Optimization of multi-GEM systems

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05.12.2018
RD51-Mini-Week, CERN
Overview

- Electron efficiencies
- Ion efficiencies
  - Avalanche- and drift-contributions
  - Ion-blocking capabilities of GEMs
- Optimization of a 3-GEM-system
- Optimization of a 4-GEM-system
Definition of electron transfer efficiencies
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Collection efficiency:
\[ \varepsilon_{\text{coll}} = \frac{N_{\text{incoming}} - N_{\text{top}}}{N_{\text{incoming}}} \]

Extraction efficiency:
\[ \varepsilon_{\text{extr}} = \frac{N_{\text{transferred}}}{N_{\text{transferred}} + N_{\text{bottom}}} \]

\[ G_{\text{abs}} = \frac{N_{\text{transferred}} + N_{\text{bottom}}}{N_{\text{incoming}}} \]
\[ G_{\text{eff}} = \varepsilon_{\text{coll}} G_{\text{abs}} \varepsilon_{\text{extr}} \]

- In general, these efficiencies depend on the geometric parameters and the applied electric fields.
- Measurement: Instead of number of electrons, use the time-derivative, the current.
Simulation framework – Advanced GEM Simulator

optical scan or user input

gain distribution, efficiencies, parameter plots

gain distribution, efficiencies, parameter plots

charge drift and multiplication

fieldmaps

12 core workstation
Garfield++

ANSYS

parameter file (geom. parameters, voltages)
Comparison to measurements

(1) Simulated and measured collection efficiency for (MP)-GEM (ArCO2 (90-10)).

(2) Simulated and measured extraction efficiency for (MP)-GEM (ArCO2 (90-10)).
Definition of ion-transfer efficiencies

Collection efficiency:

\[
\varepsilon_{\text{coll}}^{\text{aval}} = \frac{N_{i,\text{created}} - N_{i,\text{bot}}}{N_{i,\text{created}}}
\]

Extraction efficiency:

\[
\varepsilon_{\text{extr}}^{\text{aval}} = \frac{N_{i,\text{transferred}}}{N_{i,\text{transferred}} + N_{i,\text{top}}}
\]

\[
\varepsilon_{\text{extr}}^{\text{drift}} = \frac{N_{i+1,\text{transferred}}}{N_{i+1,\text{transferred}} + N_{i+1,\text{top}}}
\]

Single electron avalanche simulation in a (St)-(LP)-(LP)-(St)-stack (NeCO2N2 (90-10-5))
Ion-transfer – Why multiple efficiencies?

• For every stage, there is not only one distribution to the ion backflow (except single GEM).
• For electrons: everything that happens originates from the same source, the primary electrons. They propagate experiencing gain and transfer efficiencies.
• For ions, there is an additional source in every GEM, contributing separately. They propagate experiencing only transfer efficiencies.
• Ions originate from the point of ionization, inside the GEM-holes.
• Ions follow the field lines.
→ Ions have a spatially fixed distribution depending on:
  GEM orientation / hole placement and transfer fields.
• For avalanche part: transfer field-dependence only. →Simulation…
All created ions are going into the hole. Depending on the field, they get extracted.

(1) Collection efficiency for avalanche-ions ((St)-GEM).

(2) Extraction efficiency for avalanche-ions ((St)-GEM).
Avalanche-ions – Where do they go?

(St)-GEM. Ion extraction-points, projected on XY-plane. (1) $E_{\text{above}} = 1000 \frac{V}{cm}$, (2) $E_{\text{above}} = 2000 \frac{V}{cm}$, (3) $E_{\text{above}} = 3000 \frac{V}{cm}$, (4) $E_{\text{above}} = 4000 \frac{V}{cm}$.
Avalanche-ions – Where do they go?

(LP)-GEM. Ion extraction-points, projected on XY-plane. (1) \( E_{\text{above}} = 1000 \, \text{V/cm} \), (2) \( E_{\text{above}} = 2000 \, \text{V/cm} \), (3) \( E_{\text{above}} = 3000 \, \text{V/cm} \), (4) \( E_{\text{above}} = 4000 \, \text{V/cm} \),

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Avalanche-ions – Where do they go?

