Timing Performance of Thin Low-Gain-Avalanche-Diodes (LGAD)

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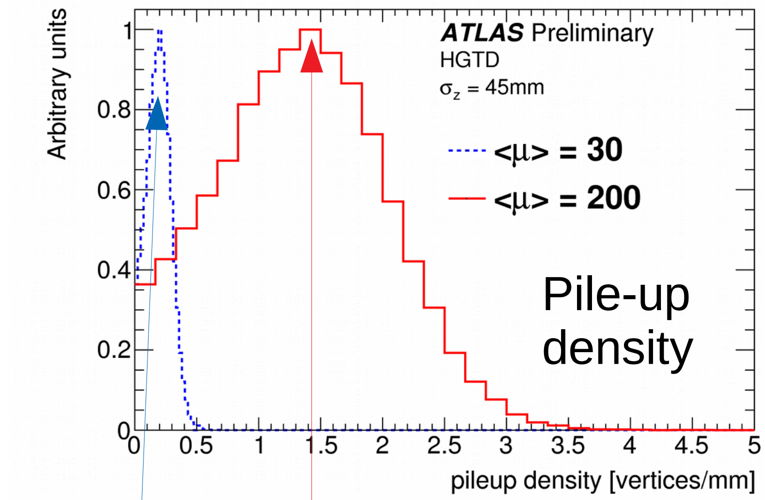
Motivation for LGAD Development

- The **Large Hadron Collider** in Geneva will undergo a luminosity upgrade in 2026. (the HL-LHC project)
- The luminosity after the upgrade will be 10 times higher than the original designed value **=> increase of pile-up.**
- **ATLAS**, one of the detectors at the LHC, will undergo an upgrade at the same time (Phase-II upgrade).
  - Will include a new layer of silicon detector in the end-cap, the High-Granularity-Timing-Detector (**HGTD**)
    - Reduce the pile-up contamination in tracks and vertexes
    - Improvement with the track-to vertex association, b tagging, lepton isolation, jet/Et_{miss}.
    - Improves the minimum bias triggers and serves as fast luminosity monitor.

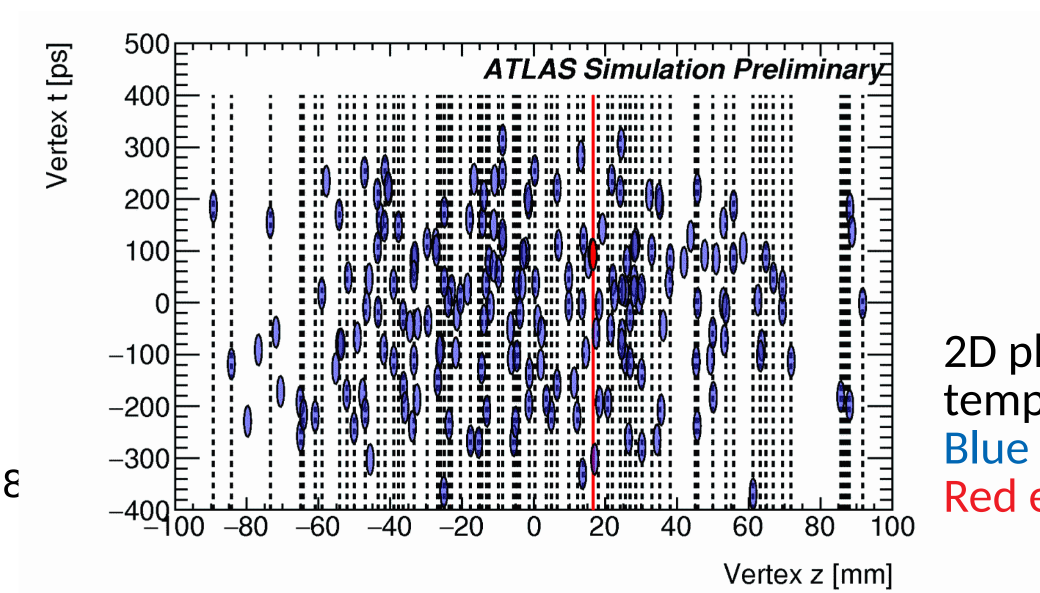


Blue: Run2

Red: Luminosity upgrade

The pile-up density will be 4 to 5 times higher than the Run2 after the luminosity upgrade.

Figures from TP CERN-LHCC-2018-023

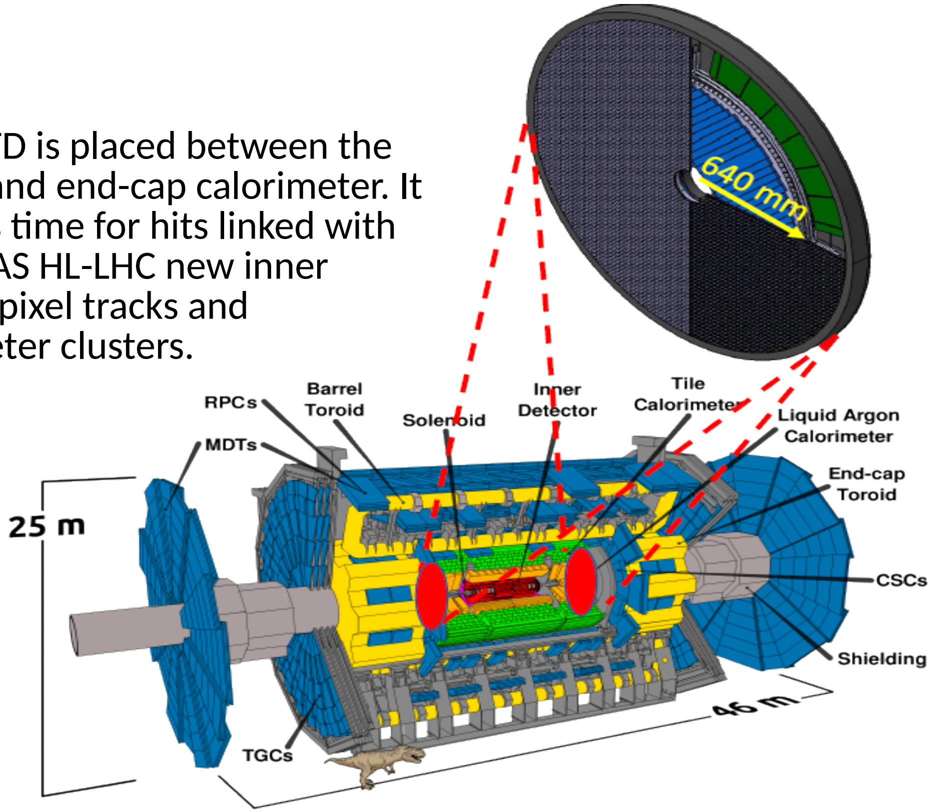


2D plot of vertex location with temporal information.
Blue ellipses: pile-up interaction.
Red ellipse: hard scatter.

The HGTD Design Requirements

- **Timing resolution of 30 ps/track** (2 to 3 timing measurements per track).
- Radiation hardness: lifetime **radiation level up to 4.5×10^{15} neq/cm^2.**
- Spatial resolution required for track matching: **segmentation of 1.3×1.3 mm^2** (<10% occupancy)

The HGTD is placed between the tracker and end-cap calorimeter. It Provides time for hits linked with ITk (ATLAS HL-LHC new inner tracker) pixel tracks and calorimeter clusters.



Pseudorapidity coverage	$2.4 < \|\eta\| < 4.0$
Thickness in z	75 mm (+50 mm moderator)
Position of active layers in z	3435 mm $< z <$ 3485 mm
Radial extension:	
Total	110 mm $< R <$ 1000 mm
Active area	120 mm $< R <$ 640 mm
Time resolution per track	30 ps
Number of hits per track:	
$2.4 < \|\eta\| < 3.1$	2
$3.1 < \|\eta\| < 4.0$	3
Pixel size	1.3×1.3 mm^2
Number of channels	3.54M
Active area	6.3 m^2

Table 2.1: Main parameters of the HGTD.

