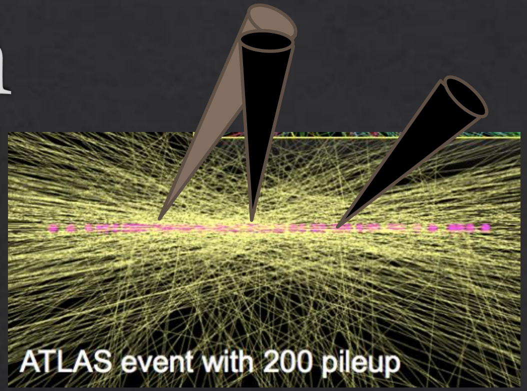
Recent development of HPK AC-LGAD detectors

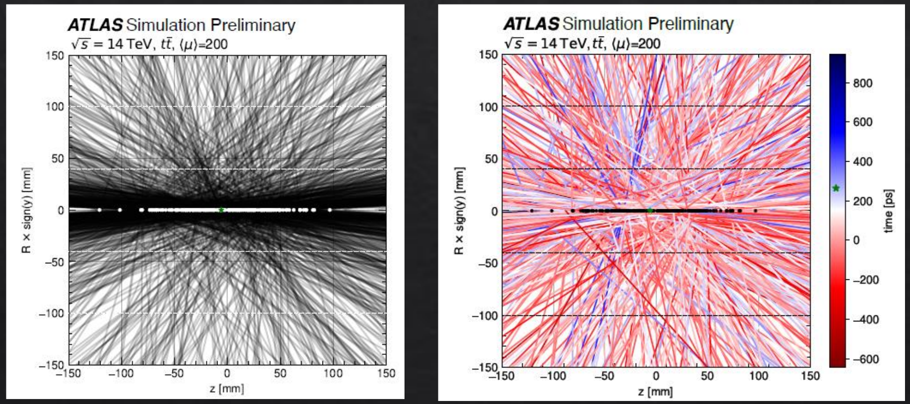
Koji Nakamura (KEK)

Impact for tracker with time resolution

- Collider experiment gets high energy and high intensity.
  →Future Tracking detector should have timing information for all hits!
- Tentative Requirement
  - 30ps timing resolution &~o(10)um spatial resolution
  - (hadron collider) ~o(10^{16})n_{eq}/cm^2 radiation tolerance

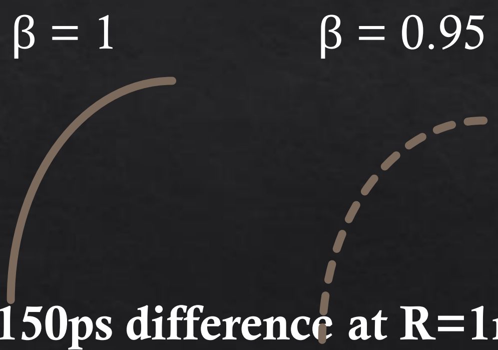


4D tracking !



Solve pileup hits in an event

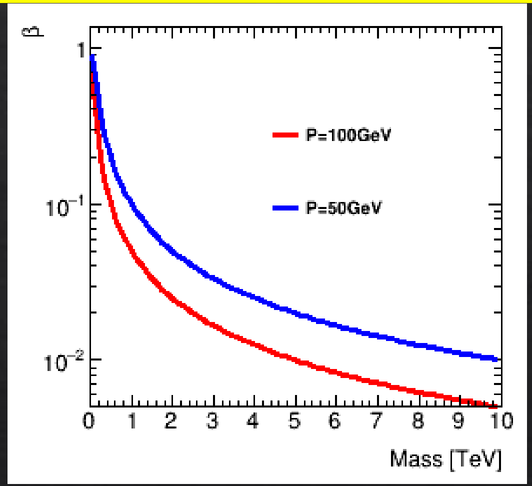
Particle identification



150ps difference at R=1m

K+ π+ separation

Mass spectrum for new particle



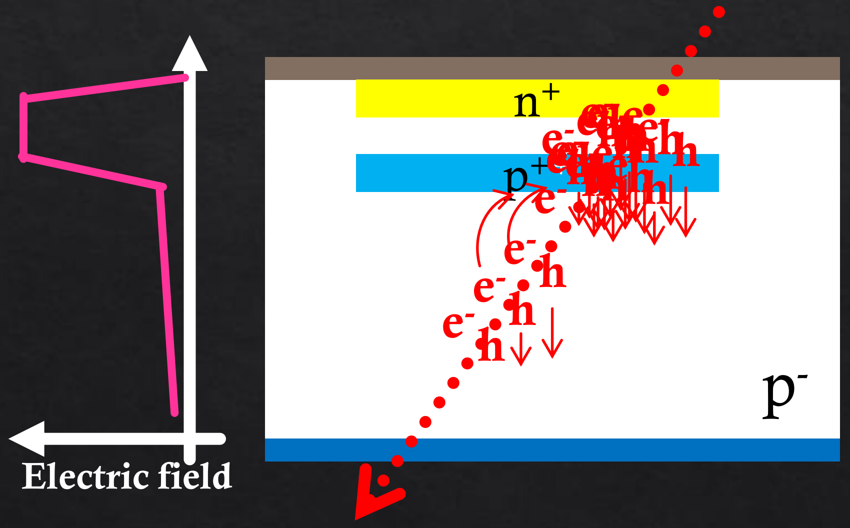
β measurement to obtain mass

e.g. Mass measurement for Long lived chargeno

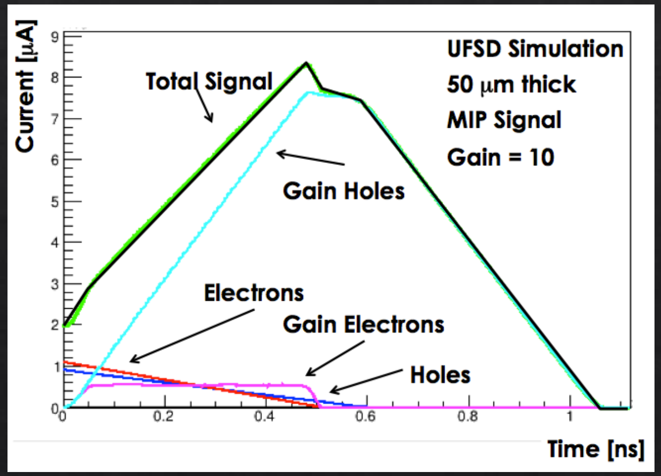
Low Gain Avalanche Diode (LGAD)

- Low gain Avalanche Diode (LGAD)
  - General n^+-in-p type sensor with p^+ gain layer under n^+ implant to make very high Electric Field at the surface.

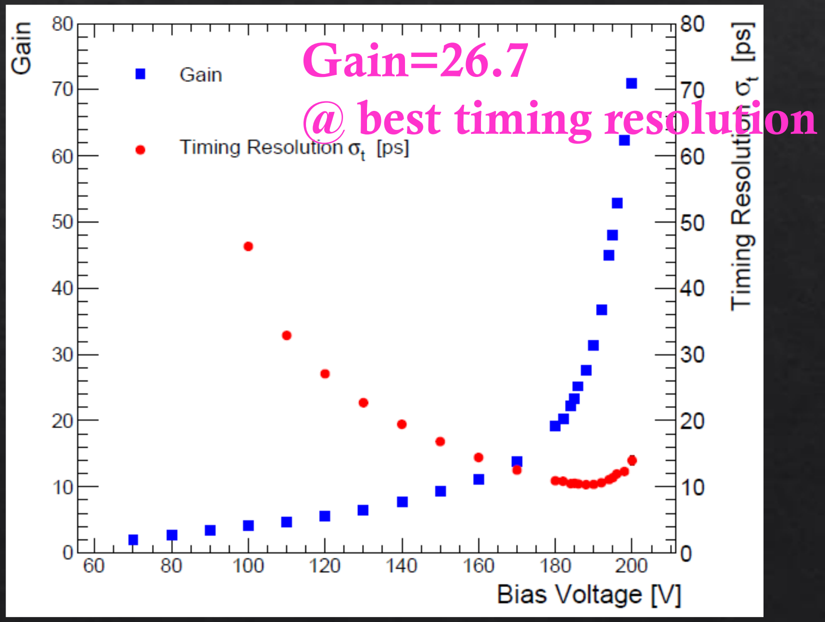
    → Good timing resolution.
  - **30ps timing resolution achieved already in 2015.**



Signal drivers : **Gain Holes**

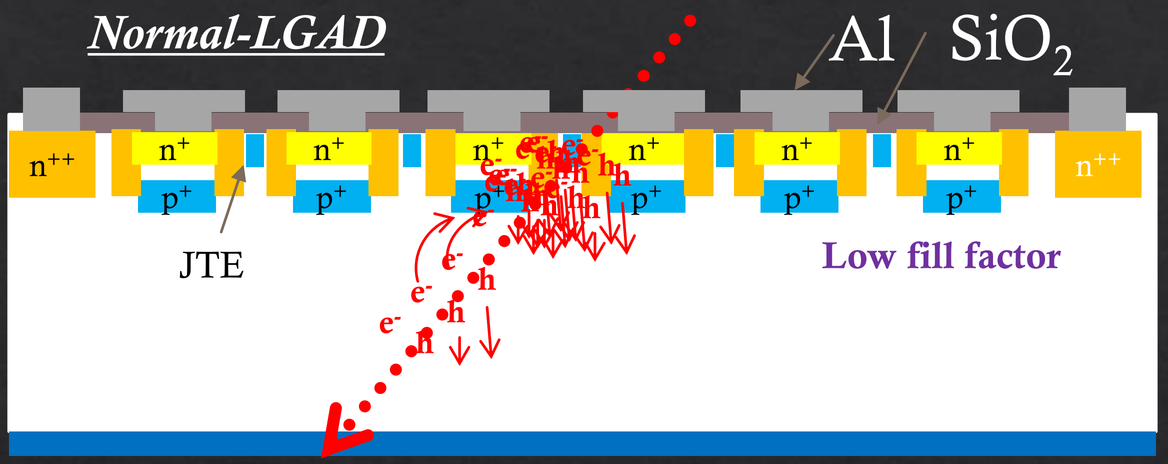


Gain measurement (AC-LGAD):



Spatial resolution of LGAD

- Segmented LGAD :
  - To have spatial resolution, strip sensors has been processed.
  - Need **Junction termination extension(**JTE) and p-stop structure to have individual gain layer →**Low fill factor (20% for 80um strip)**



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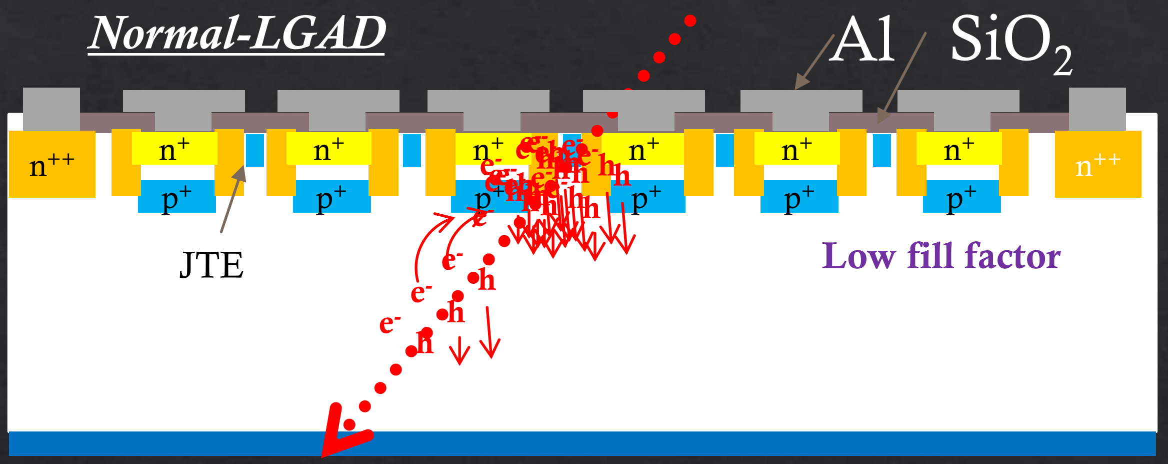
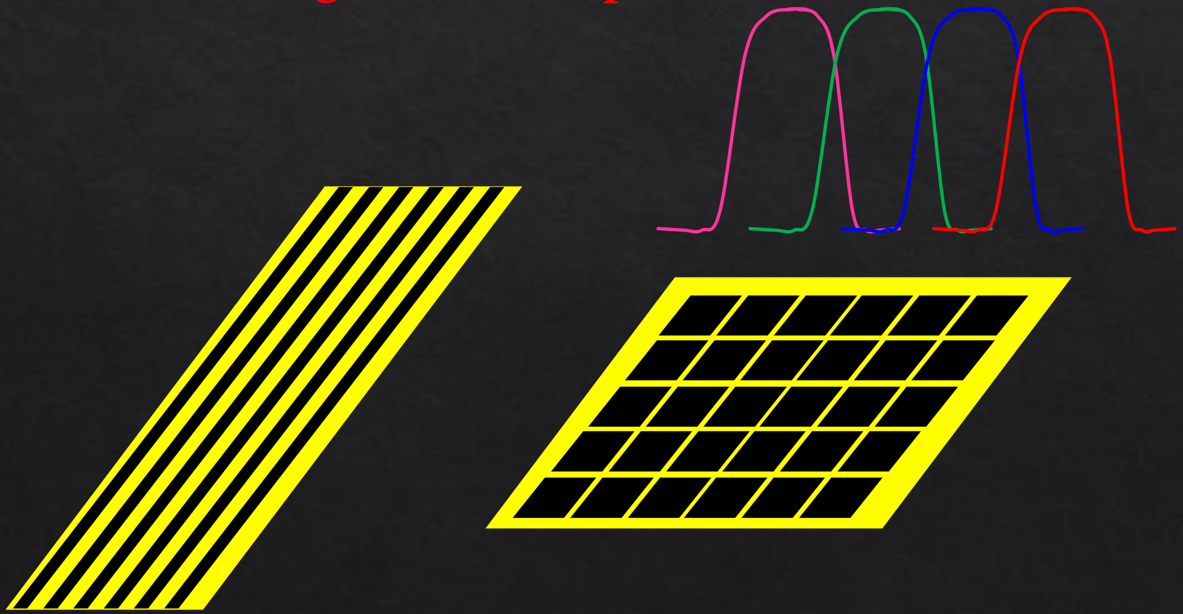
  - Need **Junction termination extension(**JTE) and p-stop structure to have individual gain layer →**Low fill factor (20% for 80um strip)**
- **Uniform gain layer with AC-Coupled electrode. (AC-LGAD)**
  - **In principle, 100% fill factor.**
  - **Signal shared on neighboring electrodes.**
    - Need optimization of n+ resistivity



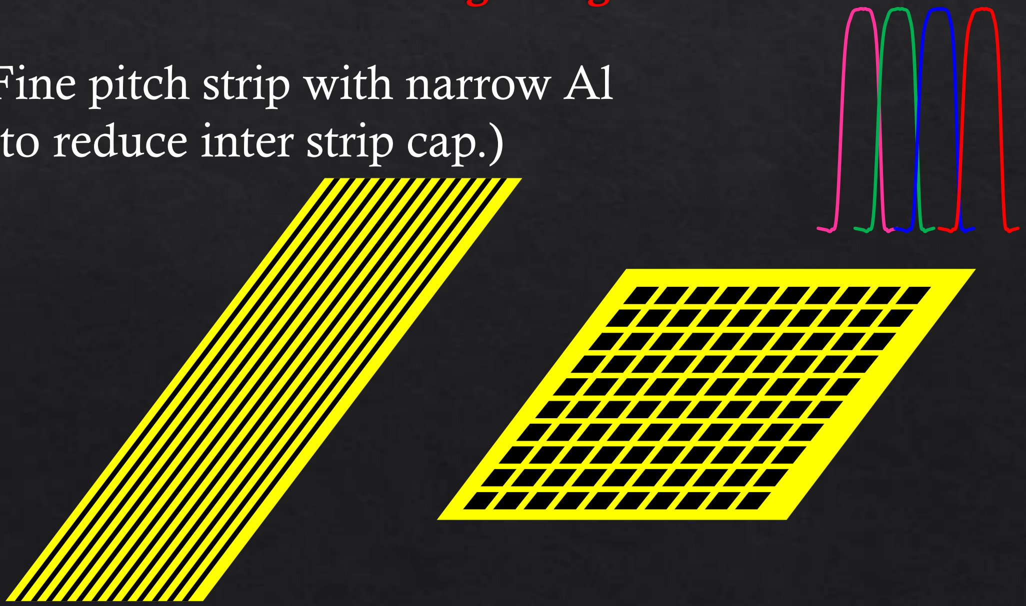
Two approaches to have good spatial resolution

- ***Charge sharing approach***
  - **For lepton collider or other low occupancy colliders.**
  - Reconstruct particle position using charge sharing (charge fraction to next channels)
    - Relatively low n+ implant resistivity
  - **Pros. : Smaller number of channel →Save ASIC power consumption.**
  - **Cons. : Smaller signal size. Need high resolution ADC. Large detector capacitance**



- ***Fine pitch electrode approach***
  - **For High occupancy experiment like hadron collider.**
  - Reduce crosstalk (charge sharing)
    - High n+ implant resistivity
  - **Pros. : smaller occupancy and smaller data size like digital readout. Smaller detector capacitance.**
  - **Cons. : Limitation of spatial resolution by electrode size. # of channels get huge…**

Fine pitch strip with narrow Al
(to reduce inter strip cap.)



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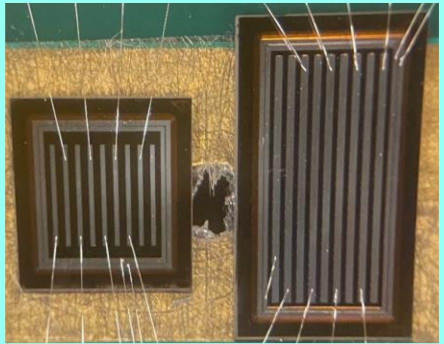
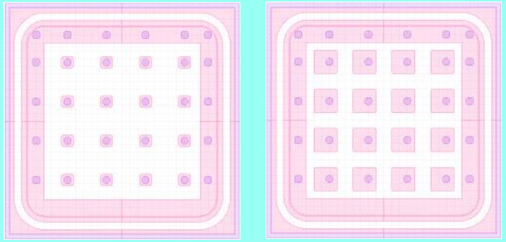
BNL prototype 500um pitch strip

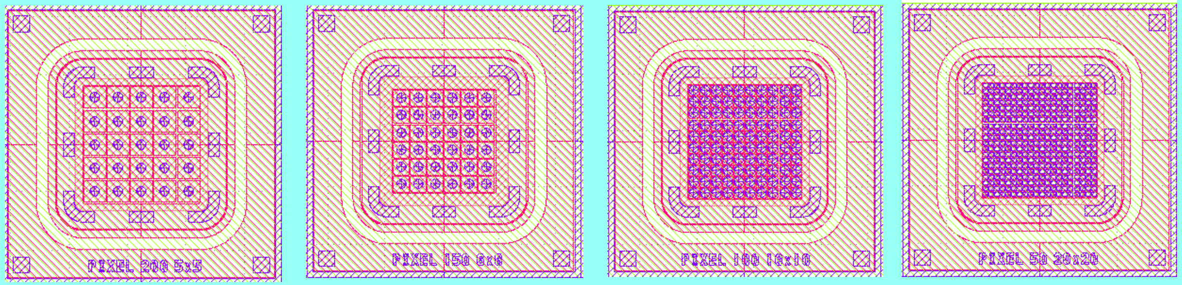


HPK EIC prototype (500um pitch)



Both BNL and HPK produced 500um pitch pad/strip for future colliders (e.g. EIC)

200um 150um 100um 50um



KEK-Tsukuba group with HPK successfully develop :
100um (50um) pitch Pixel detector
80um pitch Strip detector

Achievement : Spatial resolution

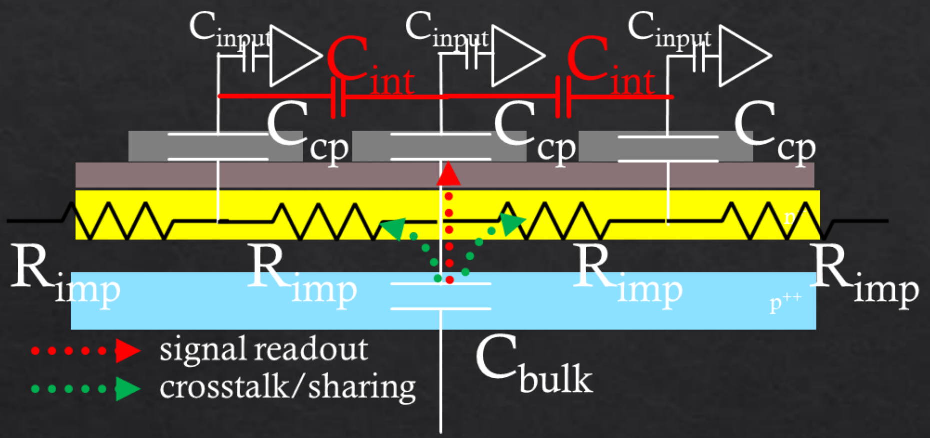
- Charge split : Impedance ratio

$$Q = \frac{Z_{R_{imp}}}{Z_{R_{imp}} + Z_{C_{cp}}} Q_0$$

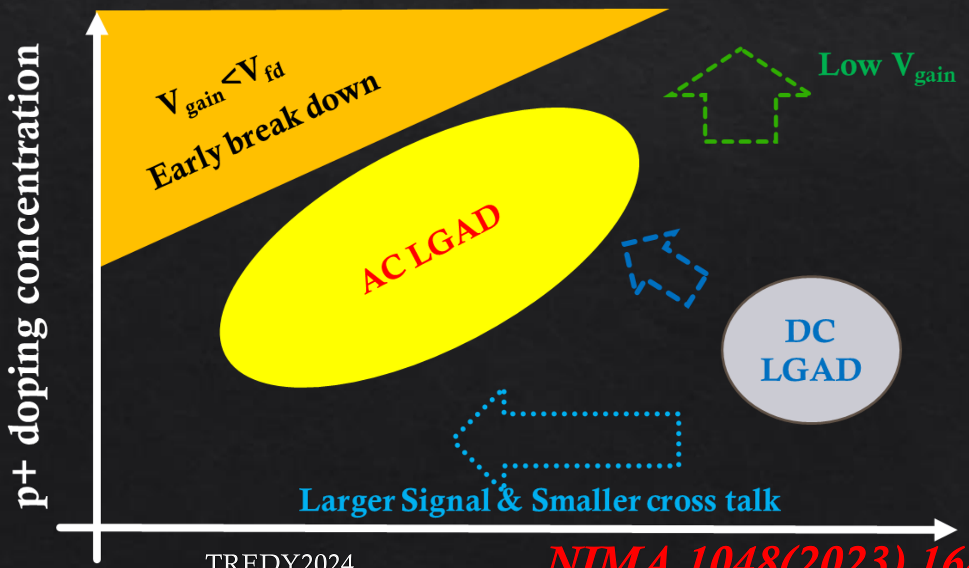
Assuming $Z_{Cbulk}, Z_{cint} >> Z_{Ccp}$…

- Amount of produced charge: Q_0
- Readout Charge : Q

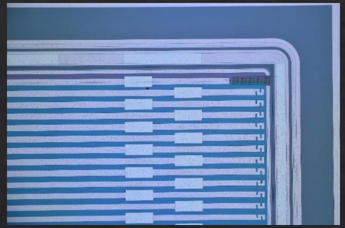
Read out principle of AC-LGAD

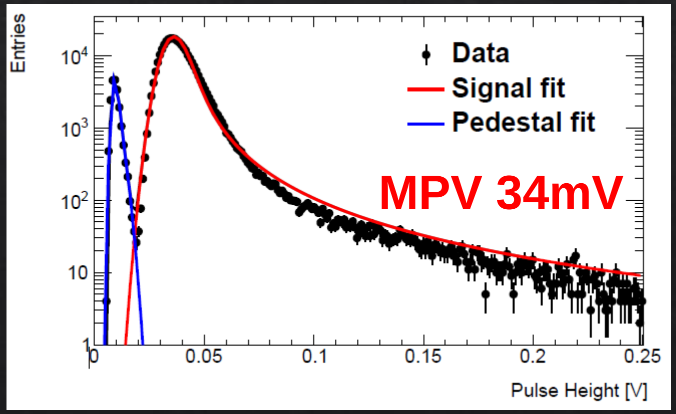


Parameter space for doping concentration

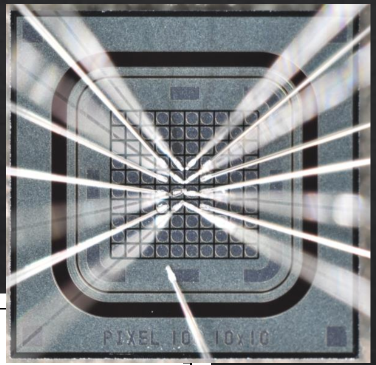


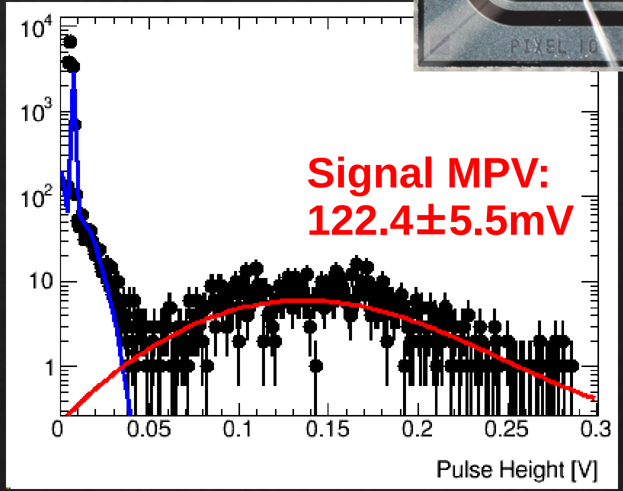
Strip type
80um pitch
(10mm)





Pixel Type
100um pitch





First fine segment AC-LGAD detector !

