Tracking Detectors for the LHC Upgrade

- Layout
- Signal
- Noise

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Upgraded in 3 main Phases:

- Phase 0 – maximum performance without hardware changes
  Only IP1/IP5, $N_b$ to beam beam limit $\rightarrow L = 2.3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Phase 1 – maximum performance while keeping LHC arcs unchanged
  Luminosity upgrade ($\beta^*=0.25\text{m}, \# \text{ bunches},..$) $\rightarrow L = 5 - 10 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Phase 2 – maximum performance with major hardware changes to the LHC
  Energy (luminosity) upgrade $\rightarrow E_{\text{beam}} = 12.5 \text{ TeV}$ NOT cheap!
The sLHC as a necessity!

In 2015, the inner parts of the LHC detectors will have seen 8 years of beams and need to be replaced mainly because of radiation damage.

The LHC discovery potential has an even shorter time span:

The relative statistical errors on measurements are given by $1/\sqrt{N}$, i.e $1/\sqrt{\int L dt}$

A good measure of the discovery potential is the time to half the statistical error

At the LHC in 2012, after two years at full luminosity, the time to halve the errors is 8 years! Jim Strait (US LARP)

For the sLHC this might occur in 2018, when the collider just reached the full luminosity!

Thus, the time of largest discovery potential is the few years after the accelerator has reached full luminosity.

Until that time, at about 50% - 80% of the final integrated luminosity, the detector should have preserved its peak performance.
Discovery Potential of sLHC

LHC --> sLHC Luminosity Scenario

Schedule of Upgrades

Machine:
Convert LHC ’13 – ’14

Detectors:
Need to start ‘04
R&D ‘04 - ‘09
Construction ’10 - ’13
Installation ’14

Are we too late already??
### Expected Detector Environment

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>sLHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ [TeV]</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Luminosity [cm$^{-2}$s$^{-1}$]</td>
<td>$10^{34}$</td>
<td>$10^{35}$</td>
</tr>
<tr>
<td>Bunch spacing $\Delta t$ [ns]</td>
<td>25</td>
<td>12.5/25</td>
</tr>
<tr>
<td>$\sigma_{pp}$ (inelastic) [mb]</td>
<td>$\sim 80$</td>
<td>$\sim 80$</td>
</tr>
<tr>
<td># interactions/x-ing</td>
<td>$\sim 20$</td>
<td>$\sim 100/200$</td>
</tr>
<tr>
<td>$dN_{ch}/d\eta$ per x-ing</td>
<td>$\sim 150$</td>
<td>$\sim 750/1500$</td>
</tr>
<tr>
<td>$&lt;E_T&gt;$ charg. Part. [MeV]</td>
<td>$\sim 450$</td>
<td>$\sim 450$</td>
</tr>
<tr>
<td>Tracker occupancy</td>
<td>1</td>
<td>5/10</td>
</tr>
<tr>
<td>Dose central region</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>LAr Pileup Noise [MeV]</td>
<td>300</td>
<td>950</td>
</tr>
<tr>
<td>$\mu$ Counting Rate [kHz]</td>
<td>1</td>
<td>10</td>
</tr>
</tbody>
</table>

* Normalized to LHC values: $10^4$ Gy/year $R=25$ cm

Problems are daunting → Have a Workshop!

Goals for ATLAS (CMS) Upgrade @ $10^{35}$

- **Detector Performance**
  - Strive to have same detector performance @ $10^{35}$ as will be achieved @ $10^{34,33}$
    - Energy stays the same
    - Needed for rare modes such as $H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$, $Z_L - Z_L$
    - Physics emphasis may narrow to study of massive objects produced centrally decaying
    - Some compromises may be necessary, e.g. less coverage at high $|\eta|$

- **Detector Reliability**
  - Strive to have detector elements and electronics sufficiently rad-hard as to be able to run for long periods @ $10^{35}$ (~1,000 fb$^{-1}$/yr)
    - Assume that replacement of components on ~ one year time scale would be unacceptable

- **Upgrade R&D Program to be mindful of these goals**
  - Detailed simulation of radiation environment @ $10^{35}$ : scaling possible?

