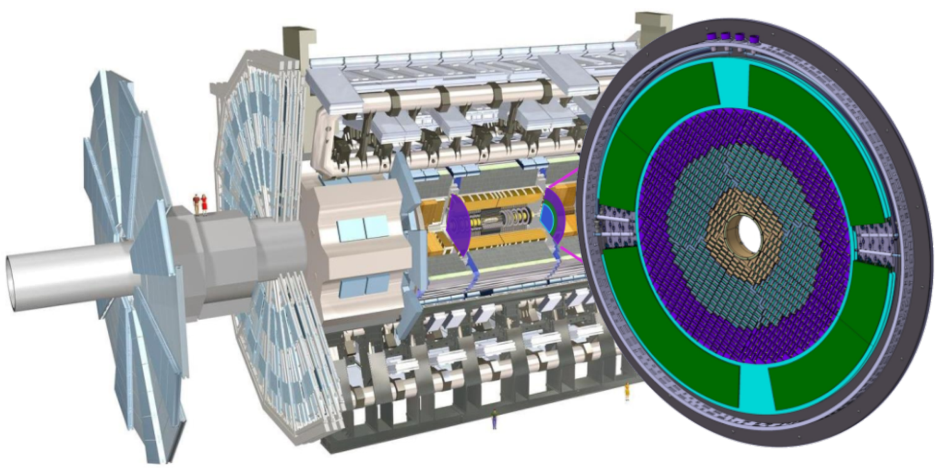
Characterization of LGAD sensors for the High Granularity Timing Detector in the ATLAS Phase-II upgrade project

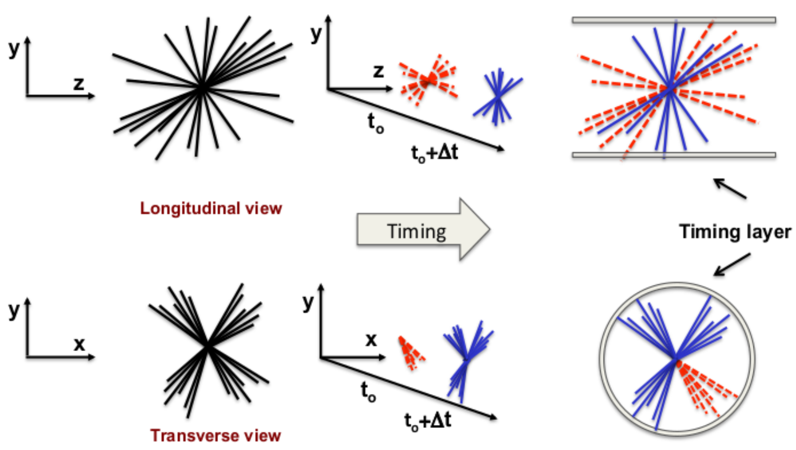
HL-LHC

- During the new phase of the LHC experiment, High Luminosity LHC, the instantaneous peak luminosity will increase to $7.5 \cdot 10^{34}$ cm^{-2} s^{-1}, more than three times the maximum value ever reached
- The total integrated luminosity will be 4000 fb^{-1}
- The number of the pile-up interactions per bunch crossing will increase to an average of 200 for an interaction density of 1.8 collisions/mm corresponding to nearly 1.44 reconstructed vertices/mm
- The ATLAS detector will undergo different upgrades to withstand the increased pile-up and to reach the physics goals of the HL-LHC project
- A new detector called High Granularity Timing Detector (HGTD) will be installed in the ATLAS forward region to improve the events reconstruction performance of the ATLAS detector

HGTD

- The HGTD will perform high precision timing measurements to improve the events reconstruction performance and to mitigate the effects of the pile-up increase
- It will associate a time information to the tracks reconstructed by ITk in the forward region
- The tracks to vertex association will rely on both geometric and timing compatibility



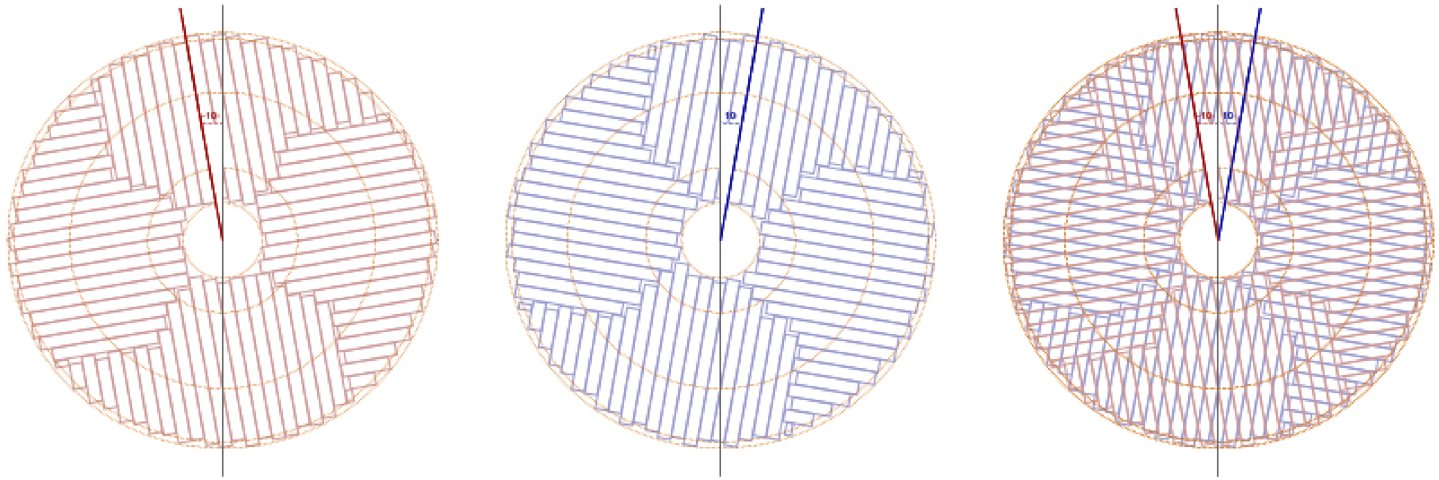


HGTD

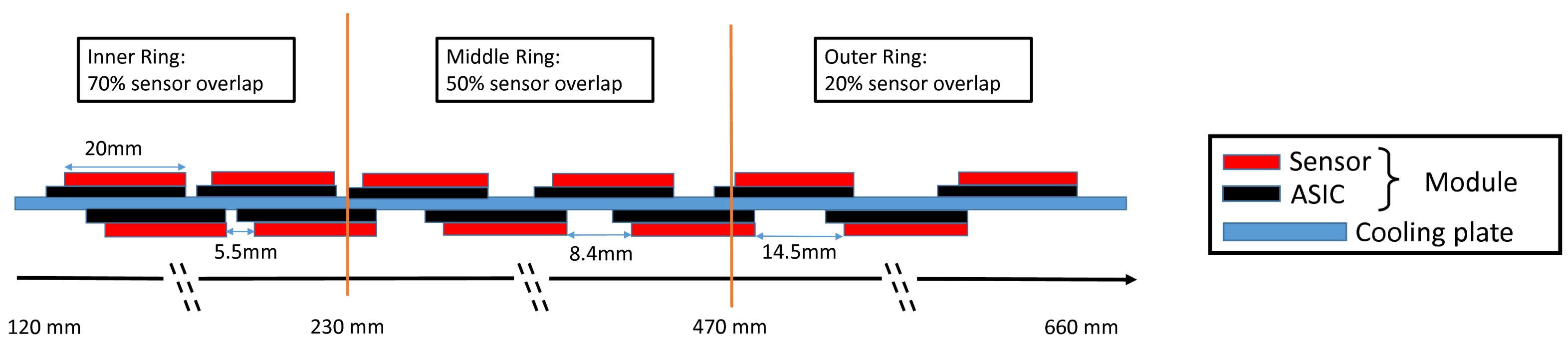
- These time measurements will be peformed by LGAD (Low Gain Avalanche Detector) sensors
- The LGAD timing resolution shoulb be 30 ps at the beginning of the data taking and 70 ps at the end
- The LGAD gain should be at least 20 at the beginning of the data taking and at least 8 at the end
- The degradation of the LGAD performance with time is caused by radiation damage
- To mitigate the degradation the sensors will be installed on two-sided layers that will be mantained at a temperature of -30° C
- These layers will be divided in 3 separate regions in radius that will be replaced during the experiment to reduce the total radiation taken by the sensor to a maximum fluence of $2.5 \cdot 10^{15}$ n_{eq} cm^{-2}

HGTD modules

- The LGADs pads will have a size of 1.3 mm × 1.3 mm
- HGTD will mount 8032 sensors modules, each module is made by 30 × 15 pads for a total size of 4 cm × 2 cm



(a) First layer (b) Second layer (c) Overlay



LGAD

- LGADs are a type of n-in-p silicon detectors with an additional doped layer that introduces in the detector a charge muliplication region. This layer is callled gain layer.
- LGAD time resolution depends on:
  - Landau fluctuations:

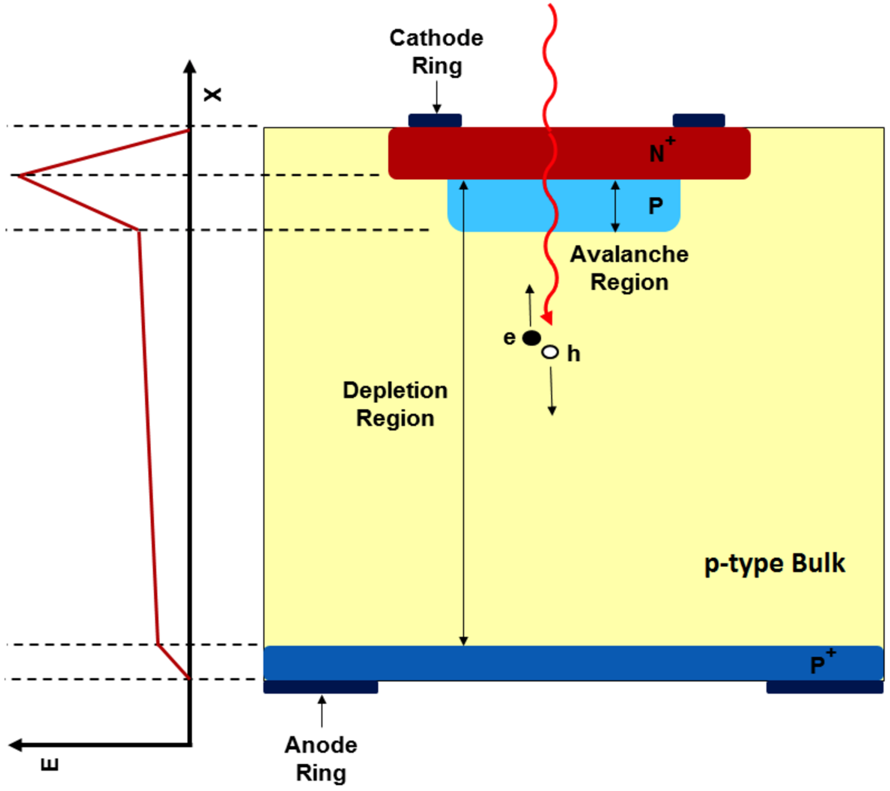
    $$\sigma_L \propto l \propto t_{rise}$$

  - Jitter noise:

    $$\sigma_j = \frac{N}{dV/dt} \simeq \frac{t_{rise}}{S/N}$$

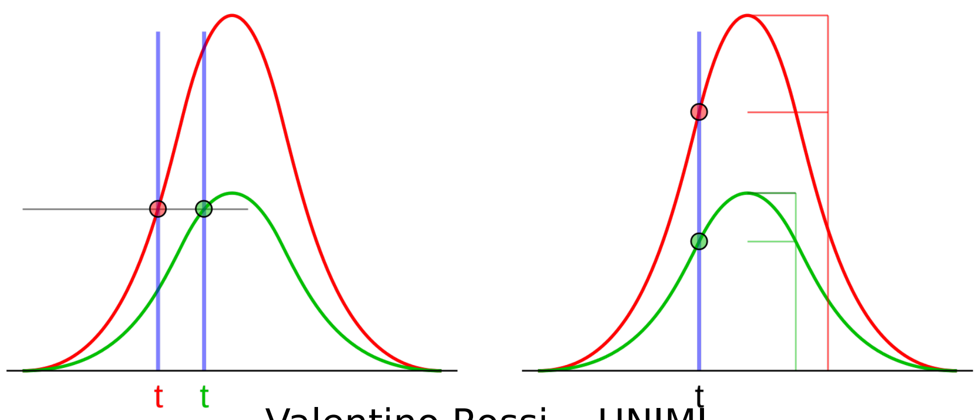
  - Time-walk effect:

    $$\sigma_t = \left[\frac{V_{th}}{S/t_{rise}}\right]_{RMS}$$



LGAD time resolution

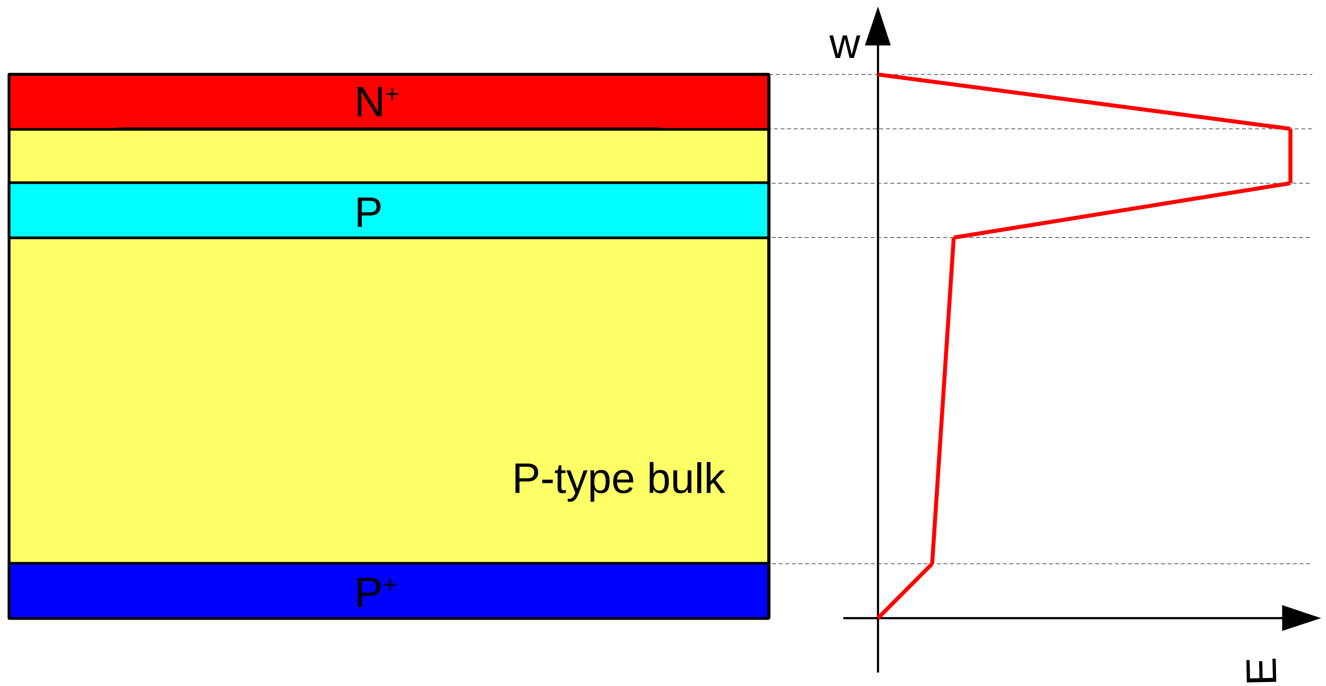
- **Landau fluctuations**: they are the fluctuation of the charge deposited in the sensor when a particle traverses it
- **Jitter noise**: the jitter noise is caused by the electronic noise affecting the signal of the sensor. The fluctuations on the voltage amplitude of the signal make difficult to estimate the exact time when the signal tranverse a certain threshold level
- **Time-walk noise**: with a simple threshold triggering, such as applying the same threshold level at different amplitutde, the output time estimation fluctuates. These fluctuations cause an error in the estimation of the trigger time and they depend on the signal peak height. The effect could be largely reduced by using a threshold trigger that is corrected using the pulse amplitude or width.



Acceptor removal mechanism

- Radiation damage in highly doped silicon causes the decrease of the doping concentration degrading the gain of the sensor and consequently its time resolution
- This effect is called acceptor removal mechanism
- This mechanism consists in the formation of electrical traps in the stucture of the silicon that absorb the dopants thus reducing their density
- The number of dopants (N) reduction after an irradiation of fluence Φ can be represented with the equation: $N = N_0 \exp(-c\,\phi)$
- An LGAD with **carbon impurities** inserted in the gain layer is **more resistant to the radiation effects** since the carbon is absorbed by the traps instead of the dopant
- Another feature that an LGAD could exploit to **mitigate the performance loss** caused by irradiation is a **deep gain layer**

Deep Gain Layer



An LGAD has a deep gain layer if the layer of highly doped material is inserted deeper in the sensor. An LGAD with a deep gain layer has a larger region with high electric field so the charge multiplication is larger and the sensor has a higher gain. The break-down voltage (V_{BD}) of a deep gain layer sensor is lower than a standard one.

LGAD analyzed

- 4 types of LGAD sensors were analyzed
- 2 were produced by Hamamatsu Photonics (HPK), Japan
- 2 were produced by Fondazione Bruno Kessler (FBK), Italy
- Several data analyzed here were provided by the laboratories of the University of California Santa Cruz (UCSC)

LGAD analyzed

	Dopant	Deep gain layer	Carbon impurities	Thickness (μm)
HPK 3.2	Boron	yes	no	50
HPK 2	Boron	yes	no	50
FBK 3	Boron	no	yes	55
FBK 3.2	Boron	yes	yes	45

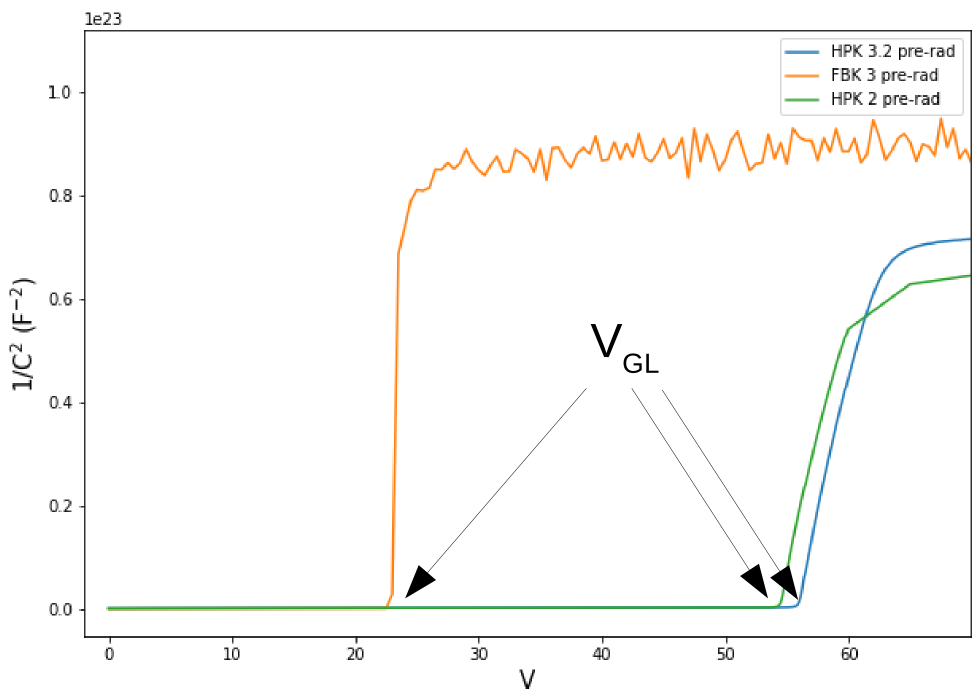
- The sensors analyzed were both irradiated and non irradiated
- The sensors were irradiated in the JSI research reactor of TRIGA type in Ljubljana

Measurements performed

- **The static parameters measurements**: the capacitance-over-voltage scans done in the UCSC laboratories allow to estimate the radiation hardness of the LGADs.
- **The β-telescope measurements**: the data from the UCSC β-telescope laboratories were use to perform a characterization of the LGADs sensor in terms of gain, time resolution and rise time.
- **The interpad gap mesurements**: 2D laser scans were performed to 2×2 LGAD pads in the laboratory of the Università Statale di Milano were used to determine if the interpad gaps fullfill the HGTD requirements.

