Optimization of multi-GEM systems

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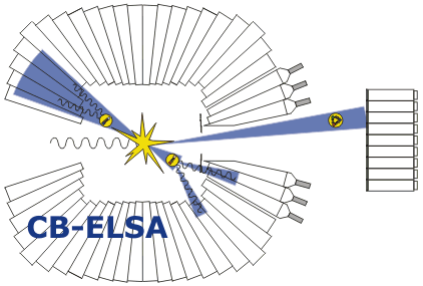
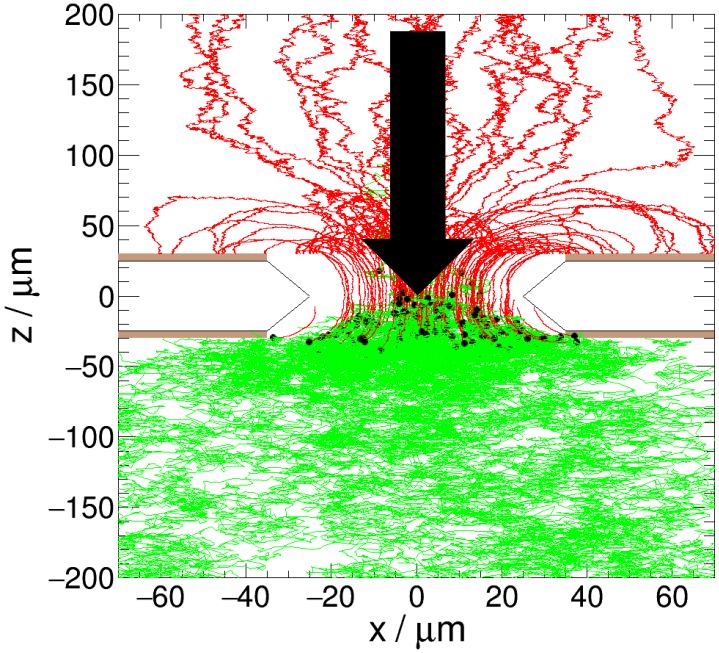
RD51-Mini-Week, CERN



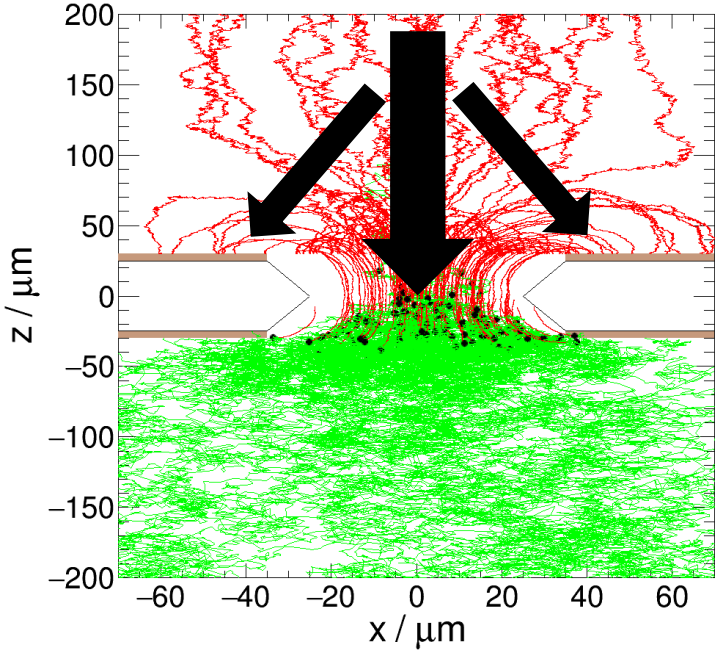
Overview

- 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

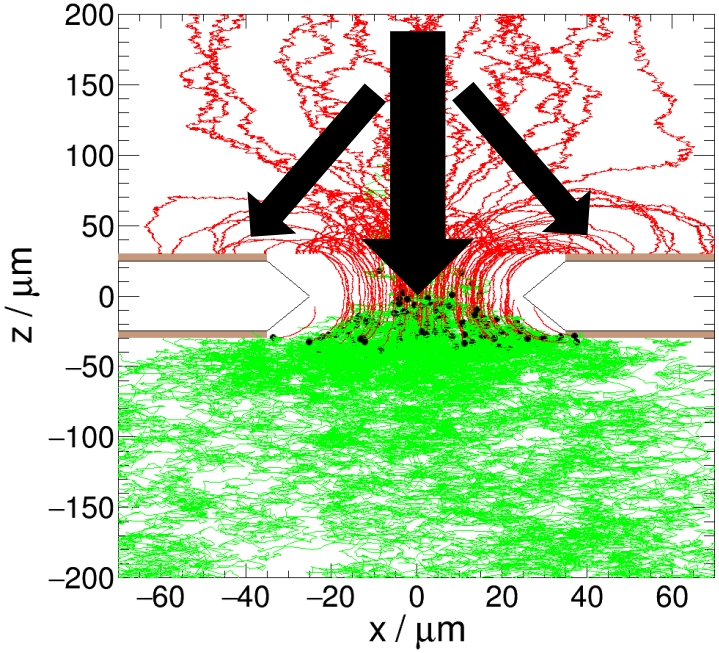
Definition of electron transfer efficiencies

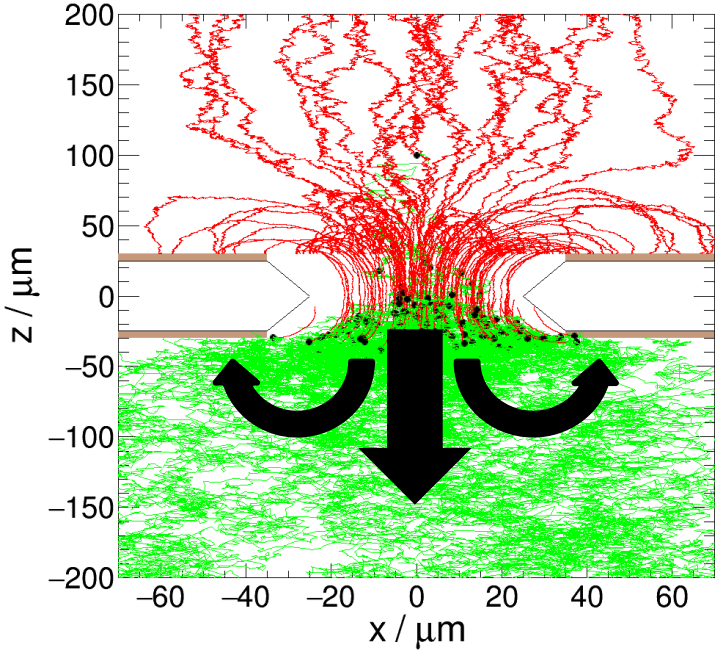


Definition of electron transfer efficiencies



Definition of electron transfer efficiencies





Definition of electron transfer efficiencies

Collection efficiency:

$$\varepsilon_{\mathrm{coll}} = \frac{N_{\mathrm{incoming}} - N_{\mathrm{top}}}{N_{\mathrm{incoming}}}$$

Extraction efficiency:

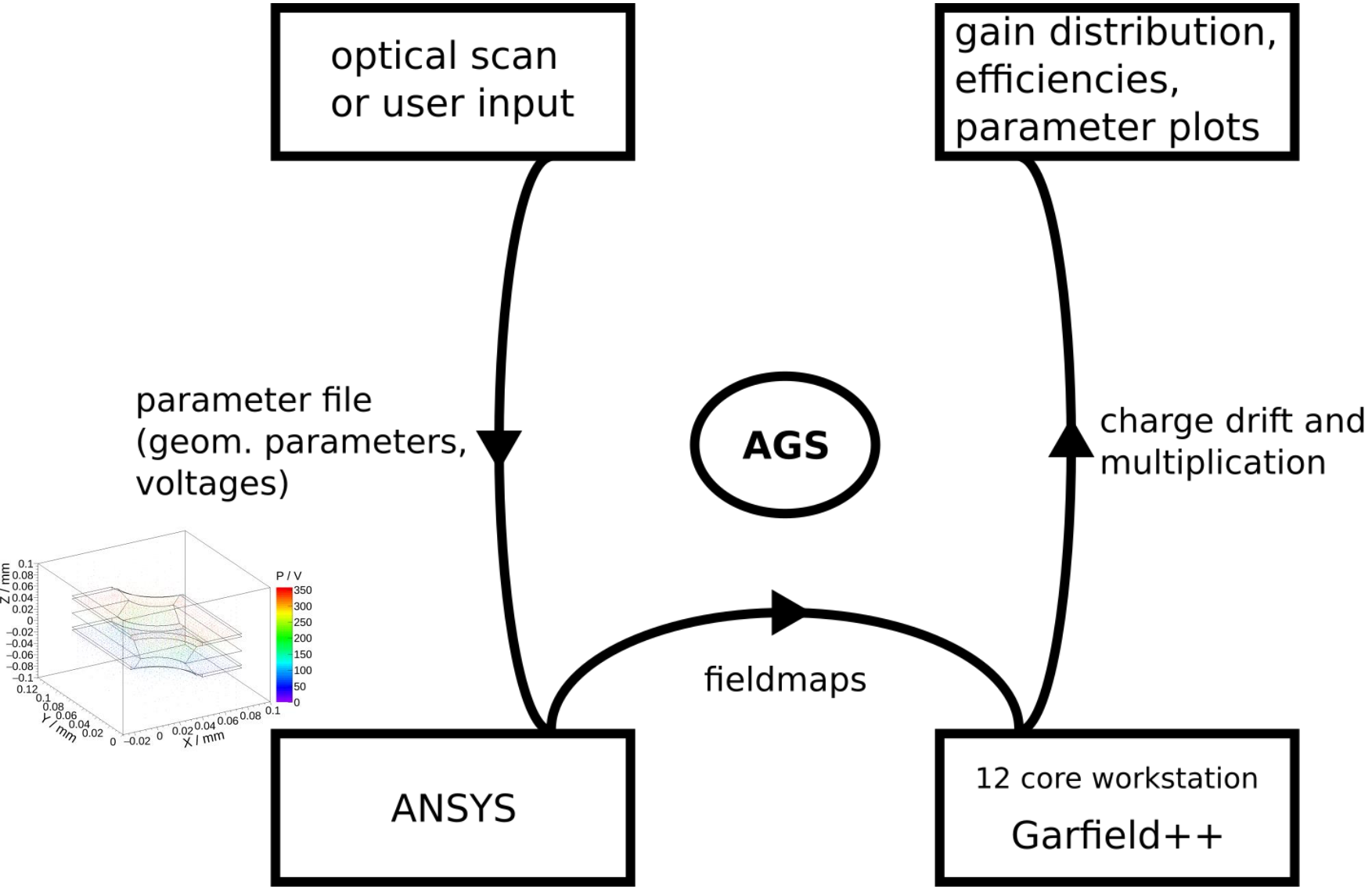
$$\varepsilon_{\mathrm{extr}} = \frac{N_{\mathrm{transferred}}}{N_{\mathrm{transferred}} + N_{\mathrm{bottom}}}$$

$$G_{\mathrm{abs}} = \frac{N_{\mathrm{transferred}} + N_{\mathrm{bottom}}}{N_{\mathrm{incoming}}}$$

