LGAD development for

High Granularity Timing Detector (HGTD)

ATLAS LHC High luminosity upgrade

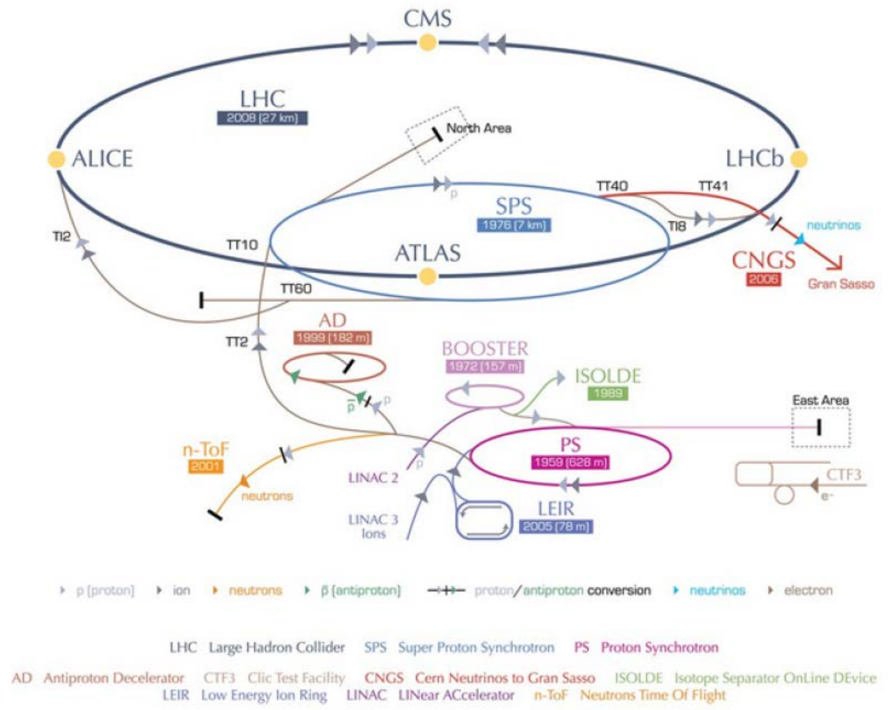
RD50 Workshop, Lancaster (UK)

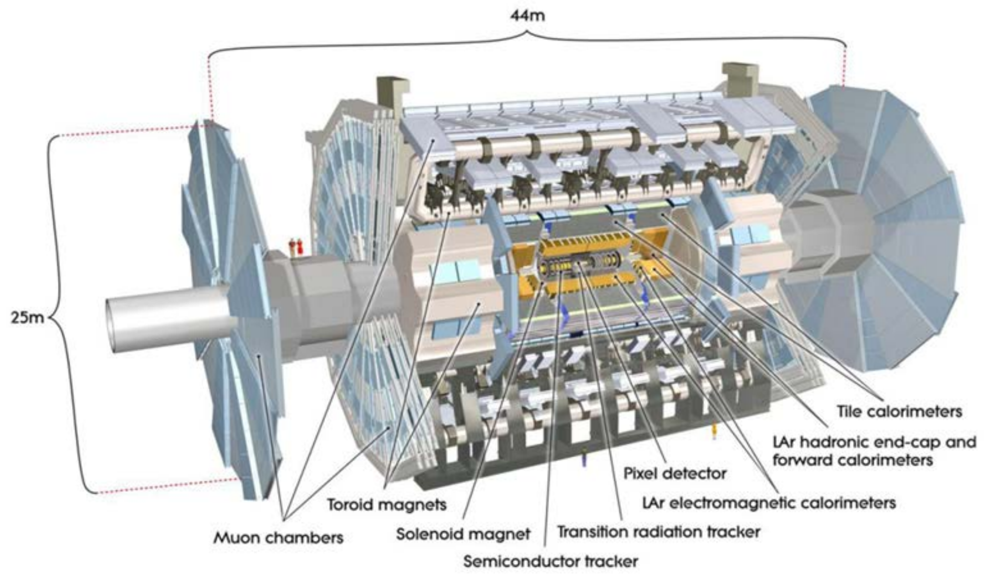
Dr. Simone M. Mazza (SCIPP, UC Santa Cruz),
on behalf of the SCIPP UCSC group

ATLAS and LHC high luminosity

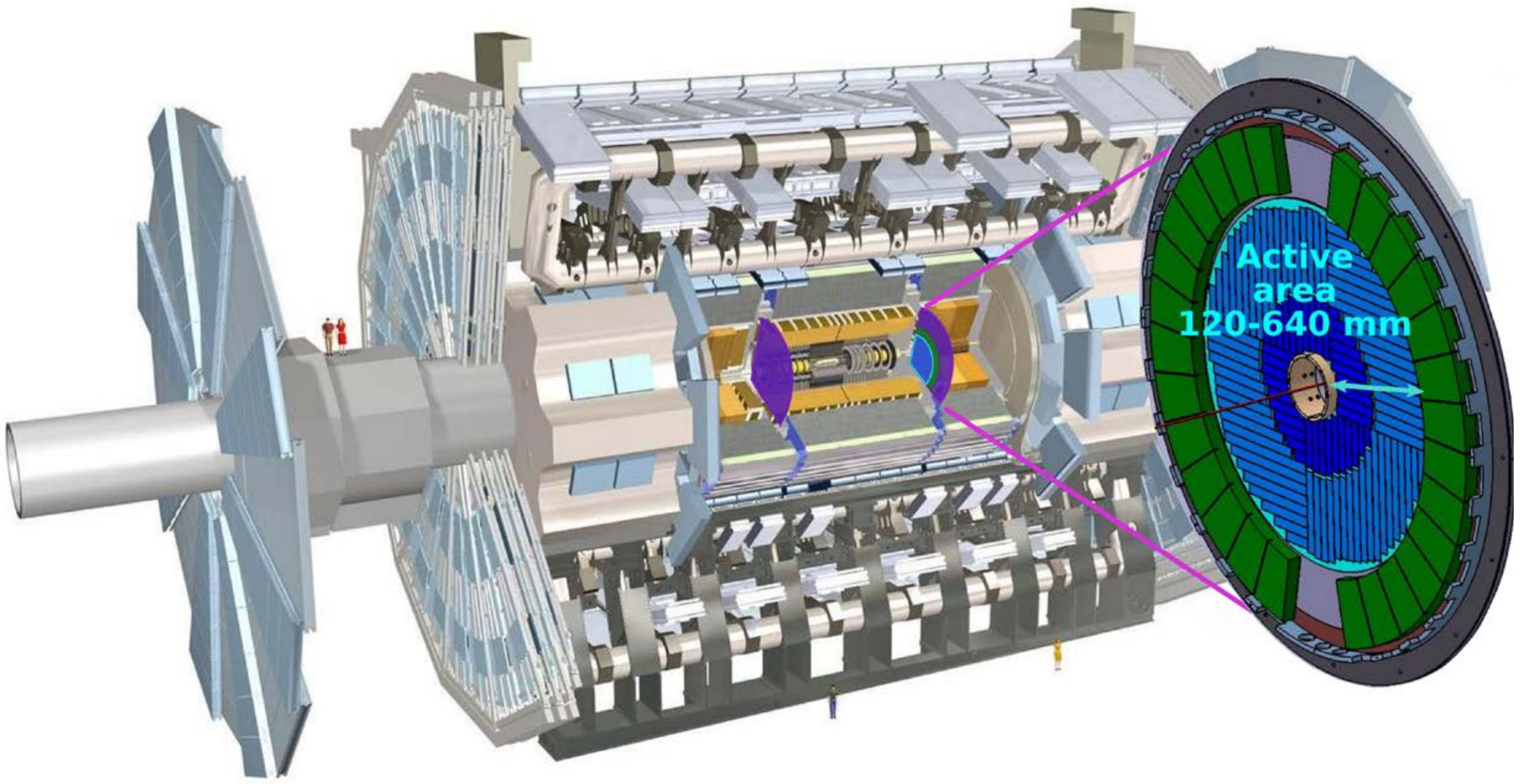
- **LHC:** 14 TeV proton-proton collider at CERN, Geneva
- **ATLAS:** one of the four main experiments at the LHC
  - General purpose detector for discovery of new physics and precise measurements
  - Layered detector: tracker, electromagnetic calorimeter, hadronic calorimeter, Muon spectrometer
- LHC will be upgraded in 2024-2026 to High Luminosity LHC
  - HL-LHC
  - Instantaneous luminosity higher than present conditions

- To maintain performance ATLAS will be upgraded (phase-II) for HL-LHC
  - The inner detector will be replaced (ITk project)
  - New readout electronics for EM and Hadronic calorimeters
  - Upgraded muon detector
  - TDAQ system will be completely re-worked
  - New end-cap timing pixel detector: **HGTD**





HGTD position in ATLAS



High Granularity Timing Detector (HGTD) will replace current MinBias detector

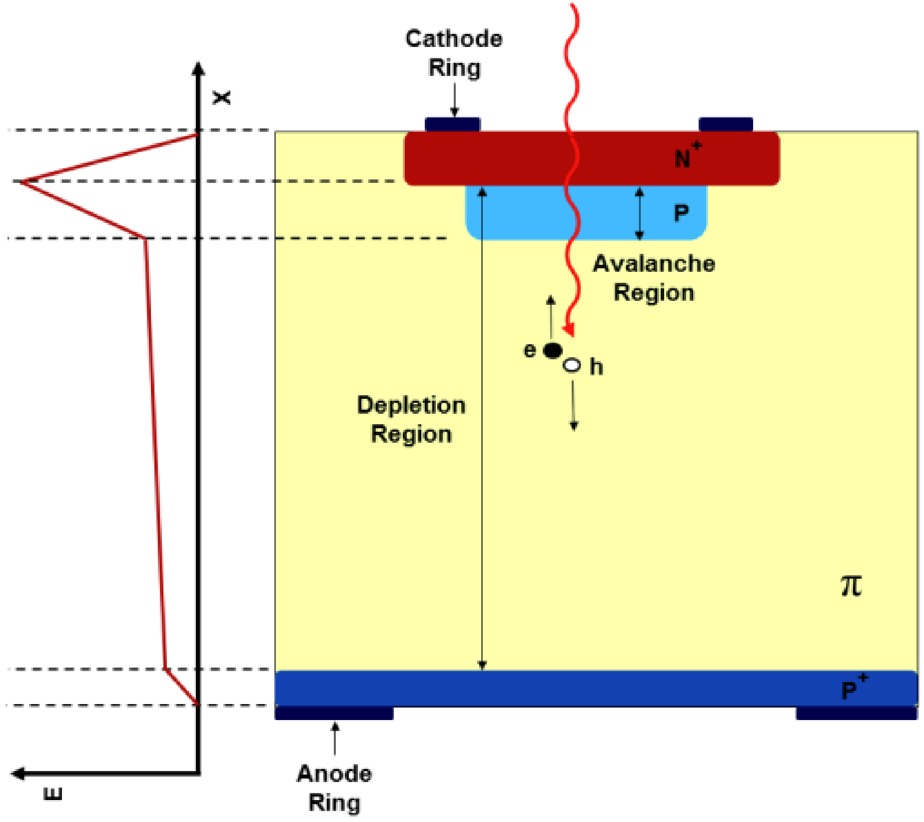
Requirements

- Time resolution < 30-50ps per track
- Occupancy < 10%
- **Radiation hardness** up to **5.4E15** N_{eq}/cm^2

Pseudo-rapidity coverage	$2.4 < \|\eta\| < 4.0$
Thickness in z	75 mm (+50 mm moderator)
Position of active layers in z	$z = \pm 3.5$ mm
Radial extension:	
Total	110 mm $< r <$ 1000 mm
Active area	120 mm $< r <$ 640 mm
Pad size	1.3 mm × 1.3 mm
Active sensor thickness	50 µm
Number of channels	3.59 M
Active area	6.4 m^2
Average number of hits per track	
$2.4 < \|\eta\| < 3.1$	≈2
$3.1 < \|\eta\| < 4.0$	≈3
Collected charge	> 2.5 fC
Average time resolution per hit (start and end of lifetime)	
$2.4 < \|\eta\| < 3.1$	≈ 40 ps (start) ≈ 70 ps (end)
$3.1 < \|\eta\| < 4.0$	≈ 40 ps (start) ≈ 85 ps (end)
Average time resolution per track (start and end of lifetime)	≈ 30 ps (start) ≈ 50 ps (end)

HGTD sensors - LGADs

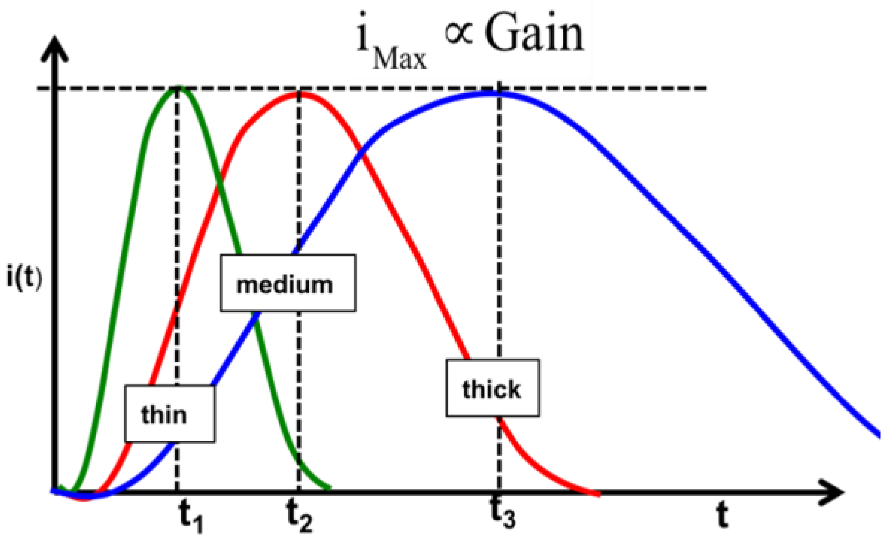
- LGAD: silicon detector with a thin (<5μm) and highly doped (~10^{16} P++) multiplication layer
  - High electric field in the multiplication layer
- LGADs have intrinsic modest internal gain (10-50)
  - $G = \frac{Q_{LGAD}}{Q_{PiN}}$ (collected charge of LGAD vs same size PiN)
  - Better signal to noise ratio, sharp rise edge
- 50 μm, 35 μm thin detectors
  - Thinner detectors have shorter rise time and less Landau fluctuations



