Low-Gain Avalanche Diode silicon sensors performance for the ATLAS High-Granularity Timing Detector (HGTD) for the HL-LHC

Zhijun Liang, on behalf of the ATLAS collaboration
(IHEP, Chinese Academy of Sciences)

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The 28th International Workshop on Vertex Detectors

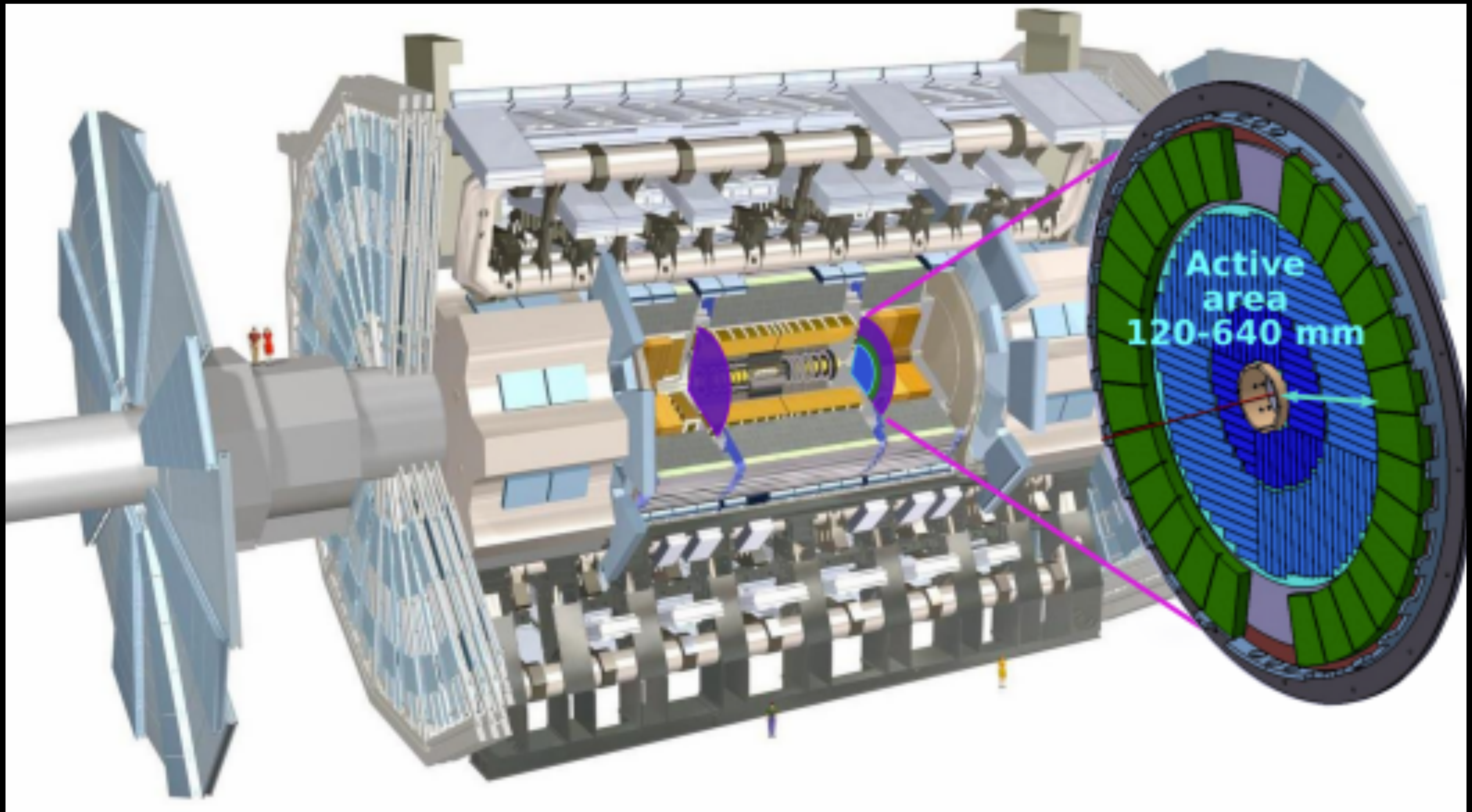
ATLAS EXPERIMENT

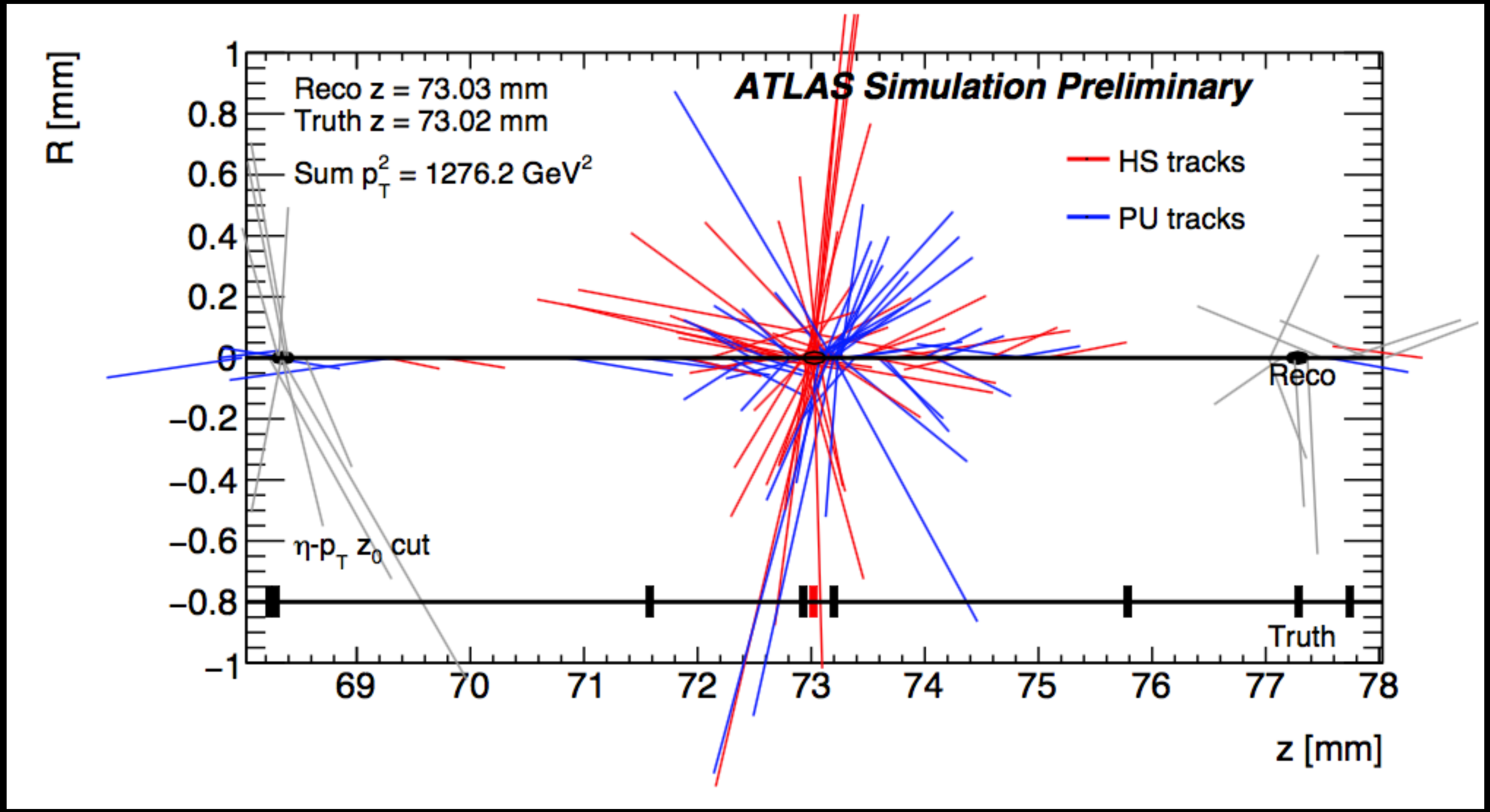
中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Introduction to High-Granularity Timing Detector

High-Granularity Timing Detector (HGTD) is proposed for ATLAS phaseII upgrade

- Timing resolution per track is required to be better than **50ps**
- Reduce pileup contribution by a factor of 5
- **6.4m² area** silicon detector and ~ **5x10⁶ channels**
- Radiation hardness requirement: **2.5x10¹⁵ N_{eq} /cm²** and **2MGy**

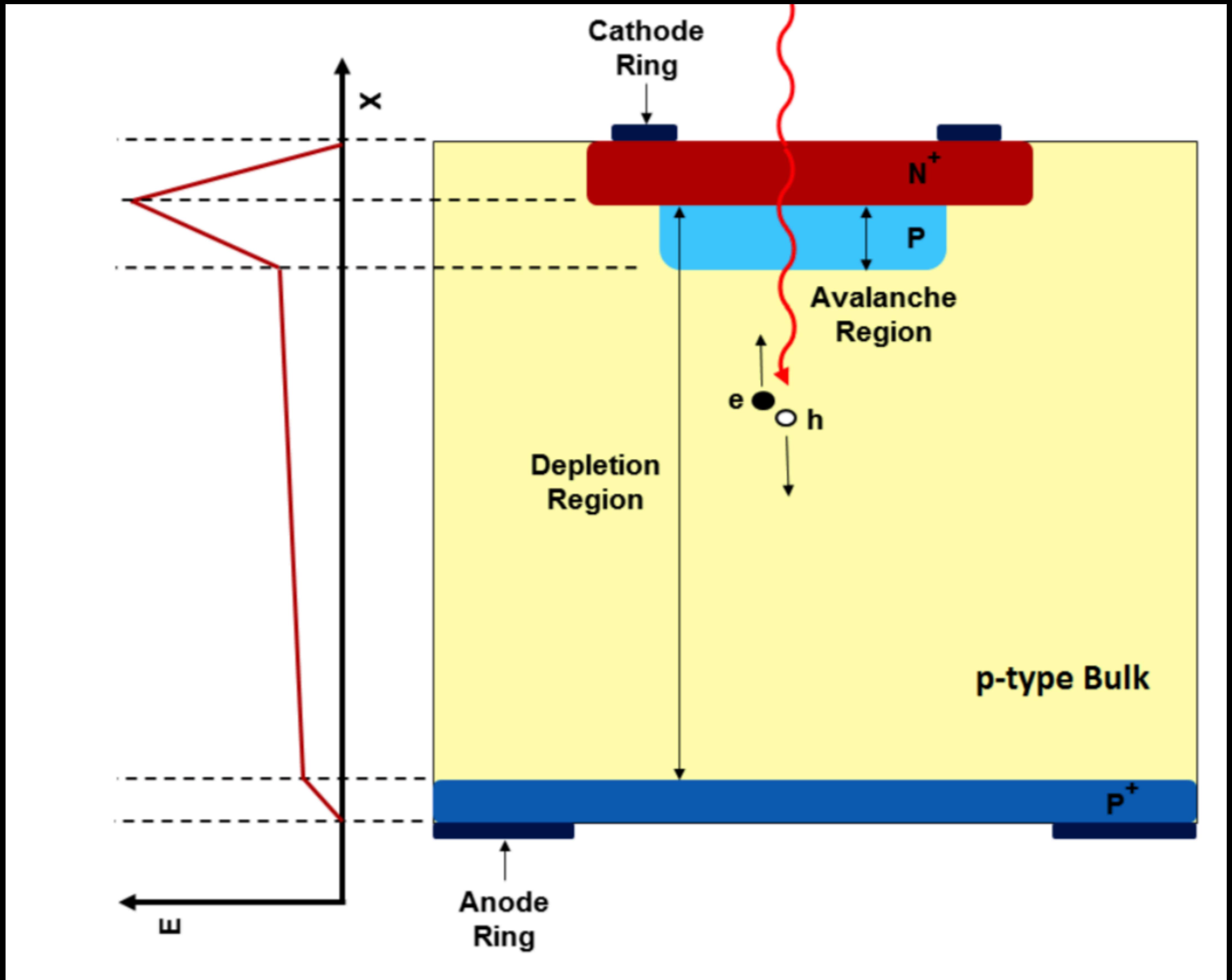




Low-Gain-Avalanche-detector

Low-Gain-Avalanche-detector(LGAD)

- Compared to APD and SiPM, LGAD has modest gain (10-50)
- high drift velocity, thin active layer (fast timing)
- High S/B, no self-triggering



Manufacturers of LGAD

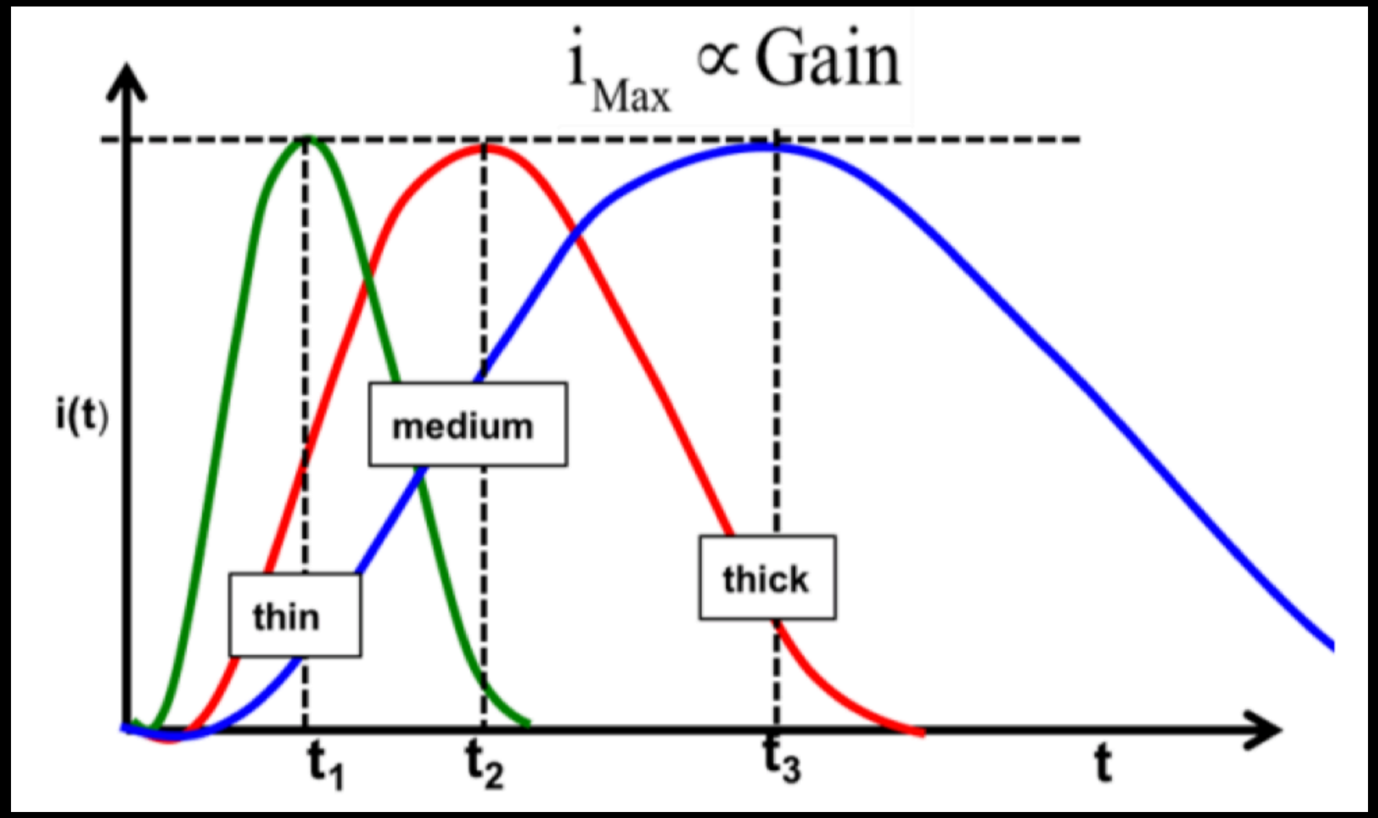
CNM (Spain), HPK (Japan), FBK (Italy), BNL (USA)， IHEP-NDL (China)

Low-Gain-Avalanche-detector

$$\sigma_t^2 = \sigma_{TimeWalk}^2 + \sigma_{LandauNoise}^2 + \sigma_{Distortion}^2 + \sigma_{Jitter}^2 + \sigma_{TDC}^2$$

Landau Noise term:

- Signal fluctuation due to non-uniform charge deposition
- Minimized by reducing thickness of the sensor (50um)