NIMA 1048(2023) 168009

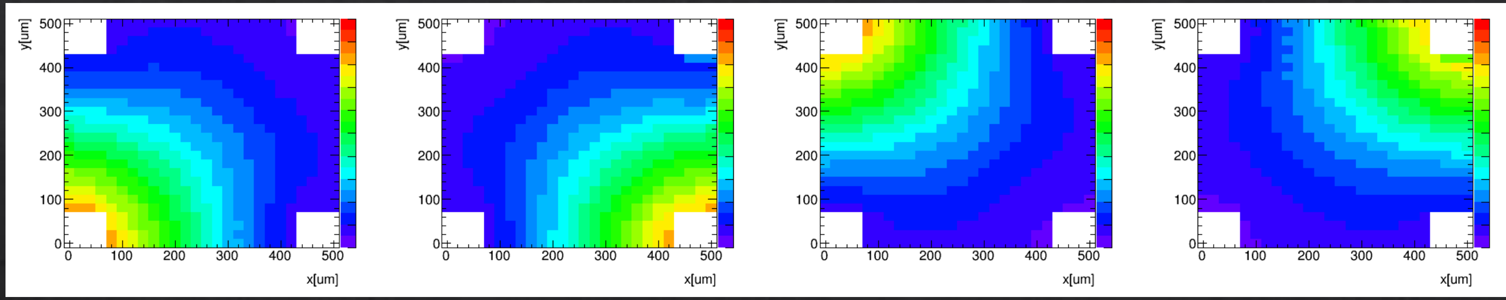
VERTEX2022(arXiv:2305.12355)

Charge sharing approach

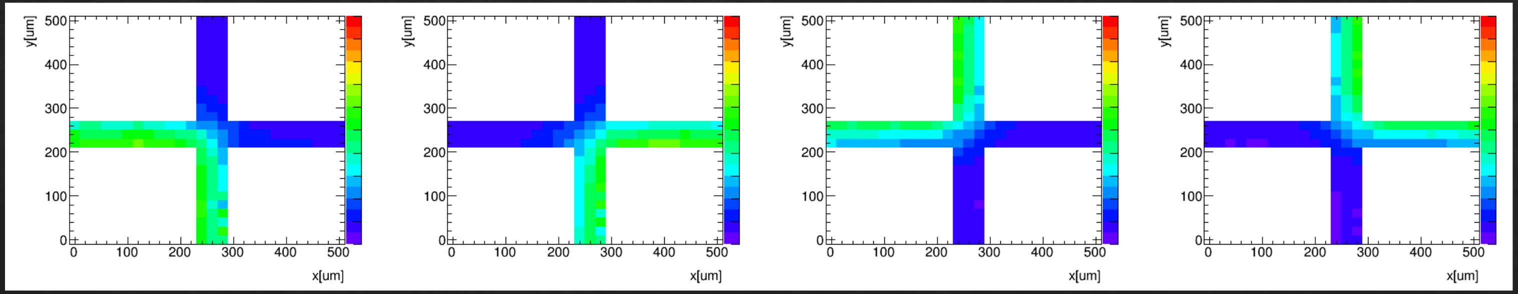
R_{imp} [Ω/□] \ C_{cp} [pF/mm²]			
1600	E120	E240	E600
400	C120	C240	C600

- Fabricated 500um pitch pad type sensor with various electrode size for EIC prototype.
- Scanned Laser injection position in 500um x 500um area.

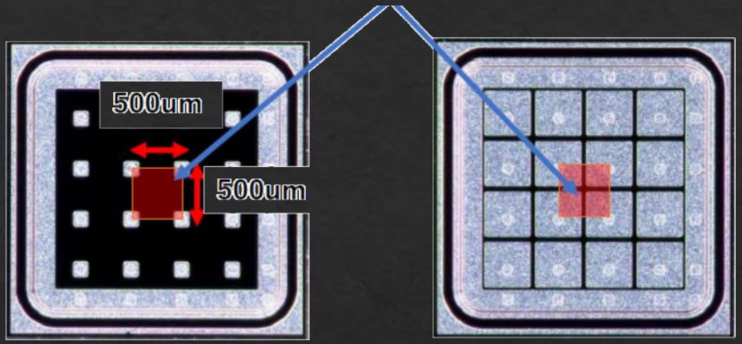
150um Al size



450um Al size

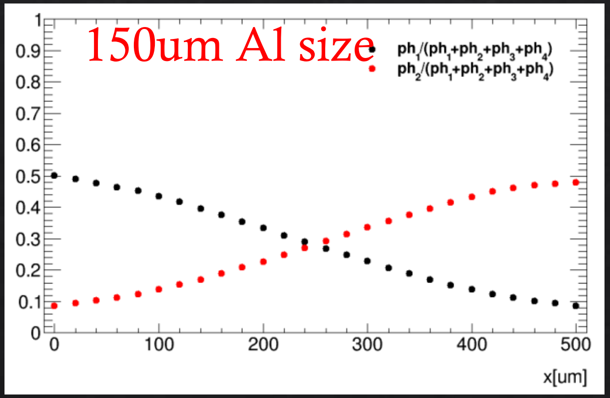


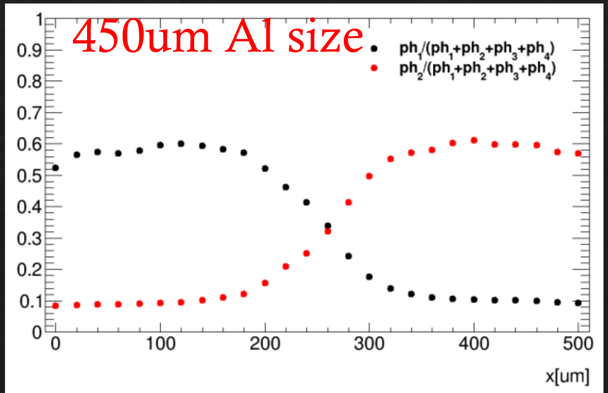
Scanned Area



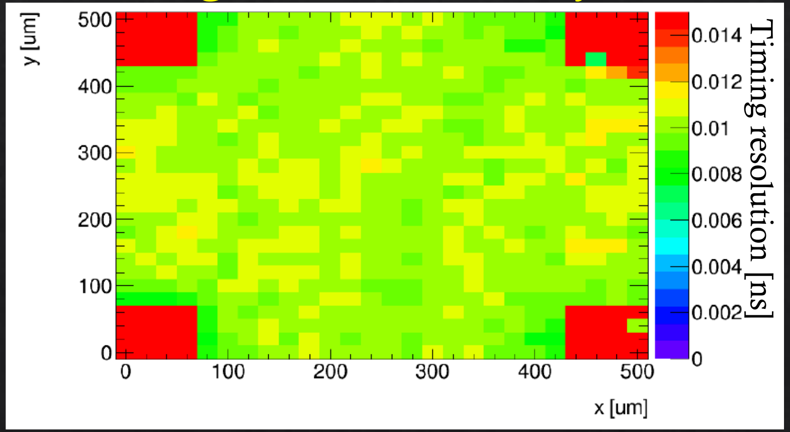
150um Al size | 450um Al size

Smaller Electrode size showed quite linear behavior of charge ratio





Timing resolution is very uniform



Timing resolution of LGAD sensor full picture

$$\sigma_t^2 = \sigma_{tw}^2 + \sigma_j^2 + \sigma_L^2$$

$$\sigma_j = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} = \frac{\sigma_n}{\left|\frac{S}{t_r}\right|} = \frac{t_r}{\left|\frac{S}{\sigma_n}\right|}$$

S : pulse height
σ_n : Noise
t_r : rise time

~~σ_{tw} :Time walk~~

σ_j: Jitter (electronics)

σ_L: Charge collection noise

Charge Collection noise :
50um thick sensor : ~30ps timing resolution
20um thick sensor : ~15ps timing resolution
Thinner sensor should have better timing resolution.

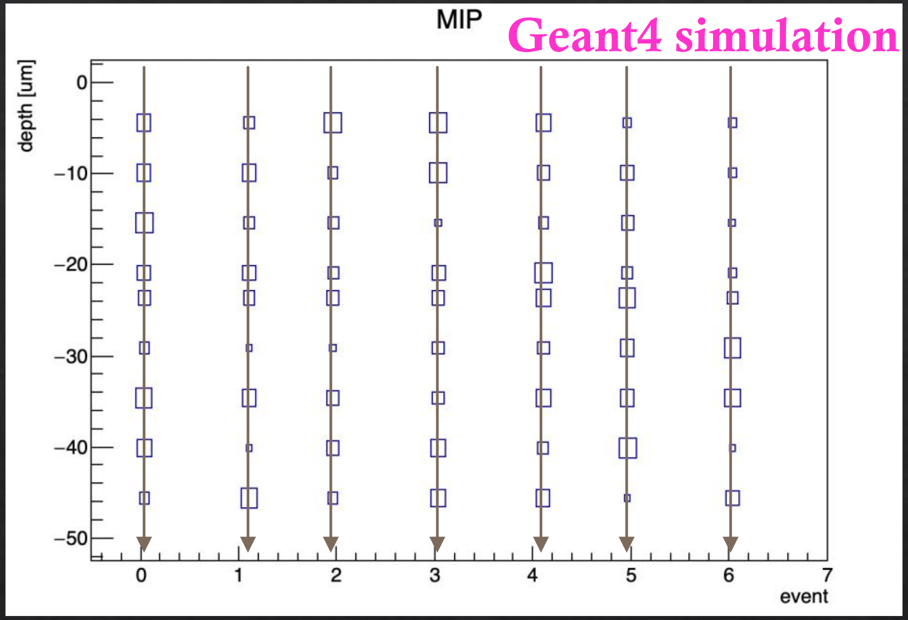
Pros and Cons of Low Gain Avalanche Detector

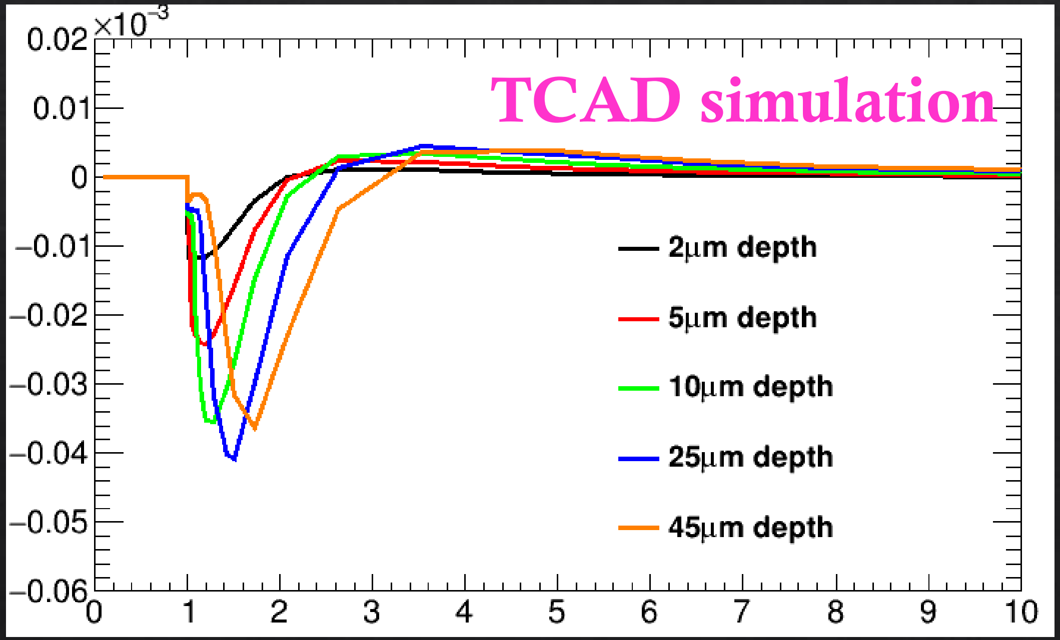
- Pros
  - LGAD have gain : x25 times larger signal size
    - Should be a lot better jitter.
  - Having slightly faster turn on (To be confirmed)
- Cons
  - LGAD have Charge Collection noise
    - Thinner sensor have smaller noise
      - But thinner sensor have smaller signal
- Finally important point is jitter of ASIC i.e. σ_n
  - If smaller σ_n possible, 10um thick LGAD with 10ps resolution may be possible?

Charge Collection Noise (Landau Noise)

- For Minimum Ionization Particle (MIP), charge deposition is not uniform depth profile.
  - This effect makes timing resolution get worse.
    - The slower turn on for charge at deep region. (**the thinner sensor the better**)
    - Signal increase by depth but saturated at some point (25um in simulation)

Non-Uniform charge deposition





$$I_{ind} = \sum_i q_i \vec{v}_{drift,i} \cdot \vec{E}_{w,i}$$

Thinner active thickness will help to reduce the effect

50um thick sensor : ~30ps CCN → 35ps in actual device achieved.

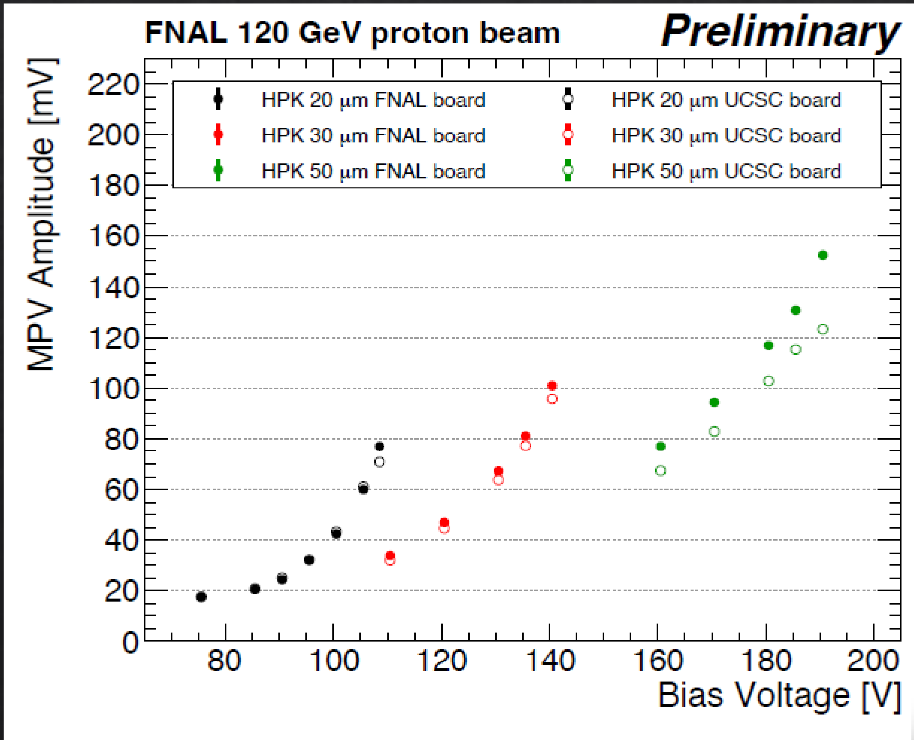
20um thick sensor : ~15ps CCN → 20ps in actual device achieved.

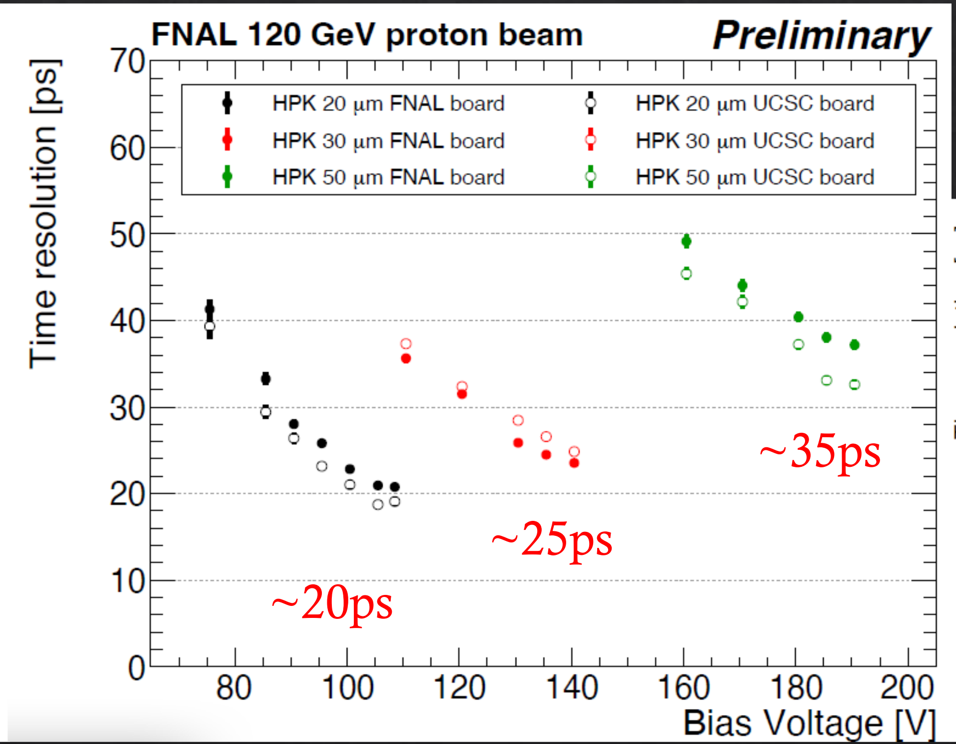
➔10um thick sensor?

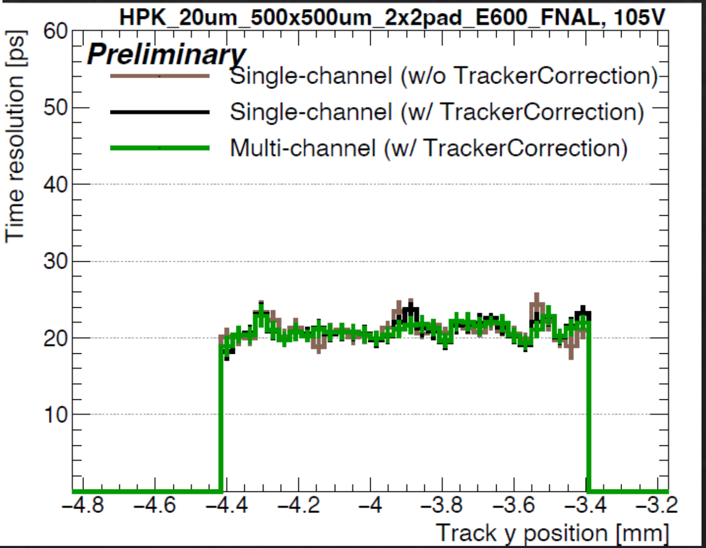
Smaller signal size (worse jitter) but better CCN.

