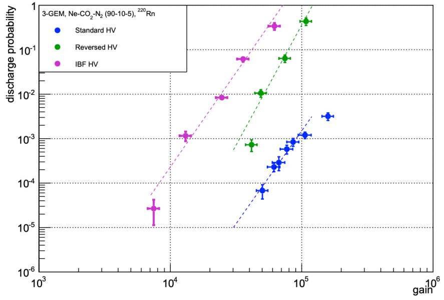


JINST 7 (2012) C06009



NIM A 958 (2020) 162359

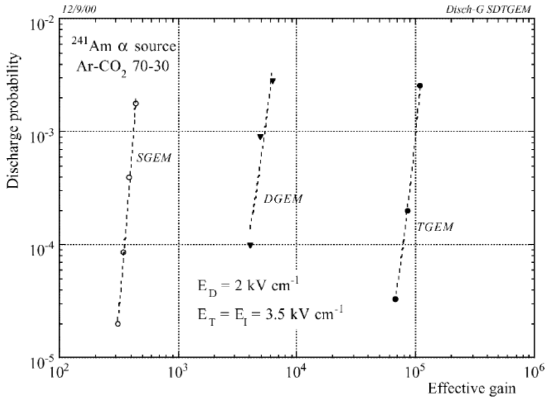


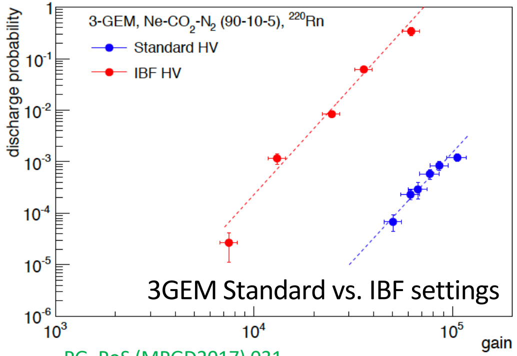


ALICE TPC Upgrade TDR Addendum, CERN-LHCC-2015-002

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





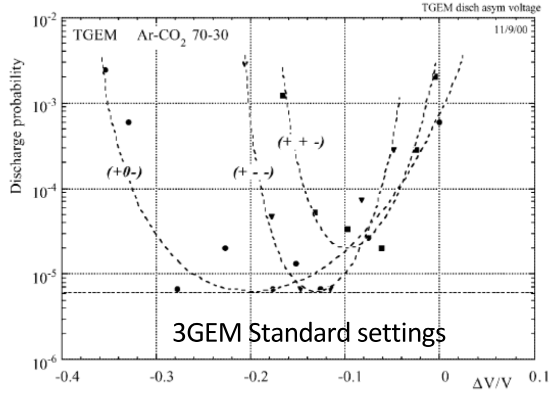
PG, PoS (MPGD2017) 031

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

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

- ~10^{-10} 1/α
- 6.4×10^{-12} 1/hadron

CERN-LHCC-2015-002

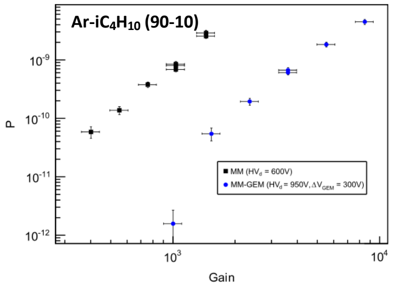


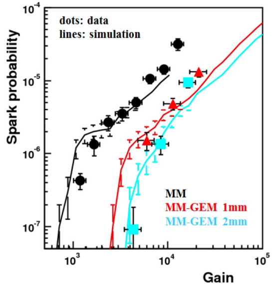
S. Bachmann *et al.*, NIM A 479 (2002) 294.

Hybrid stacks (examples)

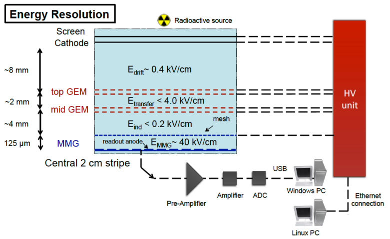
- GEM + MMG (e.g. B. Moreno et al, NIMA654(2011)135, S. Procureur et al. JINST 7 (2012) C06009)

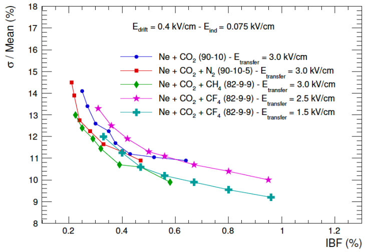
> - Clear influence of the pre-amplification stage (GEM) on the stability of MMG
> - Lower charge densities reach MMG (cf. 1 and 2 mm gaps)
> - Confirmed with GEANT simulations





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





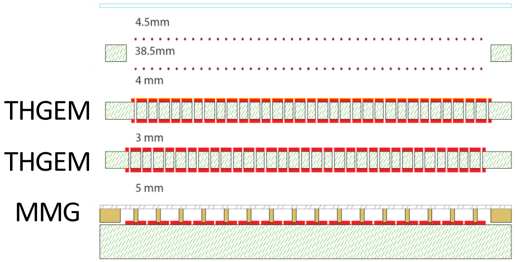
Spark rates at G∼2000

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

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

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

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



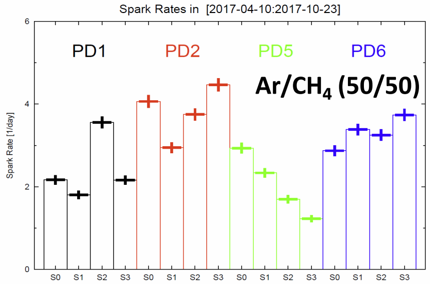
Nominal G ∼ 30000 with:

