中國科學院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Recent development of ultra-fast timing detector in Cina and its potential application in CEPC

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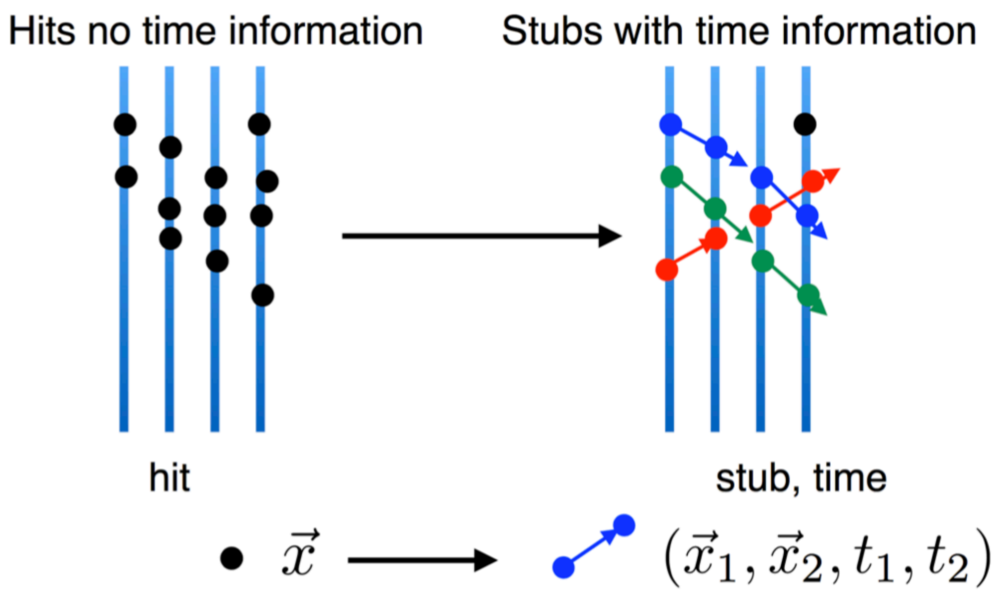
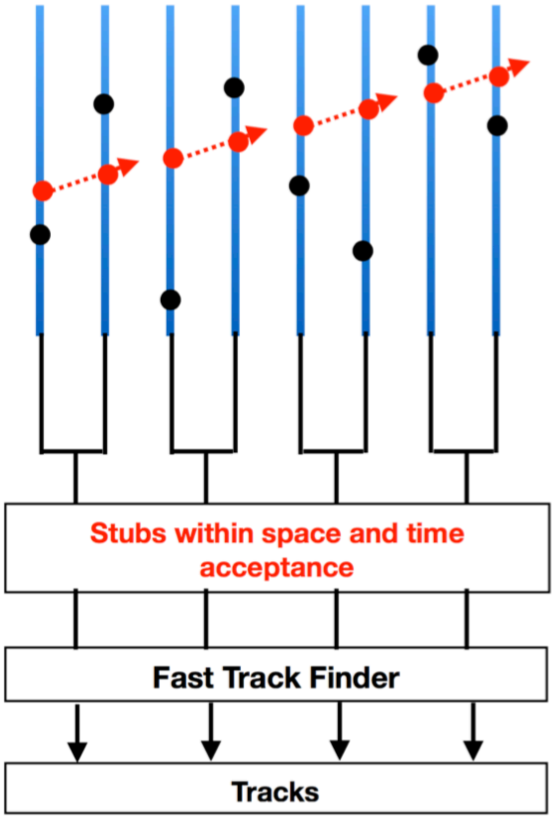
Institute of High Energy Physics ,
Chinese Academy of Science

CECP workshop 2019

Timing detector for CEPC

- 4D tracking for CEPC particle flow reconstruction.
- Need a silicon technology with both time and spatial resolution

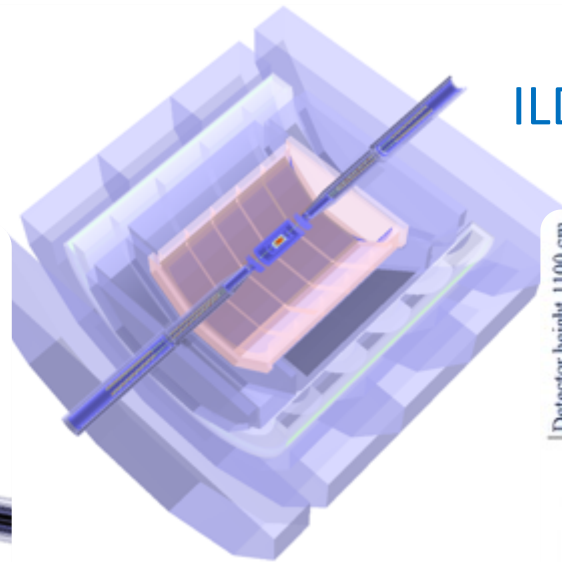




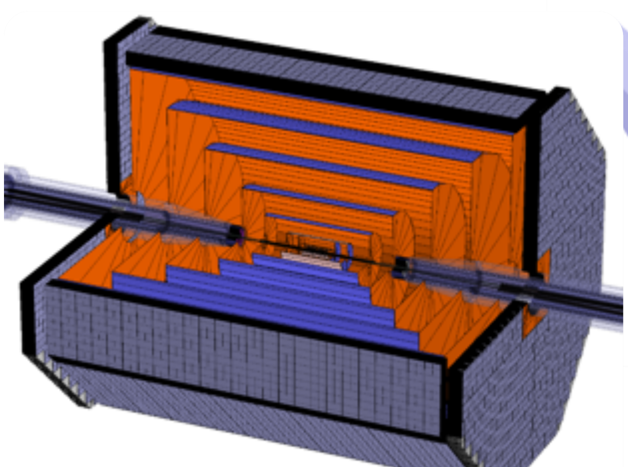
https://iopscience.iop.org/article/10.1088/1748-0221/11/11/C11040/pdf

Timing detector for CEPC

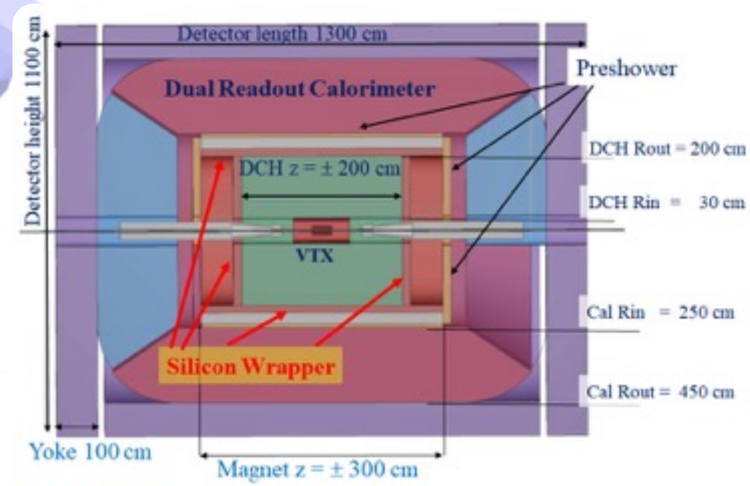
- For full silicon concept, there is no particle identification
  - Need a silicon technology with both time and spatial resolution



ILD-Like, Baseline design



Full silicon



IDEA

Particle identification for CEPC

- K/pi separation for CEPC flavor physics for full silicon concept
  - 10ps time solution can provide 2~3 sigma K/pi separation at 5~7GeV

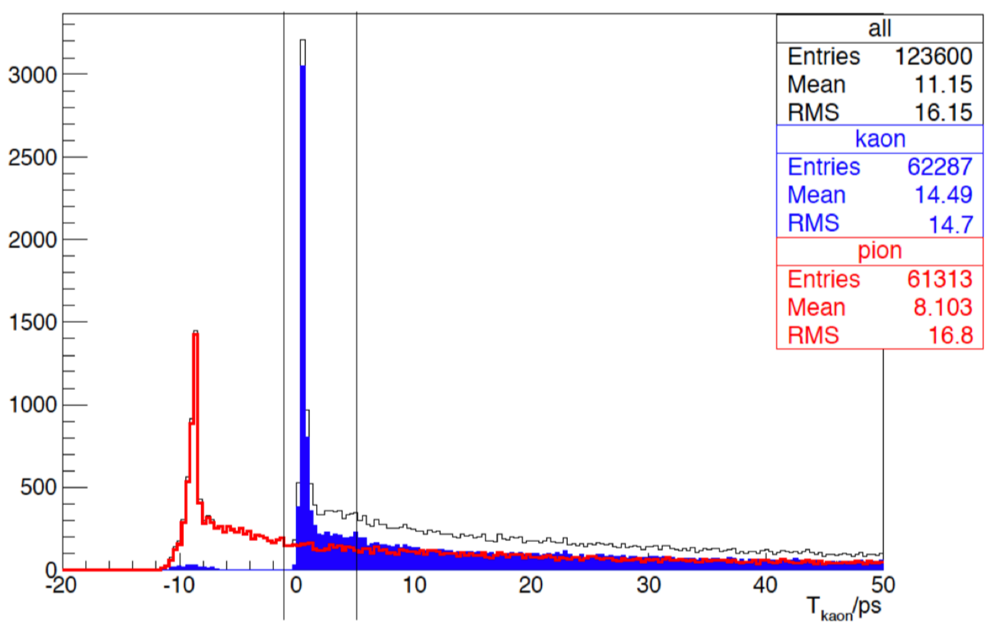
$$\Delta t = 0.5*L/c*(\gamma_1^{-2} - \gamma_2^{-2}) = 0.5*L/c*E^{-2}(m_1^2 - m_2^2)$$

mass(pion) = 139 MeV; mass(Kaon) = 493 MeV;

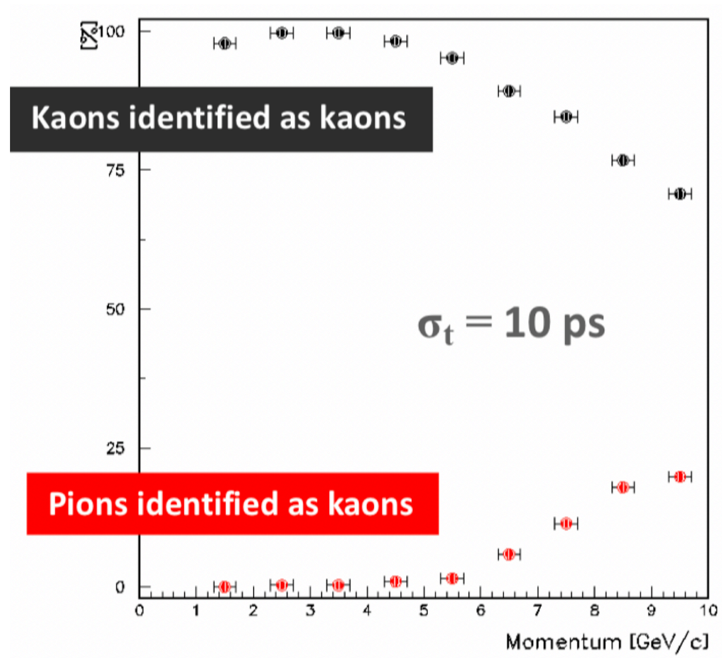
$$\Delta t = k*LE^{-2} = 380*L/m*(E/GeV)^{-2}\ ps$$

Study from CEPC (by Manqi)