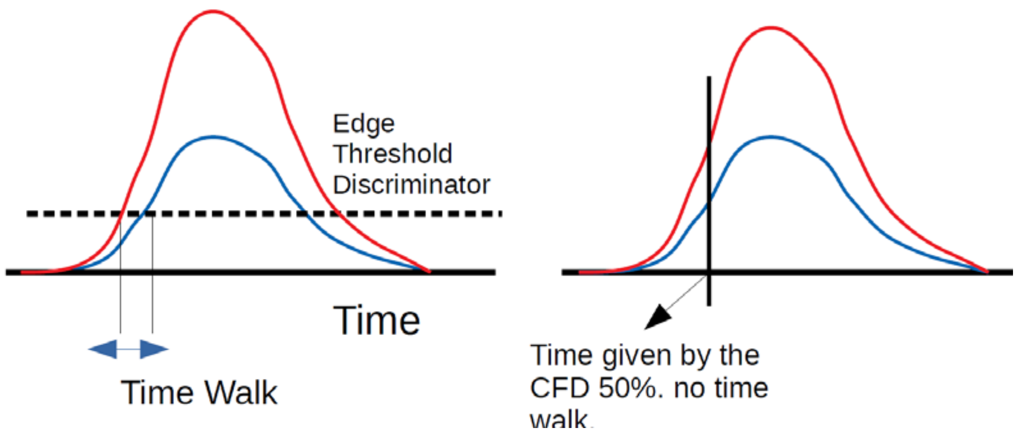
- **Time resolution < 30 ps**

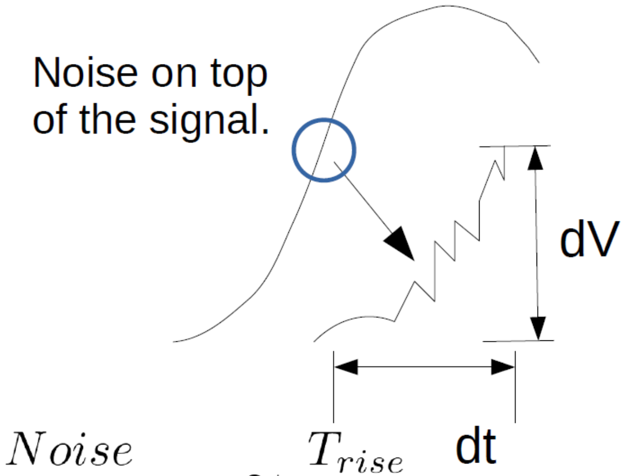
$$\sigma^2_{timing} = \sigma^2_{time\,walk} + \sigma^2_{Landau\,noise} + \sigma^2_{Jitter} + \sigma^2_{TDC}$$

- Several vendors of thin LGADs for HGTD
  - HPK (Japan), FBK (Italy), CNM (Spain), BNL (USA), IHEP (China)



LGADs timing resolution





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

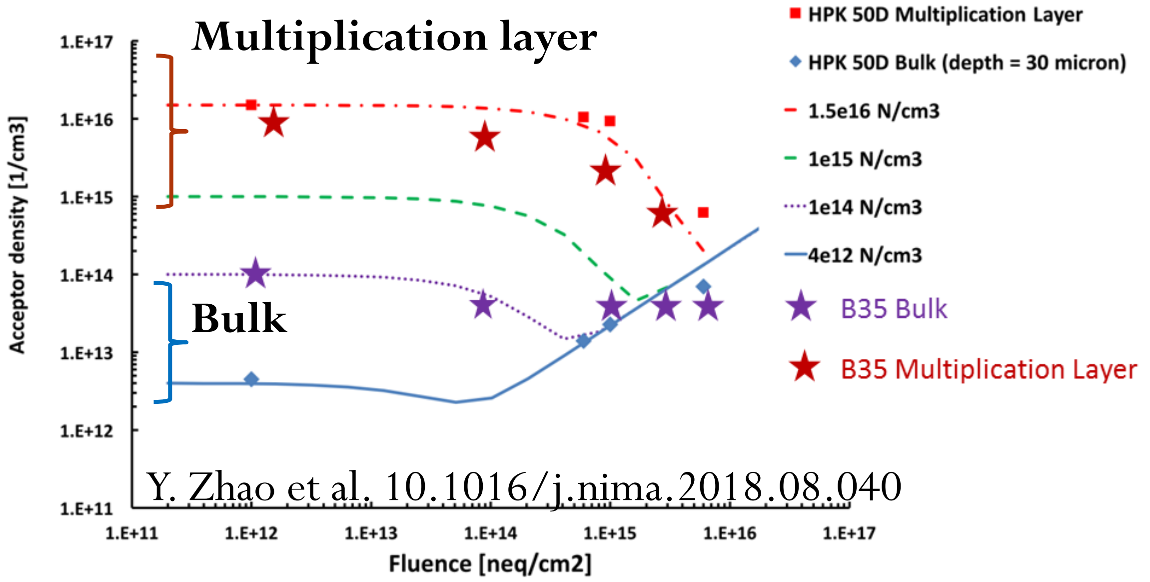
Sensor time resolution main terms

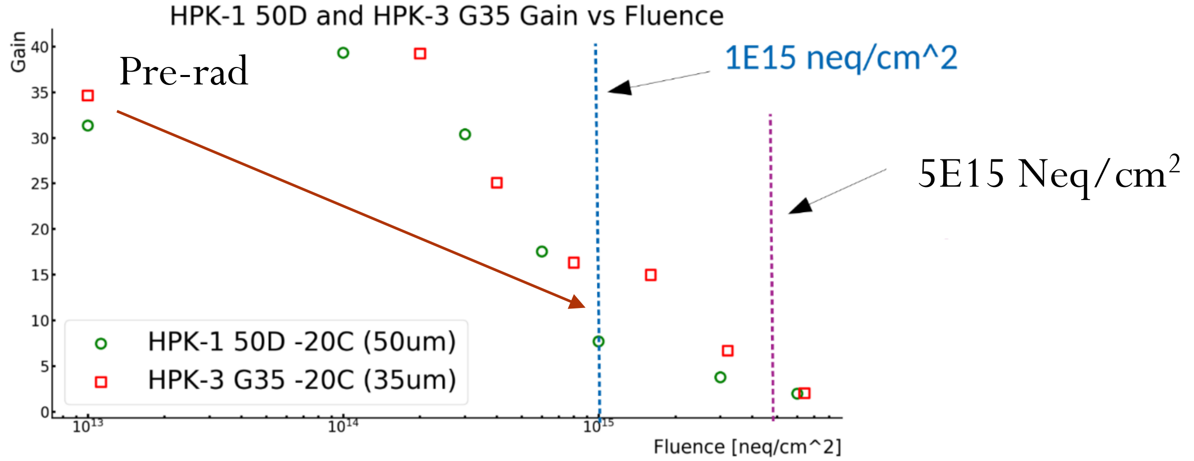
$$\sigma^2_{timing} = \sigma^2_{time\,walk} + \sigma^2_{Landau\,noise} + \sigma^2_{Jitter} + \sigma^2_{TDC}$$

- Time walk:
  - Minimized by using for time reference the % CFD (constant fraction discriminator) instead of time over threshold
  - In HGTD electronics TOA (Time of Arrival) of the signal is corrected with TOT (Time over threshold)
- Landau term:
  - Reduced for **thinner sensors** (50,35 µm)
- Jitter:
  - Proportional to $^1/_{\frac{dV}{dt}}$
  - Reduced by increasing S/N ratio with gain

Radiation damage on LGADs

- Most widely accepted radiation damage explanation for LGADs is **acceptor removal**
  - M. Ferrero et al. arXiv:1802.01745, G. Kramberger et al. JINST **10** (2015) P07006
- Radiation damage for LGADs can be parameterized
  - $N_A(\phi) = g_{eff}\phi + N_A(\phi{=}0)e^{-c\phi}$
- Acceptor creation: $g_{eff}\phi$
  - By creation of deep traps
- Initial acceptor removal mechanism: $N_A(\phi{=}0)e^{-c\phi}$
  - Ionizing radiation produces interstitial Si atoms
  - Interstitials inactivate the doping elements (Boron) via kick-out reactions that produce ion-acceptor complexes
  - **Reduction of gain**





Y. Zhao presentation at ULITIMA conference

https://indico.fnal.gov/event/ANLHEP1390/session/8/contribution/68/material/slides/0.pdf

Irradiation campaigns on LGADs

- Irradiation campaign on LGADs
- Sensors were irradiated at
  - JSI (Lubiana) with ~1 MeV neutrons
  - PS-IRRAD (CERN) with 23 GeV protons
  - Los Alamos (US) with 800 MeV protons
  - CYRIC (KEK, Japan) with 70 MeV protons
  - X-rays at IHEP (China)
- Neutron irradiation for fluence
  - From 1E13 Neq/cm^2 → 1E16 Neq/cm^2
- Proton (and X-ray) irradiation for fluence and ionizing dose
  - Up to 4MGy

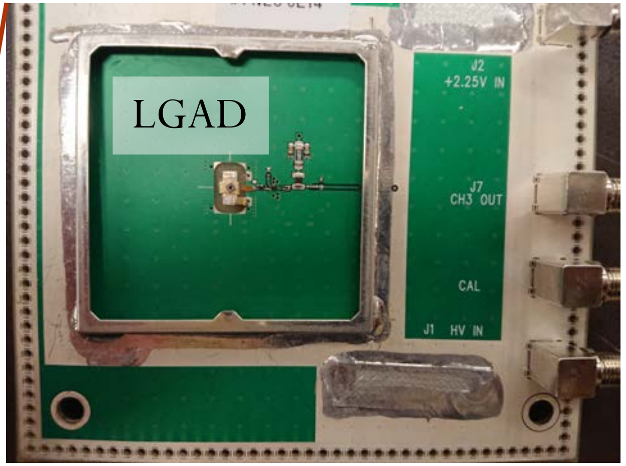
Jožef Stefan Institute

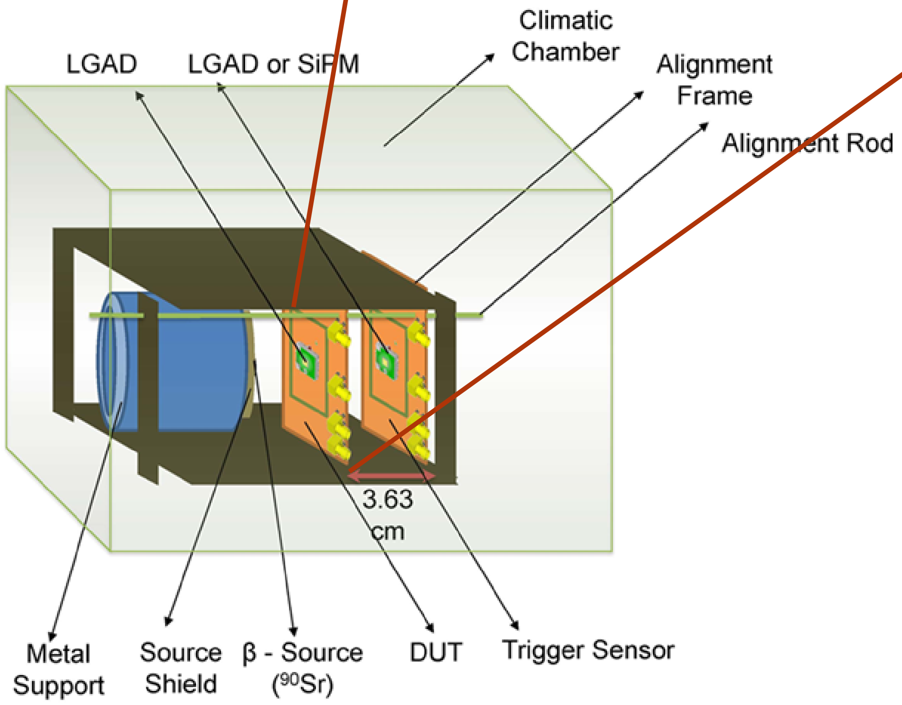
CERN | IRRAD Proton Facility

Los Alamos NATIONAL LABORATORY

KEK

Sensor testing – Sr90 telescope

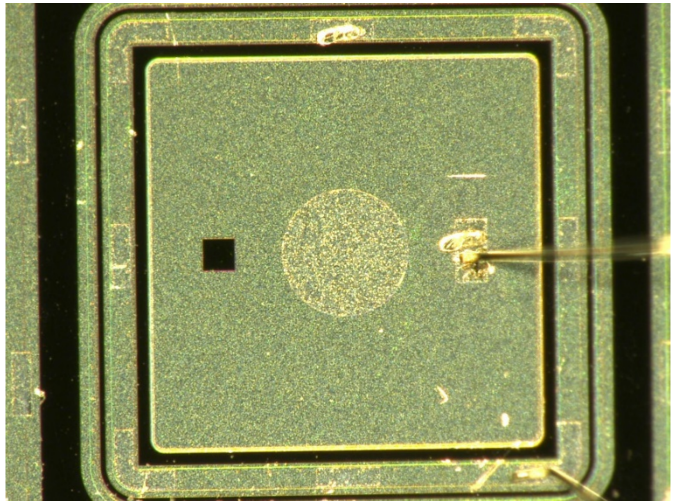


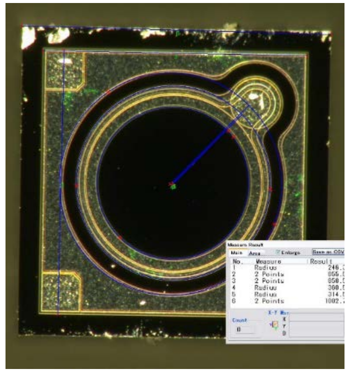


- Dynamic laboratory testing
  - Using MiP electrons Sr90 β-source
  - Signal shape, noise, collected charge, gain, **time resolution**
- β-telescope
  - Sensors mounted on analog readout board designed at UCSC (Ned Spencer, Max Wilder, Zach Galloway) with fast amplifier (22 ohm input impedance, bandwidth > 1GHz)
  - Trigger sensor (fast timing trigger) on the back
    - DUT (Device Under Test) is read in coincidence
  - Setup in climate chamber to run cold and dry
    - 20C/-20C/-30C
  - (no position information)

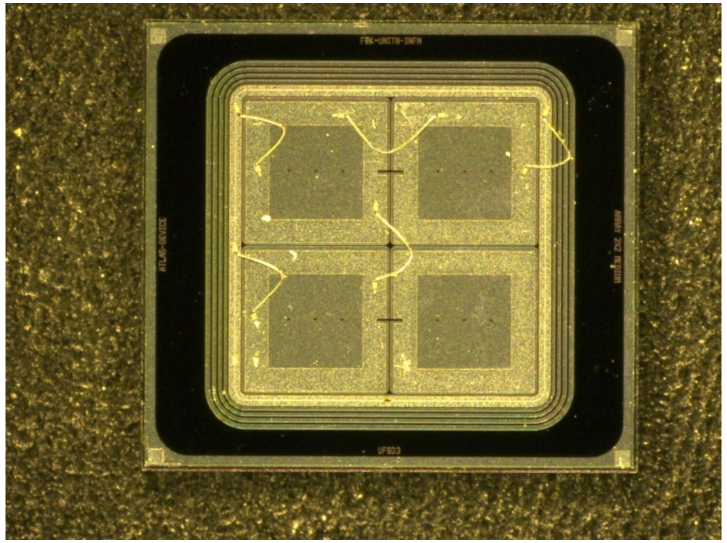
HGTD sensors under study

- 4 sensors in consideration for HGTD at the moment
  - Hamamatsu (HPK) and Fondazione Bruno Kessler (FBK)
- HPK Type 3.1
  - 50 um detector, thin gain layer
- HPK Type 3.2
  - 50um, deep and thin gain layer