THGEM1 gain × T1 ∼20

THGEM2 gain × T2 ∼15

MMG gain ∼100

Moderate gains of single structures

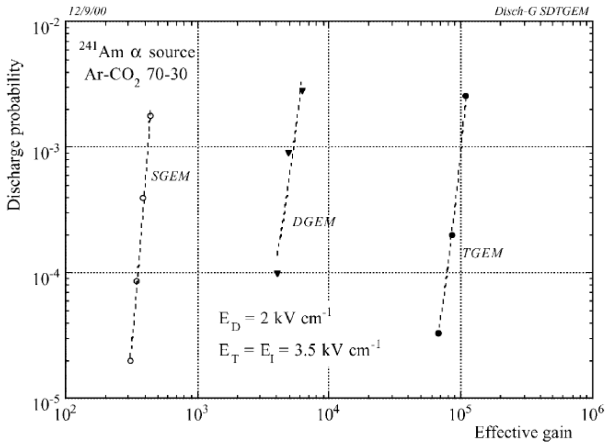


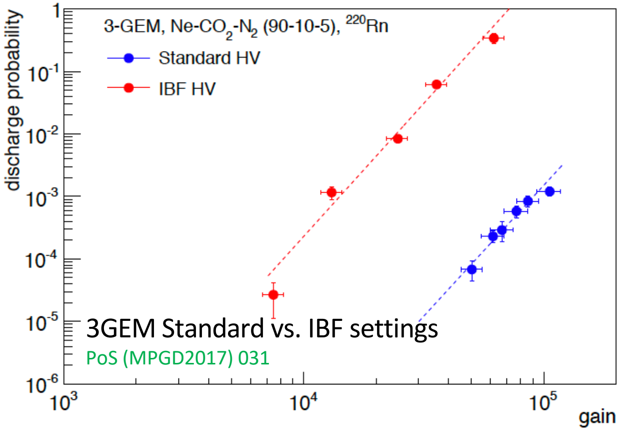
Moderate spark rate in all segments, constant in time

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)





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

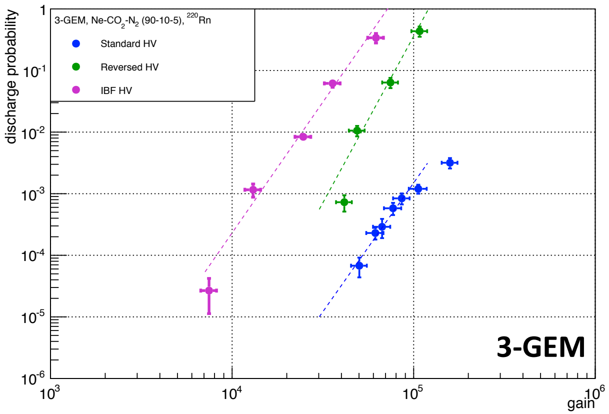
4GEM spark rates in $Ne-CO_2-N_2$ (90-10-5), G~2000:

- ~10^{-10} 1/α
- 6.4×10^{-12} 1/hadron

CERN-LHCC-2015-002

DISCHARGE STUDIES

- Influence of HV settings



- Different HV settings have been tested with a 3-GEM configuration
- "Standard" → "IBF"
  - 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 E_α = 6.4 MeV rate = 0.2 Hz	$\sim 10^{-10}$			$< 2\times10^{-6}$	$< 7.6\times10^{-7}$	
^{241}Am E_α = 5.5 MeV rate = 11 kHz						$< 1.5\times10^{-10}$
^{239}Pu+^{241}Am+^{244}Cm E_α = 5.2+5.5+5.8 MeV rate = 600 Hz		$< 2.7\times10^{-9}$	$< 2.3\times10^{-9}$	$(3.1\pm0.8)\times10^{-8}$		$< 3.1\times10^{-9}$
^{90}Sr E_β < 2.3 MeV 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)

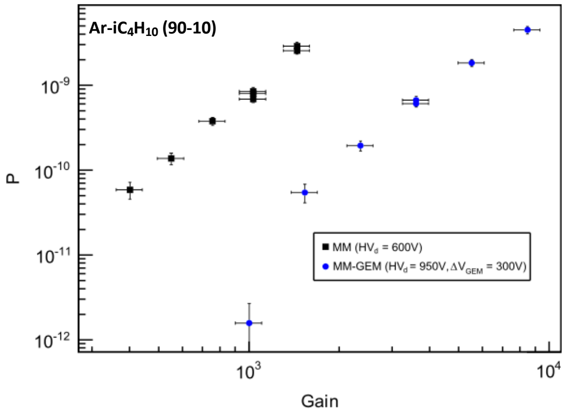
- Clear influence of the pre-amplification stage (GEM) on the stability of MMG
- Lower charge densities reach MMG (cf. 1 and 2 mm gaps)
- Confirmed with GEANT simulations
- GEM+MMG characterized by good ion backflow performance

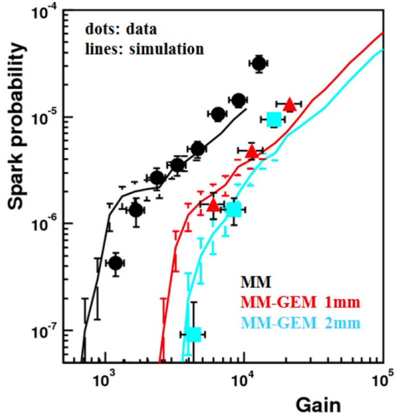
  (e.g. E. Aiola et al. NIM A 834 (2016) 149)
- Considered for future CEPC TPC (China) or HYDRA TPC at R3B (GSI)

  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