GTS

Garfield-based Triple-GEM Simulator

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CGEM-IT project, BESIII experiment

**BEijing Spectrometer III**
- τ & charm factory
- $E_{\text{cms}} = 2 - 4.6$ GeV
- @BEPC, Beijing, P.R.C.
- current tracking system: inner + outer drift chamber

In 2020, replace the inner chamber with a **Cylindrical Triple-GEM - Inner Tracker**

- $\sigma_p/p = 0.5\%$ @1 GeV/c
- $\sigma_x = 130$ μm
- $\sigma_z = 1$ mm
- solid angle coverage 93%
- $X_0 < 1.5\%$
- particle rate $\sim 10^4$ Hz/cm$^2$
Digitization of a triple-GEM

simulate the triple-GEM response to the passage of the ionizing particle

from the generation of the electrons...

...to the signal formation
Available tool: GARFIELD++

STRAIGHTFORWARD CHOICE!

Reading from the webpage https://garfieldpp.web.cern.ch

is a toolkit for the detailed simulation of detectors which use gases or semi-conductors as sensitive medium.

the main area of application is currently in micropattern gaseous detectors.

Ionisation → Heed generates ionisation patterns of fast charged particles

Electric fields → interfaces with the finite element programs (Ansys, Elmer, Comsol and CST) which can compute approximate fields in nearly arbitrary 3D configurations with dielectrics and conductors

Transport of electrons → Magboltz is used for computing electron transport and avalanches in nearly arbitrary gas mixtures
Available tool: GARFIELD++

BUT (CPU) TIME IS PRECIOUS!

GOAL: use this digitization inside the full detector simulation → needs to be fast

We tried to run the complete simulation of a triple-GEM:
• ionization
• three stages of amplification
• drift of the electrons
on the distributed computing environment based on
for BESIII experiment, but it took more than one day!

GARFIELD++ capabilities

Parametrization!

More speed
Looking for inspiration

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 49, NO. 4, AUGUST 2002

A Complete Simulation of a Triple-GEM Detector

W. Bonivento, A. Cardini, G. Bencivenni, F. Murtas, and D. Pinci

Primary Ionization
- # clusters
- # electrons/cluster

GEM properties
- Gain
- Transparency

Drift properties
- Lorentz angle & Diffusion (in the four gaps)

Signal formation
- Induction
- Readout
Our final solution

**GARFIELD++**

- studies of various parameters

comparison between the standalone code and **GARFIELD**

implementation of a standalone code

tuning to testbeam data

**GARFIELD–based**

**Triple–GEM**

**Simulator**
GARFIELD++ simulations
GARFIELD++ simulations

- geometry, field, HV described in ANSYS
- development of the avalanche from GARFIELD++
- planar GEM chambers considered

The triple-GEM was simulated in steps
more details will follow

- used different HV settings
- used different field settings
- with and without magnetic field on
GTS implementation & comparison to GARFIELD++
GTS scheme

various steps are independent $\rightarrow$ can be studied separately
Ionization

Various steps are independent $\rightarrow$ can be studied separately.

- Ionization
- Drift properties
- GEM properties
- # e$^- \text{ in collision}
- # collisions
Ionization

• **primary ionization** – Poissonian process
  → *relative position* from exponential distribution
  → the number of the ionizations follows

• **secondary ionization** – from tables [F. Sauli (1977) *Principles of Operation of Multiwire Proportional and Drift Chambers*; A. Sharma *Properties of some gas mixture used in tracking detectors*]
  → consistent with GARFIELD++ simulations

**Simulations**

Electron clusters were extracted for M.I.P. (150 GeV/c muons) → will be extended to other particles and energies

**Two approximations**

• ionization electrons generated
  only in the drift gap

• secondary electrons with the same origin of the primaries
GEM properties

Various steps are independent → can be studied separately
Transparency

Collection efficiency

\[
\frac{\text{# electrons into the hole}}{\text{# generated electrons}}
\]

Extraction efficiency

\[
\frac{\text{# electrons from the hole}}{\text{# electrons in the avalanche}}
\]
Transparency

Collection efficiency
\[ \frac{\text{# electrons into the hole}}{\text{# generated electrons}} \]

Extraction efficiency
\[ \frac{\text{# electrons from the hole}}{\text{# electrons in the avalanche}} \]

Simulation
- shoot 10k e\(^-\), 150 \(\mu\)m above the GEM
- count e\(^-\), 150 \(\mu\)m below the GEM
- avalanche OFF

\[ T = \varepsilon_{\text{coll}} \varepsilon_{\text{extr}} \]
Gain fluctuations $\rightarrow$ Polya distribution

\[ P(G) = C_0 \frac{(1 + \theta)^{1+\theta}}{\Gamma(1 + \theta)} \left( \frac{G}{\bar{G}} \right)^{\theta} \exp \left[ - (1 + \theta) \frac{G}{\bar{G}} \right] \]