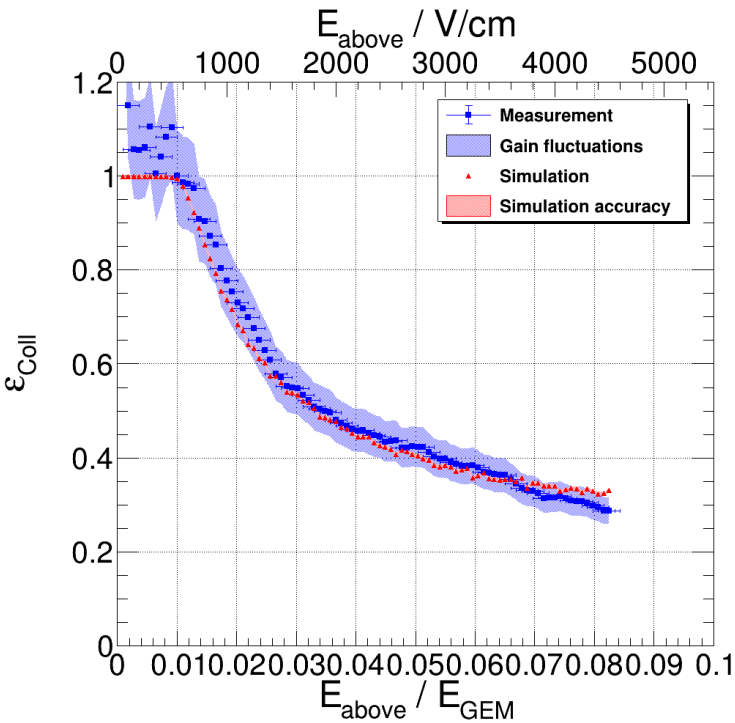
$$G_{\mathrm{eff}} = \varepsilon_{\mathrm{coll}} G_{\mathrm{abs}} \varepsilon_{\mathrm{extr}}$$

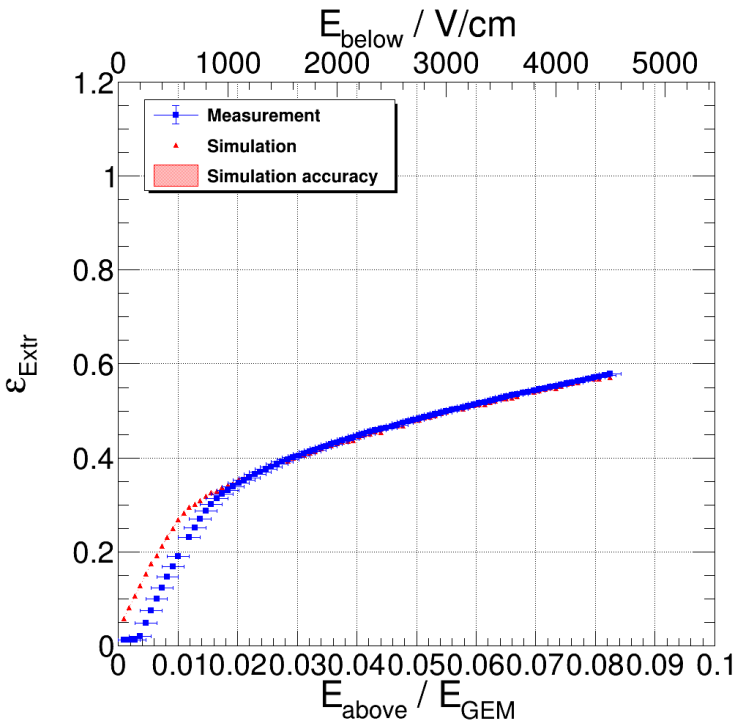
- In general, these efficiencies depend on the geometric parameters and the applied electric fields.
- Measurement: Instead of number of electrons, use the time-derivative, the current.

Simulation framework – Advanced GEM Simulator



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:

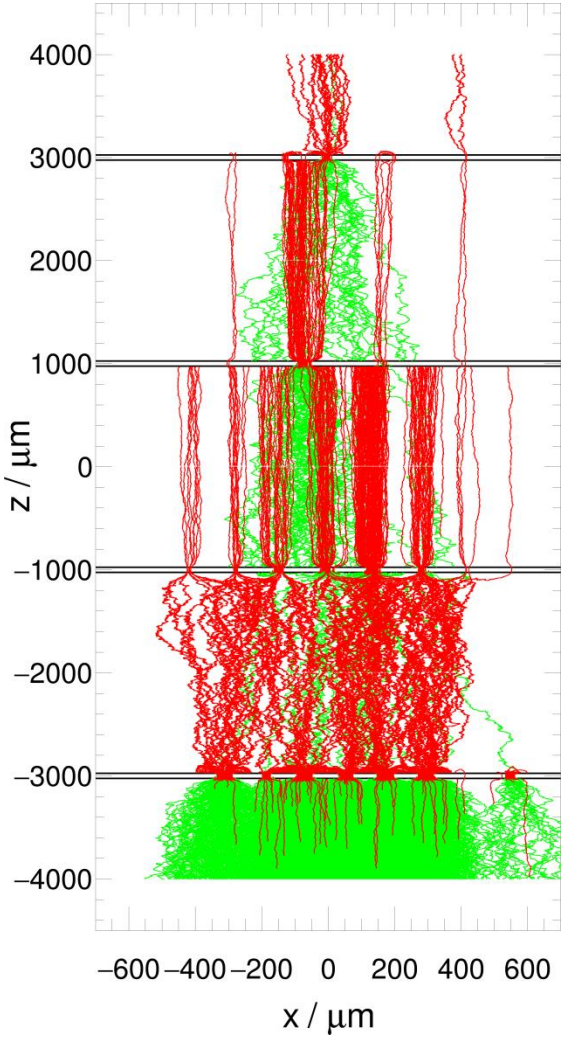
$$\varepsilon_{\text{coll}}^{\text{aval}} = \frac{N_{i,\text{created}} - N_{i,\text{bot}}}{N_{i,\text{created}}}$$

$$\varepsilon_{\text{coll}}^{\text{drift}} = \frac{N_{i+1,\text{extracted}} - N_{i+1,\text{bot}}}{N_{i+1,\text{extracted}}}$$

Extraction efficiency:

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

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



Single electron avalanche simulation in a (St)-(LP)-(LP)-(St)-stack (NeCO2N2 (90-10-5))

Ion-transfer – Why multiple efficiencies?

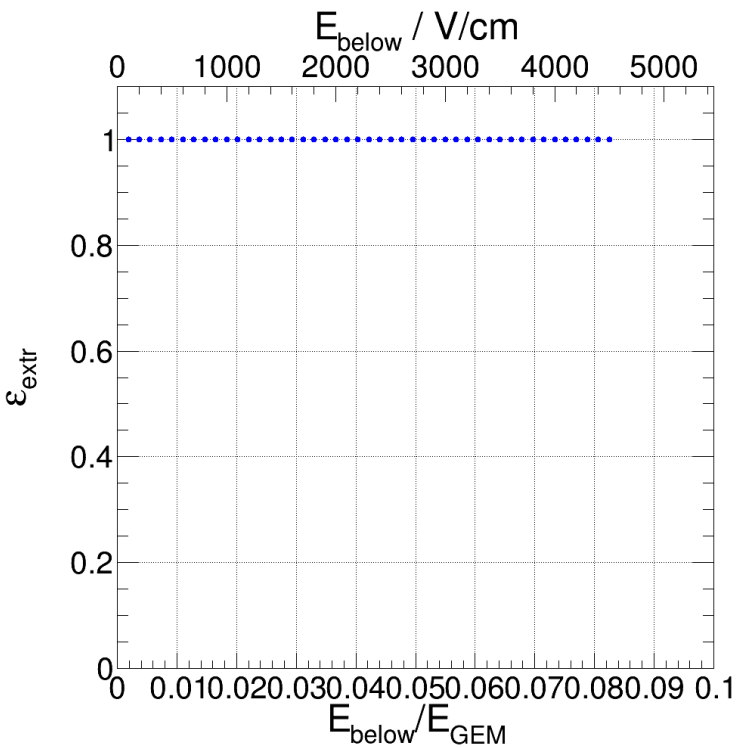
- For every stage, there is not only one distribution to the ion backflow (except single GEM).
- For electrons: everything that happens originates from the **same source**, the primary electrons. They propagate experiencing **gain** and **transfer efficiencies**.
- For ions, there is an **additional 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.

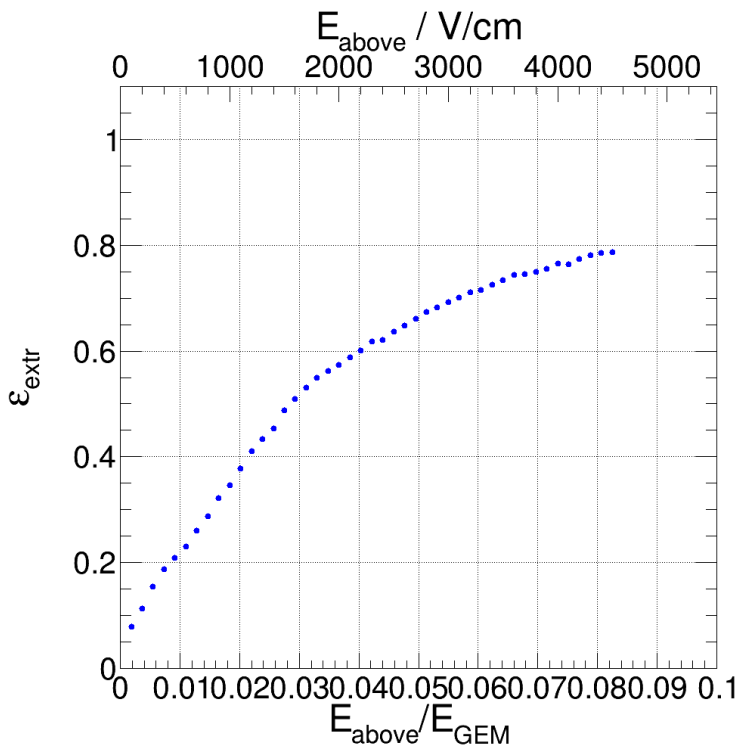
- For avalanche part: transfer field-dependence only. →Simulation…

Ion-transfer efficiencies – avalanche contribution

All created ions are going into the hole.



