Development of HPK Capacitive-Coupled LGAD (AC-LGAD) detectors

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Detectors with high timing resolution

Future high energy physics experiments

- Higher Energy
- Higher luminosity

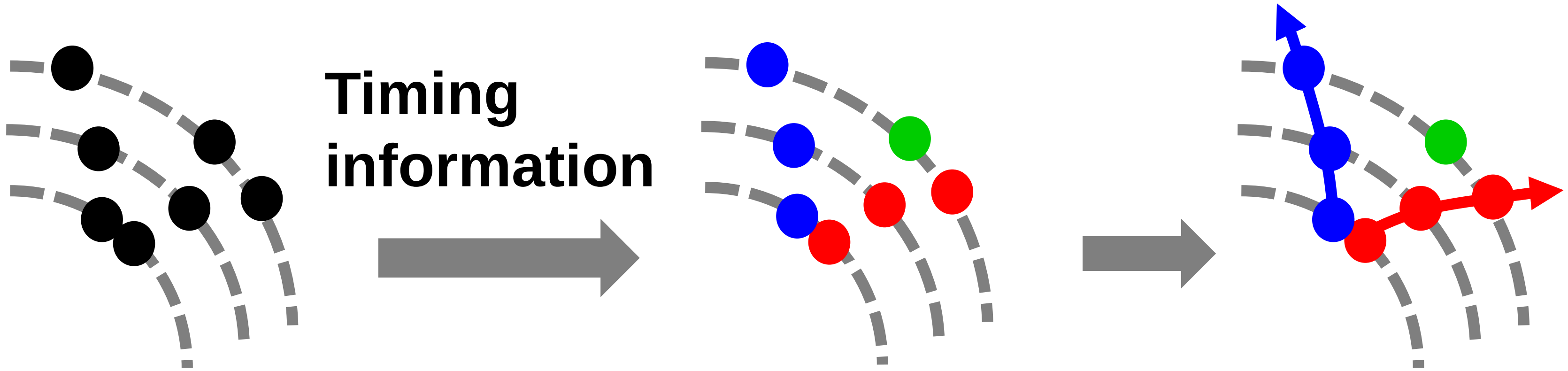
→ **Event pile-up will be an issue**

- 140pileup@HL-LHC
- 1500pileup@FCC-hh

↓ **Solution**

Detector with…

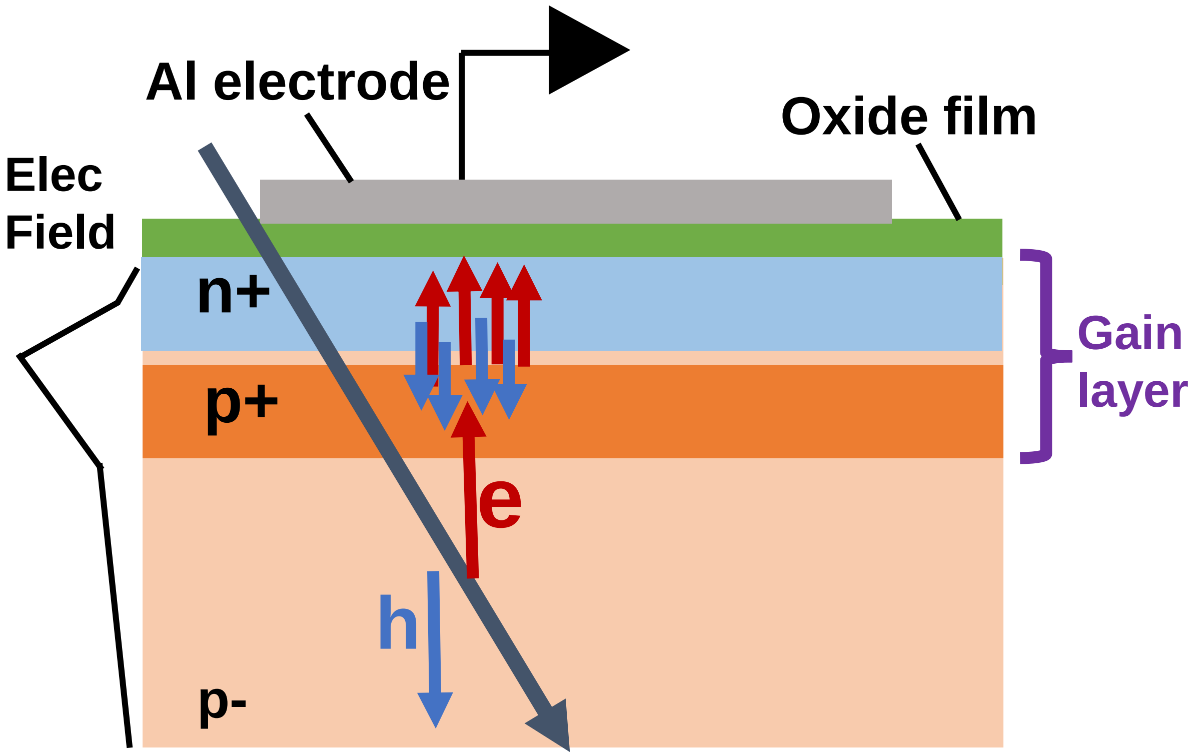
- Good spatial resolution
- Good timing resolution



More robust reconstruction!

LGAD technology

●Low-Gain-Avalanche-Diode



Operation principle of LGAD

p+ implantation below the n+ implantation to make gain layer

Local high electric field in p+ layer develops avalanche

Large amount of e/h pairs are created per initial electron

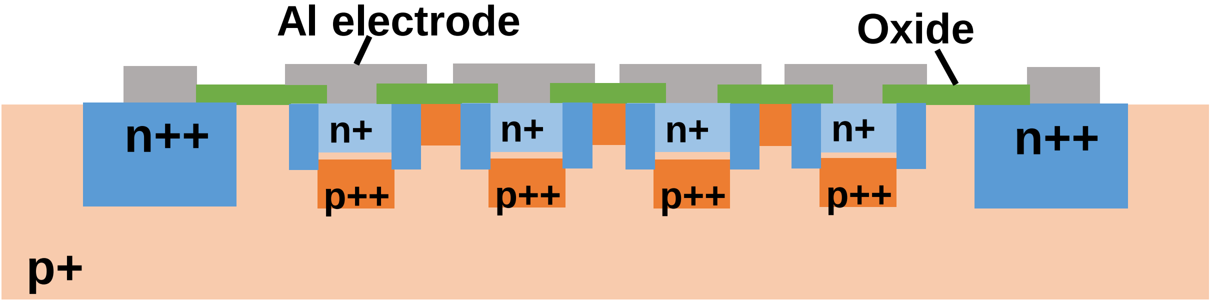
Creation of large signal in the vicinity

Good timing resolution

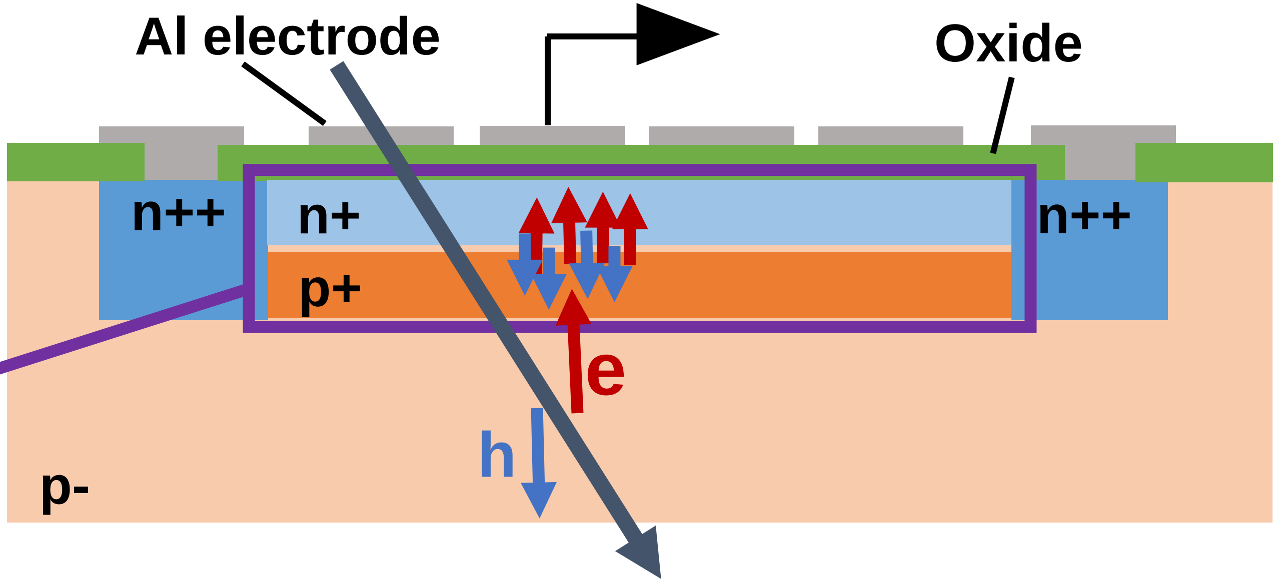
AC-LGAD detector

- **DC-LGAD**
  - Each electrode has individual gain layer
  - With Junction Termination Extension and p-stop

  ➡ **Low fill factor**



- **AC-LGAD**



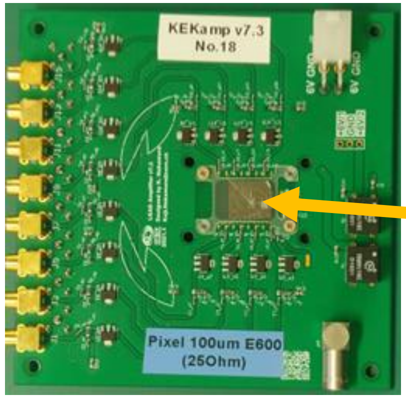
Uniform gain layer under segmented electrodes

AC-LGAD detector has been successfully developed down to 100um pitch pixel detector with 100% fill factor

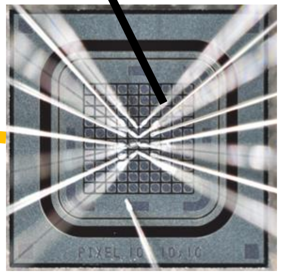
arxiv:2305.12355

Measurement setup

- **Sensors on amplifier board**
  - Wire-bonded sensor electrodes to amp inputs
  - Each amp channel employs two-stage fast charge sensitive amp IC
  - 16 channels available for one board



