Overview on
Low Gain Avalanche Detectors

J. Lange

for many people working on this

Terascale Detector Workshop München, 28 February 2018

Institut de Física d'Altes Energies

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BIST Barcelona Institute of Science and Technology

RD50

ATLAS

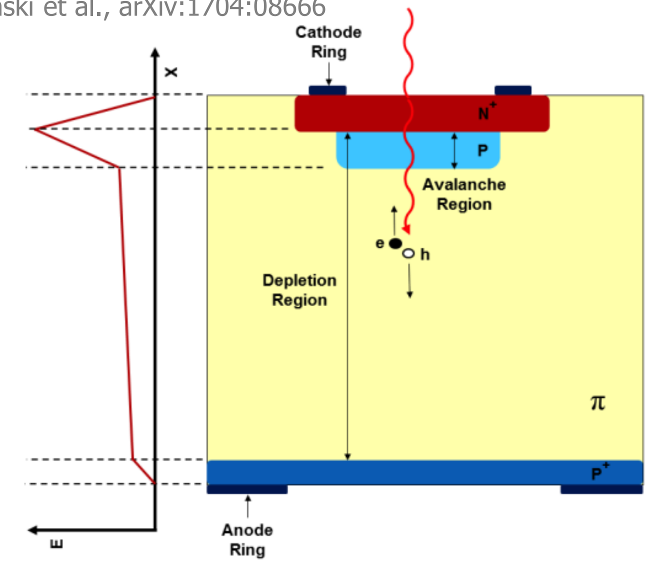
LGAD in a Nutshell

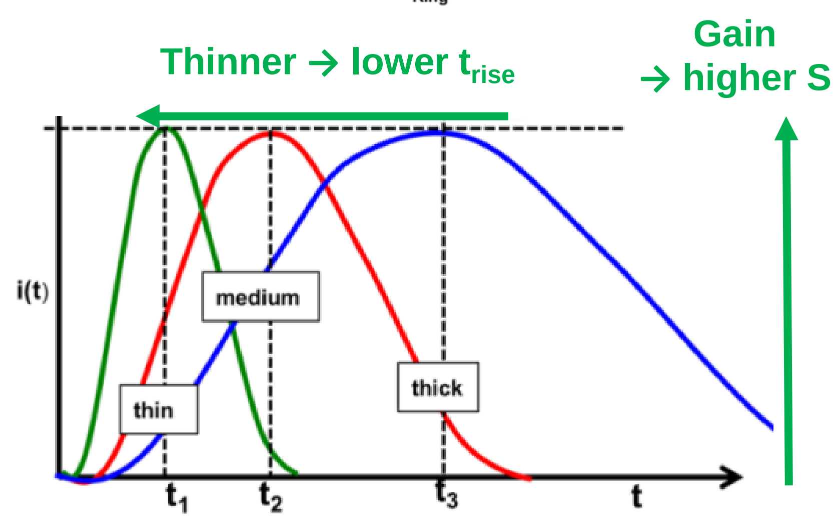
- Developed by CNM Barcelona and CERN RD50 collaboration
  - Now also Hamamatsu, FBK, BNL, Micron
  - Inspired by charge multiplication in irradiated Si detectors
    J. Lange et al., NIM A622(2010)49
- Could be considered as large APD/SiPM with lowered gain + segmentation for charged particle tracking/X-rays
- But historical development/philosophy is other way round:
  Standard segm. n-p silicon detector + built-in p multiplication layer
  → High E field
  → Moderate gain ~10-20
  → Increases signal
  → Keeps noise limited
  } Increased S/N
- Multiplication allows thinner detectors (now 35-50 μm)
  → Fast charge collection (~1 ns)
  → Small rise time (~400 ps)

→ Excellent time resolution < 30 ps

$$\sigma_{\text{Jitter}} = \frac{N}{(dV/dt)} \simeq \frac{t_{\text{rise}}}{(S/N)}$$

G. Pellegrini et al., NIM A765 (2014) 12
H. Sadrozinski et al., arXiv:1704:08666





LGAD Signals

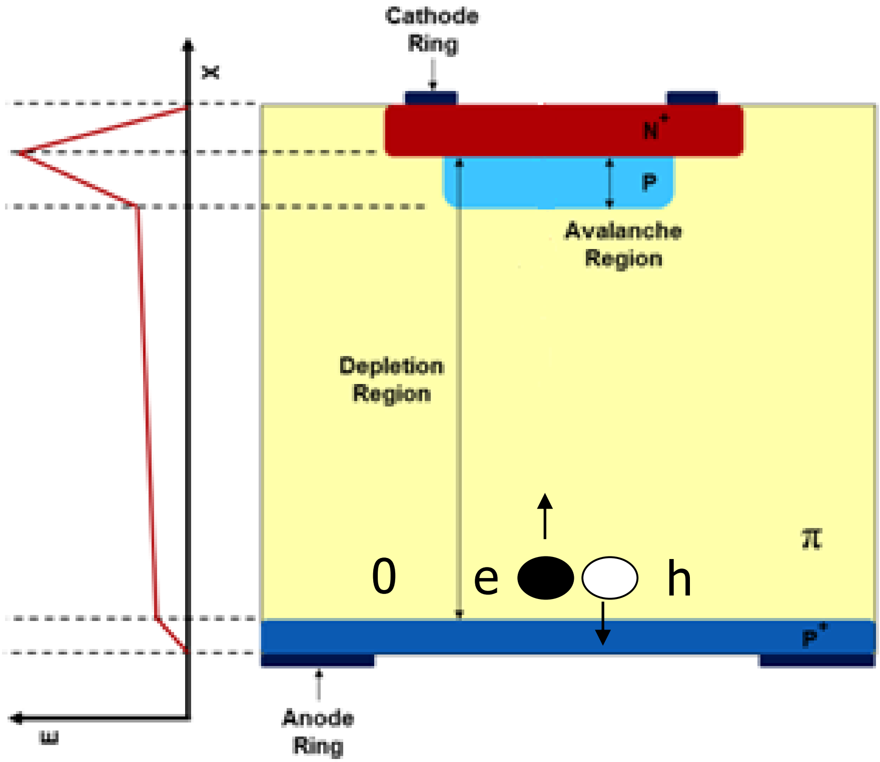
Signal Formation – Back Side Injection

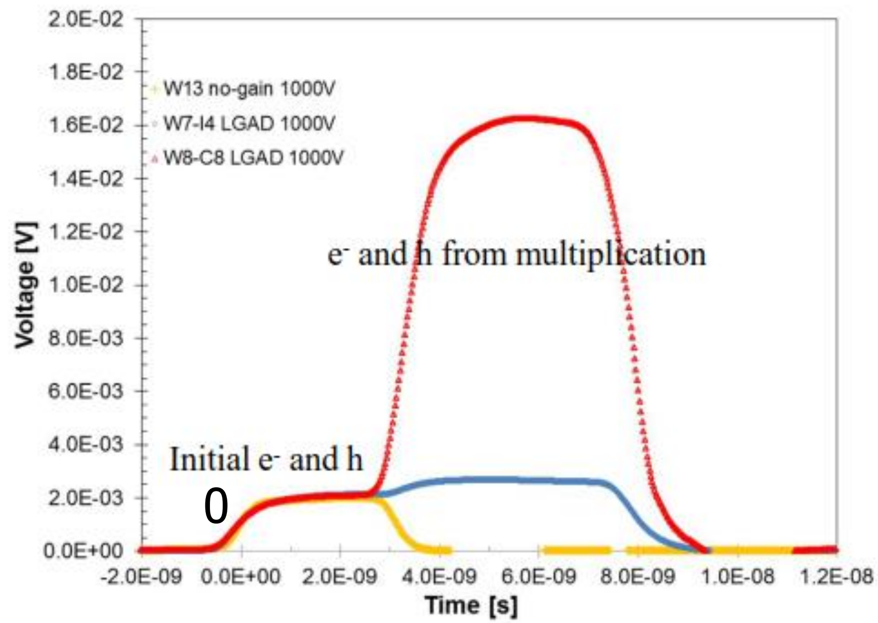
- Measurable signal induced by Ramo theorem

$$I_{e,h}(t) = \frac{eN_{e,h}(t)}{d} v_{dr_{e,h}}(t)$$

- Back side charge injection (alpha or red laser) -> Follow charge carrier as probe of E field and multiplication