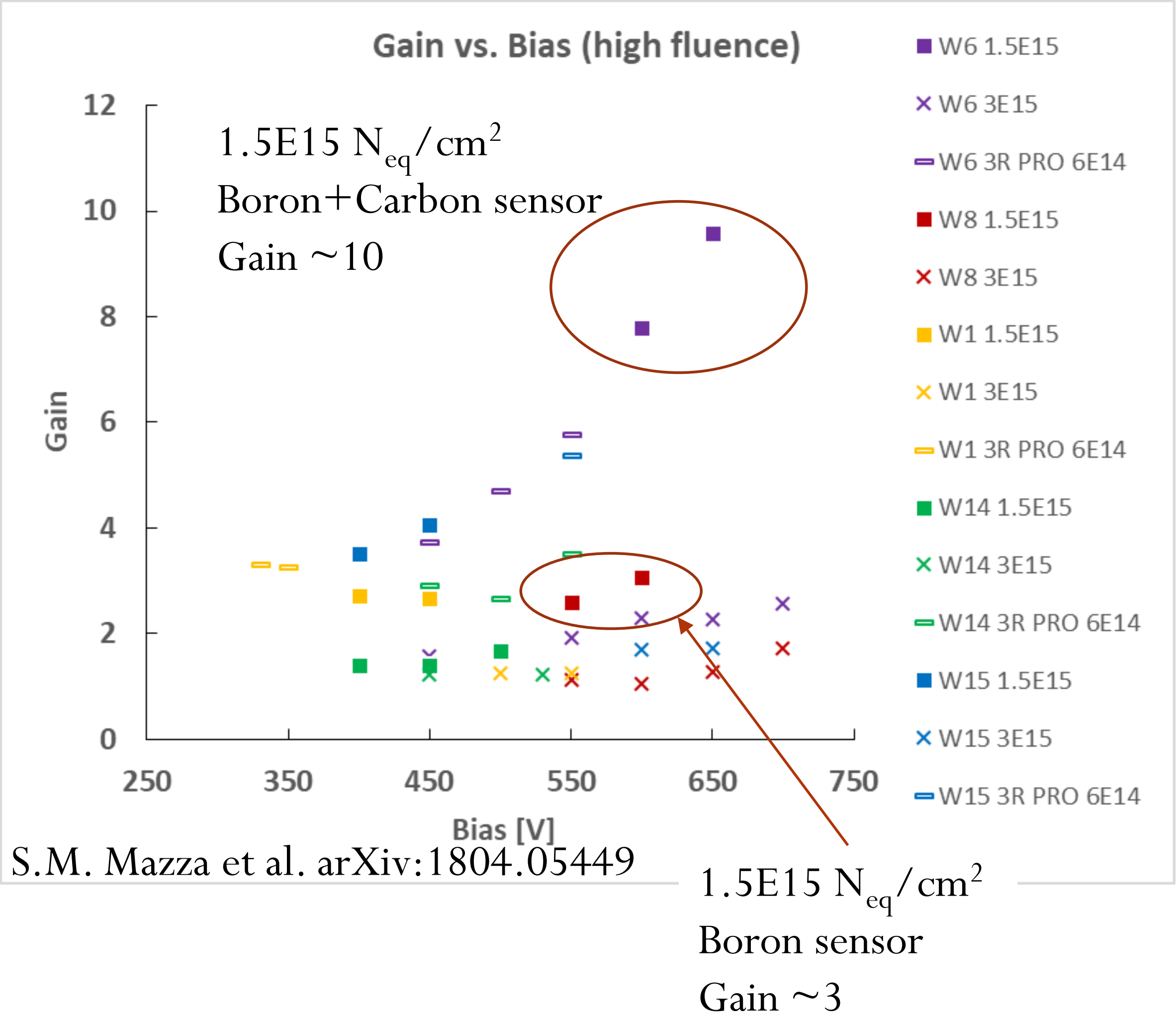
- HPK G30 (prototype)
  - 35um
  - Will be updated soon with new production
- FBK UFSD3
  - 50um, Carbon implantation



Mitigation of radiation damage on LGADs

- Studies ongoing to mitigate the effect of radiation damage on multiplication layer
- Gallium as dopant instead of Boron (proven not effective and more expensive)

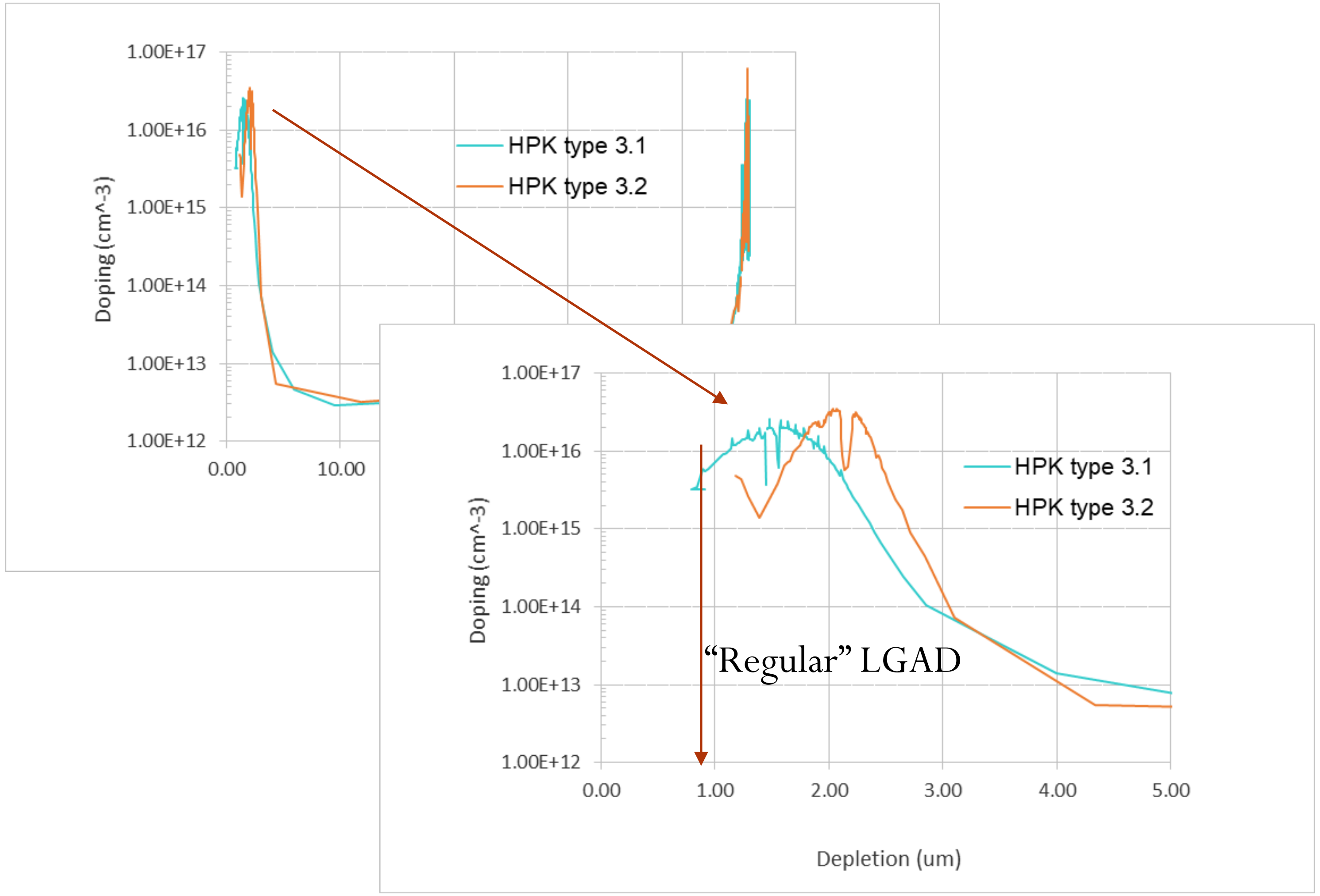
- Carbon infusion **(FBK)**
  - Carbon is electrically inactive (no effect pre-irradiation)
  - Slight reduction of gain pre-rad because of implantation procedure
  - Reduces acceptor removal after irradiation



S.M. Mazza et al. arXiv:1804.05449

M. Ferrero et al. arXiv:1802.01745
Y. Zhao et al. 10.1016/j.nima.2018.08.040

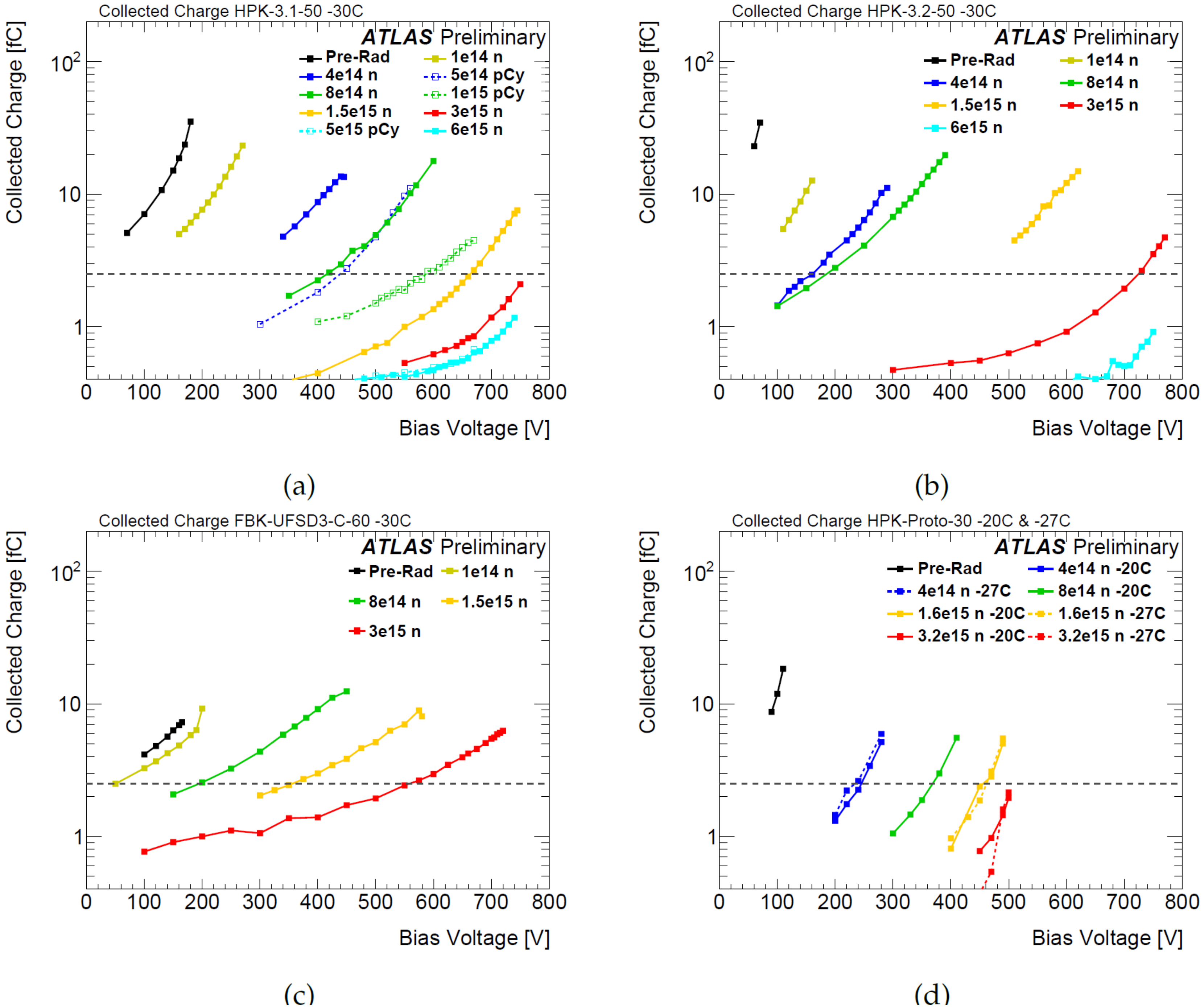
Deep multiplication layer



- Thin but highly doped multiplication layer **(HPK 3.1, HPK 3.2**)
  - Higher initial doping concentration would take more time to be inactivated
- Deep multiplication layer **(HPK 3.2)**
  - High field for larger volume
  - Very high gain pre-rad, operational issues
- Multiplication layer between 1um to 2um in instead of 0.5-1 um

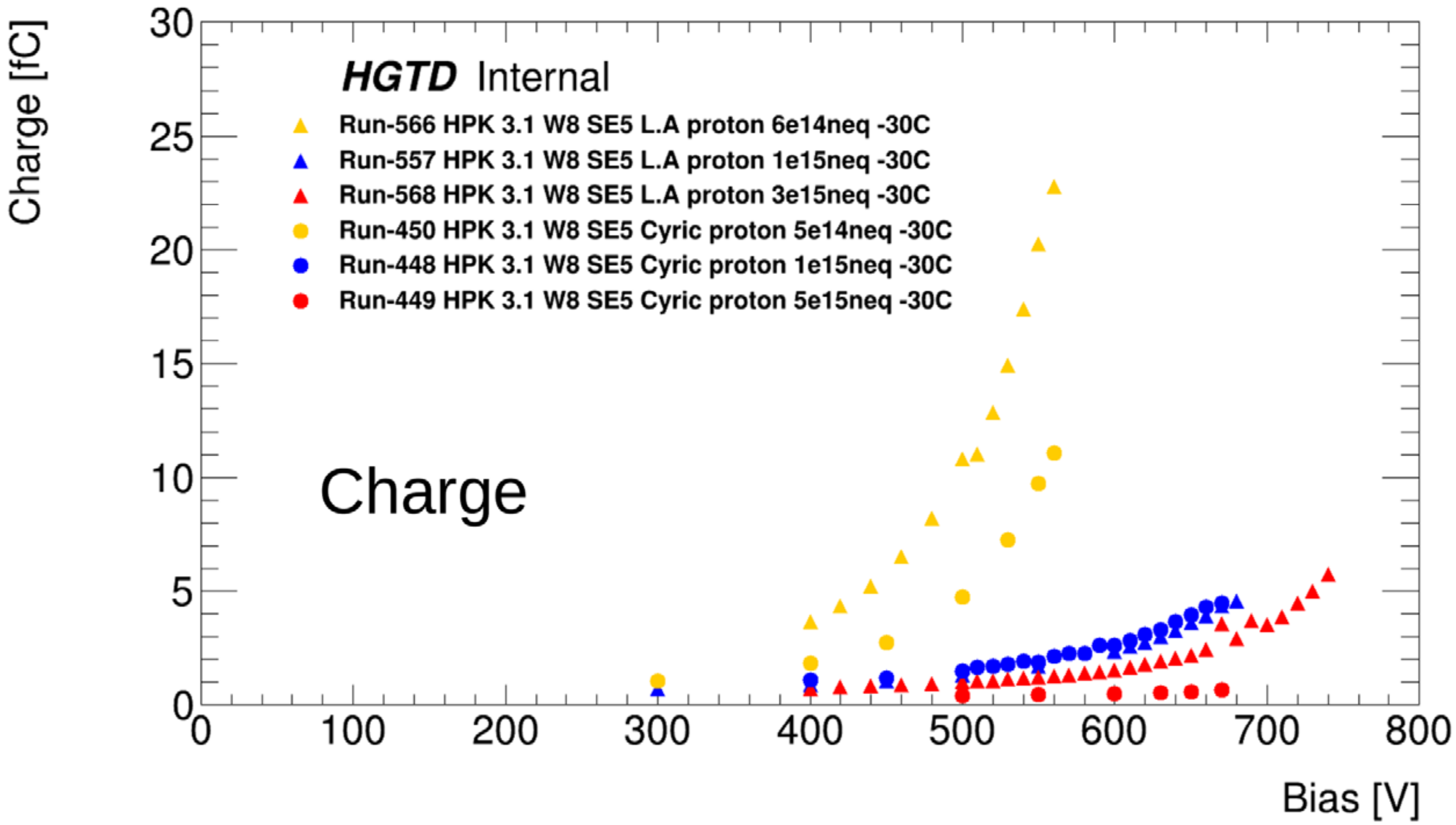
Collected charge

- HPK 3.1 behaves good until 1.5E15 Neq
- HPK 3.2 is generally better after irradiation than 3.1 up to 3E15 Neq
- FBK shows the higher collected charge for 3E15 Neq
- HPK 30um shows the lowest collected charge (because of thickness)
  - However operates at lower voltages (less power dissipation)



https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LArHGTDPublicPlots#2018_2019_Sensor_Performance_TDR