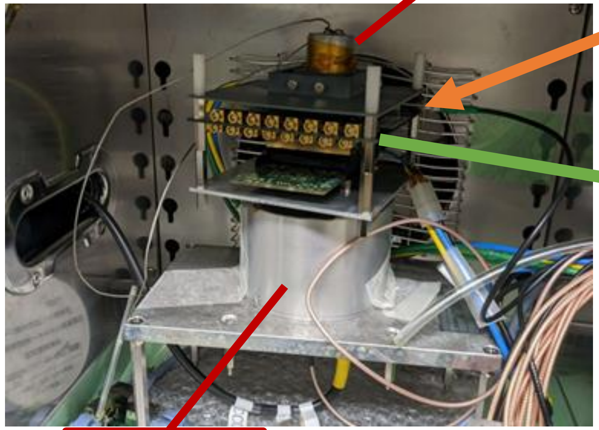
Wire bonding



LGAD Sensor

- **Beta-ray**

^{90}Sr



MCP-PMT 240
as timing reference

MCX cable

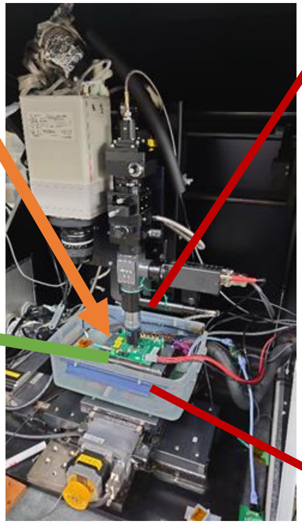
  - Electron from ^{90}Sr beta decay
  - In the bath to keep the temperature

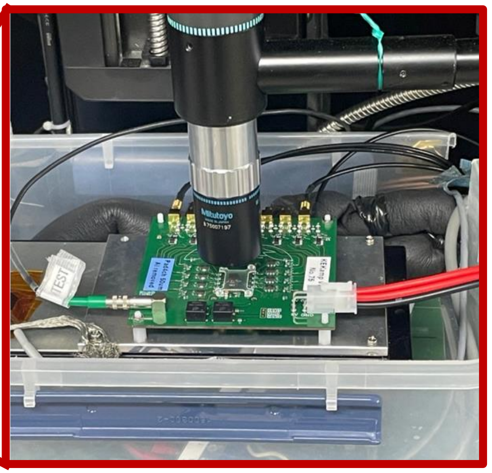
DAQ system

LeCroy Waverunner 8000
- 350MHz – 2GHz
- 10GS/s
- 8ch

- **IR laser**

MCX cable





  - Infra red laser (1065nm)
  - Laser size σ~1um
  - Inject through slit made in the sensor

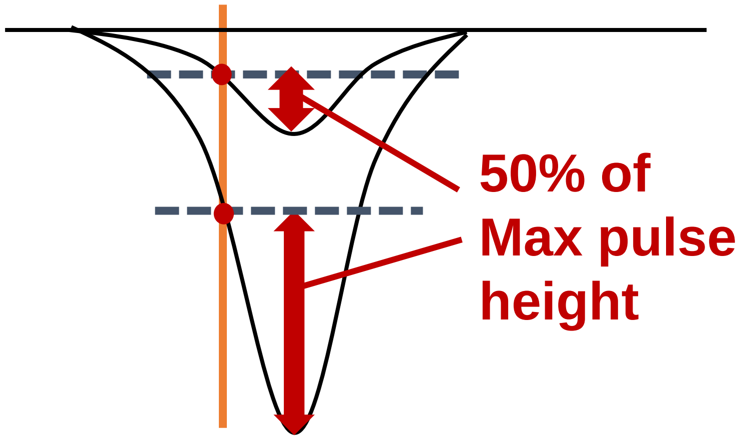
Timing resolution

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

Time walk

➡ Minimize contribution by adopting constant fraction

- Use a fraction of pulse height max instead of a fixed threshold



Jitter

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

σ_n : noise sigma , t_r : rise time
S : signal size

Big signal size is important to reduce jitter effect

+ the smaller noise as well

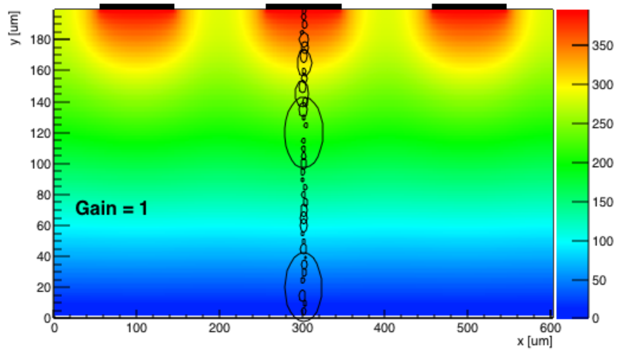
➡ Determine the best bias voltage

Landau noise

- Non uniform energy deposition of MIP

➡ **Thinner** sensors should reduce this effect

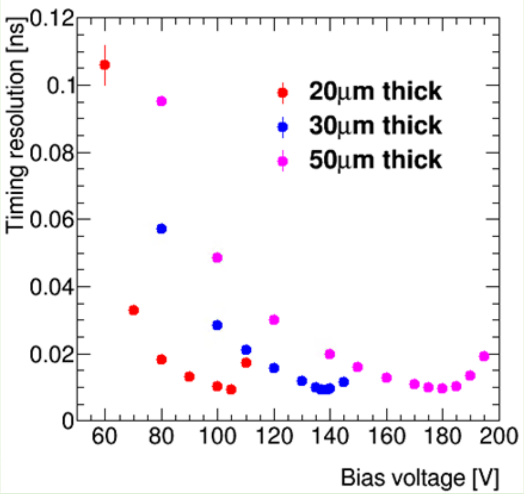
- Laser measurement results do not include this effect



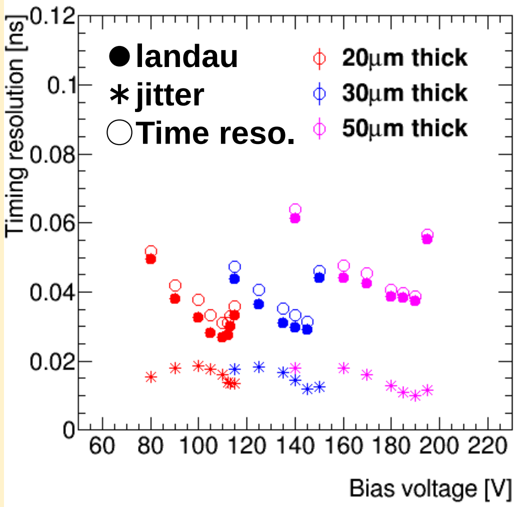
Timing resolution results

- **Laboratory measurement**

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



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

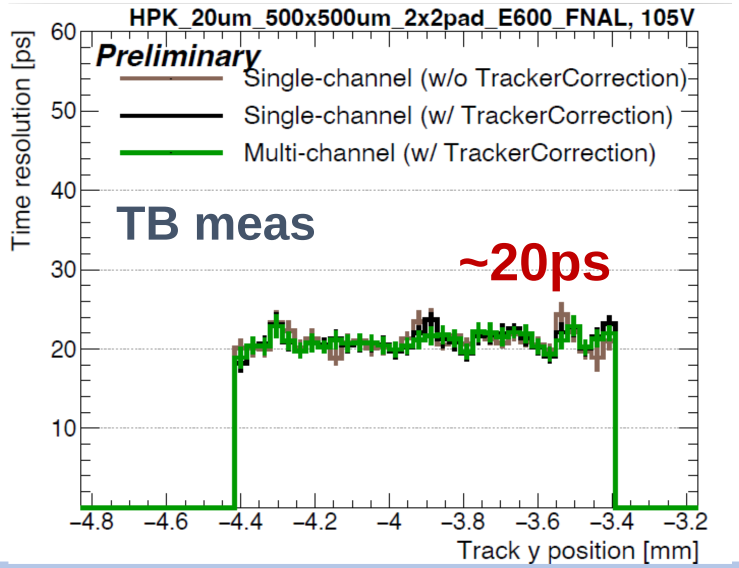


Lab meas	50um	30um	20um
Timing resolution	38.8ps	31.5ps	31.2ps
Jitter	9.8ps	11.8ps	15.9ps
Landau noise	37.5ps	29.2ps	26.8ps

Thinner samples have better timing resolution due to landau noise

- **Beam test measurement**
  - 2x2 pad with 500um square electrodes
  - Injected 120GeV Proton beam at FTBF

Uniform timing resolution over the detector has been observed



Radiation damage on LGAD

Future high energy physics experiments

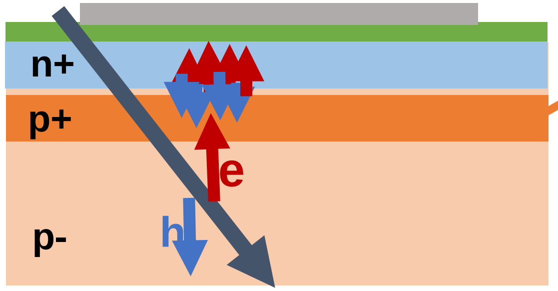
- Higher Energy
- Higher luminosity

➡ Detectors will be exposed to large amount of radiation

- e.g. Inner trackers in HL-LHC ATLAS at $4000 fb^{-1}$

$2\times10^{16}\ n_{eq}/cm^2$ 10MGy

<u>Acceptor removal</u>



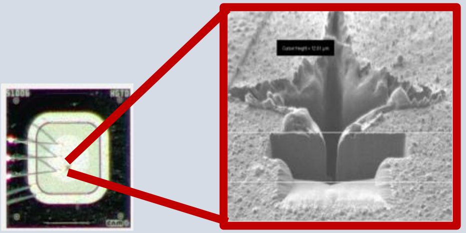
- One of the major effects of radiation damage of LGAD
- Acceptor doping concentration in gain layer is reduced by radiation damage

Shallow dope → Radiation damage → Defect complexities

➡ need to apply **higher bias voltage**

<u>Single Event Burnout</u>

- For bias voltage with average E-field of >12V/um, a large energy deposit happens to create a crater
- Our sensors are 50um ➡ upper limit is **600V**