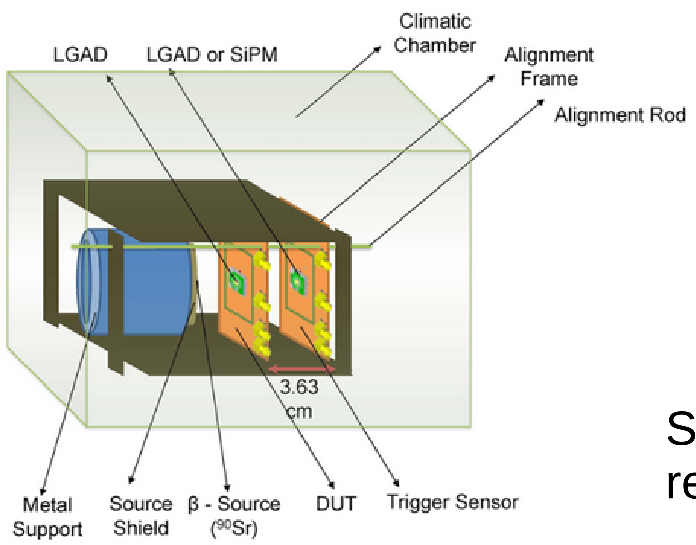
Table from TP CERN-LHCC-2018-023

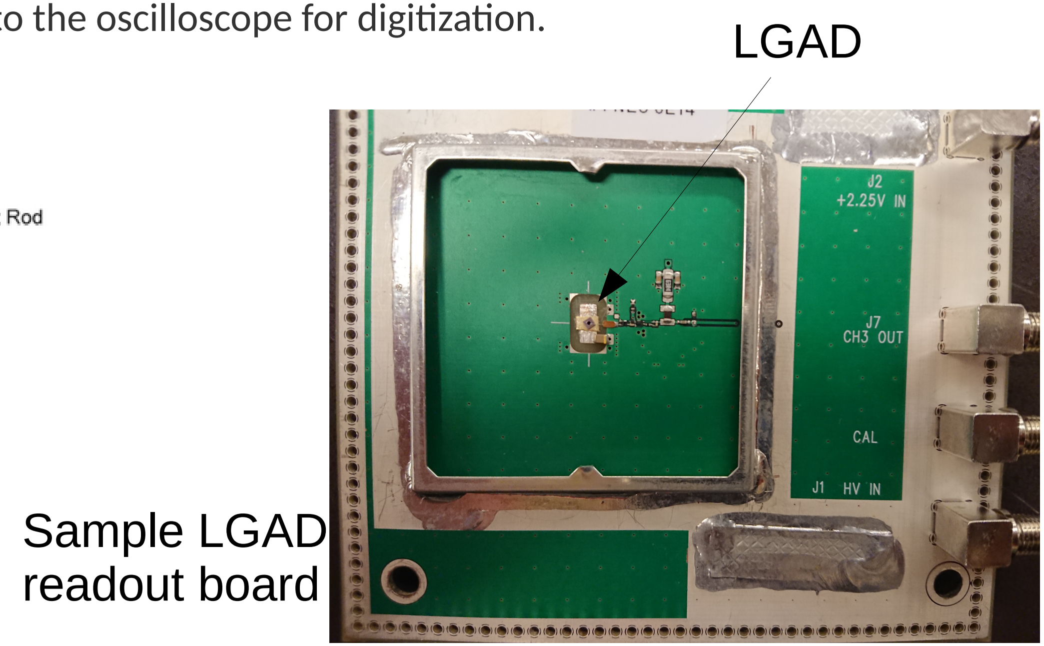
Manufacturers, Development, and Sample Irradiation

- The HGTD will be equipped with silicon pixel sensors called the **Low-Gain-Avalanche-Diode (LGAD)**.
- Currently we are working with three manufactures on the development of LGADs in collaboration with CMS:
  - Centro Nacional de Microelectrónica (CNM) in Spain.
  - Fondazione Bruno Kessler (FBK) in Italy.
  - Hamamatsu Photonics (HPK) in Japan.
- Samples discuss here are irradiated without bias in the JSI research reactor of TRIGA type in Ljubljana with neutron.
- In this presentation, we focus on the **latest results of 50um and 35um thick LGADs from HPK**, with
  - Measurement setup, introduction of LGADs.
  - Introduction of fast timing.
  - radiation damage effects on LGADs.
  - performance before and after neutron irradiation up to fluence of $6x10^{15}$ neq/cm^2.
  - Observed advantages of going to thinner sensors (35um).
  - and mention of additional application (X-ray)

Measurement Setup (Beta-Telescope) at UCSC

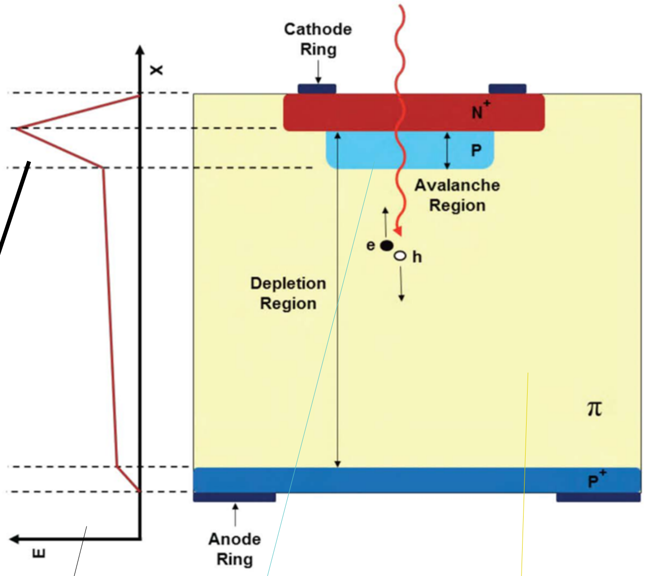
- The timing and charge collection measurements with **minimum ionization particle (MIP)** is done with
  - beta particles from the Sr-90 source, and
  - A fast HPK LGAD trigger with timing resolution of 15 ps for coincident event selection.
  - A climatic chamber for temperature and humidity control.
- Generated signals are read through an analog readout board designed at UCSC (Ned Spencer, Max Wilder, Zach Galloway) with
  - Analog amplifier of 22 ohm input impedance, and bandwidth > 1GHz.
- The analog signals are then sent to the oscilloscope for digitization.





The LGAD Structure

- The Low-Gain-Avalanche-Diode (LGAD), designed by the CNM, is similar to the standard avalanche photo-diode (APD), except:
  - LGADs make use of the n^{++}-p^{+}-p structure (n^{++} is N^{+}, p^{+} is P, and p is π in the figure)
    - Highly doped n-type thin layer.
    - A moderately doped p-type multiplication (gain) layer.
    - a resistive p-bulk.
  - **High E-field region in the gain layer allows impact ionization (multiplication process => provide gain)**
  - **Moderate gain of ~10 to 70 without breakdown to increase the signal-to-noise ratio(SNR).**
  - **Timing resolution as good as 20ps before irradiation for MIPs.**



E-field along the LGAD depth.

Multiplication (gain) layer

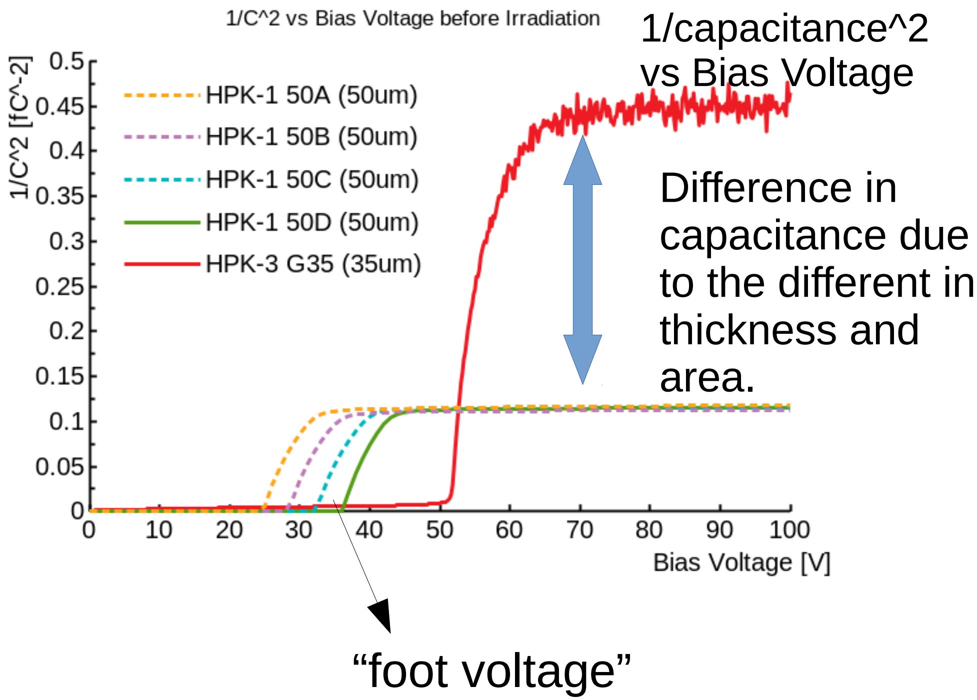
Resistive p-bulk with N~10^{12}-10^{13} cm^{-3}

Gain and the Depletion Voltage of the Multiplication Layer.

