Development an AC-LGAD sensor with fine time and spatial resolutions

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KEK, U.Tsukuba^A^

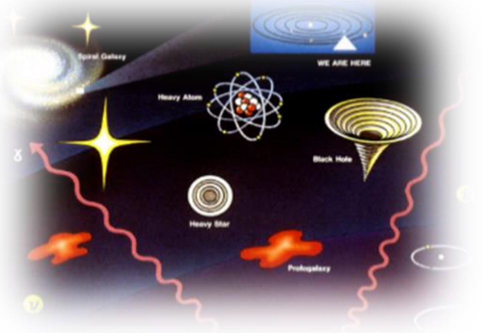
Motivation

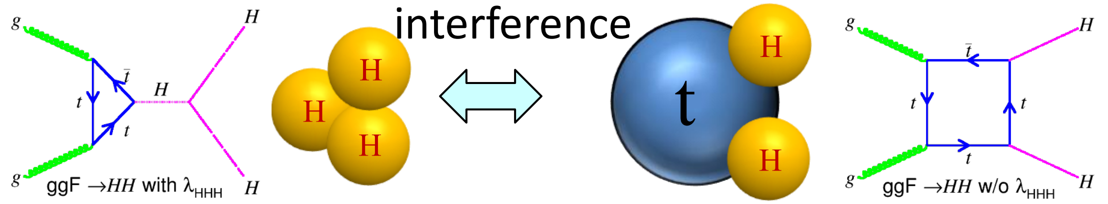
Higgs discovery and measurement by LHC experiment

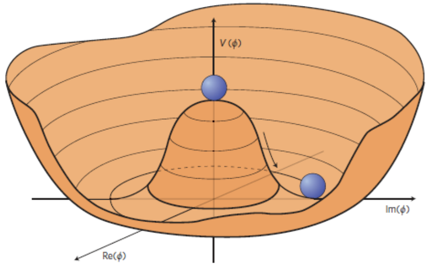
New era!

- ***“Vacuum”***
  - “Vacuum” is nothing? Filled by Higgs boson?
  - How Higgs boson/field condensed to the “Vacuum”?
  - Need to determine/observe the shape of Higgs Potential.

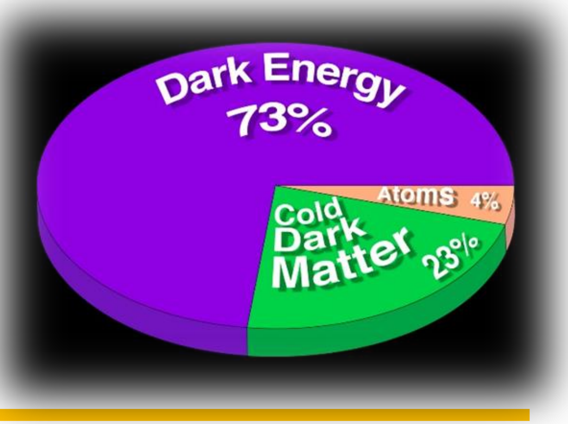
  →Observe/measure “Higgs self coupling”.







- ***“Dark Matter/Energy”***
  - We only know 4%. What’s the others?
  - Beyond the Standard Model?



Next generation of Collider experiment

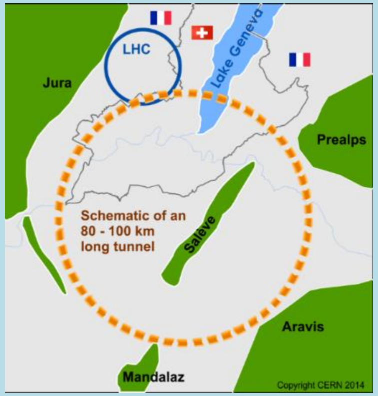
- Need "Higher Luminosity" and/or "Higher Energy"
  - ***High Luminosity LHC (HL-LHC)***

    Coming soon
    - 20 times more data (~3000-4000fb^{-1}) at **14TeV**
    - Plan : Start at 2027
  - ***High Energy LHC (HE-LHC)***

    Discussion Started
    - Use Super Conducting Magnet with Higher Magnetic field(16T)
    - **28TeV** collider in the same tunnel as LHC.
  - ***Future Circular Collider (FCC-hh)***

    Discussion Started
    - Use Super Conducting Magnet with Higher Magnetic field(16T)
    - **100TeV** collider with 100km tunnel at CERN.
  - ***International Linear Collider (ILC)***

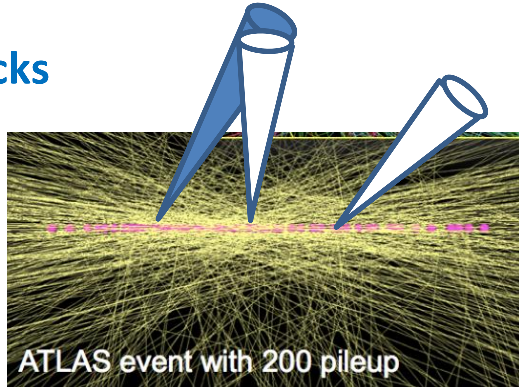
    Final decision soon
    - 250GeV e+ e- collider in Japan



Inner Tracking system

Very high density tracks

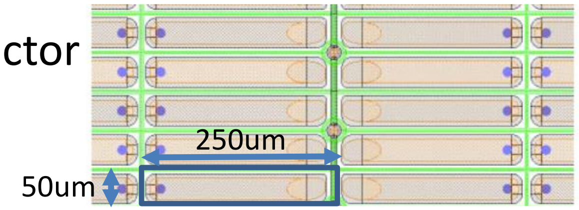
140 pileup @ HL-LHC
1500 pileup @ FCC-hh



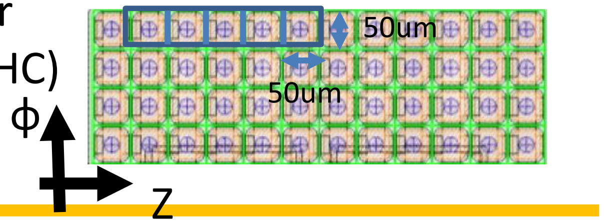
Only way to solve this so far…

finer pixel pitch

Current detector
(ATLAS IBL)



New detector
(Pixel @HL-LHC)

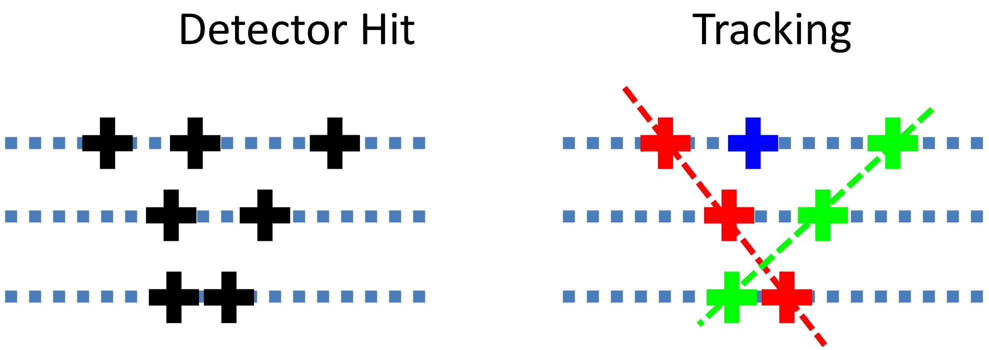


Future Semi-conductor Tracking Detectors

- **Further finer pitch pixel detector → Limited by front end Electronics (min : 50x50um^2)**
  - In addition to spatial resolution, **Timing resolution helps!**

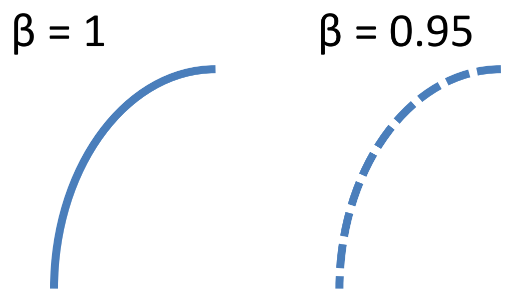
  →New generation of Tracking detector should have timing information for all hits!
- **Tentative Requirement**
  - **30ps timing resolution**
  - **~o(10)um spatial resolution (Pixel type).**
  - **(hadron collider) ~o(10^{16})n$_{eq}$/cm^2 radiation tolerance**

4D tracking !



Solve pileup hits in an event

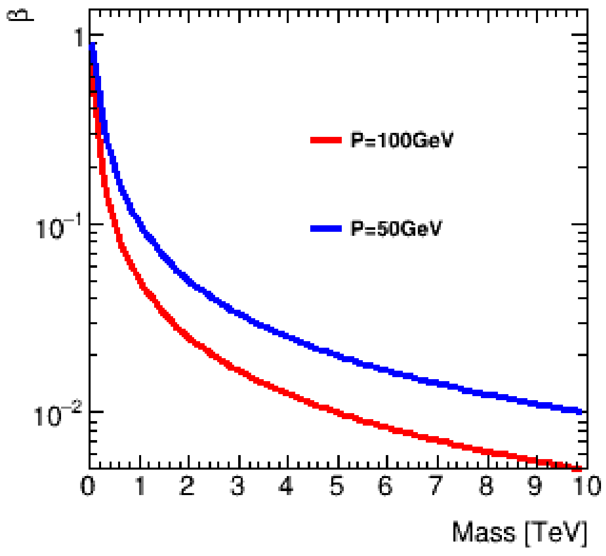
Particle identification



150ps difference at R=1m

K+ π+ separation

Mass spectrum for new particle

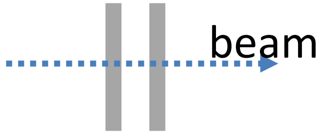


β measurement to obtain mass

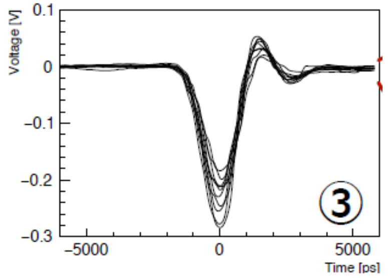
e.g. Mass measurement for Long lived chargeno

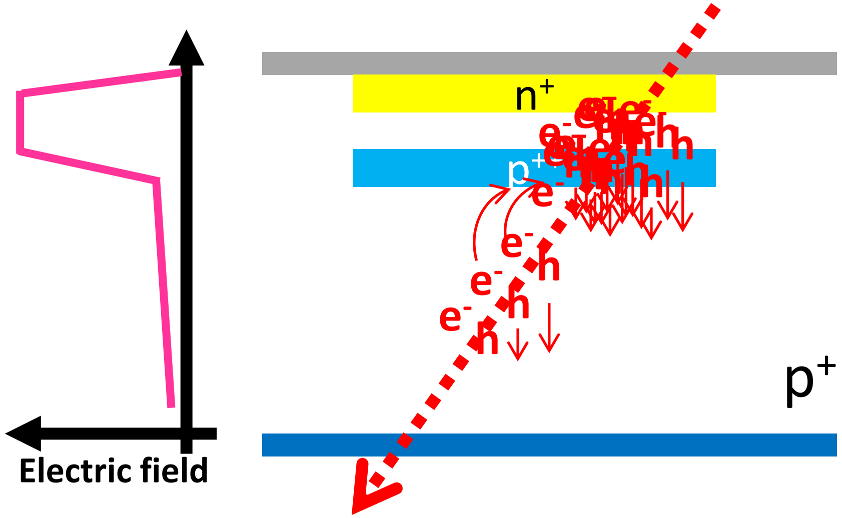
Low gain Avalanche Diode (LGAD)

- Low gain Avalanche Diode (LGAD)
  - General n^+-in-p type sensor with p^+ gain layer under n^+ implant to make higher Electric Field → Good timing resolution.
  - **30ps timing resolution achieved already.**
  - Next development
    - **Finer electrode separation for spatial resolution**
    - **Radiation tolerance**