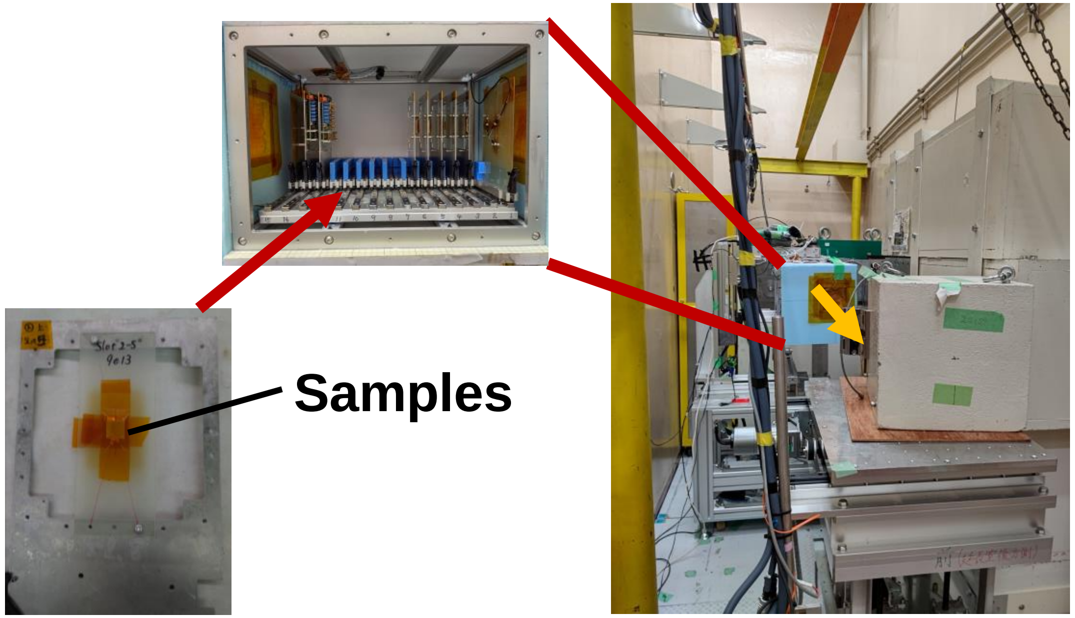
Ideas to improve radiation hardness

- **Need to reduce the bias voltage after the irradiation**
  ➡ **need to reduce the effect of acceptor removal**

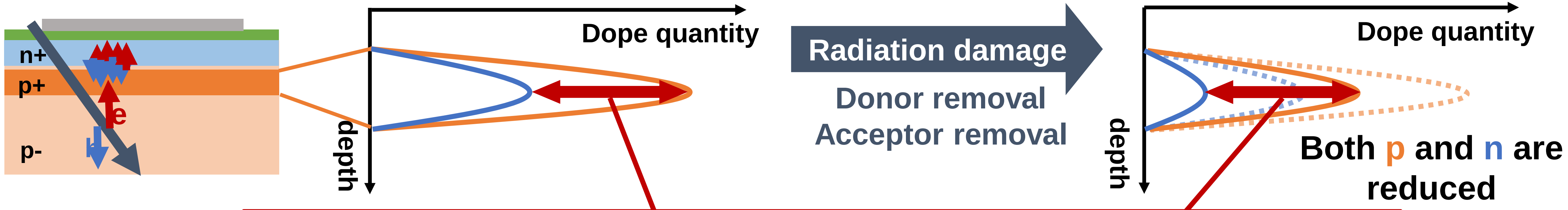
⬇

Compensation	Partially-Activated-Boron

- **Made samples ➡ Irradiation test ➡ IV & Signal measurement**
- **Irradiation test**
  - CYRIC at Tohoku University
  - 70MeV proton beam at 7nA~1600nA
  - Temperature was set to -15℃
  - Uniform scanning over the sensors
  - 7×10^{15}, 3×10^{15}, 6×10^{14}, 8×10^{13} n_{eq}/cm^2

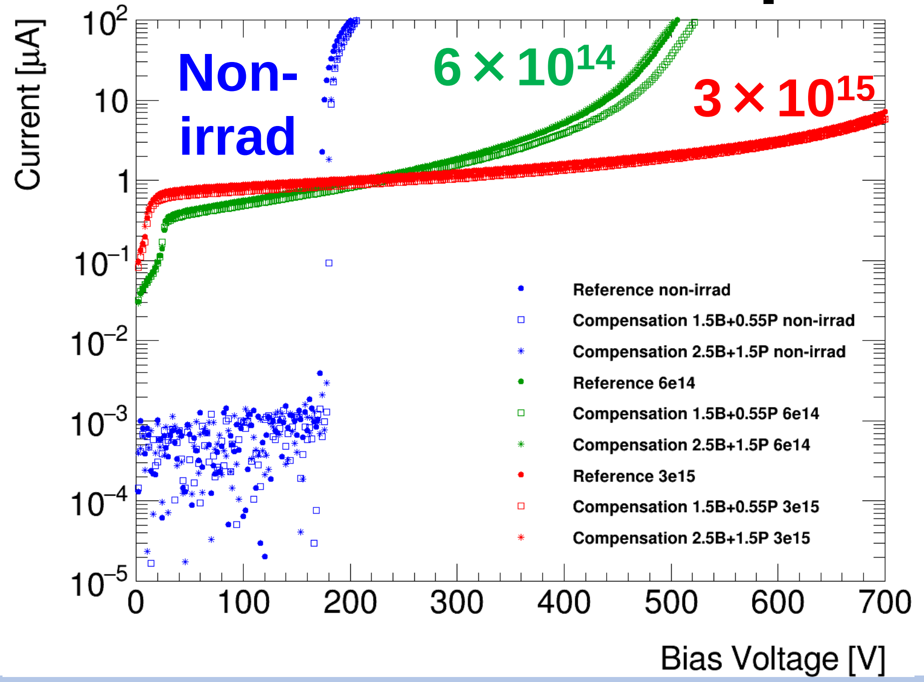


Compensation(I)



Amount of effective p+ may not reduce if donor removal is fast enough

● Result of first samples



– Tested samples

	p+ Boron	n+ Phosphorous	effective p+
2.5B+1.5P	2.5a	1.5a	a
1.5B+0.55P	1.5a	0.55a	0.95a
Reference	a	0	a

– IV curves are overlapped with reference sample

No significant improvement has been observed

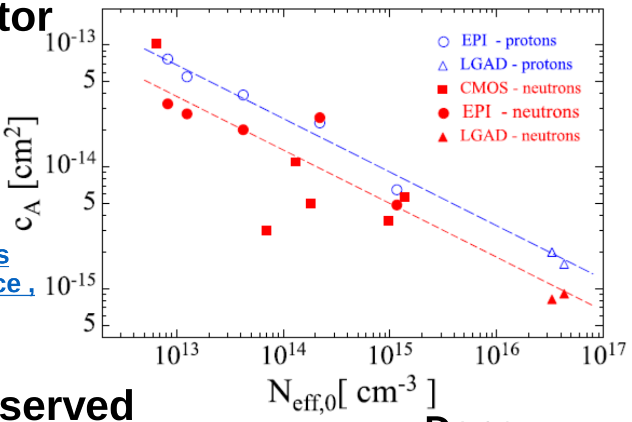
Compensation(II)

- **Higher dope concentration will help suppressing acceptor removal effect**
  - Reduce the **reduction factor** of acceptor $N_A(\emptyset) = N_A(0) \cdot e^{-C_A \emptyset}$
- **Result of higher dope concentration samples**

	p+ Boron	n+ Phosphorous	effective p+
10B+9.2P	10a	9.2a	0.8a
5B+4.05P	5a	4.05a	0.95a
Reference	a	0	a

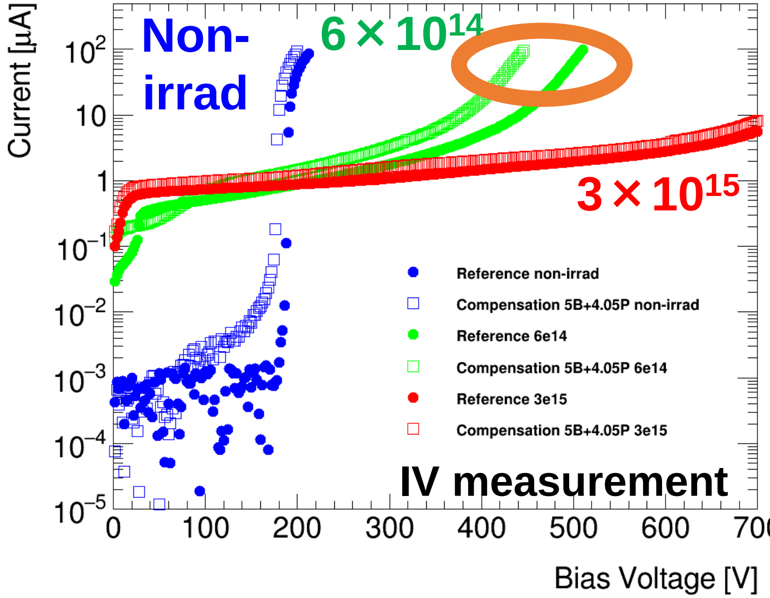
➡No signal have been observed

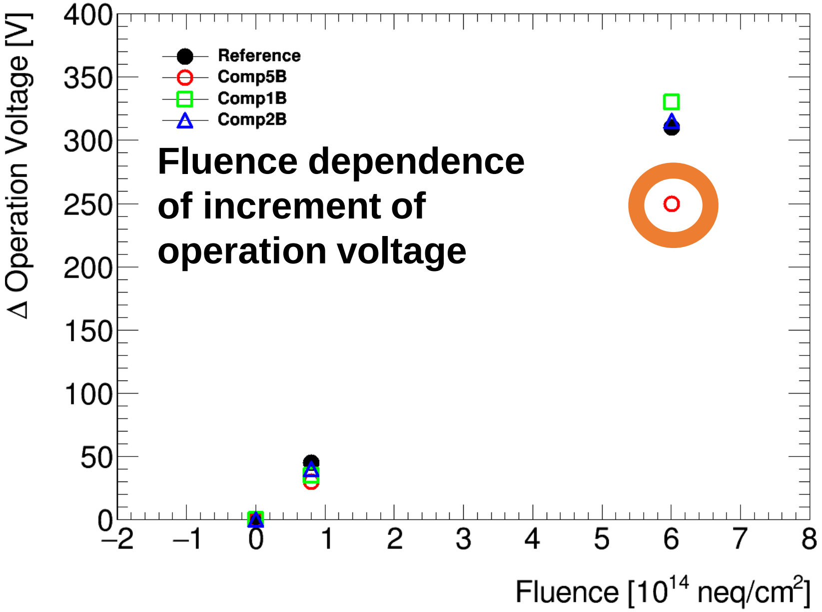
Reduction factor of acceptor



Dope concentration

IEEE Transactions on Nuclear Science , 65, Issue: 8, 2018





- Signal measured using ^{90}Sr β
- Operation voltage is defined as the voltage with the largest S/N