- A useful parameter to describe the properties of LGADs is the **gain: the ratio of collected charges in a LGAD to a PiN diode of the same thickness as the LGAD, under same operation conditions. (same bias voltage, temperature, radiation level, etc...)**
  - **A normalized quantity that is independent of the LGAD thickness**, and
  - directly relates to the doping density of the multiplication (gain) layer.
- Another useful parameter is the **"foot voltage"**: **the amount of bias voltage needed to fully deplete the gain layer**.
  - related to the multiplication (gain) layer doping density.
  - Determined with capacitance measurements.

Gain and the Depletion Voltage of the Multiplication Layer. (Continued)

- The "foot voltage" is extracted from the C-V measurement. See figure below.
- The "foot voltage" is proportional to the doping density of the gain layer. This can be shown with HPK-1 50um sensors that have 4 different doping density level (table below right).
  - The doping density changes with step 10% according to the manufacture. (50A lowest => 50D highest.)



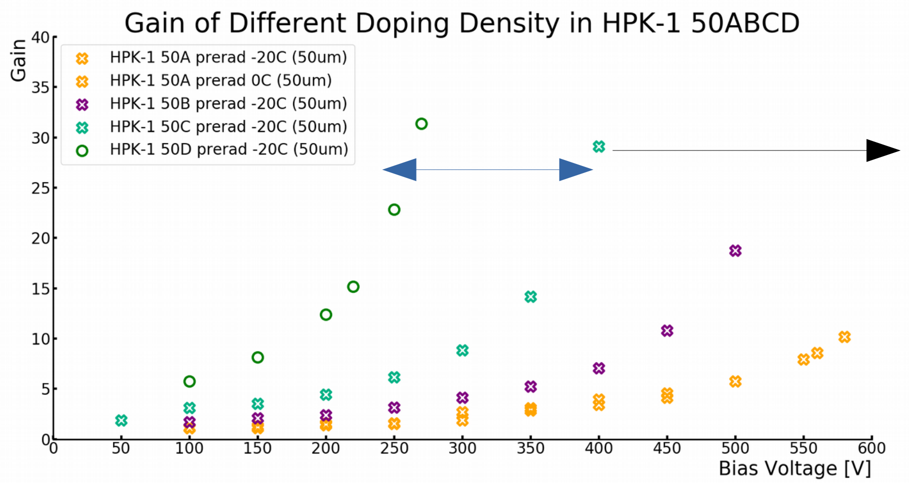
LGAD	"foot voltage" [V]
HPK-1 50A (50um)	24
HPK-1 50B (50um)	28
HPK-1 50C (50um)	32
HPK-1 50D (50um)	36
HPK-3 G35 (35um)	50

The thickness is measured from the top of the N^+ layer to the end of the resistive p-bulk (π).

Gain and the Depletion Voltage of the Multiplication Layer. (Continued)

- Since the multiplication process happens within the gain layer, the measured gain should increase with the gain layer doping density.
- Measurements of gain for the HPK-1 50um before irradiation are shown below
  - The different gain curves correspond to the 4 different doping densities.
  - For a fixed bias voltage, the gain increases with the gain layer doping density (or the “foot voltage”), as expected.

HPK 50um gain measurement in terms of bias voltage before irradiation.



The difference of these two measured gain curves arises from the 10% difference in the doping density of the gain layer.

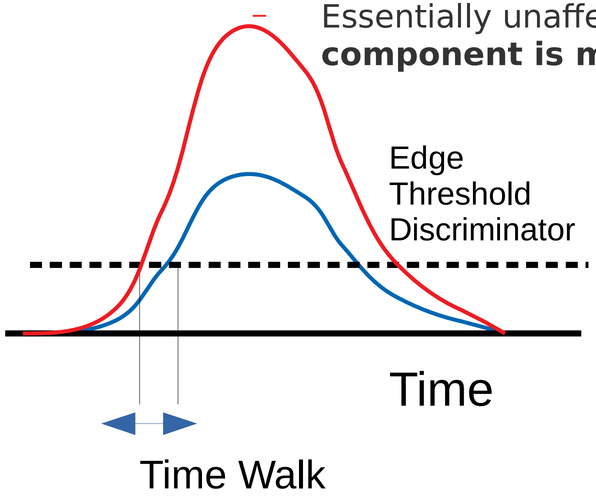
Higher gain layer doping density (larger “foot voltage”)

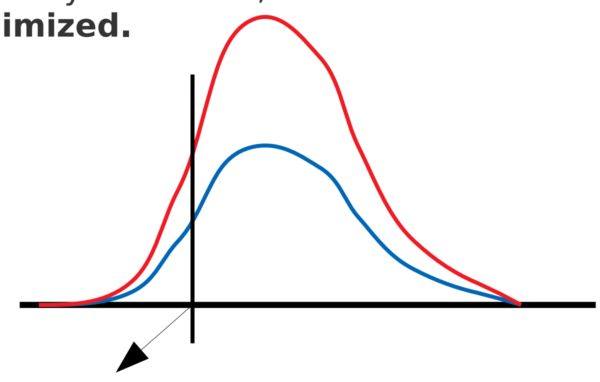
lower gain layer doping density (smaller “foot voltage”)

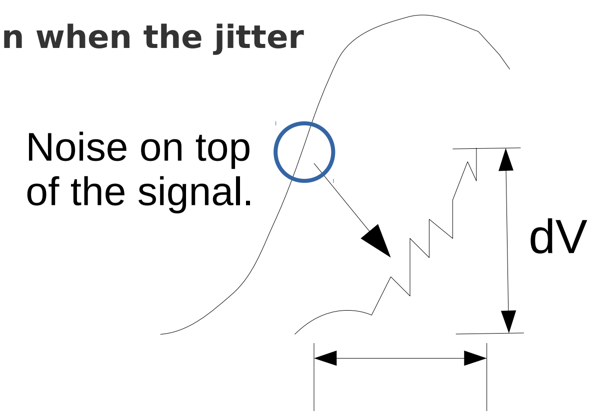
Timing Resolution

$$\sigma^2_{timing} = \sigma^2_{time\,walk} + \sigma^2_{Landau\,noise} + \sigma^2_{Jitter} + \sigma^2_{TDC}$$

- **Timing resolution:** the measured RMS of the **timing difference (or TOF of a MIP) between the device-under-test (DUT) and the trigger.**
- **Time walk:** Variation in time when a fixed edge threshold discriminator is applied to signals with similar rise time but different height.
  - **Constant-fraction-discriminator (CFD)**, which marks the time at a given % of the signal height, **can be used to remove the time walk effect.** (Time walk correction by calibrating signal height is also possible)
- **Jitter: Variation in time caused by the noise in the system.**
- **Landau noise:** local fluctuation due to the non-uniform deposition of energy in material. (for MIP)
  - **The effect reduces with sensor thickness.**
  - Essentially unaffected by irradiation; **dominates the timing resolution when the jitter component is minimized.**







$$\sigma_{Jitter} = \frac{Noise}{dV/dt[CFD\%]} \approx \frac{T_{rise}}{SNR}$$

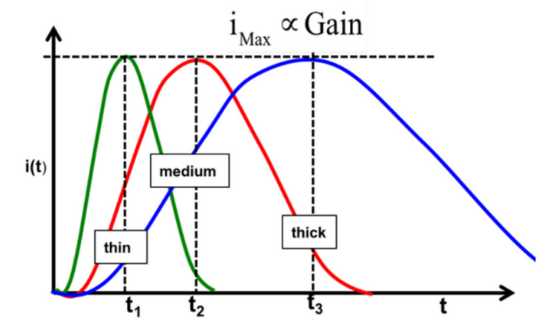
How to Achieve Fast Timing – Minimizing the Jitter Component

$$\sigma_{Jitter} = \frac{Noise}{dV/dt[CFD\%]} \approx \frac{T_{rise}}{SNR}$$

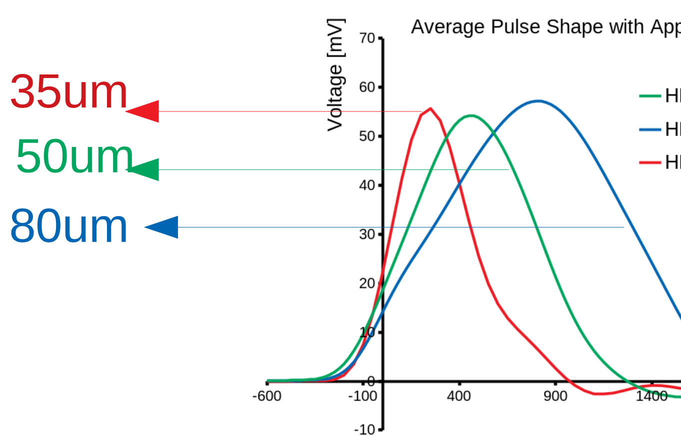
- By examining the jitter component, minimizing the jitter is crucial for fast timing, which requires
  - **Low signal readout noise.**
  - Large signal height and fast rise time

    => **maximized slew rate.**
- To reduce the jitter, the thinner LGAD (35um) has the advantages over the thicker LGADs.
  - **Same gain, same signal height (Pmax).**
  - **Thinner => faster rise time => larger slew rate => jitter goes down.**
  - Predicted with simulations; agrees with observed measurements.
- In addition, simulations and data show that **signal height increases with the gain**.

