Development status and plan for precision timing detector(LGAD)

Koji Nakamura (KEK)

Recent developments

- ***Successfully developed AC-LGAD detector with both time and spatial resolution.***
  - Good SN ratio samples with 80um pitch strip and 100um x100um pitch pixel detector
  - 20um active thick sensor achieved 20ps timing resolution!
- ***Recently detailed understanding of developed device are on-going***
  - Gain measurement by the samples w/ and w/o gain layer. 堀越君
  - Signal sharing study for large pitch with small electrodes. 村山君
  - Quantitative understanding of Charge Collection Noise by simulation. 西野君
- ***New prototype and future development***
  - Study of Radiation hard gain layer. 今村さん VERTEX2023 ORAL Presentation
  - Readout Electronics for hybrid pixel detector 中村
  - Monolithic AC-LGAD detector (funding requests)

Operating and Planning Collider Experiment

World highest energy collider !

2011～ **Large Hadron Collider (LHC experiment)**

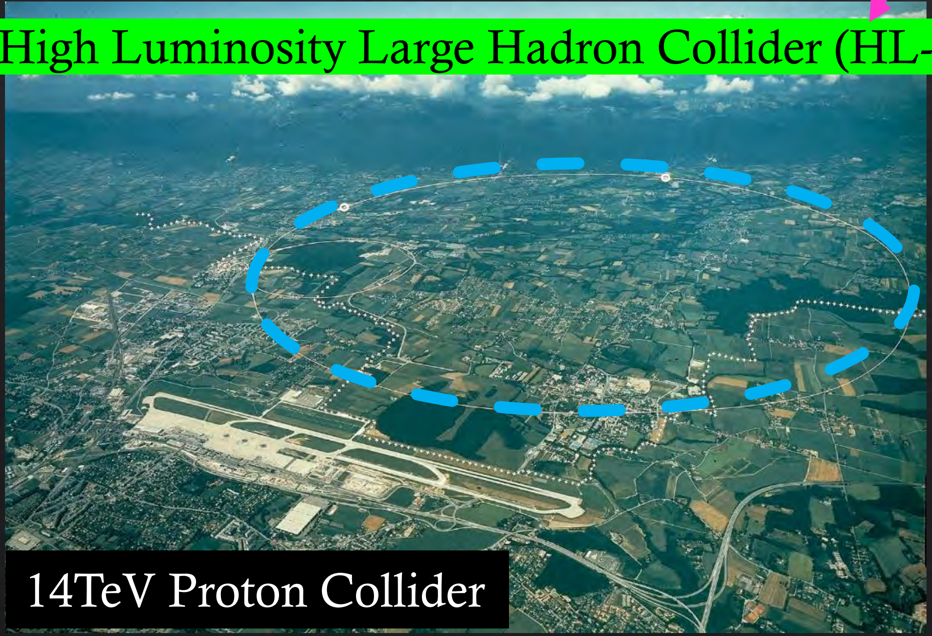
13.6TeV Proton collider

x10 Luminosity

Approved & constructing

2029～

High Luminosity Large Hadron Collider (HL-LHC)

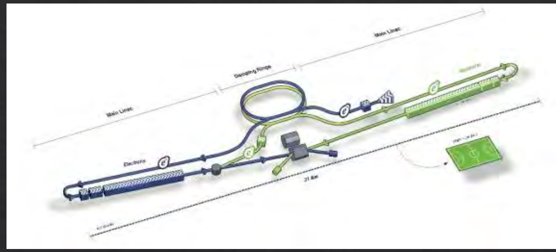


14TeV Proton Collider

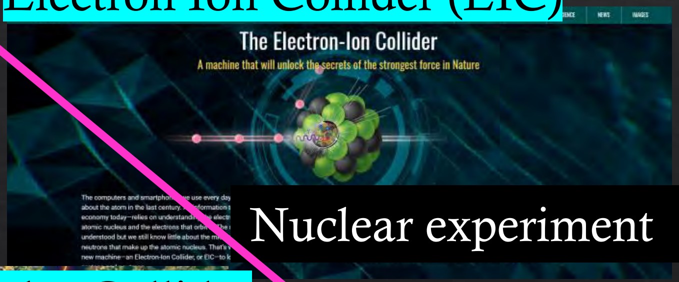
Planning Experiment

International Linear Collider (ILC)

Focusing on Higgs measurement (e+e-)



Electron Ion Collider (EIC)



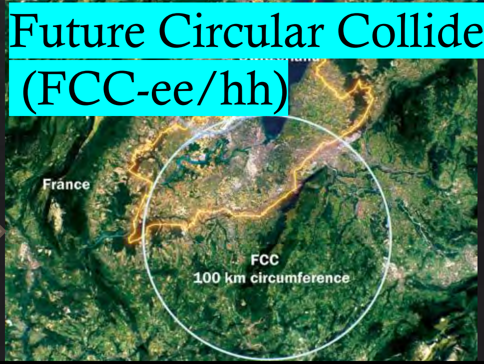
Nuclear experiment

High Energy LHC

Twice Energy

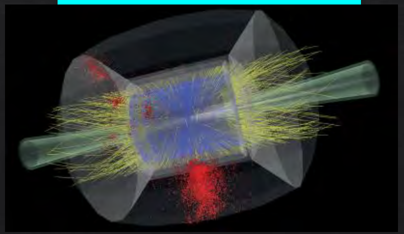
7 times Energy

Future Circular Collider (FCC-ee/hh)



100TeV Proton Collider

Muon Collider



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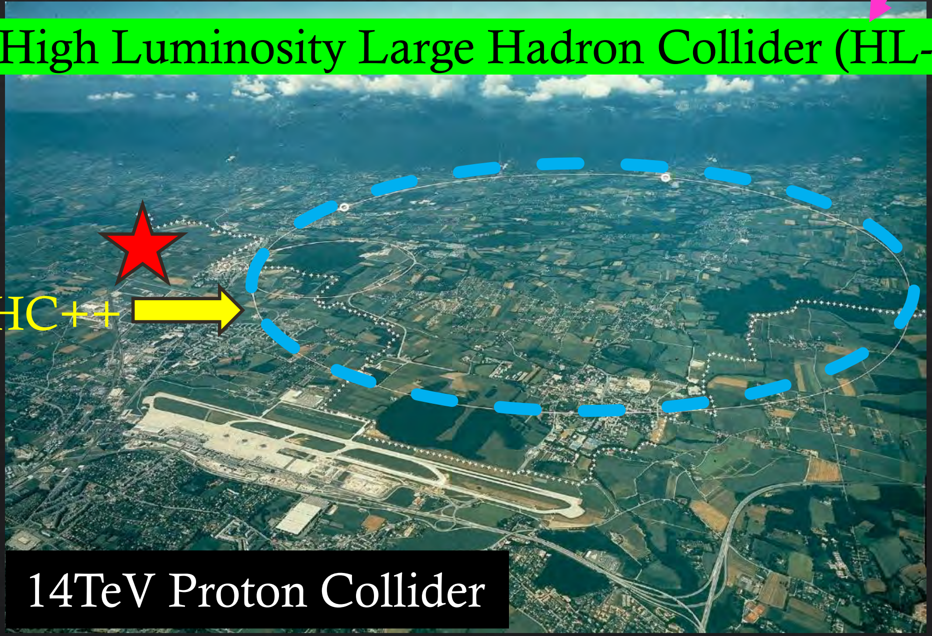

2034?

HL-LHC++

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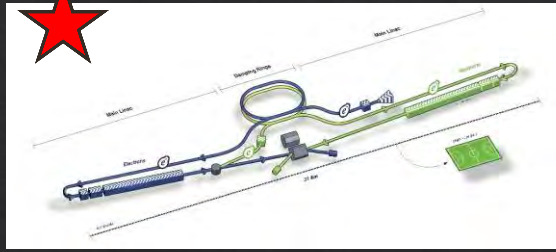

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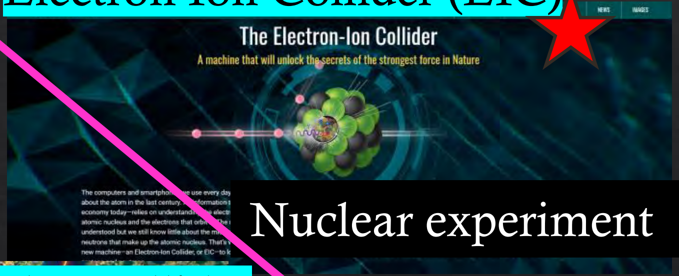

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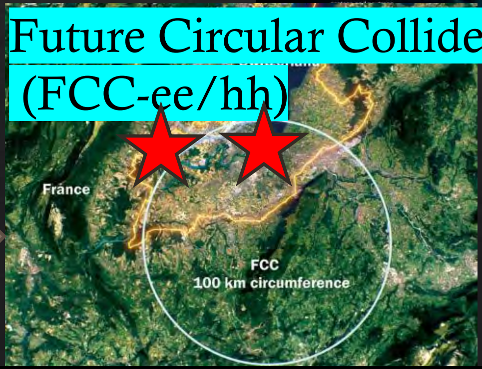

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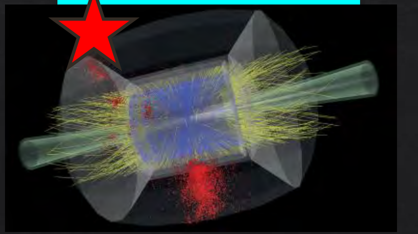
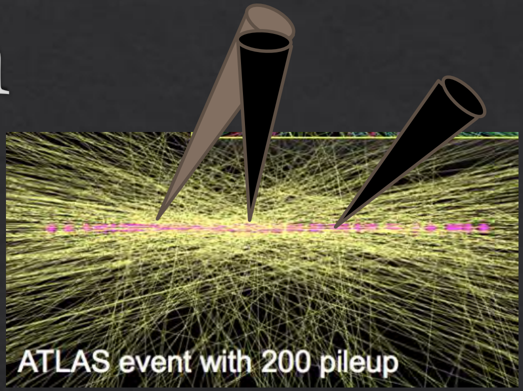


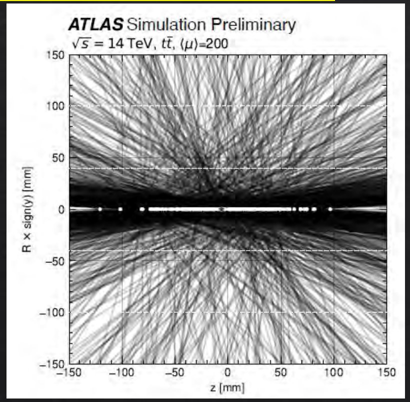
Timing detector is necessary for all of these colliders

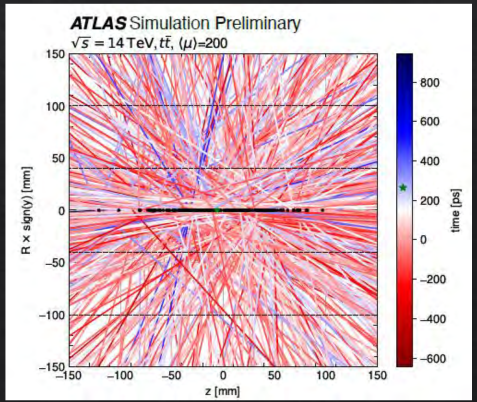
Impact for tracker with time resolution



- **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**

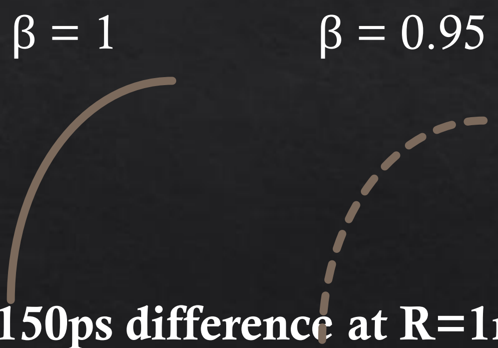
4D tracking !





Solve pileup hits in an event

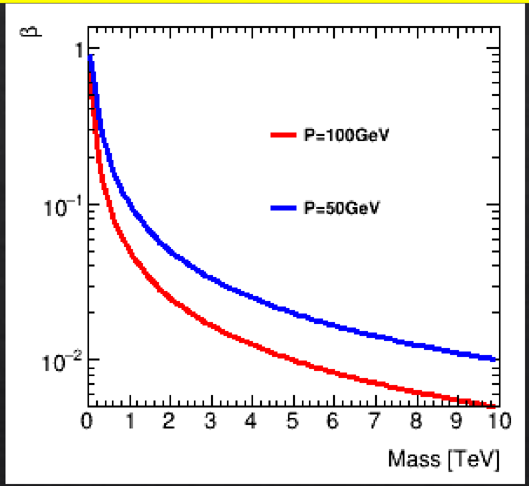
Particle identification



150ps difference at R=1m

K+ π+ separation

Mass spectrum for new particle



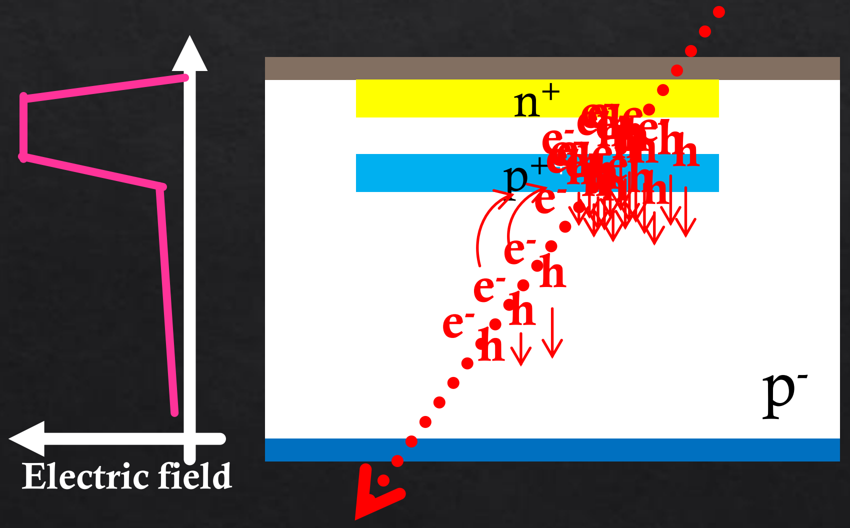
β measurement to obtain mass

e.g. Mass measurement for Long lived chargeno

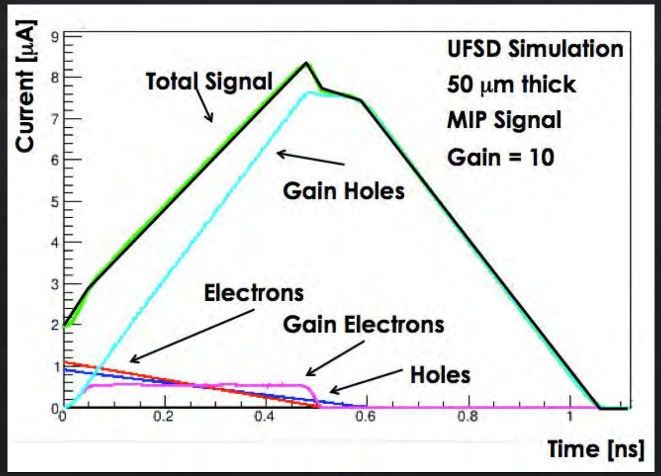
Low Gain Avalanche Diode (LGAD)

- 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.**

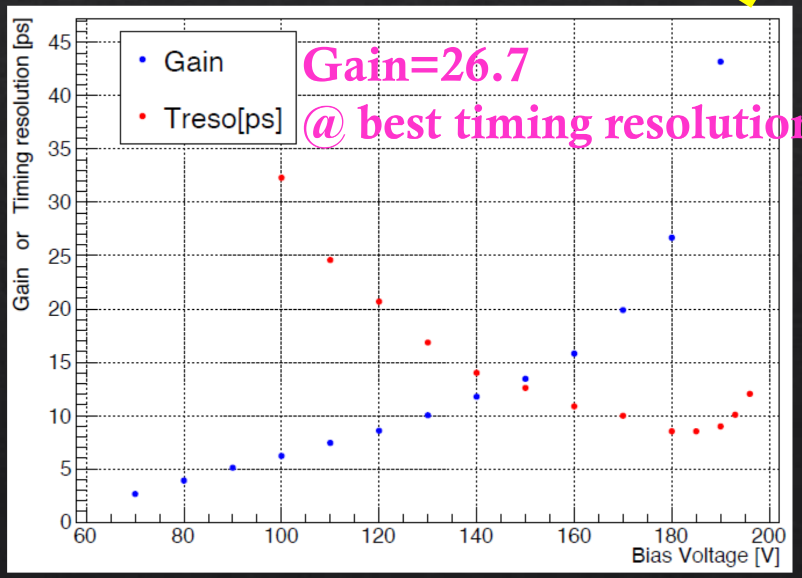


Signal drivers : **Gain Holes**



Gain measurement :

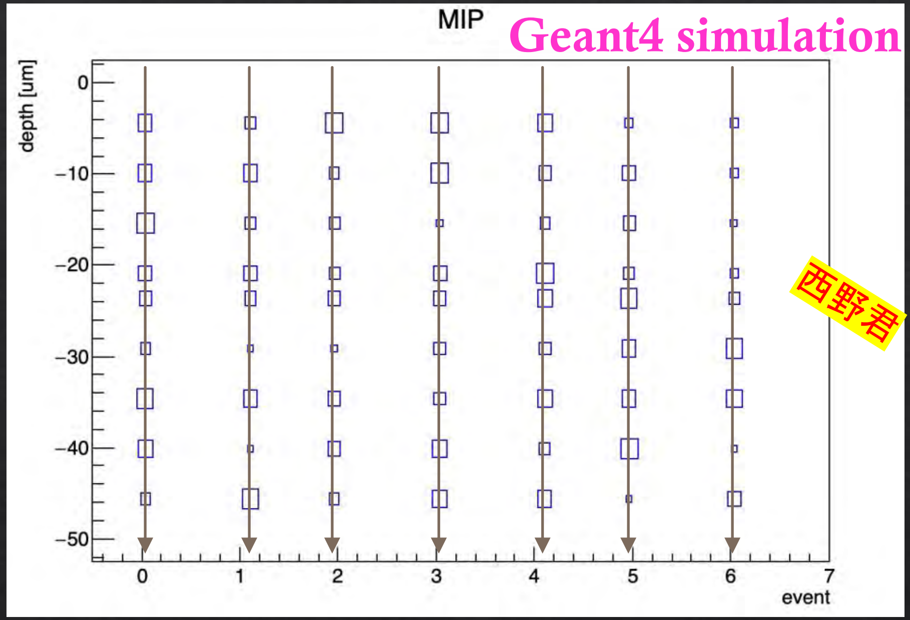
堀越君

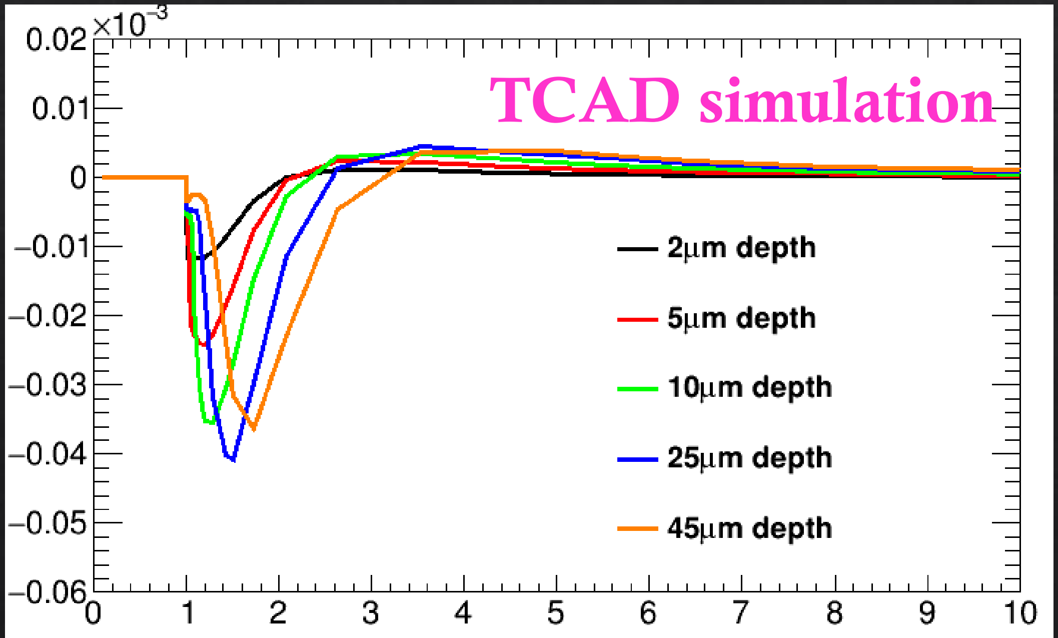


Charge Collection Noise (Landau Noise)

- 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.