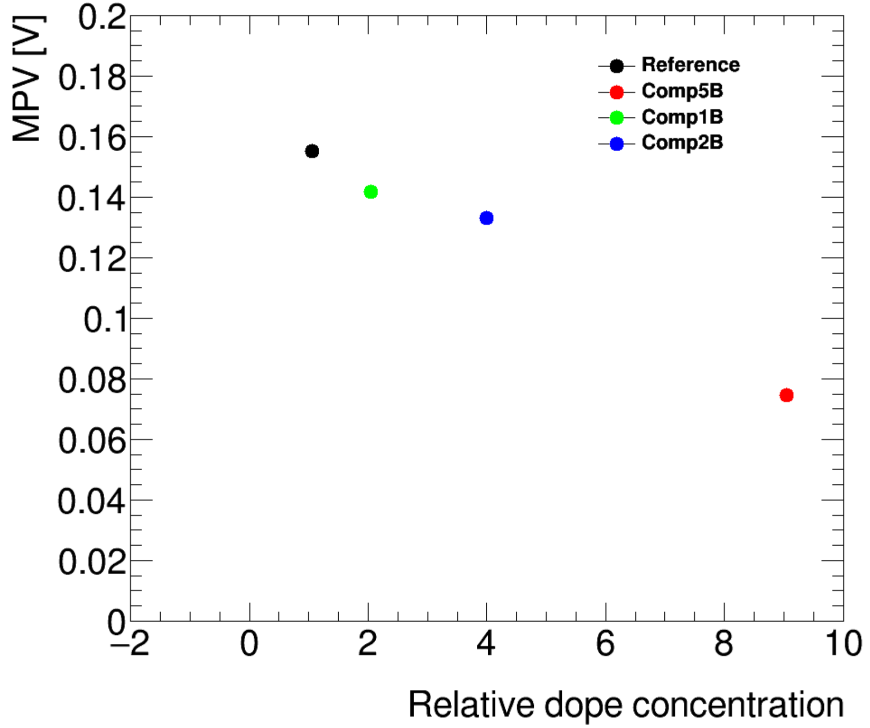
Compensation with high dope concentration reduces acceptor removal effect

Compensation – MPV of non-irradiated samples

- **Higher dope concentration seems reduce acceptor removal more**

  ⬌ **No signal has been observed with 10B+9.2P sample…**

- **Signal MPV dependence on dope concentration**



Relative dope concentration is the dope concentration normalized by reference one

– **Only for non-irradiated samples**

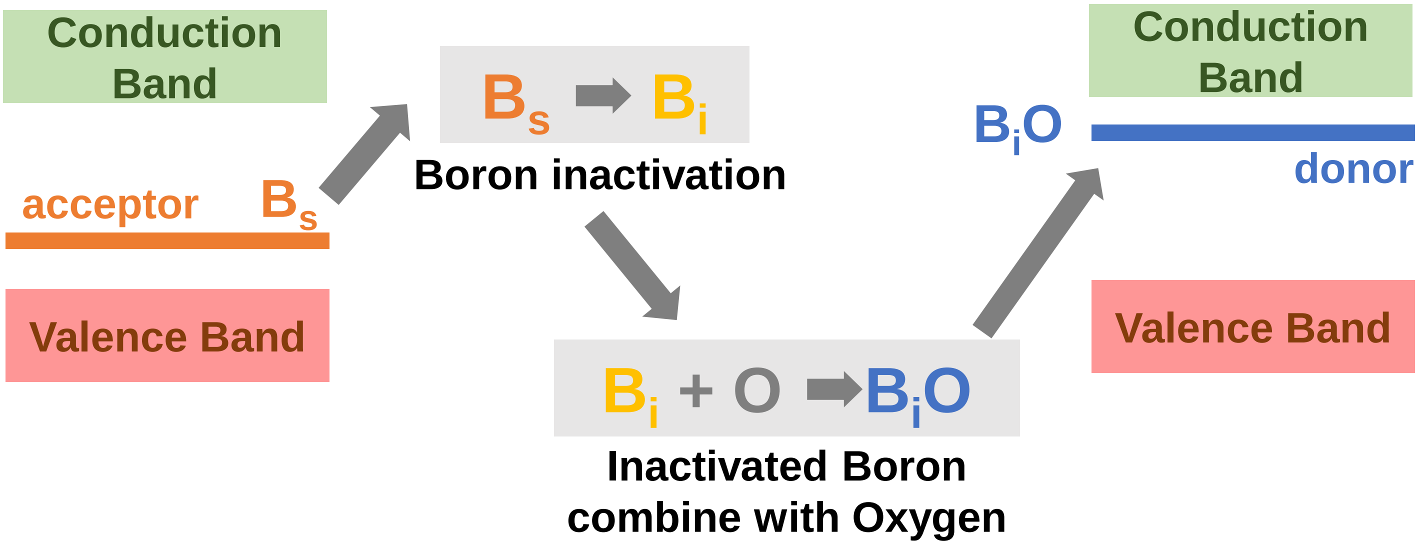
Signal size is reduced by total dope concentration of gain layer implantation

➡ **Difficult to improve by simply increasing dope concentration**

- **Compensation method will be developed with carbon dope as the next step…**

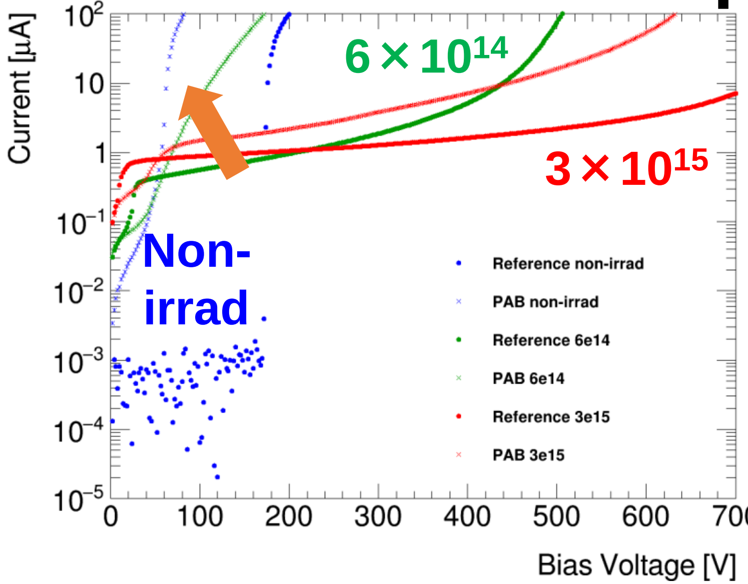
Partially-Activated-Boron(I)

B_s substitutional Boron
B_i interstitial Boron



- Clean up the oxygen before irradiation to prevent B_i from becoming B_iO - new donor
- B_i deliberately left in p+ layer takes oxygen with it

- Result of first samples



- Break down voltage was ~50V
  ➡ Not enough to observe signal
- Break down voltage of irradiated samples seem less than reference sample …?

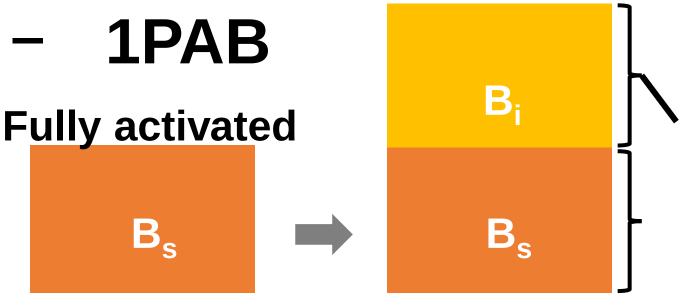
➡ Break down voltage tuned samples have been tested as second samples

Partially-Activated-Boron(II)

B_S substitutional Boron
B_i interstitial Boron

- **Second samples … Inject additional boron over fully activated boron**
  - **1PAB**

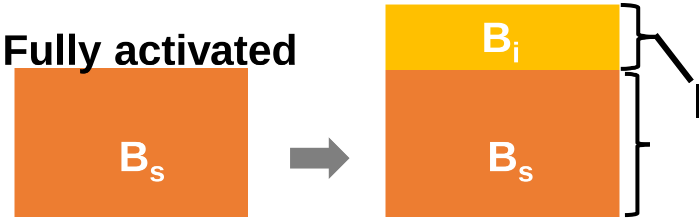
Fully activated



Injected B_i the same amount as activated B_s

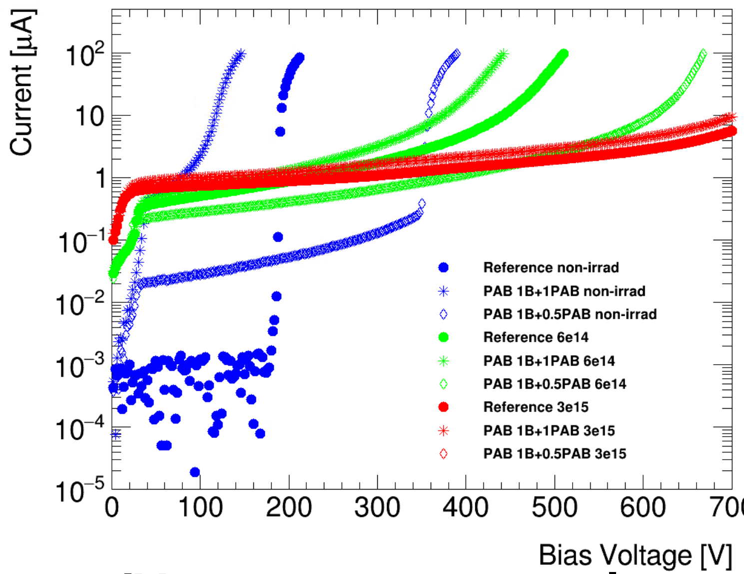
  - **0.5PAB**

Fully activated

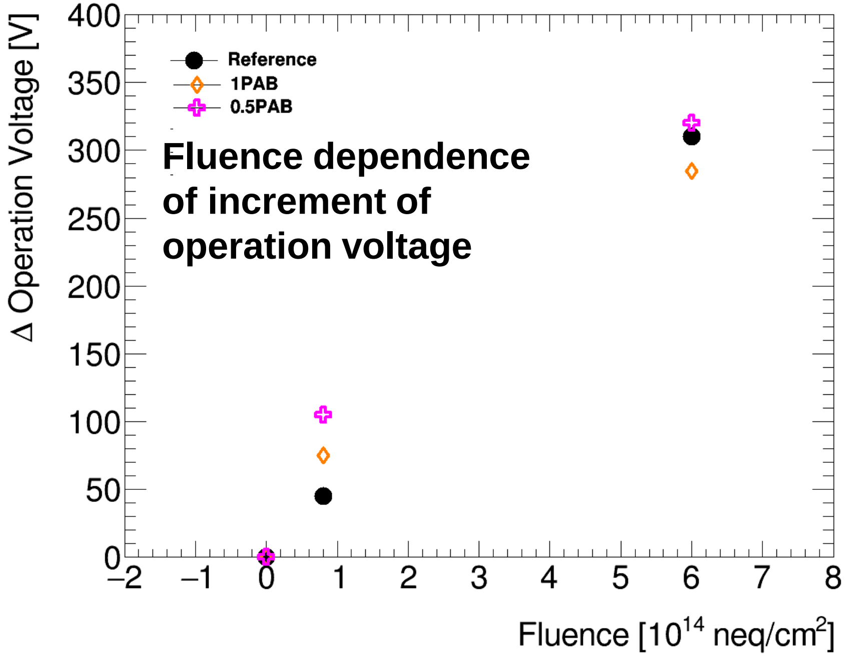


Injected B_i the half amount as activated B_s

- **Result of break down voltage tuned samples**



IV measurement results



- Signal measured using ^{90}Sr β
- Operation voltage is defined as the voltage with the largest S/N