$\bar{G}$ = intrinsic gain mean value

$\theta$ $\rightarrow$ connected to variance
Gain fluctuations $\rightarrow$ Polya distribution

[G. Iakovidis PhD Thesis, Research and Development in Micromegas Detector for the ATLAS Upgrade]

\[
P(G) = C_0 \frac{(1 + \theta)^{1+\theta}}{\Gamma(1 + \theta)} \left(\frac{G}{\bar{G}}\right)^\theta \exp\left[-(1 + \theta)\frac{G}{\bar{G}}\right]
\]

$\bar{G}$ = intrinsic gain mean value
$\theta$ $\rightarrow$ connected to variance

Simulation

- shoot 10k $e^-$, 150 $\mu$m above the GEM
- count $e^-$ in the avalanche
  $\rightarrow$ intrinsic gain
- avalanche ON

$G_{\text{eff}} = T G_{\text{intr}}$

For each of the three GEMs
Triple – GEM full gain

Studies have shown that the actual triple-GEM full gain is not simply the product of GEM1, GEM2 and GEM3 gains!

Procedure
1. evaluate transparency + intrinsic gain by GARFIELD++
2. apply them to GEM1, GEM2, GEM3
3. fill the **effective gain** histogram will 1M events with full simulation chain, i.e. sampling:
   \[ \varepsilon_{\text{coll}, \text{GEM}_1} \rightarrow \text{gain}_{\text{GEM}_1} \rightarrow \varepsilon_{\text{extr}, \text{GEM}_1} \rightarrow \]
   \[ \varepsilon_{\text{coll}, \text{GEM}_2} \rightarrow \text{gain}_{\text{GEM}_2} \rightarrow \varepsilon_{\text{extr}, \text{GEM}_2} \rightarrow \]
   \[ \varepsilon_{\text{coll}, \text{GEM}_3} \rightarrow \text{gain}_{\text{GEM}_3} \rightarrow \varepsilon_{\text{extr}, \text{GEM}_3} \]
4. sample from it!
Drift properties

various steps are independent → can be studied separately
Drift properties

Presence of gas → Diffusion
- spread in position
- spread in time

Presence of mag. Field → Lorentz force
- shift in position
- longer times
Drift properties

Presence of gas $\rightarrow$ Diffusion
- spread in position
- spread in time

Presence of mag. Field $\rightarrow$ Lorentz force
- shift in position
- longer times

Study the different gaps separately for each gap:
- extract $\Delta x$ and $\Delta t$ distributions
- fit the $\sigma_x$, $\sigma_t$, $\mu_x$, $\mu_t$ distributions to parametrize them

Simulation
- shoot 10k e$^-\,$ in each gap
- magnetic field $B = 1T$
- avalanche OFF
- only drift ON
Position/time: shift & spread

Transfer/Induction gaps
- the electrons all enter each gap from the same level \( \rightarrow \text{NO } z \text{ dependence} \) of spread and sigma of position distribution

- Analogous behavior for time distribution
Position/time: shift & spread

Drift gap

• The ionization position is different from electron to electron $\rightarrow$ \textit{z} dependence of spread and sigma of position distribution

• Analogous behavior for time distribution

drift, shift

drift, spread
Signal formation

various steps are independent → can be studied separately
Induction of the signal: basics

The current induced on a strip on the anode:
- depends on the position
- ends when the electron arrives on the strip

To be also considered (in our case)
- we have a double view anode
- we still need to be fast!

Two options
- Full induction description
- Fast \(\rightarrow\) approximation

[W. Riegler, CERN seminar]
**Full induction: Shokley-Ramo**
(S. Ramo, in Proc. IRE 27, 584 (1939))

The **instantaneous** current induced by a charge in motion on an electrode is

$$i(t) = q_e \times v_{\text{drift}} \times W_{\text{loc}}$$

- $q_e$ – electron charge
- $v_{\text{drift}}$ – drift velocity
- $W_{\text{Loc}}$ – weighting field, i.e. the electric field generated by the electrode @ 1V, when all the other electrodes are set @ 0V

**Approximation 1**

- constant $v_{\text{drift}} = 35 \ \mu m/\text{ns}$
- ok for Ar:i-$C_4H_{10}$ (90:10) @ field values = 1.5/3/3/5 kV/cm

BUT close to the strip the field is much higher!
The **instantaneous** current induced by a charge in motion on an electrode is

\[
i(t) = q_e \times v_{\text{drift}} \times W_{\text{loc}}
\]

- \(q_e\) – electron charge
- \(v_{\text{drift}}\) – drift velocity
- \(W_{\text{Loc}}\) – weighting field, *i.e.* the electric field generated by the electrode @ 1V, when *all the other* electrodes are set @ 0V