0) e-h pairs created at back side, h immediately collected





Hartmut Sadrozinski
23rd RD50 workshop

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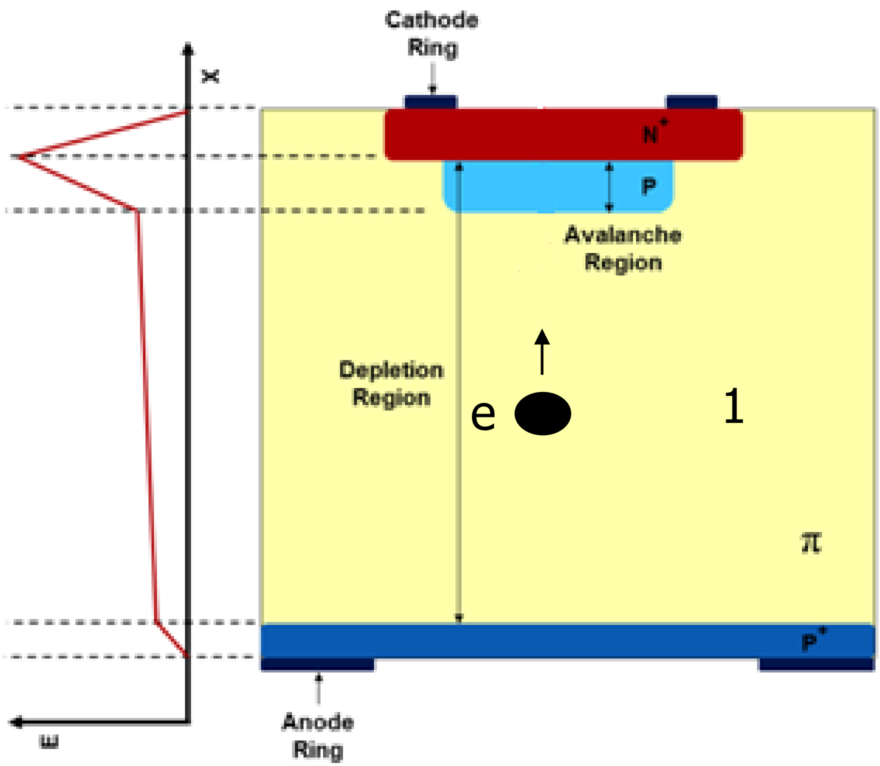
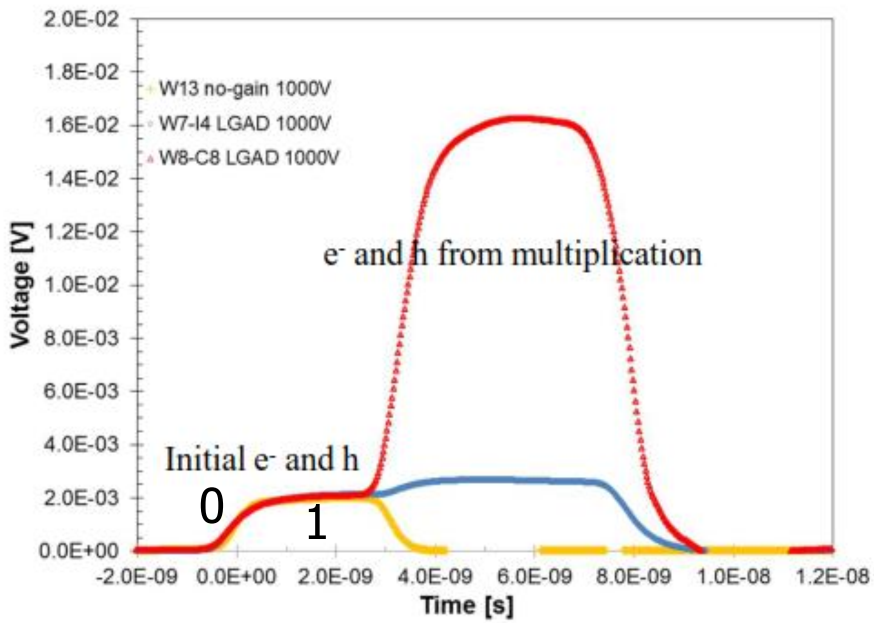
  1) e drift towards high field from back to front





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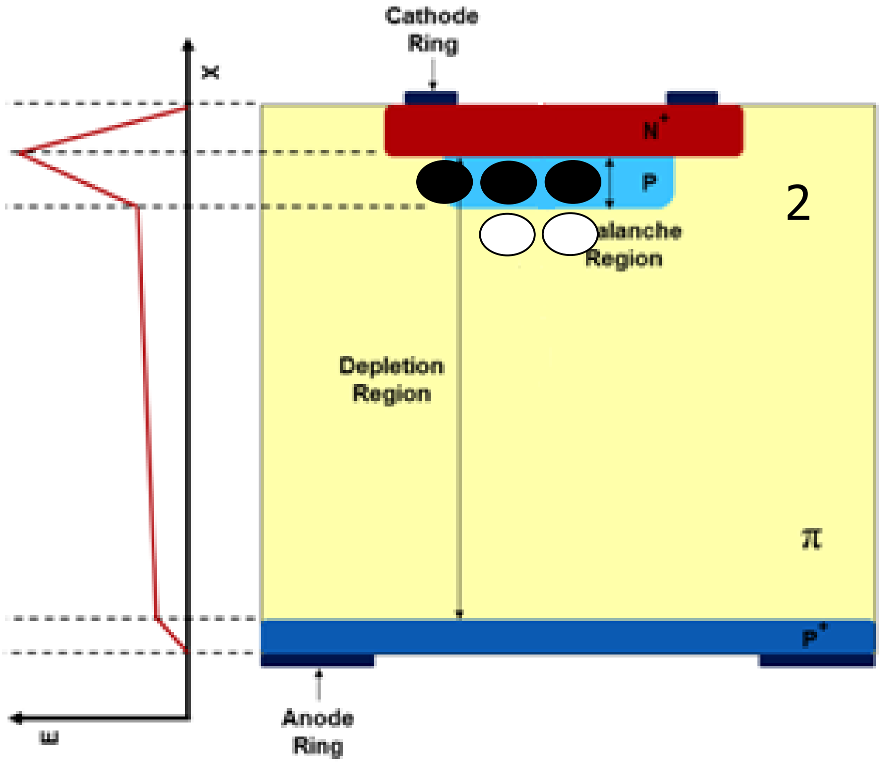

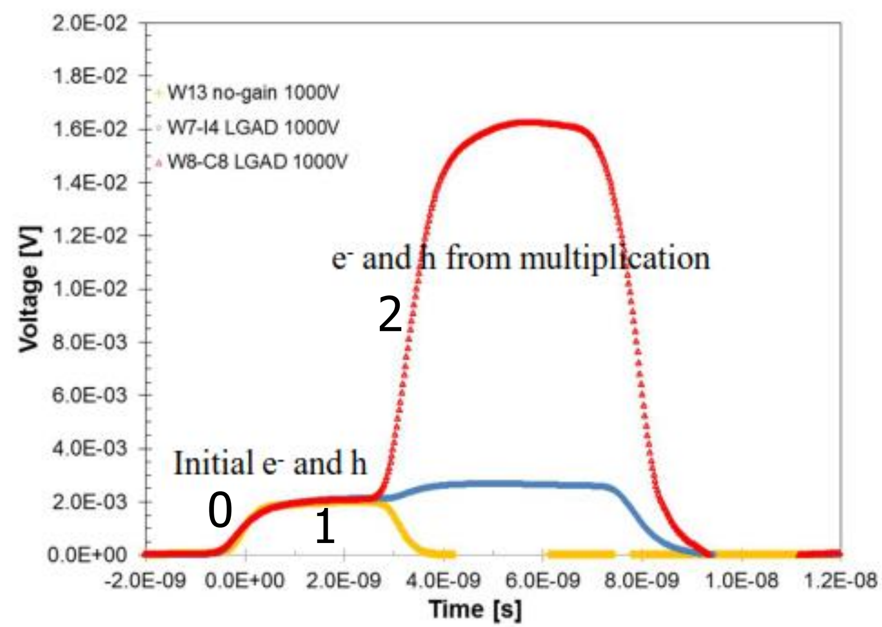

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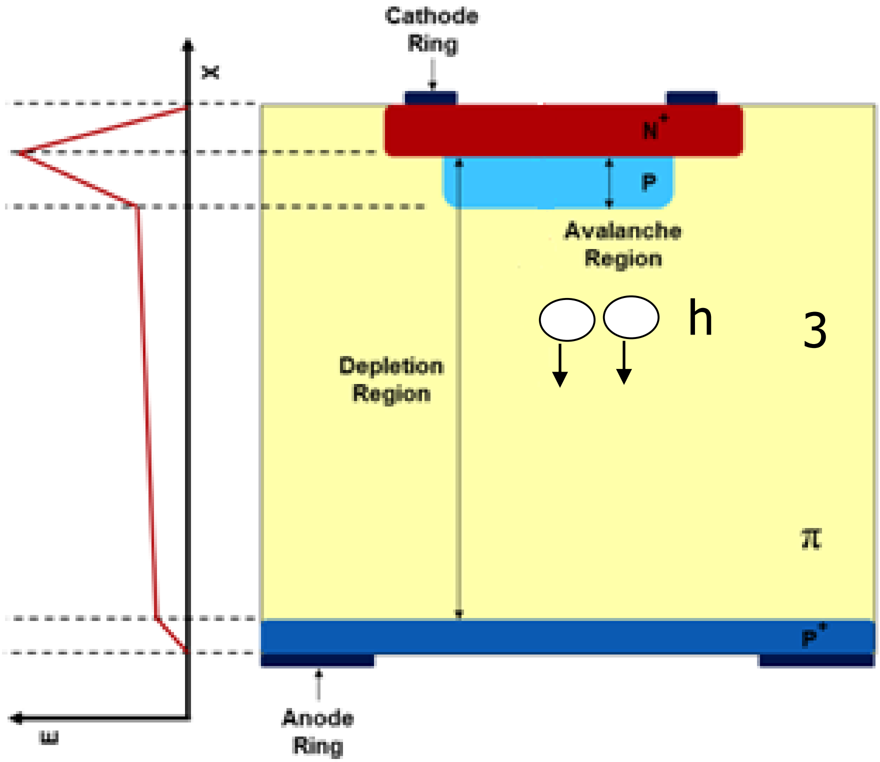
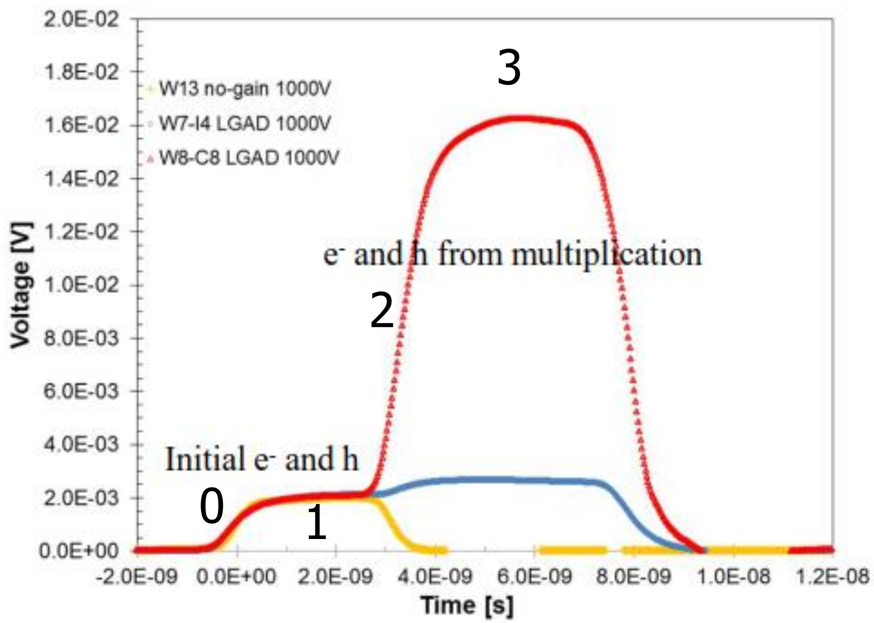
  2) e multiply in high field multiplication region