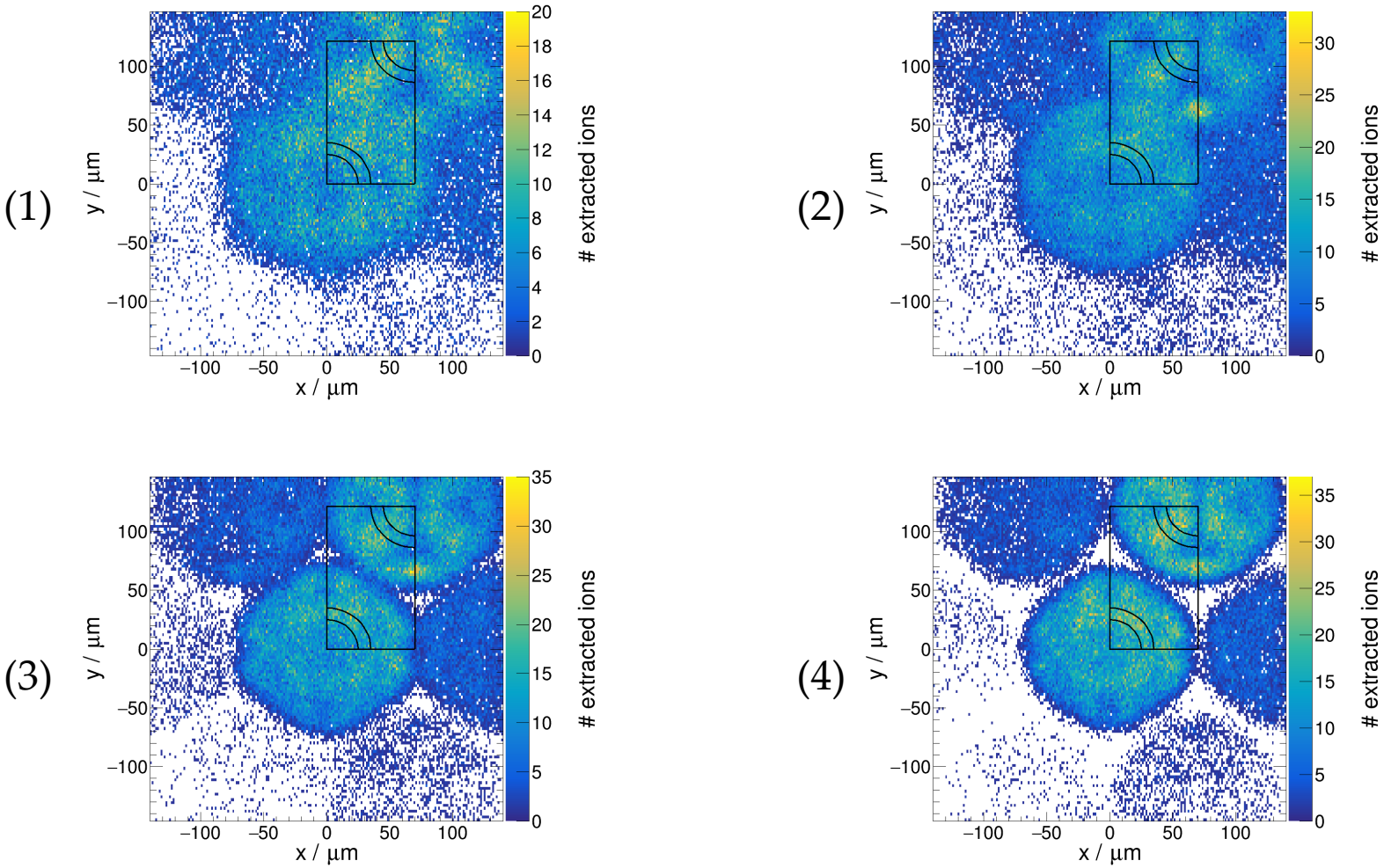
Depending on the field, they get extracted.



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

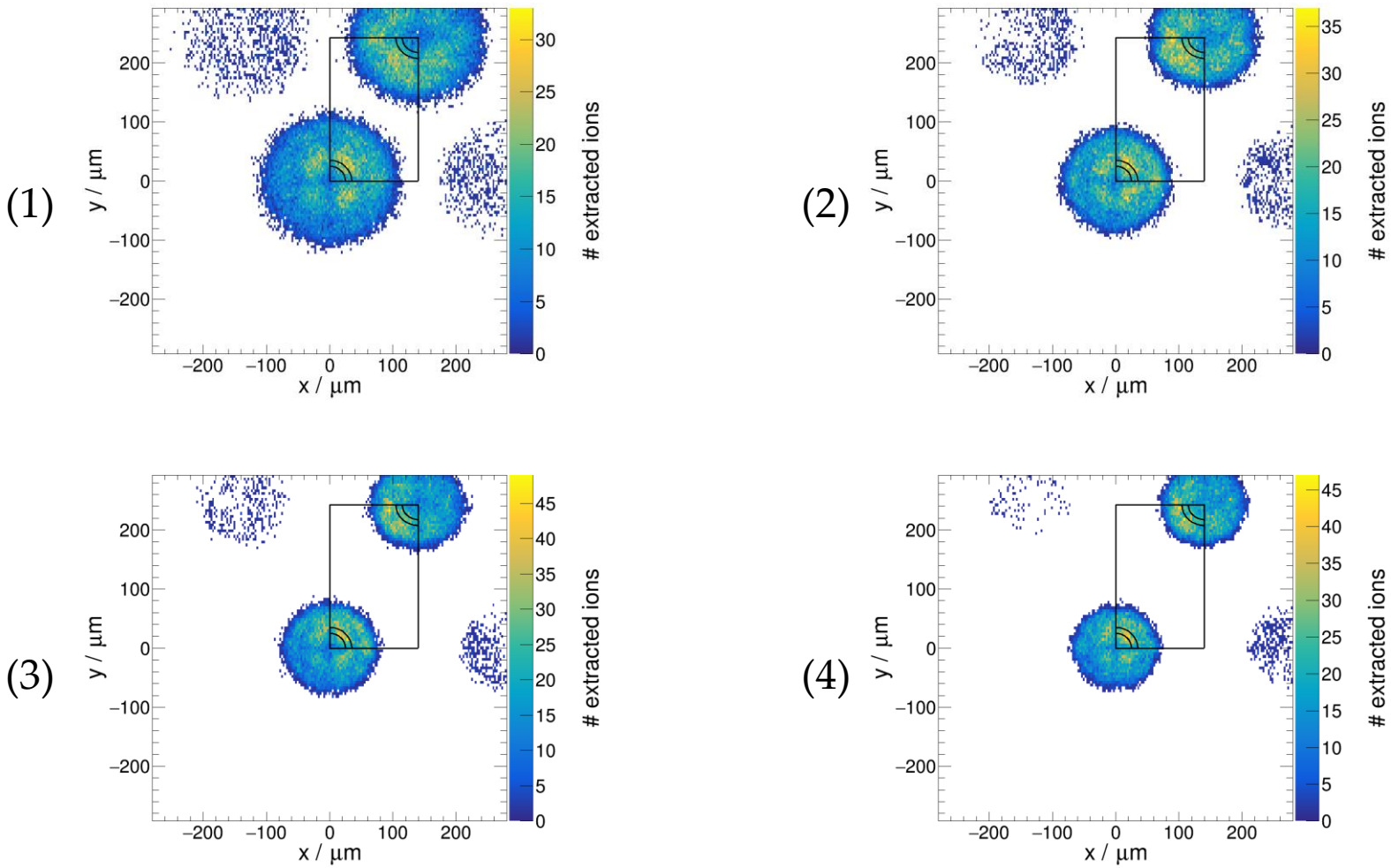
(2) Extraction efficiency for avalanche-ions ((St)-GEM).

Avalanche-ions – Where do they go?



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

Avalanche-ions – Where do they go?



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

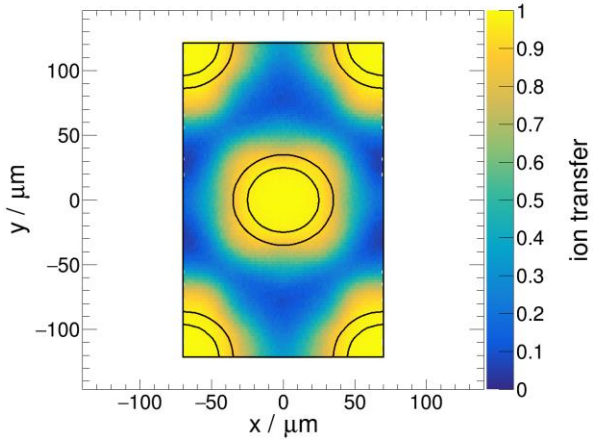
Avalanche-ions – Where do they go?

- 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 ($\varepsilon_{\mathrm{coll}}^{\mathrm{drift}}$) 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

(1)



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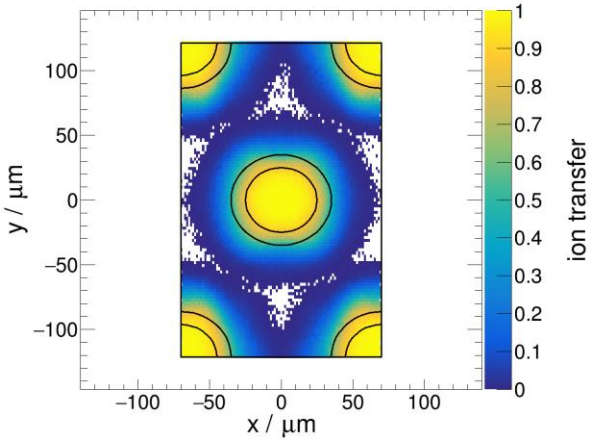
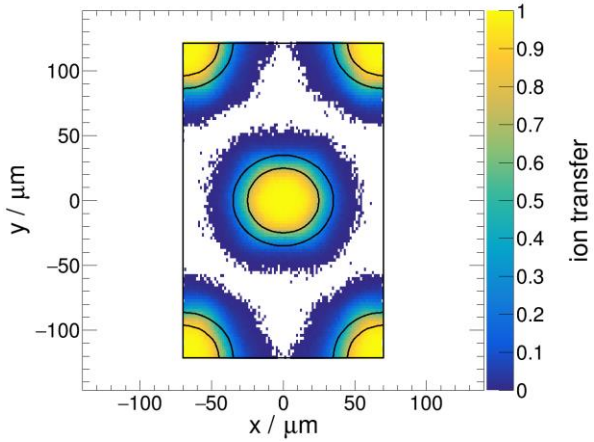