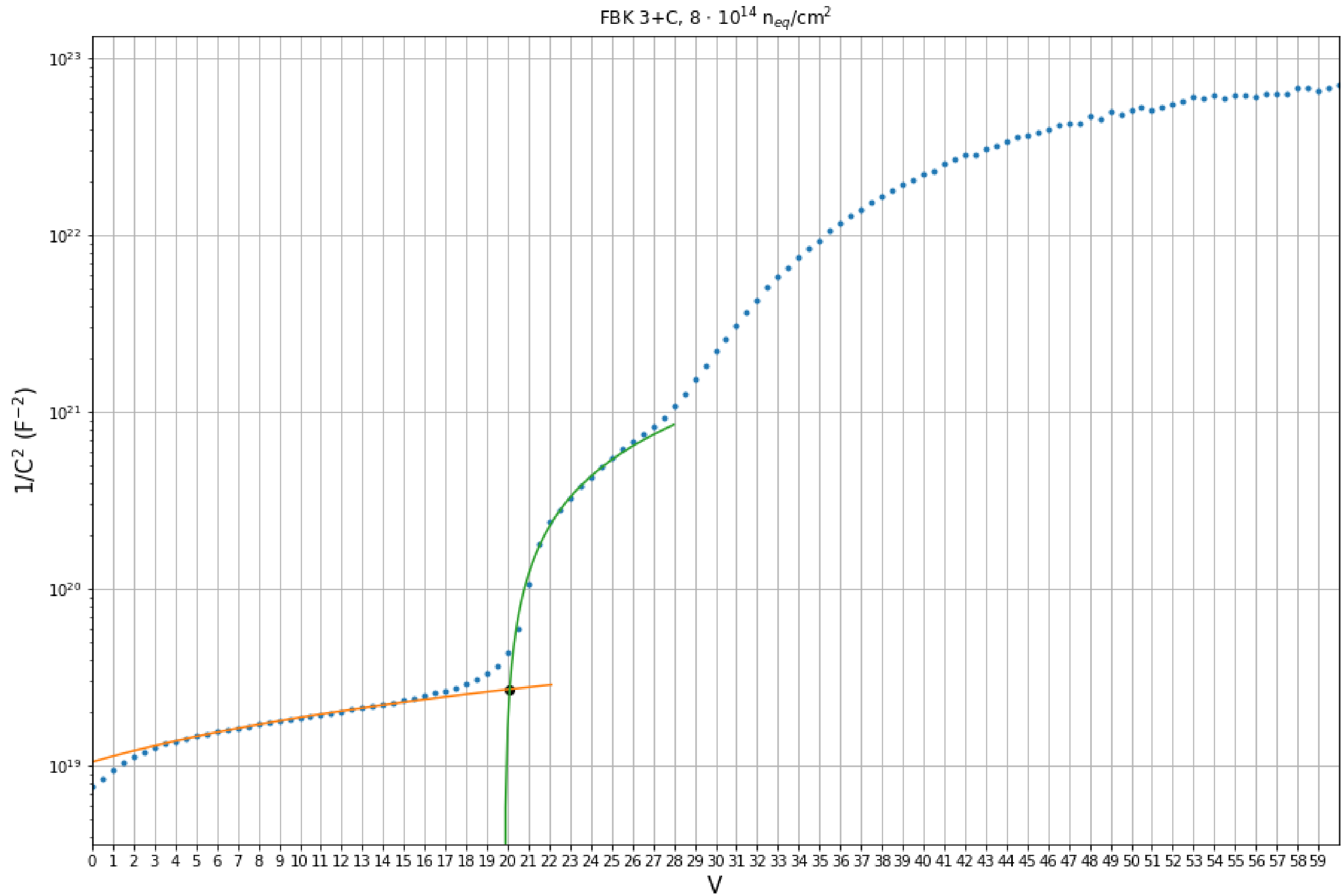
Measurement of the LGAD static parameters

- From the capacitance-over-voltage measurements the "foot" voltage (V_{GL}), the voltage of complete depletion of the gain layer was extracted.
- Its value depends on the dopant density in the gain layer.

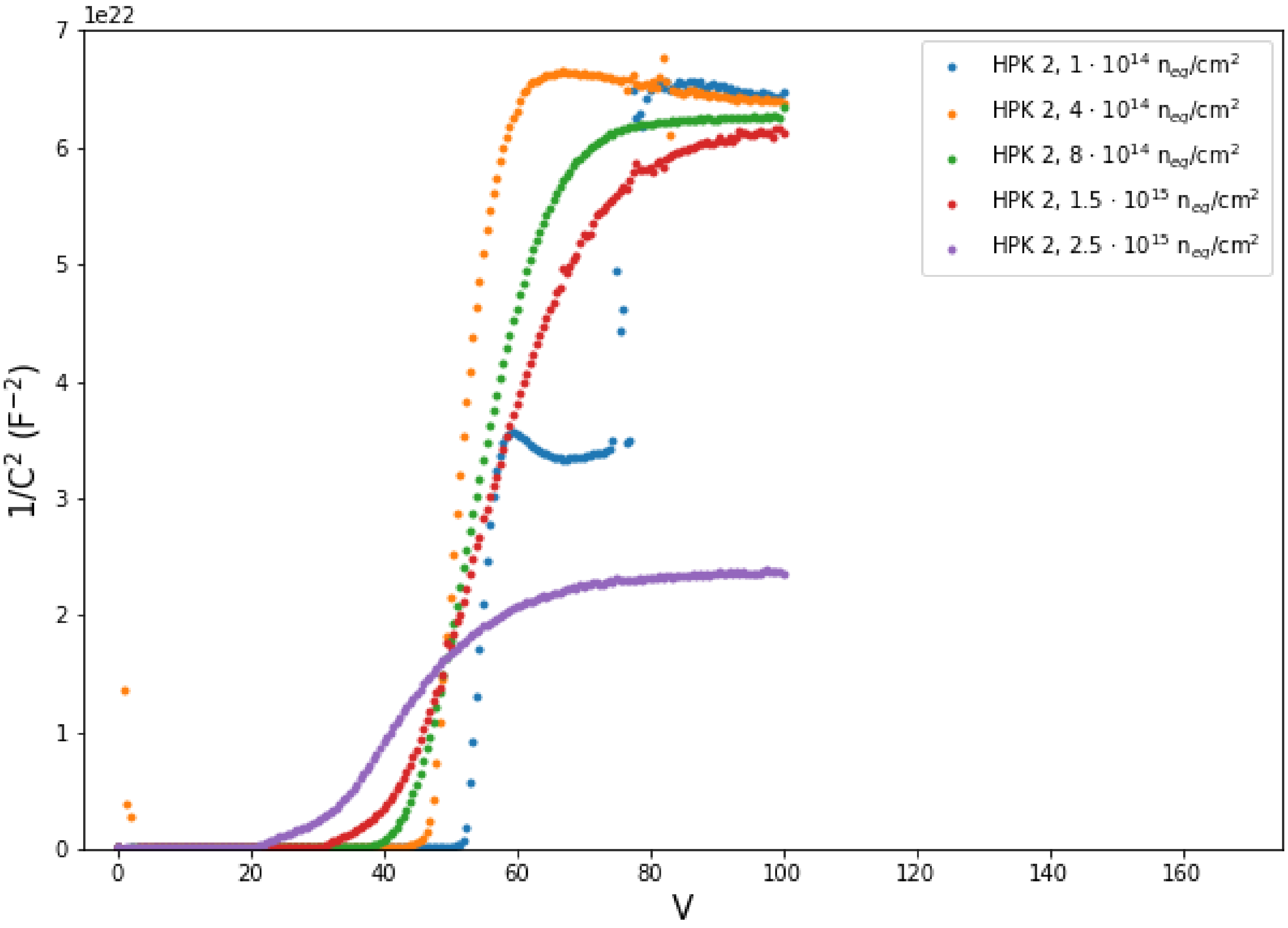


- The HPK sensors have a higher V_{GL} since they have more dopant density and a deep gain layer
- The FBK 3 sensor hasn't a deep gain layer so its V_{GL} is lower than the one of the HPK sensors

Measurement of the LGAD static parameters

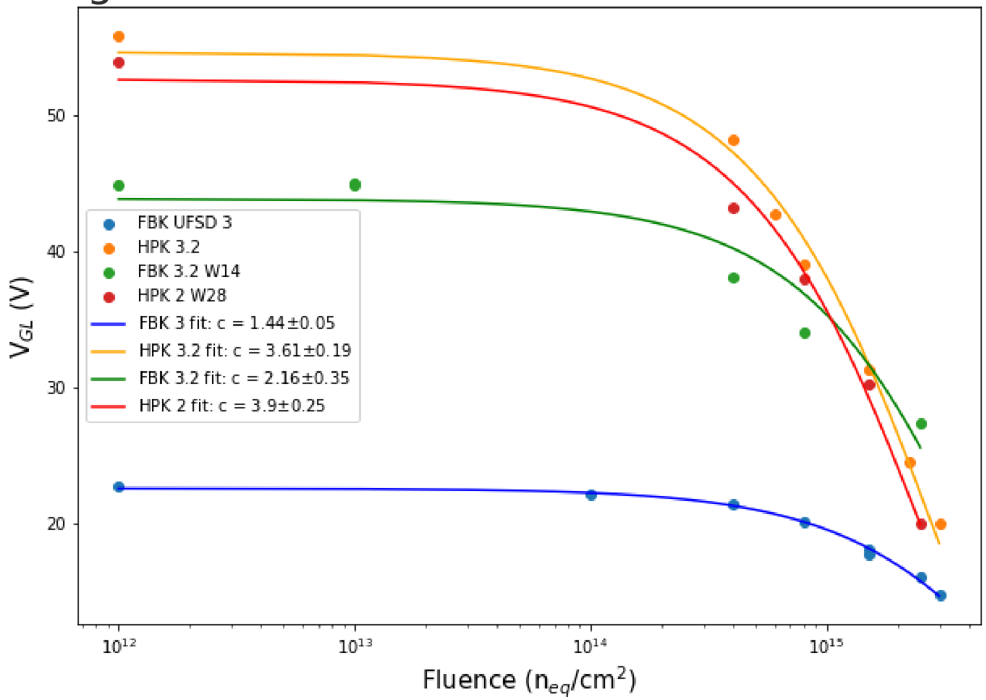


Measurement of the LGAD static parameters



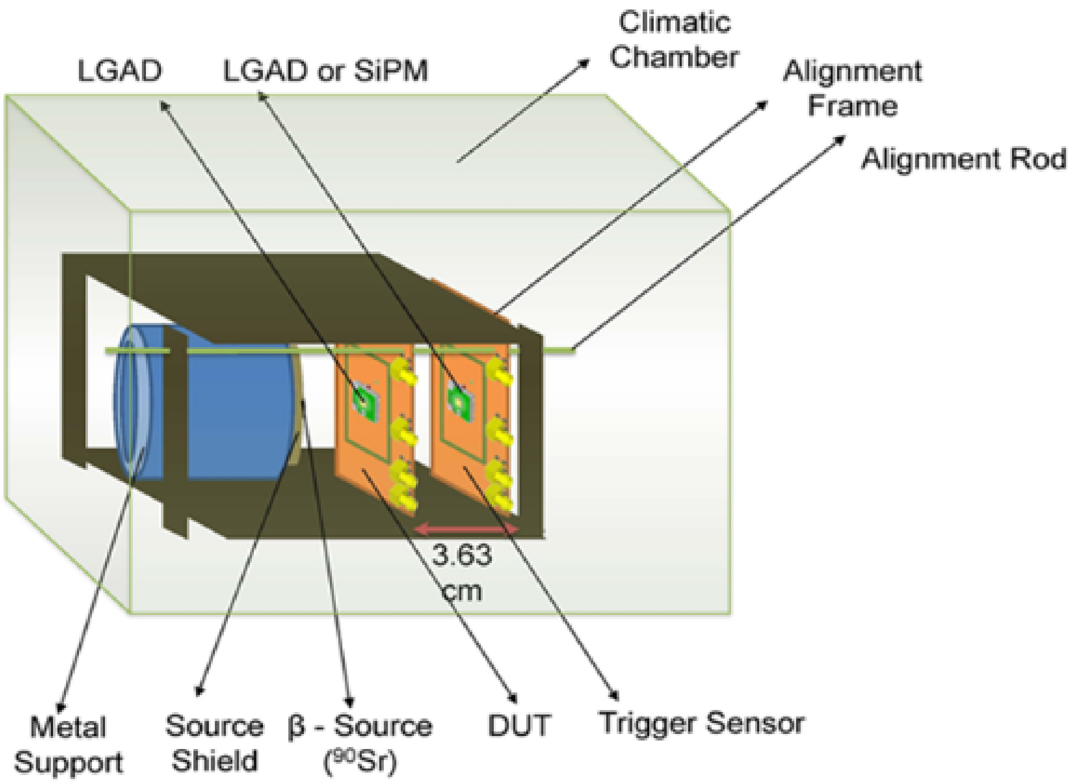
Measurement of the LGAD static parameters

- By analyzing the variations of V_{GL} for sensors exposed to different radiation levels, it is possible to estimate the impact of the radiation damage on the sensor performance
- In fact from the V_{GL} variations it was possible to extract the c-factor
- This factor indicates how "fast" the dopant density is reduced by irradiation: the higher the c-factor the most the LGAD is affected.



- The FBK 3 and 3.2 have a lower c-factor since their carbon insertions reduce the radiation damage (1.44 and 2.16 respectively).
- The HPK 3.2 and HPK 2 have a c-factor of 3.61 and 3.9, so they are more sensitive to the radiation damage
- The HPK curves are very similar because their doping profile is similar

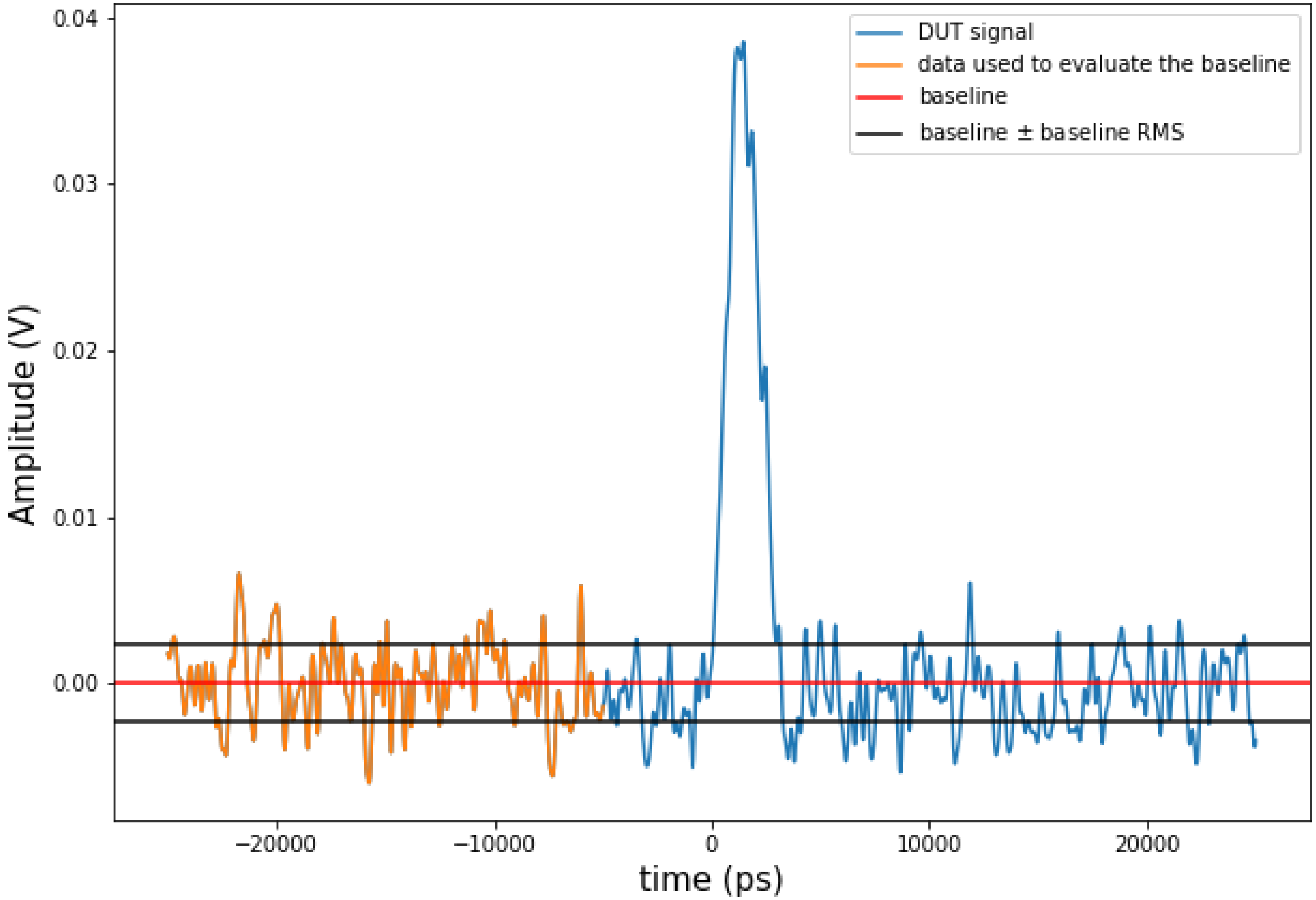
Timing and gain performance



The measurements are taken using a β-telescope (^{90}Sr). The radiation is used to excite both the device under test (DUT) and the a trigger sensor. The trigger sensor is used as temporal reference to estimate the DUT resolution. It has a known time resolution (15 or 17 ps). The two sensors are aligned using a metallic frame. This frame is inserted in a climatic chamber that allows to perform the measurements at a constant temperature.

When hit by an electron, the sensors emit a signal that is read by the read-out electronics. The read-out board is comprised by a custom made inverting amplifier followed by a commercial 20 dB amplifier. The read-out board has a total trans-impedance of 4700 Ω. The signal waveforms are recorded and saved using a digital oscilloscope.

