R&D on LGAD radiation hardness in the HL-LHC environment

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on behalf of the SCIPP UCSC group
LGADs

- LGAD: silicon detector with a thin (<5 μm) and highly doped (~10^{16} P++) multiplication (gain) layer
  - High electric field in the multiplication layer
- LGADs have intrinsic modest internal gain (10-50)
  - \( G = \frac{Q_{LGA D}}{Q_{PIN}} \) (collected charge of LGAD vs same size PiN)
  - Better signal to noise ratio, sharp rise edge
- Allows thin detectors (50 μm, 35 μm, 20 μm)
  - Thinner detectors have shorter rise time and less Landau fluctuations
- **Time resolution < 30 ps**
  - \( \sigma_{\text{timing}}^2 = \sigma_{\text{time walk}}^2 + \sigma_{\text{Landau noise}}^2 + \sigma_{\text{Jitter}}^2 + \sigma_{\text{TDC}}^2 \)
- Several vendors of thin LGADs under study
  - HPK (Japan), FBK (Italy), CNM (Spain), BNL (USA), NDL (China)
**HGT D, ATLAS and LHC high luminosity**

- **LHC**: 14 TeV proton-proton collider at CERN (Geneva)
- **ATLAS**: one of the four main experiments at the LHC
  - General purpose detector for discovery of new physics and precise measurements
- LHC will be upgraded in 2026 to High Luminosity LHC (HL-LHC)
  - Instantaneous luminosity higher than present conditions
- ATLAS detector will be upgraded for HL-LHC
- **HGT D: High Granularity Timing Detector**
  - 2 disk of LGAD detectors in the forward region
  - Provide timing measurements of tracks
  - **35 to 70 ps of time resolution on hits (less on tracks)**
  - **Radiation hardness up to** \(2.5 \times 10^{15}\) Neq
  - [cds.cern.ch/record/2623663](http://cds.cern.ch/record/2623663)
- CMS will also be upgraded with an end-cap timing layer (ETL)
  - [cds.cern.ch/record/2667167](http://cds.cern.ch/record/2667167)
- **HGT D and ETL are the first application of LGADs in HEP**
Radiation damage
Radiation damage on LGADs

- Most widely accepted radiation damage explanation for LGADs is **acceptor removal**

- Radiation damage for LGADs can be parameterized
  \[ N_A(\phi) = g_{eff} \phi + N_A(\phi=0)e^{-c\phi} \]

- Acceptor creation: \( g_{eff} \phi \)
  - By creation of deep traps

- Initial acceptor removal mechanism: \( N_A(\phi=0)e^{-c\phi} \)
  - Ionizing radiation produces interstitial Si atoms
  - Interstitials inactivate the doping elements (Boron) via kick-out reactions that produce ion-acceptor complexes
  - Reduction of doping \( \rightarrow \) reduction of gain
  - C factor depending on detector type

Y. Zhao et al. 10.1016/j.nima.2018.08.040

Y. Zhao presentation at ULLITIMA conference
https://indico.fnal.gov/event/ANLHEP1390/session/8/contribution/68/material/slides/0.pdf
Mitigation of radiation damage: Carbon

- **FBK** (Fondazione Bruno Kessler) sensors
- With (and without) Carbon infusion
  - FBK-C and FBK-noC
- Carbon is electrically inactive (no effect pre-irradiation)
  - Slight reduction of gain from the implantation process
- Catch interstitials instead of Boron
- → Reduces acceptor removal after irradiation

![Graph showing Gain vs. Bias for high fluence.]

<table>
<thead>
<tr>
<th>Fluence</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5E15 Neq/cm²</td>
<td>Boron+Carbon sensor, Gain ~10</td>
</tr>
<tr>
<td>1.5E15 Neq/cm²</td>
<td>Boron sensor, Gain ~3</td>
</tr>
</tbody>
</table>

S.M. Mazza et al. arXiv:1804.05449
M. Ferrero et al. arXiv:1802.01745
Y. Zhao et al. 10.1016/j.nima.2018.08.040
Mitigation of radiation damage on LGADs

- **HPK** (Hamamatsu Photonics) sensors
  - HPK-3.1 and HPK-3.2
- Thin but highly doped gain layer
  - Higher initial doping concentration
  - Takes more time to be inactivated
- Deep gain layer
  - High field for larger volume
- Gain layer between 1um to 2um in
  instead of ~0.5-1 um
Gain layer fraction
Gain layer and CV

- Capacitance over voltage (CV)
  - Study doping concentration profile and full depletion of the sensor
- Study of the “foot” for LGADs on $1/C^2$:
  - $1/C^2$ flat until depletion of multiplication layer
  - Proportional to gain layer active concentration
- Bulk doping concentration proportional to the slope in $1/C^2$
- After radiation damage the “foot” changes proportionally to the gain layer doping

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Gain layer vs. Fluence: The Effect of Carbon

- Acceptor removal constant (C) is different for different types of sensors
  - The FBK Carbon sensors has smaller range for “foot” voltage
  - The HPK 3.2 shows a much larger declination and broader range of “foot” voltages
- Carbon seems to give significant improvement where C is about factor 3 smaller for FBK
- However HPK has a much higher initial foot due to the buried gain layer

\[ N_D = N_0 e^{-c\phi} \]
Sensor testing – Sr90 telescope

- Dynamic laboratory testing
  - Using MiP electrons Sr90 $\beta$-source ($\beta$-telescope)
  - Signal shape, noise, collected charge, gain, **time resolution**