(3)



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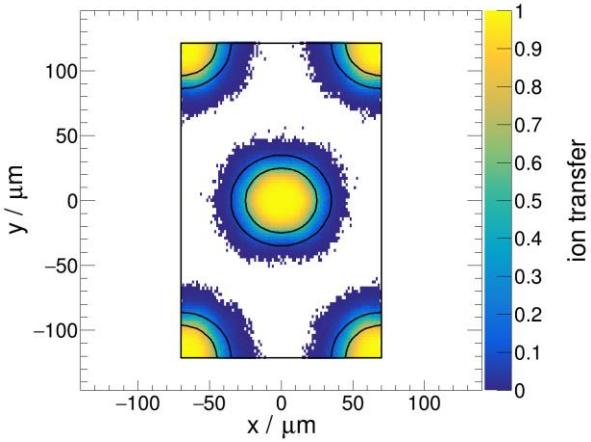
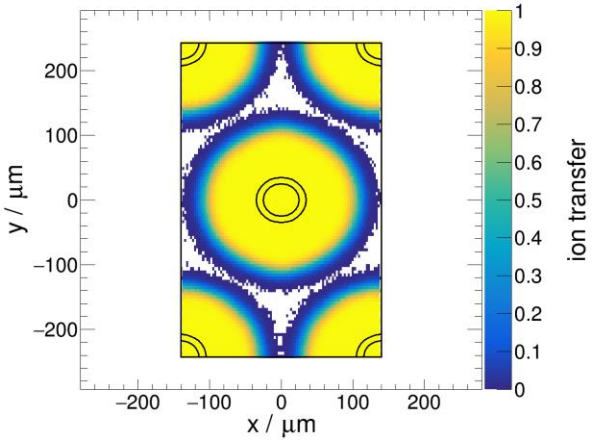


(St)-GEM. Drift-ion spatial transfer efficiency. (1) $E_{\mathrm{below}} = 1000\,\frac{\mathrm{V}}{\mathrm{cm}}$, (2) $E_{\mathrm{below}} = 2000\,\frac{\mathrm{V}}{\mathrm{cm}}$, (3) $E_{below} = 3000\,\frac{\mathrm{V}}{\mathrm{cm}}$, (4) $E_{\mathrm{below}} = 4000\,\frac{\mathrm{V}}{\mathrm{cm}}$,

Drift-ions – Transfer efficiency

(1)



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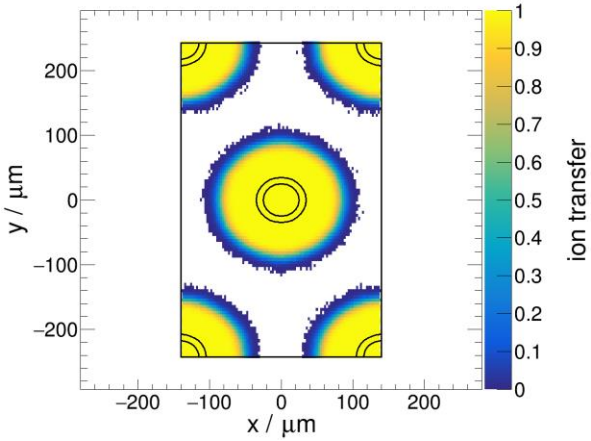

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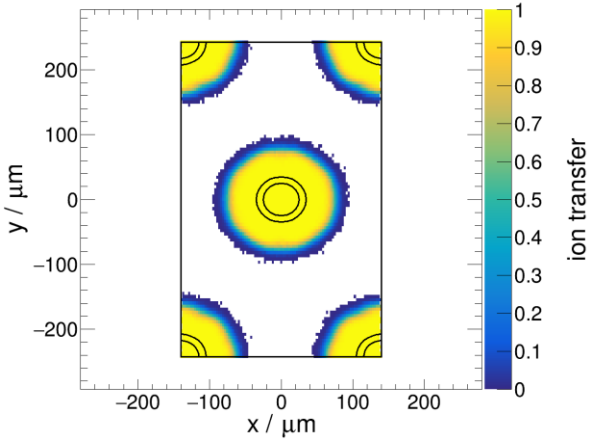

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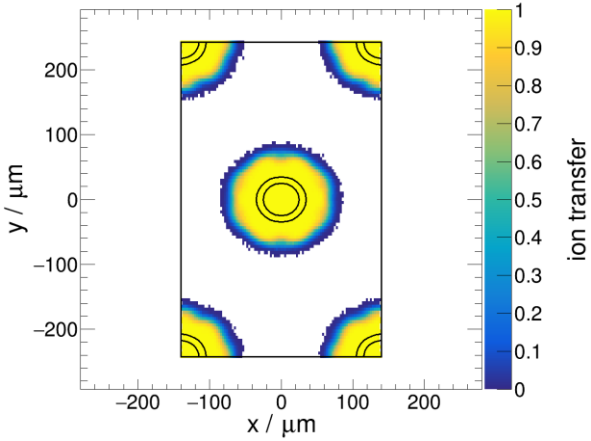


(LP)-GEM. Drift-ion spatial transfer efficiency. (1) $E_{\text{below}} = 1000\,\frac{\text{V}}{\text{cm}}$, (2) $E_{\text{below}} = 2000\,\frac{\text{V}}{\text{cm}}$, (3) $E_{\text{below}} = 3000\,\frac{\text{V}}{\text{cm}}$, (4) $E_{\text{below}} = 4000\,\frac{\text{V}}{\text{cm}}$,

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.
- 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.**

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:

$E_0 = 2490\ \mathrm{V/cm}$

$\mathrm{d}U_{\mathrm{GEM1}} = 410\ \mathrm{V}$

$E_1 = 3730\ \mathrm{V/cm}$

$\mathrm{d}U_{\mathrm{GEM1}} = 374\ \mathrm{V}$

$E_2 = 3730\ \mathrm{V/cm}$

$\mathrm{d}U_{\mathrm{GEM1}} = 328\ \mathrm{V}$

$E_3 = 3730\ \mathrm{V/cm}$

Optimization of a 3-GEM-system

COMPASS-default $s = 0.85$:

$E_0 = 2116.5\ \mathrm{V/cm}$

$\mathrm{d}U_{\mathrm{GEM1}} = 349\ \mathrm{V}$

$E_1 = 3170.5\ \mathrm{V/cm}$

$\mathrm{d}U_{\mathrm{GEM1}} = 318\ \mathrm{V}$

$E_2 = 3170.5\ \mathrm{V/cm}$

$\mathrm{d}U_{\mathrm{GEM1}} = 279\ \mathrm{V}$

$E_3 = 3170.5\mathrm{V/cm}$

$U_{\mathrm{Cathode}} = 3487\ V$

Stack-optimizer →

Optimized settings

$E_0 = 2116.5\ \mathrm{V/cm}$

$\mathrm{d}U_{\mathrm{GEM1}} = 345\ \mathrm{V}$

$E_1 = 1490\ \mathrm{V/cm}$

$\mathrm{d}U_{\mathrm{GEM1}} = 312\ \mathrm{V}$

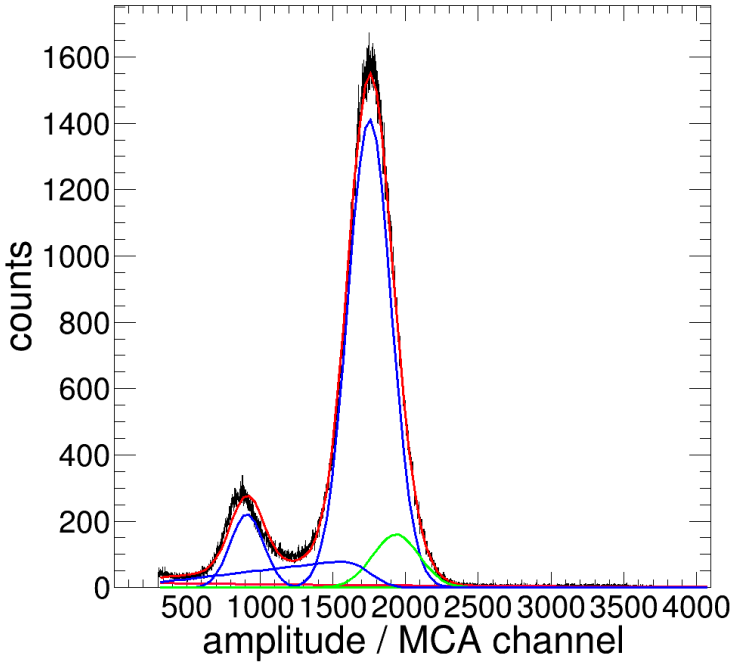
$E_2 = 1341\ \mathrm{V/cm}$

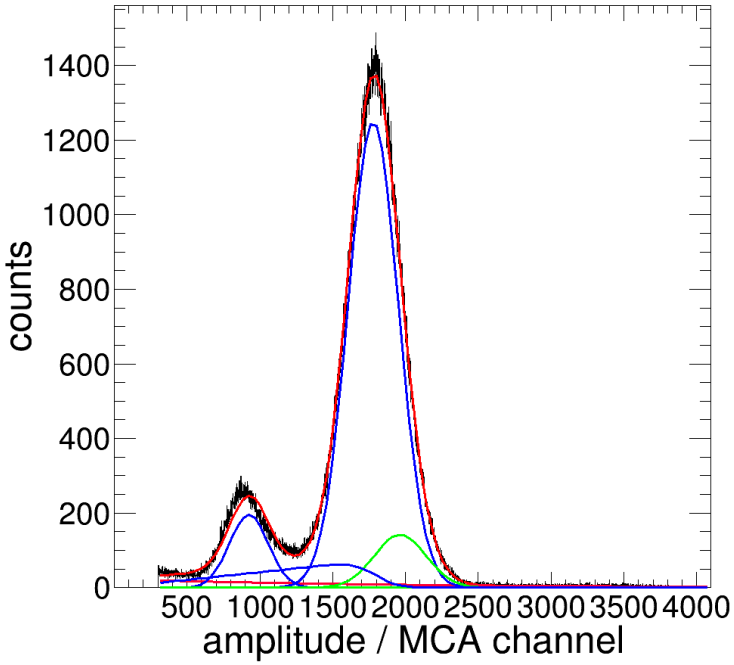
$\mathrm{d}U_{\mathrm{GEM1}} = 274\ \mathrm{V}$

$E_3 = 3170.5\mathrm{V/cm}$

$U_{\mathrm{Cathode}} = 2775\ V$

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:

$E_{\mathrm{drift}} = 400\ \mathrm{V/cm}$
$U_{\mathrm{GEM1}} = 270\ \mathrm{V}$
$E_{\mathrm{T1}} = 4000\ \mathrm{V/cm}$
$U_{\mathrm{GEM2}} = 230\ \mathrm{V}$
$E_{\mathrm{T2}} = 4000\ \mathrm{V/cm}$
$U_{\mathrm{GEM3}} = 288\ \mathrm{V}$
$E_{T3} = 100\ \mathrm{V/cm}$
$U_{\mathrm{GEM4}} = 359\ \mathrm{V}$
$E_{T4} = 4000\ \mathrm{V/cm}$

Stack-optimizer →

Optimized ALICE-settings:

$E_{\mathrm{drift}} = 400\ \mathrm{V/cm}$
$U_{\mathrm{GEM1}} = 270\ \mathrm{V}$
$E_{\mathrm{T1}} = 1685\ \mathrm{V/cm}$
$U_{\mathrm{GEM2}} = 230\ \mathrm{V}$
$E_{\mathrm{T2}} = 289\ \mathrm{V/cm}$
$U_{\mathrm{GEM3}} = 288\ \mathrm{V}$
$E_{T3} = 2912\ \mathrm{V/cm}$
$U_{\mathrm{GEM4}} = 359\ \mathrm{V}$
$E_{T4} = 3500\ \mathrm{V/cm}$

Optimization of a 4-GEM-system: IROC-06

ALICE-settings:

$E_{\mathrm{drift}} = 400\ \mathrm{V/cm}$
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Stack-optimizer →

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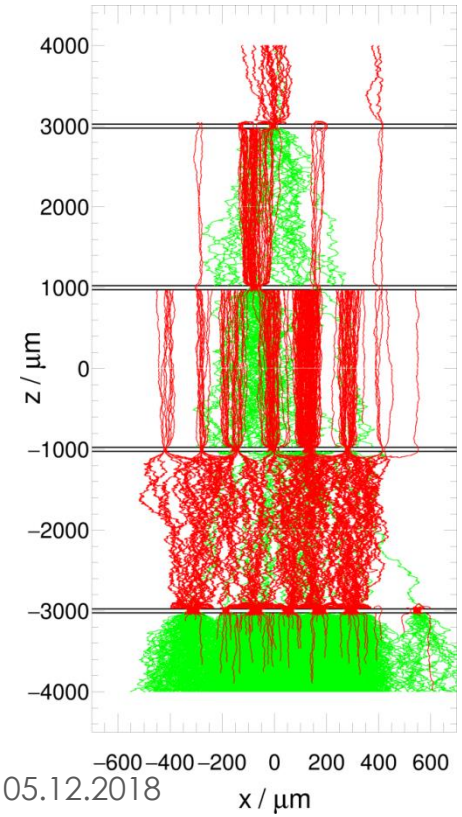

Optimization of a 4-GEM-system: IROC-06

ALICE-settings:

$E_{\mathrm{drift}} = 400\ \mathrm{V/cm}$
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$E_{T4} = 4000\ \mathrm{V/cm}$

Stack-optimizer →

Optimized ALICE-settings:

$E_{\mathrm{drift}} = 400\ \mathrm{V/cm}$
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$E_{\mathrm{T1}} = 1685\ \mathrm{V/cm}$
$U_{\mathrm{GEM2}} = 230\ \mathrm{V}$
$E_{\mathrm{T2}} = 289\ \mathrm{V/cm}$
$U_{\mathrm{GEM3}} = 288\ \mathrm{V}$
$E_{T3} = 2912\ \mathrm{V/cm}$
$U_{\mathrm{GEM4}} = 359\ \mathrm{V}$
$E_{T4} = 3500\ \mathrm{V/cm}$

↓

$G_{\mathrm{eff}} = 148.5 \pm 10.4$
$R_{5.9\mathrm{keV}} = 10.4\ \%$
$IB = 3.7\ \%$

↓

$G_{\mathrm{eff}} = 1270.3 \pm 68.6$
$R_{5.9\mathrm{keV}} = 10.2\ \%$
$IB = 2.7\ \%$

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.

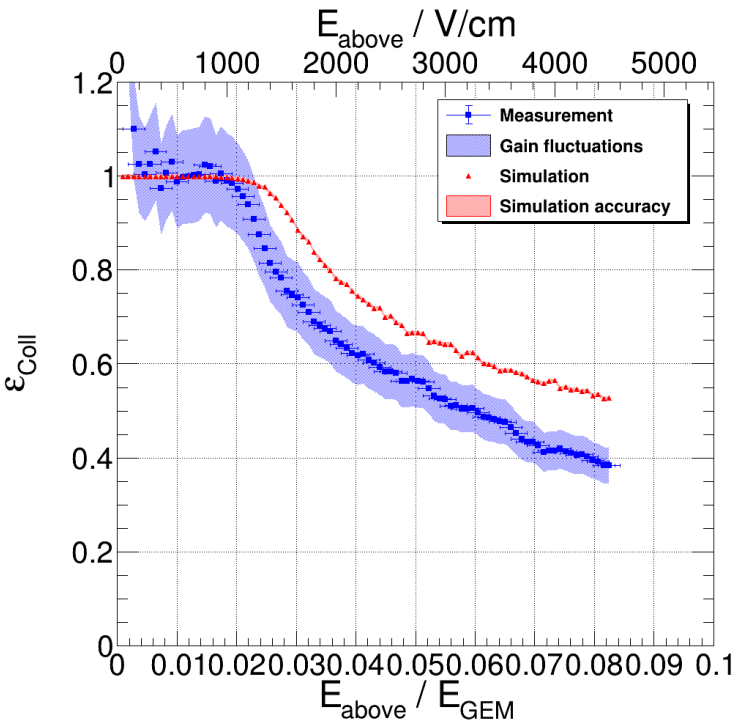
Outlook

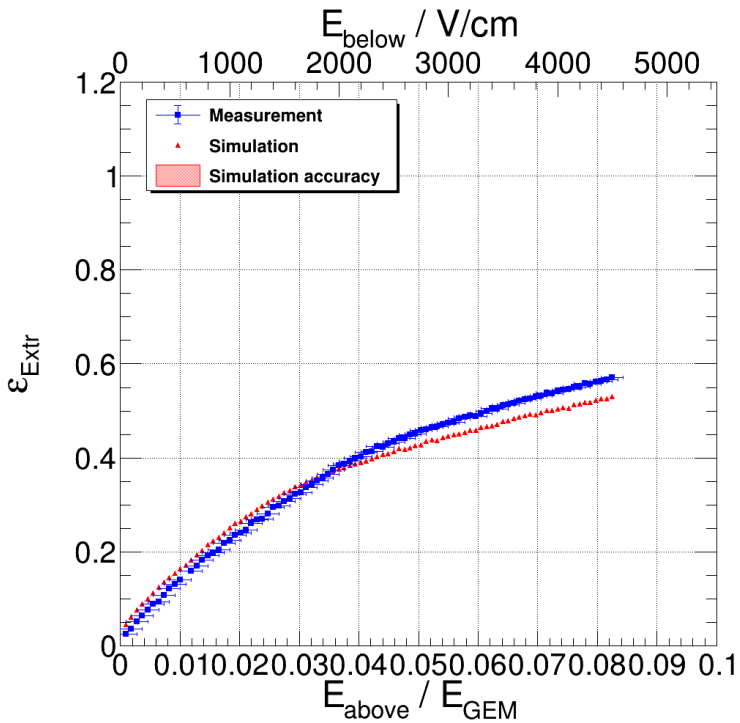
- Avalanche ions can be studied in simulation.
- Drift ions require exact knowledge of GEM-positioning and applied fields.
- There are preferable combinations of GEM-geometries with respect to the hole overlap:
  - (St)-GEM provides homogeneous ion distribution for fields up to $\sim 3500\ \mathrm{V/cm}$.
  - (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