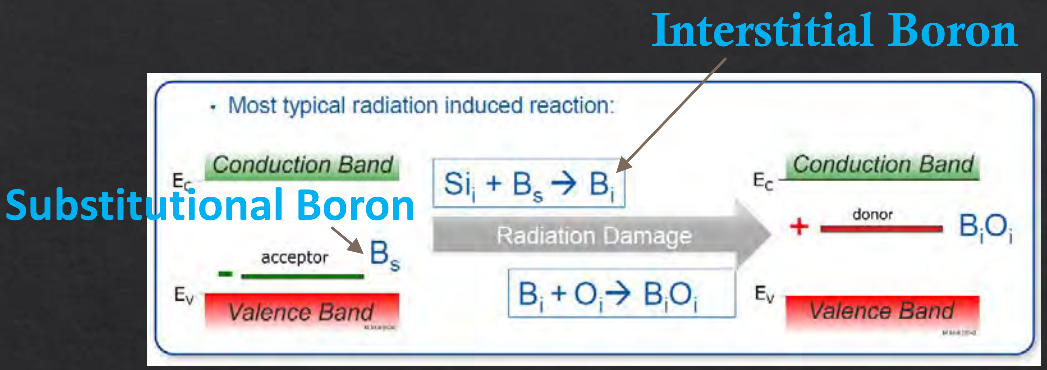
20um thick sensor : ~15ps CCN → 20ps in actual device achieved.

➔10um thick sensor?

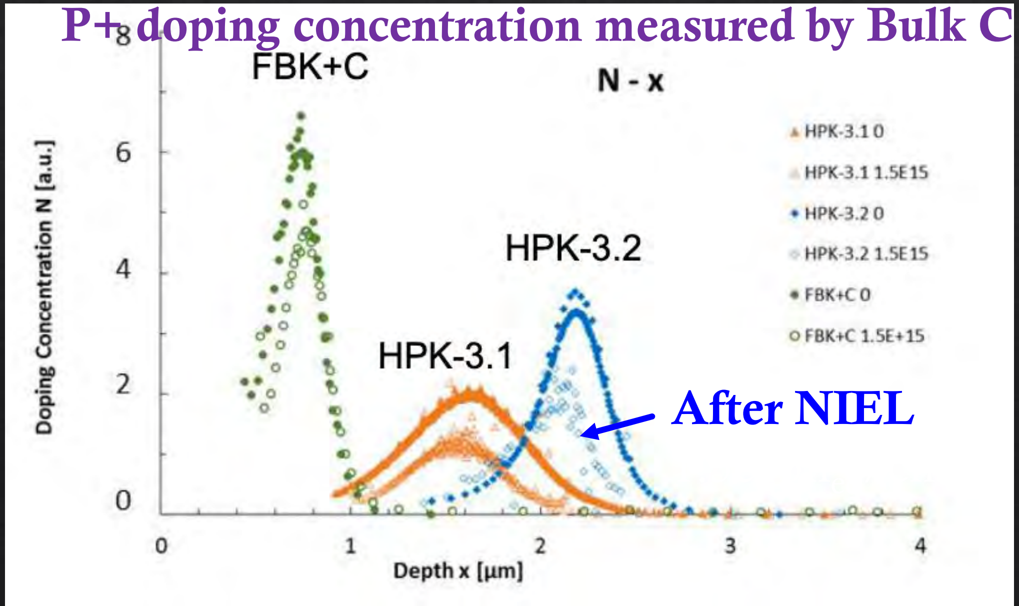
Smaller signal size (worse jitter) but better CCN.

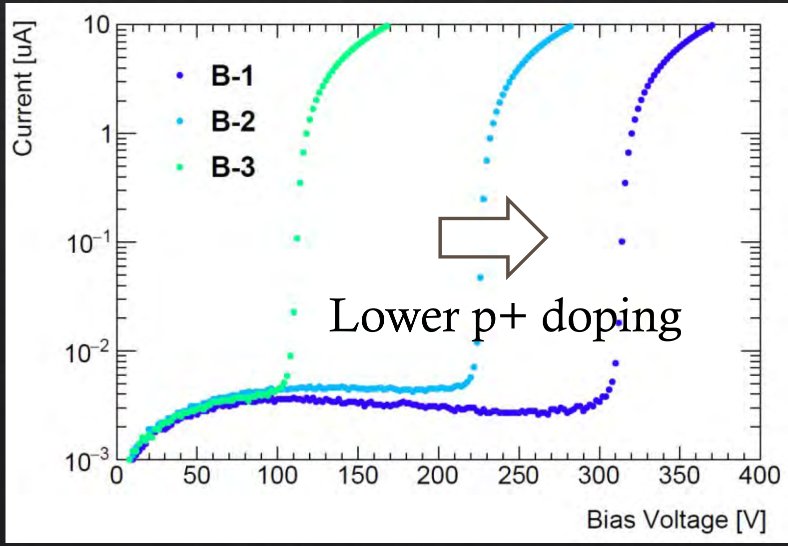
Radiation tolerance of LGAD detector

- 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



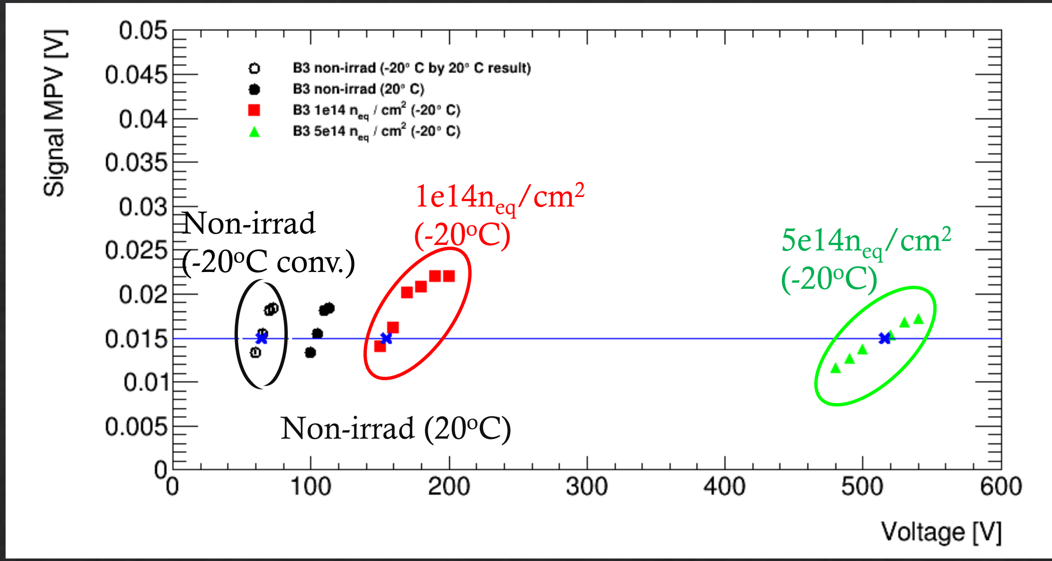
Acceptor removal (low p+ concentration) introduce weaker field :
→ Need higher voltage to keep high electric field at gain layer

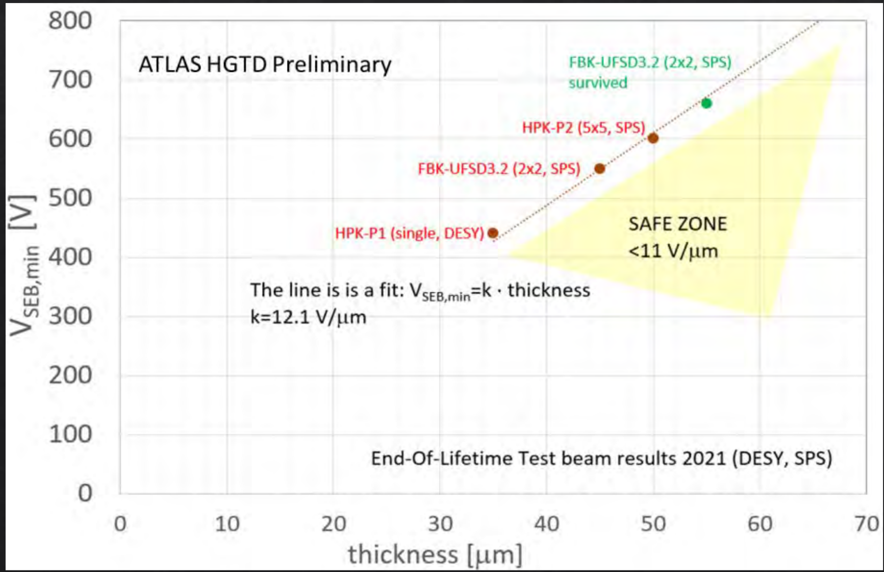




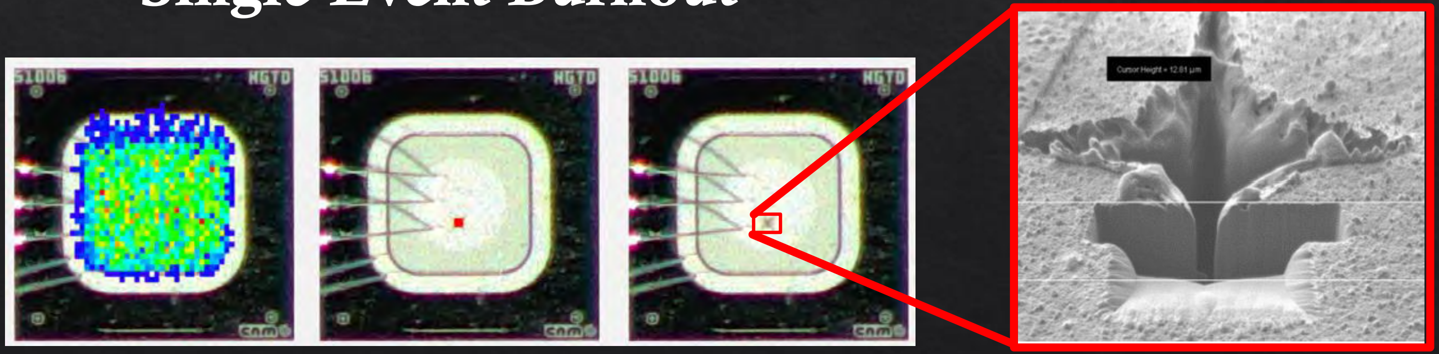
Why "Acceptor removal" is an issue?

- 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.



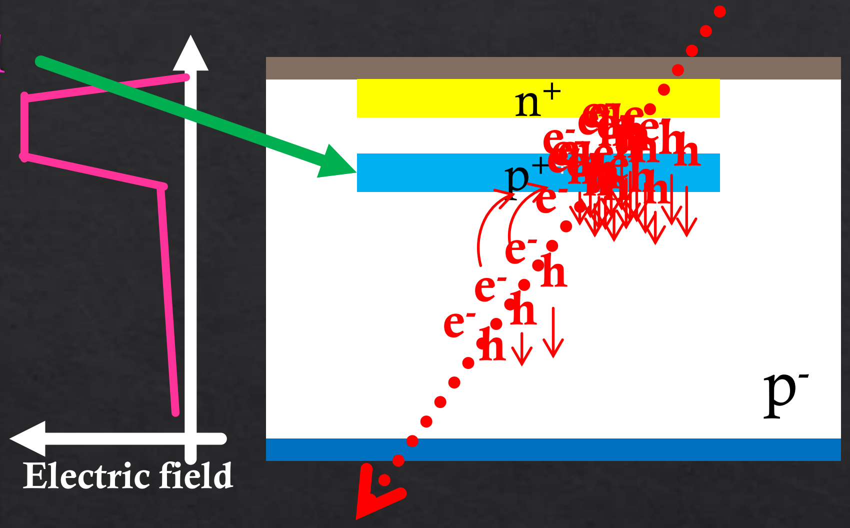


Single Event Burnout



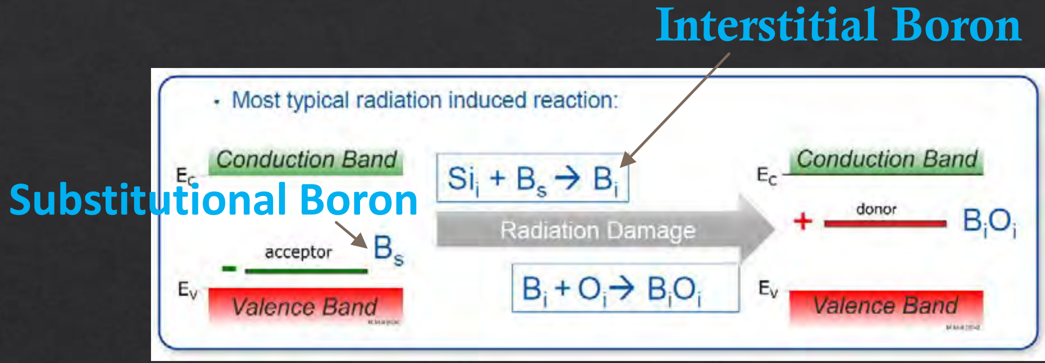
New idea for improvement of Radiation Tolerance?

- 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

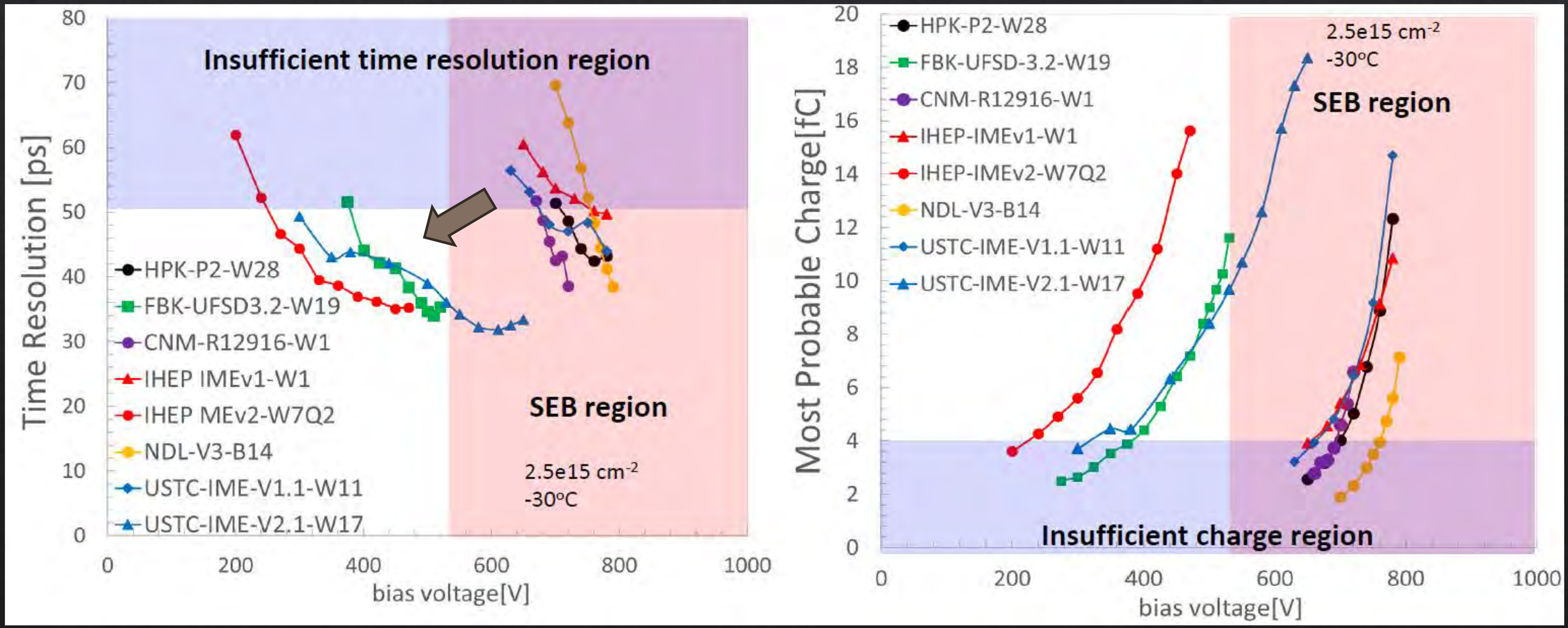


Carbon annealing

- 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 $B_i + C_s \rightarrow B_iC_s^* \rightarrow B_s + C_i$



Compensation method

今村さん

- 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.

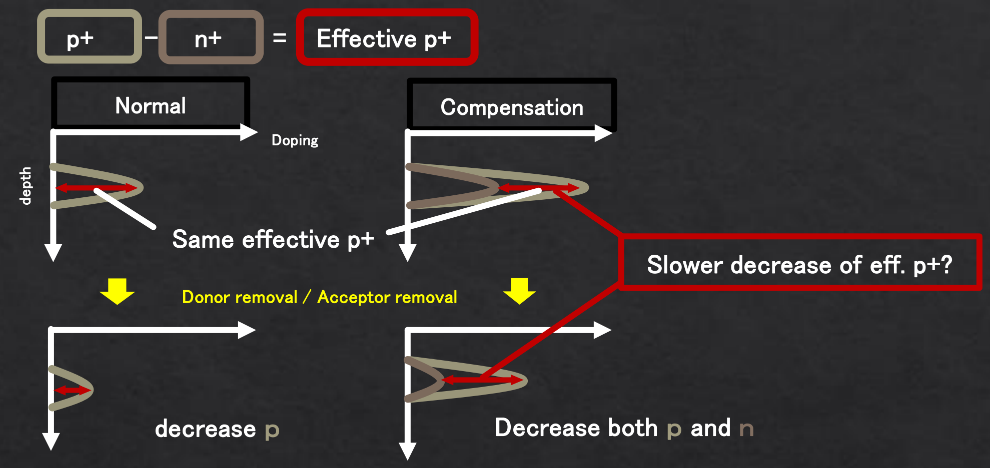
Performed a couple of Irradiation Campaign at CYRIC