Timing and gain performance



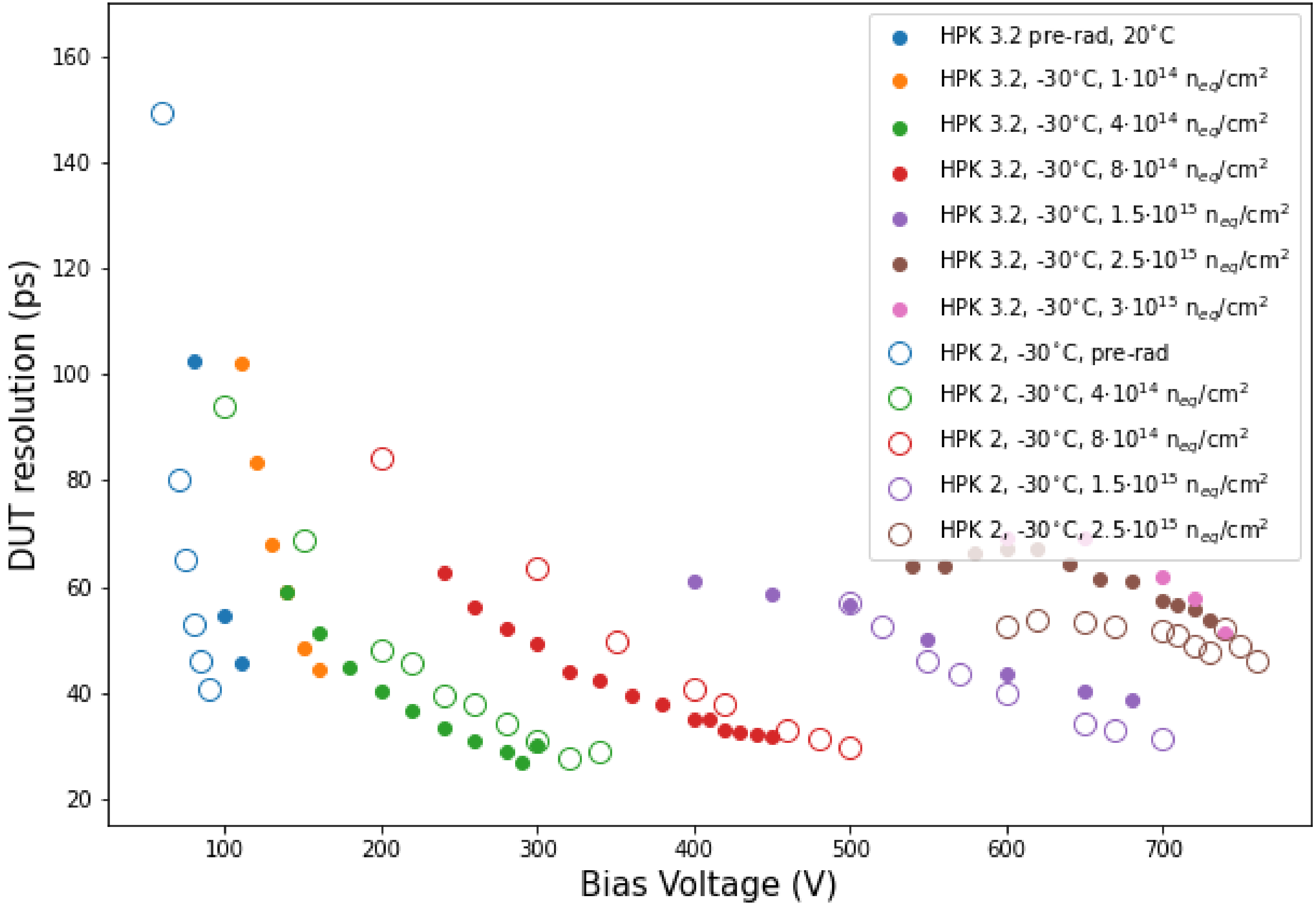
The waveforms recorded using the oscillocope from the UCSC β-telescope laboratories were used to perform a characterization of the LGADs sensors in terms of gain, time resolution and rise time.

Timing and gain performance

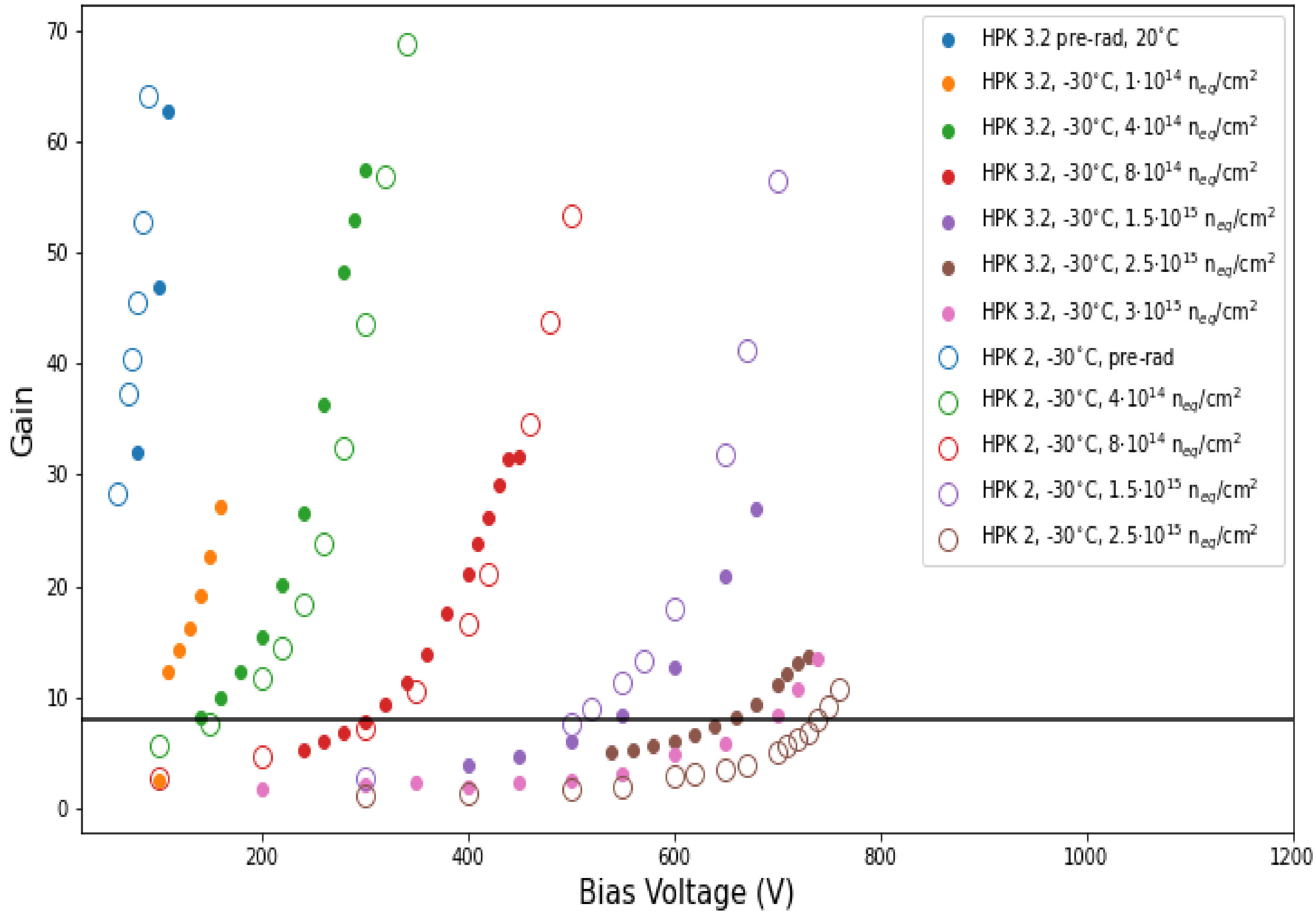
- Time resolution is estimated as the RMS of the distribution of the difference between the time when the DUT signal reach 50% of its maximum amplitude and the time when the trigger signa reach 20% of its maximum amplitude
- The charge collected by the sensor is estimated as the integral of the DUT signal between 500 ps and 5000 ps divided by the transimpedance of the readout board (4700 Ω)
- The gain of the sensor is estimated when possible by dividing the collected charge by the charge collected by a PiN diode with the same thickness and the same irradiation level as the LGAD under test.
- The rise time of the DUT signal is calculated as the difference between the time when the signal reaches 90% of its maximum amplitude, and the time when the signal reaches 10% of its maximum amplitude

HPK sensors type comparison

Time Resolution

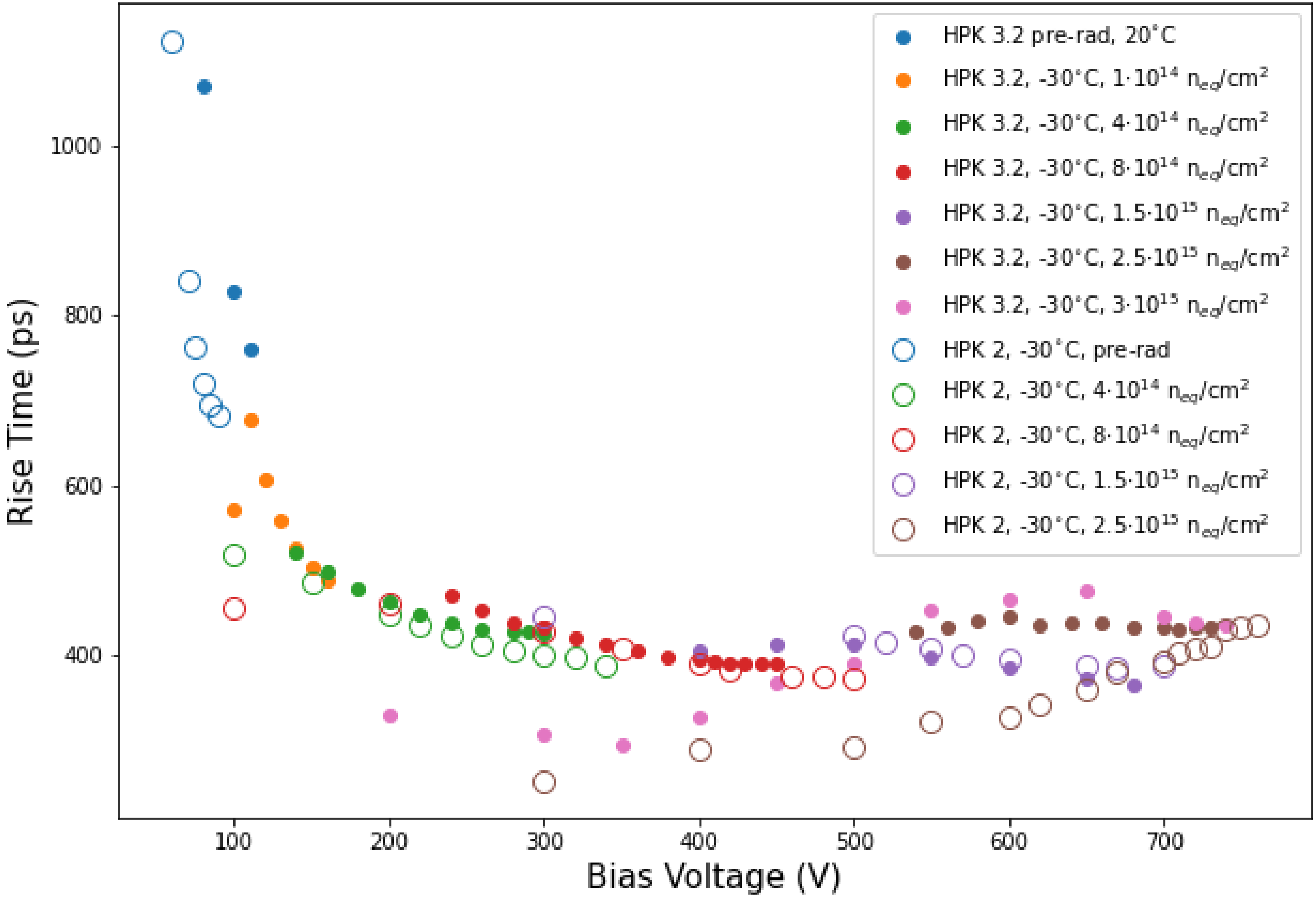


Gain



Gain
Bias Voltage (V)
0
10
20
30
40
50
60
70
200
400
600
800
1000
1200
HPK 3.2 pre-rad, 20°C
HPK 3.2, -30°C, 1·10^14 n_eq/cm^2
HPK 3.2, -30°C, 4·10^14 n_eq/cm^2
HPK 3.2, -30°C, 8·10^14 n_eq/cm^2
HPK 3.2, -30°C, 1.5·10^15 n_eq/cm^2
HPK 3.2, -30°C, 2.5·10^15 n_eq/cm^2
HPK 3.2, -30°C, 3·10^15 n_eq/cm^2
HPK 2, -30°C, pre-rad
HPK 2, -30°C, 4·10^14 n_eq/cm^2
HPK 2, -30°C, 8·10^14 n_eq/cm^2
HPK 2, -30°C, 1.5·10^15 n_eq/cm^2
HPK 2, -30°C, 2.5·10^15 n_eq/cm^2

Rise time



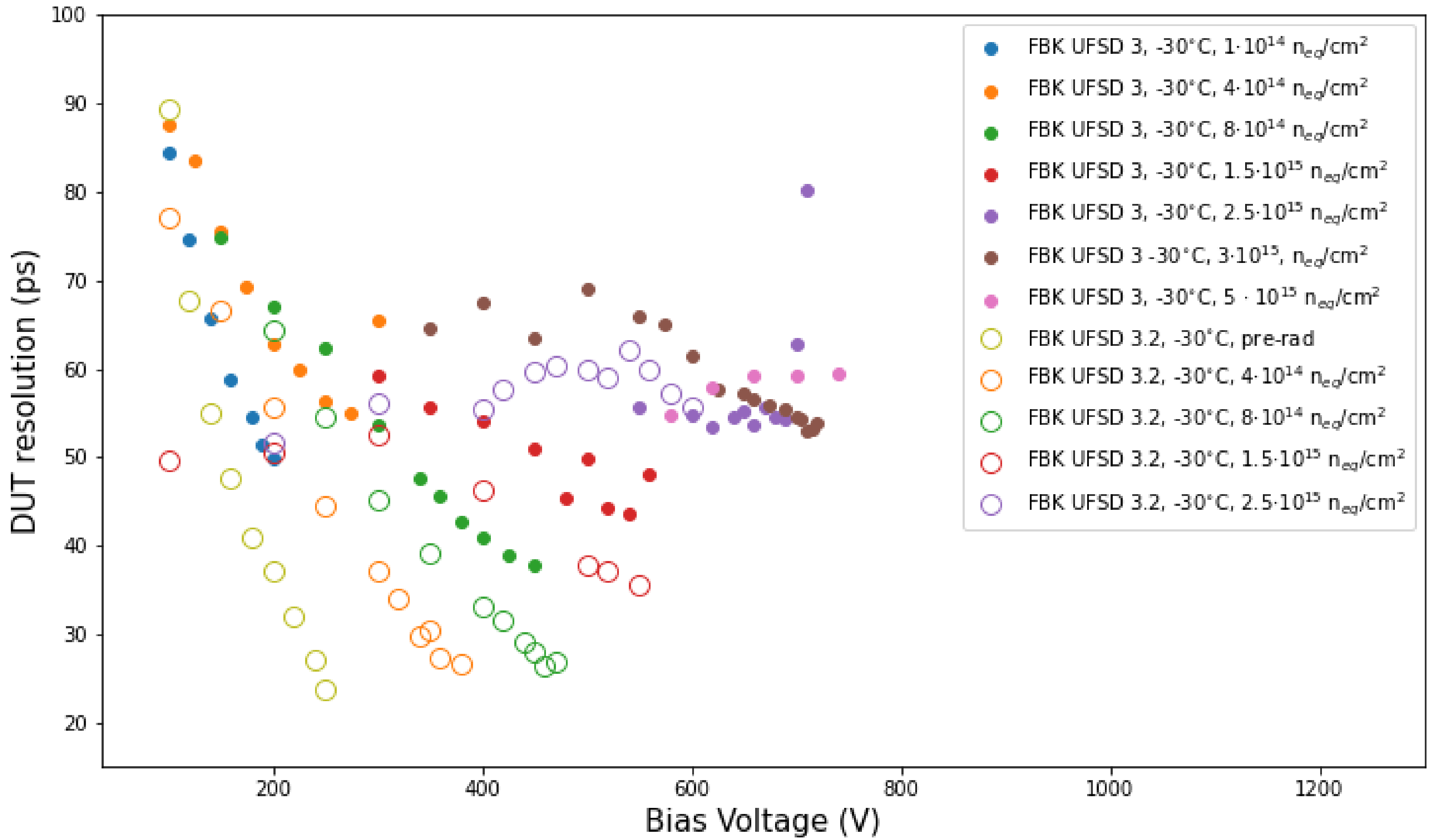
HPK 3.2 pre-rad, 20°C
HPK 3.2, -30°C, 1·10^14 n_eq/cm^2
HPK 3.2, -30°C, 4·10^14 n_eq/cm^2
HPK 3.2, -30°C, 8·10^14 n_eq/cm^2
HPK 3.2, -30°C, 1.5·10^15 n_eq/cm^2
HPK 3.2, -30°C, 2.5·10^15 n_eq/cm^2
HPK 3.2, -30°C, 3·10^15 n_eq/cm^2
HPK 2, -30°C, pre-rad
HPK 2, -30°C, 4·10^14 n_eq/cm^2
HPK 2, -30°C, 8·10^14 n_eq/cm^2
HPK 2, -30°C, 1.5·10^15 n_eq/cm^2
HPK 2, -30°C, 2.5·10^15 n_eq/cm^2
Rise Time (ps)
Bias Voltage (V)
1000
800
600
400
100
200
300
400
500
600
700