  3) multiplication h drift towards the back





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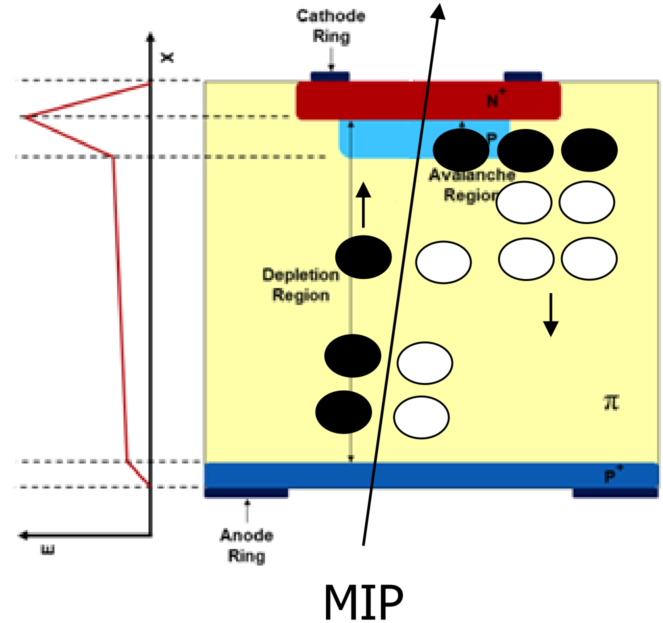
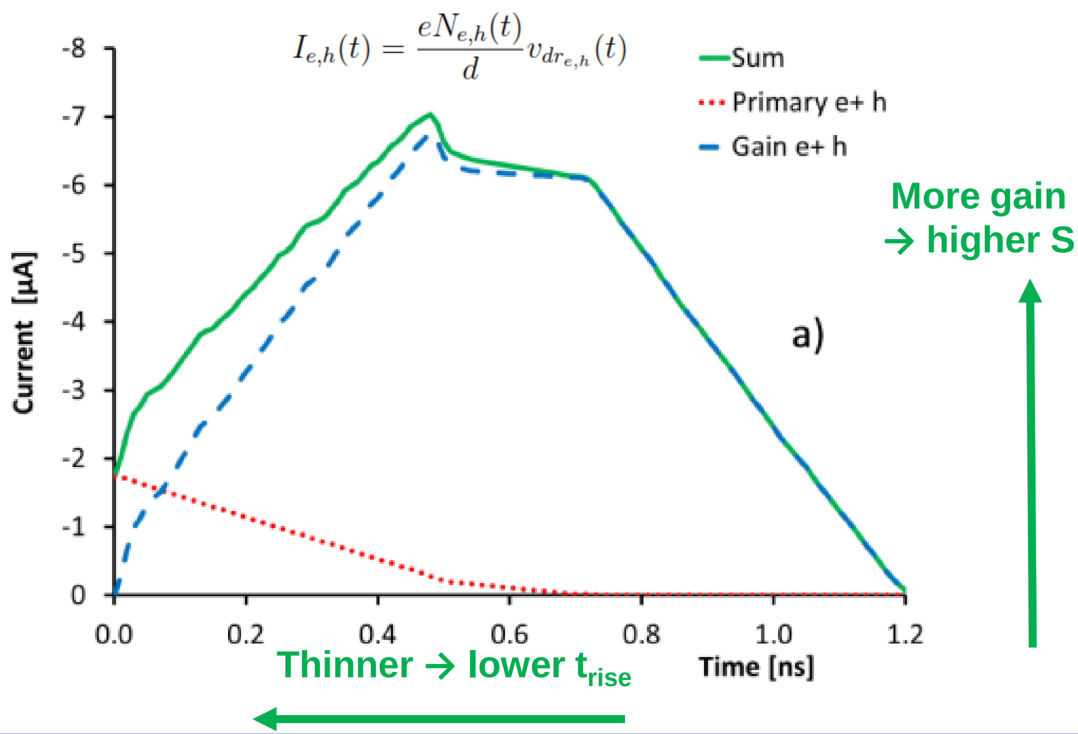
Signal Formation – MIP

- MIP is ionizing along its path
  - Rather uniformly in depth
  - But Landau fluctuations present
- Signal formation is sum of individual charge packages
  - Primary e+h
  - Constant multiplication until all e have reached front side ("gain e+h")
  - Then only h signal



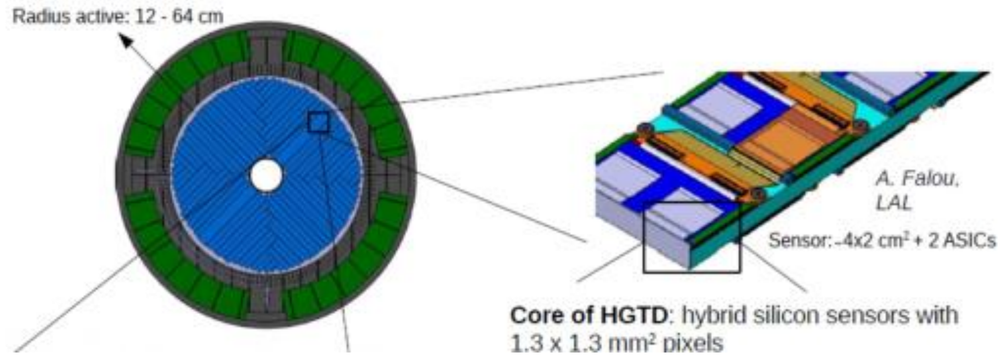


Weightfield2 Simulation

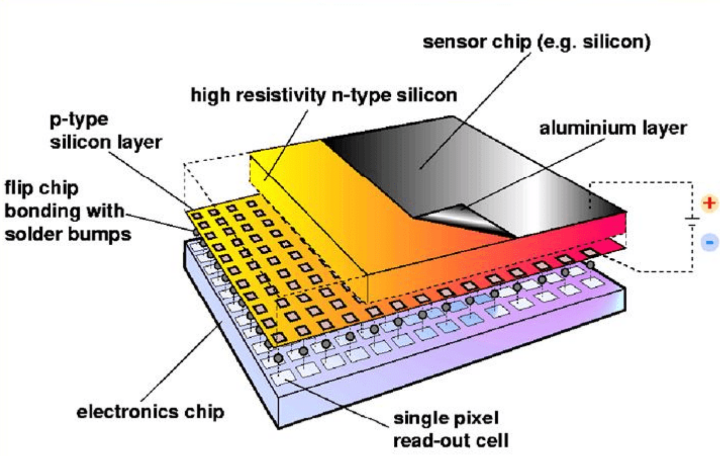
F. Cenna et al., NIM A 796

LGAD Applications

- HEP timing detectors
  (ATLAS HGTD, CMS ETL, AFP, CT-PPS)
  - Pile-up rejection:
    assign each particle a vertex via collision time
  - 30 ps time resolution
  - Pads ~1 mm²



- "4D tracking" (future)
  - ~50 µm pixel + ~30 ps timing
  - "All in one"



- Photon science: soft X-ray
  - Soft X-rays ~1 keV
  - Gain boosts small signal above ASIC thresholds
    → standard ASICs (AGIPD, Medipix, …) + infrastructure can be used

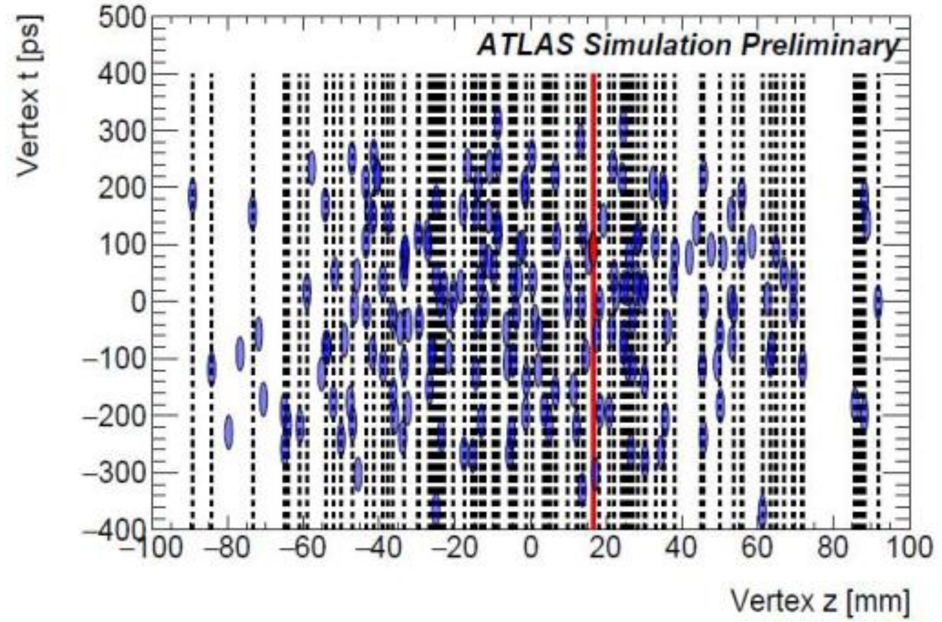
- Medical: Radiotherapy
  - Measure high rate beams + ToF for precise energy (~10-100 MeV p)

- …?