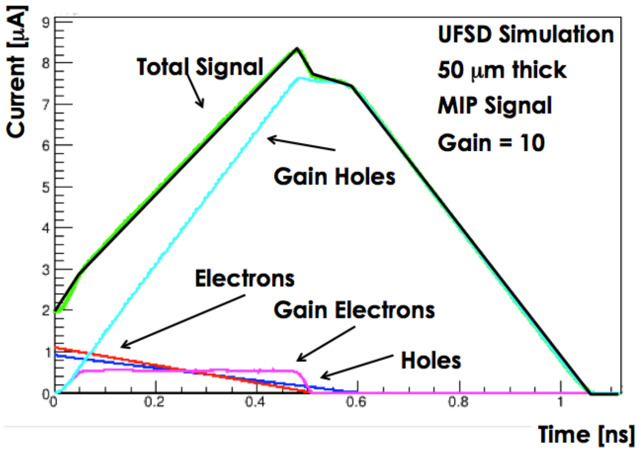


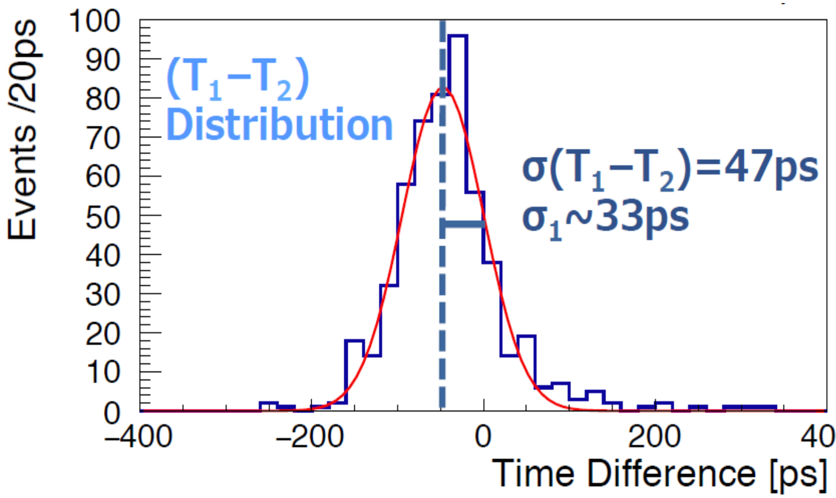
Measure time difference





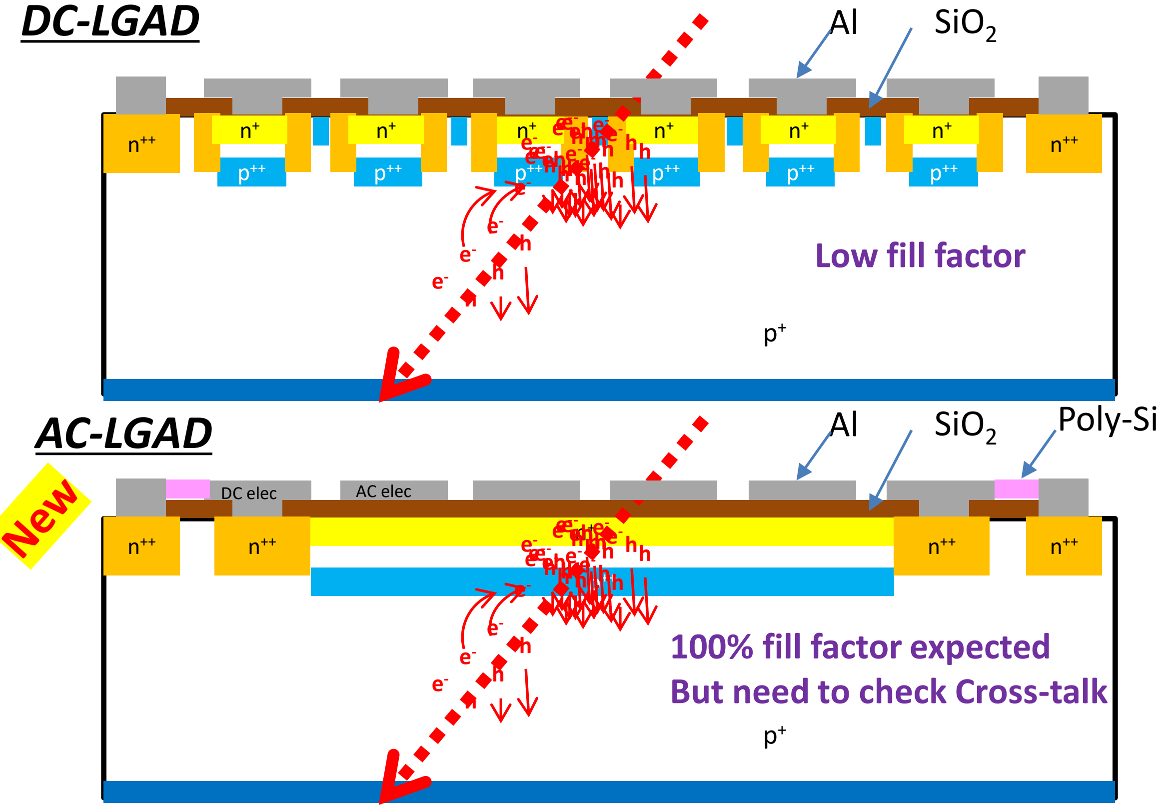
Signal drivers : **Gain Holes**

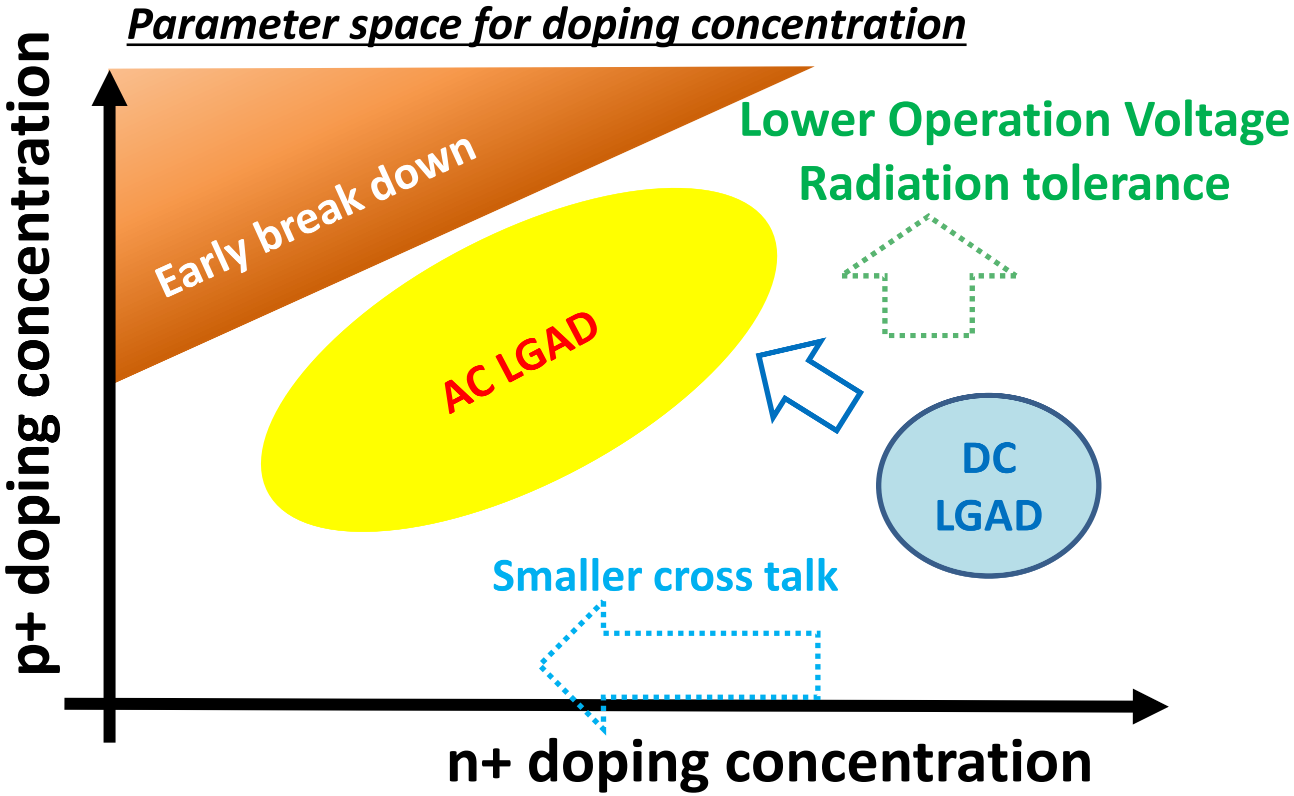




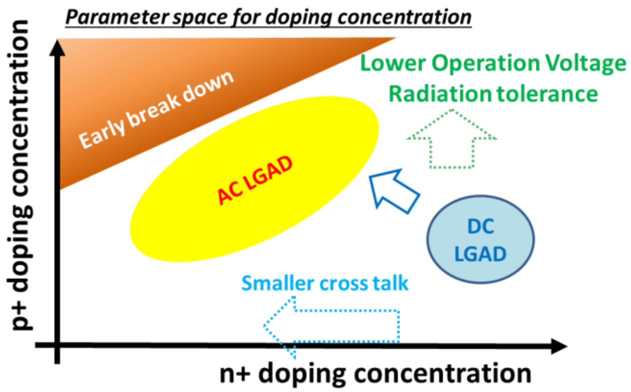
Detector with both spatial and timing resolution

- First prototype with 80um pitch strip (DC-LGAD)→**Only 20% of active area has gain**
- Common gain layer with AC-coupled readout (AC-LGAD) → **Uniform gain expected!**
  - **Cross talk expected in the n^+ implant → Increase resistivity of n^+ implant**

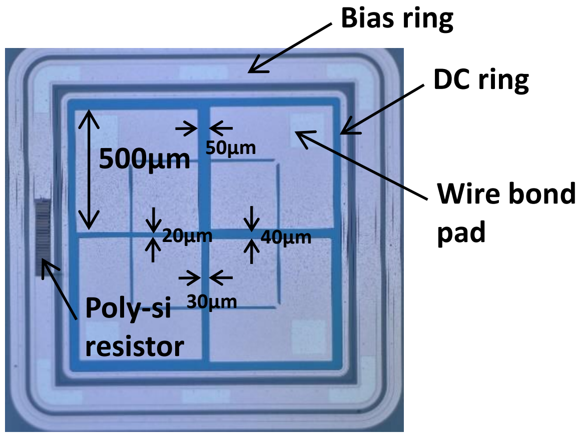




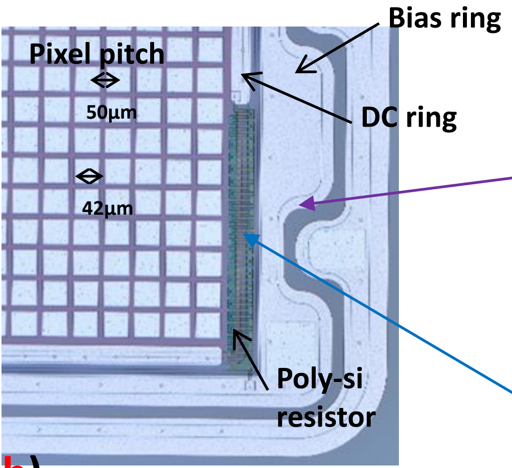
First AC-LGAD by HPK



Pad type sensor (4x 500umx500um)



Pixel type sensor (14x14 50umx50um)



GNDed DC ring via Poly-si

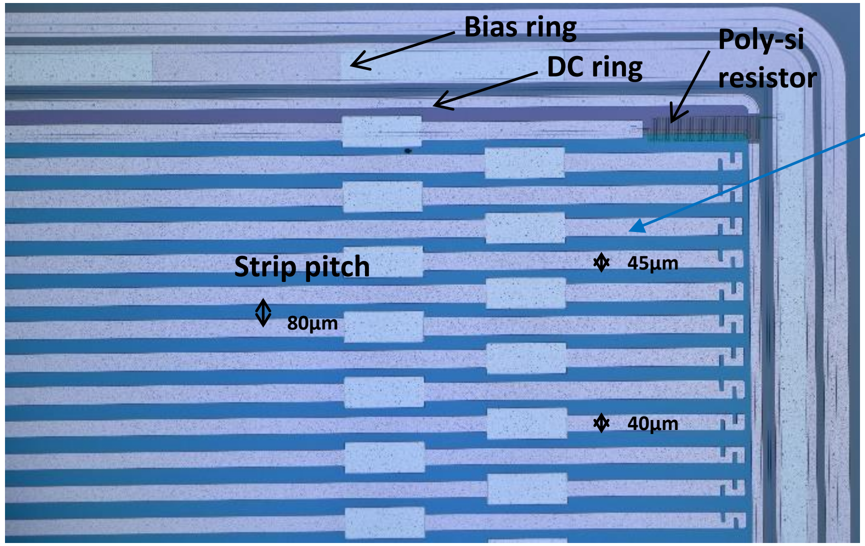
→ To remove charge in n+

Varied Al size (AC coupling capacitance)

Pixel : 42/38/34/30 um width/length

Strip : 45/40/35/30 um width

Strip type sensor (16x 80um pitch)



n+ and p+ doping concentration

p+ doping

		N+ doping concentration / resistivity		
		C(Ax10 resistivity)	B(Ax3.3 resistivity)	A (~DC-LGAD)
P+ doping concentration	3 (high)		B-3	A-3
	2 (mid)	C-2	B-2	A-2
	1 (low)	C-1	B-1	

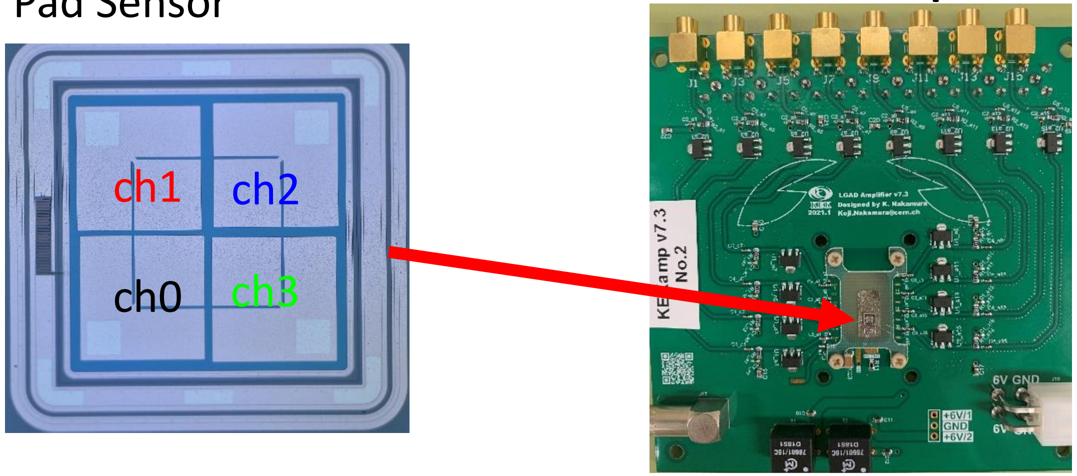
n+ doping

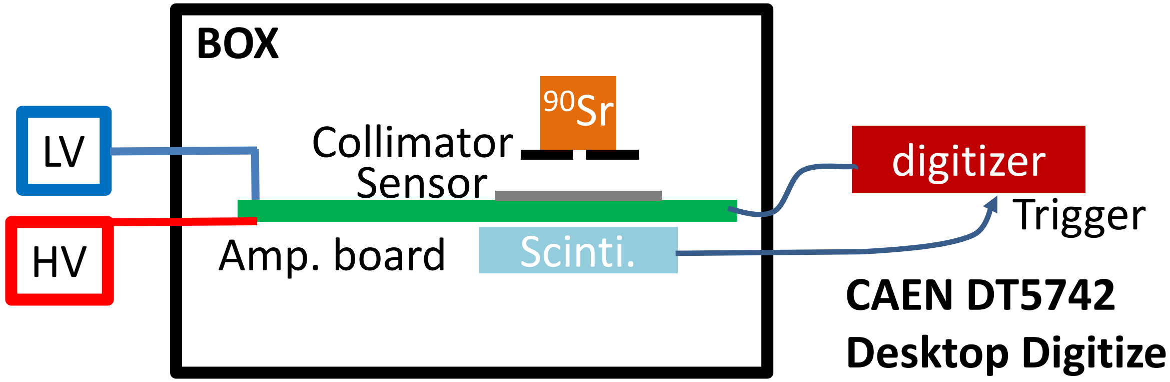
Measurement setup and signal observation

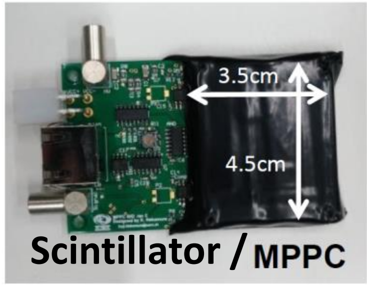
- Lab setup
  - Designed high speed amplifier board.
  - Signal recorded by CAEN DT5742 digitizer
  - ^{90}Sr β lay source
  - Triggered by Scintillator (MPPC readout)

Pad Sensor

KEK 16 ch Discrete Amp.

