Performance of the Low Gain Avalanche Diodes after irradiation developed by NDL and IHEP in China

36th RD50 Workshop (CERN - - online Workshop)

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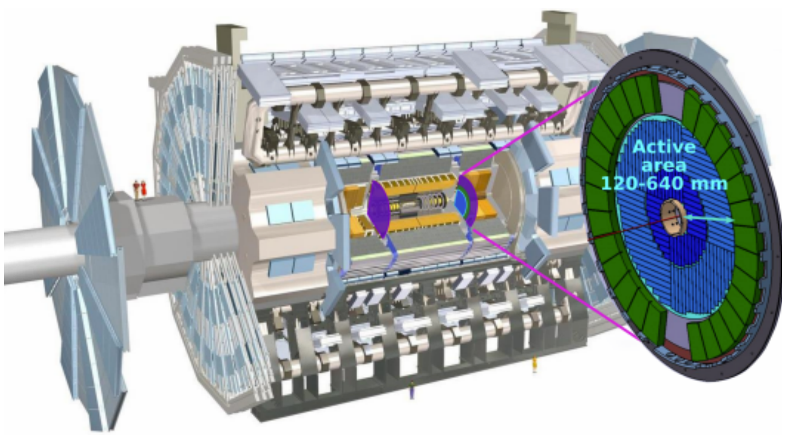
2020.6.4

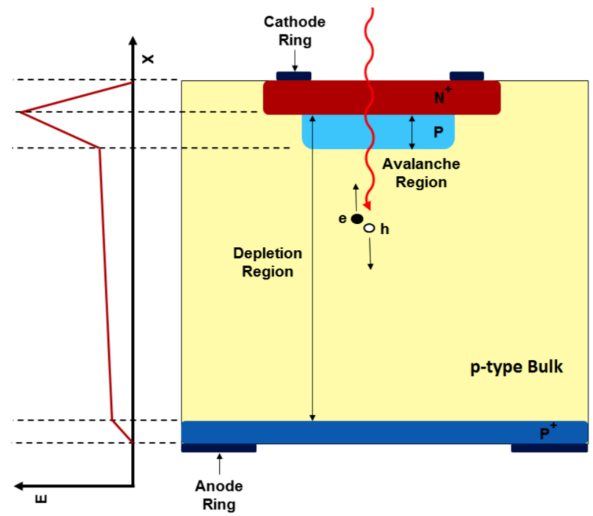
Outline

- **Introduction to HGTD and IHEP-NDL LGAD**
- **Irradiation study**
  - X ray irradiation
  - Neutron irradiation
- **Summary**

High-Granularity Timing Detector

- **High-granularity timing detector (HGTD)**
  - For **ATLAS** phase II upgrade to reduce pile up
  - Employ the Low Gain Avalanche Diode (LGAD) technology





- **Radiation hardness ATLAS requirements**

LGAD sensors after radiation : **2.5×10^{15} N_{eq} /cm^2** and **2 MGy**
  - Timing resolution : **< 70 ps**
  - Collected charge： **> 4 fC**
  - Leakage current per pad: **< 5 μA**

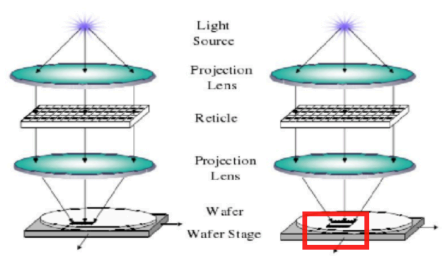
IHEP NDL Sensor Production

- **Atlas LGAD Foundry:**

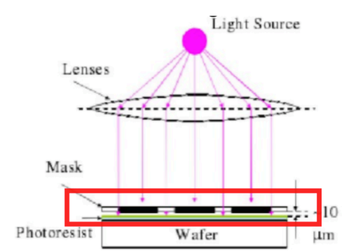
  CNM (Spain),HPK (Japan),FPK (Italy), BNL (US) **,IHEP-NDL (from China)**

- **IHEP cooperatea with Novel Device Laboratory (NDL) in the early 2019**
- **Introduction to NDL:**http://www.ndlsipm.net/contacteng.html
  - Foundry for SiPM.
  - Thickness of epitaxial layer: 33um
  - Epitaxial layer Resistivity: 100 Ohm.cm or 300 Ohm.cm
  - Have both contact mask and step-in projective mask machine. step-in for 2 x 2 LGAD sensors, contact mask for 15 x 30 LGAD sensors

