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DISCHARGES IN GASEOUS DETECTORS:

A VIEW FROM MPGD EXPERIENCE

RPC
2024
Santiago de Compostela
(Spain)

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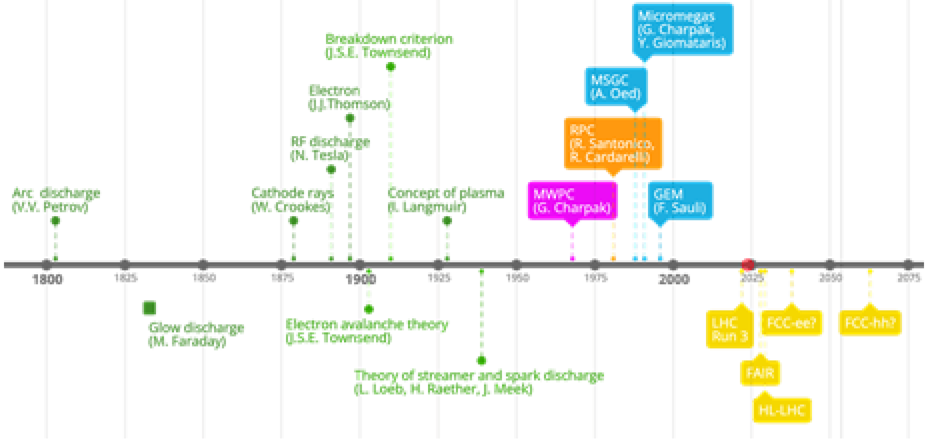
12.09.2024

SHORT OVERVIEW

For a longer overview see two outstanding presentations at RD51 Collaboration meeting in Munich, 2018:

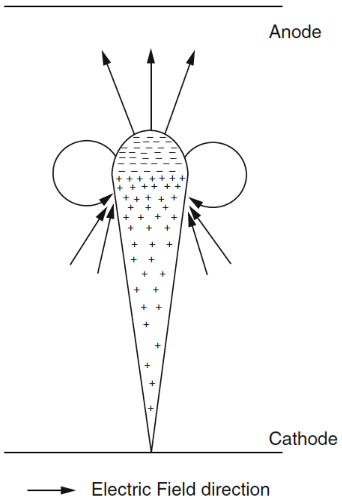
- V. Peskov, *„ Discharge phenomena in gaseous detectors “ (link)*
- P. Fonte, *“Simulations of discharge phenomena” (link)*

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 MPGDs
- Understanding gas discharges helps to avoid their occurrence and mitigate their effects!

Streamer theory



D. Xiao, Springer 2016

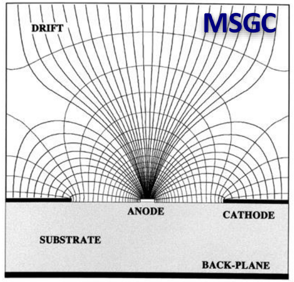
- A single *e* starting at the cathode builds up an avalanche (ionization) that crosses the gap
- Electrons in the avalanche move very fast compared to the ions (regarded as stationary)
- The space-charge E-field will cause significant distortions which
  - strengthen the electric field of the head and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

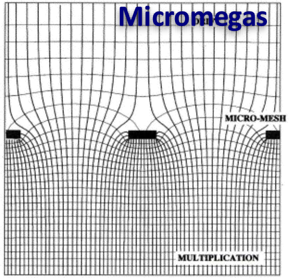
- **Raether criterion:** $Q_{max} = e^{\alpha d} > 10^8$ is the condition for streamer formation and self-sustained discharge (as in Townsend)

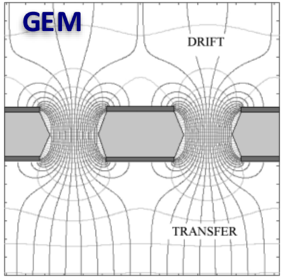
- **Meek criterion:** radial E-field intensity of the space-charge (head of the avalanche) is ~equal to the applied field;

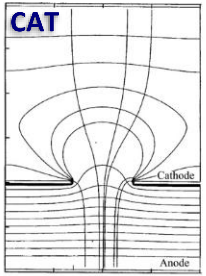
(Supplemented by **Loeb condition** on the electron density in the avalanche of 0.7×10^{12} cm^{-3} to ensure sufficient photoionisation)

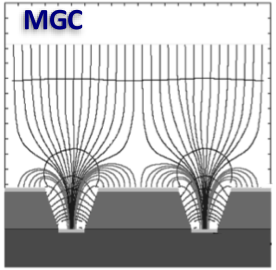
Discharges in MPGDs







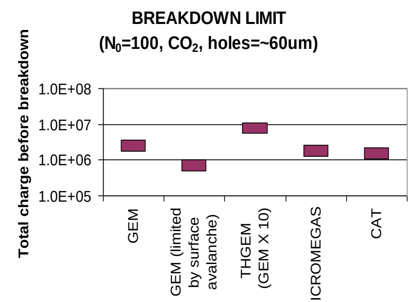




- Streamers can develop by the same mechanism as in PPAC → no quenching by field reduction (i.e. full breakdown)
- Critical charge measurements in MPGDs point to a **limit of 10^6-10^7 *e***, depending on the reference
- Different geometries, gases, source (x-ray, alphas) → **is the limit the same if studied differentially?**

F. Sauli, Amsterdam, 2008

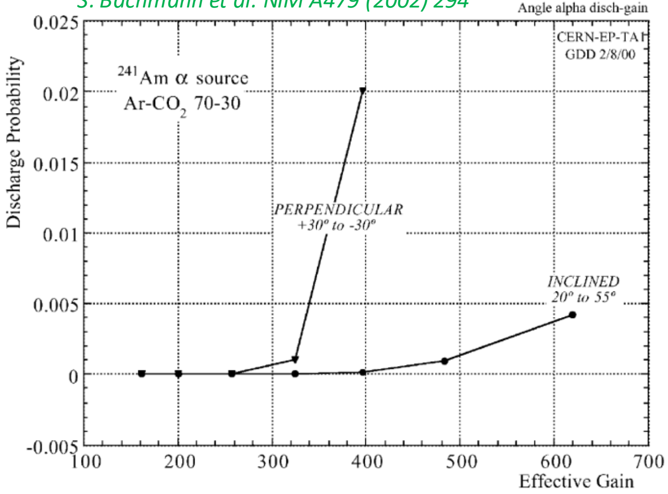
	DETECTOR	MAX GAIN	MAX CHARGE
i	MSGC	2000	$4\ 10^7$
ii	ADV PASS MSGC	1000	$2\ 10^7$
iii	MICROWELL	2200	$4.4\ 10^7$
iv	MICROMEGAS	3000	$6\ 10^7$
v	GEM	2000	$4\ 10^7$