### Approximation 2

- get electron position on the anode by Lorentz angle & diffusion parametrizations
- compute induced \(dq\) instead of \(i(t)\)
- compute induced \(dq\) for steps of 1 ns (\(v_{\text{drift}}\) constant)

\[
\frac{dq}{dt} = q_e \times \frac{dx}{dt} \times \frac{dV_w}{dx}
\]

*\[ dq = q_e \times dV_w \]*
Full induction: weighting field

(W. Riegler, CERN seminar)

Approximation 3

computed analytically with only one view → charge sharing introduced by a tuning factor to account for electric field focussing effect
Fast induction of the signal

Once all the electrons have arrived on the anode:
- the signal is finished
- the charge on the $i$-th strip = the number of electrons collected by the strip

FAST INDUCTION simulates

Charge = # electrons collected by $i$-th strip
Time = time of arrival of the $e^-$ on the $i$-th strip

Charge vs strip ID @ 45°

Optimum matching

fast induction is $x$ 30 faster than the full!
1. Detector induction $\rightarrow$ simulate the induced $dq$ in 1 ns time steps
2. Pre-amplifier $\rightarrow$ ∀ time step, add $dq$ to the integrated charge
3. Shaper $\rightarrow$ create 27 functions (one for each APV-25 time bin, 25 ns each)

\[
h(t) = S_p \times \frac{t-t_0}{\tau} \exp\left(-\frac{t-t_0}{\tau}\right).
\]

$\rightarrow$ get the induced charge in each 25 ns and apply the transfer function
∀ time bin, evaluate all the previous function @ $t_i$ and sum them up!

Compute noise $\rightarrow$ ∀ time bin, sample from Gaussian ($\mu$, $\sigma$) $\rightarrow$ add to the charge
APV-25 ASIC simulation

The *charge* is the peak value of the signal

The *time* comes from a Fermi-Dirac fit of the rising edge

*as in real signal reconstruction*
Tuning to real data
Tune what to what? ...and why?

comparison to the test beam data collected on April 2018

<table>
<thead>
<tr>
<th>RD51 testbeam</th>
<th>triple-GEM specifics</th>
</tr>
</thead>
<tbody>
<tr>
<td>• GOLIATH dipole magnetic field</td>
<td>• planar triple-GEM, 10 x 10 cm²</td>
</tr>
<tr>
<td>• H4 beam line, SPS-NA (CERN)</td>
<td>• double view readout, APV-25</td>
</tr>
<tr>
<td>• 150 GeV/c muons</td>
<td>• gas: Ar:i-C₄H₁₀ (90:10)</td>
</tr>
</tbody>
</table>

**Settings we kept in the GTS simulation**

- conversion factor : 30 ADC = 1 fC (*)
- threshold : 45 ADC = 1.5 fC
- noise sigma: 15 ADC = 0.5 fC

(*) K. A. Ntekas, CERN-THESIS-2016-019
Tuning to real data

need to check the consistency between simulation and real data, due to:
• various approximations applied
• measured charge >> simulated one → **tuning factor** on gain!

**Scan**
particle incident angle [0°, 40°], B = 0
**Tuning factor on**
Gain, diffusion
**Sentinel variables**
• measured charge
• cluster size
• position resolution (charge centroid)
• position resolution (μ–TPC)

**Procedure**
• for each gain and diffusion values, simulate 7 angles: 0, 5, 10, 15, 20, 30, 40
• for each angle, run 20k muons → statistical error around 1%
• compute $\chi^2 = \chi^2_{\text{charge}} + \chi^2_{\text{cl.size}} + \chi^2_{\text{CCresol.}} + \chi^2_{\mu-\text{TPCresol.}}$
• evaluate $\chi^2/\text{NDF}$
Tuning to real data

Best result $\chi^2/\text{NDF} \sim 3 \iff \text{gain tuning} = 6.8 \iff \text{diffusion tuning} = 1.5$

* (experimental - simulated)/experimental
Conclusions

We would like to hear your opinions to understand if we are on the right path!

Our two main source of doubts:

- **gain evaluation**
  - We obtained a **gain tuning factor = 6.8**
  - GARFIELD GEM gain has a factor ∼2 missing → roughly 8 on a triple-GEM
  → we still have to account for the charge sharing: another x2 factor?
  → other explanations to this tuning factor? Any ideas?

- **weighting field & induction**
  - Used analytic WF for one view + matching between full and fast inductions
  → For our double view, the idea is to just count the electrons falling on the strips (x/v) with a probability (evaluated from data) to account for:
    - charge sharing between the views
    - electric field focusing effect on the strip
    - other? shall we consider the change of drift velocity close to the strips?

- other suggestions about points we did not consider?
Thank you for your attention!

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