Comments

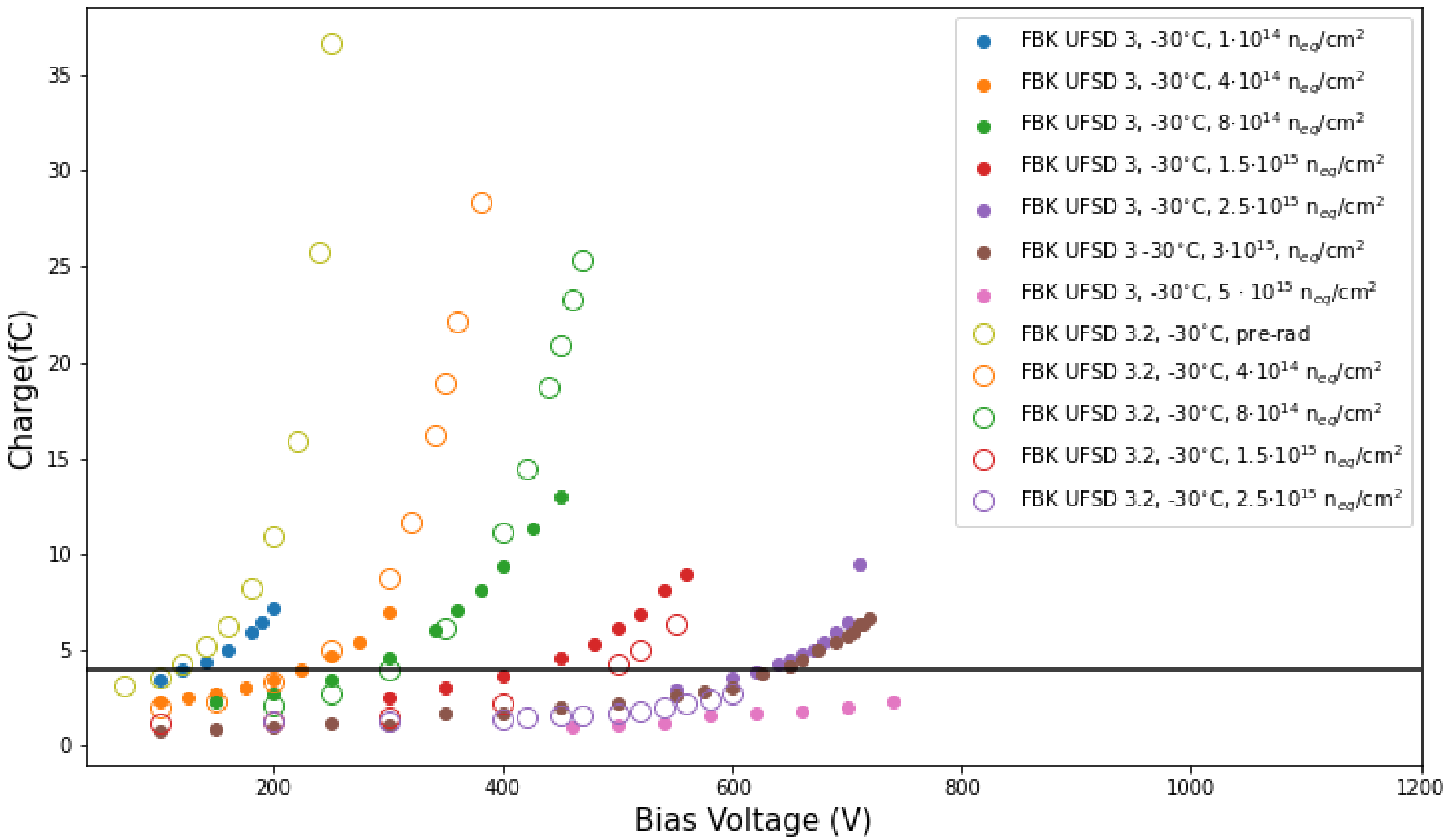
- The main difference between the performance of the new HPK model and the old can be seen in the pre irradiation performance:
  - The HPK 3.2 model has a resolution higher than 100 ps at a temperature of -30°C and at 20°C has a resolution of 50 ps at 100 V
  - The HPK 2 model has a resolution of 44 ps at 90 V at a temperature of -30 °C
- At medium fluences the HPK 2 sensor has a better performance in both gain and resolution
- At higher fluences and high bias voltages the two sensors have a rise time of approximately 400 ps. This result is the consequence of the fact that the two sensors have similar thickness

FBK sensors type comparison

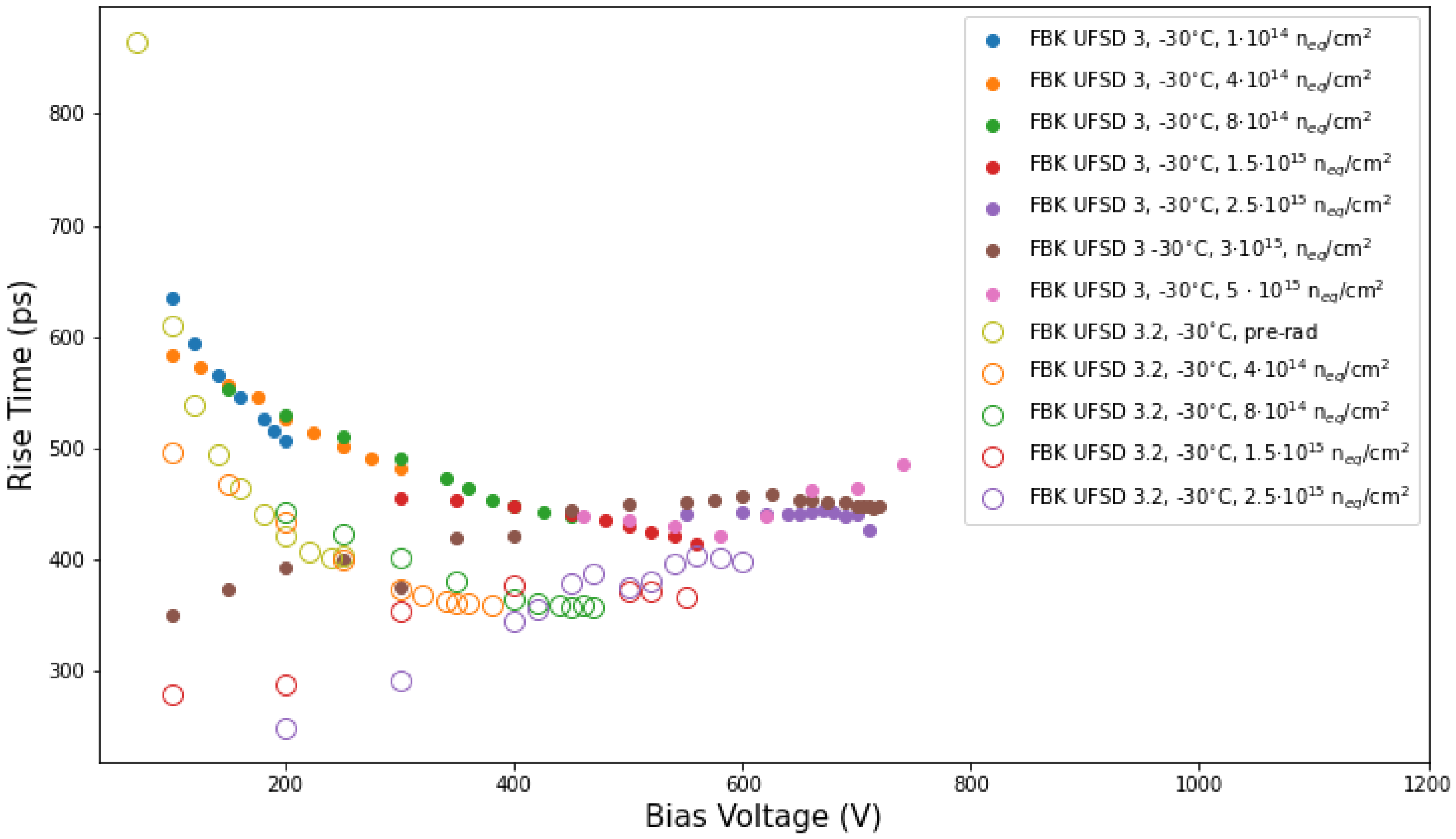
Time Resolution



Collected charge



Rise time

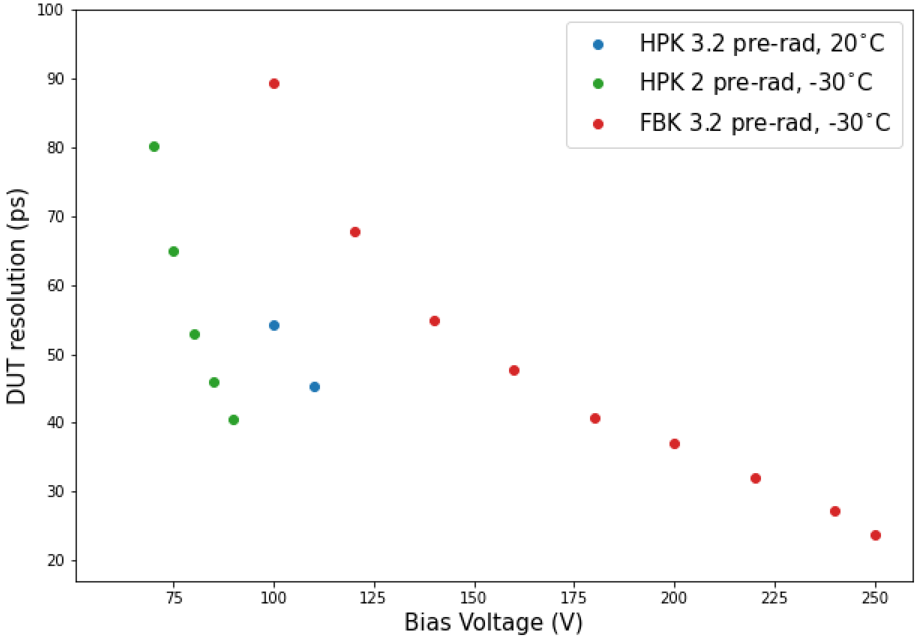


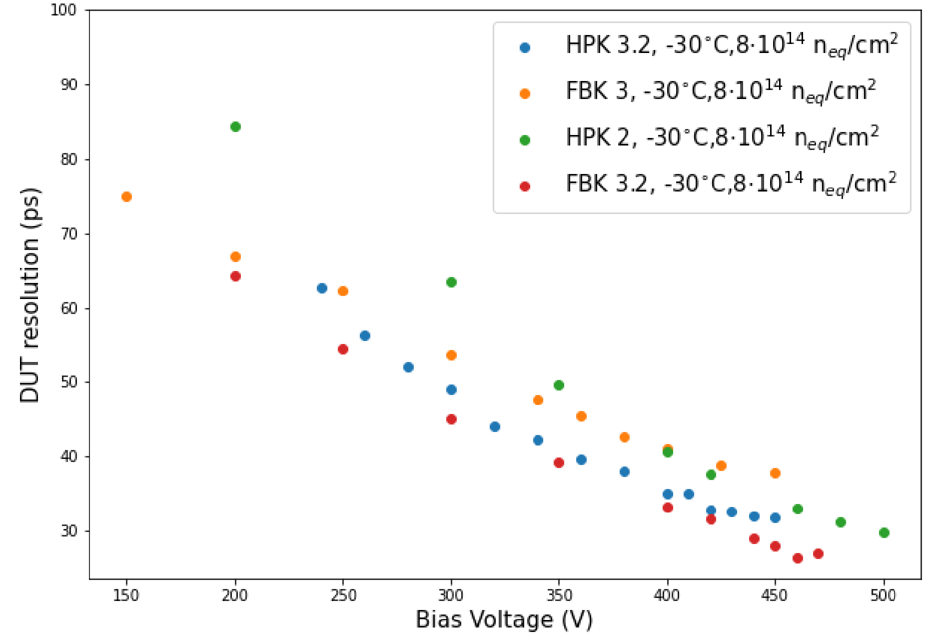
Rise Time (ps)
Bias Voltage (V)
300
400
500
600
700
800
200
400
600
800
1000
1200
FBK UFSD 3, -30°C, 1·10^{14} n$_{eq}$/cm^2
FBK UFSD 3, -30°C, 4·10^{14} n$_{eq}$/cm^2
FBK UFSD 3, -30°C, 8·10^{14} n$_{eq}$/cm^2
FBK UFSD 3, -30°C, 1.5·10^{15} n$_{eq}$/cm^2
FBK UFSD 3, -30°C, 2.5·10^{15} n$_{eq}$/cm^2
FBK UFSD 3 -30°C, 3·10^{15}, n$_{eq}$/cm^2
FBK UFSD 3, -30°C, 5 · 10^{15} n$_{eq}$/cm^2
FBK UFSD 3.2, -30°C, pre-rad
FBK UFSD 3.2, -30°C, 4·10^{14} n$_{eq}$/cm^2
FBK UFSD 3.2, -30°C, 8·10^{14} n$_{eq}$/cm^2
FBK UFSD 3.2, -30°C, 1.5·10^{15} n$_{eq}$/cm^2
FBK UFSD 3.2, -30°C, 2.5·10^{15} n$_{eq}$/cm^2

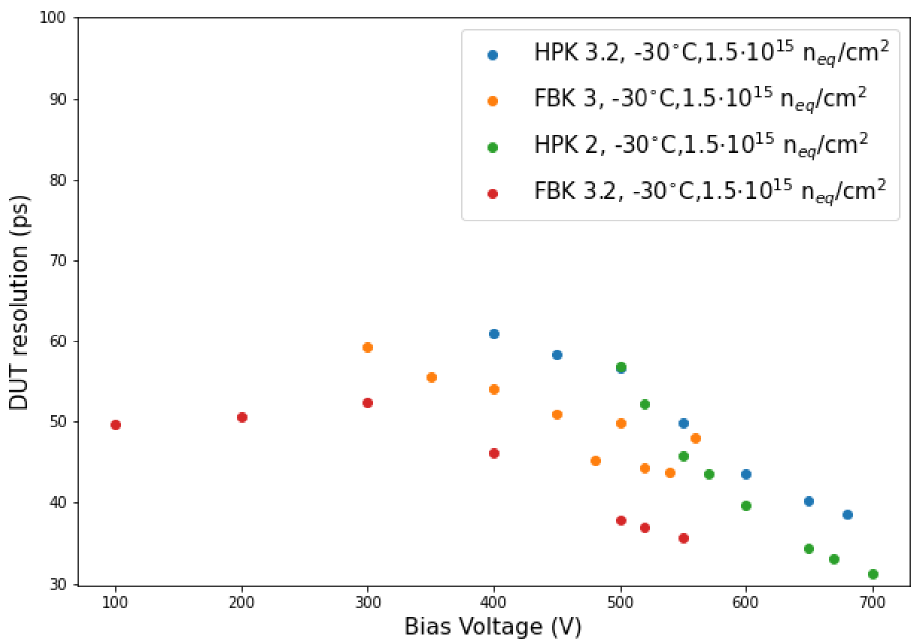
Comments

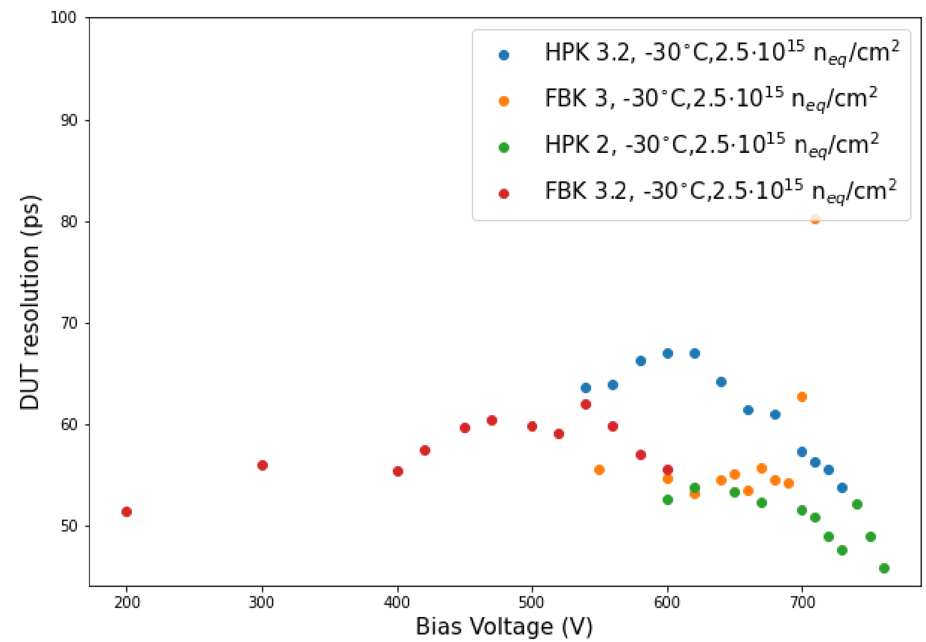
- The main differences between the FBK new and old productions are:
  - the FBK 3.2, showed a better resolution and a larger collected charge at radiation level lower than $2.5 \cdot 10^{15}$ n_{eq} cm^{-2} than the FBK 3, this is expected since the FBK 3.2 model has a deep gain layer
  - Unexpectedly the FBK 3.2 model **at the radiation level of $2.5 \cdot 10^{15}$ $n_{eq} cm^{-2}$** has a break-down at 600 V. As a consequence **it collects less than 4 fC of charge, the minimum charge required to the HGTD read-out electronics to work properly**
  - The FBK 3.2 production has different variations, currently other measurements are being performed to see if the problem persists on other FBK 3.2 variations

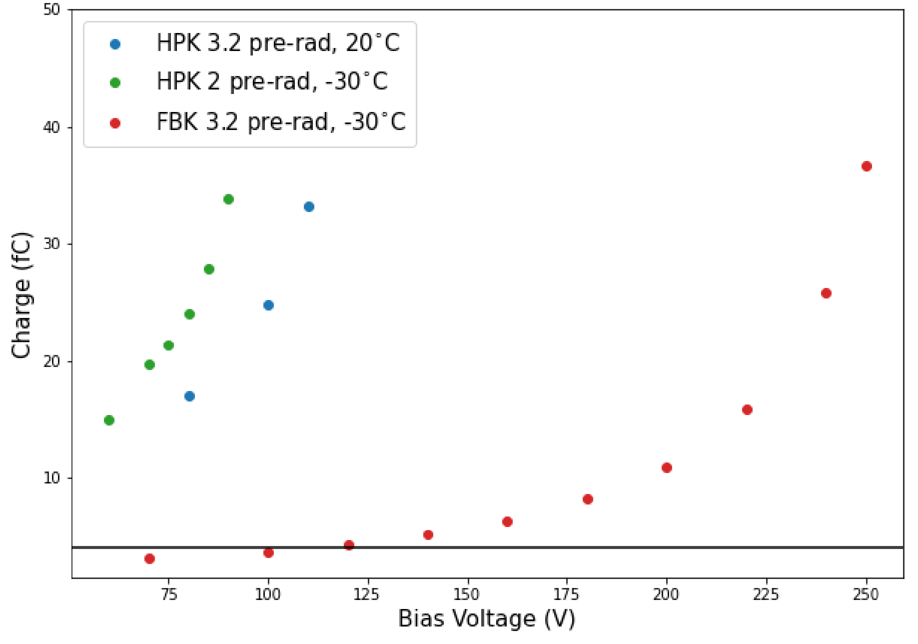
Comparison between the HPK and FBK models


HPK 3.2 pre-rad, 20°C
HPK 2 pre-rad, -30°C
FBK 3.2 pre-rad, -30°C
DUT resolution (ps)
Bias Voltage (V)

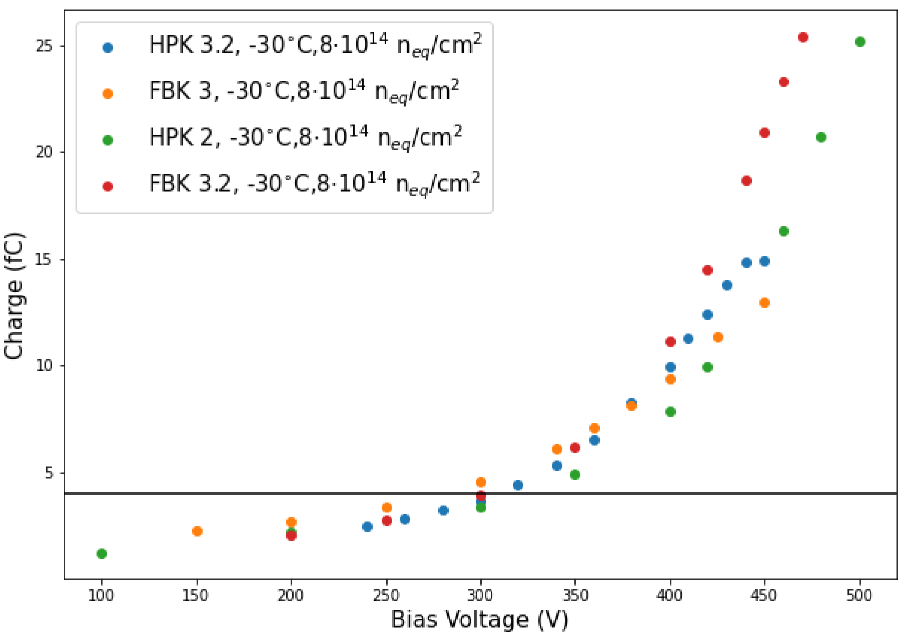

HPK 3.2, -30°C,8·10^14 n_eq/cm^2
FBK 3, -30°C,8·10^14 n_eq/cm^2
HPK 2, -30°C,8·10^14 n_eq/cm^2
FBK 3.2, -30°C,8·10^14 n_eq/cm^2
DUT resolution (ps)
Bias Voltage (V)