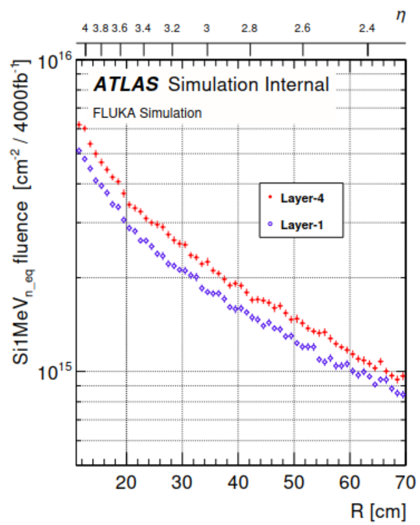
HL-LHC Timing Layers

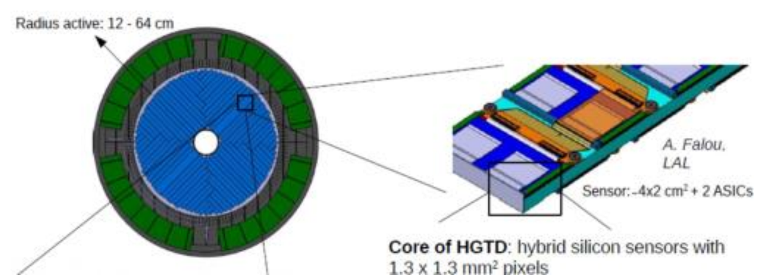
- The quest: assign each particle a vertex
  - Tracker resolution in some regions not precise enough (e.g. at high eta)
  - Collision time is independent vertex information
    → further pile-up suppression
    → helps to keep performance
    (b-tagging, jet pile-up, lepton isolation,…)
- New planned timing detectors for ATLAS and CMS
  - ~30 ps time resolution/track, 1-5e15 n_{eq}/cm^2 rad.-hard
  - LGAD pads ~1 mm², ~10 m² of Si each

See talk by L. Masetti



	ATLAS	CMS
Name	HGTD	ETL
Eta	2.4-4.0	1.6-3.0 (+barrel)
Layers	2-3	1
Resol. [ps]	30	30-35
Pad [mm²]	1.3x1.3	1.0x3.0
Max. Fluence [n_{eq}/cm^2]	5 (1 repl.)	1

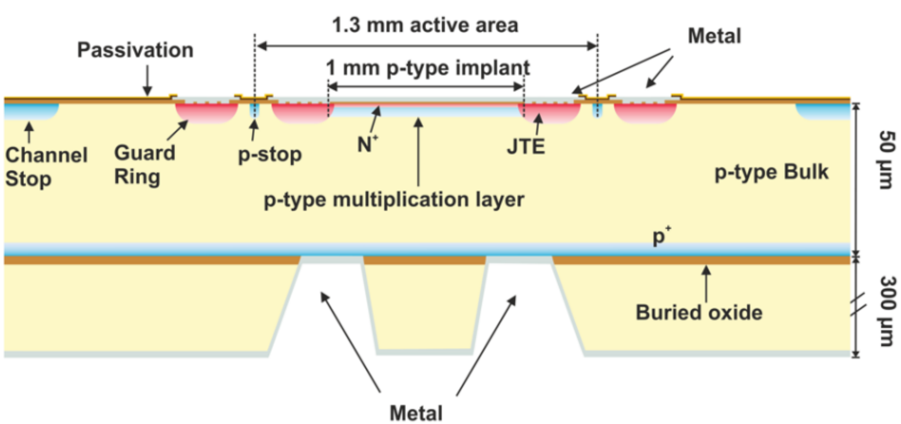




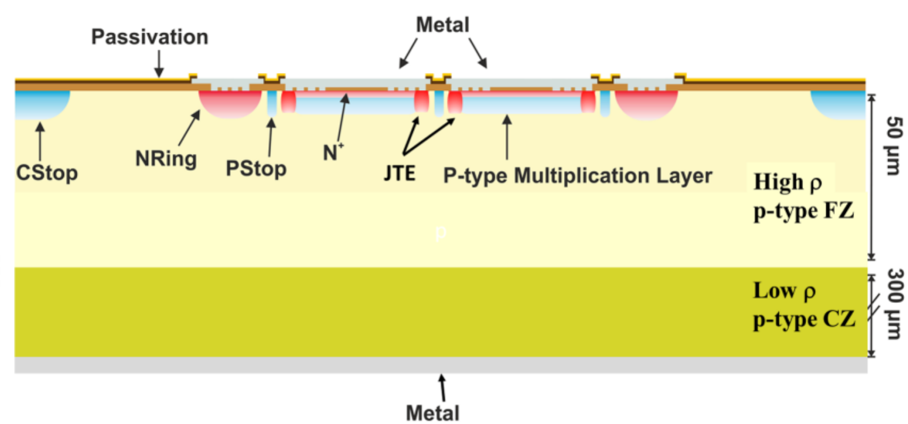
LGAD Technology

- Produced by CNM, FBK, HPK, BNL, Micron
- Pioneered on 300 µm thickness and 4”
- Now 6” and different technologies for 35-50 µm active thickness/substrate (Epi, SOI, Si-Si)
- Usually B used for highly doped p-type multiplication layer
  - Also Ga and additional C-spray under investigation for improved radiation hardness (see later)
- Junction terminations (e.g. JTE) needed to avoid local high fields and early breakdown at implantation edges
  - Drawback: no-gain inter-pad gap

CNM SOI, single pad



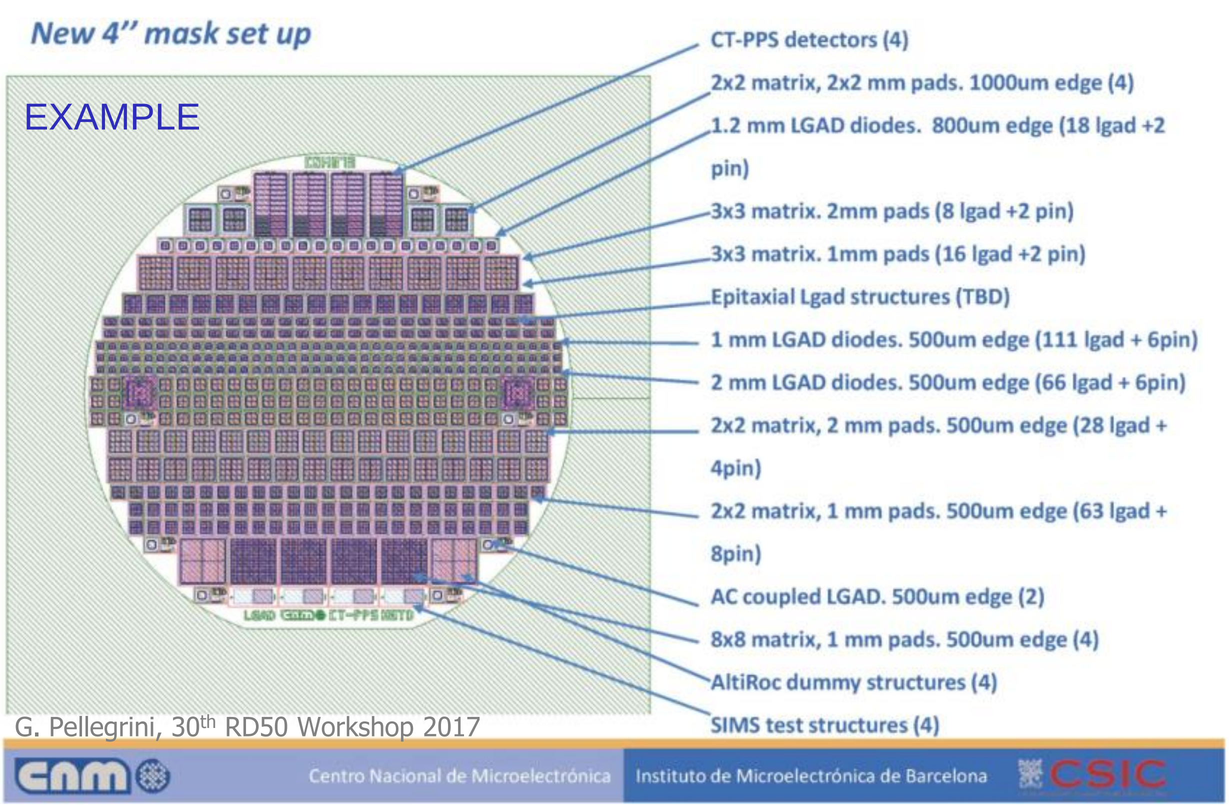
CNM Si-Si, 2x2 array



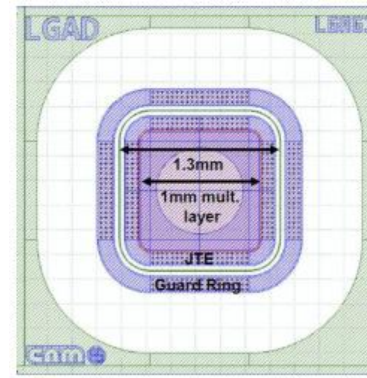
G. Pellegrini, 30th RD50 Workshop 2017

LGAD Devices

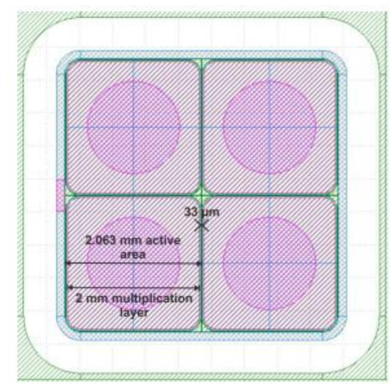
- Variety of different test structures
  - Single pads of different size (1-2 mm), arrays of different pad multiplicity (up to 8x8), partly with UBM option for hybridization (bump-bonding to ASIC), fill factor variations, etc…
- Some runs also include strips/pixels
- New runs with large size sensors (~2x2 cm²) being produced



