High Luminosity LHC

- **High Luminosity LHC: 2026 and beyond**
  - Instantaneous luminosities up to $L \approx 7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (currently $\sim 2 \times 10^{34}$)
  - Pile-up $\langle \mu \rangle = 200$ interactions per bunch crossing (currently $\sim 34$)

- **Resolution in longitudinal direction ($z$) reduced in forward regions**
  - Physics and object performance reduced as a result
  - Ambiguities in track-to-vertex information
  - Pile-up density $> z_0$ resolution

- **Add timing information to improve track-to-vertex association**
HGTGD

- Active area coverage: $2.4 < |\eta| < 4.0$
- Number of hits per track:
  - 2: $2.4 < |\eta| < 3.1$
  - 3: $3.1 < |\eta| < 4.0$
- Pad size: 1.3 x 1.3 mm$^2$
  - Keep occupancy low

- Radiation damage is a main concern:
  - $R < 32$ cm: $3.7 \times 10^{15}$ n$_{eq}$/cm$^2$ and 4.1 MGy (with safety factors)
  - **Replacement at 1/2 lifetime** (~ 30 % of ASICs and sensors)

- Sensors will be operated at -30 C to mitigate impact

- **LGADs of 50 $\mu$m thickness**
  - Thin: faster rise time, less impact from radiation
Global view of HGT

- Detector to be installed on each of two calorimeter extended barrels.
- Two instrumented double sided layers (mounted in 2 cooling disks).
- Overlap between modules on inner and outer ring.

- Doubled sided Silicon layers Front & Back disks
- Peripheral Electronics
- Front cover
- Back cover
- Inner ring
- Outer ring
- CO2 cooling manifolds
- EC LARG Cryostat
- Moderator/outer part
- Moderator/inner part
- Back cover

80% sensor overlap
20% sensor overlap

22 mm
19.5 mm

Sensor
ASIC
Cooling plate
Module

X (or Y)
Sensor and ASIC: HGTDT Module

- **Low Gain Avalanche Detectors (LGADs)**
  - n-p silicon planar detector + multiplication layer
  - Moderate gain
  - Excellent time resolution < 30 ps pre-irradiation
  - Fast rise time ~ 0.5 ns

- **Testing various vendors: CNM, HPK, FBK**
  - Different doping materials, substrates, thickness

- **Bump bonded to ASIC**
  - ATLAS LGAD Timing Integrated ReadOut Chip (ALTIROC)
  - Provide TOA and TOT
  - Target time resolution < 25 ps

- **Tests of ALTIROC0/1**
  - ALTIROC0: single-pixel analog readout
    (pre-amplifier + discriminator)
  - ALTIROC1: full single-pixel readout
    (analog + TDC) in 5×5 arrays

- **ALTIROC2: final 15×15 version**
  - Submission expected end of 2019
**Time Resolution**

\[
\sigma_{total}^2 = \sigma_{Landau}^2 + \sigma_{jitter}^2 + \sigma_{timewalk}^2 + \sigma_{TDC}^2 + \sigma_{clock}^2
\]

- **Landau fluctuations** from deposited charge as charged particle traverses the sensor: <25 ps pre-irradiation: thin sensors

- **Largest components from jitter** (total target <25 ps)
  - TDC granularity (<5 ps)

\[
\sigma_{Landau}^2 = \left( \frac{t_{rise}}{S/N} \right)^2
\]

\[
\sigma_{jitter}^2 = \left( \frac{V_{thr}}{S/t_{rise}} \right)_{RMS}^2
\]

- **Clock distribution:** <10 ps

*Figures taken from 1704.08666*
Sensor studies: doping

- Gain and charge as a function of bias voltage for a CNM LGAD with different doping doses of the multiplication layer.