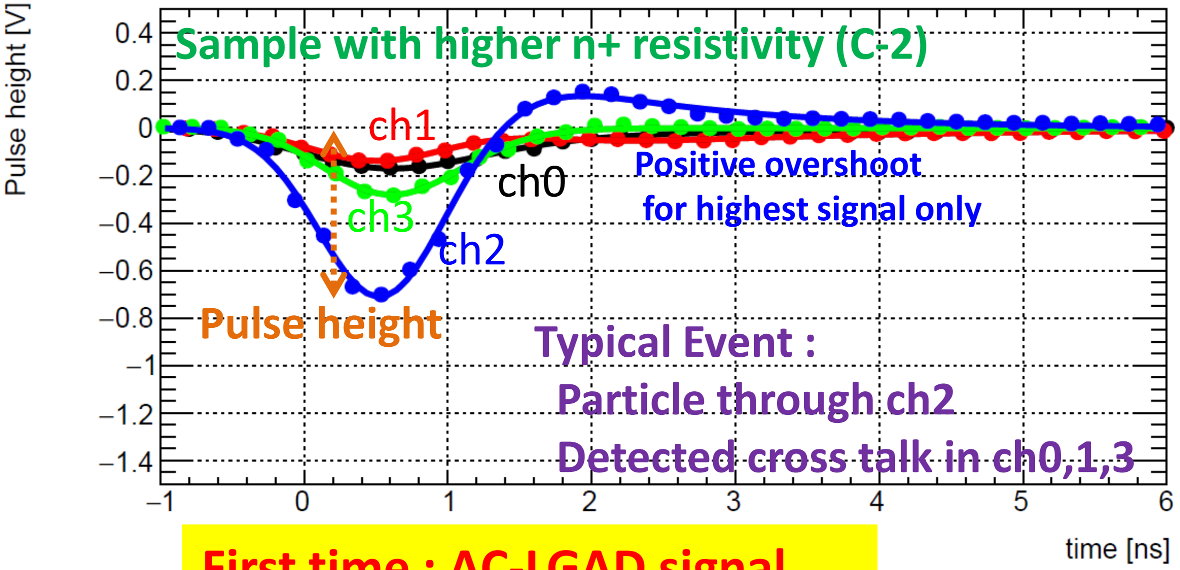






Scintillator / MPPC

CAEN DT5742
Desktop Digitizer
5GS/s 10bit
12bit ADC 2V full range



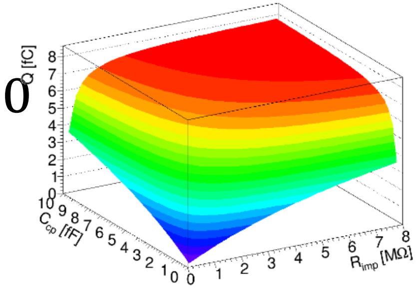
First time : AC-LGAD signal observed with small crosstalk

Equivalent circuit for Signal readout

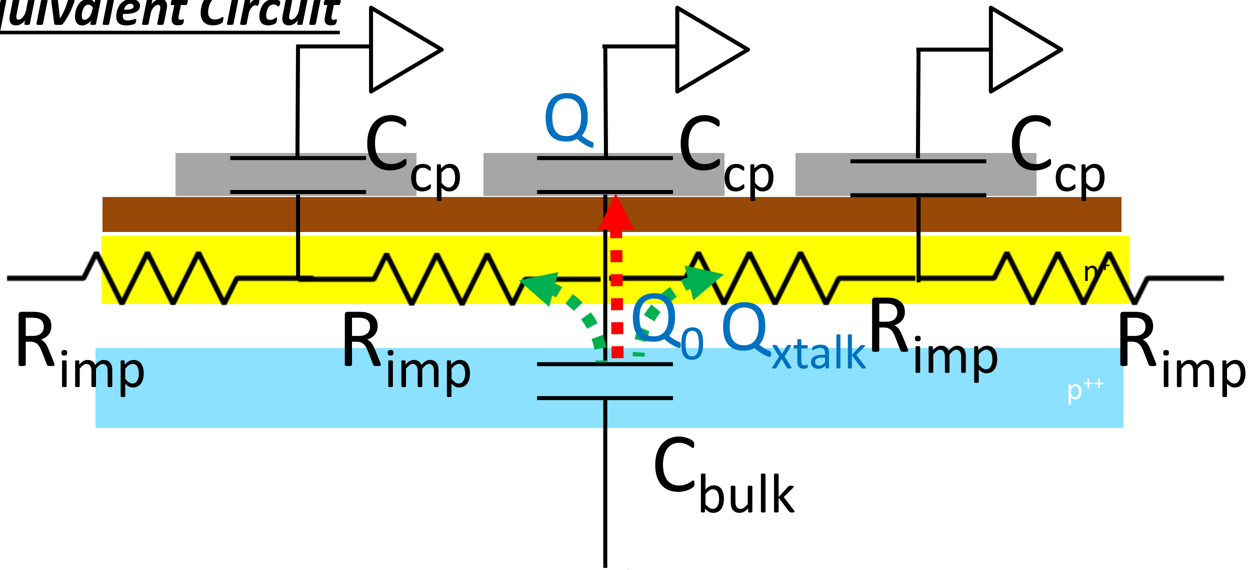
- Crosstalk and Readout charge

Assuming $Z_{cbulk} >> Z_{Ccp}$…

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



Equivalent Circuit



  - Generated charge Q_0
  - Readout charge Q

To have larger signal

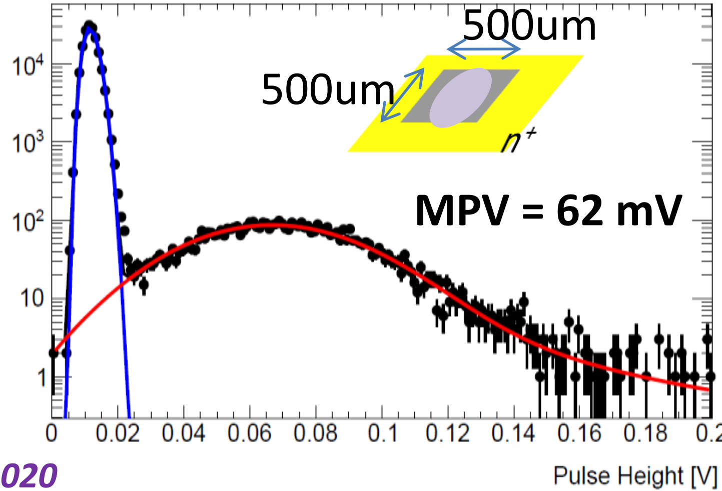
Larger C_{cp}

Larger R_{imp}

JPS : 12aT3-7 Sayuka Kita (Tsukuba)

See more detail in Last THoU member meeting in 30th Nov 2020

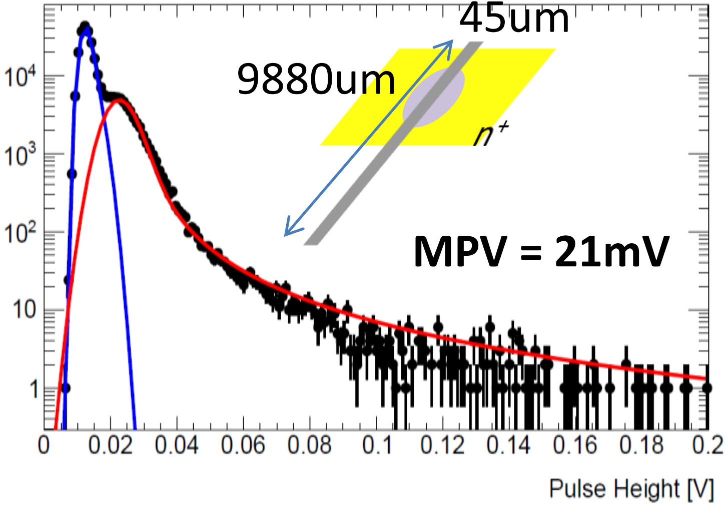
Pad type



Signal

x3

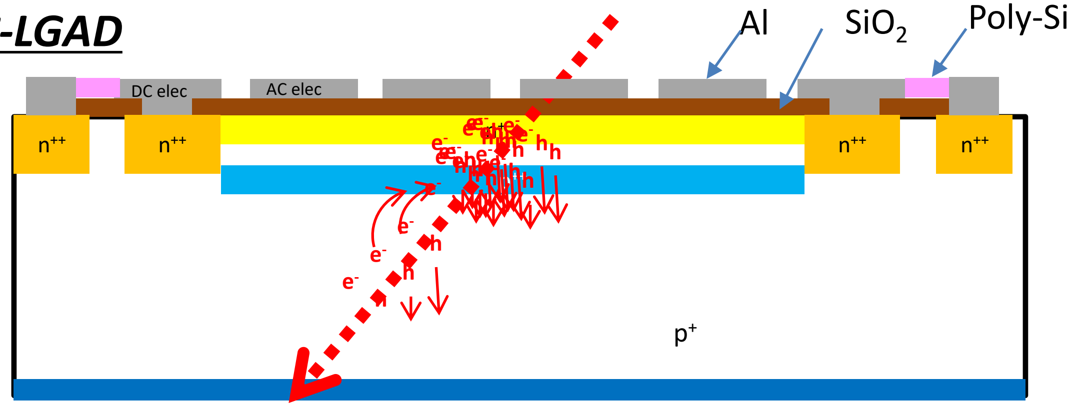
Strip type



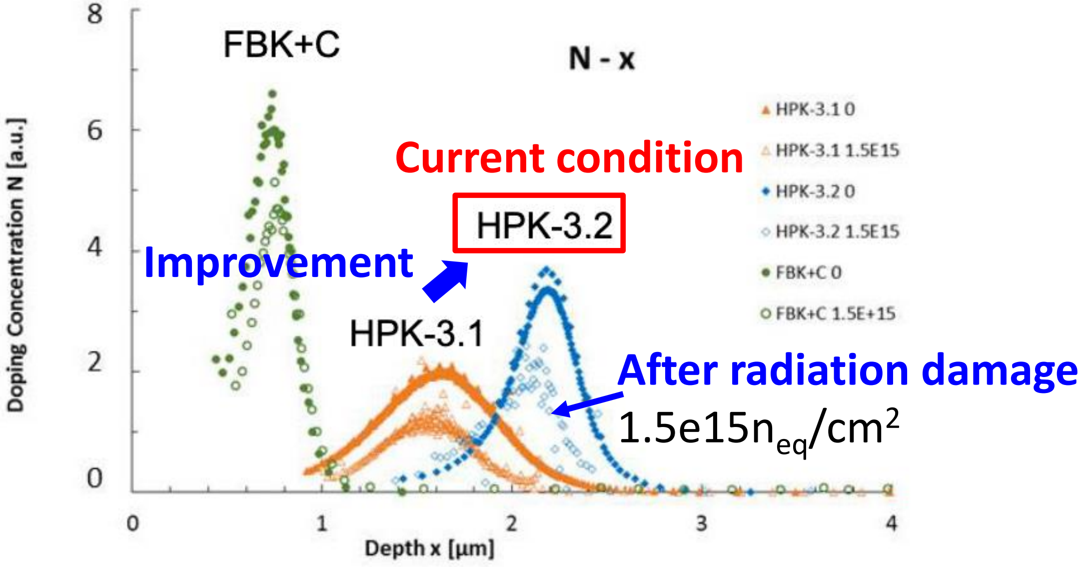
Radiation Effect in LGAD sensor

- The same as general n^+-in-p sensor
  - Bulk damage (NIEL) : Lattice defect.
  - Surface damage(TID) : Positive charge @ SiO_2-Si
- In addition to this **”Accepter Removal”**
  - *p*+ (Boron) accepter change to doner level

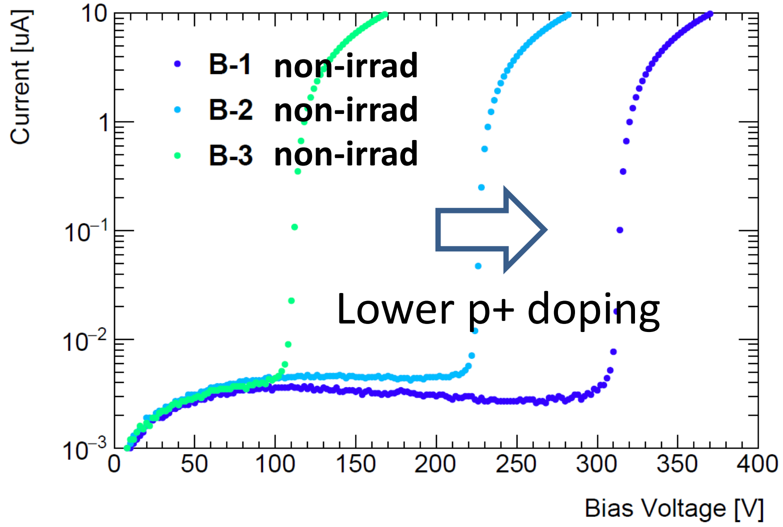
AC-LGAD



p+ doping profile measured by bulk capacitance



What happened if p+ dope reduced by accepter removal?



Reduce p+ doping concentration

↓

Higher Gain (operation) Voltage

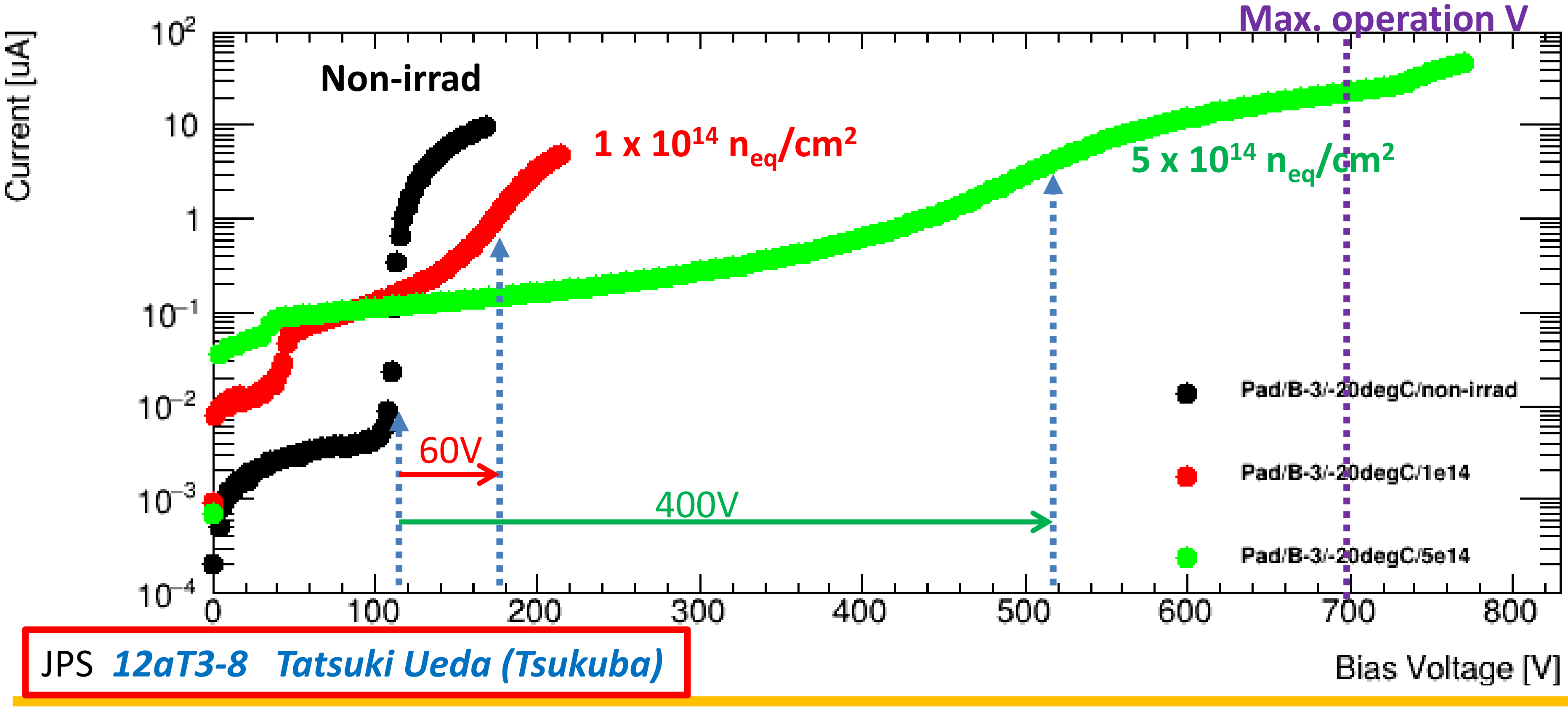
↓

Operation Voltage > Max voltage (~700V)

→ **End of life**

IV performance after irradiation

- Irradiated sensors at CYRIC (Tohoku university) with 70MeV Proton.
- Operation/Gain voltage get higher by irradiation (almost linearly)
  - Current sensor does not work after $1\mathrm{x}10^{15} n_{eq}/cm^2$ fluence or more.