No significant improvement has been observed

Conclusion

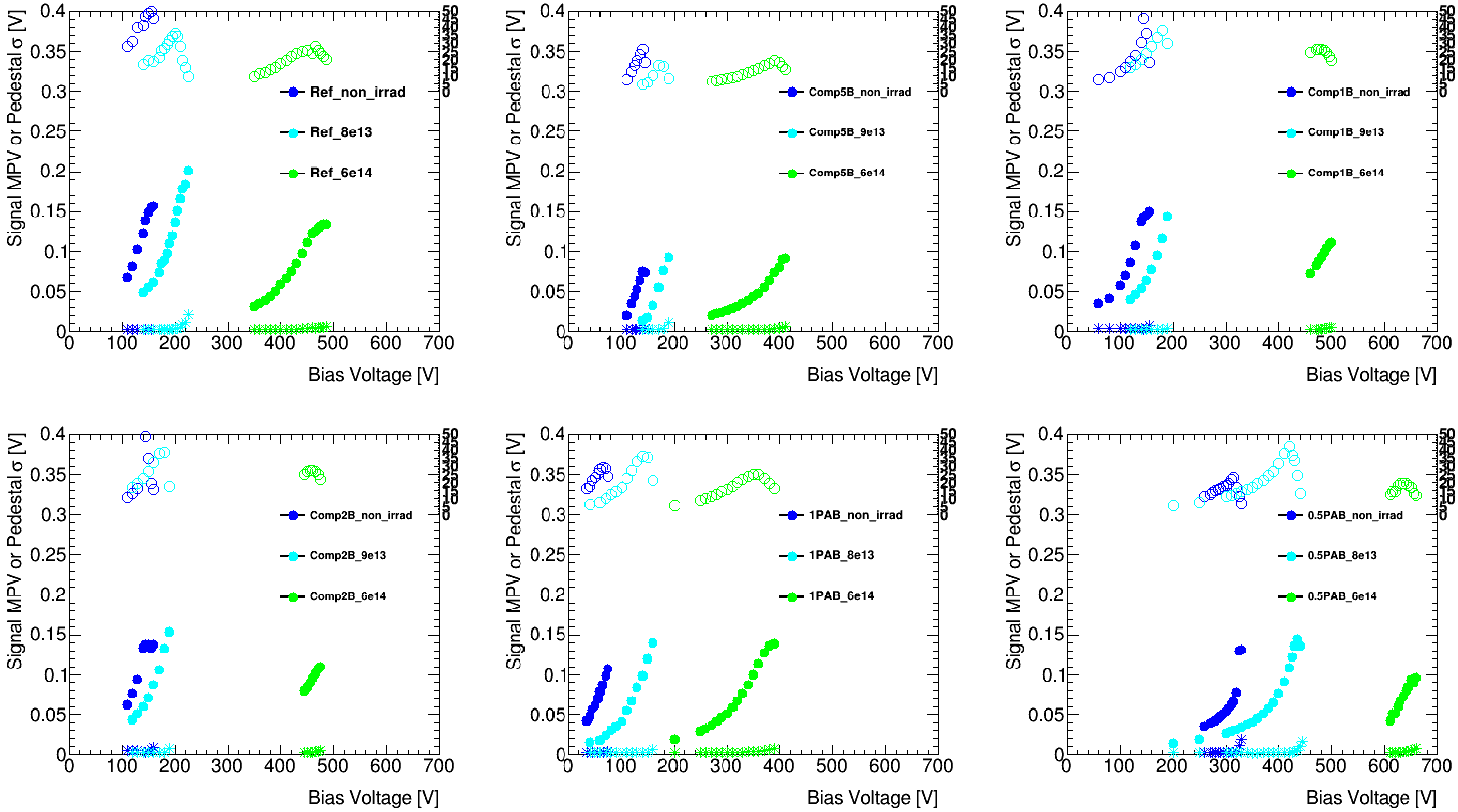
- **Detector with high timing resolution is needed**
  - LGAD detector is being investigated as a detector with superior timing resolution
- **AC-LGAD detector is successfully developed**
  - Finely segmented pixel sensor solving fill factor problem
  - ~30ps timing resolution with laboratory measurement setup
  - ~20ps timing resolution with 120GeV proton beam
  - Uniformed timing resolution
- **Two novel ideas to improve radiation hardness have been tested**
  - Compensation method

    higher dope concentration seems effective in reducing acceptor removal effect, but shows smaller pulse
  - Partially-Activated-Boron method

    No significant improvement has been observed so far

Back up

Bias voltage dependence of signal and noise



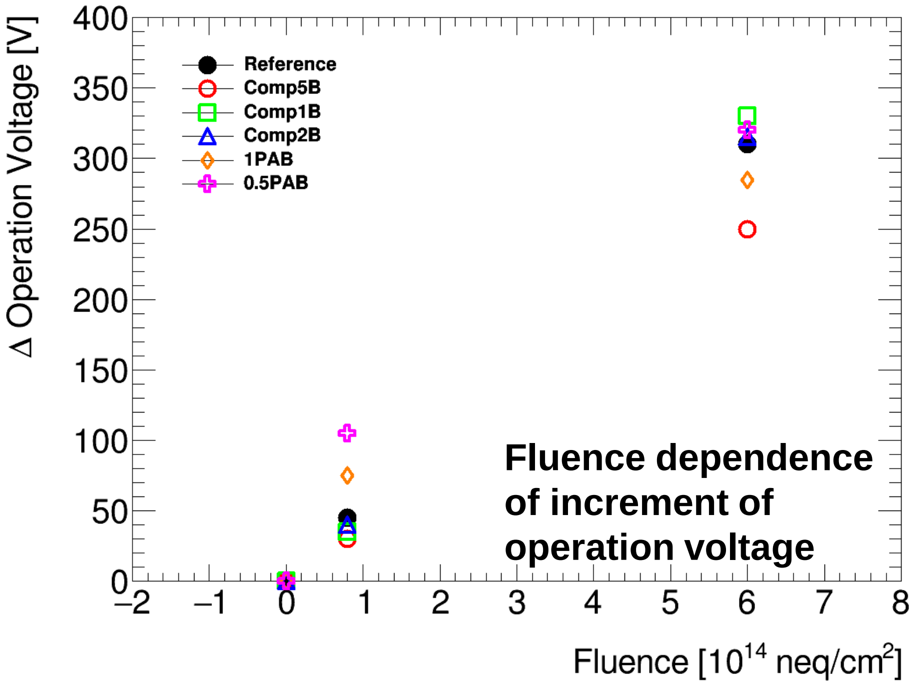
Tested samples and results

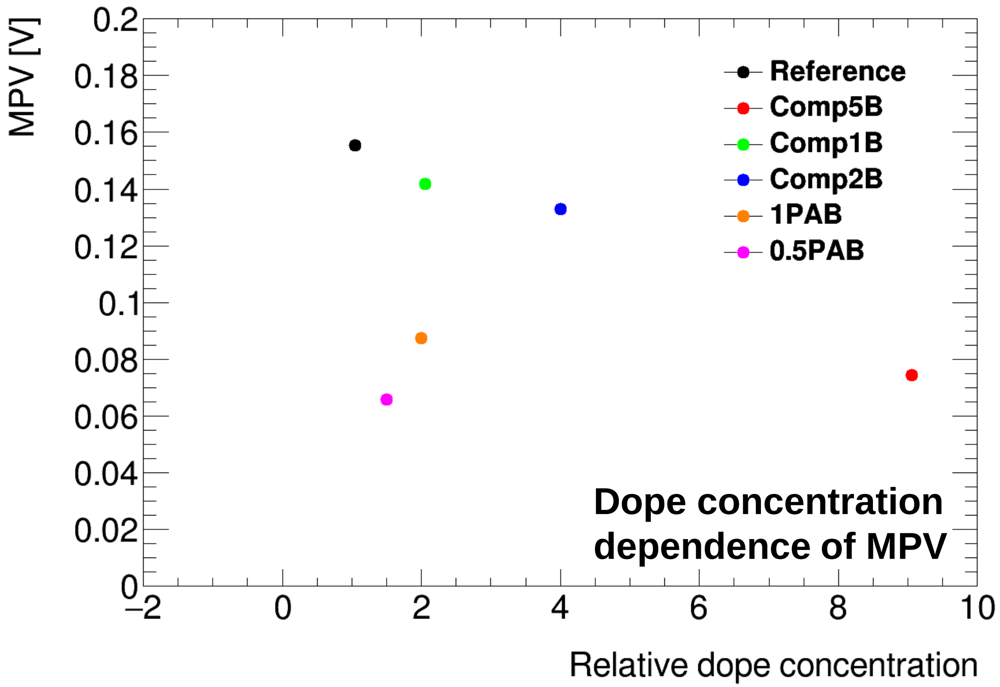
Compensation

	p+ Boron	n+ Phosphorous	effective p+
10B+9.2P	10a	9.2a	0.8a
5B+4.05P	5a	4.05a	0.95a
2.5B+1.5P	2.5a	1.5a	a
1.5B+0.55P	1.5a	0.55a	0.95a
Reference	a	0	a