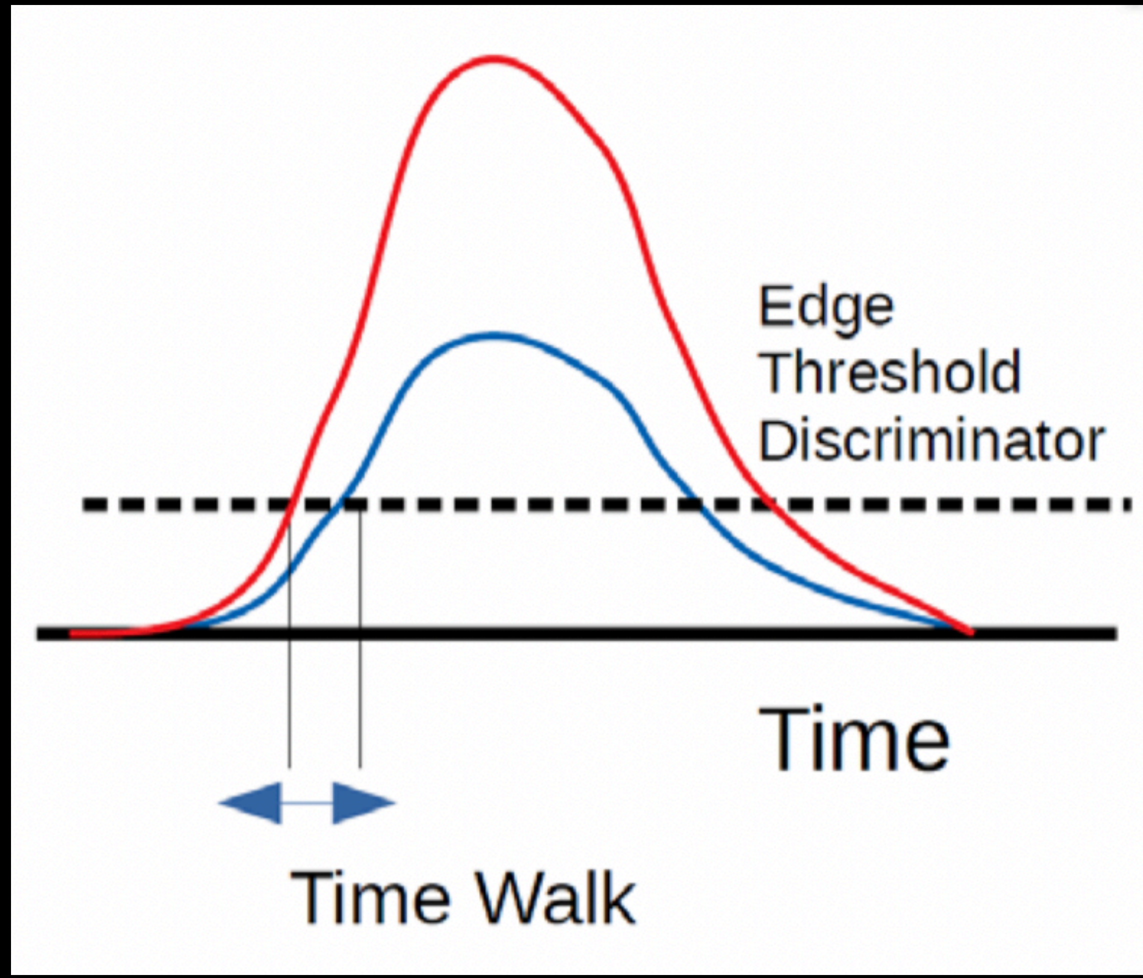


Jitter

$$\sigma_{jitter}^2 = \left(\frac{t_{rise}}{S/N}\right)^2$$

- Need gain to increase S/N
- Need thin detector to decrease t_{rise}

fixed threshold



Time walk

$$\sigma_{timewalk}^2 = \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{\mathrm{RMS}}\right)^2$$

- corrected using the amplitude estimate with the time over threshold (TOT).

[1] G. Pellegrini et al., NIM A765 (2014) 12
[2] H.-W. Sadrozinski et al., arXiv: 1704.08666
[3] F. Cenna et al, NIM A796 (2015) 149-153

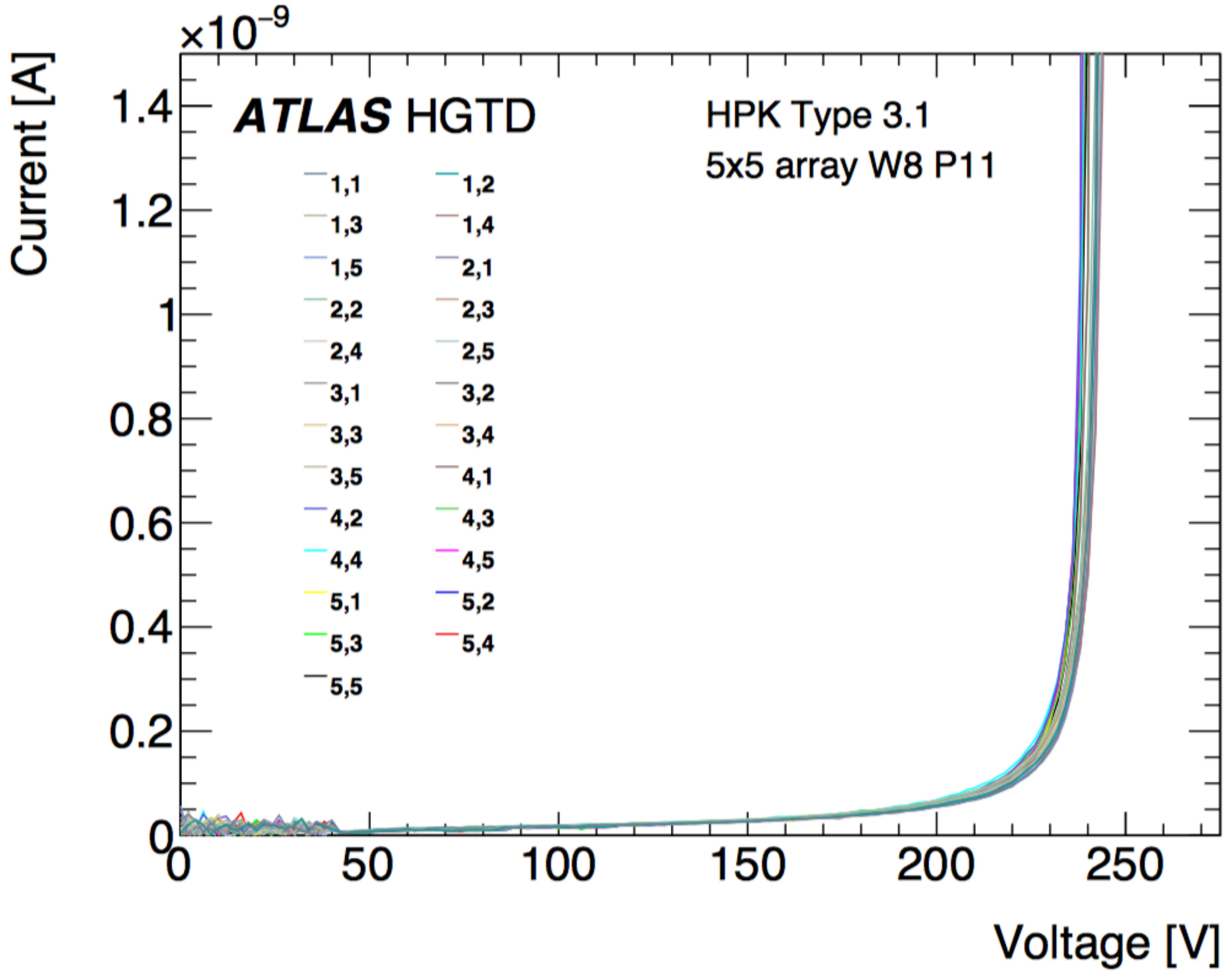
Large LGAD sensor

Full size sensor for HGTD module

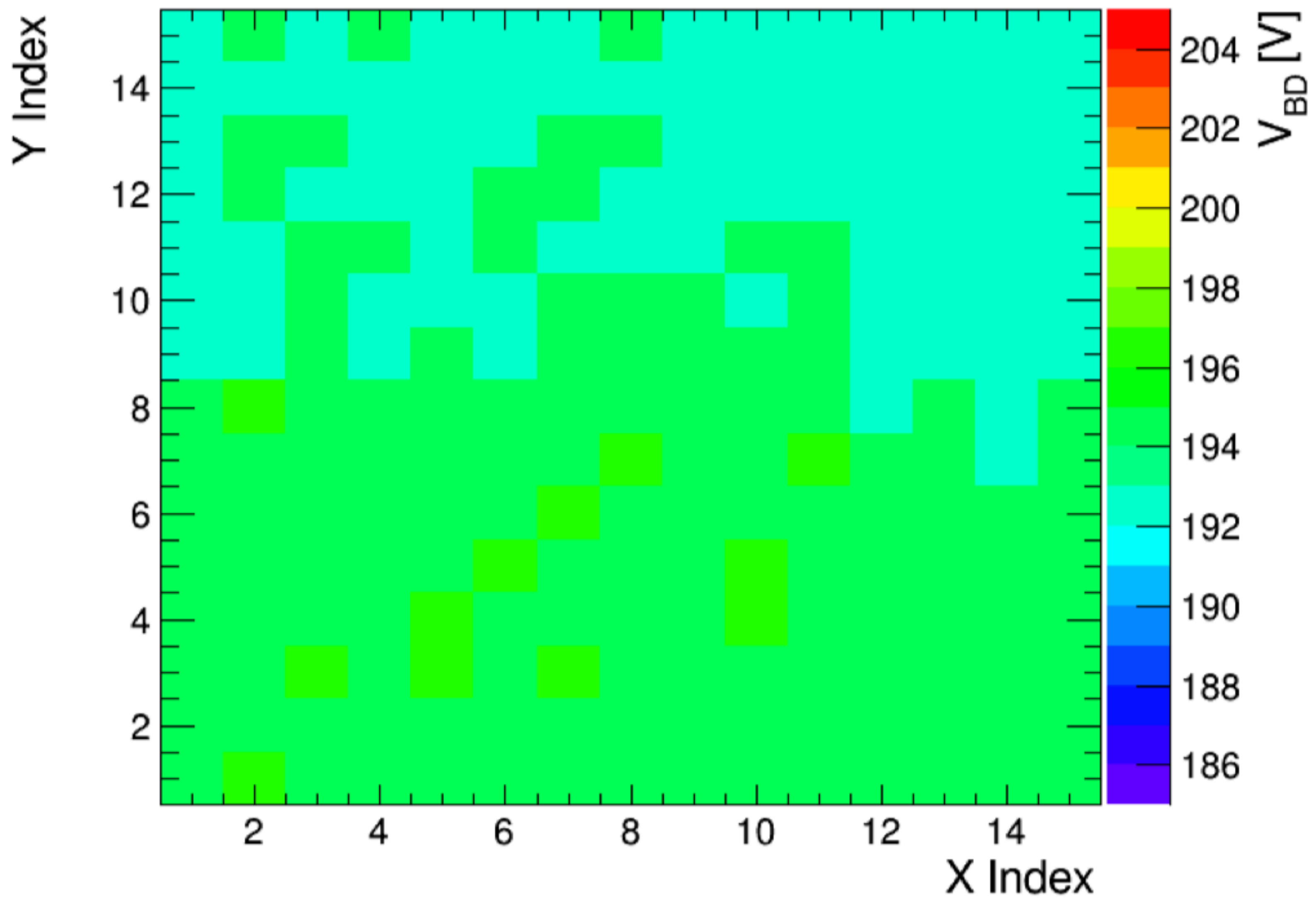
- 2cm x 4cm (15 x30 ch)
- Minimized by reducing thickness of the sensor (50um)

HPK 15x15 ch LGAD prototype

- Good uniformity in leakage current, gain and breakdown voltage



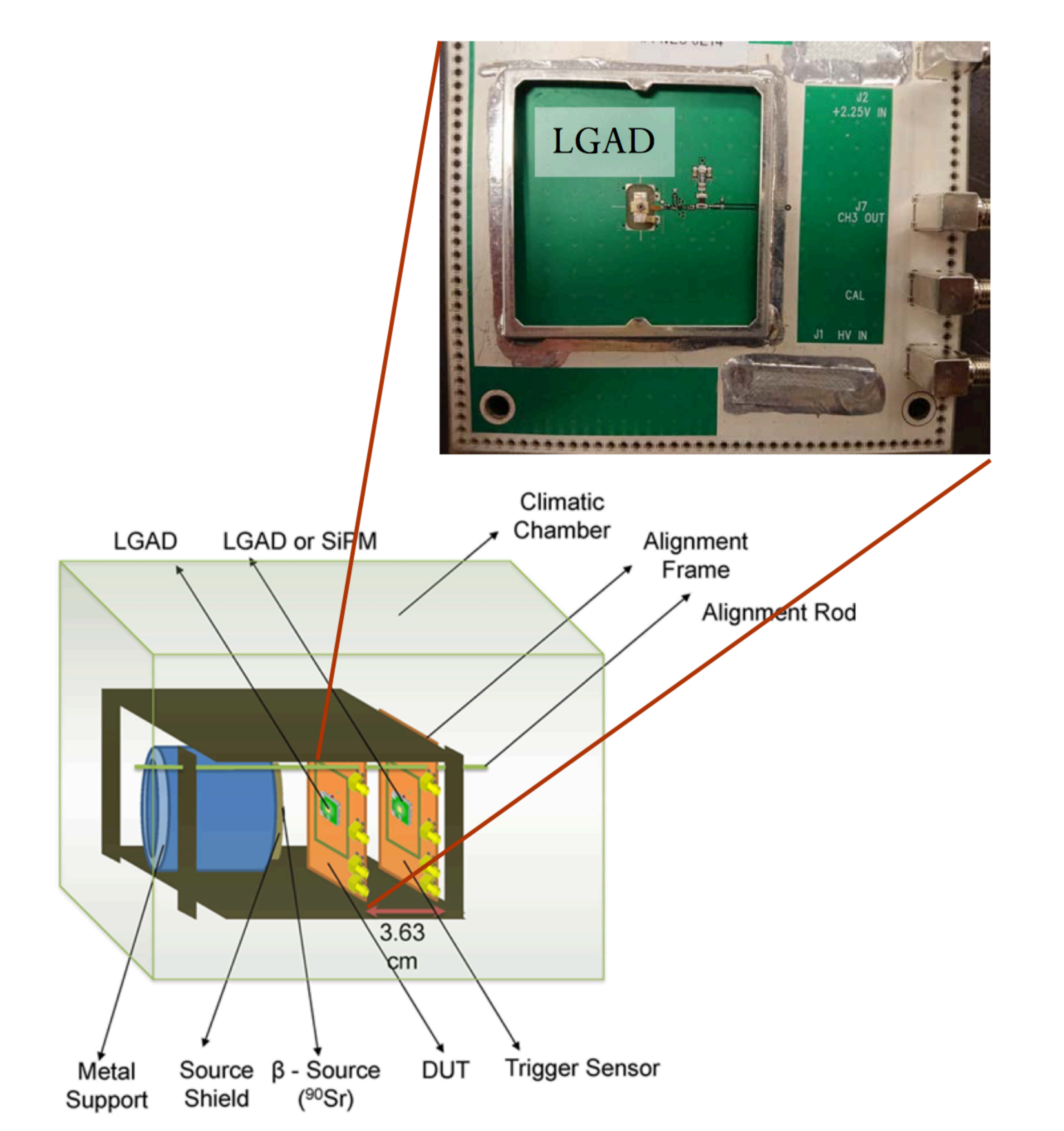
(a) All I-V curves of a 5 × 5 array.



(b) V_{BD} map of a 15 × 15 array.