JPS *12aT3-8 Tatsuki Ueda (Tsukuba)*

Signal Size

Fluence	Signal MPV
Non-irrad	35±2 mV
$1\mathrm{x}10^{14} n_{eq}/cm^2$	39±1 mV
$5\mathrm{x}10^{14} n_{eq}/cm^2$	30±2 mV

$5\mathrm{x}10^{14} n_{eq}/cm^2$ may have slight decrease of signal (But keep at least ~75%)

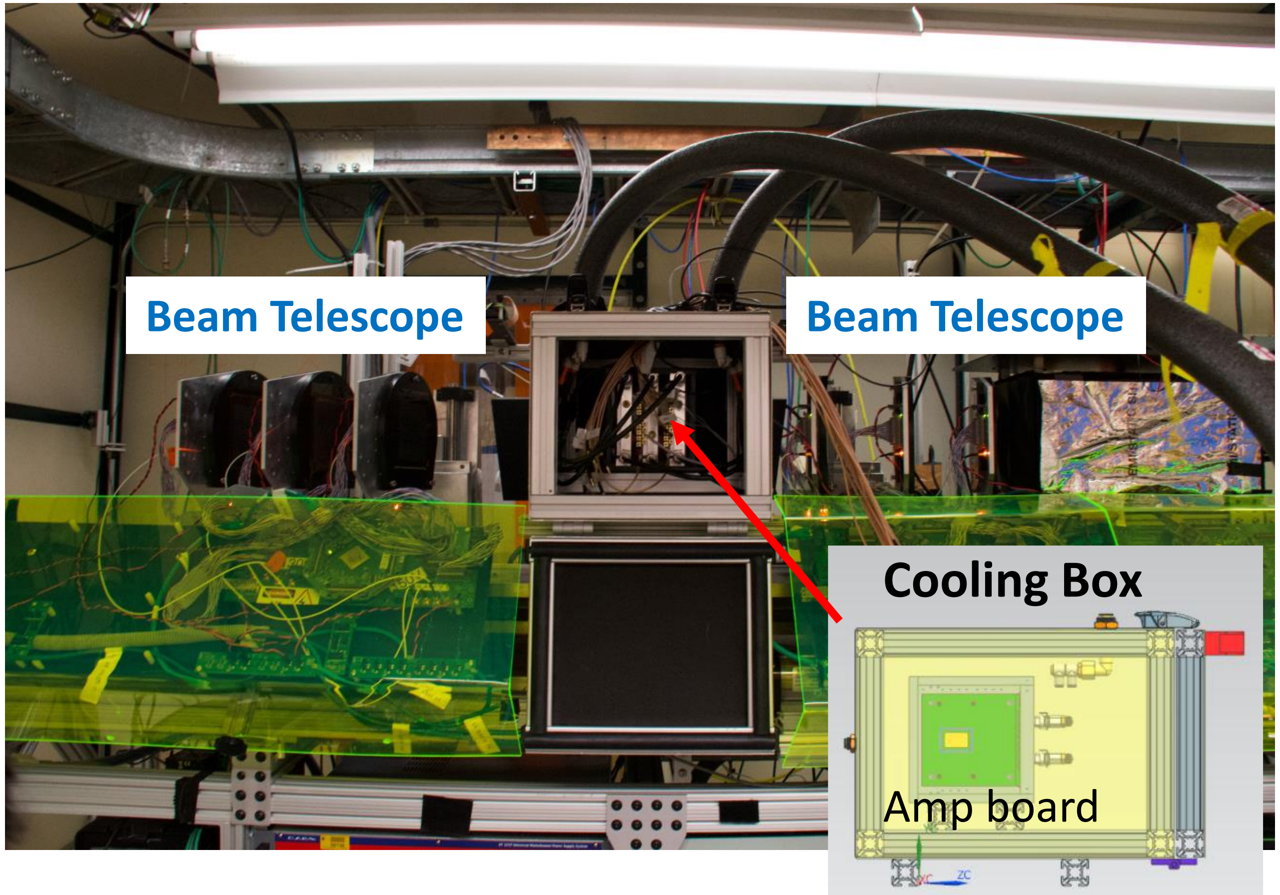
Test beam in Feb 2021 @ Fermilab

Not participate in person due to COVID-19

Fermilab Test Beam Facility (FTBF)

120GeV proton beam

Strip Detector based Telescope : ~15um pointing resolution



Readout by Ocilloscope

LeCroy
WR8208HD scope
12bit, 10GSa/s, 2GHz
8 channel

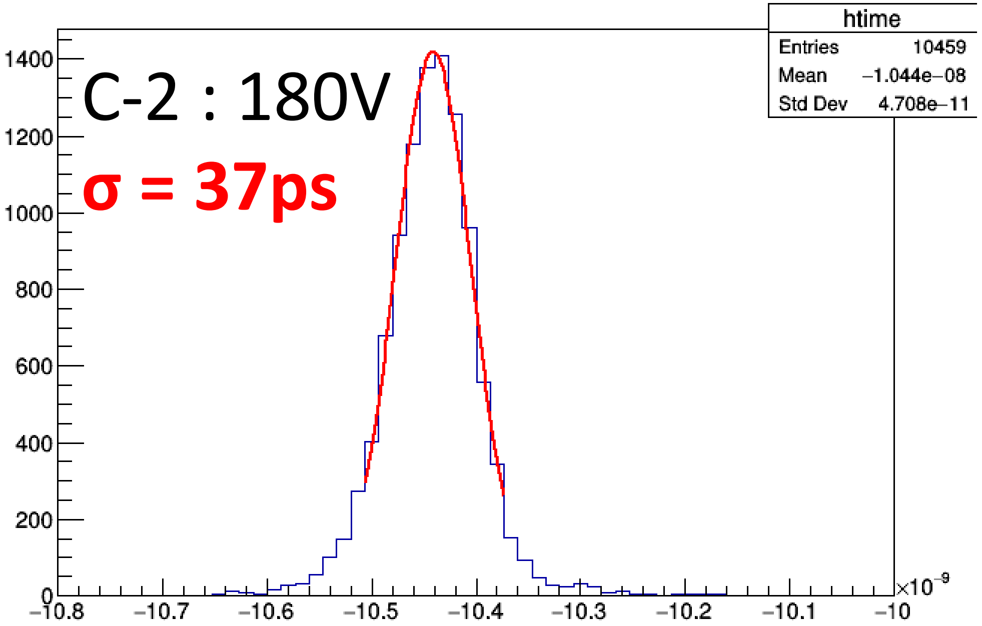
Timing reference Detector

PHOTEK
MCP photomultipliers (PMT140)
450ps FWHM with 5e3 Gain
~5ps timing resolution
(SPEC: Multi-photon jitter below 10 ps)

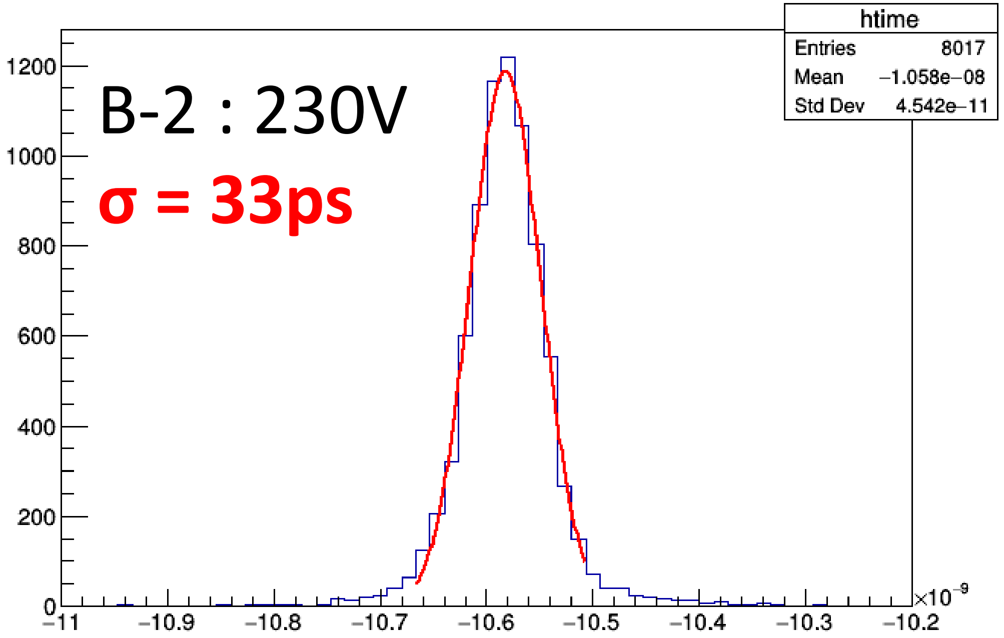
Time resolution measurement @ testbeam

- Used PHOTEK : MCP PMT140 as a timing reference detector
  - Including 5ps PMT140 time resolution (<1% effect)

Very fresh results : Obtained 30-40ps time resolution for a couple of types of sensors