Improvement of timing resolution

- To reduce Landau noise : Fabricated 50um, 30um and 20um thick sensors
  - Signal size (amplitude) is smaller in thinner sensors.
  - **20um thick sensor has the best timing resolution : ~20ps**
  - **Uniform timing resolution at the gap region as well.**





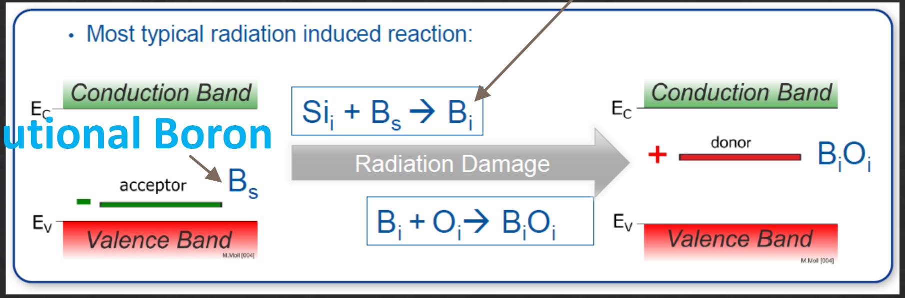


Radiation tolerance of LGAD detector

- Like normal silicon device
  - Bulk damage (NIEL) : Si lattice damage
  - Surface damage (TID) : charge up at SiO_2-Si
- **In addition ”Acceptor Removal”**
  - *p*+ in Gain layer reduced

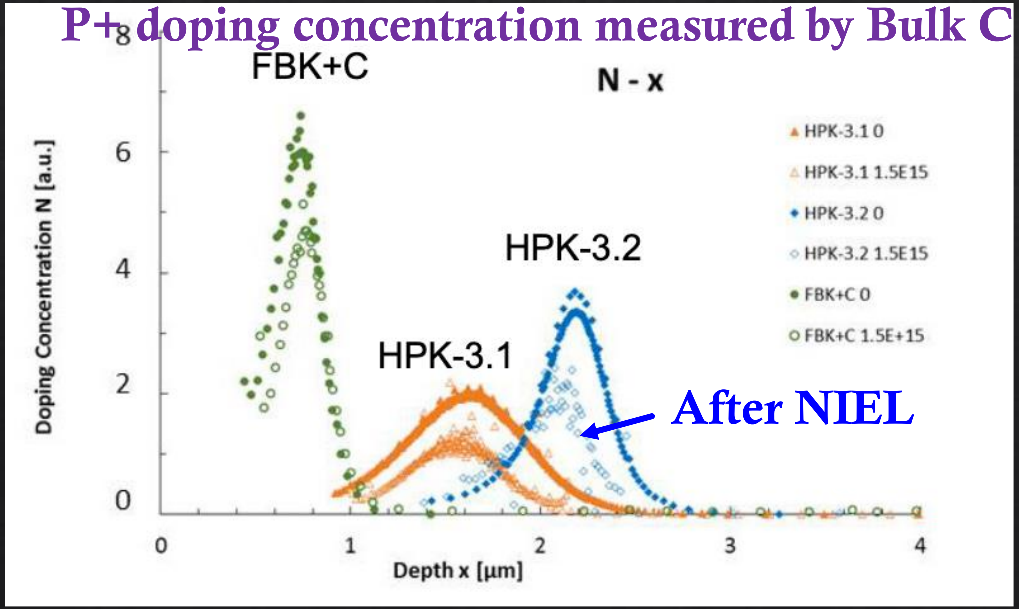
Interstitial Boron

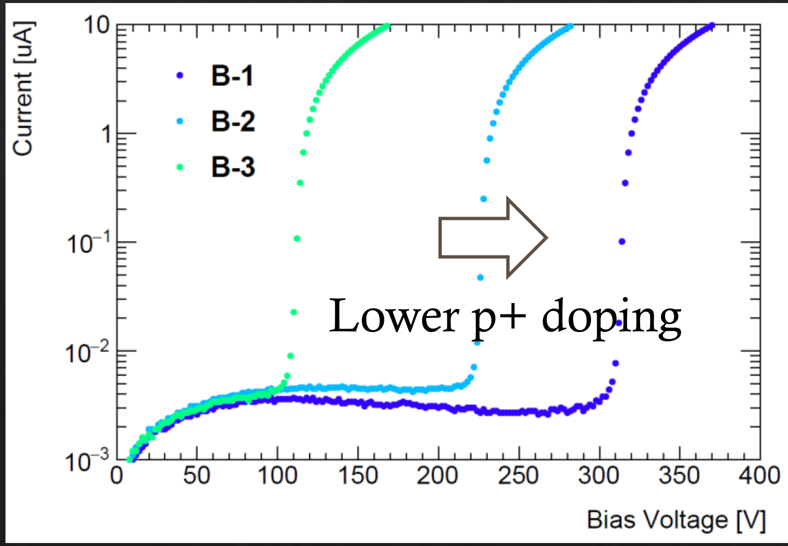
Substitutional Boron



Acceptor removal (low p+ concentration) introduce weaker field :
→ Need higher voltage to keep high electric field at gain layer

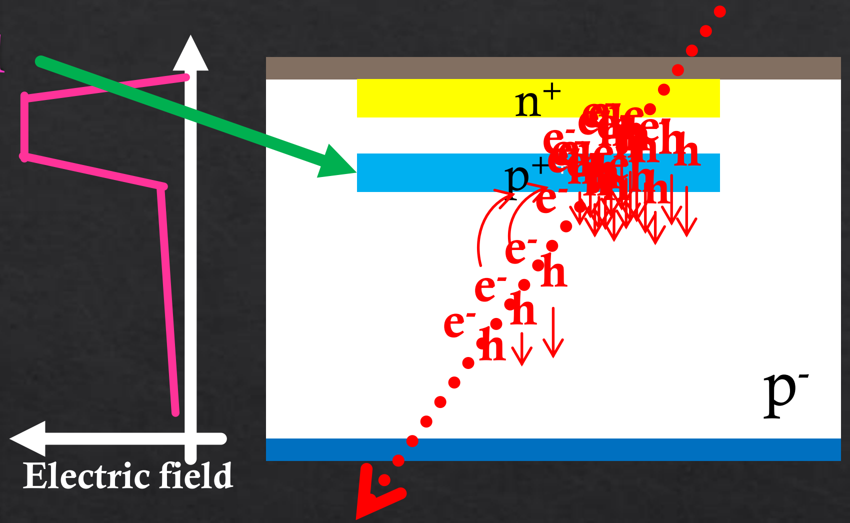
P+ doping concentration measured by Bulk C





New idea for improvement of Radiation Tolerance?

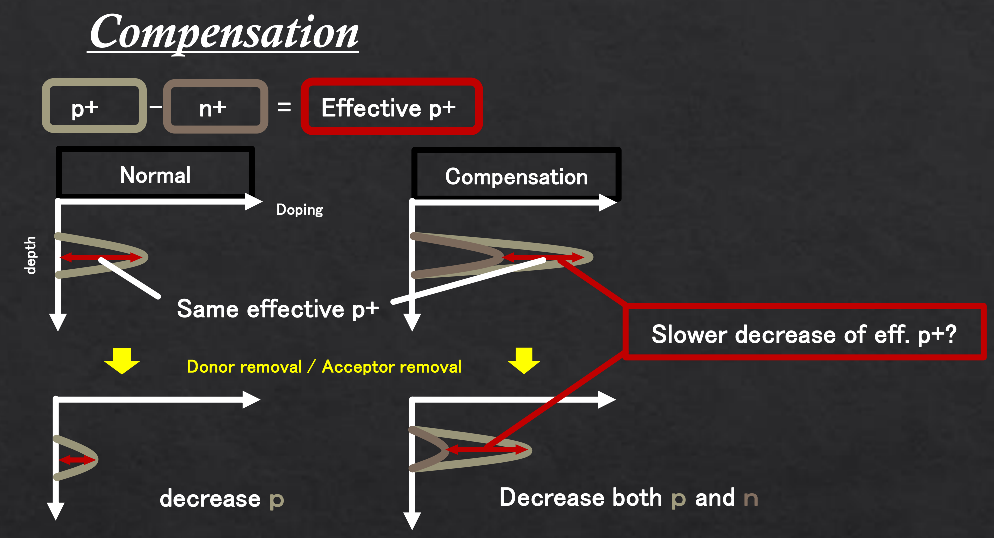
- Protection of p+ gain layer is a key point to reduce Acceptor removal
- New ideas
  - Carbon annealing **(confirmed by FBK)**
    - Improvement is just a factor of 2 or so…
  - **Compensation method**
    - Add Boron + Phosphorus
    - If acceptor removal is smaller than donner removal this method should work!
  - **Partially activated Boron (PAB)**
    - Large number of Bi at the beginning to clean up Oi



Fabricated samples with these ideas as DC-LGAD 1.3mm Pad detector

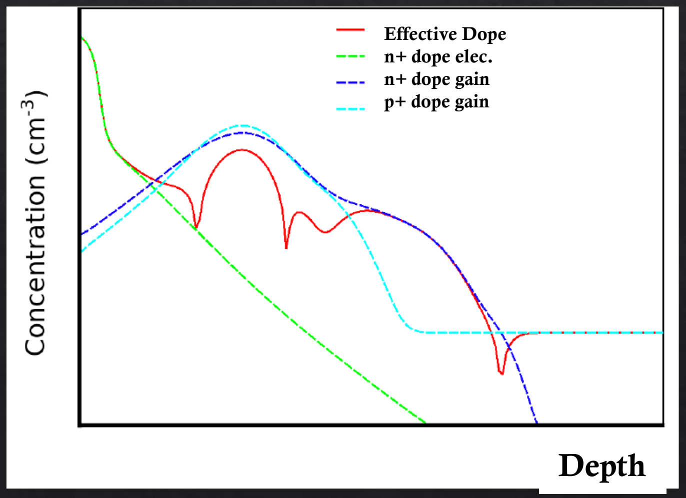
Compensation method

- Both Boron(p+) and Phosphorus(n+) are doped.
  - Operating with effective p+ (difference of p+ and n+)
    - It should work if donor removal is faster than acceptor removal
  - Due to the mass difference of Boron and Phosphorus, depth profile of p+ and n+ are slightly different. (effective dope is not simple Gaussian like depth profile)



HPK could successfully produced working LGAD with a few types of compensation parameters.

Difficulty of doping profile :



Performed a couple of Irradiation Campaign at CYRIC

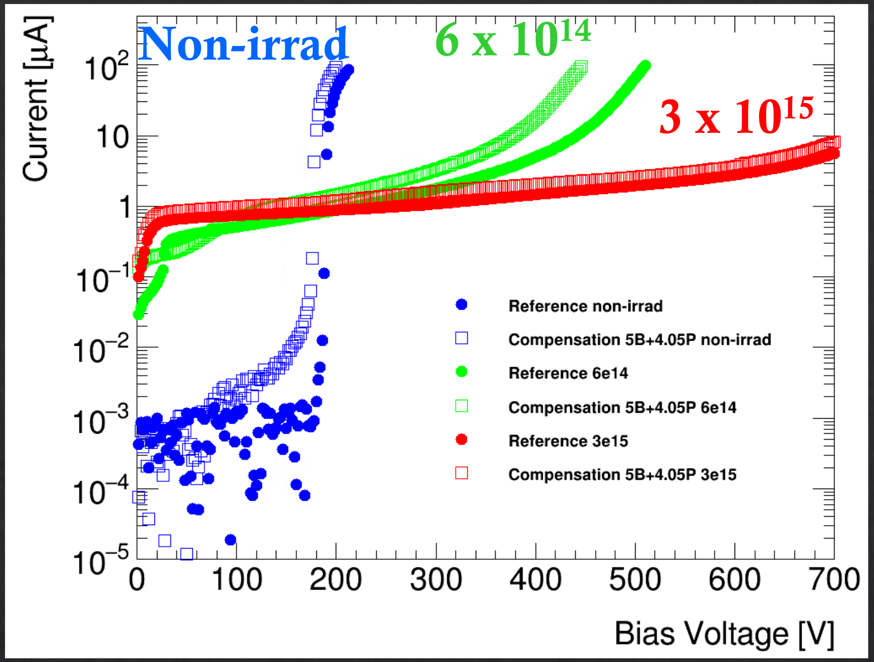
1B (reference), 1.5B+0.55P, 2.5B+1.5P, 5B+4.05P, 10B+9.2P

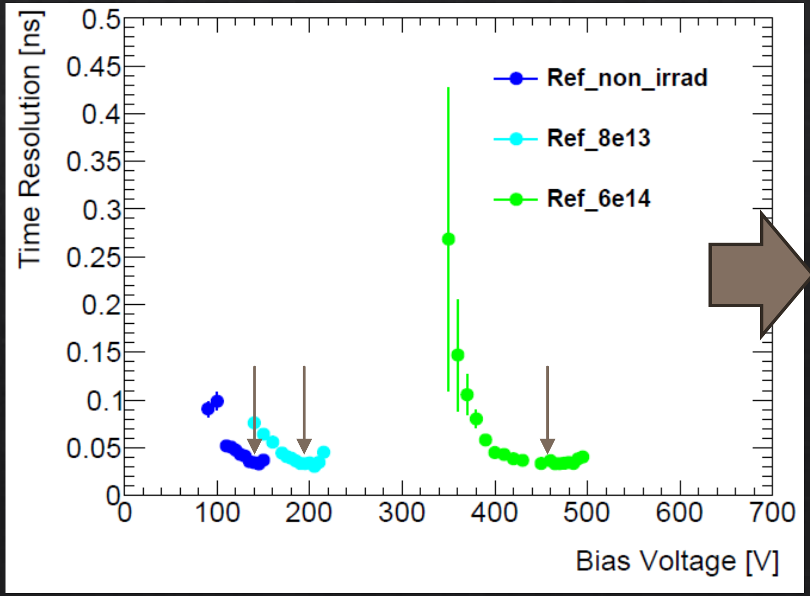
B : Boron

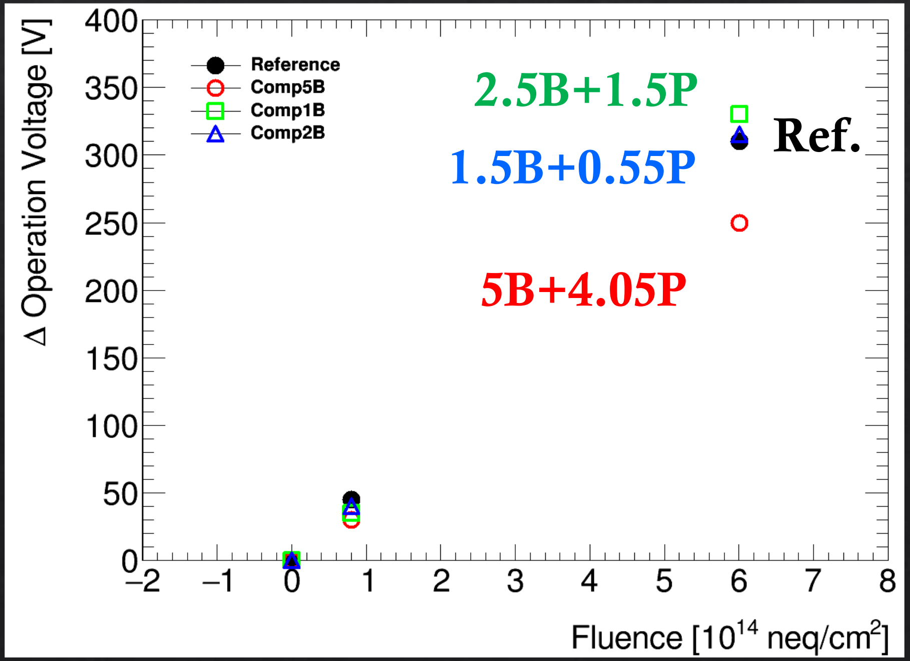
P : Phosphorus

Compensation results

- Tested different compensation ratio
  - 1B (reference)
  - 1.5B+0.55P : No visible improvement
  - 2.5B+1.5P : No visible improvement
  - 5B+4.05P : Saw slight improvement (~50V)
  - 10B+9.2P : No significant signal observed
- What does this mean?







VERTEX2023(arXiv:2401.08108)

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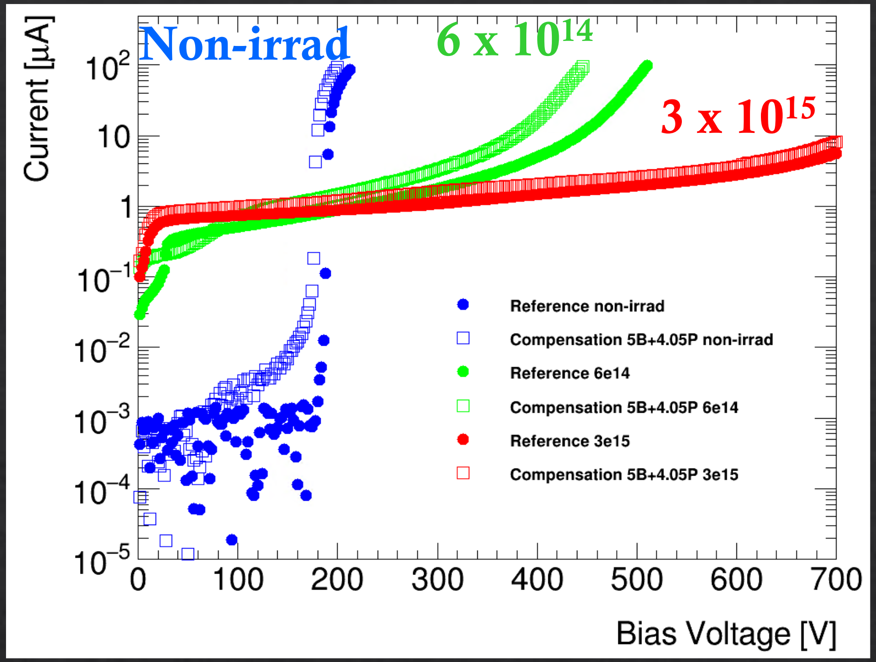

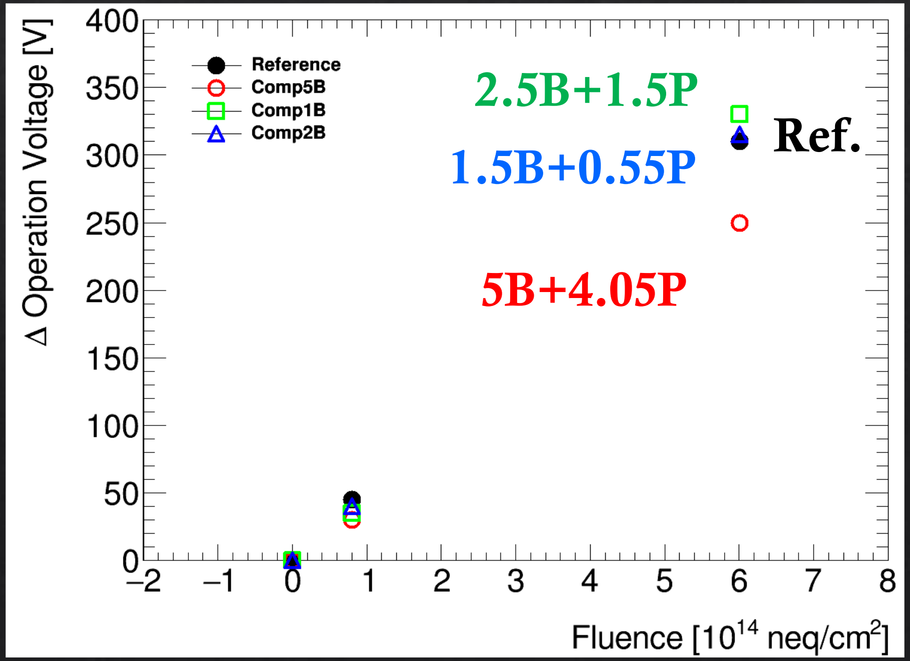

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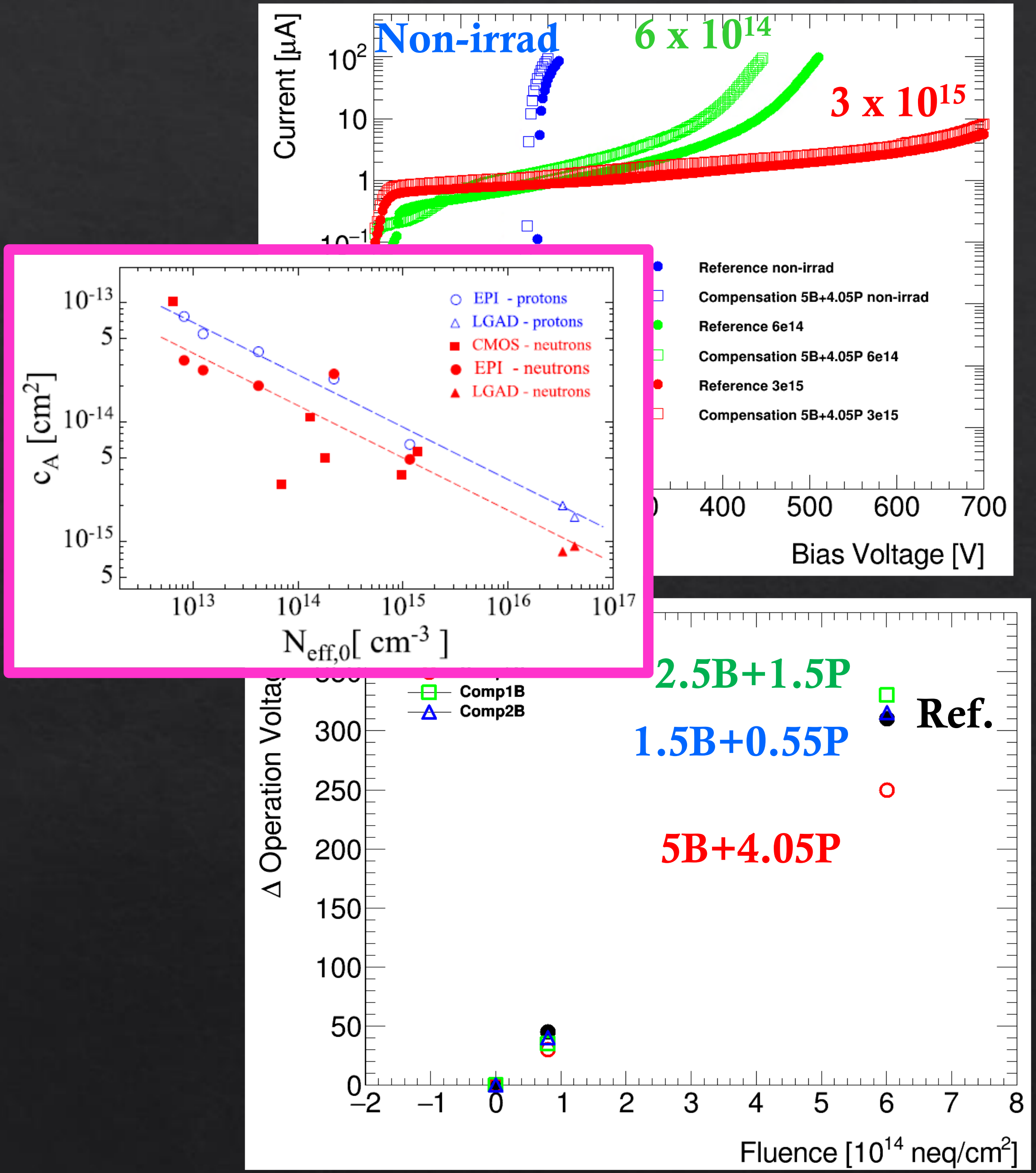

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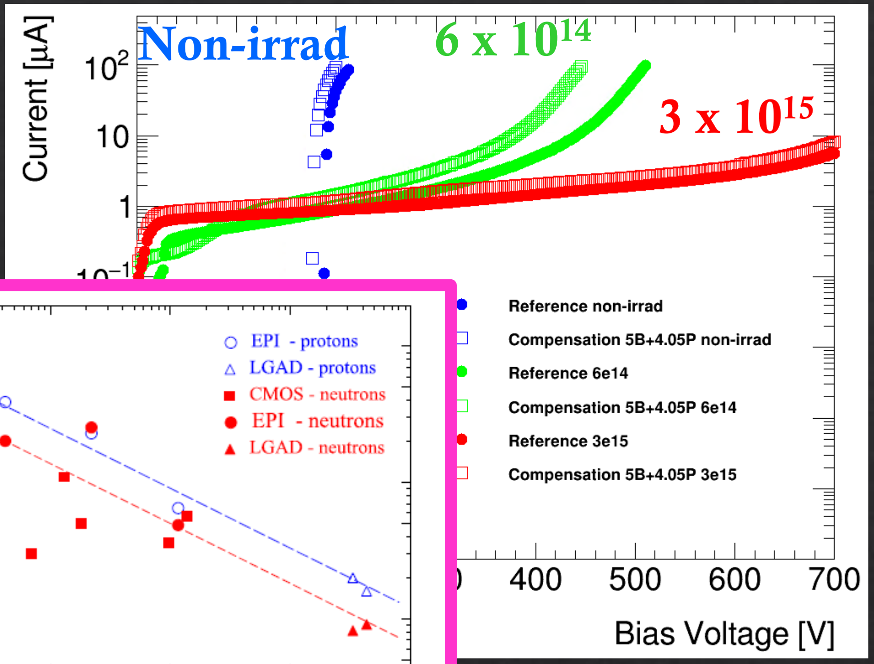
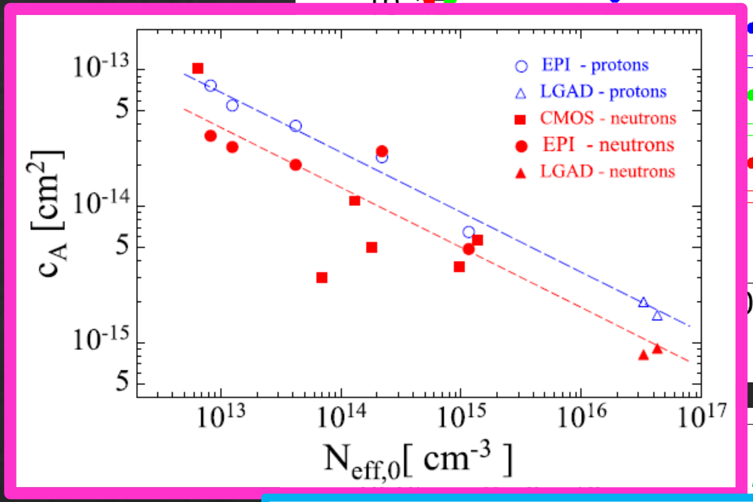
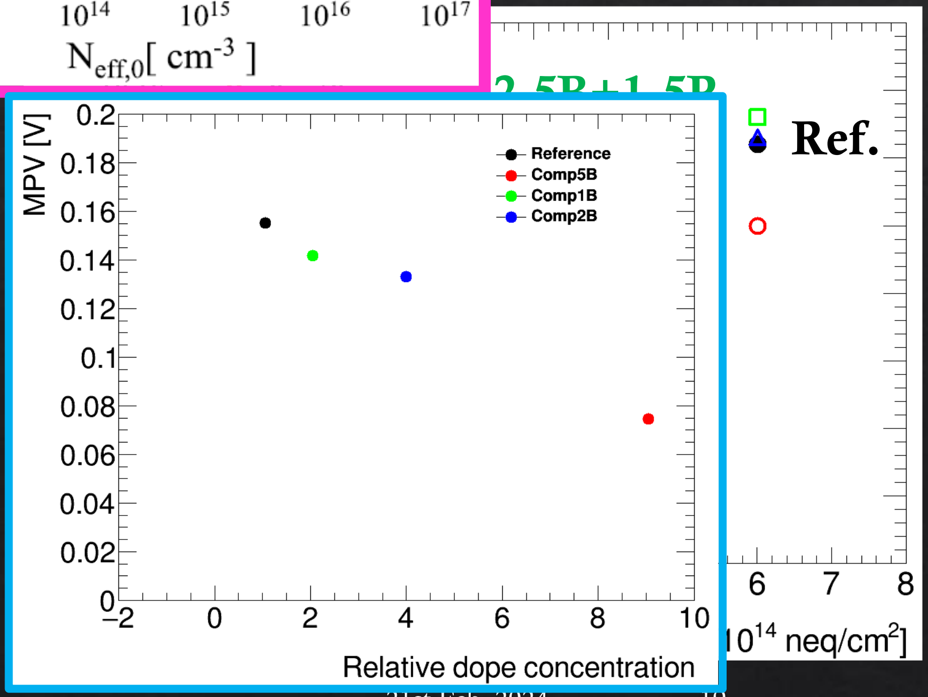
    - **→ larger doping concentration have smaller acceptor removal**
  - **However larger compensation have risk of reduction of signal size**
    - **→ larger implantation makes smaller signal size**



