Optimal use of charge information for HL-LHC pixel readout

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also known as...

Finding the dots

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are pushing the energy frontier of particle physics

At the heart of each is a **pixel detector**
Pixel Detectors for Particle Detection

Measure deposited charge (from dE/dx)

Readout chip

bump bond

depletion region

Readout chip
electron

electron

MIP

electrode

h^+

not to scale

4
How we measure charge: Time over threshold (ToT)

~80 electron-hole pairs per micron (MIP)

For 50 x 50 x 150 sensor: 12 ke @ |\( \eta \)| = 0 and 4 ke @ |\( \eta \)| → \( \infty \)

ToT is encoded \( 2^N \) bits; e.g. \( N = 4 \) for the ATLAS IBL modules
How have we used charge?

Resolution

Less path length = less charge; can be used to improve residual

Split merged clusters using charge distribution

Particle Identification (PID)

Sensitive to heavy long lived particles beyond the SM
The future: Higher bandwidth, hit rate, radiation damage

GHz/cm²  ~0.1%/pixel/BC
Gbps/cm²  ~streaming live audio from each pixel
1 Grad

RD53 Collaboration is designing a chip to meet these specs
How can we optimize future use of charge?

Parameters

Digitize N bits, store (in buffer) \( M \leq N \) bits.

One unit of ToT = \( f(Q|\alpha) \)

\( Q = \) charge
\( \alpha = \) the tuning

Metrics

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>in-pixel pileup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classification</td>
<td>how many particles deposited charge?</td>
</tr>
<tr>
<td>Resolution</td>
<td>cluster position</td>
</tr>
<tr>
<td>Particle Identification</td>
<td>( \delta )-rays, soft SM particles, long-lived BSM</td>
</tr>
</tbody>
</table>
Example: Linear Conversion (~what is in ATLAS now)

\[ \text{ToT}(Q) = Q \times \frac{\text{ToT}\@\text{MIP}}{Q\@\text{MIP}} \quad \text{MIP} := 80 \text{ e}/\mu\text{m at perp. incidence} \]

\~Will focus on this example for the rest of the talk\~

N.B. linear correlations don’t tell the whole story! Need to check the various use-cases.
Optimizing the use of charge

Tuning should depend on angle! \( \text{charge} \propto \text{path length} \)

- Correlation between \( Q, \text{ToT} \)
- Hit Rate = 4.12 GHz/cm²
- Probability for loss from pileup hit
- Geant4 (Allpix) + Digitization
  - \(| = 1\), radius = 39 mm, \(|\eta| = 1\), N bits = 4

50 X 50 x 150 \( \mu \text{m}^3 \)
radius = 39 mm

(not the best metric, since over-emphasizes the high tail)
Counting longer increases precision but also **in-pixel pileup**

*Could mitigate by counting faster than 40 MHz, but if fixed:*

there is a tradeoff between dynamic range
(charge / ToT + N bits) and efficiency

**N.B. can’t just reduce N bits - still need to discharge overflow!**
Fast (analog) discharge

What if you could ~instantly remove charge when the counter reached $2^N - 1$?

![Graph showing inefficiency before reaching overflow and while in overflow.]

- Geant4 (Allpix) + Digitization
- $50 \times 50 \times 150 \mu m^3$, radius = 39 mm, $l_H = 1$
- ToT bits = 4, threshold = 600 e, small hits included
- Hit Rate = 4.12 GHz/cm$^2$

Inefficiency before reaching overflow
- Inefficiency while in overflow

This contribution doesn’t gain from a fast discharge

\[
\sum_{ToT=2^N-1}^{\infty} \text{Pr}(ToT) \times \text{Pr}(2\text{nd hit at or before ToT BC's})
\]

\[
\sum_{ToT=2^N-1}^{\infty} \text{Pr}(ToT) \times (1 - e^{-ToT \times r})
\]

- Inefficiency before reaching overflow
- Inefficiency while in overflow

- Fast (analog) discharge

- What if you could ~instantly remove charge when the counter reached $2^N - 1$?
Inside dense environments (jets/τ), clusters can merge.

Merged clusters can result in lost tracks and poor track parameter estimation.

It is therefore critical for high p_T physics to be able to split clusters.
Classification

Single pixel classification, using only charge

Separation power

\[ \frac{1}{2} \int dx \frac{(p_1(x) - p_2(x))^2}{p_1(x) + p_2(x)} \]
Classification

Single pixel classification, using only charge

Separation power

\[ \text{Separation power} = \frac{1}{2} \int dx \frac{(p_1(x) - p_2(x))^2}{p_1(x) + p_2(x)} \]
The tendency seems reasonable: improves with number of bits & distance increasing.

The improvements saturates at number of bits \(= 4 \sim 5\).

Large number of bits: True positive \(\approx 1\).

Number of bits > 1: larger has a better result – more information in the track.

Number of bits = 1: binary case. No clear distribution of ToT in pixels – the result is hard to say.