Step-in projection mask aligner

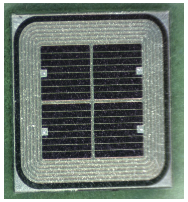


Contact mask aligner

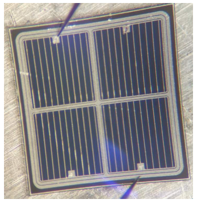


IHEP NDL Sensor Production

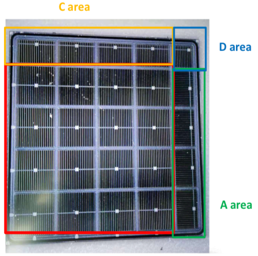
- **Three batches LGAD sensor fabricated in one year (2019).**



1st Batches

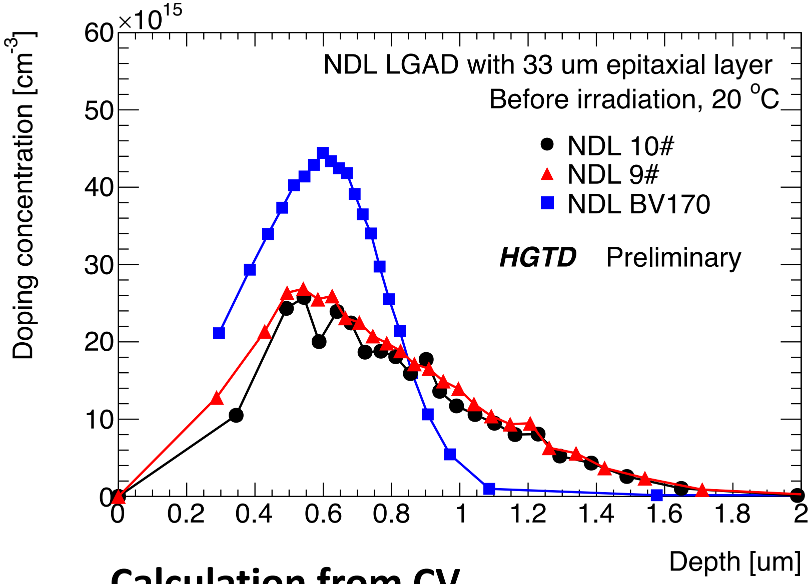


2nd Batches



2rd Batches:

- **Parameters of the Batches**
  - **Epitaxial layer: 33 µm**
  - **Different wafer resistivity : 100 Ω·cm，300 Ω·cm**
  - **Guard ring: grounded，floating**
  - **Different doping profile**



Calculation from CV

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Irradiation Campaign

- **Total ionization dose (TID) study for NDL LGAD sensors**
  - X ray irradiation experiment at IHEP, TID up to 100kGy
  - Irradiation machine: MutlRad160
  - Dose rate: 174 Gy/min