- **For ATLAS, upgrade of Inner Detector (Tracker) is highest priority**
  - No subsystem is entirely in the clear - extending operation to $10^{35}$ will pose problem
ATLAS ID Upgrade

ATLAS Upgrade Steering Group

US-ATLAS Upgrade Program:
- Strip Electronics (SiGe)
- Module Integration
- Short strips (p-type and 2D)
- 3D detectors
- Pixel electronics

Replace entire ID (200m²)
- Keep Modularity
  -> (Pixels, Barrel, 2 endcaps)
- Catch up with CMS:
  -> replace gaseous TRT detectors
- Find Rad-hard Sensors
- Optimize Sensor Geometry
- Increase Multiplexing

The layout of the CMS inner tracker

Hartmut Sadrozinski “Tracking Detectors for the sLHC”

5th RESMD Florence Oct 2004
sATLAS Tracker Regions

**Integrated Luminosity**
(radiation damage) dictates the detector technology

**Instantaneous rate**
(particle flux) dictates the detector geometry

**Straw-man layout** (Abe Seiden):

- **Inner**: $6 \text{ cm} \leq r \leq 12 \text{ cm}$
  - 3 layers pixel pixels style readout

- **Middle**: $20 \text{ cm} \leq r \leq 55 \text{ cm}$
  - 4 layers short strips space points

- **Outer**: $55 \text{ cm} \leq r \leq 1 \text{ m}$
  - 4 layers “long strips” single coordinate

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Fluence for 2,500 fb$^{-1}$

- Inner Pixel
- Mid-Radius Short Strips
- Outer-Radius “SCT”
Pile-up, Occupancy

**The 10x higher luminosity increases the rate of min.bias events**

For $10^{34}$, occupancies and cluster merging are less severe ($x2$) in pile up events than in B jets from Higgs decay. At $10^{35}$ the situation is reversed by $\sim x 5$.

**Solution:**

Adjust geometry of detectors to radius, can scale from SCT:
Reduce detector length from 12 cm to 3 cm, at twice the radius $\rightarrow$ factor 16 less occupancy.
OR use 6 cm long detectors at twice the radius with 12.5 ns bucket timing.

**A major constraint on the tracker is the existing ATLAS detector**

- Implies a maximum radius of about 1 m and a 2 Tesla magnetic field.
- Gap for services is a major constraint.
- Limited Granularity?
  (Outer silicon layers require more services than the TRT!)
  Space available does not allow for the increase due to granularity.
Region of Outer-Radius $r > 55$ cm

No SSD problems are expected for the outer region – if the detectors work at the LHC!

But the limited space in the outer region ($r > 50$ cm) will require careful tradeoff decisions between detector length, F.E. power, noise and amount of multiplexing and granularity.

Present SCT Module used between 30 and 57 cm

Future ATLAS sID “Stave”?
(a la CMS and CDF)
between 20cm and 1m
Allows testing of large Sub-Assembly
Material Reduction Challenge: FEE Problem!

ATLAS
Many Modules = Many Servives

CMS ALL Si TKR:
10% Active detector
10% Support
80% “Electronics”

Increased Multiplexing required

(Sandro Marchioro LECC 2003)
Region of Mid-Radius $20 \text{ cm} < r < 55 \text{ cm}$

Scaling of the SCT rates allow a readout region of about $80 \mu m \times 1 \text{ cm}$

but this is too coarse a $z$–measurement.

Options:

(1) **Short-strips (long-pixels) with dimension of order $80 \mu m \times 2 \text{ mm.}$**

   Requires very many channels (power).

(2) **Longer detector dimensions (3 cm length), coupled with faster electronics.**

   With improve rise-time by a factor two (assuming machine crossing frequency is doubled) get a factor of 4 due to detector length and a factor of 2 due to electronics wrt present SCT, compensating for higher luminosity.