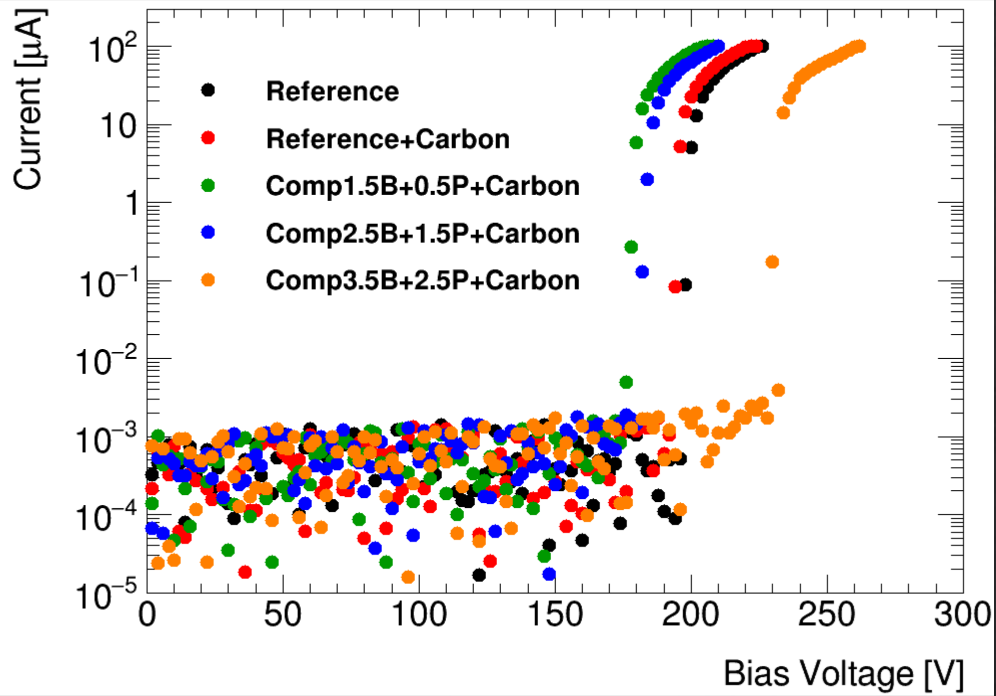




VERTEX2023(arXiv:2401.08108)

Compensation + Carbon Samples

- Successfully fabricated Compensation + Carbon sample.
  - Carbon has been doped at wafer maker (not HPK) with quite wide depth profile.
    - Doping profile may be sub-optimal.
    - But fist samples are produced and working as LGAD sensor.
  - Break down Voltage is 180V-230V range for various samples.



	p+ Boron	n+ Phosphorous	effective p+
Compensation 1.5P+0.5P+Carbon	1.5a	0.5a	a
Compensation 2.5P+1.5P+Carbon	2.5a	1.5a	a
Compensation 3.5P+2.5P+Carbon	3.5a	2.5a	a
Reference+Carbon	a	0	a
Reference	a	0	a

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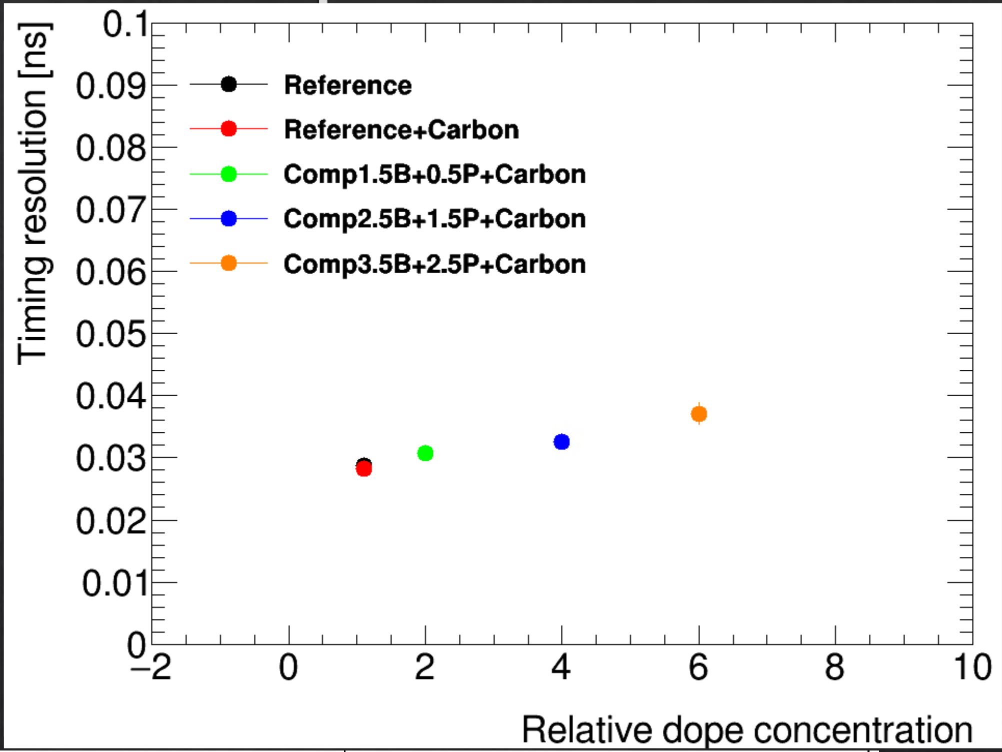
    - Doping profile may be sub-optimal.
    - But fist samples are produced and working as LGAD sensor.
  - Break down Voltage is 180V-230V range for various samples.
  - Timing resolution is deteriorated by increasing doping concentration

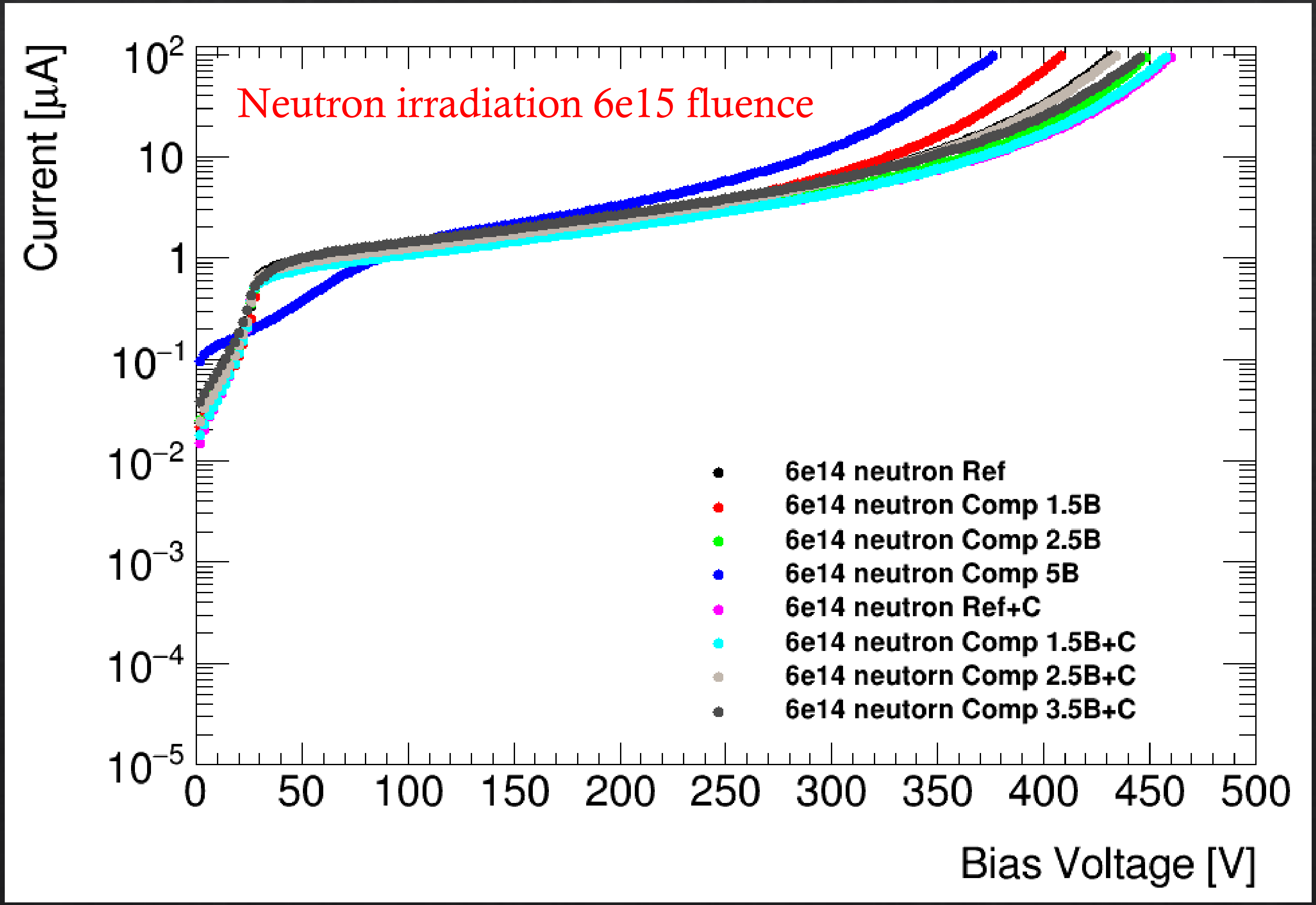


Irradiated these samples have just back from JSI

	p+ Boron	n+ Phosphorous	effective p+
Compensation 1.5P+0.5P+Carbon	1.5a	0.5a	a
Compensation 2.5P+1.5P+Carbon	2.5a	1.5a	a
Compensation 3.5P+2.5P+Carbon	3.5a	2.5a	a
Reference+Carbon	a	0	a
Reference	a	0	a

Compensation + Carbon Samples

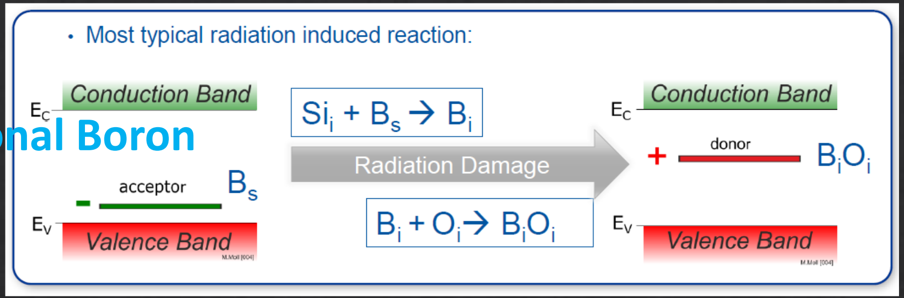
- As a result, we don't see any improvement by Carbonated or Carbonated compensation.
  - Probably…
    - Carbon doping is too low. (need x10)
  - For next production…
    - Will increase Carbon doping if it helps.



Partially-Activated Boron

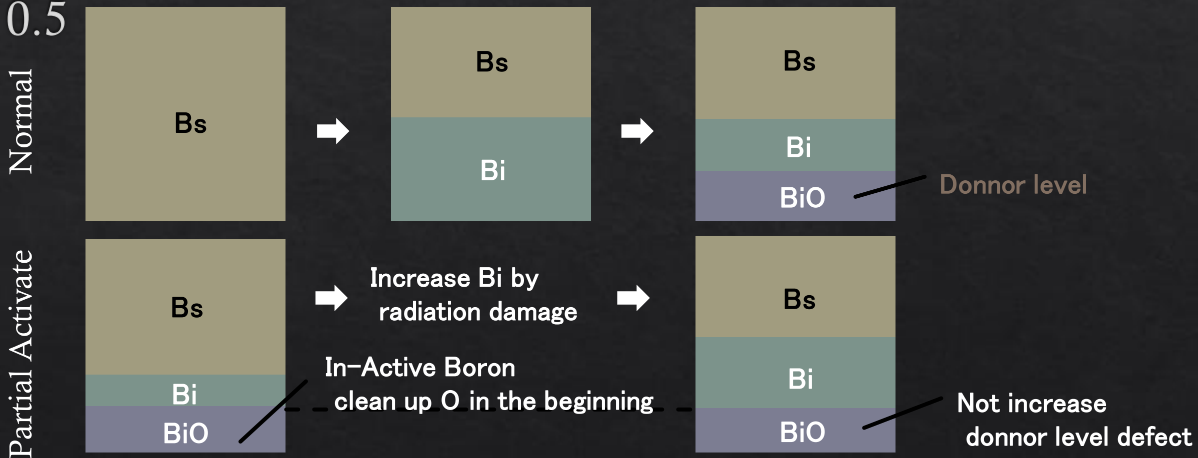
- If non-activated Boron are remaining:
  - Probably Oi is cleaned up by Bi+Oi->BiOi process.
- Doped larger Boron but baked with lower temperature not to activate all Boron. (i.e. lots of Bi with some Bs)
  - First prototype shows very low Vbd before irradiation. (i.e. too much active Bs) : x2.5 Boron doped, baked at 500°C
    - No signal observed.
  - Second prototype : 1B completely baked. Dope additional 0.5 or 1 Boron without baking. (i.e. 1B+0.5PAB, 1B+1PAB)

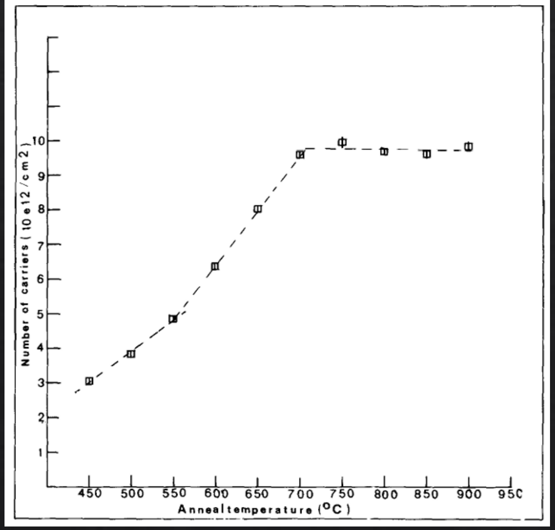
Interstitial Boron



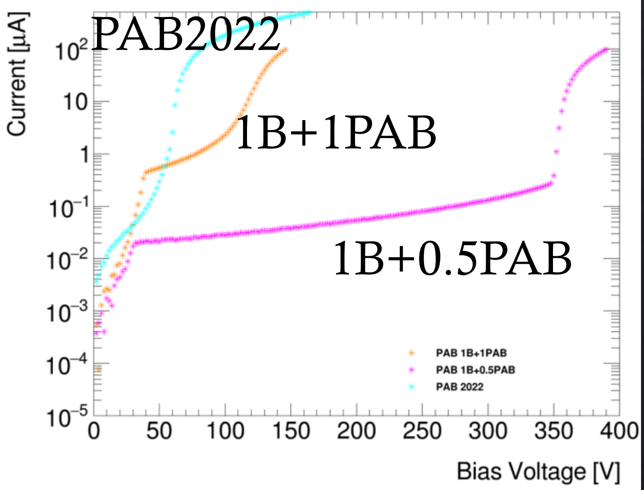
Substitutional Boron

Partially activated Bolons (PAB)



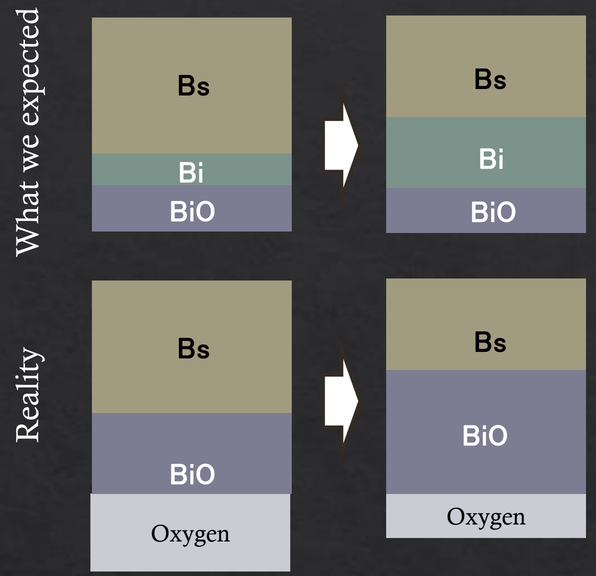


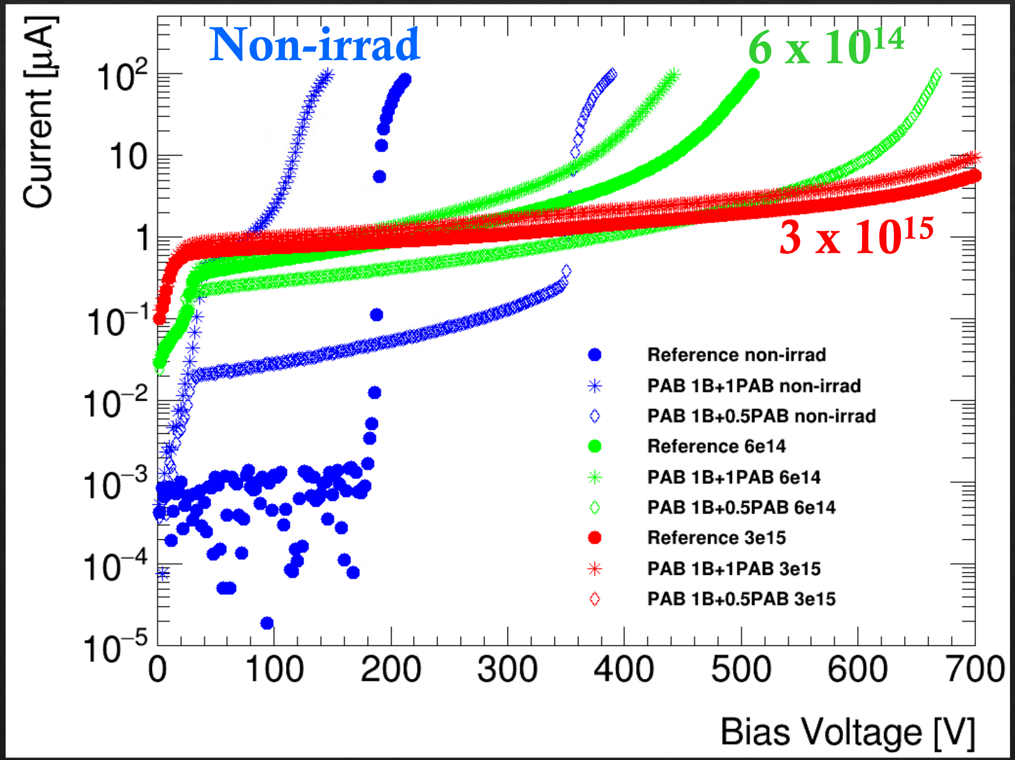
S.Oosterhoff et. al. Solid-State Electronics, 28(5) 1985

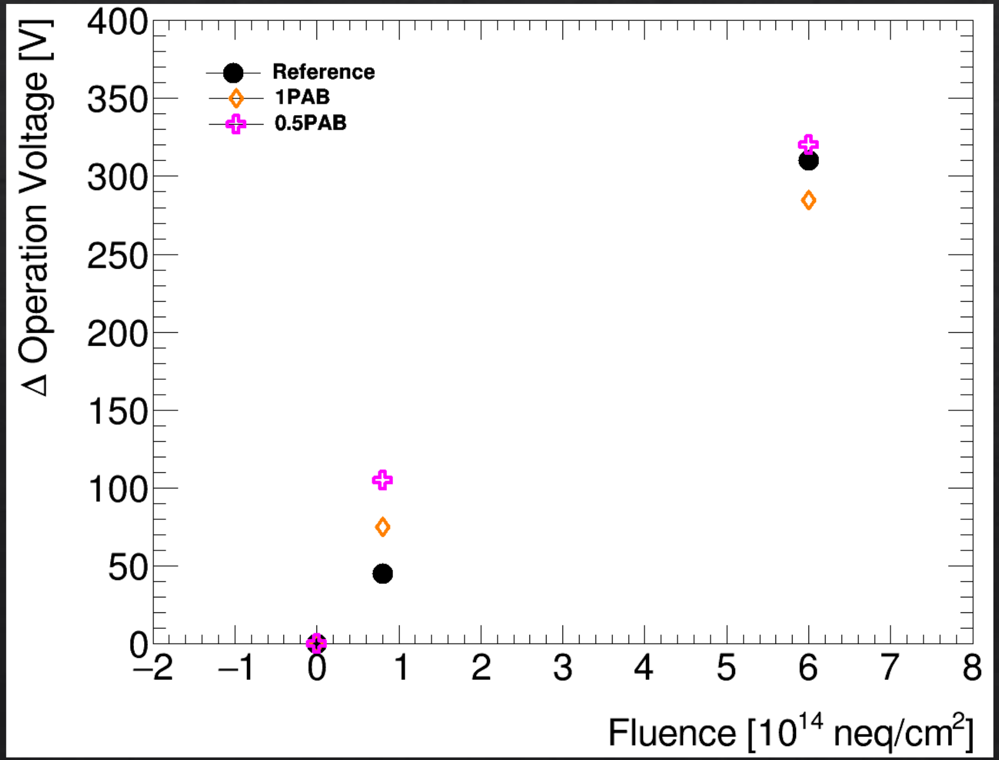


Partially-Activated Boron results

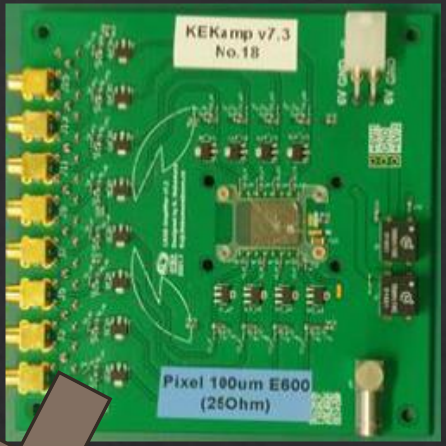
- As a results of PAB samples :
  - All different type of PAB samples don't show significant improvement.
    - May be assumption was wrong?
    - Recently observed very high Oxygen contamination in the Epi layer by SIMS.
      - Not enough Non-Active Boron?
      - Does this work for the wafers with smaller Oxygen contamination?