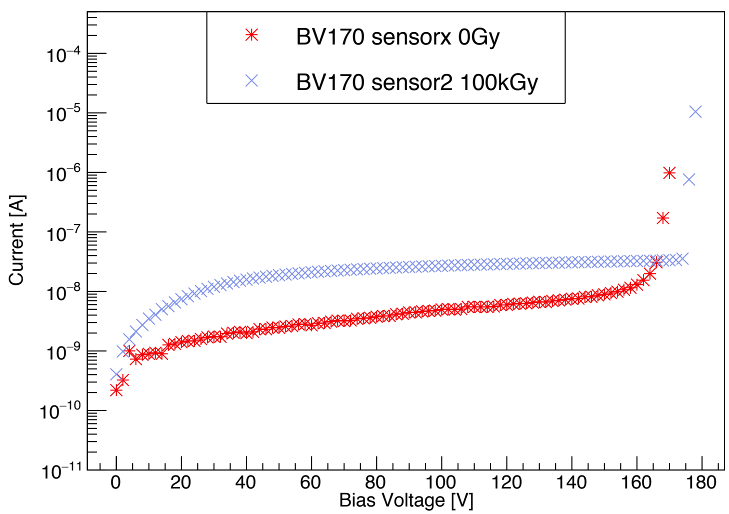
X-ray irradiation machine

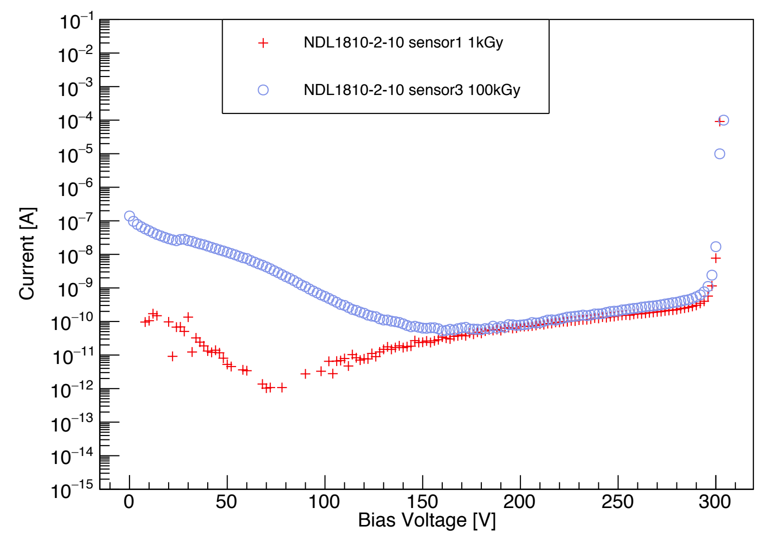
- **In the future**, the TID dose will accumulate up to 2 MGy

I-V after X ray Irradiation

- **NDL sensors**

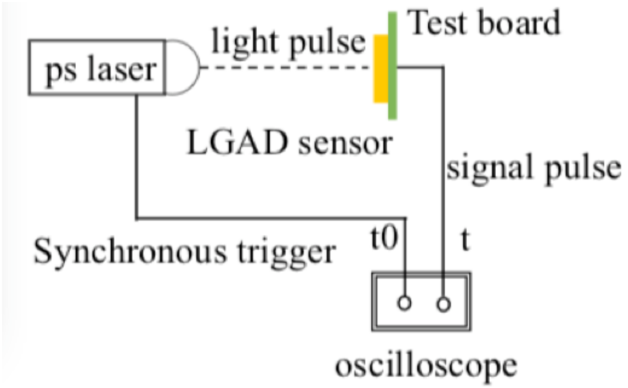
  Leakage current for NDL BV170 is **0.5 μA** and NDL #10 is lower than **1 x 10^{-3} μA.** The leakage current of the rests is about **1 μA**.





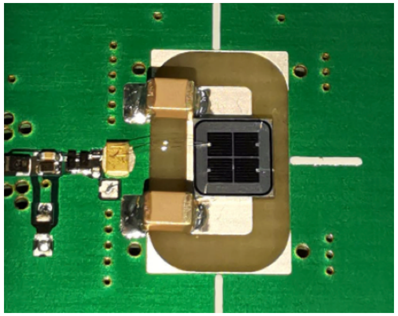
Laser Setup

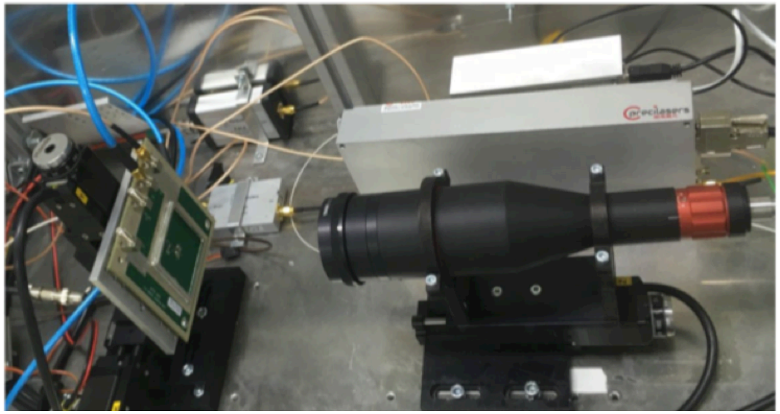
- **Testing timing response for NDL LGAD sensor with TCT laser system**
  - Replace the TCT laser with pico-second pulse laser
  - pico-second Laser Pulse width : 7ps; wavelength: 1064nm, , Frequency: 20MHz
- **Evaluate the jitter contribution**
  - Less than 10ps
  - Laser power is larger than MIP