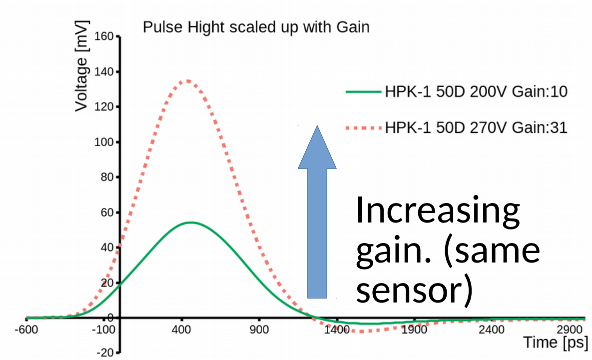
=> Go thin and increase the gain



Simulated signals for thin, medium, thick sensors with same gain.



Observed Average signals from measurements.

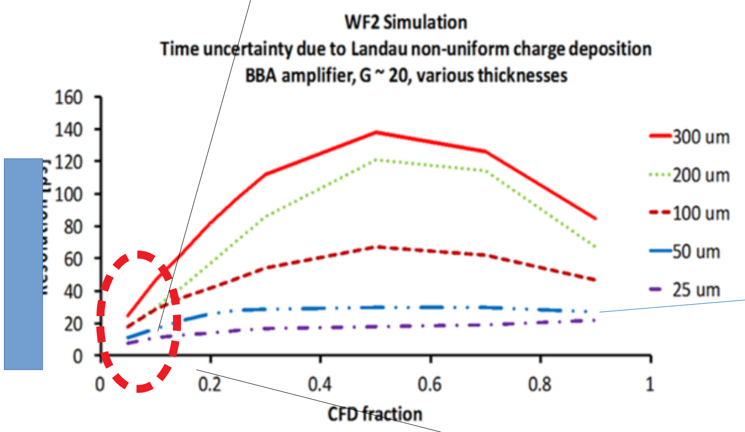


The Limitation from the Thickness
The Landau Noise

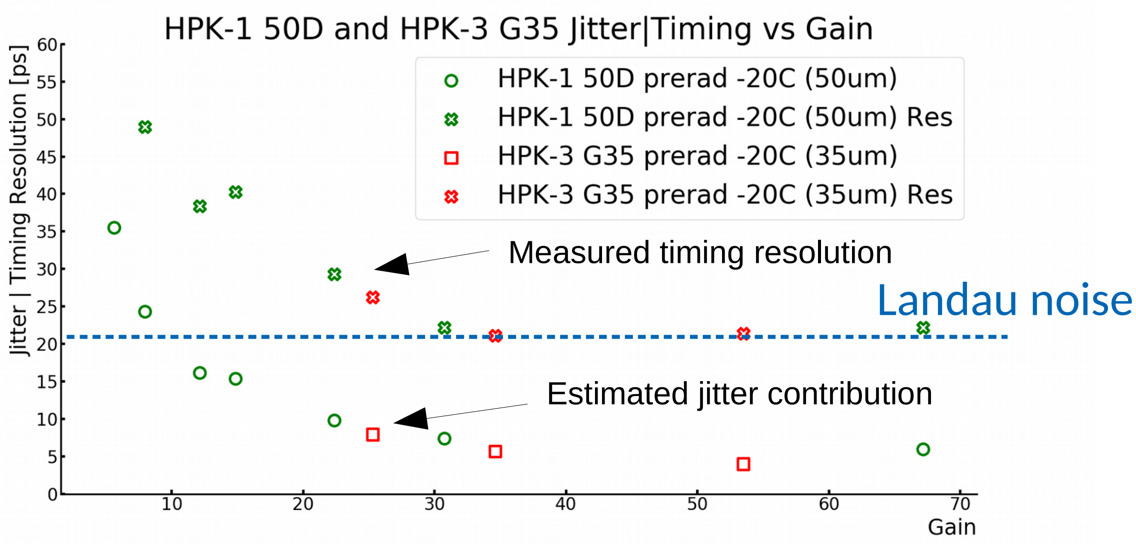
- The jitter component becomes negligible as the gain increases, but the timing resolution will not continue to decreases.

  => The timing resolution is taken over by the **Landau noise** component.

- Landau noise can be suppressed by raising the gain and lowering the CFD percentage (to 7% to 10%).
  - Similar to “first electron” timing in drift chambers.



Simulated Landau noise vs CFD percentage for various thickness.
(N. Cartiglia. Weightfield 2 Simulation Software)



50um and 35um at high gain have the same timing resolution with low CFD percentage.

Radiation Damage, Acceptor Removal of the Gain Layer

- Radiation damage on Silicon sensors is the result of atom dislocation in the crystal structure due to collisions from incoming particles
  - For the case of LGAD, the major radiation effect that degrades the performance is the removal of acceptors in the multiplication layer with irradiation dose Φ.
- The mechanism behind the acceptor removal is still unknown.

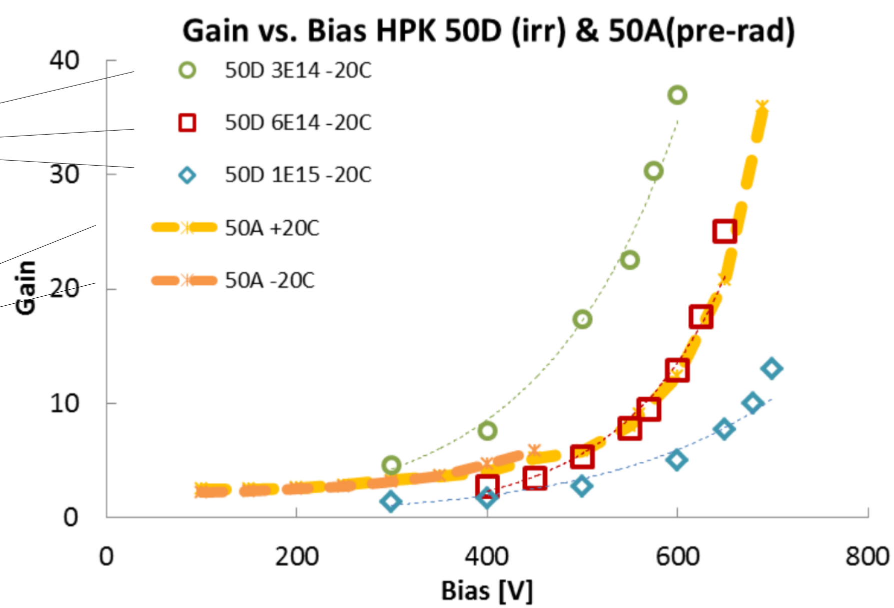
$$N_A(\phi) = g_{eff}*\phi + N_A(\phi = 0) *exp(-c*\phi)$$

  - **Plausible explanation: inactivation of Boron in the multiplication layer.** (For more details, please check out M.Ferrero et al. **arXiv:1802.01745**)
- The radiation effects can be seen in the gain measurement. Measurement with HPK-1 50D after irradiation is shown below
  - The gain of 50D after irradiation with fluence 6E14 neq/cm^2 overlaps with the 50A curve.
  - Corresponds to 70% of the initial doping density of the gain layer.

  => this is the effect of acceptor removal.

