

# Charge-Up Effect – Simulations with Garfield++

Philip shows some exponentials

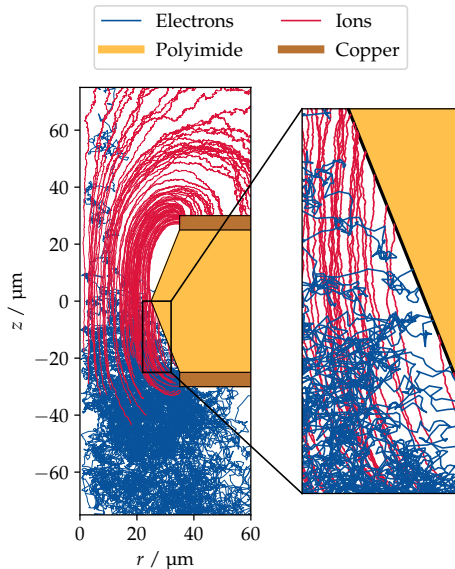
Philip Hauer

~~December 11 2019~~

December 18 2019



# GARFIELD++ AND THE CHARGE-UP EFFECT



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## SIMULATIONS OF THE CHARGING-UP EFFECT IN GAS ELECTRON MULTIPLIERS

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A PREPRINT — TO BE SUBMITTED TO *Nucl. Instr. and Meth. A*

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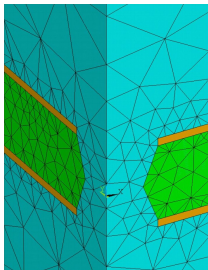
November 28, 2019

### ABSTRACT

Gas Electron Multipliers (GEM) are widely used as amplification stage in gaseous detectors exposed to high rates, e.g. in the Time Projection Chamber of the ALICE (A Large Ion Collider Experiment) experiment after its upgrade. The GEM consists of a polyimide foil which is coated by two thin copper layers. GEM foils are known to collect charges on the polyimide part in its holes during the amplification process. This is accompanied by a change of the effective gain. The effect is commonly known as the “charge-up effect”.

In Progress

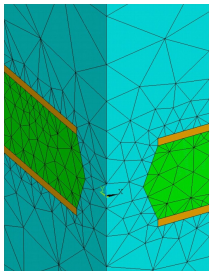
# SIMULATION WORKFLOW



ANSYS

Calculate electrostatic  
potential with  
finite element methods

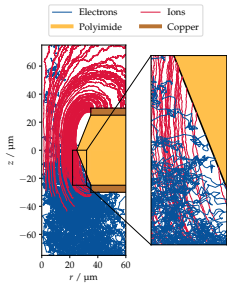
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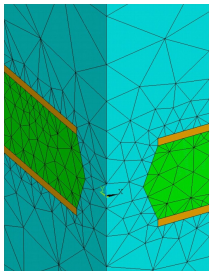
ANSYS  
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Garfield++  
Microscopic simulation  
of the movement  
of electrons and ions



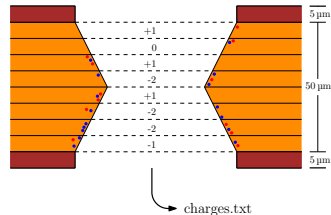
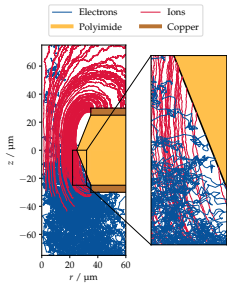
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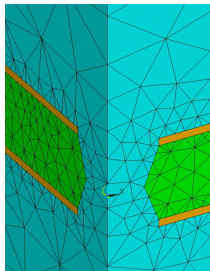
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Calculate electrostatic potential with finite element methods

**Analysis**  
Find location of charged particles that end up on the polyimide

**Garfield++**  
Microscopic simulation of the movement of electrons and ions



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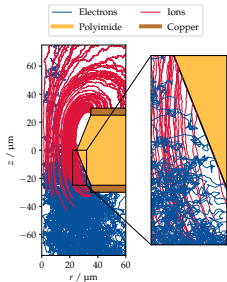
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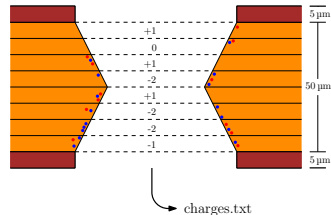
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Microscopic simulation of the movement of electrons and ions

Framework implemented by Steffen Urban

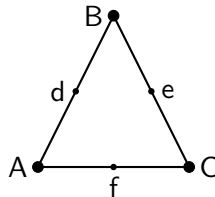
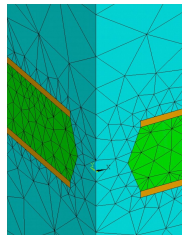
Idea from P.M.M Correia et al.  
[doi: 10.1088/1748-0221/9/07/P07025]



Repeat this a few hundred times



- ▶ **AN**alysis **SY**stem
- ▶ Solves problems with finite element method (FEM)
  - ▶ Linear and non-linear problems
  - ▶ Fluid mechanics, acoustic, thermodynamic, electromagnetism....
- ▶ Divides the system into small cells
  - ▶ Adaptive meshing
  - ▶ Complicated problem (!)
- ▶ Solves Poisson equation on nodes
  - ▶ Result: Electrostatic Potential
  - ▶  $\vec{E}(x, y, z) = -\vec{\nabla}V(x, y, z)$



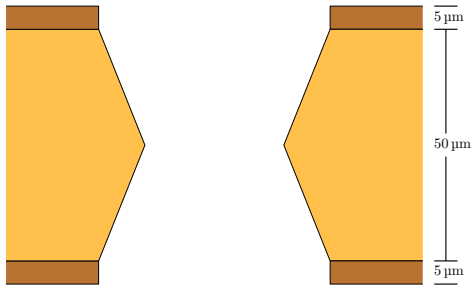
$$V(x, y) = p_0x^2 + p_1y^2 + p_2xy + p_3x + p_4y + p_5$$

- ▶ Simulating particle detectors
  - ▶ Not only gaseous detectors (!)
- ▶ Interface to finite element programs
  - ▶ ANSYS
- ▶ Interface to Magboltz
  - ▶ MC of electron drift and diffusion in gases  
[doi: 10.1016/S0168-9002(98)01233-9]
- ▶ Interface to Heed
  - ▶ Models ionization produced by fast charged particles in gases  
[doi: 10.1016/j.nima.2005.08.064]
- ▶ Creating gas files
  - ▶ Drift velocity and diffusion
- ▶ Avalanche creation
- ▶ Microscopic tracking of electrons
  - ▶ Each collision is simulated (!)
- ▶ Simulate movement of ions
- ▶ Spatial and temporal information
  - ▶ Charge creation
  - ▶ Charge movement
- ▶ Signal induction