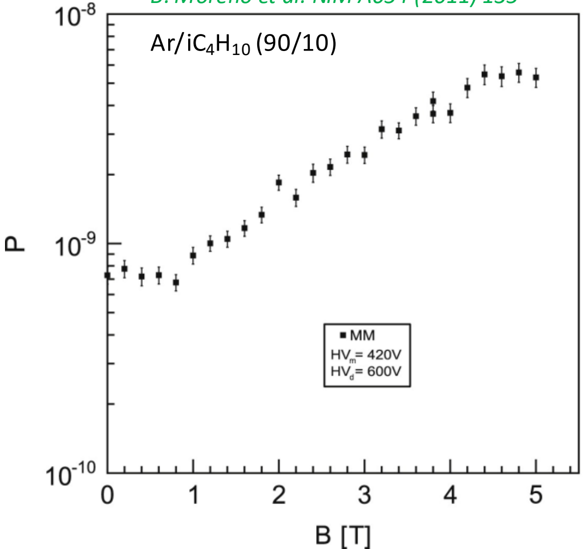


P. Fonte, RD51 meeting, Munich, 2018

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 (surface) charge density

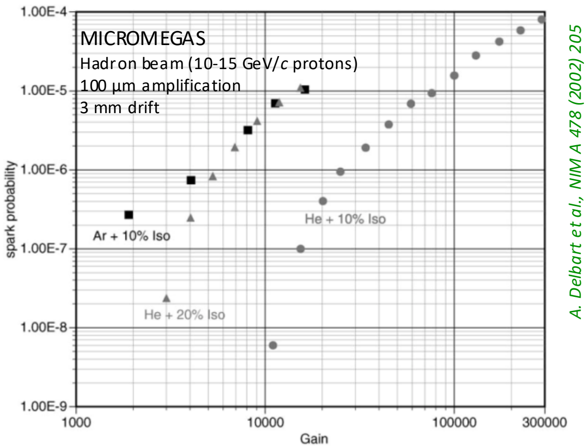

S. Bachmann et al. NIM A479 (2002) 294


B. Moreno et al. NIM A654 (2011) 135

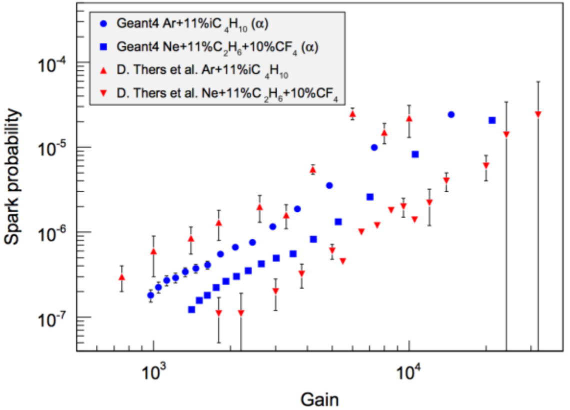
Critical charge in MPGDs

- Clear gas dependencies
- Discharge probability reduced for lighter gases ➞ charge density
- Clear correlation between discharge rate and $\langle Z \rangle$ of a gas mixture

- 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
- **Charge limits – different for different mixtures?**



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

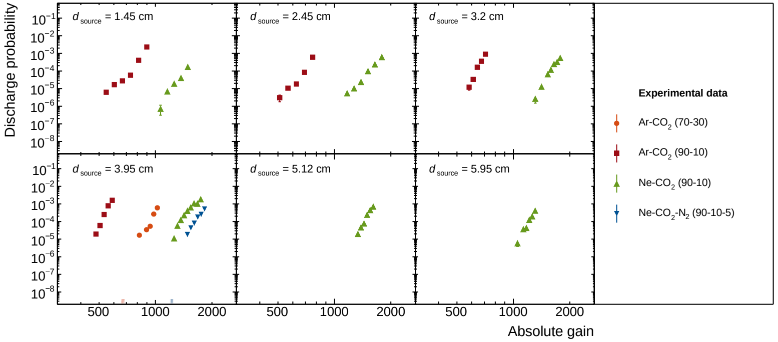


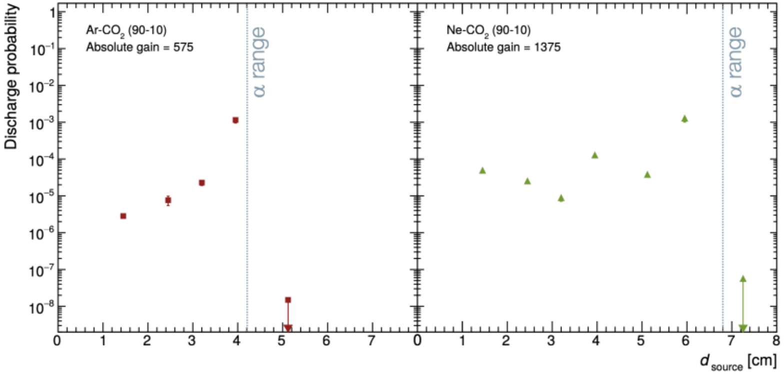
S. Procureur et al. NIM A621 (2010) 177

GEMs and THGEMs

GEM discharge probability

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





- Discharge probability of a single, standard GEM upon irradiation with alpha particles:
  - – Lower breakdown limits in Argon than Neon-based mixtures
  - – Abrupt drop of discharge rate for source distances larger than alpha range
  - – Observations consistent with the primary charge density hypothesis
    - Alpha range in Ne longer than in Argon
    - W_i (Ar) < W_i (Ne)

Gas	v_d [cm/µs]	D_L [$\sqrt{cm}$]	D_T [$\sqrt{cm}$]	W_i [eV]	r_α [cm]
Ar-CO$_2$ (70-30)	0.932	0.0138	0.0145	30.2	4.2
Ar-CO$_2$ (90-10)	3.26	0.0244	0.0268	28.8	4.8
Ne-CO$_2$ (90-10)	2.66	0.0223	0.0219	38.1	6.8
Ne-CO$_2$-N$_2$ (90-10-5)	2.52	0.0218	0.0224	37.3	6.9

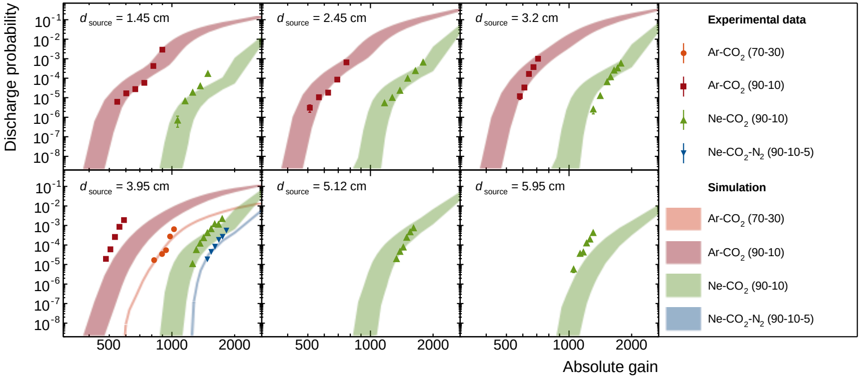
Critical charge limits in GEMs

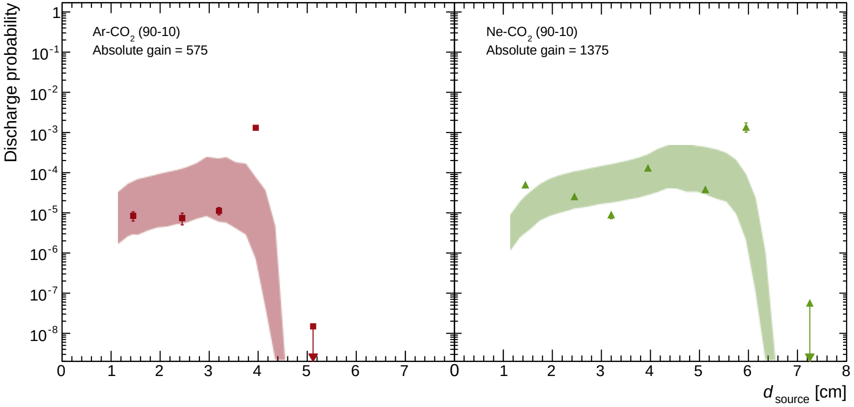
PG et al., *NIM A 870 (2017) 116*

- GEANT4 – based model describes data fairly well over several orders of magnitude
- Only primary ionization and basic gas properties taken into account (D_L, D_T, v_d)
- No additional normalization!

Gas	Q_{crit}
Ar-CO_2 (90-10)	$(4.7 \pm 0.6) \times 10^6$
Ne-CO_2 (90-10)	$(7.3 \pm 0.9) \times 10^6$

- **Primary charge density → driving factor for discharge formation**
- **Different Q_{crit} for different gases → no universal Raether limit.**

