Simulation of Low Gain Avalanche Detectors(LGAD) for LHCb operation in Run 5

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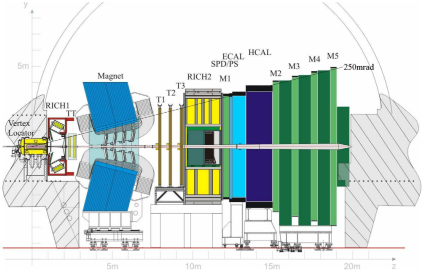
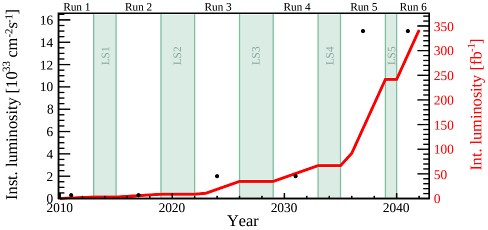
Overview

Run 5 Conditions

LHCb Run 5 comes with increased challenges due to the increase in collected Luminosity.

- Pile-up of ≈ 42
- Increase in radiation damage of $\mathcal{O}(10)$
- Increase in VELO track density of $\mathcal{O}(10)$

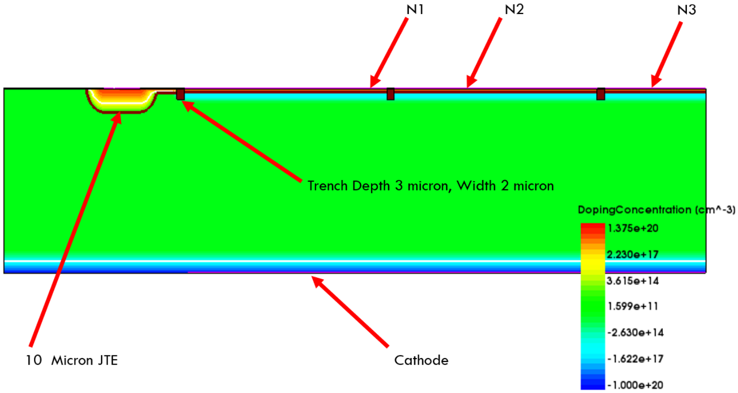




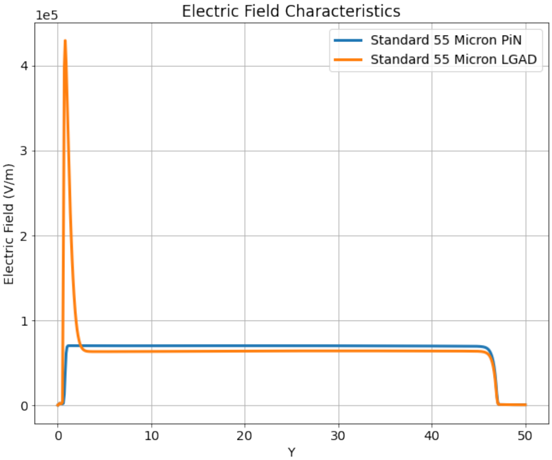
So to meet these challenges high granularity, radiation hard, fast timing sensors are being developed. LGAD is one candidate developed for installation in the VELO detector.

LGAD Doping Profile

The simulated profile has a distinct $n^{++}, p^{+}, p^{-}, p^{++}$ profile and is shown here with JTE (Junction Termination Extension) and trench termination.



General Device Overview (Electric Field)



The $n^{++}, p^{+}, p^{-}, p^{++}$ design of the LGAD doping gives it a unique field structure with a distinct multiplication layer. LGAD devices as such have the following properties.

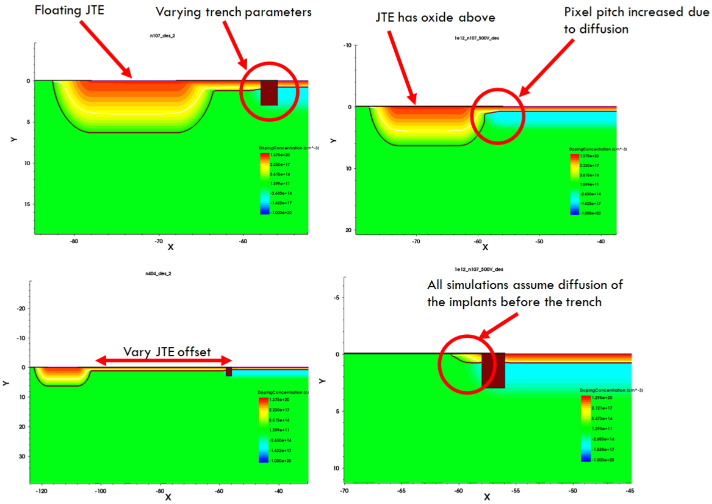
- Proportional Gain of $\mathcal{O}(10)$.
- Timing resolution of $\approx 20ps$