Hit Time Spectrum Calibrated To Kaon Speed, 10GeV

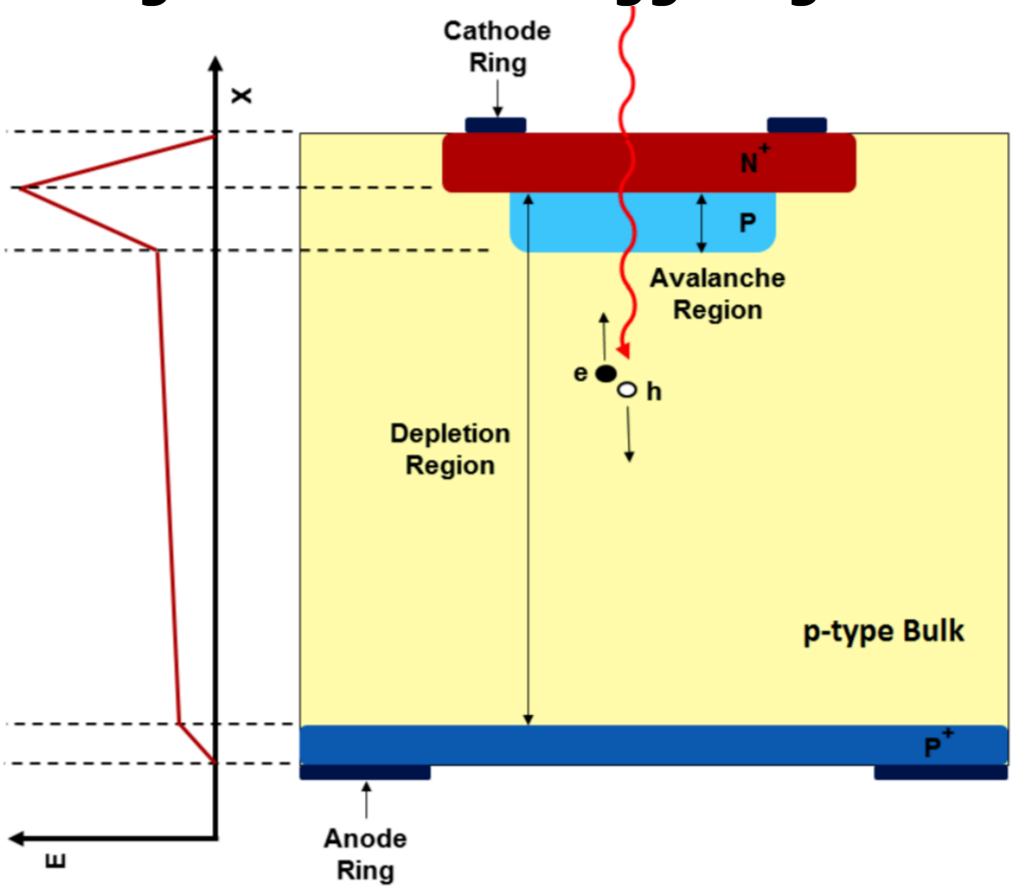


Study from Topside



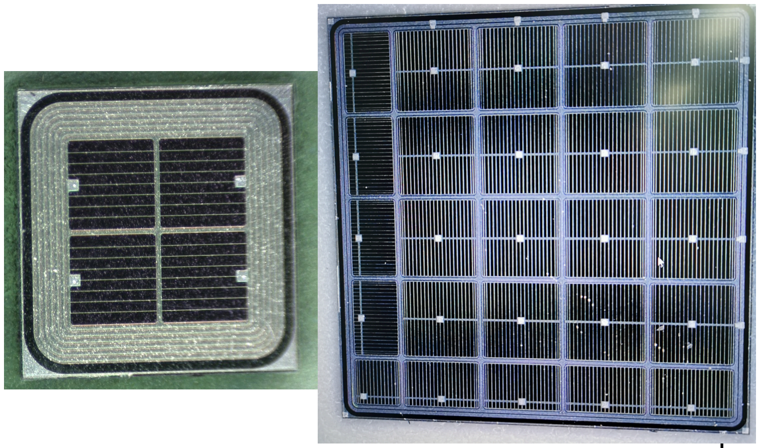
Low gain Avalance detector (LGAD)

- **Low-Gain-Avalanche-detector (LGAD)**
  - **Compared to APD and SiPM, LGAD has lower gain (~10)**
  - **high drift velocity, thin active layer (fast timing)**
  - **High S/B, no self-triggering**



LGAD Foundry:
- ➢ **HPK (Japan)**
- ➢ **CNM(Spain)**
- ➢ **FBK (Italy)...**
- ➢ **IHEP-NDL (China)**

Prototype of IHEP-NDL LGAD sensors



LGAD sensor R & D in China：NDL LGAD sensor

– LGAD sensor with Epitaxial layer
- NDL is foundry for SipM. They started at LGAD R & D with IHEP in 2019.
- Three batches LGAD sensor fabricated in 2019.
- Thickness of epitaxial layer: 33um
  - epitaxial layer Resistivity: 100 Ohm.cm or 300 Ohm.cm

http://www.ndl-sipm.net/contacteng.html

NDL can provide reliable and cost effective SiPMs with typical delivery time from 1 week to 3 months.

Novel Device Laboratory（NDL）
Address: XueYuan Nan Lu No.12
Hai Dian District, Beijing, China,100875
Tel: +86-10-62207419, Fax：+86-10-62207419
Email：info@ndl-sipm.net

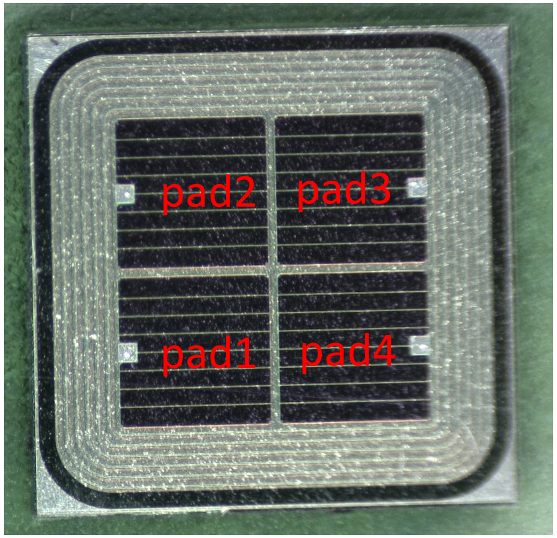
Photoelectric Instrument Factory of Beijing Normal University
Address: 1st floor in block B of Dormitory 4 Xin Wai Da Jie No.19, Hai Dian District, Beijing, China
Tel: 010-58807630
Email: 58807630@163.com
Web: http://www.peifbnu.com/plus/view.php-aid=72.html

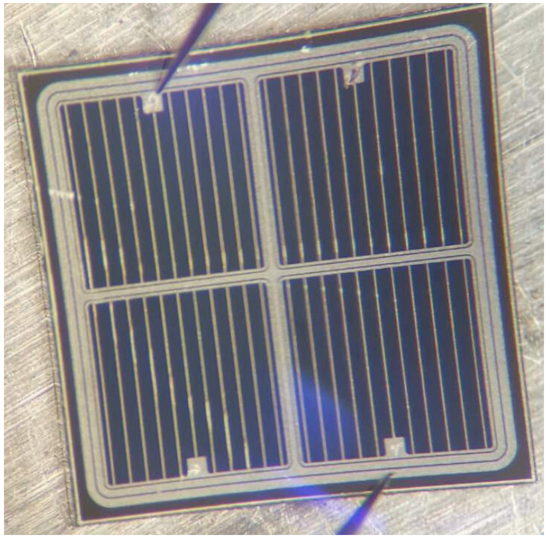
IHEP-NDL sensor design

- 6 guard ring (floating, no metal contact) : BV170, BV60
- (new!!) 2 guard ring (with metal contact, can be grounded) : Type 9#, 10#
- Higher breakdown voltage (VBD) with new guard ring design

	VBD	V_Depleted	Layout	Wafer	Gain
Type 13# (BV170)	~165V	~100V	6GR	100Ω.cm	40
Type 12#(BV60)	~95V	~40V	6GR	300Ω.cm	40
Type 10# (new!)	~300V	~40V	2GR	300Ω.cm	80
Type 9# (new!)	~250V	~40V	2GR	300Ω.cm	80

6 guard ring design
No Metal contact
Guard ring floating

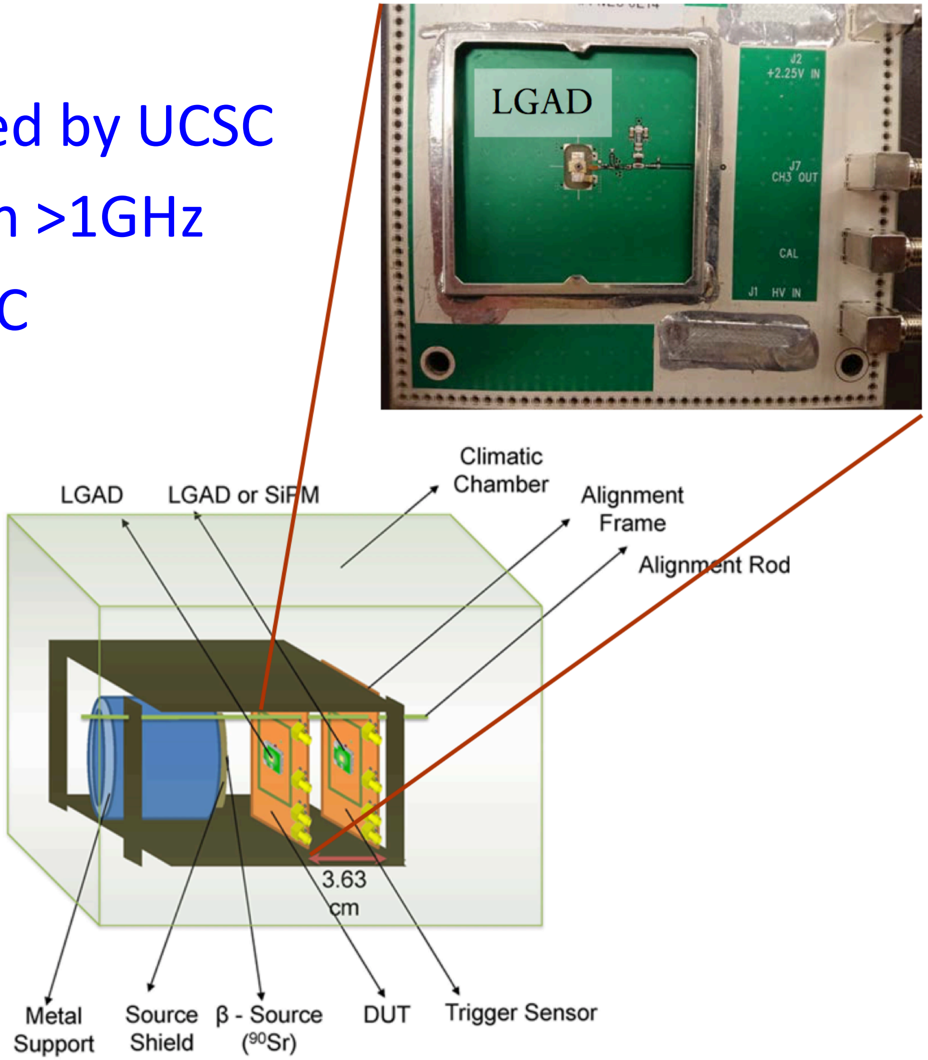




2 guard ring design (new!!)
With metal contact
Can be grounded

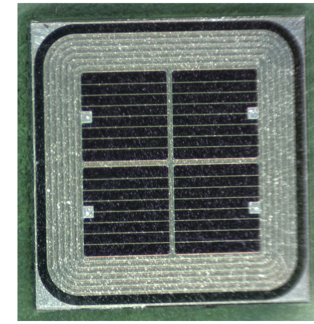
Beta test

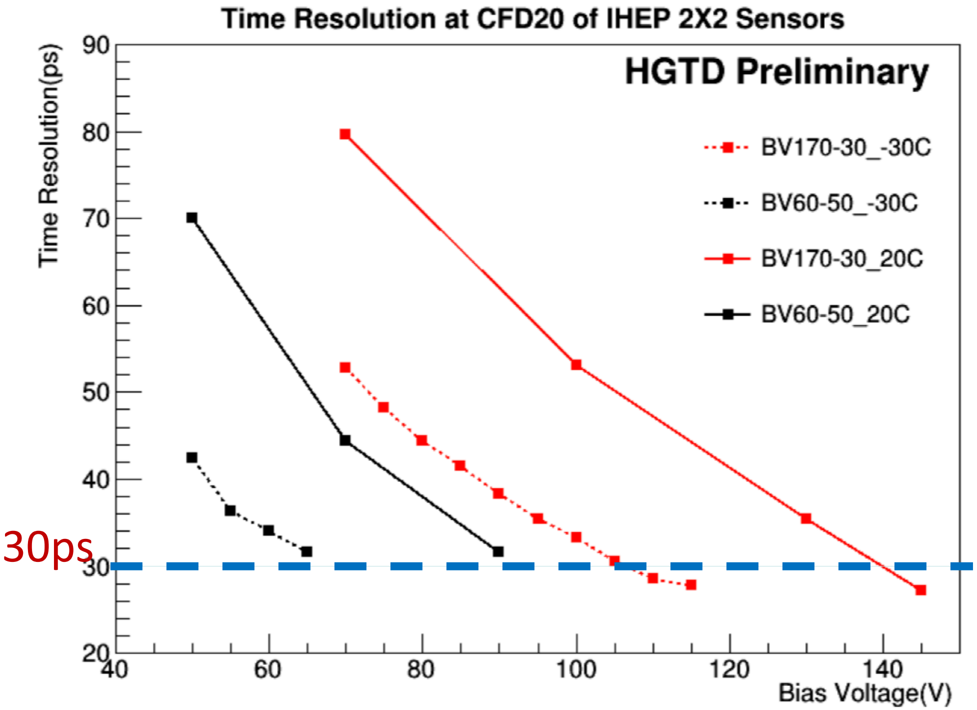
- Beta test (collected charge, gain, time resolution)
- Electrons by Sr90 Beta source
- Single channel board developed by UCSC
- Fast amplifier with bandwidth >1GHz
- Climate chamber to run at -30C