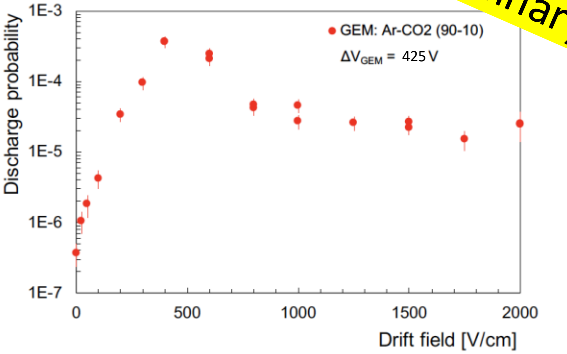


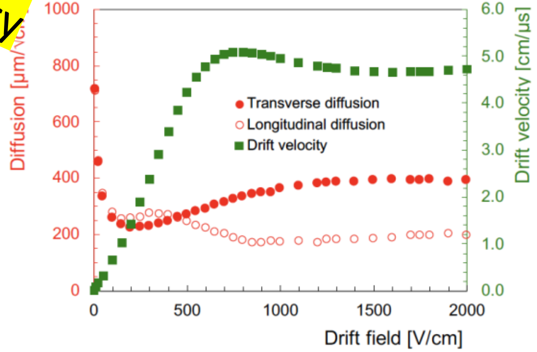


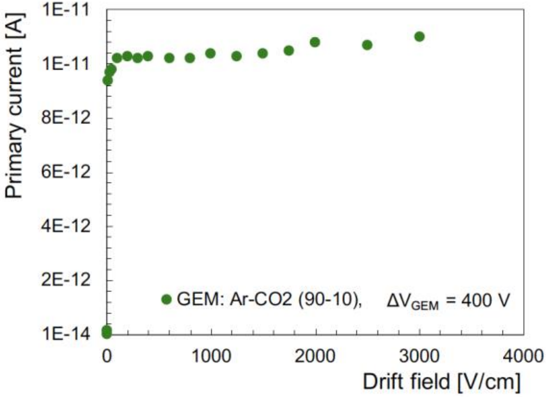
Charge transport influence

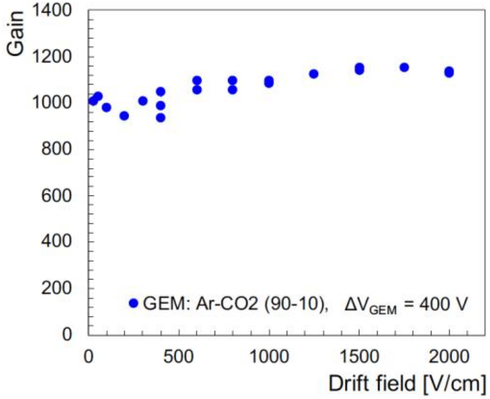
- Clear influence of a field **above** the GEM on its stability
- Correlation with drift parameters: diffusion ➞ charge density ➞ discharge probability
- Increase for *E* < 400 V/cm not related to gain
- Drop for *E* > 400 V/cm not related to the collection efficiency

Preliminary









Charge transport influence

- Clear influence of a field **above** the GEM on its stability
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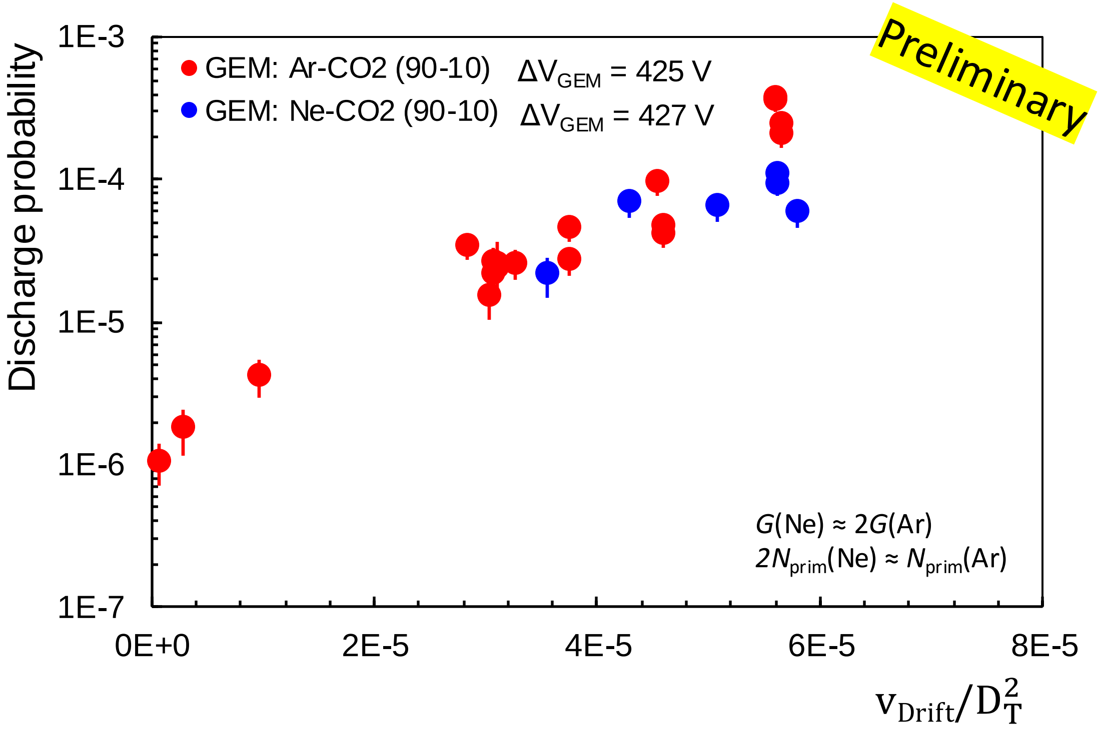
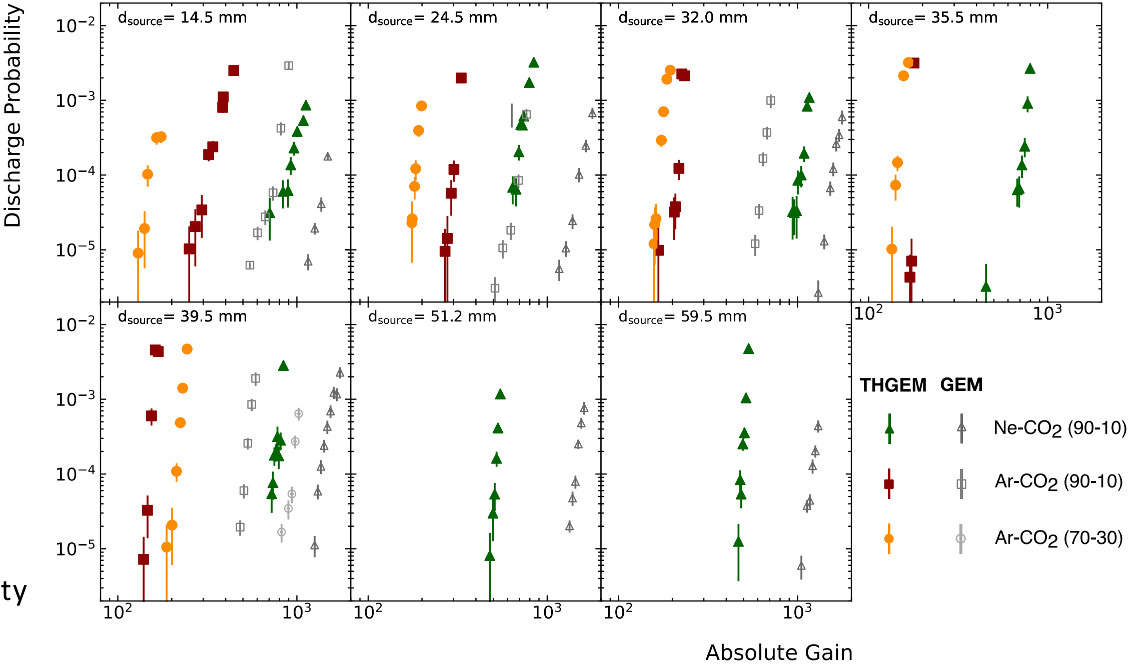
- **Scaling with v_{Drift}/D_T^2**



THGEM Discharge probability

NIM A 1047 (2023) 167730

- Single THGEM (COMPASS-RICH)
- ⟨*Z*⟩ dependence
  - Ne more stable than Ar → charge density
- *d*d_{source} dependence
  - Abrupt drop of the discharge rate for d_{source} > alpha range
- Quencher content dependence
  - Larger CO_2 content does not increase stability
- THGEMs less stable than GEMs
  - Primary electrons shared by lower number of holes in THGEMs