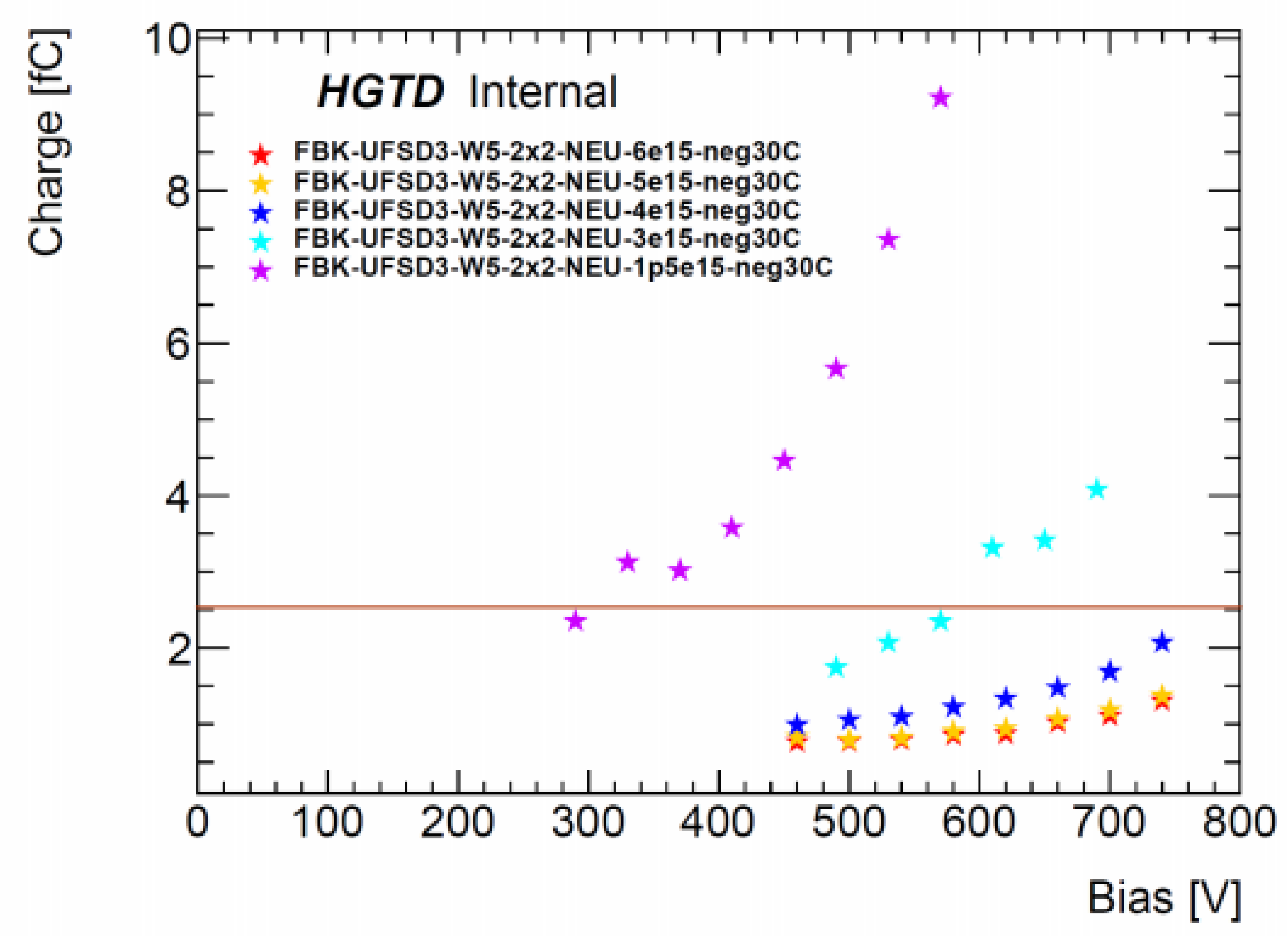
Other facilities with proton irradiation



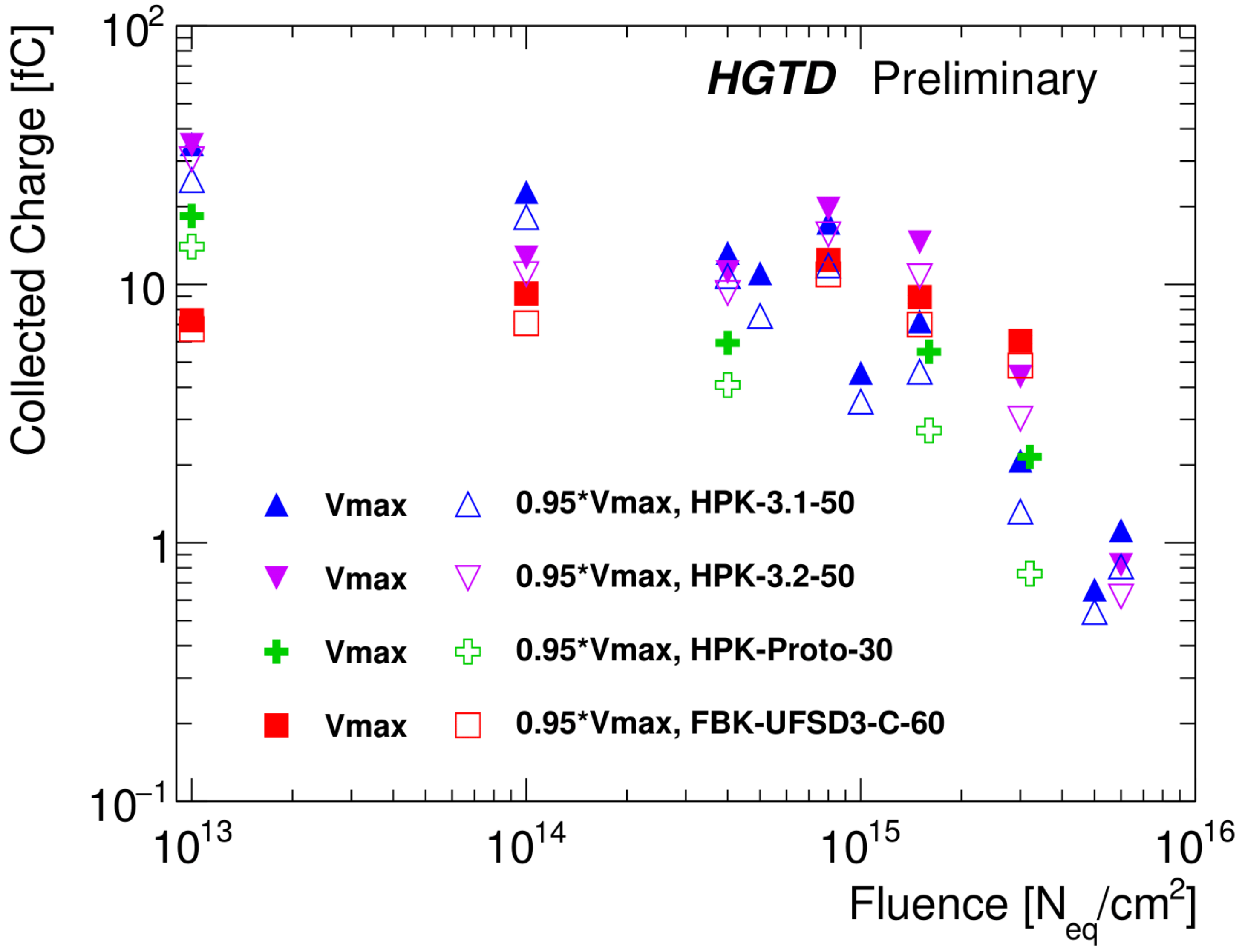
- HPK 3.1 tested also at proton irradiation facilities
  - Los Alamos (US) with 800 MeV protons
  - CYRIC (KEK, Japan) with 70 MeV protons
- The two proton irradiation match in term of NIEL factor at 1e15 Neq
- Unfortunately we received HPK 3.1 sensors after CERN IRRAD facility shutdown
- Results are in agreement with neutron data in terms of equivalent fluence

Collected charge for FBK carbon

- High fluence data updated since TDR public plots
- Carbon seems to be effective up to 3E15 Neq
- Then performance drops quickly for 4E15 Neq
  - At 5E15 and 6E15 Neq behaves like a PiN



Collected charge over fluence



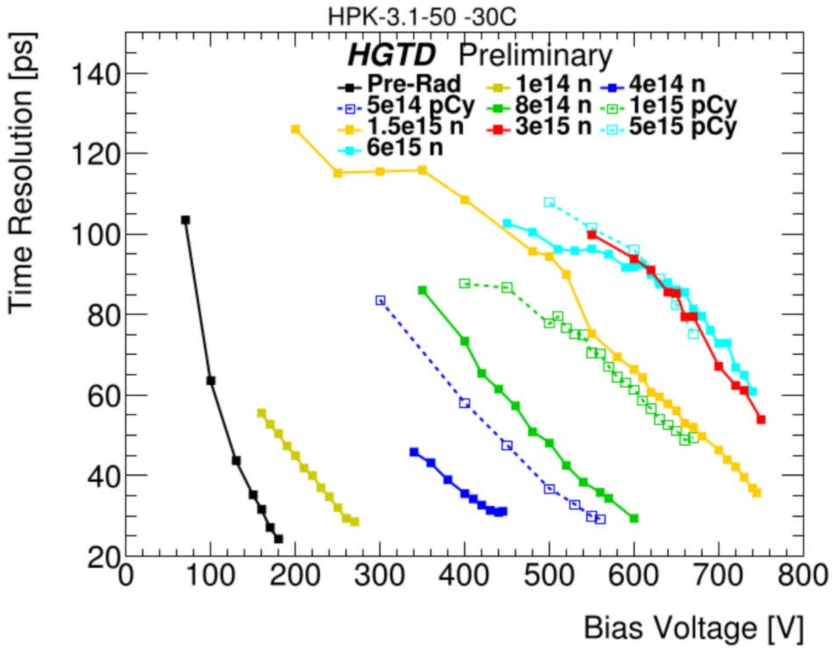
- Shown for Vmax and 0.95*Vmax
  - Indication of properties change with bias Voltage
- 30um detector has a very "steep" behavior
  - Collected charge changes abruptly with bias Voltage at high fluences

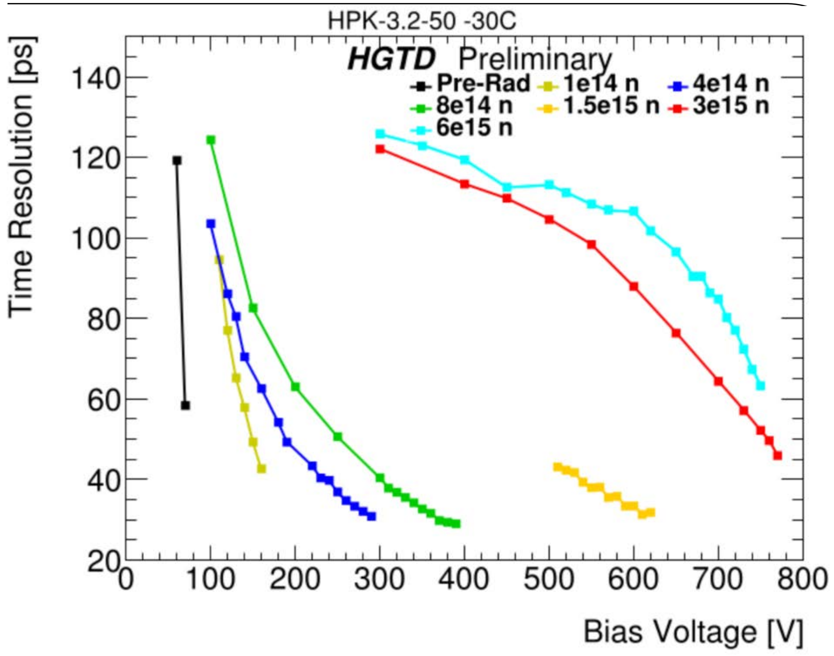
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LArHGTDPublicPlots#2018_2019_Sensor_Performance_TDR