HPK 3.2, -30°C,1.5·10^15 n_eq/cm^2
FBK 3, -30°C,1.5·10^15 n_eq/cm^2
HPK 2, -30°C,1.5·10^15 n_eq/cm^2
FBK 3.2, -30°C,1.5·10^15 n_eq/cm^2
DUT resolution (ps)
Bias Voltage (V)

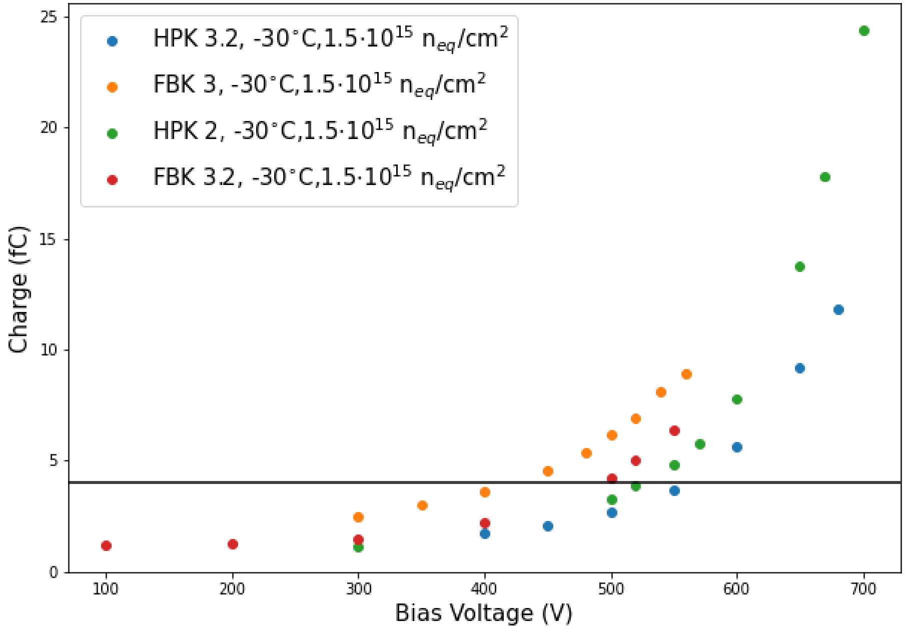

HPK 3.2, -30°C,2.5·10^15 n_eq/cm^2
FBK 3, -30°C,2.5·10^15 n_eq/cm^2
HPK 2, -30°C,2.5·10^15 n_eq/cm^2
FBK 3.2, -30°C,2.5·10^15 n_eq/cm^2
DUT resolution (ps)
Bias Voltage (V)



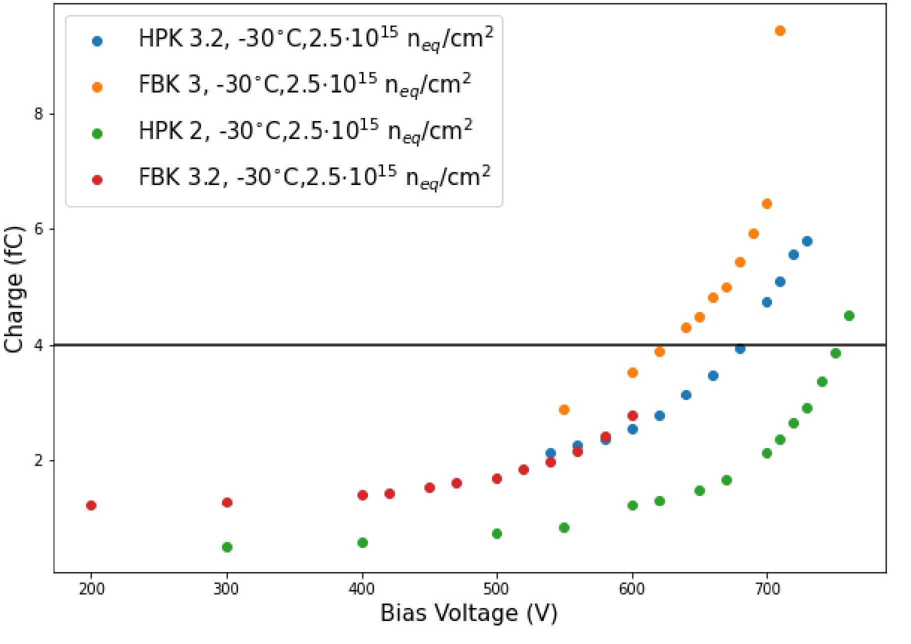
HPK 3.2 pre-rad, 20°C
HPK 2 pre-rad, -30°C
FBK 3.2 pre-rad, -30°C
Charge (fC)
Bias Voltage (V)



HPK 3.2, -30°C,8·10^14 n_eq/cm^2
FBK 3, -30°C,8·10^14 n_eq/cm^2
HPK 2, -30°C,8·10^14 n_eq/cm^2
FBK 3.2, -30°C,8·10^14 n_eq/cm^2
Charge (fC)
Bias Voltage (V)



HPK 3.2, -30°C,1.5·10^15 n_eq/cm^2
FBK 3, -30°C,1.5·10^15 n_eq/cm^2
HPK 2, -30°C,1.5·10^15 n_eq/cm^2
FBK 3.2, -30°C,1.5·10^15 n_eq/cm^2
Charge (fC)
Bias Voltage (V)



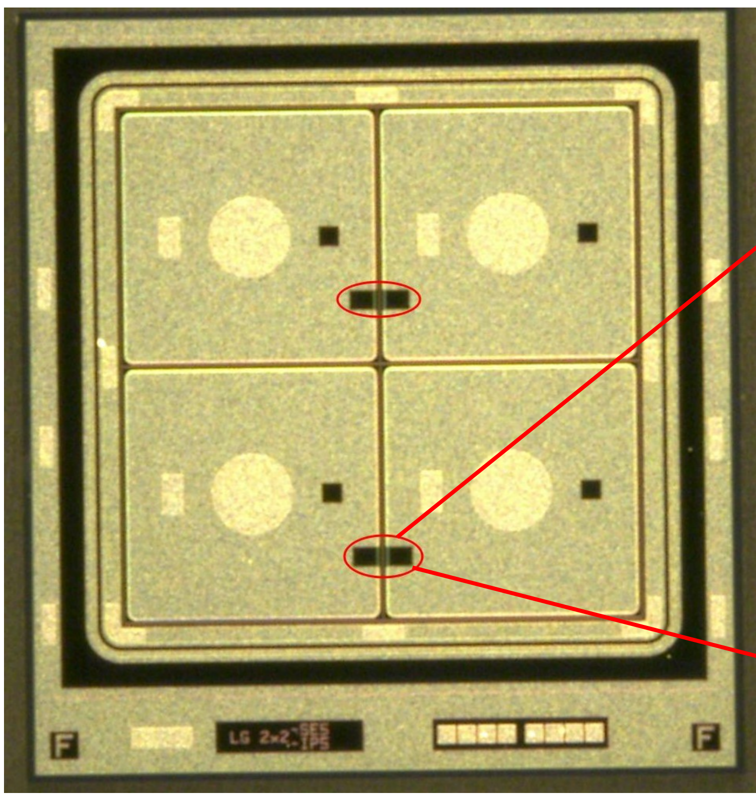
HPK 3.2, -30°C,2.5·10^15 n_eq/cm^2
FBK 3, -30°C,2.5·10^15 n_eq/cm^2
HPK 2, -30°C,2.5·10^15 n_eq/cm^2
FBK 3.2, -30°C,2.5·10^15 n_eq/cm^2
Charge (fC)
Bias Voltage (V)

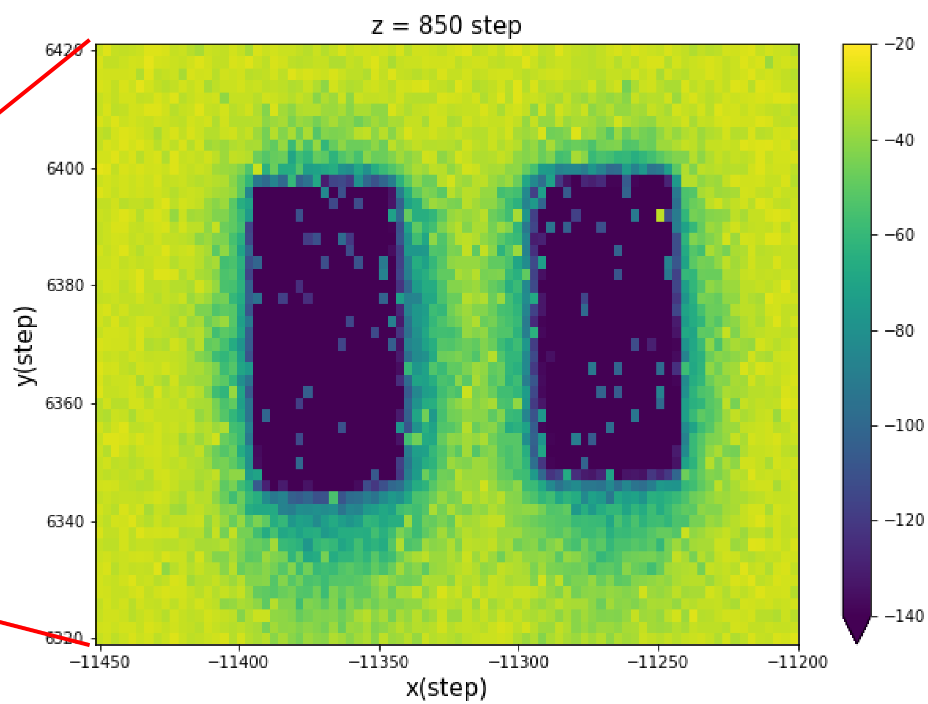
Comments

- In conclusion by comparing the four different productions:
  - the sensor type HPK 2 seems to be the most suitable to be installed on HGTD, it shows at high radiation levels a resolution lower than the other three sensors and an acceptable collected charge.
  - The FBK 3.2 model tested here shows a better performance both in the resolution and collected charge than all the other sensors at low radiation level
  - The early break-down at 600 V at the highest irradiation level makes the FBK 3.2 charge collection capabilities insufficient at the higher radiation level.
  - In this work only one of the different variations of FBK 3.2 were analyzed, currently other measurements are being performed to see if the problem persists on the full FBK production

Interpad gap measurements

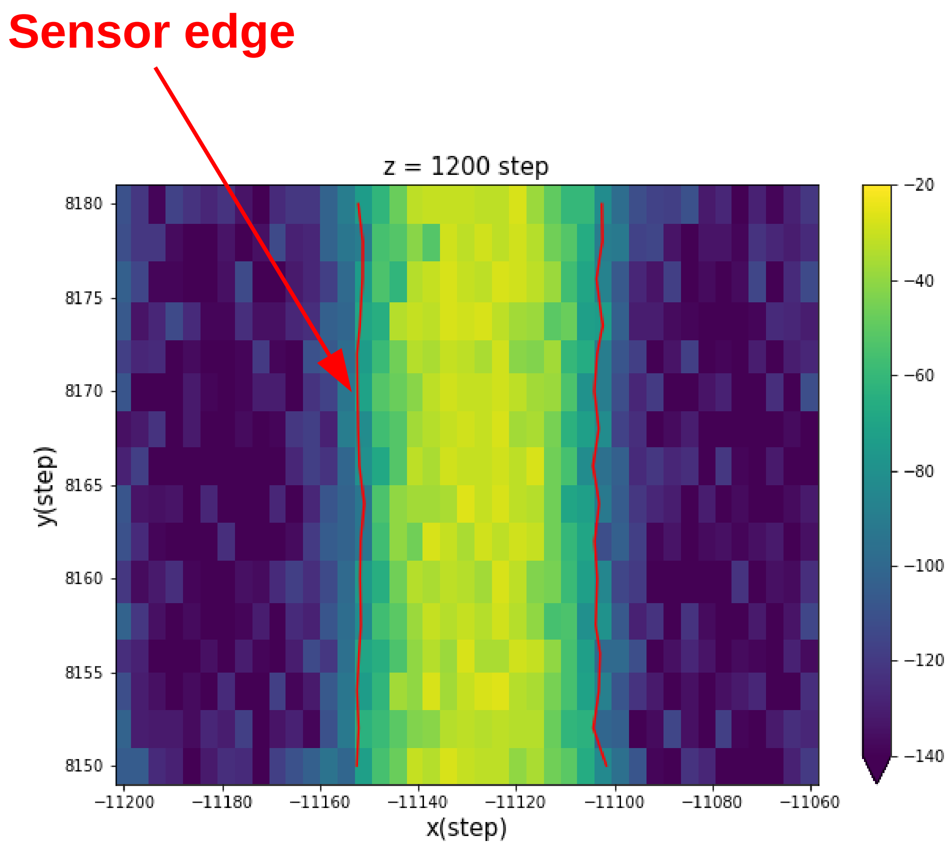
- In the laboratory of the Università Statale di Milano 2D laser scans were performed on non irradiated 2×2 HPK 2 pads to measure the values of the interpad gap
- The HPK 2 LGAD type was chosen as the main focus of the measurements since it seemed the more suitable to be installed on HGTD

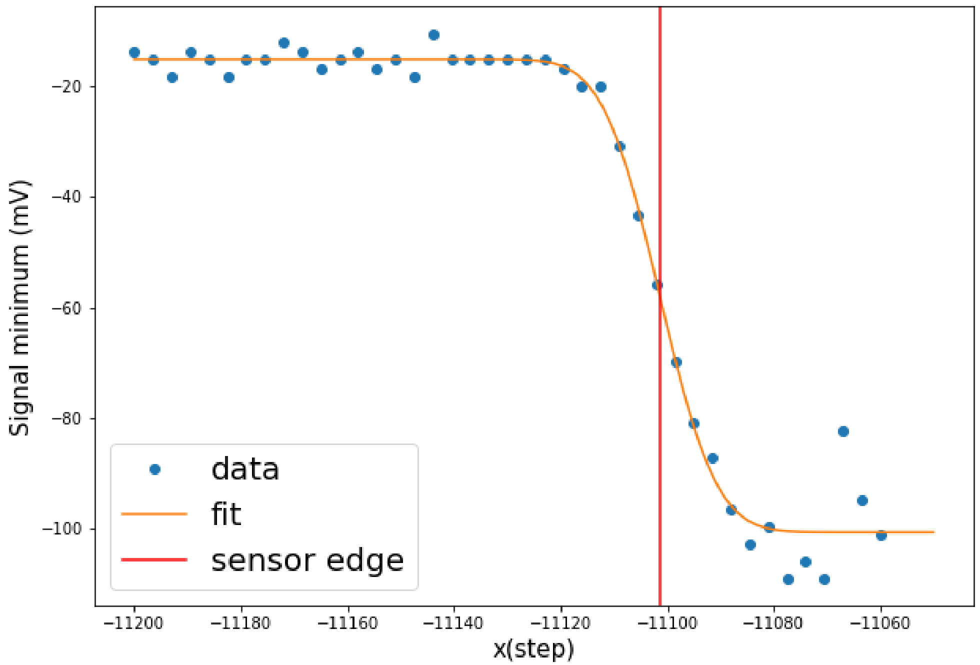




Interpad gap measurements

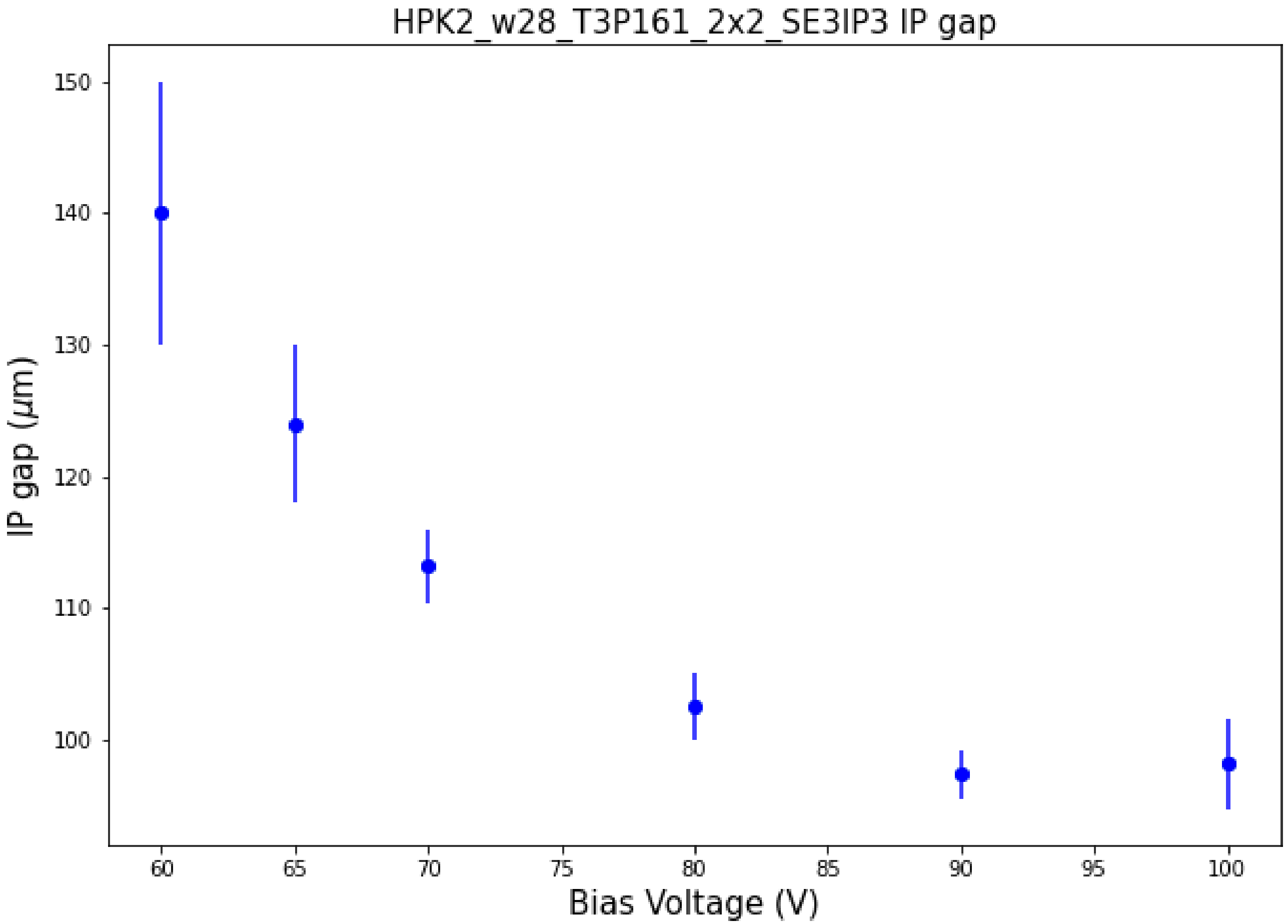
- The position of the sensor edge was estimated using an error function