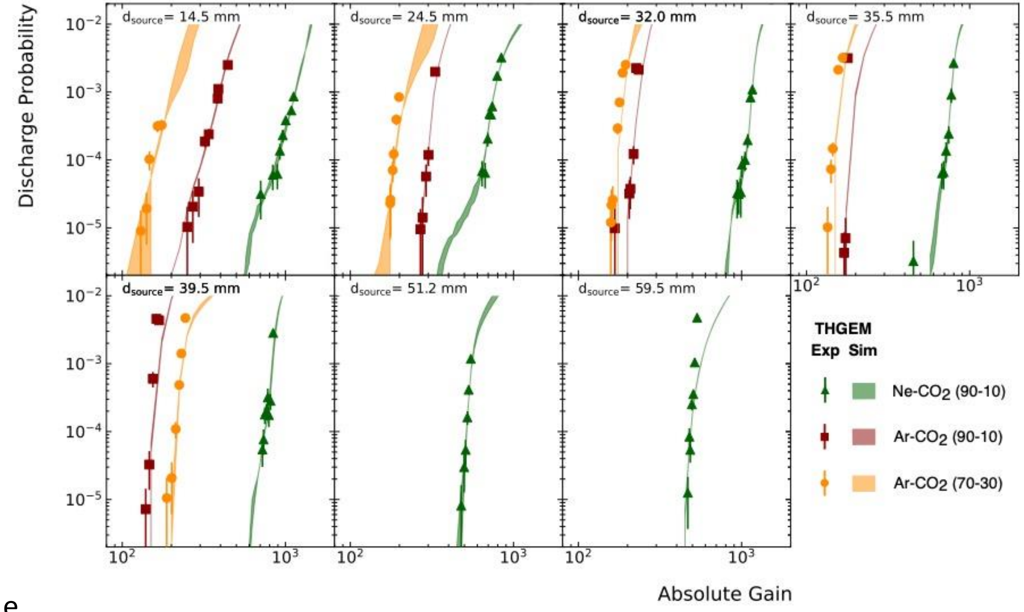
Simulation fits

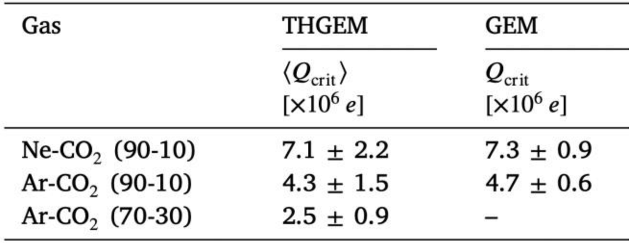
NIM A 1047 (2023) 167730

- Simulated discharge curves 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!
- The primary charge limits shall be considered per single holes, not normalized to the hole volume.



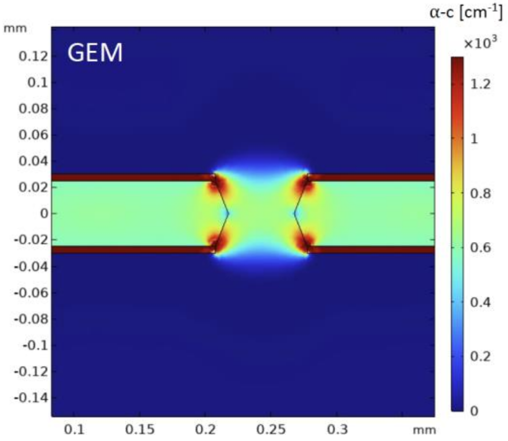


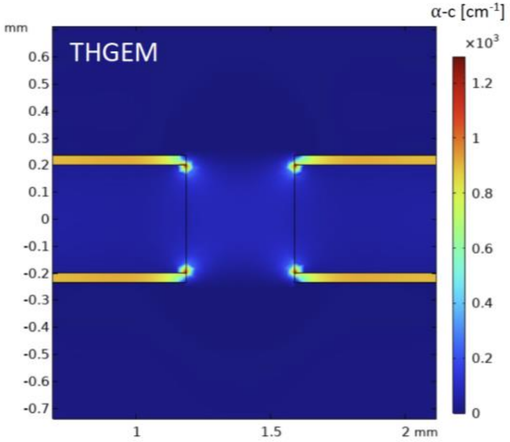
Gas	THGEM	GEM
	$\langle Q_{\mathrm{crit}} \rangle$ $[\times 10^6\ e]$	Q_{crit} $[\times 10^6\ e]$
$Ne\text{-}CO_2$ (90-10)	7.1 ± 2.2	7.3 ± 0.9
$Ar\text{-}CO_2$ (90-10)	4.3 ± 1.5	4.7 ± 0.6
$Ar\text{-}CO_2$ (70-30)	2.5 ± 0.9	–

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}





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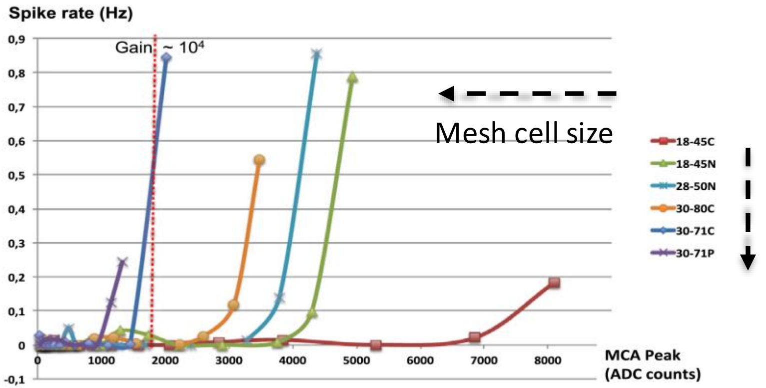
MICROMEGAS

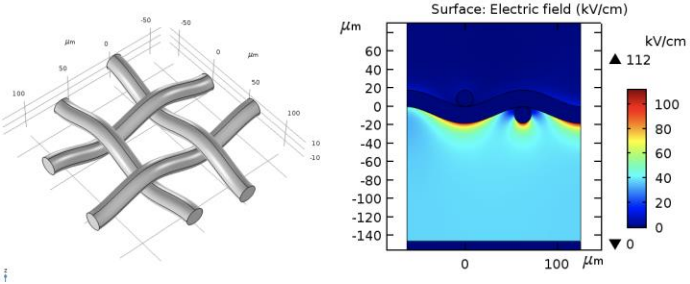
Situation in Micromegas

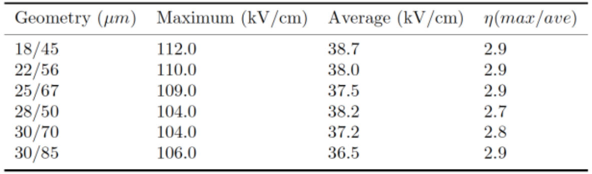
- Can Micromegas mesh cells be considered as individual amplification units, as GEM holes?
- If so → discharge probability shall scale with the MMG mesh cell size, i.e. higher discharge rate for large-cell meshes (small LPI)
- Difficulty → mesh parameters strongly influence E-field (high fields may further reduce the stability of the detector)
- Measurements with ^{55}Fe suggest using high-LPI meshes (Alviggi et al.)
- Field considerations with COMSOL® suggest low-LPI and thick meshes (Bhattacharya et al.)



Mesh cell size

M. Alviggi et al., NIM A 958 (2020)162359



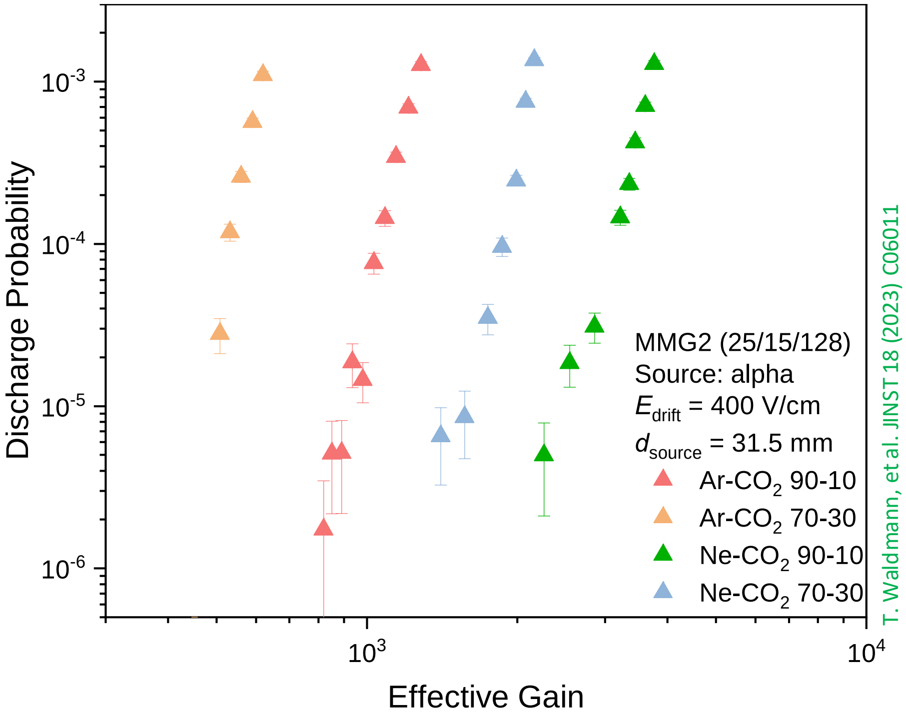


Geometry (μm)	Maximum (kV/cm)	Average (kV/cm)	$\eta(max/ave)$
18/45	112.0	38.7	2.9
22/56	110.0	38.0	2.9
25/67	109.0	37.5	2.9
28/50	104.0	38.2	2.7
30/70	104.0	37.2	2.8
30/85	106.0	36.5	2.9

D.S. Bhattacharya et al., J. Phys. Conf. Ser. 1498 (2020) 012032

⟨Z⟩ dependence

- Same dependency on the gas mixture as in previous measurements with GEMs and THGEMs
- For streamer and spark discharge development, more quencher does not mean more stability!
- Same order observed with other MMG types
- Primary charge density!