- Sensors mounted on analog readout board designed at UCSC (Ned Spencer, Max Wilder, Zach Galloway) with fast amplifier (22 ohm input impedance, bandwidth $> 1$GHz)
  - Readout by fast oscilloscope
- Trigger sensor (fast timing trigger) on the back
  - DUT (Device Under Test) is read in coincidence
- Setup in climate chamber to run cold and dry
  - 20°C/-20°C/-30°C
LGAD performance after irradiation

- Performance of HPK-3.2 and FBK-C is good up to $3 \times 10^{15}$ Neq (sensors irradiated at JSI with neutrons)
- Gain of $\sim 8$ ($\sim 4\text{fC}$ of collected charge) and 50ps time resolution
- Independent effect of Carbon (FBK) and deep gain layer (HPK)
Deep (HPK-3.2) vs non deep (HPK-3.1)

With (FBK-C) and without (FBK-noC) Carbon
LGAD performance

- Time resolution vs gain has a behavior that is mostly independent from radiation damage
  - Collected charge of ~8 needed to achieve ~50ps of time resolution

- Both sensor show reasonable performance up to 3E15 Neq
  - Fulfilling requirements for HL-LHC timing layers
  - After 3E15 Neq still a challenge
  - Combination of Deep gain layer and Carbon?

- Other LGAD manufacturers under study:
  - CNM (Spain), NDL (China), BNL (US)
Fluence uncertainty
Variation of performance after irradiation

- HPK sensors irradiated with neutrons at JSI (Lubjiana)
- Variation of performance of the order of 10%
  - In the voltage to obtain X fC of charge (or gain X)
- Pre-rad difference in performance instead is <1%
  - Where is the variation coming from?

- Plot on the right: HPK Type 3.2 sensors all irradiated at 1.5E15 Neq
Correlation of foot and gain layer

- Gain layer can be probed by
  - Measuring the gain (beta-scope)
  - Measuring the foot (CV)
- Gain shows a 10% variation after irradiation
- Measured foot also shows a 10% variation
- Plot together foot voltage and voltage to achieve 4fC (Gain ~8)
  - Linear correlation (a few outliers)
  - Performance variation is real
- JSI quoted fluence uncertainty is ~10%
  - Most probably is the cause of performance uncertainty
Conclusions

- **Options available to increase the radiation hardness of LGADs**
  - Carbon
  - Thin and deep gain layer
- LGADs from several vendors show **reasonable performance up to 3E15Neq**
  - Good gain (8-10) and time resolution (50-60ps)
- Making the mark for the first applications at timing layers of ATLAS/CMS at HL-LHC
- New productions from HPK, FBK, CNM and NDL are coming in 2020
- Including the **combination of deep gain layer and carbon**: FBK-UFSD-3.2
  - Stay tuned!
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Backup
Irradiation campaigns on LGADs

- Irradiation campaign on LGADs
- Sensors were irradiated at
  - JSI (Lubiana) with ~1 MeV neutrons
  - PS-IRRAD (CERN) with 23 GeV protons
  - Los Alamos (US) with 800 MeV protons
  - CYRIC (KEK, Japan) with 70 MeV protons
  - X-rays at IHEP (China)
- Fluence: 1E13 Neq/cm$^2$ → 1E16 Neq/cm$^2$
- Ionizing dose up to 4MGy
- Waiting for the FNAL facility!
Future prospect – deep gain layer + Carbon

- Combine Carbon (FBK-UFSD-3) with deep implantation (HPK-3.2)
- Preliminary simulation with Weightfield2 predict a collected charge of 5 fC at 6E15 Neq!

[Graphs showing collected charge as a function of bias voltage for different materials and scenarios, with annotations for each dataset and comparison to simulation results.]

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https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LArHGTDPublicPlots#2018_2019_Sensor_Performance_TDR
LGADs timing resolution

Sensor time resolution main terms

\[ \sigma_{\text{timing}}^2 = \sigma_{\text{time walk}}^2 + \sigma_{\text{Landau noise}}^2 + \sigma_{\text{Jitter}}^2 + \sigma_{\text{TDC}}^2 \]

- Time walk:
  - Minimized by using for time reference the % CFD (constant fraction discriminator) instead of time over threshold
  - In HGTD electronics TOA (Time of Arrival) of the signal is corrected with TOT (Time over threshold)

- Landau term:
  - Reduced for thinner sensors (50, 35 μm)

- Jitter:
  - Proportional to \( \frac{1}{dV/dt} \)
  - Reduced by increasing S/N ratio with gain
**Acceptor removal**

**Unfortunate fact:** irradiation de-activate p-doping removing Boron from the reticle

\[ N(\phi) = N(0) \times e^{-c\phi} \]

Two possible solutions: 1) use Gallium, 2) Add Carbon

- **Boron**
  - Radiation creates interstitial defects that inactivate the Boron: \( \text{Si}_i + \text{B}_s \rightarrow \text{Si}_s + \text{B}_i \)
  - \( \text{B}_i \) might interact with Oxygen, creating a donor state

- **Gallium**
  - From literature, Gallium has a lower probability of becoming interstitial

- **Carbon**
  - Carbon competes with Boron and Gallium in reacting with Oxygen