Electrostatic Simulation Methodology

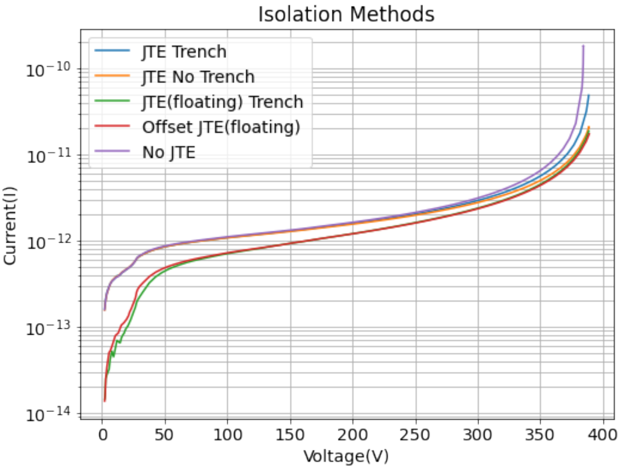
Electrostatic simulations were used to investigate various edge termination combinations of the LGAD devices. Simulations extend across the edge pixel (N1) and centre pixel (N2) to ensure consistent device behaviour.

- A target DC Bias of 1000V is set an the device at 248K.
- A scan takes place towards this voltage with a break current of $6e{-}8$A at the contacts.
- IV curves are returned for breakdown characteristics

Edge Termination Designs



Termination Results

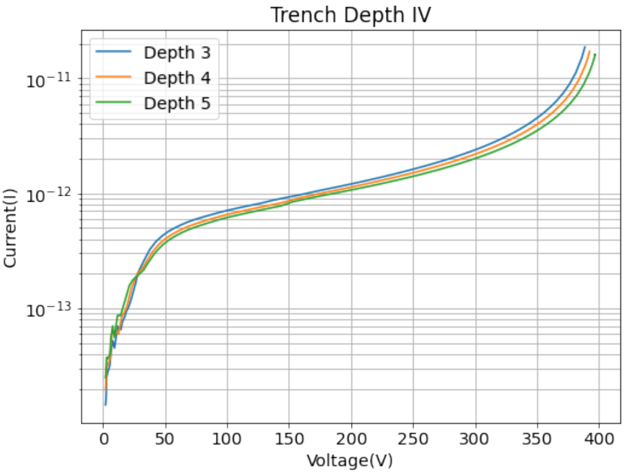


Edge Termination

Edge Termination breakdown scans were carried out across several termination combinations. Key results were.

- No significant difference between different termination types.
- Higher leakage current without JTE at low bias.
- Consistent behaviour between N1 and N2 pixels

Trench Results



Trench Depth

Similarly, simulations were carried out across a variety of trench depths (3-5μm) and widths (0.5-2μm). Key results were.

- No significant difference between different trench combinations.
- Changes due to width were dominated by numerical precision.

Transient Simulation Methodology

Transient simulation allows us to caluculate, gain response, fill factor and the effects of radiation direct from simulation. We achieve this with the following procedure.

- A DC Bias of 320V is achieved across the device at 248K
- A **"Heavy Ion"** model MIP(minimum ionizing particle) with LET (Linear Energy Transfer) $1.2e{-}5pC/\mu m$ is projected through the device.
- The device current is integrated to infer the collected charge (CC)
- Gain is calculated as $\frac{CC_{LGAD}}{CC_{PiN}}$

Gain Suppression

The MIP LET is kept intentionally low to avoid gain suppression effects as reported in **Gain Suppression Mechanism Observed in Low Gain Avalanche Detectors**. This suppression is hypothesised to be linked to charge density in the gain region.

Charge Evolution

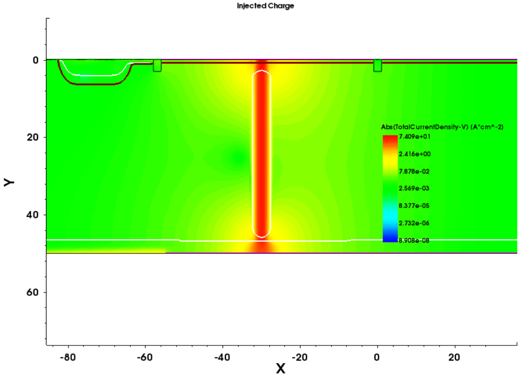


Figure: Charge Injected at (0ps)