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

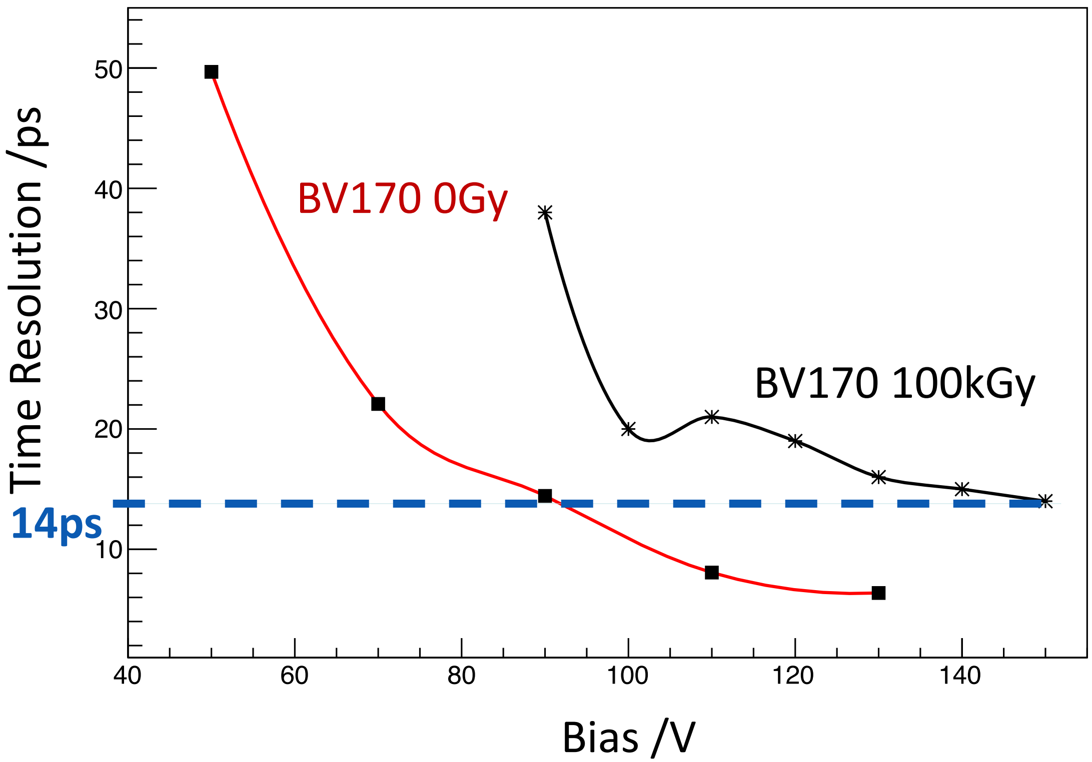
Wirebond one pixel
to UCSC single channel board





Time Resolution from Laser Test

- **After 100kGy**
  - The timing resolution contributed from jitter is about 14 ps
  - The time resolution have a potential to satisfy the request 70 ps



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  - **Neutron irradiation**
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Neutron Irradiation and Test

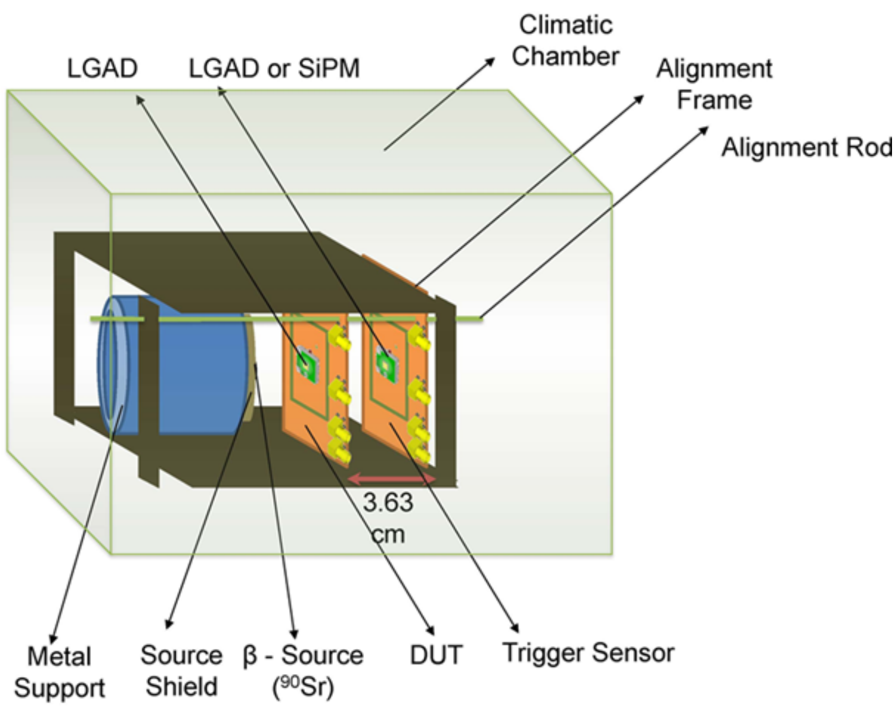
- **Non-ionization damage study on LGAD sensor with neutrons**
  - Reactor neutrons: TRIGA research reactor of the the **Jozef Stefan Institut (JSI)** in Ljubljana
  - Fluence up to **2.5 x 10^{15} n_{eq}/cm^2 (**1 MeV equivalent neutrons per cm2 **)**
- **Annealing:** after irradiation, the devices were annealed for 80 min at 60 ^{o}C