HPK 15x15 LGAD prototype

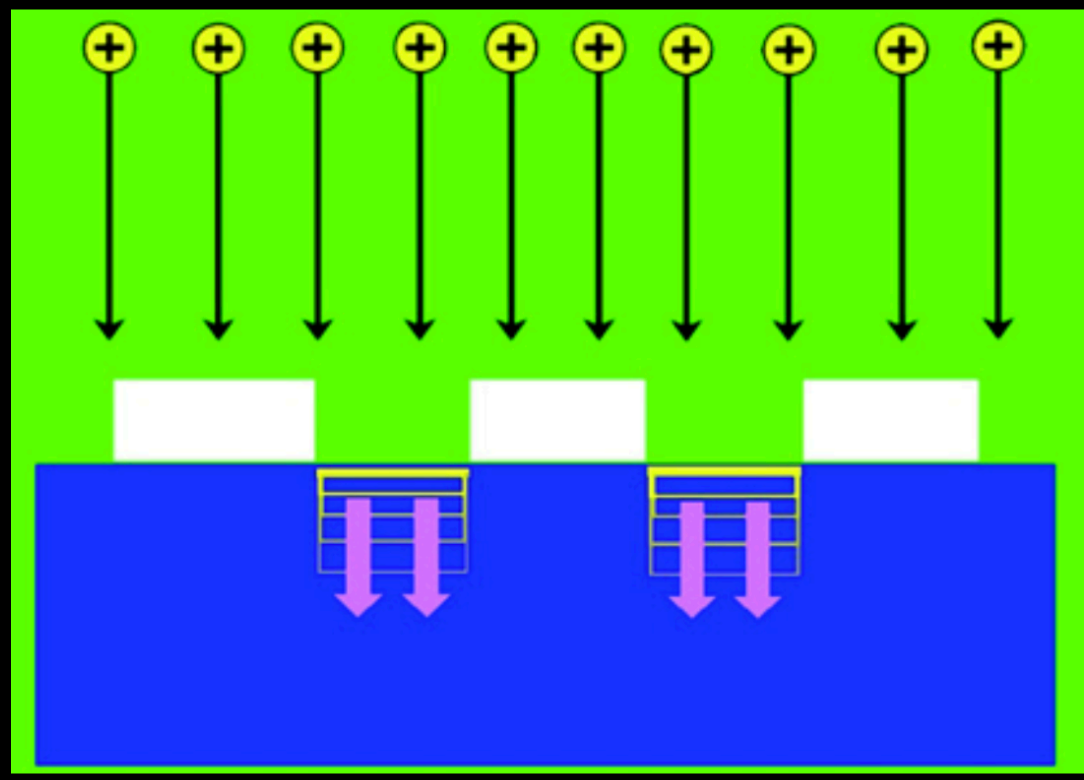
Sensor testing



Beta test (collected charge, gain, time resolution)

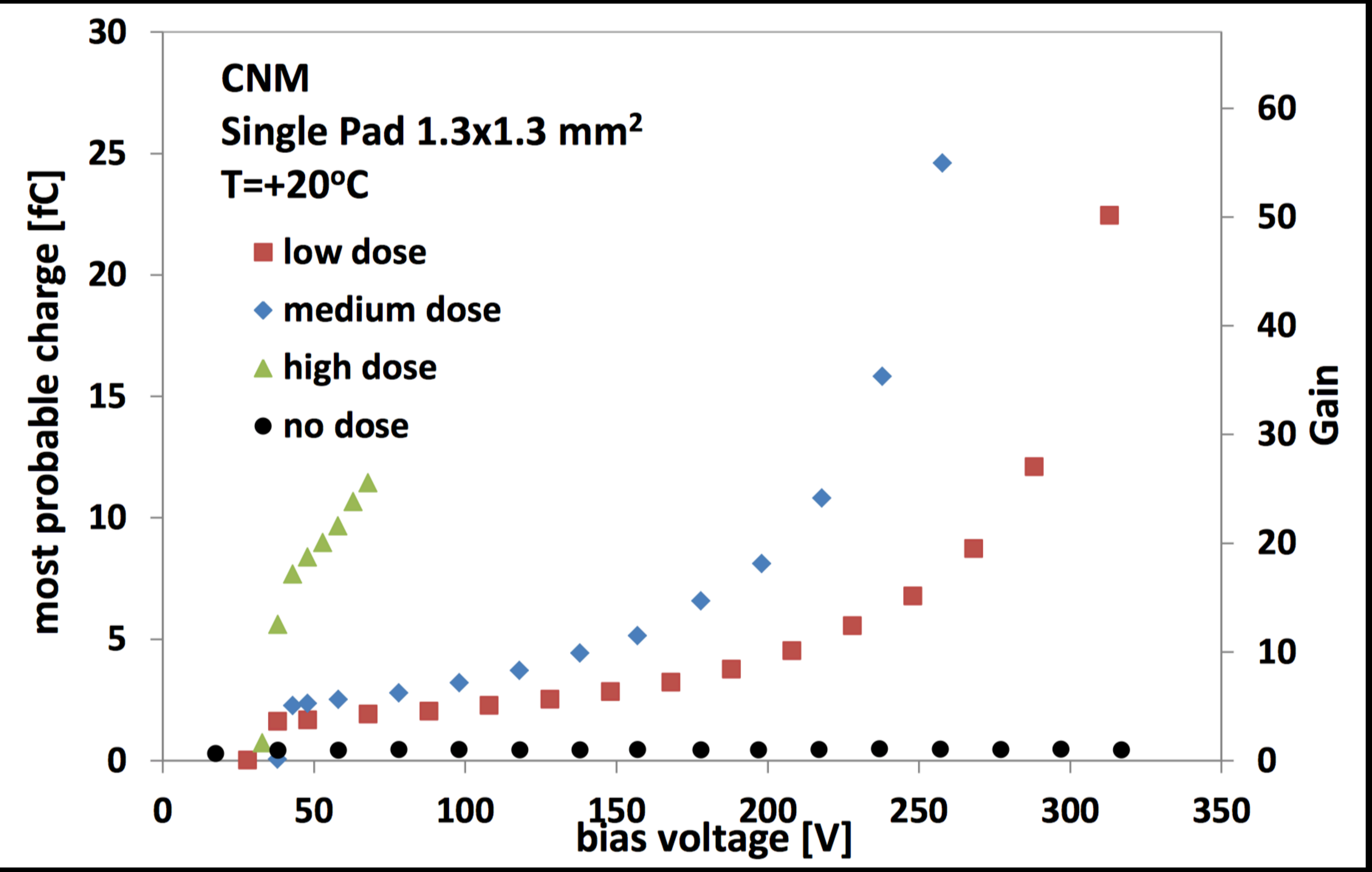
- Electrons by Sr90 Beta source
- Single channel board developed by UCSC
- Fast amplifier with bandwidth >1GHz
- Climate chamber to run at -30C

LGAD sensor study: doping

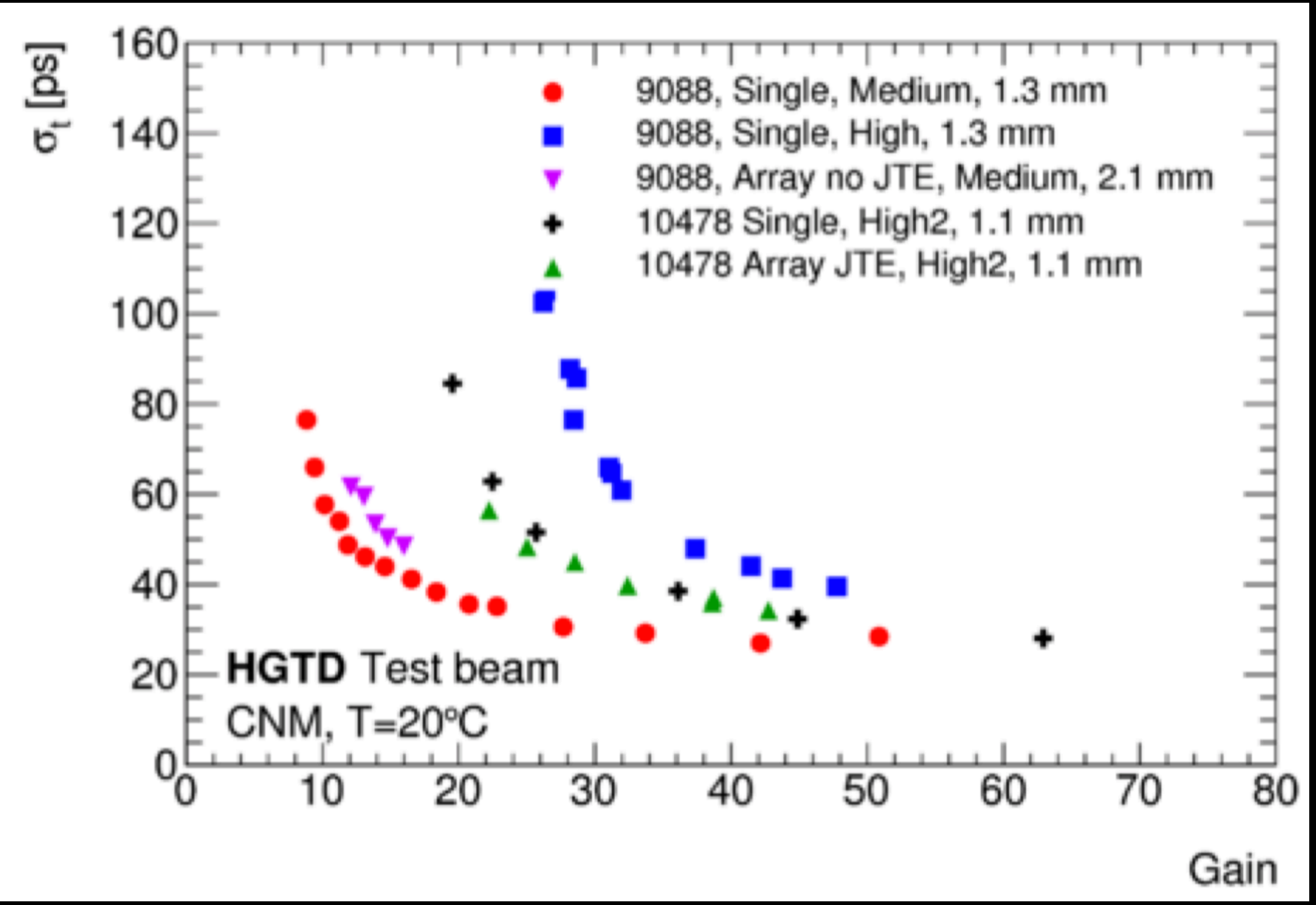


- Gain and charge as a function of bias voltage for a CNM LGAD with different doping doses of the multiplication layer.
- Time resolution of sensor of 30 ps achievable