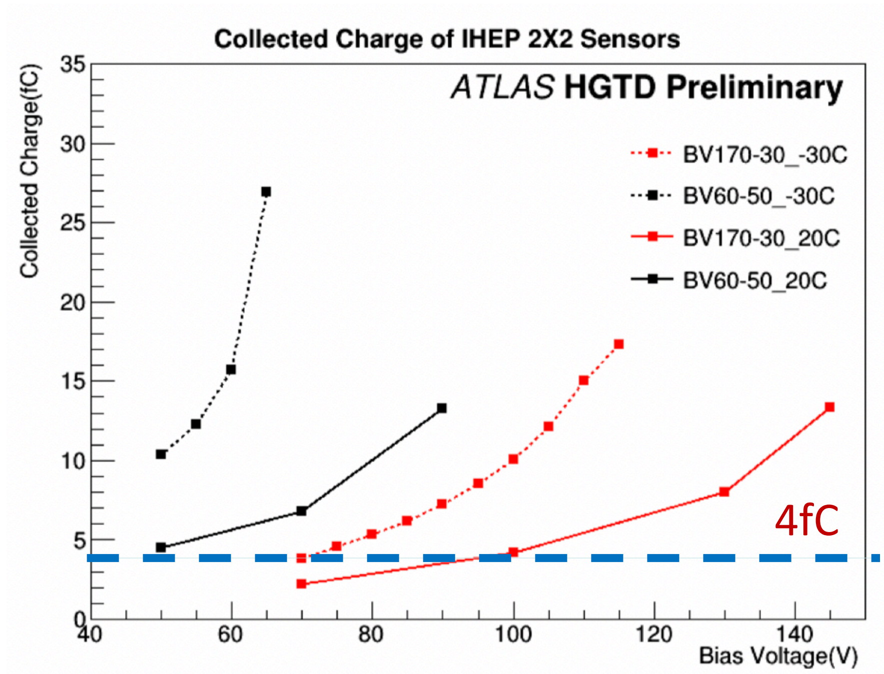


IHEP-NDL LGAD sensor performance

- New LGAD foundry in China: The Novel Device Laboratory
  - ➢ just start prototyping LGAD sensor early 2019
  - ➢ Two prototype of 2x2 LGAD, 5x5 LGAD
  - ➢ Time resolution is about 30ps
  - ➢ Charge collection: 10~30 fC



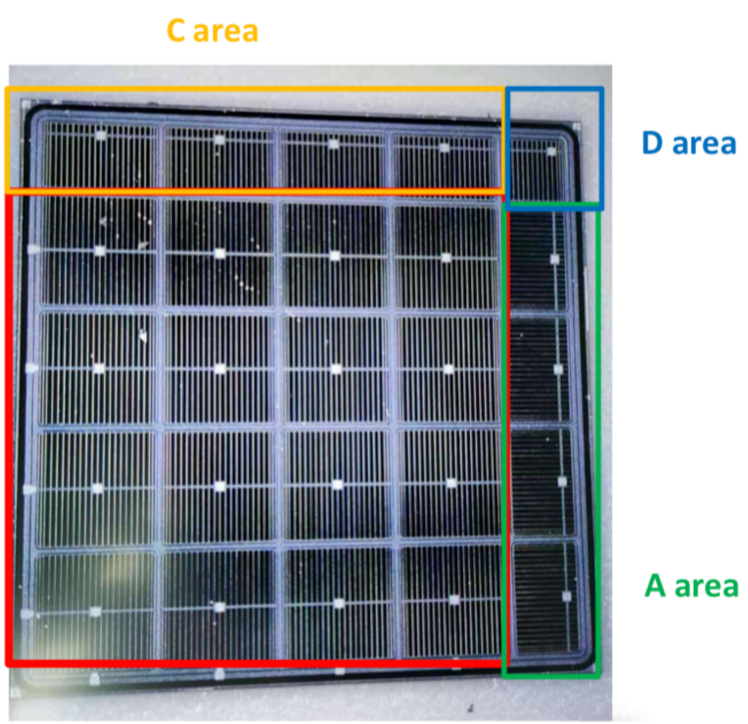


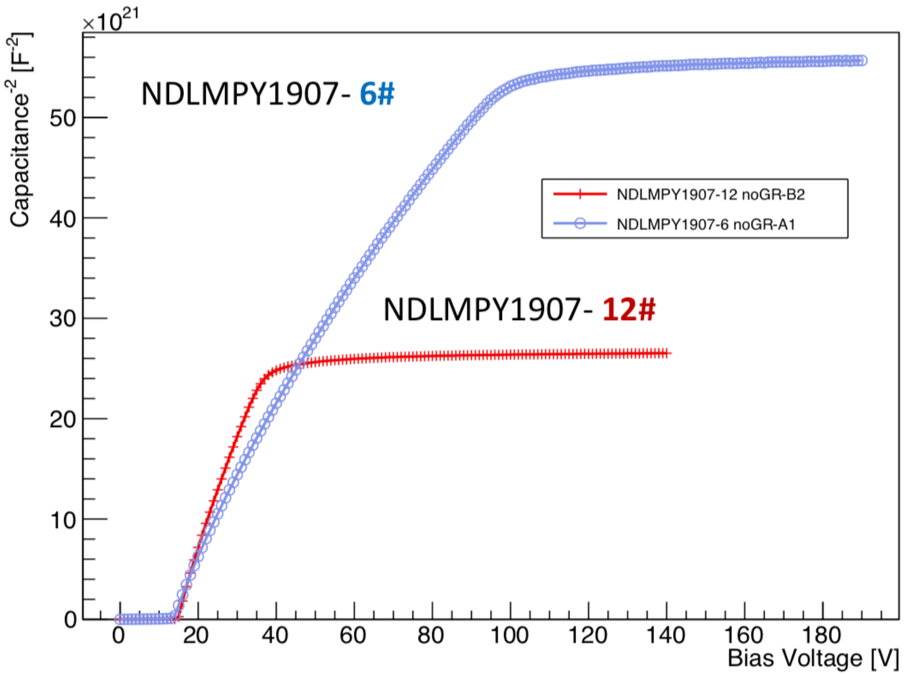


5x5 NDL sensors

- Two type of NDL 5x5 sensors are fabricated in Sep 2019

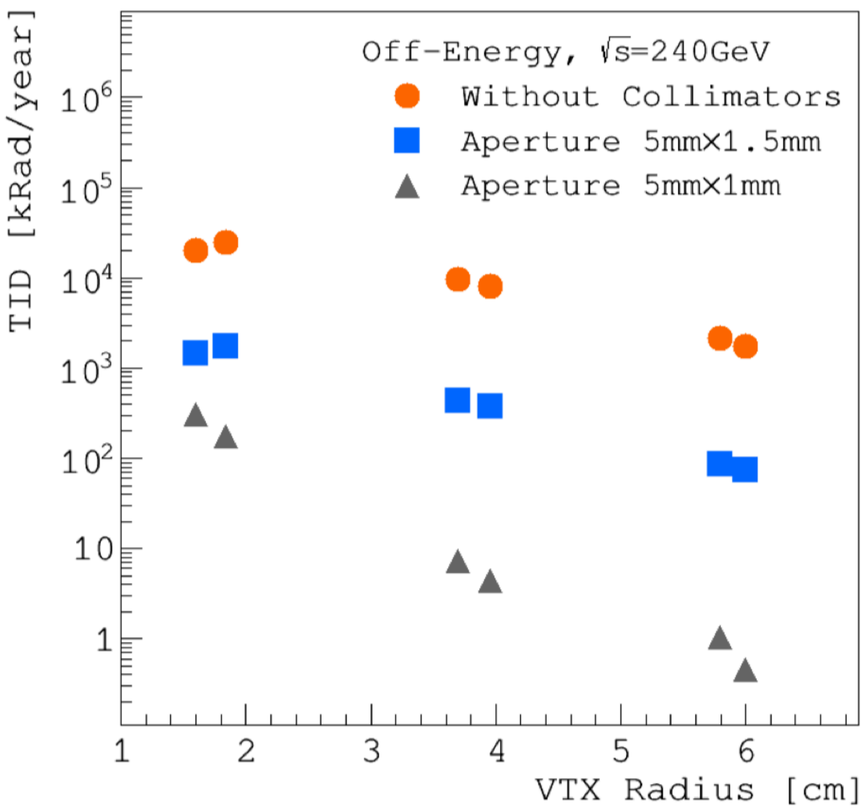
	VBD	V_Depleted	Layout	Epi layer(33um) resistance	Gain
NDL 5x5 6#	~250V	~120V	2 guard ring	100Ω.cm	10~20
NDL 5x5 12#	~235V	35V	2 guard ring	300Ω.cm	10~20

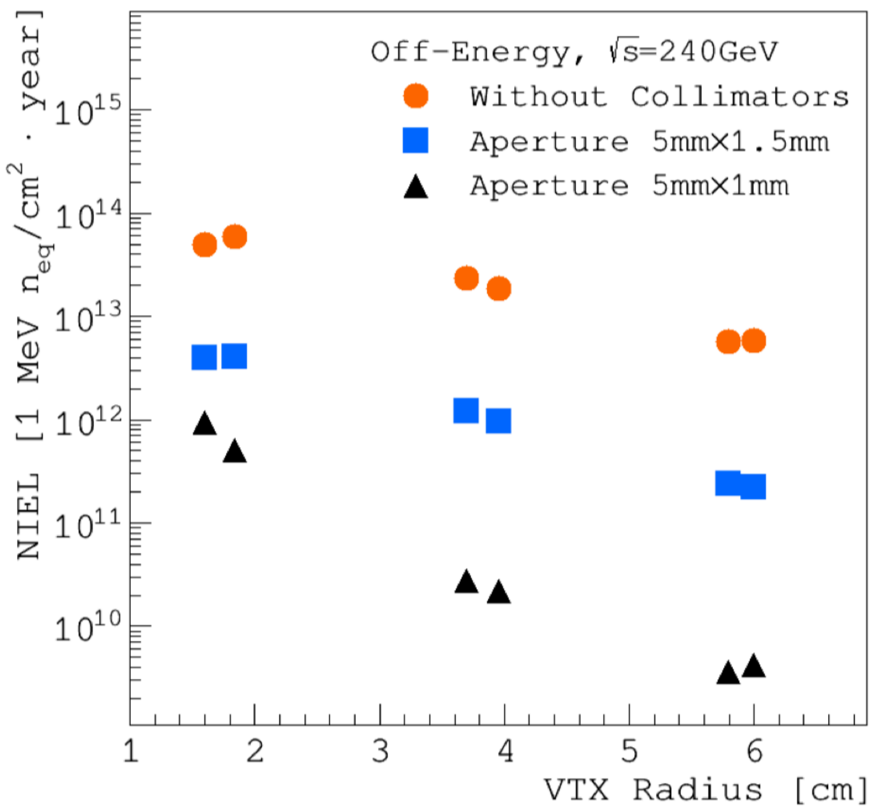




Irradiation hardness requirement

- The requirements will change with different MDI design
- Total ionization dose(from CDR): ~ 10MRad (100kGy)
- Fluence (from CDR): ~$10^{13} N_{eq}/cm^2$

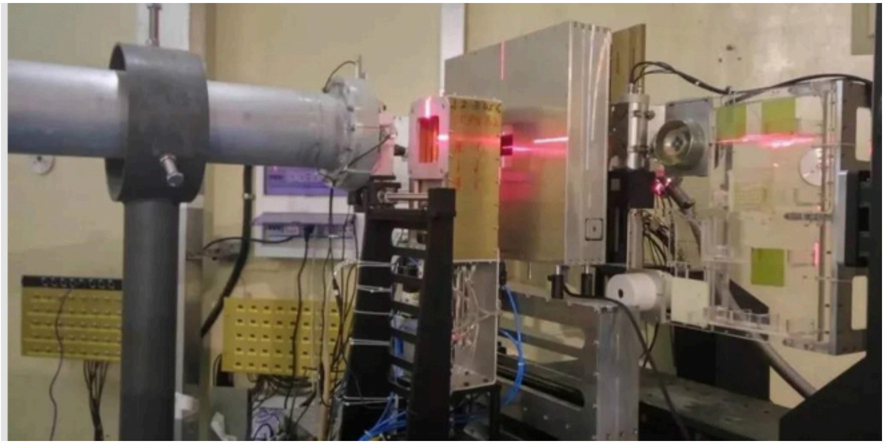




Irradiation campaign

- Irradiation hardness is important for HGTD project
- IHEP is responsible for irradiation tests
  - Leading total ionization dose (TID) study for sensor and module
    - X ray irradiator in IHEP, TID up to 200MRad
  - Carried out one irradiation campaign for non-ionization damage
    - Collaboration with China atom energy institute (CIAE) for 100MeV proton irradiation
    - Fluence up to $4x10^{15}$ n_{eq}/cm^2