• Spatial distribution of the extraction points depends on the applied field.
• The stronger the field, the more concentrated the ions in a smaller region (ions follow the fieldlines, weak diffusion).

• Extracted ions from one stage are input \( (\varepsilon_{\text{coll}}^{\text{drift}}) \) for the next GEM.
• Their exact position of origin and the applied field in between two GEMs is needed to describe the efficiency.
• **How does the starting position of drift-ions influence their transfer efficiency?**
Drift-ions – Transfer efficiency

(St)-GEM. Drift-ion spatial transfer efficiency. (1) $E_{\text{below}} = 1000 \frac{V}{\text{cm}}$, (2) $E_{\text{below}} = 2000 \frac{V}{\text{cm}}$, (3) $E_{\text{below}} = 3000 \frac{V}{\text{cm}}$, (4) $E_{\text{below}} = 4000 \frac{V}{\text{cm}}$. 

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(LP)-GEM. Drift-ion spatial transfer efficiency. (1) $E_{\text{below}} = 1000 \frac{V}{\text{cm}}$, (2) $E_{\text{below}} = 2000 \frac{V}{\text{cm}}$, (3) $E_{\text{below}} = 3000 \frac{V}{\text{cm}}$, (4) $E_{\text{below}} = 4000 \frac{V}{\text{cm}}$. 
Ions – What we know so far

- Avalanche ions are extracted to confined regions, given by the hole pattern of the GEM and the applied transfer field.
- Drift ions are transferred if they start in regions close to the holes in the GEM they are approaching.
- Ion transfer is much more delicate than electron transfer as it strongly depends on the (mis)alignment of neighboring foils.
Ions – What we know so far

• Avalanche ions are extracted to confined regions, given by the hole pattern of the GEM and the applied transfer field.
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• *Ion transfer is much more delicate than electron transfer as it strongly depends on the (mis)alignment of neighboring foils.*

Optimize on electron transfer:
• Reduce the absolute gain (maximum voltage) needed.
• Reduce the total number of ions.
Optimization of a 3-GEM-system

COMPASS-default:

\[ E_0 = 2490 \text{ V/cm} \]
\[ dU_{\text{GEM1}} = 410 \text{ V} \]
\[ E_1 = 3730 \text{ V/cm} \]
\[ dU_{\text{GEM1}} = 374 \text{ V} \]
\[ E_2 = 3730 \text{ V/cm} \]
\[ dU_{\text{GEM1}} = 328 \text{ V} \]
\[ E_3 = 3730 \text{ V/cm} \]
Optimization of a 3-GEM-system

COMPASS-default $s = 0.85$:  
\[ E_0 = 2116.5 \text{ V/cm} \]
\[ dU_{\text{GEM1}} = 349 \text{ V} \]
\[ E_1 = 3170.5 \text{ V/cm} \]
\[ dU_{\text{GEM1}} = 318 \text{ V} \]
\[ E_2 = 3170.5 \text{ V/cm} \]
\[ dU_{\text{GEM1}} = 279 \text{ V} \]
\[ E_3 = 3170.5 \text{ V/cm} \]

Stack-optimizer

\[ U_{\text{Cathode}} = 3487 \text{ V} \]

Optimized settings  
\[ E_0 = 2116.5 \text{ V/cm} \]
\[ dU_{\text{GEM1}} = 345 \text{ V} \]
\[ E_1 = 1490 \text{ V/cm} \]
\[ dU_{\text{GEM1}} = 312 \text{ V} \]
\[ E_2 = 1341 \text{ V/cm} \]
\[ dU_{\text{GEM1}} = 274 \text{ V} \]
\[ E_3 = 3170.5 \text{ V/cm} \]

\[ U_{\text{Cathode}} = 2775 \text{ V} \]
Optimization of a 3-GEM-system

(1) COMPASS settings in ArCO2 (90-10),
scaling 0.85: $\mu_{\text{photo}} = 1752$, $R_{5.9\text{keV}} = 8.4\%$

