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LGADs for timing detectors at HL-LHC

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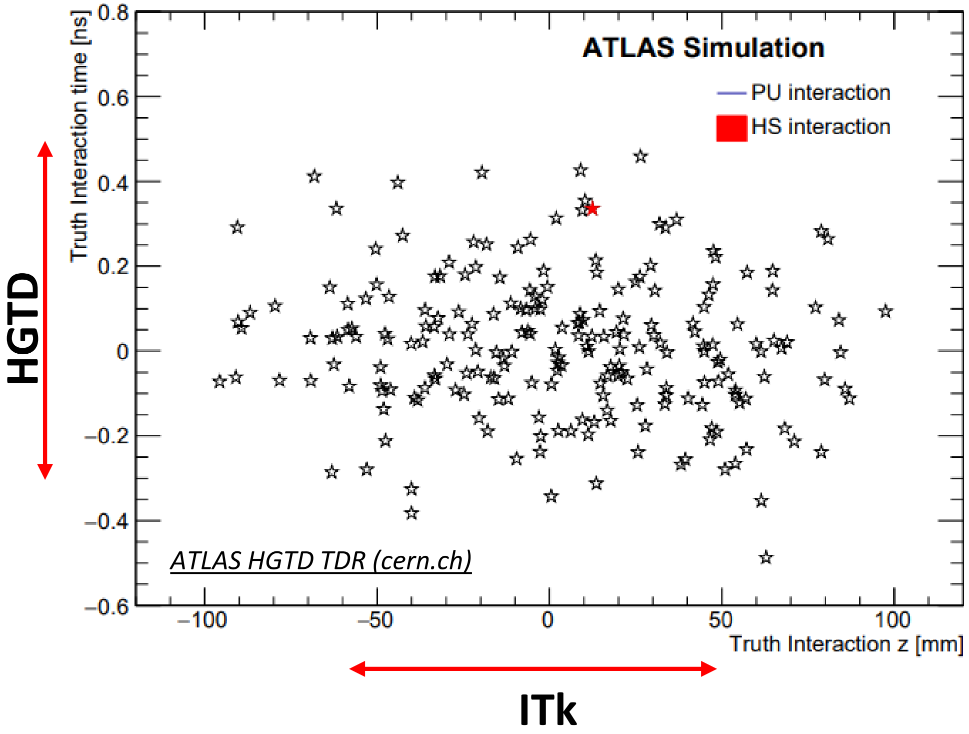
Outline

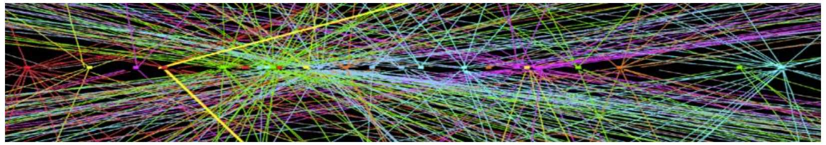
- Timing detectors at HL-LHC
- Basics of timing measurement
- Basics of LGADs
- Performance of prototype sensors before irradiations
- Performance of prototype sensors after irradiations
- Surprises learned
- ASICs for LGADs
- Conclusions

Timing detectors at HL-LHC

HL-LHC upgrade Phase II (2027->)

- number of pileup collisions will increase to 140-200
- huge task to assign reconstructed particles to individual collisions and to extract interesting collisions
- Is there a way to separate vertices also not only in space but **also in time?**





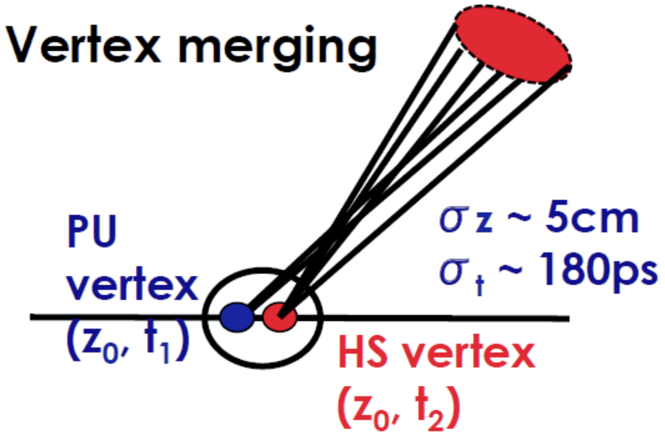
on average 1.6-2.35 vertices per mm

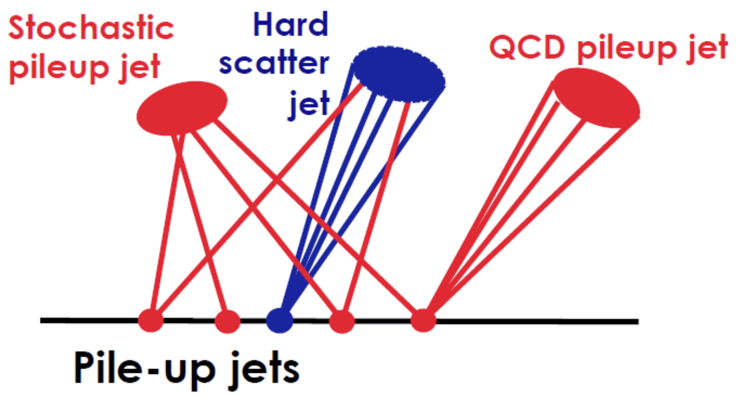
At LHC the vertices are distributed (Gaussian) with: σ_z=5 cm & σ_t=180 ps

Tracking detectors provide resolution of primary vertices in forward region typically >1 mm, which leads to merging of several collision vertices

It is a task of the timing detectors to provide track timing resolution of around of <50 ps for minimum ionizing particles.

Motivation for timing detectors

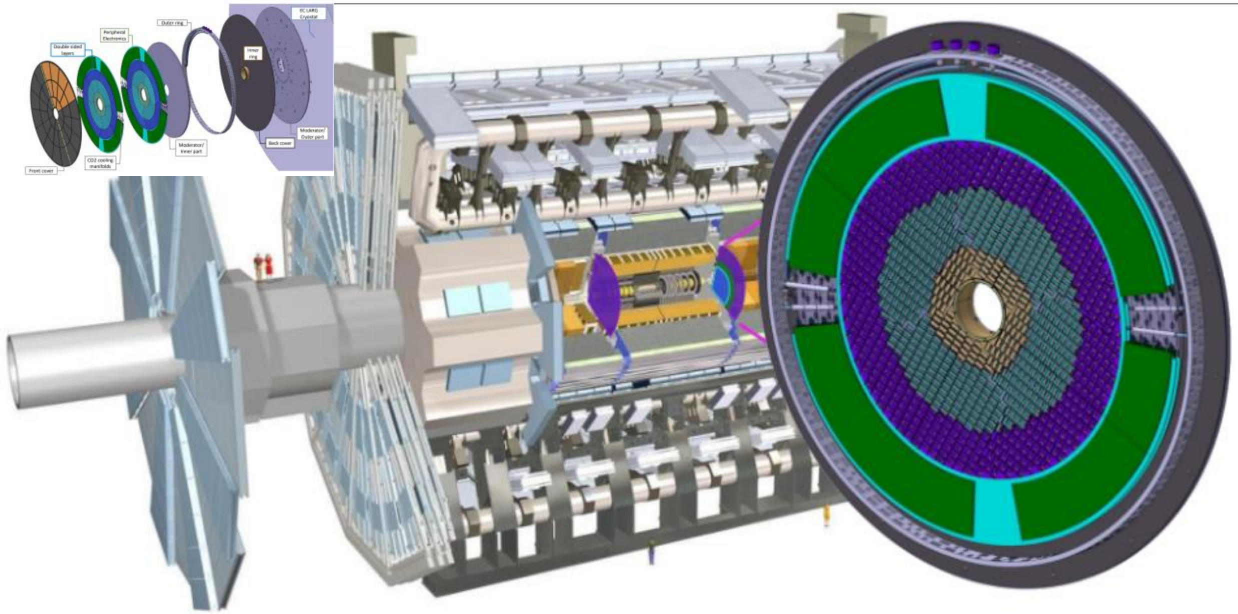




Main goals of timing measurments:

- Resolving primary vertex (pileup tracks contamination)
- cleaning up the pile up contamination (track fraction) in jets (at 1.6 collisions/mm from ~20% to ~3%)
- improvement of lepton isolation in high pileup environment
- improvement in forward PU jet suppression – larger fraction of Hard Scatter jets

ATLAS – High Granularity Timing Detector



ATLAS-HGTD TDR

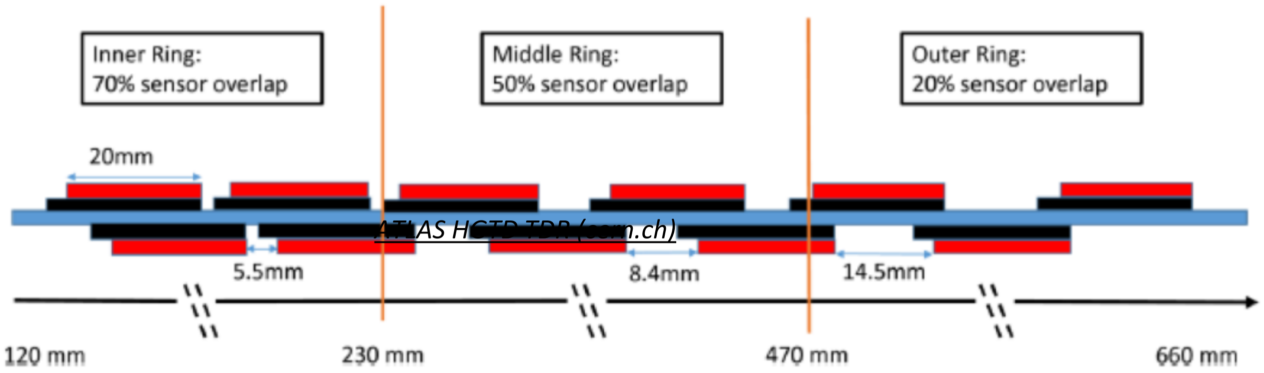
Layout :

- Two double-instrumented disks per end-cap

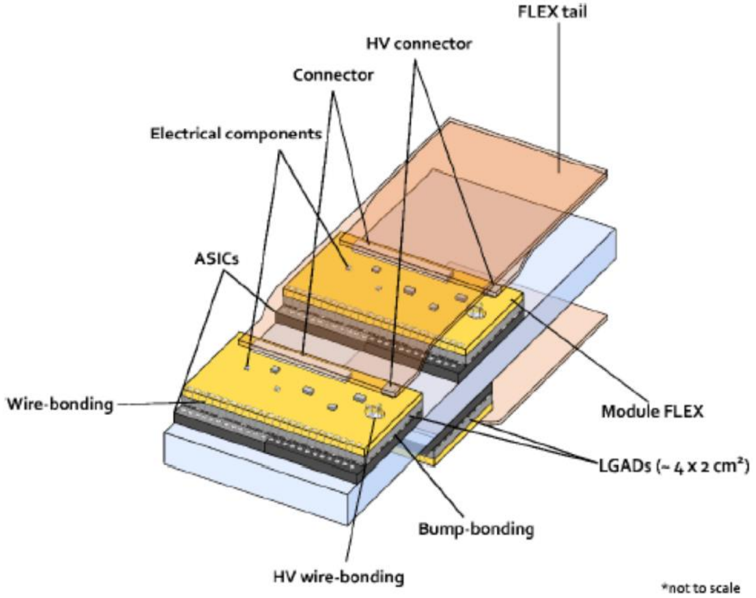
~2.0 – 2.4 - 2.6 points/track

2.4 < |η| < 4, 120 mm < r < 640 mm , z=350 cm

- 3.6 M channels operating at -30^{o}C (6.4 m^2 of Si)



[ATLAS HGTD TDR (cern.ch)]

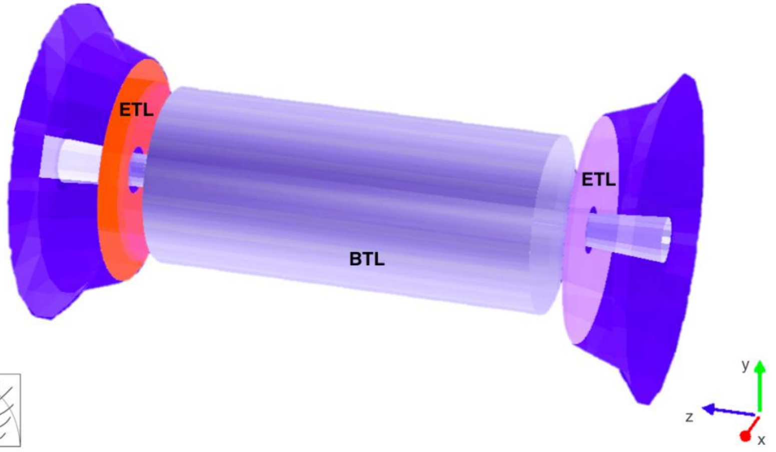


Module is very similar to the pixel modules (less concern about the material)

CMS – ETL

MTD = ETL(LGAD) + BTL(LYSO+SiPM)

CMS-MTD TDR (cern.ch)



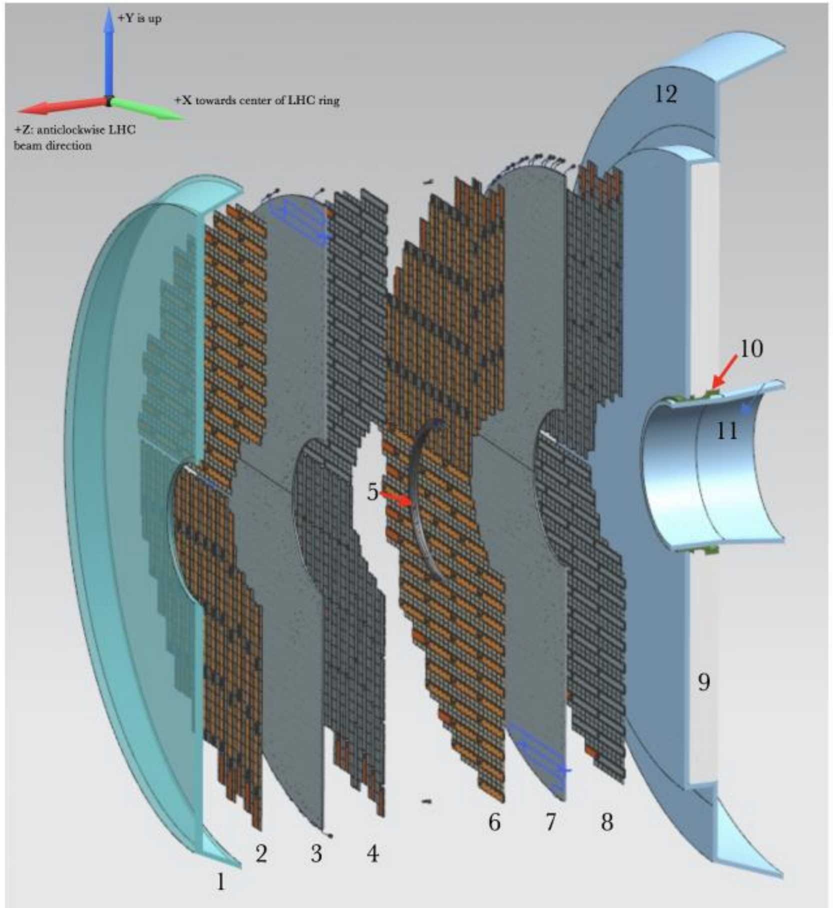
Layout :

- Two "double" disks per end-cap

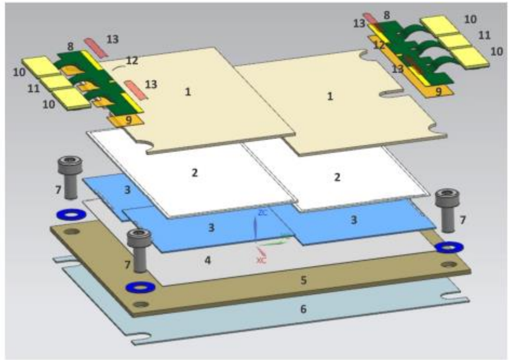
  ~2 points/track

  1.6 < |η| < 3, 315 mm < r < 1200 mm

- 8.5 M channels (14 m^2 of Si)



1: ETL Thermal Screen
2: Disk 1, Face 1
3: Disk 1 Support Plate
4: Disk 1, Face 2
5: ETL Mounting Bracket
6: Disk 2, Face 1
7: Disk 2 Support Plate
8: Disk 2, Face 2
9: HGCal Neutron Moderator
10: ETL Support Cone
11: Support cone insulation
12: HGCal Thermal Screen



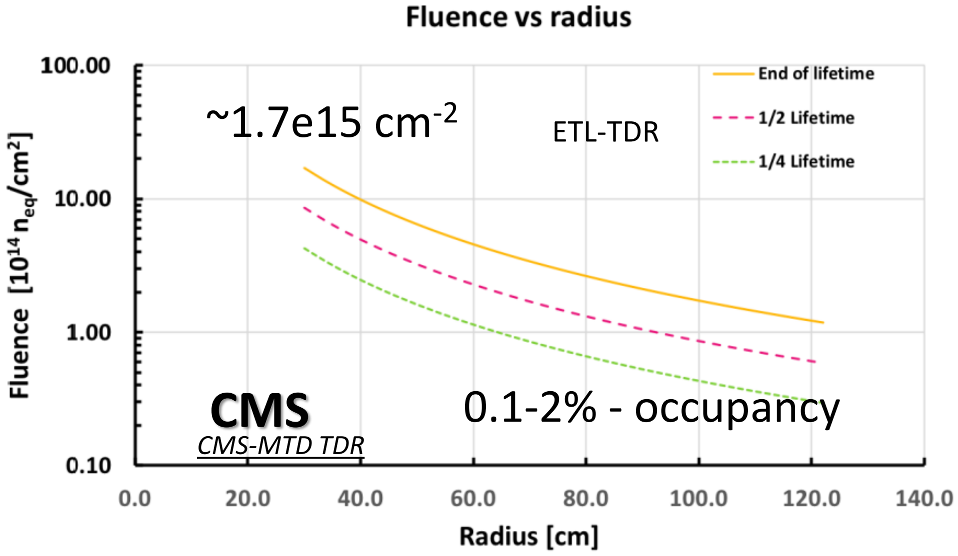
1: AlN module cover
2: LGAD sensor
3: ETL ASIC
4: Mounting film
5: AlN carrier
6: Mounting film
7: Mounting screw
8: Front-end hybrid
9: Adhesive film
10: Readout connector
11: High voltage connector
12: LGAD bias voltage wirebond
13: ETROC wirebonds

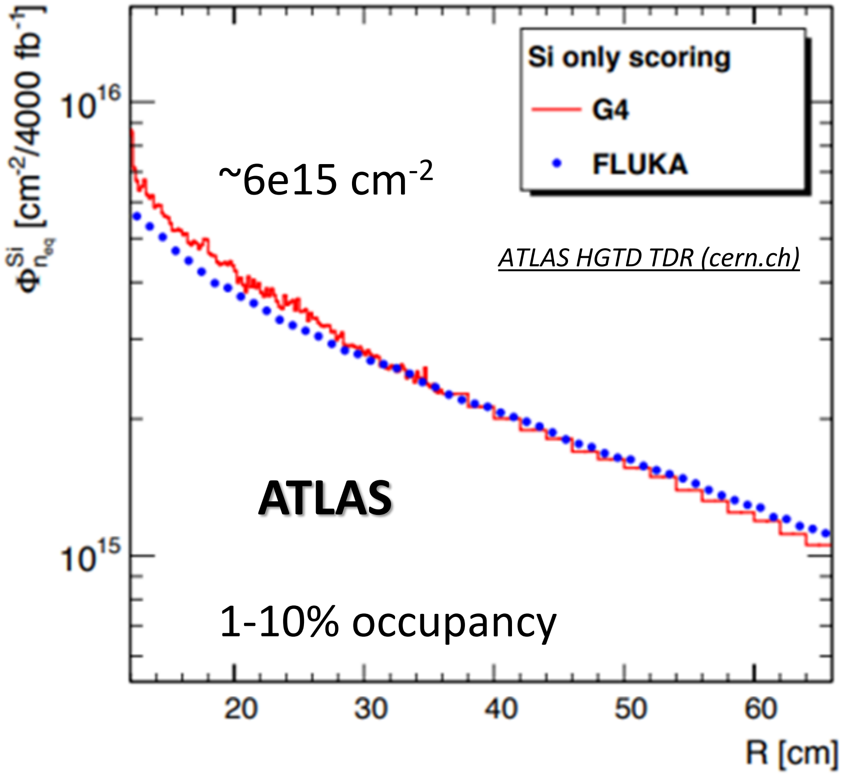
Different module arrangement and connectivity as ATLAS but essentially also "pixel" module

Requirements for timing detectors

- both CMS and ATLAS will require sensors that provide in connection to electronics track timing resolution of <50 ps – if it gets worse than the timing detectors lose their physics motivation
- the main obstacle is that sensors have to survive in high radiation environment (TID up to CMS~1MGy, ATLAS~2.2 MGy)
- occupancy <10% (ATLAS), <2% (CMS), hit efficiency and position resolution:
  - size of the **sensing element 1.3x1.3 cm^{-2}**
- compactness of sensor assemblies – very small space available
- difference to trackers – simultaneously achieved

good tracking efficiency, low noise occupancy and excellent time resolution





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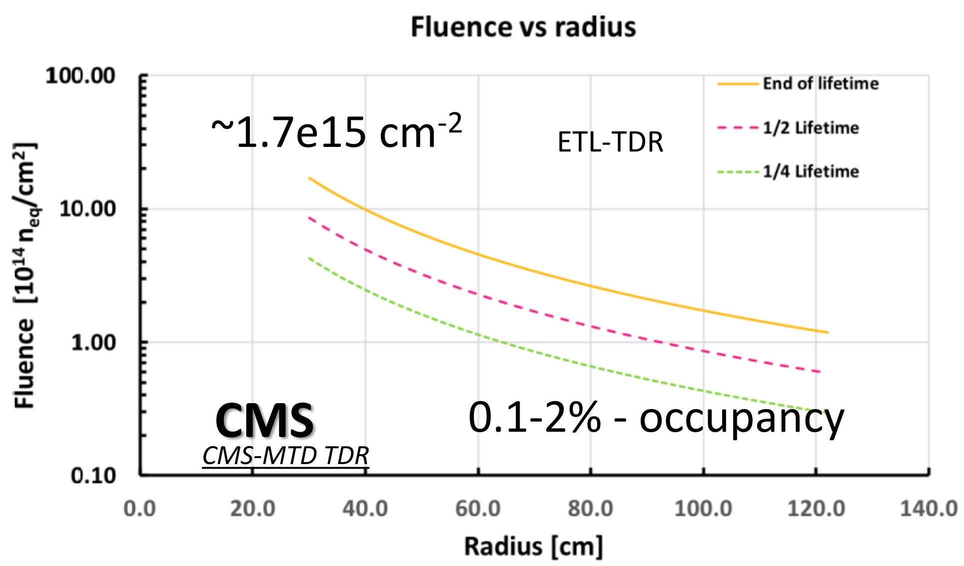
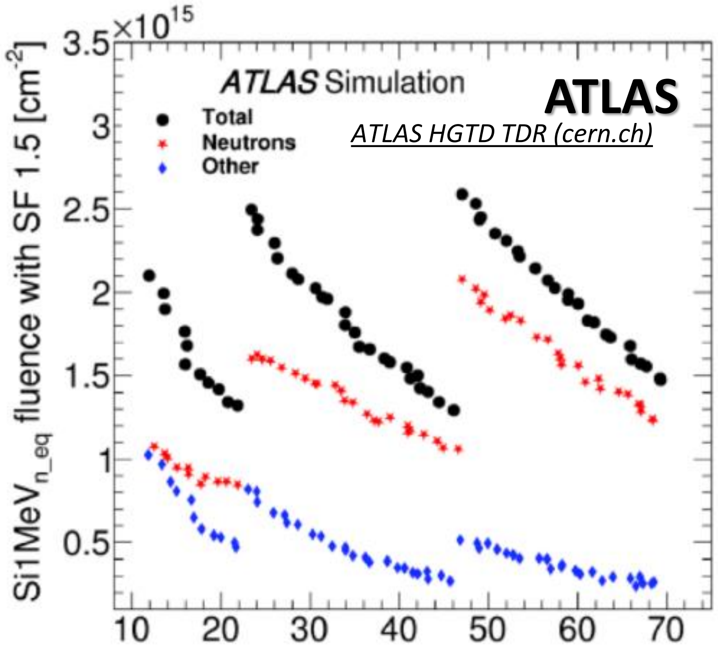


ATLAS will do replacements:

- Inner ring (IR) R< 230 mm - every 1000 fb^{-1}
- Middle ring (MR) R>230 mm && R<470 mm – every 2000 fb^{-1}
- Outer ring (OR) R>470 mm (42% of HGTD) – never

SIZEABLE CONTRIBUTION OF CHARGED HADRONS TO TOTAL FLUENCE

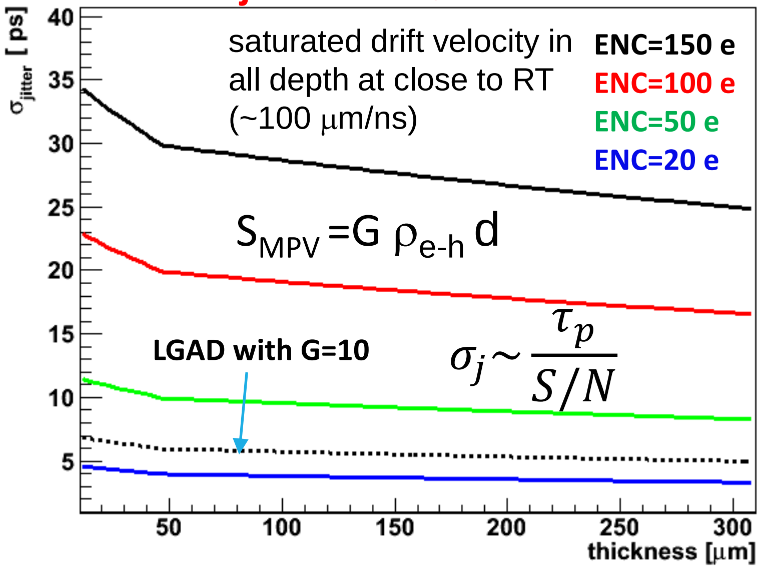


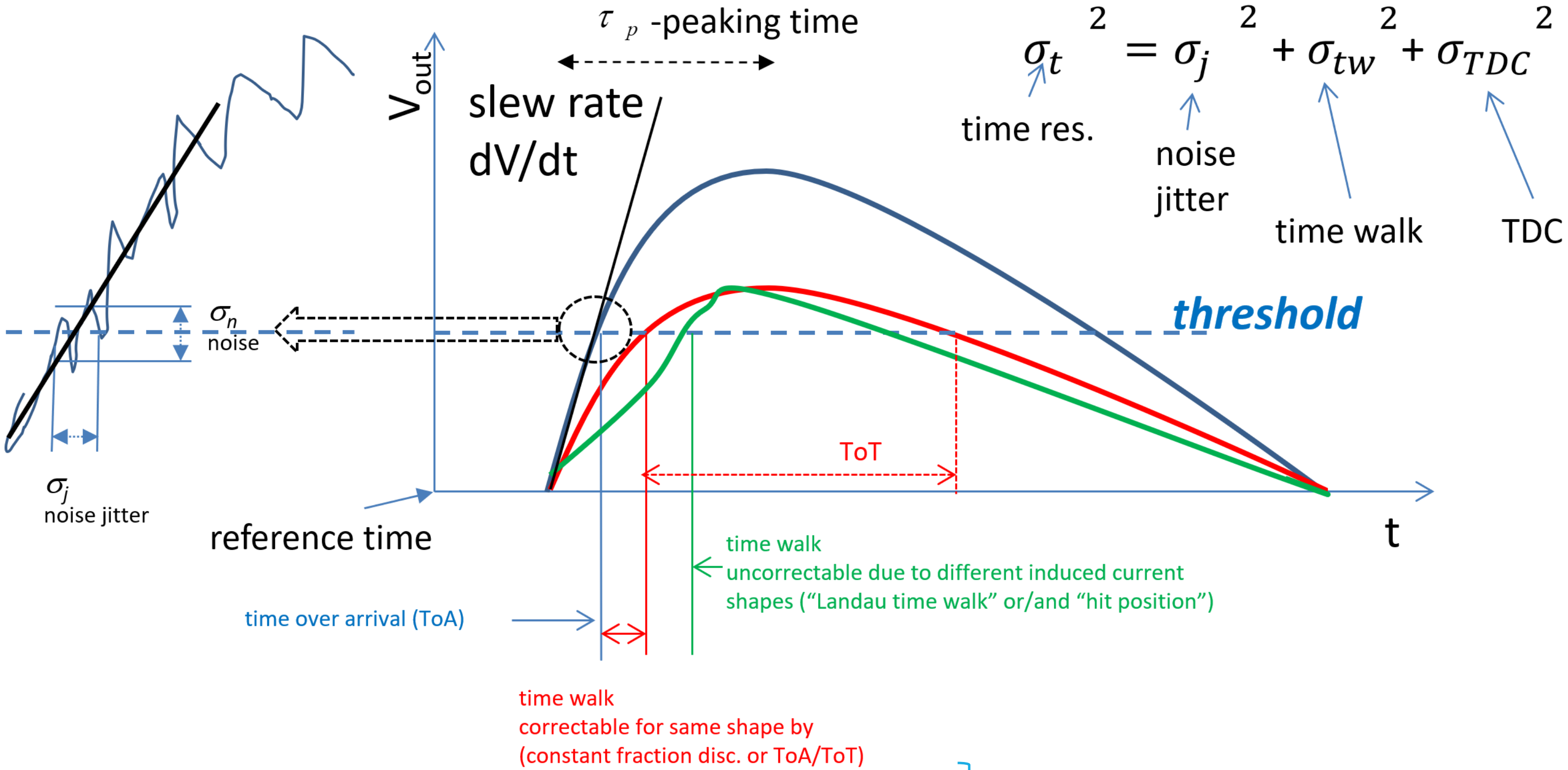
Basics of timing measurement

Basics of timing detectors

$$\sigma_j = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} \approx \frac{\sigma_n}{\left|\frac{S}{\tau_p}\right|} = \frac{\tau_p}{S/N}$$