- CNM single-pad sensors and arrays
  - With and without JTE
  - Medium and high doping

- Time resolution of sensor of 30 ps achievable
Sensor studies: radiation studies

- **Sensor irradiated campaigns:**
  - neutrons at IJS (Ljubljana)
  - protons at PS-IRRAD (CERN)

- **Up to fluences of** \(6 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2\)

- Bias voltage increase recovers Gain loss due to higher fluences

**Graph:**

- Most probable charge or gain dependence on bias voltage for different fluences (in \(n_{\text{eq}}/\text{cm}^2\)):
  - CNM single-pad run 9088 with medium dose
  - HPK 50D/50C single-pad sensors

- Annealing studies also on-going
Sensor studies: charge and time

- Collected charge and time resolution for HPK 50 \( \mu \)m at -30 \( C \)
  - CC of 1 fC for all fluences, 2.5 fC up to \( 3 \times 10^{15} \) neq/cm\(^2\)

- 50 ps achievable up to \( 3 \times 10^{15} \) neq/cm\(^2\)
Sensor studies: time resolution

- Time resolution as a function of neutron fluence
  - **HPK 50D** at breakdown (VBD) and with headroom (VHR) at -20 °C
  - *Headroom defined to be ~ 10 % or more below breakdown*
  - **HPK B35** at VBD
  - Time resolution found to be 20 ps before irradiation and 50 ps at $6 \times 10^{15} \text{n}_{eq}/\text{cm}^2$

- VBD and VHR dependence on neutron fluence
Sensor studies: bias voltage vs radius

- **Given the fluence vs. R dependency:**
  - Bias voltage of sensors will need to be adjusted during detector lifetime

- **Required bias voltage vs. fluence** for different fluence levels at R = 300 mm

- A rapid increase is seen between:
  - $1 \times 10^{14}$ and $3 \times 10^{14} \text{ neq/cm}^2$

- Increase bias voltage over lifetime of detector and as a function of R

- Also include replacement of inner section
Arrays: 15 x 15 pads

- Studies of 15 x 15 LGAD arrays on-going (half-size of final sensor)
  - Full size for HGTD: 30 x 15
  - 2 x 4 cm²

- Microscope photo of an HPK-ATLAS Type 3.1 15x15 array.

- $V_{BD}$ map of a 15 x 15 HPK type 3.1 array
  - Measurement at room temperature
  - Neighbours and GR floating

- Excellent uniformity observed

- Feasibility of large-size LGAD arrays demonstrated
HGTD testbeams

• HGTD testbeams at CERN and SLAC
  • CERN: North Area SPS H6 A/B beamlines with 120 GeV pions
  • 9 testbeam periods since 2016

• 2018 Program (4 testbeams):

• Sensors:
  • Proton vs neutron irradiation
  • Boron / Gallium implanted
  • Carbon diffused
  • 50 and 35 $\mu$m thickness
  • HPK, FBK, CNM, BNL sensors
  • Arrays with different inter-pad distances

• ASIC:
  • 2×2 array sensors bump-bonded to ALTIROC0

HGTD Testbeam Paper

Cold box for DUTs

Cold box for SiPMs

Telescope (MIMOSA planes)
Arrays: efficiencies and time resolution

- Hit efficiency (left)
- Time resolution (right)
  - Top: Un-irradiated
  - Bottom: $6 \times 10^{14}$ $n_{eq}/cm^2$

- Efficiency $\sim 100\%$
  - Inter-pad gap slightly more efficient after irradiation
  - Voltage threshold is 3 times larger than the noise (~5mV)

- Radiation impact slightly visible on timing resolution
  - SiPM used for timing reference
Arrays: efficiencies vs threshold

- Signal amplitude for un-irradiated and irradiated $6 \times 10^{14}$ $n_{eq}/cm^2$
  - Signal amplitude is reduced after irradiation

- Signal efficiency vs the amplitude threshold
  - Efficiency drops much quicker for irradiated LGAD with higher threshold

- Hit efficiency as a function of collected charge
  at a noise occupancy of 0.1 % and 0.01%
**ASIC: ALTIROC**

- **ALTIROC** will be bump-bonded to the LGAD
  - Have to withstand high radiation levels
    - 2.0 MGy at the edge of non-replacing ring
  - Each single readout channel needs to fit within the sensor pad
  - Provide TOA and TOT
  - Rise time ~0.5ns (as sensor) to minimise jitter
  - Designed for < 5 $\mu$A sensor leakage current per sensor pad