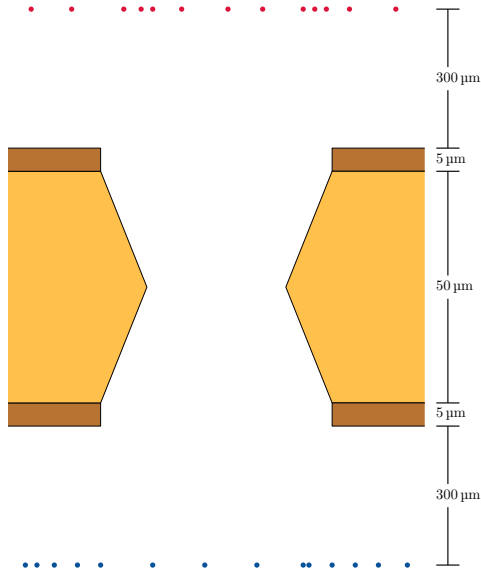
# ANALYSIS OF SIMULATIONS

- ▶ Where do the charges end up?



# ANALYSIS OF SIMULATIONS

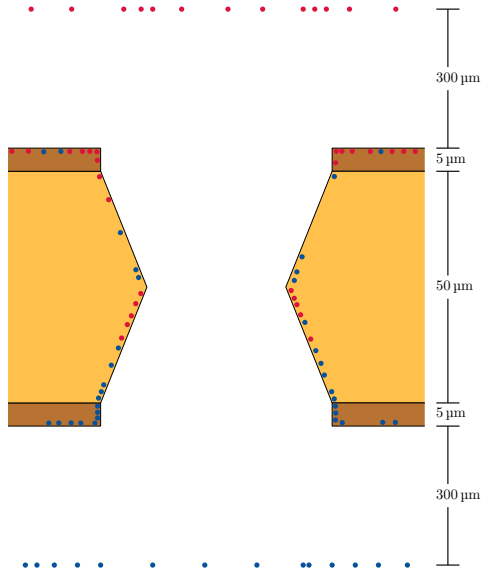
- ▶ Where do the charges end up?
  - ▶ End of the simulated volume





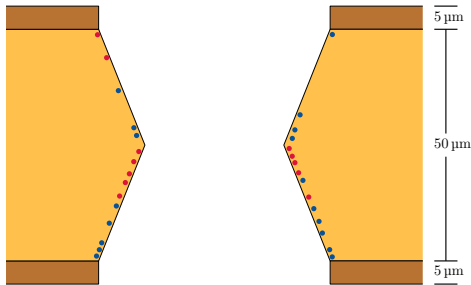
# ANALYSIS OF SIMULATIONS

- ▶ Where do the charges end up?
  - ▶ End of the simulated volume
  - ▶ Copper
  - ▶ Polyimide



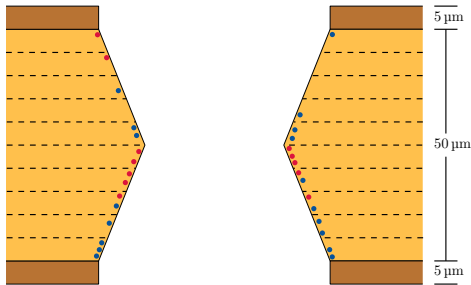
# ANALYSIS OF SIMULATIONS

- ▶ Where do the charges end up?
  - ▶ End of the simulated volume
  - ▶ Copper
  - ▶ Polyimide
- ▶ Charges on polyimide interesting



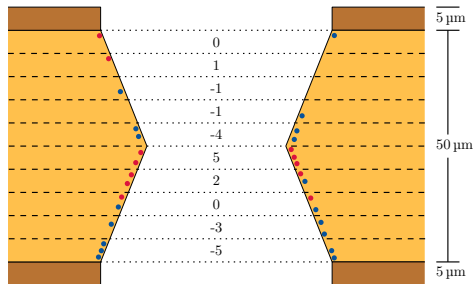
# ANALYSIS OF SIMULATIONS

- ▶ Where do the charges end up?
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  - ▶ Copper
  - ▶ Polyimide
- ▶ Charges on polyimide interesting
- ▶ Divide polyimide into slices



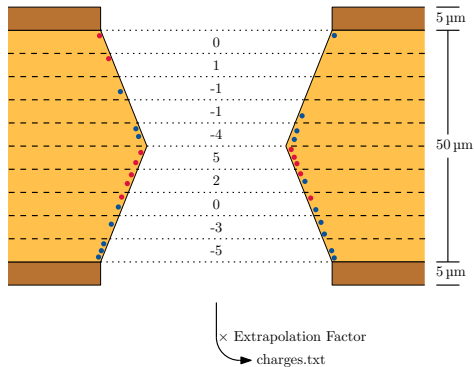
# ANALYSIS OF SIMULATIONS

- ▶ Where do the charges end up?
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  - ▶ Polyimide
- ▶ Charges on polyimide interesting
- ▶ Divide polyimide into slices
- ▶ Count net charge on each slice



# ANALYSIS OF SIMULATIONS

- ▶ Where do the charges end up?
  - ▶ End of the simulated volume
  - ▶ Copper
  - ▶ Polyimide
- ▶ Charges on polyimide interesting
- ▶ Divide polyimide into slices
- ▶ Count net charge on each slice
- ▶ Multiply by constant and dynamic extrapolation factor
- ▶ Apply these charges as surface charges in ANSYS





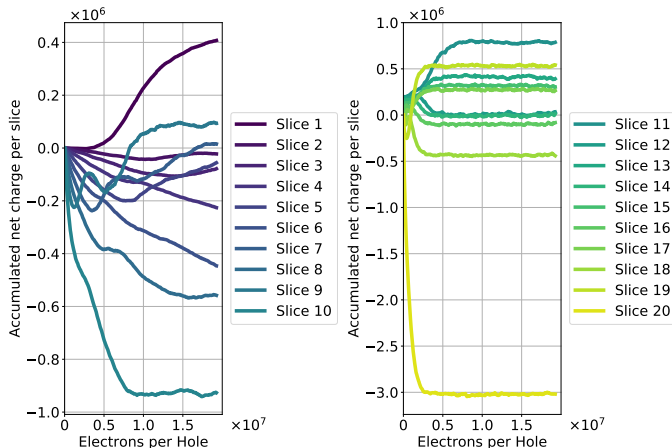
# ANALYSIS OF SIMULATIONS

## Settings:

- ▶  $E_{\text{Drift}} = 400 \text{ V/cm}$
- ▶  $U_{\text{GEM}} = 350 \text{ V}$
- ▶  $E_{\text{Induct}} = 2000 \text{ V/cm}$