Single Pad

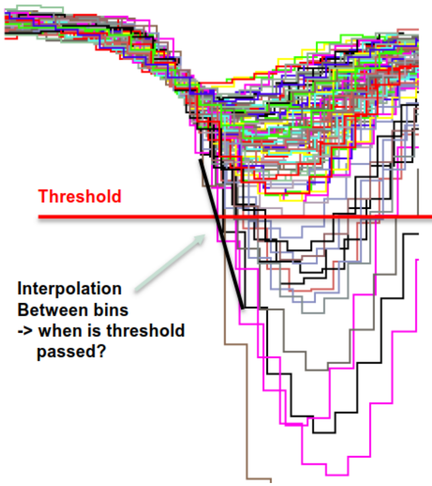


2x2 Array

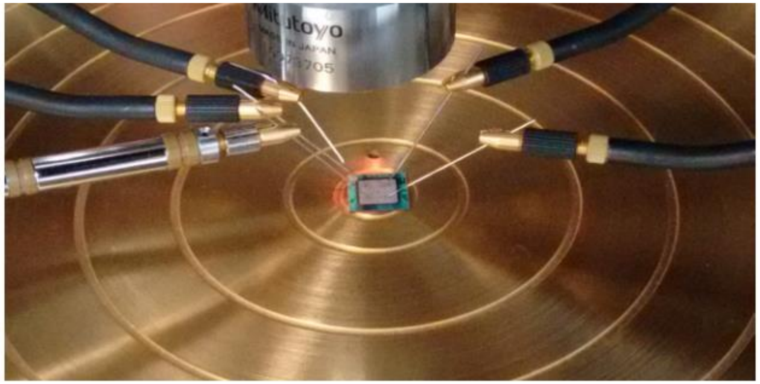


Performance Measurements

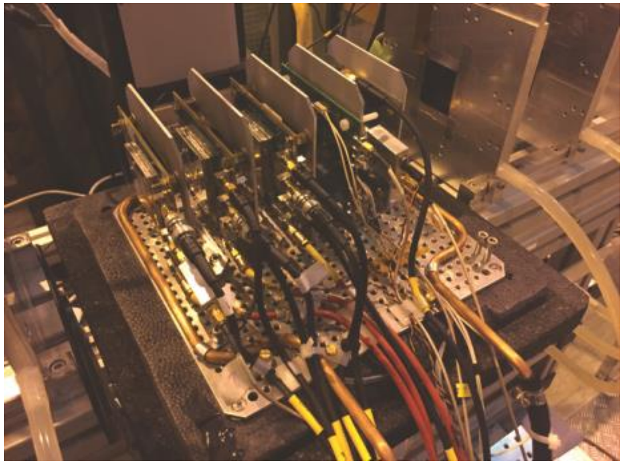
- Laboratory electrical testing (IV, CV)
  - Verify LGAD performance, breakdown voltage, doping level, test yield
- Laboratory dynamic testing (β, α, laser) and beam tests with MIPs
  - Signal shape, noise, charge, gain, time resolution, uniformity
- Time resolution analysis
  - Measured from spread of time difference of ToA of different devices
  - Typically well-known reference device used (good LGAD or Quartz+SiPM ~10 ps)
  - Time walk corrected via amplitude/ToT correction or Constant Fraction Discrimination



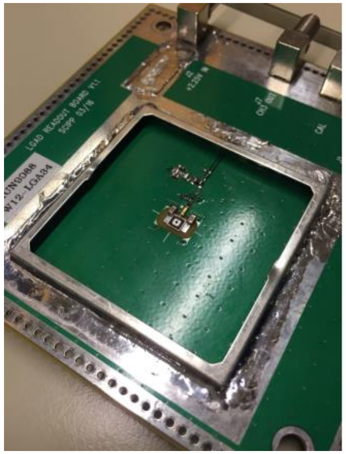
Electrical Testing



HGTD beam test

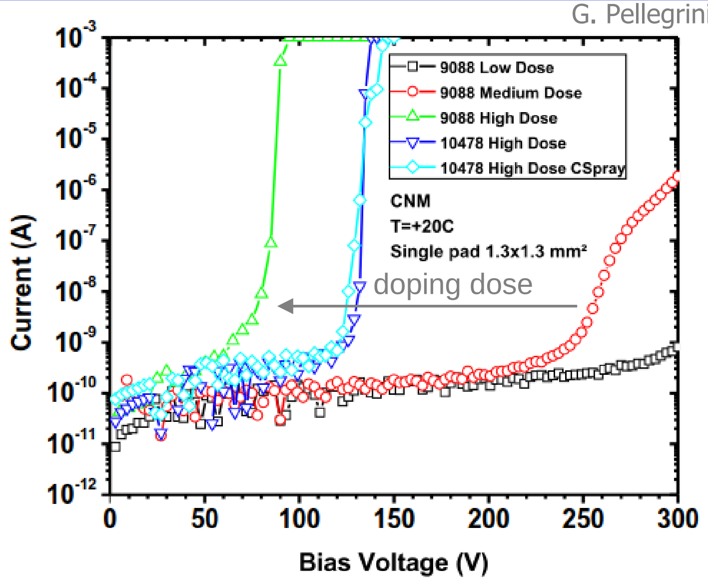


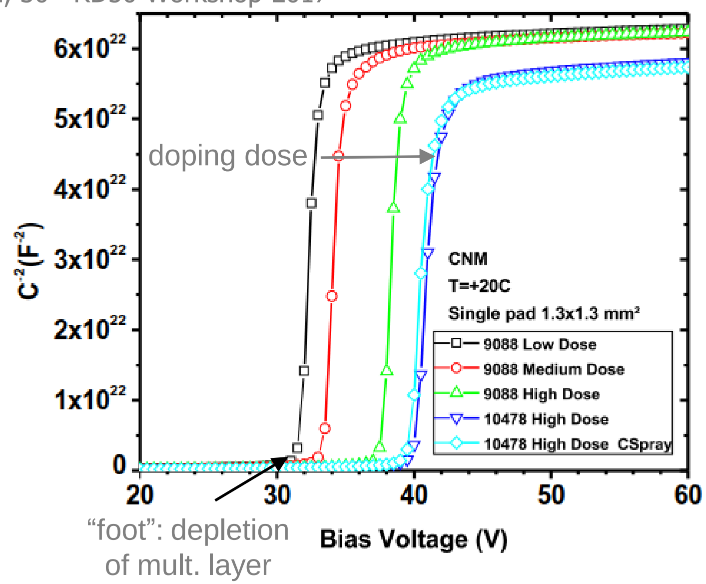
Fast Readout Board

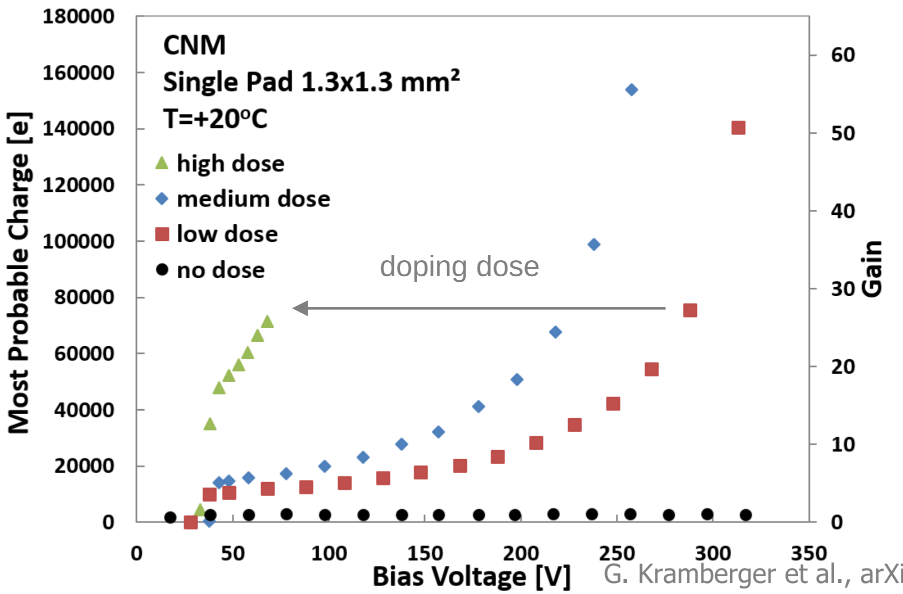


Electrical Characterization and Gain

G. Pellegrini, 30th RD50 Workshop 2017



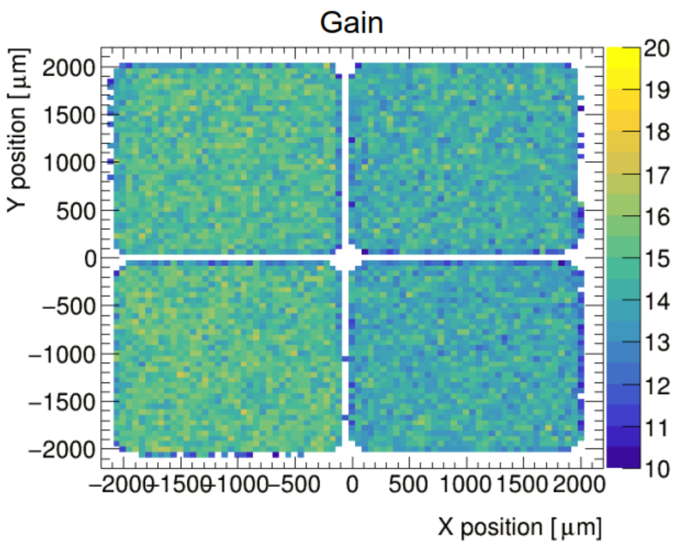




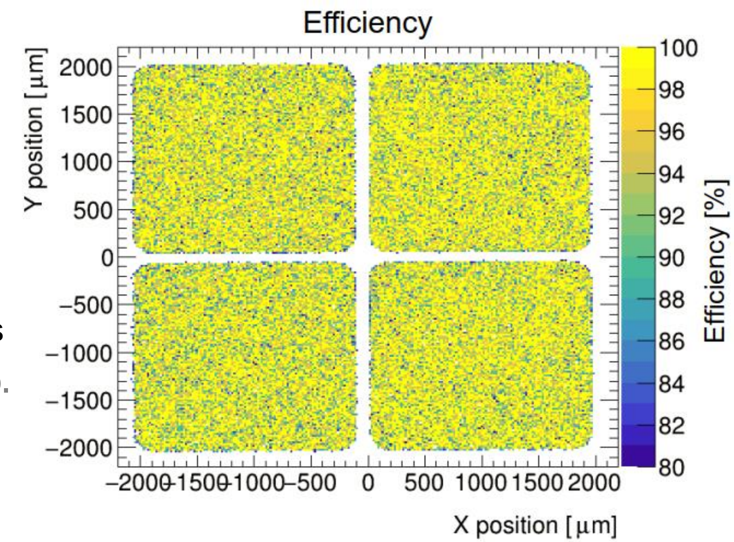
G. Kramberger et al., arXiv:1711.06003

- Break down, depletion of multiplication layer (“foot”) and gain depend on dose of multiplication layer
- Gains of up to 50-100 reached (baseline ~20)
  - Need less V for same gain at higher dose