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

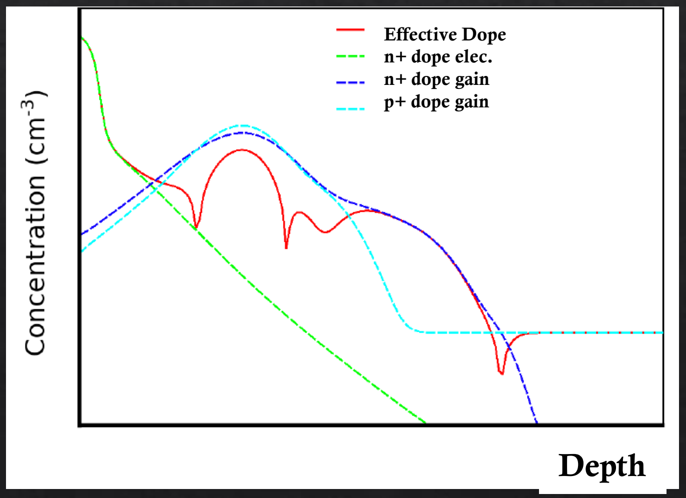
B : Boron

P : Phosphorus

Compensation

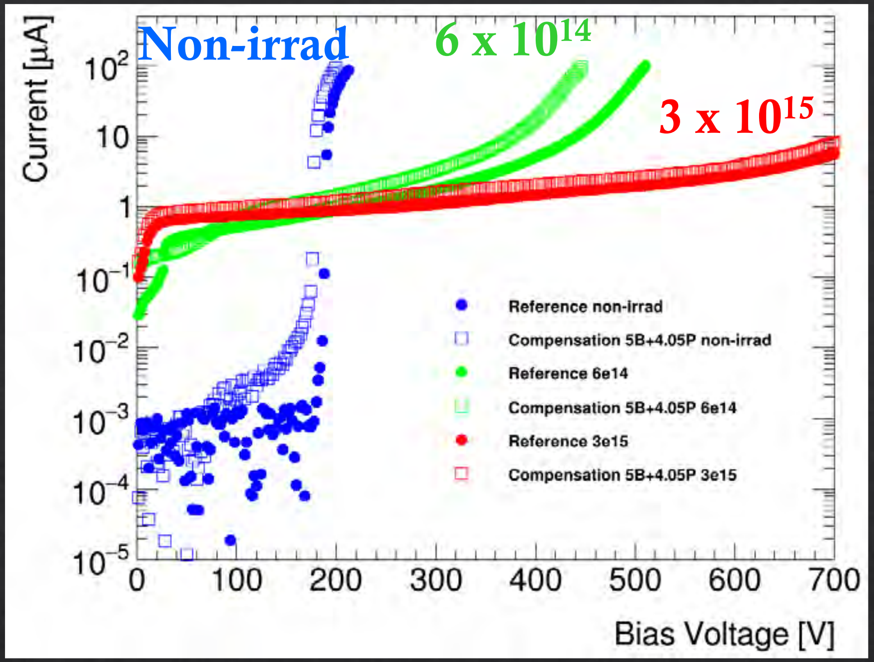


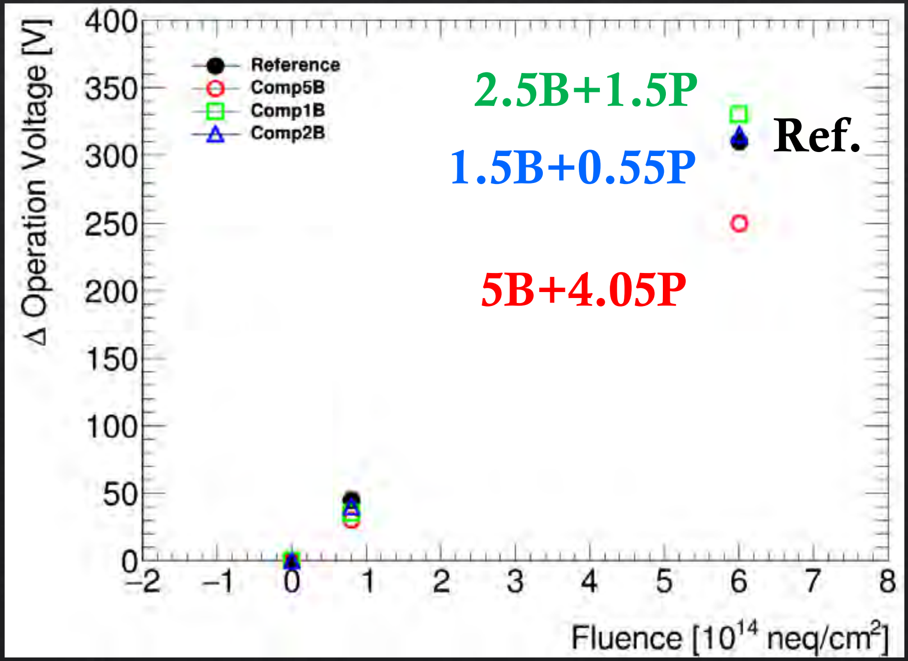
Difficulty of doping profile :



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 : See slight improvement (~50V)
  - 10B+9.2P : No significant signal observed
- What does this mean?





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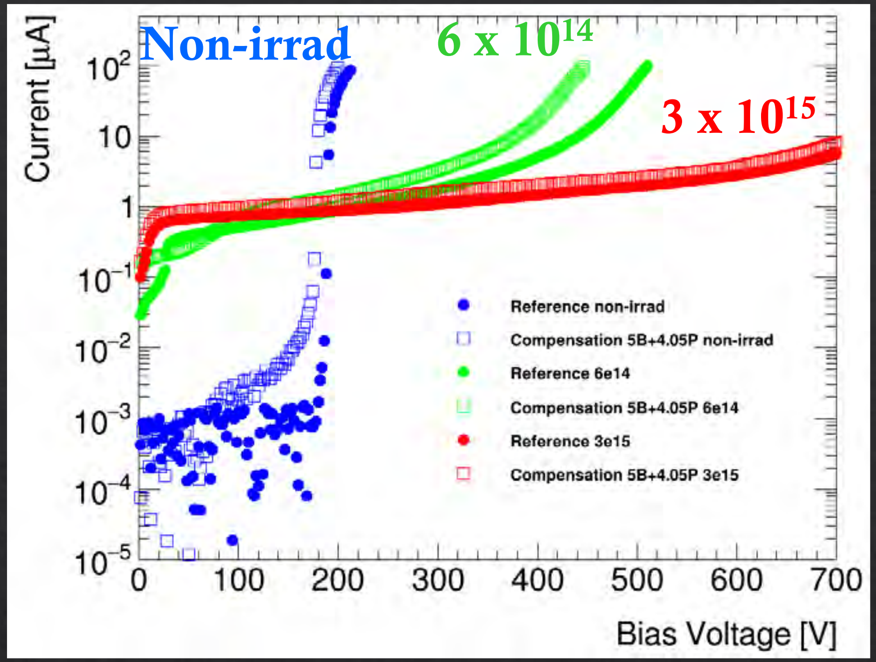

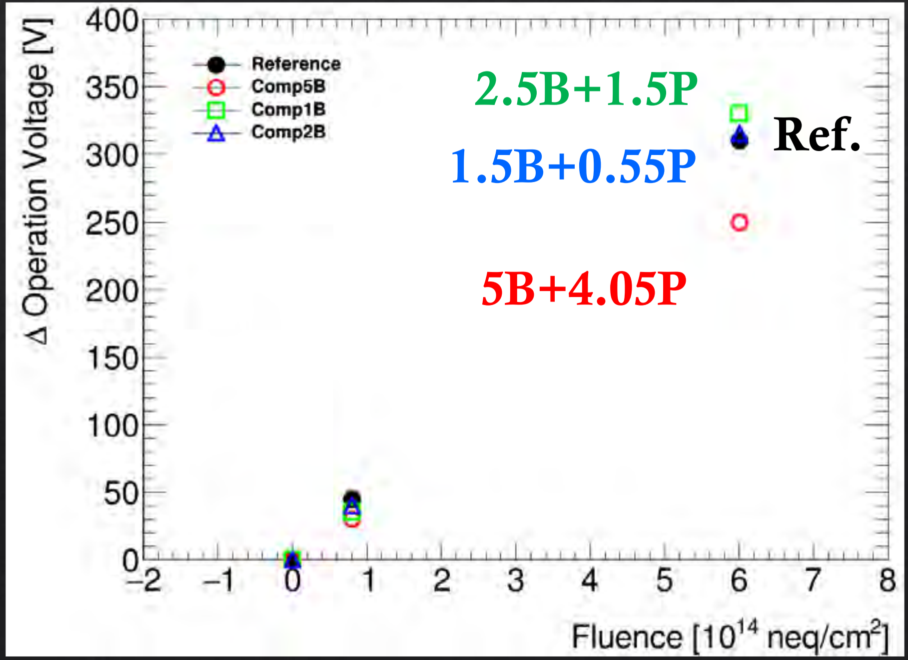

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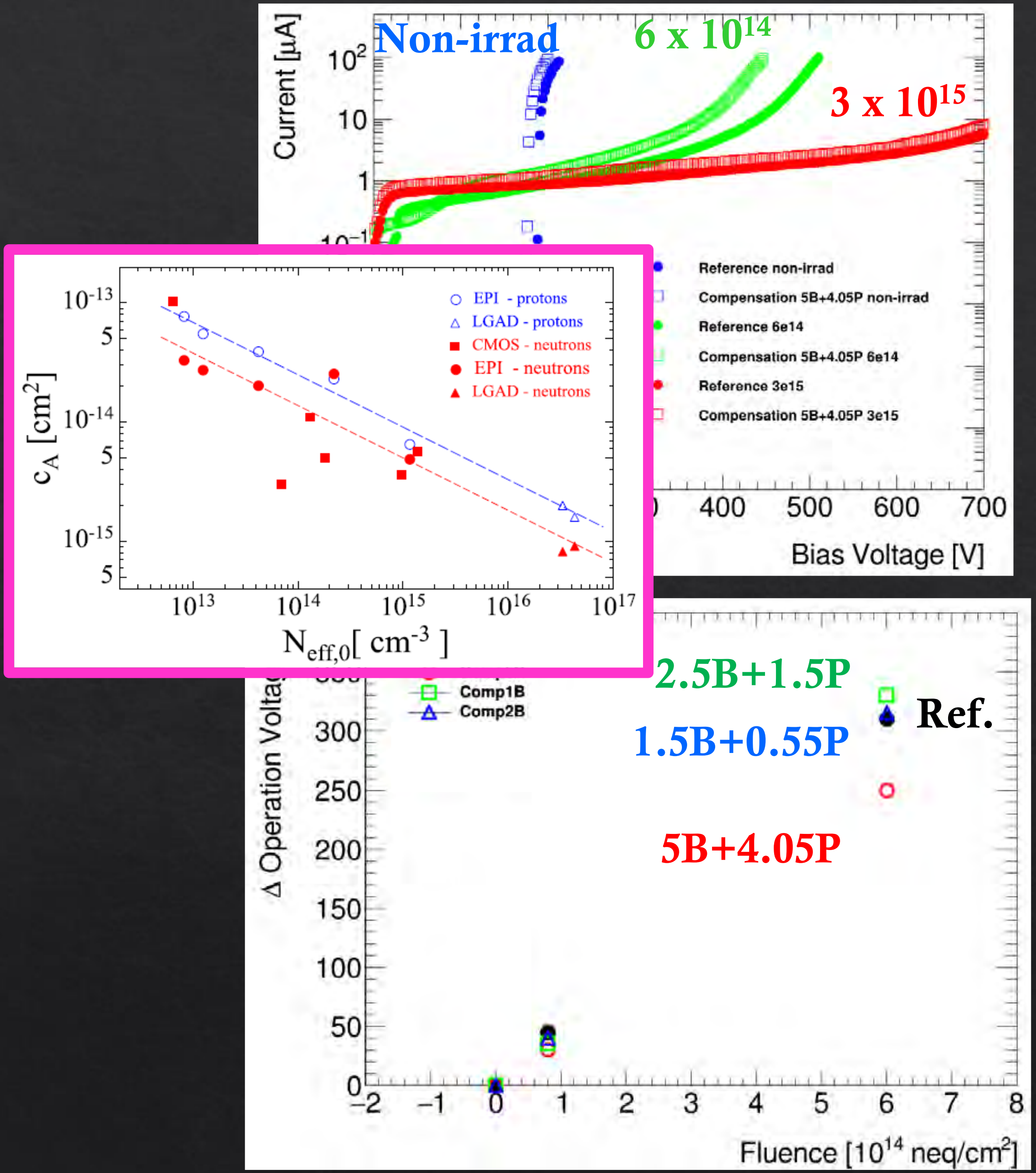

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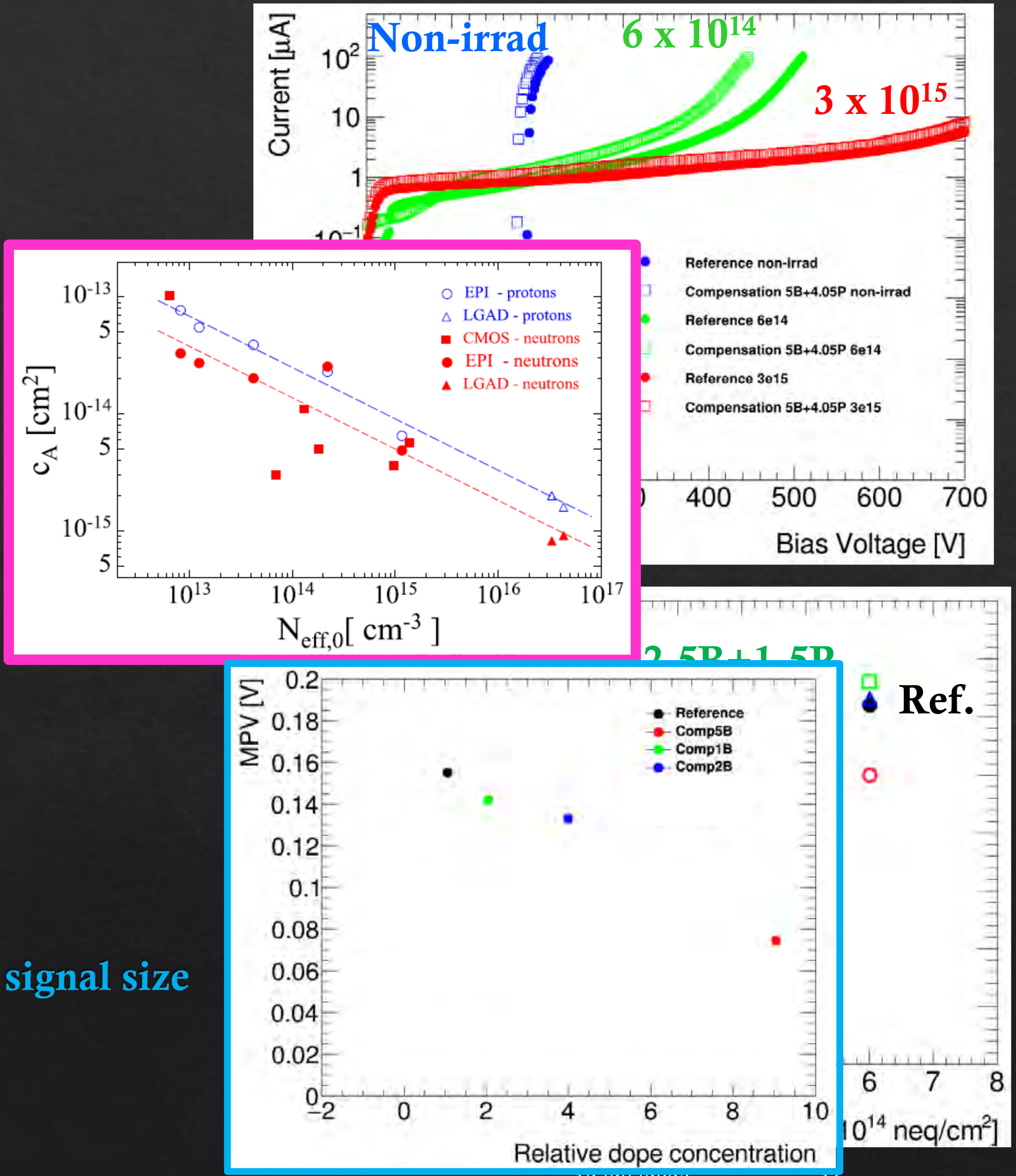

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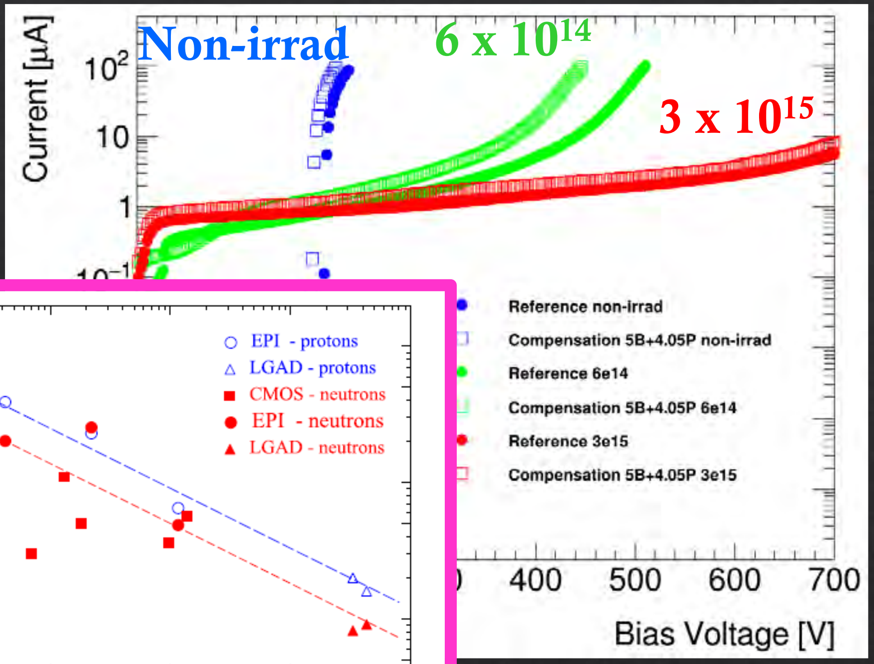
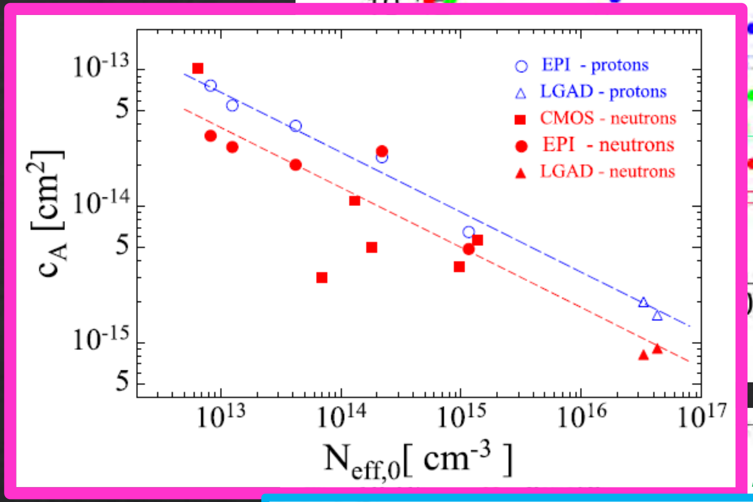
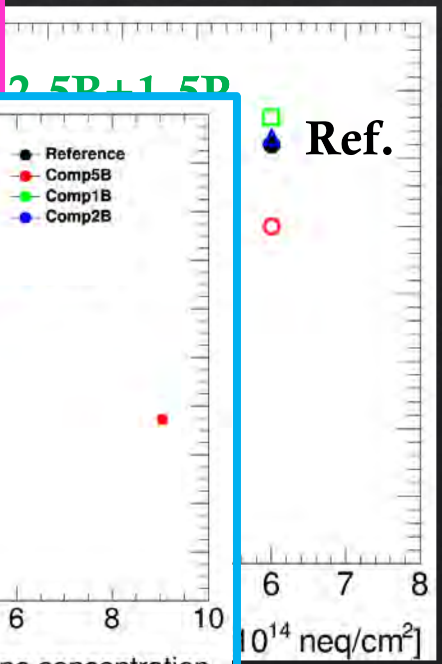
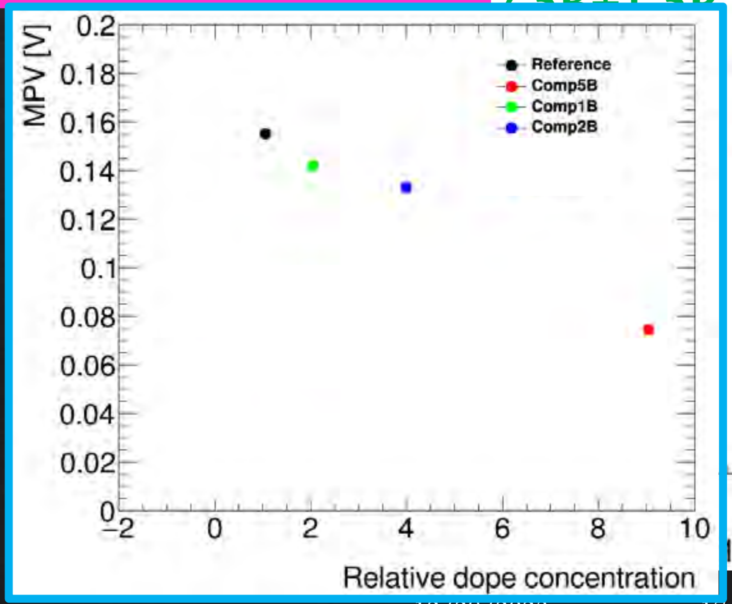
We have new compensation sample with Carbon
→ Shipped to JSI for irradiation.