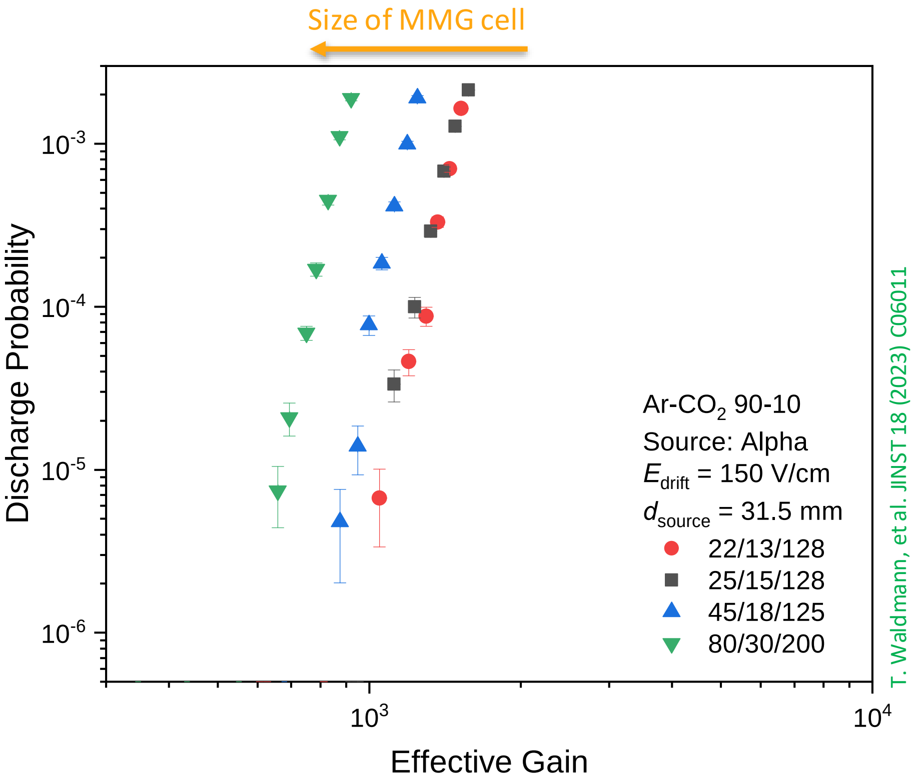


T. Waldmann, et al. JINST 18 (2023) C06011

Discharge stability

- Electron transparency ~98% for all MMG
- d_{source} shorter than alphas maximum range
- Discharge rate scales with the mesh cell size (optical transparency)
- The influence of high fields can be disregarded by measurements with low charge densities
- Mesh cell as an independent amplification structure

- High-rate & wide dynamic range operation
  - → number of cells shall be increased
  - → quencher plays a role in terms of charge densities
- Operation at high gains & lower charge densities
  - → field uniformity (peak fields, woven/calendered mesh, etc)
  - → better quenchers needed (open geometry) to reduce photon feedback

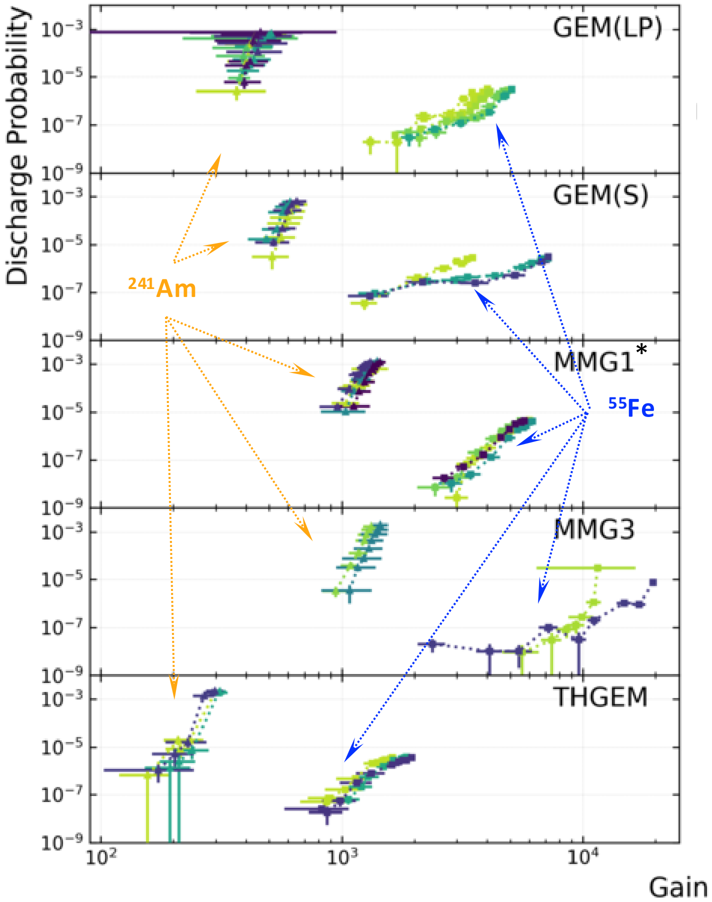


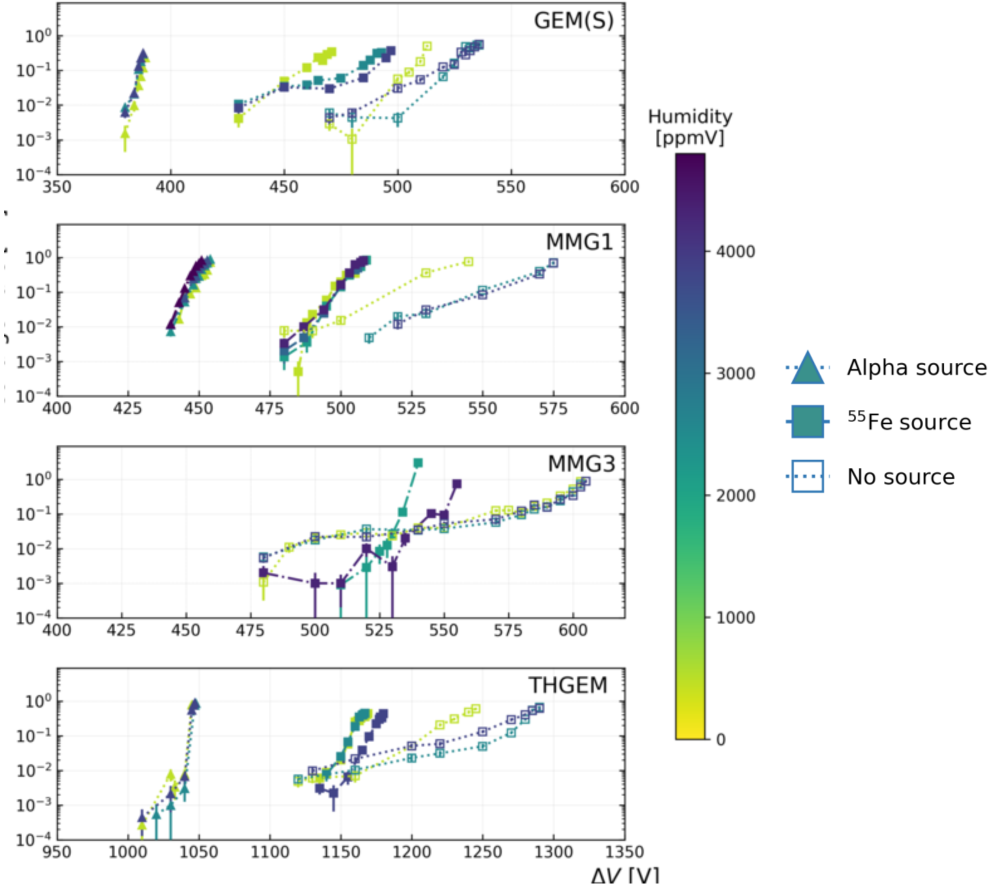
T. Waldmann, et al. JINST 18 (2023) C06011

What about water?

No-resistive layers!