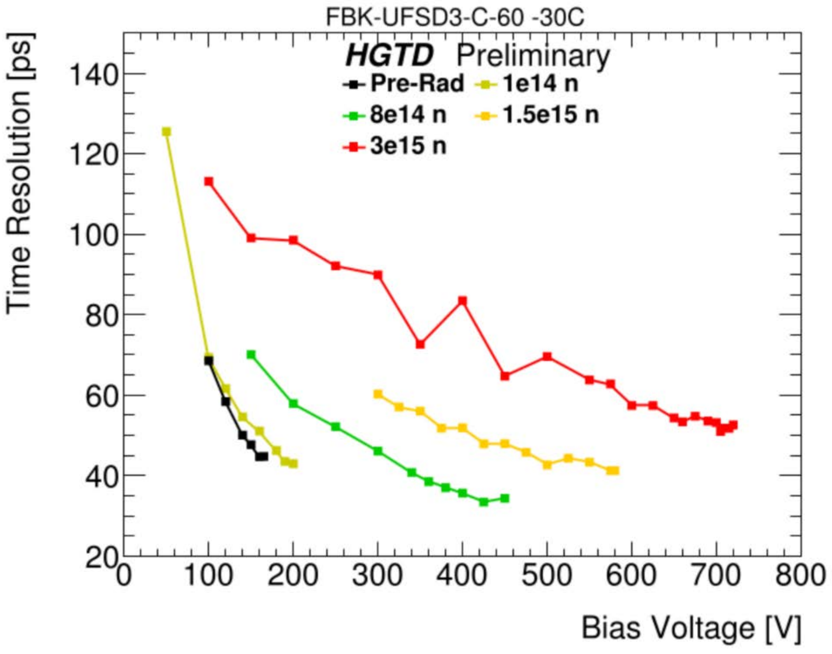
Time resolution

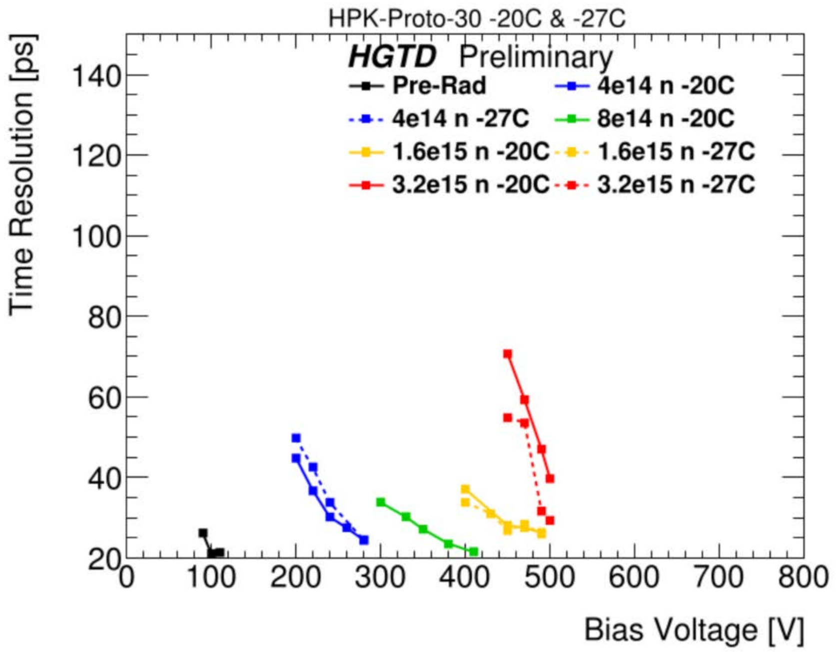
- HPK 3.1 has <40ps of time resolution up to 1.5E15 Neq
  - Then 55ps for 3E15 Neq
- HPK 3.2 has 45ps of time resolution at 3E15 Neq
  - However bad pre-rad performance (60ps)

- FBK has worse time resolution pre-rad but post-rad performance in line with HPK
- HPK 30um has the best time resolution
  - <20ps pre-rad and 40ps at 3E15Neq









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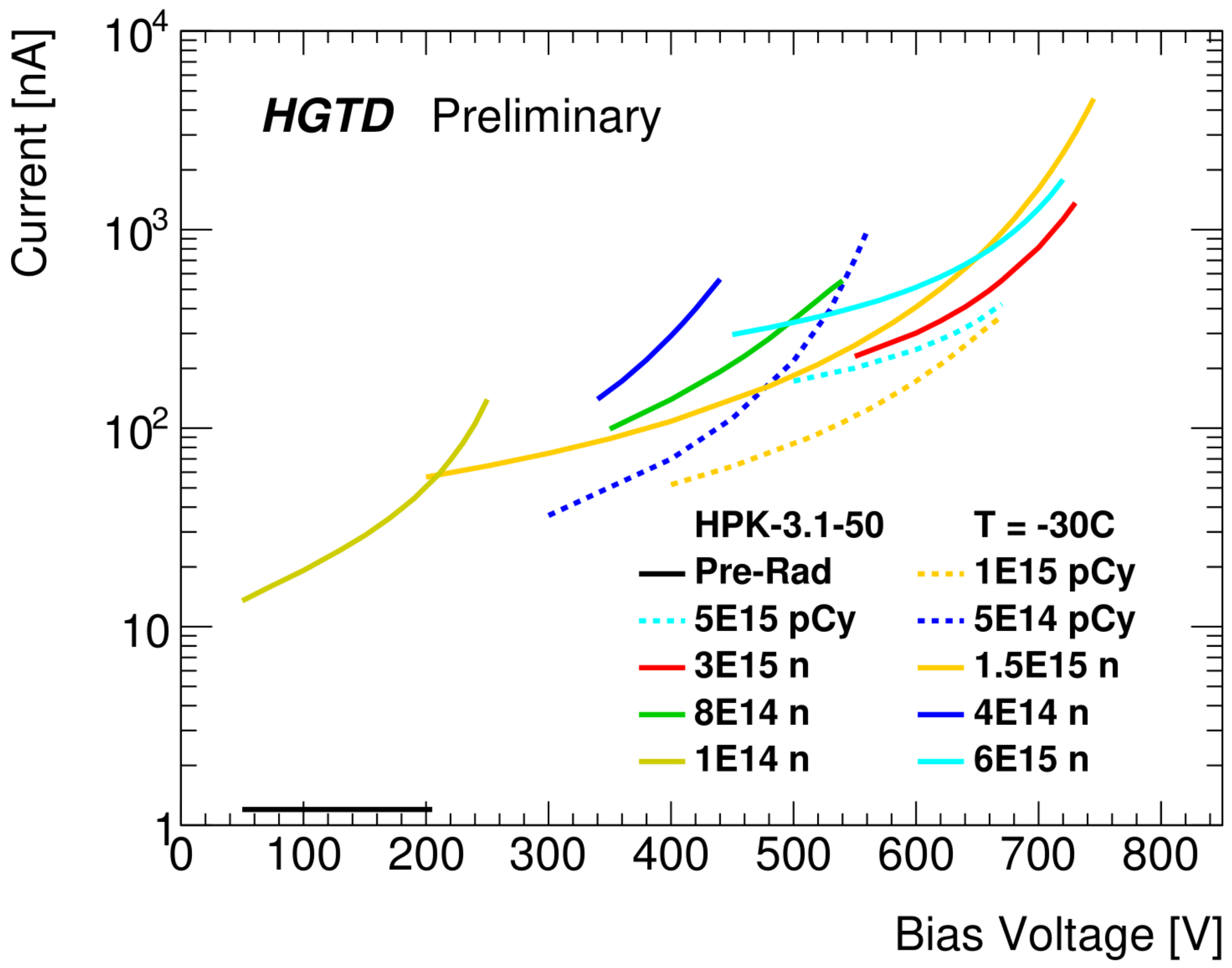
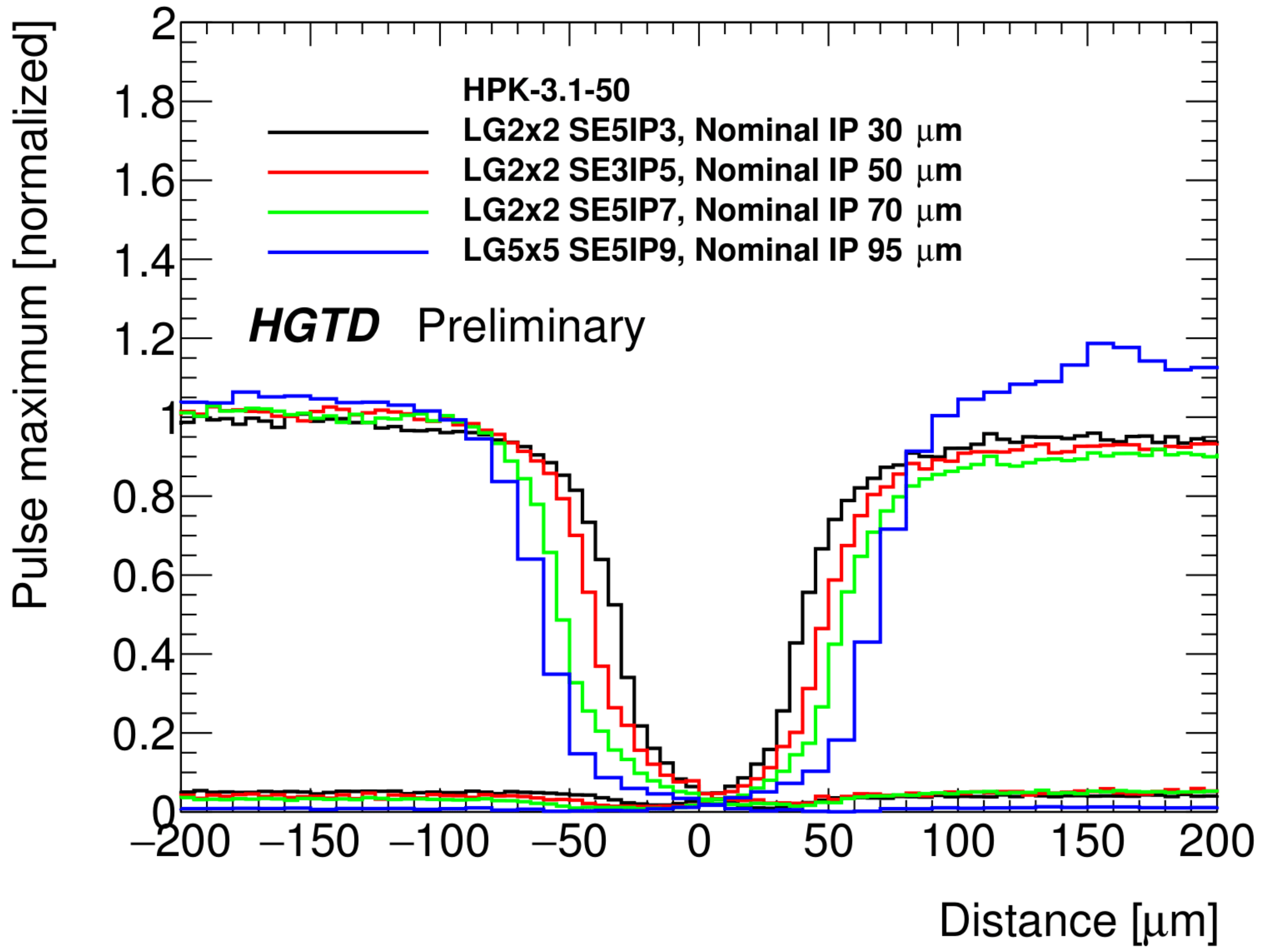
Leakage current increase with fluence



- Current for each pad of an array
  - For HPK-3.1, other sensors have similar current
- Pre-rad current is ~1 nA
- A few uA for the highest fluence
- 5uA maximum manageable per-pad by HGTD electronic readout (ALTIROC)

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LArHGTDPublicPlots#2018_2019_Sensor_Performance_TDR

Sensor testing – Laser TCT

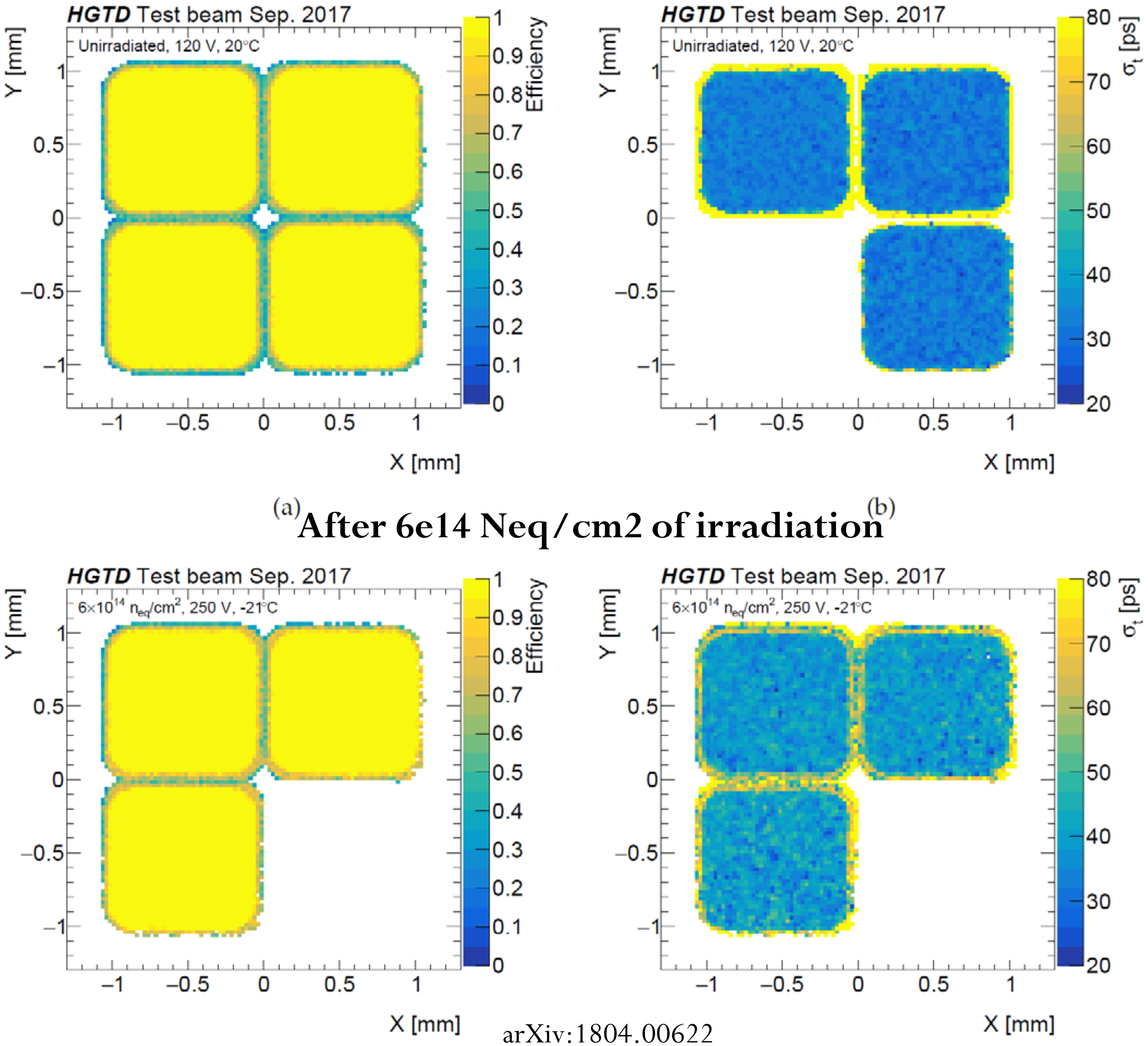


- Measurement of several sensors with different inter-pad gap
  - Using IR laser
- 50%-50% between pads is 70-130um
  - ~40um higher than the value quoted by the vendor
  - Also depending on bias Voltage applied to the sensor
- This was observed to vary with voltage