Collected charge vs P+ layer doping



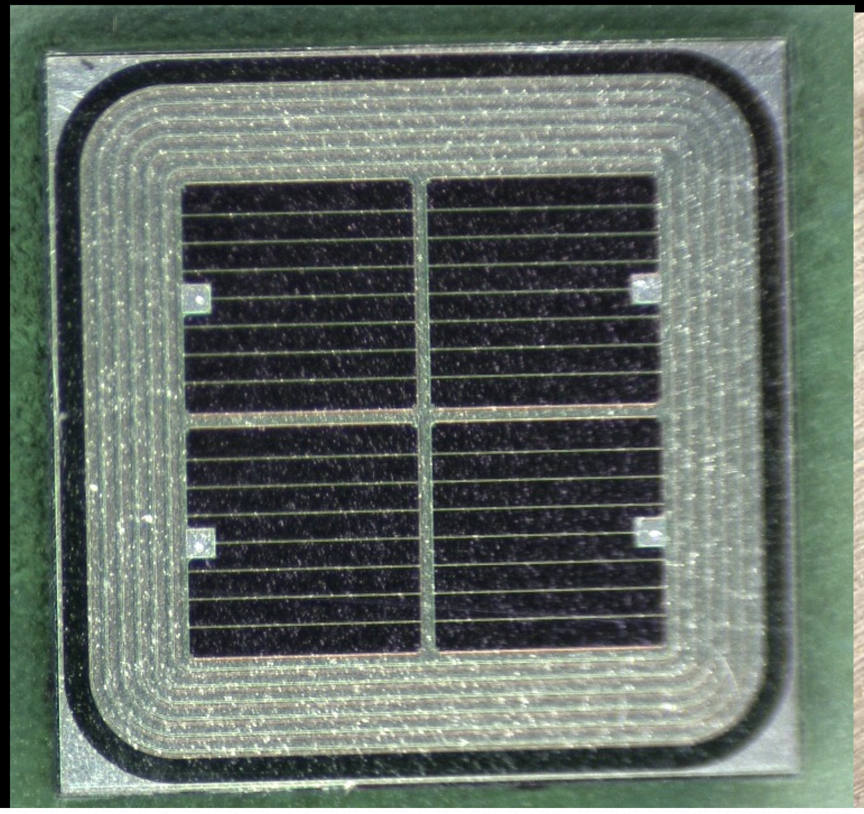
Timing resolution vs P+ layer doping

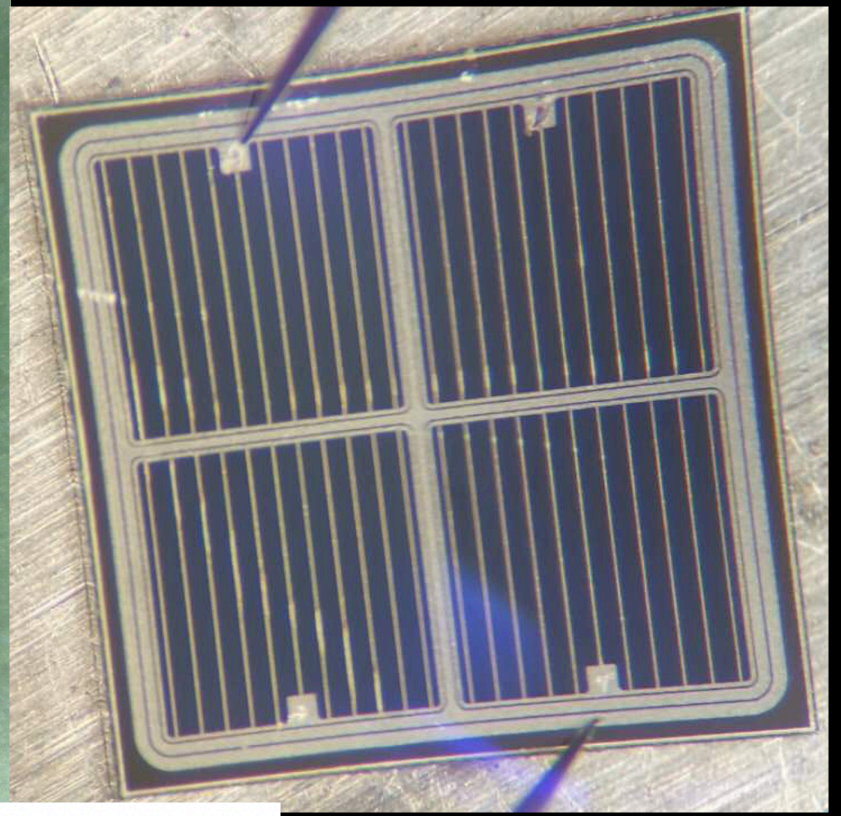


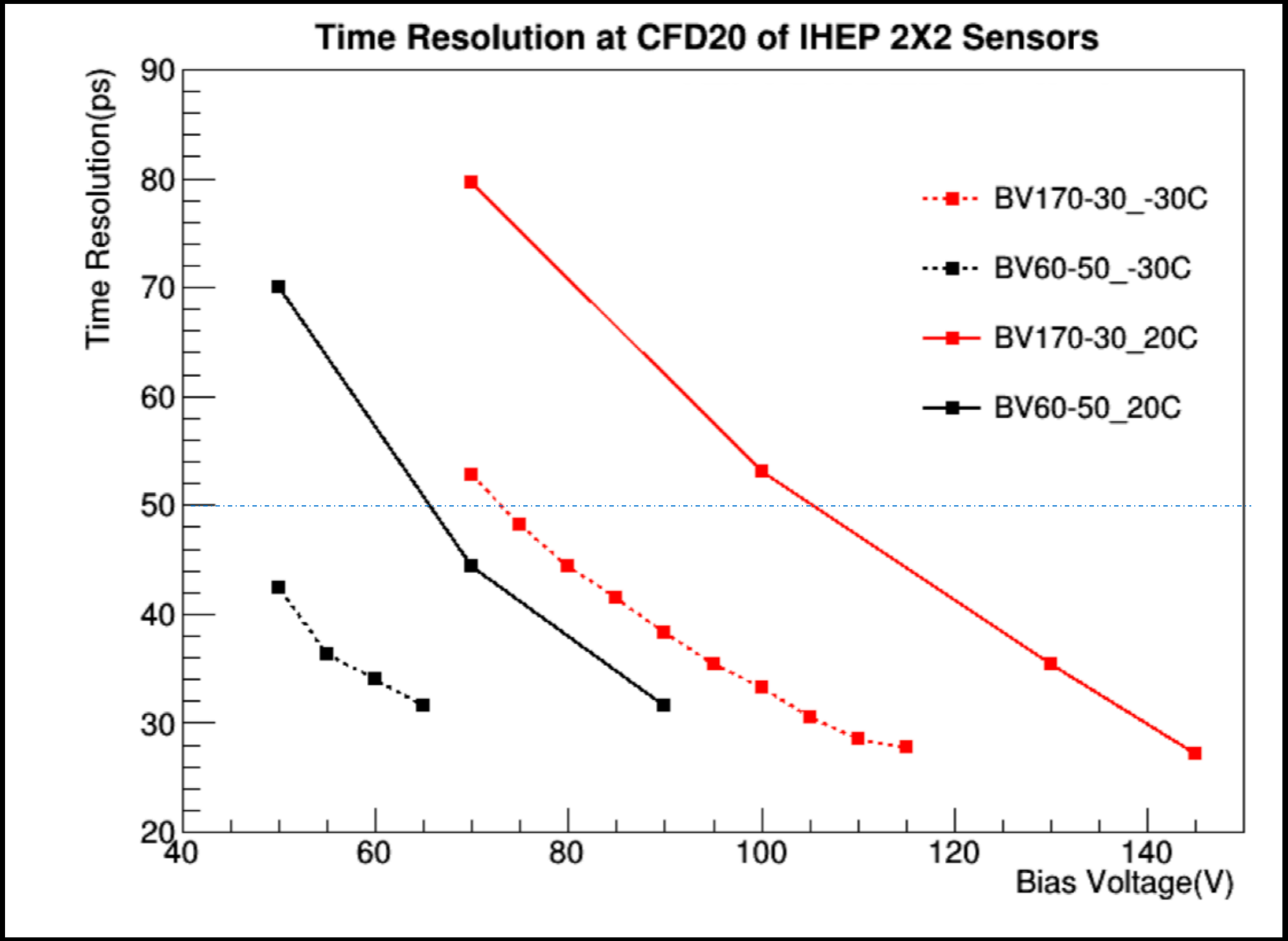
LGAD sensor : new foundry in China

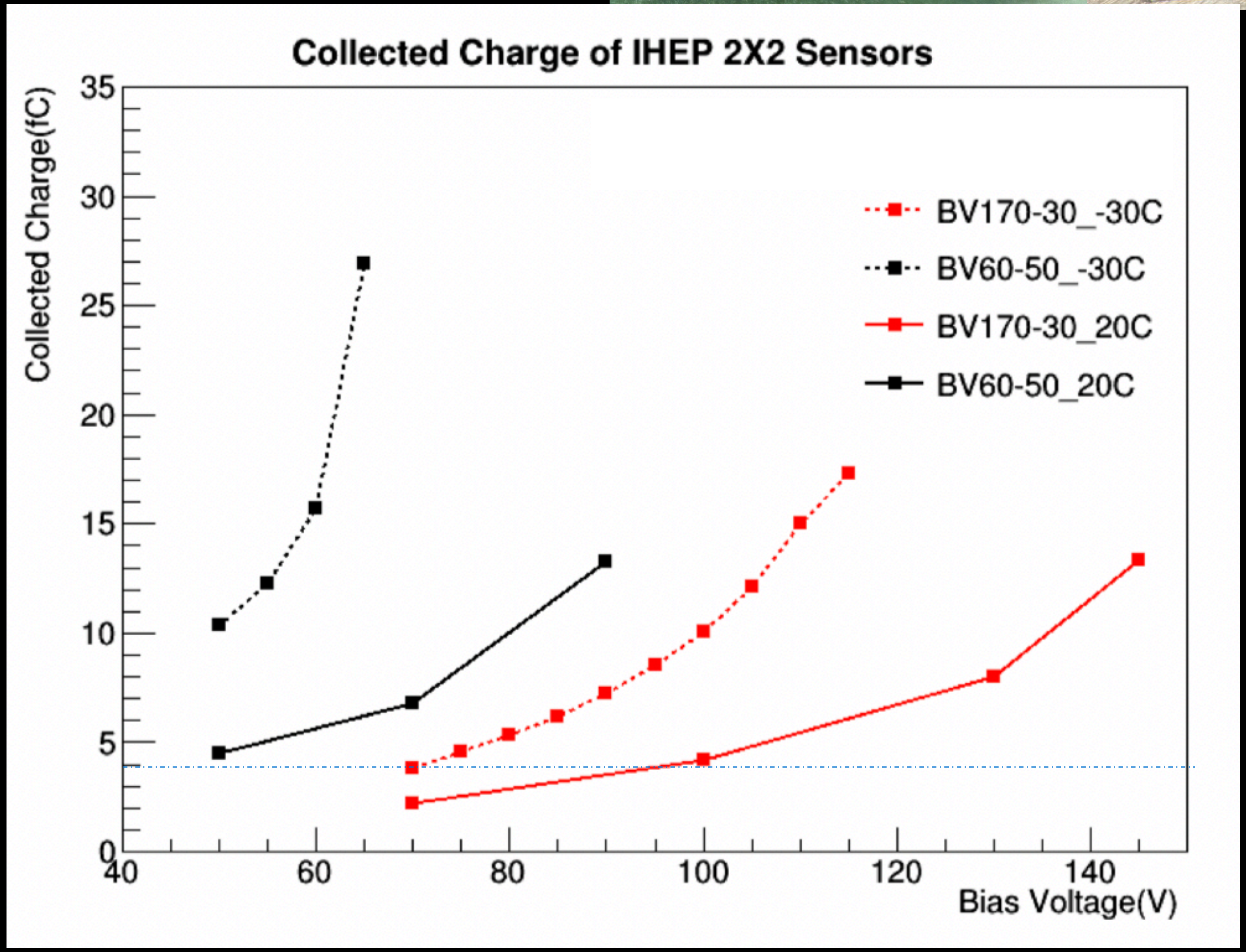
New LGAD foundry in China: The Novel Device Laboratory

- **just start prototyping LGAD sensor early 2019**
- **Two prototype of 2x2 LGAD, 5x5 LGAD**









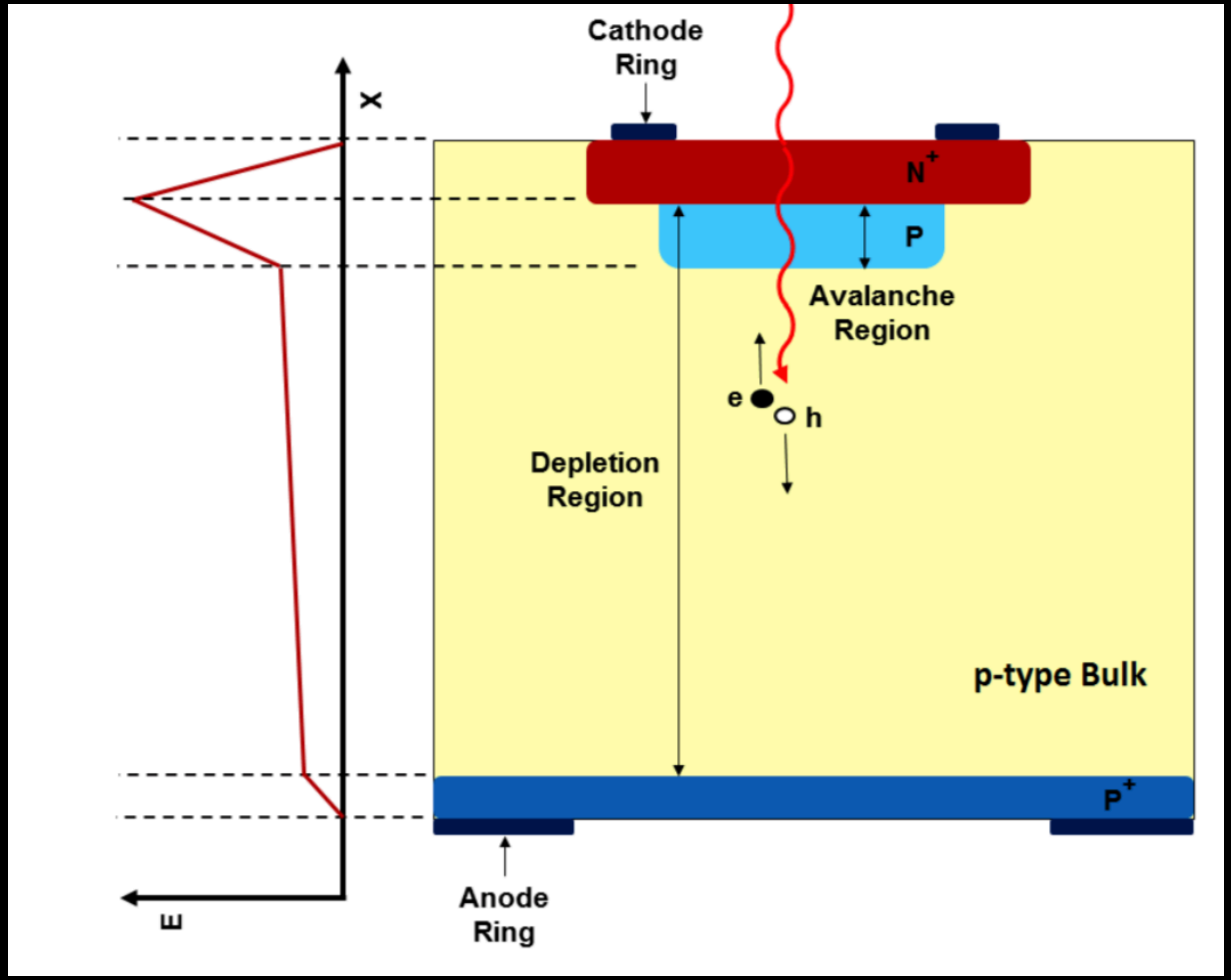
Radiation damage on LGADs

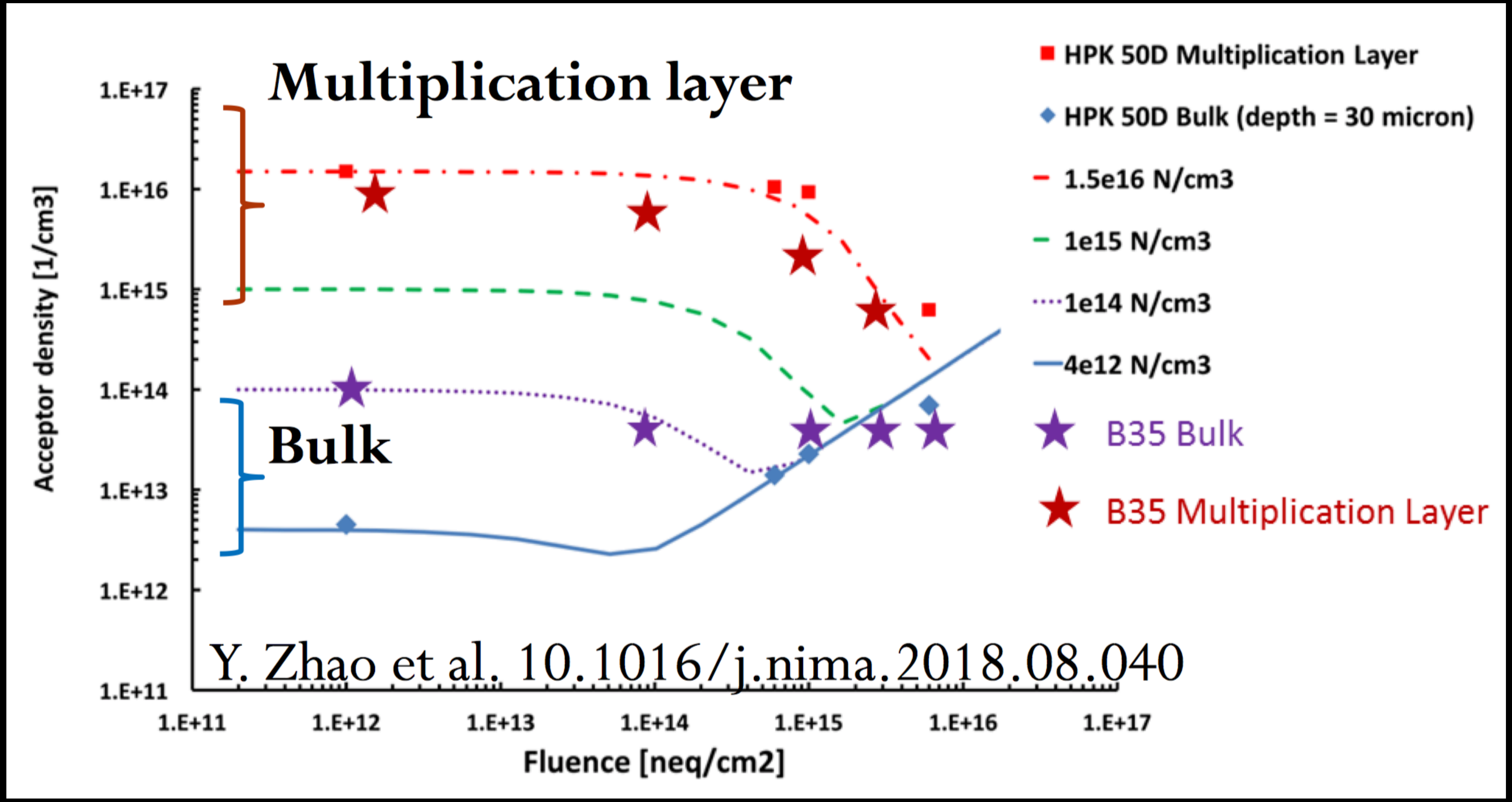
Radiation damage effect for LGAD

- Acceptor removal
- Interstitials inactivate the doping elements (Boron) via kick-out reactions that produce ion-acceptor complexes
- Reduction of gain, collected charge

$$N_A(\phi) = g_{eff}\phi + N_A(\phi{=}0)e^{-c\phi}$$

Acceptor creation   Acceptor removal





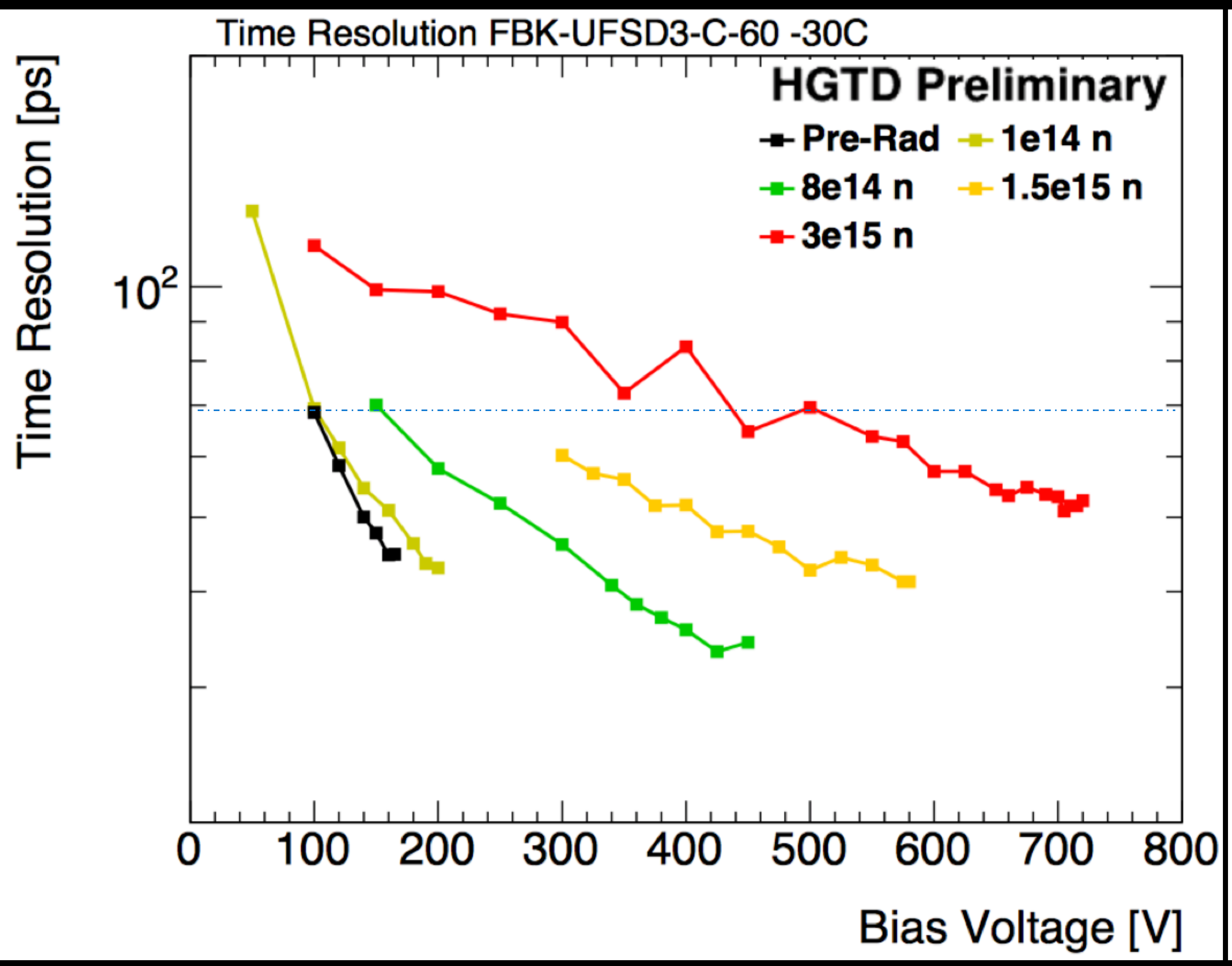
M. Ferrero et al. arXiv:1802.01745,
G. Kramberger et al. JINST 10 (2015) P07006

Sensor testing—timing resolution

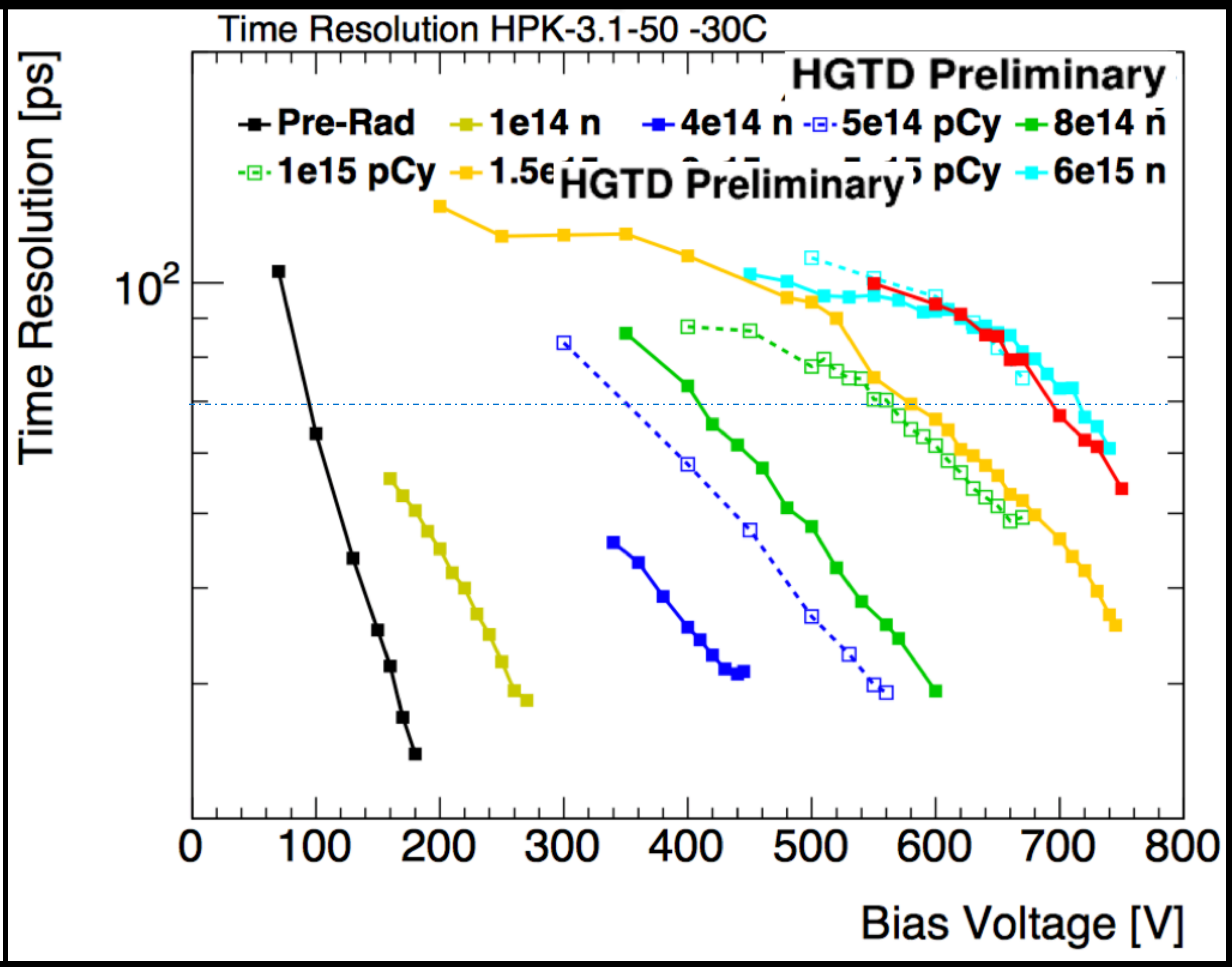
Timing resolution requirement: <50ps at 2.5×10^{15} Neq /cm^2