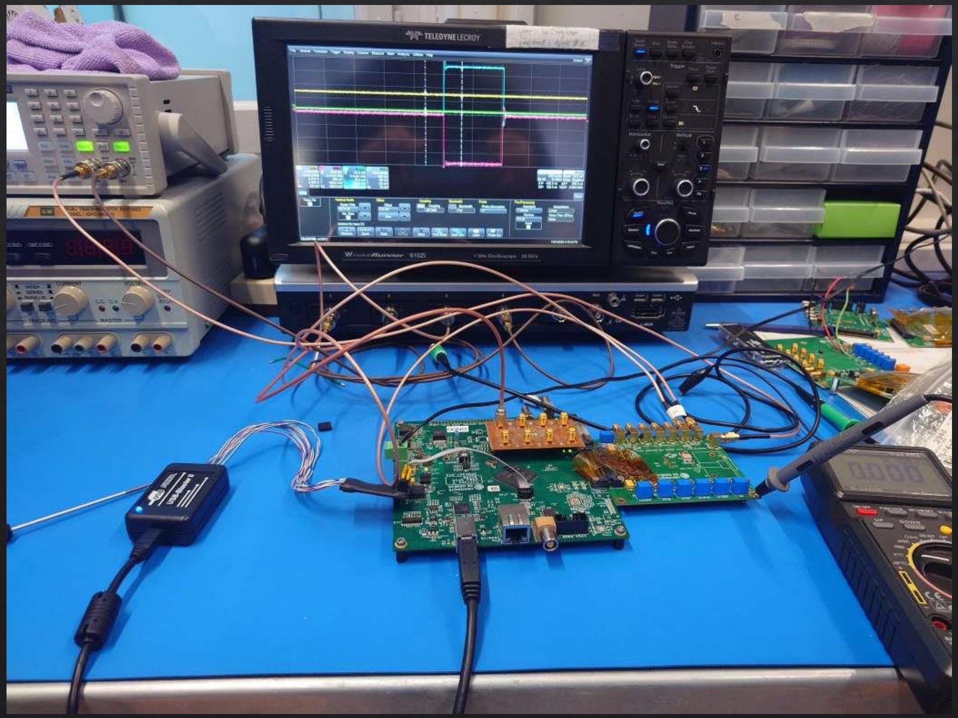


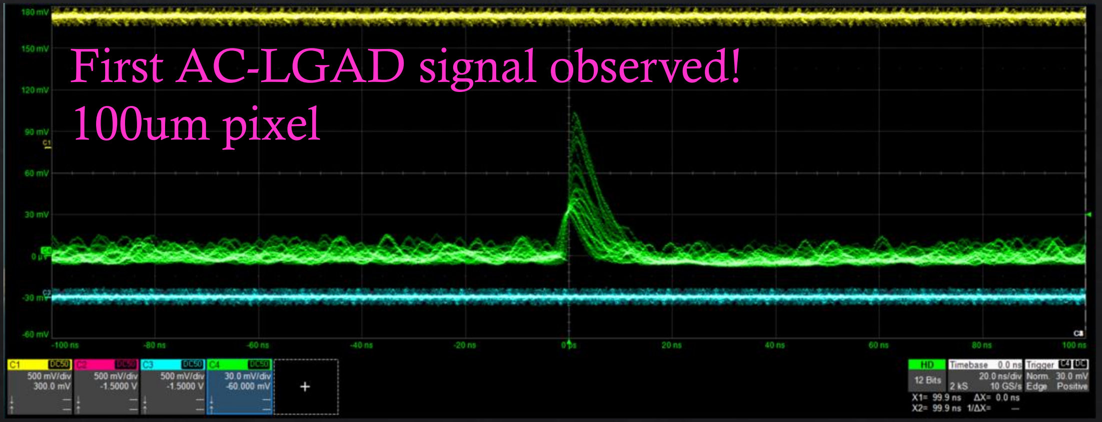
Readout Electronics



- Various ASIC developed for ATLAS/CMS/EIC detector (i.e. ALTIROC/ETROC/EICROC)
  - Various possibility but may be good to optimize for small Cdet
- Low noise pre-amplifier and Comparator with time walk correction is important for timing resolution.
  - Still signal size based time walk correction is popular method
  - Recently Constant Fraction Discriminator is implemented to the ASIC by Fermilab group.
- Si-Ge Bi-CMOS ASIC : IHP 130nm process designed by Uni. Geneva
  - Originally the architecture developed for monolithic detector.
  - 100um x 100um pitch 10x10 input electrodes.
  - There are 3ch analog readout and 1ch discriminator output.

Si-Ge Readout Setup @ Univ Geneva & KEK





Conclusion

Fine pitch LGAD!

ACLGAD with 80um pitch strip sensor
Good S/N ratio : 99.98% at 1e-4 noise rate
ACLGAD with 100um x 100um pixel sensor
Larger signal than strip sensor!!

Good time resolution

20um thick ACLGAD successfully developed
We achieved ~20ps level time resolution!
→ Need to test pixelated LGAD

Need Improvement

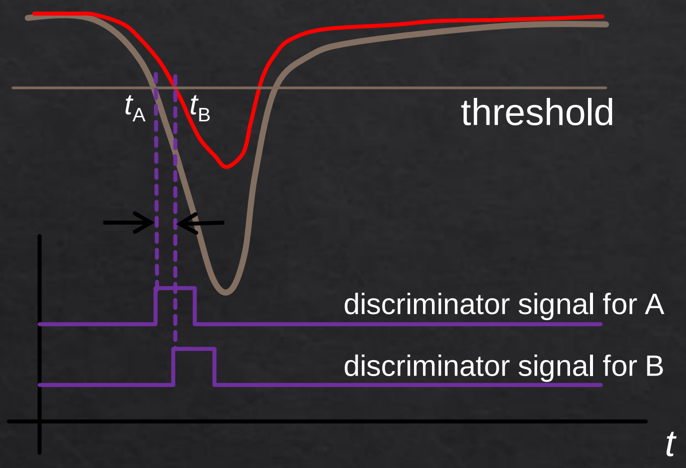
LGAD detector with Radiation tolerance
Tested Compensation and Partially activated Boron :
both are not promising
→Next Compensation with high carbon dope

Backup

How to improve the timing resolution?

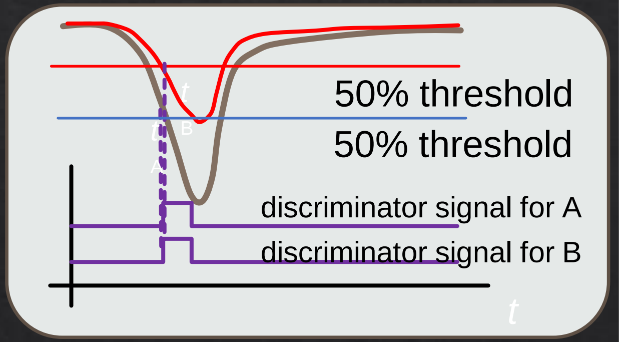
Two reasons which make worse timing resoulution :

1. Time walk



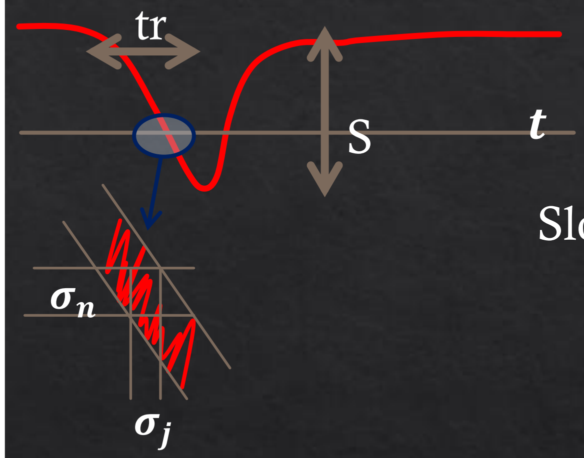
Different arrival time for small and large signals

Solution:
The effect will be negligible using constant fraction thr.



This is a matter of arrival time definition.

2. Time jitter



Arrival time is randomly change by noise.

$$\sigma_j = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} = \frac{\sigma_n}{\left|\frac{S}{t_r}\right|} = \frac{t_r}{\left|\frac{S}{\sigma_n}\right|}$$

Size of noise

Slope of vol.

Size of signal

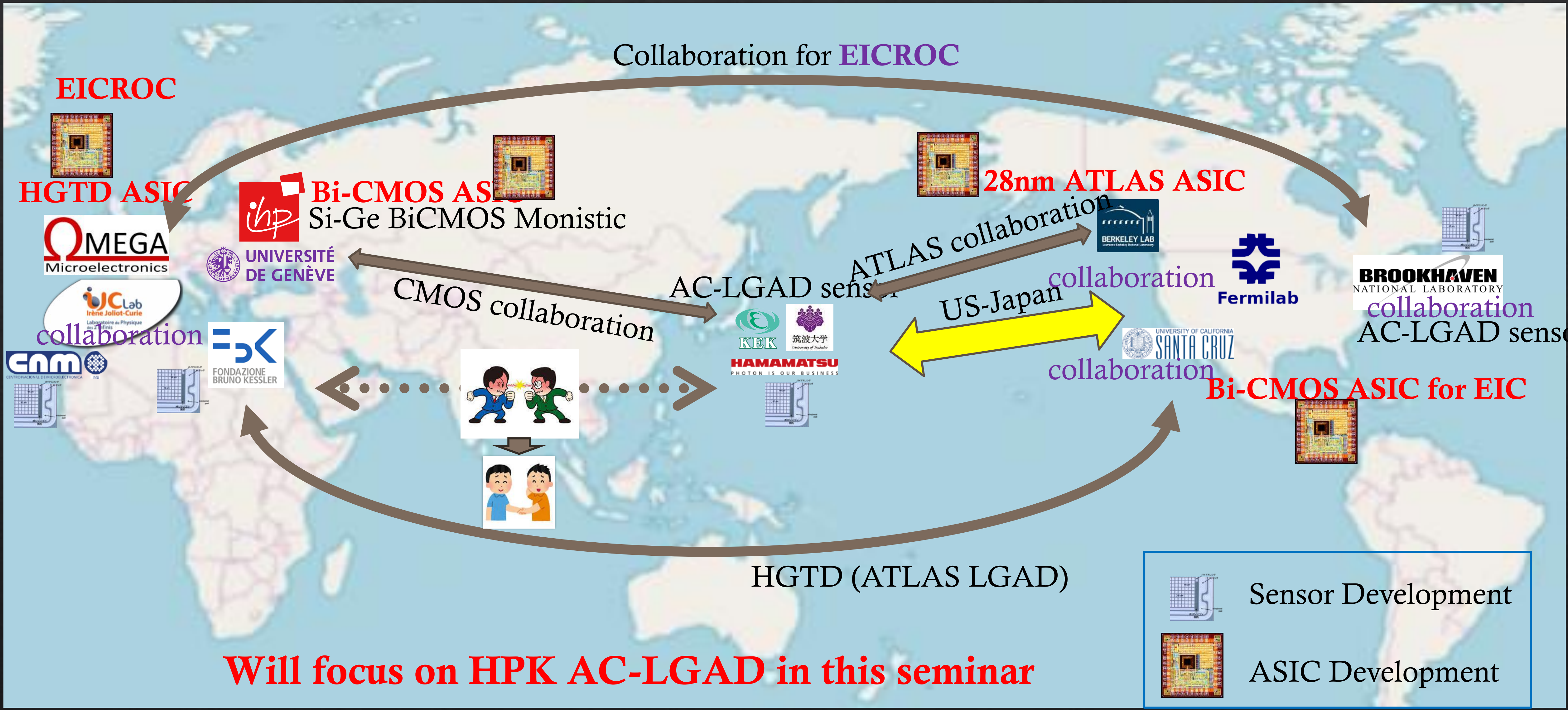
Ramping time

Solution :
To make smaller jitter

1. **Smaller noise**
2. **Larger signal**
3. **Faster ramping time**

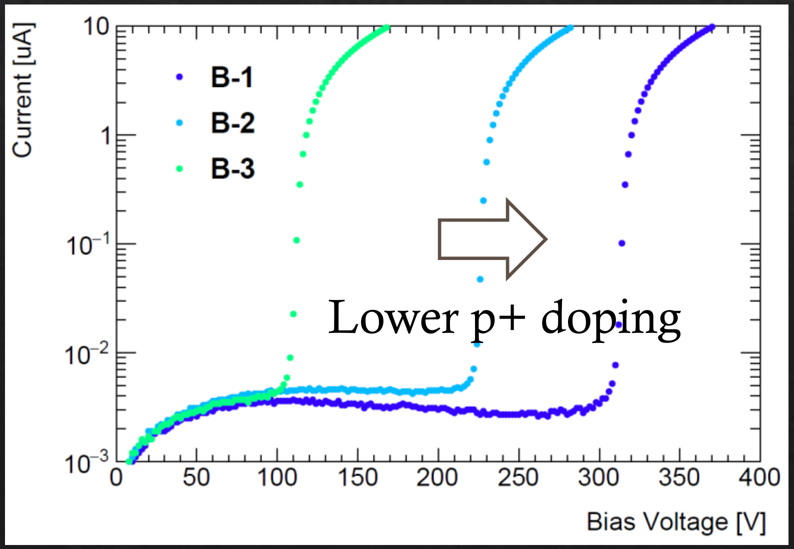
Faster signal turn on and good S/N ratio should be the key to improve timing resolution

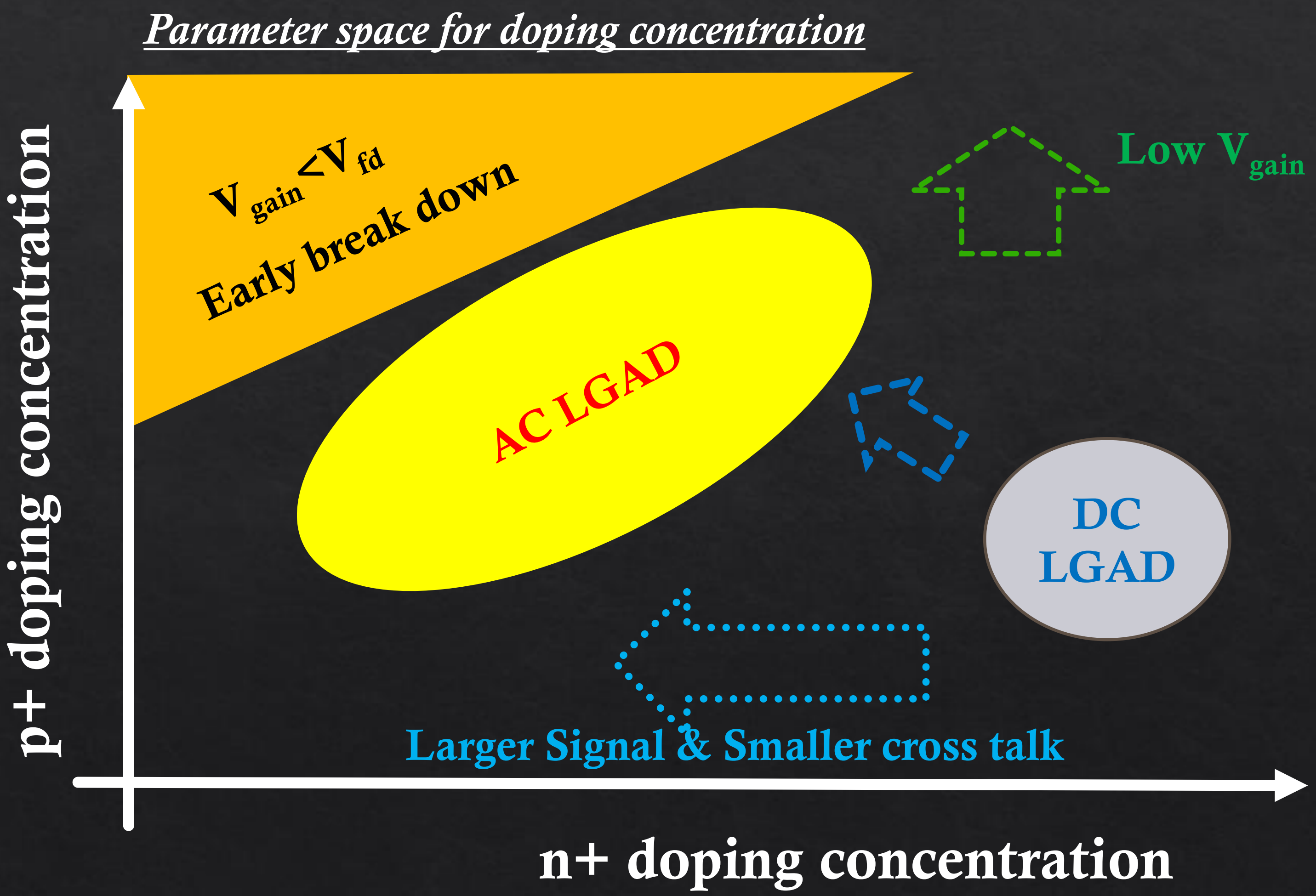
AC-LGAD collaboration



Optimization of process parameters

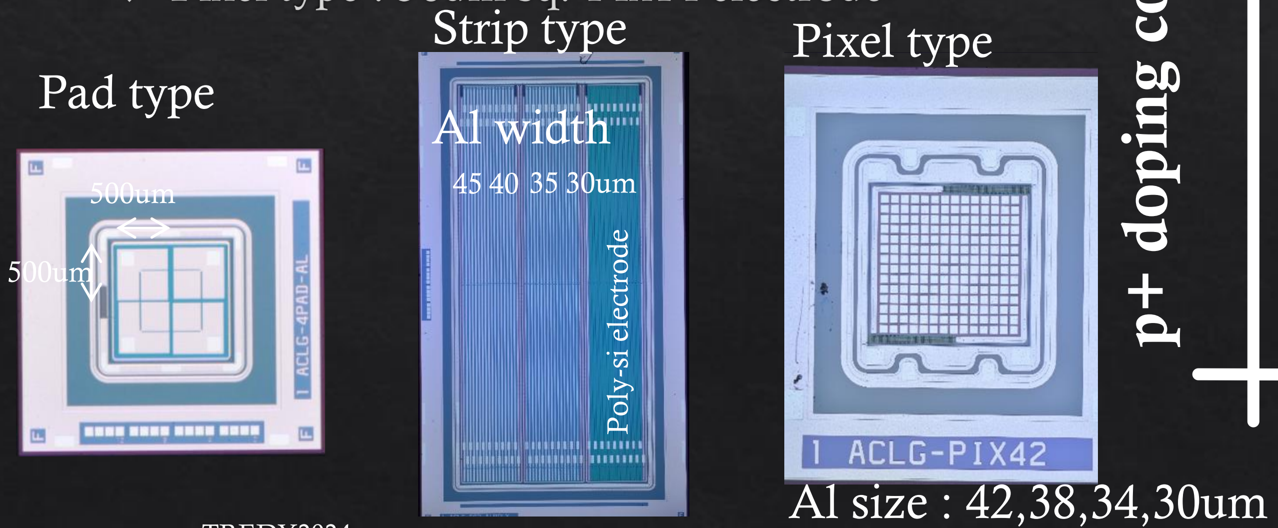
- Parameter space in n+ and p+ doping concentration has been optimized.
  - n+ concentration should be lower than Normal (DC) LGAD to reduce charge sharing (Crosstalk).
  - p+ doping concentration is used to tune operational voltage (i.e. avalanche voltage)



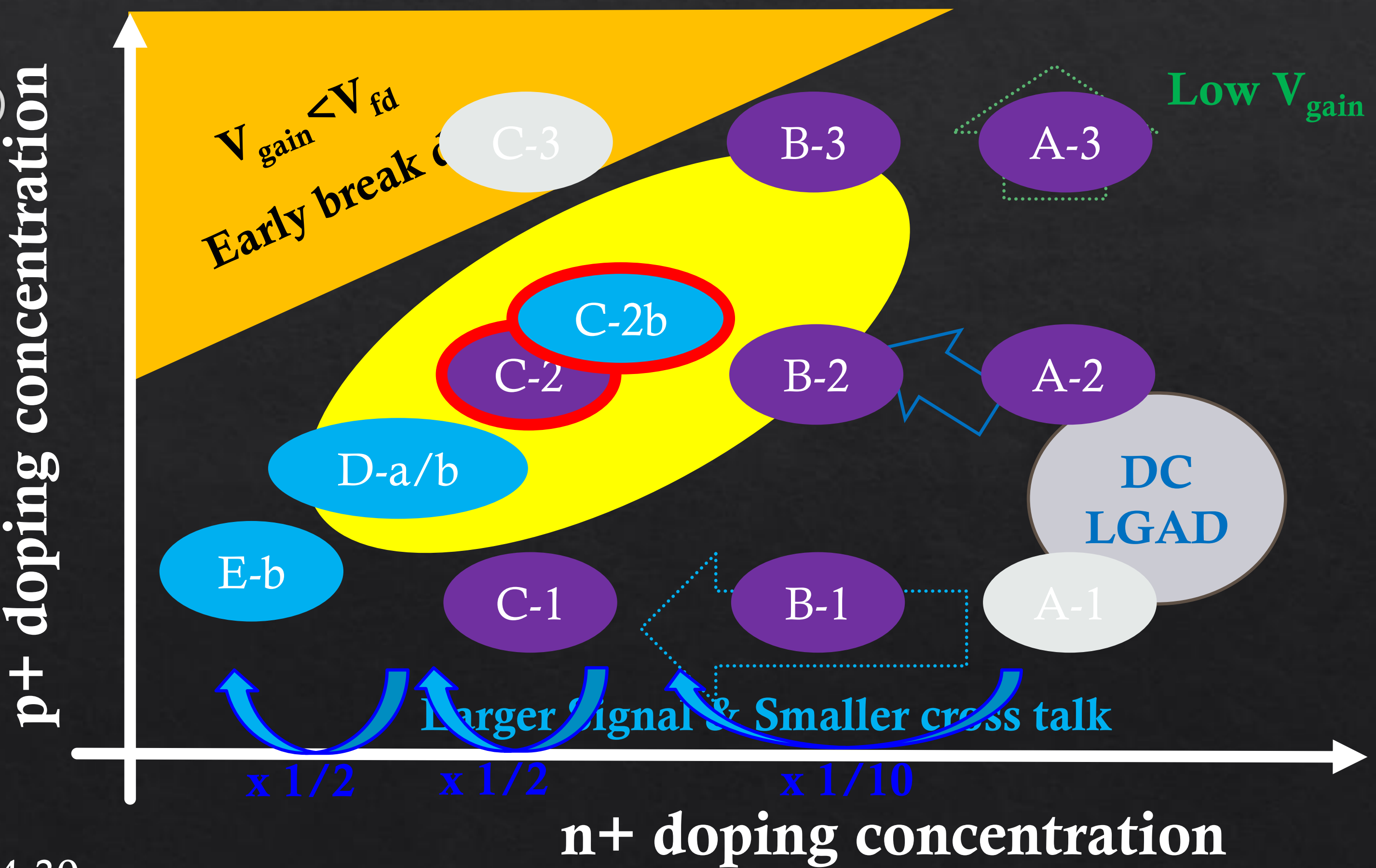


Optimization of process parameters

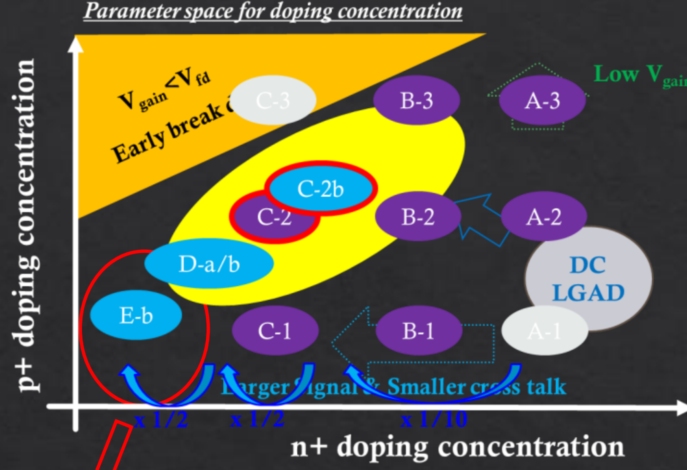
- JFY2015-JFY2018 DC-LGAD
  - **We contributed only first prototype.** HGTD took over.
- JFY2019, JFY2020 AC-LGAD production
  - Vary n+ and p+ dope (A-E, 1-3)
  - Vary thickness of SiO_2 (capacitance : C_b=1.5xC_a)
- Electrode type
  - Pad type: 500um sq. 4pad/sensor
  - **Strip type : 80um pitch**
  - Pixel type : 50um sq. 14x14 electrode