S.M. Mazza et al. arXiv:1804.05449

Test beam

Non irradiated sensors

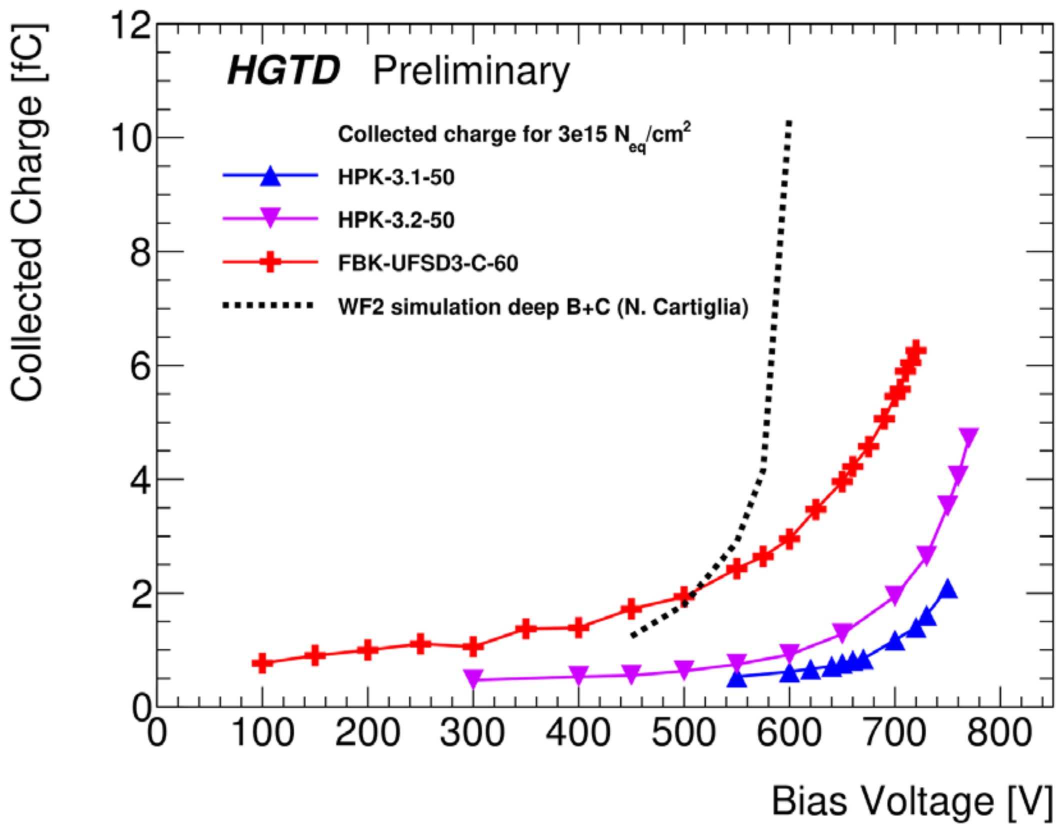


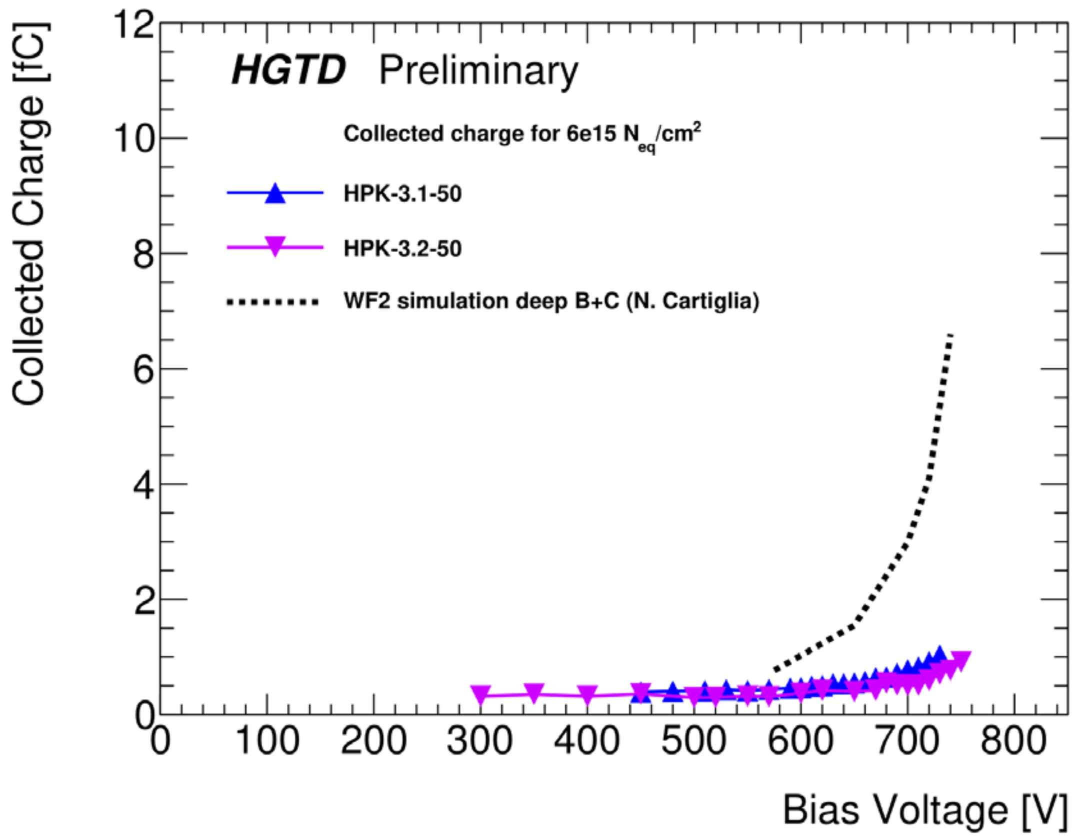
- Hit efficiency studied with Pions test beam at CERN
- Results for 2x2 CNM arrays
  - Un-irradiated detectors (top)
  - Efficiency ~100% in the center, ~50% in the edges and interpad region
  - Time resolution ~30ps in the center, up to 80ps in the edges
- After an irradiation of 6E14 N_{eq}/cm^2
  - Efficiency is still ~100% in the center but time resolution is higher (40-50ps)
- Test beam were also conducted at Fermilab, SLAC and DESY

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LArHGTDPublicPlots#2018_2019_Sensor_Performance_TDR

Future prospect – deep + Carbon

- Combine Carbon (FBK) with deep implantation (HPK 3.2)
- Preliminary simulation with Weightfield2 predict a collected charge of 5 fC at 6E15 Neq!
- FBK will do a production that will be ready by Dec. 2019





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Conclusions

- **Several options to increase the radiation hardness of LGADs**
  - Carbon, thin and deep gain layer
  - Reasonable performance up to 3E15Neq
  - Ionization dose (Protons) does not seem to have an additional effect
- **Next steps**
  - Analyze bulk irradiation (5x sensors per fluence) of HPK Type 3.1 and 3.2
  - Test irradiated HPK Type 1.1, 1.2, 2 (new 35um sensors)
  - Sensor resistance after irradiation
- **Sensors combining Carbon and deep implantation should be ready Dec. 2019**

- **HGTD is going forward**
  - TDR is being updated, it will be ready for April 2020
- New public results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LArHGTDPublicPlots

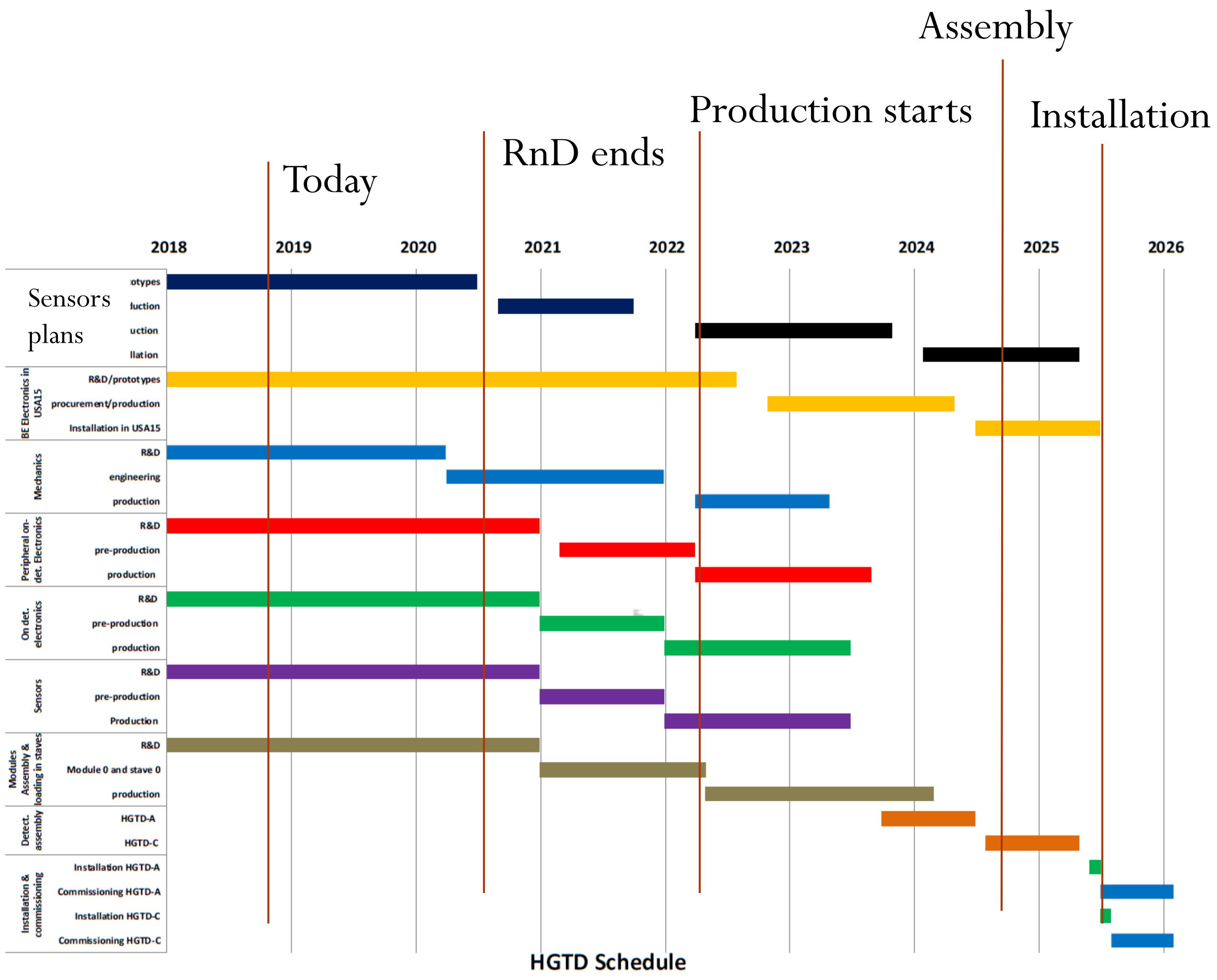

Figure 6.1: Gantt chart showing the schedule of the various activities in the HGTD project.

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This project was supported in part by a Launchpad Grant awarded by the Industry Alliances & Technology Commercialization office from the University of California, Santa Cruz.

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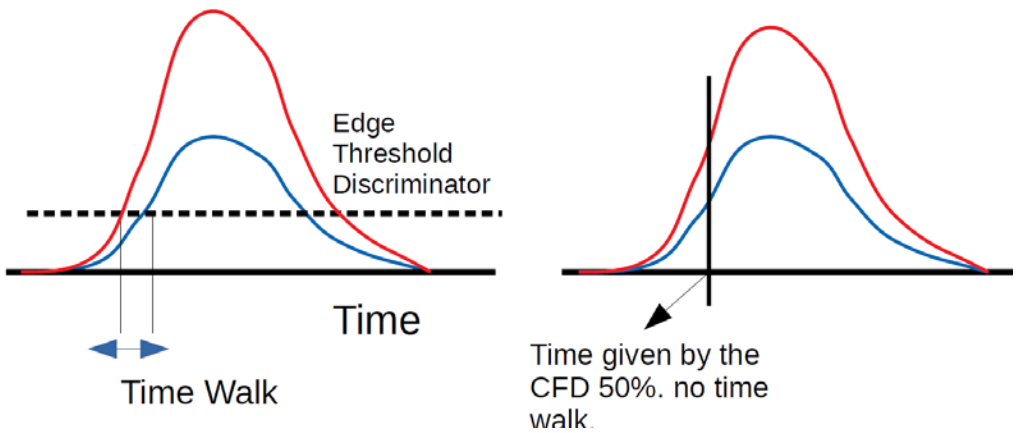
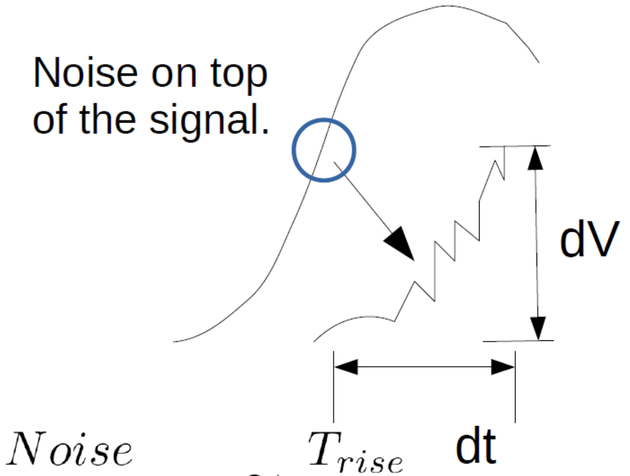
Backup