- **HPK-3.2 LGAD with deep implantation of multiplication layer**
- **FBK LGAD sensor meet this requirements as well**

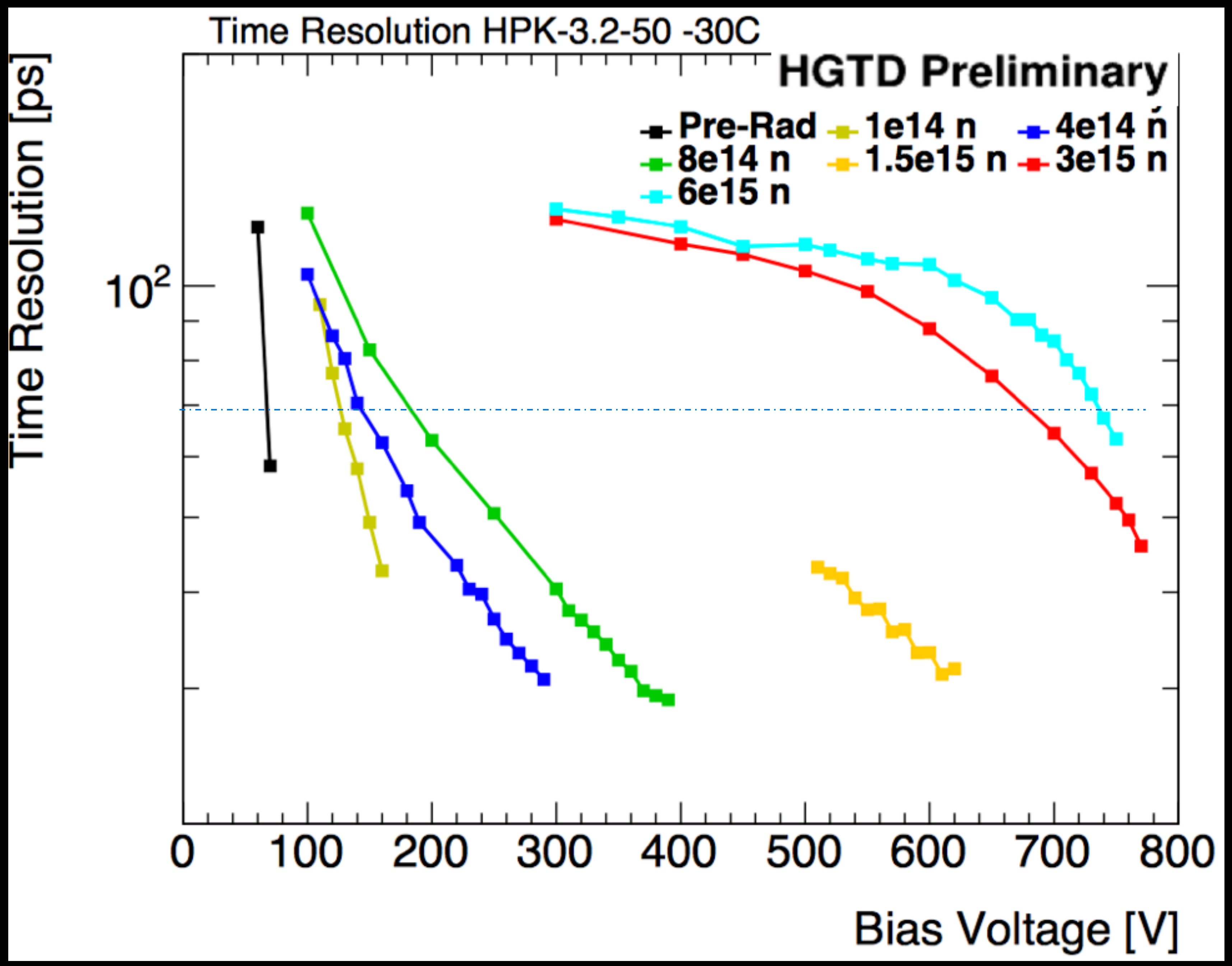
FBK



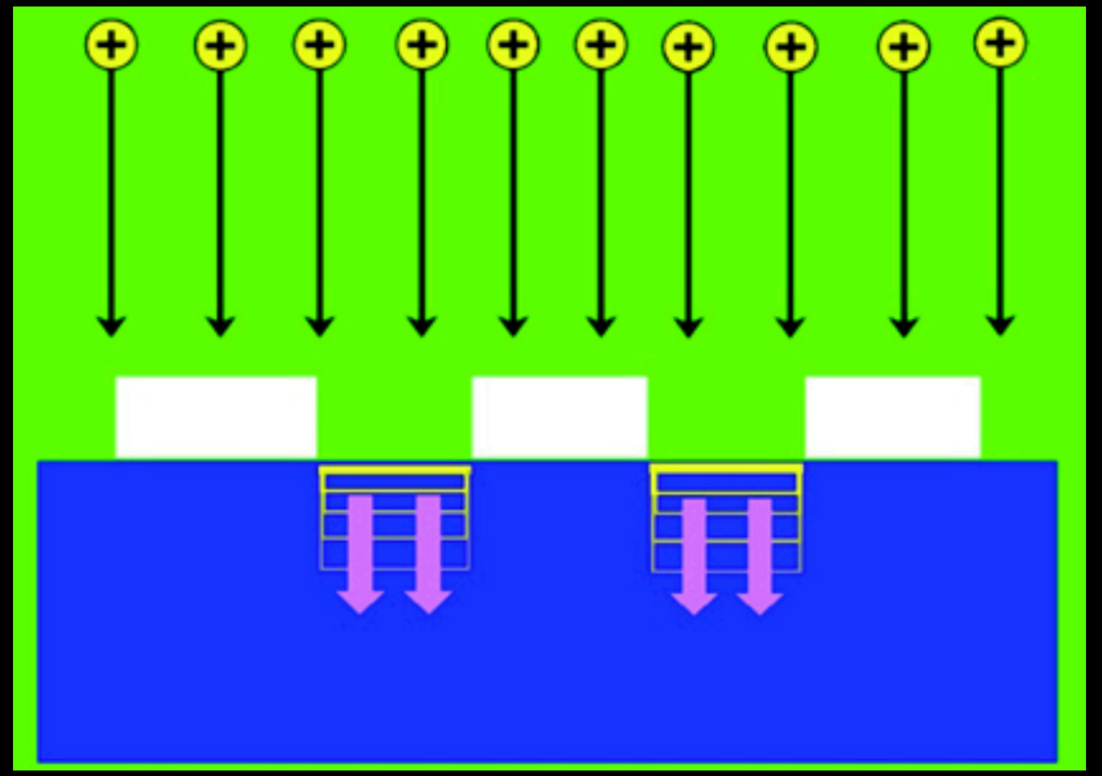
HPK-3.1



HPK-3.2



Sensor testing—collected charge

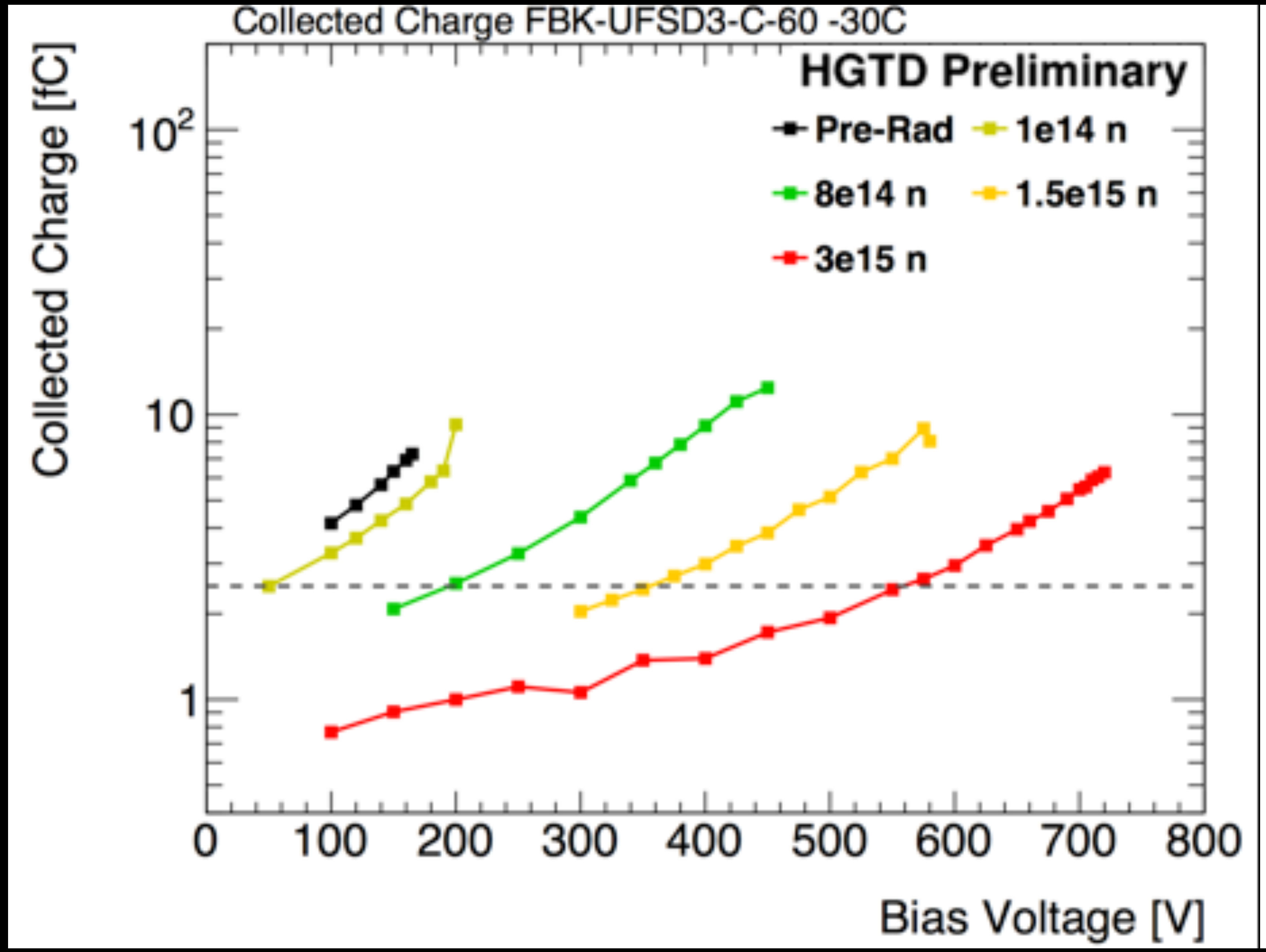


Collected charge requirement: >4fC at 2.5x10^{15} Neq /cm^2

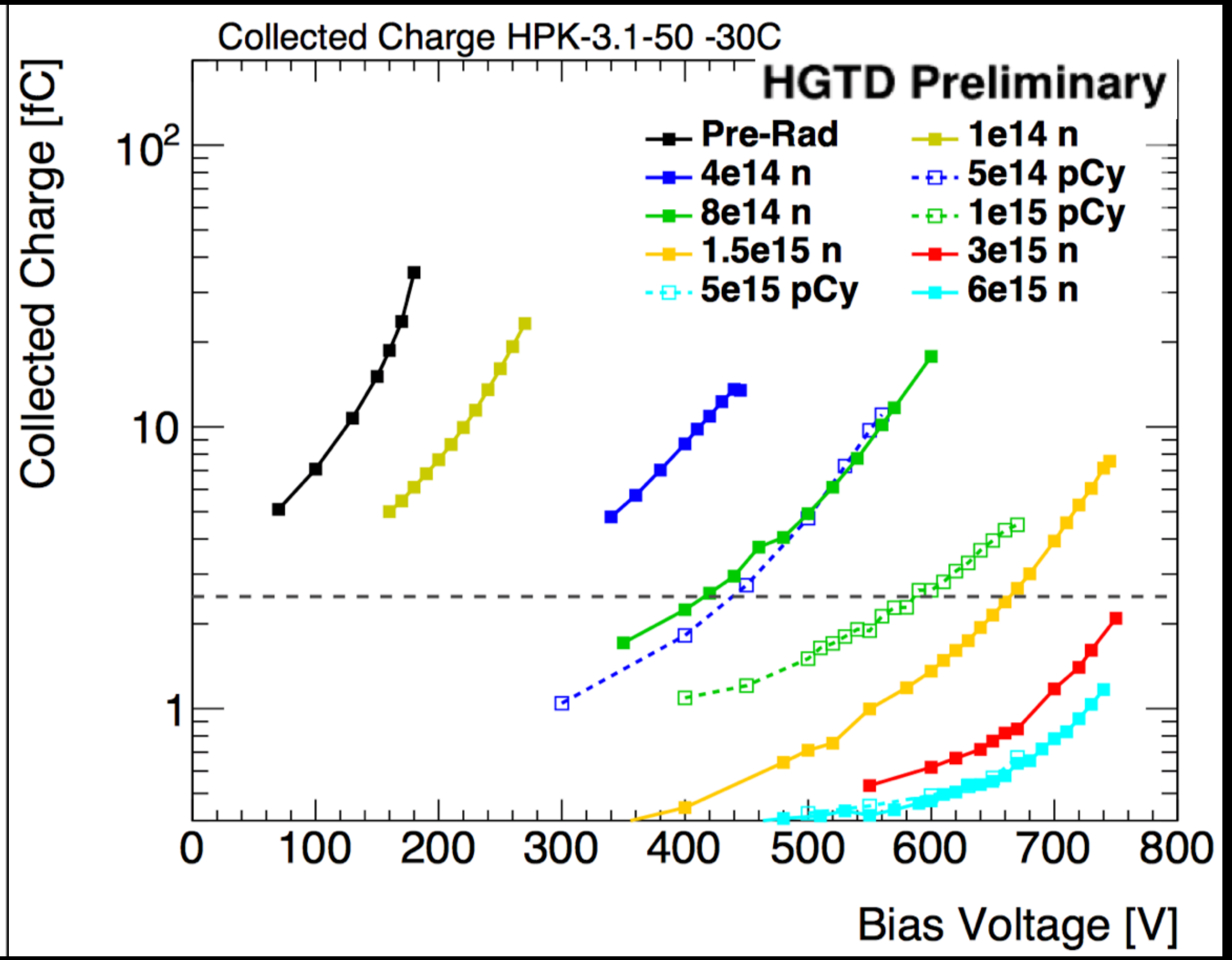
- Need enough charge for ASIC readout
- HPK-3.2 LGAD with deep implantation of multiplication layer
- FBK LGAD sensor meet this requirements as well