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)

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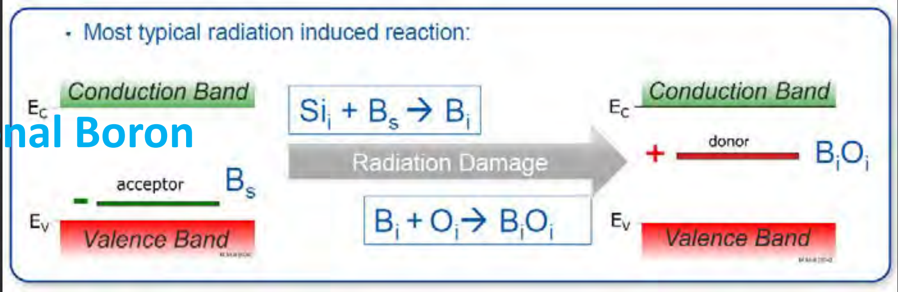
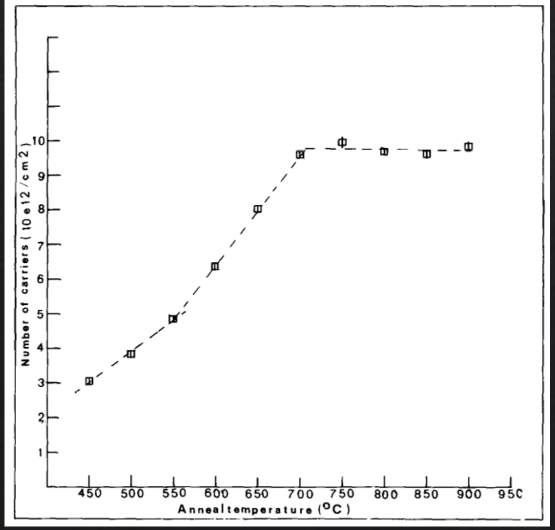
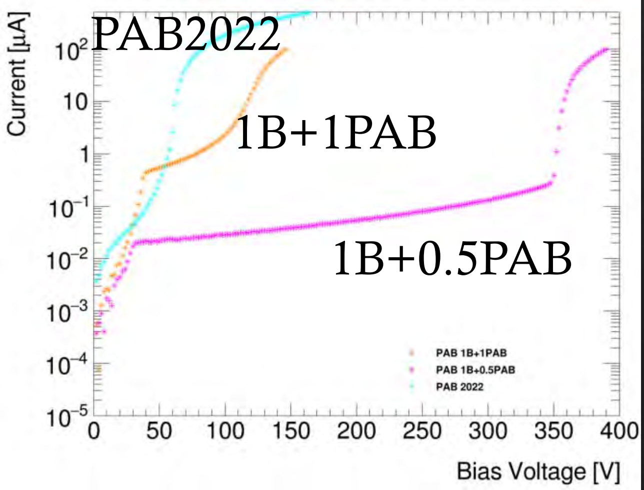
Interstitial Boron



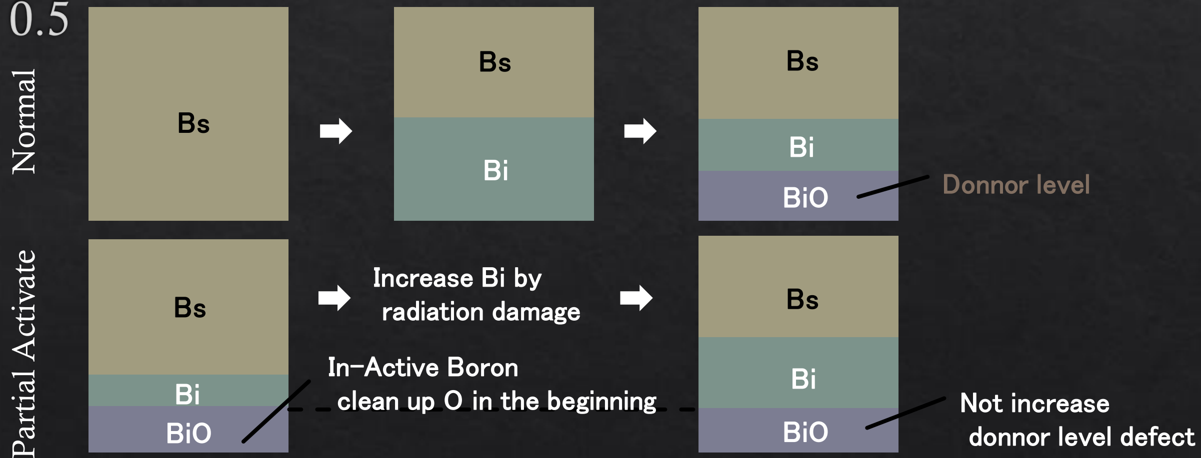
Substitutional Boron



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

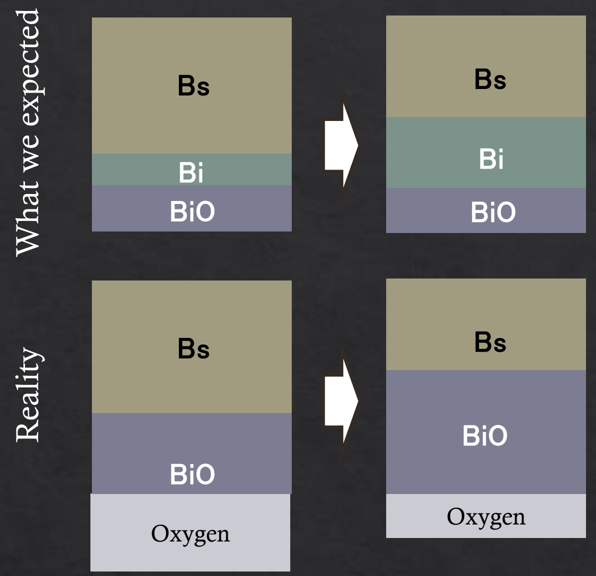


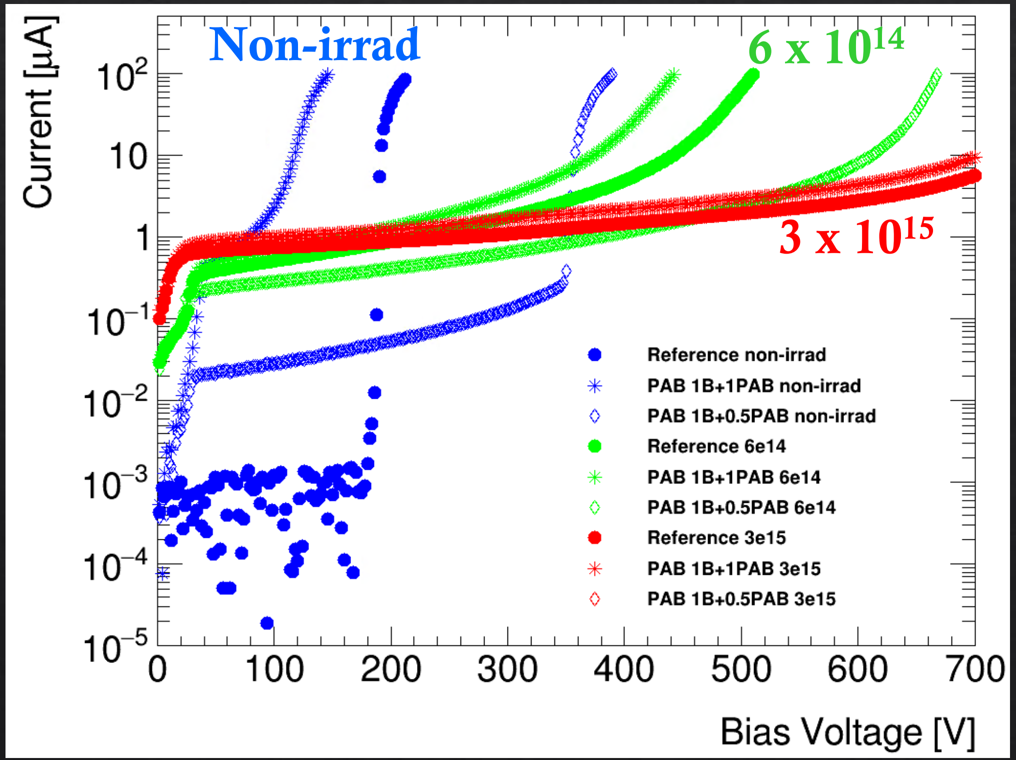
Partially activated Bolons (PAB)

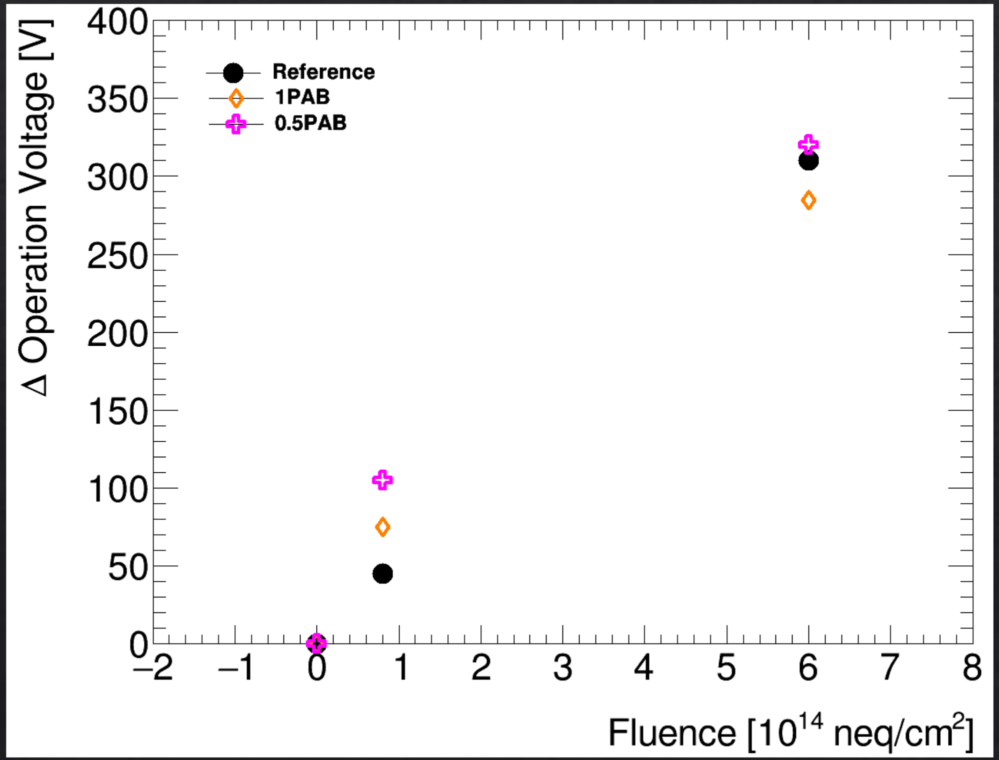


Partially-Activated Boron results

- 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?

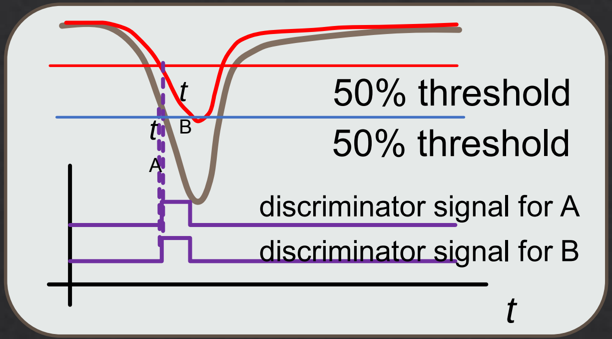


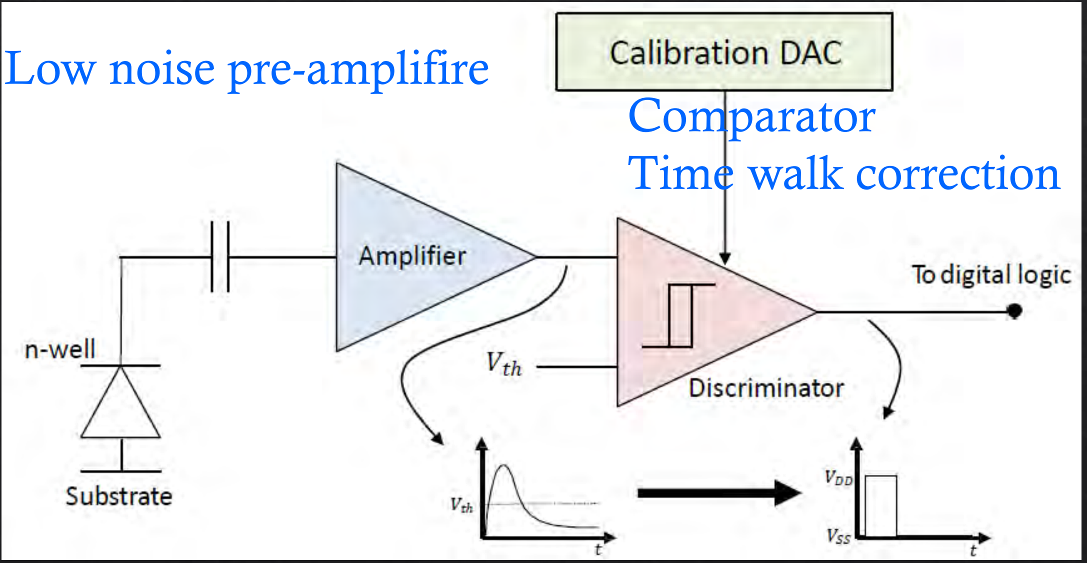


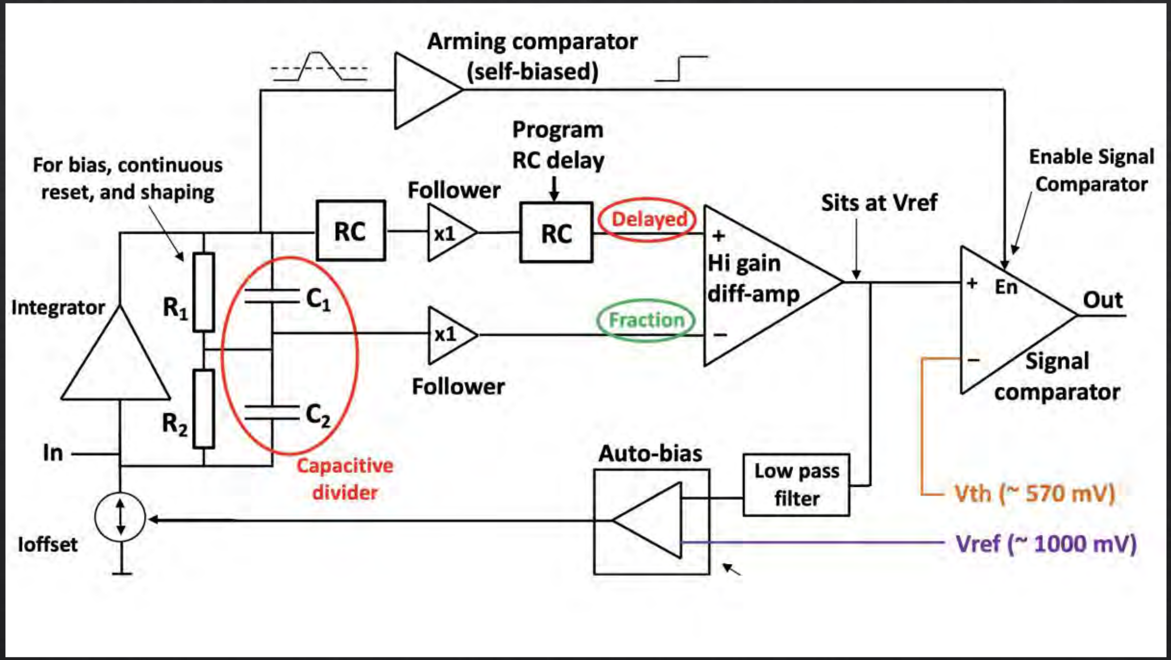


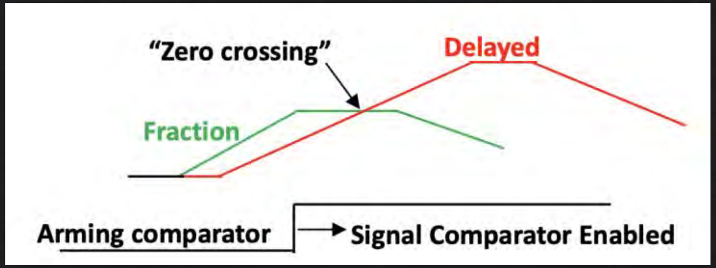
Readout Electronics

- Various ASIC developed for ATLAS/CMS/EIC detector (i.e. ALTIROC/ETROC/EICROC)
- 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 ASIC

- 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.

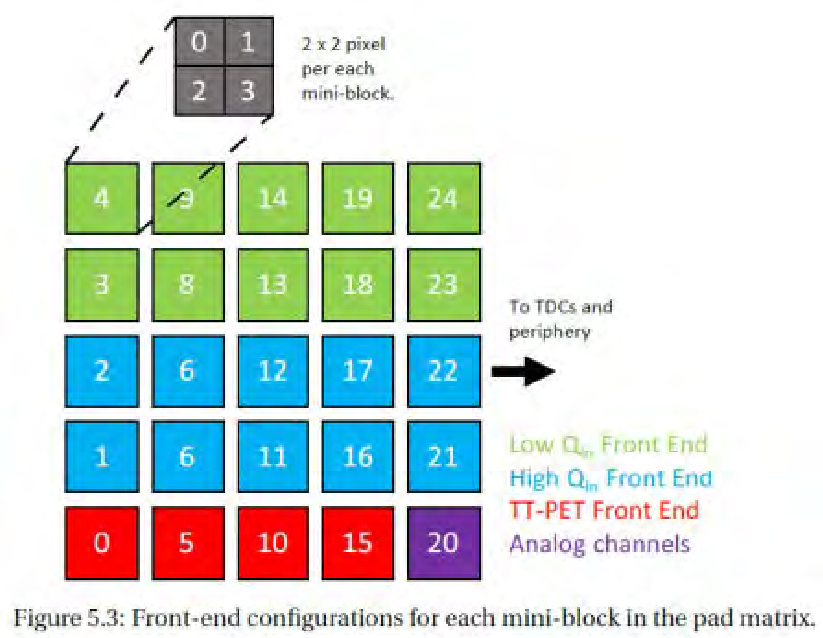
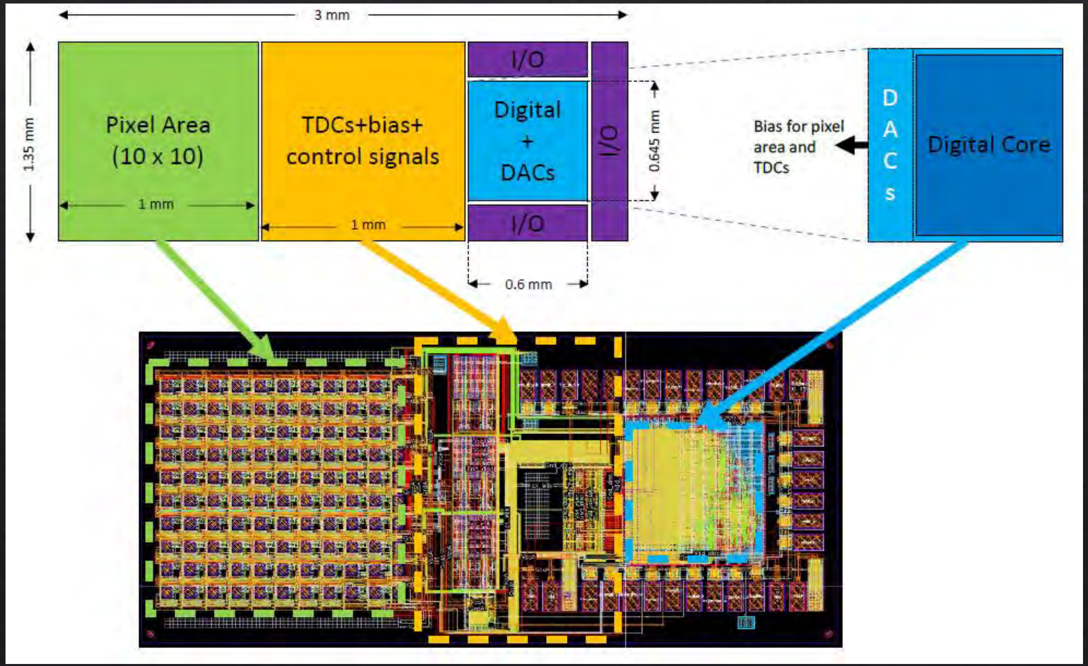
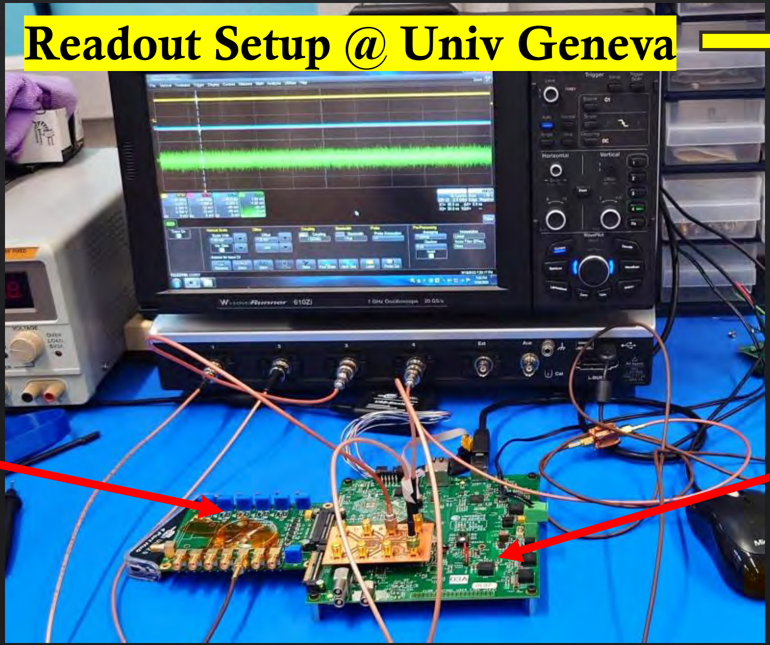


Figure 5.3: Front-end configurations for each mini-block in the pad matrix.