100MeV Proton irradiation campaign in CIAE

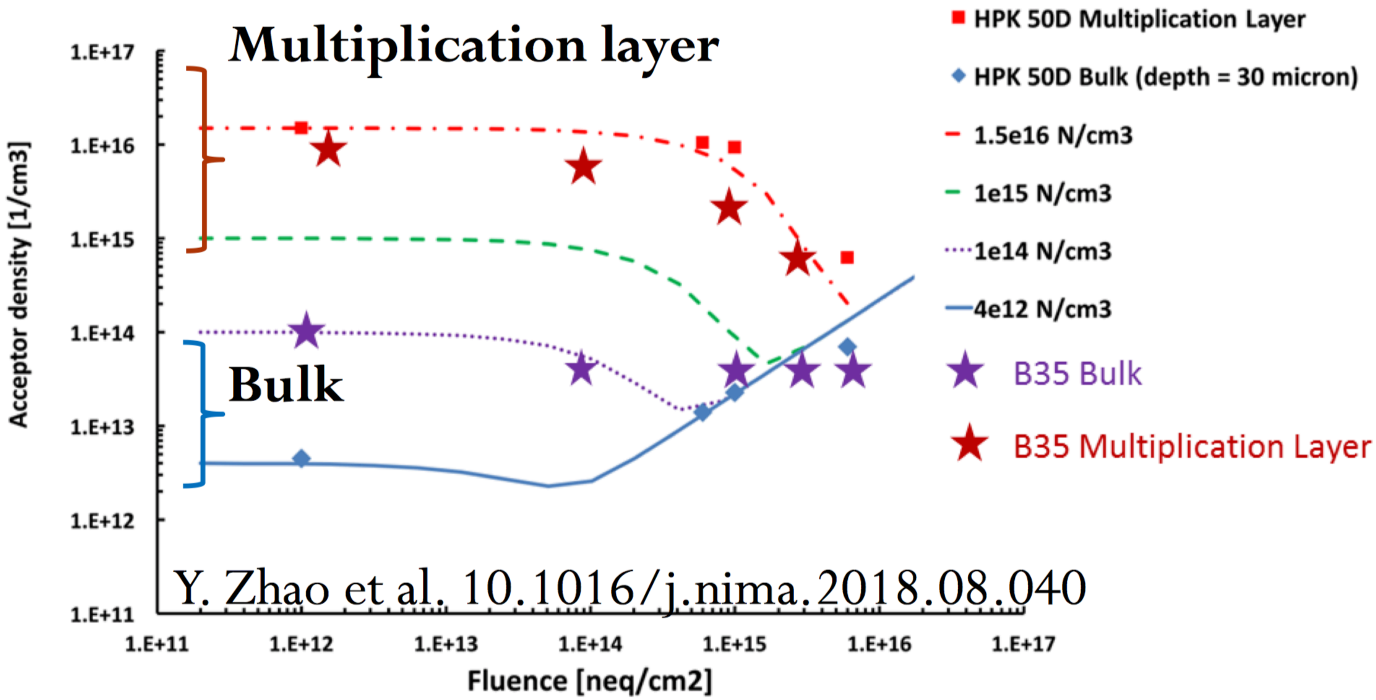


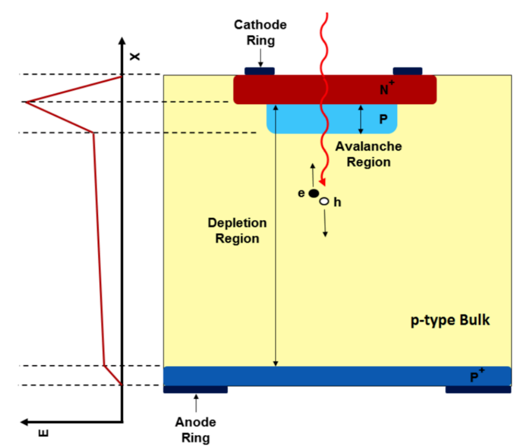
X ray irradiation in IHEP

Radiation damage effect for LGAD : Acceptor removal

- 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

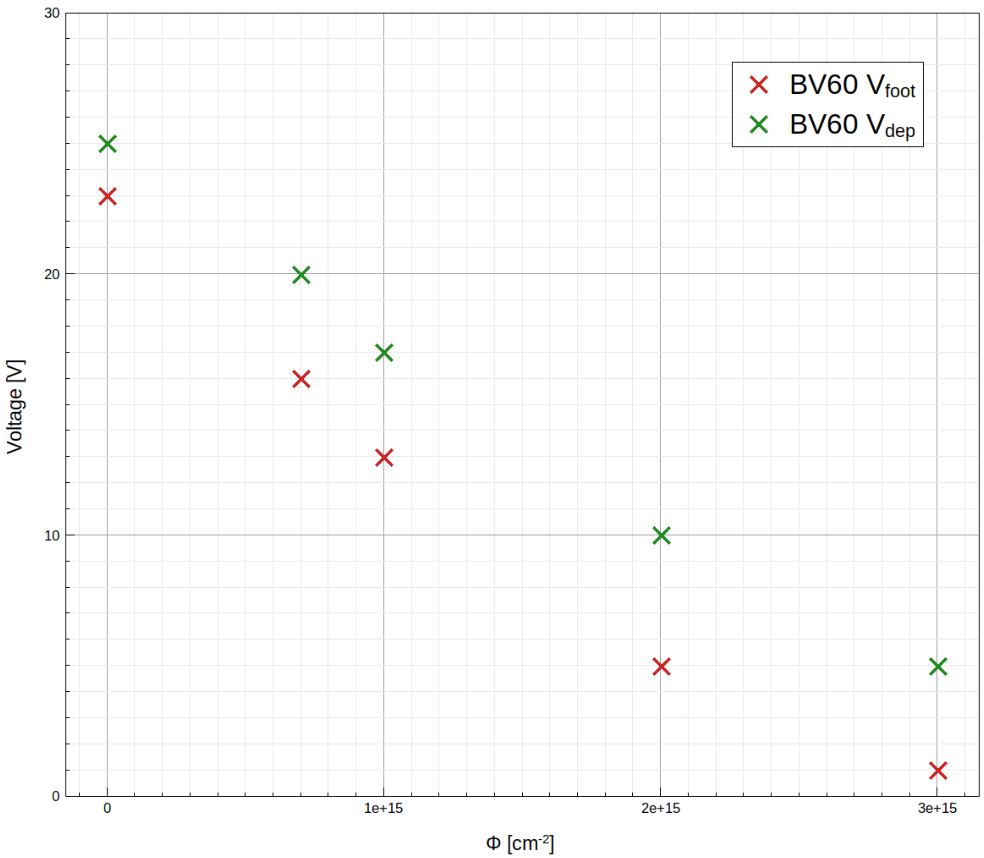
$$N_A(\phi) = g_{eff}\phi + N_A(\phi{=}0)e^{-c\phi}$$

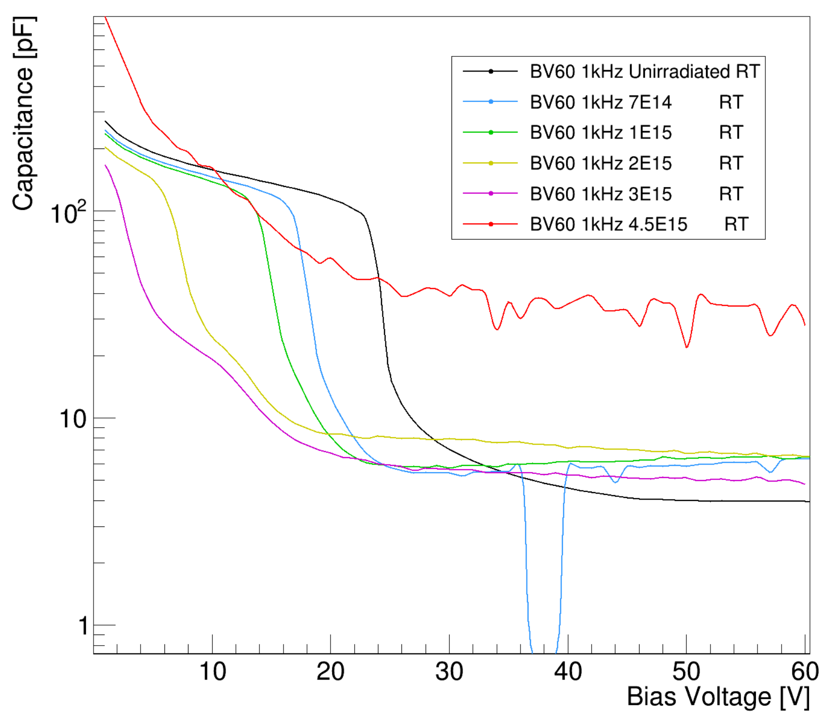




First Results of CIAE irradiation: NDL sensors

- Depleted voltage and foot voltage Vs fluence
  - Much easier to depleted the LGAD sensor after 1e15 N_{eq}/cm^2
  - It should be good for CEPC application ($10^{13} N_{eq}/cm^2$)
  - Need more study for LHC application

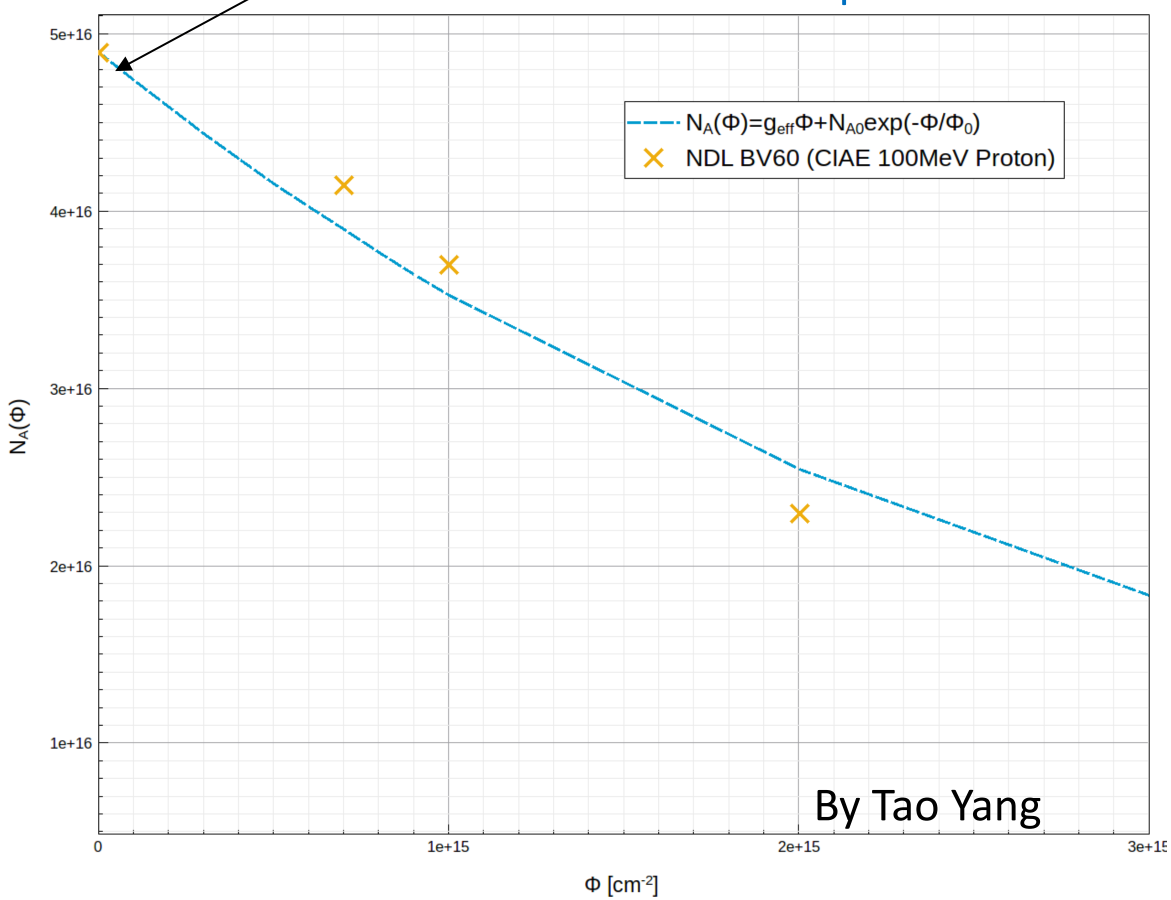


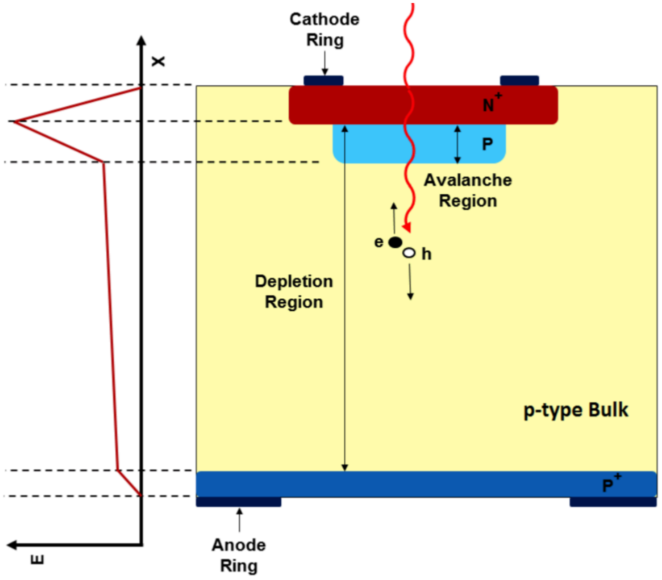


Acceptor removal effect

- P+ doping density decrease after irradiation
  - Need more study for LHC application
  - It should be good for CEPC application (10^{13} N_{eq}/cm^2)