deep implantation of p+

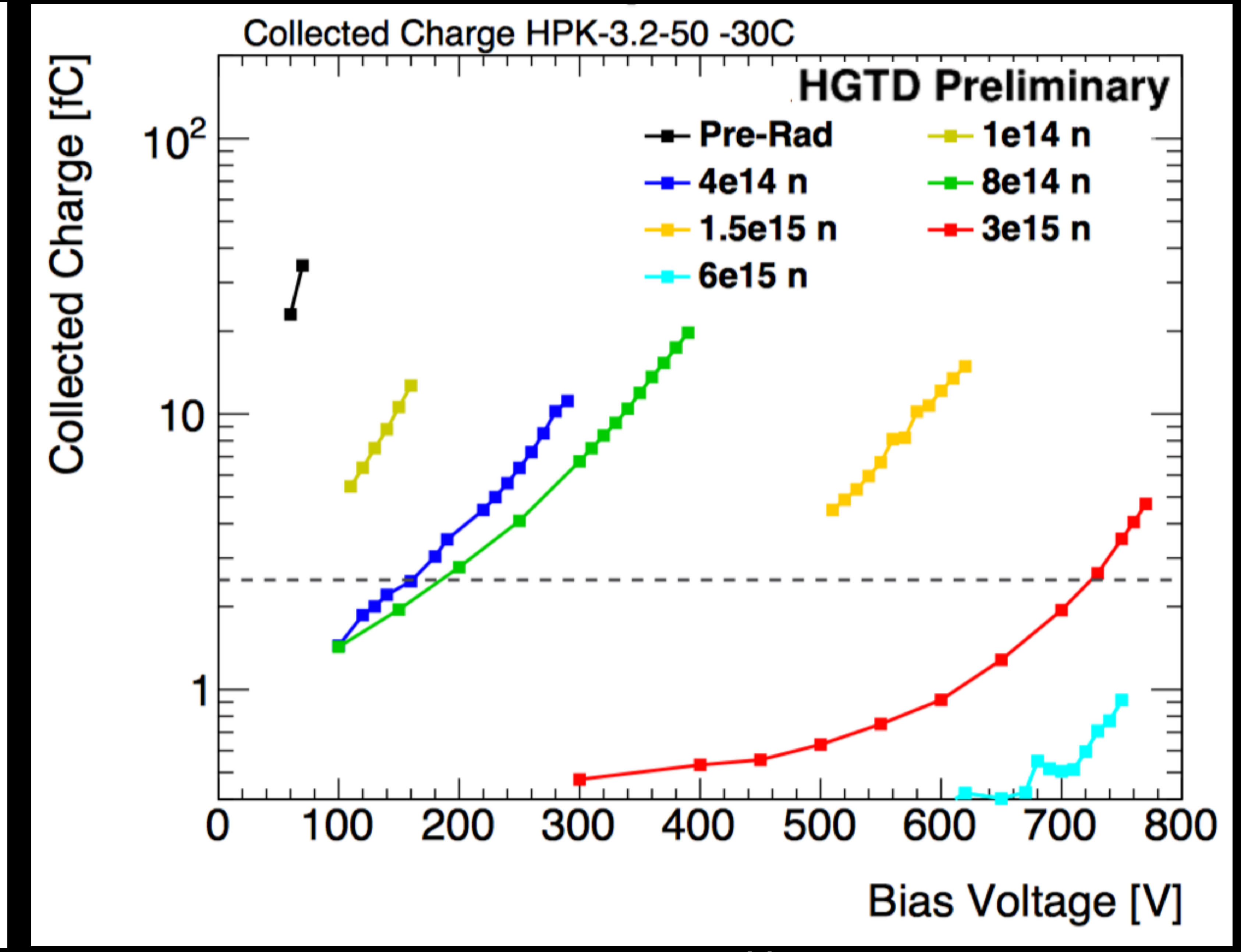
FBK



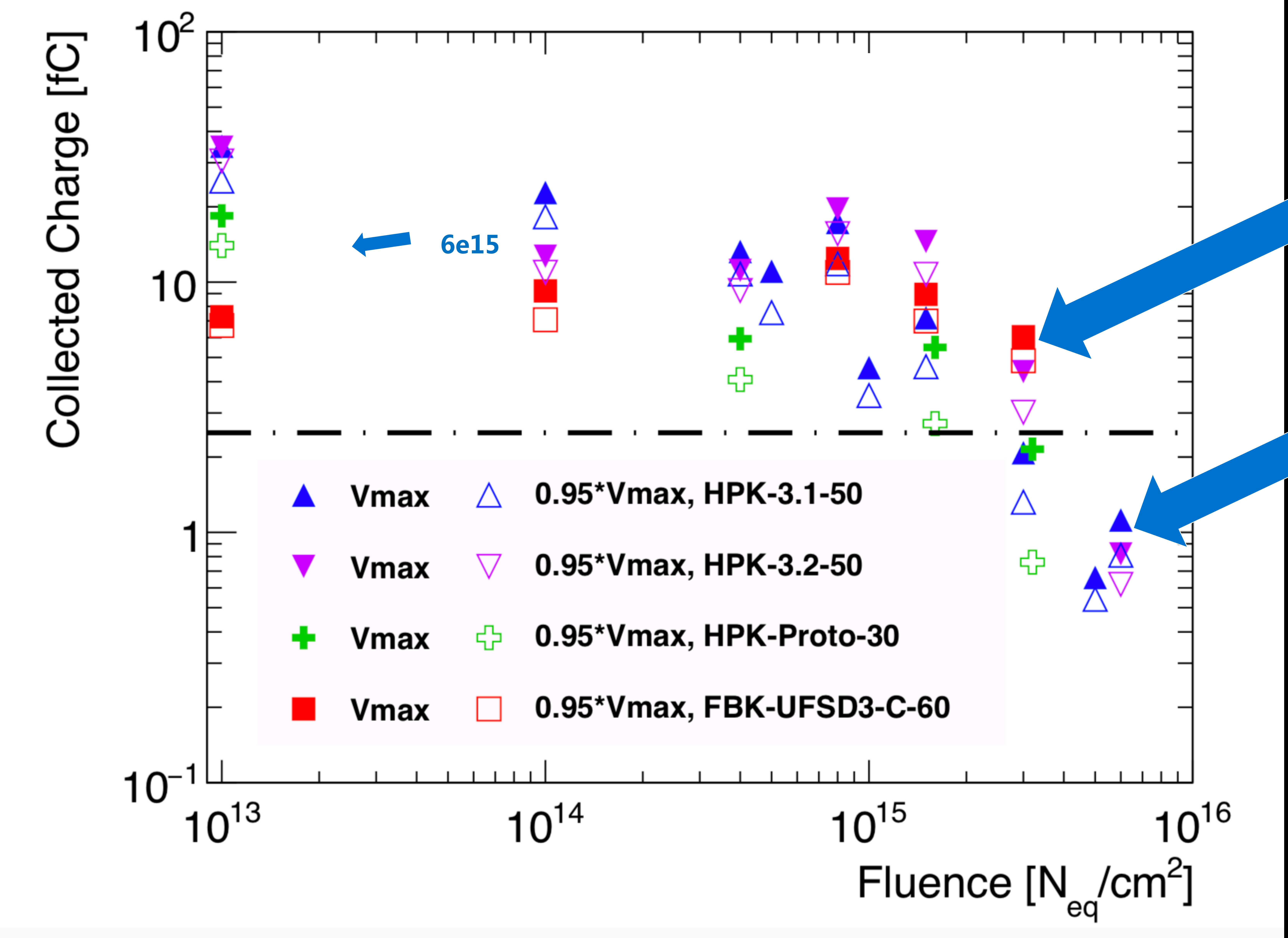
HPK-3.1



HPK-3.2



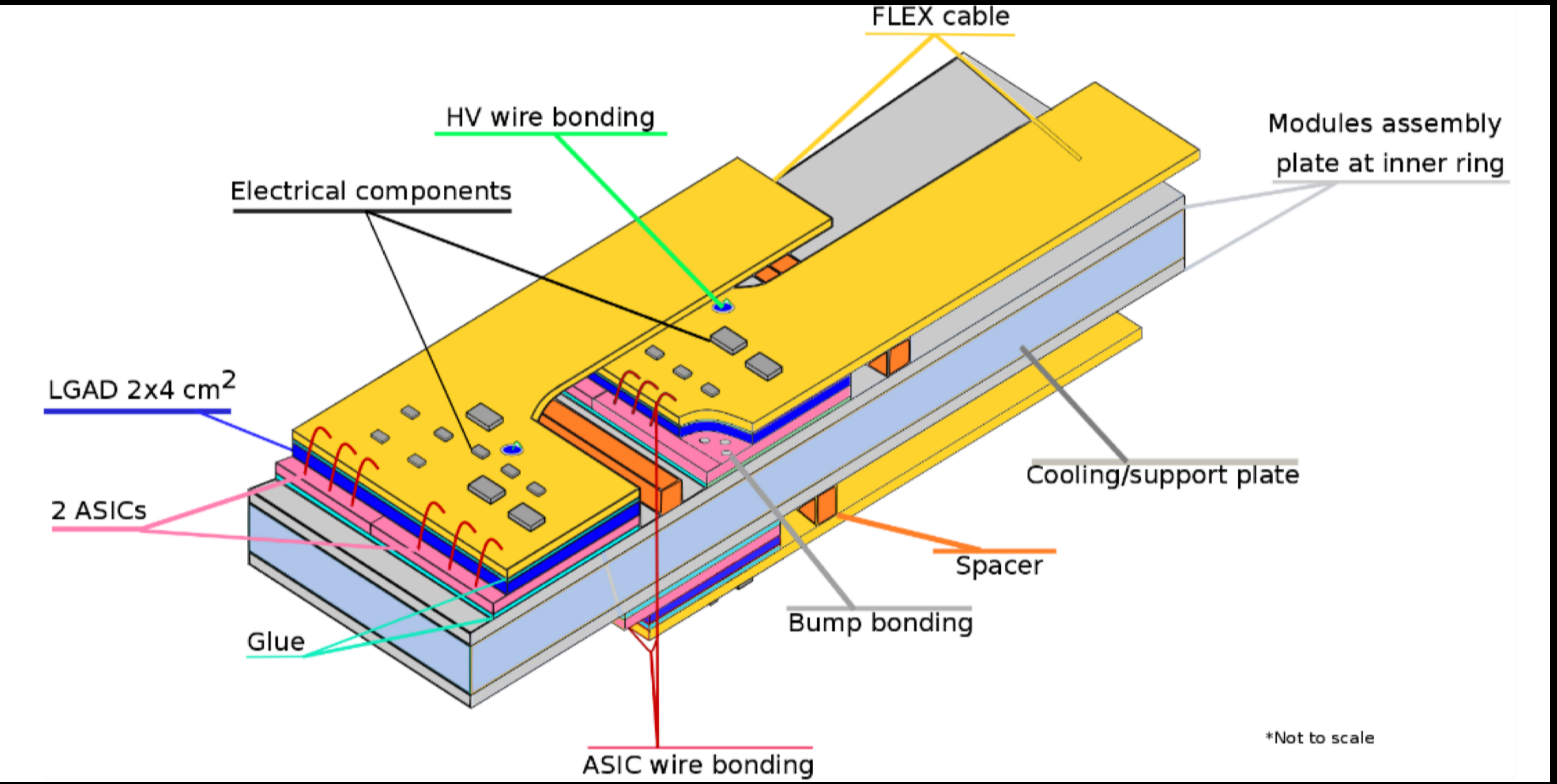
Sensor testing—collected charge



3e15

6e15

Module assembly



Full size Module :1 LGAD + 2 ASIC

- 15x30 channels
- 2cm x 4cm

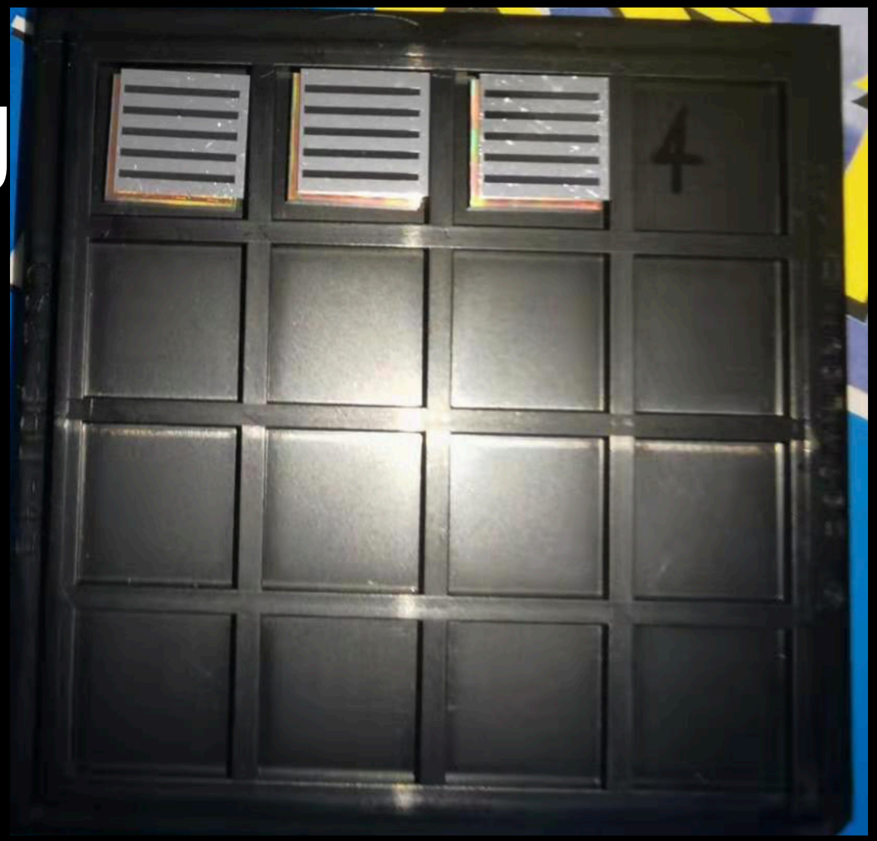
Existing module prototype

- 5x5 channels
- Daughter board + FPGA mother board

5x5 ch LGAD sensor
ALTIROC1_V2 ASIC

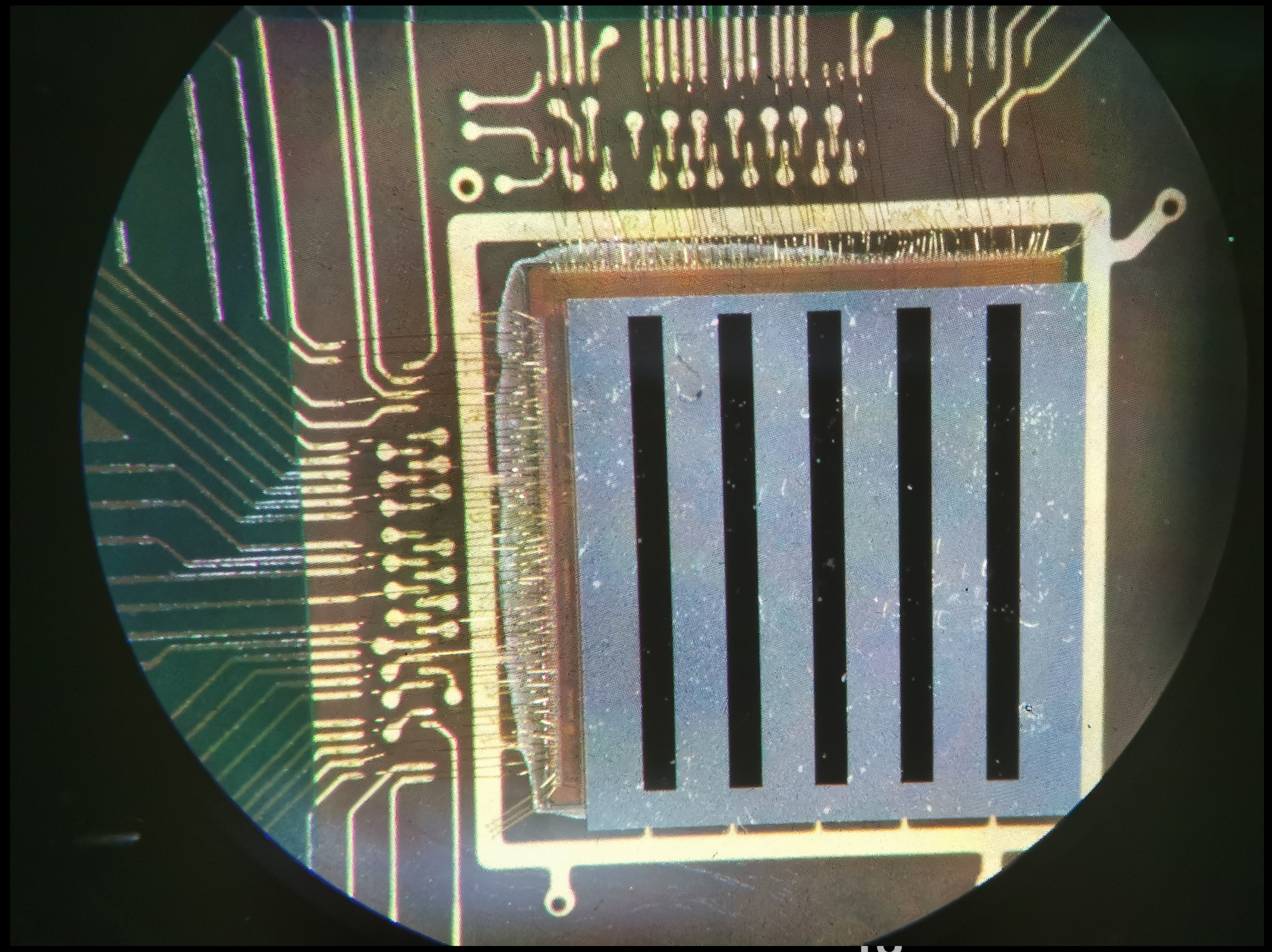
Bump bonding

Bare modules



wire bonding

Module on test board

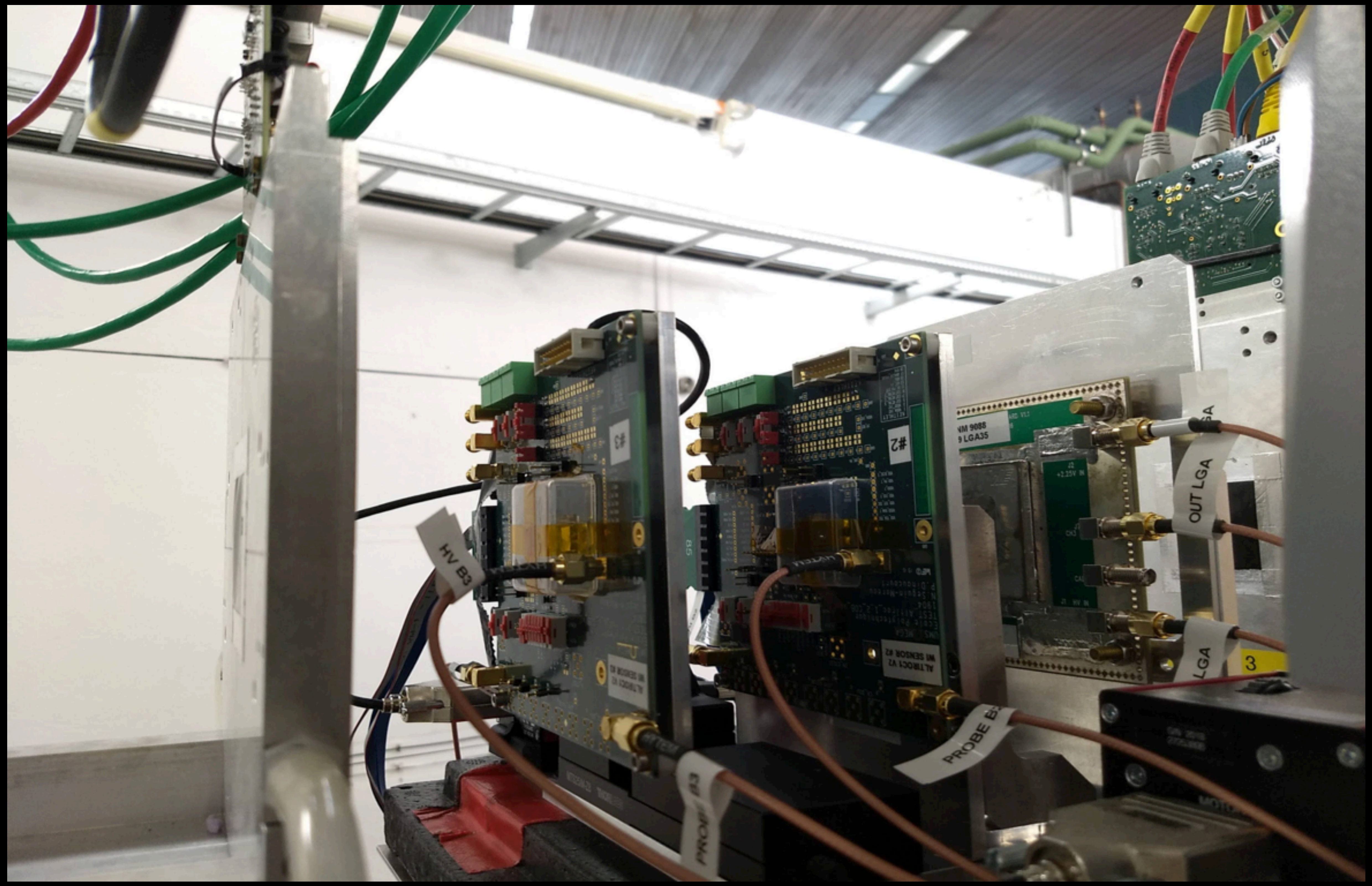


Test beam setup

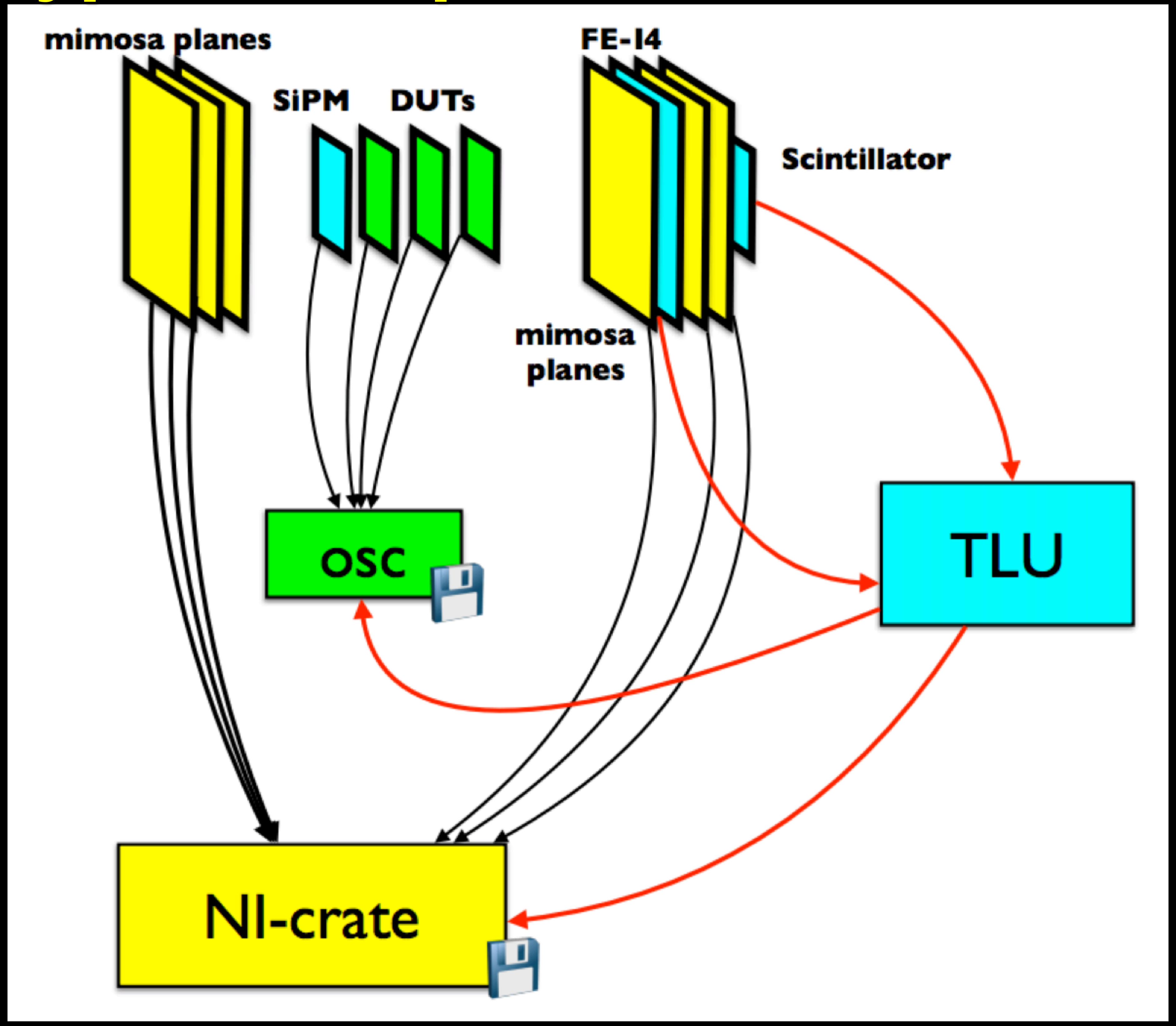