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





*Scaled gain – transparency < 100%

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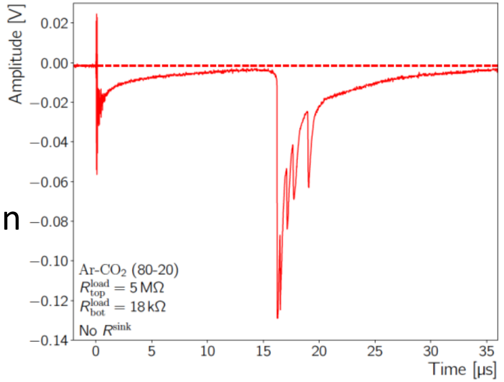
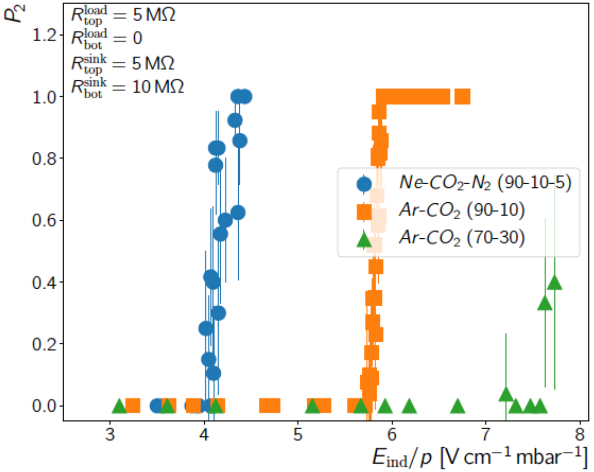
SECONDARY DISCHARGES

Secondary discharge formation*

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

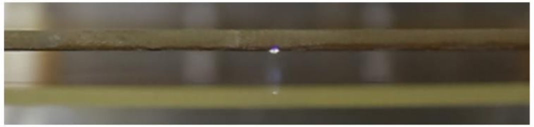
- Leading theory: heating of the cathode after the primary discharge
  - A. Deisting, et al. NIM A 937 (2019) 168
  - A. Utrobicic, et al. NIM A 940 (2019) 262
- Mitigation strategies established - quenching with external *R* elements, *C* reduction
  - L. Lautner, PG, et al. JINST 14 (2019) P08024
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



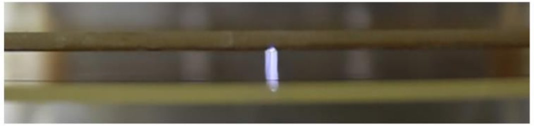


A. Deisting, et al. NIM A 937 (2019) 168

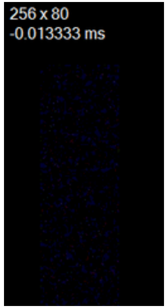
a) Primary discharge



b) Secondary discharge



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



A. Utrobičić et al.
MPGD 2019,
La Rochelle

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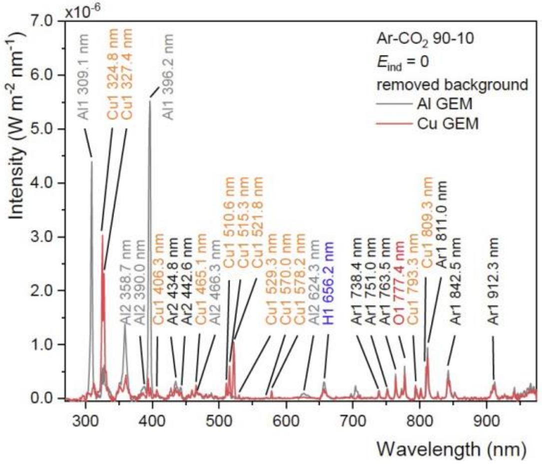
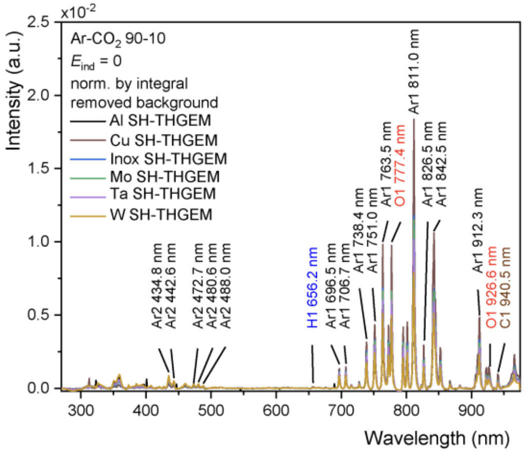
* See pioneering studies by *S. Bachmann et al. NIM A479 (2002) 294 & V.* Peskov, P.Fonte (2009) arXiv:0911.0463

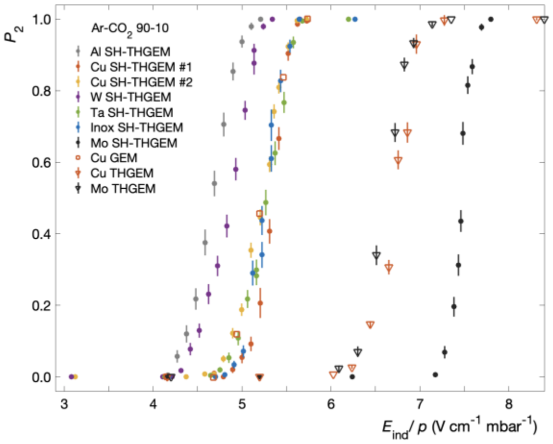
Discharge spectroscopy

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



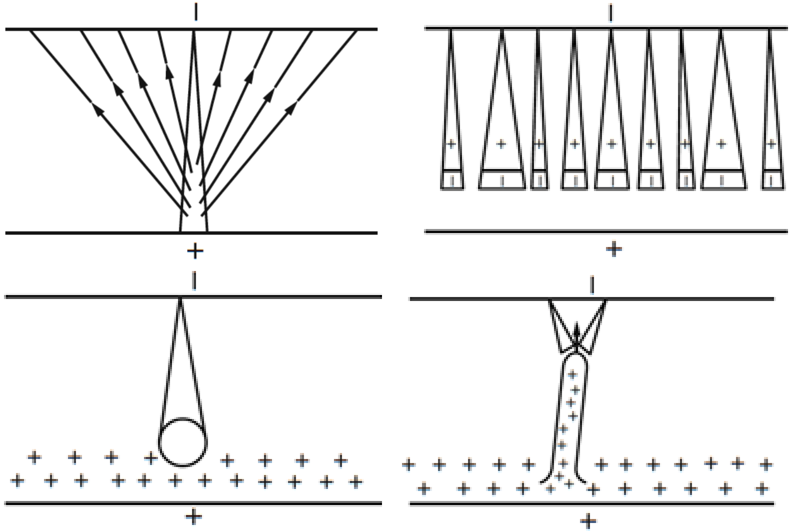
- Measuring emission spectra of the light emitted during primary discharges
- Cu and Al emission lines observed in GEM discharges
- vaporisation → presence of foil material in discharge plasma
- THGEMs with various electrodes → no emission lines corresponding to foil cladding
- No or strongly reduced material vaporisation from discharges in THGEM hole geometry → lower temperature reached?
- Secondary discharges still prevalent in THGEMs
- No direct connection between material vaporisation and secondary discharge formation
- Influence of the cathode material properties or surface quality (Mo, polished Cu exceptionally stable)

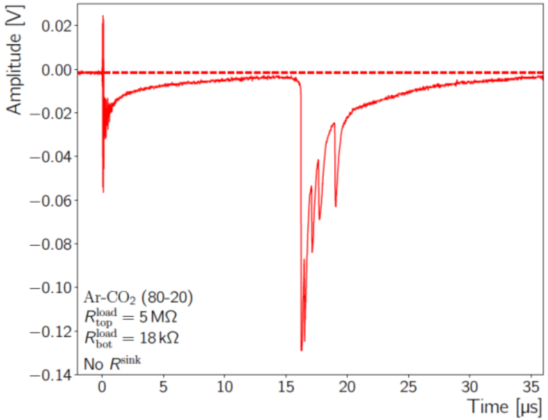




Secondary discharge formation - hypothesis

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





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

AVOIDING Q_{crit}

Choice of gas for spark dischagre mitigation – lower N_{prim}

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

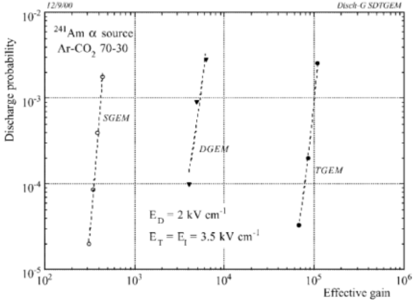
  → well-quenched gases preferable but watch out charge densities!
- Reduce gain as much as allowed by the signal-to-noise ratio requirements