σ_j - Jitter ($\tau_p \sim t_{collection}$)





- large electrode size of (~1.7 mm^2) with C~4 pF
- fast electronics (transimpedance amplifier) with τ_p~1 ns

gain in thin sensors is needed

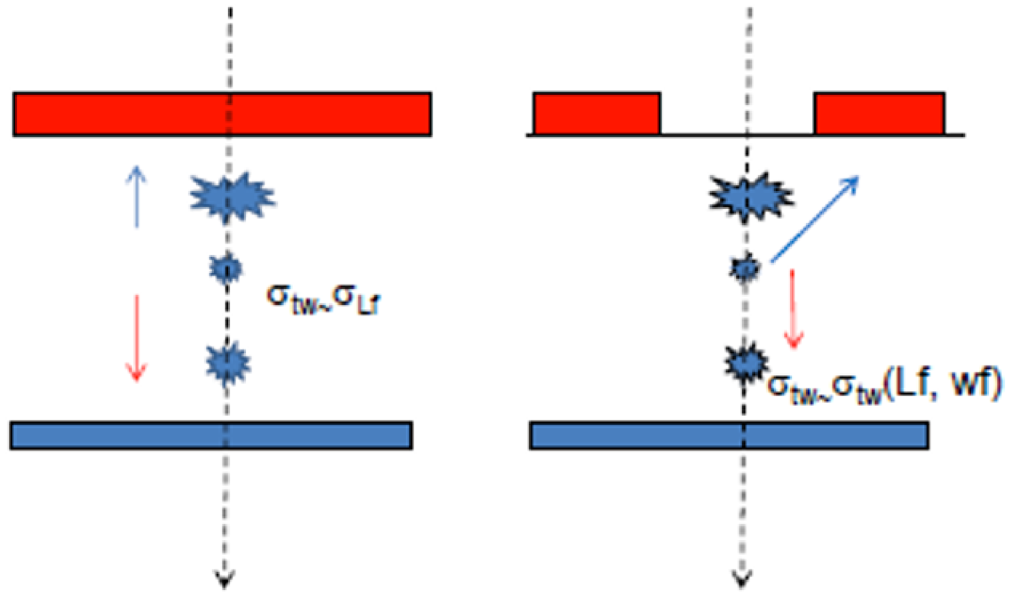
- 3D sensors excluded due to very large capacitance for given cell size
- Depleted CMOS as standard planar detector won't be able to reach desired resolution

Measuring time – time walk

σ_{tw}-time walk component includes σ_{wf} σ_{lf} σ_{Q}, :

$$\sigma_{tw}^2=\sigma_{wf}^2 + \sigma_{lf}^2 + \sigma_Q^2$$

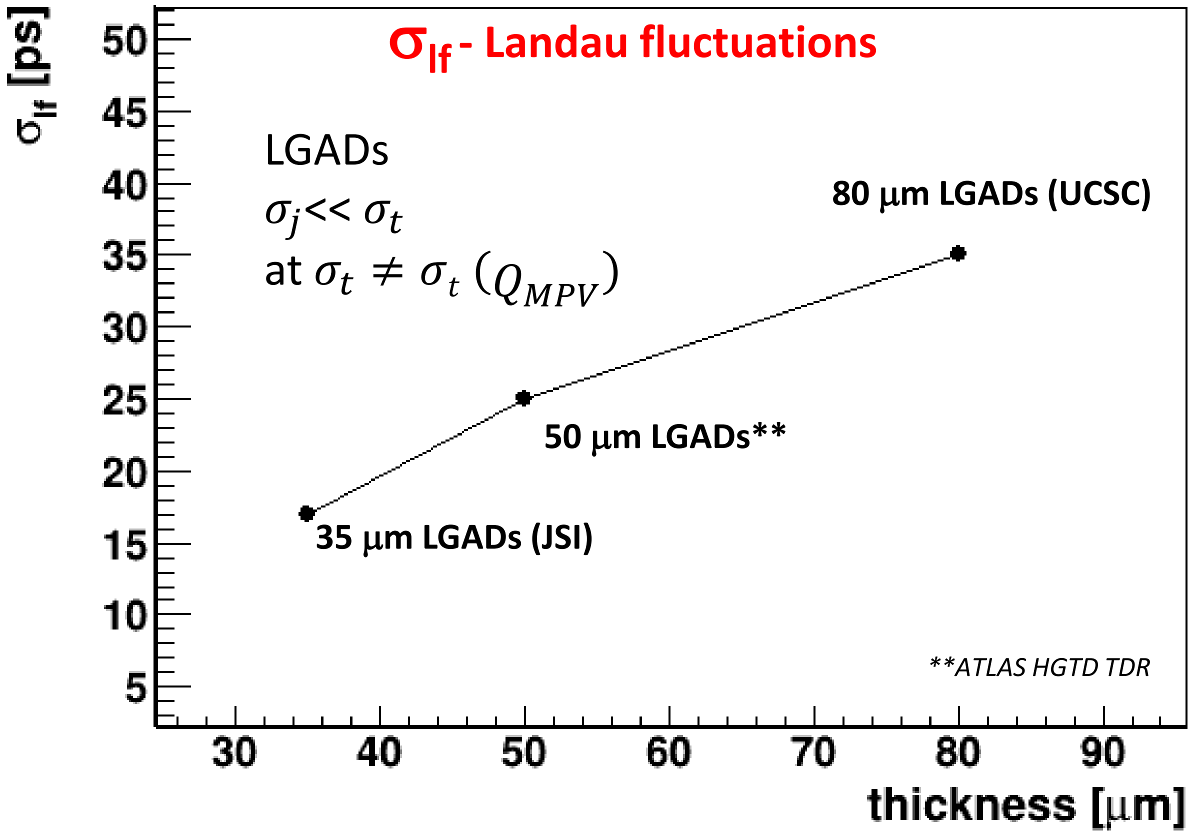
- σ_Q - fluctuations in amount of deposited charge –> correctable with ToA-ToT or CFD (not trivial)
- σ_{lf} - Landau fluctuations in shape of the signal -> depends on hit position (segmented devices)
- σ_{wf} / σ_{un} – weighting/electric field contribution (distortion component/un-perfection) -> depends on hit position in segmented devices

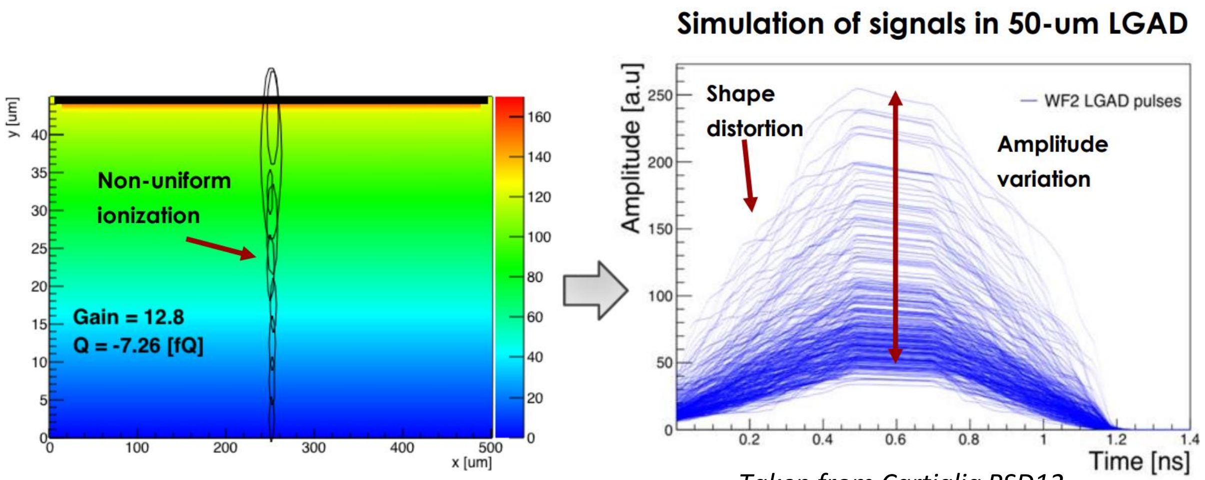


- large **pad dimensions >> thickness** required to mitigate weighting field effect
- Saturated drift velocity required over the volume to reduce the dependence of time of charge arrival to gain layer (saturated velocities ~100 μm/ns) – induced currents are ~1 ns long
- Landau fluctuations can bot be removed – there by nature

time resolution limited to ~25 ps for 50 μm thick sensors

Landau fluctuations





Taken from Cartiglia PSD12

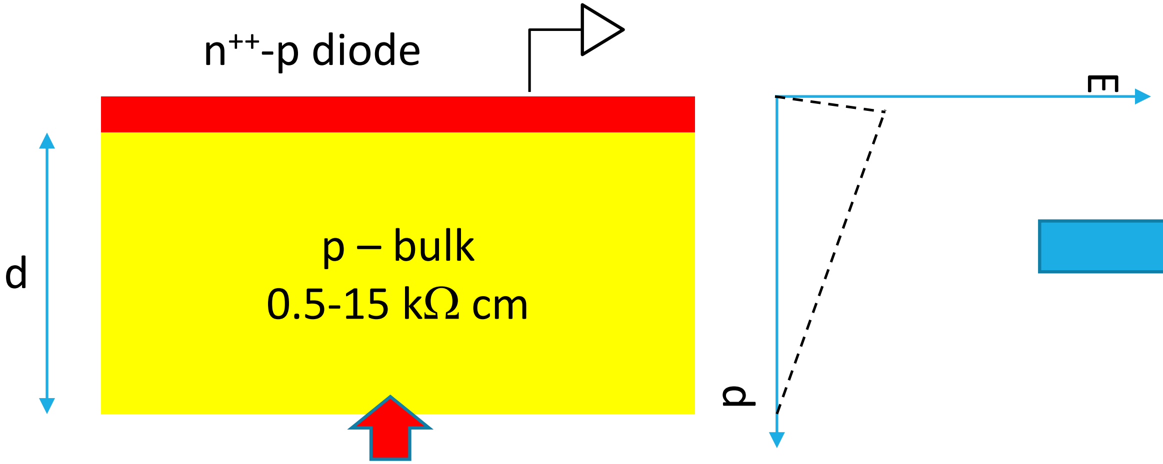
LGADs (planar sensors with gain) seem to be ideal solution to reach superb resolution for large pixels/pads

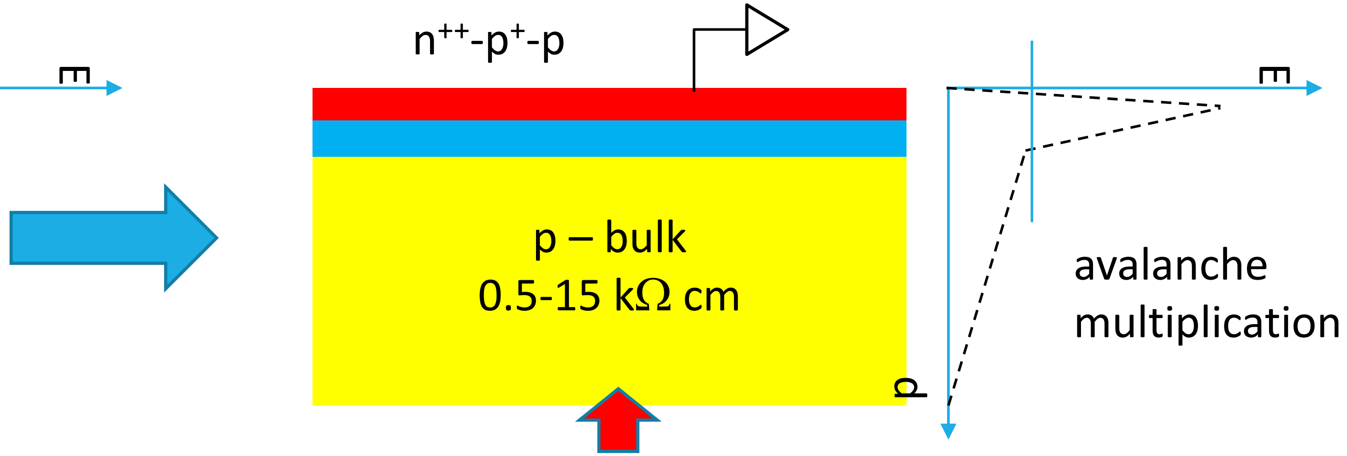
- large capacitance (noise) can be offset by gain -> good S/N (with discrete electronics 80-100)
- In order to reach the desired time resolution the thickness is limited to <80 μm

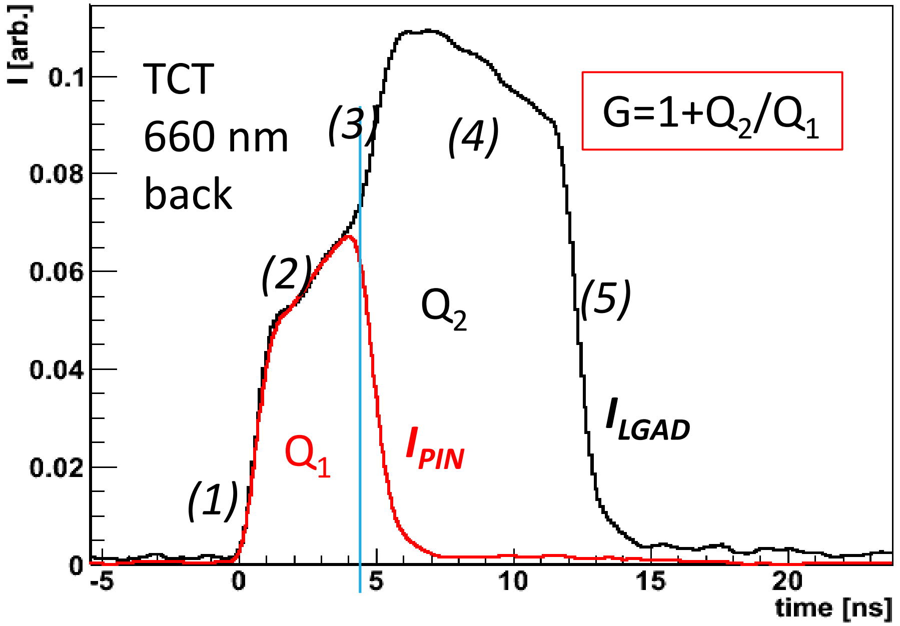
Basics of LGADs

It all started with transferring the APD idea to particle detectors:
G. Pellegrini et al., "Technology developments and first measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications", NIM A765 (2014) p12.

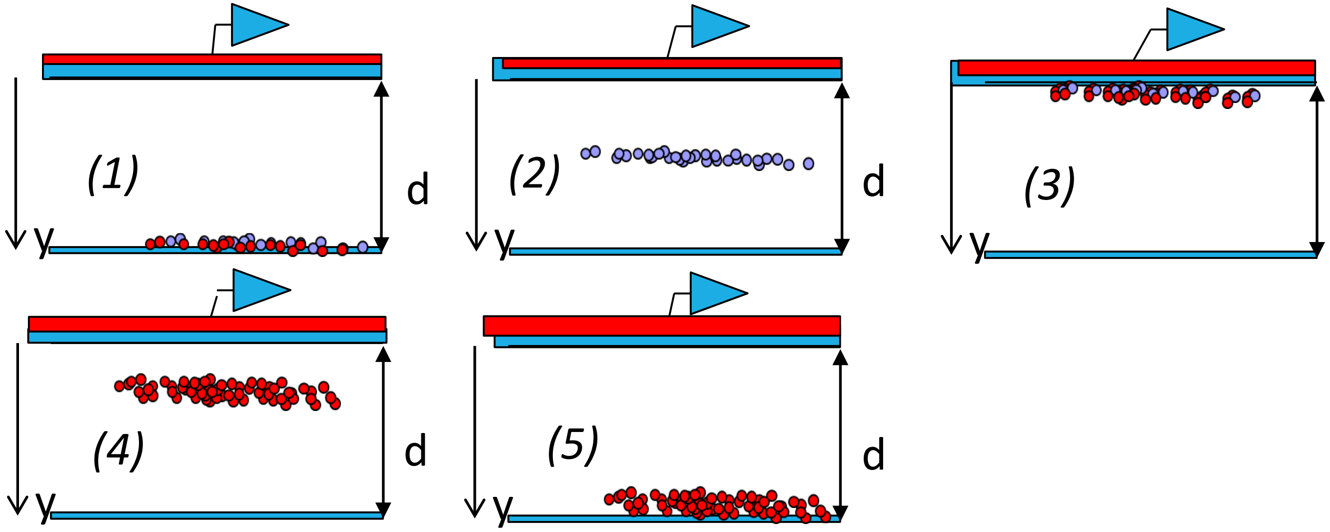
Low Gain Avalanche Detectors (LGAD)



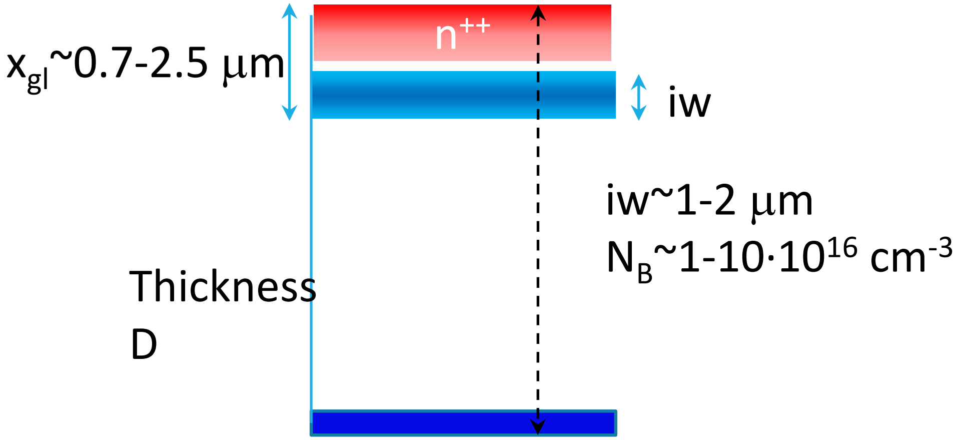




Injection of electrons at the back of the sensor by red laser.

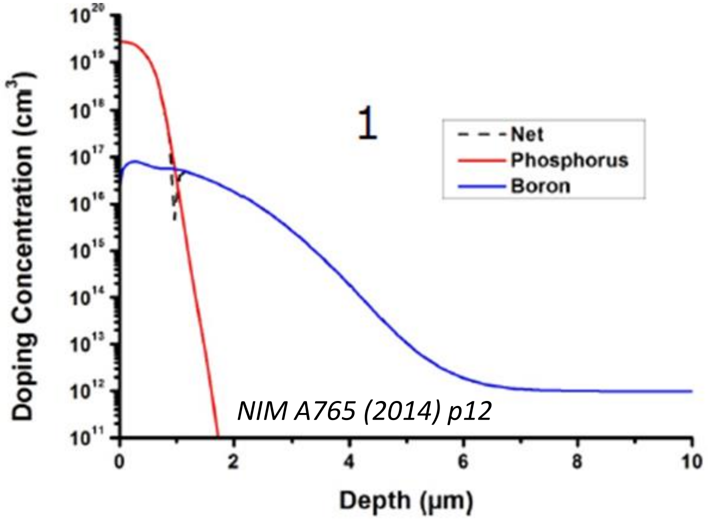


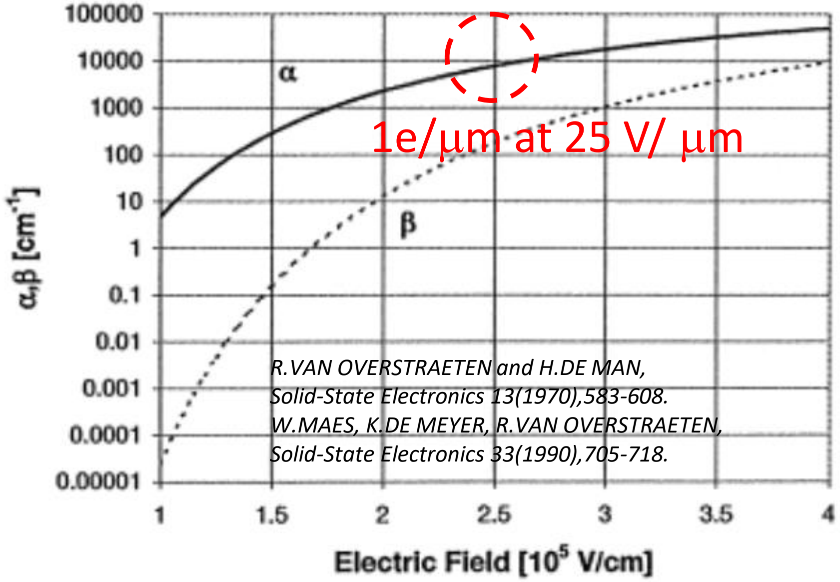
Gain layer design



Parameters determining the gain layer (subject of extensive R&D):

- x_{gl} - gain layer depth (depth of the p+ implant) - 0.7-2.5 μm
- iw – implant width (determined by the processing) - 1-2 μm
- Impurities added to reduce the changes of gain layer doping after irradiation - most notable carbon



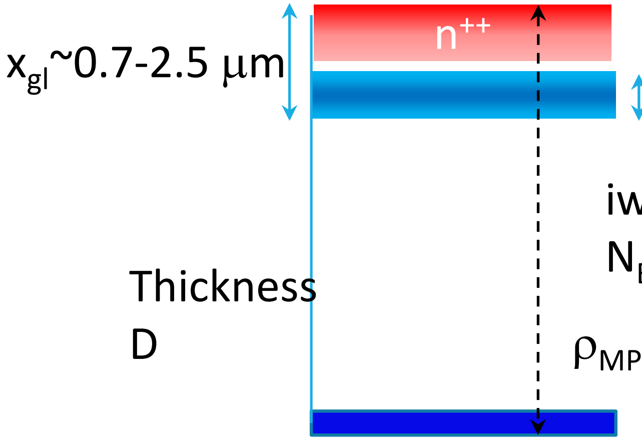


$$dN_e = N_e \cdot \alpha \cdot dx$$

Doping should be such that in GL E>25 V/μm

- large x_{gl} - large gain layer depletion voltage less steep Q-V plot/larger gain post-radiation
- small x_{gl} – more doping/less acceptor removal
- Impurities added to reduce the changes of gain layer doping after irradiation - carbon

Signal and noise



iw~1-2 µm

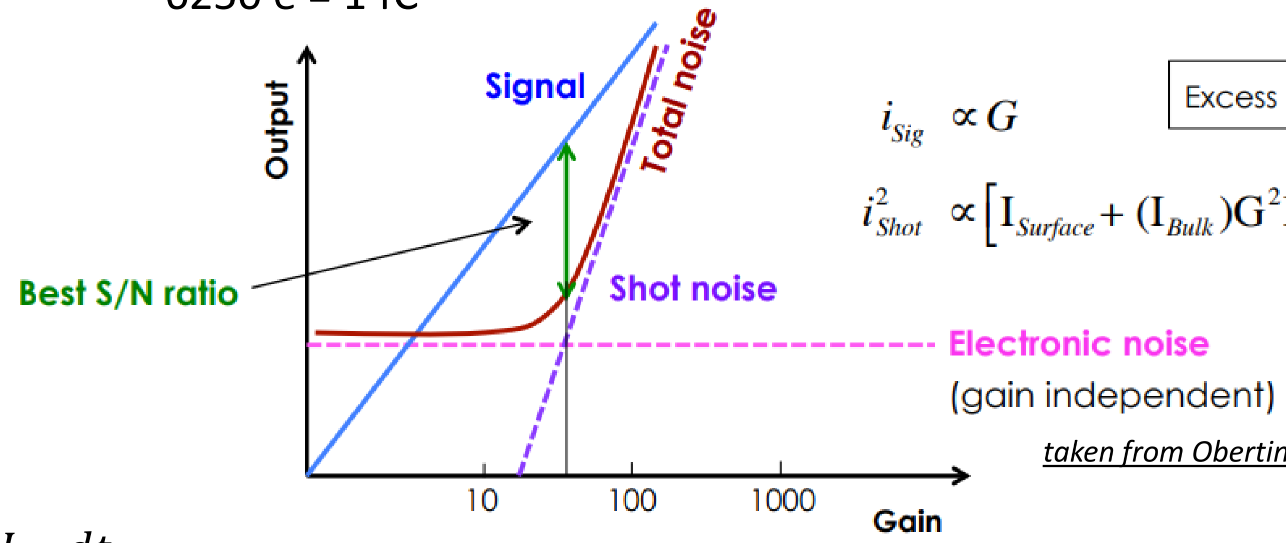
N_B~1-10·10^{16} cm^{-3}

ρ_{MPV}~65 e-h/µm

Gains are limited to G<100 – due to increase of noise

Signals are usually given in fC more appropriate than electrons:

6250 e = 1 fC



$i_{Sig} \propto G$

$i^2_{Shot} \propto [I_{Surface} + (I_{Bulk})G^2F]$

Excess Noise Factor

taken from Obertino,Vertex2017

Signal in sensors in given by Ramo's theorem:

$I = q\vec{v}\vec{E}_w$ for particle track $Q(t) = \sum_{e-h} \int_{t=0}^{t_{int}} I_{e,h} dt$