Fulvio Martinelli et. al. Si-Ge Bi-CMOS





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Chip Card

GPIO Board dev. by Uni.Ge ALTERA FPGA

Si-Ge ASIC test

- Use analog channels to readout signal and check by Oscillo scope.
- Design issue : input resistor located under WB pad →short in very high probability…
- Only one channel connected to Discriminator output is working!

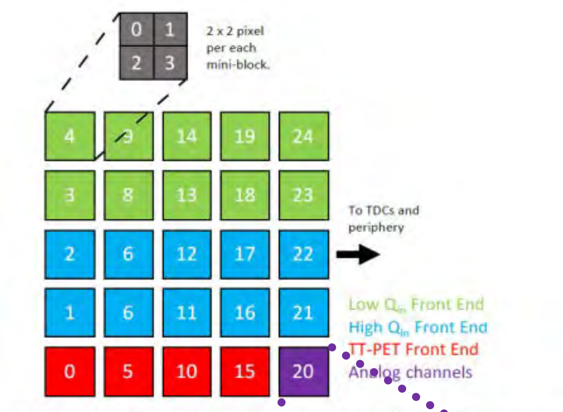
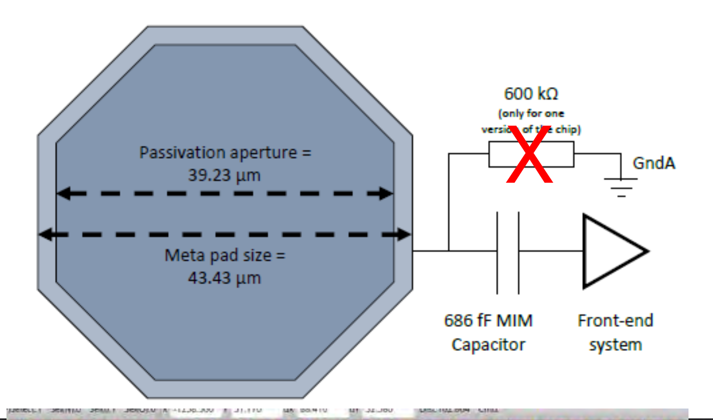
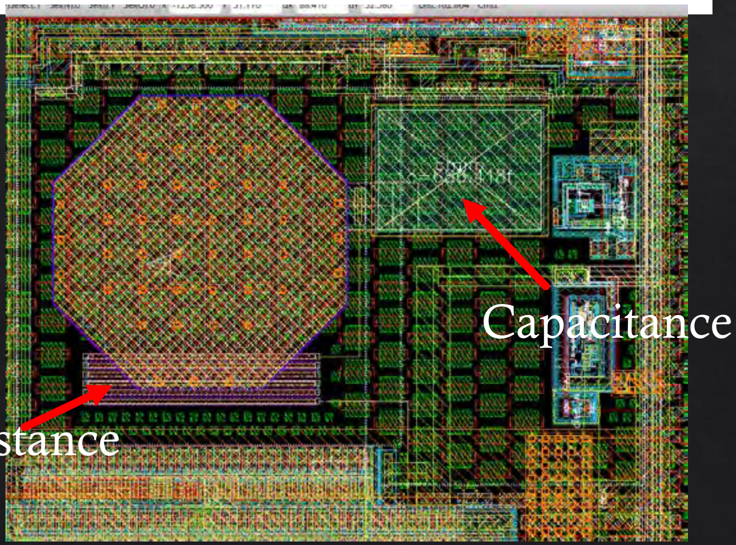
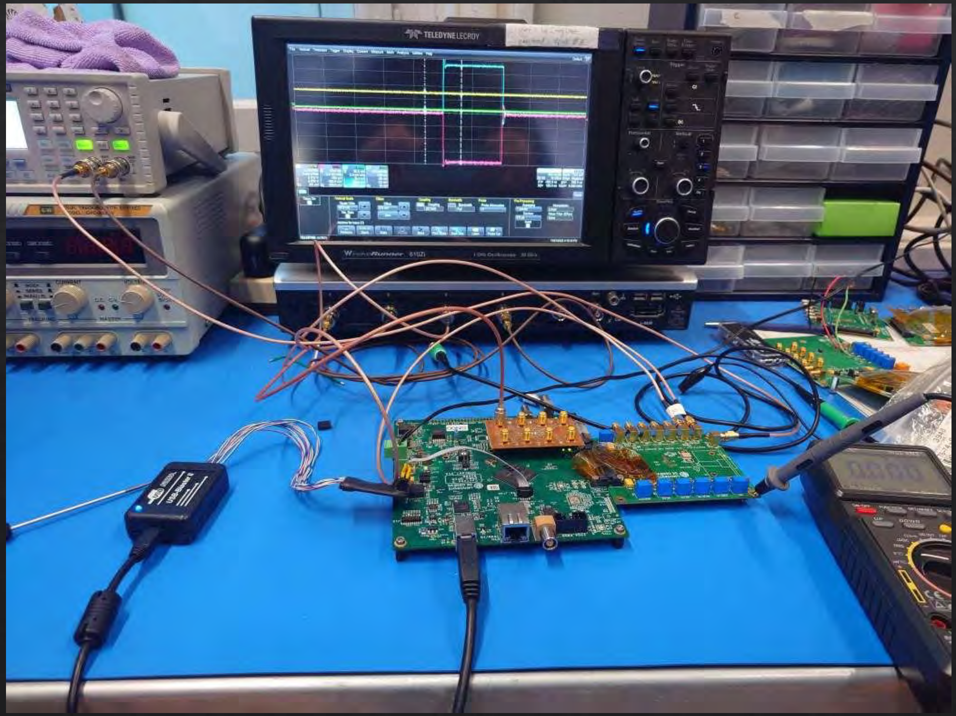


Figure 5.3: Front-end configurations for each mini-block in the pad matrix.





Differential discriminator signal has been observed.
Will try to solve WB issue.



Conclusion & Future

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

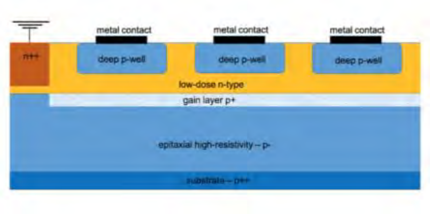
20um thick ACLGAD successfully developed
We achieved ~20ps level time resolution!
→ Need to test pixelated LGAD

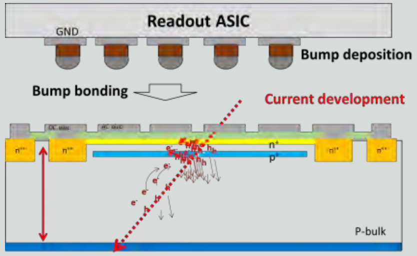
Home work

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

- Large prototype
  - 20mm x 20mm sensor flip-chipped to ITkpix chip. → Gain Uniformity
- Better timing resolution
  - Need 10um thick AC-LGAD
  - Small signal → Low noise ASIC development

Monolithick AC-LGAD	Hybrid AC-LGAD
• Low material (for e+e-) • Fast production rate. • No bonding Capacitance.	• Adapt high speed output • Good Radiation hardness





Conclusion & Future

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Larger signal th

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We achieved ~20ps
→ Need to test

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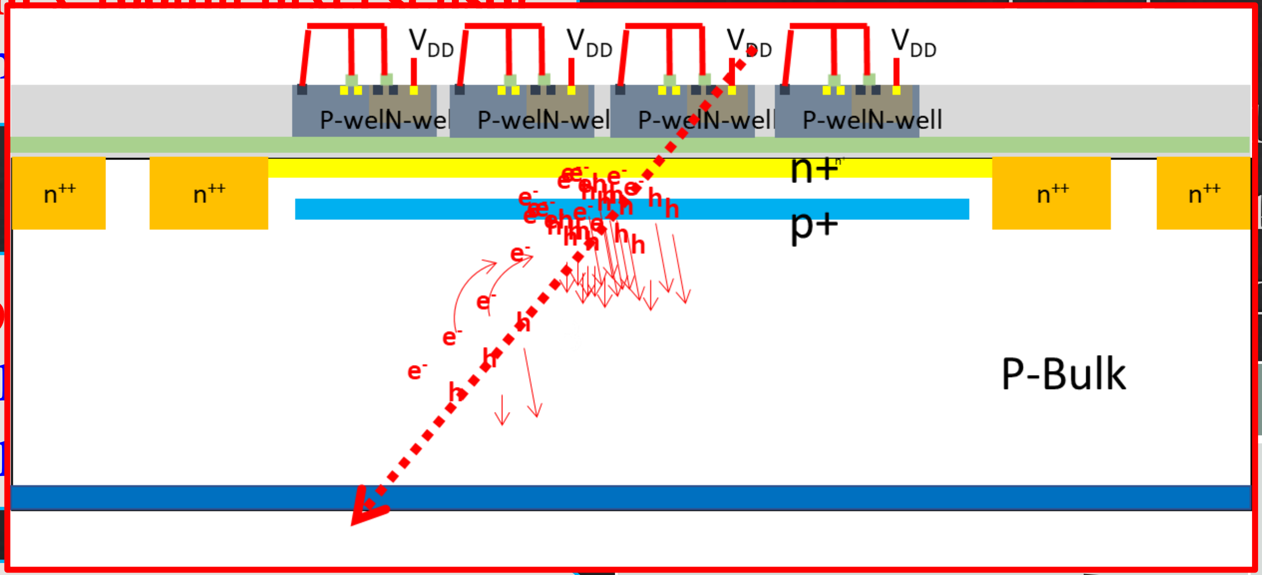


- ⟐ Large prototype
  - ⟐ 20mm x 20mm sensor flip-chipped to ITkpix chip. → Gain Uniformity

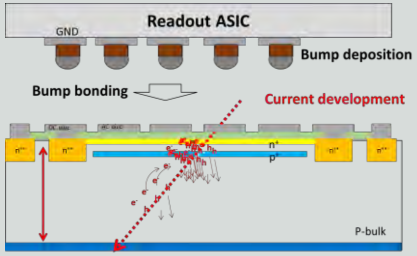
lution

k AC-LGAD

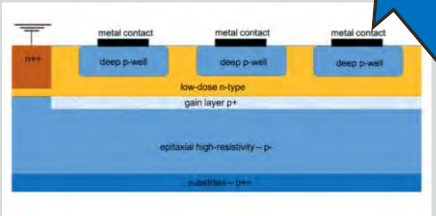
Low noise ASIC development

Hybrid AC-LGAD

- Adapt high speed output
- Good Radiation hardness



- No bonding Capac ice.



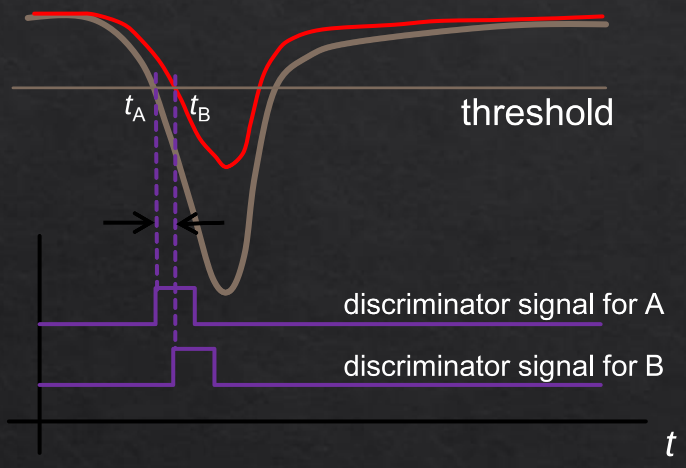
SOI monolithic AC-LGAD

backup

How to improve the timing resolution?

Two reasons which make worse timing resoulution :

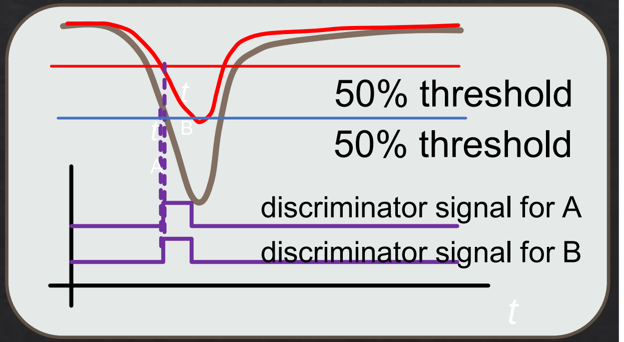
1. Time walk



Different arrival time for small and large signals

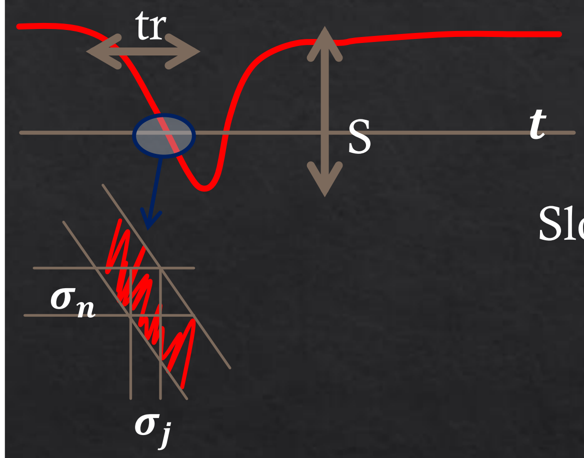
Solution:

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.

Size of noise

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

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

Two approach

- ***<u>Readout ASIC (amplifier) with smaller noise</u>***
  - 3D detector with CMOS ASIC
    - Time Spot
    - RD53 ASIC (28nm)
  - Monolithic detector with Si-Ge BiCMOS
    - Monolith (Univ. of Geneva) by IHP
- ***<u>Making sensor with larger signal and faster turn on</u>***
  - **Low Gain Avalanche Diode (LGAD)**

Size of noise

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

Slope of vol.

Size of signal

Ramping time

These two approaches may realize at the same time.

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

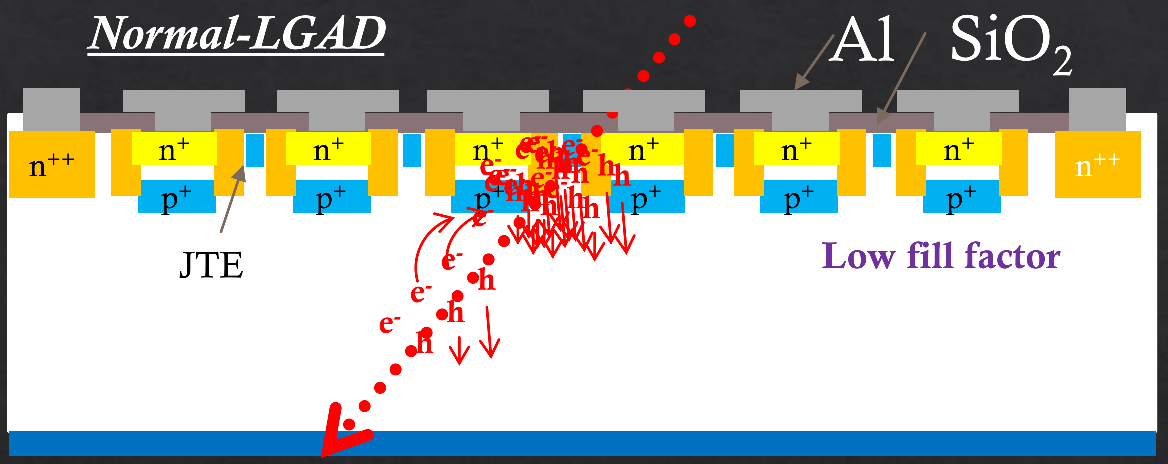
Charge Collection noise :
50um thick sensor : ~30ps timing resolution
20um thick sensor : ~15ps timing resolution
Thinner sensor should have better timing resolution.

Pros and Cons of Low Gain Avalanche Detector

- Pros
  - LGAD have gain : x35 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?