(2) Optimized settings in ArCO2 (90-10):
$\mu_{\text{photo}} = 1778$, $R_{5.9\text{keV}} = 7.9\%$
Optimization of a 4-GEM-system: IROC-06

ALICE-settings:
\[ E_{\text{drift}} = 400 \text{ V/cm} \]
\[ U_{\text{GEM1}} = 270 \text{ V} \]
\[ E_{T1} = 4000 \text{ V/cm} \]
\[ U_{\text{GEM2}} = 230 \text{ V} \]
\[ E_{T2} = 4000 \text{ V/cm} \]
\[ U_{\text{GEM3}} = 288 \text{ V} \]
\[ E_{T3} = 100 \text{ V/cm} \]
\[ U_{\text{GEM4}} = 359 \text{ V} \]
\[ E_{T4} = 4000 \text{ V/cm} \]

Optimized ALICE-settings:
\[ E_{\text{drift}} = 400 \text{ V/cm} \]
\[ U_{\text{GEM1}} = 270 \text{ V} \]
\[ E_{T1} = 1685 \text{ V/cm} \]
\[ U_{\text{GEM2}} = 230 \text{ V} \]
\[ E_{T2} = 289 \text{ V/cm} \]
\[ U_{\text{GEM3}} = 288 \text{ V} \]
\[ E_{T3} = 2912 \text{ V/cm} \]
\[ U_{\text{GEM4}} = 359 \text{ V} \]
\[ E_{T4} = 3500 \text{ V/cm} \]
Optimization of a 4-GEM-system: IROC-06

ALICE-settings:

\begin{align*}
E_{\text{drift}} &= 400 \, \text{V/cm} \\
U_{\text{GEM1}} &= 270 \, \text{V} \\
E_{T1} &= 4000 \, \text{V/cm} \\
U_{\text{GEM2}} &= 230 \, \text{V} \\
E_{T2} &= 4000 \, \text{V/cm} \\
U_{\text{GEM3}} &= 288 \, \text{V} \\
E_{T3} &= 100 \, \text{V/cm} \\
U_{\text{GEM4}} &= 359 \, \text{V} \\
E_{T4} &= 4000 \, \text{V/cm}
\end{align*}

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E_{T3} &= 2912 \, \text{V/cm} \\
U_{\text{GEM4}} &= 359 \, \text{V} \\
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Optimization of a 4-GEM-system: IROC-06

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\[ U_{\text{GEM3}} = 288 \text{ V} \]
\[ E_{T3} = 100 \text{ V/cm} \]
\[ U_{\text{GEM4}} = 359 \text{ V} \]
\[ E_{T4} = 4000 \text{ V/cm} \]

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\[ E_{\text{drift}} = 400 \text{ V/cm} \]
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\[ U_{\text{GEM4}} = 359 \text{ V} \]
\[ E_{T4} = 3500 \text{ V/cm} \]

\[ G_{\text{eff}} = 148.5 \pm 10.4 \]
\[ R_{5.9\text{keV}} = 10.4 \% \]
\[ IB = 3.7 \% \]

\[ G_{\text{eff}} = 1270.3 \pm 68.6 \]
\[ R_{5.9\text{keV}} = 10.2 \% \]
\[ IB = 2.7 \% \]
Summary

- Electron efficiencies are understood and well described.
Summary

In a stack, one can block ions by

- **Geometrical blocking:** Applying a low extraction field, having a homogeneous ion-distribution and only transmitting from below the holes or
- applying a high extraction field and minimizing the area where ions are extracted to, and minimize the hole overlap with the next GEM.

- **Electrostatic blocking:** Applying a high extraction field and blocking the ions at the next GEM or
- applying a low extraction field, to reduce the total number of extracted ions.