Uniformity in Beam Test

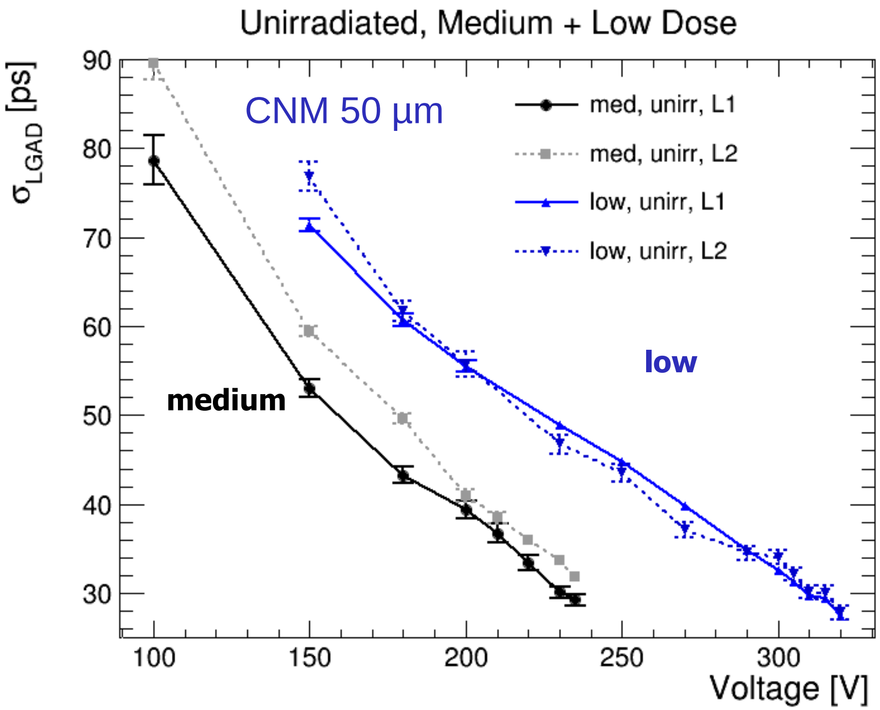


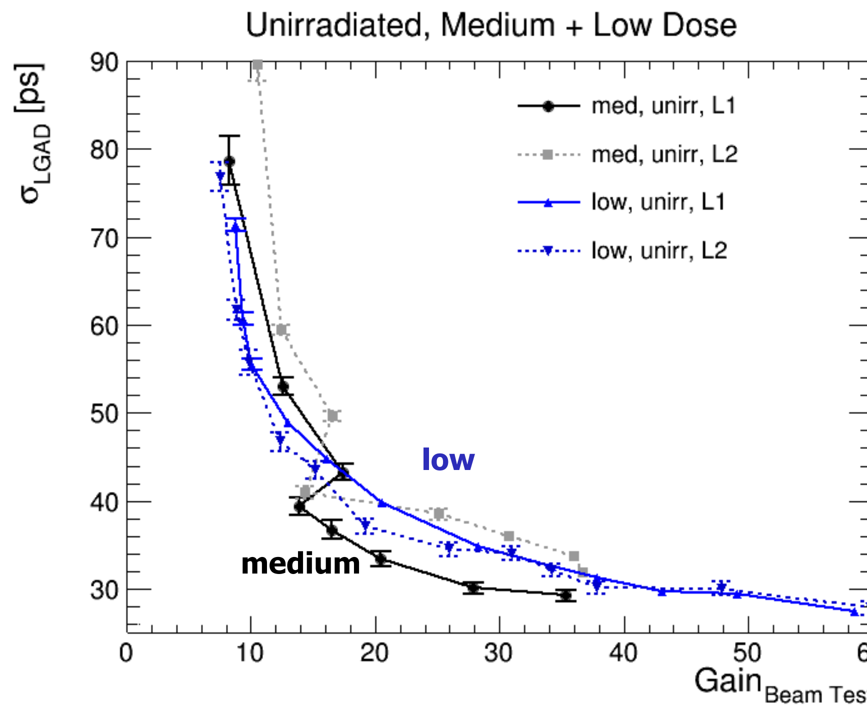
CNM
2x2 Arrays
HGTD Beam Tests
Publication in prep.



- Gain uniform over array
- Hit efficiencies uniformly 96-99%
- 70-100 µm no-gain inter-pad gap for current designs

Time Resolution Unirradiated





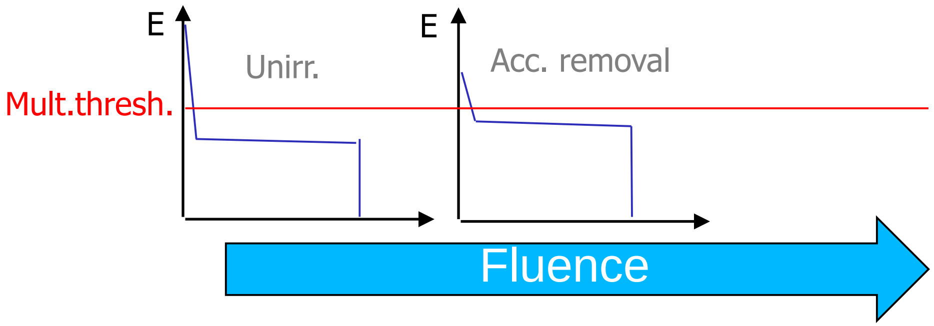
J. Lange et al., JINST 12 (2017) P05003

- Time resolution <30 ps / layer achieved
- Higher V needed for lower dose for same performance
- Universal behaviour as a function of gain
  - If noise is same and v_{drift} saturated
- Similar performance for all vendors and different groups

N. Cartiglia et al., NIM A850 (2017) 83
J. Lange et al., JINST 12 (2017) P05003
HGTD beam test (publication in prep.)
Z. Galloway et al., arXiv:1707.04961

Radiation Effects

- Max. fluence requirements: ~5e15 n_{eq}/cm^2
- Trapping of charge carriers
  → mitigated in thin sensors (50 μm)
- Increase of leakage current with fluence
  → mitigated by cooling down to -20 to -30°C
- Modification of effective doping concentration
  - Removal of initial dopants (“acceptor removal”)
    → removes multiplication layer
    → degrades gain and time resolution



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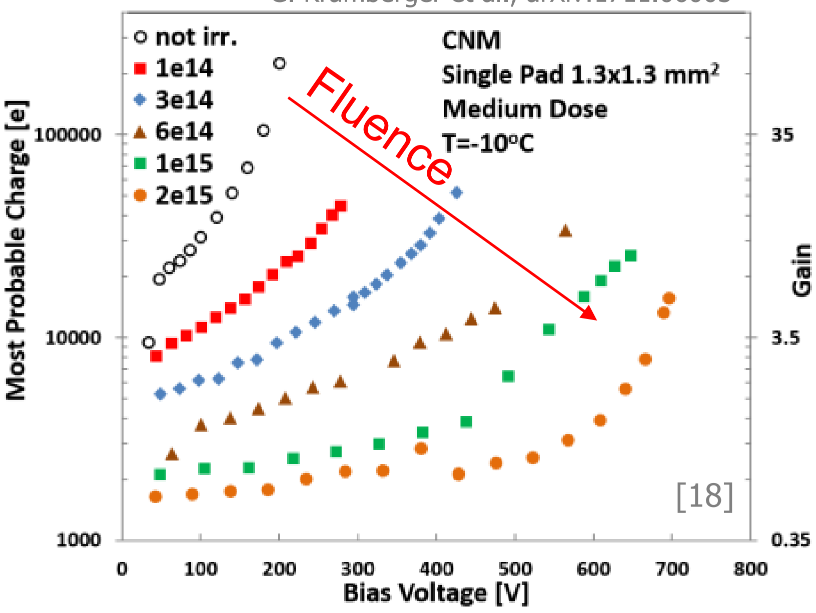

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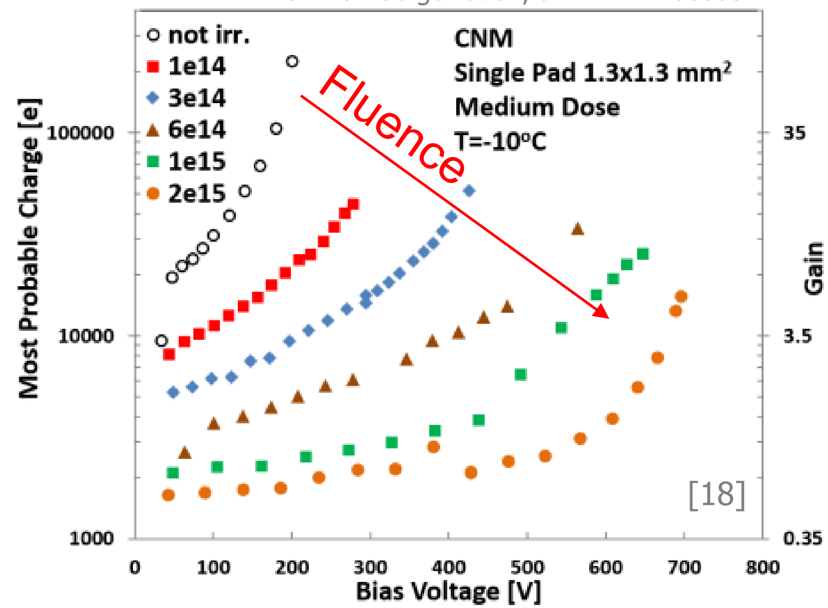
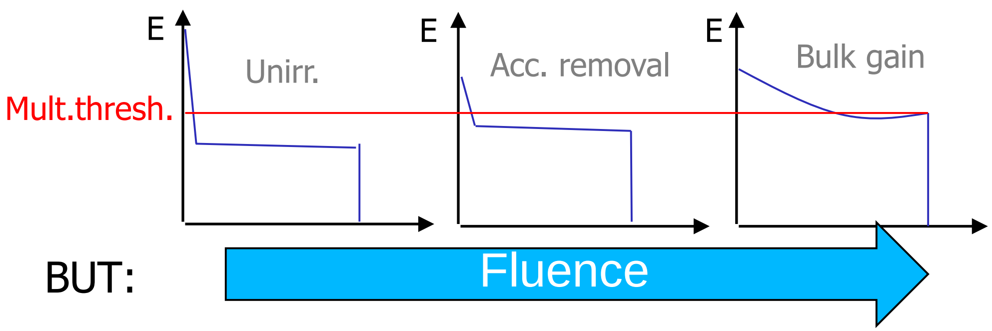