Interpad gap measurements

- The measurements show that the gap dimension decreases at higher bias voltages



Comments

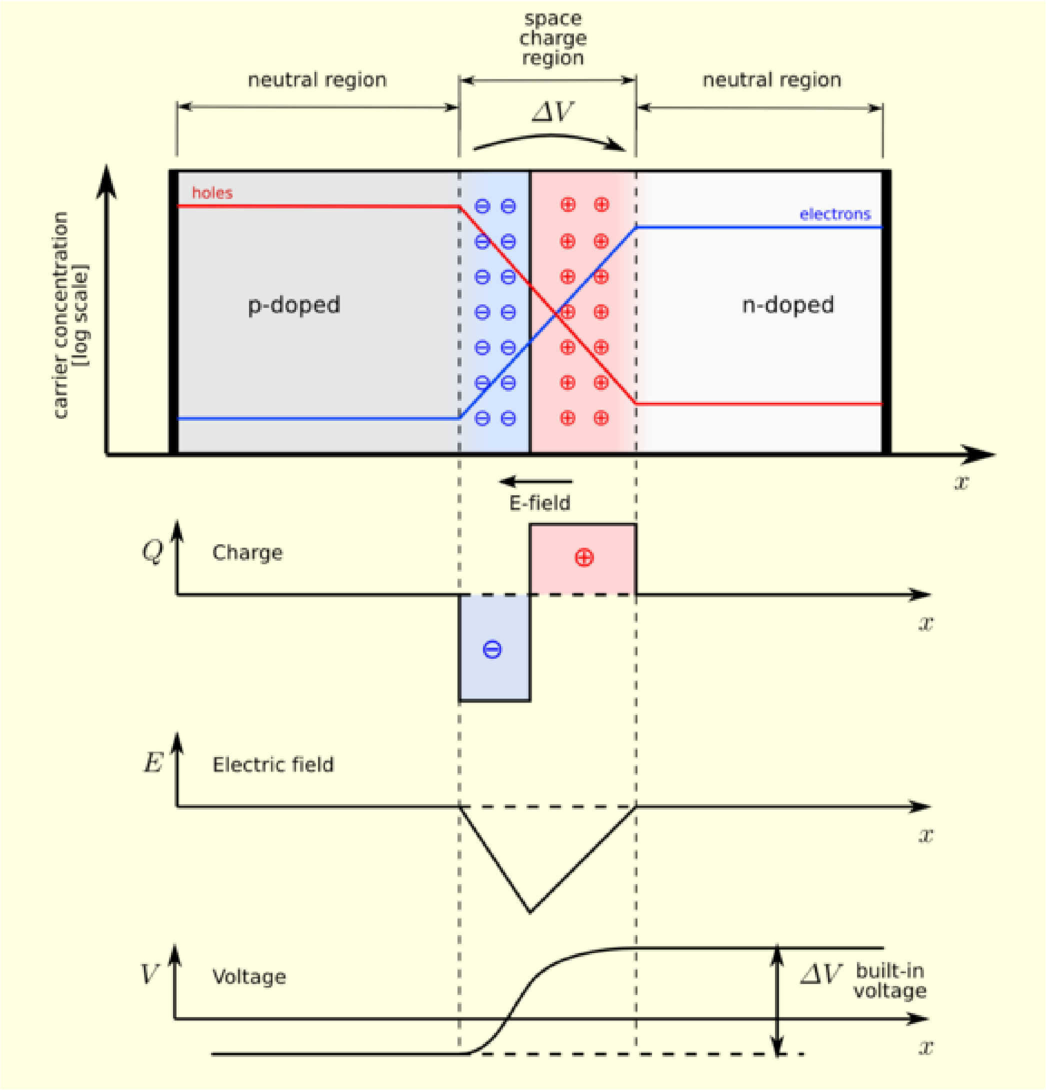
- To fullfill the HGTD requirement of 90% fill factor the interpad gap should be lower than 70 μm. Therefore the measured interpad gap doesn't satisfy the HGTD requirement before irradiation, but its value should decrease at higher irradiation fluences

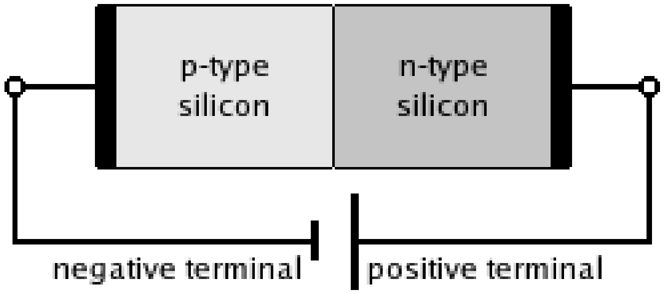
Conclusions

- The HGTD 2 sensors seems to have the best performance and seems to be the most suitable to be installed on HGTD
- The FBK 3.2 would also be a suitable canditate for the HGTD if the premature break-down problem doesn’t affect all the FBK new production

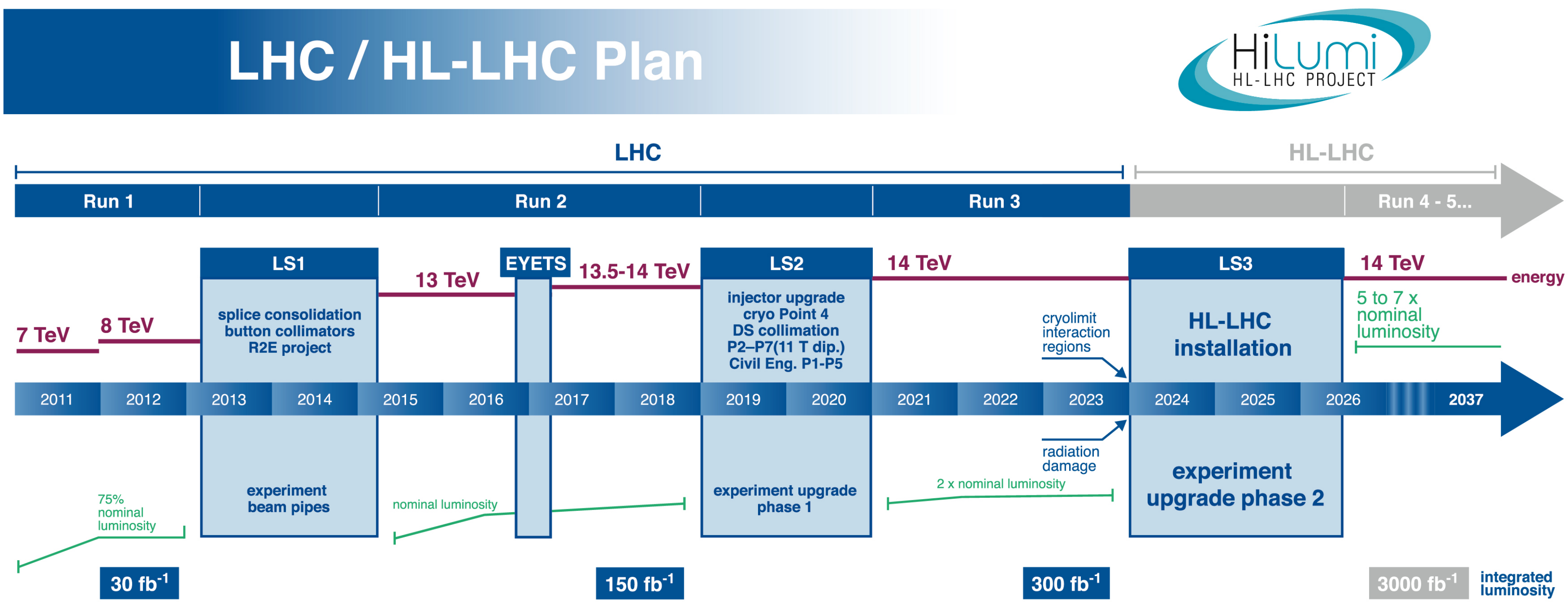
Back-up

p-n junction

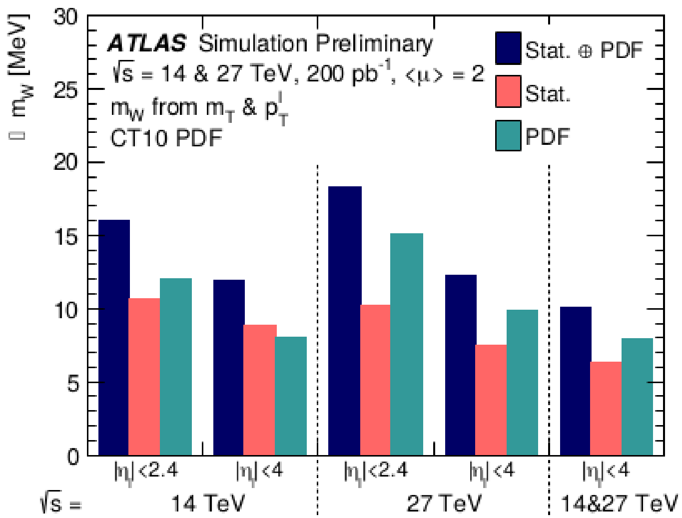

space
charge
region
neutral region
neutral region
ΔV
holes
electrons
p-doped
n-doped
carrier concentration
[log scale]
x
E-field
Q
Charge
x
E
Electric field
x
V
Voltage
ΔV
built-in
voltage
x