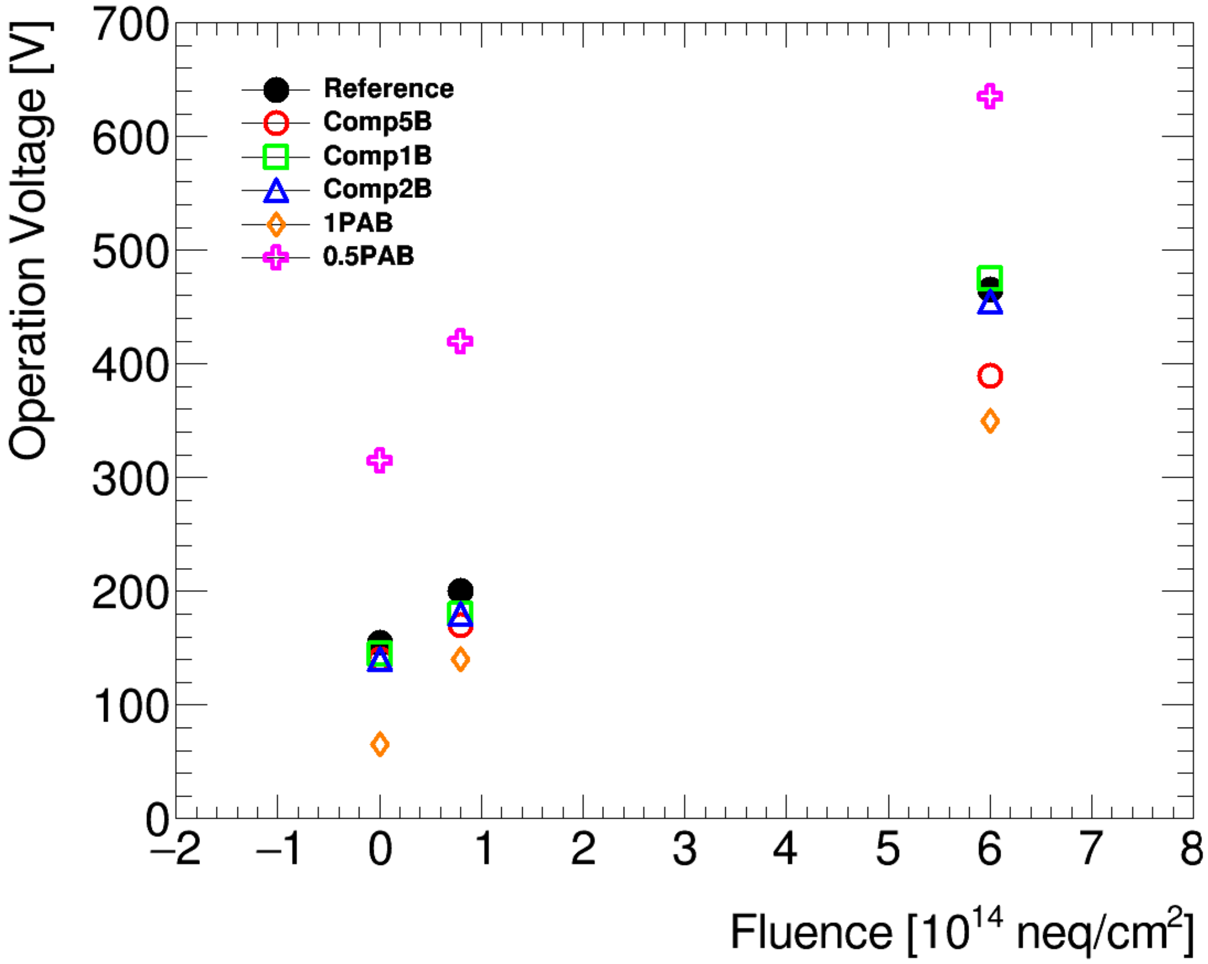
Partially-Activated-Boron

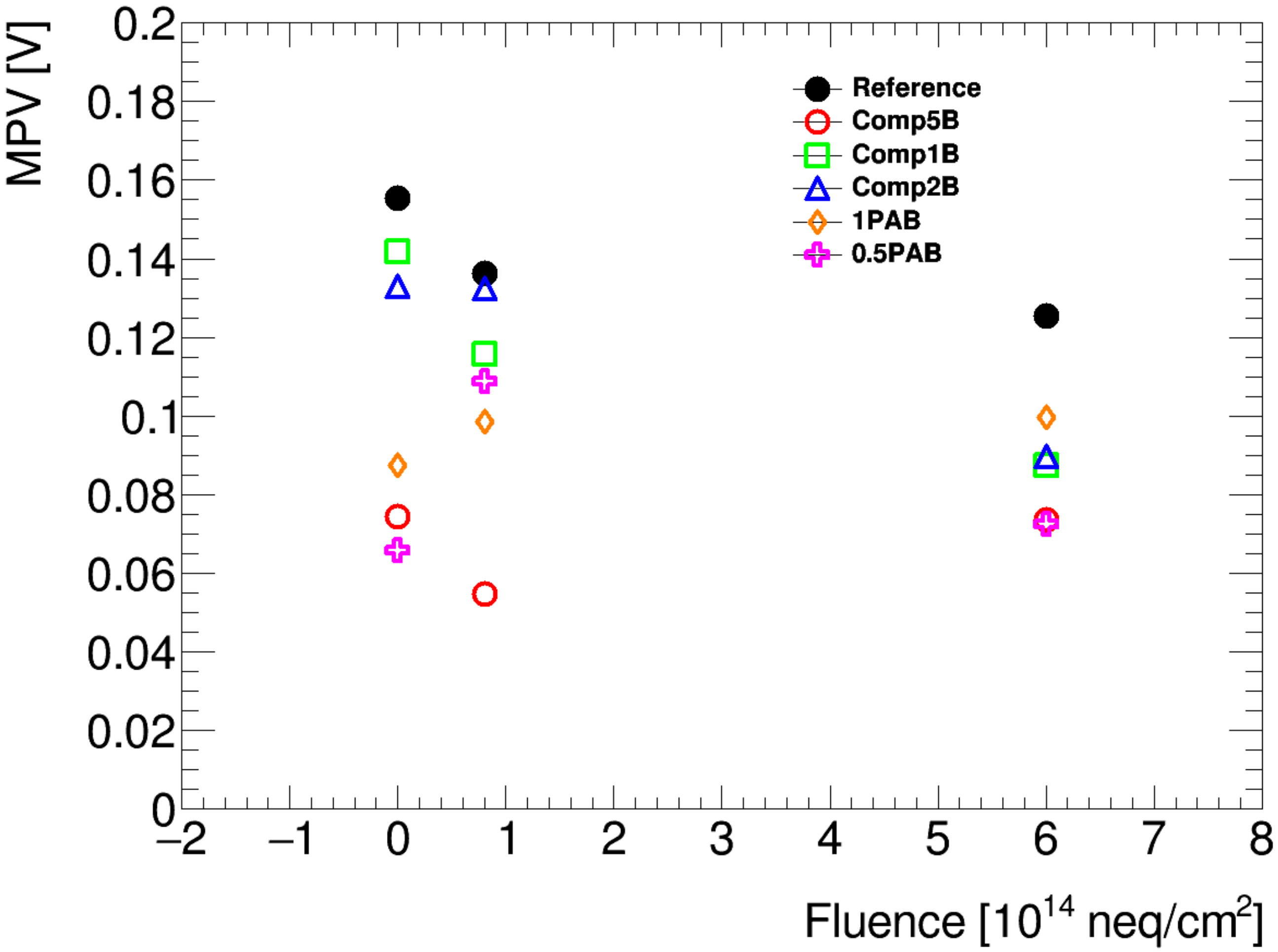
- **1PAB**
  - Once the activation is complete, inject an equal amount of Boron and left inactivated
- **0.5PAB**
  - Once the activation is complete, inject a half amount of Boron and left inactivated





Degradation due to radiation damage



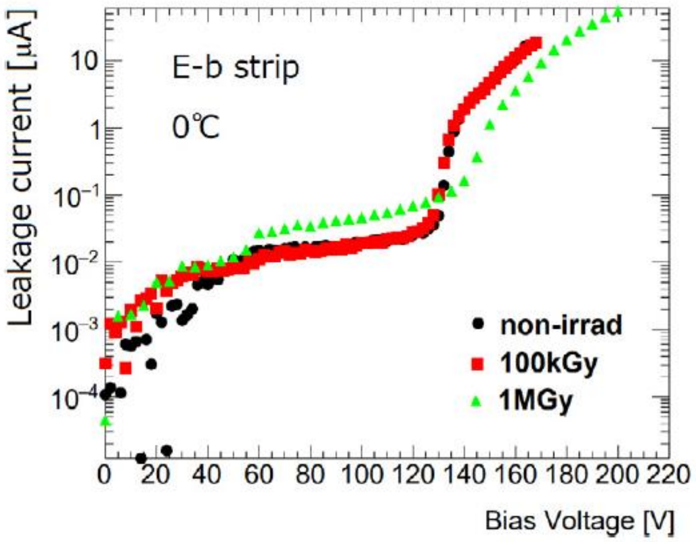


Increase in operation voltage – non-linear function of fluence

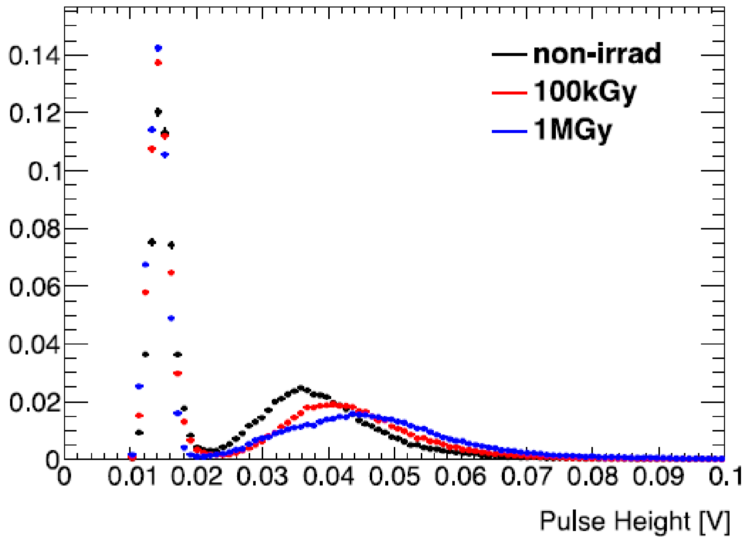
Reduction of signal size

TID damage

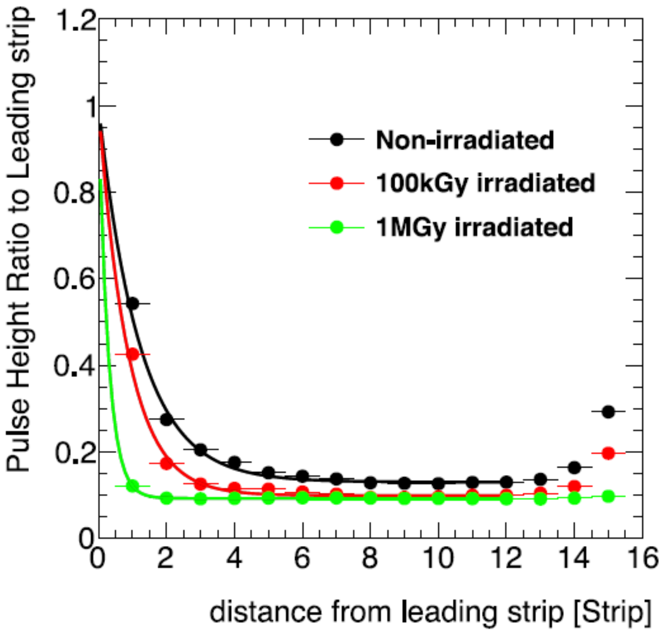
- **Already studied**
  - **Gamma ray irradiation with ^{60}Co**