Charge: $Q \sim (G-1)\,\rho D\; e^{-\frac{t_{d,h}}{\tau_{eff,h}}}\; e^{-\frac{t_{d,e}}{2\tau_{eff,e}}} + \frac{\rho D}{2}\left(e^{-\frac{t_{d,e}}{2\tau_{eff,e}}} + e^{-\frac{t_{d,e}}{2\,\tau_{eff,e}}}\right)$

trapping of multiplied holes

due to trapped primary electrons

trapping of primary carriers

$t_{d,e}$~$v_{sat,e}/D$ ~ 500 ps in 50 µm

$t_{d,h}$~$v_{sat,h}/D$ ~ 700 ps in 50 µm

$\tau_{eff,h}$~$\tau_{eff,h}$> 1.5 ns at 2e15 cm^{-2}

$Q \sim GD\rho$

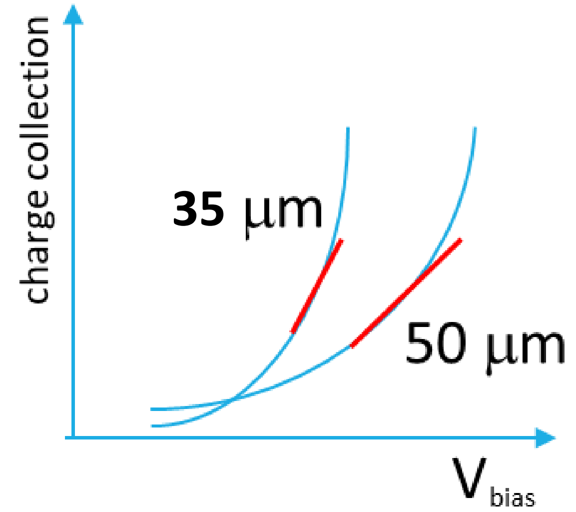
G= Q_{LGAD}/Q_{PIN}

Thickness of the LGADs

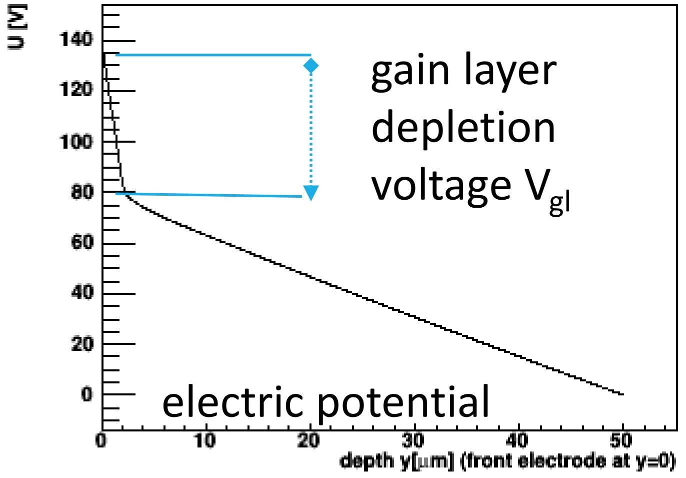
Produced LGADs for timing ranged from 35-80 μm. Smaller thickness results in:

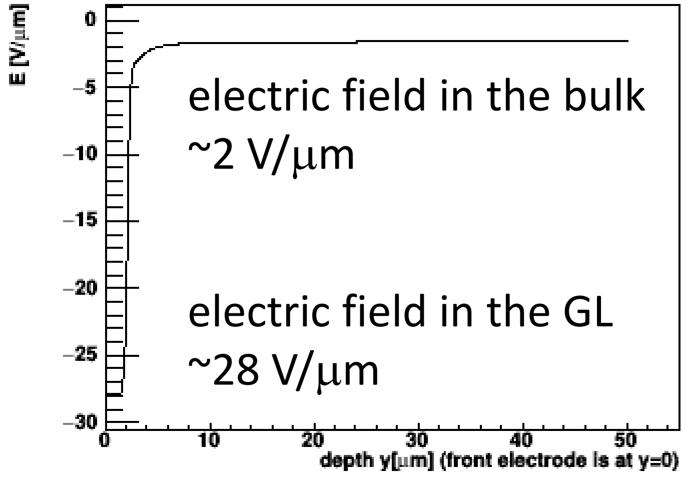
- faster signal – less Landau fluctuations
- smaller bias voltage required for given gain after irradiation – less power dissipation
- larger capacitance
- less charge generated by mip particle
- **steeper *dQ/dV* – difficult to control the operation voltage particularly for sensors where the variation of fluence is significant over the sensors**

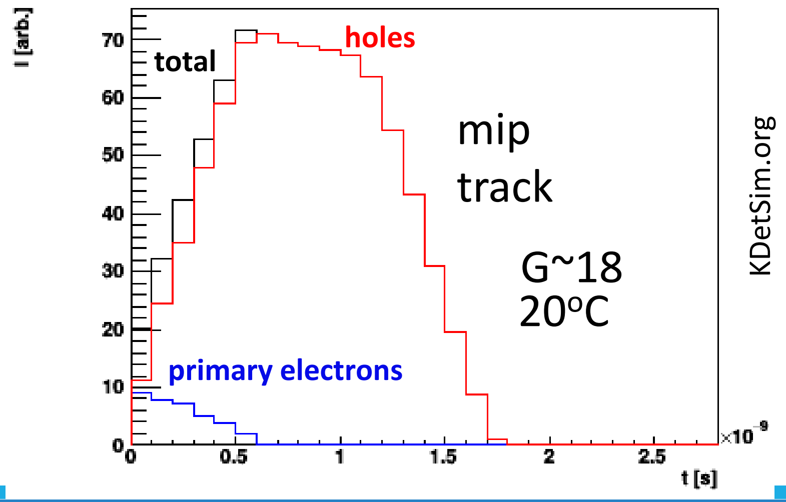
45-55 μm was chosen as a baseline for both ATLAS/CMS



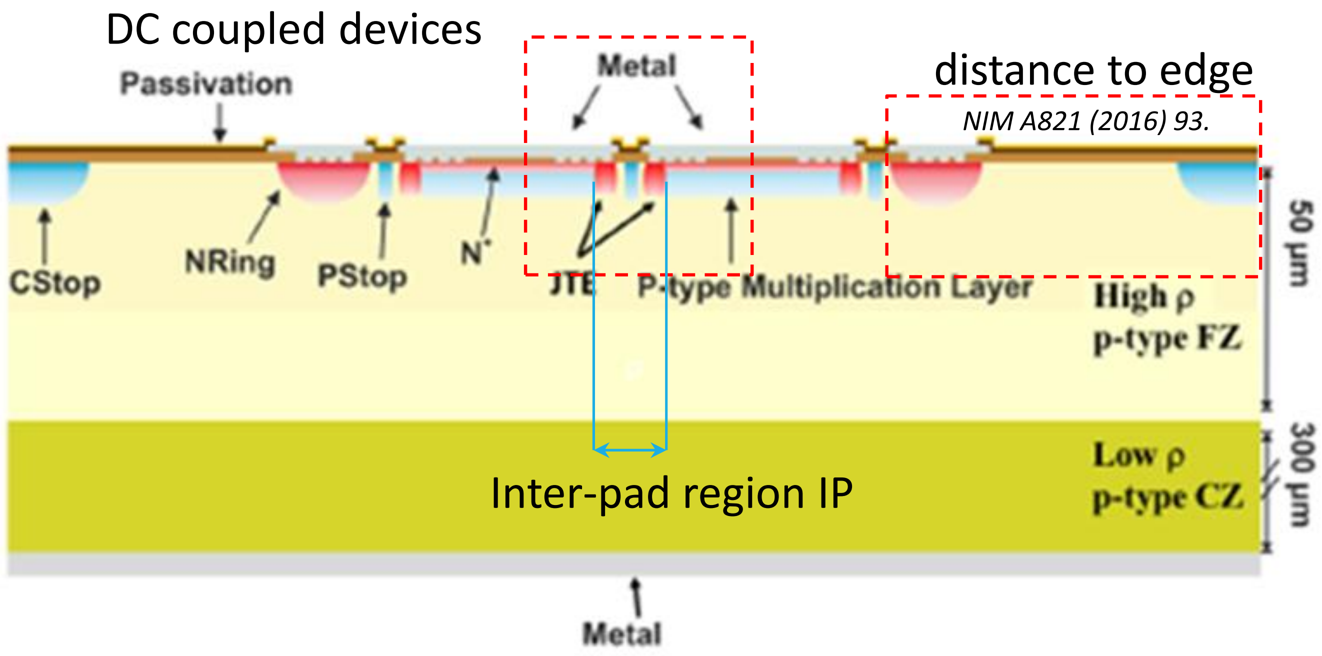
Simulation of the signal in 50 μm thick device:

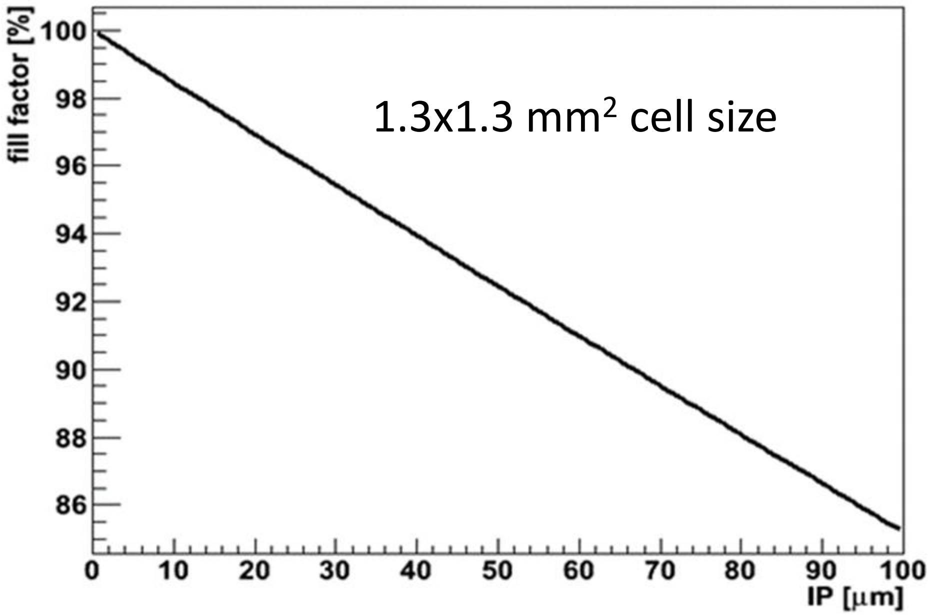






Segmented LGADs and Inter-pad region





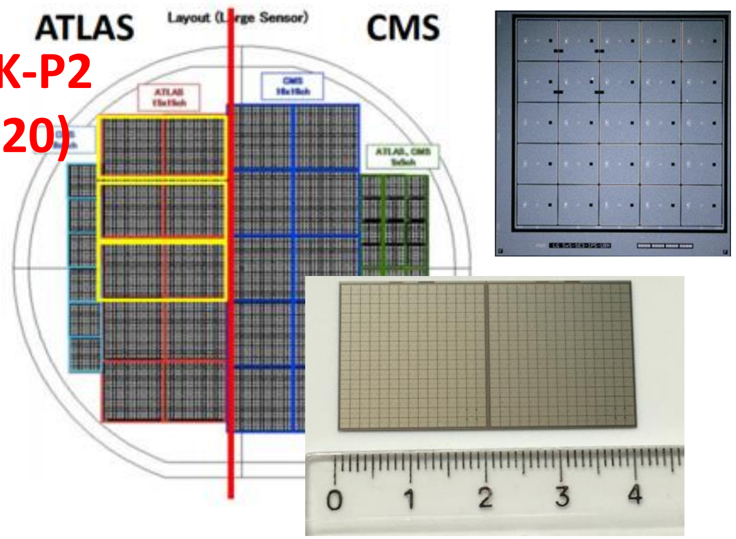
- JTE enables efficient isolation of the electrode – allows for segmentation of the LGAD – the key to multi electrode LGADs
- Inter-pad region is the distance between two electrodes. It is effectively the non-active region as it is without the gain and effectively reduces the "fill factor" of the LGAD
- The IP distance can't be too small as in a case of a bad connection – floating pad there is a danger of an early breakdown (~30-90 μm)
- Distance to edge determines the breakdown through the edges and is 300-500 μm

Performance of prototype sensors before irradiations

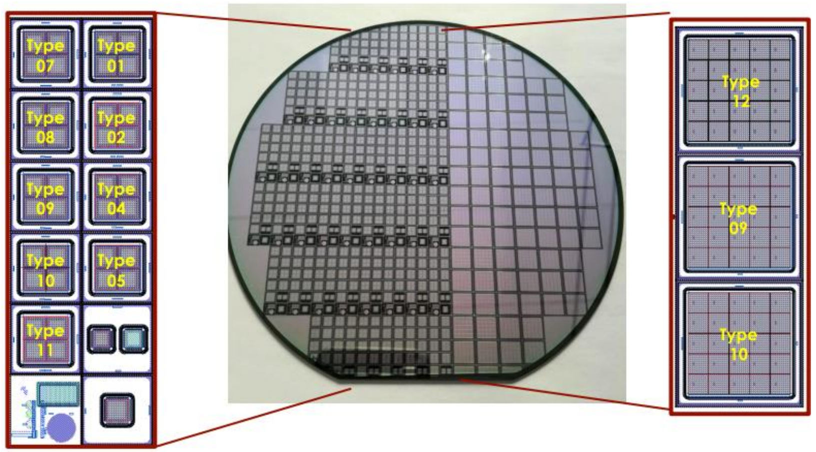
All R&D on LGADs has been done in close collaboration of ATLAS, CMS and RD50 groups.

Latest prototypes produced by different vendors

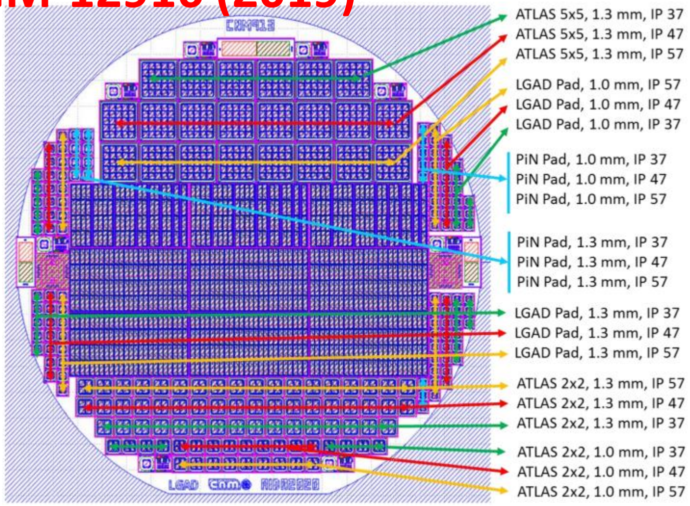
HPK-P2 (2020)

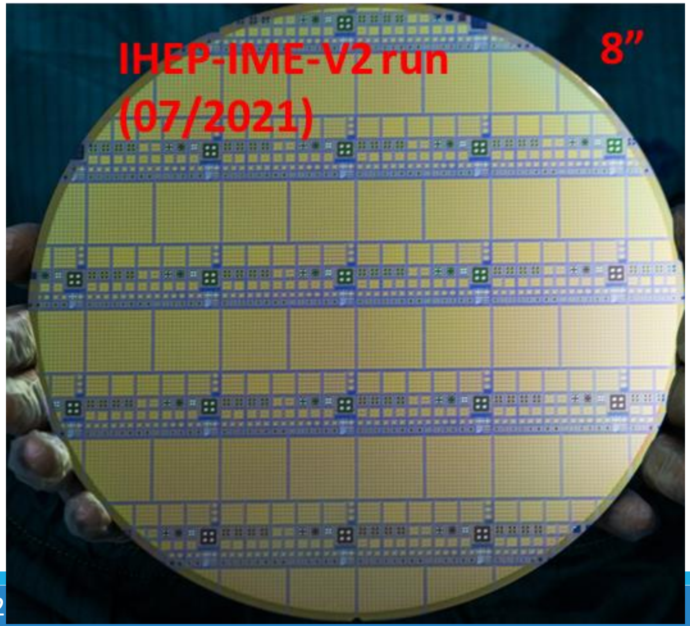


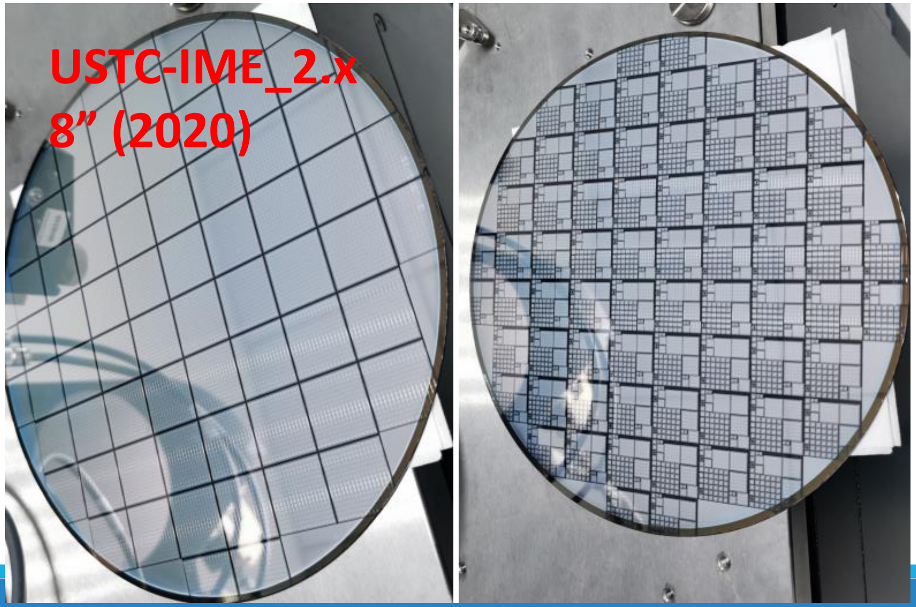
FBK-UFSD 3.2 (2020)

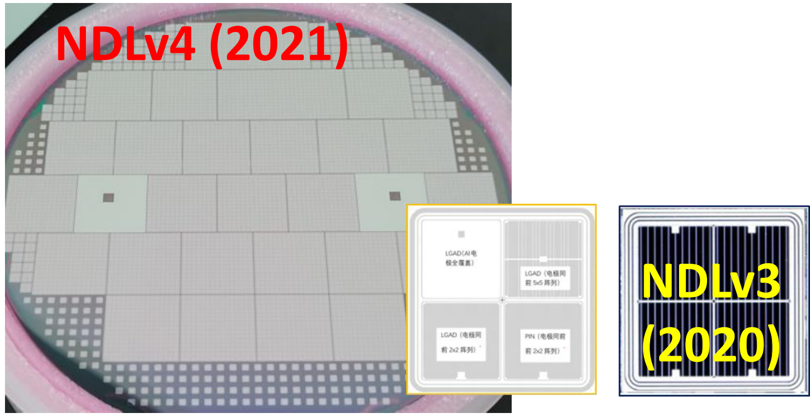


CNM-12916 (2019)





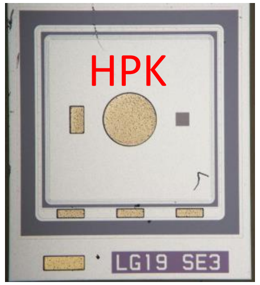


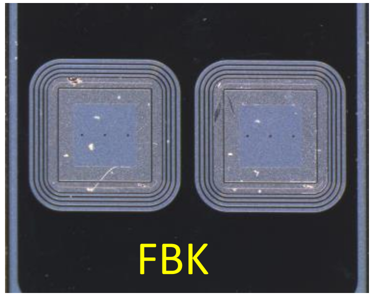


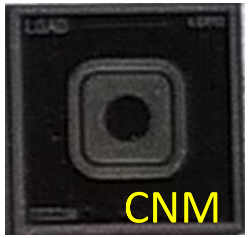
PLANAR TECHNOLOGY – more vendors (e2V, BNL, Micron …)

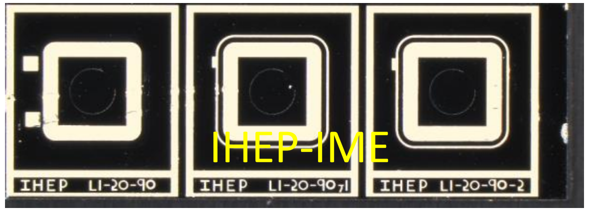
Sensor types studies – few examples

SINGLES

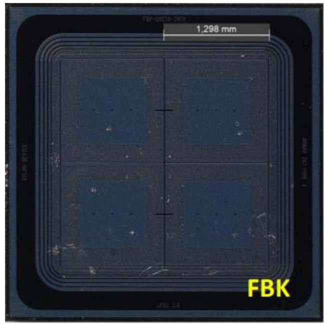


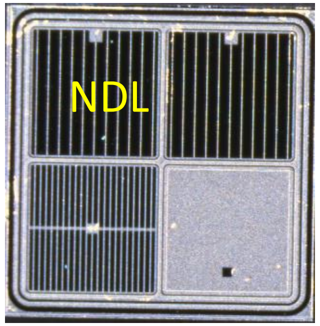




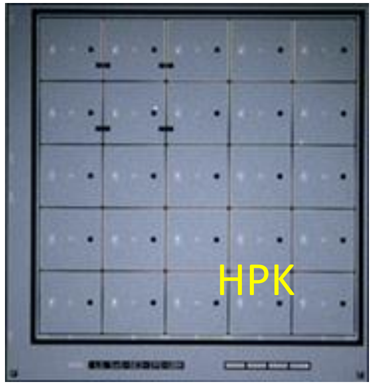


2x2 array

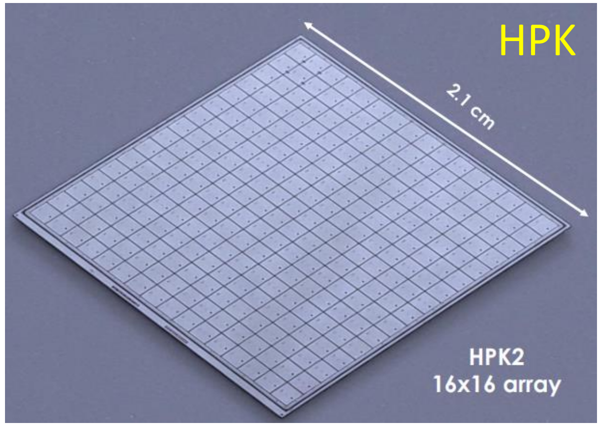


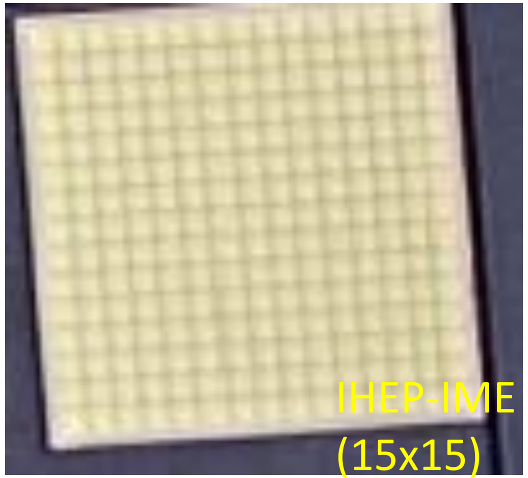


5x5 array



Full size sensors 15x15(16x16) arrays





Recent productions (>2020)

Manufacturer	Name	D [μm]	GL [μm]	V_{gl} [V]	Dopant/C	SE [μm]	IP [μm]	Max. Array Size
HPK (HPK-P2) (6”)	P2 (4 splits)	~50	~2.2	50.5-54.5	B/NO	300-500	30-70	Single,2x2,3x3,5x5,15x15,15x30
FBK (6”)	UFSD 3.2	~45,55	~1-2	25-50	B/YES	500	28-49	Single, 2x2,5x5
NDL (6”)	V3, V4	~50	~1	~29	B/NO			2x2
IHEP-IME (8”)	V1, V2	~50	~1	~25	B/YES			Single, 2x2, 5x5
USTC-IME (8”)	V1.1, V2.0, V2.1	~50	~2	30-40	B/YES		30-90	Single,2x2,5x5,15x15
CNM (6”)	R12916 (AIDAv2)	~50	~1	~40	B/NO			Single, 2x2, 5x5

HPK serves as “gold standard” to which others are compared – the key results will be shown HPK

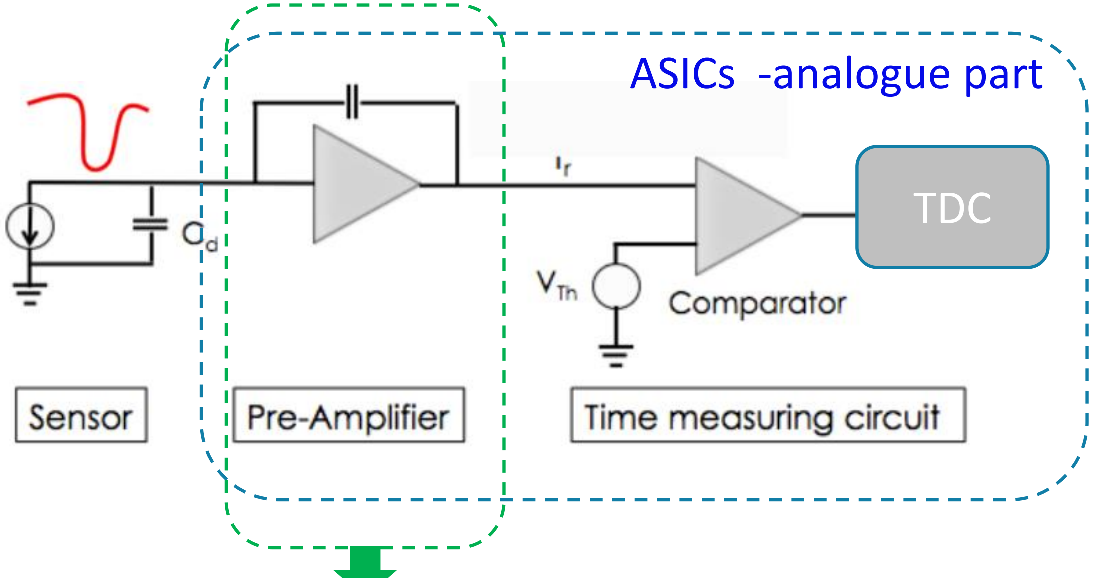
Mains specifications are in the TDRs.

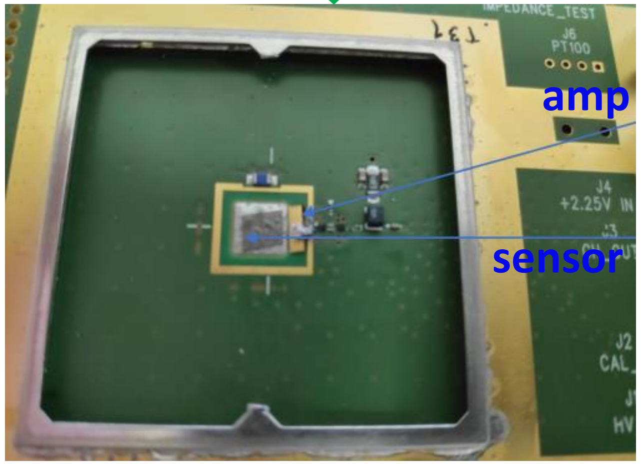
The key property is collection of **4 (ATLAS) /5 (CMS) fC** (G~8/10) at **safe operation voltage** over the entire lifetime of the experiments (2.5e15 cm^{-2})

It was shown with discrete electronics that the required time resolution and efficiency can be achieved with >4 fC and also for expected ASICs performance <70 ps for single hit resolution.