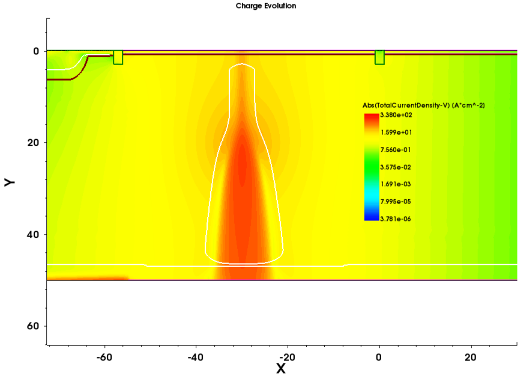
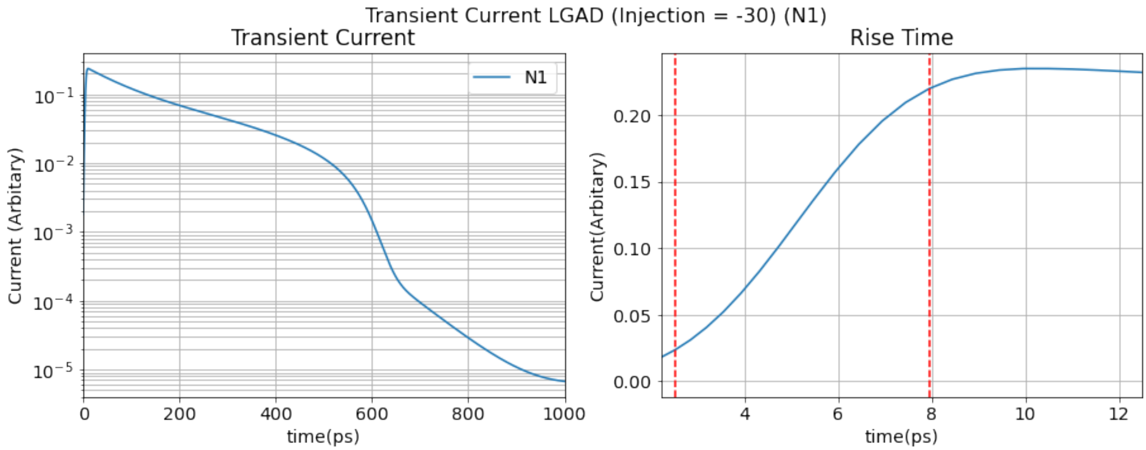


Figure: Charge Evolution (75ps)

Collected Current



Radiation Damage Models

Bulk and surface radiation effects are modeled according to the **TCAD Radiation Damage Model AIDA Delivery Report**. The proposed model implements the following.

- Oxide charge build up and interface trap formation.
- Deep level trap formation.

Note

Irradiated devices will need to be characterised to extract more realistic model parameters for future simulation.

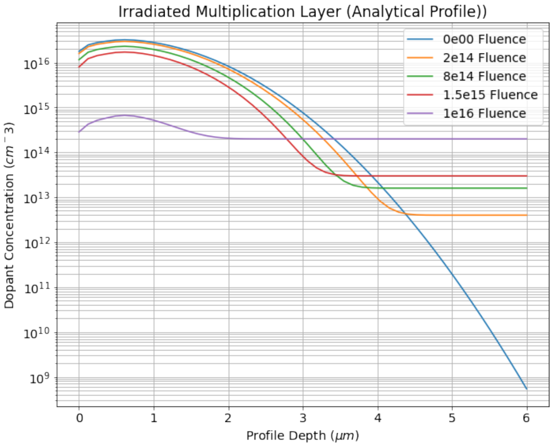
Acceptor creation and removal in the gain layer is empirically calculated prior to simulation using

$$N_A(\phi) = g_{eff}\phi + N_A(0)e^{-c(N_A(0),x)\phi} \quad (1)$$

where ϕ is the Fluence, g_{eff} is some creation factor and $N_A(0)$ is the acceptor level before irradiation. The coefficient c can alternatively expressed as.

$$-c(N_A(0), x) = -\alpha N_A(0, x)^{-\beta} \quad (2)$$

Radiation Damage (Gain)



The following factors from **here** were used to calculate the updated gain layer profiles for simulation.

- $g_{eff} = 0.02cm^{-1}$
- $\alpha = 9e{-}7$
- $\beta = 0.574$

Serious damage to the multiplication profile only really occurs in excess of $1e^{15}$. Trap and oxide charge effects are then included on top of these profiles in simulation.