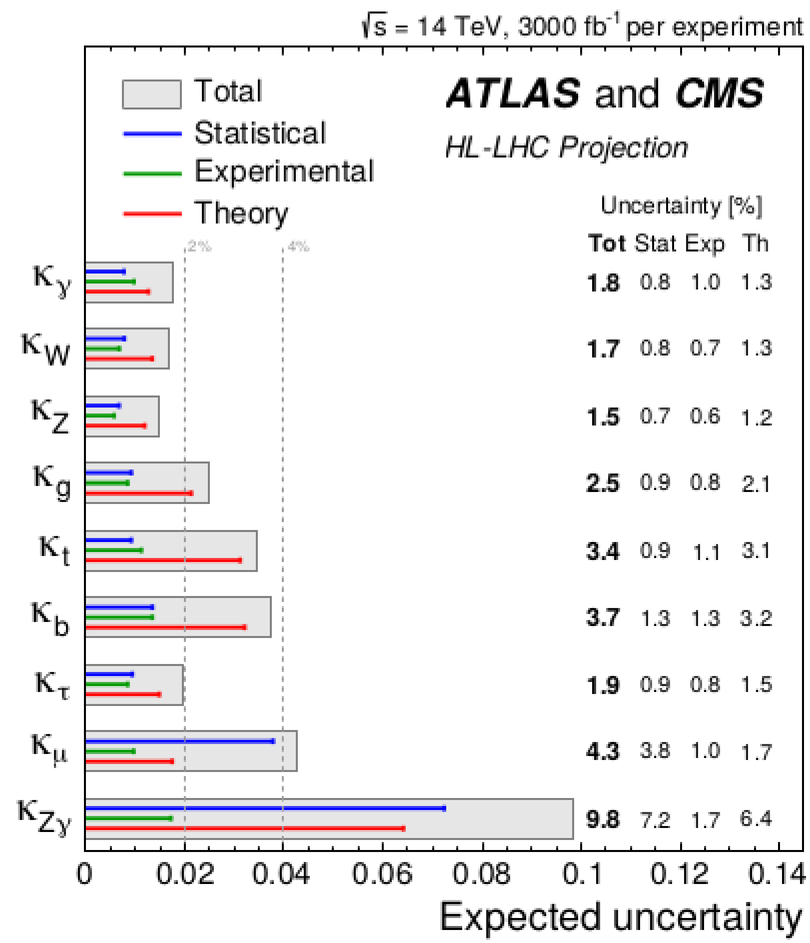

p-type
silicon
n-type
silicon
negative terminal
positive terminal

HL-LHC schedule

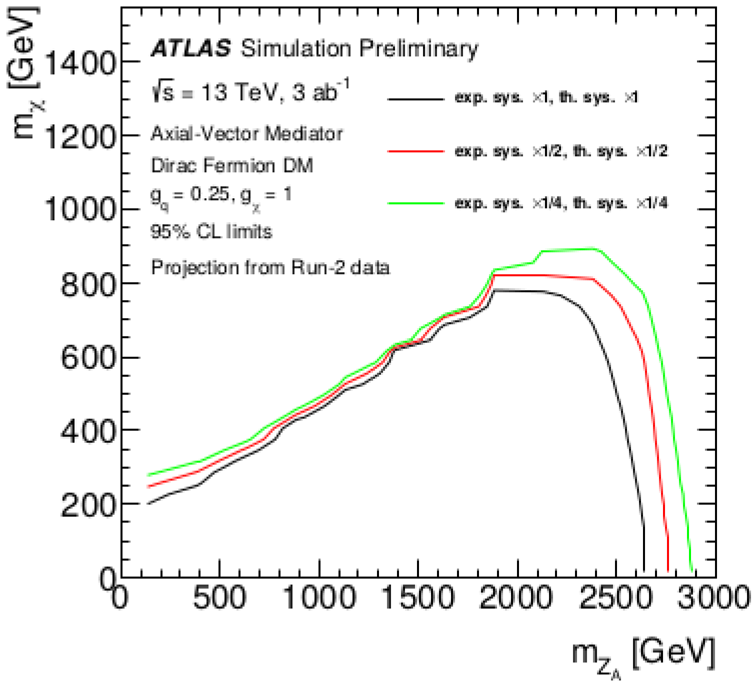


HL-LHC physics upgrades

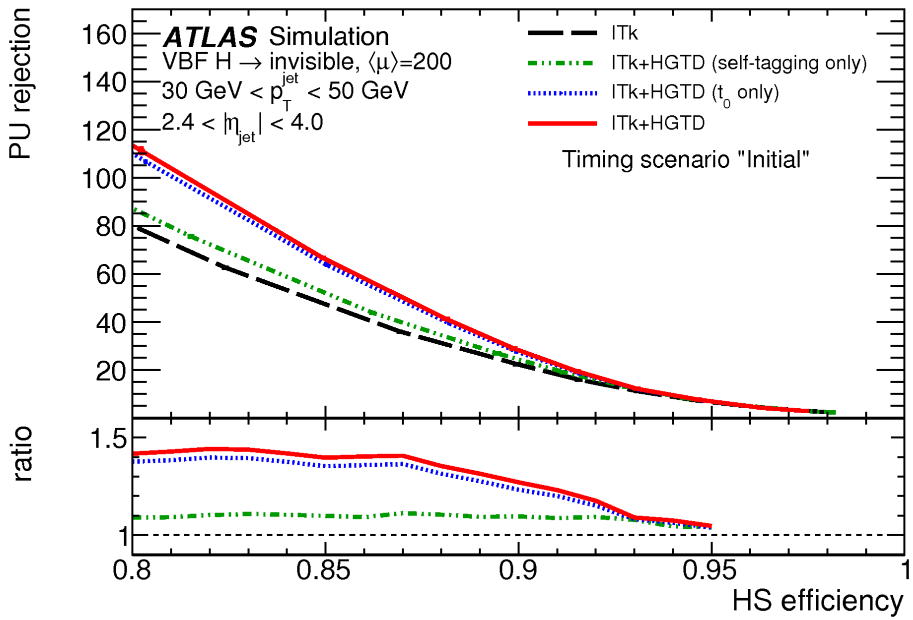


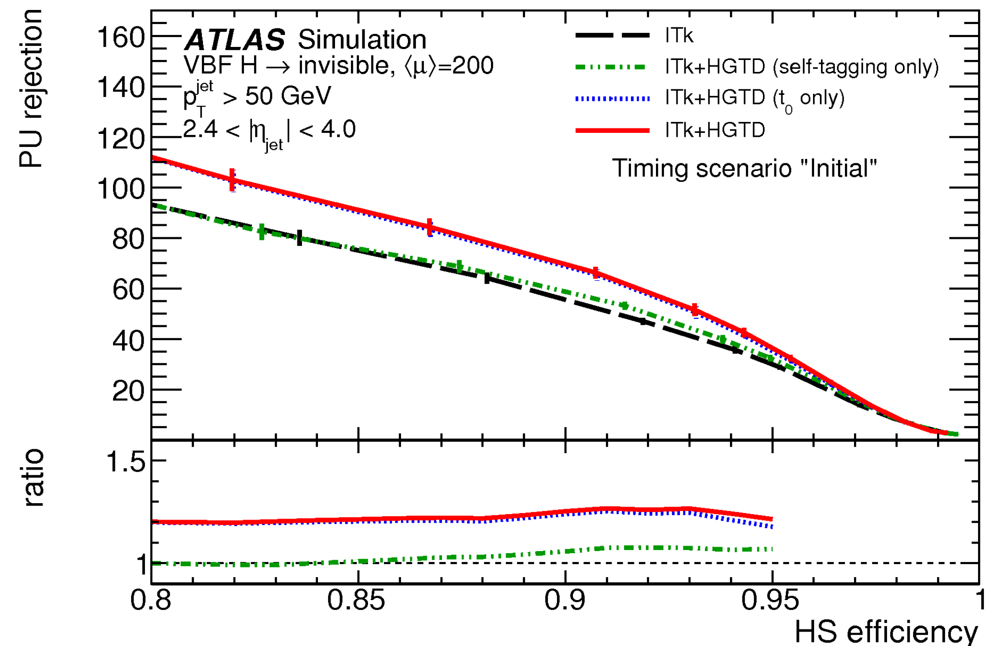


HL-LHC physics upgrades

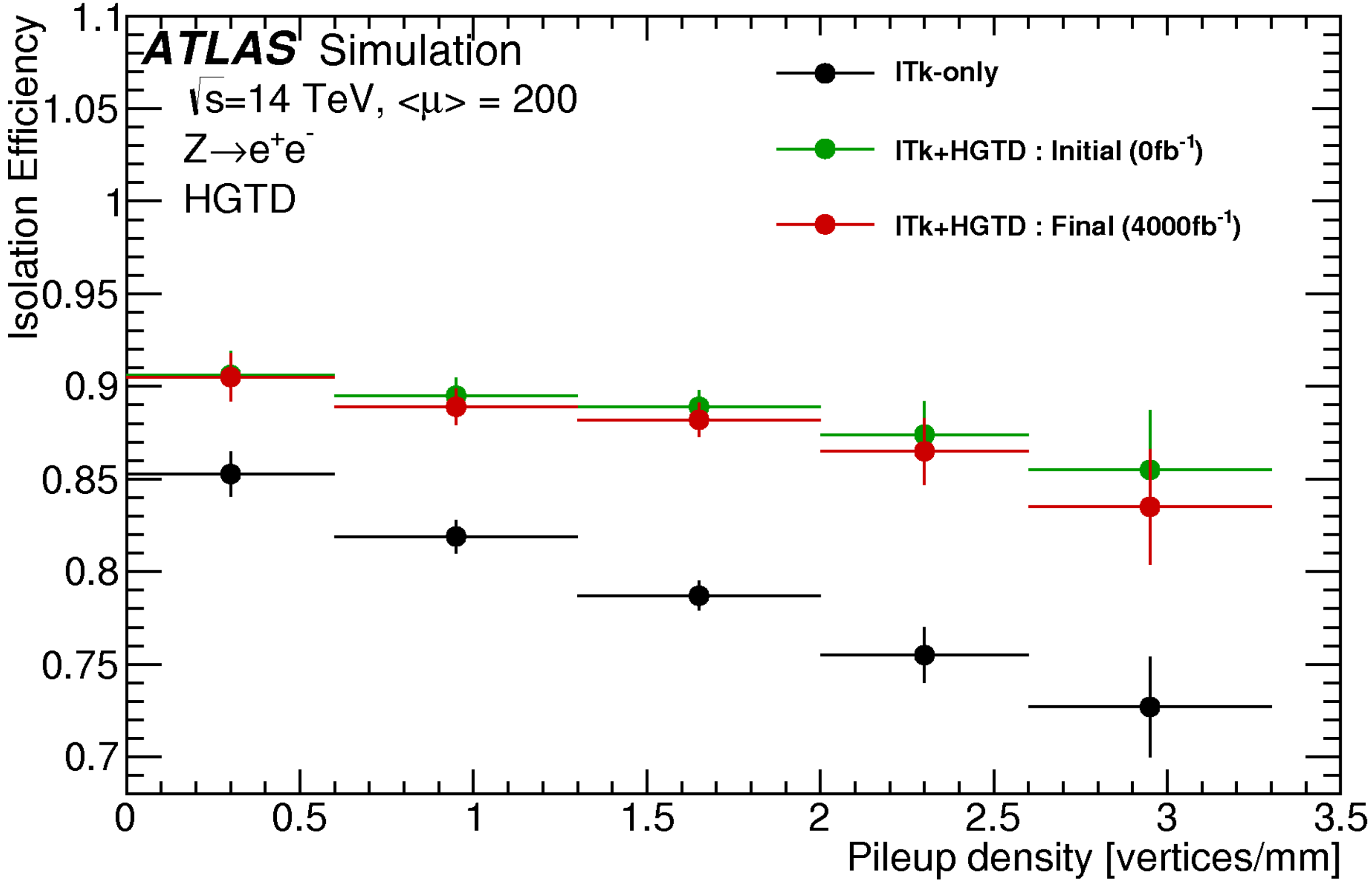


HGTD physics upgrade

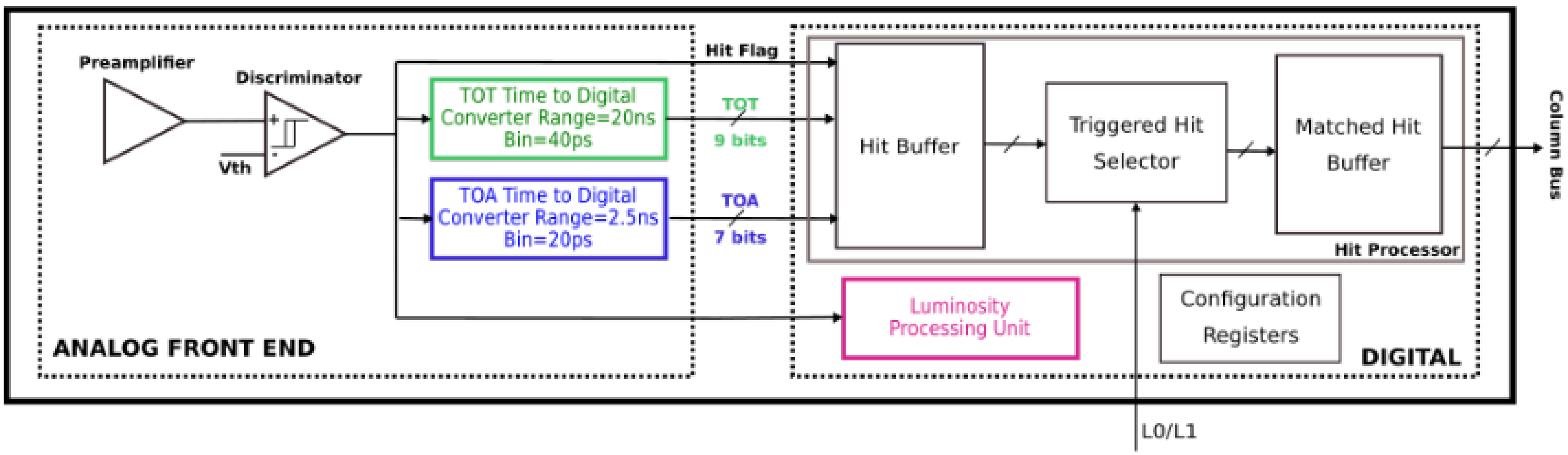




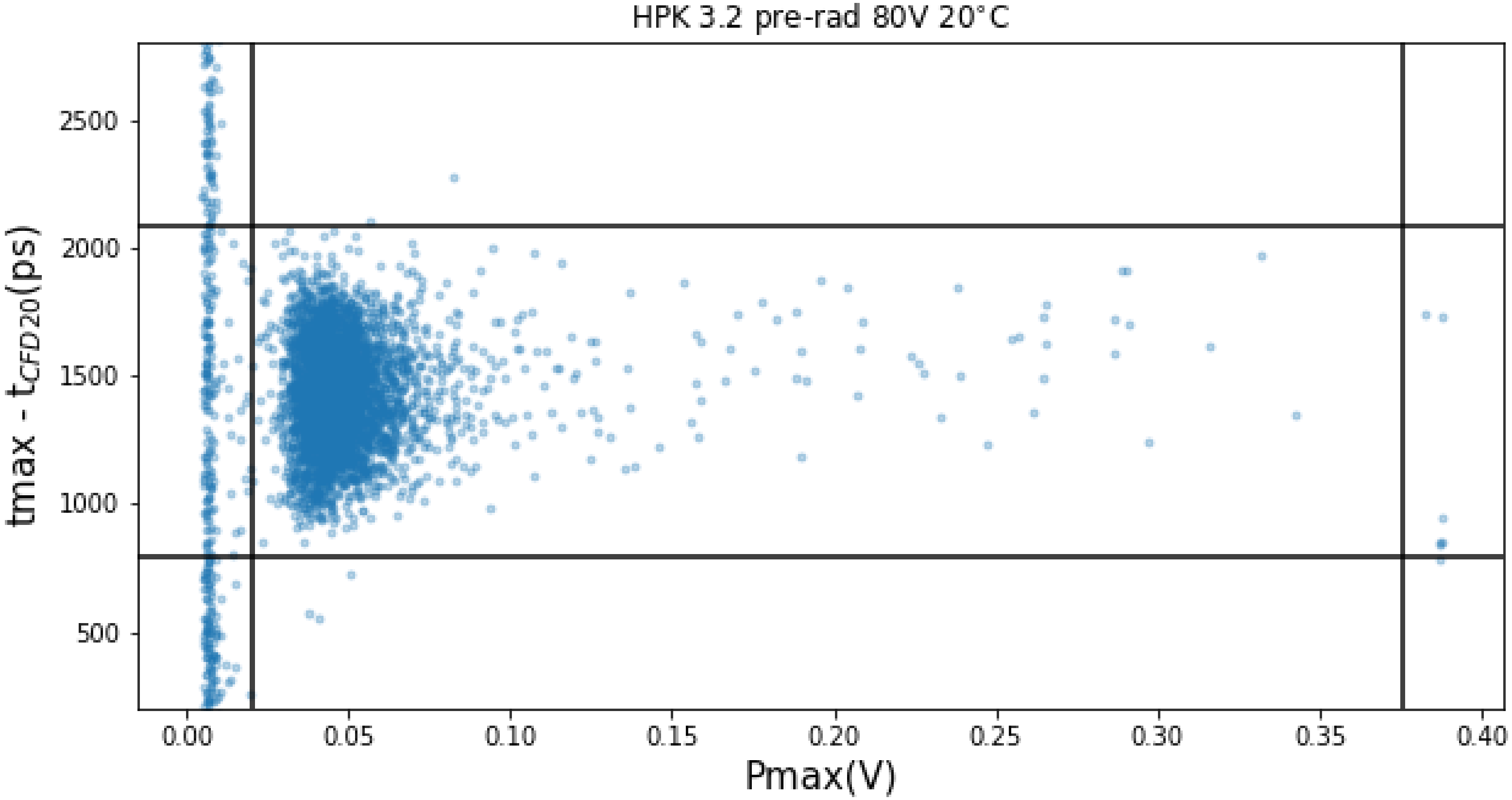
HGTD physics upgrade



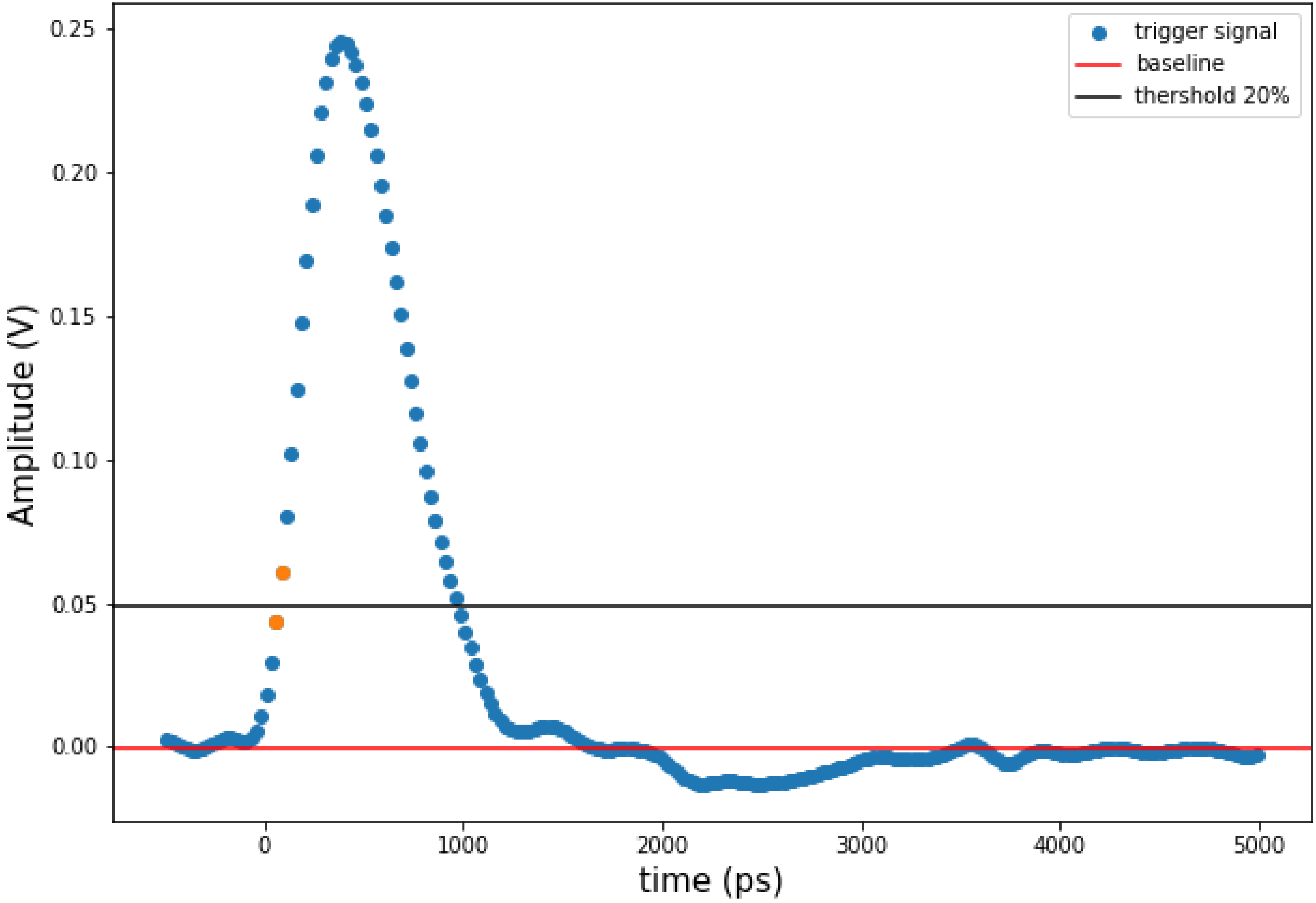
ALTIROC


Preamplifier
Discriminator
Vth
Hit Flag
TOT Time to Digital Converter Range=20ns Bin=40ps
TOA Time to Digital Converter Range=2.5ns Bin=20ps
TOT
9 bits
TOA
7 bits
Hit Buffer
Triggered Hit Selector
Matched Hit Buffer
Hit Processor
Column Bus
Luminosity Processing Unit
Configuration Registers
ANALOG FRONT END
DIGITAL
L0/L1