A lot of test beam study performed for HGTD

- sensor testing: Single channel board+ Oscilloscope
- Module testing: ALTIROC chip is used for readout + Oscilloscope for debug
- Minosa telescope for tracking (position information)

Setup in November 2019 testbeam
5x5 module testing



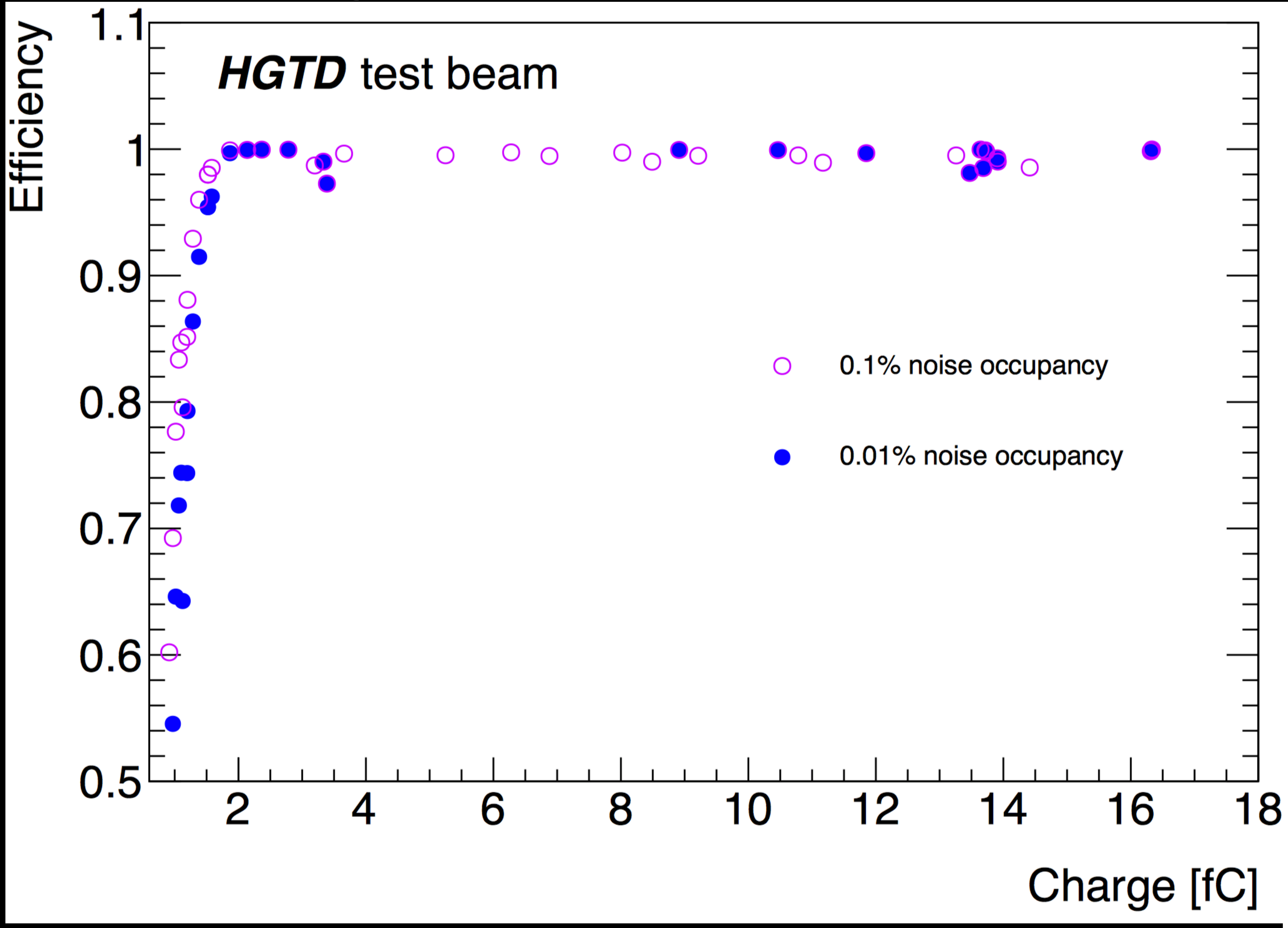
Typical setup in HGTD testbeam

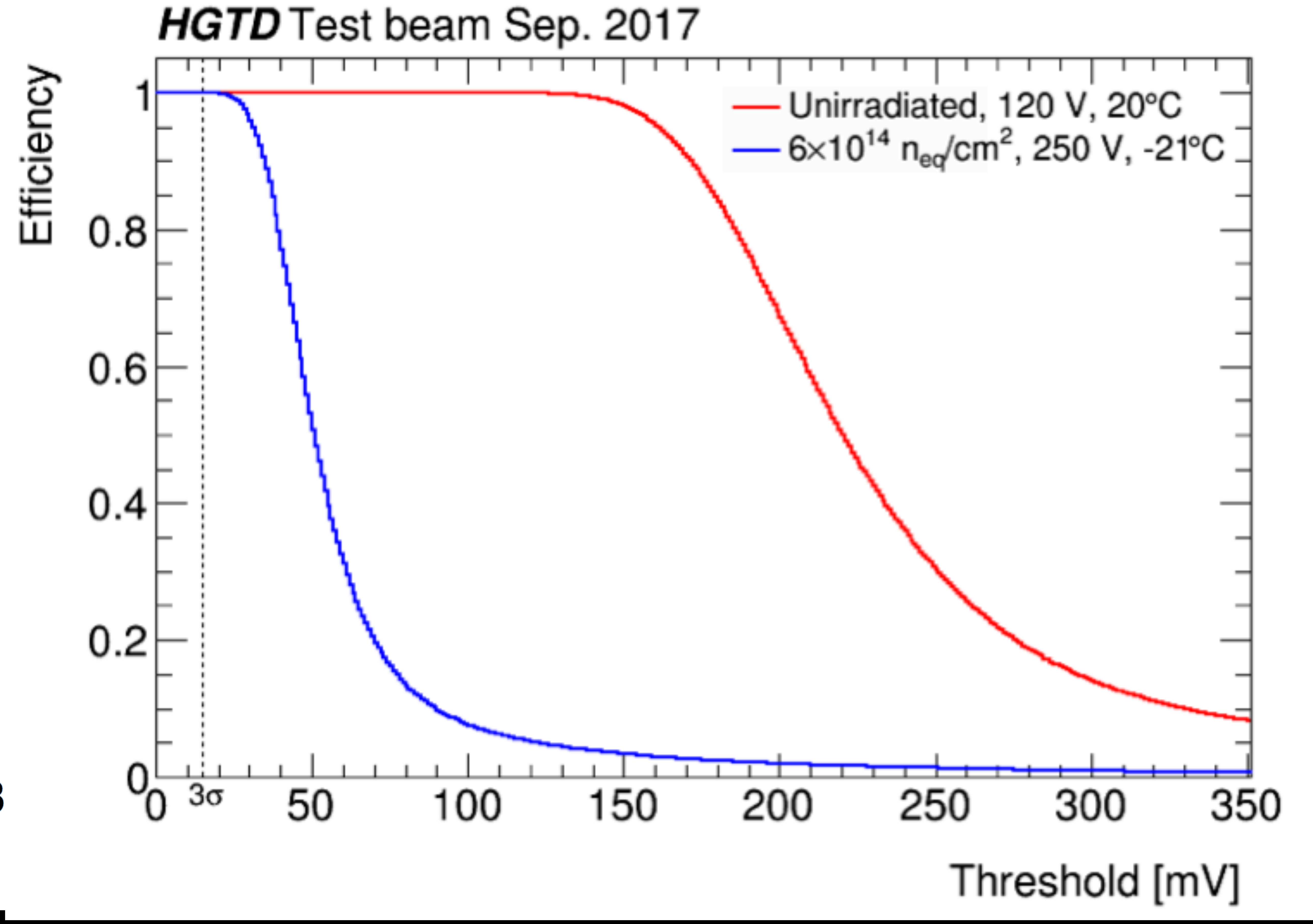


Arrays: sensor efficiencies vs threshold

Hit efficiency vs collected charge at a noise occupancy of 0.1 % and 0.01% (Sensor only result)

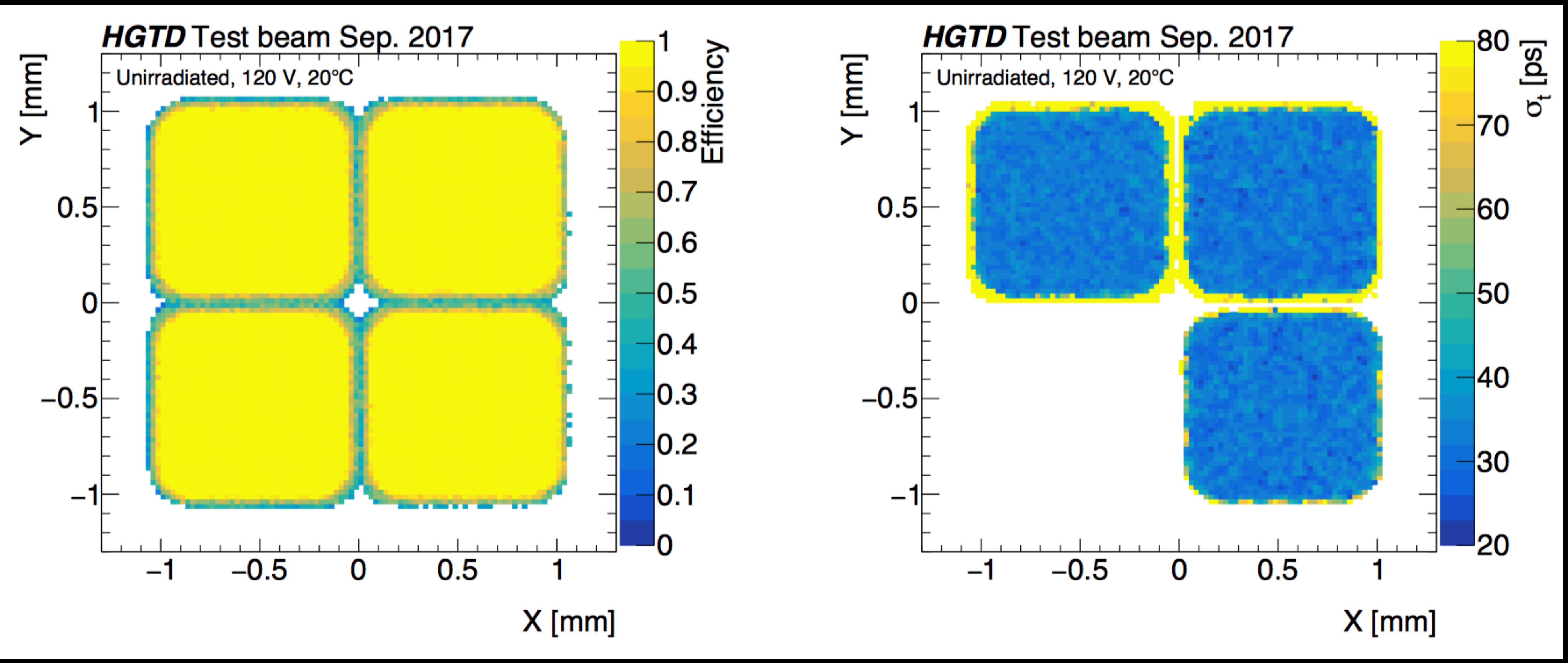
Signal efficiency vs the amplitude threshold (Sensor only result)