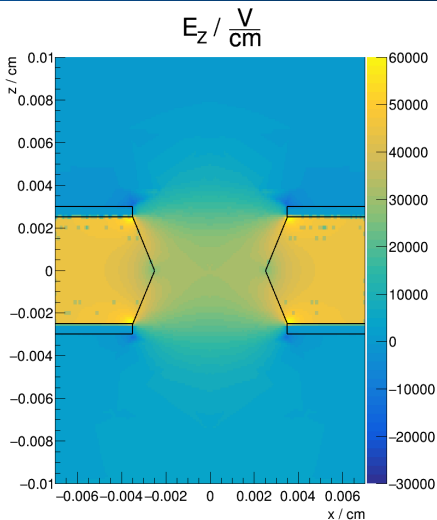
## Observations:

- ▶ Neighboring slices accumulate oppositely charged net charges
  - ▶ E.g. Slices 19 & 20
- ▶ “Multipole-like structure”

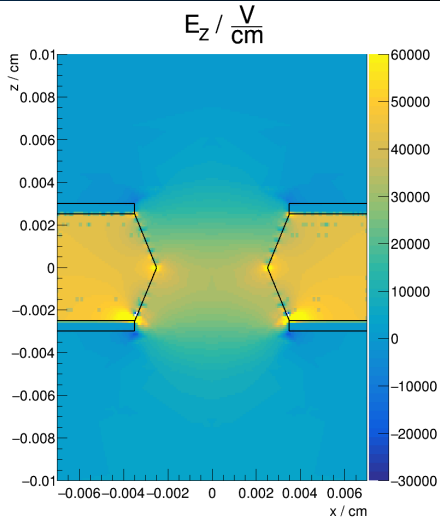


⇒ Unrealistic behavior!

# ANALYSIS OF SIMULATIONS – ELECTRIC FIELD

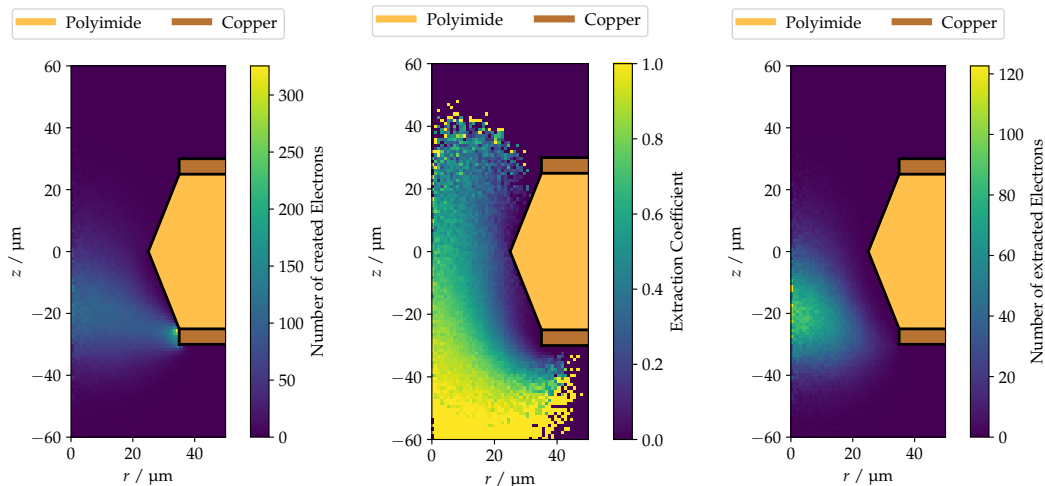


Initial state



After simulating charge-up

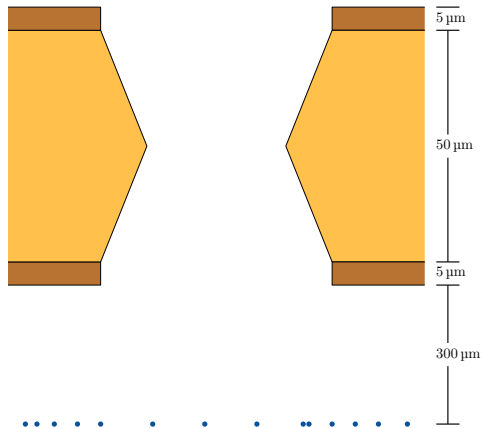
# ANALYSIS OF SIMULATIONS – ELECTRON CREATION



⇒ Effective gain should not be influenced by multipoles!

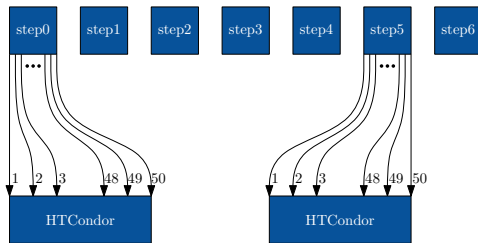
# ANALYSIS OF SIMULATIONS – EFFECTIVE GAIN

- ▶ Where do the charges end up?
  - ▶ End of simulated volume
  - ▶ Copper
  - ▶ Polyimide
- ▶ Electrons at the lower end of simulated volume interesting
- ▶ Count them
  - ▶ Effective gain
- ▶ Only valid if one single initial electron



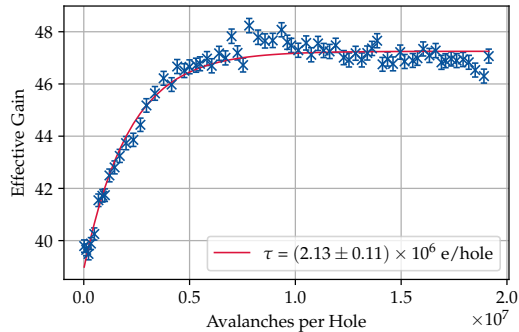
# EFFECTIVE GAIN – SIMULATIONS WITH HTCONDOR

- ▶ Most of the time: 350 steps
  - ▶ Effective gain changes with each step
  - ▶ A precise simulation of the effective gain needs  $\approx 10\,000$  initial electrons
  - ▶ Computationally very expensive!
- ▶ But: Easy to parallelize
- ▶ Only simulate every fifth step
  - ▶ A reasonable trade-off:
    - ▶ 50 jobs for every fifth step (= 3500 jobs in total)
    - ▶ Each job 400 single initial electrons
    - ▶ Equals 20 000 initial electrons
    - ▶ 1 400 000 initial electrons in total for one setting (!)