Measuring the performance of the detectors

modified plot from N. Cartiglia





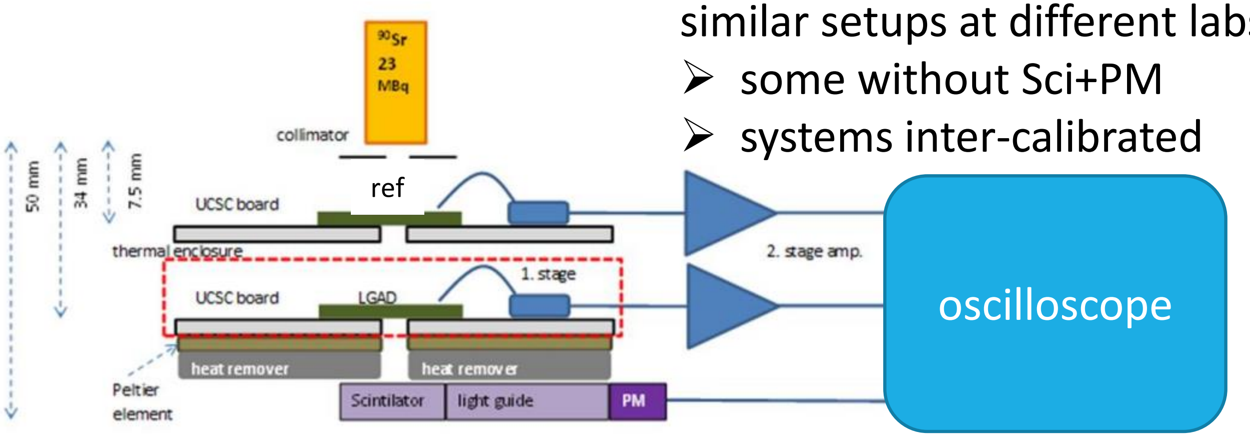
UCSC boards is mostly used

- transimpedance amp (470Ω), Si-Ge
- wide bandwidth 3 GHz
- 1 and 4 Ch. versions

Less constraints with respect to the ASICs – exploring the limits of the sensors.

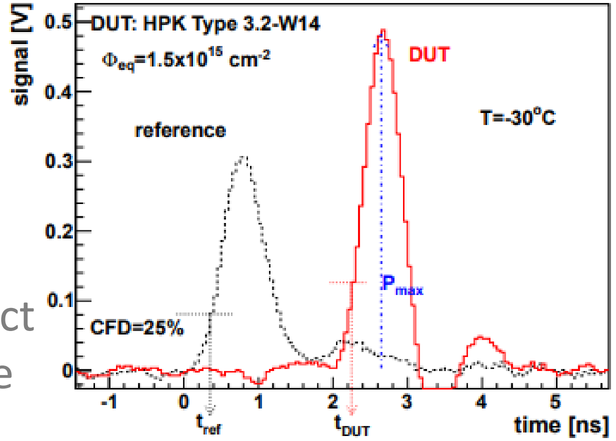
Beta scope – used for ^{90}Sr and in test beams

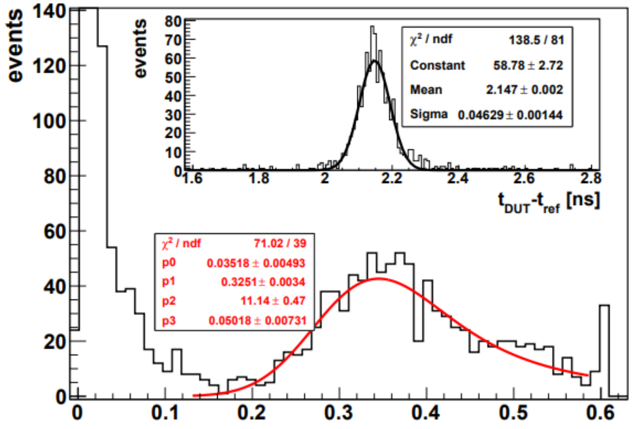
Timing and Charge measurements



similar setups at different labs

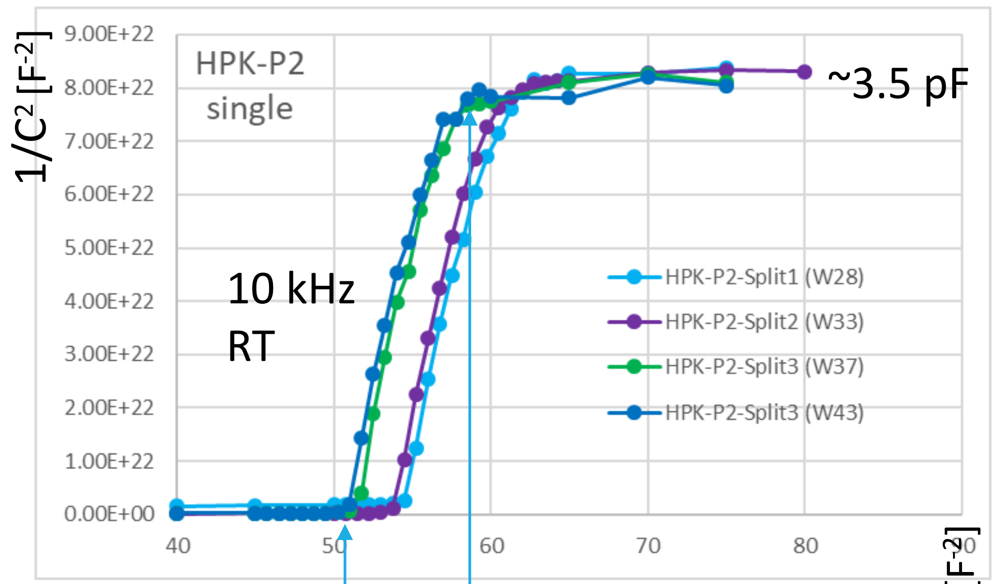
- some without Sci+PM
- systems inter-calibrated

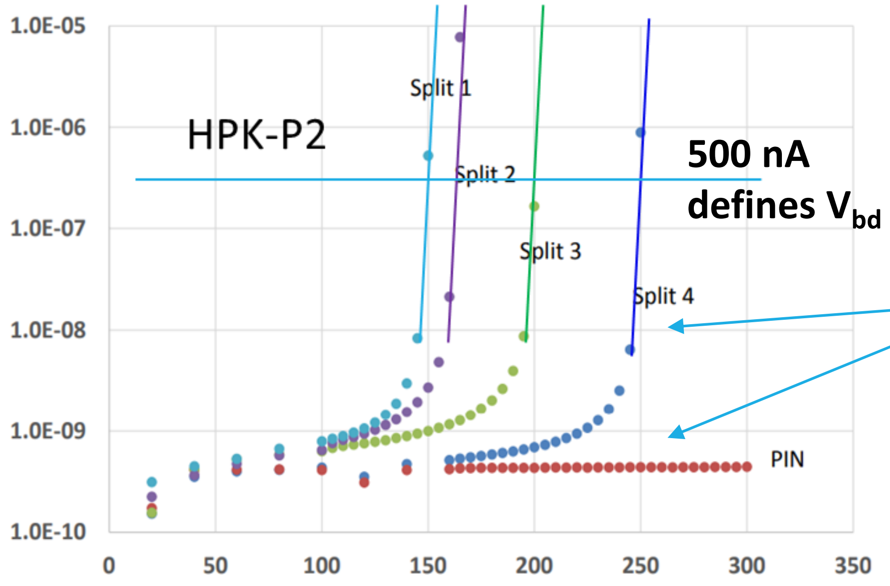


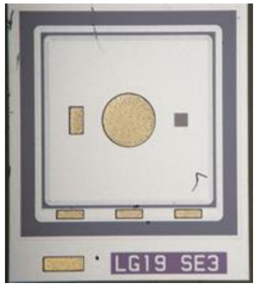


CV-IV measurements (HPK as example)

HPK-P2 is a 3rd iteration of HPK LGAD production – deep gain layer design with 4 different GL doping splits (2% apart) resulting in V_{bd} from 140 V to 250 V – controlling very accurate doping is the key to LGAD production.

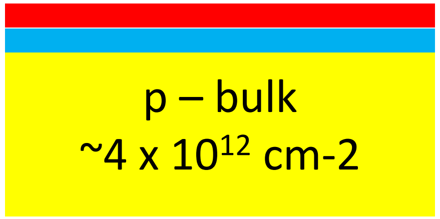






devices break down through the bulk

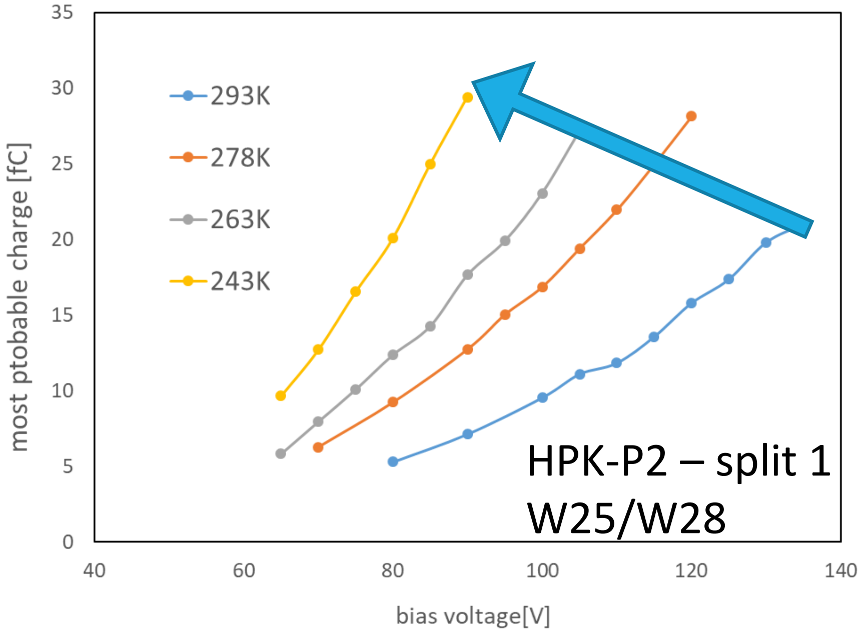
$$N_{eff} \propto V_{fd} - V_{gl}$$
$$N_B \propto V_{gl}$$

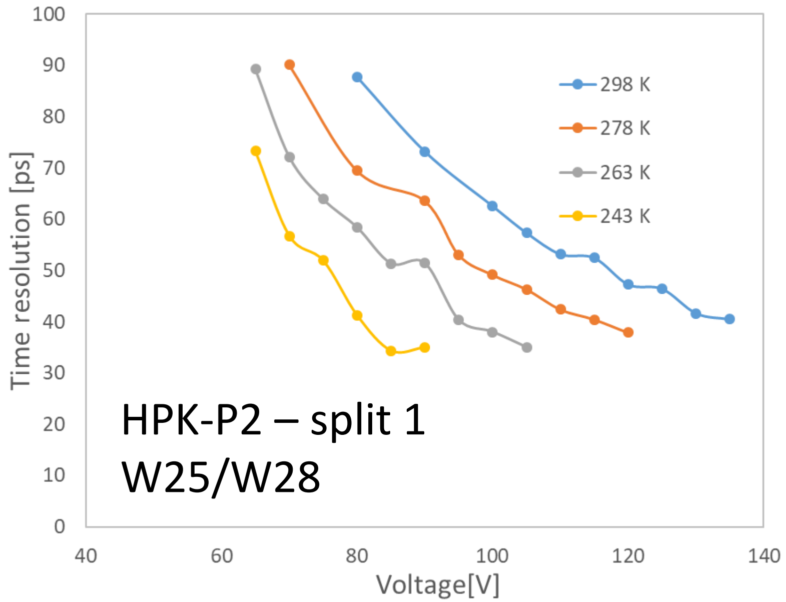


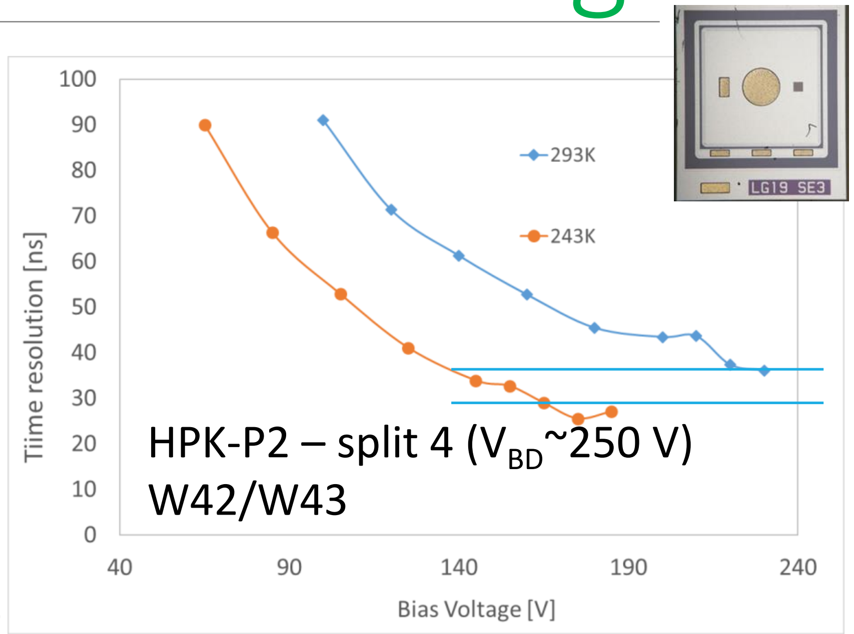
At full depletion drop of 52 V in GL and 7 V in the bulk

HPK has demonstrated excellent quality of production with >99.8% pads functioning on large sensors arrays.

Temperature dependence of gain and timing

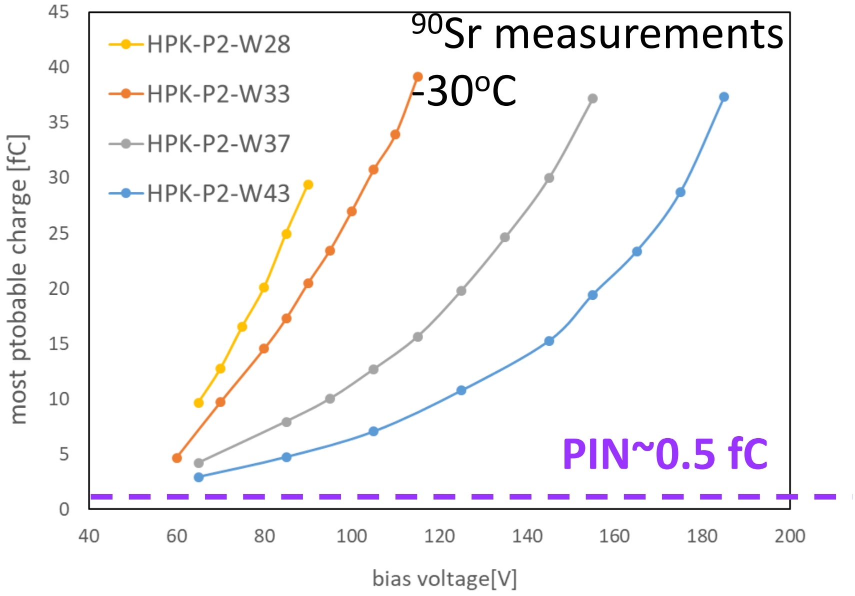


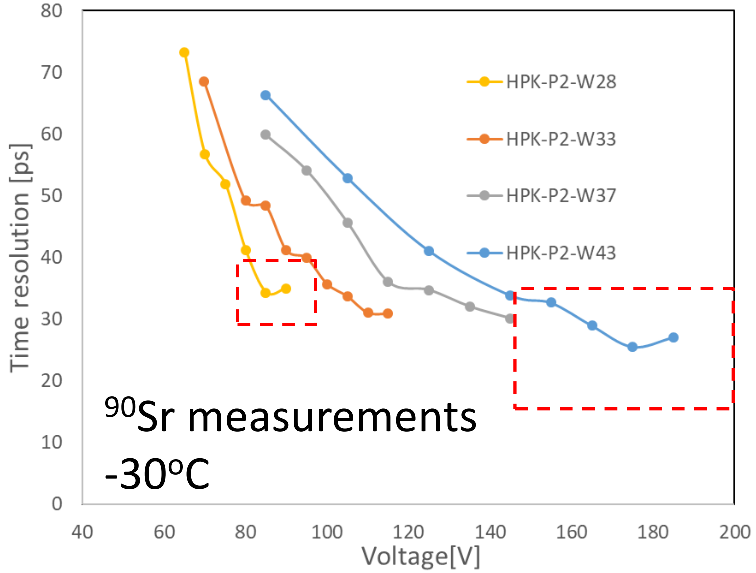


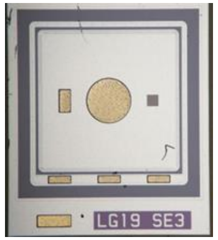


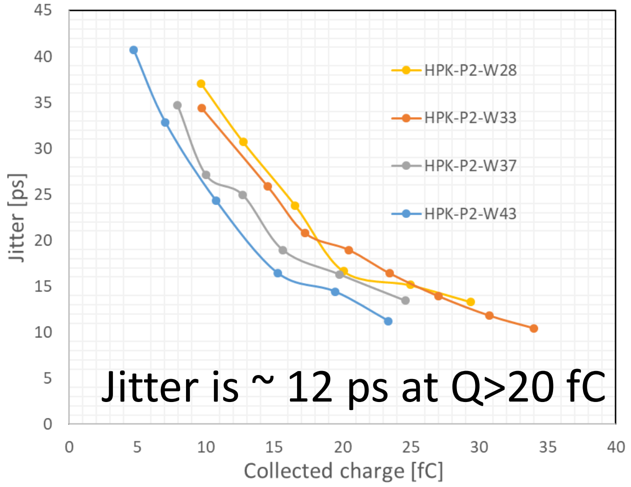
- Impact ionization – gain mechanism is a strong function of temperature – so breakdown voltages at -30°C are much lower than at room temperature (50-80 V) – variation of temperature over the sensors in experiments has to be well controlled in narrow window of few degrees
- If electric fields are high enough to provide drift velocities close to saturation lower temperature decrease the drift time and by that improves the time resolution.

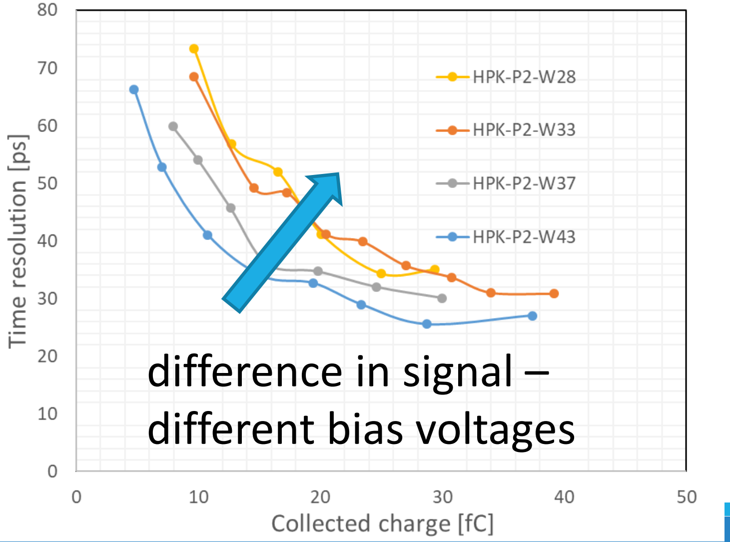
Charge/Timing for different HPK splits







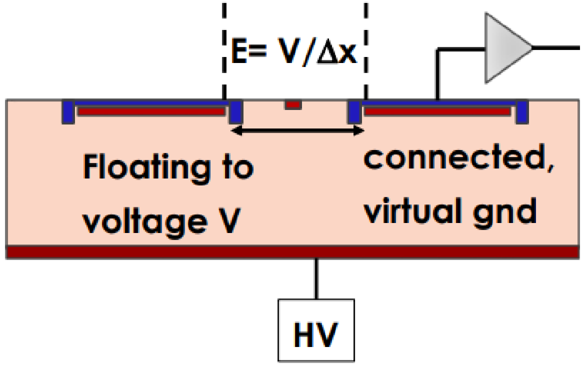




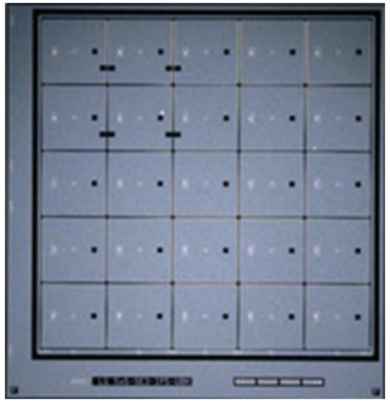
- small difference in doping concentration results in very different performance
- larger initial doping offers an advantage after irradiations, but requires operation close to the breakdown voltage - in considerations by ATLAS due to large fluences
- lower doping allows for larger suitable voltage range away from breakdown

Inter-pad performance

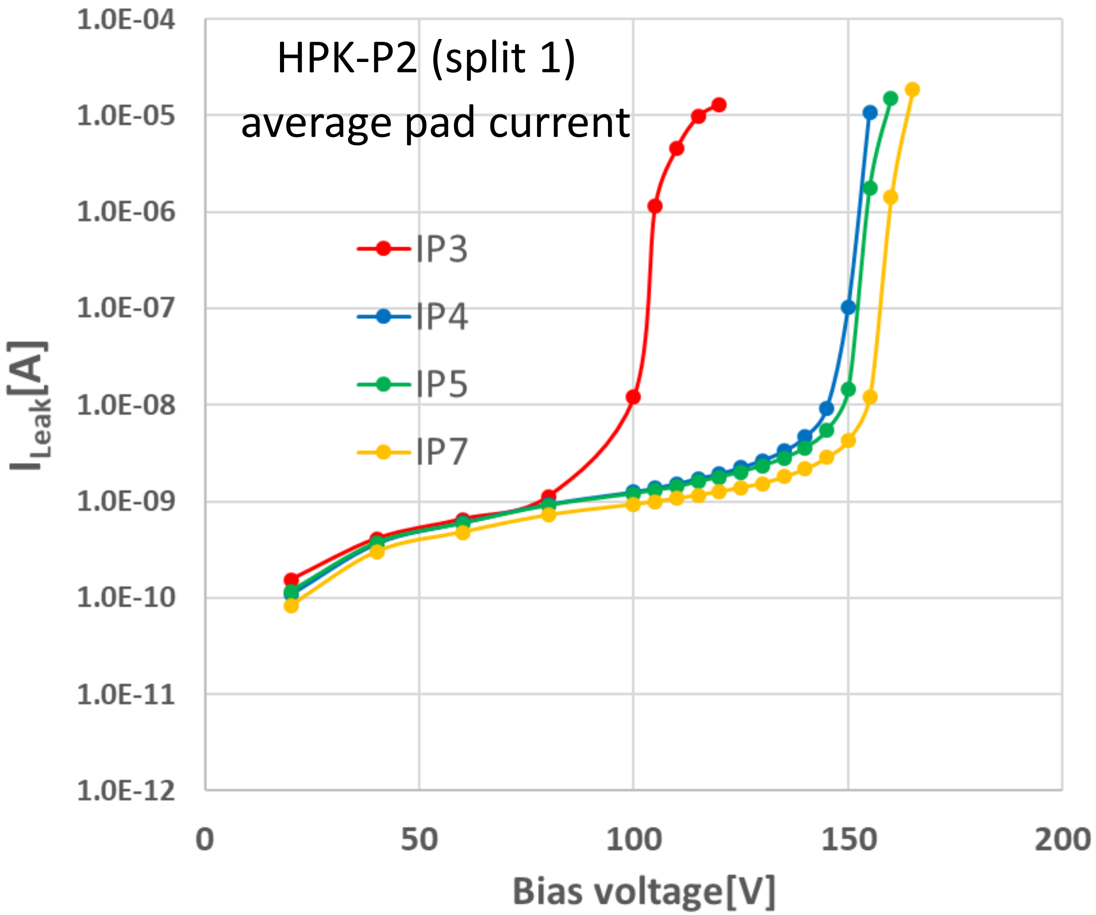
Optimized gain layer design – example of HPK-P2 run



IP3=30 μm
IP4=40 μm
IP5=50 μm
IP7=70 μm



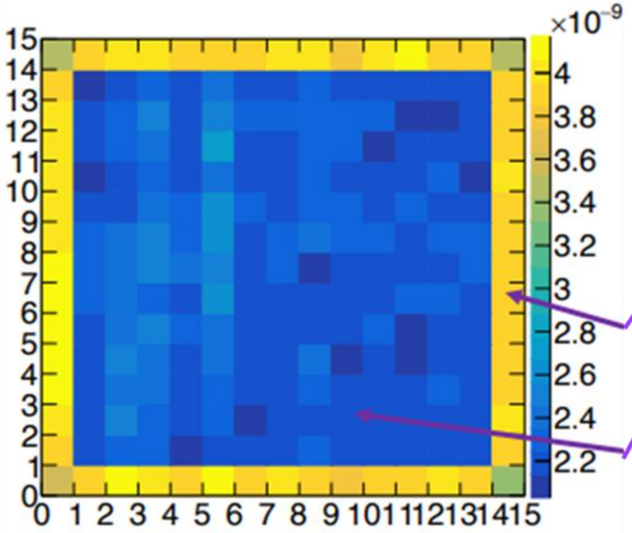
single pad measurement over the surface of the detector with other pads floating



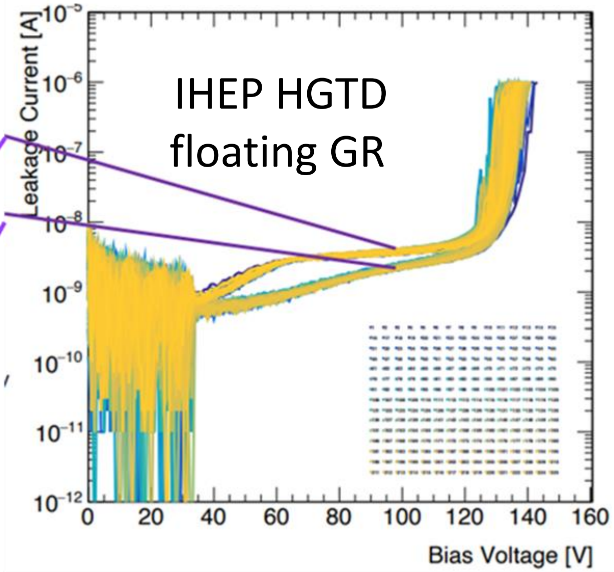
IP3 – is too aggressive
Similar studies done for other producers.

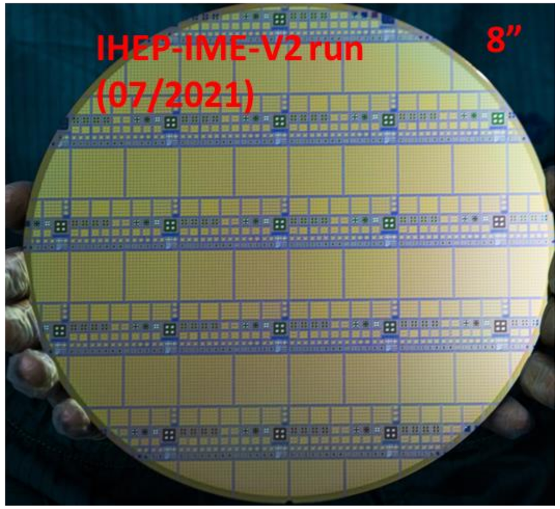
Full size devices

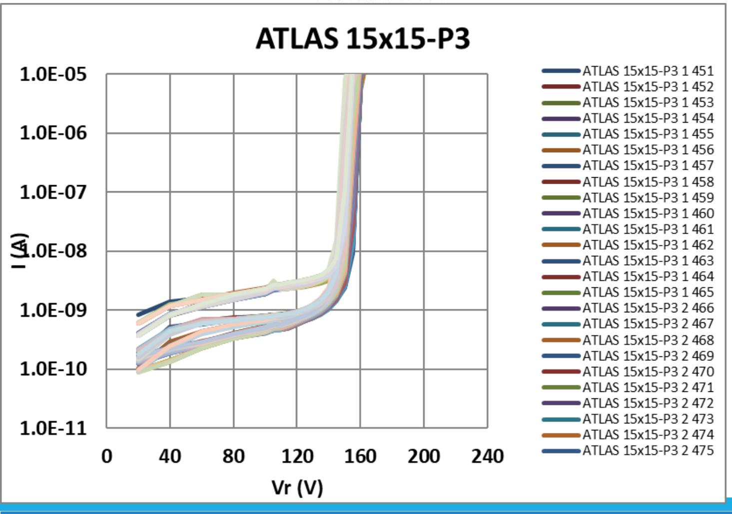
More information on IMEv2 at the coming RD50 workshop.