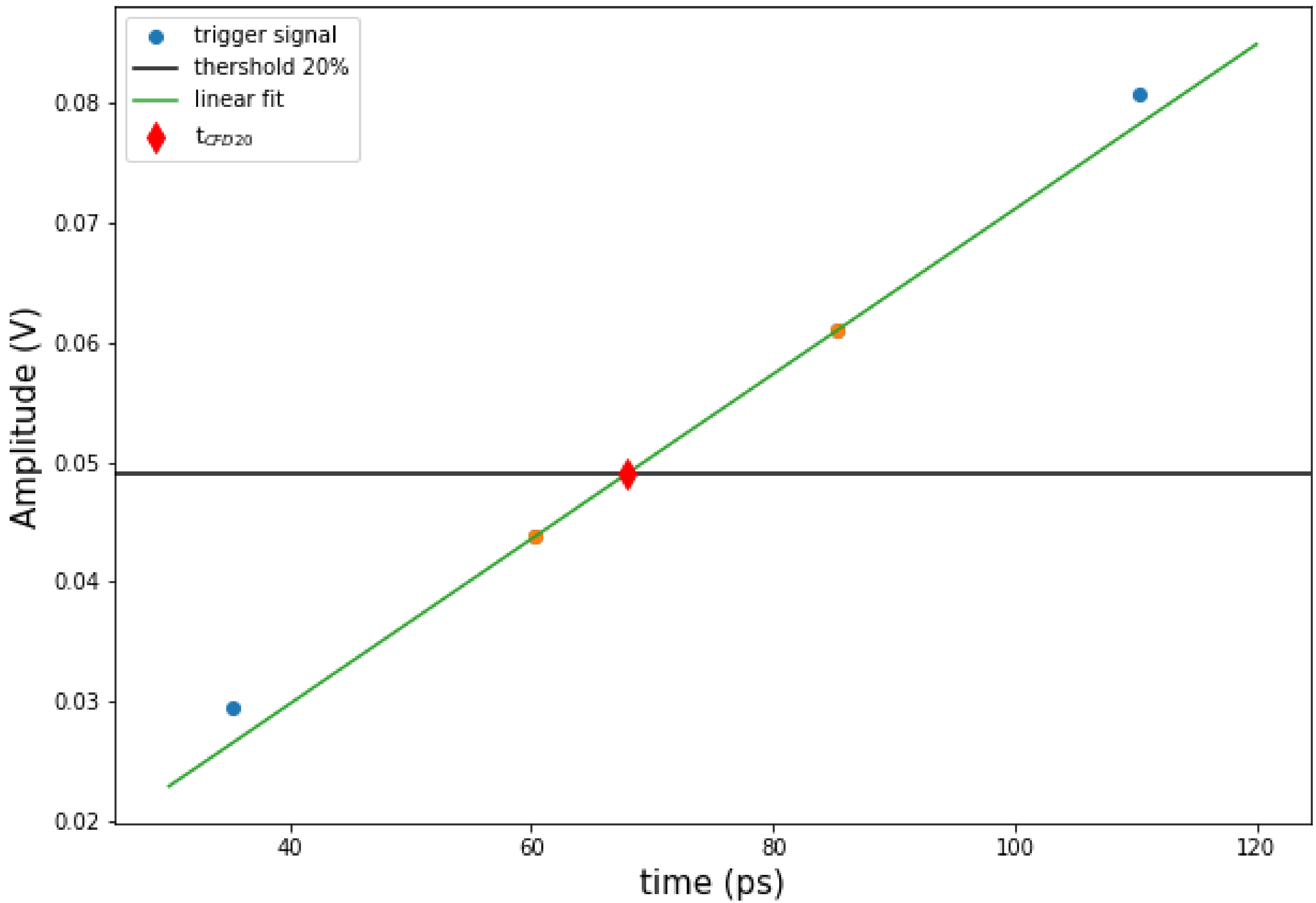
Data selection



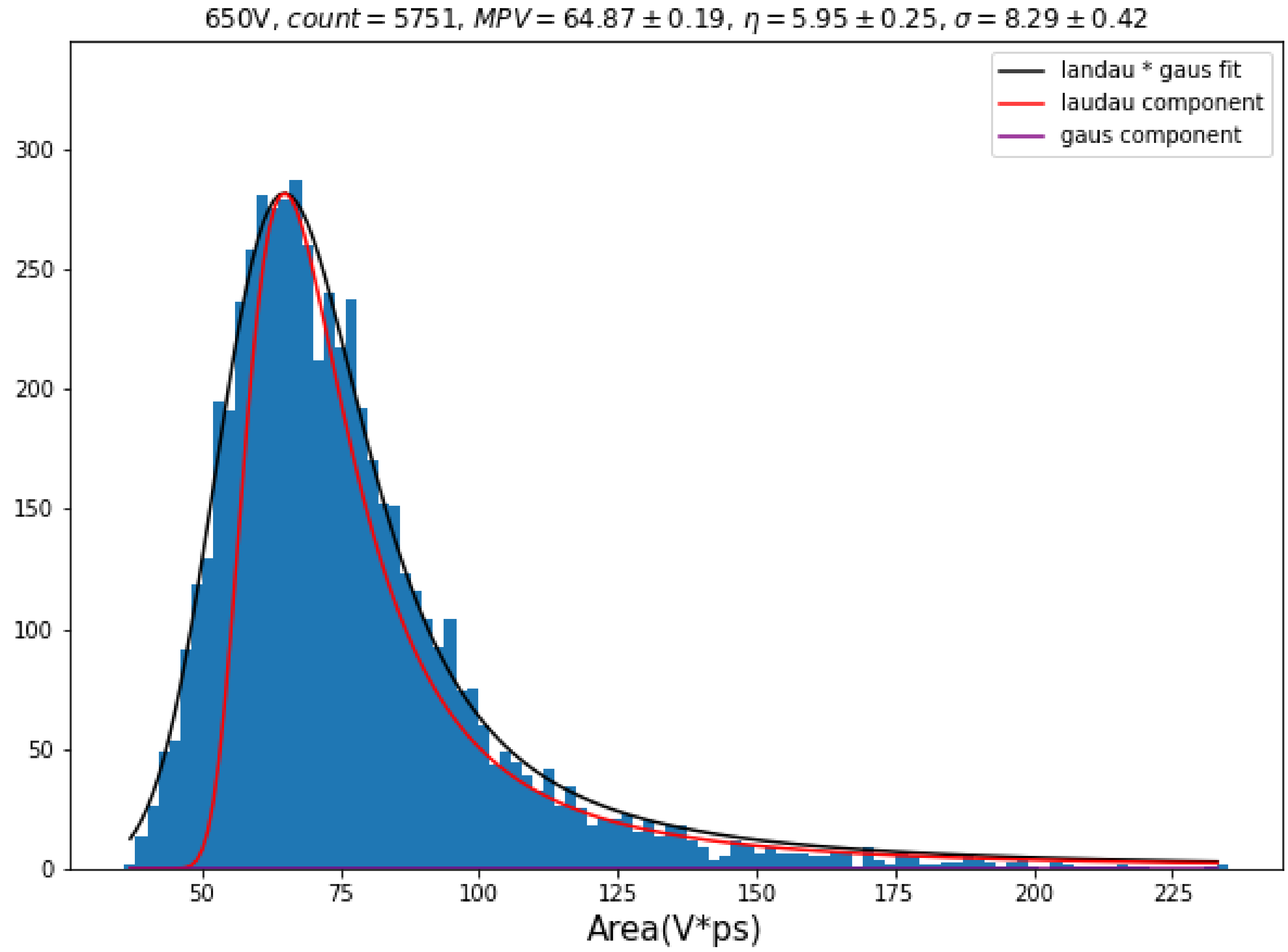
Data analysis: time resolution



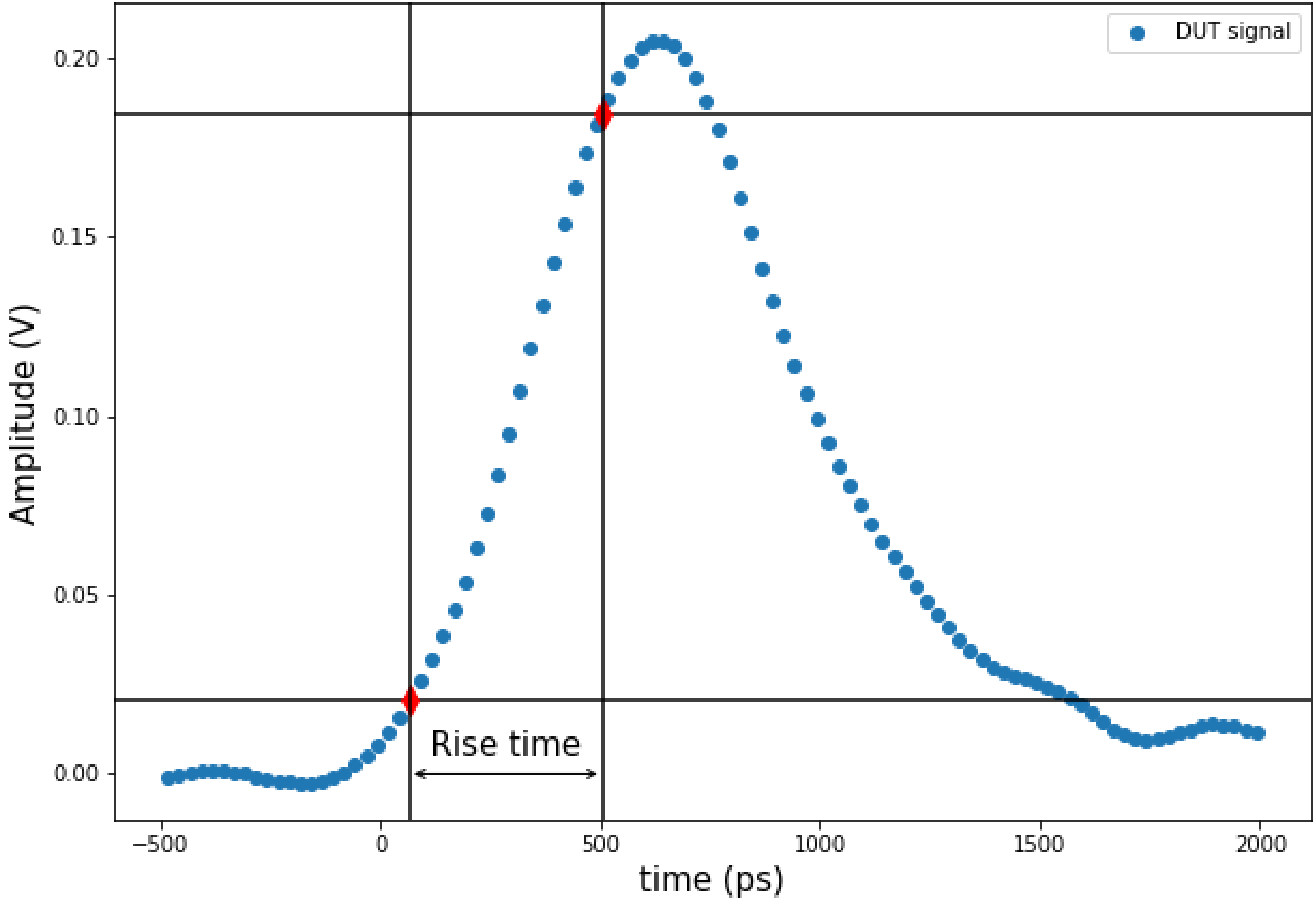
Data analysis: time resolution



Data analysis: signal area



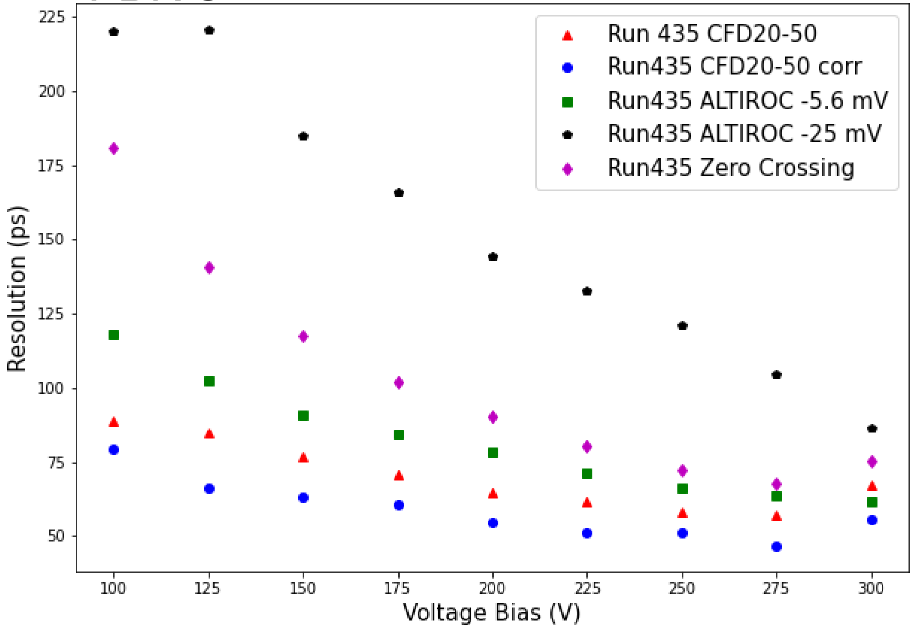
Data analysis: rise time



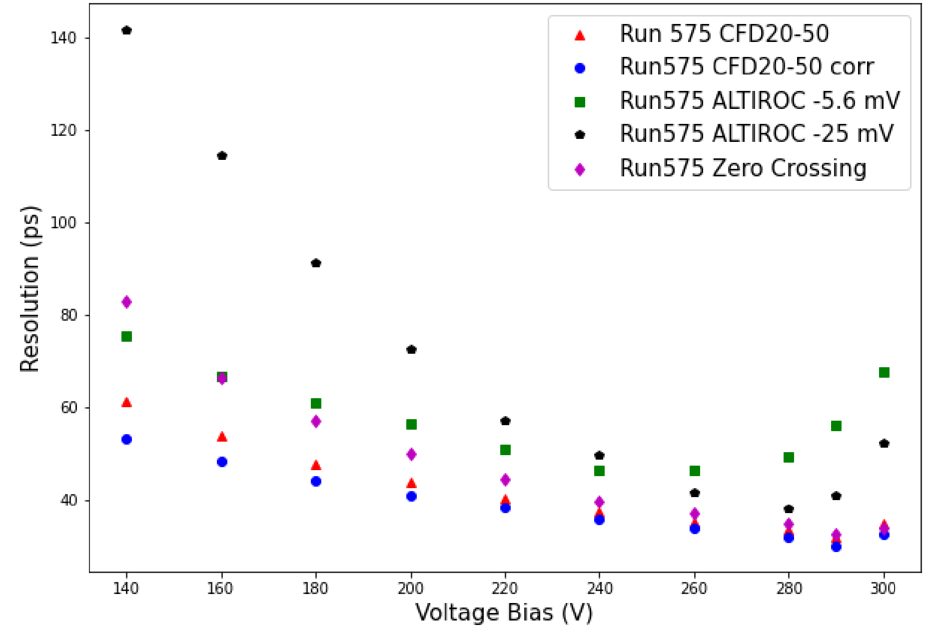
Time resolution estimation using different algorithms

- I analyzed data on the 4 LGAD models irradiated at the same fluence of $4 \cdot 10^{14}$ n_{eq} cm^{-2} using different algorithms to estimate the time resolution
- Each method mimics a type of read-out electronic board:
  - CFD: mimic a constant fraction discrimainator. It's the same method used to estimate the resolution in the previous slide
  - ALTIROC: mimic the read-out board that will be used in HGTD
  - CFD CORRECTED: is a combination of the ALTIROC and CFD algorithms
  - ZERO CROSSING: mimic a discriminator

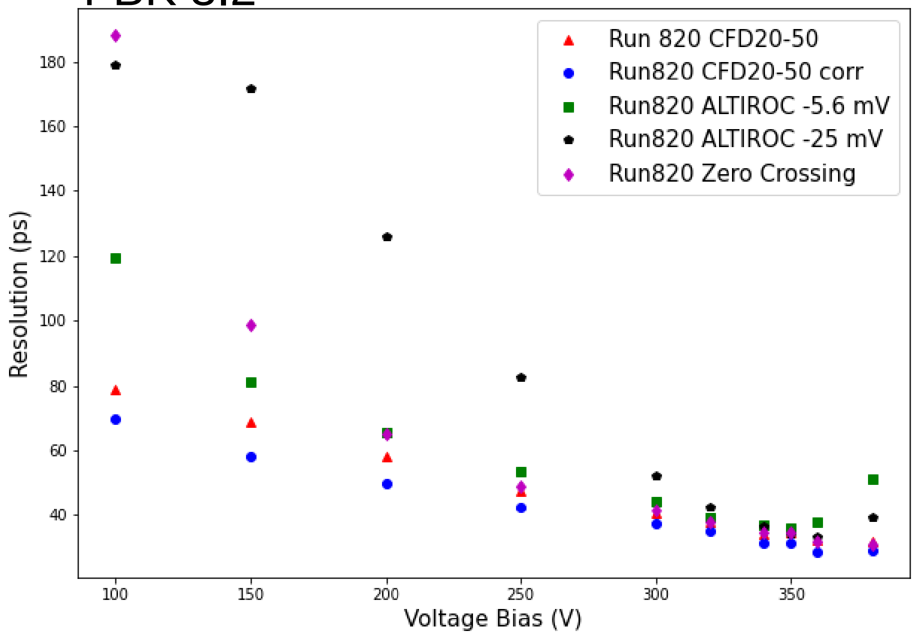
FBK 3



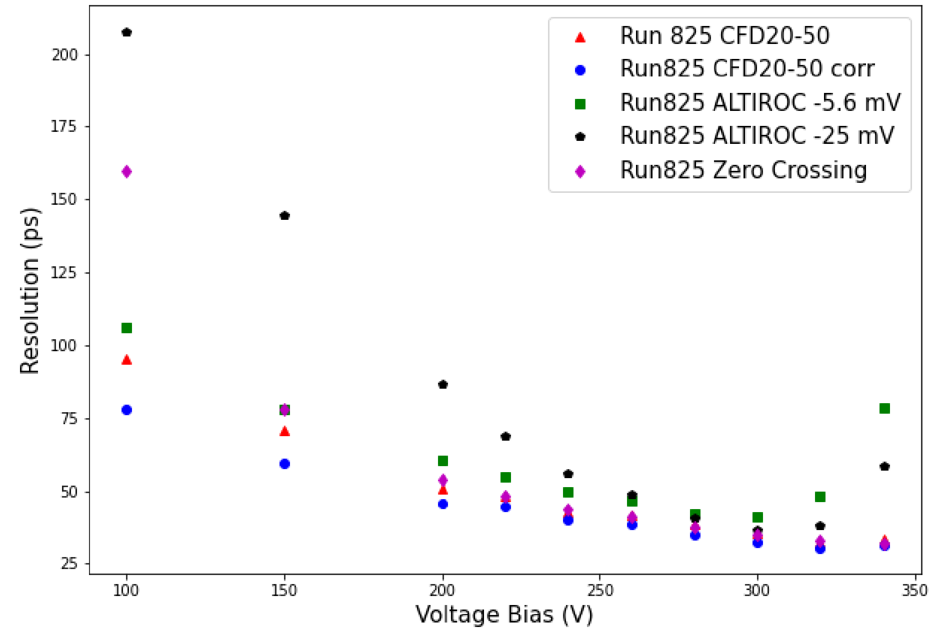
HPK 3.2



FBK 3.2



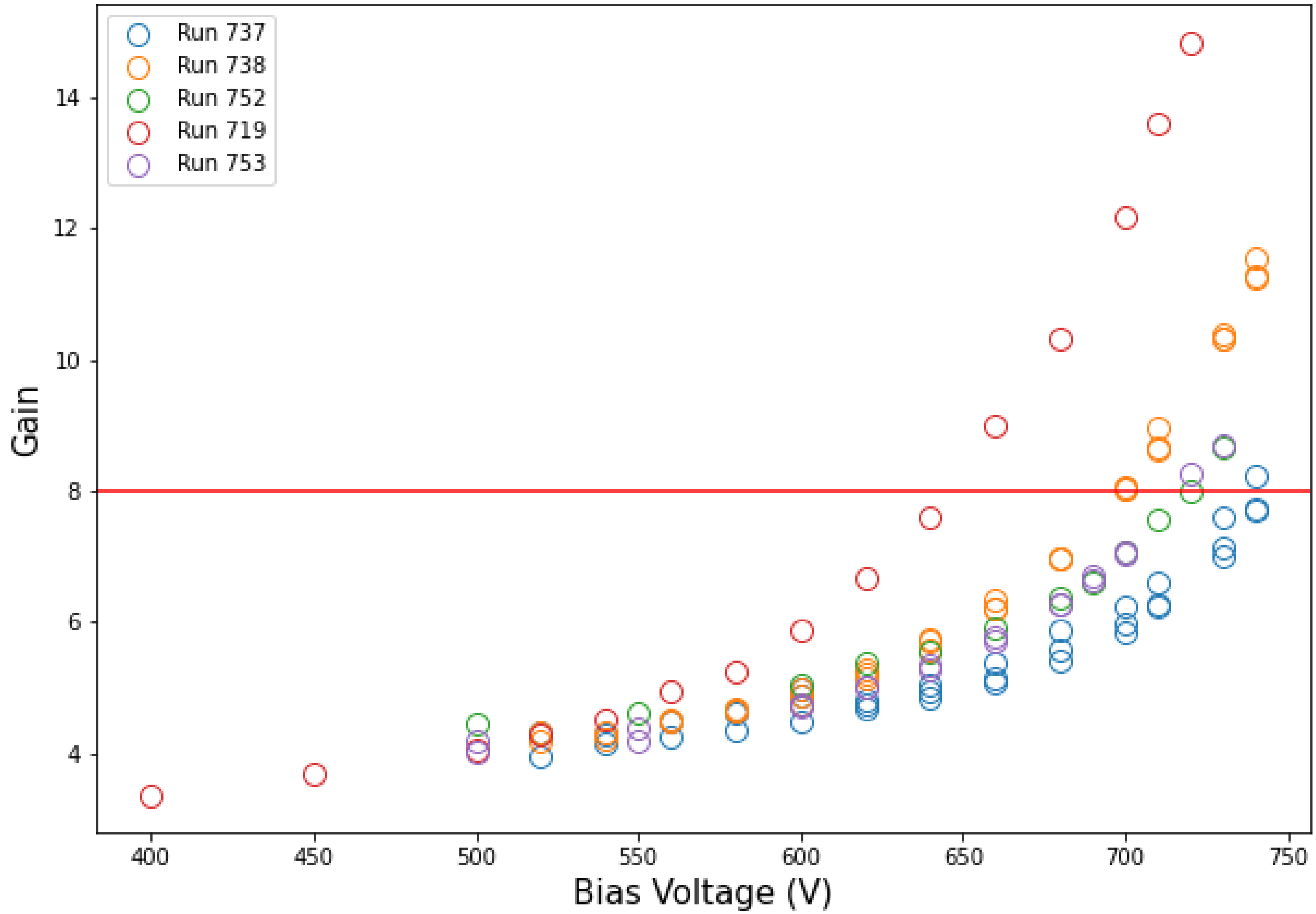
HPK 2



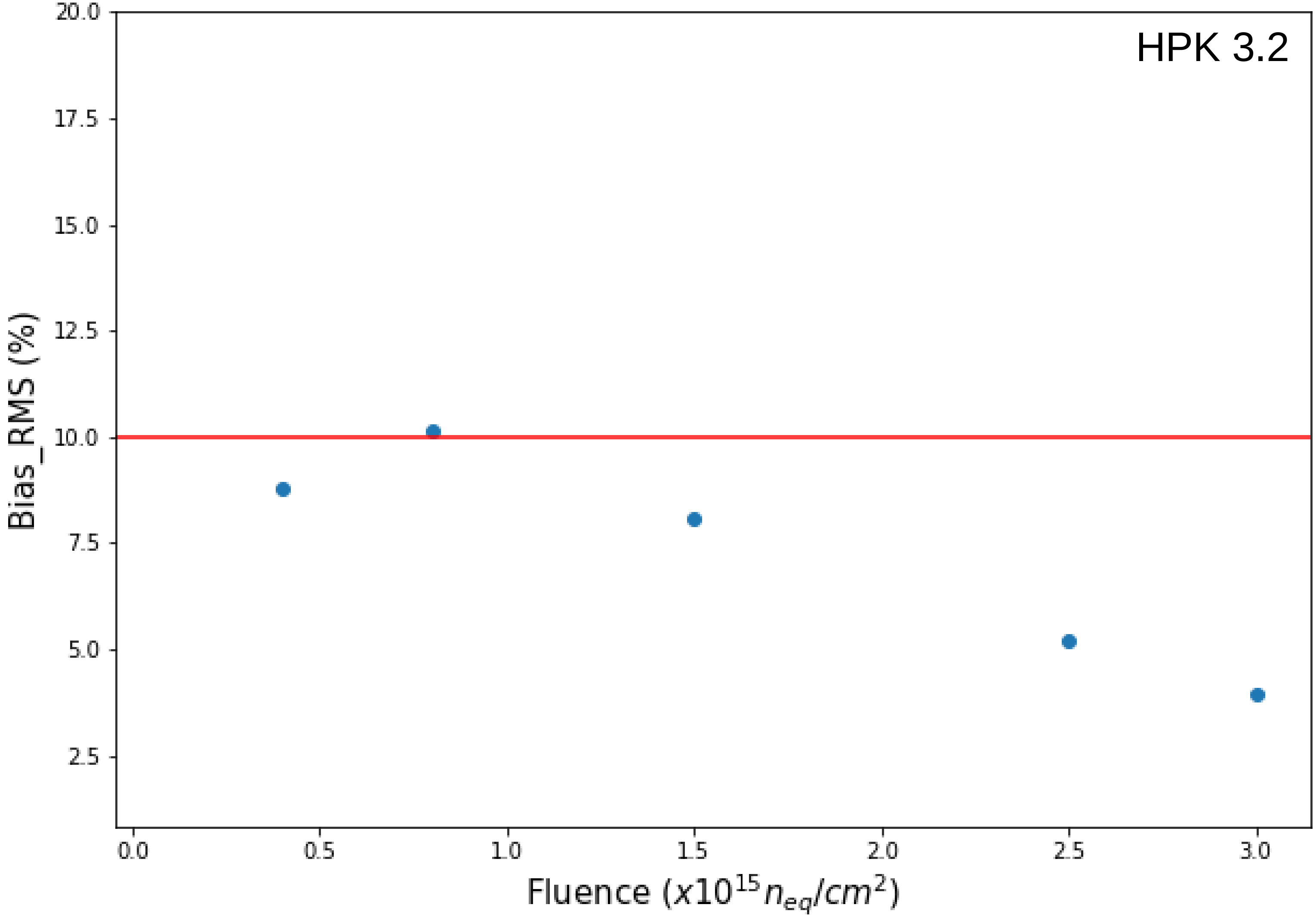
Comments

- The best results overall are given by the CFD corrected method and the second best results are given by the CFD
- Implementing these two methods using an electronic boards is difficult because they require a complex signal processing
- The ALTIROC method was the one chosen used in the HGTD read-out electronics because is easier to implement in an electronic board

Fluence uncertainty



Fluence uncertainty



Fluence uncertainty