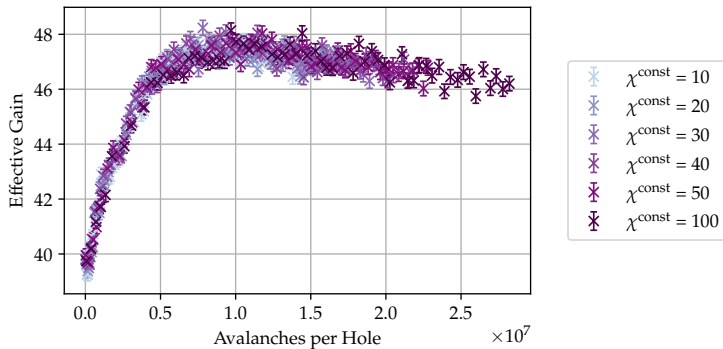
# DEVELOPMENT OF THE EFFECTIVE GAIN

- ▶ Effective gain increases exponentially
- ▶ “Time constant” can be compared to measurements
  - ▶  $(8.3 \pm 0.4 \begin{smallmatrix} +4.0 \\ -2.8 \end{smallmatrix}) \times 10^6$  e/hole
  - ▶  $(5.2 \pm 0.4 \begin{smallmatrix} +1.8 \\ -1.3 \end{smallmatrix}) \times 10^6$  e/hole
- ▶ Percentual increase  $\approx 20\%$
- ▶ Reasonable extrapolation factor?
- ▶ What about different voltage settings?



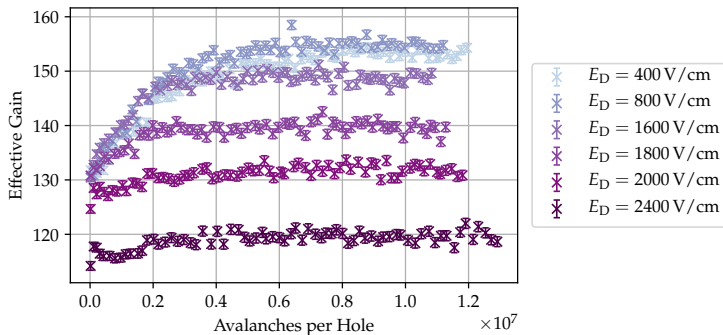
# DIFFERENT CONSTANT EXTRAPOLATION FACTOR

- ▶ Higher extrapolation desirable
- ▶ Should not influence characteristics
- ▶  $\chi^{\text{const}}$  varied between 10 and 100
- ▶ Results look similar
- ▶ Choose a conservative value of  $\chi^{\text{const}} = 30$



# DIFFERENT DRIFT FIELDS

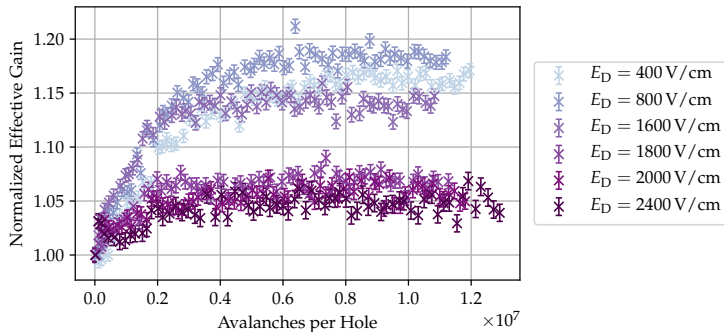
- ▶ Changed  $U_{\text{GEM}}$  to 400 V





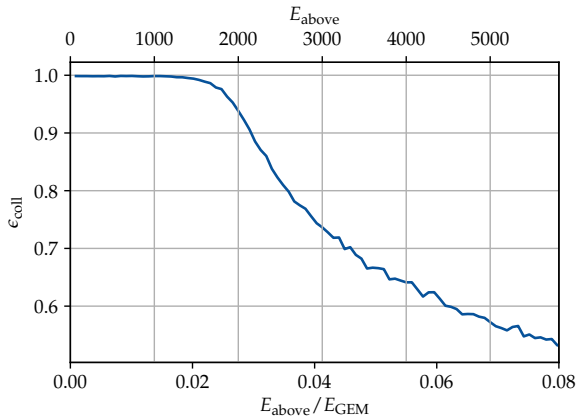
# DIFFERENT DRIFT FIELDS

- ▶ Changed  $U_{\text{GEM}}$  to 400 V
- ▶ Higher drift fields lead to smaller increase
- ▶ Why?  $\rightarrow \epsilon_{\text{coll}}$



# DIFFERENT DRIFT FIELDS

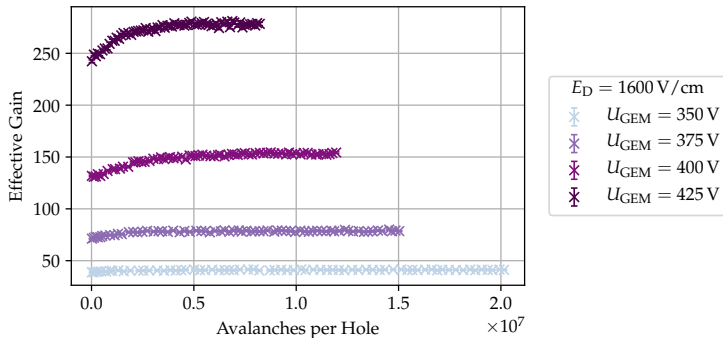
- ▶ Changed  $U_{\text{GEM}}$  to 400 V
- ▶ Higher drift fields lead to smaller increase
- ▶ Why?  $\rightarrow \epsilon_{\text{coll}}$
- ▶ Depends on  $E_{\text{Drift}}/U_{\text{GEM}}$



Upper scale for  $U_{\text{GEM}} = 400 \text{ V}$

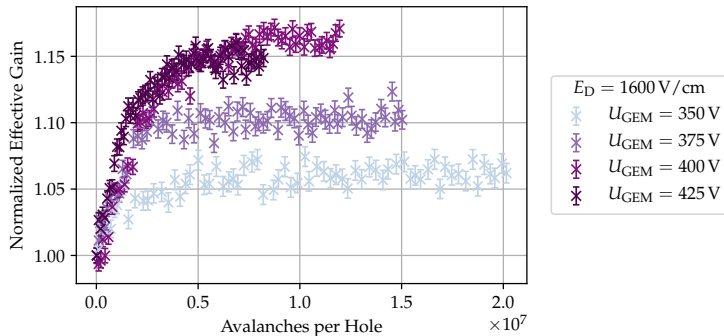
# DIFFERENT DRIFT FIELDS

- ▶ Higher drift fields lead to smaller increase
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- ▶ Depends on  $E_{\text{Drift}}/U_{\text{GEM}}$
- ▶ Could be interesting for ALICE settings