Beta Test Setup

- **Beta test (time resolution , collected charge)**

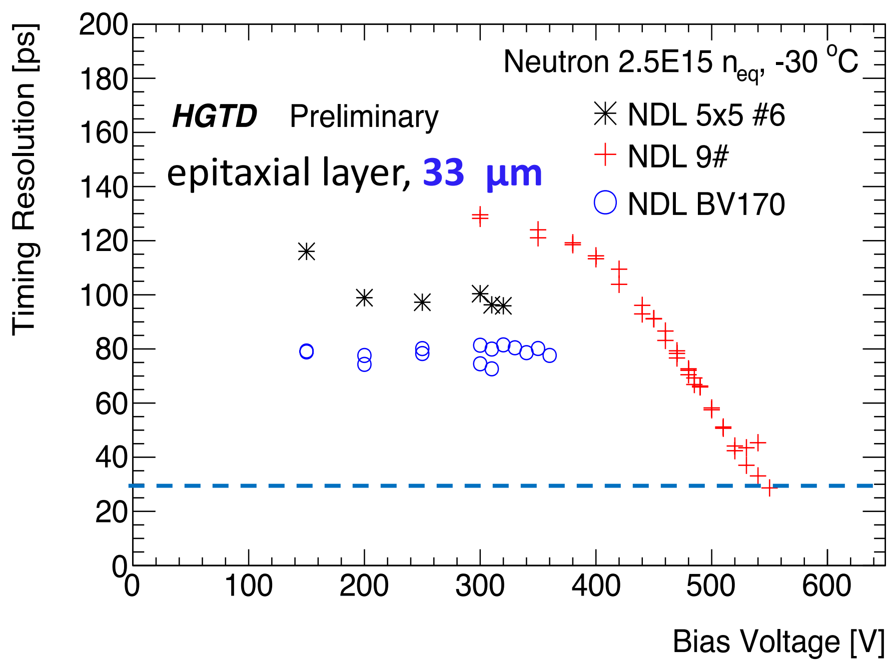
  Done by UCSC

  – Electrons by Sr90 Beta source
  – Single channel board developed by UCSC
  – Fast amplifier with bandwidth >1GHz



Timing Resolution

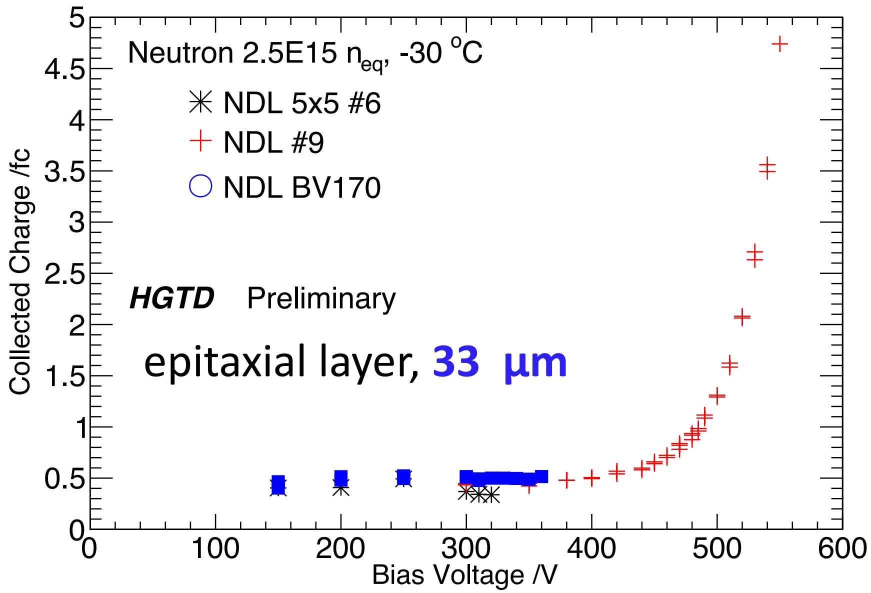
- **NDL #9:** 30 ps at about 562 V, 35 ps at 550 V **(satisfy the requirement of ATLAS, < 70 ps)**
- **NDL 5 × 5 #6 and BV170 :** best timing resolution : ~ 96 ps, ~ 74 ps
- The better timing resolution of 9# was most possible due to **higher wafer resistance** (300 Ω·cm). BV170 and NDL #6 (100 Ω·cm)