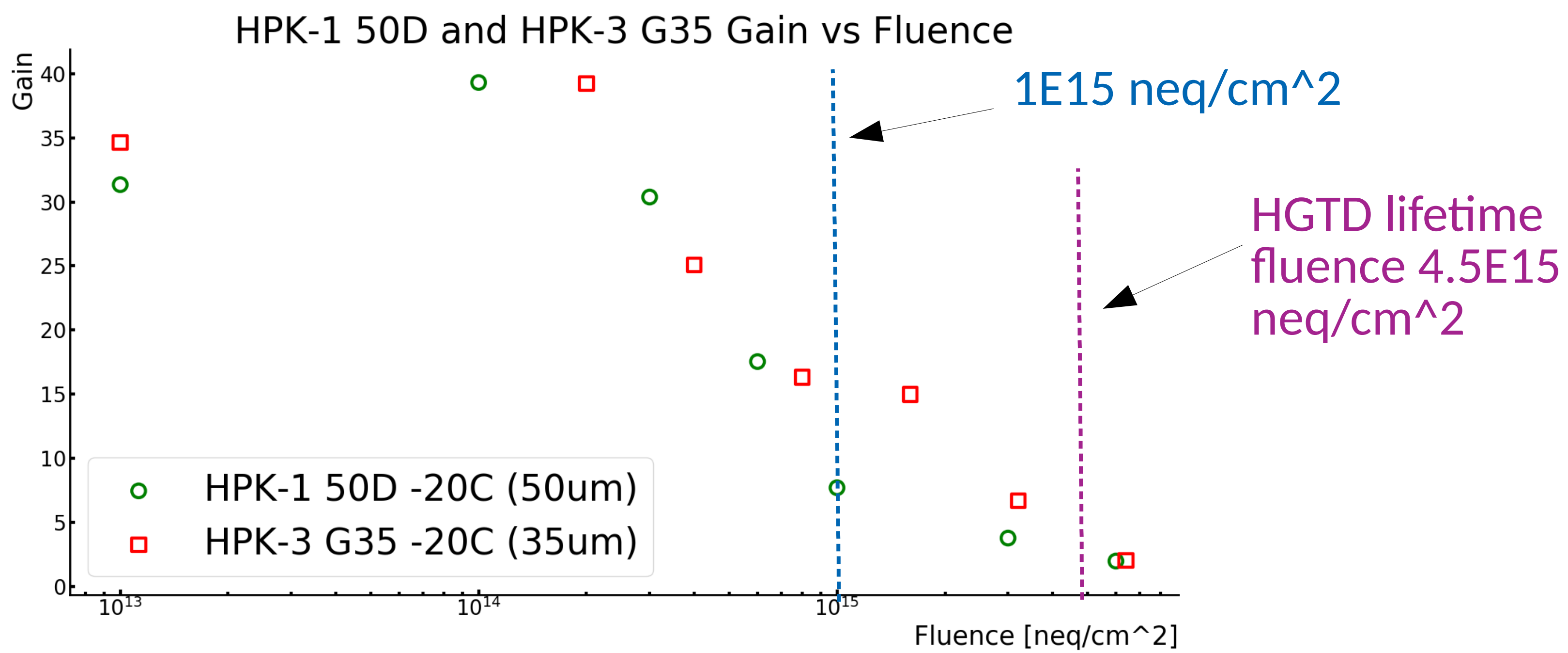
50D after irradiation with fluence of 3E14, 6E14, and 1E15.

50A **before irradiation.** (Dash yellow curve)



Gain Reduction At Different Fluence

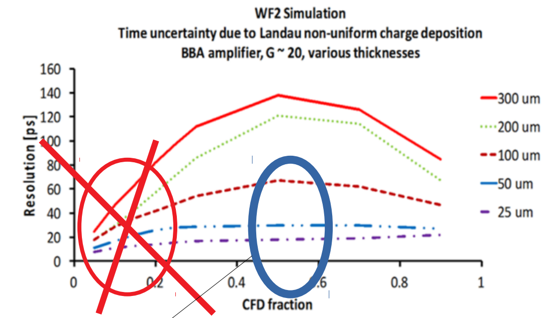
- The gain reduces due to acceptor removal, but the original value can in principle be compensated with higher bias voltage.
- However, the radiation also lowers the sensor break-down voltage. The plot below shows the gain at the maximum bias voltage before break-down.



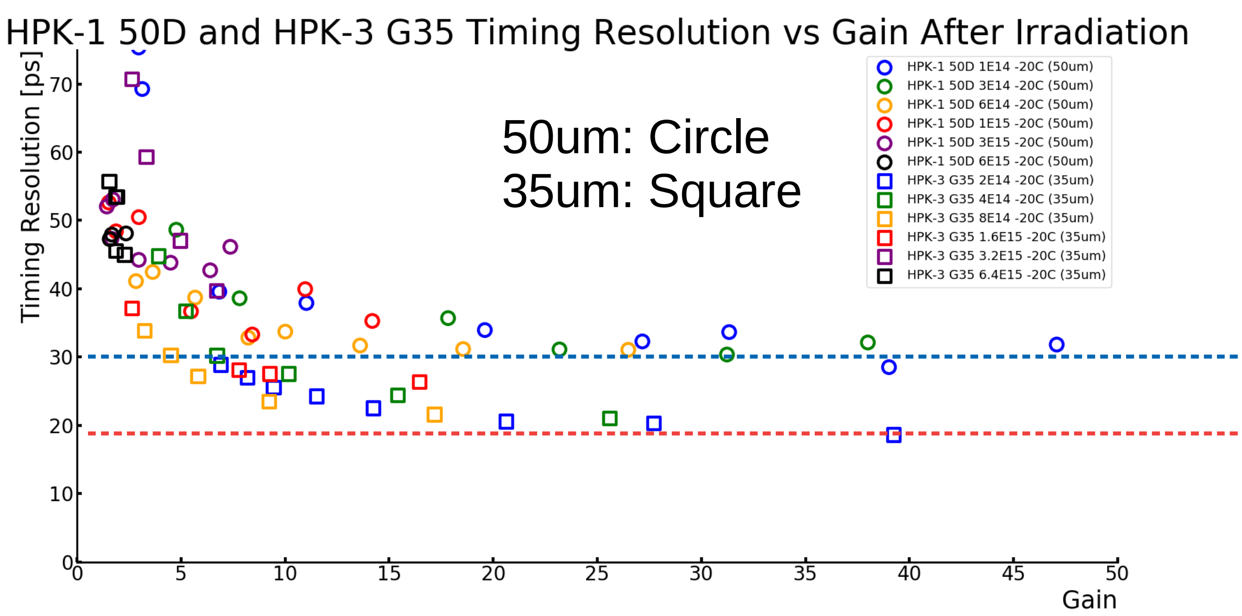
Timing Performance After Irradiation

- Since the gain reduces with doping density due to acceptor removal, a higher CFD percentage needs to be used to account for the reduce of signal height
  - **The Landau noise becomes dominant.**
  - **As we saw for jitter, thinner is better.**

    (smaller Landau noise)



Gain is reduced. Low CFD is not applicable. CFD is around 50%.



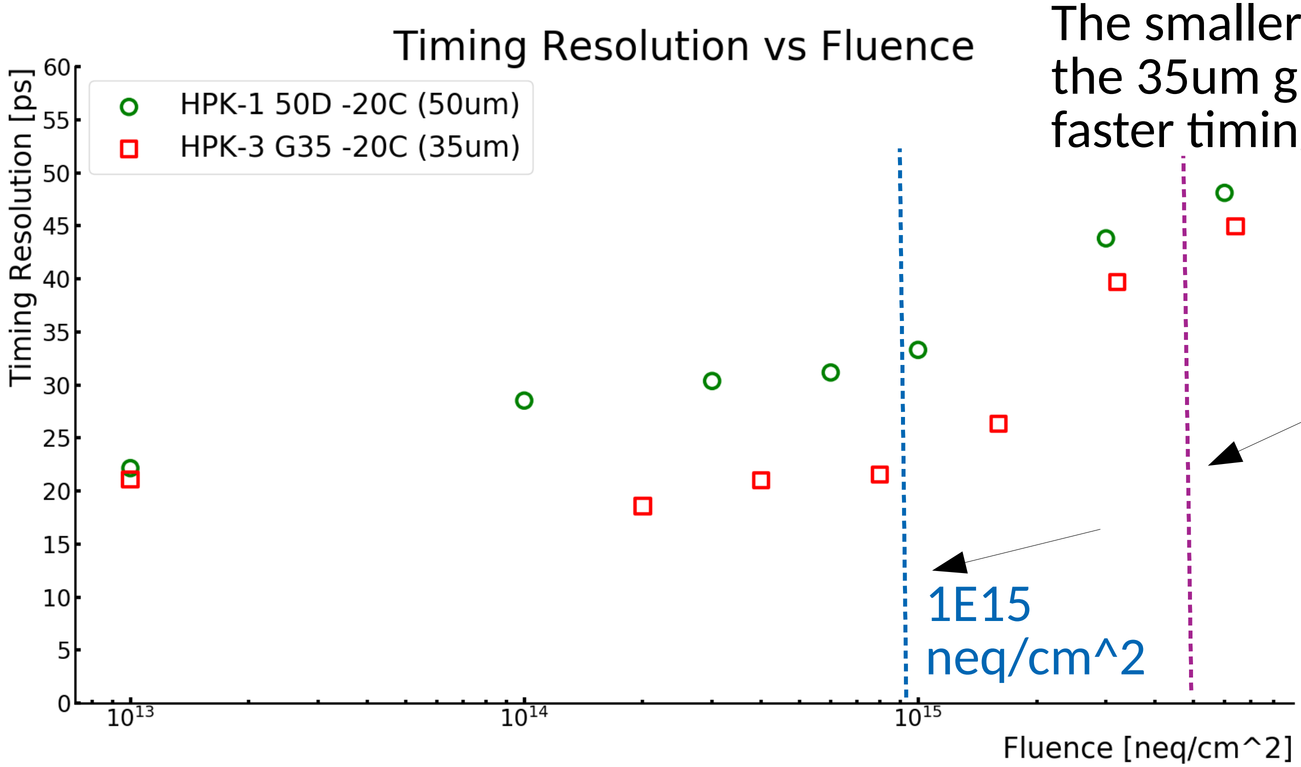
Measured timing resolution of 50um (50D) and 35um (G35) after irradiation.