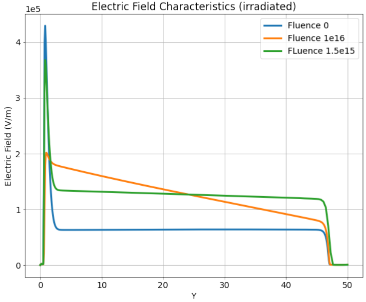
Expected Fluence

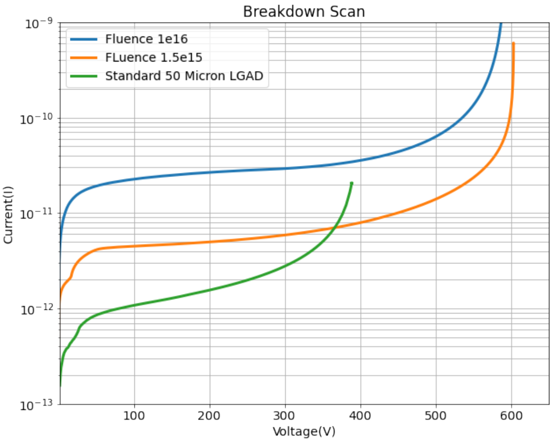
$\phi_{Run4} = 0.86x10^{16} n_{eq}/cm^2$
$\phi_{Run5} \approx 1.00x10^{17} n_{eq}/cm^2$

Radiation Damage (Breakdown)

Breakdown

In irradiated devices breakdown is significantly inhibited by any reduction to the maximum electric field.

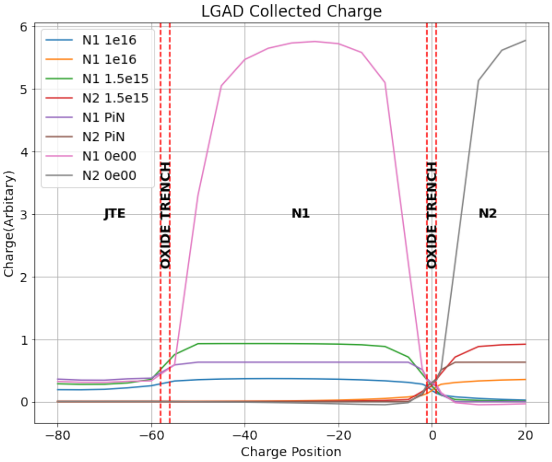




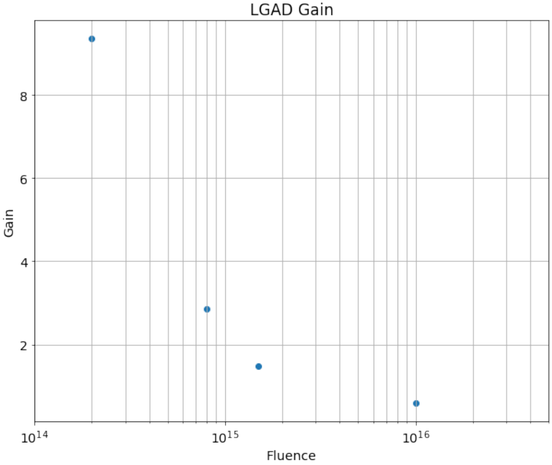
Radiation Damage (Charge Collection)

Charge collection was calculated by injecting charge at various points along the device plane.

- The charge collection of the device at high Fluence is seen to drop off rapidly, with performance at 1e16 being significantly degraded in relation to the unirradiated PiN diode.
- Performance between pixels N1 and N2 appears stable under simulation with minimal charge sharing.



Radiation Damage (Gain loss)



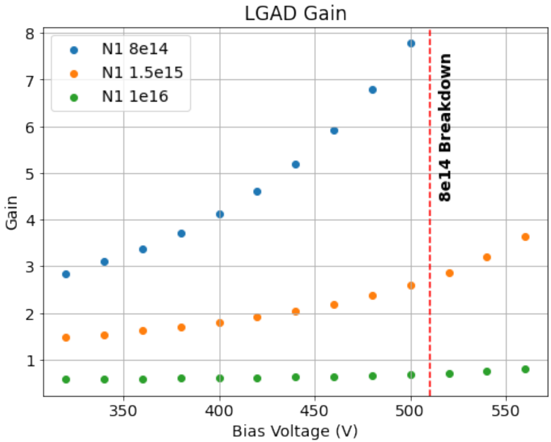
To calculate the loss of gain with respect to the Fluence the gain was calculated at the centre (-30) of pixel N1.

- LGAD gain was significantly affected by increasing Fluence.
- The effect is non linear due to the combination of trap formation and acceptor removal.

Radiation Damage (Gain Recovery)

Gain recovery is modeled by injecting charge into devices at a higher bias.

- Gain can be recovered at low fluences.
- In high fluence cases recovery is not possible.



Outlook

- LGAD is a promising fast timing high granularity sensor candidate.
- Electrostatic simulations have shown good stability across termination types.
- Transient Simulations has demonstrated gain recovery at moderate Fluences.
- Radiation response needs further characterisation through test beam.

Any Questions!