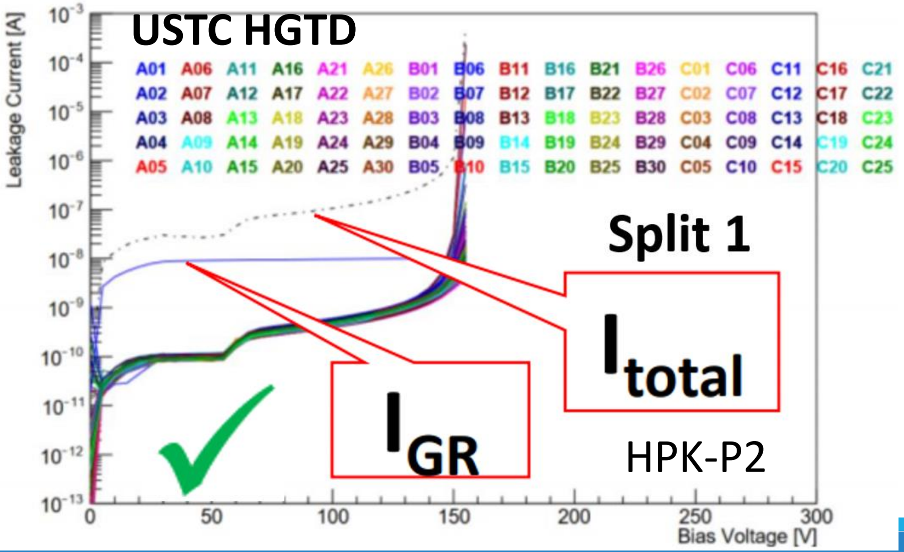


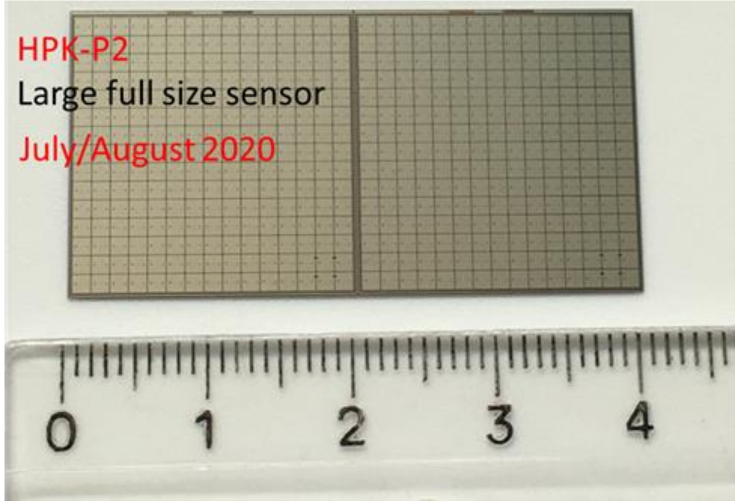
ATLAS-HGTD preliminary





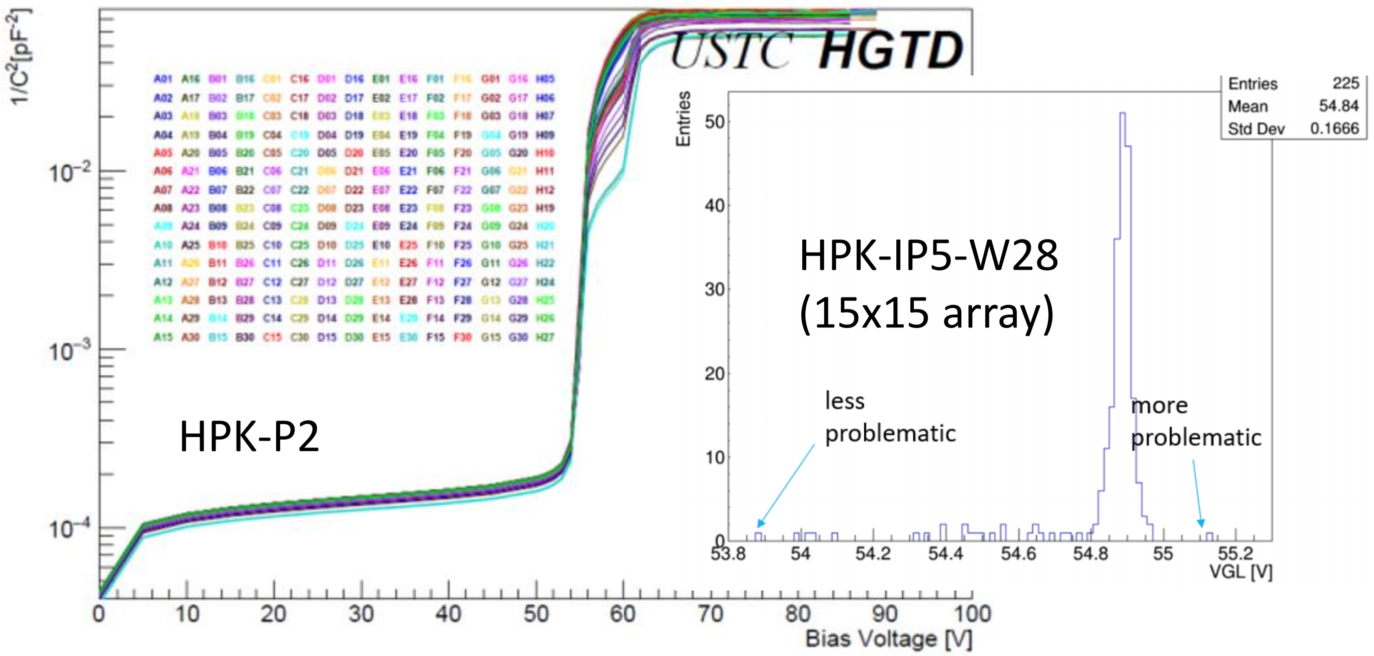




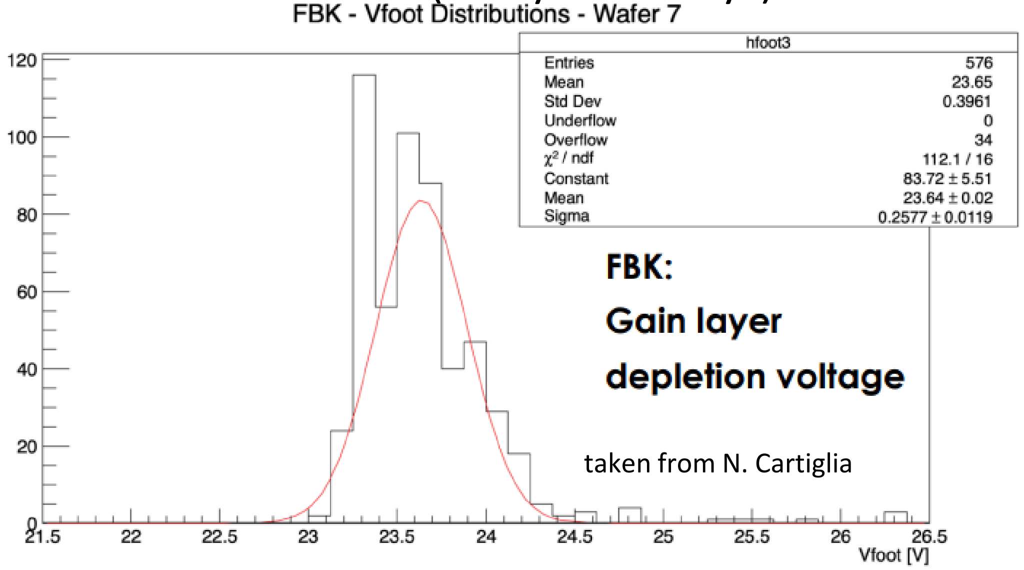


Full size devices

Can different vendors produce large arrays that are uniform?



FBK-UFSD3.2 W7 (many 5x5 arrays)

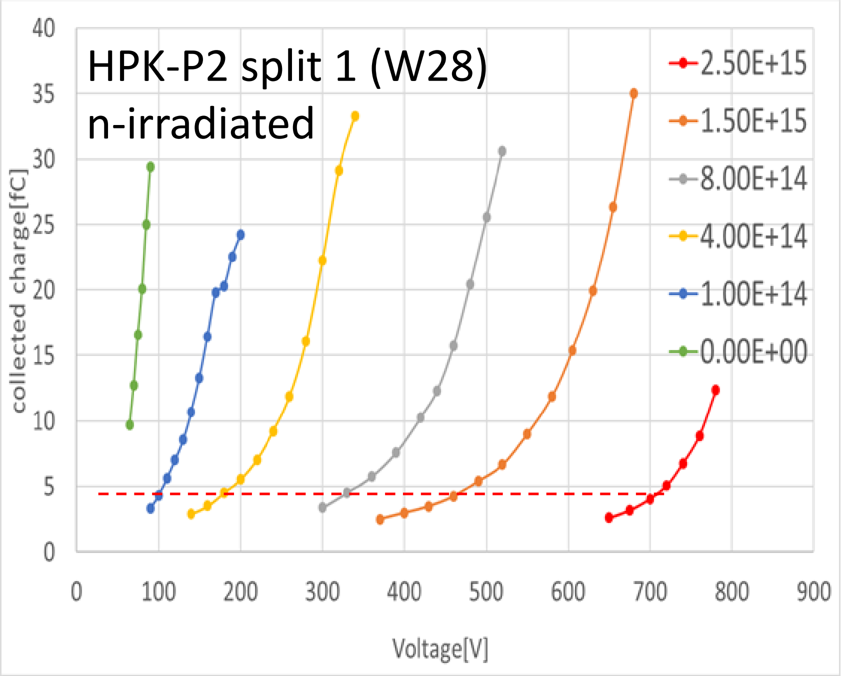


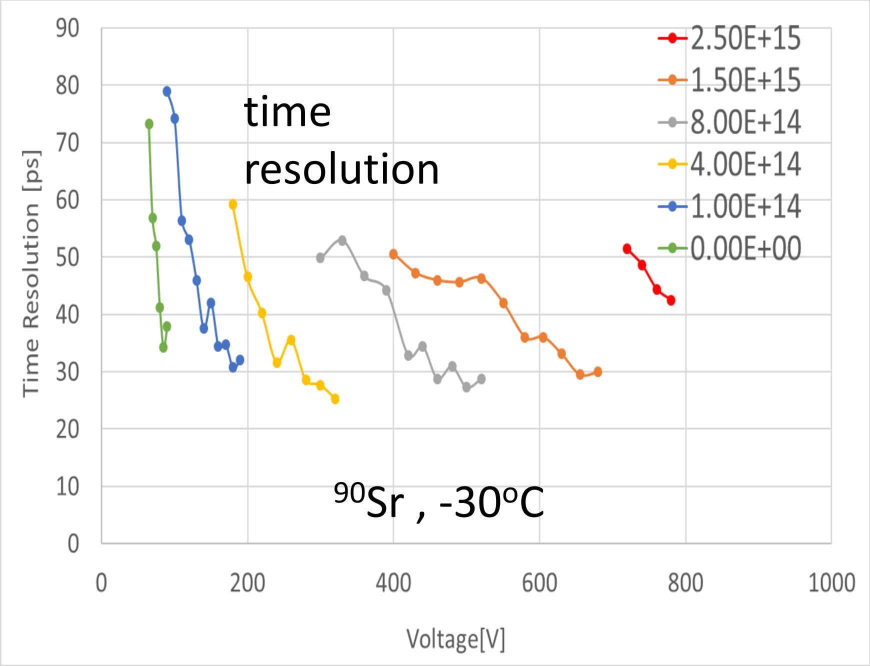
The production of uniform gain layer on large devices has been shown for several vendors.

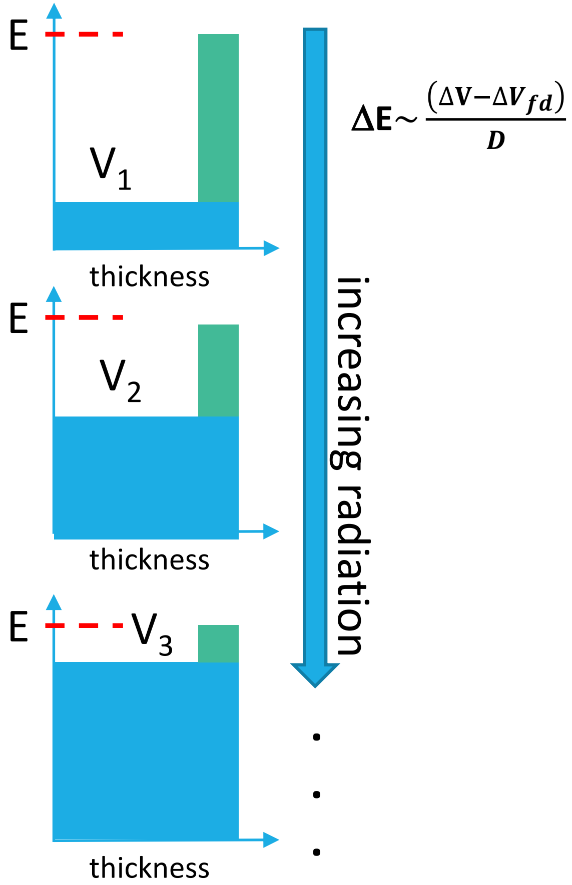
Performance after irradiations
(radiation hardness of thin LGADs)

Radiation hardness of sensors (HPK-P2)

The decrease of V_{gl} leads to the loss of gain/collected charge – compensation by increasing the bias voltage.





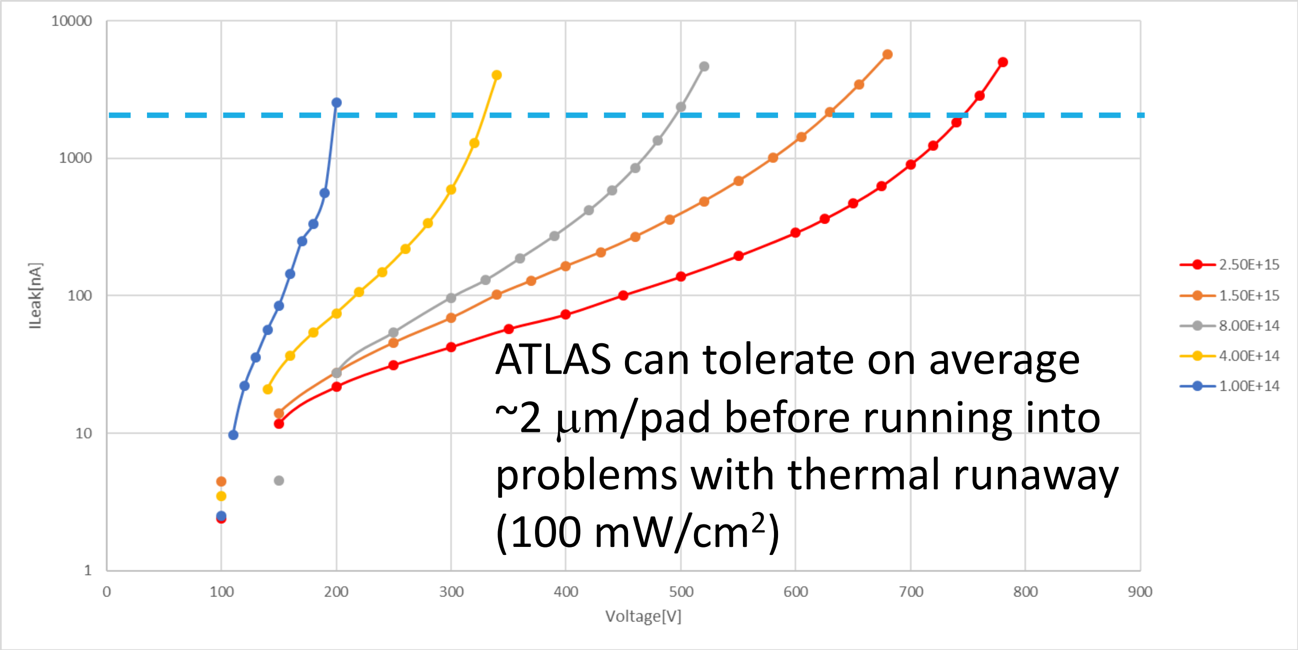


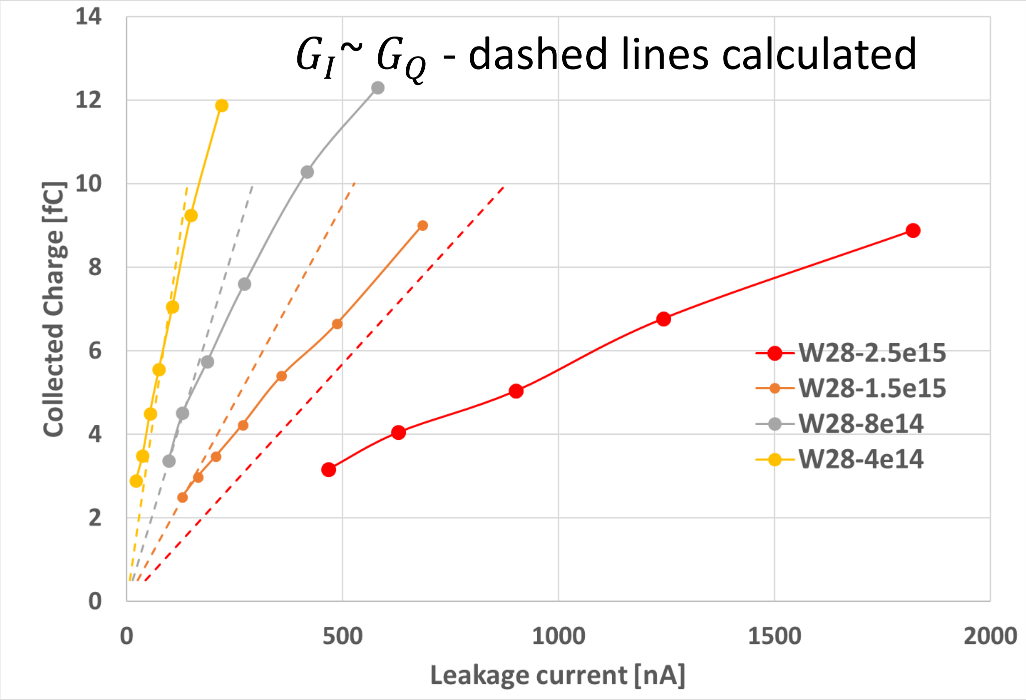
- active layer: $N_{eff,deep}=g_c \cdot \Phi_{eq}=0.02\ cm^{-1} \cdot 2.5e15\ cm^{-2}=5e13\ cm^{-3}$ -> $V_{fd}-V_{gl}<100$ V
- larger electric field means faster drift – saturated drift velocity $(V-V_{fd})/D>5\ V/\mu m$ – better time resolution at a given gain as before irradiation
- GAIN Layer: the concentration of acceptors is reduced through so called "acceptor removal" -> determines the radiation hardness – deep defects have very little impact on gain layer

Compensation ends once the bulk multiplication starts ~ 750-800 V (smaller field, but large distance)

Radiation hardness of sensors – leakage current

Radiation with hadrons requires much higher bias for operation of detectors to fulfil the requirements





- Leakage current is more complicated than for standard silicon devices

  $I_{leak}=I_{gen} \cdot G_I$; $G_I \sim G_Q$;

  G_Q measured on the time scale of drift time ~1 ns (no time for de-trapping)

  G_I measured on the time scale of current meter > ms.

  $I_{gen}=\alpha \cdot \Phi_{eq} \cdot S \cdot D$; independent on the device with GR connected

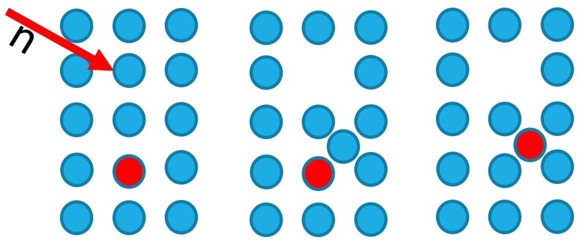
Deviation from $G_I=G_Q$ line at high fluences charge gets multiplied less than the current?
Samples from different producers give roughly the same current at the same charge and fluence.

Effective acceptor removal

Gain of the LGADs depends on the doping of the gain layer -> the doping of the gain layer is affected by the irradiation, due to the process called "acceptor removal".

R. Wunstorf et al, NIMA 377 (1996) 228.)
J. Adey, PhD Thesis, Univeristy of Exceter, 2004
J. Adey et al., Physica B 340–342 (2003) 505–508

Acceptor removal



Interstitial channel : I + Bs → Bi (dominant channel)
(electrically inactive Bi can form different defect complexes)

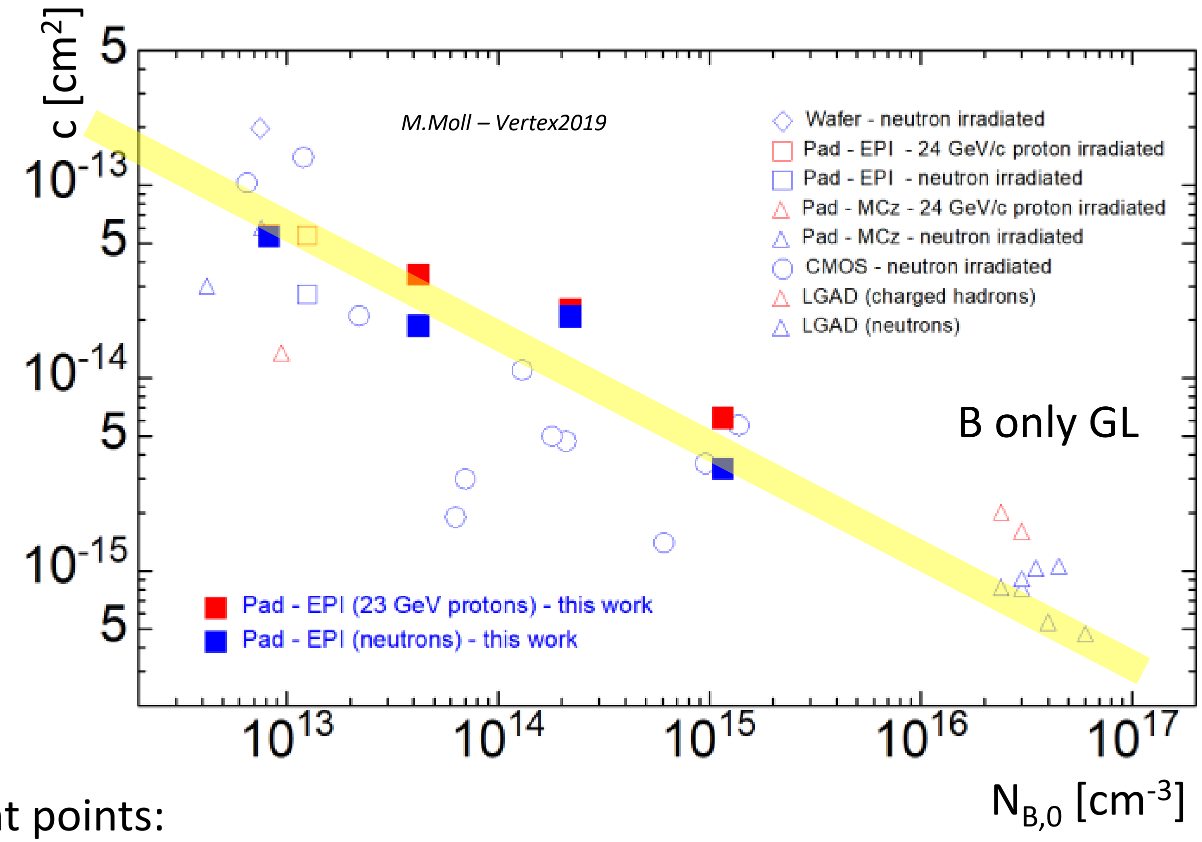
$$dN_B = -\sum_i c_i \cdot N_B d\Phi \quad , \quad c = \sum_i c_i\,([O],[C],[B])$$

$$N_B = N_{B,0} \exp(-c\,\Phi_{eq})$$

Assuming linear relation between N_B and V_{GL}:

$$V_{GL} = V_{GL,0} \cdot \exp(-c \cdot \Phi_{eq})$$

$c(N_{B,0})$ - *M. Ferrero, NIM A919 (2019) p16.*



Two important points:

- **the higher the concentration the lower the removal – favours small *iw***
- **charged hadrons are more damaging than neutrons**

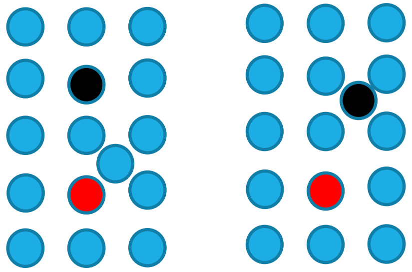
Design of radiation hard GL

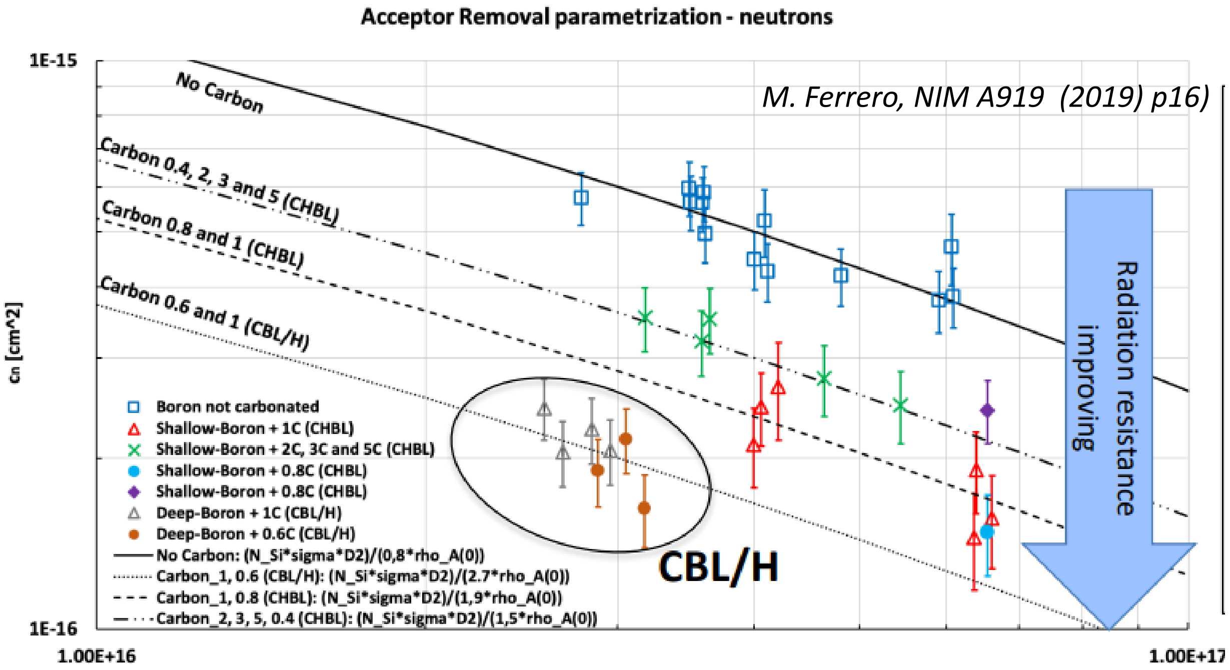
Two approaches :

- Replacement of B with Ga, which has higher displacement energy -> the results of the limited runs showed no significant benefit in terms of acceptor removal
- Additional impurities added to gain layer which reduces the acceptor removal constant
  - carbon is trap for interstitial silicon atoms which are then not available for displacement of Boron -> hence smaller removal rate
  - **Carbon however forms defects during processing of the samples, hence the initial currents are usually larger (up to one/two orders of magnitude)**
- Carbon enrichment is not straightforward, however

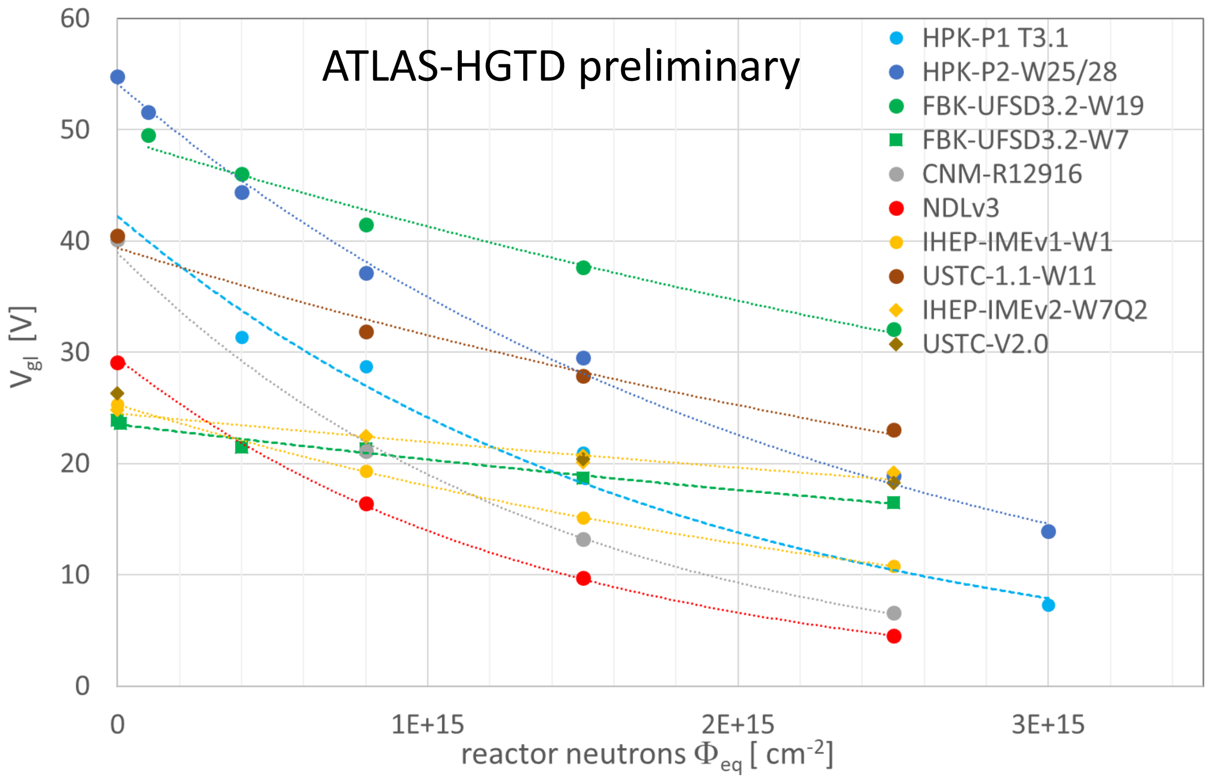
~3 producers of LGADs have so far shown to master it.