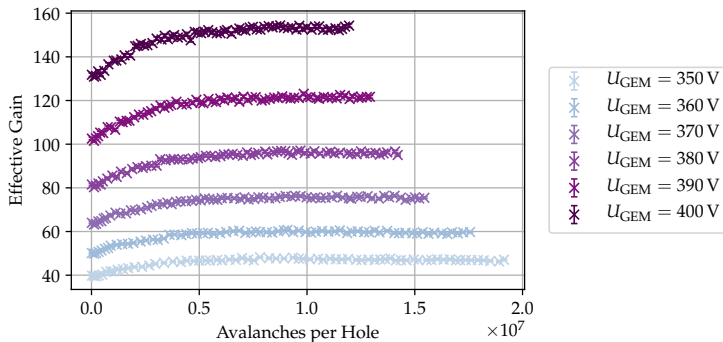
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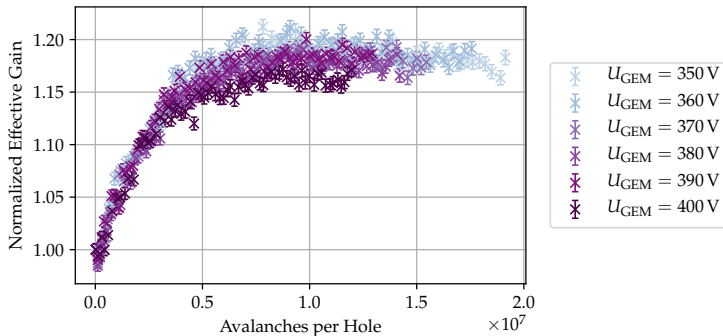
# DIFFERENT GEM VOLTAGES

- ▶ Changed  $U_{\text{GEM}}$  from 350 V to 400 V
- ▶ Total gain different



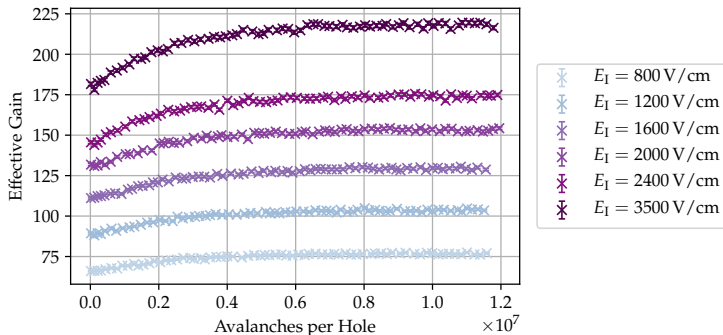
# DIFFERENT GEM VOLTAGES

- ▶ Changed  $U_{\text{GEM}}$  from 350 V to 400 V
- ▶ Total gain different
- ▶ Normalized to first value
- ▶ No dependency
- ▶ Contradicts measurements



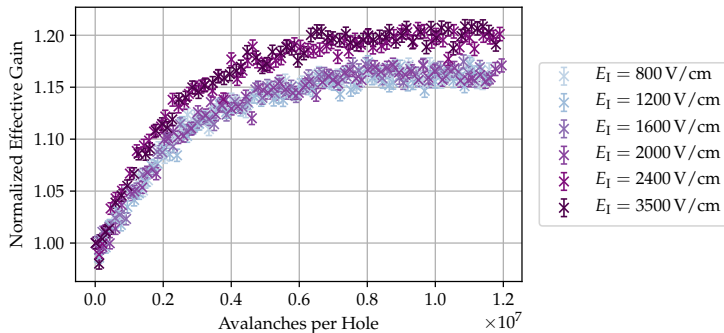
# DIFFERENT INDUCTION FIELDS

- ▶ Changed  $E_{\text{Induct}}$  from 800 V/cm to 3500 V/cm
- ▶ Extraction efficiency different



# DIFFERENT INDUCTION FIELDS

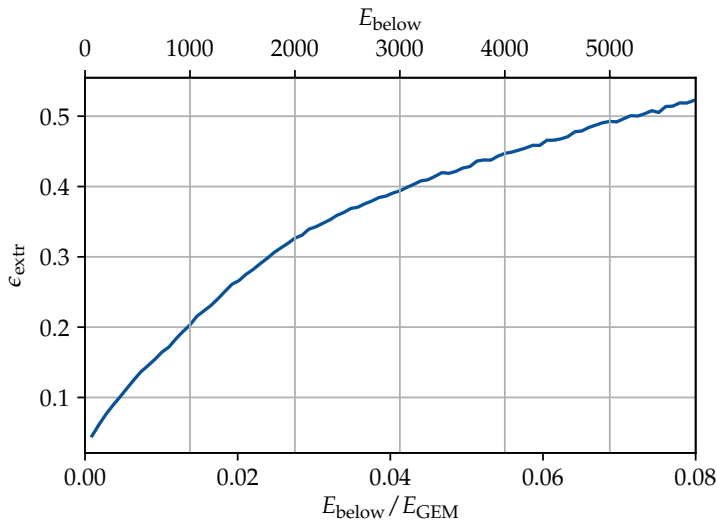
- ▶ Changed  $E_{\text{Induct}}$  from 800 V/cm to 3500 V/cm
- ▶ Extraction efficiency different
- ▶ Normalized to first value
- ▶ No (strong) dependency





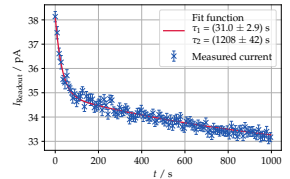
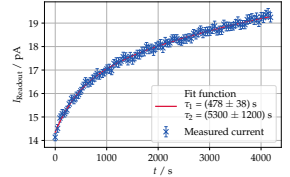
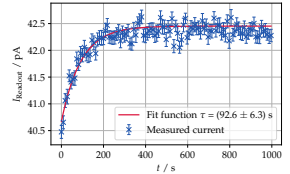
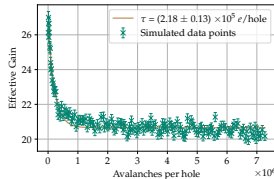
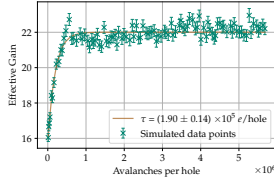
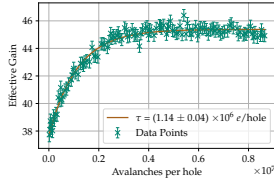
# DIFFERENT INDUCTION FIELDS

- ▶ Changed  $E_{\text{Induct}}$  from 800 V/cm to 3500 V/cm
- ▶ Extraction efficiency different
- ▶ Normalized to first value
- ▶ No (strong) dependency
- ▶ Slope of extraction efficiency?!