50um: 30ps

35um: 20ps

Timing Performance at Different Irradiation Level

- The figure below shows the timing resolution at the maximum gain before breakdown for each fluence.
- The timing resolution starts to degrade after 1E15 neq/cm^2.
- The advantage of thinner LGADs (35um): **Faster timing once detectors start taking data.**

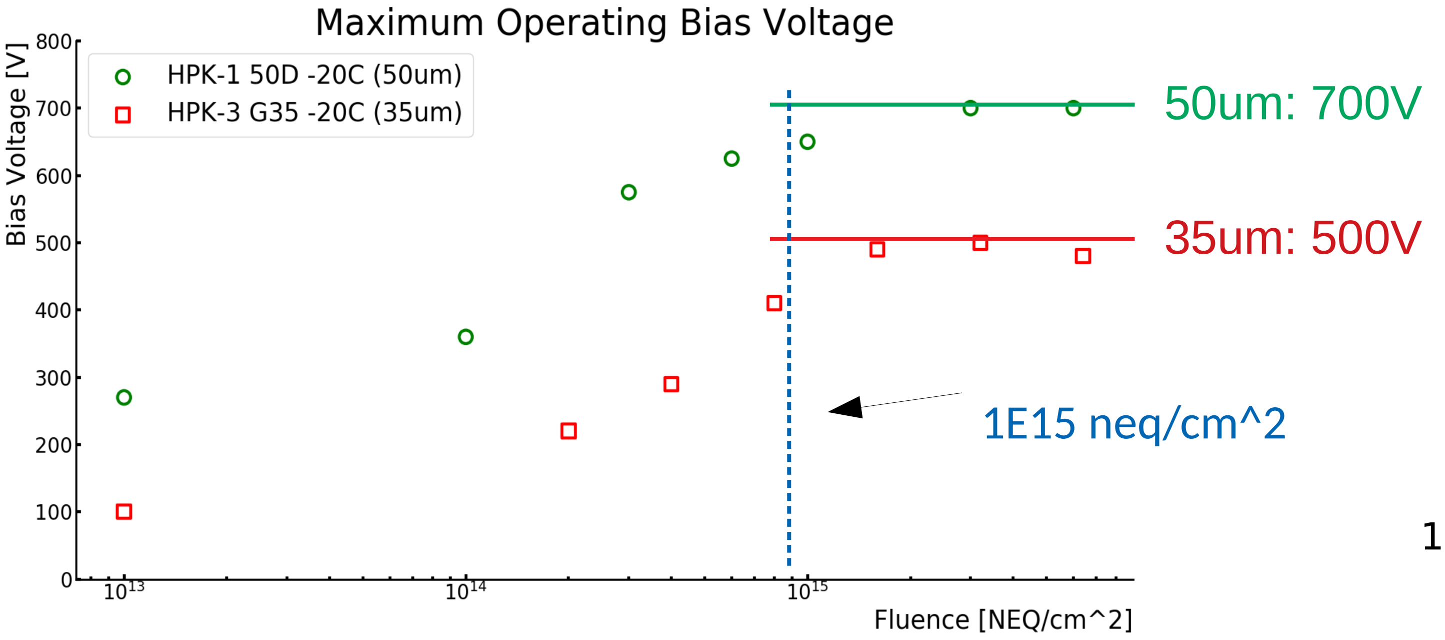


The smaller Landau noise in the 35um gives an overall faster timing resolution.

Operating Bias Voltage

- The bias voltage needs to change over time to account for the radiation damage and maintain the timing performance in the experiment.
- The bias voltage at the maximum gain is show below for each fluence
  - The change of bias voltage over irradiation level is approximately the same for both thicknesses: delta V ~ 400V.
  - The ratio of the bias voltage for the two thicknesses is constant
  - **The maximum bias voltage only depends on thickness**

    => Thinner sensors, lower bias voltage

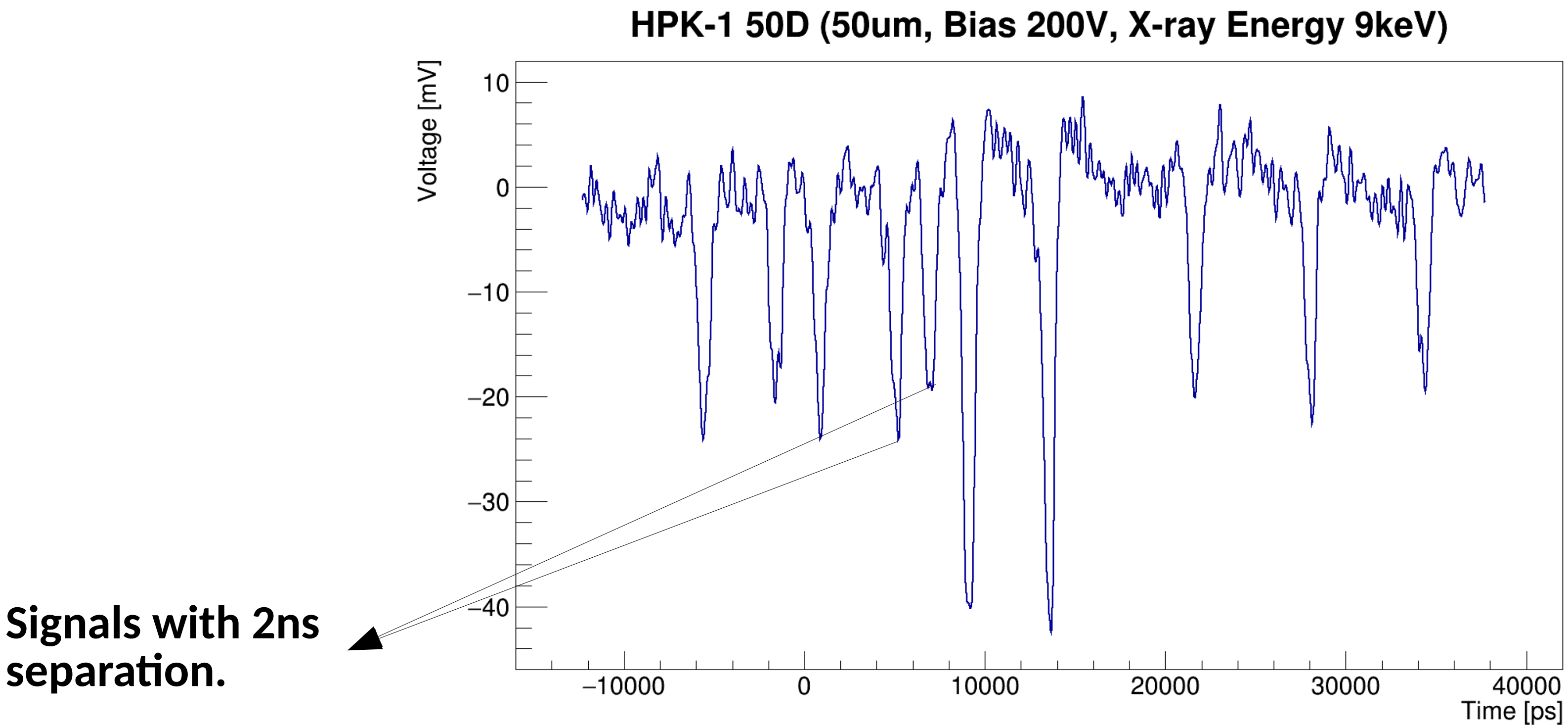


Additional Application (X-ray Detection)

- Moderated gain provides good SNR
  - **low energy x-ray detection.**
- **Reasonable good timing resolution.** (less than or euqal to 100ps was measured in test-beam.)
- Fast signal collection time
  - **narrow signal width**. (better than 1ns)
  - Small pulse pile-up effect. => **suitable for high repetition rate measurement.**
  - **Resolve individual beam spill.(see next slide)**