**Small-angle stereo arrangement similar to present SCT:**

Confusion area in matching hits in the back-to-back stereo arranged detectors is proportional to the detector length squared.

Compared to the present SCT, confusion would be reduced by factor of 16 due to reduced length and factor of 2 due to faster electronics, I.e. improvement wrt present ATLAS.
Sensors for Mid-Radius Region $20 \text{ cm} < r < 55 \text{ cm}$

**Short Strips ~ 3 cm long**
- 2 sets on one detector with hybrid straddling the center a la SCT

**Single-sided**
- $\sigma_z \approx 1 \text{ cm}$

**Back-to-back single-sided stereo**
- $\sigma_z \approx 1 \text{ mm}$

**Explore availability of p-type substrates (RD50)**
- No type inversion
- Collect electrons
- Partial depletion operation (increased headroom)
2D Interleaved Stripixel Detector (ISD)

Advantage:
2d from single layer, Single-sided processing

Disadvantage:
½ signal (charge sharing), 2-3 (?) times higher capacitance
Detailed Pixel System Layout
(including power & price tag)
Roland Horisberger

Summary
- Propose 3 Pixel Systems that are adapted to fluence/rate and cost levels
- Pixel #1 max. fluence system ~400 SFr/cm²
- Pixel #2 large pixel system ~100 SFr/cm²
- Pixel #3 large area system Macro-pixel ~40 SFr/cm²
- 8 Layer pixel system can eventually deal with 1200 tracks per unit pseudo-rapidity
- Use cost control and cheap design considerations from very beginning.
- Can this be done for 2012/13 ????

CMS: Inside out “Fat” pixels, strips
ATLAS Outside in “Skinny” strips, pixels

Hartmut Sadrozinski “Tracking Detectors for the sLHC” 5th RESMD Florence Oct 2004 15
Signal : Performance Targets

sLHC Tracker has 3 radial regions with 10x fluence increase

“move LHC systems outward”

Based on present performance, (i.e. without drastic improvement of electronics), guess at a specification of the collected charge needed in the 3 regions:

<table>
<thead>
<tr>
<th>Radius [cm]</th>
<th>Fluence [cm²]</th>
<th>Specification for Collected Signal (CCE in 300 um)</th>
<th>Limitation due to:</th>
<th>Detector Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 55</td>
<td>$10^{14}$</td>
<td>20 ke- (~100%)</td>
<td>Leakage Current</td>
<td>“present” LHC SCT Technology, Consider: n-on-p</td>
</tr>
<tr>
<td>20 - 55</td>
<td>$10^{15}$</td>
<td>10 ke- (~50%)</td>
<td>Depletion Voltage</td>
<td>“present” LHC Pixel Technology ? Consider: n-on-p</td>
</tr>
<tr>
<td>&lt; 20</td>
<td>$10^{16}$</td>
<td>5 ke- (~20%)</td>
<td>Trapping Time</td>
<td>RD50 - RD39 - RD42 Technology 3-D!</td>
</tr>
</tbody>
</table>
Signal: Trapping

Charge trapping in Si SSD:

Collected Charge $Q = Q_o \cdot \varepsilon_{\text{depletion}} \cdot \varepsilon_{\text{trapping}}$

$\varepsilon_{\text{depletion}}$ depends on $V_{\text{bias}}$, $V_{\text{dep}}$ -> effective detector thickness $w$

$\varepsilon_{\text{trapping}} = \exp(-\tau_c / \tau_t)$,

$\tau_c$: Collection time, $\tau_t$: Trapping time

Trapping time is reduced with radiation damage:
(RD50, Krasel et al. for electrons/holes, measured up to $10^{15}$ cm$^{-2}$ in n-type

$1/ \tau_t = 5\cdot(\Phi/10^{16})$ ns$^{-1}$ )

Trapping time $\tau_t \sim 1/ \Phi$ (but collection time saturates at high fields!)