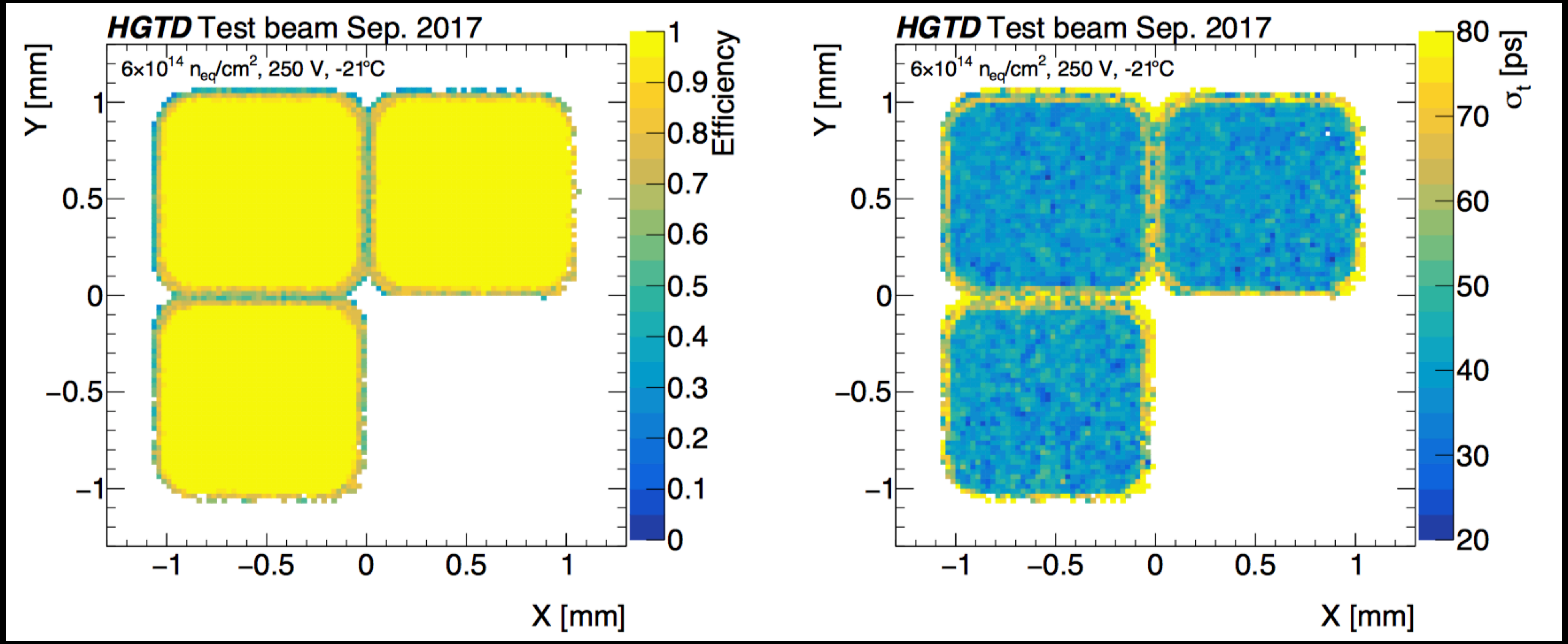


Test beam: timing and uniformity

Before irradiation



After 6e14 Neq/cm2 of irradiation

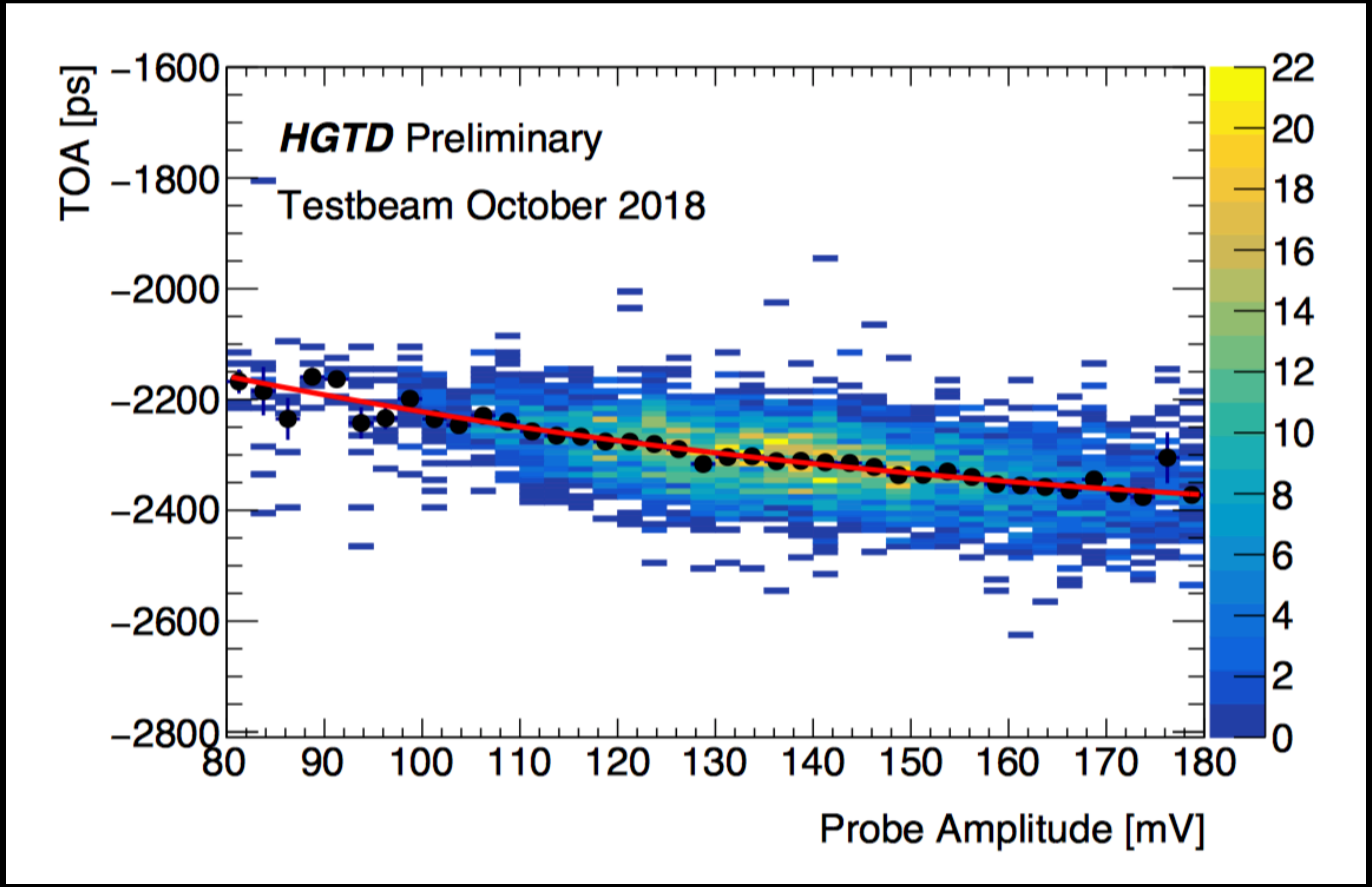


- Pions test beam at CERN
- Results for 2x2 CNM arrays
- Radiation impact slightly visible
- Efficiency ~ 100 %
- Inter-pad gap is efficient after irradiation

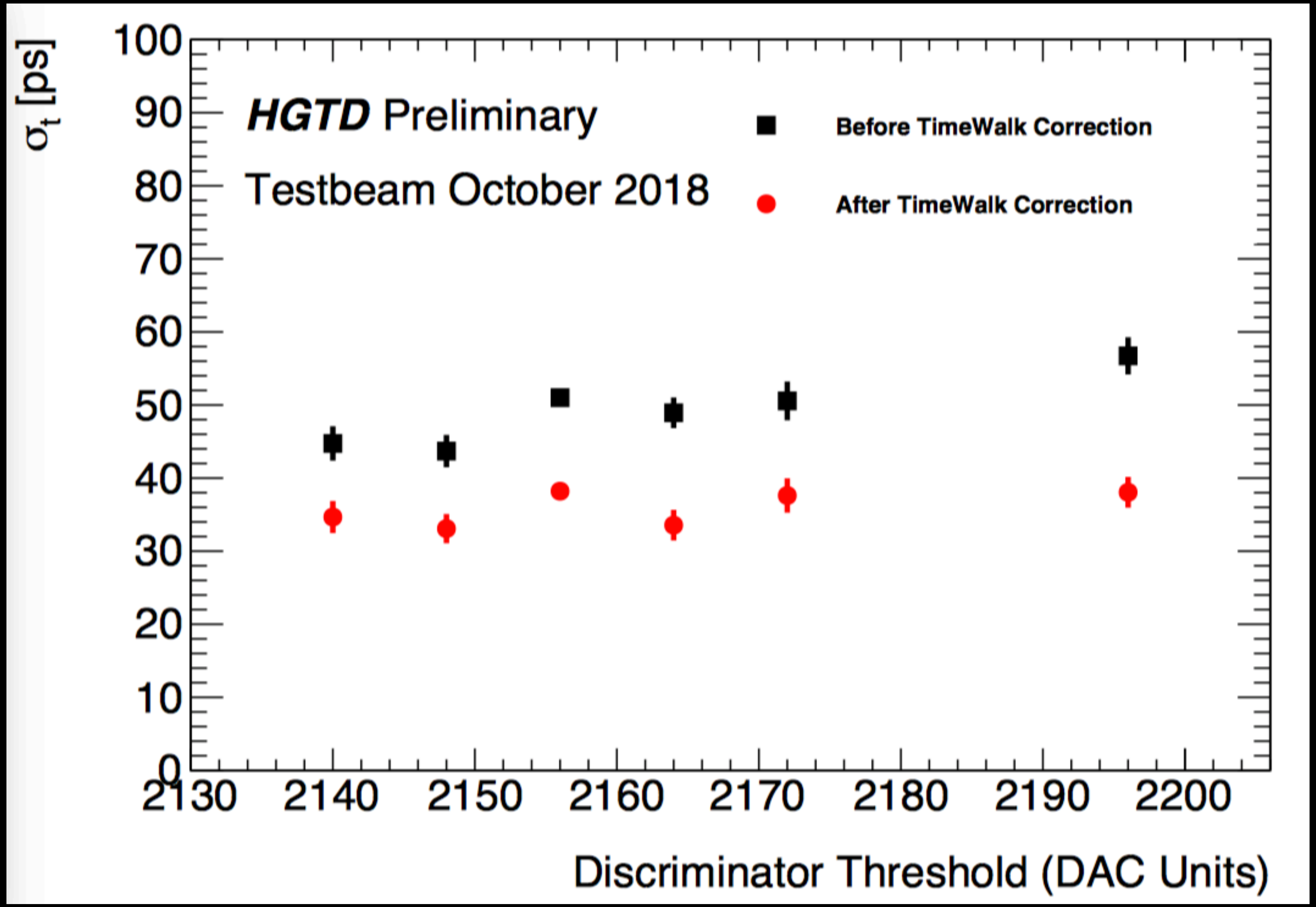
Test beam: module prototype performance

- Testbeam results from ALTIROC0 bump-bonded to 2x2 array
- Can achieve 35 ps with timewalk correction

TOA(Time of arrival) variation Vs the amplitude of preamplifier output



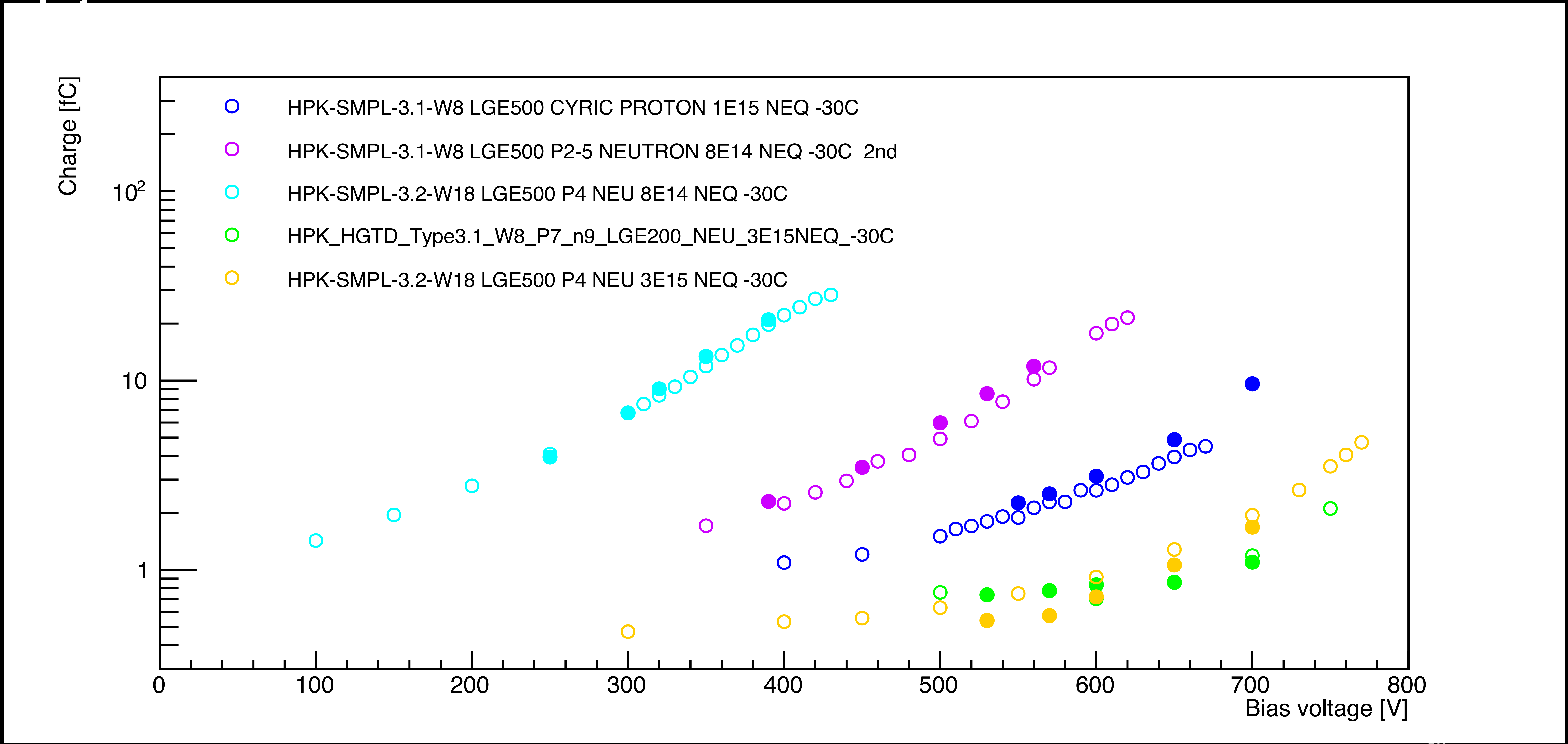
Time resolution as a function of the threshold



Test beam Vs Lab test: collected charge

Consistent result between test beam and Beta source testing in lab

open symbols and lab beta source measurements, filled symbols DESY TB



Summary

- **HGTD project is going forward as scheduled**

- **Several companies (FBK, CNM, HPK, NDL) producing LGADs prototypes fulfilling (or very close) to fulfill HGTD requirements.**
- **< 50 ps per hit up to 2.5x10^{15} N$_{eq}$ /cm^2 with thin LGAD sensors**
- **2x2 ch and 5x5 ch module prototype tested in testbeam**
- **Full size (15x30 ch) sensors will be available mid 2020.**

- **HGTD Technical Design Report (TDR) will submit to LHCC on April 2020**