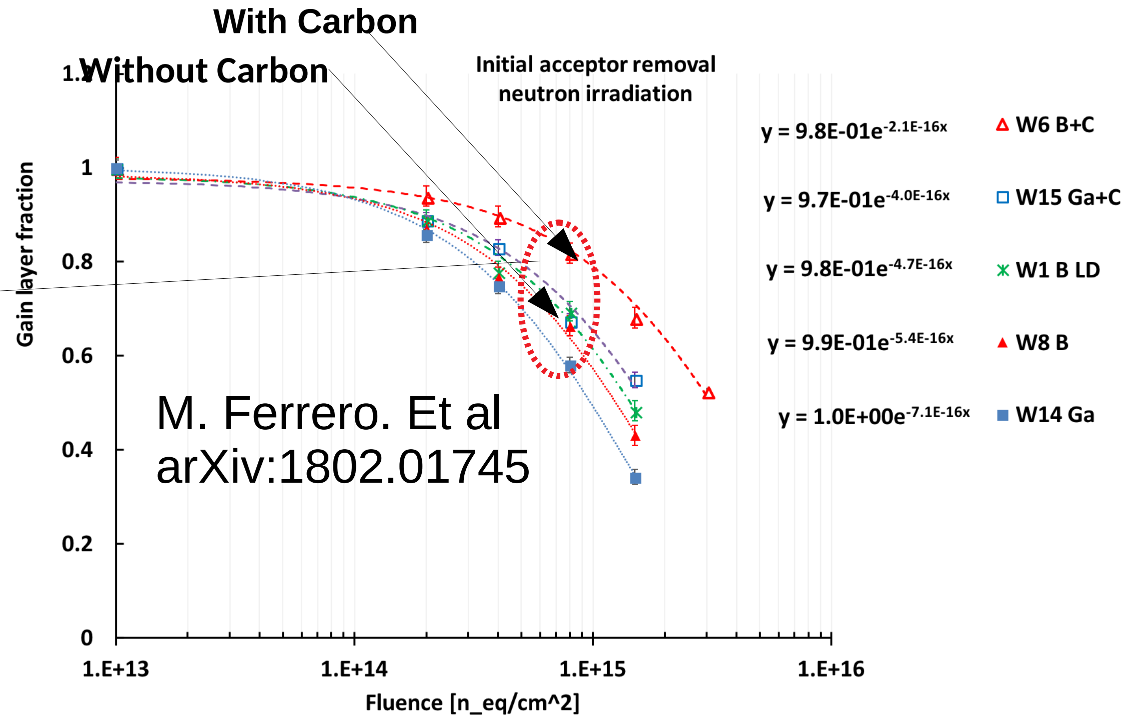
Additional Application (X-ray Detection)

- Test-beam at **Stanford Synchrotron Radiation Light-source (SSRL)**
  - High rate X-ray (500MHz)
  - Energy range: 6keV to 16keV
- **More details were presented in the poster section.**



Reducing the Accptor Removal Effect with Carbon Spray

- Study on the acceptor removal for LGADs with different dopants and “Add-on” with C-V measurements has been done and shown below.
  - The fraction doping density is shown at different fluence level.
- Proposed Methods of preventing acceptor removal on the gain layer
  - **Start with higher initial doping.**
  - **Addition of Carbon (spray) appears to be beneficial (study still ongoing) .**
    - **For MIP measurement comparison of with and without Carbon, please refer to S.Mazza arXiv:1804.05449)**.



More doping remains at the same irradiation level with Carbon spray.

Conclusion

- **LGADs are fast silicon sensors with timing resolution of 20 ps before irradiation.**
- After irradiation:
  - **LGADs can maintain stable timing performance up to fluence of 1E15 neq/cm^2.**
  - **Tolerable degradation for higher fluence.**
- In the camparison of HPK 50um and 35um LGADs
  - Thinner sensors have smaller jitter at the same gain.
  - Landau noise is smaller for thin sensors.
  - Required bias voltage is lower for thin sensors.
  - **The thinner sensors have better performance in general.**

    => Suggest to go thin
- **Next:**
  - **Try with 20um sensors to suppress the Landau noise.** (Testing ongoing.)
  - **Performance of LGAD pixel arrays =>** study of dead area and spatial resolution.
  - **Radiation Hardness improvement.**

Contributors

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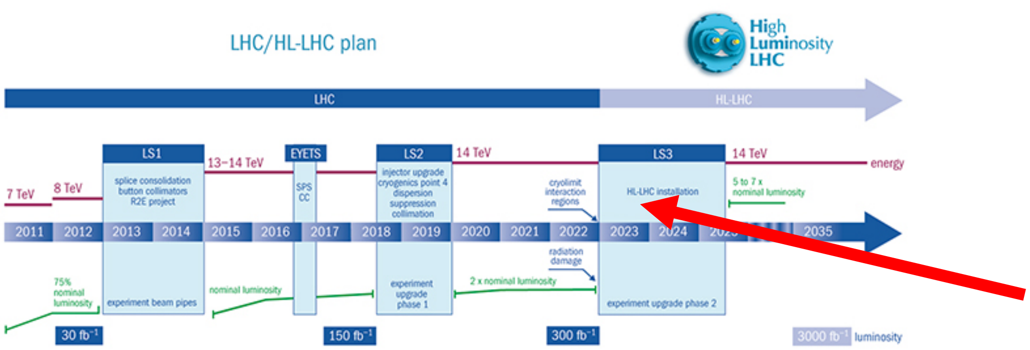
HGTD Timeline



Activity name	Start	Finish
Sensor R&D	Q1/18	Q3/19
Final Sensor and pre-production	Q4/19	Q3/20
Sensor production and tests	Q4/20	Q4/21
ASIC R&D	Q1/18	Q3/19
ASIC final chip and pre-production	Q4/19	Q3/20
ASIC production and tests	Q4/20	Q4/21
Module assembly R&D	Q1/18	Q2/20
Module 0	Q3/20	Q2/21
Module production	Q3/21	Q4/23
Module loading	Q3/22	Q1/24
Layer integration HGTD-A	Q3/23	Q4/23
Layer integration HGTD-C	Q1/24	Q3/24
Off-detector electronics R&D	Q1/18	Q4/19
Off-detector electronics prototype production	Q1/20	Q4/20
Off-detector electronics production	Q1/21	Q2/22
Mechanics R&D	Q1/18	Q1/20
Mechanics components prototypes	Q2/20	Q4/20
Mechanics components production	Q2/21	Q4/21
Services R&D	Q1/18	Q2/19
Services prototypes	Q3/19	Q4/19
Services production	Q3/22	Q2/23
Services installation	Q1/24	Q4/24
Back End, LV/HV in USA15 installation	Q3/23	Q2/25
Installation HGTD-A	Aug/24	Sept/24
Commissioning HGTD-A	Q1/25	Q4/25
Installation HGTD-C	Dec/24	Jan/25
Commissioning HGTD-C	Q1/25	Q4/25

Back-up

Doping Density.

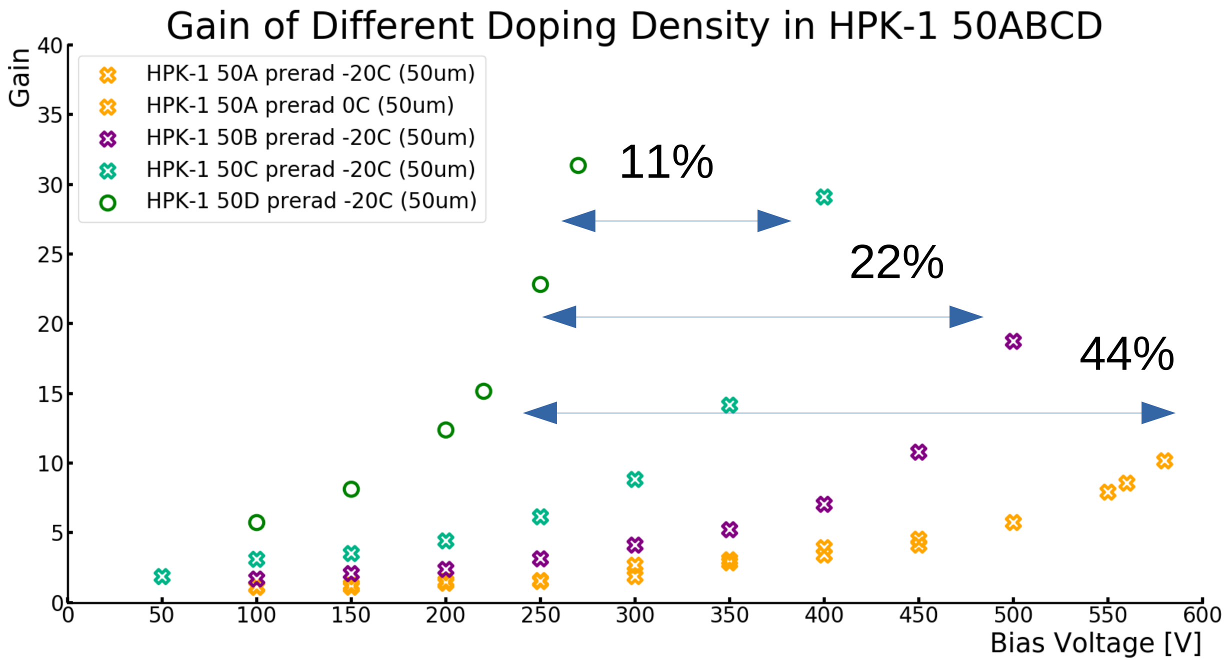
- The doping density can be shown equal to

$$N = \frac{2}{q\epsilon A^2} \frac{1}{\frac{d(1/C^2)}{dV}}$$

Split of Gain curves for Different Gain Layer Doping Density.