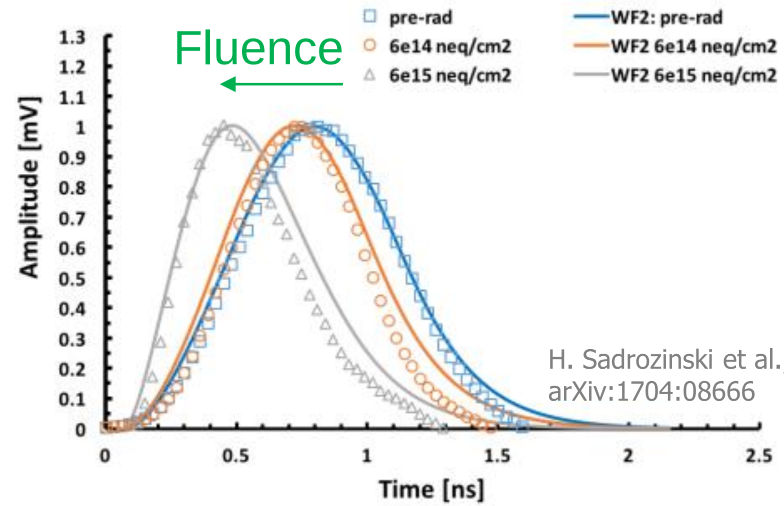


BUT:

- Introduction of radiation-induced acceptor-like defects in bulk
- Higher break down voltage after irradiation

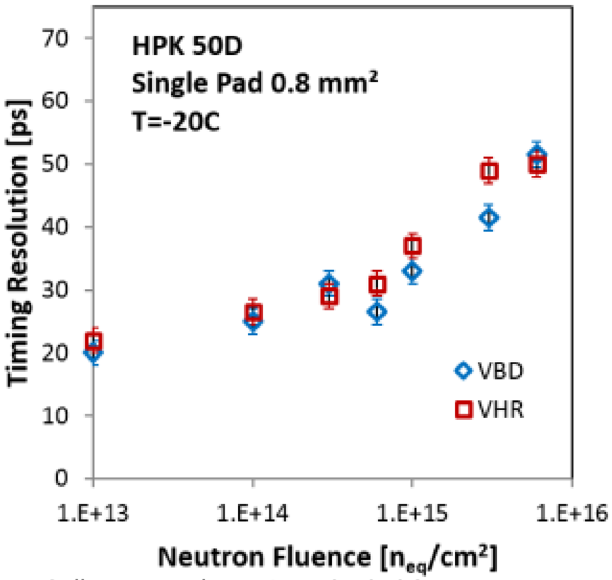
→ introduces gain in the bulk (even in PIN)
→ decrease in rise time
→ partly compensates loss of built-in multiplication layer

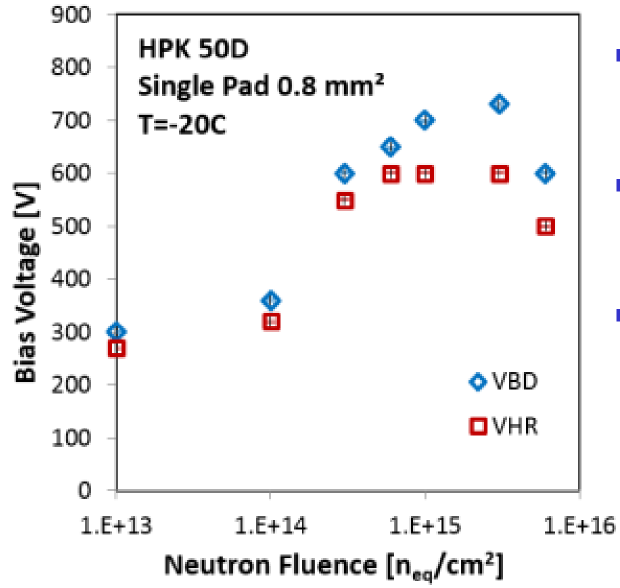
J. Lange et al., NIM A622 (2010) 49



H. Sadrozinski et al., arXiv:1704:08666

Time Resolution Irradiated HPK 50 µm

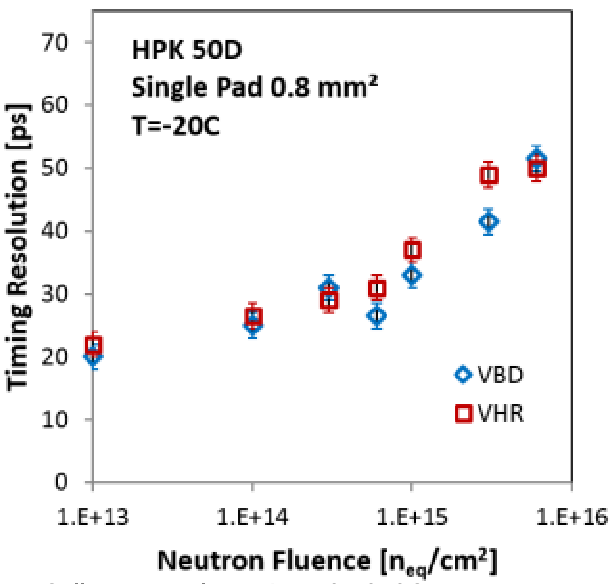


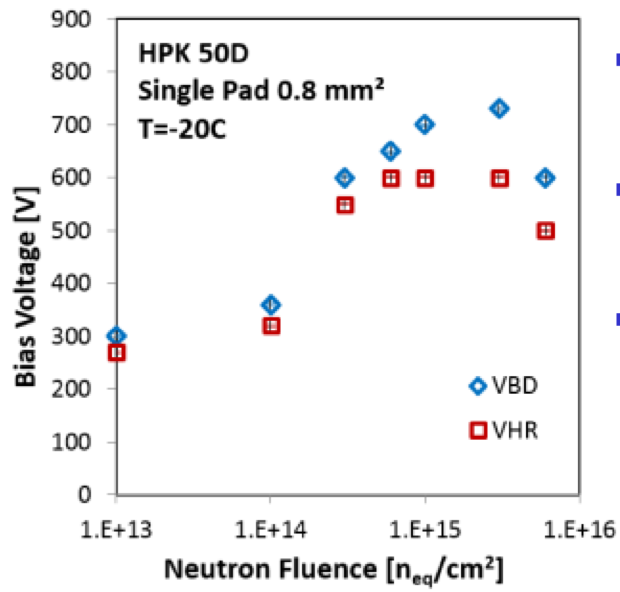


Z. Galloway et al., arXiv:1707.04961

- Degradation of time resolution with fluence
- **50 ps/layer maintained up to 6e15 n_{eq}/cm^2**
- 2 operation points studied
  - Bias at break down VBD
  - Bias including “head room” VHR → can afford 10% less than VBD

Time Resolution Irradiated HPK 50 µm





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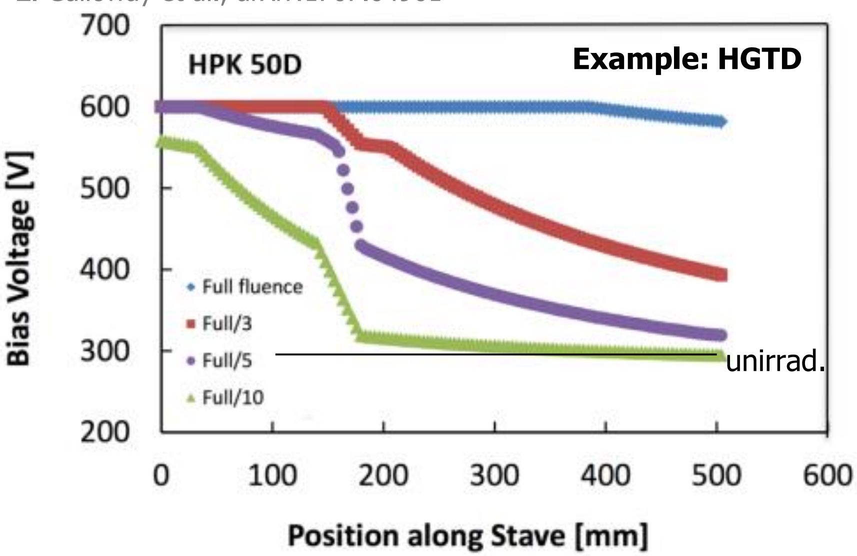


Operational aspects

- Vop needs steady adjustment responding to radiation damage as a function of radius
  - For HPK 50D from 300-600 V (VHR estimator of Vop)
  - Monitored via ToT and time resolution
- Modules along stave need different Vop
  - Limited ganging

Towards Higher Radiation Hardness

- Goal: reduce acceptor removal

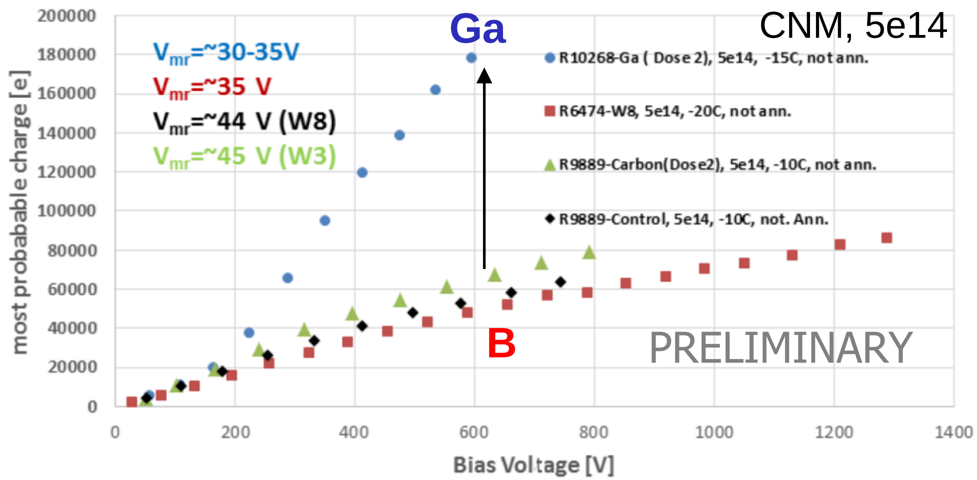
  $$Si_i + B_s \rightarrow B_{i^-} \rightarrow B_i + O_{i^-} \rightarrow B_i - O_i$$

  1. Ga heavier than B → harder to remove
  2. C-spray: C easier to remove → sink for Si_i

- Ga-LGAD
  - First results on CNM 300 µm Ga-LGAD test structures promising
    - But possible bias due to high initial doping
    - 50 µm run on-going
  - First results on FBK 50 µm Ga-LGAD: no effect