C-2 : 180V

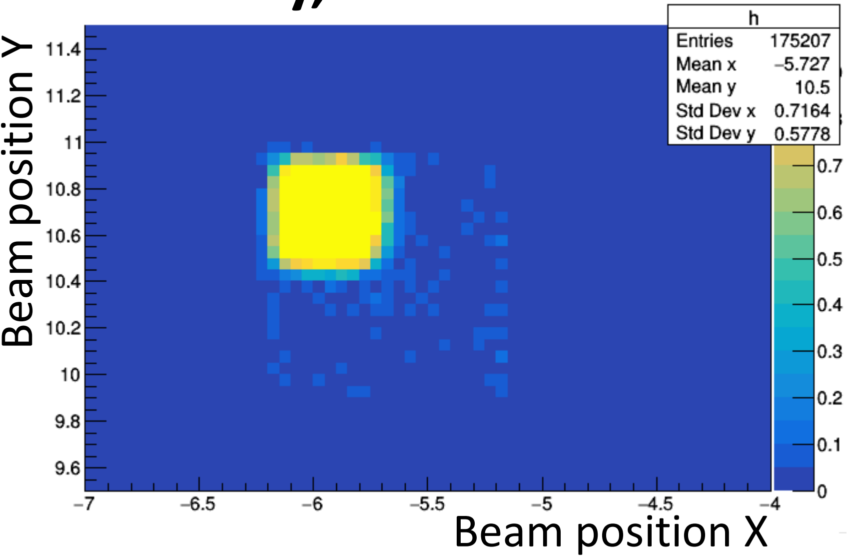
σ = 37ps


B-2 : 230V

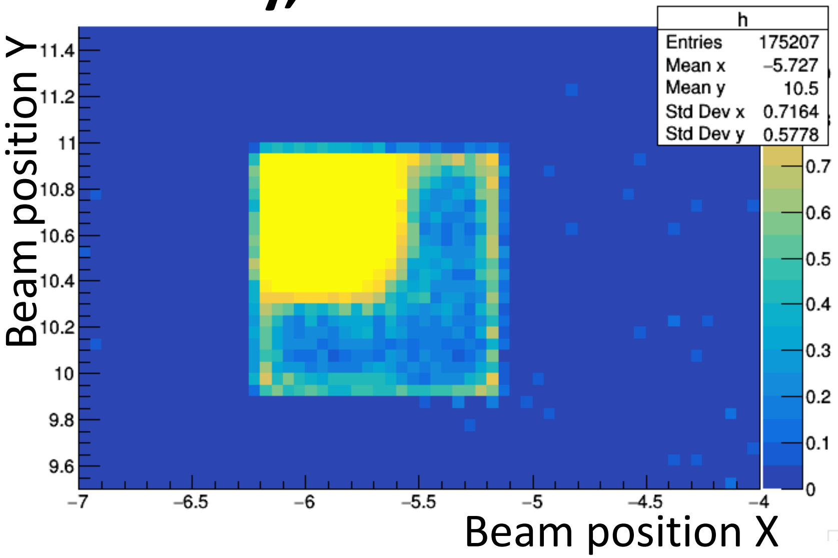
σ = 33ps

Efficiency and signal sharing @ testbeam

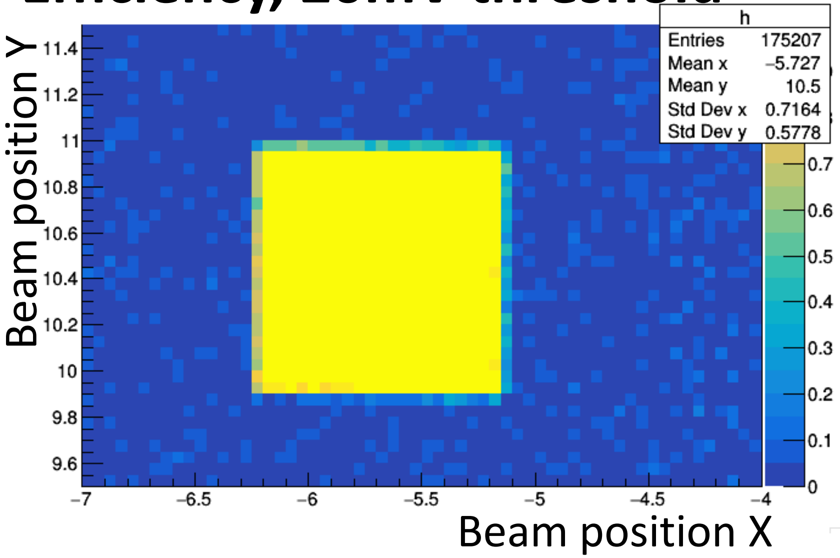
Efficiency, 90mV threshold



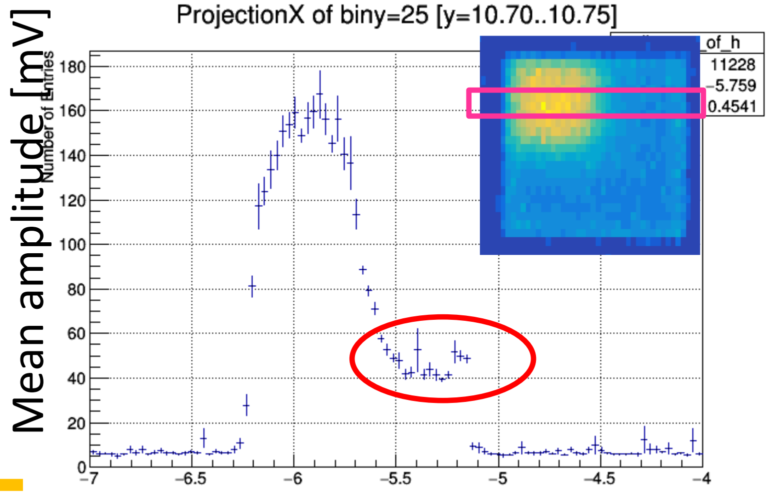
Efficiency, 45mV threshold



Efficiency, 20mV threshold



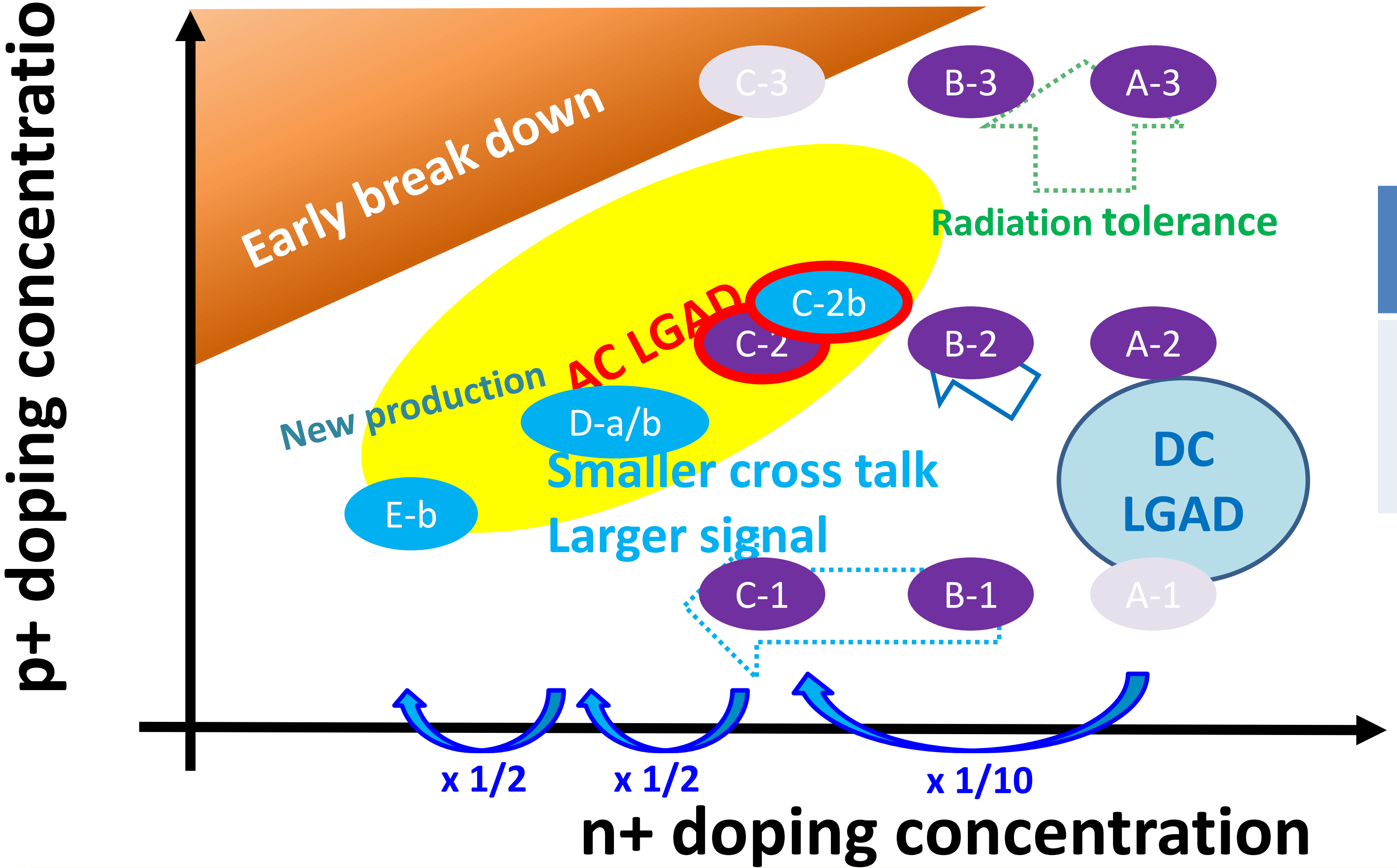
- Efficiency measurement for the top left pad.
  - Close to 100% efficiency @ 90mV threshold
  - ~40mV crosstalk observed. (consistent to lab meas.)



Need more study for the reason of flat crosstalk. (inter elec. Cap?)

New samples (4 types of sensors)

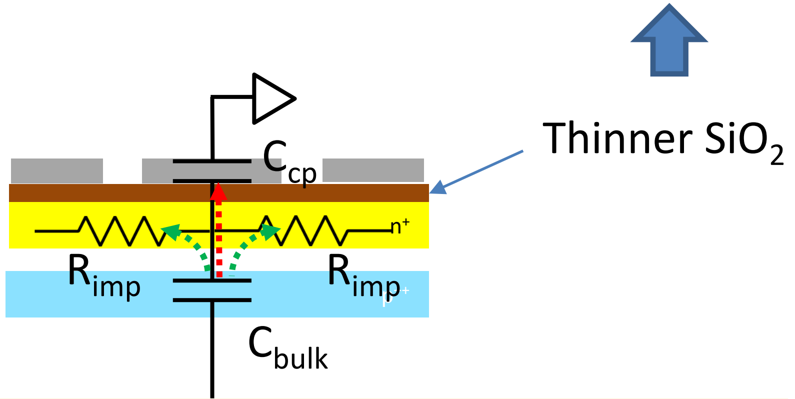
Parameter space for doping concentration



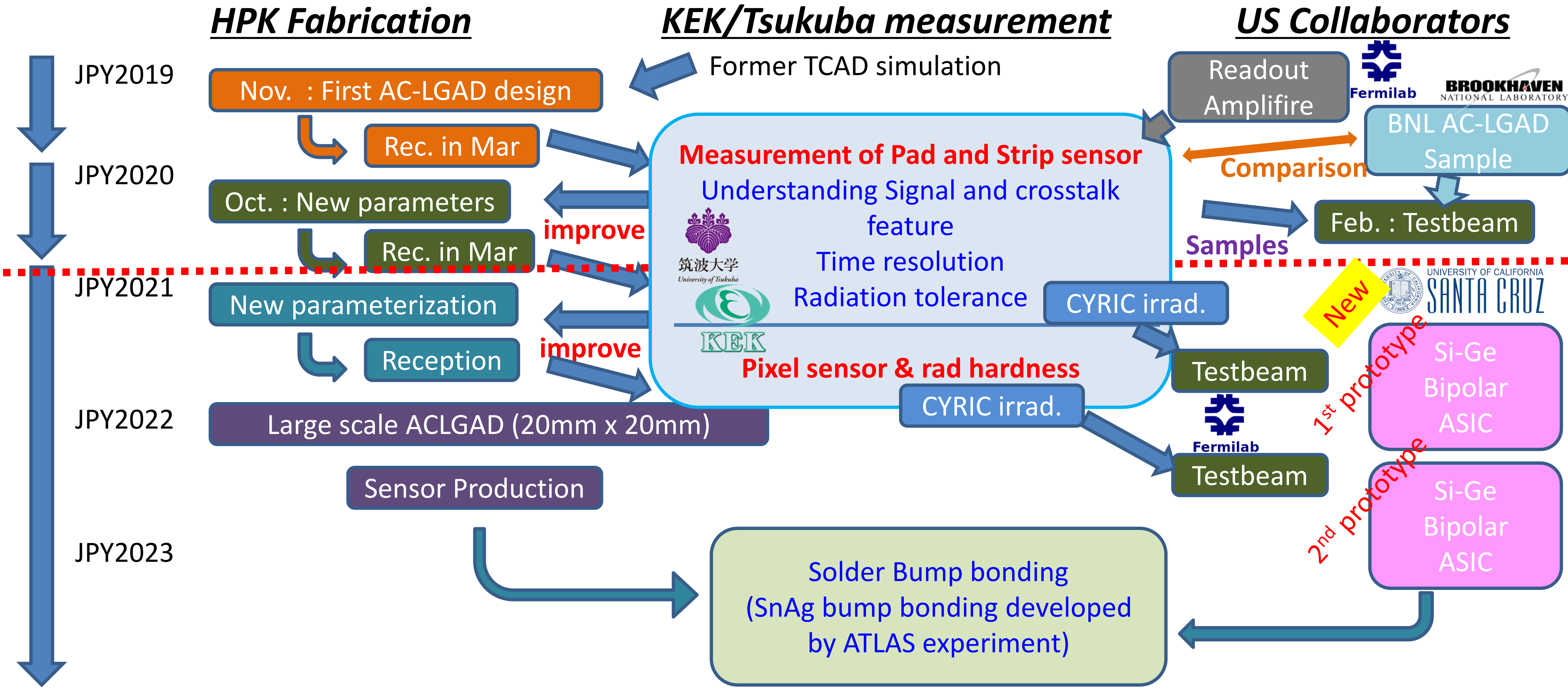
● Existing Samples

● New Samples (26th Mar)

		Coupling capacitance	
		Nominal x 1	Nominal x 1.5
n^+ resistivity	Ax10	C-2	C-2-b
	Ax20	D-a	D-b
	Ax40		E-b



Summary and plan



HPK Fabrication

KEK/Tsukuba measurement

US Collaborators

JPY2019

Nov. : First AC-LGAD design

Rec. in Mar

JPY2020

Oct. : New parameters

Rec. in Mar

JPY2021

New parameterization

Reception

JPY2022

Large scale ACLGAD (20mm x 20mm)

Sensor Production

JPY2023

Former TCAD simulation

improve

improve

Measurement of Pad and Strip sensor

Understanding Signal and crosstalk feature

Time resolution

Radiation tolerance

CYRIC irrad.

Pixel sensor & rad hardness

CYRIC irrad.

Solder Bump bonding
(SnAg bump bonding developed
by ATLAS experiment)