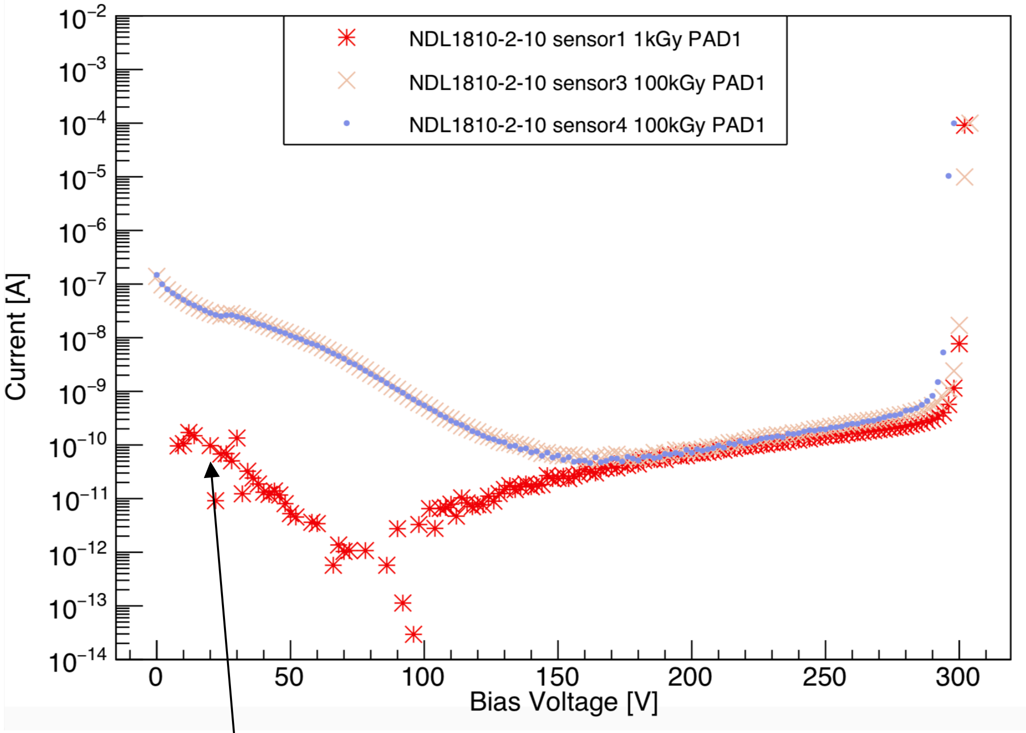
CEPC irradiation hardness requirement





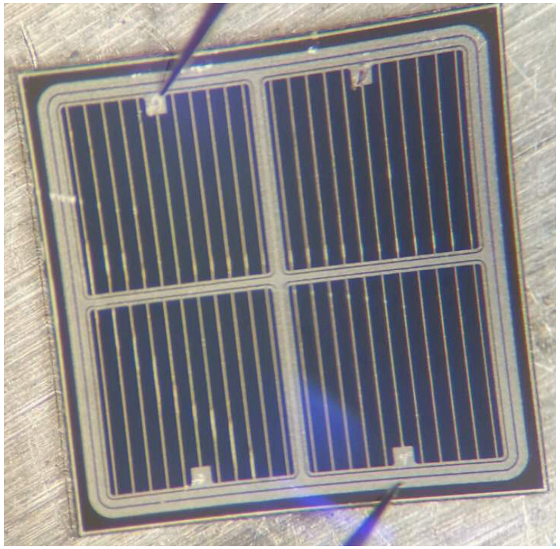
I-V after X ray irradiation :NDL sensor (1)

	VBD	V_Depleted	Layout	Wafer	Gain
Type 13# (BV170)	~165V	~100V	6GR	100Ω.cm	40
Type 12#(BV60)	~95V	~40V	6GR	300Ω.cm	40
Type 10#	~300V	~40V	2GR	300Ω.cm	40
Type 9#	~250V	~40V	2GR	300Ω.cm	80



Due to Metal pad in Guard ring?

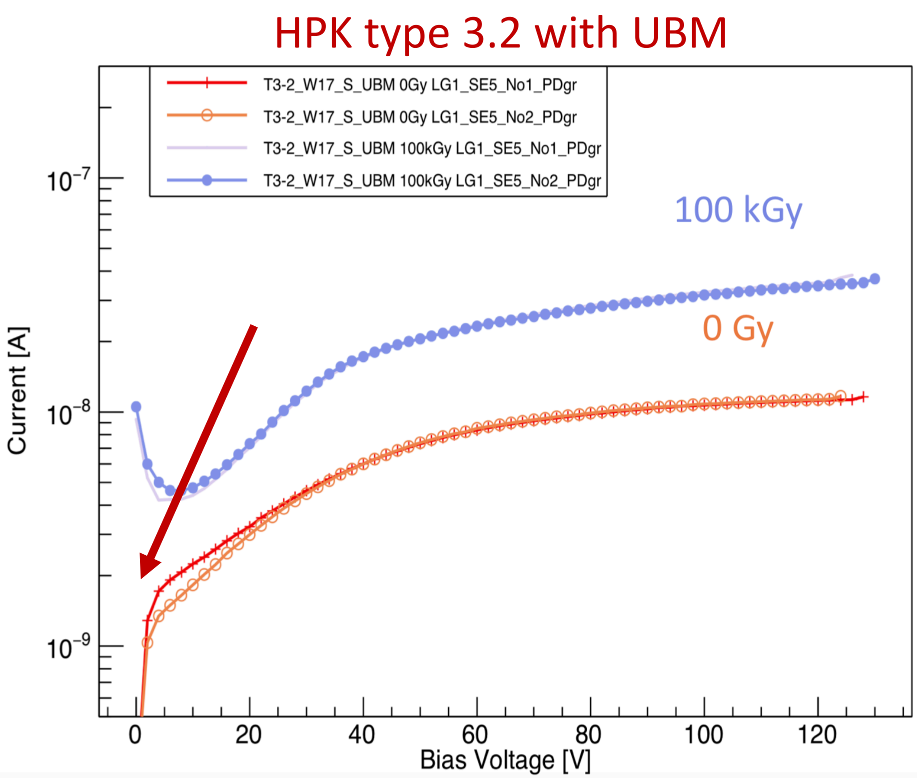
- I_leak is lower after irradiation
  - ~ 0.1 nA
- I_leak is large at low V_bias
  - can improve by adjusting GR

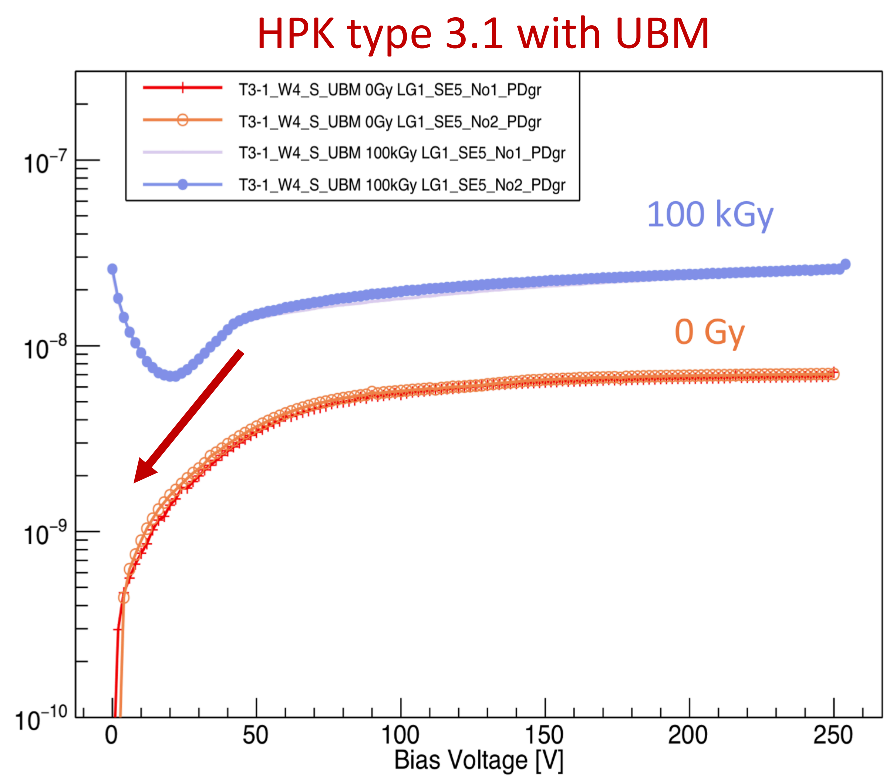


From Yunyun

I-V after X ray irradiation : HPK sensor

- Guard Ring current at 100kGy increases
  - >= 4 times compared the current at 0Gy.

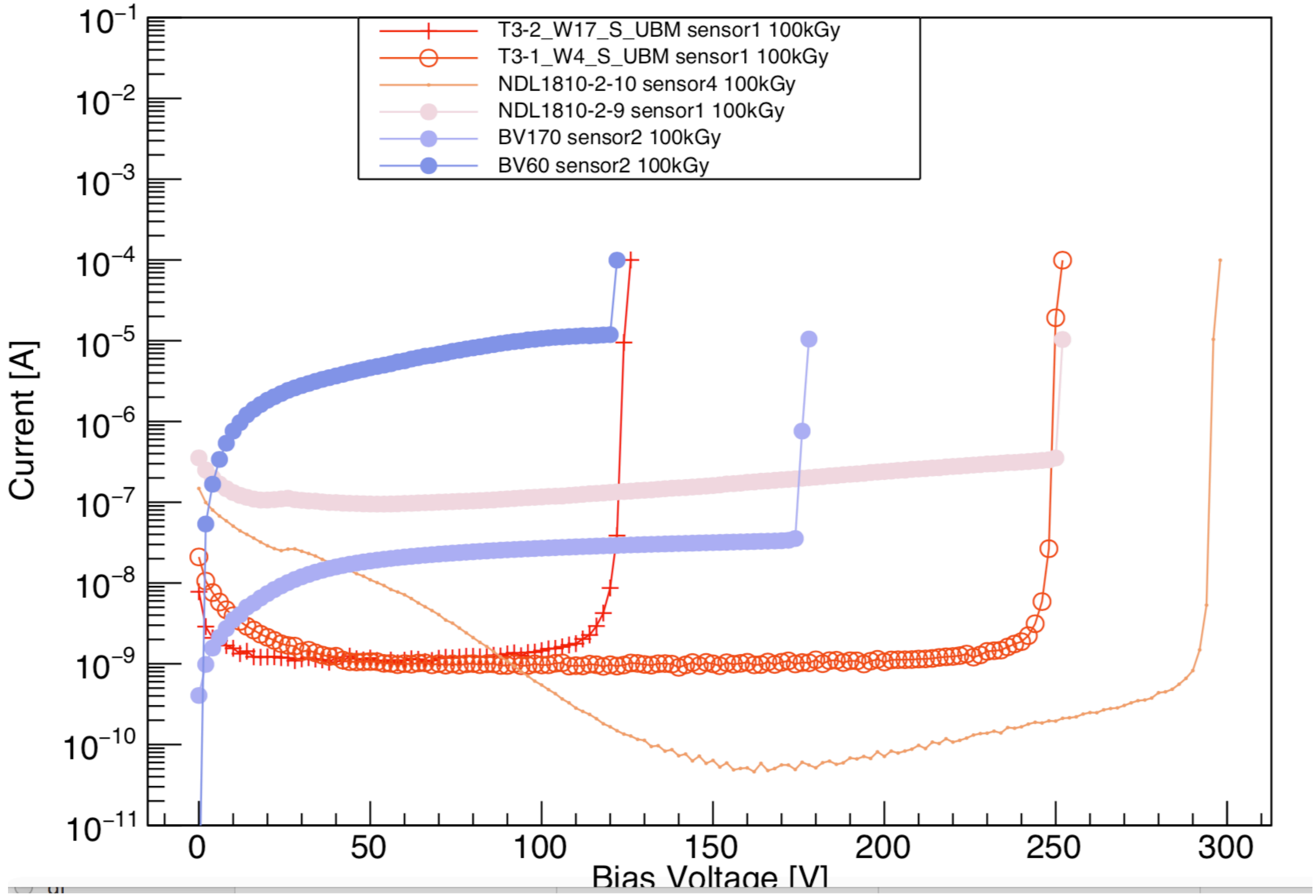




From Yunyun

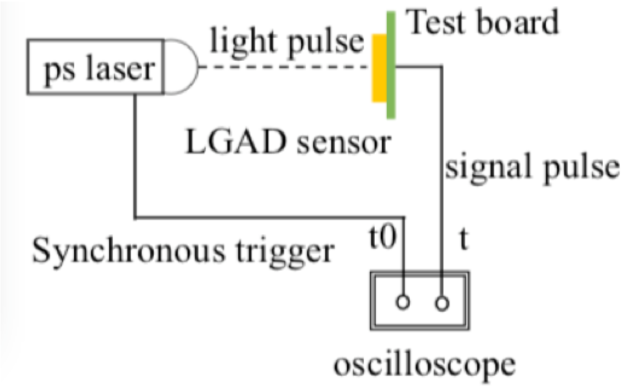
I-V after X ray irradiation : comparisons