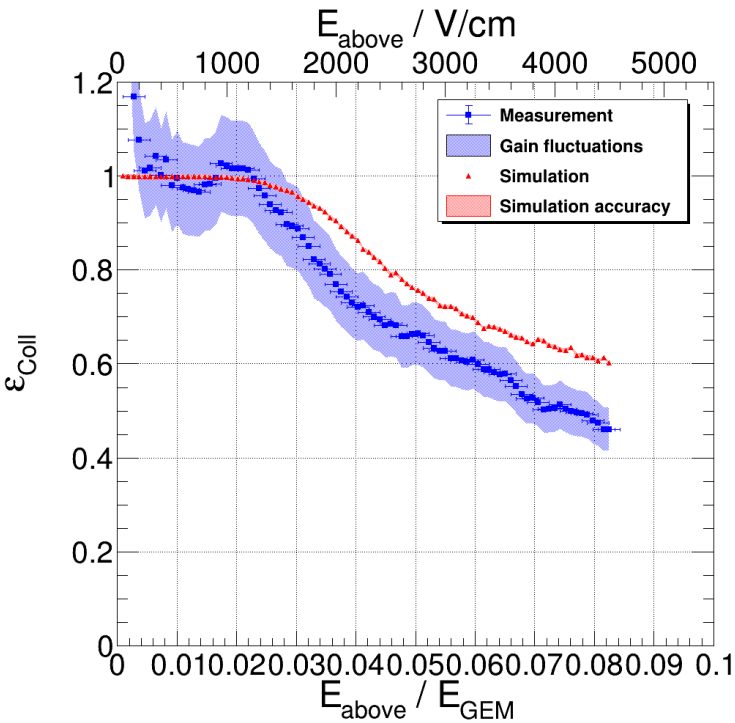


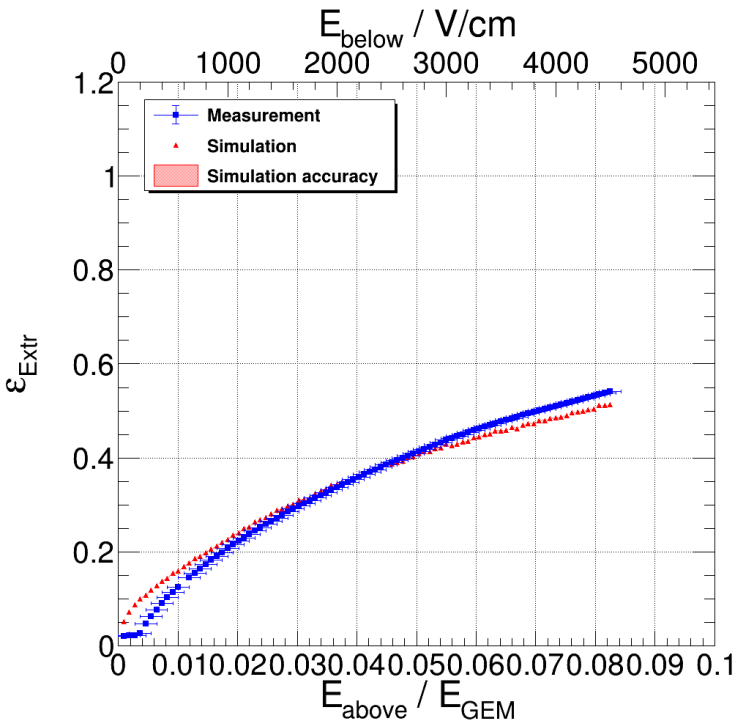


(1) Simulated and measured collection efficiency for St-GEM

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

Comparison to measurements

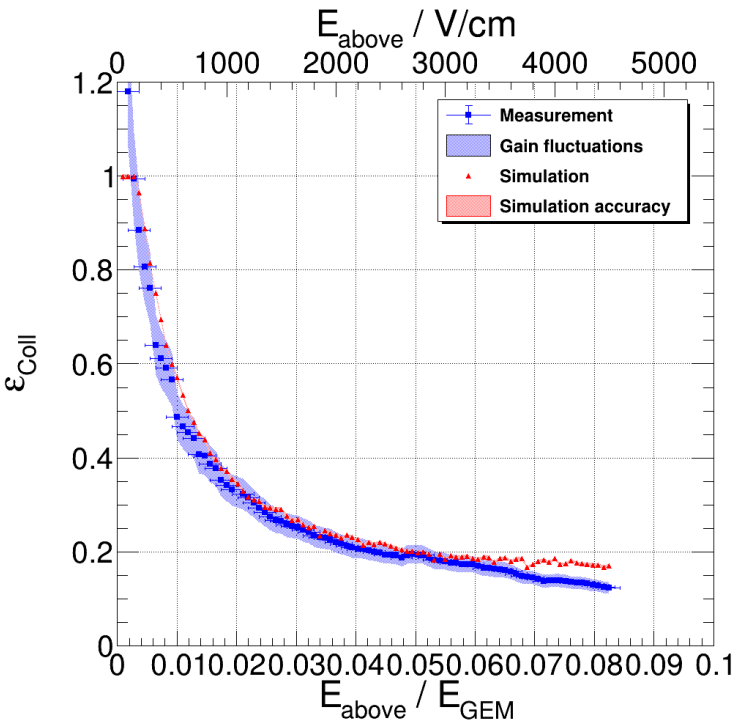


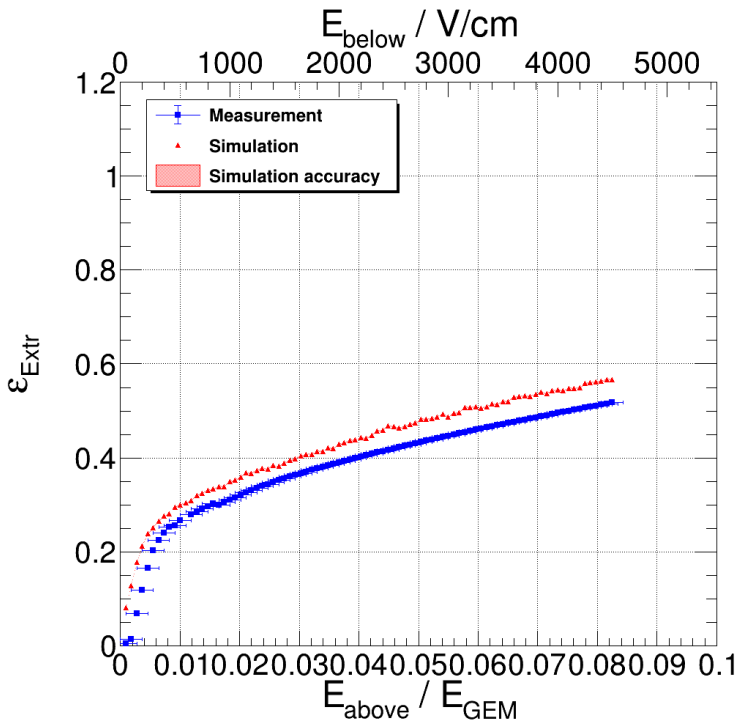


(1) Simulated and measured collection efficiency for S-GEM

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

Comparison to measurements



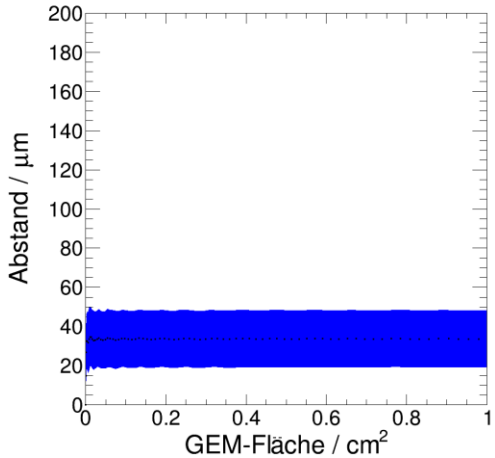


(1) Simulated and measured collection efficiency for L-GEM

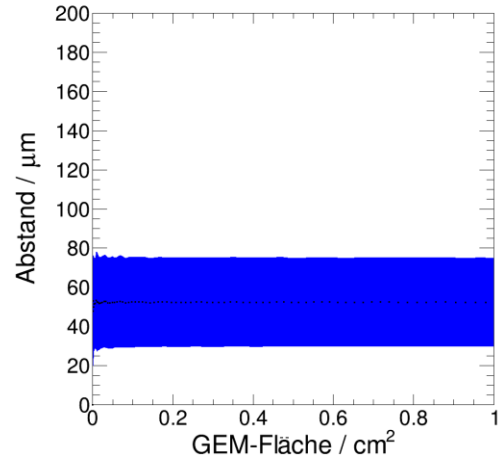
(2) Simulated and measured extraction efficiency for L-GEM

Ions – geometric blocking capabilities

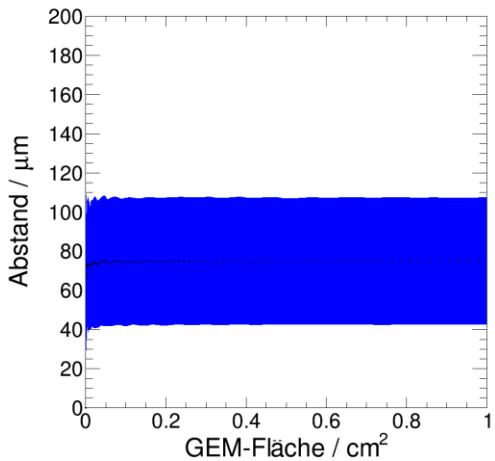
(1)



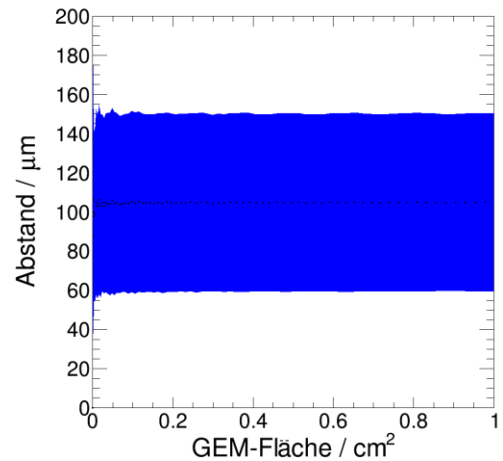
(2)



(3)



(4)



(1) (St)(SP), (2) (St)(St), (3) (St)(MP), (4) (St)(LP)

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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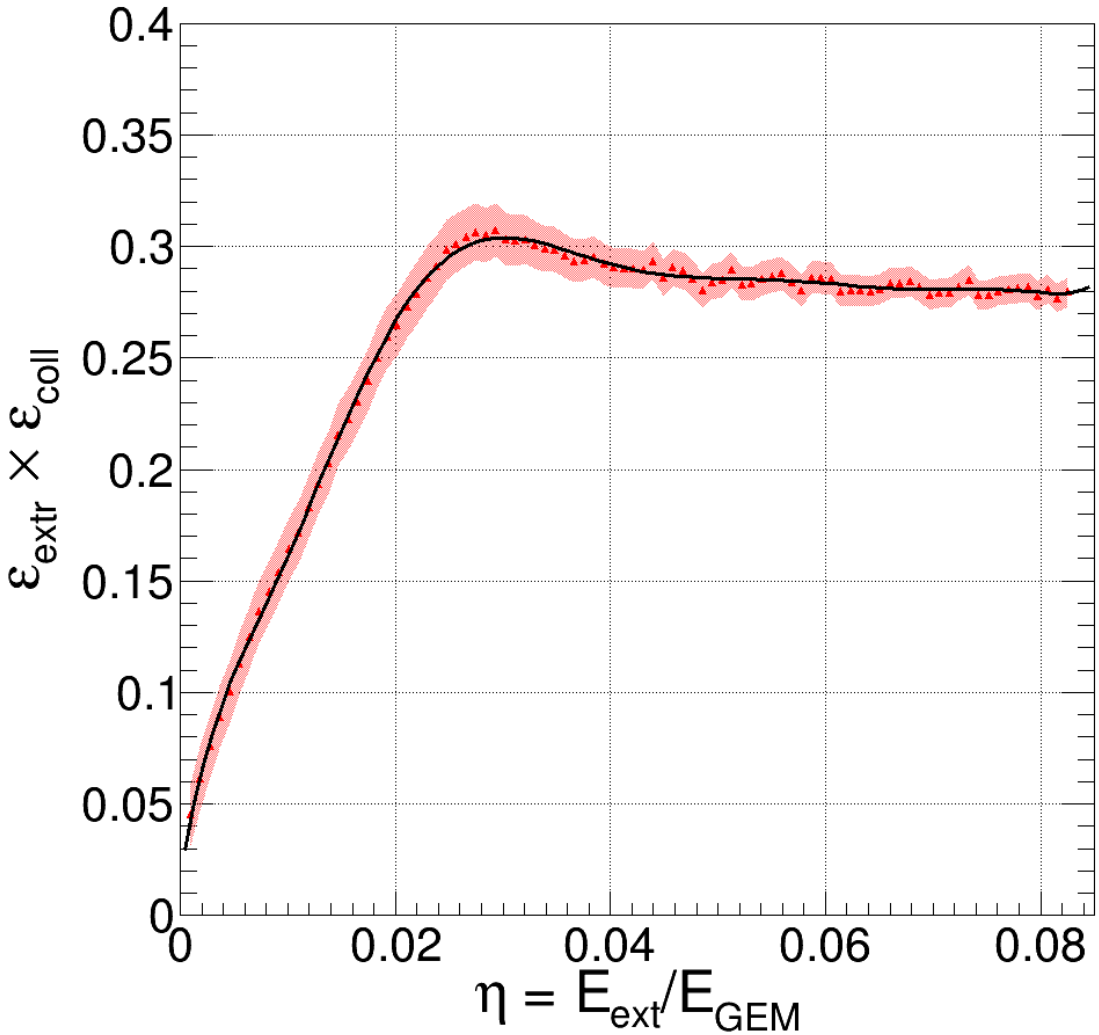
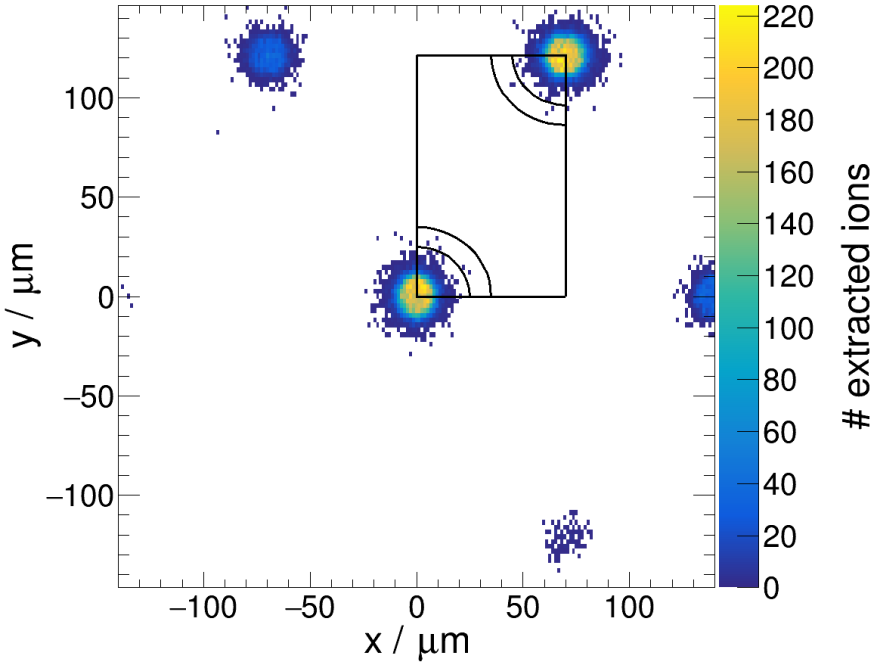
- For ALICE: $IB \leq 1\ \% \ \rightarrow \varepsilon(G_{\text{eff}} = 2000) = 20$.
- ALICE-settings: $\varepsilon \approx 6$ at $G_{\text{eff}} = 148.5$.
- Optimized ALICE-settings: $\varepsilon \approx 35$ at $G_{\text{eff}} = 1270.3$.
- Optimized ALICE-settings with reduced gain in GEM4 (biggest contribution to the IB): $\boldsymbol{\varepsilon \approx 3.5}$ at $\boldsymbol{G_{\text{eff}} \approx 150}$.