$\tau_t = 1.8$ ns for $\Phi = 1.1\cdot10^{15}$ cm$^{-2}$

$\tau_t = 0.2$ ns for $\Phi = 1.0\cdot10^{16}$ cm$^{-2}$

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Charged Trapping in Si: the Good News

Efficiency of Charge Collection in 280 um thick p-type SSD
G. Casse et al., (RD50): After $7.5 \times 10^{15}$ p/cm$^2$, charge collected is $> 6,500$ e$^-$

Charge collection in Planar Silicon Detectors might be sufficient for all but inner-most Pixel layer?
For 3-D after $1 \times 10^{16}$ n/cm$^2$, predicted charge collected is 11,000 e$^-$
Charge collection in P-type SSD

Trapping times 1.8 x larger than extrapolated from previous measurements.
Difference p-type vs. n-type?
Signal of ATLAS pixel beam test data

T. Lari (previous analysis by T. Rohe et al.)

For fluence of $1.1 \times 10^{15}$ n/cm$^2$, $\tau_t = 3.5$ ns (i.e. 2x measurement of Krasel et al.)
3-d Detectors

Differ from conventional planar technology, p+ and n+ electrodes are diffused in small holes along the detector thickness (“3-d” processing). Depletion develops laterally (can be 50 to 100 µm): not sensitive to thickness.

De-couple depletion / collection
from charge generation:
Generated charge ~ thickness
Collected charge ~ electrode distance

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Evaluation of collected charge

Trapping is the great equalizer

Lari et al

Redo at higher Bias Voltage?

Estimate for 3D

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Detector Materials for Pixels for $R \approx 6$ cm

<table>
<thead>
<tr>
<th>Material</th>
<th>Collected Signal After $10^{16} \text{cm}^{-2}$</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>RT</td>
<td>$\sim 2.5 \text{ ke}^{-}$</td>
</tr>
<tr>
<td>Si -Epi</td>
<td>RT</td>
<td>$\sim 2 \text{ ke}^{-}$</td>
</tr>
<tr>
<td>Si</td>
<td>Cryo</td>
<td>?</td>
</tr>
<tr>
<td>Si</td>
<td>3-D</td>
<td>$\sim 11 \text{ ke}^{-}$</td>
</tr>
<tr>
<td>SiC</td>
<td>Epi</td>
<td>$&lt; 2 \text{ ke}^{-}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diamond</td>
<td>Poly</td>
<td>$&lt; 3 \text{ ke}^{-}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diamond</td>
<td>Single</td>
<td>“Same as Poly?”</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Signal-to-noise ratio S/N is essential for performance of the tracking system.

**RMS noise** $\sigma$ [electrons]  
depends on shaping time and size (i.e., C, i) of the detector channel

**Threshold Thr**  
set to suppress false hits $\text{Thr} = n^* \sigma + \text{threshold dispersion}$

SCT: $\sigma \approx 600 + C^* 40 \approx 1500e$,   \[ n = 4, \quad \text{-->} \quad \text{Thr} \approx 6,000e \]

Pixels: $\sigma = 450e$,   \[ n = 5, \quad \text{-->} \quad \text{Thr} \approx 2,500e \]

threshold dispersion = 300

Since single-bucket timing is needed, use short shaping times $\tau_R = 15\text{ns}$.
yet there is still a problem with time walk: signal is in time  
only if it exceeds the threshold by large amount ("overdrive")

"In-time threshold" = physical threshold + overdrive $\approx 2^* \text{physical threshold}$

Average signal must exceed the "In-time threshold"
Time walk for fast shaping

- Time walk performance (relative to 100Ke) with Cfb=5fF for CDet from 0f

![Graph showing time walk vs threshold](image)

- Overdrive for Cfb=5fF and CDet=200fF predicted to be only 1500e for 2f time walk. For CDet=400fF, this deteriorates to 2500e.