- **Bunch by bunch luminosity measurement capability**
• Testbeam results from ALTIROC0 bump-bonded to 2x2 array

• TOA variation as a function of the amplitude of preamplifier output
  • Correction for time walk with polynomial fit

• Time resolution as a function of the threshold
  • Includes both sensor (~ 25 ps) and jitter
  • Jitter deduced to be ~ 25 ps
Roadmap

- The HGTD will mitigate pile-up effects and improve object/physics performance

- Intense R&D program on-going
  - Single-pad / 5x5 and 15x15 arrays tested in lab and testbeam
  - During the last year we have profited from a very open and fruitful collaboration with RD50 and CMS colleagues

- < 50 ps per hit achievable up to $3 \times 10^{15}$ with 50 $\mu$m thin LGAD sensors
  - Average at least 2 hits per track over all HGTD active area

- Final sensor design choices still need to be made
  - Doping, thickness, inter-pad gap

- ALTIROC0 has shown good timing resolution in testbeams
  - Bench test measurements of ALTIROC1 on-going

- HGTD Technical Design Report (TDR) due to be submitted to LHCC on April 5th
HL-LHC Timeline

- Timeline for the LHC accelerator operation and planned upgrades
## HGTD Main Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HGTD Phase-II Detector Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pseudo-rapidity coverage</td>
<td>2.4 $&lt;</td>
</tr>
<tr>
<td>Thickness in $z$</td>
<td>75 mm (+50 mm moderator)</td>
</tr>
<tr>
<td>Position of active layers in $z$</td>
<td>$z = 3443, 3454, 3468, 3479$ mm</td>
</tr>
<tr>
<td>Radial extension:</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>110 mm $&lt; R &lt; 1000$ mm</td>
</tr>
<tr>
<td>Active area</td>
<td>120 mm $&lt; R &lt; 640$ mm</td>
</tr>
<tr>
<td>Pad size</td>
<td>1.3 $\times$ 1.3 mm$^2$</td>
</tr>
<tr>
<td>Sensor thickness</td>
<td>50 $\mu$m</td>
</tr>
<tr>
<td>Number of channels</td>
<td>3.59 M</td>
</tr>
<tr>
<td>Active area</td>
<td>6.4 m$^2$</td>
</tr>
<tr>
<td>Average number of hits per track:</td>
<td></td>
</tr>
<tr>
<td>2.4 $&lt;</td>
<td>\eta</td>
</tr>
<tr>
<td>3.1 $&lt;</td>
<td>\eta</td>
</tr>
<tr>
<td>Time resolution per track</td>
<td>$&lt; 50$ ps</td>
</tr>
</tbody>
</table>
LGADs

- LGAD cross-section

- 2 × 2 array of CNM run 10478 including a JTE around each sub-pad (Si-Si wafer)

- Response based on thickness
Testbeam Activities

Telescope: 6 MIMOSA planes and 4 scintillators

HV for DUTs
Cold box for DUTs
FE-I4
HV for SiPMS
LV for boards and second stage amplifiers
Cold box for SiPMs
Oscilloscopes for read-out

Signal!
Interpad Regions

- Signal efficiency in the interpad region for an unirradiated array of four LGAD sensors
Testbeam Setup

- DUTs: LGADs sitting inside a cooling box
- SiPMs: for timing reference which sit in a separate cooling box (closed to light)

- Mimosa planes: Telescope used for tracking position / efficiency
- FeI4 + Scintillator: used for triggering

- Trigger Logic unit receives signal from FE-I4 and scintillator and sends signal to oscilloscope and NI-crate to save data
HGTD Illustrations

- Illustration of the HGTD, showing the peripheral on-detector electronics in green and the layout of the readout rows

- Assembly of the modules in one half disk with cooling pipes visible
The number of hits as a function of the position in the HGTD is shown for an overlap of 80% at $R < 320$ mm and 20% at larger radii.