ATLAS HGTID upgrade and LGAD detectors

Simone M. Mazza
HGTD: 7 countries - 22 Institutes

Countries that expressed some interest to contribute to the HGTD construction (** institute with individual members up to now and no formal EoI)

- **CERN**
- **France (3):**
  - LAL/Orsay
  - LPNHE/Paris
  - Omega/Paris
- **Germany (2):**
  - Justus-Liebig-Univ., Giessen (**)
  - Johannes-Gutenberg-Univ. of Mainz
- **Slovenia (1):**
  - IJS/Ljubljana
- **Spain (2):**
  - CNM-IMB-CSIC/Barcelona
  - IFAE/Barcelona

- **Sweden (1):**
  - KTH Royal Institute of Technology/Stockholm
- **Taiwan (1):**
  - Academia Sinica/Taipei
- **United States (10):**
  - ANL/Argonne
  - SMU/Dallas
  - BNL/Upton
  - Ohio State Univ. /Ohio
  - Univ. of California Santa Cruz/Santa Cruz
  - Univ. of Iowa/Iowa City
  - Univ. of Oregon/Eugene (**)
  - Univ. of Pennsylvania/Philadelphia
  - State Univ. of New York at Stony Brook/NY
  - SLAC/Stanford

Discussion ongoing with a new Institute (new country)

Discussion started about possible CORE contributions (information from 6/7 countries)
HGTD motivation

- HL-LHC pile-up will be higher (4-5 times) than run-II
  - Beam profile $\sigma_z = 50$ mm, $\sigma_t = 180$ ps
  - The pileup density is comparable or larger than the longitudinal impact parameter resolution of the ITK above $\eta > 2.5$

- A new layer (HGDT) of silicon detectors with precise timing measurement is necessary to maintain/improve performance at high pseudo-rapidity
  - Improves track-to vertex association, b tagging, lepton isolation, jet/E$_{\text{miss}}$
  - Reduce the pileup contamination in tracks and vertexes
  - Improved luminosity measurement
  - Act as new minimum bias trigger
Timing resolution and tracking

- High timing resolution can improve both tracking algorithm and vertexing algorithm

\[ \frac{t_0 - t_{\text{vtx}}}{\sigma_{t_0}} < 2 \]

Pile-up jet misidentified as hard-scatter jet

Simone Michele Mazza

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HGDT timing resolution + ITk spatial resolution will reduce pile-up track and vertex contamination in HL-LHC conditions.
HGTD position and layout

EMEC

Replace current MBS

HGTD
HGTDT position and layout

2.4 < \eta < 4.2
\Delta Z = 75 \text{ mm} (+50 \text{ mm moderator})
4 (or 2+1) Si (LGAD) layers
1.3 \times 1.3 \text{ mm}^2 \text{ granularity}
\sigma_t = 30 \text{ ps} (< 60 \text{ ps/mip/layer})
Physics performance

- Improved track to vertex association
  - Affects jets, lepton isolation, missing transverse energy…
- Provide an accurate estimate of the bunch-by-bunch luminosity
- New minimum bias trigger

- Reduction of missing transverse energy tails
- 10-20% higher lepton isolation efficiency
Physics performance - jets

- HGTD improves jet performance in forward region (eta>2.4)
- Improved efficiency for hard-scatter jets
- Improved Pile-up jet rejection in the Jet vertex fraction algorithm
- Improved light jet rejection for b-jets
Physics potential

Enhance the physics potential of ATLAS

- Better PU jet rejection $\rightarrow$ VBF/VBS final states with activity in the forward region
- Improved b-tagging $\rightarrow$ Final states with forward b-jets
- Improved lepton isolation $\rightarrow$ Standard Model measurements that require forward leptons (weak mixing angle)
- Vertices with timing $\rightarrow$ Long lived particles at high pseudorapidity
- Improved luminosity $\rightarrow$ overall improvement in physics potential