# SINGLE CONICAL GEMs

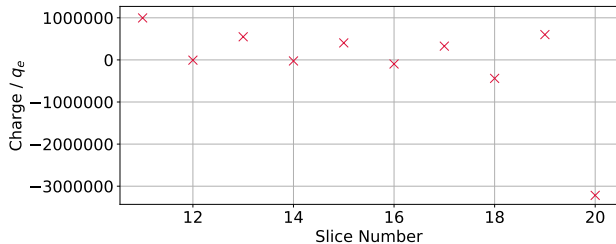
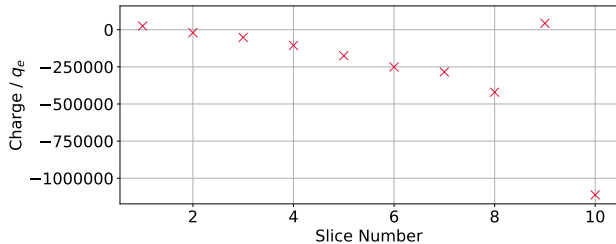
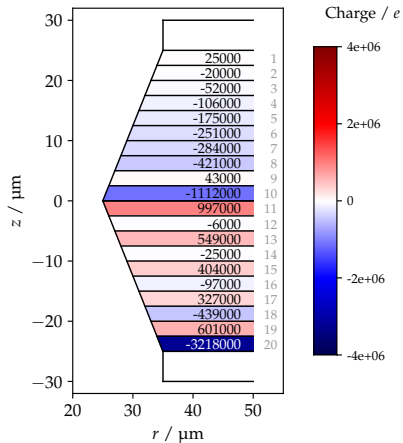
- ▶ Up to now: DC GEMs
- ▶ Charge collection should depend on geometry
- ▶ Tapered side down: Electrons
- ▶ Same behavior
- ▶ Tapered side up: Ions
- ▶ Behavior different but agrees with first measurements



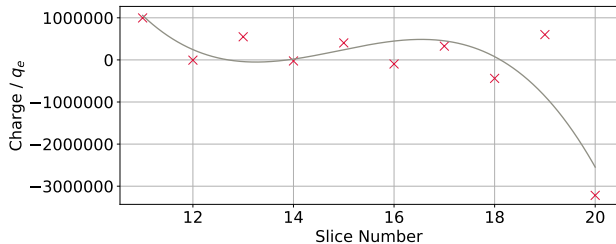
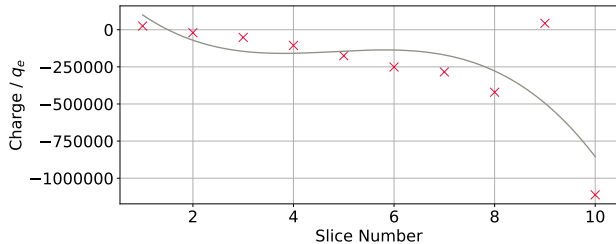
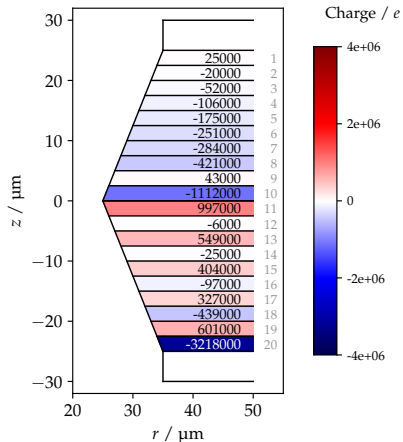
# DON'T FORGET THE PROBLEM....

- ▶ Every simulation: Multipoles (!)
  - ▶ Continuous charge distribution best solution
    - ▶ In FEM not feasible
    - ▶ No alternative to FEM (up to now..)
  - ▶ Test a few options
    - ▶ Charge distribution with a function
    - ▶ Re-bin charge distribution
    - ▶ Percentage charge exchange between neighboring slices
- ⇒ Charge transfer between slices

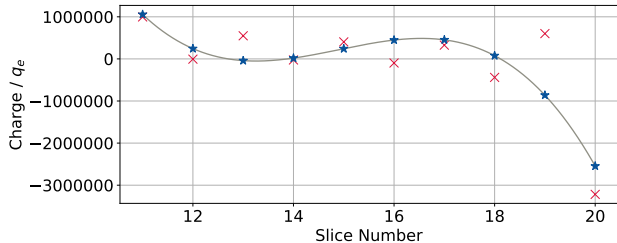
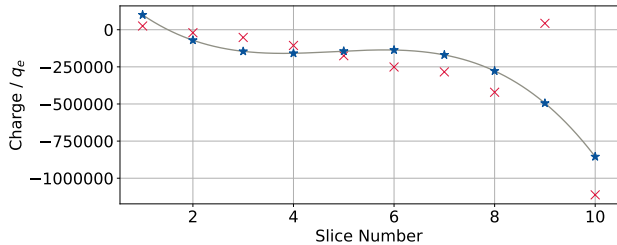
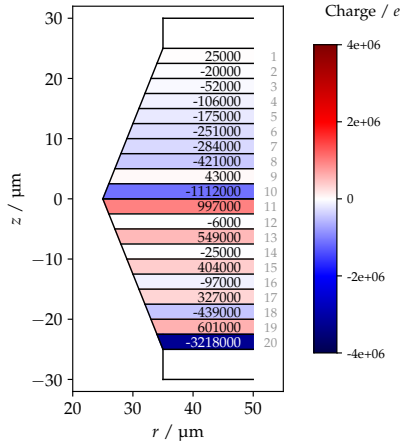
# APPLICATION OF A FUNCTION



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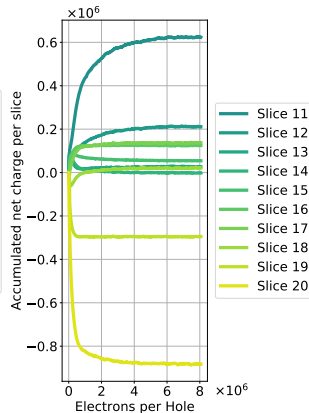
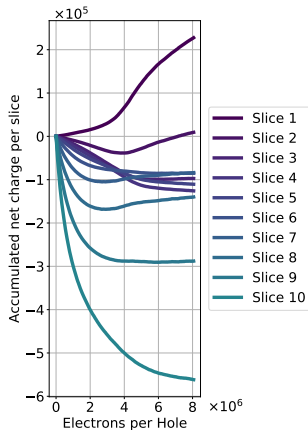