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

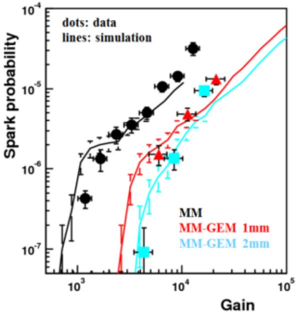
Build stacks – diffuse primary charge

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

NIM A479 (2002) 294

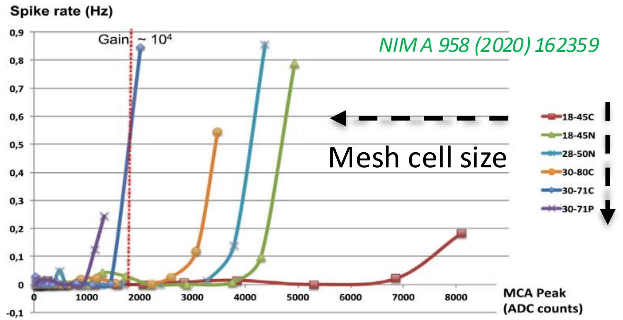


JINST 7 (2012) C06009



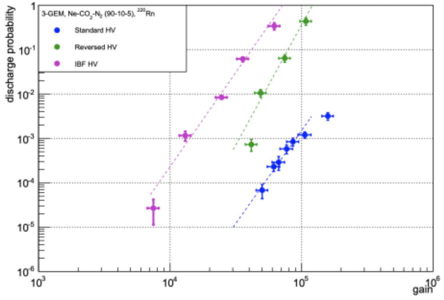
- **GEM + MMG hybrids and multi-MMG stacks**

  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)



NIM A 958 (2020) 162359

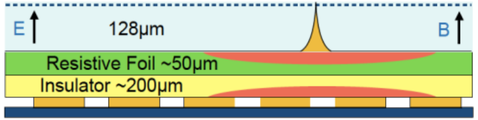
- **Optimized HV settings** (lower amplification towards bottom of a stack)
  - Violated in case the stack optimized for low ion backflow (TPCs)
  - Adding further foils in the stack can improve its stability, → 4GEM Readout for ALICE TPC (IBF optimized)
  - Optimize the electric field above/below the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



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

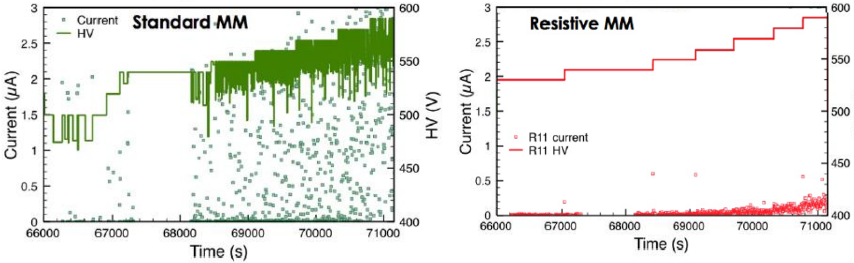
Resistive MPGDs

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



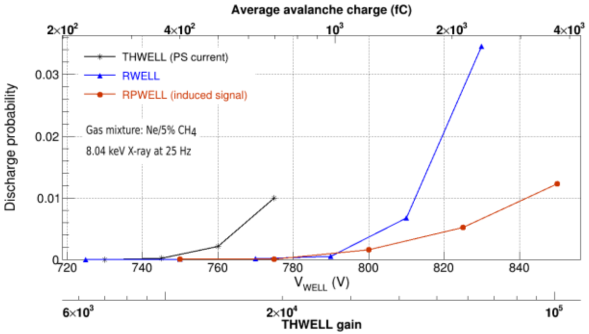
Resistive MICROMEGAS *(NIM A 629 (2011) 66, NIM A 1025 (2022) 166109)*

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



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

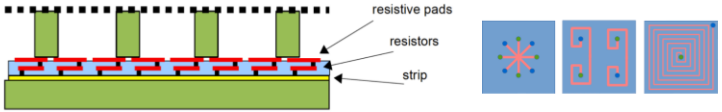
- Resistivity: 16 MΩ/□ (RWELL), $2\cdot10^{10}$ Ωcm (RPWELL)
- Stable operation at gains of up to a few 10^4 (with gain drop corrections!)



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

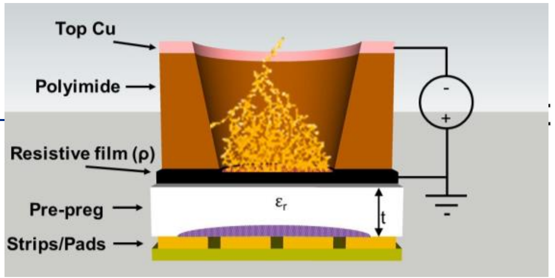
Embedded resistors *(JINST 12 (2009) P12004, NIM A 824 (2016) 510)*

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

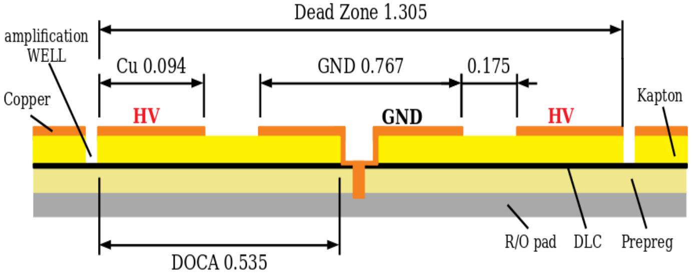


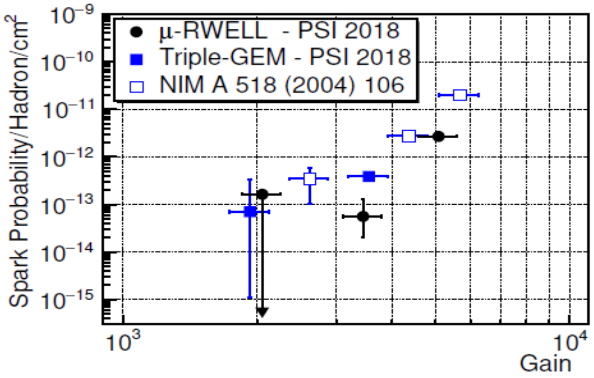
New structures: micro-RWELL

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

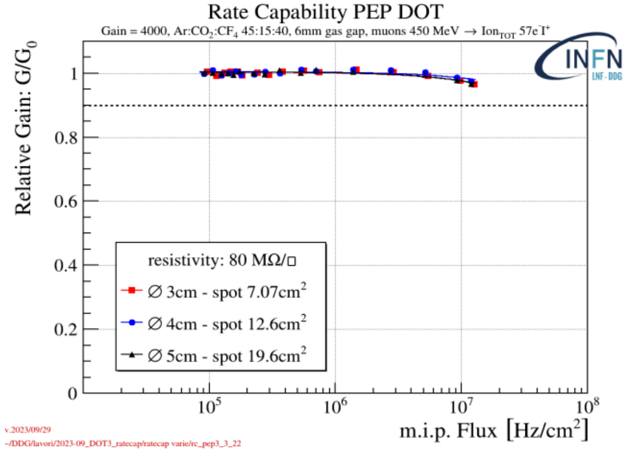


- Single-sided Gaseous Electron Multiplier (GEM) coupled to the readout anode through the material of high surface resistivity
- Single amplification stage → material budget, simplicity, industrialization, costs!
- Resistive layer → suppression of the transition from streamer to spark, with a consequent reduction of the spark amplitude.