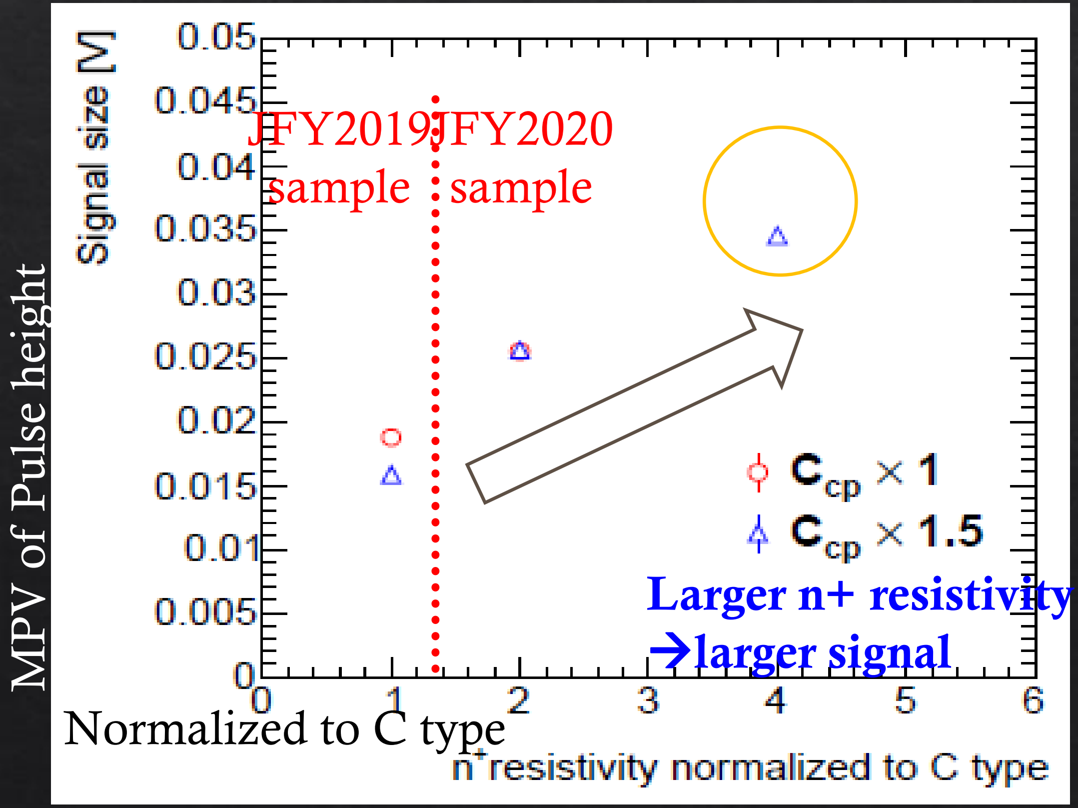
Parameter space for doping concentration

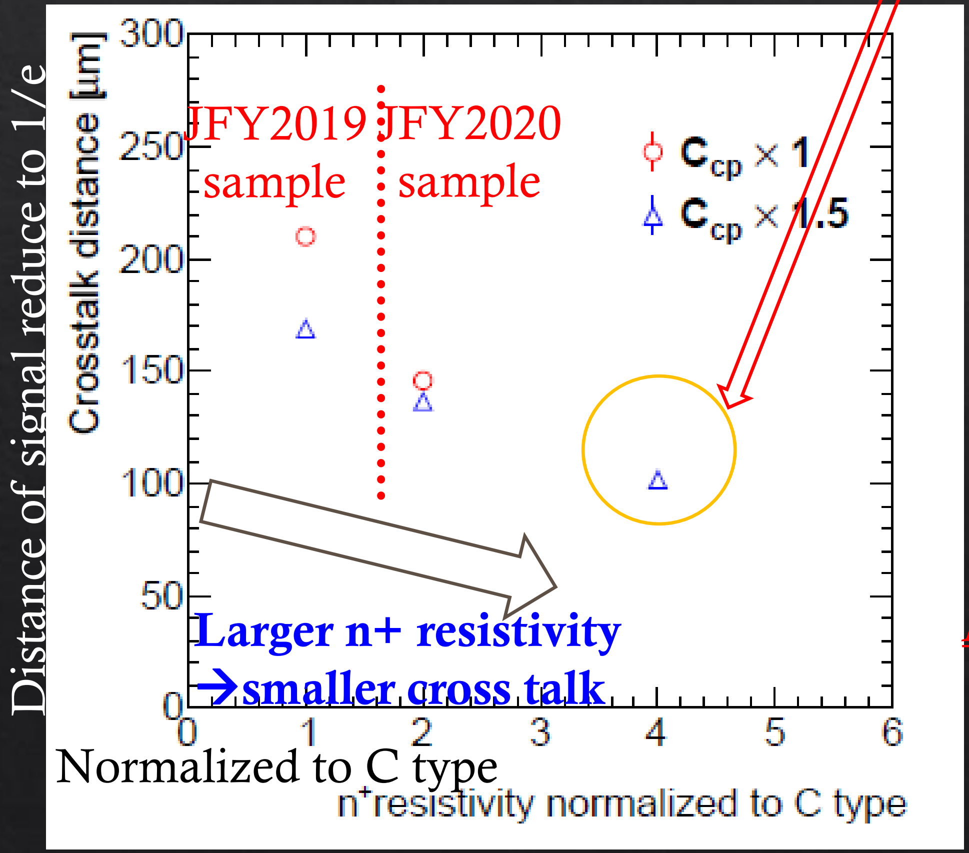


Signal size and crosstalk



- **Strip type :** Signal size and Crosstalk
  - n+ resistivity dependence of signal size and crosstalk.
  - **Large n+ resistivity →Large signal & Smaller crosstalk**





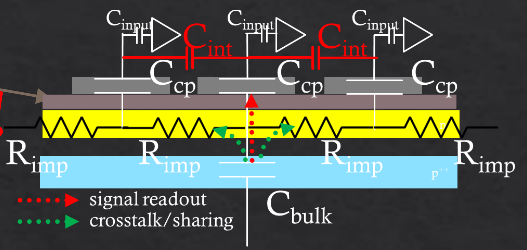
All C to E types works fine.
→ Can choose depends on application

NIMA 1048(2023) 168009

How small electrode could we achieve?

Used thinner di-electric layer (Oxide layer)

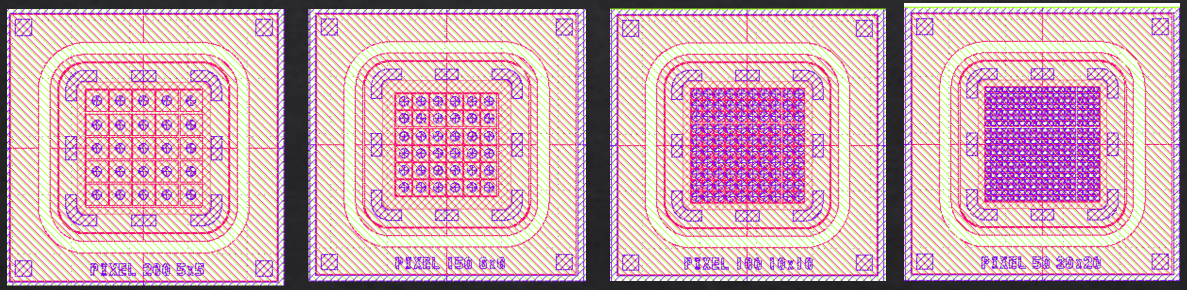
→ Electrode capacitance increased by factor of 5 !!



Pixel sensor

- Various of pitch

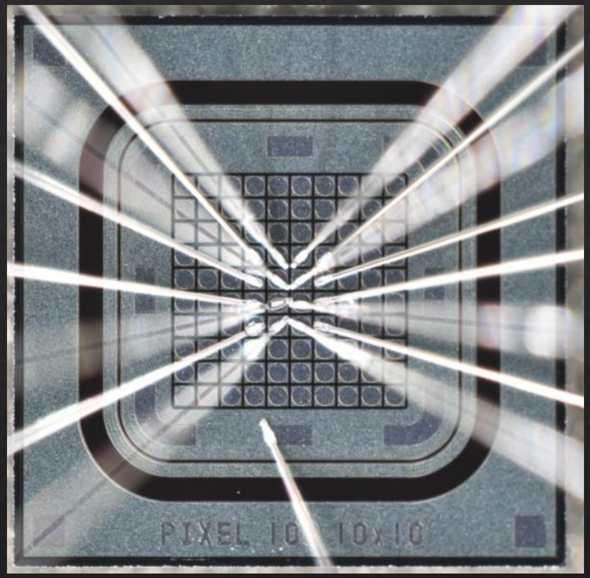
200um 150um 100um 50um



- 5 times larger Ccp compared with E-b (2020) type : E-600

R_{imp} [Ω/□]			
1600	E120	E240	E600
400	C120	C240	C600

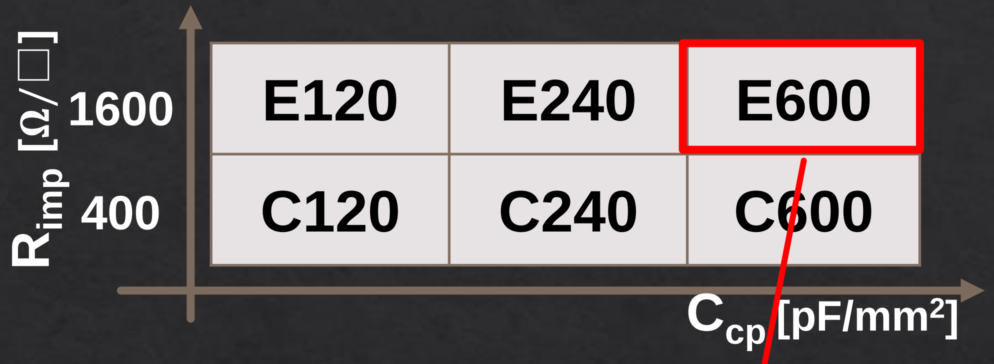
C_{cp} [pF/mm^2]



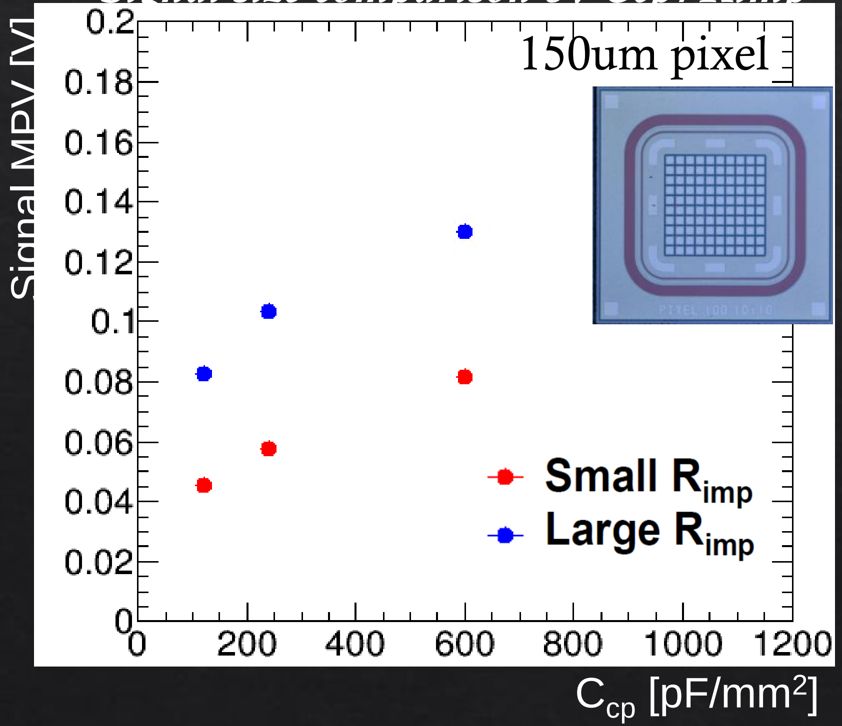
50um pitch electrode sensor has not been yet tested due to difficulty of wire bonding.

How small electrode could we achieve?

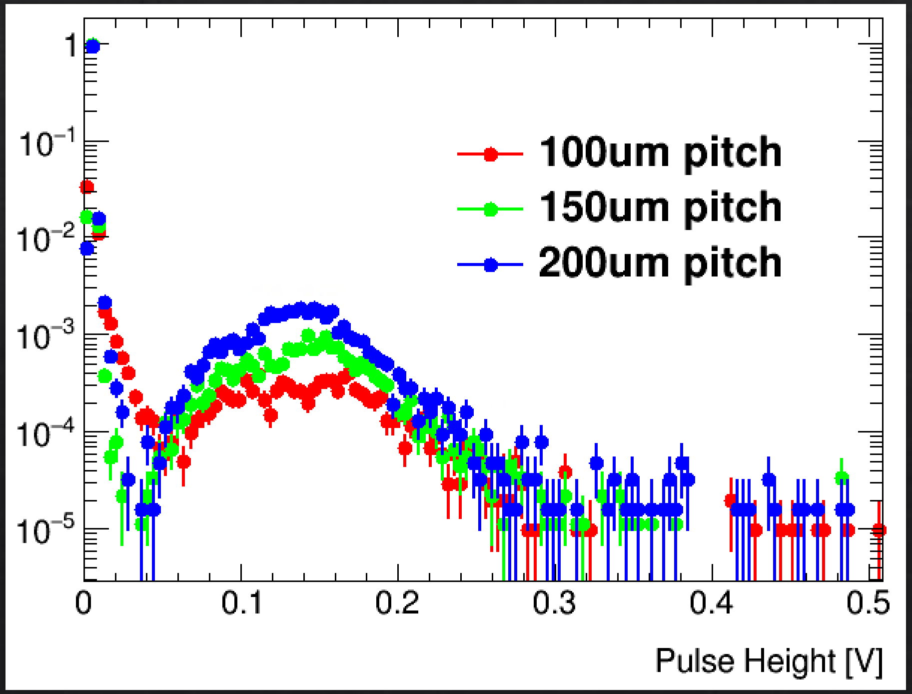
- Compared signal size of 6 types C_{cp}/R_{imp}.
  - 150um pixel sensors
  - Two n+ resistivity types and 3 Ccp types
- Compared signal size of 3 pixel size
  - 100/150/200um pitches are compared.

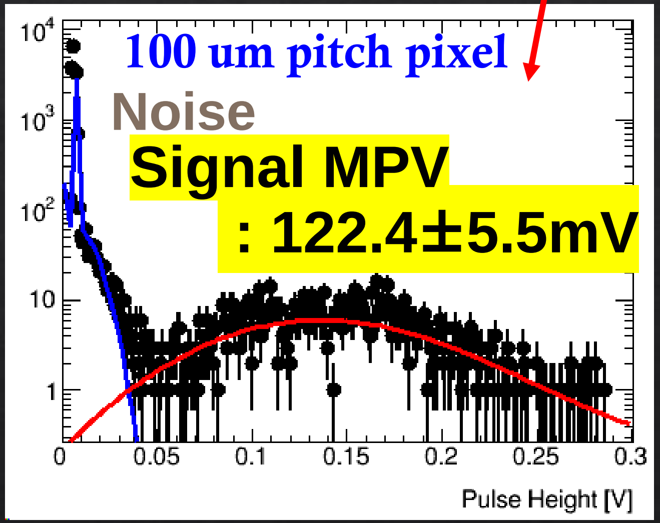


Signal size comparison by Ccp/Rimp



Pulse height comparison by pixel pitches

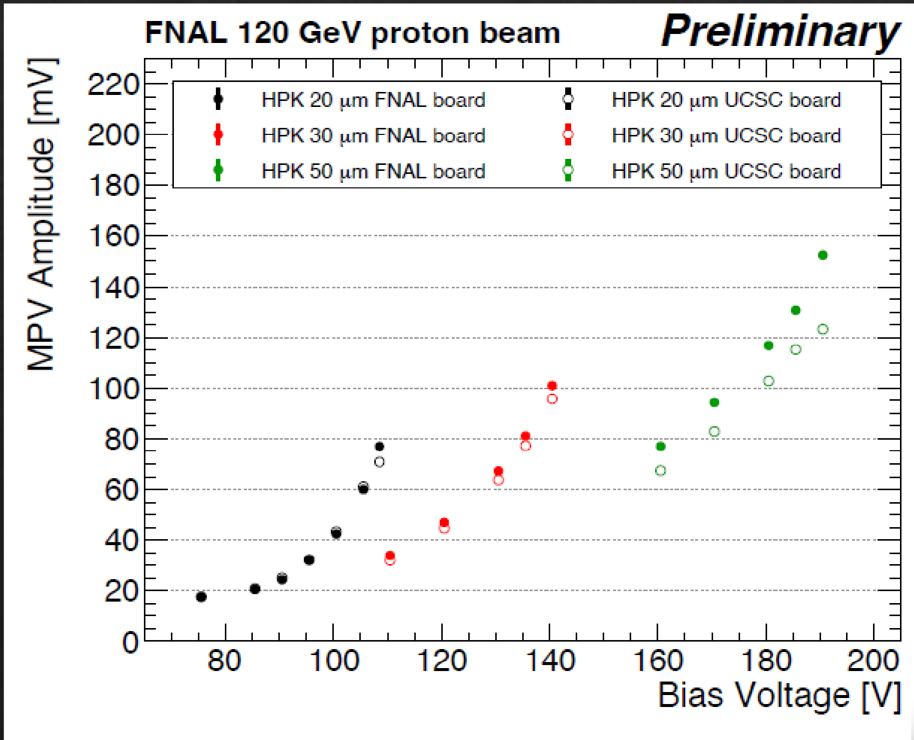


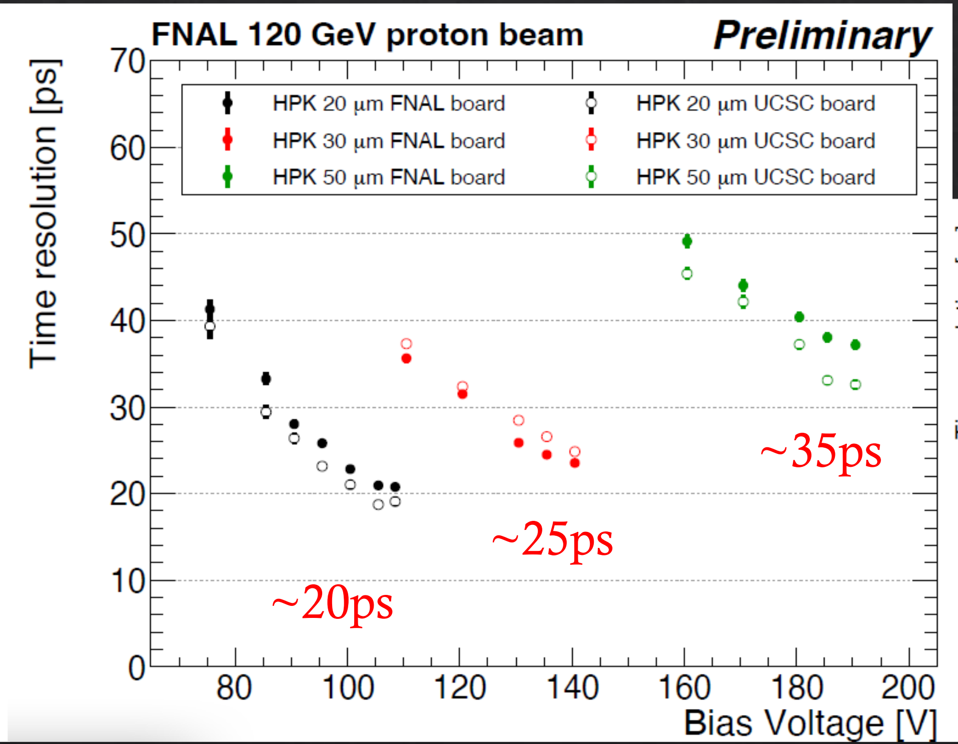


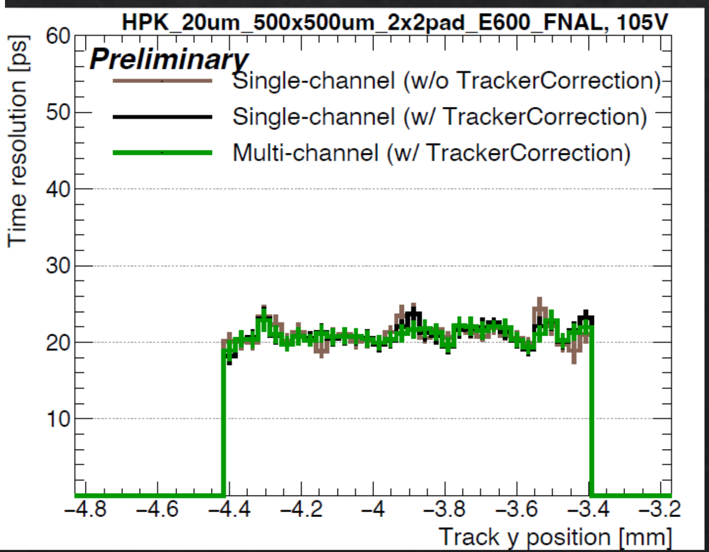
Successfully developed Good S/N 100um pitch pixel detector!