# APPLICATION OF A FUNCTION



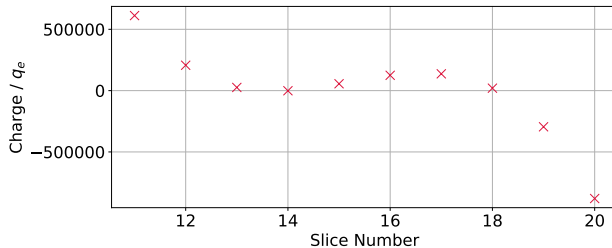
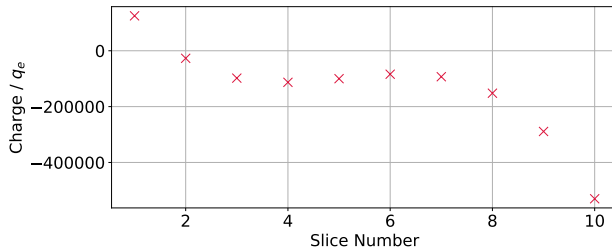
# ANALYSIS OF SIMULATIONS – POL3

- ▶ 800 steps
- ▶ No more multipoles



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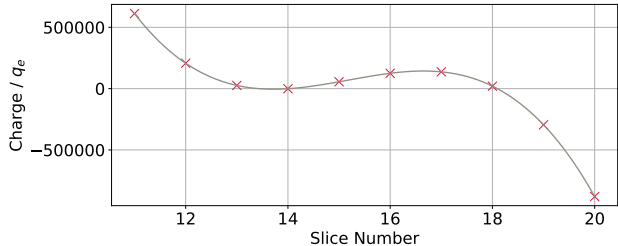
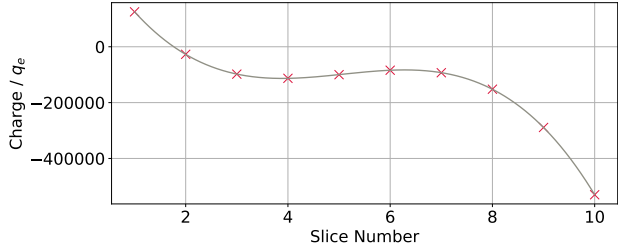
- ▶ 800 steps
- ▶ No more multipoles
- ▶ Example: step 500
- ▶ Charges are almost following pol3 already





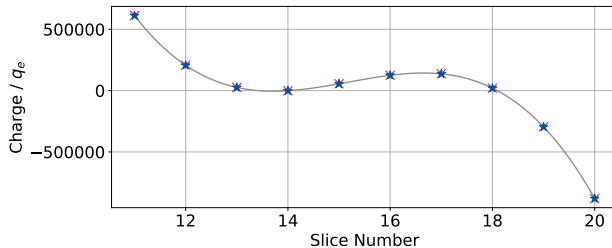
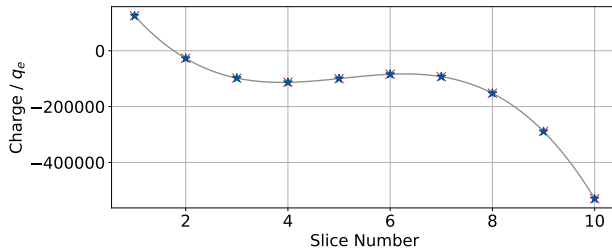
# ANALYSIS OF SIMULATIONS – POL3

- ▶ 800 steps
- ▶ No more multipoles
- ▶ Example: step 500
- ▶ Charges are almost following pol3 already
- ▶ Fit function has no big impact



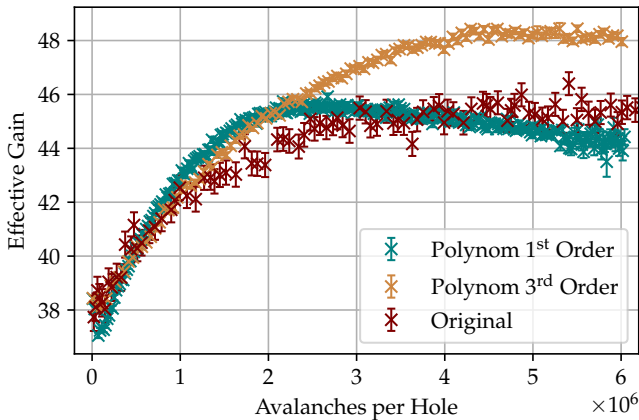
# ANALYSIS OF SIMULATIONS – POL3

- ▶ 800 steps
- ▶ No more multipoles
- ▶ Example: step 500
- ▶ Charges are almost following pol3 already
- ▶ Fit function has no big impact
- ▶ However: Multipole-like-like



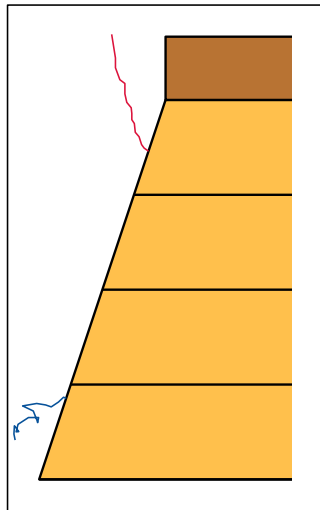
# APPLICATION OF A FUNCTION – EFFECTIVE GAIN

- ▶ Development of  $G_{\text{eff}}$
- ▶ Two different functions
- ▶ Changes the development significantly
- ▶ Question: Do we want to introduce this additional degree of freedom?



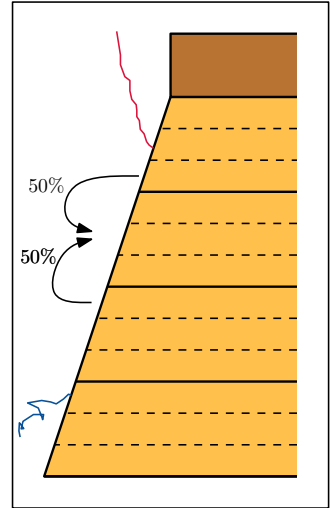
# RE-BINNING OF CHARGE DISTRIBUTION

- ▶ Simulate everything as normal
- ▶ But don't divide into 20 slices



# RE-BINNING OF CHARGE DISTRIBUTION

- ▶ Simulate everything as normal
- ▶ But don't divide into 20 slices
- ▶ Use 60 instead
  - ▶ For ANSYS: 20 slices (!)
- ▶ Smear out charges on "subslices"
- ▶ Can also be done with 40 slices