Readout Amplifire

BNL AC-LGAD Sample

Comparison

Feb. : Testbeam

Samples

Testbeam

Testbeam

New

1st prototype

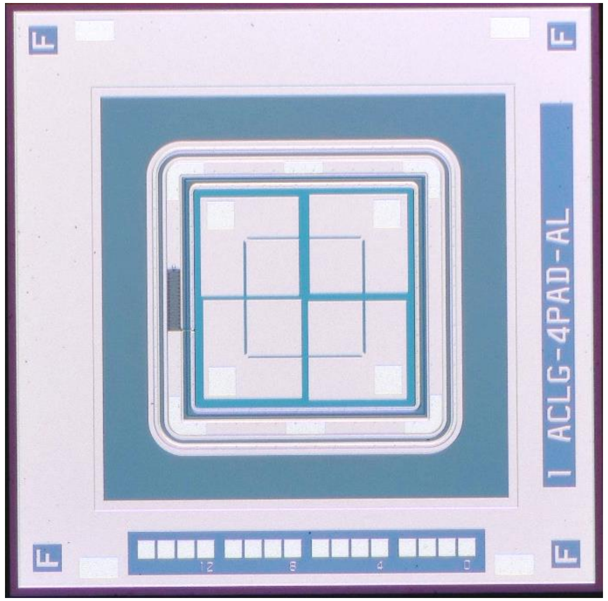
Si-Ge Bipolar ASIC

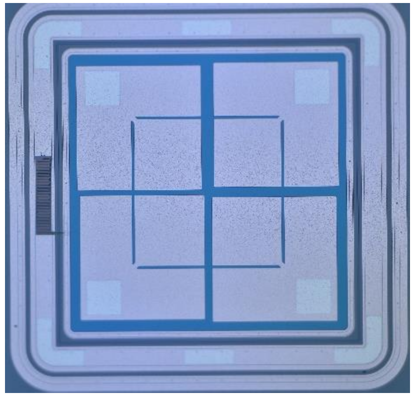
2nd prototype

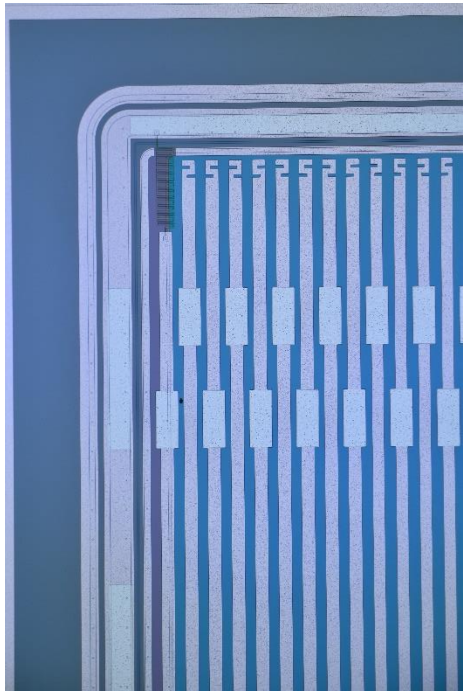
Si-Ge Bipolar ASIC

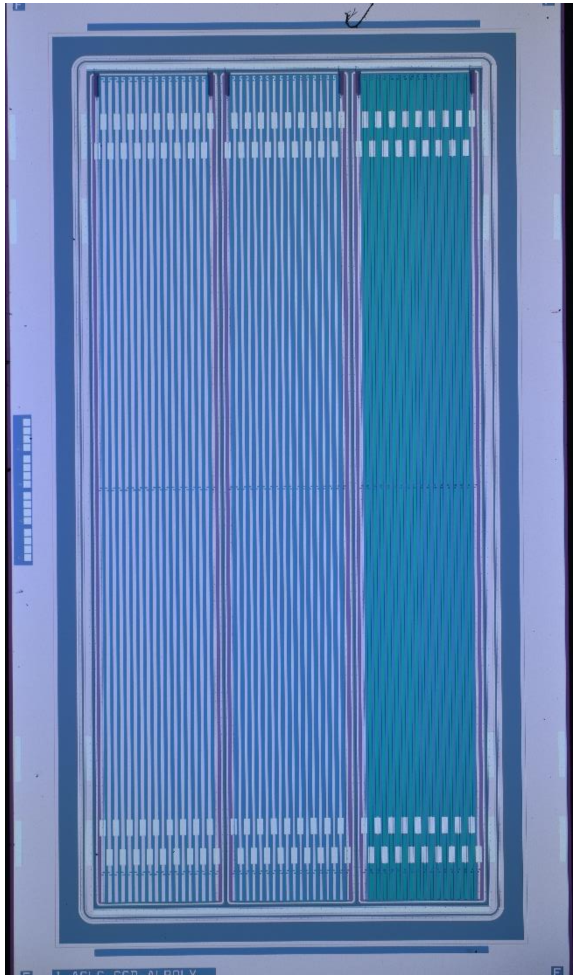
backup

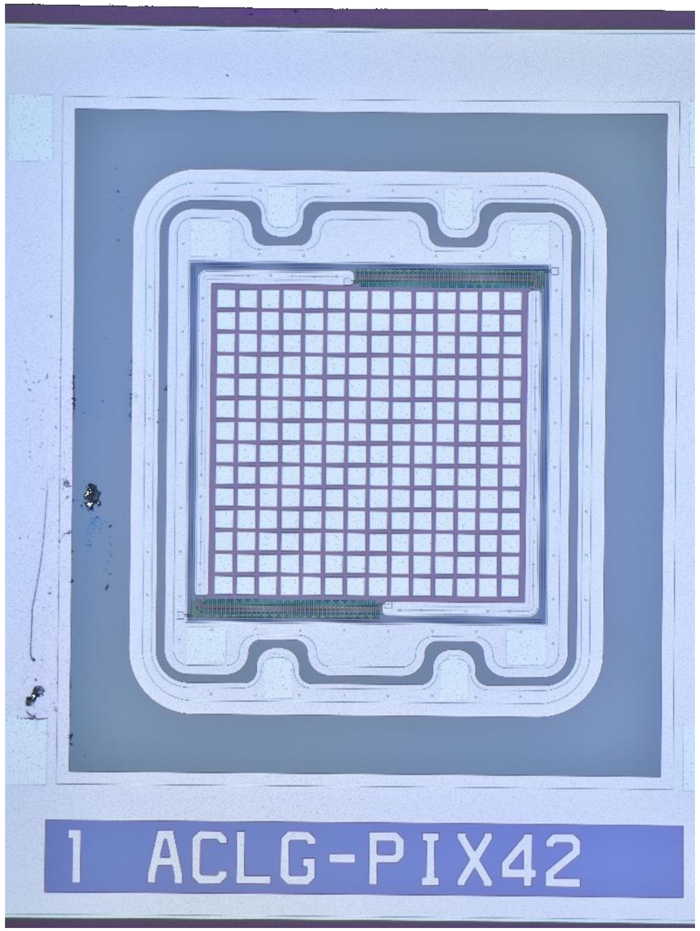
Photo



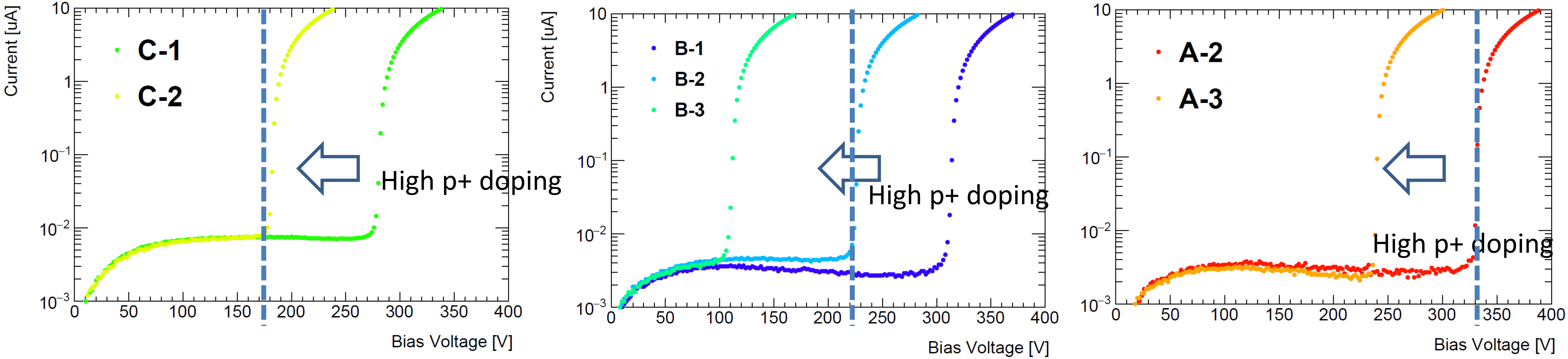








Leakage current vs Bias voltage



Break down (gain) voltage get lower

- **Higher P+ dope**
- **Lower N+ dope**

→ Radiation trelance

C-2 type :

- **Lower operational voltage**
- **Smaller crosstalk**

Variation of p+ and n+ doping concentration

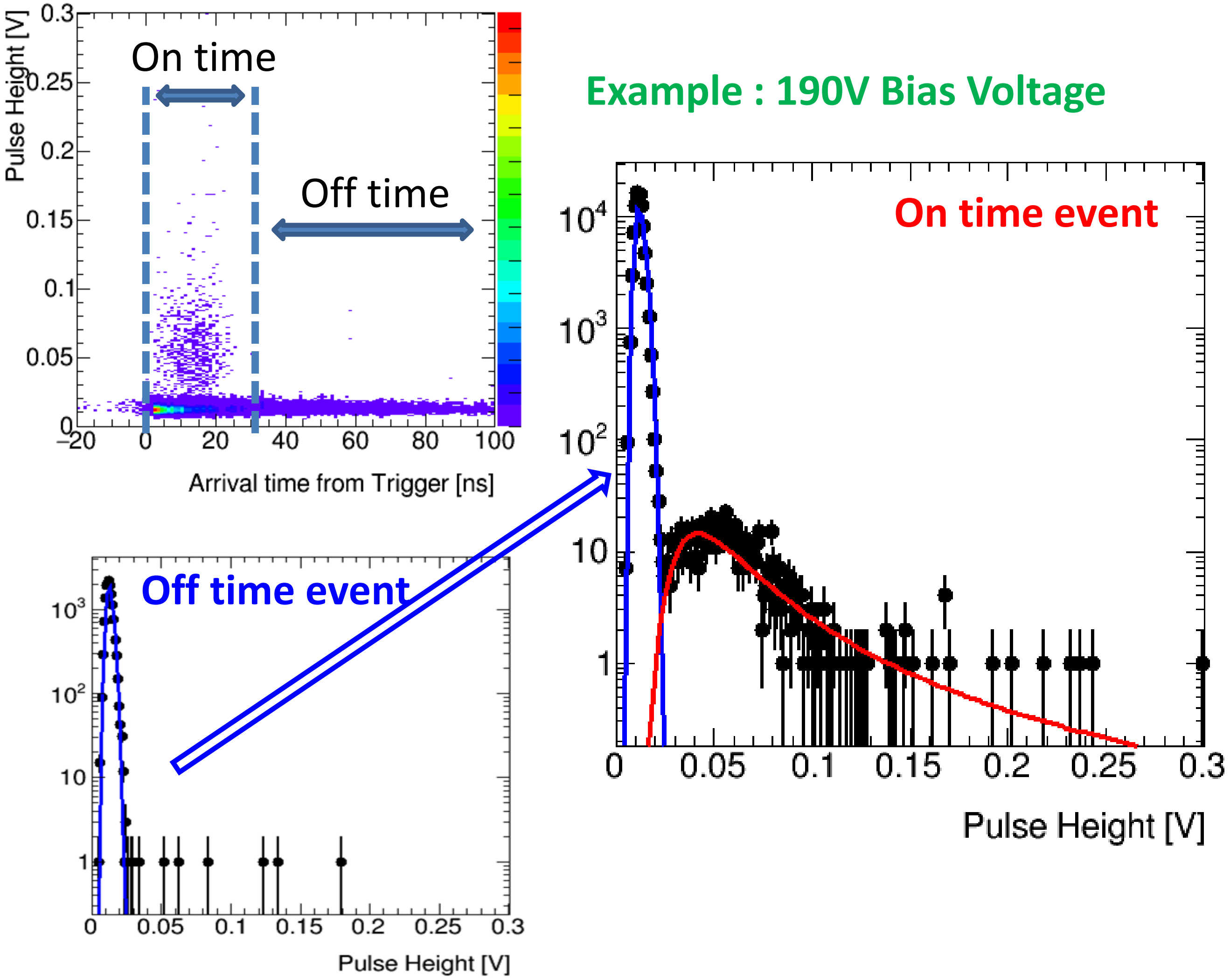
		N+ doping concentration / resistivity		
		C(Ax10 resistivity)	B(Ax3.3 resistivity)	A (~DC-LGAD)
P+ doping concentration	3 (high)		B-3	A-3
	2 (mid)	C-2	B-2	A-2
	1 (low)	C-1	B-1	

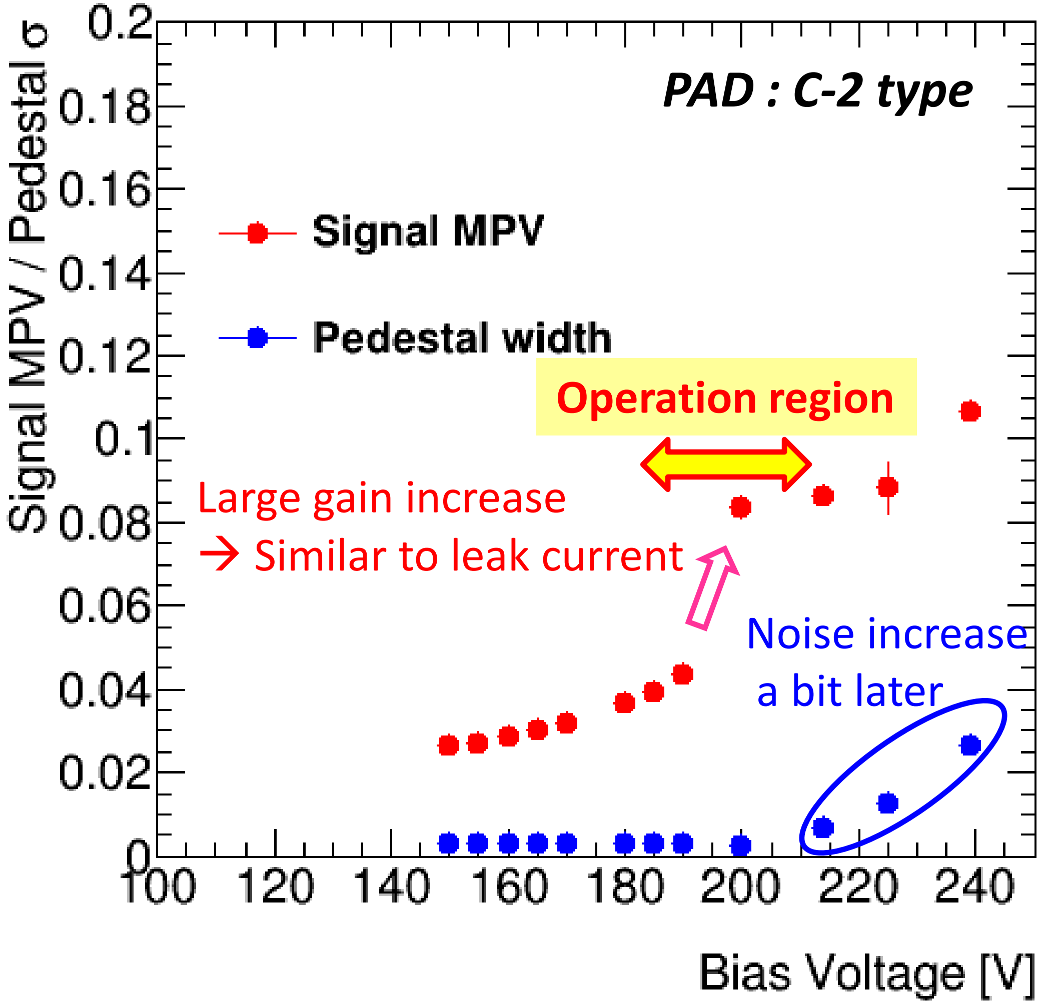
p+ doping

n+ doping

Pulse Height and Bias Voltage dependence

Pedestal distribution is evaluated from off timing region


Example : 190V Bias Voltage


Large gain increase

→ Similar to leak current

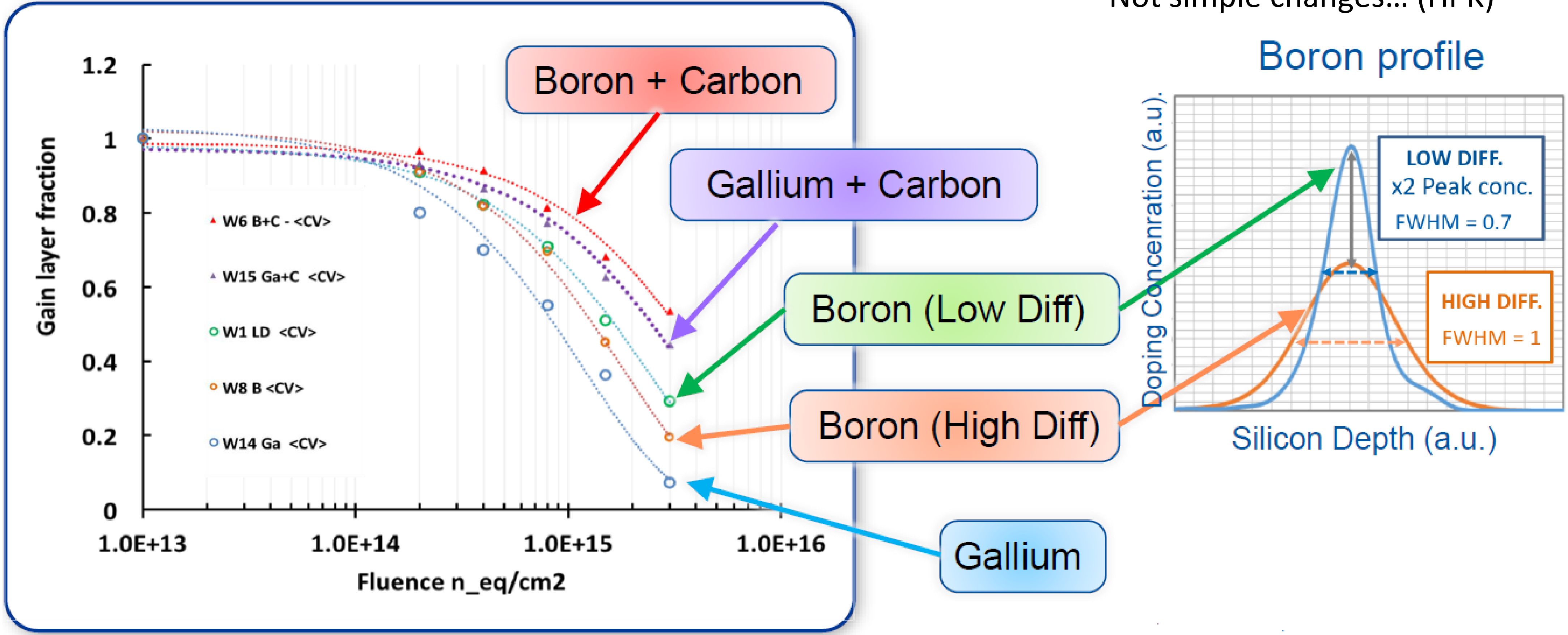
Noise increase a bit later

How to reduce “Accepter Removal” effect?

