Understanding discharge formation in GEM detectors by simulating the primary charge density


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Discharges in GEMs

- Breakdown appears when the total charge in the avalanche reaches critical value $Q_{\text{max}}$
  - $Q_{\text{max}} = G_{\text{max}} \times n_{\text{prim}} \approx 10^{7} \text{e}^{-}$
  - Beware of highly ionizing particles!
  - “High rate behavior and discharge limits in micro-pattern detectors”, A. Bressan et al. NIM A 424 (1999) 321

- Spark in GEM:
  - $\Delta V_{\text{GEM}} \to 0$
  - may be harmful to the detector and electronics
    (large energy release)

- Multi-GEM structures
  - charge spreads over many GEM holes

- Dedicated workshop on Thursday

S. Bachmann et al, NIM A479 (2002) 294
GEMs in harsh environment

- COMPASS: Up to 1 MHz/cm² in the middle segments
- LHCb: Up to 0.5 MHz/cm² in the middle segments
- TOTEM: Operated at 10 kHz/cm² in the middle
- Trackers
  - Short drift gap $\mathcal{O}$(mm), Ar-based mixtures
  - No pile-up expected
  - Up to a few electrons/hole expected (MIP)
- Troublemakers
  - Highly Ionizing fragments ($N_{\text{prim,}\alpha} = 10^4 \times N_{\text{prim,MIP}}$)
  - Charge densities in the bottom GEM, after full amplification
    (e.g. IBF-optimized multi-GEM stacks)
- Stability of your system relies on the stability of a single GEM!
  - Critical charge density & Influence of the gas?
Single-GEM measurements

- Single GEM detector, variable drift
- Standard GEM: 50/70 µm, 140 µm
- Alpha source shoots perpendicular to the GEM
- Discharge probability $P = \frac{\text{#sparks}}{(\text{time} \times \text{rate})}$
- Measured spark rates < 1 Hz

- Gas mixtures:
  - Ar-CO$_2$, Ne-CO$_2$ (90-10)
  - Ar-CO$_2$ (70-30), Ne-CO$_2$-N$_2$ (90-10-5)

"Coin" mixed source
- $^{239}$Pu + $^{241}$Am + $^{244}$Cm
- 5.2 MeV + 5.5 MeV + 5.8 MeV
- Rate = 600 Hz
Detector characteristics

- $E_{\text{ind}} = 0$, $E_{\text{drift}} = 400$ V/cm
- Measure absolute gain (true GEM multiplication)
  $\varepsilon_{\text{coll}} = 100\%$ at 400 V/cm drift
  $\varepsilon_{\text{extr}} = 0\%$ with $E_{\text{ind}} = 0$
  $G_{\text{eff}} = \varepsilon_{\text{coll}} \times G_{\text{abs}} \times \varepsilon_{\text{extr}}$

- Exponential fit to describe data
  - Used for further extra- and interpolation
  - Gain evaluated before each measurement session
    - Defined by gas choice and drift distance
  - Single point measurement $< 2h$
  - Single session time $< 8h$
  - Max p variation $< 2$ mbar $\rightarrow \Delta \text{Gain} < 1\%$
Discharge studies – charge density hypothesis

- Discharge probability strongly depends on inclination angle and amount of ionization close to the GEM
  - Shooting perpendicular increases discharge rate by ~ one order of magnitude

\[ P \sim 10^{-6} \]

\[ P \sim 10^{-5} \]

Ar-CO$_2$, G= 30,000

Ne-CO$_2$-N$_2$, G= 45,000

GEANT 4 sim
Discharge curves

- Discharge probability measured for different distances between the source and the GEM ($d_{source}$)

![Discharge curves graph](image)

<table>
<thead>
<tr>
<th>Gas</th>
<th>$\nu_d$ [cm/µs]</th>
<th>$D_L$ [cm$^2$/cm]</th>
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<th>$W_i$ [eV]</th>
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<td>Ar-CO$_2$ (70-30)</td>
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Basic gas properties computed in Magboltz and GEANT4
Discharge curves

- Discharge probability in Ar-based mixtures > 4 orders of magnitude larger than in Ne
  - Charge densities in Argon larger than in Neon (see $W_i$ and $r_a$)
  - In line with S. Procureur et al. NIM A621 (2010) 177 with MMG

![Discharge curves diagram]

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Basic gas properties computed in Magboltz and GEANT4
Discharge curves

- Clear influence of additional quencher
  - 30% of CO\(_2\) or 5% of N\(_2\)
Discharge probability vs. $d_{\text{source}}$