Einsweiler et al

- Time walk < 20 ns
  = 2.5 ke overdrive
  -> in-time threshold = 5ke

T. Lani prediction:
In-time Threshold required $\approx 0.5*Q$
Optimistic: assumes smaller pixels

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Required Frontend Noise

Assume:
In-time Threshold $\approx \frac{1}{2} \times \text{Signal}$
$\sigma \approx \frac{(\text{In-time threshold} - \text{overdrive})}{5}$
$\sigma \approx 0.1 \times \text{(In-time threshold)}$

Required noise figure for Planar Detectors:

$\sigma = 1500 \text{ e} \text{ for } 1 \times 10^{15} \text{ (sLHC outside 20 cm) “easy” for short strips?}$

$\sigma = 500 \text{ e} \text{ for } 2 \times 10^{15} \text{ (present ATLAS/CMS pixel)}$

$\sigma = 100 \text{ e} \text{ for } 1 \times 10^{16} \text{ (+ very little dispersion)}$
very tall order for hybrid pixels!
(smaller pixels still have finite inter-pixel capacitances)
### F.E.E. Technologies for sLHC:

<table>
<thead>
<tr>
<th>Technology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sub-µ CMOS</strong></td>
<td>“accidentally” rad-hard, low power, used for pixels, CMS, also in sCMS</td>
</tr>
<tr>
<td><strong>Bipolar BiCMOS</strong></td>
<td>power-noise advantages for large capacitances and fast shaping, also excellent matching technologies used in ATLAS SCT are not sufficiently rad-hard beyond the LHC because of current gain $\beta$ degrading from about 100 to about 40 at $10^{14}\text{cm}^{-2}$, limited availability</td>
</tr>
<tr>
<td><strong>SiGe BiCMOS</strong></td>
<td>very fast ($f_T &gt; 50\text{GHz}$ and $\beta &gt; 200$), used in cell phones, backend: DSM CMOS “du jour”, available IBM–MOSIS rad hardness has been measured to $10^{14}\text{cm}$ we have now test structures in the CERN beam!</td>
</tr>
<tr>
<td><strong>SiGe for sLHC?</strong></td>
<td>Expect that largest area of sLHC tracker will be made of strips, so SiGe could give an advantage, specially for short shaping times (noise, overdrive). (Power (SiGe) &lt; Power (0.25 µm CMOS) for “long” strips).</td>
</tr>
</tbody>
</table>
Single-Bucket Timing

Pulse rise time depends on both charge collection and shaping time. If rise time falls within the clock cycle, single-bunch timing is possible.

Decrease collection time with increased bias voltage.

<table>
<thead>
<tr>
<th>p-on-n</th>
<th>Collection Time [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100V</td>
</tr>
<tr>
<td>Holes</td>
<td>14</td>
</tr>
<tr>
<td>Electrons</td>
<td>5</td>
</tr>
</tbody>
</table>

Pulse rise time depends on both charge collection and shaping time. If rise time falls within the clock cycle, single-bunch timing is possible.

ATLAS SCT: Bias = 100V, Shaping 20ns
sATLAS ID: Bias = 300V, Shaping 10ns

With 20ns shaping and 100V bias, do single-bunch timing at LHC (25ns).
With 10ns shaping and 300V bias, the entire rise of the pulse is within 12 ns:
80MHz single-bunch timing is possible for sLHC, reducing occupancy by 1/2.
Summary

The LHC luminosity upgrade to $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ (sLHC)
- allows to extend the LHC discovery mass/scale range by 25-30%
- extends the LHC program in a efficient way into 2020

sLHC looks like giving a good physics return for modest cost
⇒ Get the maximum out of the (by then) existing machine
“Big Bang for the Buck” “No-brainer”

The sLHC will be a challenge for the experiments:
Detector R&D has started now to upgrade the Inner Tracker to all Si
in order to be ready to “go” soon after 2013/2014

Layout is driven by particle flux (→ short strips!) which counters the
need to increase multiplexing
Expectation is that detector technology is close (in hand?) for all but the
inner-most pixel layers.
Electronics will face major challenges: S/N, Power, Services