The different gain curves for the 50um are the results of different doping density in sample A,B,C and D.

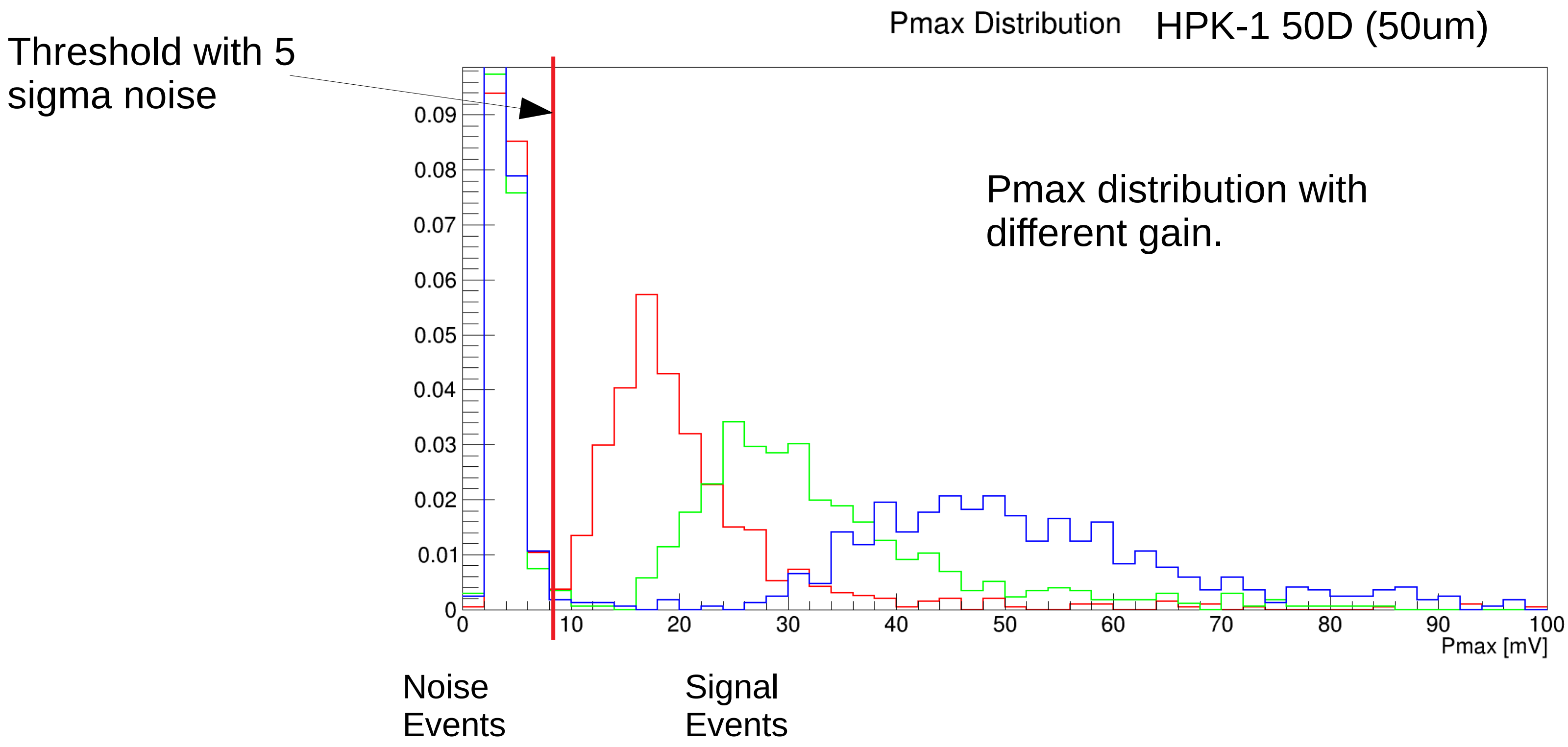
Starts from the left, the D has the highest doping, and the required bias voltage to achieve certain gain is relatively smaller than the less doped samples.



SNR and Signal Efficiency

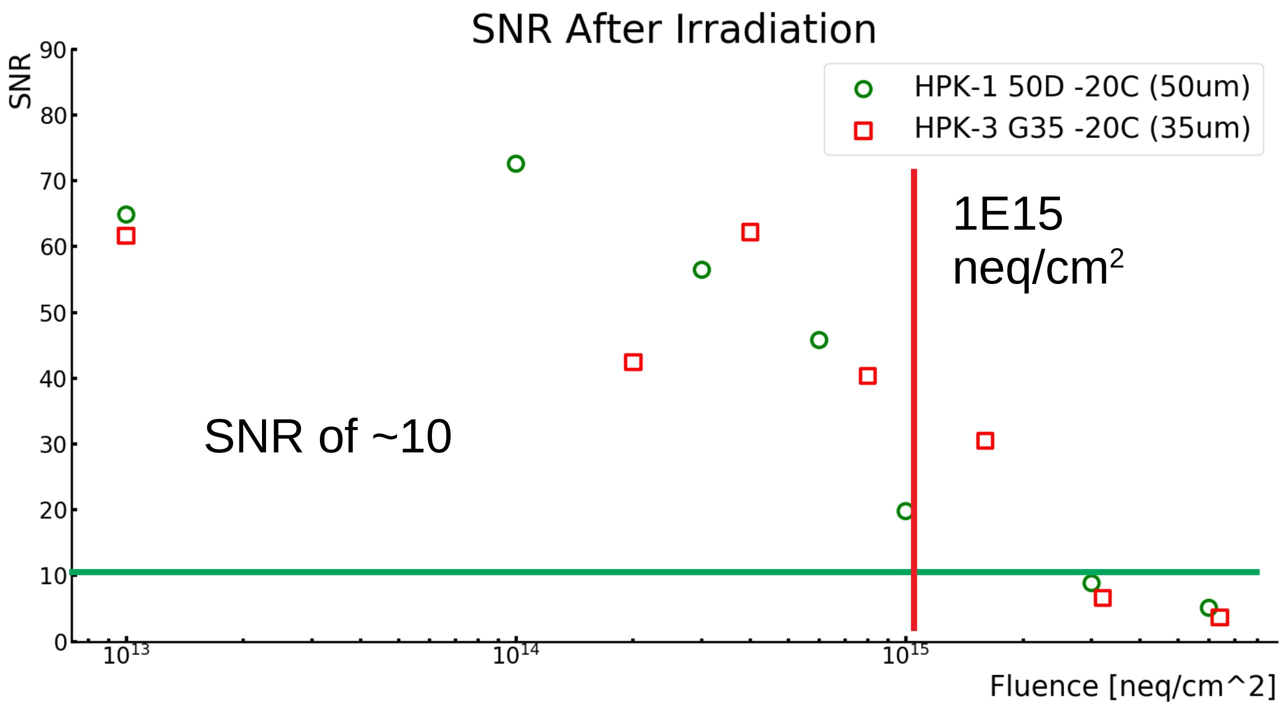
- The SNR describes the signal efficiency
  - The noise events and signals are well separated with SNR of > 10
  - The noise event and single MIP event are indistinguishable when the SNR is lower than 10

    >> SNR of 10 is the minimum required value.
  - A threshold of 5 sigma noise can be used for separating the noise event and the single MIP event with maximized efficiency.



Timing Performance After Irradiation (SNR)

- As shown that the minimum SNR to have maximum signal efficiency is ~10, this criteria is useful for determining the performance of LGAD after irradiation.
- In the figure below, the SNR transition between the minimum requirement starts at fluence of 1E15 neq/cm^2. These two LGADs are guaranteed to have maximum signal efficiency and minimized noise occupancy below this critical fluence.



Why sometimes the timing resolution is better after irradiation at the same gain?