IV measurement



Pulse height distribution



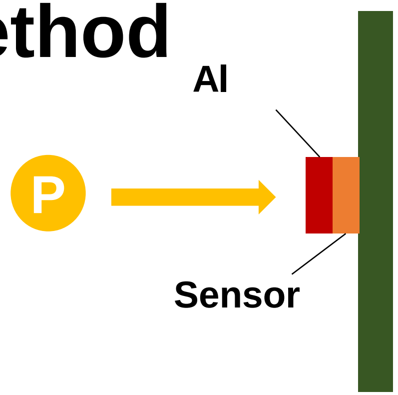
Cross talk

The effect of TID damage is small*

***Compare with proton irradiation**

Dosimetry

●Method



Proton irradiation to Al

↓

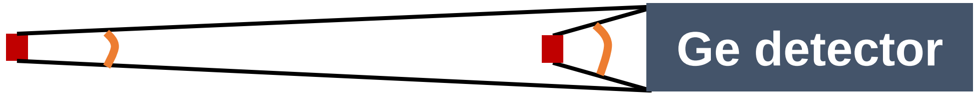
^{24}Na are produced

↓ Decay with half-lifetime 15hrs

1.37MeV&2.75MeV γ-ray

●Calibration

- ◆ Efficiency due to solid angle
  - Depending on the distance
    - ① 10mm
    - ② 30mm
    - ③ 60mm



- ◆ Energy efficiency
  - γ→ photoelectric absorption + Compton scattering

*with ^{60}Co, ^{137}Cs
→extrapolation

C_A and C_D relations

- **Assuming an exponential reduction in irradiation dose[2]**

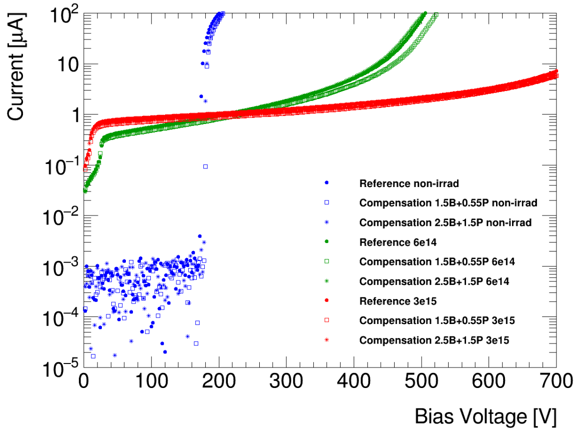
p+ $N_A(\emptyset) = N_A(0) \cdot e^{-C_A \emptyset}$

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

- C_A reduction factor of acceptor
- C_D reduction factor of donor
- $\emptyset$ irradiation dose

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

- **Using the relation from the IV measurement results**
  - Overlap among all three conditions



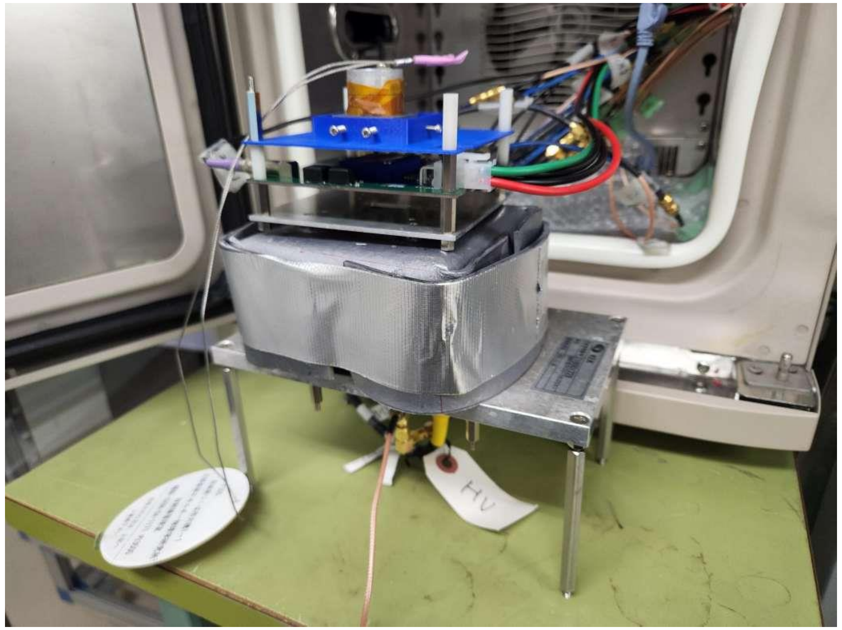
Reference: **p+** = Compensation: **effective p+**

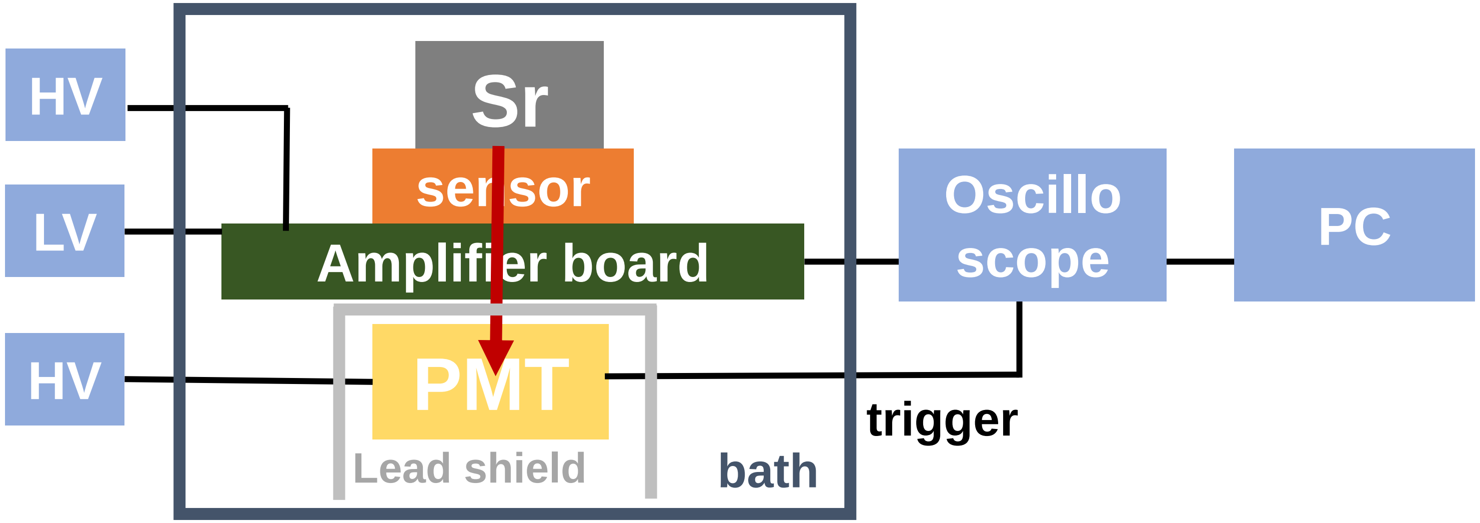
$$N_A(0) \cdot e^{-C_A \emptyset} = N_A(0) \cdot e^{-C_A \emptyset} - N_D(0) \cdot e^{-C_D \emptyset}$$