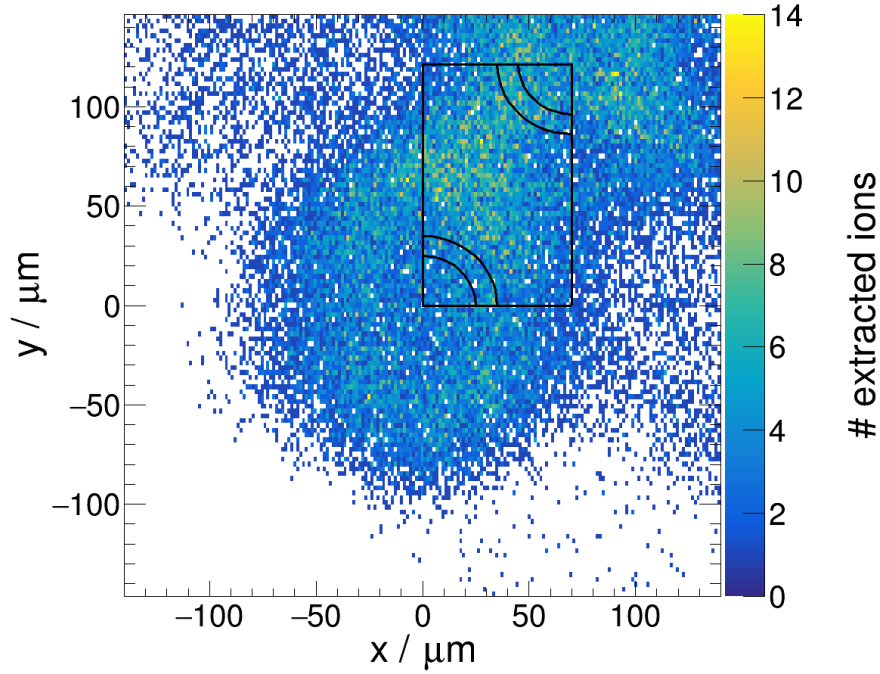
Optimization



Avalanche-ions – Where do they go?

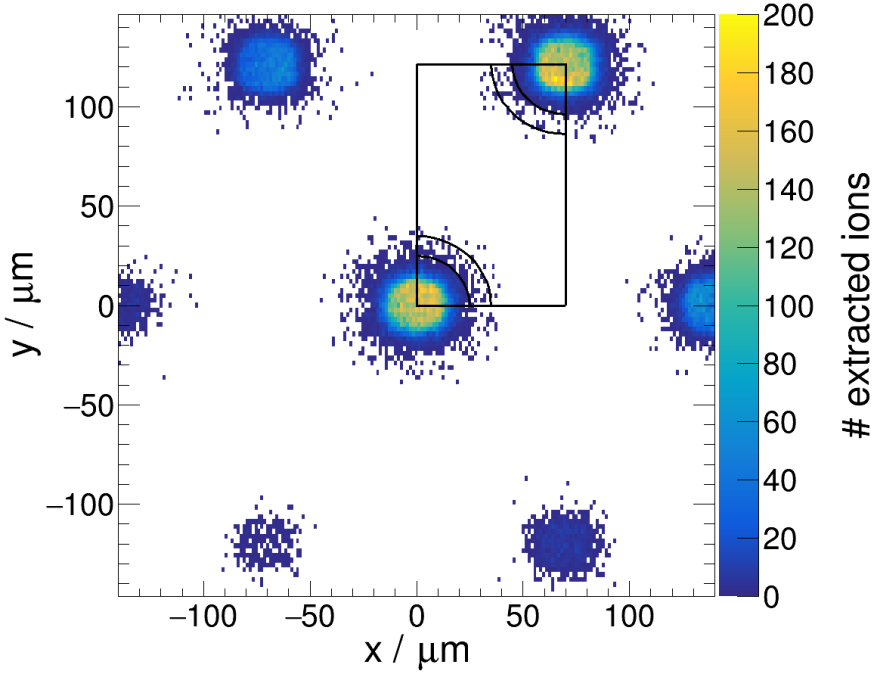


(1) (St)-GEM. Ion creation-points, projected on XY-plane. $E_{\text{above}} = 400\ \text{V/cm}$.

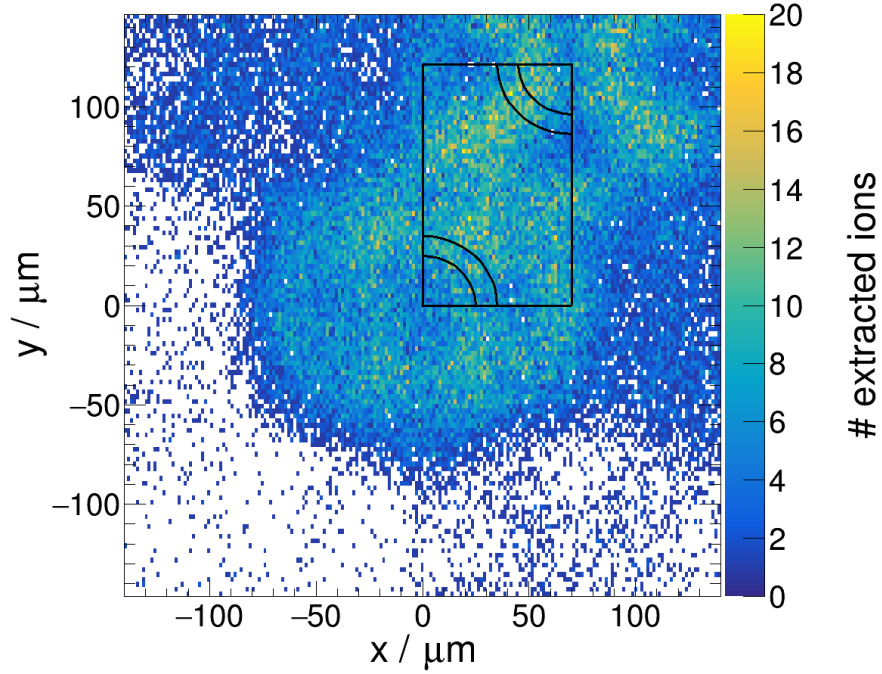


(2) (St)-GEM. Ion extraction-points, projected on XY-plane. $E_{\text{above}} = 400\ \text{V/cm}$.

Avalanche-ions – Where do they go?

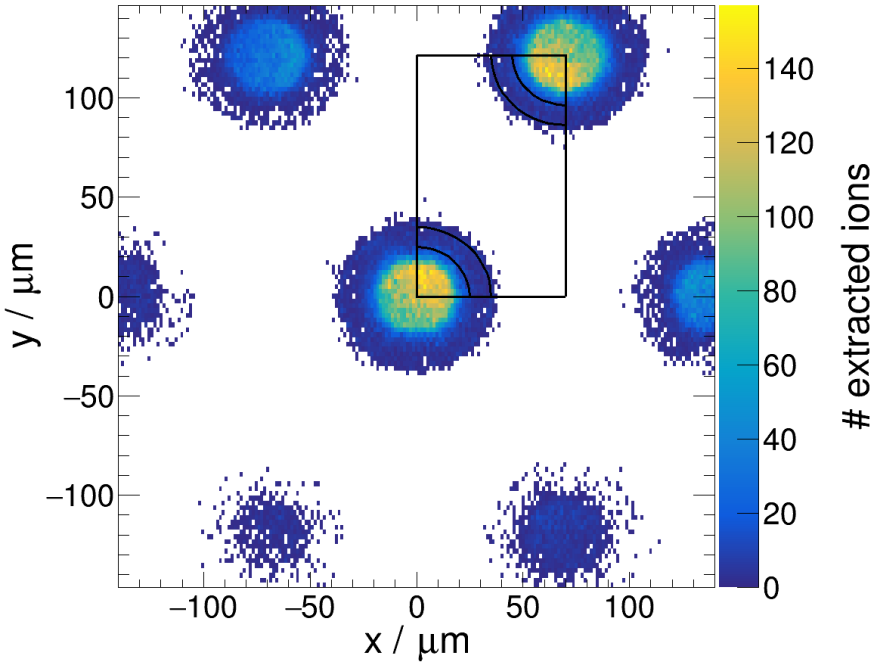


(1) (St)-GEM. Ion creation-points, projected on XY-plane. $E_{\text{above}} = 1000\ \text{V/cm}$.