- Severe drop of the probability by several orders of magnitude at the end of the $\alpha$'s range
  - Only upper limits measured
- Clear correlation with the maximum range of alphas
- Highest charge densities obtained with particles impinging the GEM area
- Probability increases with $d_{\text{source}}$
  - Resemble Bragg curve
  - Analytical solution difficult due to opening angle, …

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Basic gas properties computed in Magboltz and GEANT4
Model

- 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 at $E_{drift} = 400$ V/cm
  - Smearing with Gaussian distribution
  - Repeated for many different $d_{source}$
- Similar approach as in S. Procureur et al. NIM A621 (2010) 177
Model

- 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 $Q_{\text{crit}}$ in single GEM hole
  - When exceeded $\rightarrow$ discharge (à la Raether limit)

- Count such large primary ionization clusters and normalize to the number of all $\alpha$-particles
  - Discharge probability

- Not known: $Q_{\text{crit}}$ & the time it takes to develop a discharge $t_{\text{int}}$
  - Parameter scan + $\chi^2$ minimization
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- Not known: $Q_{\text{crit}}$ & the time it takes to develop a discharge $t_{\text{int}}$
  - Parameter scan + $\chi^2$ minimization
Results

- Model describes data fairly well over several orders of magnitude
- Only primary ionization and basic gas properties taken into account
- No additional normalization!
- $Q_{\text{crit}}$ extracted for $t_{\text{int}} = 30-50$ ns (best $\chi^2$)

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<td>Ar-CO$_2$ (70-30)</td>
<td>$\sim 5 \times 10^6$</td>
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<td>Ne-CO$_2$-N$_2$ (90-10)</td>
<td>$\sim 9 \times 10^6$</td>
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A few words on $t_{\text{int}}$

- What is the meaning of $t_{\text{int}} >> 1 \text{ ns}$?
  - Time needed to accumulate $Q_{\text{crit}}$ charges in the GEM hole
  - Build up space charge needed for streamer formation
  - Too long for electrons…

- $t_{\text{int}} \sim 50 \text{ ns}$ compatible with ion drift time in GEM hole
  - 1-2 mm integration gap above GEM

- Compatible with S. Franchino et al., Nuclear Science Symposium and Medical Imaging Conference, IEEE (2015) 1

Fig. 6. Formation and propagation of a streamer in a GEM hole in cylindrical coordinates. The colour map represents the ion density in arbitrary units.

S. Franchino, IEEE (2015) 1
A few words on $Q_{\text{crit}}$

- Different $Q_{\text{crit}}$ values extracted for different gases
  - No common Raether limit?
- Similar conclusions in S. Procureur et al. NIM A621 (2010) 177
  - Simulations cannot describe Ne- and Ar- data using only $W_i$ weights

- Intrinsic properties of the working gas (transport, amplification, streamer development) could possibly explain the differences – more studies needed

**Fig. 10.** Comparison between measured and simulated spark rate as a function of the gain for argon and neon mixtures. Data are extracted from Fig. 8 in Ref. [3].

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

- Discharge probability of a single GEM upon irradiation with alphas
  - Lower breakdown limits in Argon- than Neon-based mixtures
  - Observations consistent with the charge density hypothesis

- Charge density model describes the data fairly well over several orders of magnitude
  - $Q_{\text{crit}} = (5 - 9) \times 10^6$ electrons depending on the gas mixture

- Estimated $t_{\text{int}}$ of ~50 ns point towards ion space-charge build-up in GEM hole prior to the discharge

- Watch out particles impinging your detectors – the charge densities are the highest there!

Outlook

More studies ongoing at TUM

• Stability of HV systems for MPGD

• THGEM discharge stability
  – See talk by B. Ulukutlu on Thursday

• Discharge propagation
  – See talk by L. Lautner on Thursday

• Single-GEM stability as a function of the fields above and below Non-trivial behaviour: Maximum of the discharge probability coincides with minimum diffusion and top drift velocity
  – Hope to better constrain $t_{\text{int}}$ and $Q_{\text{crit}}$ – field dependency?
  – Discharge probability only dependent on charge transport?

Stay tuned!
Thank you very much!
Model

- 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 discharge pile-up (one alpha – max one discharge)
  - Not known: $Q_{crit}$ & $t_{int}$ → parameter scan + χ² minimization

(exemplary)
Constraining $Q_{\text{crit}}$ and $t_{\text{int}}$

- Free parameters: $Q_{\text{crit}}$ & $t_{\text{int}}$
- Compare simulations for different values of the parameters with experimental data
- Fix $Q_{\text{crit}}$ & $t_{\text{int}}$ by $\chi^2$ minimization

- $t_{\text{int}} \in [2, 400]$ ns
- $Q_{\text{crit}} \in [1, 125] \times 10^5$ e$^-$ (step of $0.5 \times 10^5$ e$^-$)