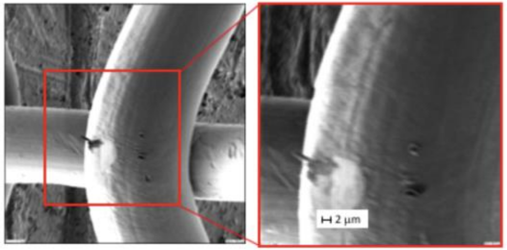
- High-rate capabilities restored by the proper grounding of the DLC layers (grooves, dots) → improved charge evacuation
- DLC grounding by **conductive DOT → rate capability** (@ 90% drop) > **10 MHz/cm^2**



Further reduction of instabilities

- **High absolute voltages and high fields must be avoided**
  - High fields around defects and residual contamination may lead to instabilities (self-sustained discharges)
  - **Quality control of the upmost importance**

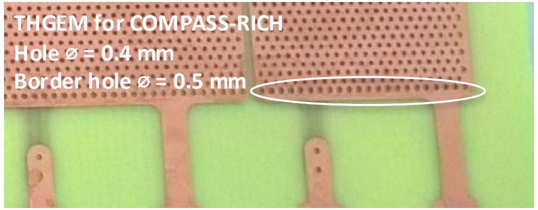
    (for MPGDs see ALICE JINST 16 (2021) P03022, CMS NIM A 1034 (2022) 166716, ATLAS NIM A 1026 (2022) 166143)



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

- **Careful design**
  - Reduce charge density per single amplification cell (e.g., small pitch GEM, large LPI MMG)
  - Segmentation → reduce the energy of a discharge
  - Avoid high fields → electrode edge effects (e.g. edge hole rows, sharp edges/corners, ...)

    influence of mechanical structures (e.g. spacers in MPGD stacks, multi-gap RPCs, ...)



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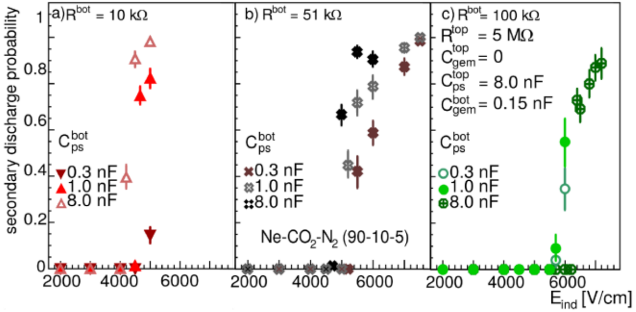
- **HV system and HV scheme optimisation**
  - Safe system (passive dividers, active dividers, cascaded PS)
  - Reduce currents, quench secondary (propagated) discharge development
  - Reduce and decouple parasitic capacitances parallel to MPGDs and transfer gaps in

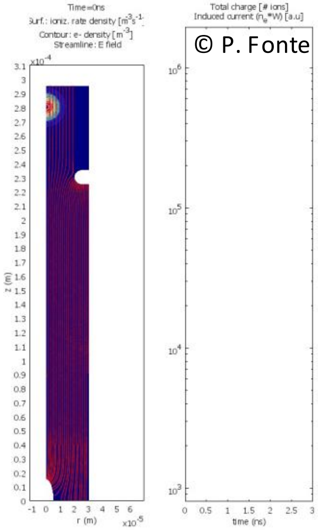
    the MPGD stacks



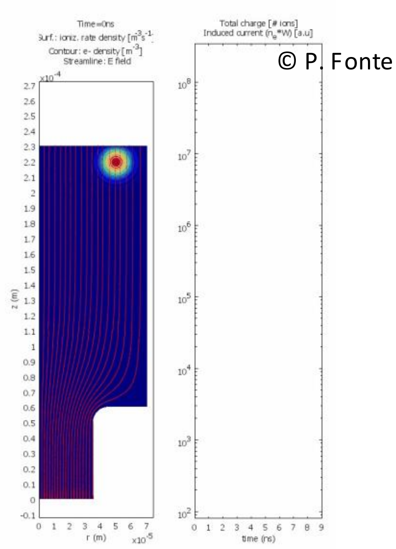
L. Lautner et al. JINST 14 (2019) P08024

Future: MPGDs in SQS mode?

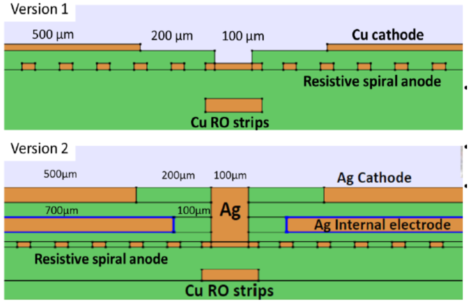
- Discharge probability could be reduced if a radial shape E-field is formed in the MPGD avalanche gap
- Both simulation and R&D effort. Still need for optimization, but ideas on the market!

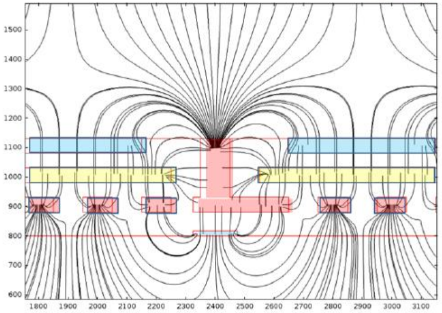


Needle + InGrid



Cathodeless CAT





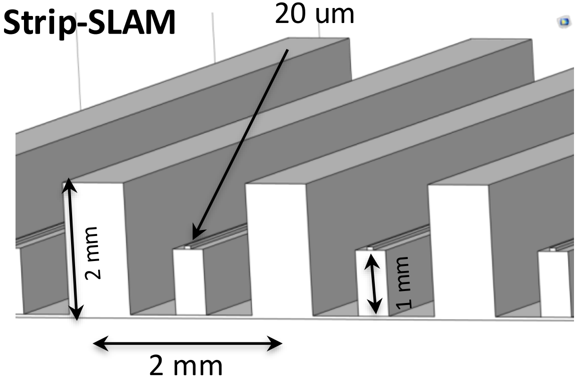
V. Cairo et al, JINST 9 (2014) C11022

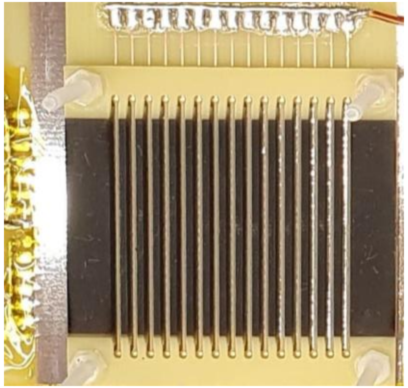
P. Fonte, "Simulations of discharge phenomena", RD51 Meeting, TU Munich 2018 (link)

Discharge Consortium in quest for Spark-Less-Avalanche-Microstructures

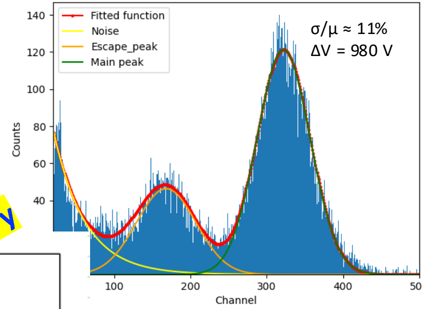
RD51 Common Project, V. Peskov, PG (2020-2023), see also T. Waldmann *et al. JINST* **18** (2023) C07009 for the Wire-SLAM Version

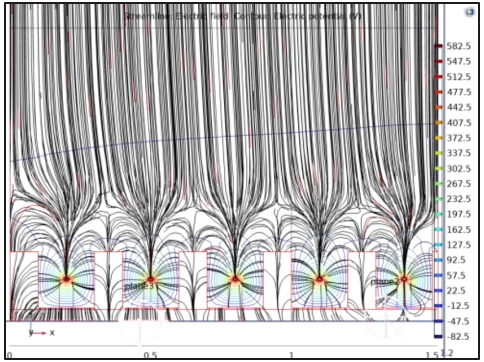
Strip-SLAM



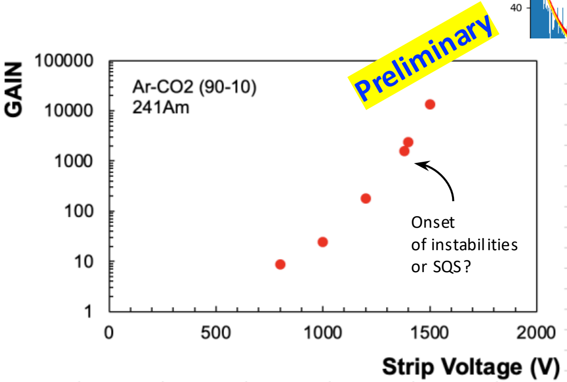


Produced by
CERN EP-DT-DD Micropattern Structures Laboratory





Radial E-field to quench streamer development



First measurements by GSI

Summer Students ’24

- P. Piotrowski (Uni Warsaw)
- I. González Álvarez (Aut. U of Madrid)

SUMMARY & OUTLOOK

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

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