- No matter whether low or high extraction field: always two contributions.
- To do: Distinguish, which combination is best to be exploited.
Outlook

• Avalanche ions can be studied in simulation.
• Drift ions require exact knowledge of GEM-positioning and applied fields.
• There are preferable combinations of GEM-geometries with respect to the hole overlap:
  o (St)-GEM provides homogeneous ion distribution for fields up to \( \sim 3500 \text{ V/cm} \).
  o (LP)-GEM has the smallest hole density, so the smallest amount of ions will be transferred from a homogeneous ion distribution.
Additional material
Comparison to measurements

(1) Simulated and measured collection efficiency for St-GEM

(2) Simulated and measured extraction efficiency for St-GEM
Comparison to measurements

(1) Simulated and measured collection efficiency for S-GEM

(2) Simulated and measured extraction efficiency for S-GEM
Comparison to measurements

(1) Simulated and measured collection efficiency for L-GEM

(2) Simulated and measured extraction efficiency for L-GEM
Ions – geometric blocking capabilities

(1) (St)(SP), (2) (St)(St), (3) (St)(MP), (4) (St)(LP)
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**IB vs ε**

- Ion backflow reminder: $IB = \frac{N_{\text{ions at cathode}}}{N_{\text{electrons at cathode}}}$.

- $IB$ does not really care about efficiency and does not directly limit the absolute number of ions in the drift volume.

- Better use $\varepsilon = \frac{N_{\text{ions at cathode}}}{N_{\text{incoming electron}}}$.

- For ALICE: $IB \leq 1 \% \rightarrow \varepsilon(G_{\text{eff}} = 2000) = 20$.

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• Ion backflow reminder: \( IB = \frac{N_{\text{ions at cathode}}}{N_{\text{electrons at cathode}}} \).

• \( IB \) does not really care about efficiency and does not directly limit the absolute number of ions in the drift volume.

• Better use \( \varepsilon = \frac{N_{\text{ions at cathode}}}{N_{\text{incoming electron}}} \).

• For ALICE: \( IB \leq 1\% \rightarrow \varepsilon(G_{\text{eff}} = 2000) = 20 \).

• ALICE-settings: \( \varepsilon \approx 6 \) at \( G_{\text{eff}} = 148.5 \).

• Optimized ALICE-settings: \( \varepsilon \approx 35 \) at \( G_{\text{eff}} = 1270.3 \).

• Optimized ALICE-settings with reduced gain in GEM4 (biggest contribution to the \( IB \)): \( \varepsilon \approx 3.5 \) at \( G_{\text{eff}} \approx 150 \).
Optimization

\[ \eta = \frac{E_{\text{ext}}}{E_{\text{GEM}}} \]

\[ \varepsilon_{\text{extr}} \times \varepsilon_{\text{coll}} \]
Avalanche-ions – Where do they go?

(1) (St)-GEM. Ion creation-points, projected on XY-plane. $E_{\text{above}} = 400 \, \text{V/cm}$.

(2) (St)-GEM. Ion extraction-points, projected on XY-plane. $E_{\text{above}} = 400 \, \text{V/cm}$.
Avalanche-ions – Where do they go?

(1) (St)-GEM. Ion creation-points, projected on XY-plane. $E_{\text{above}} = 1000 \text{ V/cm}$.

(2) (St)-GEM. Ion extraction-points, projected on XY-plane. $E_{\text{above}} = 1000 \text{ V/cm}$. 

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Avalanche-ions – Where do they go?

(1) (St)-GEM. Ion creation-points, projected on XY-plane. $E_{\text{above}} = 2000 \text{ V/cm}$. 

(2) (St)-GEM. Ion extraction-points, projected on XY-plane. $E_{\text{above}} = 2000 \text{ V/cm}$. 

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Avalanche-ions – Where do they go?

(1) (St)-GEM. Ion creation-points, projected on XY-plane. $E_{\text{above}} = 3000 \text{ V/cm}$.

(2) (St)-GEM. Ion extraction-points, projected on XY-plane. $E_{\text{above}} = 3000 \text{ V/cm}$.

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Avalanche-ions – Where do they go?

(1) (St)-GEM. Ion creation-points, projected on XY-plane. $E_{\text{above}} = 4000$ V/cm.

(2) (St)-GEM. Ion extraction-points, projected on XY-plane. $E_{\text{above}} = 4000$ V/cm.