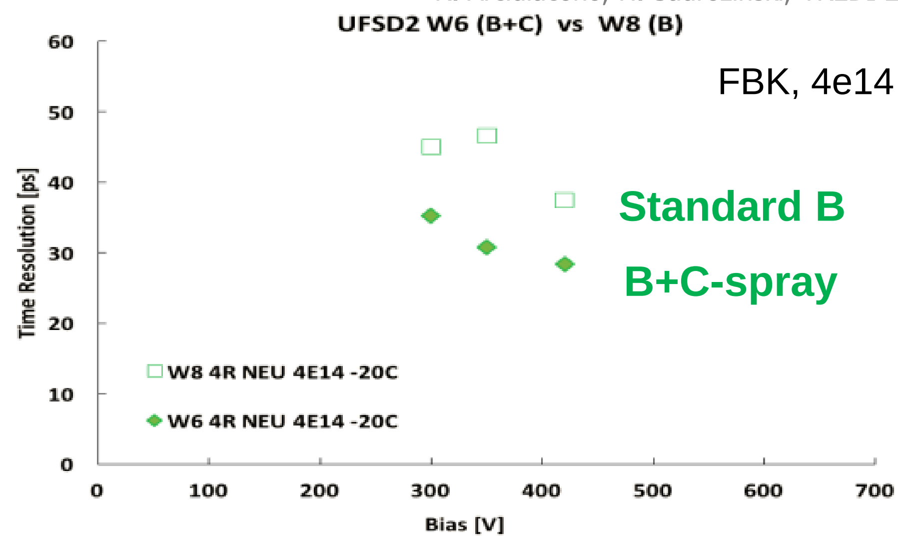
  → further studies on-going

- C-spray
  - FBK C-spray LGADs have ½ acceptor removal rate than no-C
  - Better performance at intermediate fluences <1e15 n_{eq}/cm^2

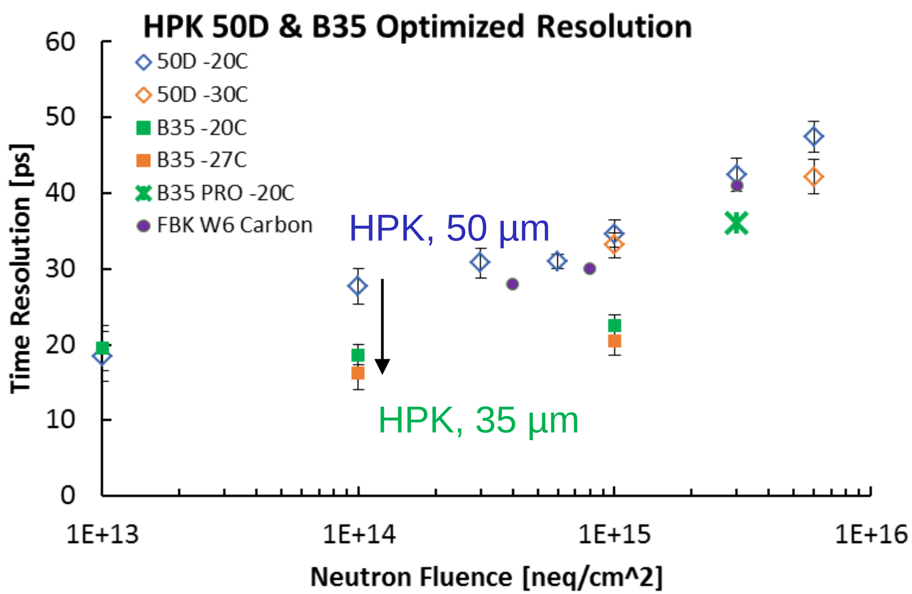


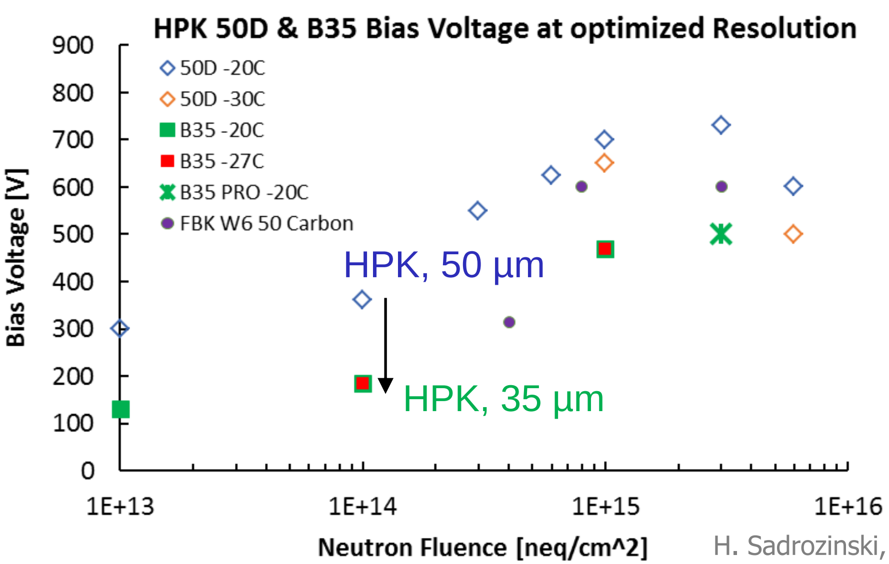
G. Kramberger, 30th RD50 Workshop

R. Arcidiacono, H. Sadrozinski, TREDI 2018



Going thinner… - 35 µm

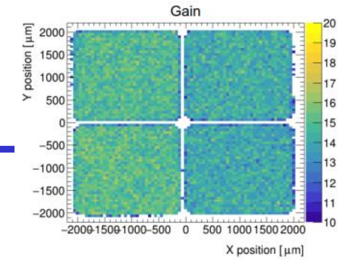




H. Sadrozinski, TREDI 2018

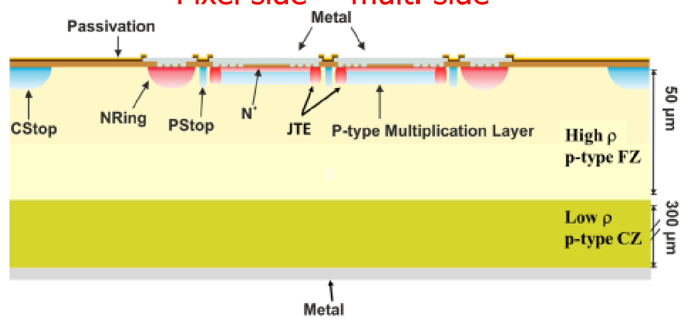
- Significantly better time resolution for 35 µm: ~20 ps up to 1e15 n_{eq}/cm^2
- … at lower bias voltage!

Better Fill Factor – Towards 4D



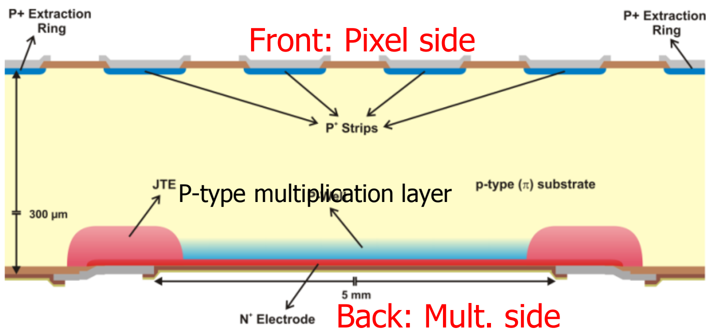
- First LGAD versions: no-gain inter-pad gap 70-100 µm
  - Only 85% fill factor for 1.3 mm large pads (HGTD) → inefficient region
  - Much worse for "real" pixels of ~50 µm pitch (e.g. Medipix) → needs to be much improved with final goal of 4D tracking

Pixel side = mult. side



- Option 1: Standard LGADs with minimized inter-pad distance
  - Optimize or skip JTE around each pixel → expect degraded breakdown, but hopefully gain still enough

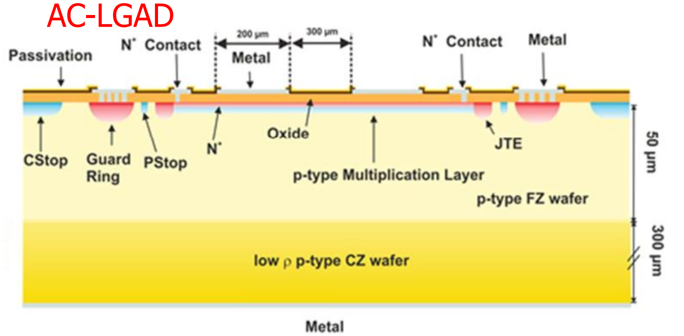
Front: Pixel side



Back: Mult. side

- Option 2: inverted LGAD (iLGAD)
  - Homogeneous multiplication layer at back-side
  - p-in-p pixels at front side: hole collection
  - Already working devices produced

AC-LGAD

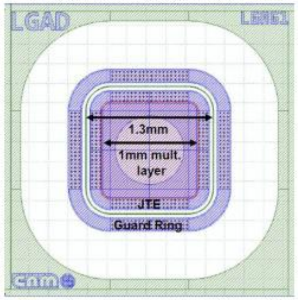


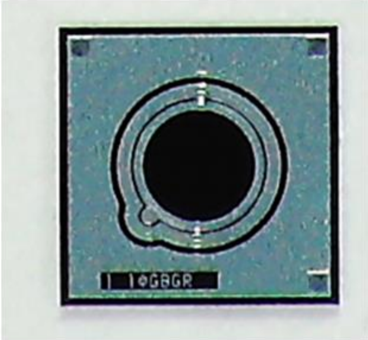
- Option 3: AC-LGAD
  - Homogeneous multiplication layer at front-side
  - Pixelation only in metal, AC-coupled to sensors via SiO_2
  - First prototype produced, new dedicated run starts soon

Conclusions

- **Successful development of fast silicon sensors in LGAD technology**
- Several LGAD manufacturers established
- Many RD50, ATLAS, CMS institutes involved in sensor testing in lab and beam tests
- Performance results (50 μm):
  - <30 ps / layer before irradiation
  - 50 ps / layer after 6e15 n_{eq}/cm^2

  → timing requirements for ATLAS+CMS HL-LHC detectors fulfilled
- Further intense development on-going for optimisation and to address open questions soon
  - Improved radiation hardness (Ga, C-spray), thinner detectors (35 μm), fill factor, large devices, …





BACKUP