Collected Charge

- **NDL #9 :** collected charge is close to 4 fC at 550 V. (**more study on noise in high Voltage bias is on going)**
- **NDL 5 × 5 #6 and BV170:** best collected charge is ~0.4 fC, ~ 0.6 fC
- **Reason for the better performance of NDL #9** is considered to be the higher wafer resistivity (300 Ω·cm), BV170 and NDL #6 (100 Ω·cm)
- **To improve the collected charge in the future**
  - The thicker epitaxial layer, **50 μm**, will be used
  - the **Carbon** would be done by cooperating with the Institute of Microelectronics (IME) in China

    http://english.ime.cas.cn



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Summary

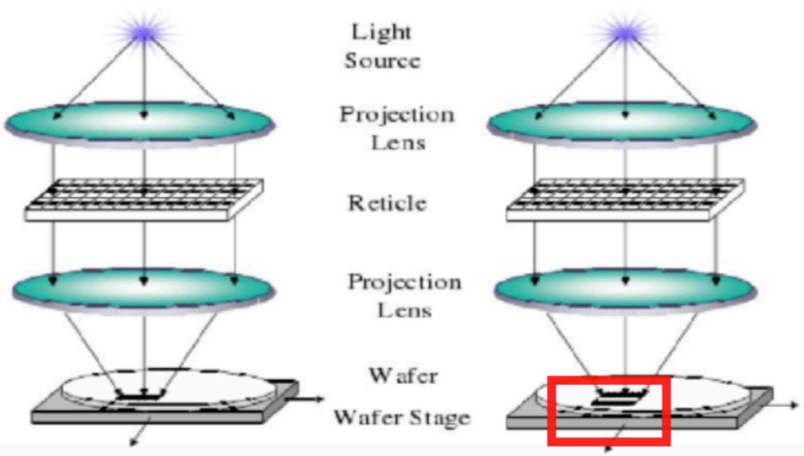
- **Irradiation hardness of NDL has been tested**
  - Verify that satisfies the ATLAS requirement until **100kGy**
  - After neutron irradiation up to **2.5 x10^{15} n_{eq}/cm^2**
    - The timing resolution of 33 NDL #9 could be **~35 ps** satisfy the ATLAS requirements < 70 ps
    - Collected charge is **close to 4 fC at 550 V**. (more study on noise in high Voltage bias is on going)
- **Radiation hardness of NDL sensor with high resistivity (300 Ω·cm) is better than those with lower resistivity (100 Ω·cm).**
- **In the future**
  - TID dose will be accumulate up to 2 MGy
  - Increase the thickness of epitaxial layer： **33 μm** -> **50 μm**
  - Carbon to increase the radiation hardness

Thank you for your attention！

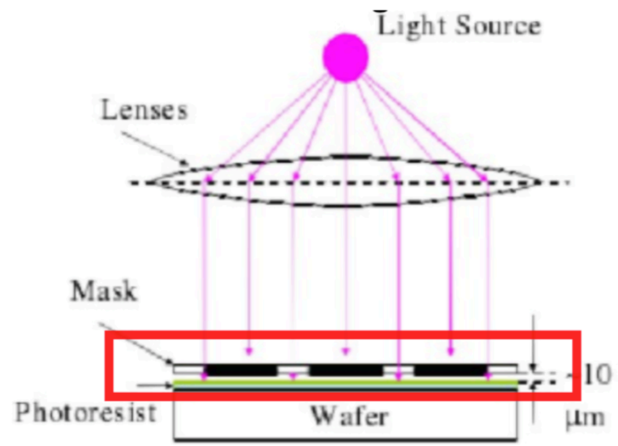
- **Back up**

- Foundry working with DNL have both contact mask and step-in projective mask machine
- NDL used step-in projection mask aligner for small sensor sensors (2x2cm reticle size)
- Will switch to contact mask aligner for larger sensor (15x30 LGAD or even larger sensors)
  - Similar mask technology as CNM or HPK
  - Layout in full wafer size, not limited by reticle size

Step-in projection mask aligner

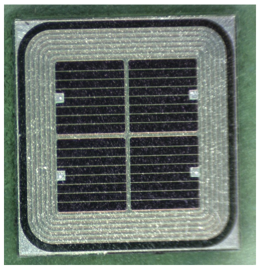


Contact mask aligner

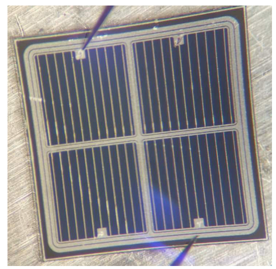


IHEP NDL Sensor Production

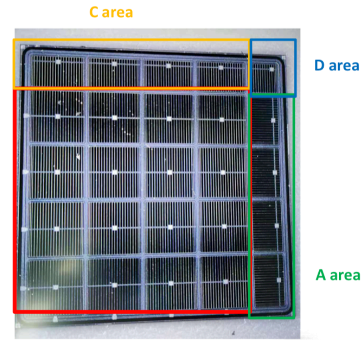
- **Three batches LGAD sensor fabricated in one year(2019).**