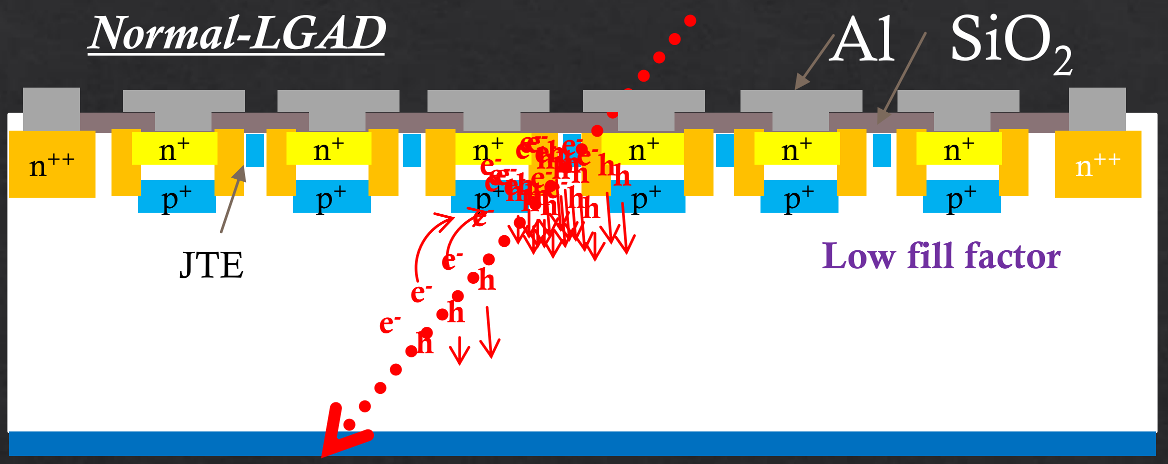
Spatial resolution of LGAD

- 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)**

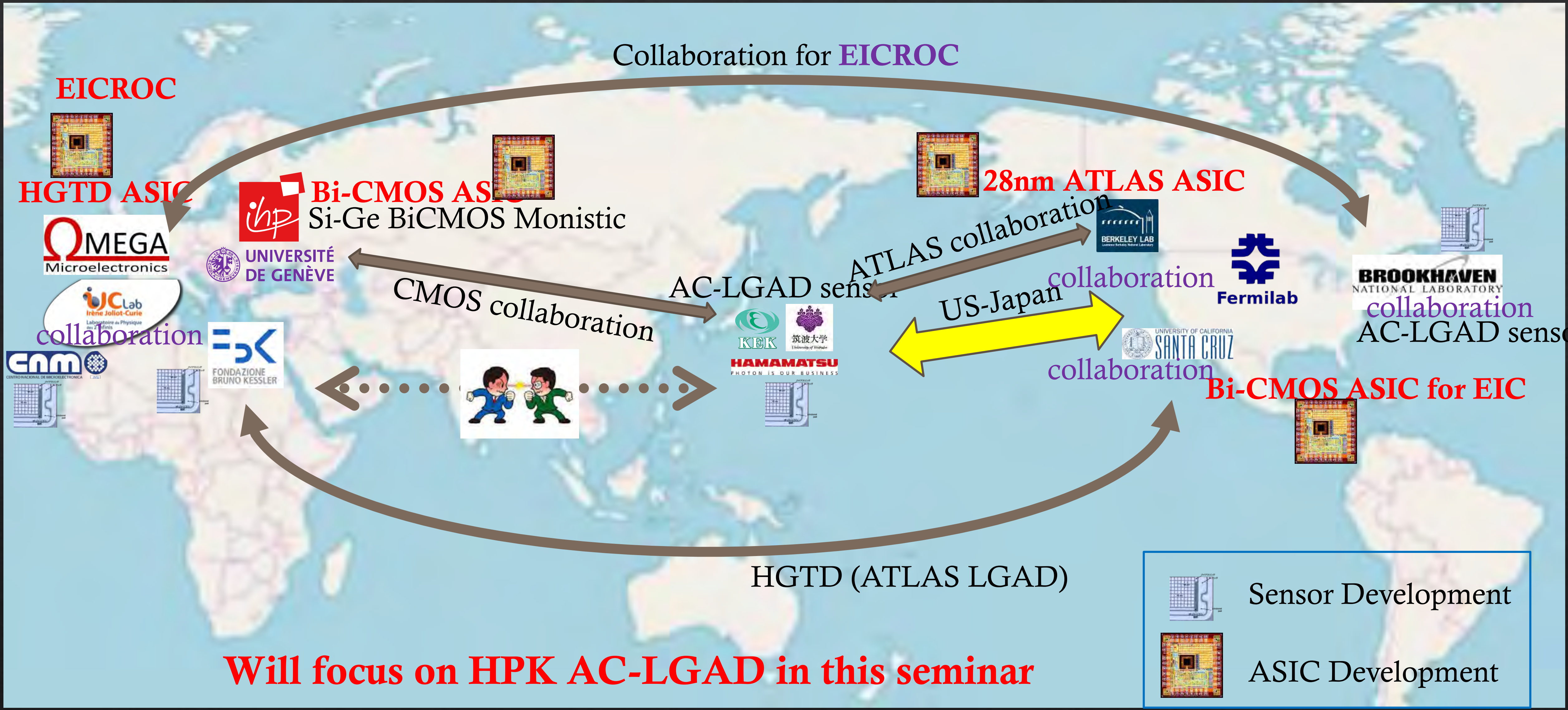


Spatial resolution of LGAD

- 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)**
- **Uniform gain layer with AC-Coupled electrode. (AC-LGAD)**
  - **In principle, 100% fill factor.**
  - **Signal shared on neighboring electrodes.**
    - Need optimization of n+ resistivity

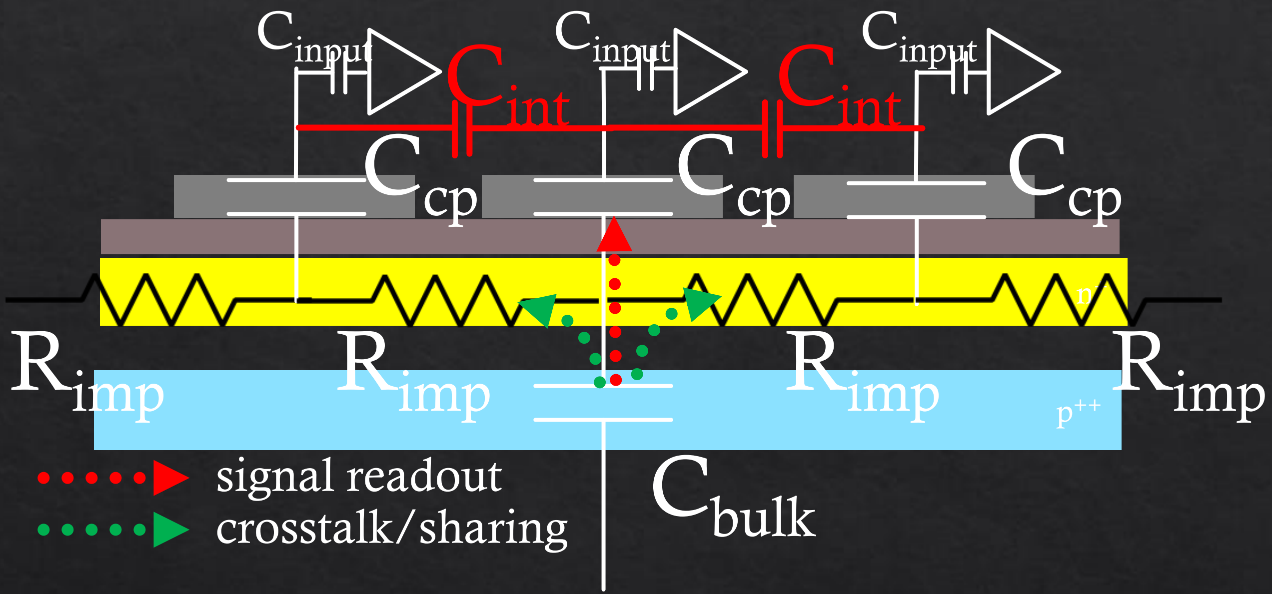


AC-LGAD collaboration



AC-LGAD sensors

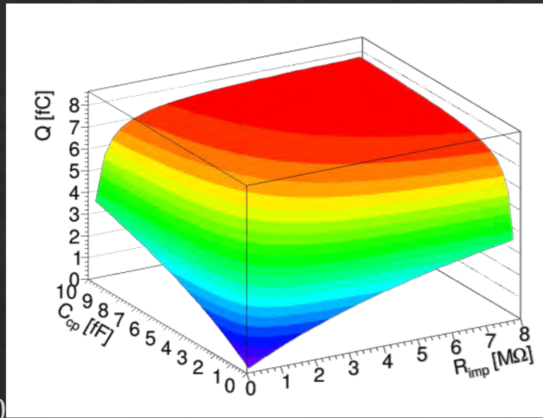
- **Read out principle of AC-LGAD**



- ⟐ Charge split : Impedance ratio

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

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



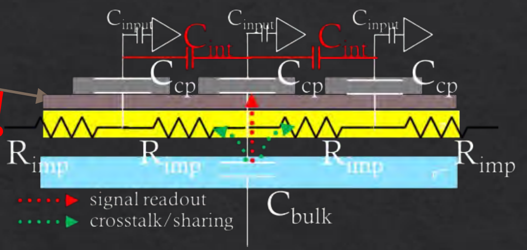
- ⟐ Amount of produced charge: Q_0
- ⟐ Readout Charge : Q

- Additional cross talk is expected due to the inter electrode capacitance C_{int}
  - Amount of cross talk may also depend on input capacitance on the electronics.
  - Effect must be understood → Sensor with smaller Cint should be important

How small electrode could we achieve?

Used thinner di-electric layer (Oxide layer)

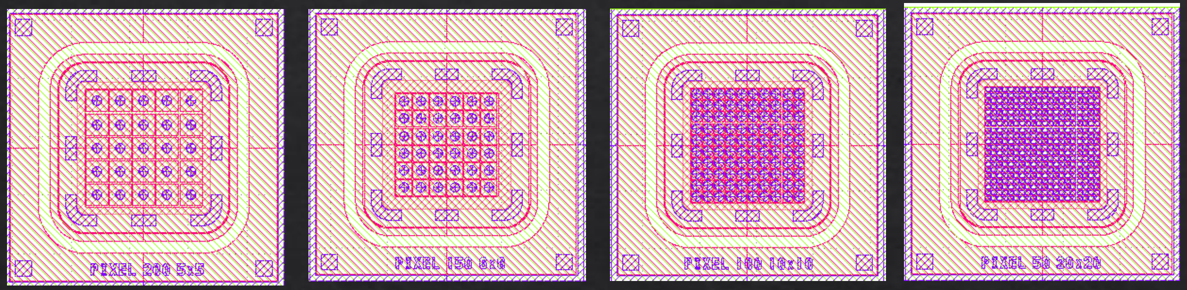
→ Electrode capacitance increased by factor of 5 !!

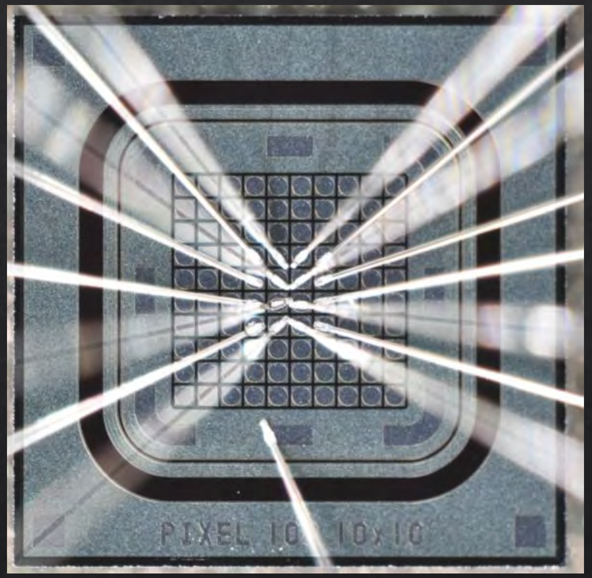


Pixel sensor

- Various of pitch

200um 150um 100um 50um





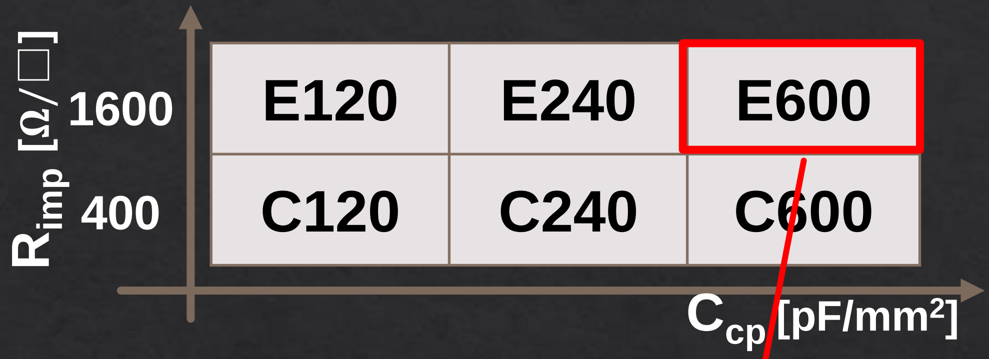
- 5 times larger Ccp compared with E-b (2020) type : E-600

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

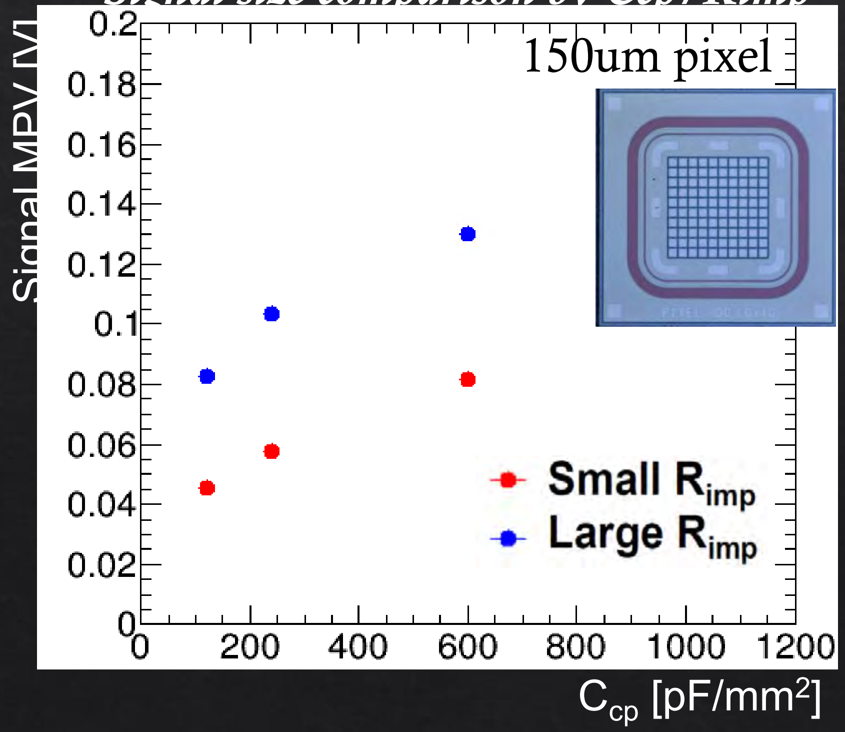
50um pitch electrode sensor has not been yet tested due to difficulty of wire bonding.

How small electrode could we achieve?

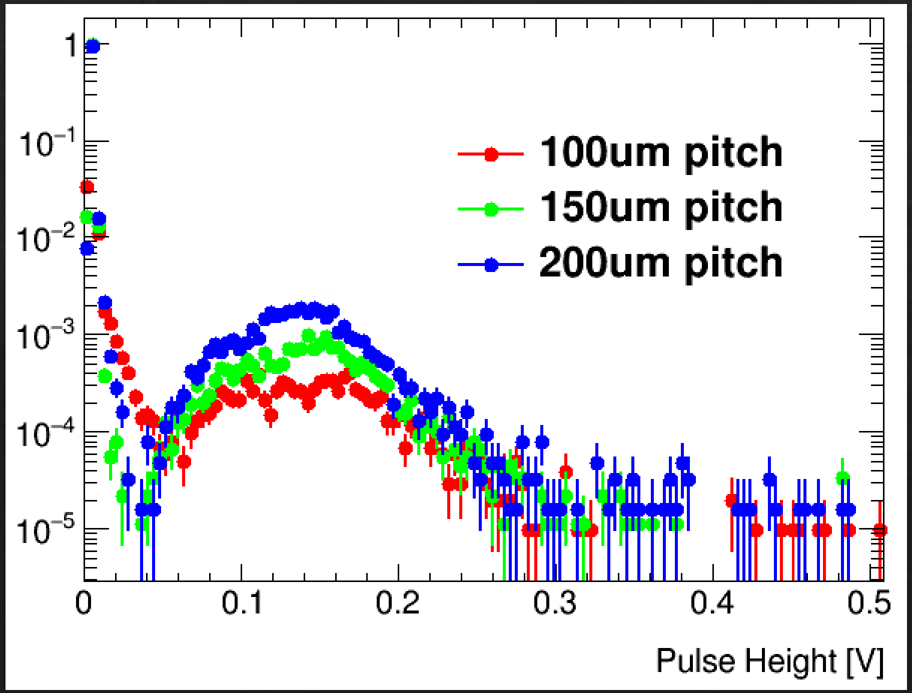
- Compared signal size of 6 types C_{cp}/R_{imp}.
  - 150um pixel sensors
  - Two n+ resistivity types and 3 Ccp types
- Compared signal size of 3 pixel size
  - 100/150/200um pitches are compared.

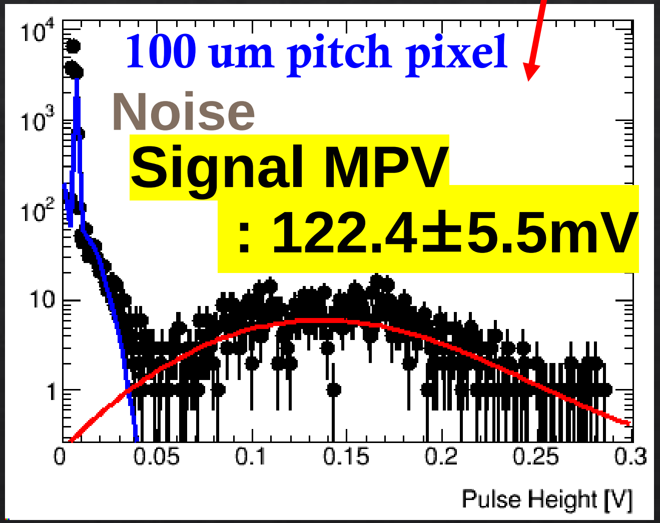


Signal size comparison by Ccp/Rimp



Pulse height comparison by pixel pitches



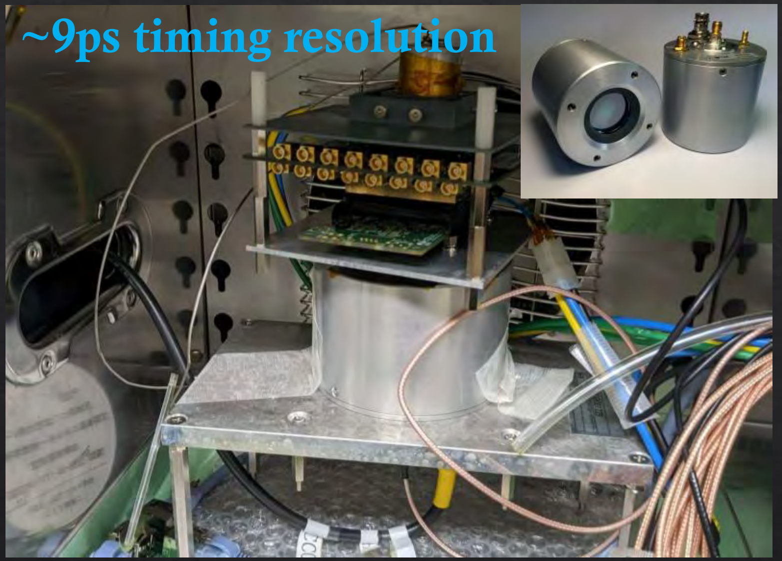


Successfully developed Good S/N 100um pitch pixel detector!