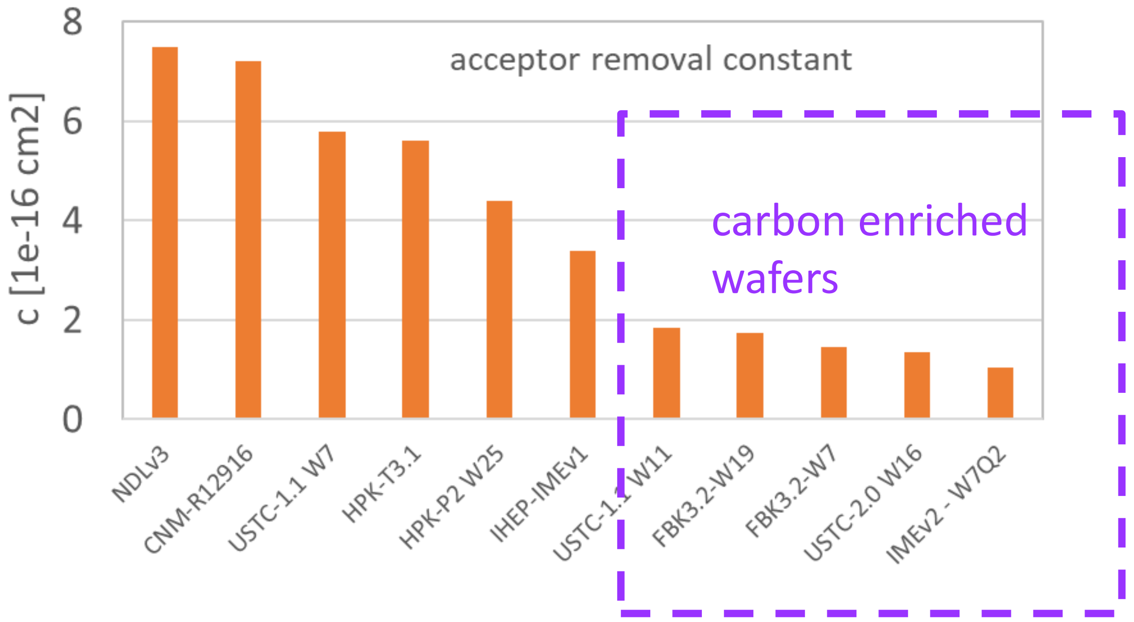
carbon as trap
for interstitials





Radiation hardness of Gain Layer



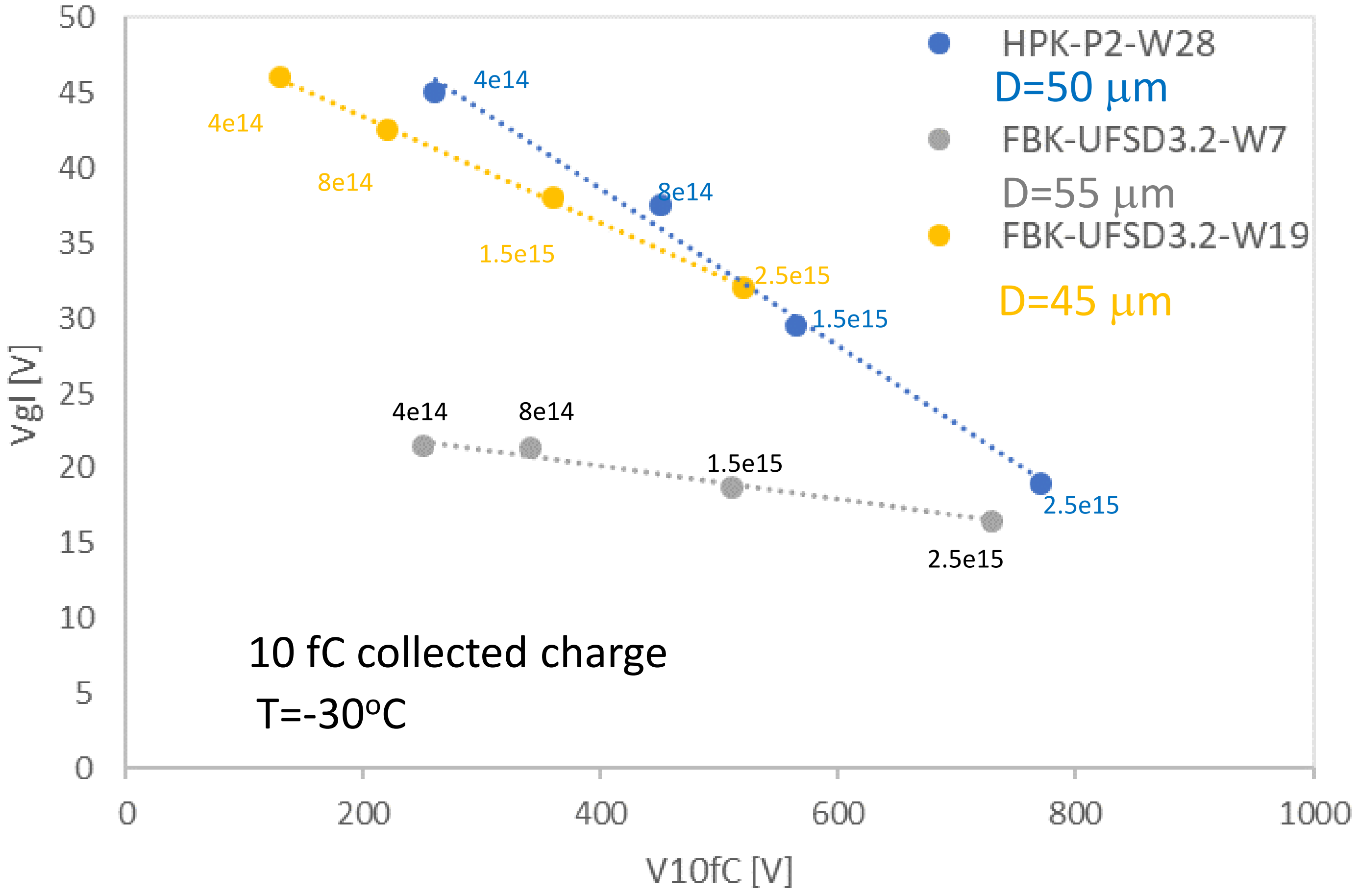


$$V_1 \sim V_2 + \frac{D(V_{gl1} - V_{gl2})}{x_{gl}}$$

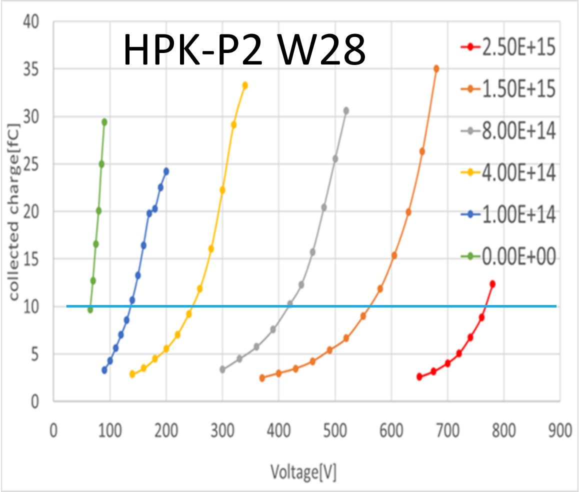
approximate voltage required to restore the performance of the same LGAD with different V_{gl}

Large difference in c between the different runs/producers – several different runs were required to master the recipe (combination of implantation depth of B and C with subsequent annealing steps)

Correlation of V_{gl} and charge collection voltage



V_{gl} is correlated with the voltage required for given charge collection – for a given design the charge collection can be predicted by the V_{gl} measurement – very useful for large number of tests



$$\frac{x_{gl}}{D} \sim -\frac{\Delta V_{gl}}{\Delta V_{10fC}}$$

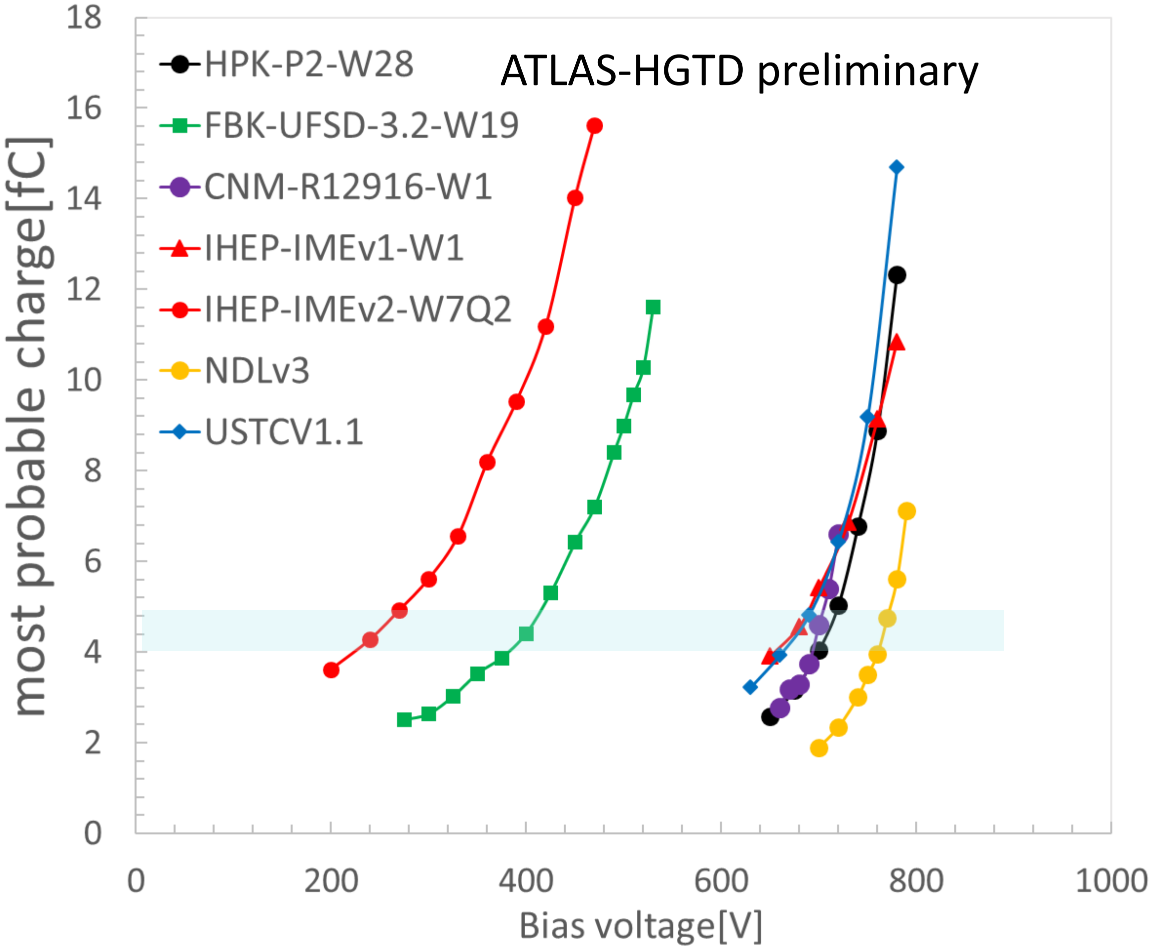
x_{gl} ~2.3 um

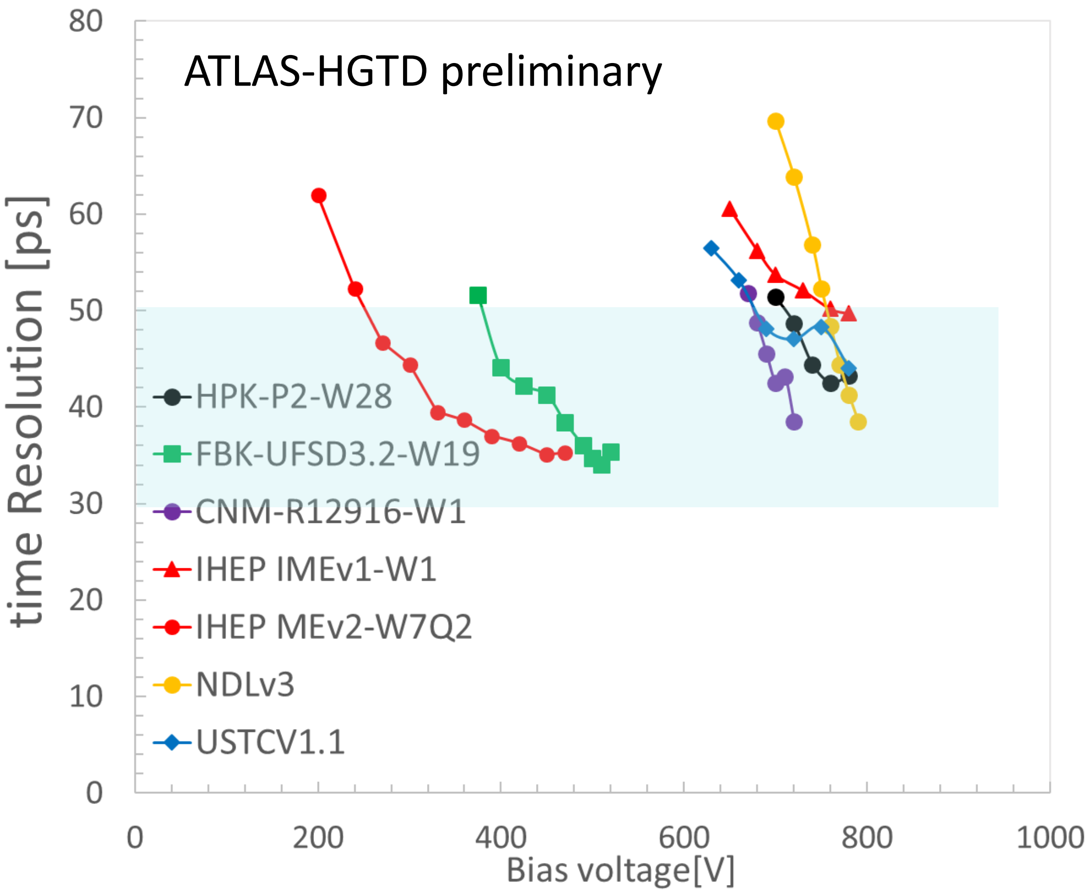
x_{gl} ~1.8 um

x_{gl} ~0.7 µm

Performance of various prototypes at 2.5e15 cm^{-2}

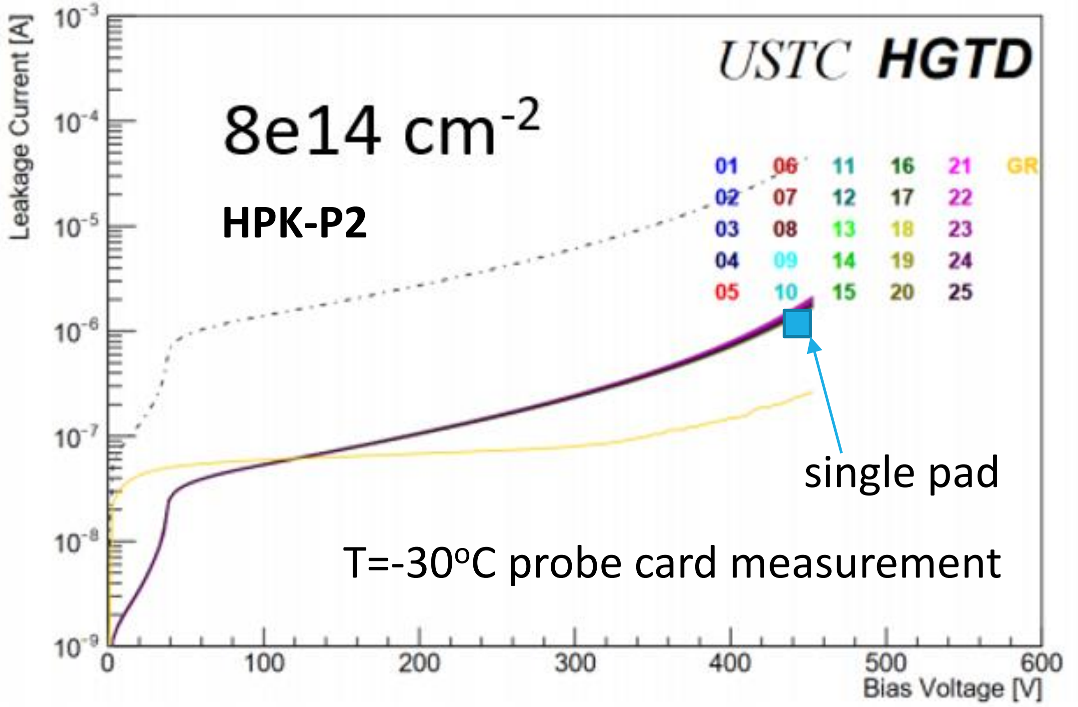
more on IMEv2 run at RD50 workshop

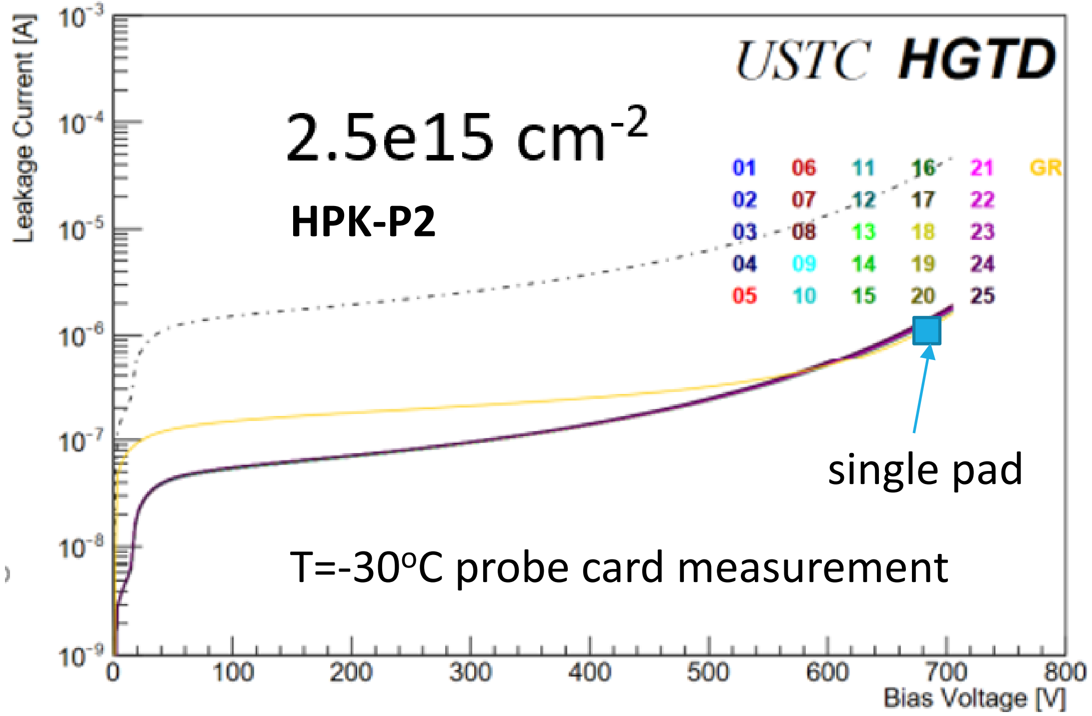


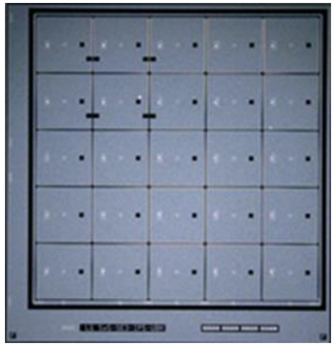


The effect of the C-enrichment is clearly very beneficial and allows the sensors to be operated at much smaller voltages – a critical point due to HV stability in the particle beam

Large size devices after irradiations

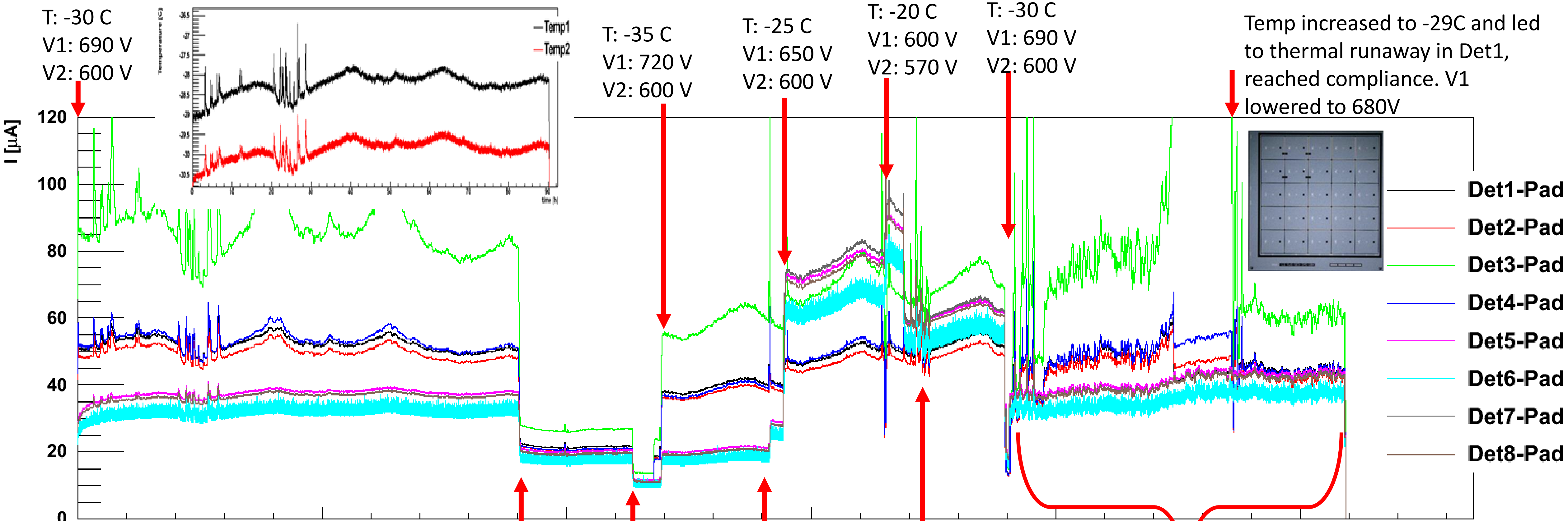






- at the same voltage single pad and large array currents are the same
- very homogenous leakage current over the sensor

Stability of operation – long term



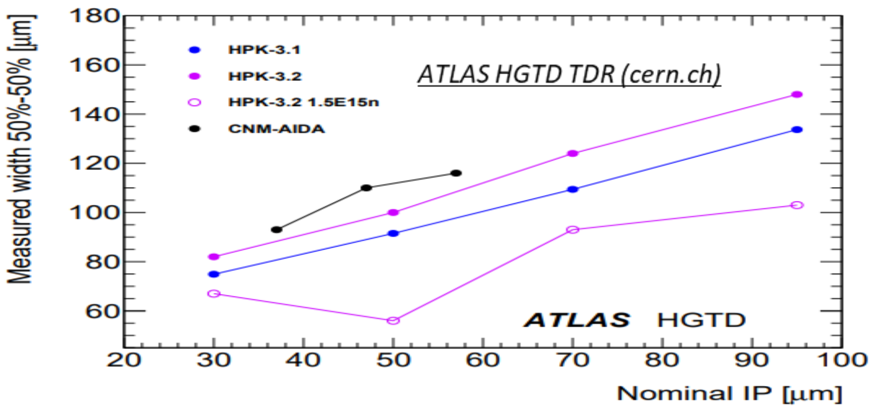
Det1	LG-5x5-SE3-IP7-UBM	2.50E+15
Det2	LG-5x5-SE5-IP7-UBM	2.50E+15
Det3	LG-5x5-SE3-IP5-UBM	2.50E+15
Det4	LG-5x5-SE3-IP4-UBM	2.50E+15
Det5	LG-5x5-SE3-IP5-UBM	1.50E+15
Det6	LG-5x5-SE3-IP4-UBM	1.50E+15
Det7	LG-5x5-SE5-IP7-UBM	1.50E+15
Det8	LG-5x5-SE3-IP7-UBM	1.50E+15