- Study by FBK LGAD sensors. Two way →

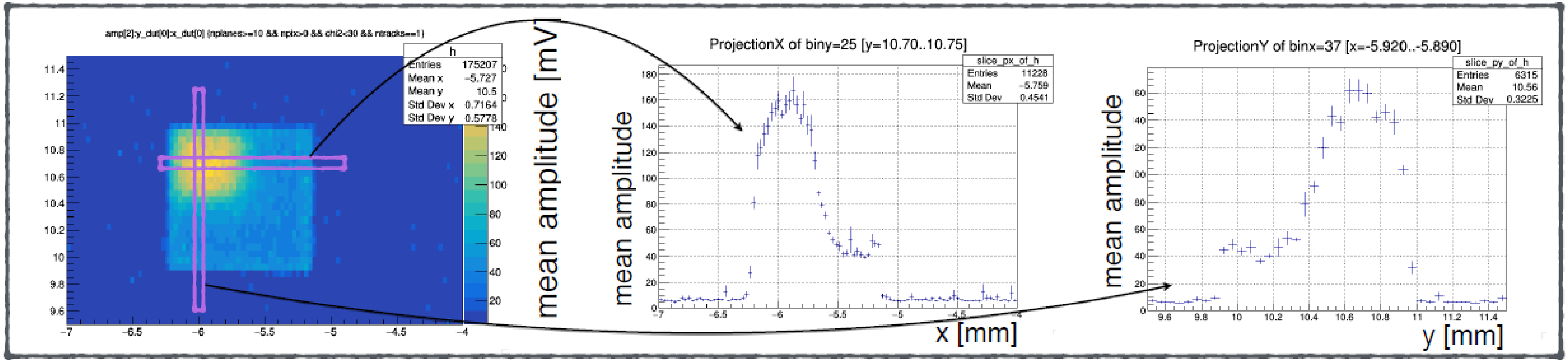
1. **Lower diffusion of Boron doping profile**
2. Adding carbon (or Gallium) to p^+ layer

→ Not simple changes… (HPK)

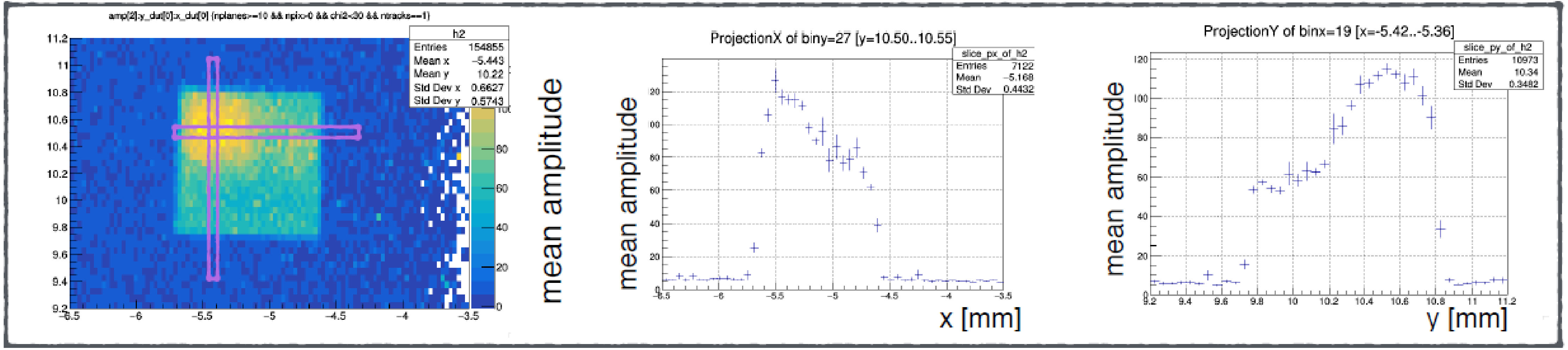


Position dependent mean amplitude

C-2: more resistive



B-2: less resistive

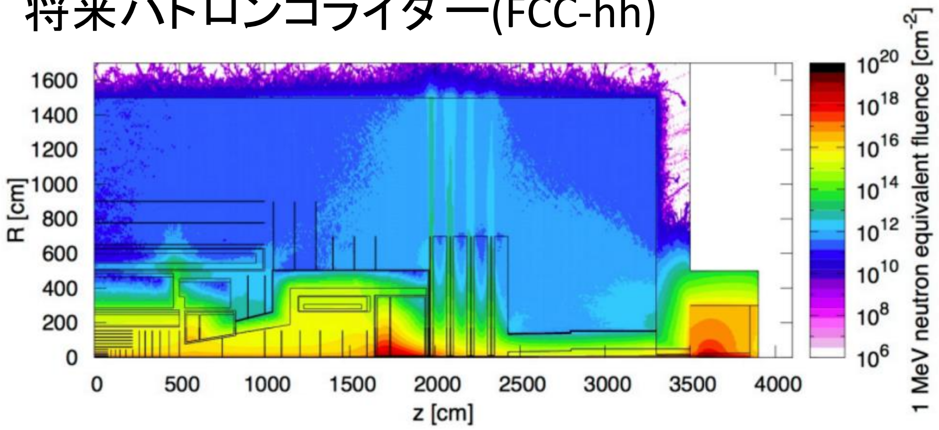


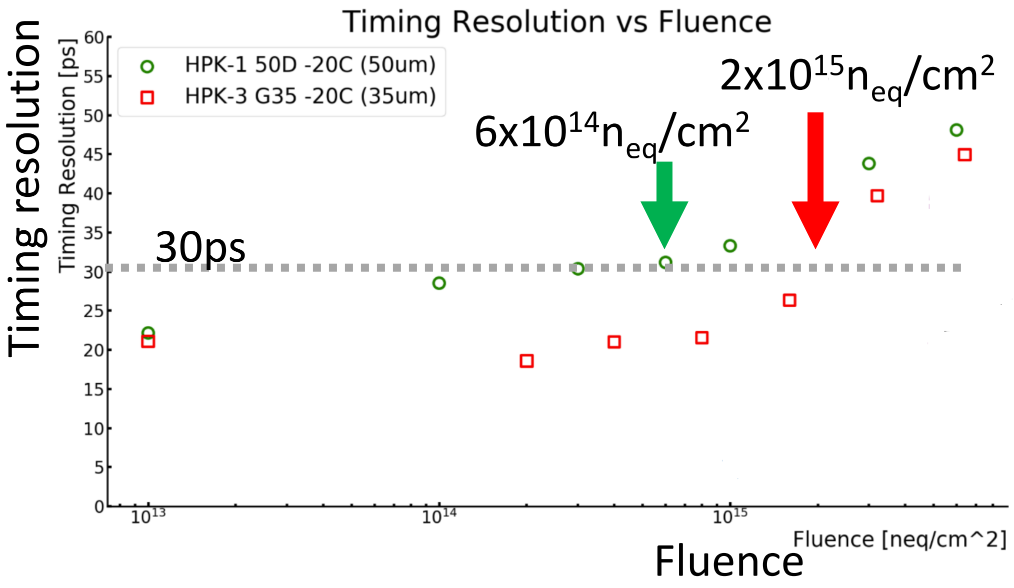
Radiation Tolerance

- ***Radiation Tolerance***

Current : 0.6-2 x $10^{15}n_{eq}/cm^2$
Goal : $1x10^{16}n_{eq}/cm^2$

将来ハドロンコライダー(FCC-hh)





Timing resolution

Fluence

30ps

$6x10^{14}n_{eq}/cm^2$

$2x10^{15}n_{eq}/cm^2$

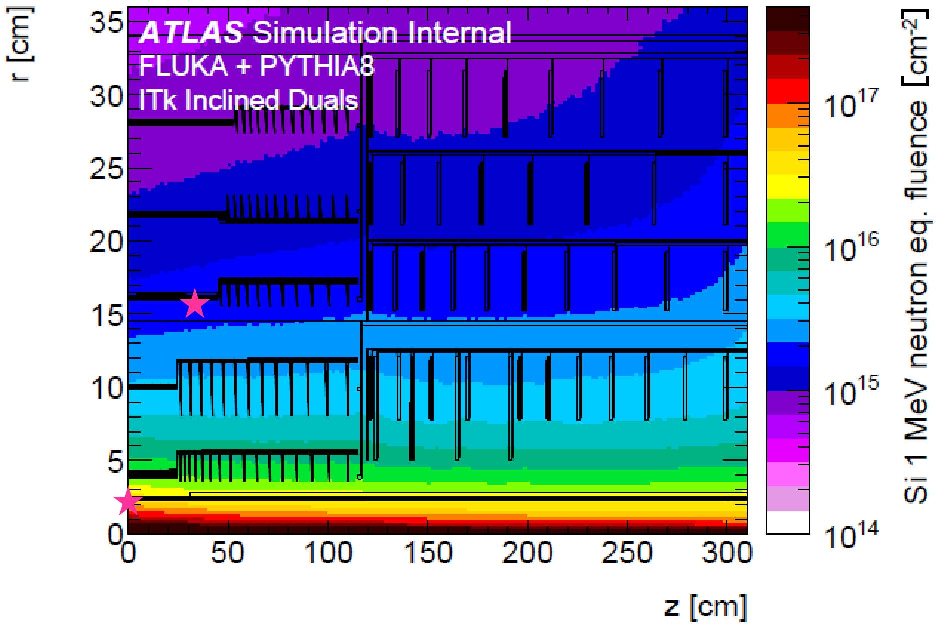
Idea for improvement?

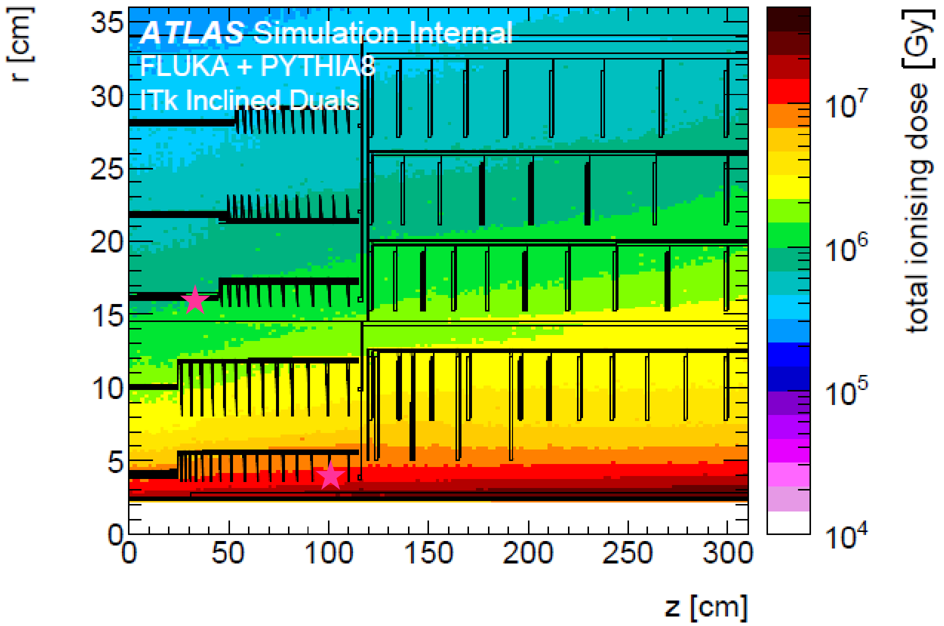
Thinner active thickness and optimized p+ doping

Radiation environment

- Expected radiation level for 4000fb^{-1}
  - Non Ionizing Energy Loss (NIEL):
    - 3rd layer: 2.8x10^{15} n$_{eq}$ /cm^2 1st layer : 2.6x10^{16}neq/cm^2
  - Total Ionizing Dose (TID) :
    - 3rd layer : 1.6MGy 1st layer : 19.8MGy

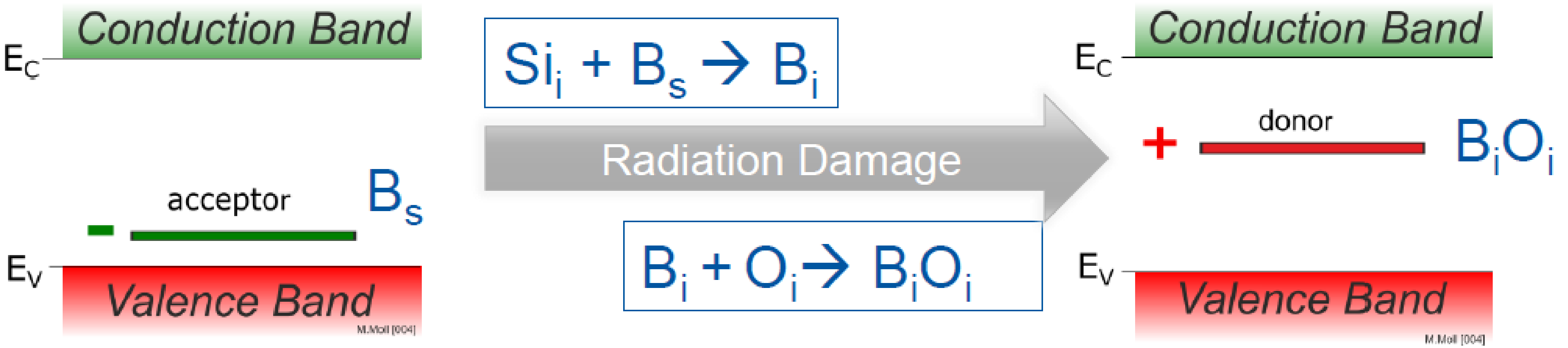
Could replace detector at the middle of runs.