Improvement of timing resolution

- To reduce Landau noise : Fabricated 50um, 30um and 20um thick sensors
  - Signal size (amplitude) is smaller in thinner sensors.
  - **20um thick sensor has the best timing resolution : ~20ps**
  - **Uniform timing resolution at the gap region as well.**

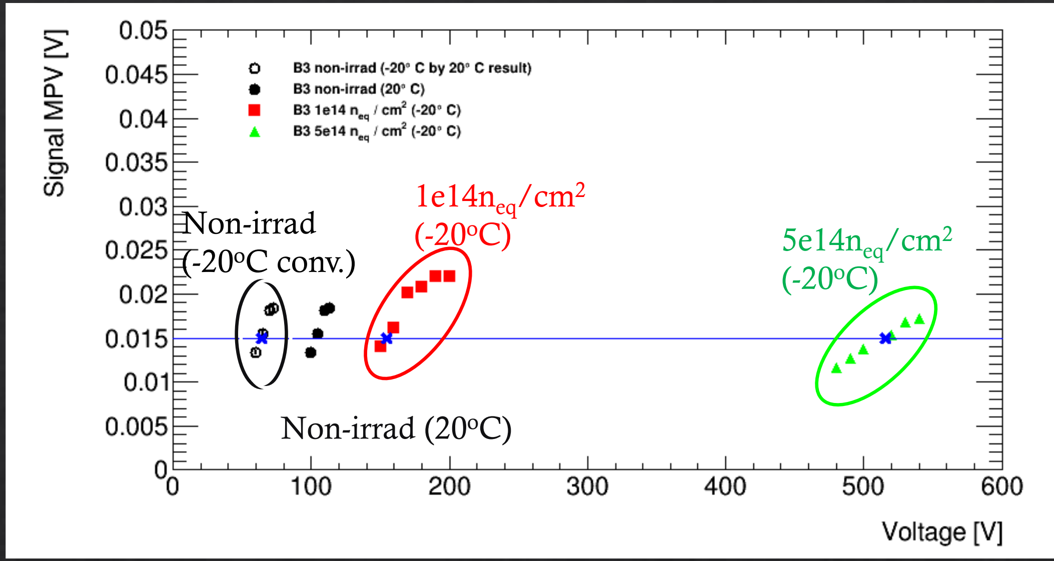


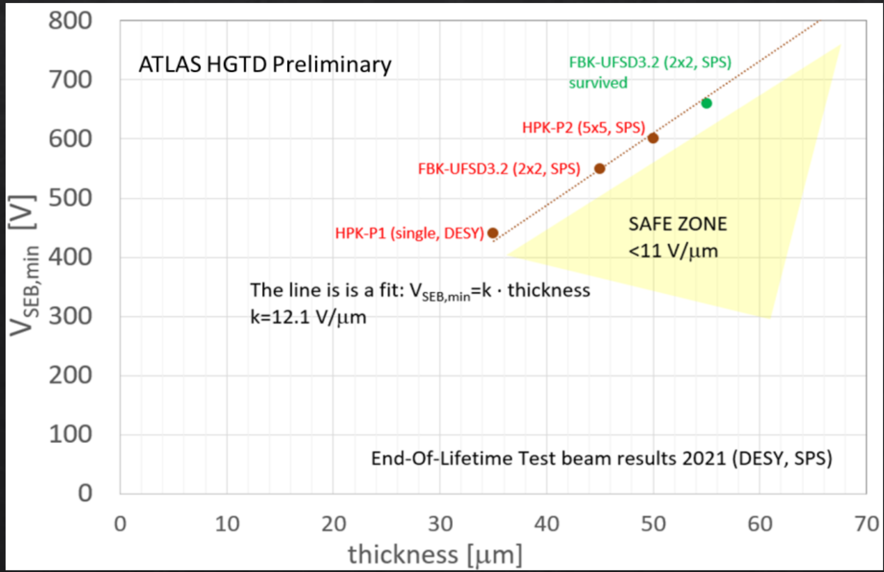




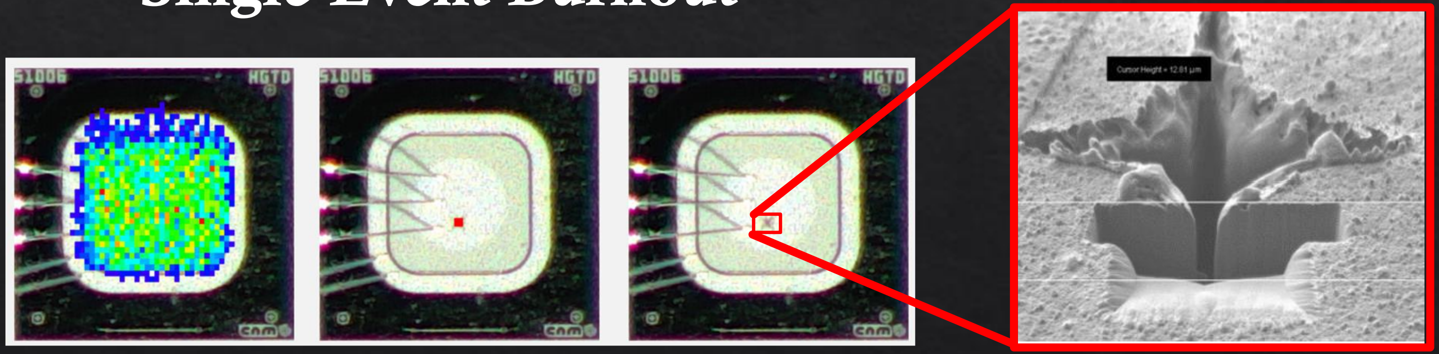
Why "Acceptor removal" is an issue?

- The issue is :
  - Active shallow acceptors are no longer active by defect.
  - Increase gain voltage by fluence.
- Possible maximum operation voltage
  - Single Event Burnout (SEB) happens if MIP particle deposited relatively high(~10MeV) energy at high electric field region.
  - This happened only ">12V/um average E field" independently by the gain layer concentration or radiation fluence.



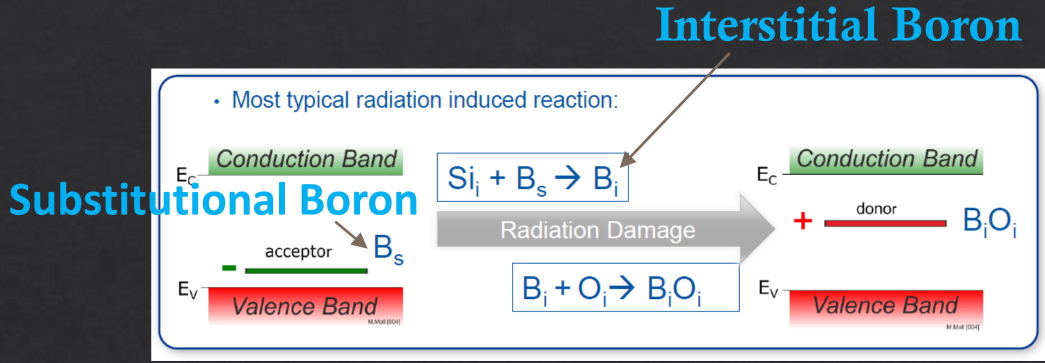


Single Event Burnout

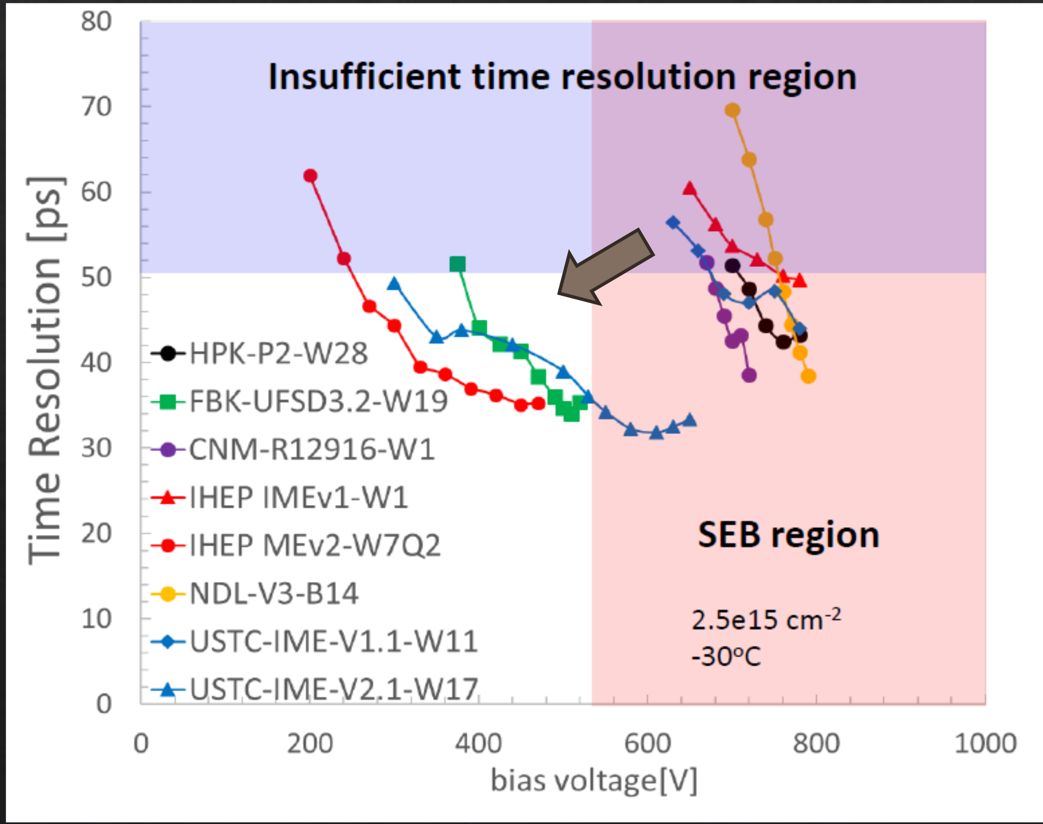


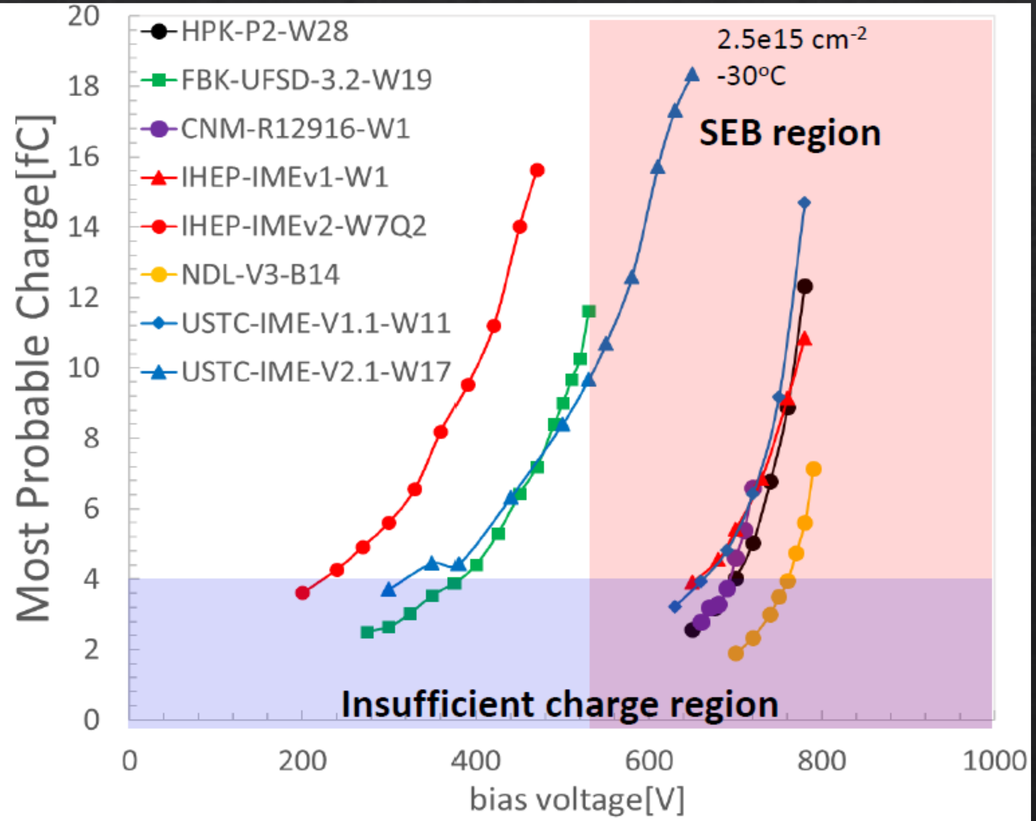
Carbon annealing

- ATLAS HGTD people studied a lot about carbon doping on p+ layer
  - Sensors with Carbon survive up to 2e15neq/cm2 : Vop can be below 550V
  - ~300V lower Vop after 2e15neq/cm2 irradiation.
  - HPK don't process carbon dope so far. (→now trying with us though)



Carbon annealing $\mathrm{B_i + C_s \rightarrow B_iC_s{}^* \rightarrow B_s + C_i}$

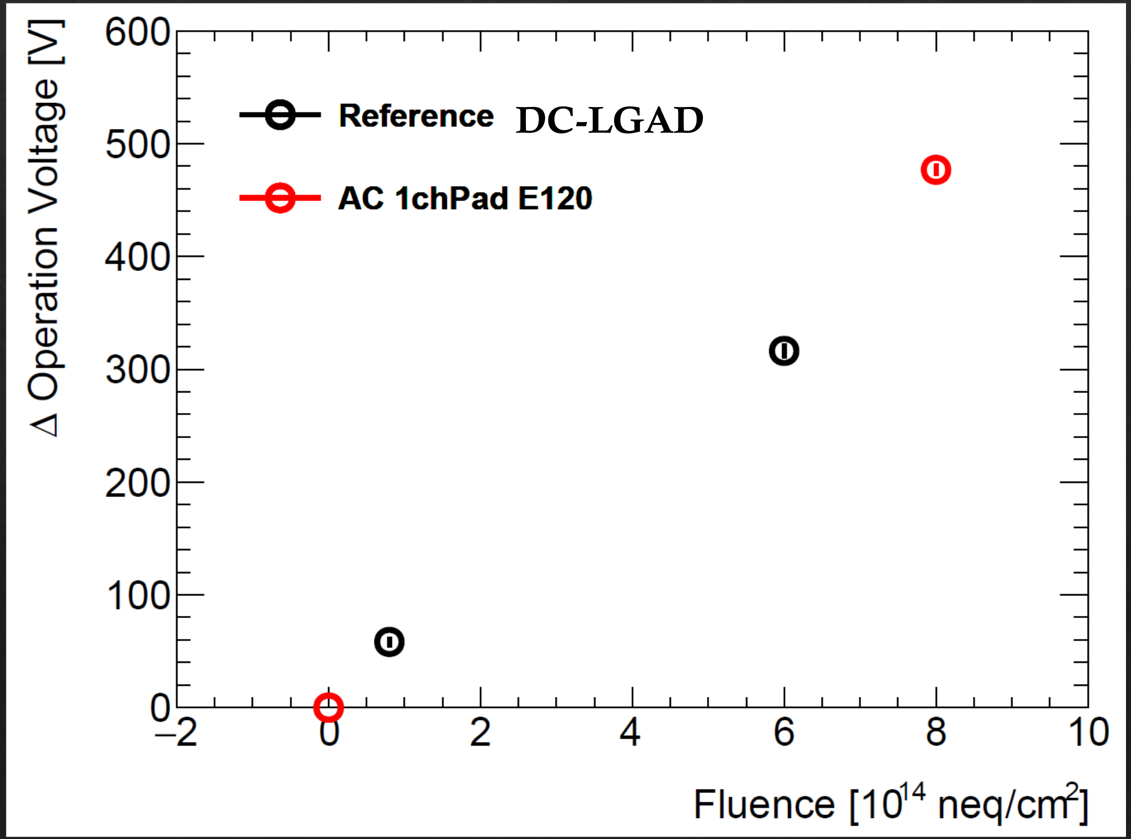




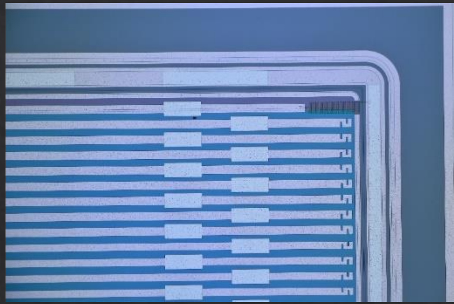
Radiation Tolerance Comparison DC/AC-LGAD

- Radiation Tolerance may be a bit different between DC-LGAD and AC-LGAD
  - p+ doping concentration is different.
  - Compared AC and DC LGAD with proton irradiated sensors.

DC- and AC- LGAD showed quite similar Radiation Tolerance



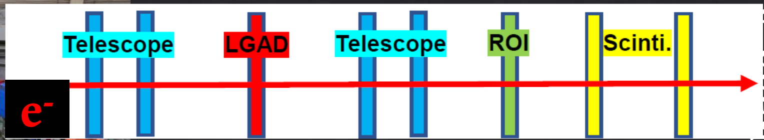
Position reconstruction by fine pitch approach



- ⟐ HPK 80um pitch strip sensor with highest implant resistivity (E-b type)
  - ⟐ Position resolution : 23um(80um/$\sqrt{12}$) is expected in case of binary readout

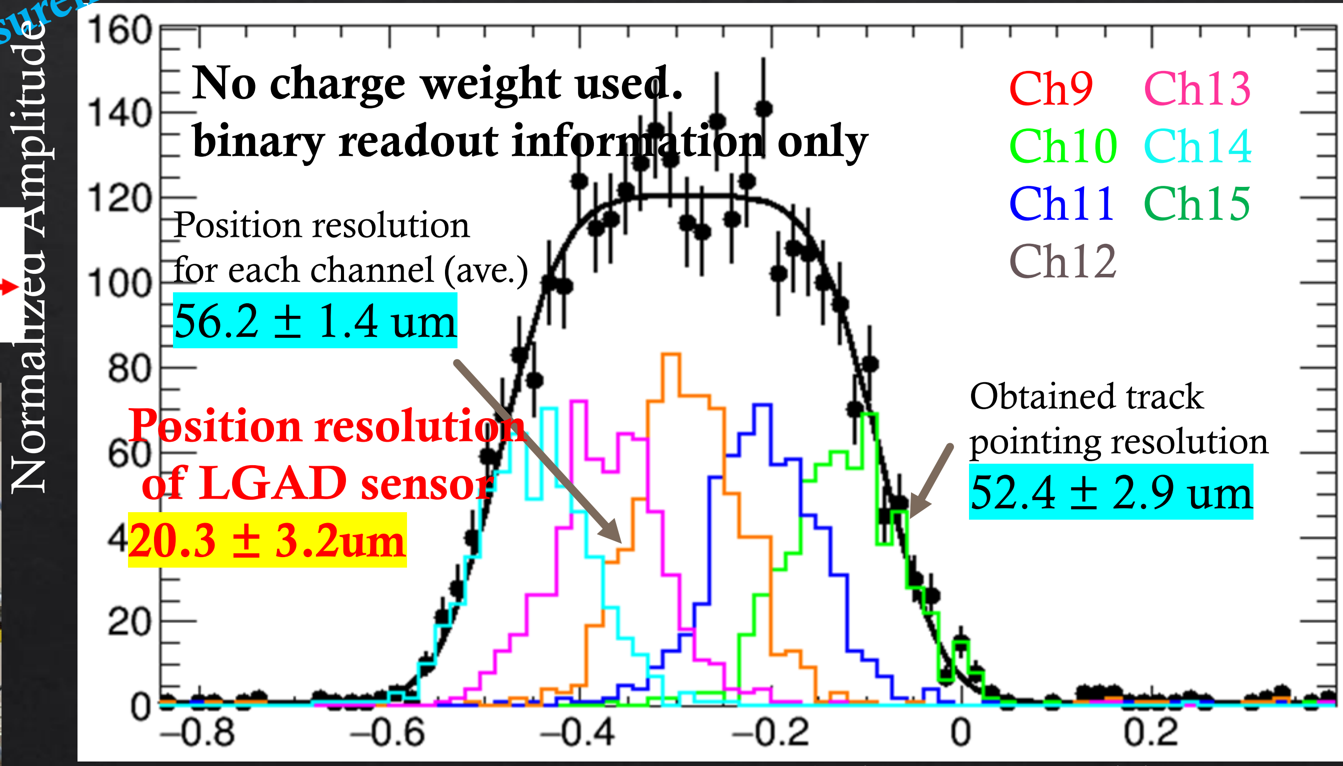
High Multiple-Scattering effect
Just repeated measurement at 120GeV proton

- Testbeam @ Tohoku University (ELPH)
  - 800MeV electron beam
  - Trigger rate : 200-400Hz
  - Strip E-b type 170V @ 20°C



4 layer of Telescope
(25um x 500um pixel)
Trigger by scintilator
Specify region (ROI)

Amplitude distribution with residual



Relative track position [mm]

Removal of Dopant

- Active dopant will reduce by exponential function by fluence (Φ)

$$N_A(\emptyset) = N_A(0) \cdot e^{-C_A \emptyset}$$

$$N_D(\emptyset) = N_D(0) \cdot e^{-C_D \emptyset}$$

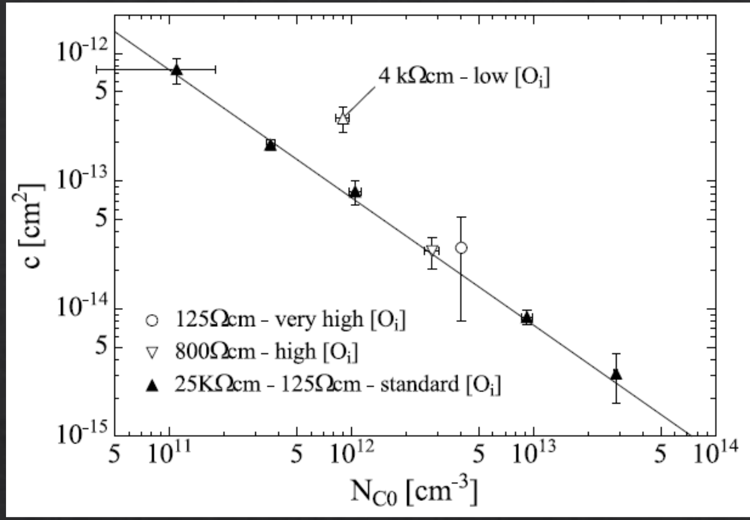
Any idea of CA and CD from past measurement?

CD=2.4 x 10^{-13} cm^2 for phosphorus and CA=2.0 x 10^{-13} cm^2 for boron in very high resistivity p-type and n-type materials (>1kΩcm).
→ How about lower resistivity ? (like 1 x 10^{16} cm^{-3} p+ concentration)

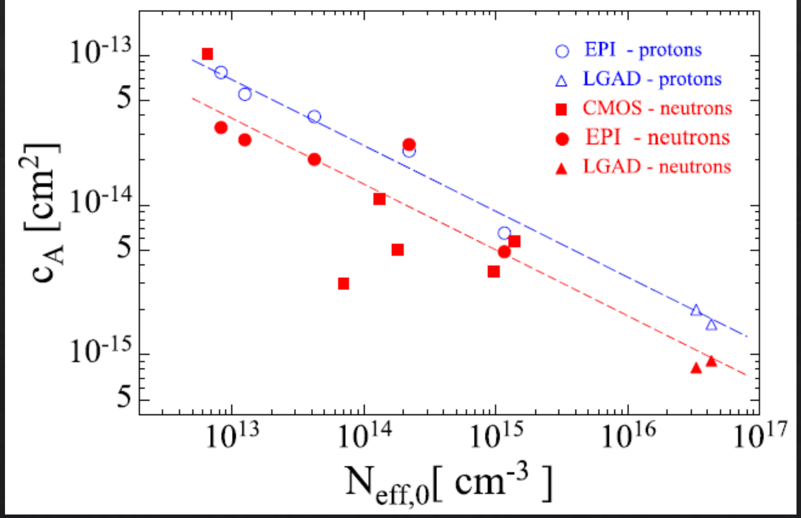
Compensated effective p+ gain layer will change by following formula

$$N_A(\emptyset) - N_D(\emptyset) = N_A(0) \cdot e^{-C_A \emptyset} - N_D(0) \cdot e^{-C_D \emptyset}$$

Donor removal



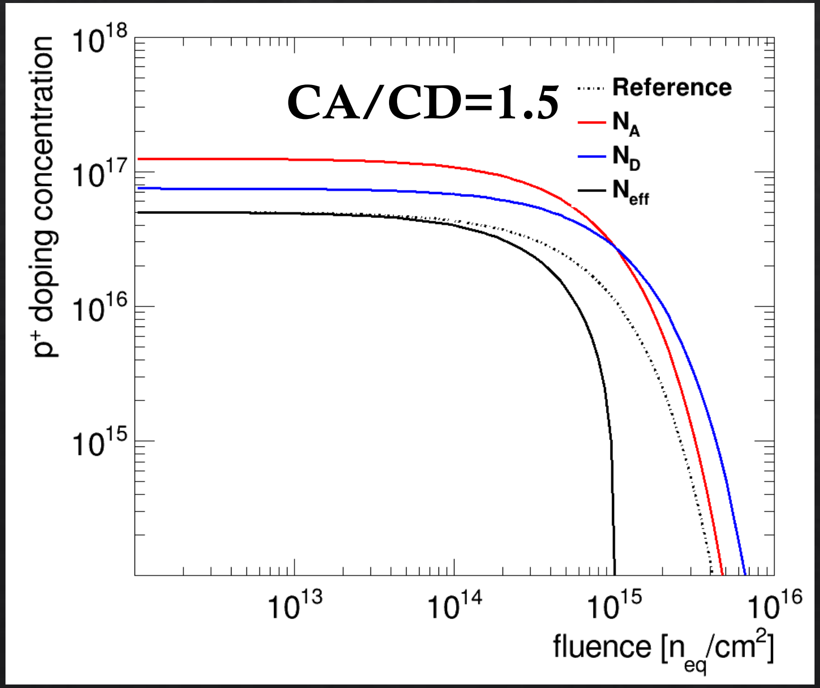
Acceptor removal



How to understand results?