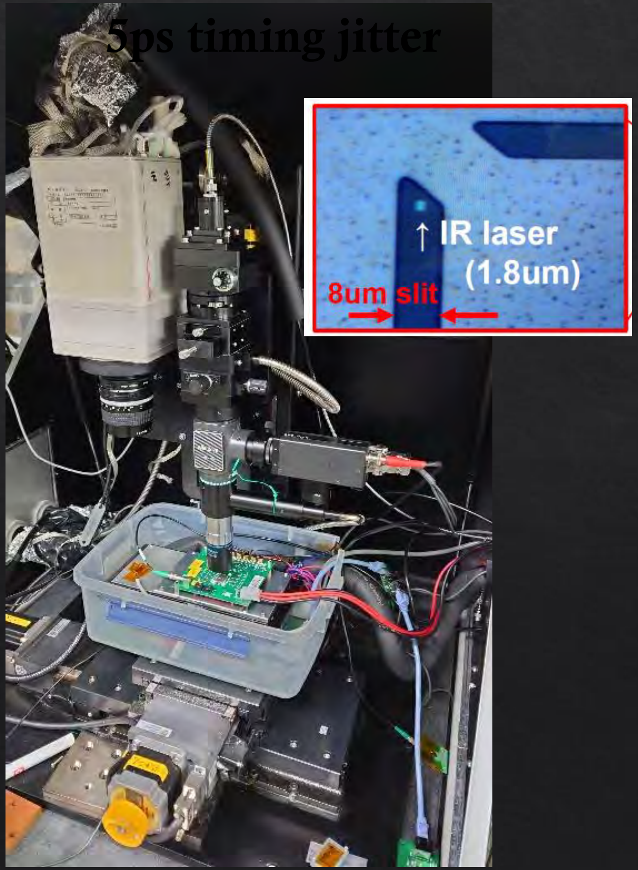
Measurement of timing resolution

- Measurement of timing resolution for fine electrode sensors are challenging.
  - Taking time if we use two layer coincidence

Photek PMT 240 ([90]Sr source)



Infra-Red (pico sec) laser



Timing resolution

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

~~σ_{tw}:Time walk~~

σ_j: Jitter (electronics) **MIP** **IR**

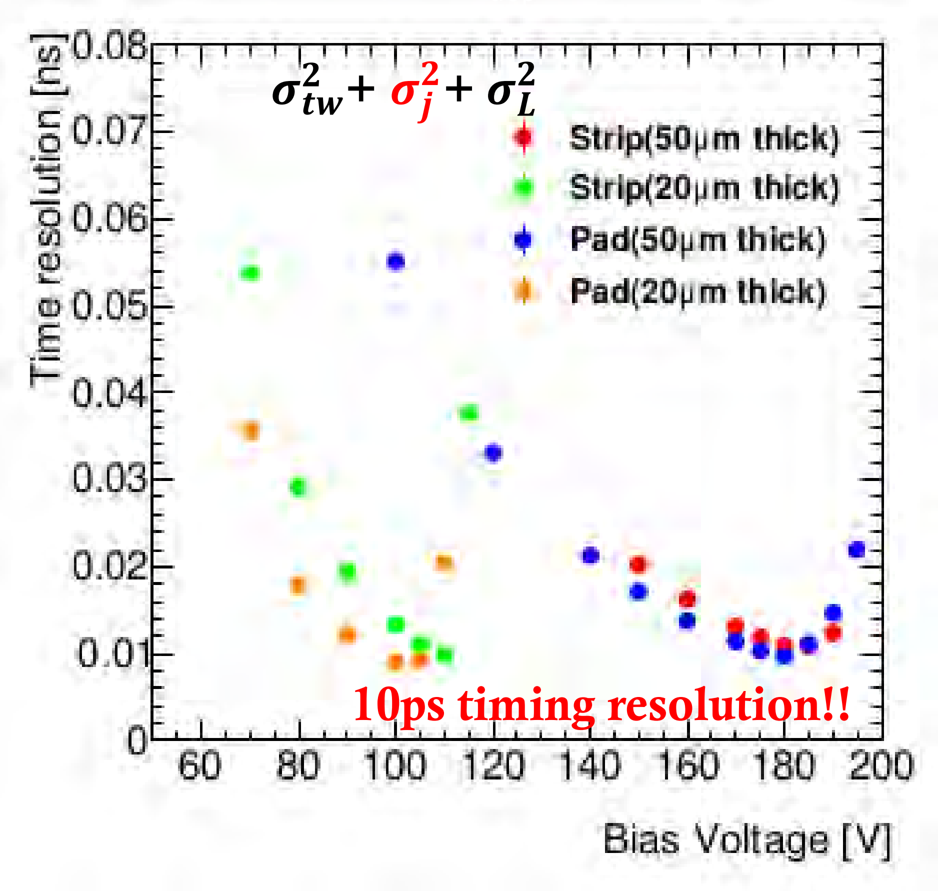
σ_L: Landau noise **MIP**

- Photek PMT240 (MCP-PMT)
  - Mes. Of timing resolution to MIP
  - **9ps PMT240 resolution (reference)**
  - **Don't know injecting position.**
- Infra-red (pico sec) laser
  - Known injecting position(Size: 1.8um)
  - **5ps jitter**
  - **No landau noise**

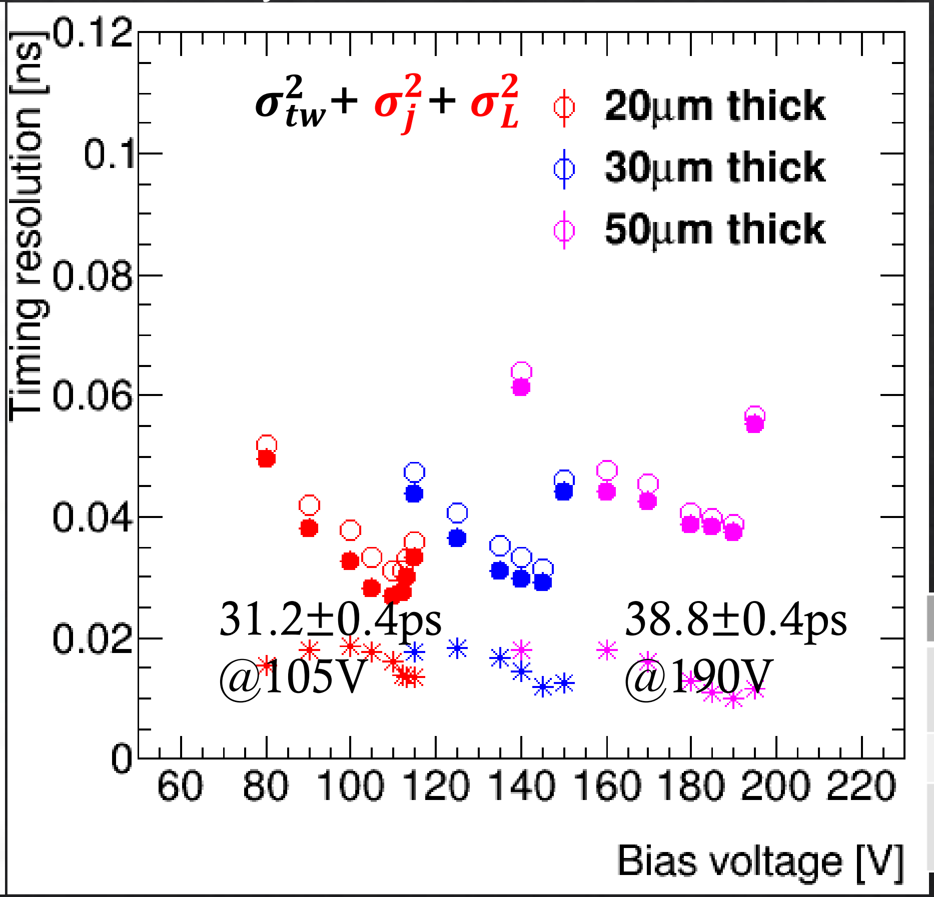
Timing resolution results

- Timing resolution measurement by two methods

Infra-red laser (E_{dep}~ a few times MIP)



Beta-ray measurement



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

By laser measurement, calculated noise for each Volt.

Calculate jitter for MIP meas.
Evaluated Landau term.

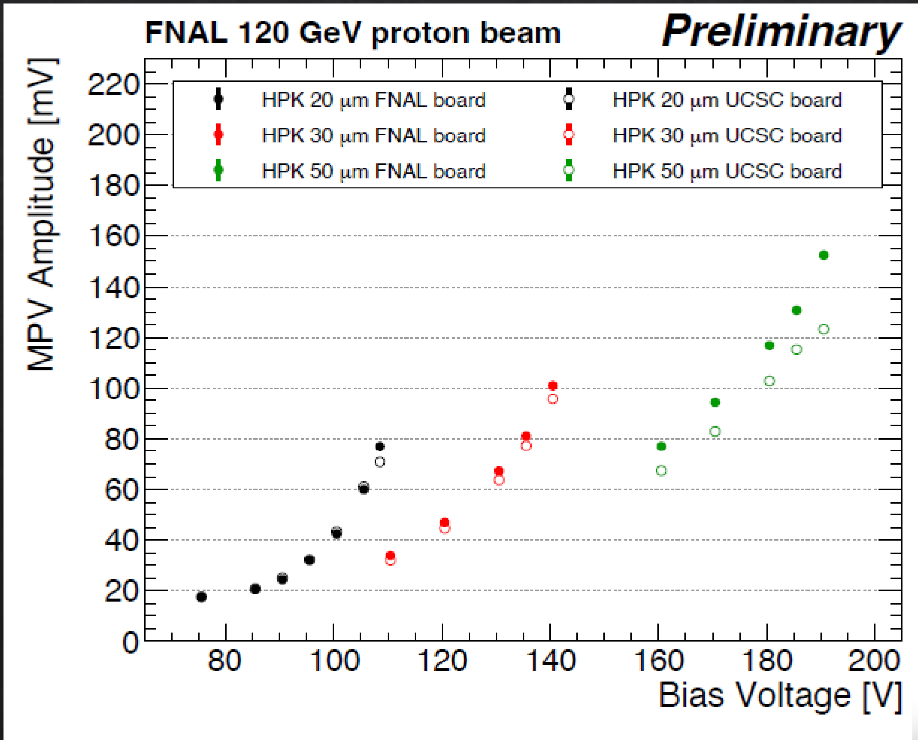
Lab meas	50um	30um	20um
Timing resolution	38.8ps	31.5ps	31.2ps
Jitter	9.8ps	11.8ps	15.9ps
Landau noise	37.5ps	29.2ps	26.8ps

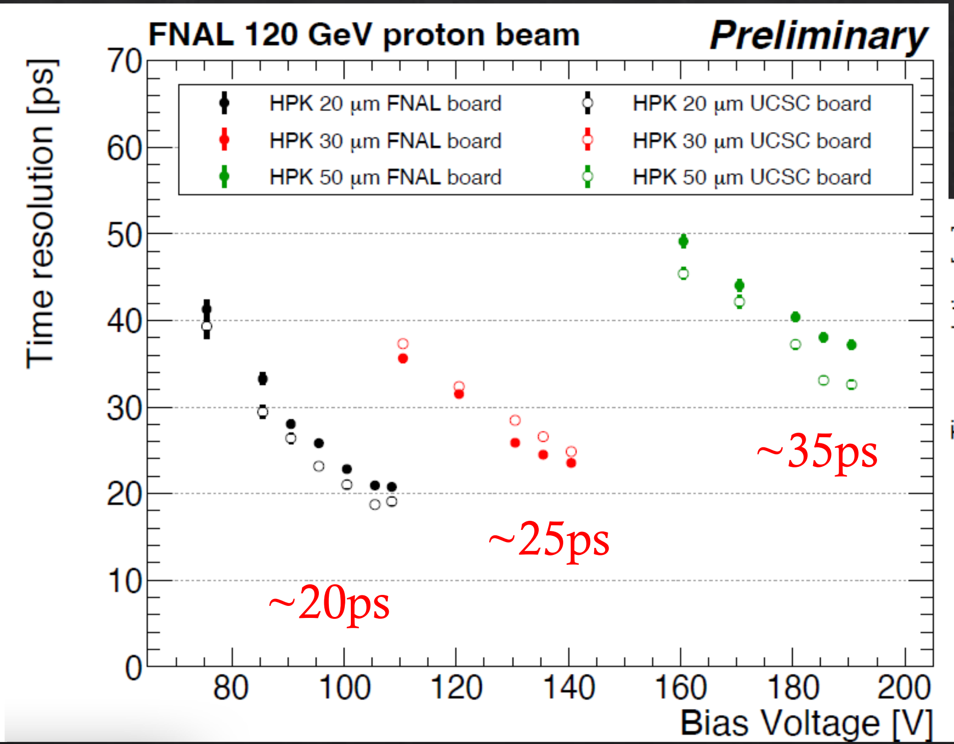
20um sensor have smaller landau term in timing resolution.

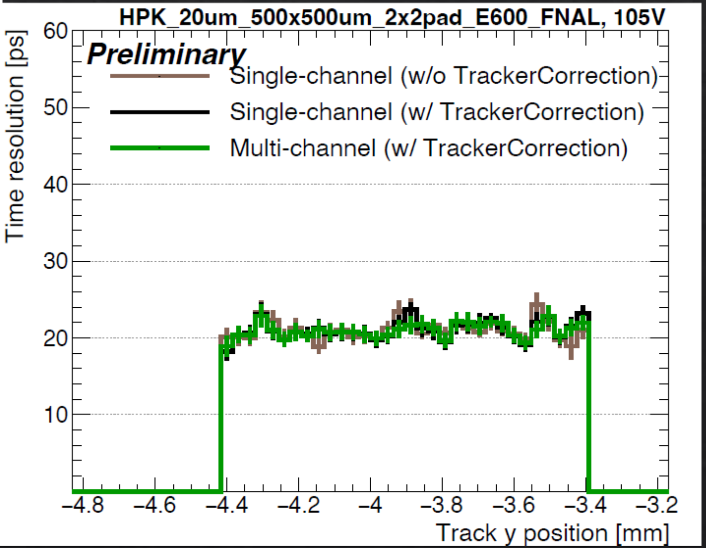
Scattering effect of beta-ray measurement should be affected → Testbeam measurement

Timing resolution measurement at testbeam

- Results for 2x2 pad sensors with 50um, 30um and 20um thickness
  - 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.**



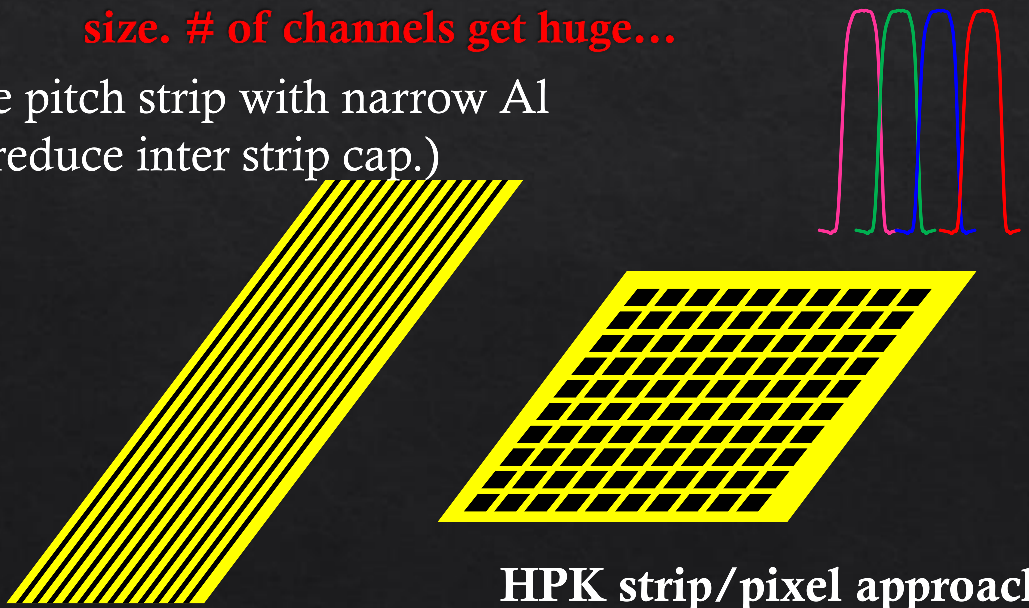




Two approaches to have good spatial resolution

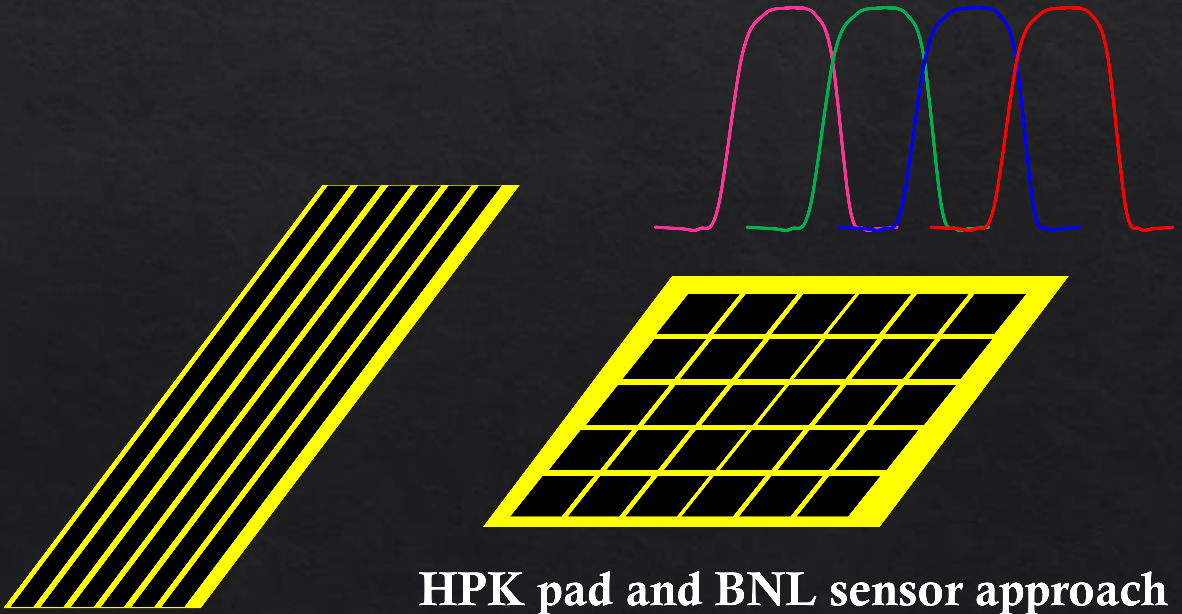
- ***Fine pitch electrode approach***
  - **For High occupancy experiment like hadron collider.**
  - Reduce crosstalk (charge sharing)
    - High n+ implant resistivity
  - **Pros. : smaller occupancy and smaller data size like digital readout**
  - **Cons. : Limitation of spatial resolution by electrode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

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



HPK strip/pixel approach

- ***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. : Very good spatial resolution if high resolution ADC used.**
  - **Cons. : Smaller signal size. Need high resolution ADC.**



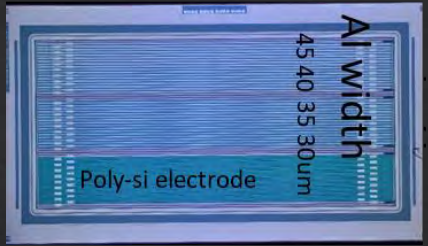
HPK pad and BNL sensor approach

Is Strip type electrode possible?

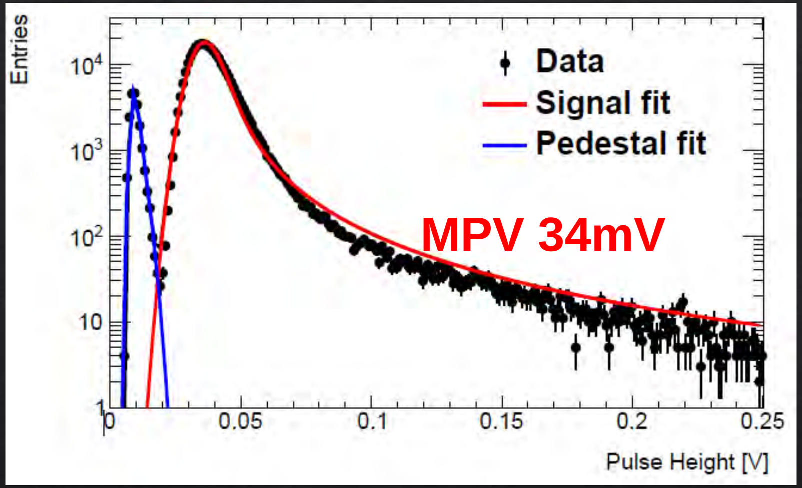
- For collider experiments, outer layers should use Strip type electrode to reduce readout channels.

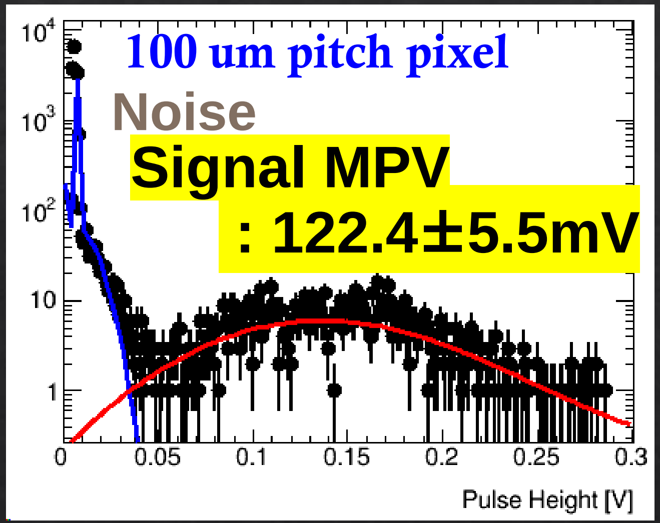
However, the signal size is much smaller than pixel sensors

80um pitch Strip



(c.f.)





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

Why so small signal?

How much effect of interstrip capacitance?

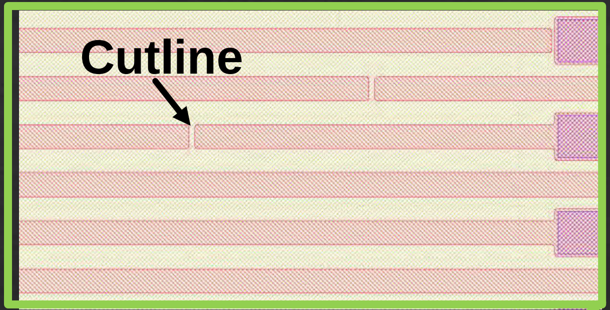
Significantly smaller signal compared with pad type detector.

How much signal attenuation in the strip?