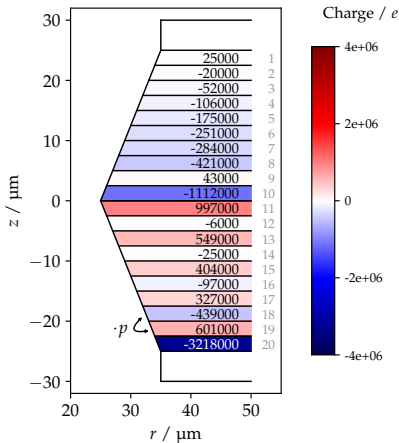


:(

No results up to now due to a bug in my software

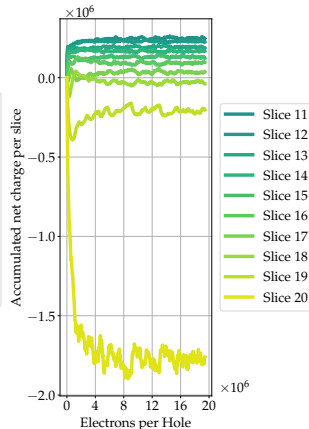
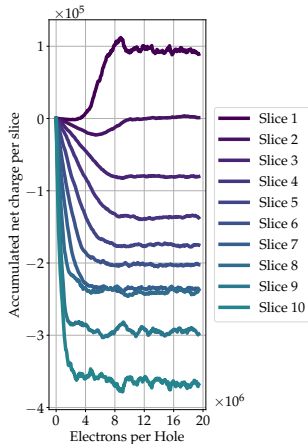
# PERCENTAGE CHARGE EXCHANGE

- ▶ Charge transfer proportional to difference
  - ▶ Factor:  $p$
  - ▶ In Example: Slice 18 & 19
  - ▶ Difference 1040000  $e$
  - ▶ Add  $p \cdot 1040000$  to slice 18
  - ▶ Subtract  $p \cdot 1040000$  from slice 19
- ▶ Resembles diffusion and current flow
- ▶ Do many simulations with different  $p$



# EXAMPLE – 1%

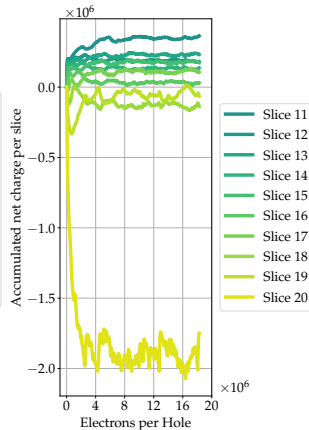
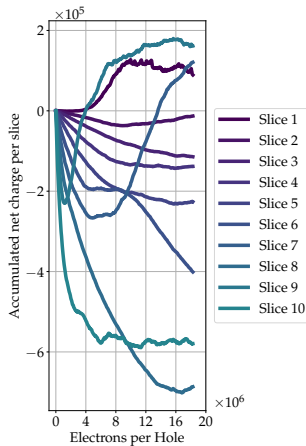
- ▶ First example with  $p = 0.01$ 
  - ▶ No more multipoles
- ▶ Additional degree of freedom
- ▶ How does it change for different  $p$ ?
- ▶ And what about the effective gain?





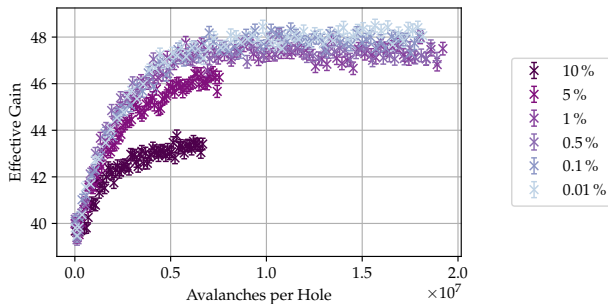
# EXAMPLE – 0.01%

- ▶ Second example with  $p = 0.0001 = 0.01\%$ 
  - ▶ Again multipoles
- ▶  $p = 0.01\%$  is too small to make a significant change
- ▶ And what about the effective gain?



# EFFECTIVE GAIN DEVELOPMENT

- ▶ Effective gain for different  $p$
- ▶  $p = 10\%$  is too much
  - ▶ From multipole considerations:  
 $p = 0.01\%$  too small
- ▶ Probably  $1\%$  is a fair trade-off



# SUMMARY – TIME CONSTANTS

$U_{\text{GEM}} / \text{V}$	$\tau / \text{e/hole}$
350	$2\,120\,000 \pm 120\,000$
360	$2\,240\,000 \pm 120\,000$
370	$2\,376\,000 \pm 91\,000$
380	$2\,560\,000 \pm 110\,000$
390	$2\,400\,000 \pm 90\,000$
400	$2\,340\,000 \pm 100\,000$

$E_{\text{Drift}} / \text{V/cm}$	$\tau / \text{e/hole}$
400	$2\,340\,000 \pm 100\,000$
800	$1\,881\,000 \pm 81\,000$
1600	$1\,995\,000 \pm 69\,000$
1800	$1\,160\,000 \pm 130\,000$
2000	$1\,940\,000 \pm 340\,000$
2400	$2\,150\,000 \pm 520\,000$

$E_{\text{Induct}} / \text{V/cm}$	$\tau / \text{e/hole}$
800	$2\,390\,000 \pm 100\,000$
1200	$2\,430\,000 \pm 100\,000$
1600	$2\,580\,000 \pm 100\,000$
2000	$2\,430\,000 \pm 100\,000$
2400	$2\,104\,000 \pm 76\,000$
3500	$2\,254\,000 \pm 69\,000$

$p / \%$	$\tau / \text{e/hole}$
10	$1\,720\,000 \pm 120\,000$
5	$2\,310\,000 \pm 110\,000$
1	$1\,952\,000 \pm 81\,000$
0.5	$1\,845\,000 \pm 71\,000$
0.1	$2\,433\,000 \pm 86\,000$
0.01	$2\,442\,000 \pm 71\,000$

# SUMMARY – SIMULATING THE CHARGE-UP EFFECT

- ▶ Iterative approach
  - ▶ Based on ANSYS and Garfield++
- ▶ Can describe measured values
  - ▶ Describes qualitative behavior nicely
  - ▶ Even for unexpected things (e.g. SC GEM)
  - ▶ But: Deviations to measurements
  - ▶ And what about multipoles?!
- ▶ Approaches to get rid of multipoles
  - ▶ Most promising: Percentage smooth
  - ▶ But it introduces another degree of freedom

# OUTLOOK – SIMULATING THE CHARGE-UP EFFECT

- ▶ Write Paper (!!!)
- ▶ Try to simulate re-binning
- ▶ Simulate different voltage settings with percentage smooth (?)
- ▶ ? Any ideas ?

Thank you for your attention!