Main cases

- VBF final states, exploiting improved forward pile-up suppression
- Searches and measurements with forward b-quarks, exploiting improved b-tagging
- $VBF H \rightarrow \tau\tau$
- $VBF H \rightarrow WW \rightarrow l\nu l\nu$
- $\Delta\mu$ 5% improvement
- $t(H \rightarrow gg)$
- $t(H \rightarrow bb)$
- $\sigma$ 10% improvement

To be studied, work in progress

- Searches and measurements with forward leptons, exploiting improved lepton efficiency
- Long lived slow particles, exploiting time measurements
- $\sin^2\theta_W$
HGTD sensor - LGADs

- HGTD Sensor requirements
  - time resolution <60 ps/layer
  - Radiation hardness to 4.5e15 neq/cm²
  - Segmentation of 1.3x1.3 mm² (<10% occupancy)

- HGTD Sensor Baseline: Low Gain Avalanche Detectors (LGADS)
  - Gain around 10 from multiplication layer
    - Better signal to noise ratio → improved timing
  - Thinner detectors have shorter rise time and less Landau fluctuations
    - At least 50 μm and testing down to 30 μm

- 3 vendors of thin LGADs
  - CNM (Spain), HPK (Japan), FBK (Italy)
LGADs timing measurement

\[ \sigma_t = \sigma_{\text{TimeWalk}} + \sigma_{\text{LandauNoise}} + \sigma_{\text{Distortion}} + \sigma_{\text{jitter}} + \sigma_{\text{TDC}} \]

\[ \sigma_{\text{TimeWalk}} = \left[ \frac{V_{th}}{S/t_{\text{rise}}} \right]_{\text{RMS}} \propto \left[ \frac{N}{dV/dt} \right]_{\text{RMS}}, \quad \sigma_{\text{jitter}} = \frac{N}{dV/dt} \approx \frac{t_{\text{rise}}}{S/N} \]

- Maximize slope \( dV/dt \) (i.e. large and fast signals)
- Signal \( \sim \) gain, expect jitter \( \sim 1/G \)
- Minimize noise \( N \)
- Time walk is corrected by using constant-fraction discriminator CFD
Detector testing at SCIPP

- Laboratory electrical testing (IV, CV): Verify LGAD performance, breakdown voltage, doping level, test yield
- Laboratory dynamic testing (β-telescope, laser): Signal shape, noise, charge, gain, time resolution, uniformity
- Understand the radiation damage: run the same tests non-irradiated and irradiated sensor
- Test beam at CERN, Fermilab and SLAC (in the future)

Time resolution vs gain:
- Left: CNM detectors tested with test beam (single-pad sensors ("S") and arrays ("A") of medium ("M") and high ("H") doping)
- Right: HPK detectors tested with β-source (different temperatures)
Irradiated sensors

- Irradiation of sensor from CNM, HPK and FBK
  - Increased bias voltage after irradiation
  - Decrease of gain (at same voltage)
  - But decrease of rise time
- Loss of gain (acceptor removal process) recovered by increasing Vbias

- Several radiation fluence:
  - $1\times10^{14} \rightarrow 6\times10^{15}$ n/cm$^2$
  - Studies ongoing on the effect on time resolution: for now $20 \rightarrow 50$ ps
Conclusions

- HGTD is going forward as scheduled
  - Official start for sensor R&D 2018
- UCSC SCIPP group is giving a significant contribute with LGAD detectors R&D

Expression of Interest ready:
- A High-Granularity Timing Detector for ATLAS Phase-2 Upgrade
- Internal only: https://cds.cern.ch/record/2290829/
Backup
LGADs structure