**NN-based splitting based on charge and cluster shape**

\[ \Pr(\text{split a 2-particle cluster}) \]

\[ \Pr(\text{split 1 particle cluster} = 10\%) \]

\[ \eta = 0 \]

\[ \eta = 1 \]

\[ \eta = 2 \]

**Classification NN input:**

- sum of ToT
- clustersize
- clustersize_x
- clustersize_y

**Pr(split a 2-particle cluster)**

**Identify merged clusters**

**Classification NN input:**

- sum of ToT
- clustersize
- clustersize_x
- clustersize_y

**Keep false positive:**

- Compare true positive

\[ \frac{\text{Prob particle particle}}{2} \]
Resolution: one-particle clusters

one-particle @ a cluster has 4 parameters: x, y, θ, φ

θ is determined by the cluster length; θ and y resolution set by how well we can resolve the two ends:

\[ y_{\text{cluster}} = \frac{1}{2}(y_{\text{head}} + y_{\text{tail}}) \rightarrow \sigma_{y_{\text{cluster}}} = \sigma_{y_{\text{head}}} / \sqrt{2} \]

\[ L_{\text{cluster}} = y_{\text{head}} - y_{\text{tail}} \rightarrow \sigma_{L_{\text{cluster}}} = \sqrt{2}\sigma_{y_{\text{head}}} \]
Resolution: one-particle clusters

Geant4 (Allpix) + Digitization (δ-ray veto), ToT bits = ∞, threshold = 600e
50 X 50 x 150 μm³, radius = 39 mm, lη| = 1

ToT = 0  ToT > 0

First pixel below threshold

ToT > 0  ToT > 0

Diffusion to second pixel

Optimal resolution:

\[ \min_f (f(y) - y)^2 \]

\[ \implies f(y) = \langle y|Q \rangle \]

Near the MIP, not much sensitivity

Ideally: as much low charge as possible!
Resolution: one-particle clusters

Optimal resolution:

$$\min_f (f(y) - y)^2$$

$$\implies f(y) = \langle y | Q \rangle$$

Near the MIP, not much sensitivity

Ideally: as much low charge as possible!
Resolution: one-particle clusters

For a fixed number of bits, prefer higher ToT @ MIP

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<td>2</td>
<td>0.19</td>
</tr>
<tr>
<td>3</td>
<td>0.16</td>
</tr>
<tr>
<td>4</td>
<td>0.15</td>
</tr>
<tr>
<td>5</td>
<td>0.14</td>
</tr>
<tr>
<td>infty</td>
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</tr>
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(for path-length corrected MIP)

Ceiling: $1/\sqrt{12} \approx 0.29$

Overflow-dominated

$\sim 7 \mu m$ at min.
Resolution: one-particle clusters

For a fixed number of bits, prefer higher ToT @ MIP

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(for path-length corrected MIP)

ceiling: $1/\sqrt{12} \sim 0.29$
Resolution: two-particle clusters

Worse than single clusters; saturates at ~3-4 bits

X-residual of a second particle

NN-based regression using charge map

Residual Standard Deviation / µm

Number of ToT bits

η = 0
η = 1
η = 2

2017/1/30 Fuyue Wang
Identifying $\delta$-rays can improve resolution

Classifying $\pi, p, k$ is interesting at low $p_T$

Searching for R-hadrons or other long-lived particles is a major ongoing search effort

As such, need to ensure we preserve sensitivity with our choice of N bits.

May even improve sensitivity with e.g. exponential charge to ToT scheme.
Can add digital logic so that N digitized bits are stored as $M \leq N$ bits.

There are \( \binom{2^N}{2^M} \) possible functions mapping N to M bits.

No surprise - the optimal maps for resolution concentrate at low ToT.
The usual paradigm is one ToT counter per pixel.

Can we save space by using one counter for two pixels?

Consider a scheme in which the sum is counted with 5 bits.
(N.B. this gives us a 1/2 bc time resolution)

In terms of ToT bits per area, this is better than the 4 bits for the ATLAS IBL and with less digital structure.
(N.B. can’t separately tune 4 and 5 bit parts)
More on the theme: neighboring pixels

ATLAS currently reads out 2 x 2 regions around hit pixels

- helps recover low charge hits

**Is this still optimal with smaller pixels?**

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**Mean Cluster Size**

- **Longitudinal**
- **Transverse**

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**IBL geometry, 8 GeV**

50 x 250 µm

(ATLAS IBL)

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50 X 50 µm² @ 3.3 cm, 8 GeV

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**Geant4 (Allpix) + Digitization (Truth) + Clustering (CCA)**
How to group hits for storage and readout

The neighbor occupancy is well above background: useful input for the hybrid ToT from earlier

does not approach unity due to non-long clusters

\( i_x = \) pixel index in x direction

\[ \begin{align*}
   \Delta & P(i_\phi, i_\eta+1 \mid i_\phi, i_\eta) \\
   \square & P(i_\phi, i_\eta+2 \mid i_\phi, i_\eta) \\
   \nabla & P(i_\phi, i_\eta+3 \mid i_\phi, i_\eta) \\
   \Delta & P(i_\phi+1, i_\eta \mid i_\phi, i_\eta) \\
   \square & P(i_\phi+2, i_\eta \mid i_\phi, i_\eta) \\
   \nabla & P(i_\phi+3, i_\eta \mid i_\phi, i_\eta)
\end{align*} \]
How to group hits for storage and readout

A simplified analysis (not full physics sim)

2 x 2 fine for Run 1

4 x 1 likely (much) better for HL-LHC (maybe even bigger?)
Conclusions / outlook

Preliminary studies suggest that **4-5 bits** is likely sufficient to maintain performance at the HL-LHC

*Several studies still on-going*

RD53A is currently under design, but we will iterate more; now is the time to ensure an **optimal use of charge** for the HL-LHC!
Gbps /cm^2 * 50 microns * 50 microns in kbps

=25 kbps

http://www.shoutcheap.com/mono-vs-stereo/