- Short summary of leakage current on working point before VBD
  - NDL 9# and 10# have the same laytout (2GR design)
  - 9# has higher p+ dose for gain layer, longer annealing time than type 10#



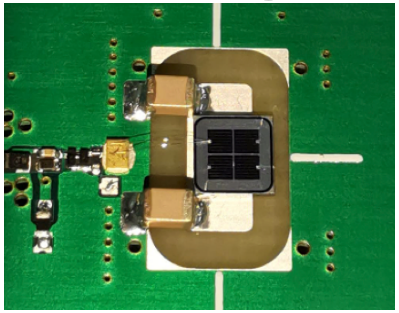
Laser test：timing resolution study

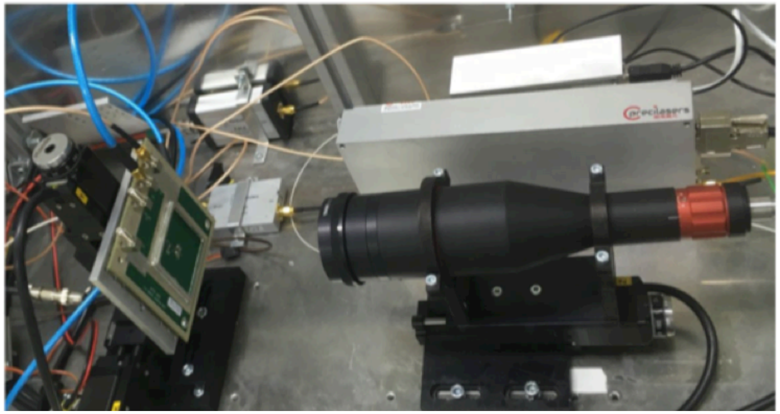
- Testing timing response for NDL LGAD sensor with TCT laser system
  - Replace the TCT laser with pico-second pulse laser
  - pico-second Laser Pulse width : 7ps; wavelength: 1064nm, , Frequency: 20MHz
- Evaluate the jitter contribution
  - Less than 10ps
  - Laser power is larger than MIP
  - Try Beta test in next step for more realistic measurement



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

Wirebond one pixel
to UCSC single channel board

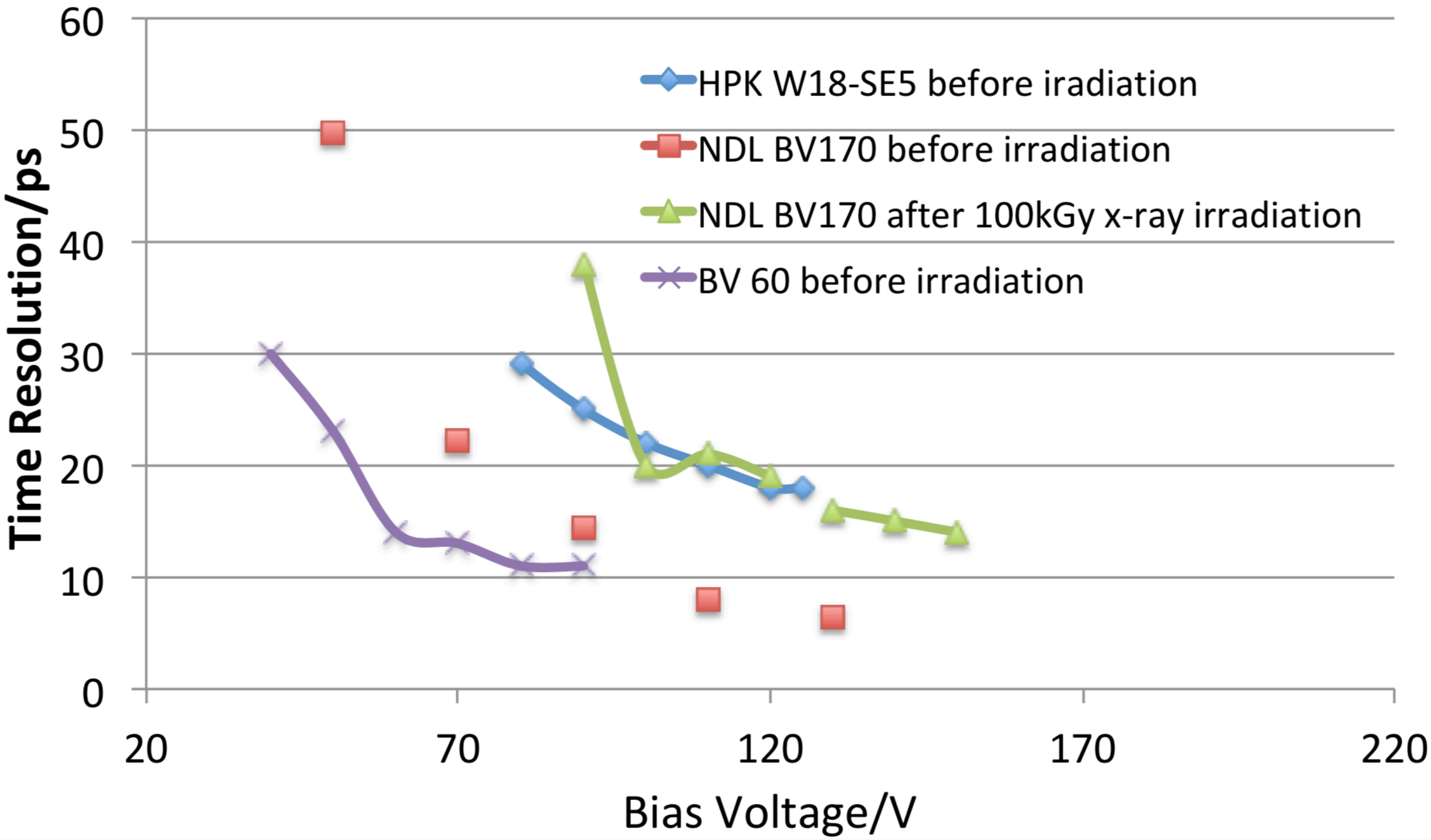




By Yuzhen, Yunyun, Suyu,Liaoshan

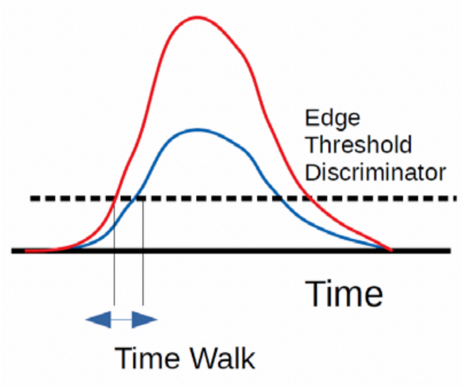
Laser test：timing resolution study

- Preliminary irradiation results
  - Time resolution of NDL LGAD is slightly worse after 100kGy



ASIC for fast timing detector

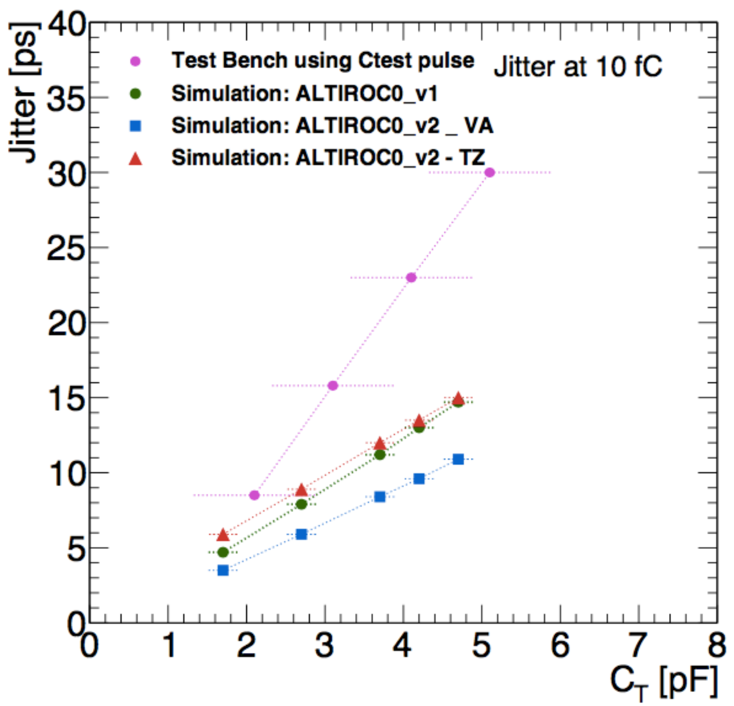
- To design ASIC for fast timing detector
  - Need to handle jitter, Time walk (TW) and TDC uncertainty
  - record Time of arrival (TOA)and Time over Threshold (TOT)
  - Correction for Time walk, precision within 10ps

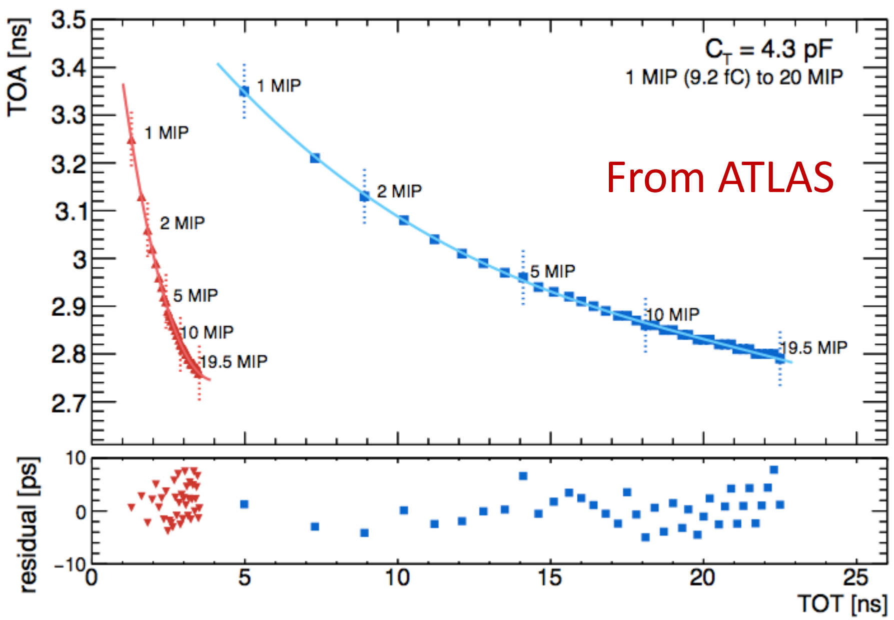


$$\sigma^2_{\text{elec}} = \sigma^2_{\text{jitter}} + \sigma^2_{\text{TW}} + \sigma^2_{\text{TDC}}$$