If CA>CD ?

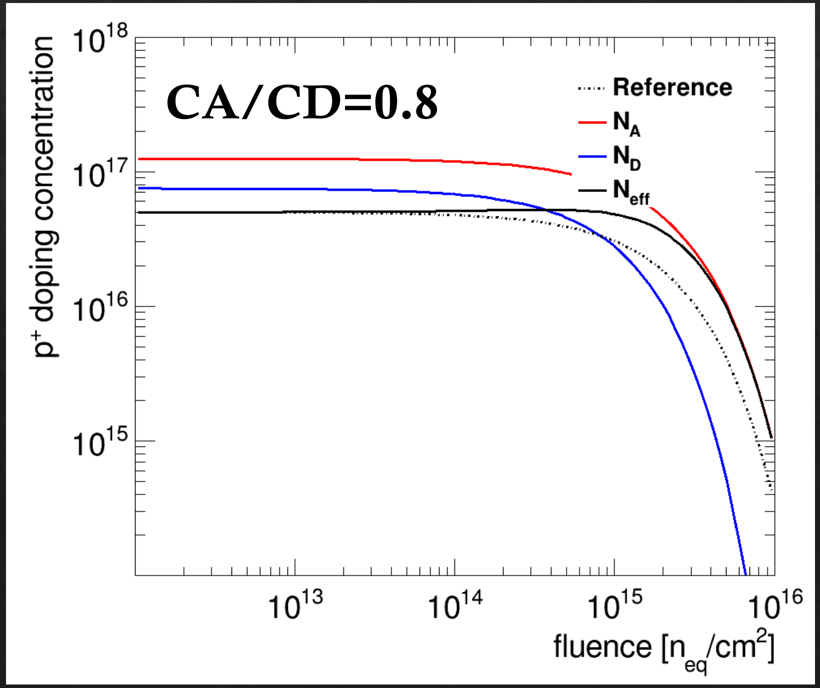
Shorter life time



If CA<CD ?

Slightly longer life time

Not detreated performance until some point



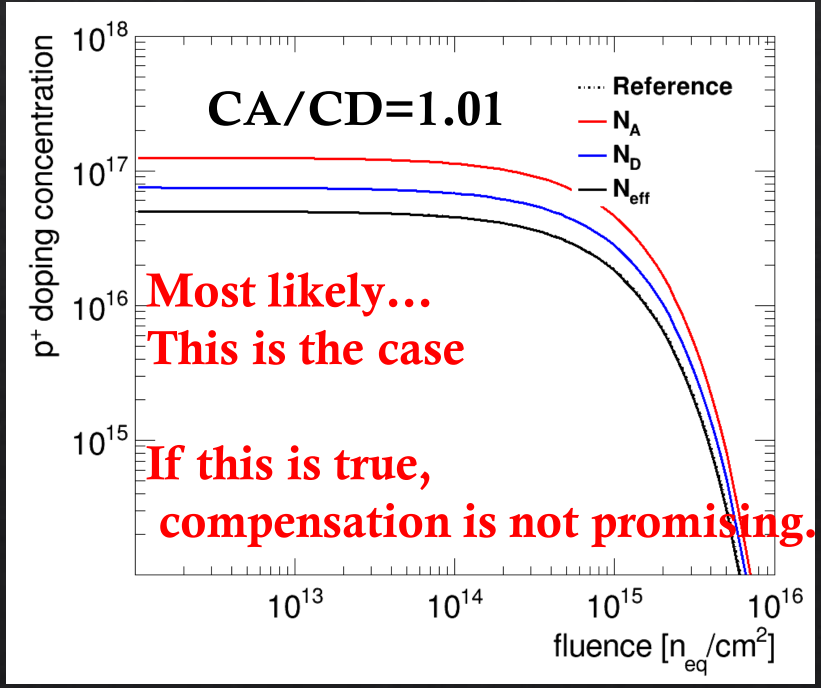
If CA=CD ?

$$N_A(\emptyset) - N_D(\emptyset) = N_A(0) \cdot e^{-C_A \emptyset} - N_D(0) \cdot e^{-C_D \emptyset}$$

$$N_A(\emptyset) - N_D(\emptyset) = (N_A(0) - N_D(0)) \cdot e^{-C_A \emptyset}$$

reference $N_A(\emptyset) = N_A(0) \cdot e^{-C_A \emptyset}$

Reduction of effective p+ must be the same as non-compensated case



Radiation tolerance results of Compensation LGAD

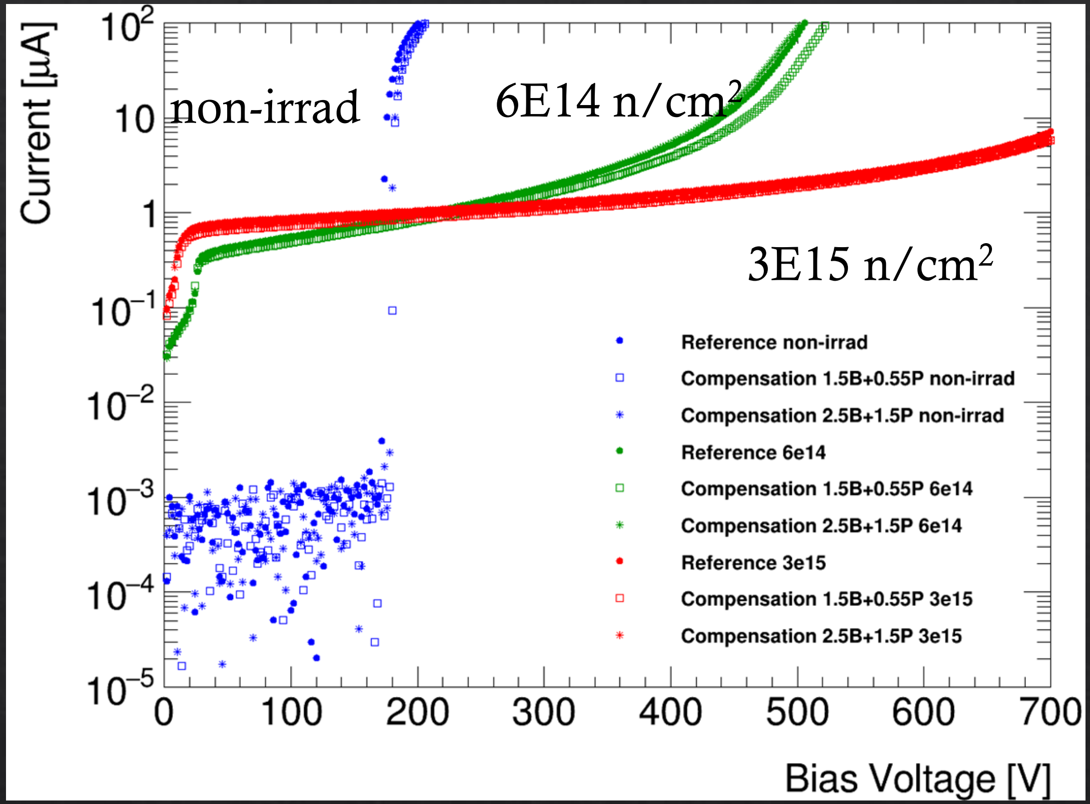
- Three different conditions are compared
  - Boron and Phosphorus doping
    - 2.5B+1.5P
    - 1.5B+0.55P
    - 1B (reference)
  - 3 different fluence points (non-irrad, 6e14, 3e15 neq/cm^2)
- Result shows not very promising
  - All three samples show very similar IV.
  - This probably means CA=CD

$$N_A(\emptyset) - N_D(\emptyset) = N_A(0) \cdot e^{-C_A \emptyset} - N_D(0) \cdot e^{-C_D \emptyset}$$

$$N_A(\emptyset) - N_D(\emptyset) = (N_A(0) - N_D(0)) \cdot e^{-C_A \emptyset}$$

reference $N_A(\emptyset) = N_A(0) \cdot e^{-C_A \emptyset}$

Reduction of effective p+ must be the same as non-compensated case



Next step:

Compensation with Carbon dope should be promising

Carbon effect :

Reduce Accepter removal

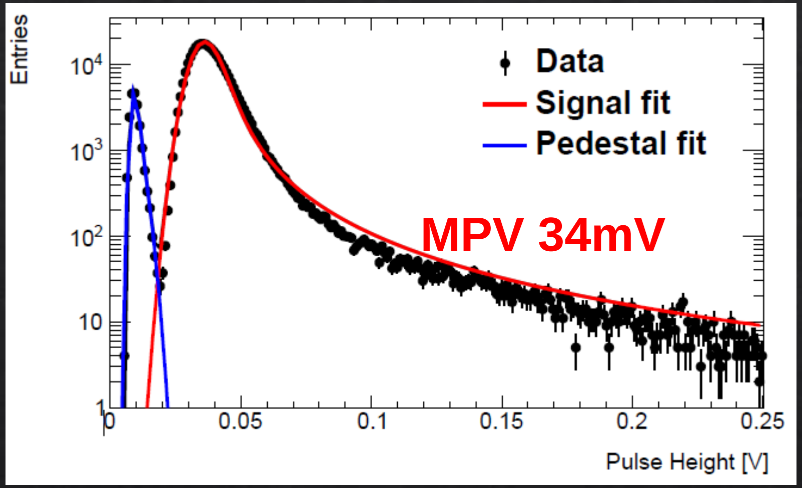
Accelerate Donner removal

Samples will be ready by late summer

Is Strip type electrode possible?

- For collider experiments, outer layers should use Strip type electrode to reduce readout channels.

80um pitch Strip



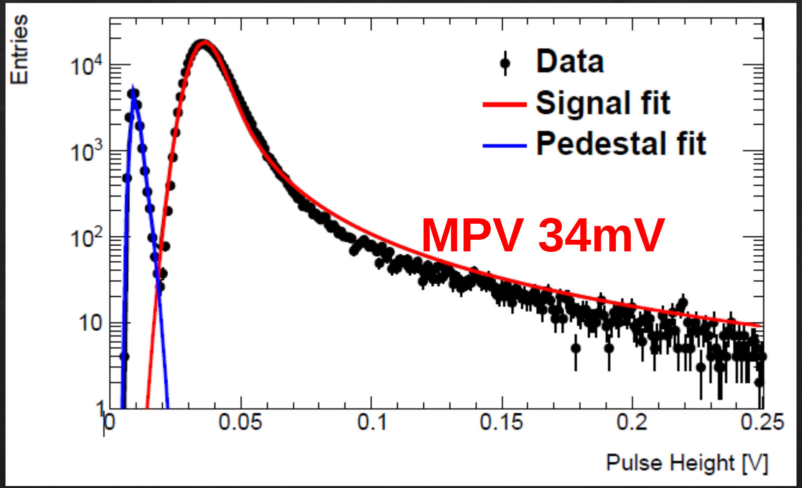
Successfully developed
Good S/N 80um pitch strip detector!

Is Strip type electrode possible?

- For collider experiments, outer layers should use Strip type electrode to reduce readout channels.

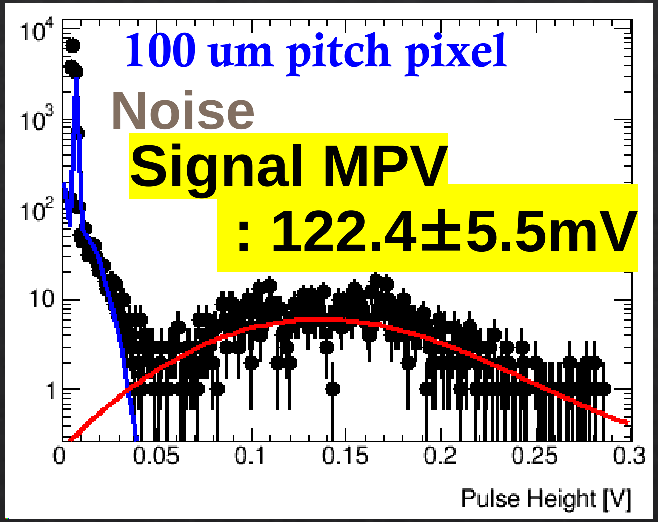
However, the signal size is much smaller than pixel sensors

80um pitch Strip



Successfully developed
Good S/N 80um pitch strip detector!

(c.f.)



Why so small signal?

How much effect of interstrip capacitance?

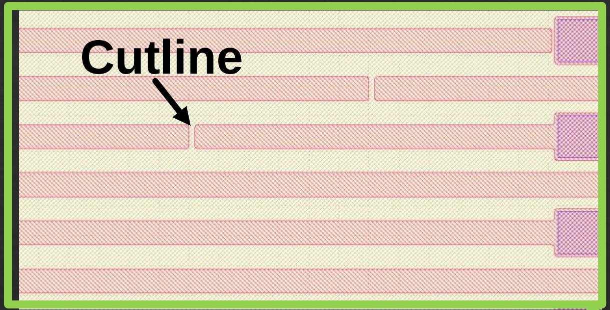
Significantly smaller signal compared with pad type detector.

How much signal attenuation in the strip?

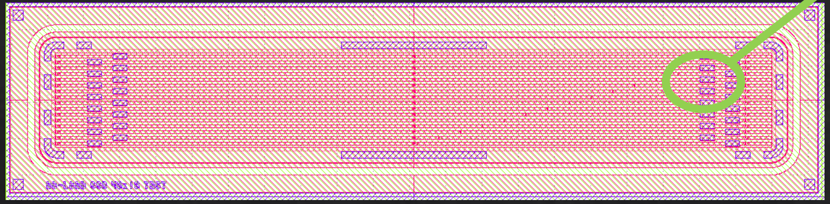
This might affect to the signal size un-uniformity and delay of signal readout.

Inter strip capacitance (Cint) effect

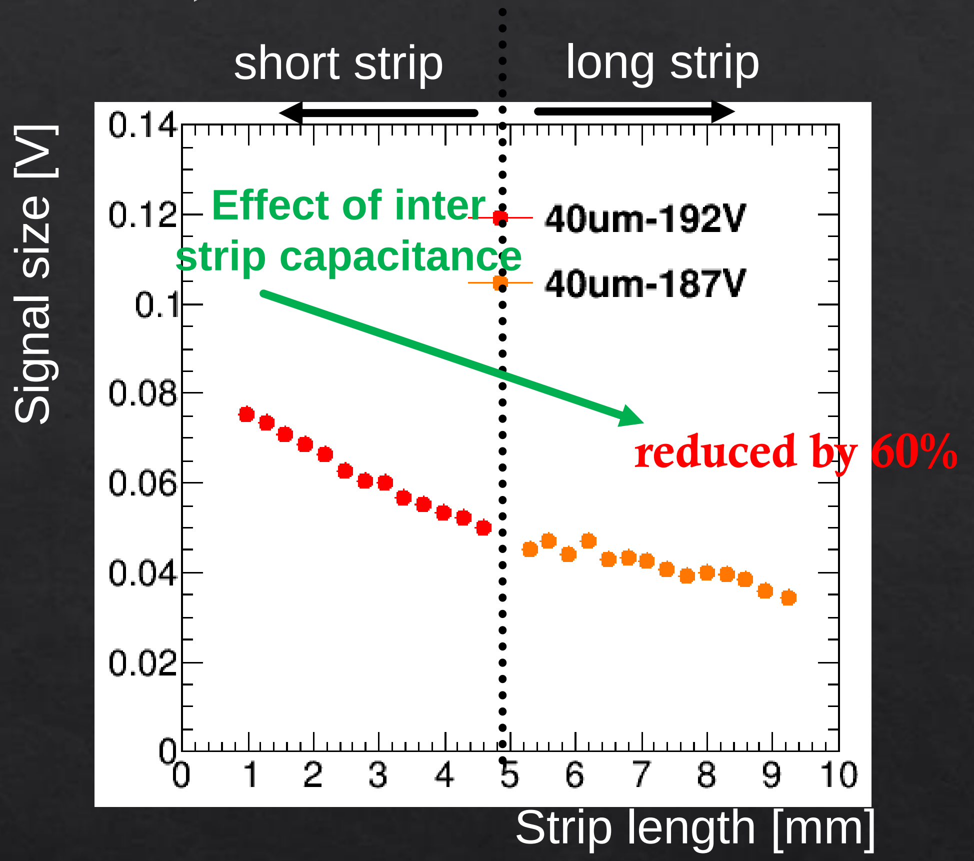
Strip sensor with cut line



- Strip sensor which has different electrode length (to study inter electrode cap.)



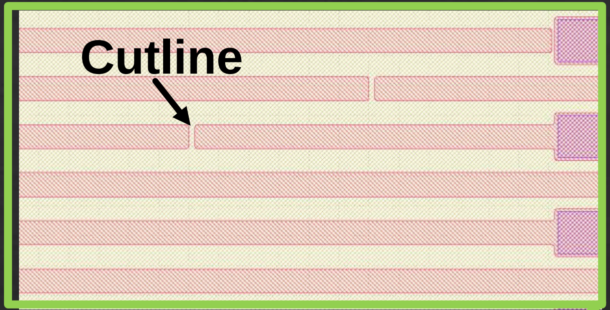
16 strips x 2



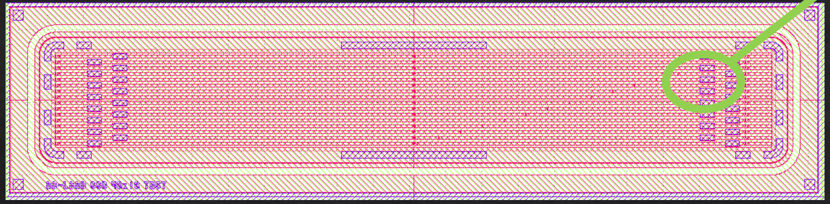
Where signal disappeared?

Inter strip capacitance (Cint) effect

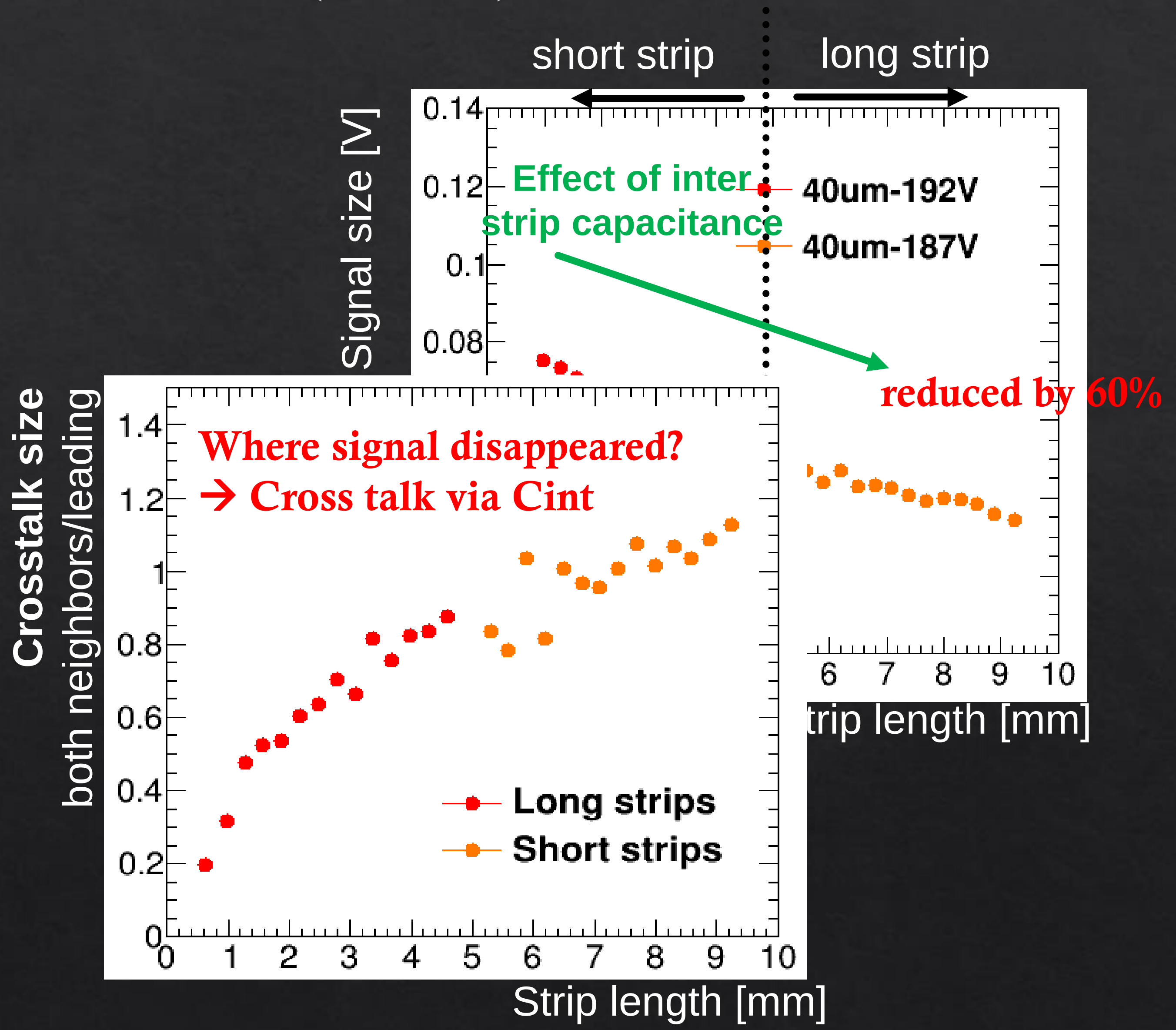
Strip sensor with cut line



- Strip sensor which has different electrode length (to study inter electrode cap.)



16 strips x 2



Future

- ***Improvement of radiation tolerance (con't)***
  - **Test Compensation + Carbon sample**
- ***Large size prototype***
  - Gain uniformity is important for larger sensor.
    - **Producing KEK R&D and EIC prototype masks**
- ***ASIC development***
  - Collaborating with Uni. Geneva (Si-Ge ASIC)
    - There is 100um pitch pixel ASIC to be connected to our AC-LGAD
  - ATLAS/CMS/EIC producing their own ASIC for the colliders.
    - **Possible to adopt smaller detector cap for pixelated AC-LGAD?**
- ***Ultimate goal is monolithic AC-LGAD***

Large size prototype
Gain Uniformity

EIC prototype
3cm length
500um pitch strip

R&D prototype
2cm x 2cm
100um pitch pixel

New Application to Collider detector