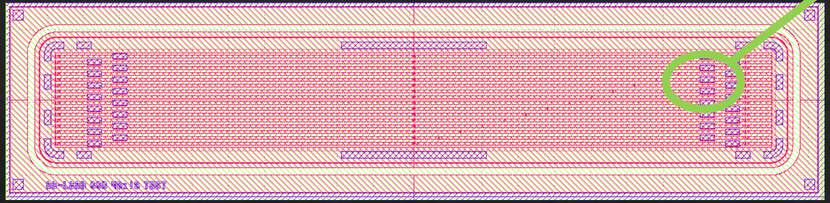
This might affect to the signal size un-uniformity and delay of signal readout.

Inter strip capacitance (Cint) effect

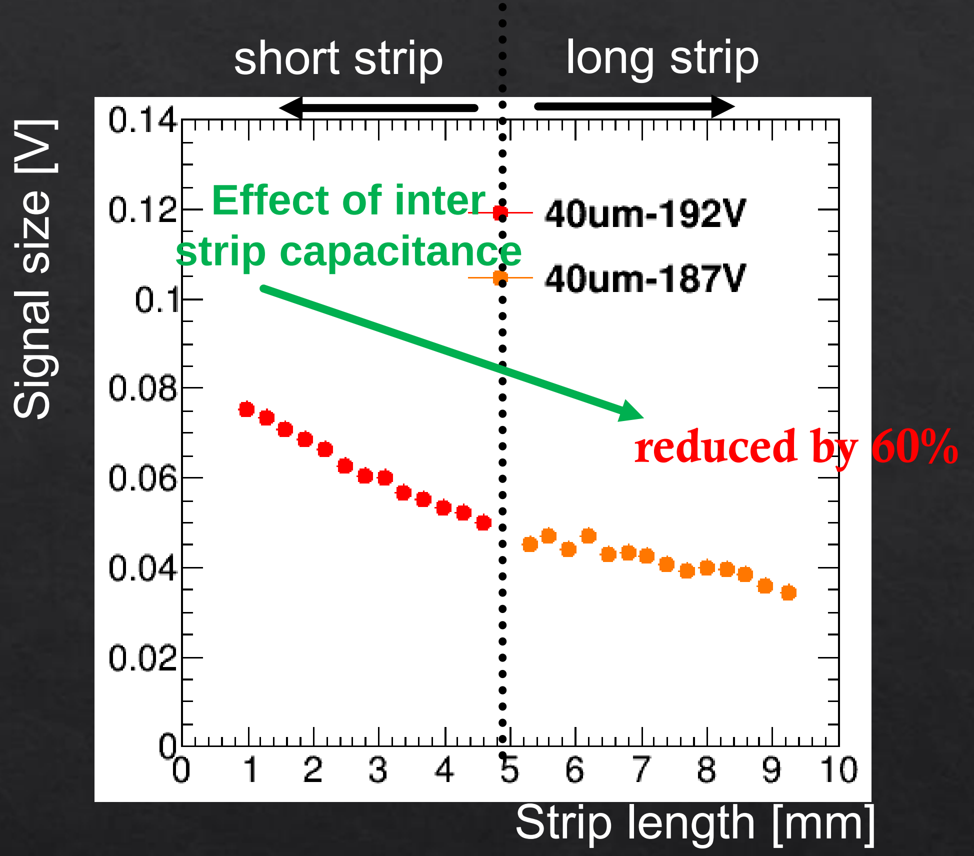
Strip sensor with cut line



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



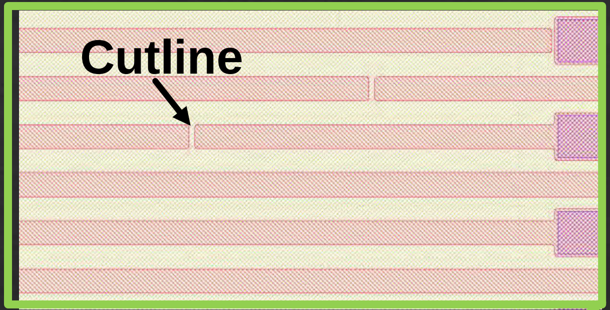
16 strips x 2



Where signal disappeared?

Inter strip capacitance (Cint) effect

<u>Strip sensor with cut line</u>



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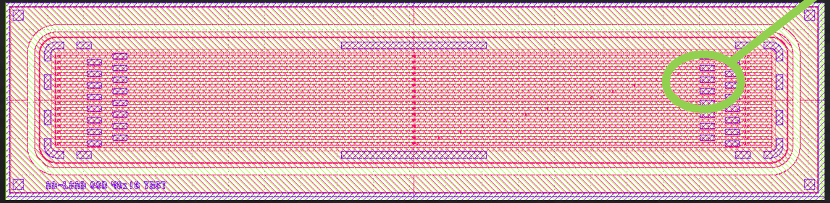
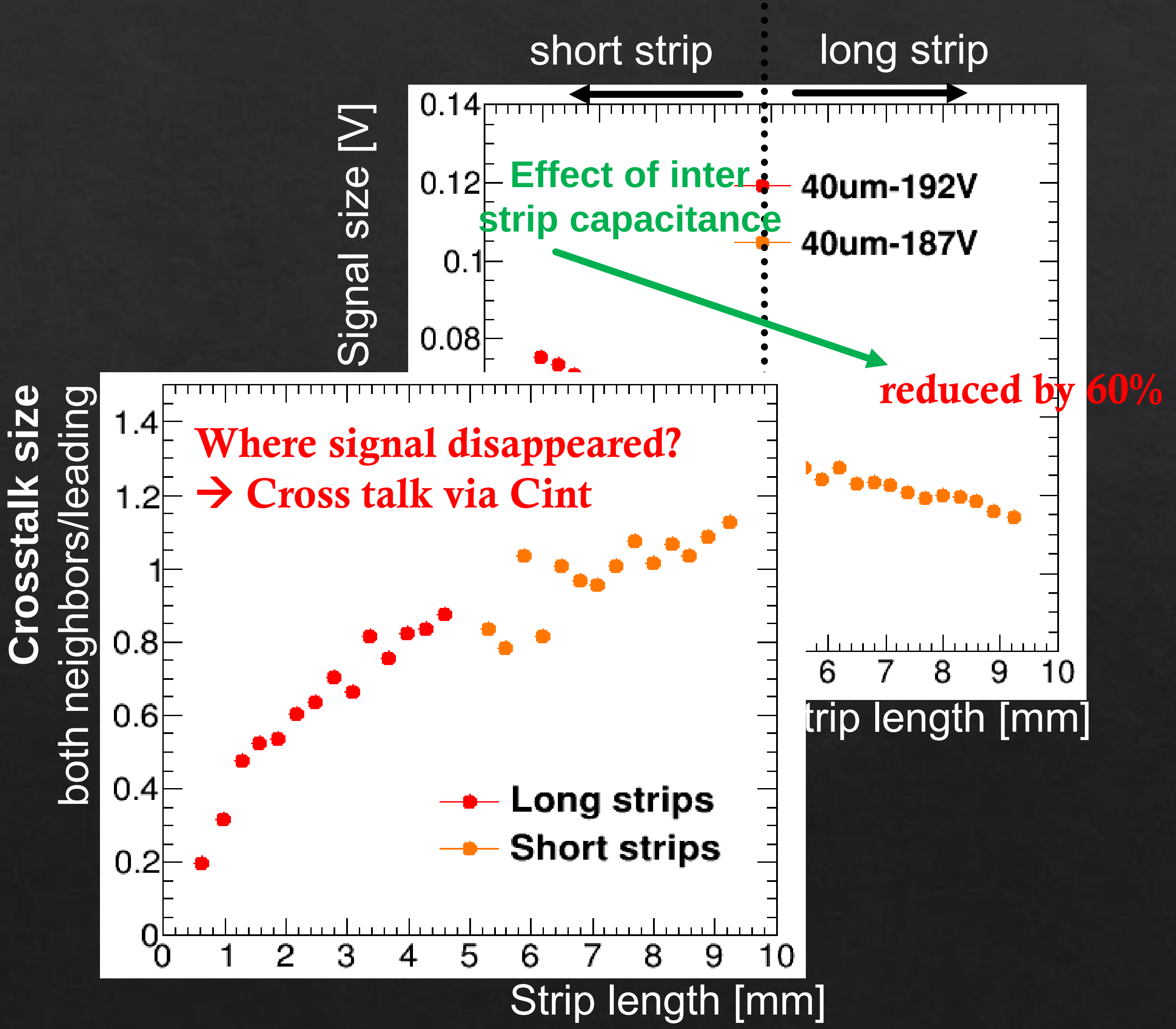


16 strips x 2



Removal of Dopant

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

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

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

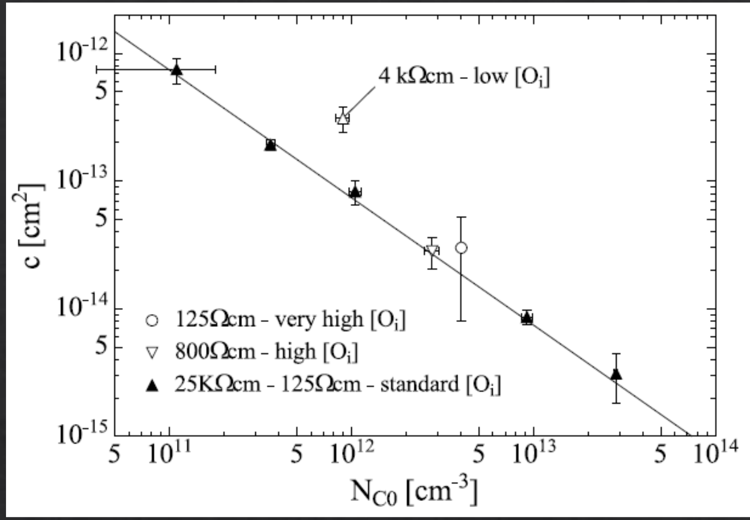
Any idea of CA and CD from past measurement?

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)

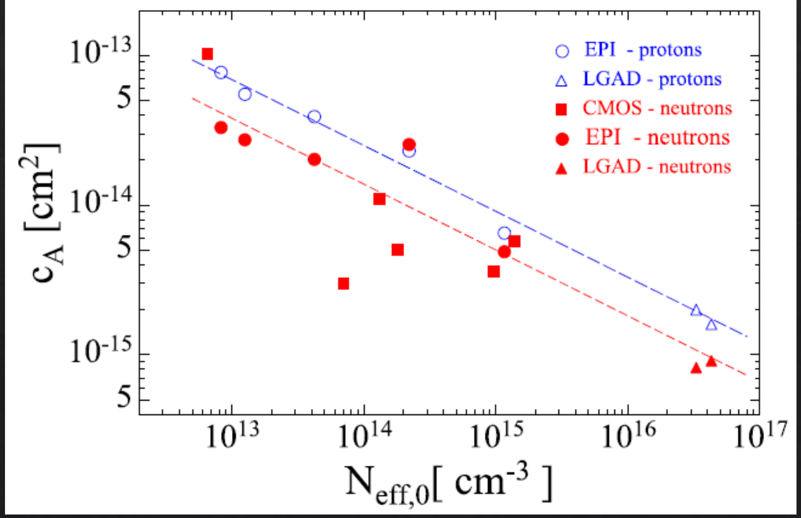
Compensated effective p+ gain layer will change by following formula

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

Donor removal



Acceptor removal



How to understand results?

If CA>CD ? If CA<CD ? If CA=CD ?

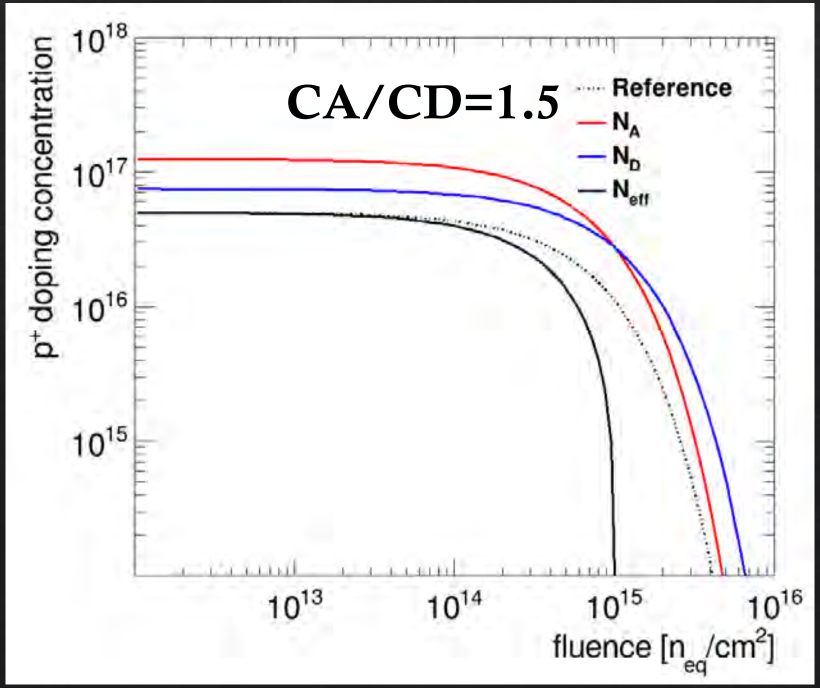
$$N_A(\emptyset) - N_D(\emptyset) = N_A(0) \cdot e^{-C_A \emptyset} - N_D(0) \cdot e^{-C_D \emptyset}$$

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

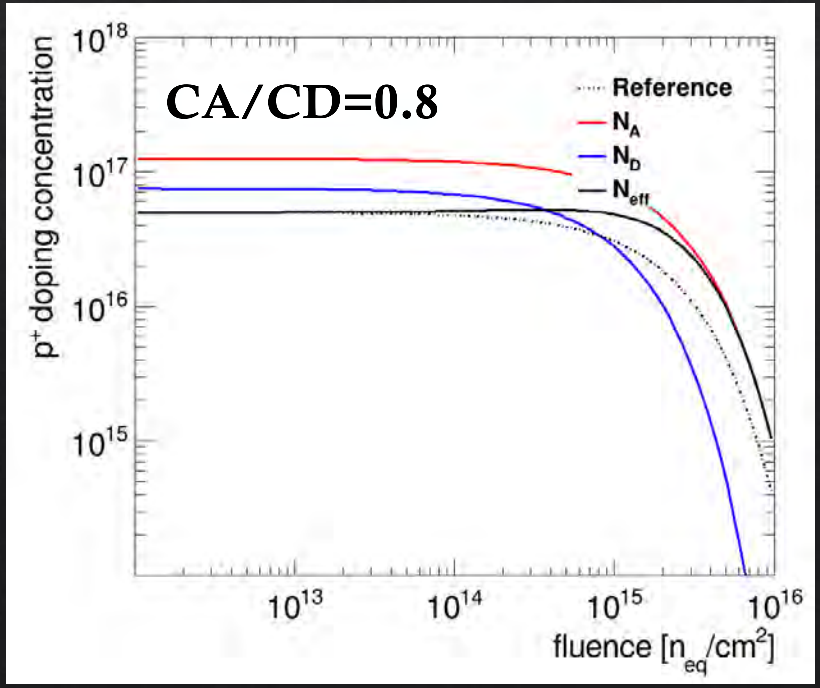
reference $N_A(\emptyset) = N_A(0) \cdot e^{-C_A \emptyset}$

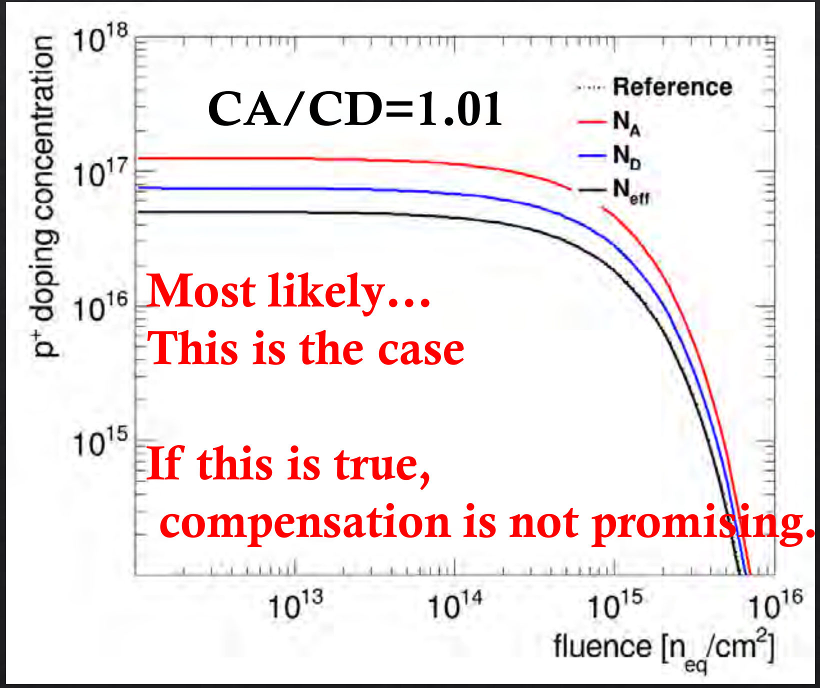
Reduction of effective p+ must be the same as non-compensated case

Shorter life time



Slightly longer life time
Not detreated performance until some point





Radiation tolerance results of Compensation LGAD

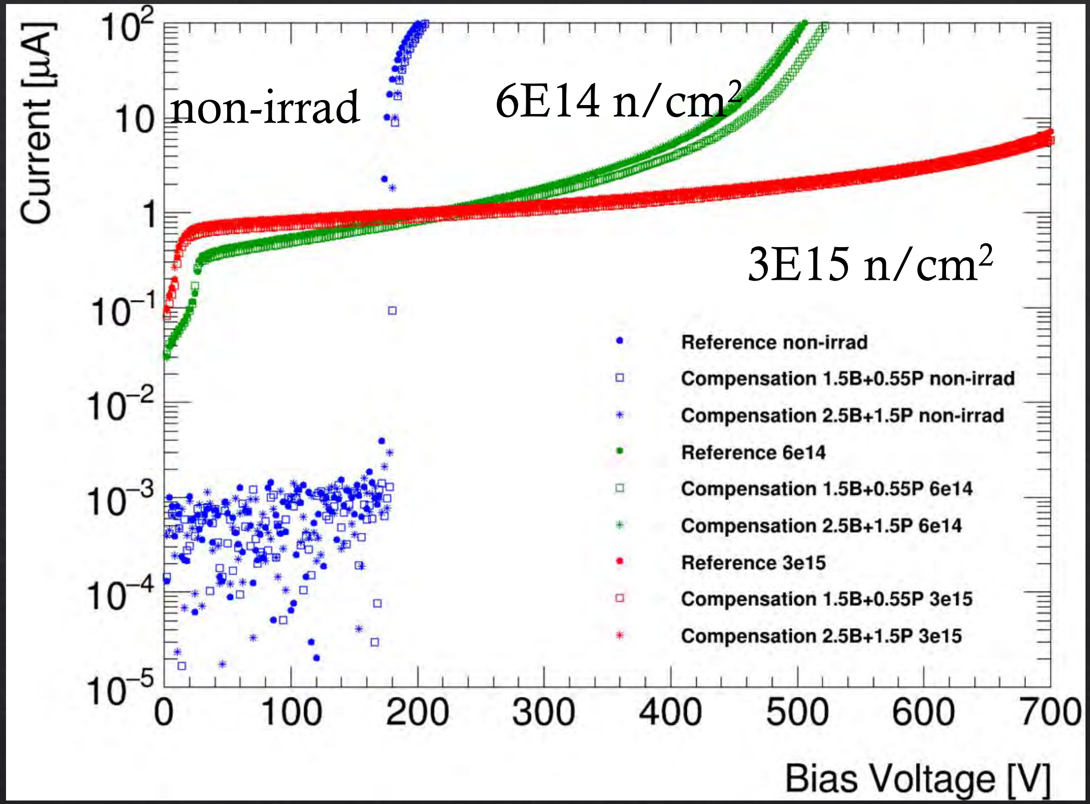
- Three different conditions are compared
  - Boron and Phosphorus doping
    - 2.5B+1.5P
    - 1.5B+0.55P
    - 1B (reference)
  - 3 different fluence points (non-irrad, 6e14, 3e15 neq/cm^2)
- Result shows not very promising
  - All three samples show very similar IV.
  - This probably means CA=CD

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

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

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

Idea for monolithic AC-LGAD detector