Reduce capacitance to reduce jitter

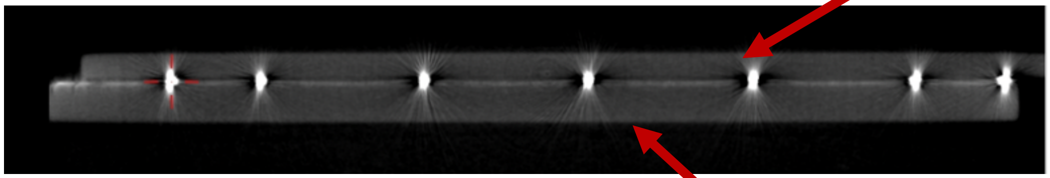
Time walk correction with TOA and TOT

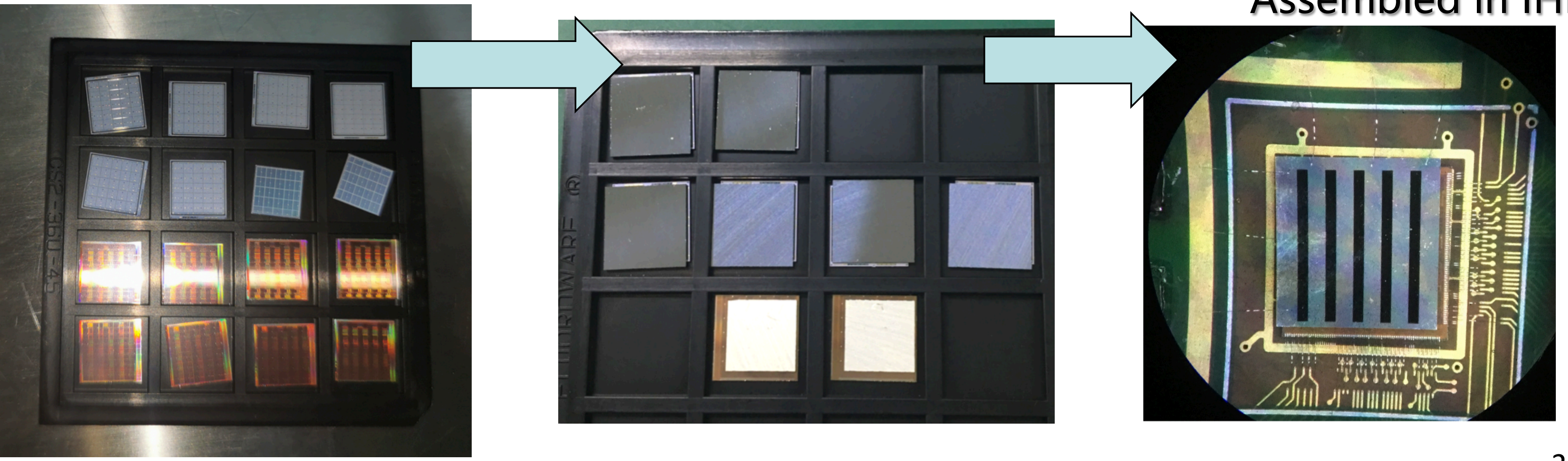




ATLAS HGTD Module

- **Full size Module :1 LGAD + 2 ASIC**
  - **15x30 channels**
  - **2cm x 4cm**
- **Existing module**
  - **5x5 channels**
  - **Built by IHEP**

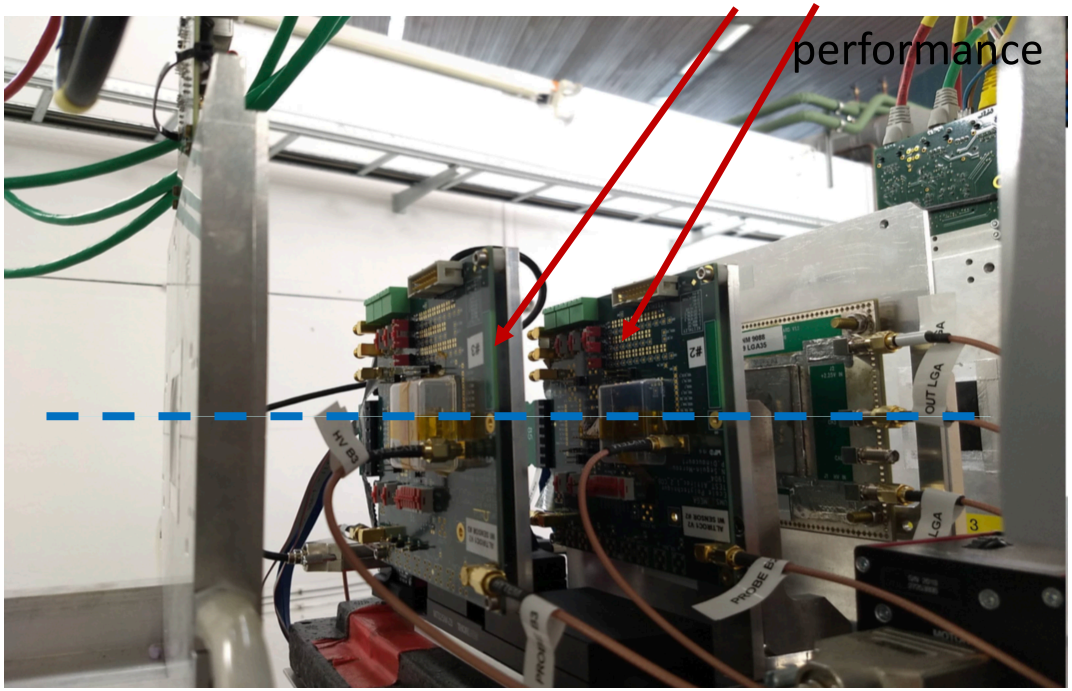




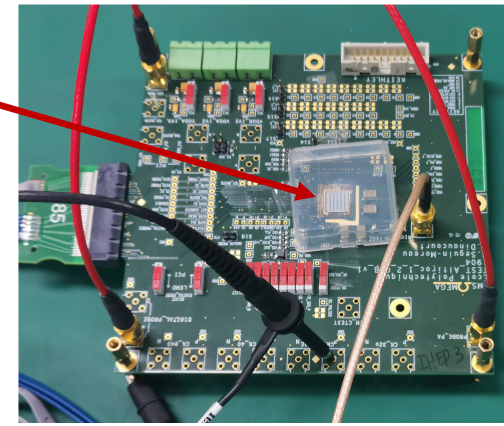
HGTD detector Module R & D

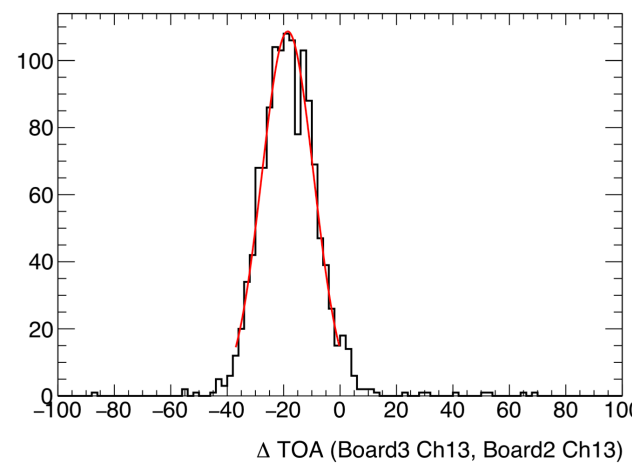
- IHEP assembled first batch of HGTD modules with ALTIROC1_v2
- IHEP modules showed good performance in DESY beam test
  - 35ps time resolution in module level

HGTD module prototypes assembled in IHEP



2019 DESY beam test for HGTD modules





IHEP module time resolution
In DESY 2019 test beam

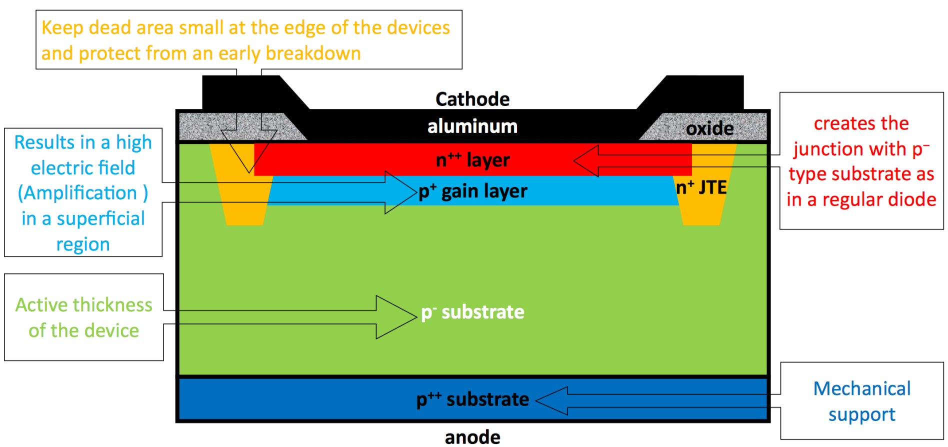
Future 4D LGAD

LGAD we have now

- One gain layer per pixel
- Relative large dead area
- Spatial resolution is not good

LGAD in the future:

- Uniform gain layer
- Small dead area
- Both time and spatial resolution



Rep. Prog. Phys. **81** (2018) 026101

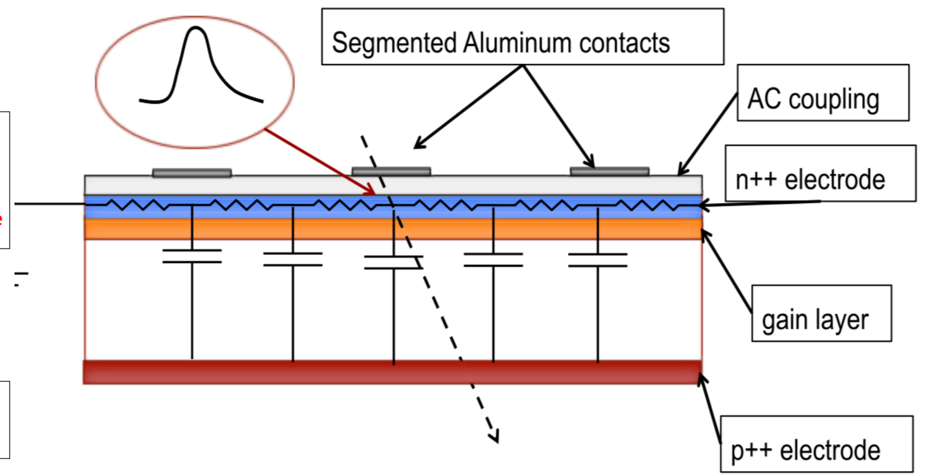


Figure 24. Sketch of segmented read-out via AC coupling.

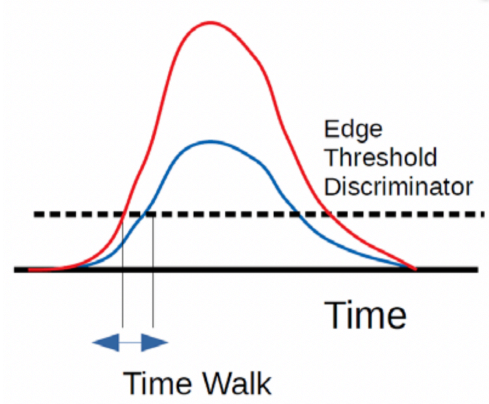
Summary

- New foundry of ultra-fast LGAD sensor in China
  - Novel device lab (NDL) in Beijing Normal university
  - 30ps time resolution in beam test and beta tests
    - ~10ps in jitter term , Landau term dominated
- Irradiation hardness of NDL has been tested
  - It meets CEPC requirements
- Next step:
  - Beam test to verify its K/pi separation power

Low-Gain-Avalanche-detector

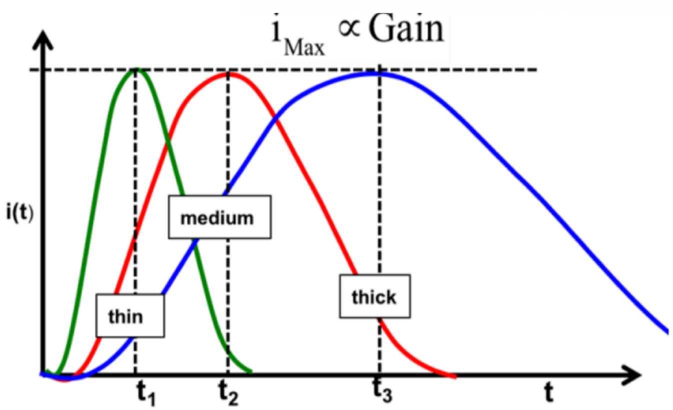
$$\sigma_t^2 = \sigma_{TimeWalk}^2 + \sigma_{LandauNoise}^2 + \sigma_{Distortion}^2 + \sigma_{Jitter}^2 + \sigma_{TDC}^2$$