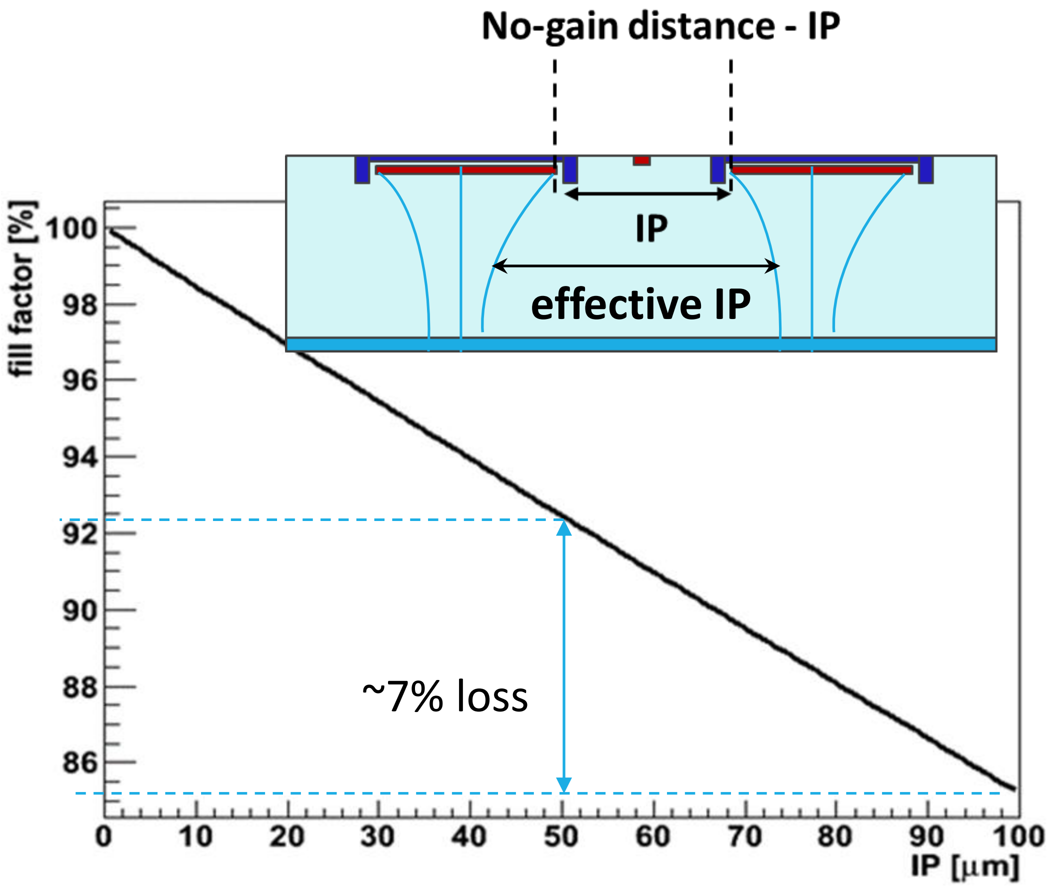
V1: Bias for Det 1-4
V2: Bias for Det 5-8

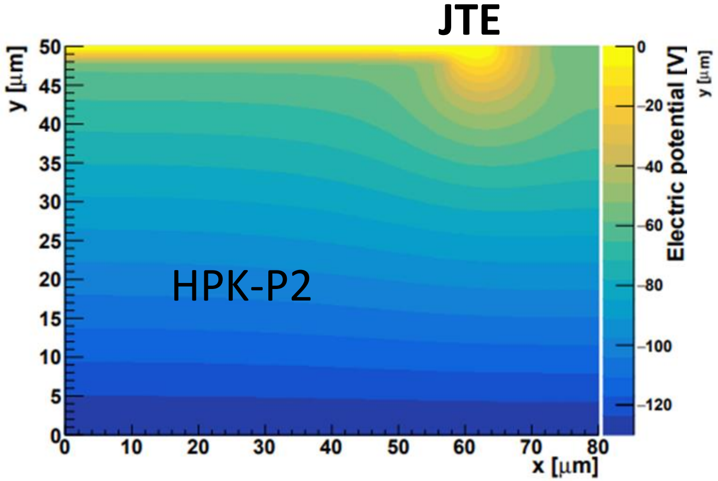
Surprises of the LGAD performance

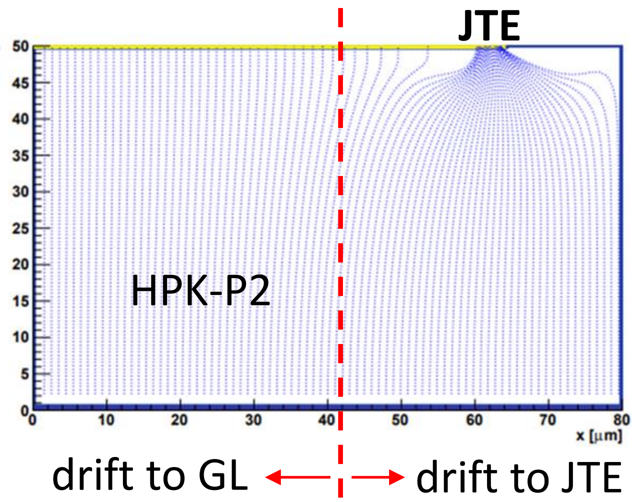
IP – fill factor

~50-60 μm larger effective IP with respect to the nominal one – loss of fill factor









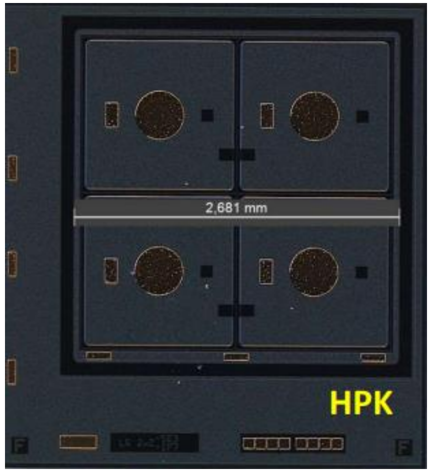
Bending depends on GL, JTE design and thickness:

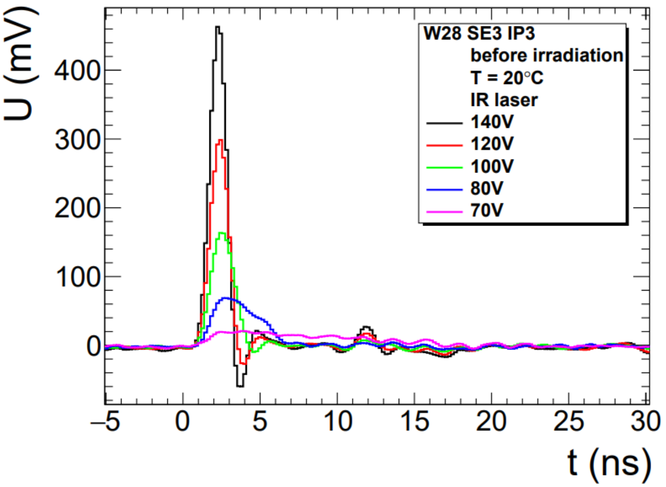
- increases for large x_{gl}
- increases for more doping
- decreases with thickness and bias voltage

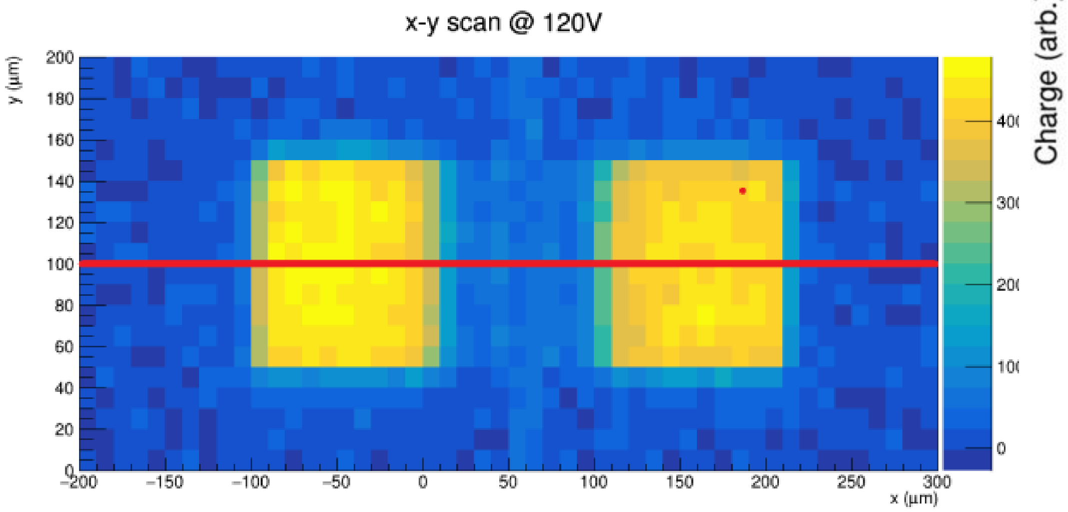
IP – fill factor

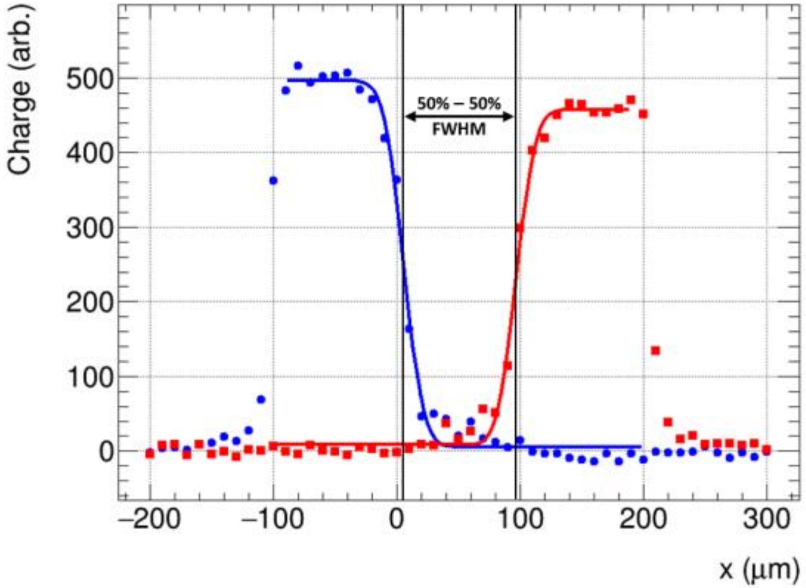
Prototype devices have opening in metallization to study the effects with Scanning-TCT:

- several devices from FBK/HPK and IME studied at different fluences
- Two neighbouring channels connected to amplifiers and readout at T=-30^{o}C



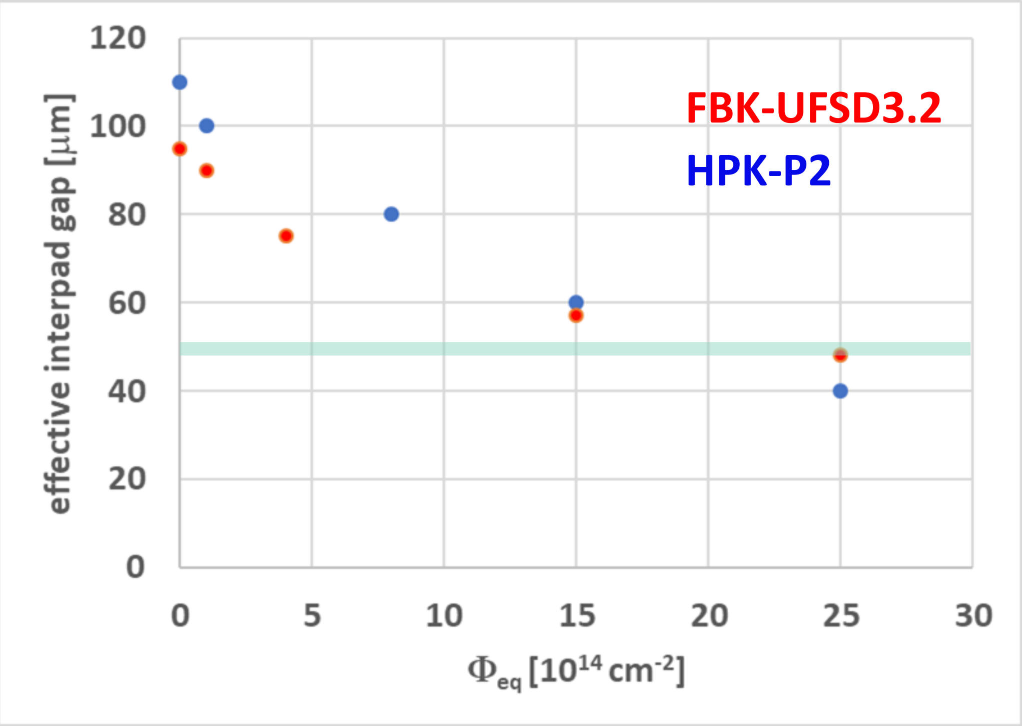






focused IR light injection along the red line

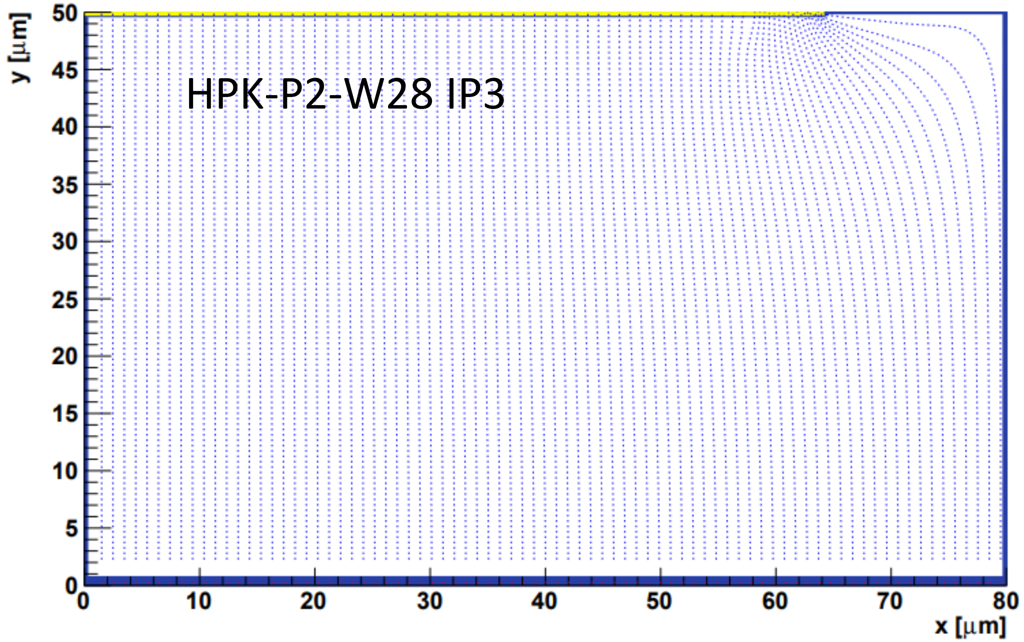
IP – fill factor



- nominal inter-pad distance ~50 μm
- T=-30°C and V_{bias}>V_{5fC}

Reduction of GL doping and increase of bulk doping with radiation reduces effective inter-pad gap hence **the fill factor increases**!

Confirmed also by simulations !

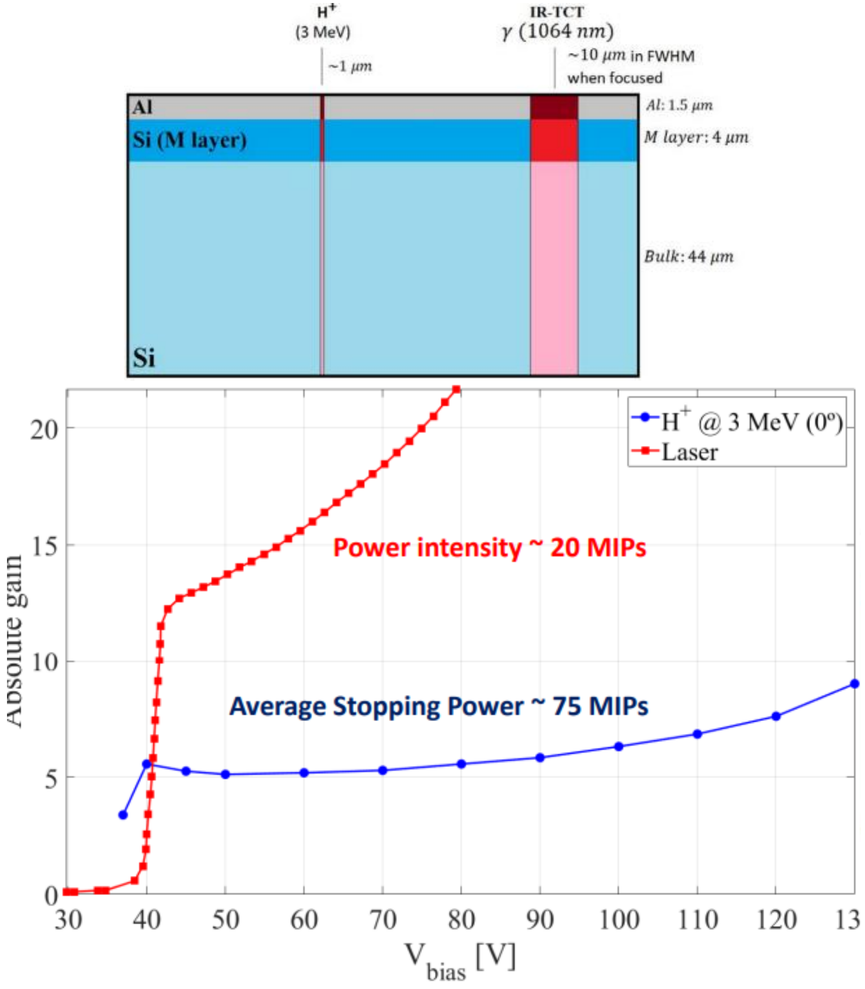


HPK-P2-W28 device irradiated to $1.5 \cdot 10^{15}$ cm^{-2} biased to 600 V

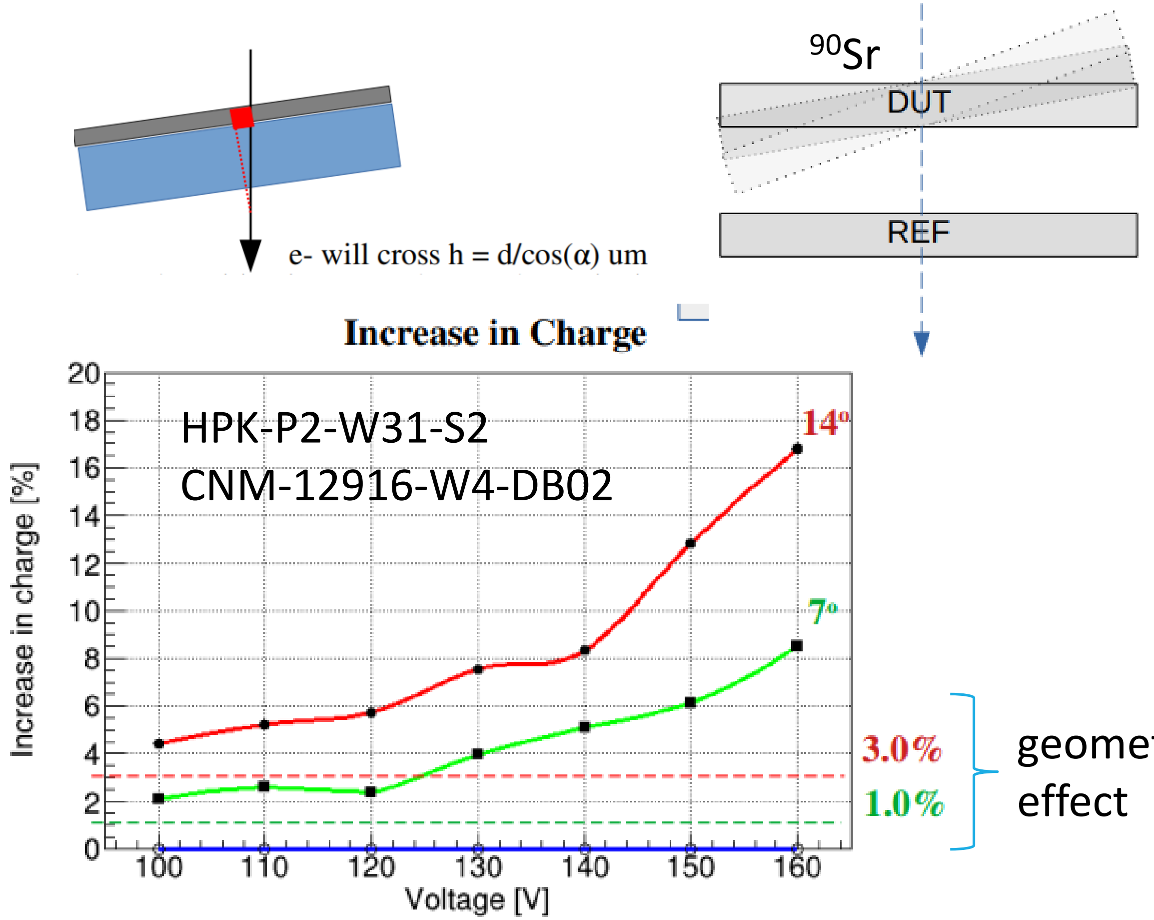
Gain and density of ionization

Multiplication depends on density of ionization

M.C. Jiménez-Ramos Gain supression by IBIC-MCJR 38th RD50 Workshop



DUTs positioned at different angles: 0, ~7, ~14 deg



geometry effect

Ecurras_GainSuppressionMechanismLGADs_RD50_CERN_JUN_2021.pdf

ATLAS tracks: 2-10°
CMS tracks: 6-22°

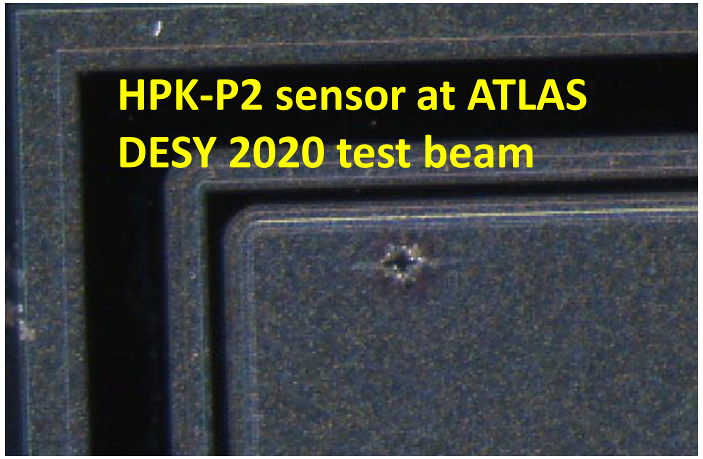
a beneficial effect for charge collection

Single Event Burnout (HV stability in the beam)

- The majority of charge collection measurements performed in the labs with ^{90}Sr sources and prototype sensors work well up to large bias voltages >700 V (very high average fields >14 V/μm) and good enough performance

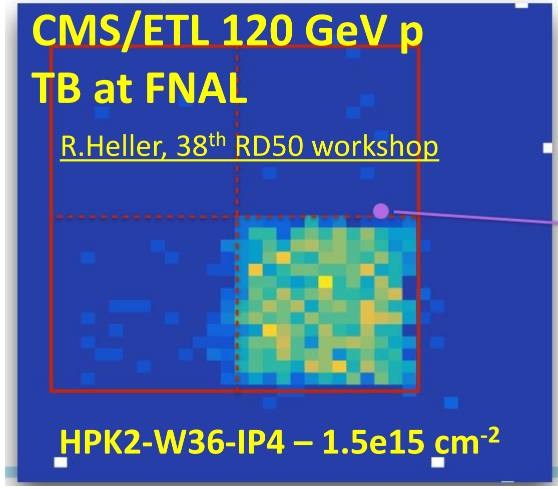
- The measurements in the test beams were more problematic:
  - Sensors in the TB die with a typical burn mark pattern – "star shaped crater"
  - They appear mostly at bias voltages that are much lower (>~100 V) than those achieved in the lab
  - They were not specific to any producer (observed for HPK/CNM prototypes) and were observed in DESY/SPS test beams

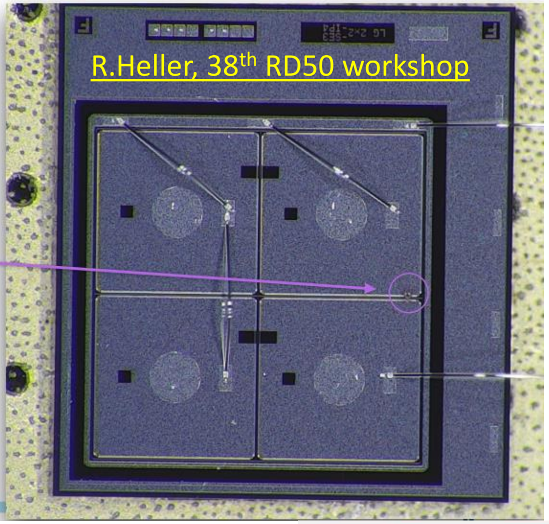
- This has been observed early in TB, but only recently systematically studied by RD50, CMS and ATLAS (a collaborative effort of all three)



SEB caused by a single beam particle

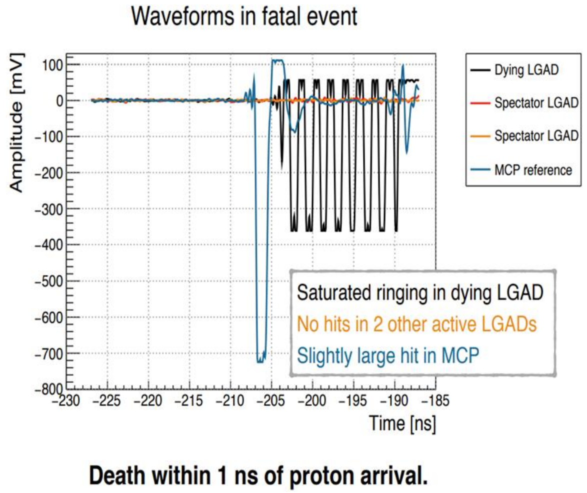
6h at 700V before beam -> 2 h at 500-600V -> died in 2 min @ 625 V

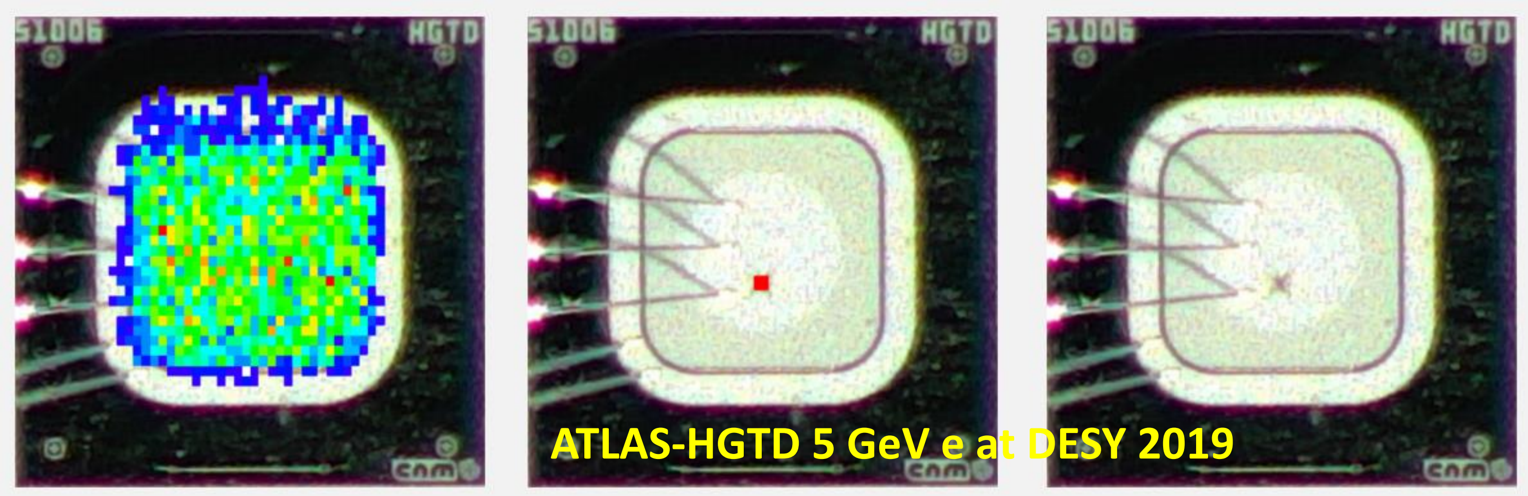




A single beam particle is responsible for the fatality

- the signal from the event in which sensor died was recorded and the tracking information point to the place of the crater.
- there seem to be no weak spot – craters appear at different places over the sensor
- after the event the sensor is "in-short" and not operational