1st Batches



2nd Batches



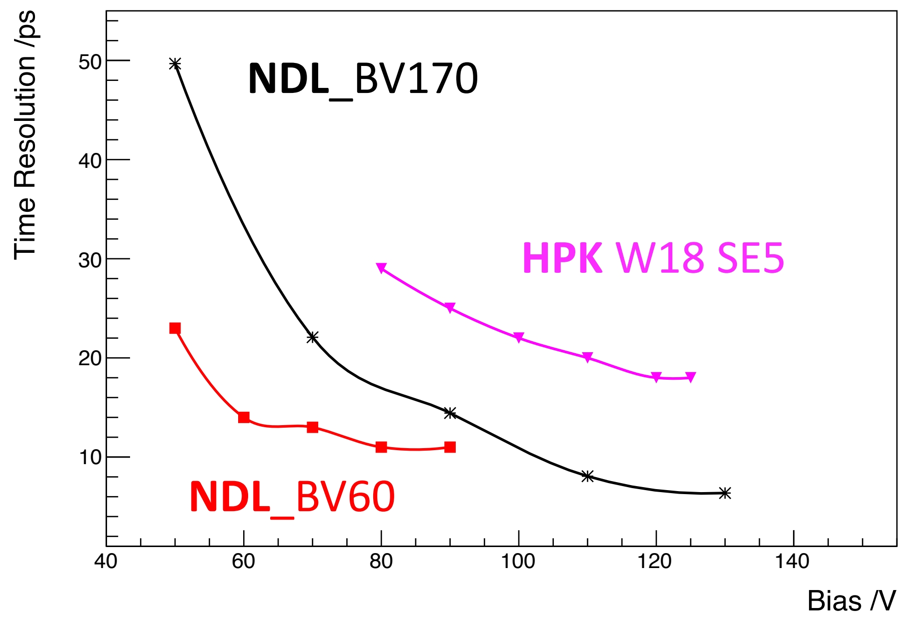
3rd Batches:

Bathes	Sensor Type	VBD (V)	V_Depleted (V)	Layout	Wafer (Ω.cm)	Gain
1st	BV170	~165	~100	6GR	100	40
	BV60	~95	~40	6GR	300	40
2nd	10#	~300	~40	2GR	300	80
	9#	~250	~40	2GR	300	80
3rd	NDL 5x5 6#	~400	~120	2GR	100	10~20
	NDL 5x5 12#	~390	~35	2GR	300	10~20

Laser test： timing resolution study

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

- **Laser test:**
  - no Landau fluctuation, ~ps Laser
  - Help to understand the jitter



- **Preliminary results**
  - The time resolution of NDL is from 3~50 ps
  - Better than HPK W18 SE5