- **Landau Noise term:**
  - ➢ **Signal fluctuation due to non-uniform charge deposition**
  - ➢ **Minimized by reducing thickness of the sensor (50um)**
- **Time walk**
  - ➢ **corrected using the amplitude**
  - – **estimate with the time over threshold (TOT).**



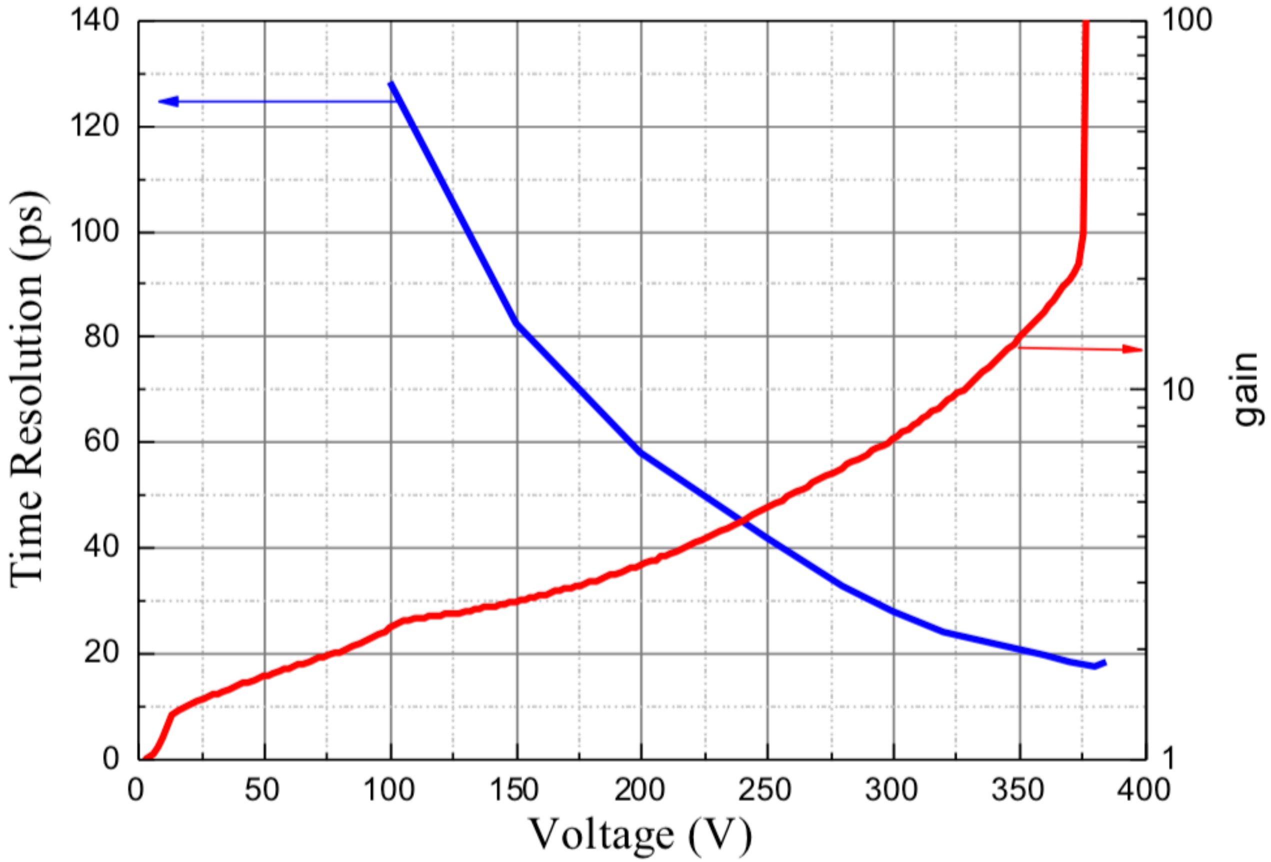
Jitter

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



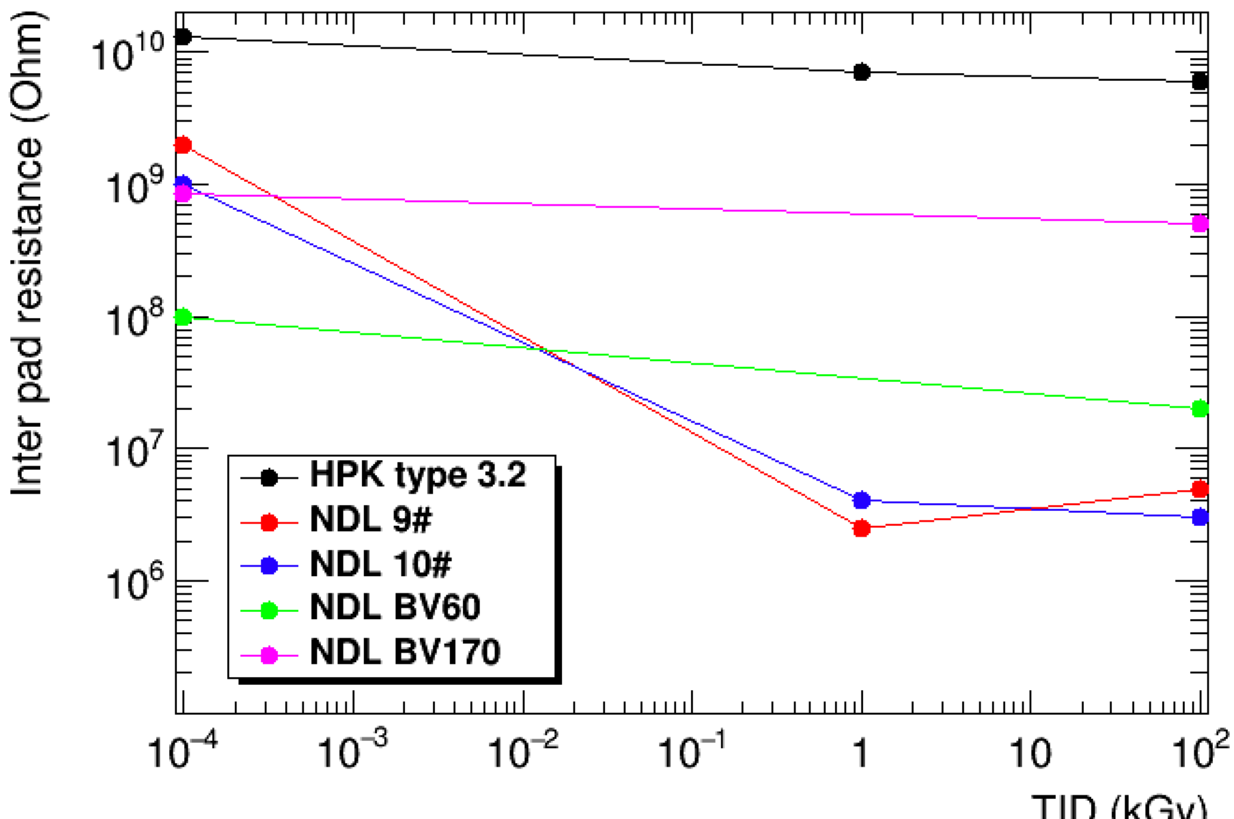
Time resolution vs gain in 5x5 NDL LGAD

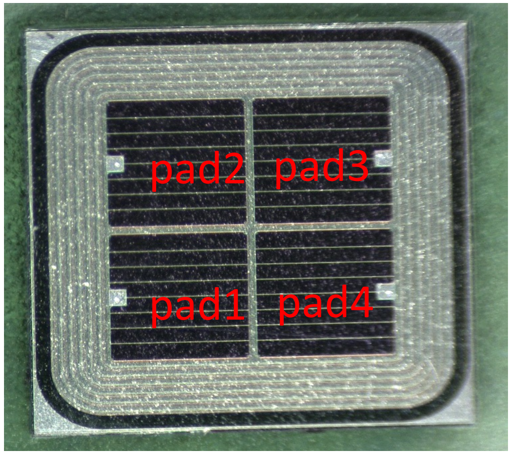
- Pico-second laser measurement
  - The power of the laser is reduced to simulate MIP
  - Jitter term can reach 20ps in this laser tests
    - PS: Landau term can not be evaluated in laser test



Inter-pad resistance

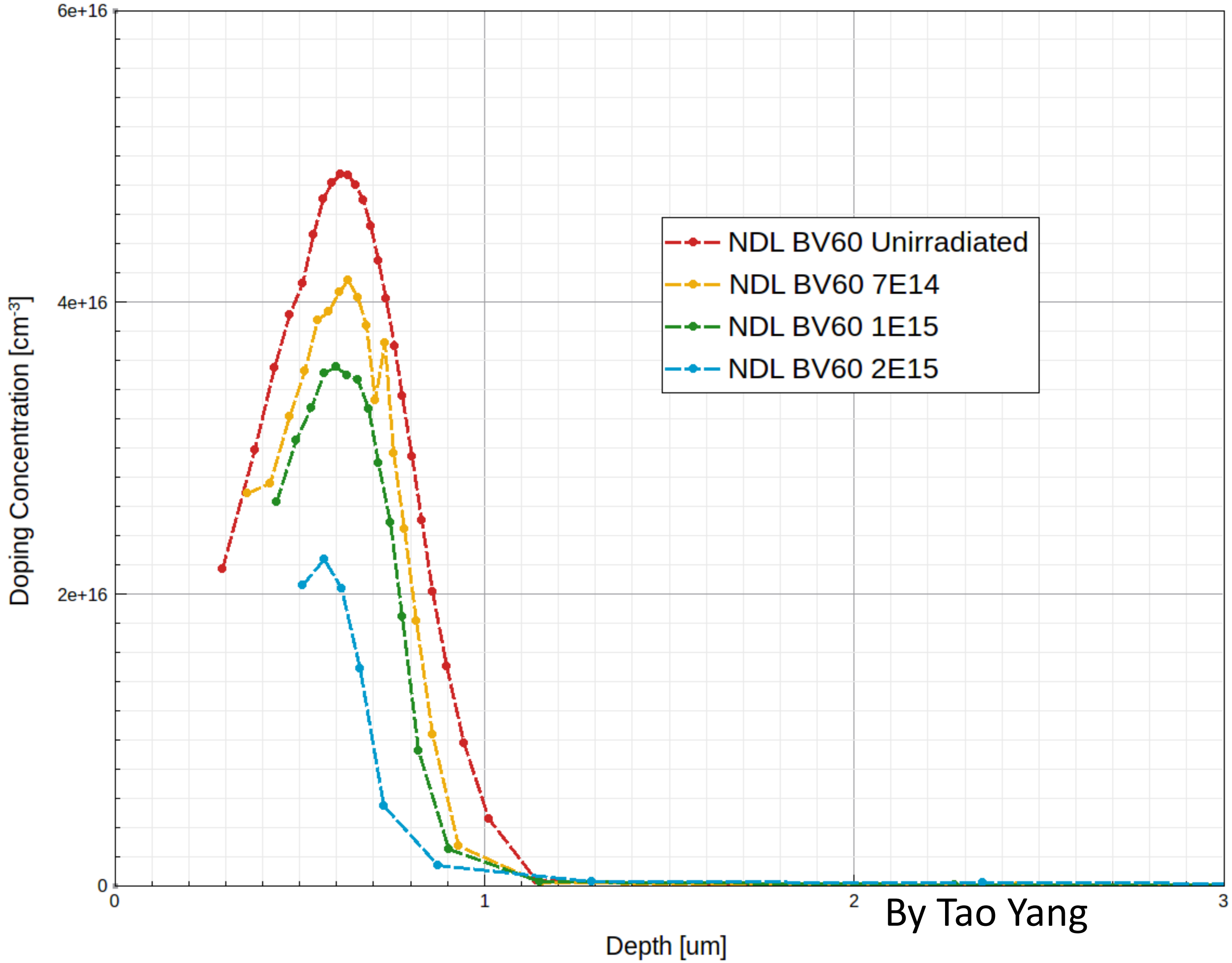
- Measure the resistance between neighbor pad in 2x2 and 5x5 LGAD
  - HPK type 3.2 (5x5) sensors showed good inter-pad isolation after irradiation
  - NDL 2x2 sensors :
    - 6GR design has better Inter-pad resistance than 2GR design after irradiation.





From Yunyun

Doping profile Vs Flence



By Tao Yang

fast readout ASIC R & D

- Fast readout ASIC (ALTIROC) R & D is one of the key for HGTD Project
  - TDC Time resolution is better than 10ps
  - Radiation hard electronics: >200MRad
- IHEP is one of key institute in ALTIROC design team
  - leading part of ALTIROC2 digital blocks design, will contribute to radiation hard design
  - Leading chip emulator development

ATLAS EXPERIMENT IFAE

EMULATOR STRUCTURE

- Use the pseudo random number generator to generate TOA and TOT
  - Seeds is used to initialize the generator
- Use TCP/UDP/IP between the PC and emulator