SEB test beam campaigns

Sensor list for both ETL and HGTD test beam carefully prepared in order to determine the answers to the following questions:

- different fluences LGAD – **does irradiation matter? - NO**
- irradiated PINs – **does intrinsic gain matter? - NO**
- 0.1 MGy γ irradiated PINs – **does bulk damage matter? - NO**
- 35,45,50 μm thick LGADs – **effect of thickness? - YES**
- different producers **– does process matter? - NO**

Average electric field in the device is the critical driver:

- safe region - < 11 V/μm
- danger region - ~11-12 V/μm
- SEB region - >12 V/μm

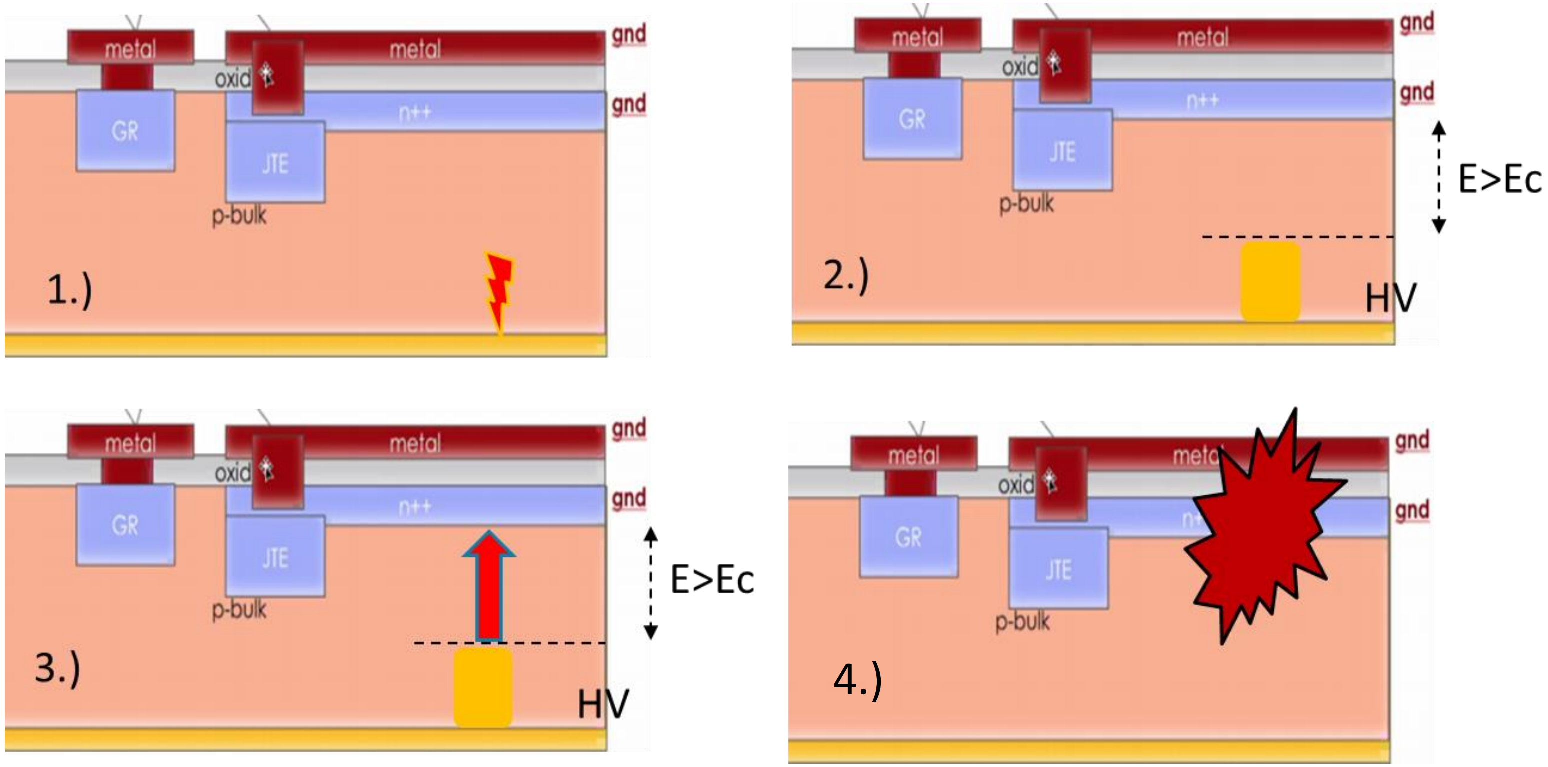
Finding in the recent test beam campaigns:
(https://indico.cern.ch/event/1029124/contributions/4411270/)

- around 10-30 k 120 GeV p are required for SEB at voltages at >12 V/μm
- around 1M 3-6 GeV electrons are required for SEB at voltages at >12 V/μm (tested 3 thicknesses)

It is crucial for both experiments to show longevity of the sensors in the beam conditions.

Most probable hypothesis for the death

This field collapse in the presence of high concentration of free carriers is the probable cause. Electric field (V_{bias}/thickness) is the key parameter determining the fatality.



1.) larger deposition of the charge (fragments producing deposition in few μm as large as 1000 mips are possible) in few μm (not possible with lab sources)

2.)larger density of carriers leading to collapse of the field (screening prevents the carriers from being swept away

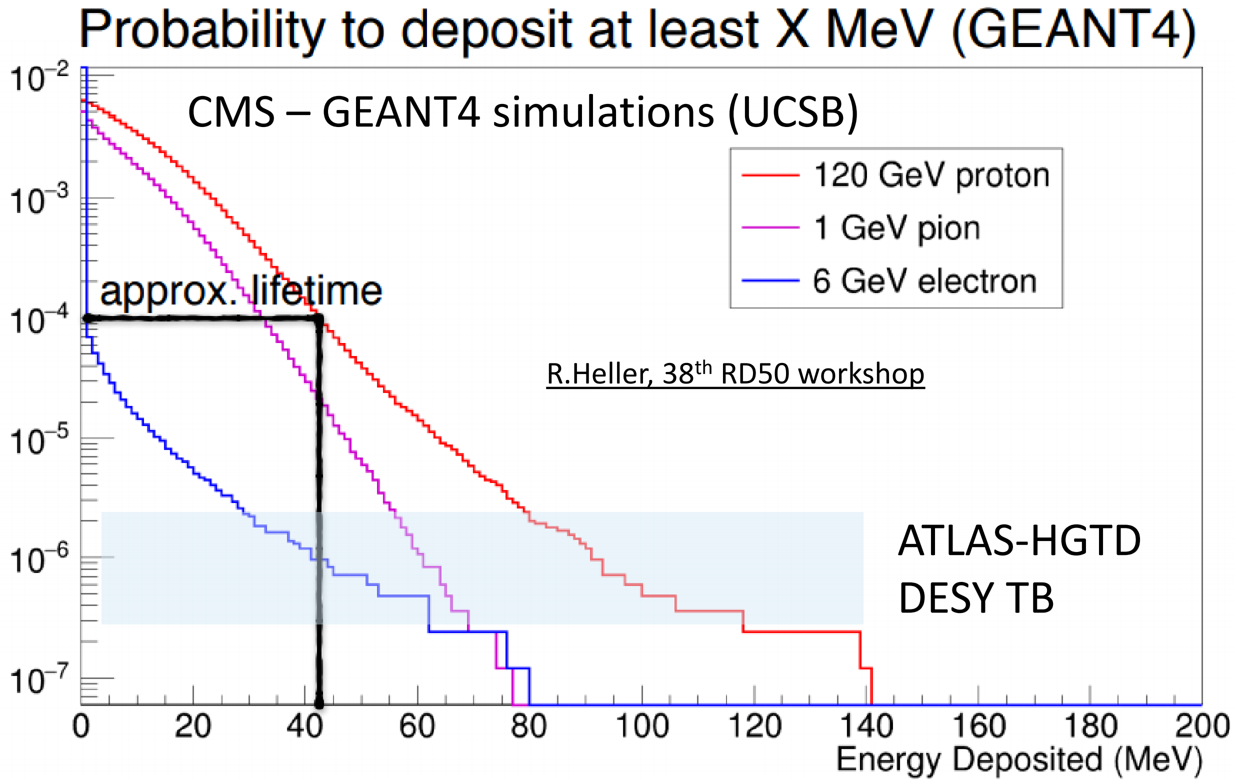
3.) once the field collapses the HV is brought closer to the pad which leads to very high field strength and to avalanche breakdown causing full discharge of sensors and bias capacitor

4.) the discharge leaves a crater behind if enough energy is stored to melt the silicon (~10 nF)

The process of large current in narrow path is called "Single Event Burnout" – **SEB**

http://telab.vuse.vanderbilt.edu/docs/albadri06-MR.pdf

Check of the SEB hypothesis



- From the rate of the required 120 GeV p hitting the sensor before it dies (10-30 kp at 625-675 V) at the threshold voltage **E_{dep}>30-40 MeV** in the active bulk is required to create the **SEB**
- Around 2-3 orders of magnitude difference between the DESY and FNAL in probability for a electron/proton to cause a fatal breakdown at similar voltages – roughly agrees with our measurements (backup slides)
- Studies with femto second lasers at ELI-Beams are compatible with the hypothesis as well (https://indico.cern.ch/event/1029124/contributions/4411279/)

So far the only solution to avoid SEB is keeping the voltage low enough wrt thickness – room for thickness optimization.

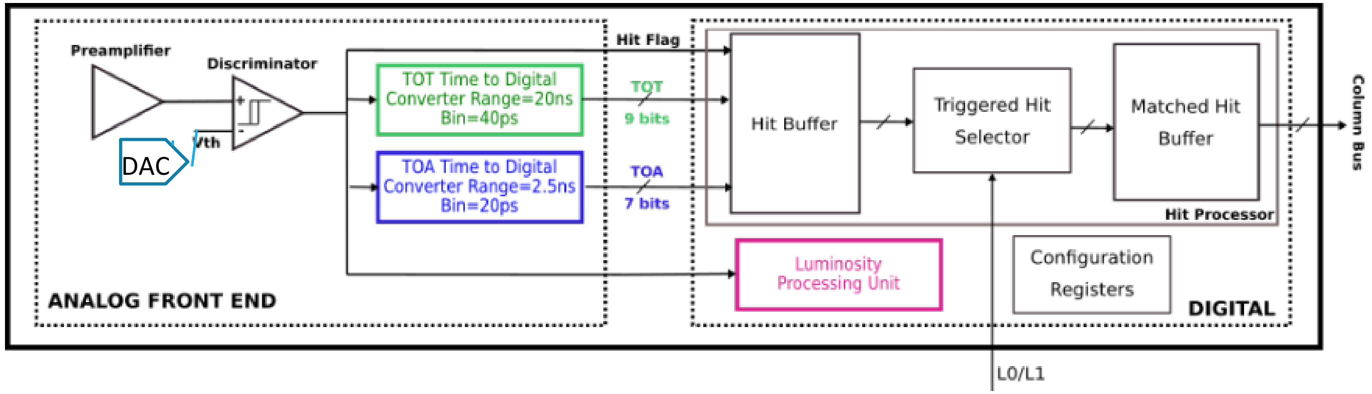
- a most obvious solution possible solutions the use of carbon enriched GL where required performance is reached at lower bias voltages.
- device optimization (HPK) to allow larger bias voltages

Due to smaller fluence the CMS is less affected even if "standard" sensors are used. ATLAS would be more affected at the end of lifetime (in the last 1000 fb^{-1})

ASICs for LGADs

timing measurement is not a property of the sensor alone

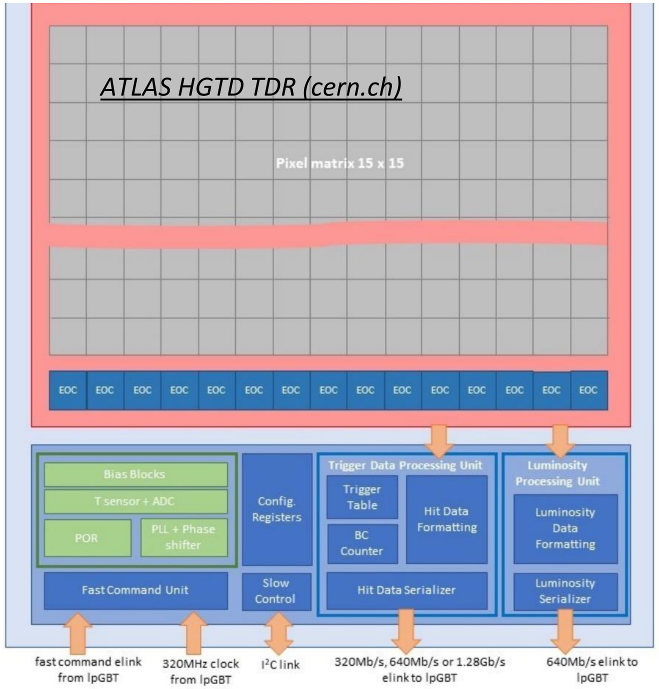
ASIC



power consumption 250 (ETROC), 300 (ALTIROC) mW/cm^2

Maximum leakage current	5 μA
Single pad noise (ENC)	$< 3000\ e^- = 0.5$ fC
Cross-talk	< 5%
Threshold dispersion after tuning	< 10%
Maximum jitter	25 ps at 10 fC
	70 ps at 4 fC
TDC contribution	< 10 ps
Time walk contribution	< 10 ps
Minimum threshold	2 fC
Dynamic range	4 fC–50 fC
TDC conversion time	< 25 ns
Trigger rate	1 MHz L0 or 0.8 MHz L1
Trigger latency	10 μs L0 or 35 μs L1
Clock phase adjustment	100 ps

ATLAS HGTD TDR (cern.ch)



In functional blocks both CMS/ATLAS ASICS are very similar some differences (LUMI processing unit-ALTIROC, waveform sampler after preamp-ETROC).

ALTIROC0/ETROC0 – preamplifier + discriminator waveform sampling on the oscilloscope

ALTROC1/ETROC1 – 5x5/4x4 array with complete analogue front end (discriminator + TDC)

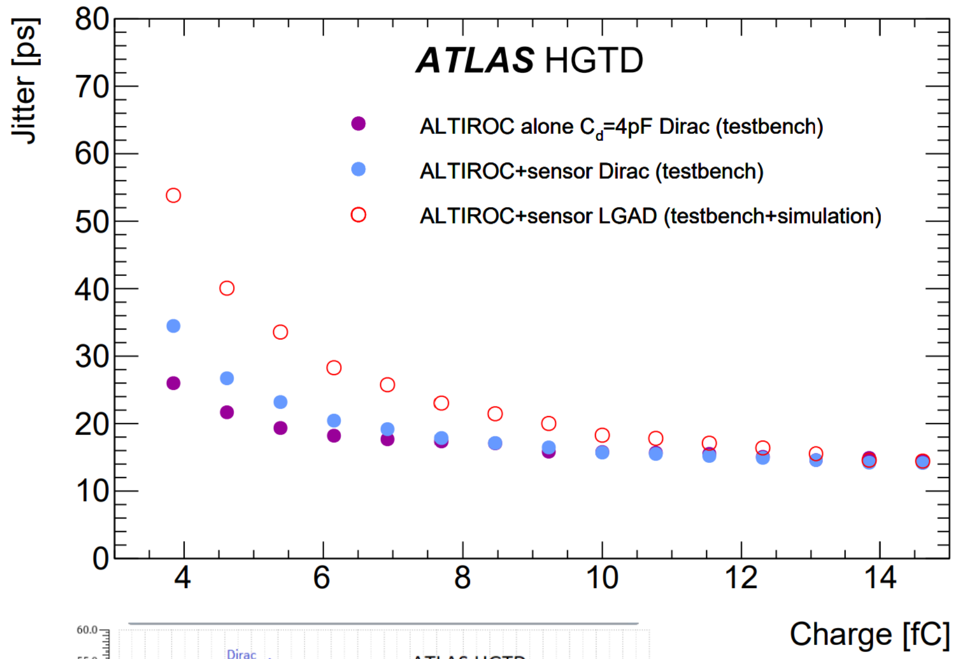
ALTIROC2/ETROC2 – 15x15/16x16 array with almost complete functionalities

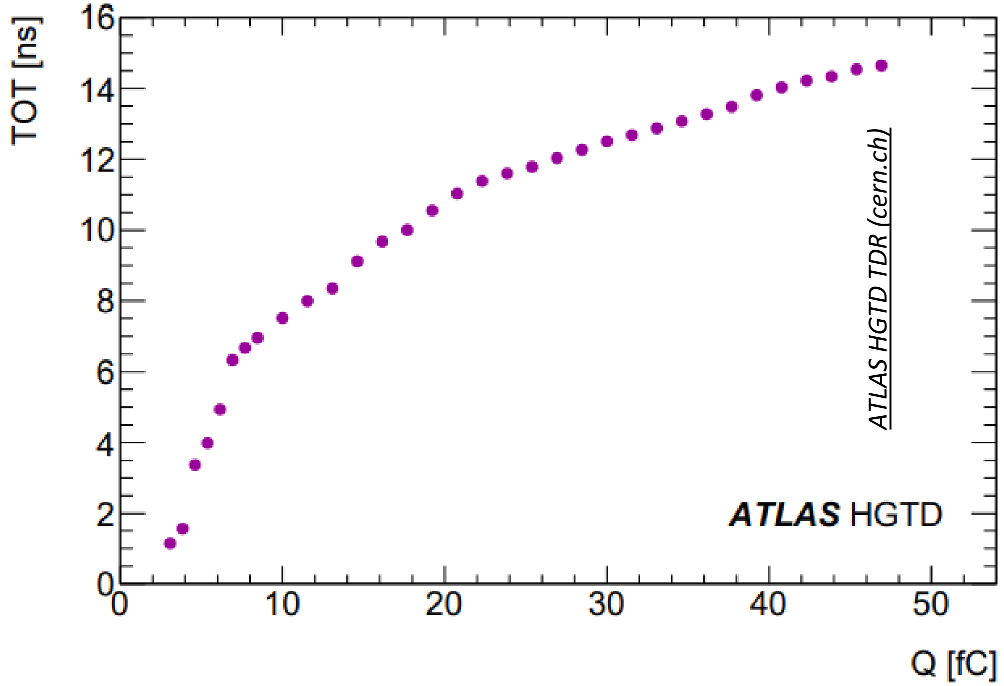
ALTIROC3/ETROC3 – final ASICS to be used in the experiments

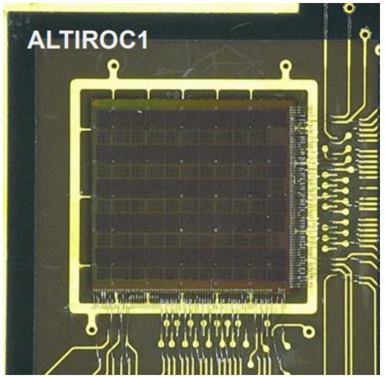
both use ToA/ToT for correction of the time walk
still under investigation is the optimum front-end amplifier

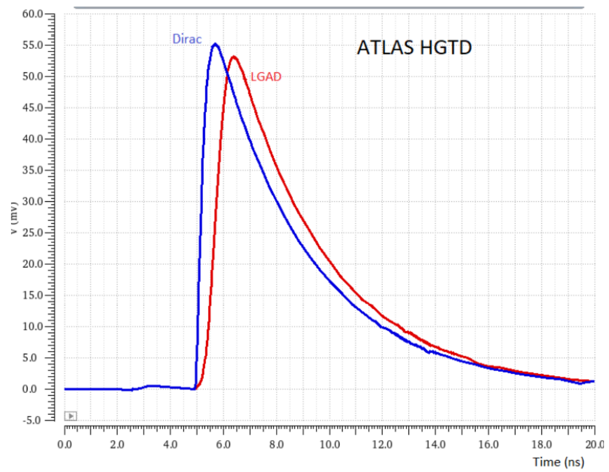
ALTIROC2 has arrived and in few months we will have first full assemblies.

ALTIROC front end performance



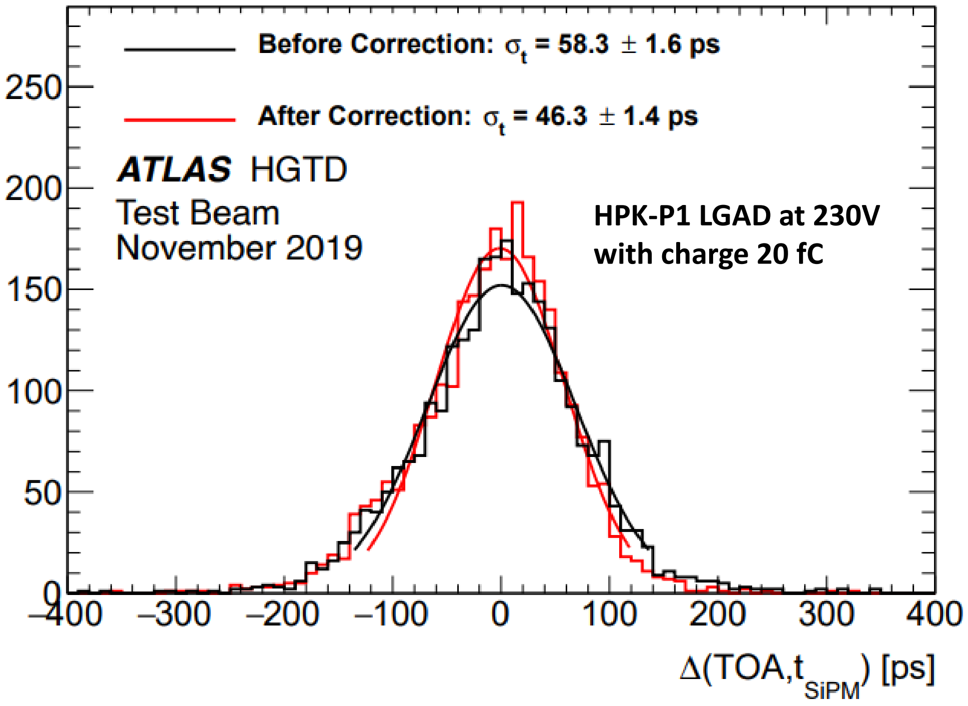






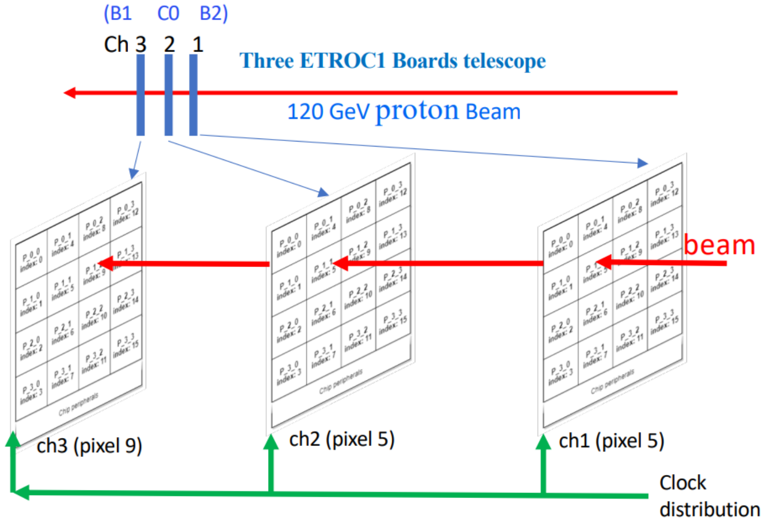
- very demanding requirement of 4 fC and <70 ps
  - thresholds can be as low as 2 fC - **full efficiency reached at ~2.5 fC**
- TDCs work well close to the specifications
- limited power consumption, very dense integration (analogue & digital) will add more challenges

ALTIROC1/ETROC1- test beam performance



LGAD Landau	25 ps	the reason for part of the high jitter found **26 (known reasons)**
Jitter+system/internal clock+time walk residual	37 ps	
TDC clock	7 ps	Total resolution: 36 ps (likely achievable for 20 fC)/ 70 ps for (4 fC)
Per hit total	46 ps	

LGAD+ETROC1 – Preliminary Test Beam Results **(HPK-P1/P2 LGAD at 230V with charge 20 fC)** Simulation /expectation

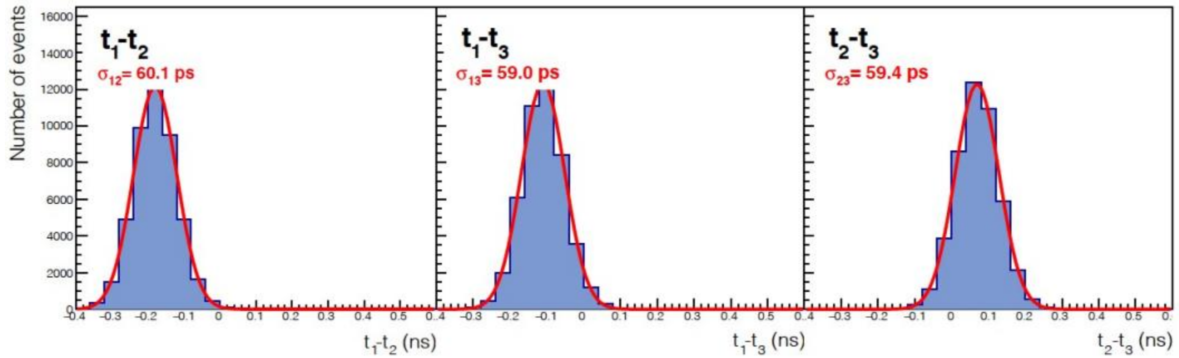


ETL Time resolution

LGAD+ preamp/discriminator + TDC bin	35 ps
Time-walk correction residual	< 10 ps
Internal clock distribution	< 10 ps
System clock distribution	< 15 ps
Per hit total time resolution	41 ps

courtesy of Ted Liu (FNAL)

Ted



Conclusions

- LGADs have come long way and are now a major choice for timing detectors for HL-LHC
  - being a planar technology it is accessible by many vendors
  - it is now the only mature technology that can offer intrinsic limit for timing resolution of ~few tens ps
  - Operation of LGADs on the other hand is much more complex than ordinary planar sensors as they are sensitive to operation conditions, density of ionization, very small fluence variations…
- The major limitation for their use is radiation damage manifested as initial acceptor removal
  - The loss of gain layer can be compensated by increase of bias voltage
  - The bias voltage is limited by so called Single Event Burnout in the highly energetic particle beam to $\langle E \rangle < 11$ V/μm
  - Carbon-enrichment of gain layer improves radiation hardness/reduces acceptor removal significantly and likely allows the use of LGADs even beyond the required fluence
  - a positive effect of radiation damage is increase of fill factor
- The production of prototype sensors for experiments is going well (~20 m^2 of LGADs required) with many vendors interested in development.
- The development of electronics is very challenging, but ASIC prototypes results are promising