$$C_A = C_D$$

Signal measurement setup

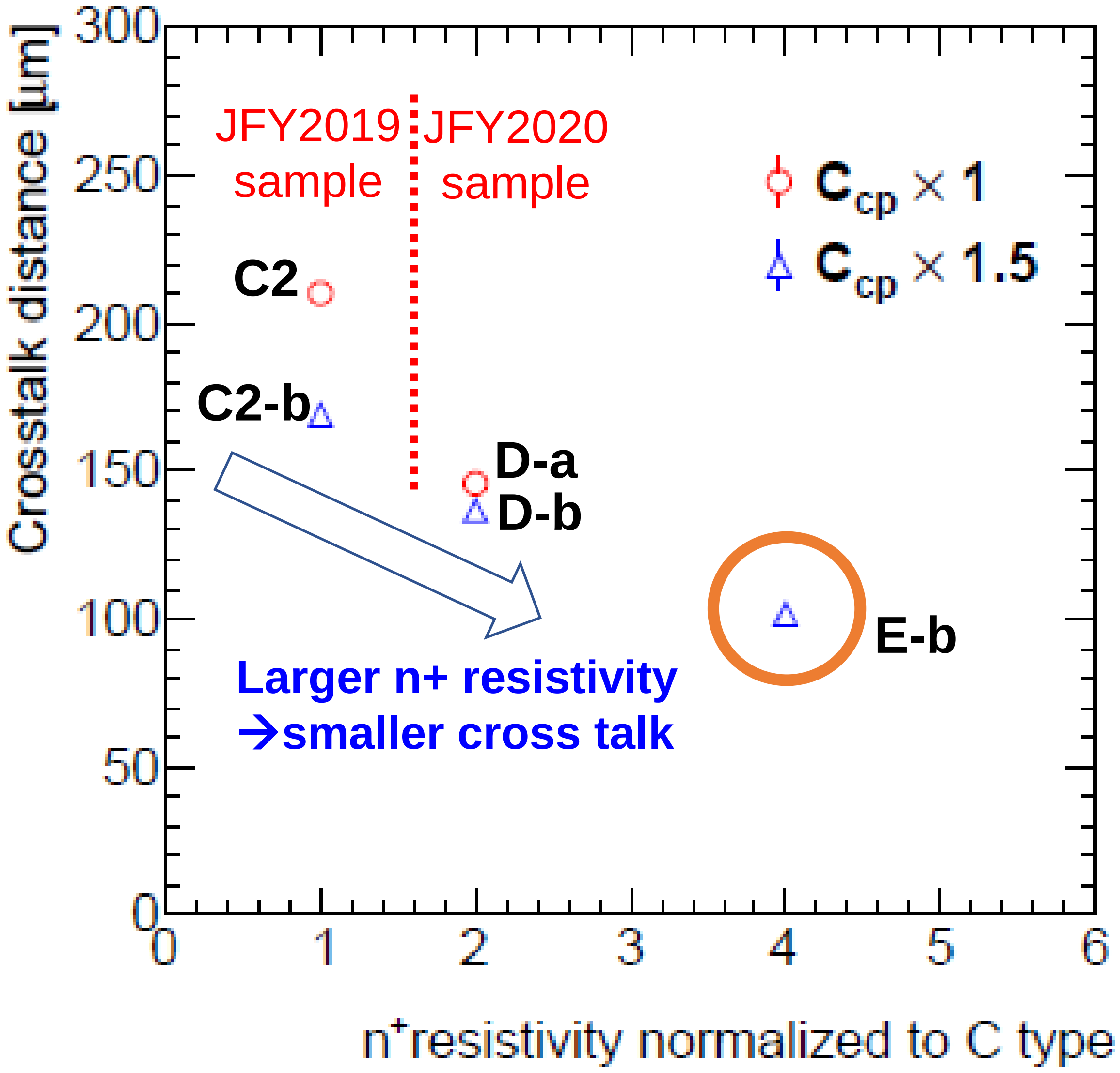
●Signal measurement with Sr90





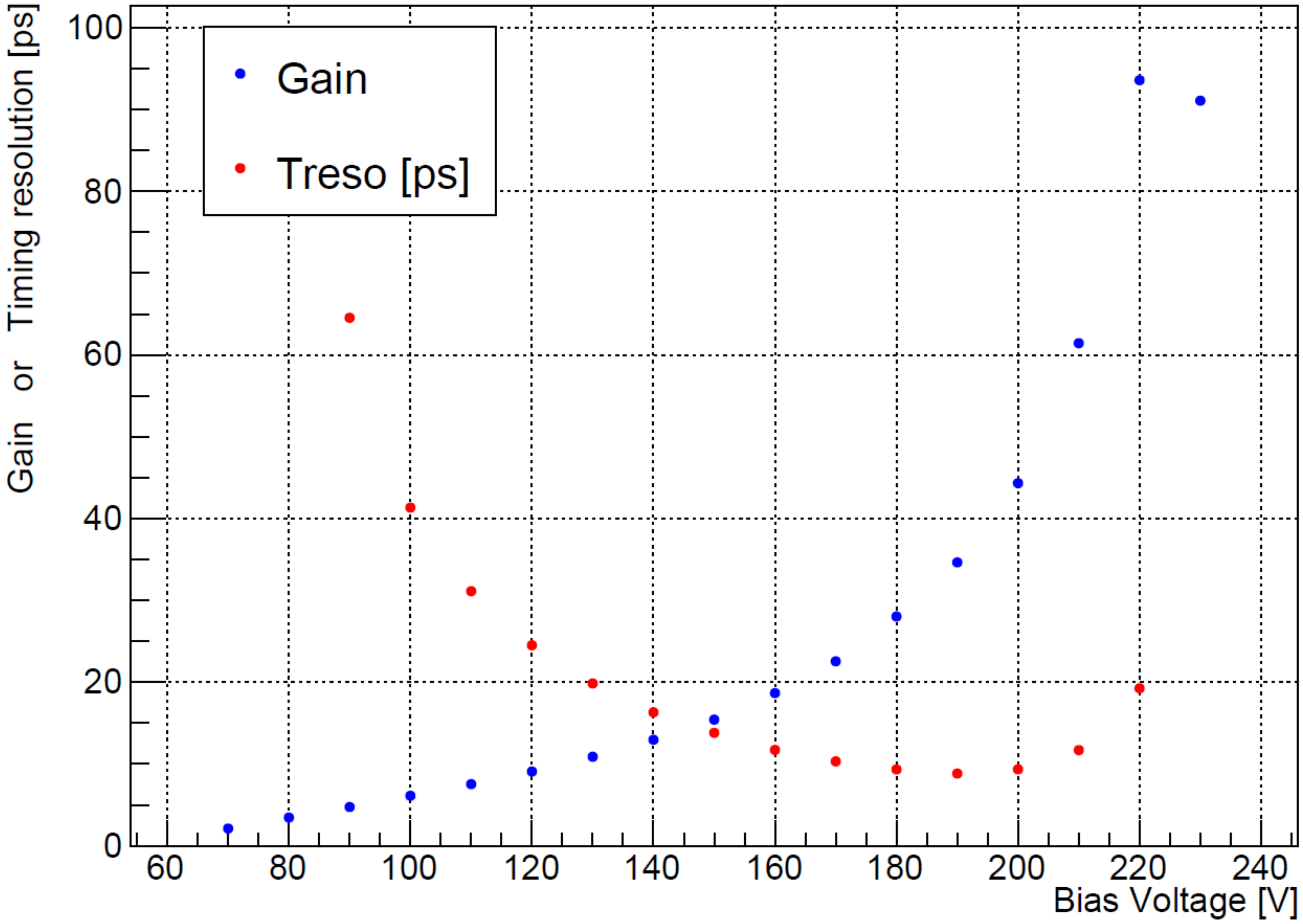
- Non-irradiated samples : 20℃
- Irradiated samples : -20℃

Cross talk of AC-LGAD

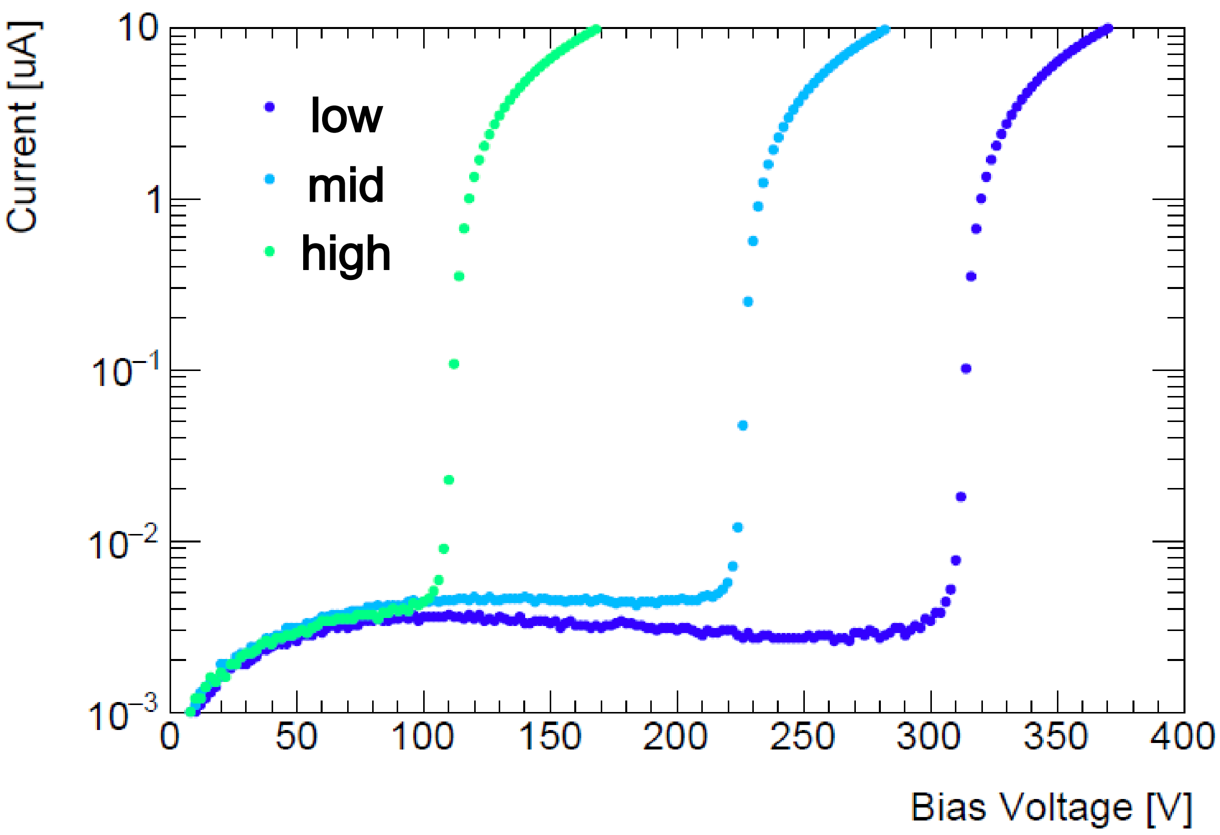


NIMA 1048(2023) 168009

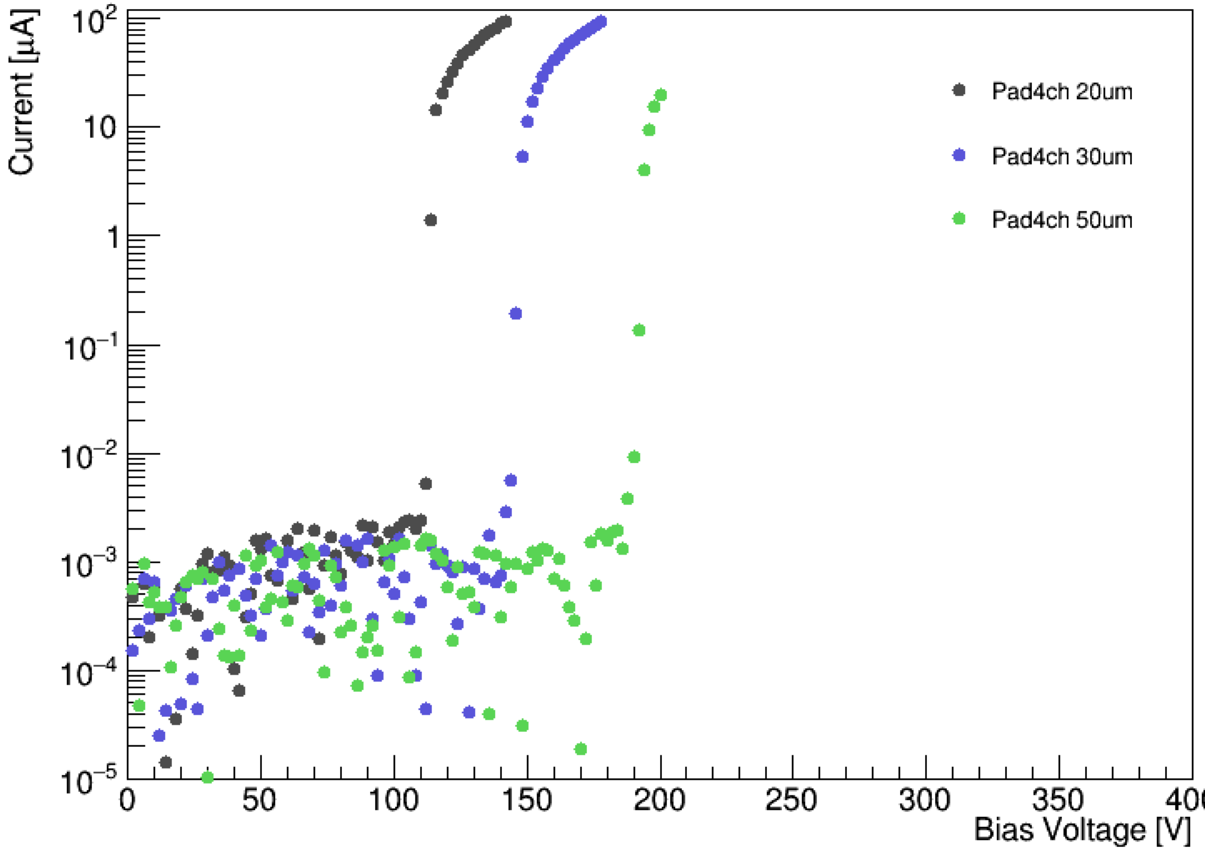
Gain of LGAD detector



Some dependence of break down voltage



Dope concentration dependence



Thickness dependence