LGADs timing resolution





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- Landau term:
  - Reduced for **thinner sensors** (50,35 µm)
- Jitter:
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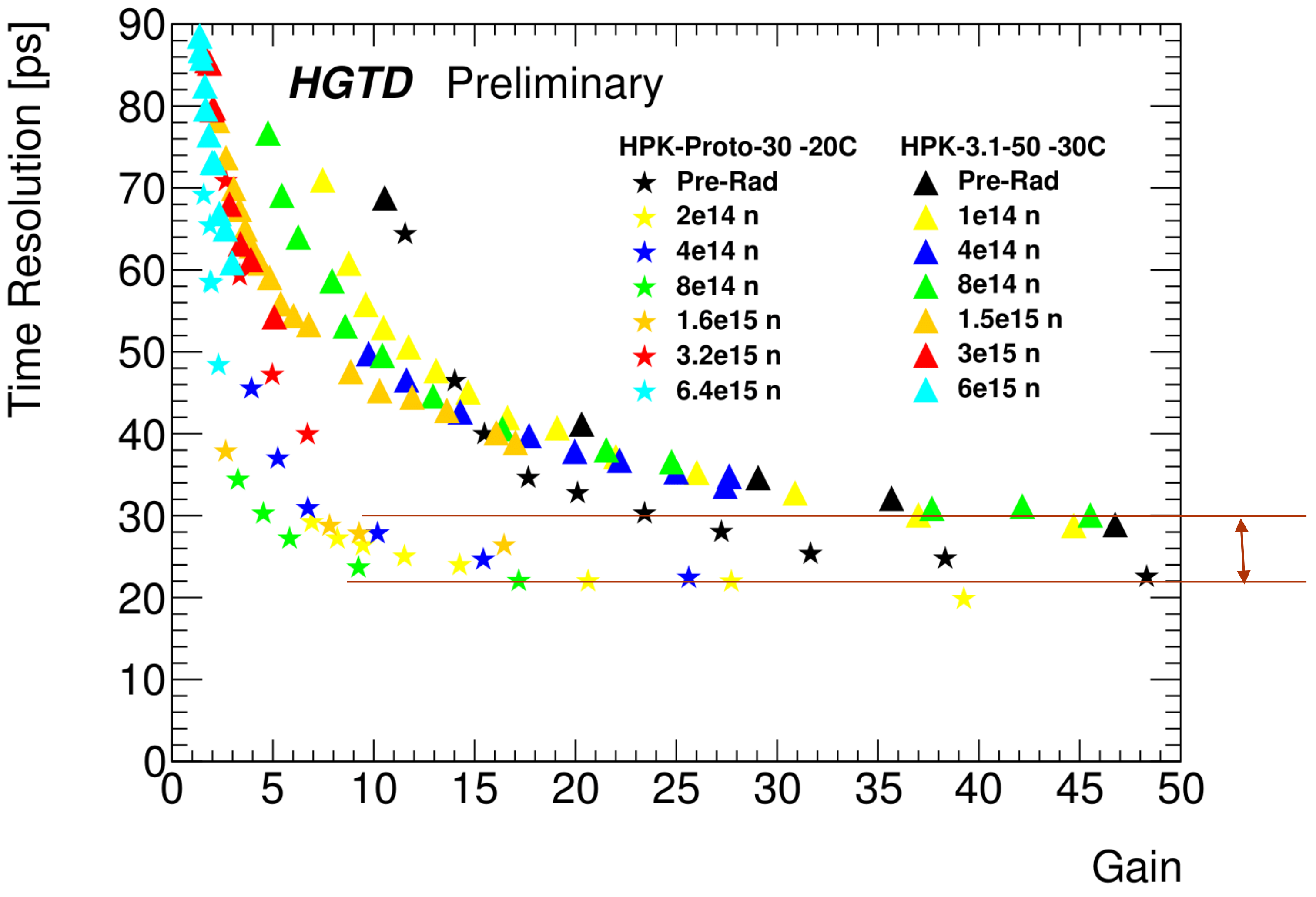
  - Reduced by increasing S/N ratio with gain

HGTD sensors 50 um vs 30 um

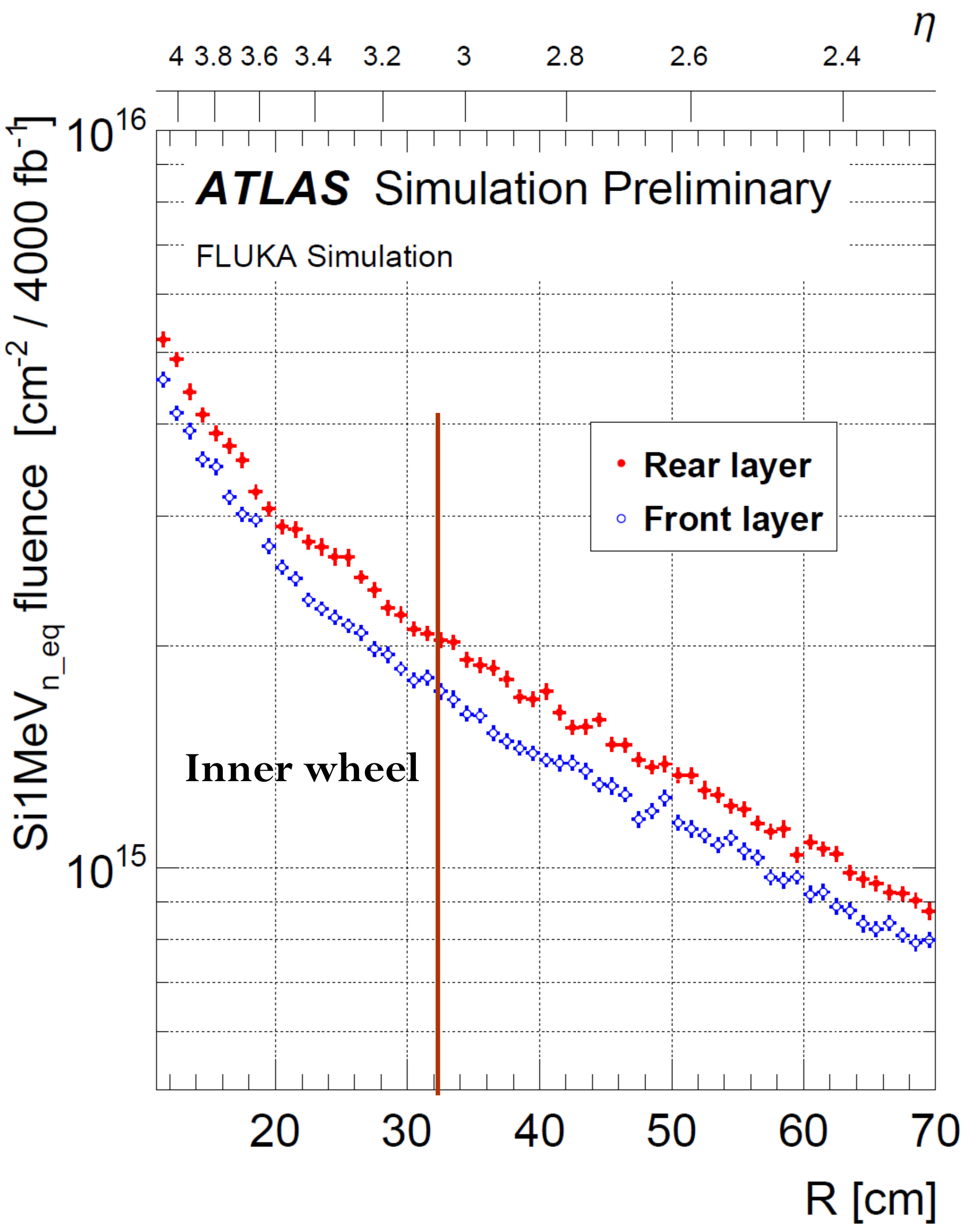


- High gain → very low jitter contribution to the time resolution
- Time resolution is driven by Landau component
  - Depends on sensor thickness

Radiation damage sustained

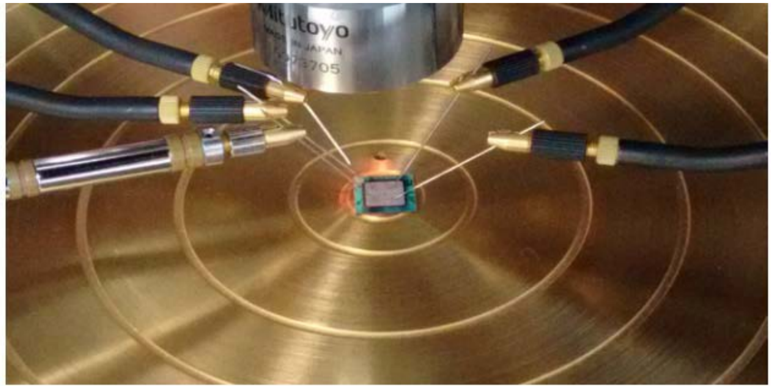
- Total fluence for HL-LHC is
  - 7.35E15 N_{eq}/cm^2 at 10 cm radius (central region).
  - 3.7E15 N_{eq}/cm^2 at 32 cm radius.
  - Values are taking into account a ~2 safety factor.

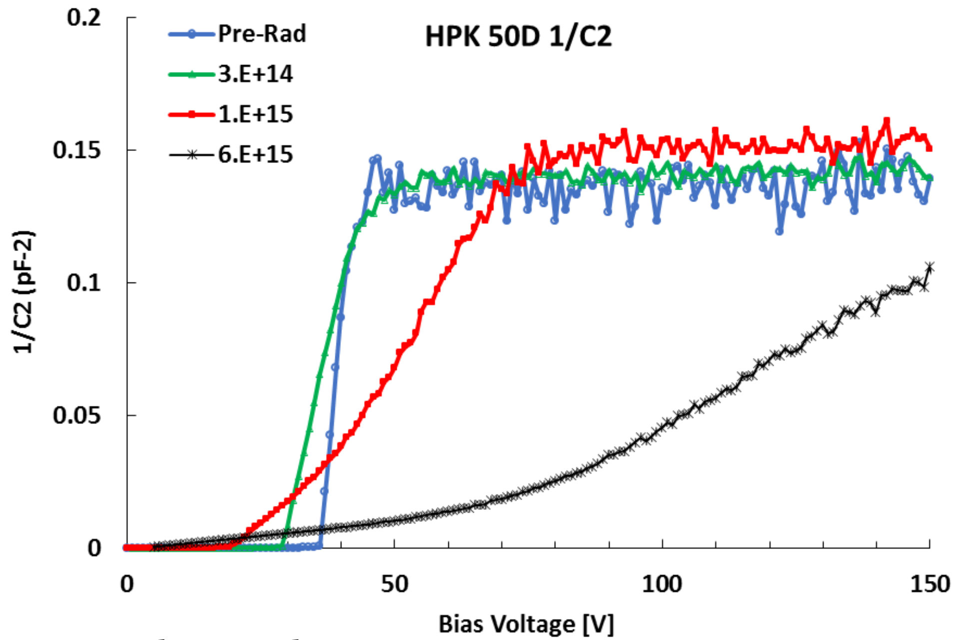
- The inner wheel of HGTD (extending up to 32 cm of radius) will be replaced at mid-run of HL-LHC because of radiation damage.
  - ~32% of sensors/ASICs will be changed



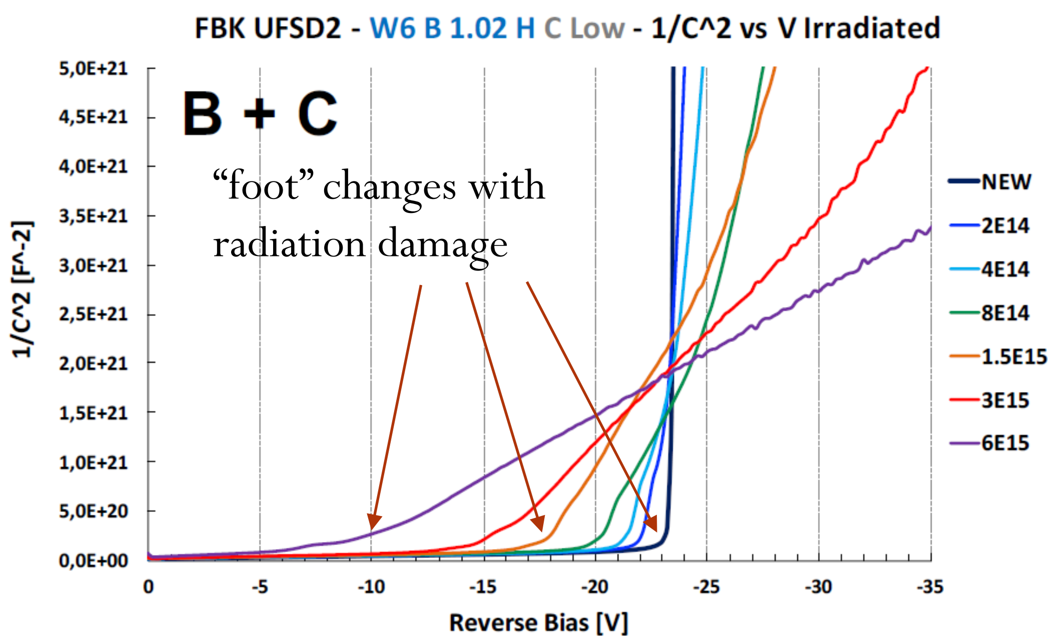
Sensor testing – IV/CV

- Current over voltage (IV)
  - Verify LGAD performance, breakdown voltage
- Capacitance over voltage (CV)
  - Study doping concentration profile and full depletion of the sensor
- Study of the “foot” for LGADs on $1/C^2$:
  - $1/C^2$ is flat until depletion of multiplication layer because of the high doping concentration
  - Proportional to gain layer active concentration
- Bulk doping concentration proportional to the slope in $1/C^2$





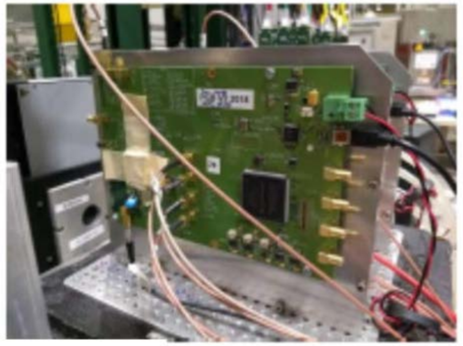
Y. Zhao et al. 10.1016/j.nima.2018.08.040