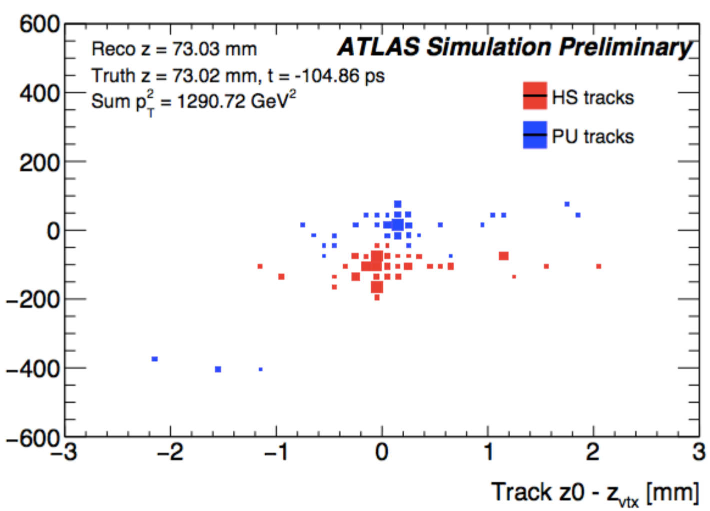
Physics Motivation

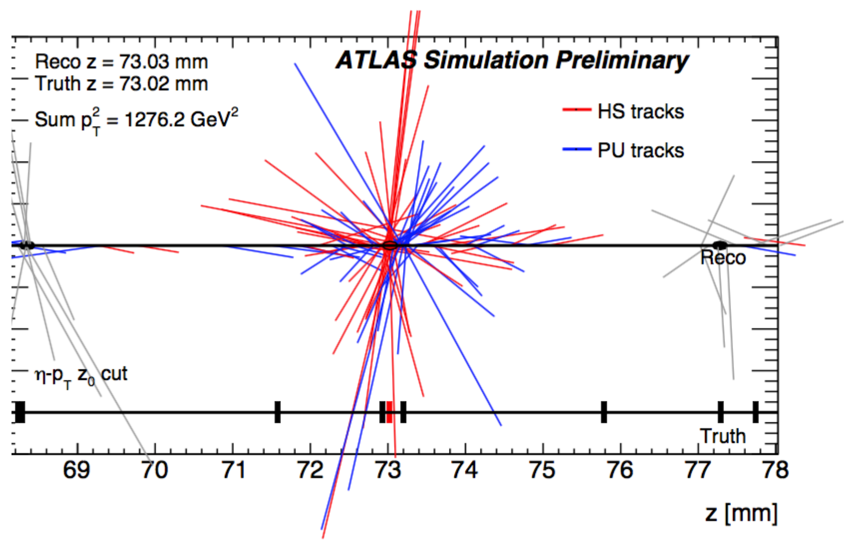
- **Pileup is the major challenges at HL-LHC**
  - Track from different vertexes close in space, but well-separated in time.
  - Explore the spread of the collision to reduce pileup background by timing
  - Need **30ps timing resolution** to reduce the pileup background by a factor of 6

100Ω.cm

- **Significant impact on some physics case**
  - VBF Higgs,Weak mixing angle measurement

Higgs signal and pileup are separated in time !





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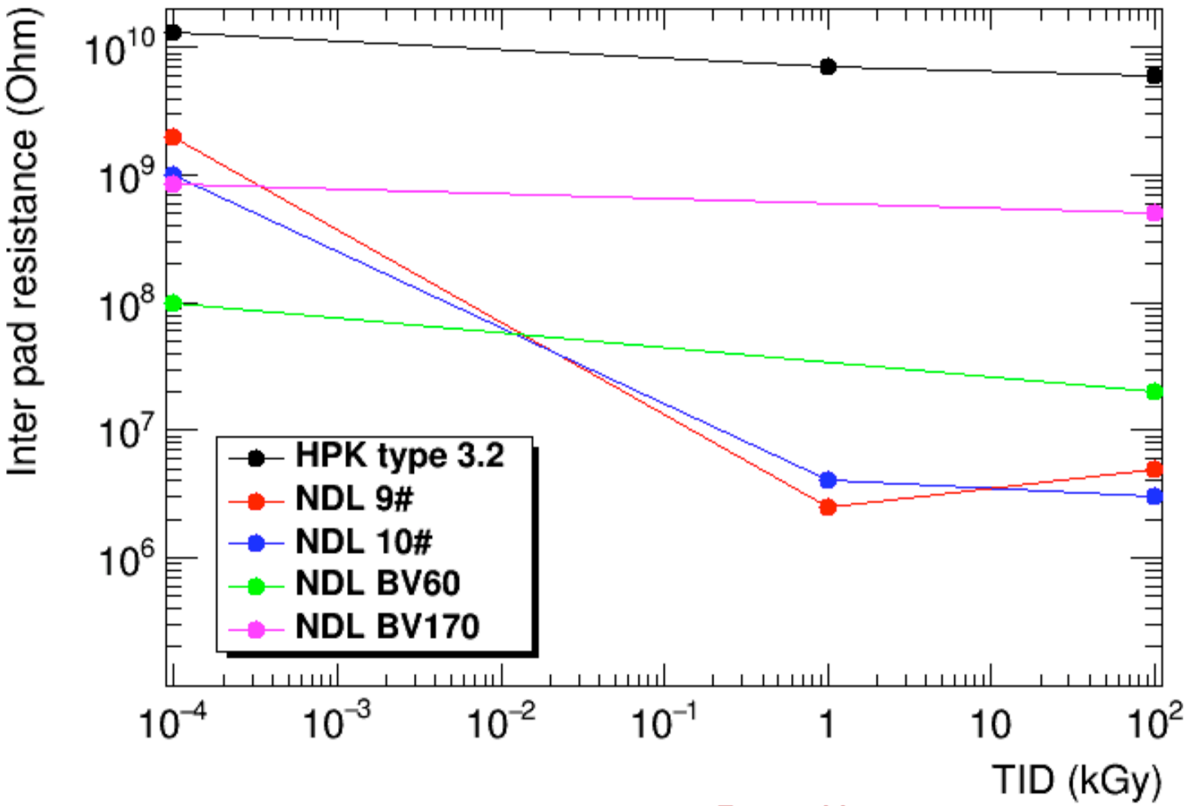
Inter Pad Resistance after Irradiation



After irradiation decrease:

NDL 10# > NDL 9# > HPK T 3.2 > NDL BV170