Accepter removal

- Most typical radiation induced reaction:



$Si_i + B_s \rightarrow B_i$

$B_i + O_i \rightarrow B_iO_i$

Phosphorus: shallow dopant
(positive charge)

BD: positive charge
higher introduction after proton than after neutron irradiation, oxygen dependent

E30: positive charge
higher introduction after proton irradiation than after neutron irradiation

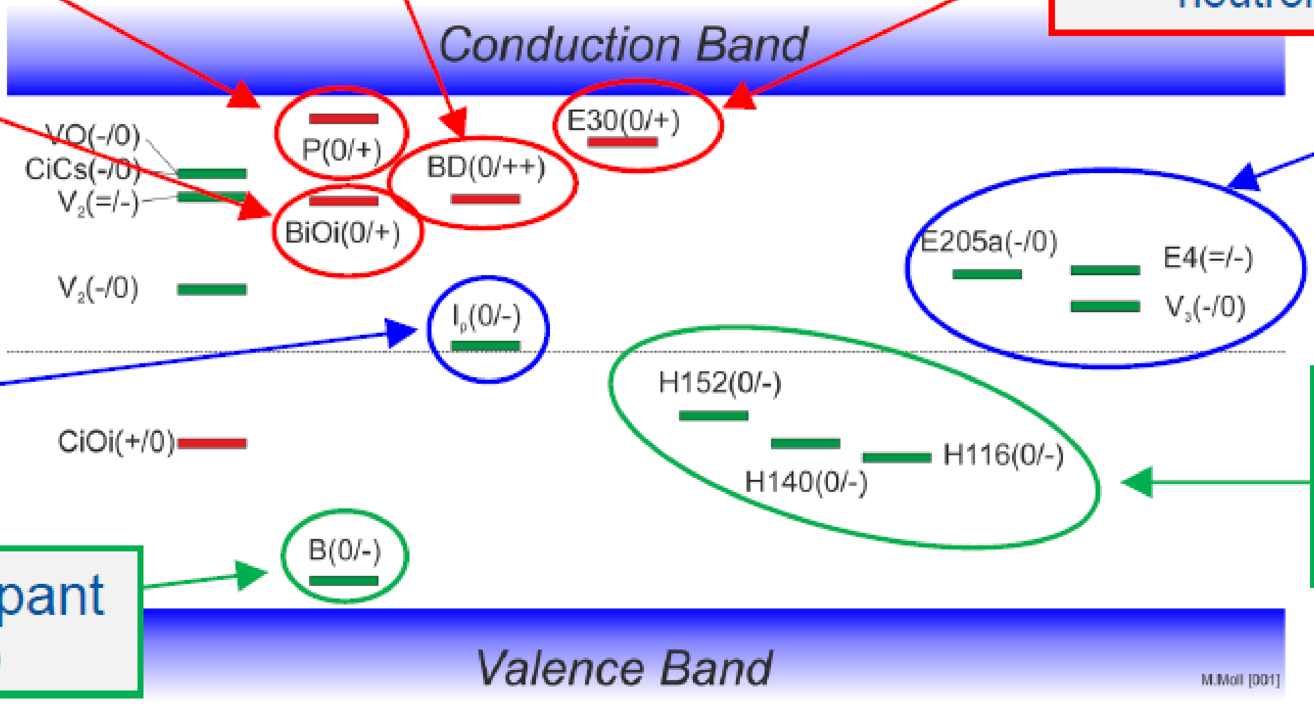
BiOi
(acceptor removal)

Leakage current: V_3

leakage current & neg. charge
current after γ irrad, V_2O (?)

Reverse annealing
(negative charge)

Boron: shallow dopant
(negative charge)

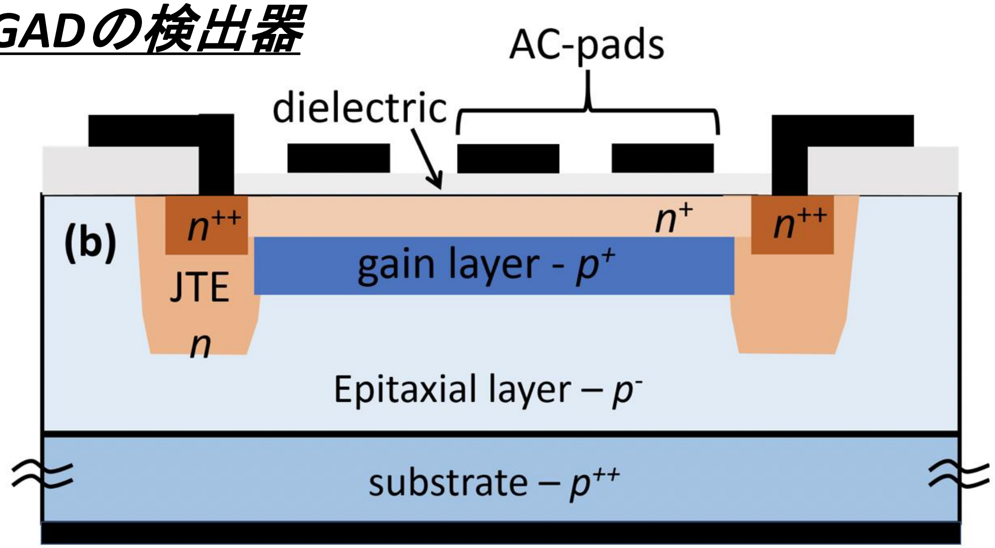


新型LGAD検出器(AC-LGAD)

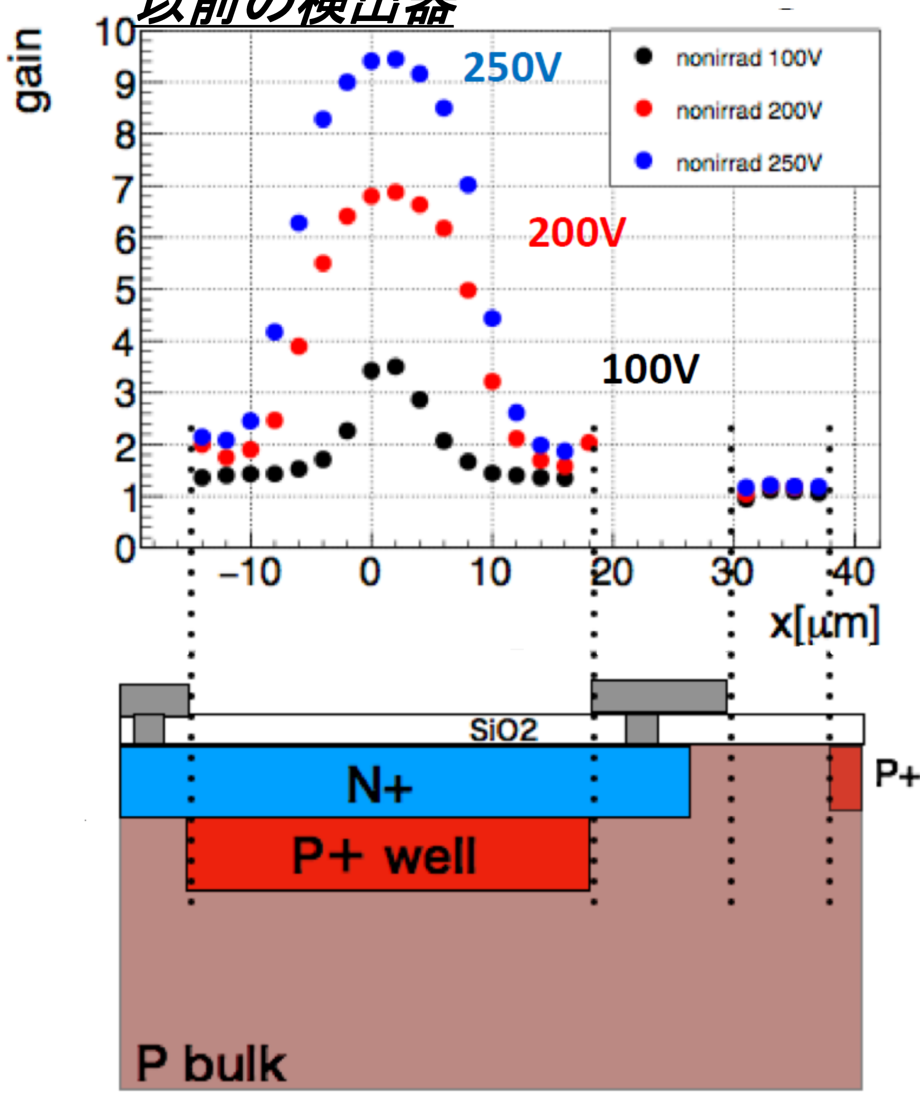
- 電極の細密化が課題
  - 以前の検出器は80umピッチのストリップ型で有感領域が20um程度
  - 各ストリップごとで増幅層が独立(大きくすると電場が不安定)
  - AC-LGAD：一つの増幅層で、AC電極を配置→n+のドープ量を減らして抵抗値を高くしてクロストークを減らす。

➔n+とp+のドープ量で増幅率が決まるので最適化が必要

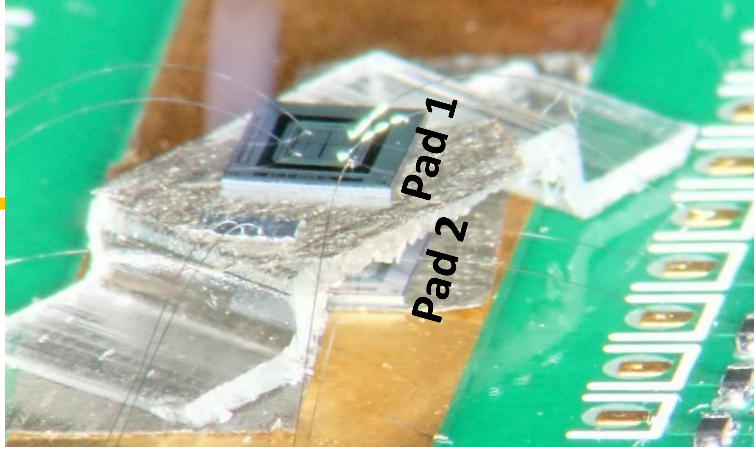
AC-LGADの検出器



以前の検出器

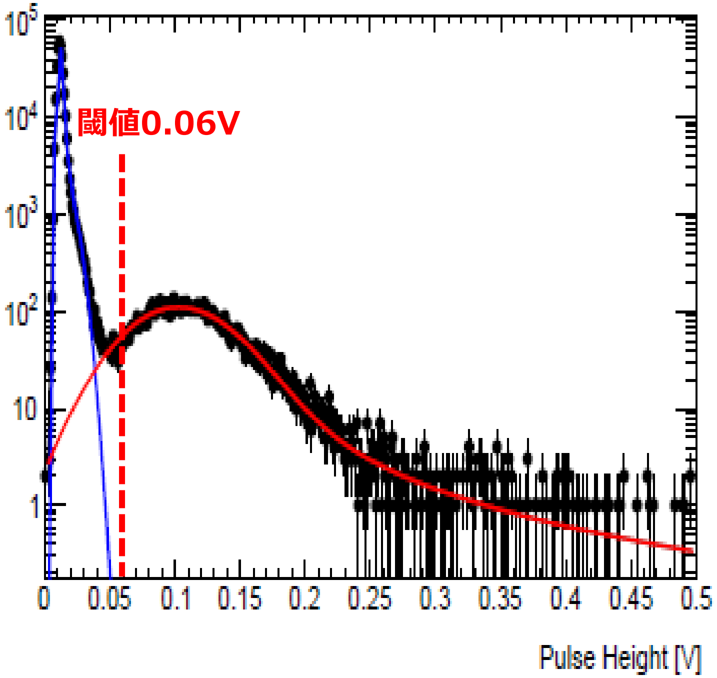


時間分解能の測定

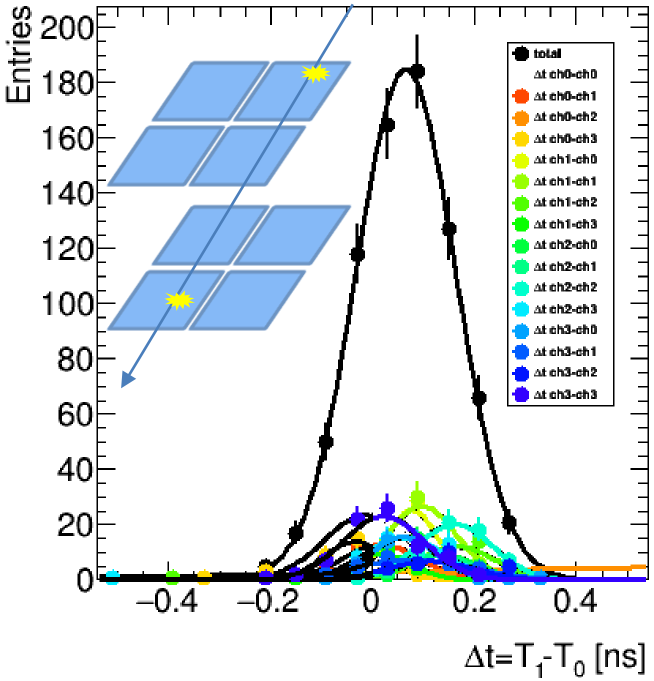


- 二枚の同種のセンサーを上下に配置
  - 時間差分布の標準偏差: $\sigma(T_1\text{-}T_2)=\sqrt{(\sigma_1)^2+(\sigma_2)^2}$
  - 同種のセンサーなので: $\boldsymbol{\sigma_t = \sigma(T_1\text{-}T_2)/\sqrt{2}}$

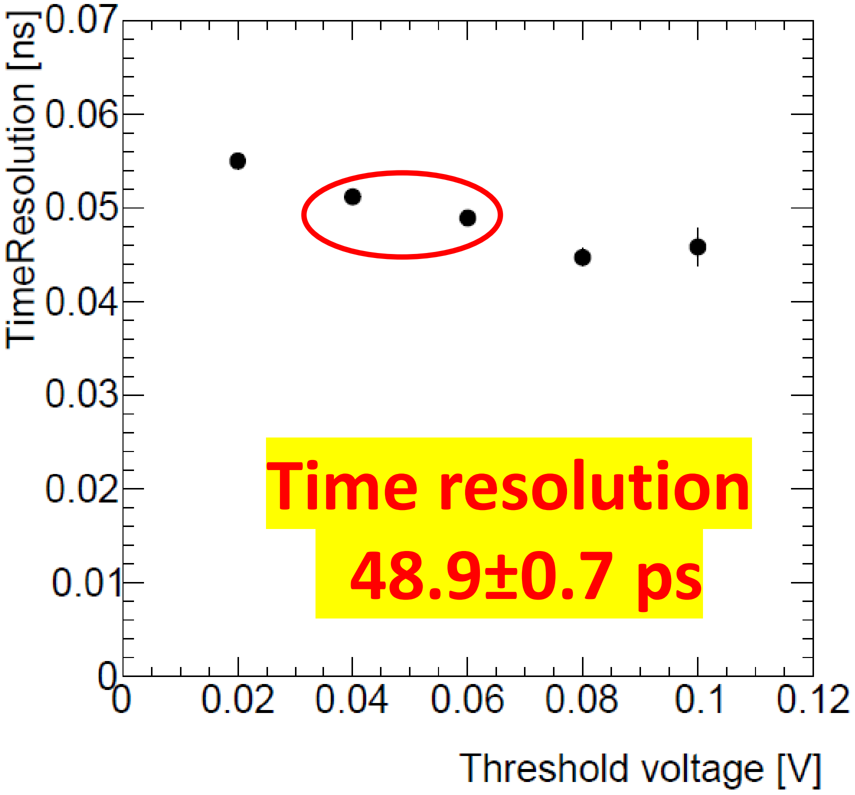
Pulse Height Distribution



Time difference of pad 1 and 2



Timing resolution with certain threshold



Time resolution
48.9±0.7 ps