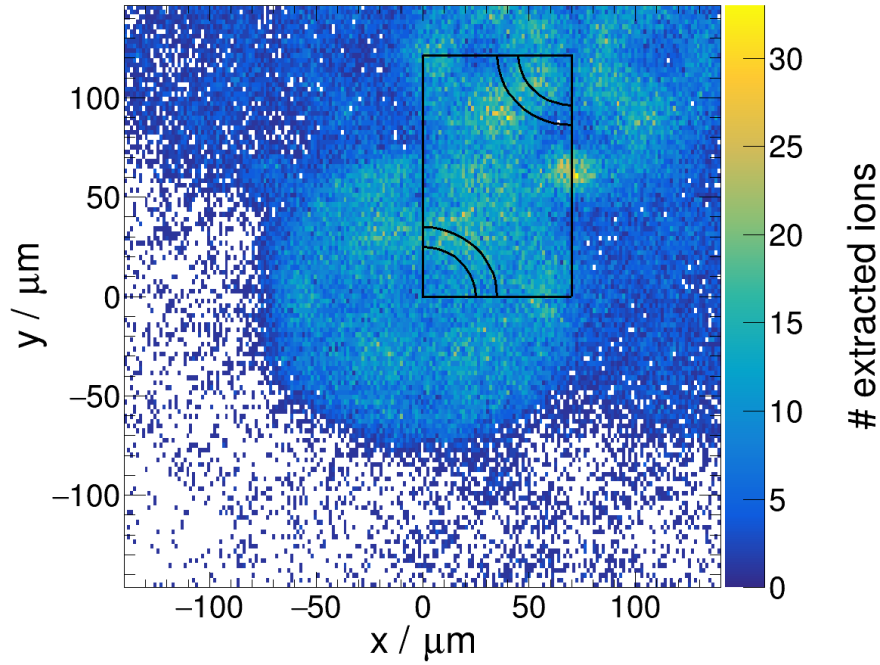


(2) (St)-GEM. Ion extraction-points, projected on XY-plane. $E_{\text{above}} = 1000\ \text{V/cm}$.

Avalanche-ions – Where do they go?

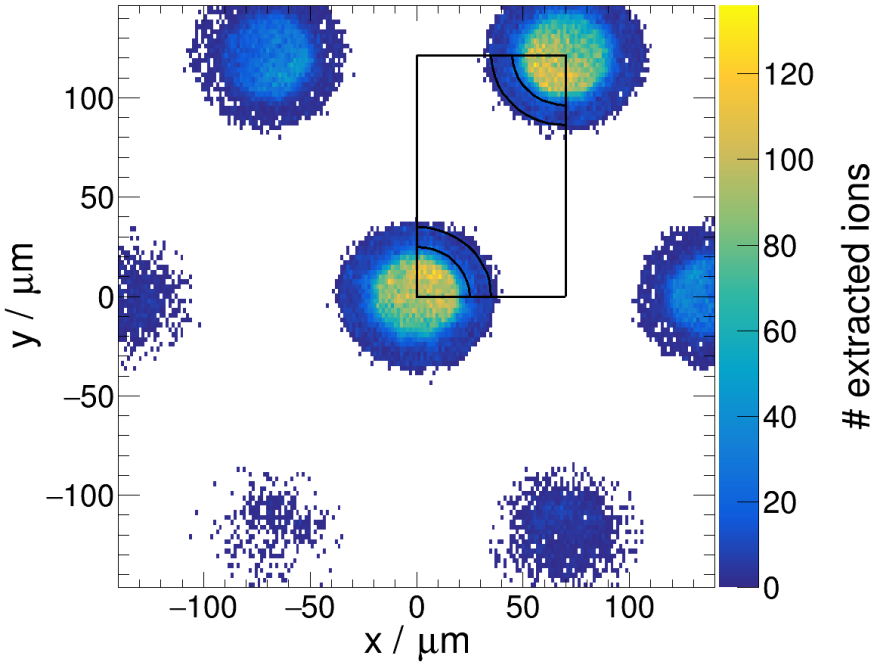


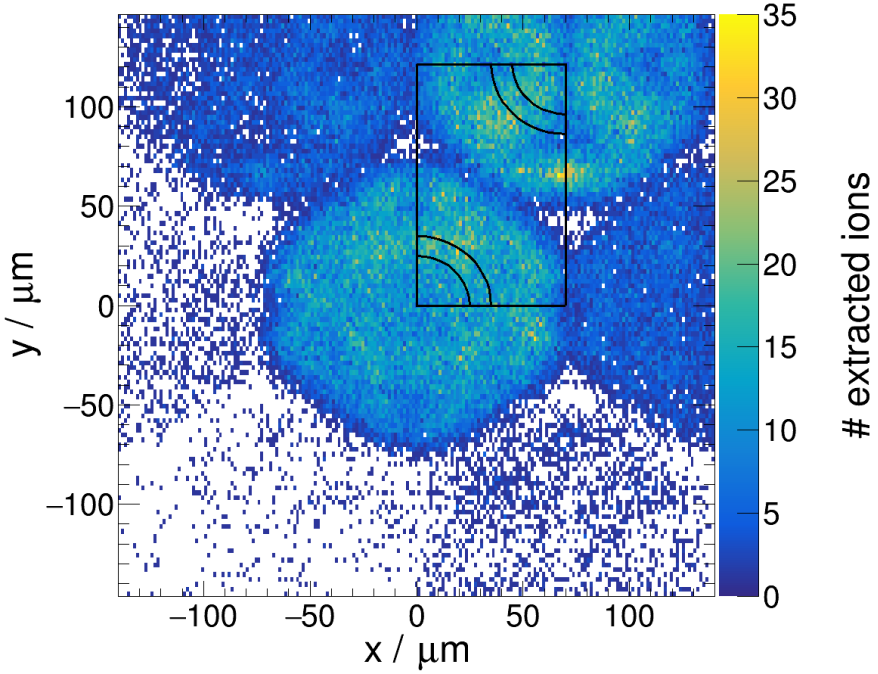
(1) (St)-GEM. Ion creation-points, projected on XY-plane. $E_{\text{above}} = 2000\ \text{V/cm}$.



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

Avalanche-ions – Where do they go?

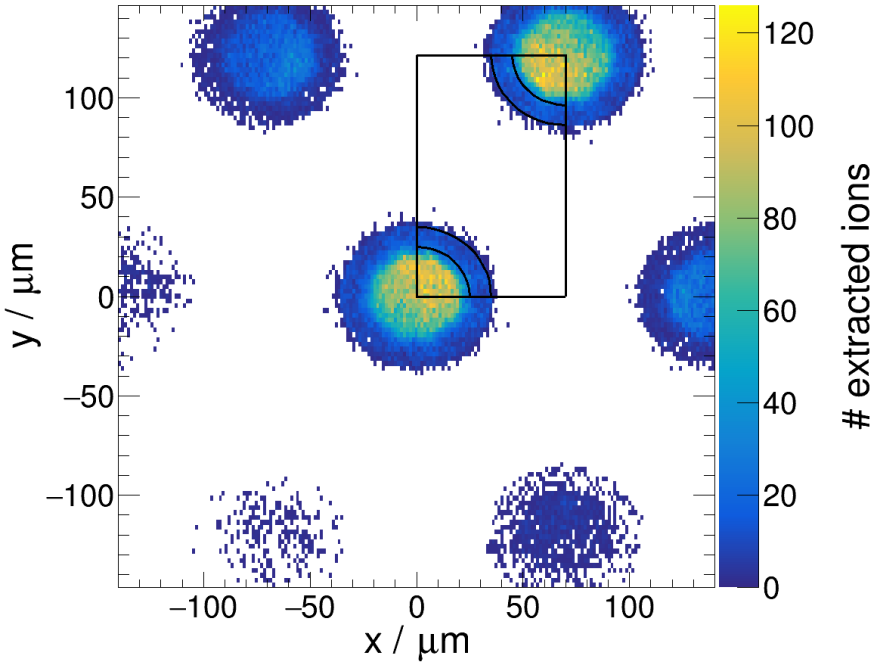




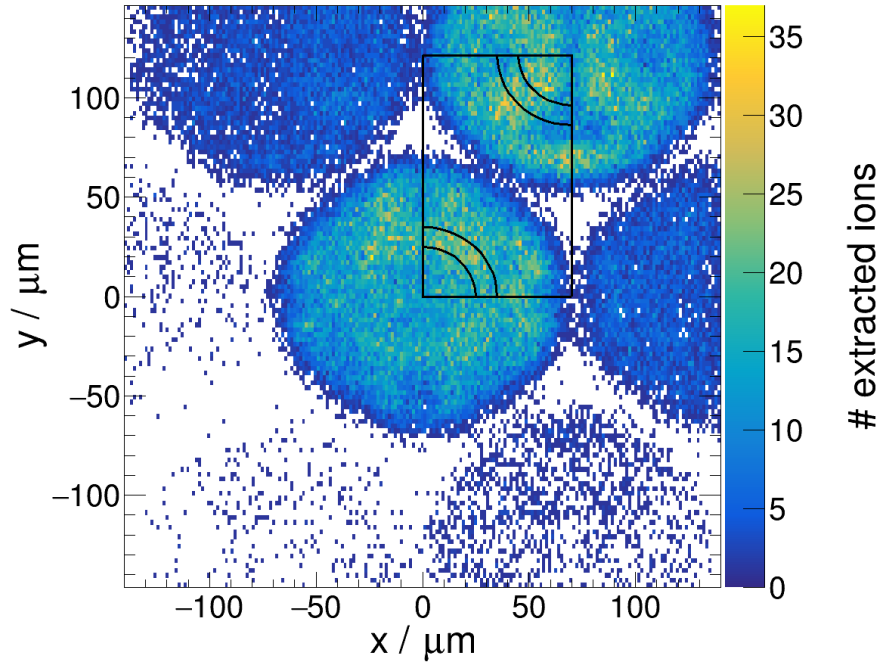
(1) (St)-GEM. Ion creation-points, projected on XY-plane. $E_{\text{above}} = 3000\ \text{V/cm}$.

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

Avalanche-ions – Where do they go?



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



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