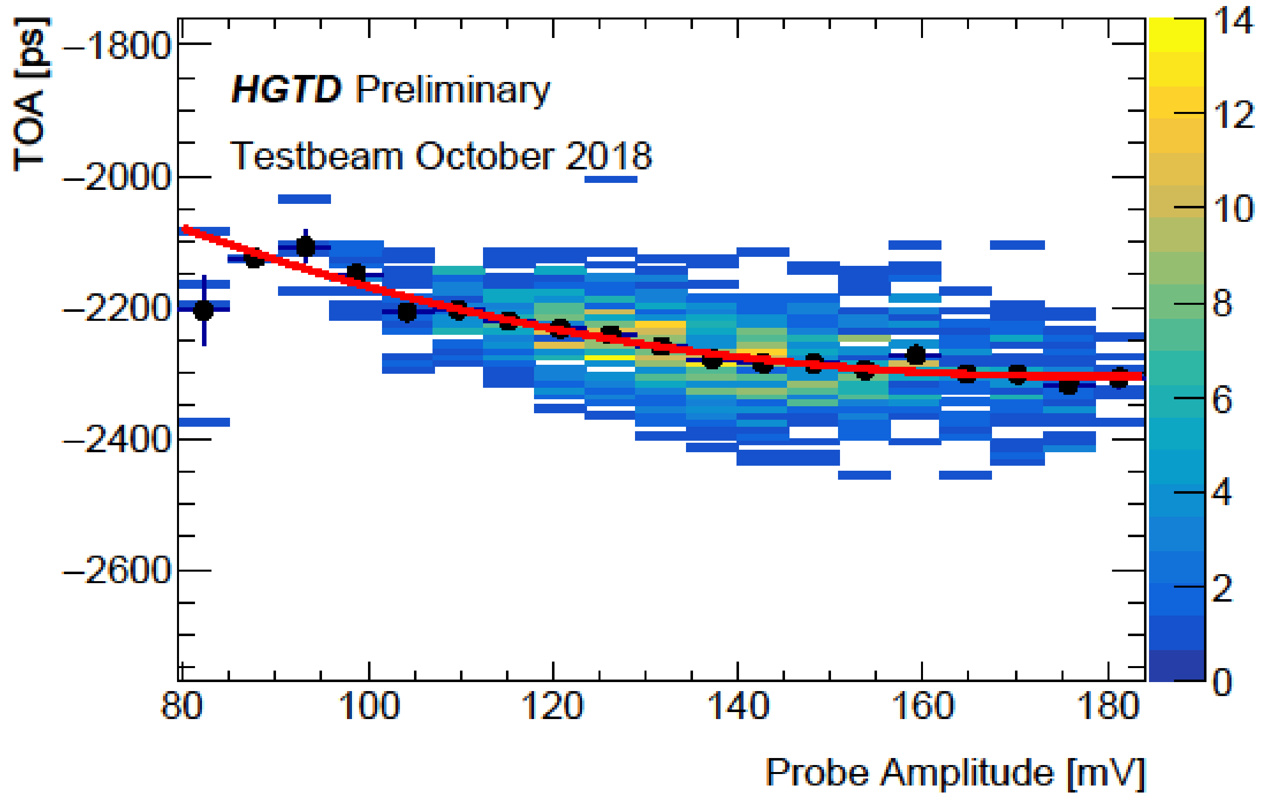


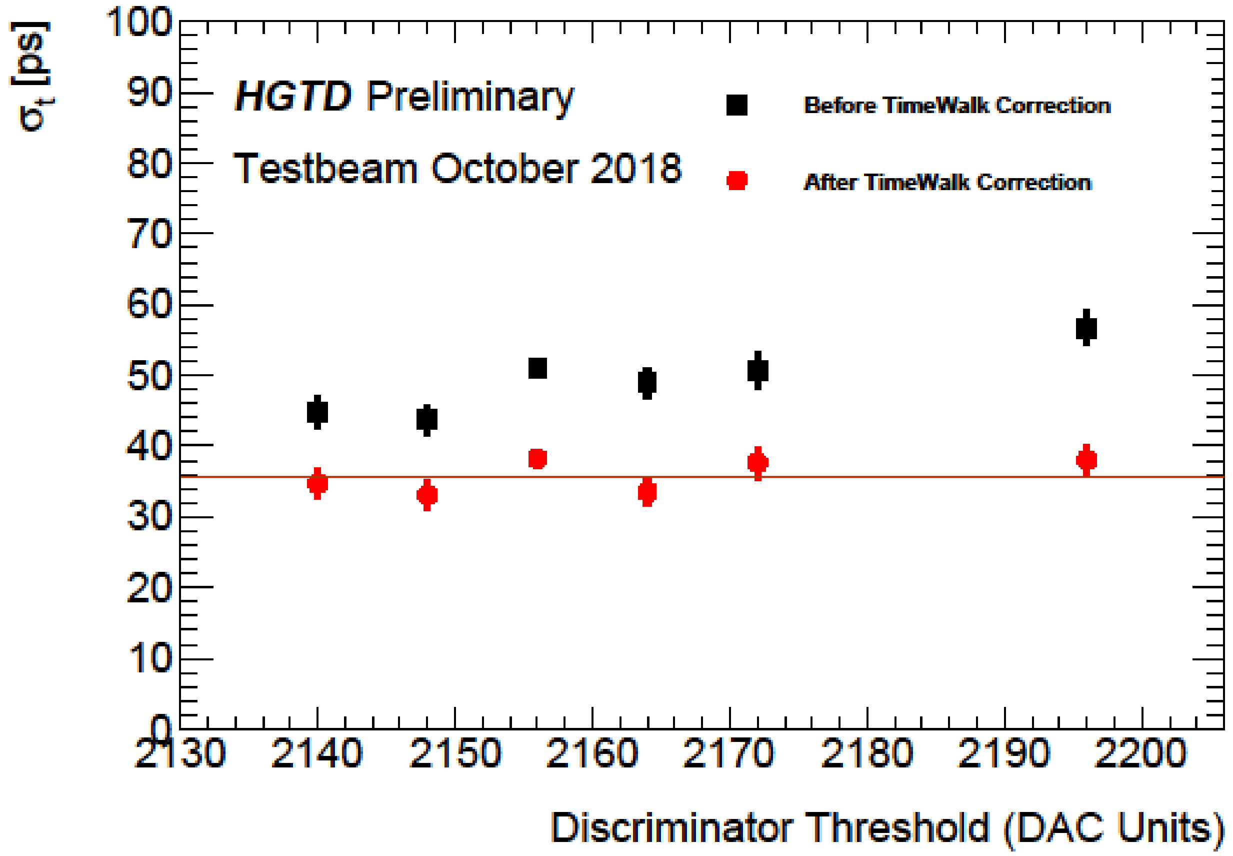
M. Ferrero et al. arXiv:1802.01745

ALTIROC 0v2 results at October CERN Test beam

- Applied correction to Time of Arrival as a function of the Amplitude
- **ALTIROC 0v2 (bump bonded to CNM 2x2 LGAD) shows 35ps of time resolution**
  - **After time walk correction**



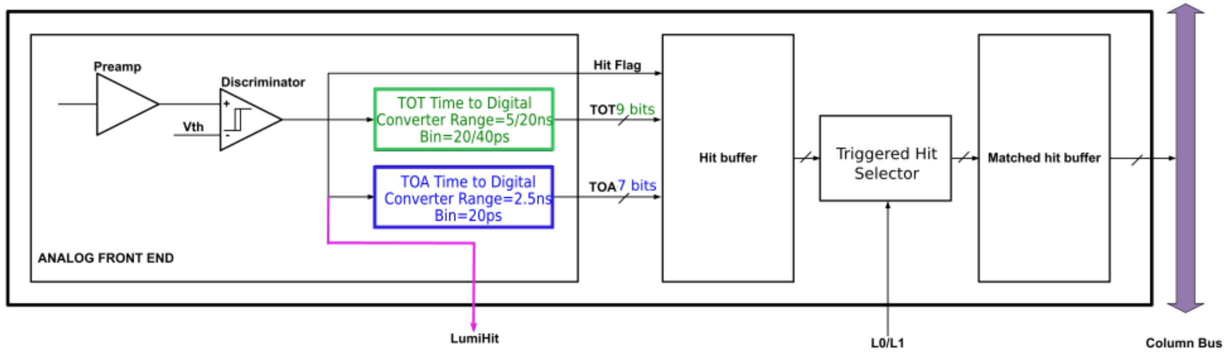


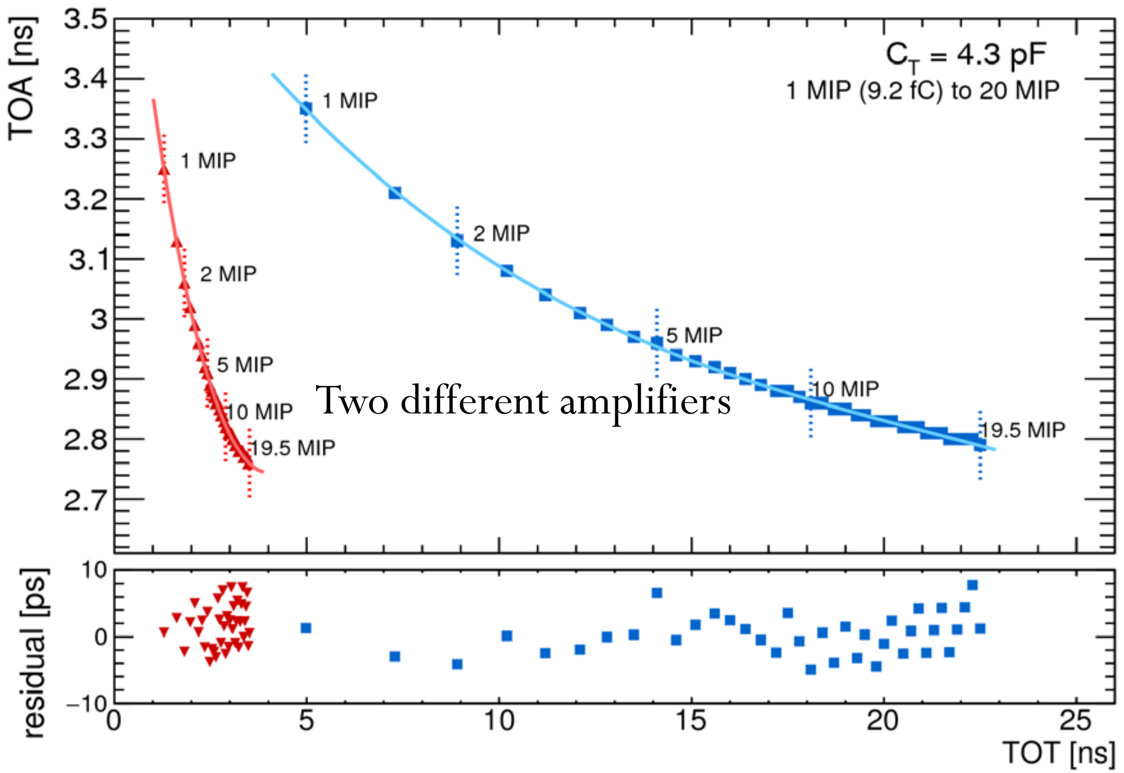


Readout electronics

- **Goal**: maintain the time resolution of the sensor
- $\sigma_{elec}^2 = \sigma_{Landau}^2 + \sigma_{jitter}^2 + \sigma_{TW}^2 + \sigma_{TDC}^2$
  - σ_{Landau}^2 sensor only
  - $\sigma_{jitter}^2 + \sigma_{TW}^2$ are from the analog electronics
- TOA (Time of Arrival) of the signal is corrected with TOT (Time over threshold)
  - Emulate the effect of % CFD in the ASIC
  - After correction $\sigma_{TW} < 10$ps
- If σ_{TDC} is ~20ps it will increase the total time resolution by 5ps (acceptable)

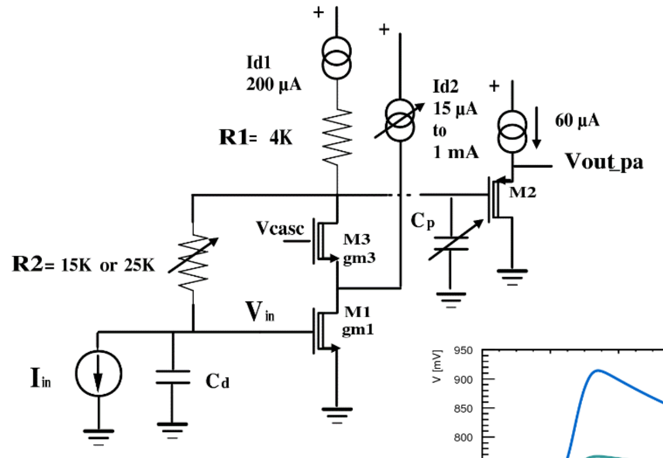
One pixel cell

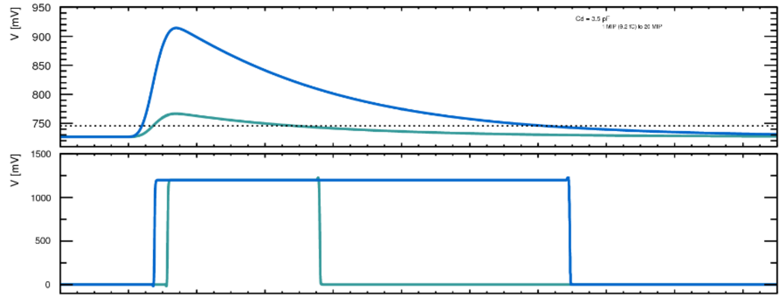


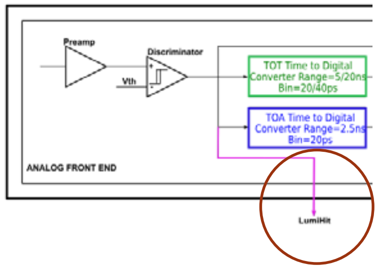


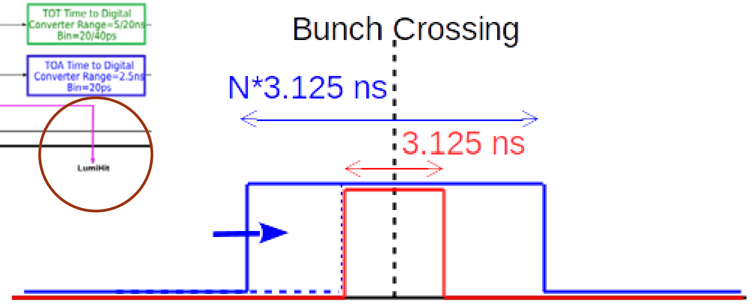
Readout electronics

- Preamplifier: broad band amplifier
  - Size of input transistor optimized to minimize noise and power consumption
  - Rise time ~0.5-1 ns (as the sensor) to minimize the jitter
  - Designed for 1-2 μA leakage current of the sensor







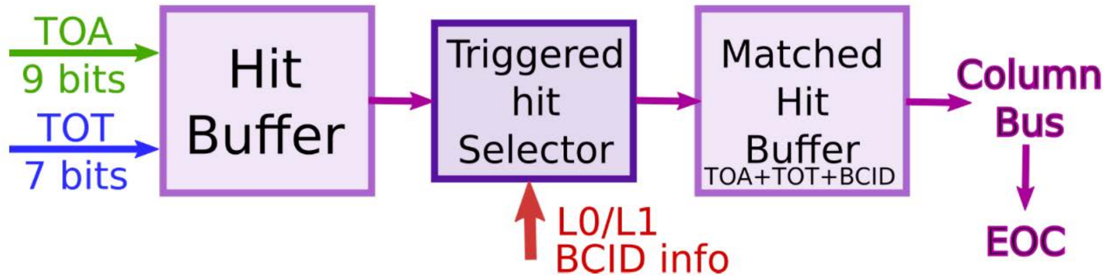


- Bunch by bunch luminosity measurement capability
  - Sums of hits in two time windows to evaluate the background bunch by bunch
  - (Only a subsets of ASICS is used for luminosity calculation)

- ASIC has to withstand high radiation levels
  - Inner circle will be replaced with the LGADs
  - Irradiation campaign will be done also on the ALTIROC chip

Readout electronics

- ToA and ToT TDCs with slow and fast delay line with 20ps (ToA) and 40ps (TOT) time measurement bins
- Per pixel hit buffer memory, passed over only if there is signal from L0/L1 triggers



- ALTIROC 0v2 tested at CERN October test beam
  - Applied correction to Time of Arrival as a function of the Amplitude
- **ALTIROC 0v2 (bump bonded to CNM 2x2 LGAD) shows 35ps of time resolution after time walk correction**
- ALTIROC 1: working with 5 × 5 LGAD arrays, testing will start soon with a test FPGA developed by SLAC