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Wafer size [inch]</th>
<th>Substrate</th>
<th>Thickness [μm]</th>
<th>Sensor types</th>
<th>Size [mm]</th>
<th>Technology enhancement</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNM</td>
<td>4” (2017 6”)</td>
<td>Epi, SoI, Si-Si-bond</td>
<td>300, 75, 45</td>
<td>Single pads, 2x2 up to 8x8 array</td>
<td>1, 2, 3</td>
<td>B-&gt;Ga substitution C implantation</td>
</tr>
<tr>
<td>FBK</td>
<td>6”</td>
<td>Si-Si-bond</td>
<td>300, 50</td>
<td>Single pads, many arrays</td>
<td>1, 2, 3</td>
<td>B-&gt;Ga substitution C implantation</td>
</tr>
<tr>
<td>HPK</td>
<td>6”</td>
<td>Si-Si-bond</td>
<td>80, 50, 30</td>
<td>Single pads, 2x2 arrays</td>
<td>1, 3</td>
<td>&lt;50 μm thick</td>
</tr>
</tbody>
</table>
LGADs structure

- Several layouts/vendors under test:
  - Single pads
  - 2x2 arrays
  - 8x8 arrays
  - AC coupled LGADS
  - AC coupled array of strips and pixels
Simulation with WF2

WF2

\[ V = 160 \text{ V} \]
Non irradiated, Gain \( \sim 10 \)

\[ V = 600 \text{ V} \]
Irradiation: \( 6e14 \) \( n_e/cm^2 \), Gain \( \sim 10 \)

\[ V = 750 \text{ V} \]
Irradiation: \( 2e15 \) \( n_e/cm^2 \), Gain \( \sim 10 \)

Data

Sr Run40 HPK 50D GBGR1 -20C

Sr Run58 HPK 50D GR 6e14neq -20C

Sr Run69 HPK 50D 6e15neq -20C
SCIPP LGAD RnD

- Laboratory electrical testing (IV, CV)
  - Verify LGAD performance, breakdown voltage, doping level, test yield
- Laboratory dynamic testing ($\beta$-telescope, laser)
  - Signal shape, noise, charge, gain, time resolution, uniformity
- Test non-irradiated and irradiated sensor
iLGAD detectors

- Segmentation of gain layer needs a junction termination extension because of the high field in the edge
  - Limits the fill factor of pixels/strips
- iLGAD: 2-sided, gain layer on the other side from the pixels
  - TCT tests on iLGAD at SCIPP
  - Unfortunately the detector/board connection breaks easily
AC-LGAD detectors

- AC-LGAD: 1 sided, N+ implant and oxide layer. No segmentation of gain layer. Contacts AC coupled to signal
  - Several studies on-going at SCIPP on AC detectors
  - Problems with detector break down at low voltage (25 V) but TCT measures shows an AC signal in strips/pixels
<table>
<thead>
<tr>
<th>HGTD position and layout</th>
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<table>
<thead>
<tr>
<th>Description</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pseudorapidity coverage</td>
<td>2.4 &lt;</td>
</tr>
<tr>
<td>Position in z</td>
<td>3420 &lt; z &lt; 3545 mm including 50 mm of moderator</td>
</tr>
<tr>
<td>Position of active layers</td>
<td>3435 &lt; z &lt; 3485 mm</td>
</tr>
<tr>
<td>Radial extension (active area)</td>
<td>110–1100 mm (120 mm–640 mm)</td>
</tr>
<tr>
<td>Number of layers</td>
<td>4 per side</td>
</tr>
<tr>
<td>Time resolution</td>
<td>30 ps / mip (&lt; 60 ps / mip / layer)</td>
</tr>
<tr>
<td>Sensor size</td>
<td>1.3 × 1.3 mm²</td>
</tr>
<tr>
<td>Number of channels</td>
<td>6.3M</td>
</tr>
<tr>
<td>Number of Si modules (2 × 4 cm² each)</td>
<td>13952</td>
</tr>
<tr>
<td>Number of ASICs (2 × 2 cm² each)</td>
<td>27904</td>
</tr>
<tr>
<td>Total active area (Si sensors)</td>
<td>11.16 m²</td>
</tr>
</tbody>
</table>
Figure 17: Evolution of the acceptor density in the bulk (blue) and in the multiplication layer (red) as a function of fluence, measured on HPK 50D sensors and predicted from Ref [1].

Figure 16: Doping profile for four fluences. The curves are based on fits to the $1/C^2$ vs. bias plots.