# 新型LGAD検出器が切り拓く次世代飛跡検出器

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KEK, U.Tsukuba^A^

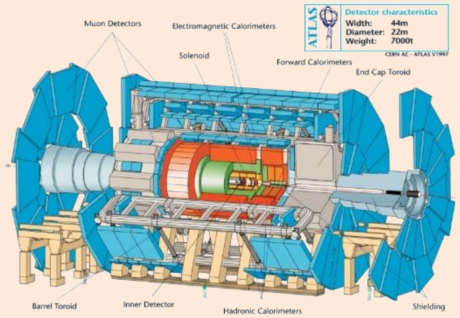
# 背景

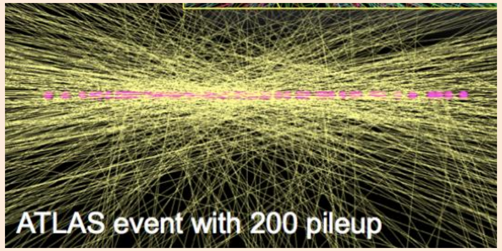
単一粒子に対して30psの時間分解能は光の速度で1cmの距離に相当する分解能！

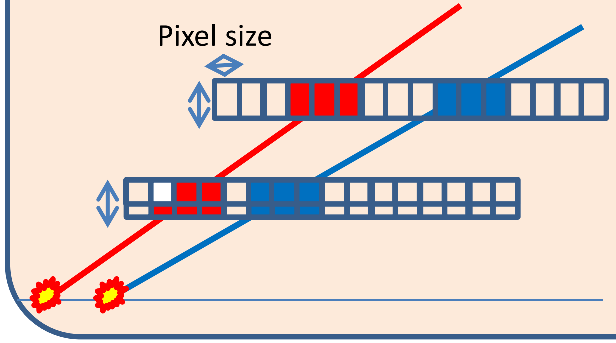
**位置分解能の改良**

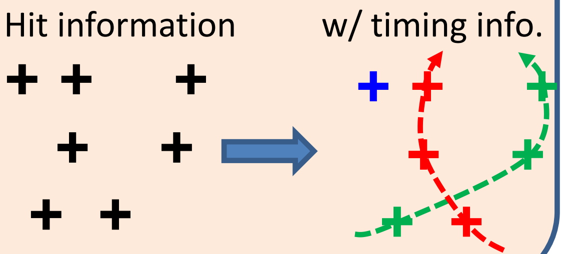
**電極の透明化**

**High Energy Collider**



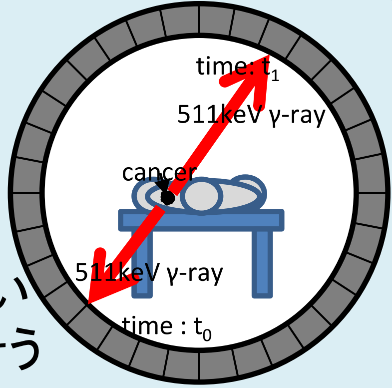






**他分野への応用**

**TOF PET**



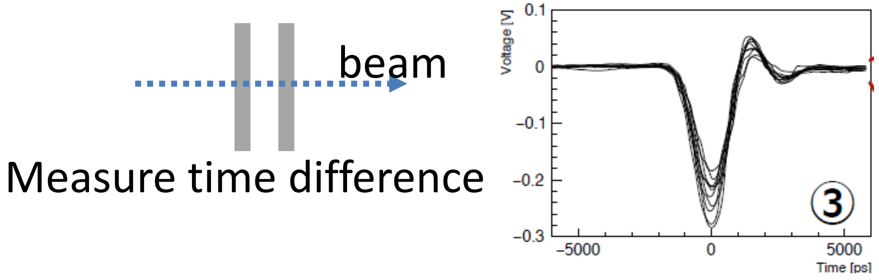
検出効率が低い
単純ではなさそう

**可視光や赤外線に感度があるとイメージング等に応用可能か？**

**高速光イメージング**
**バイオサイエンス**

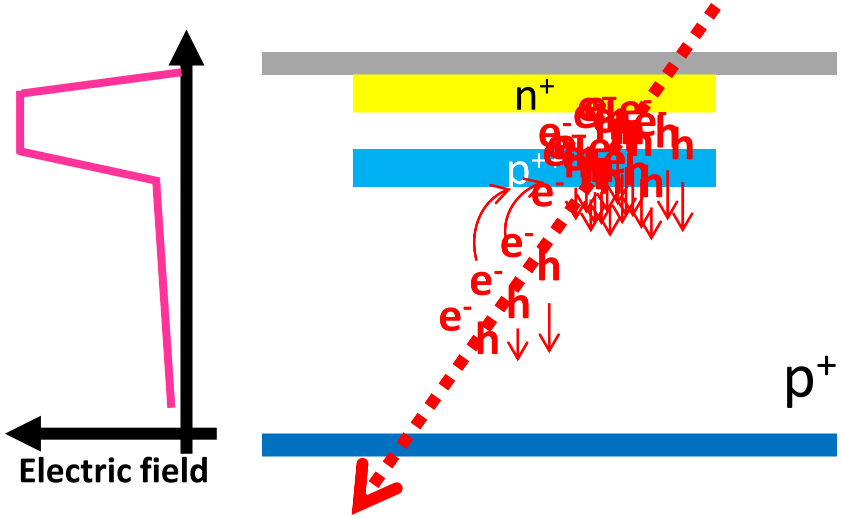
# Low gain Avalanche Diode (LGAD)

- 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**

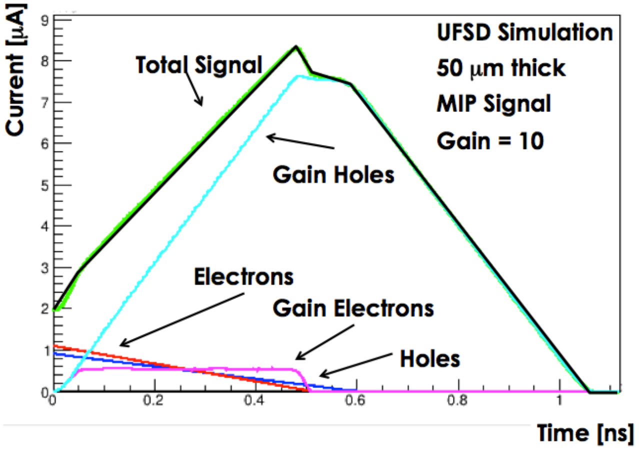


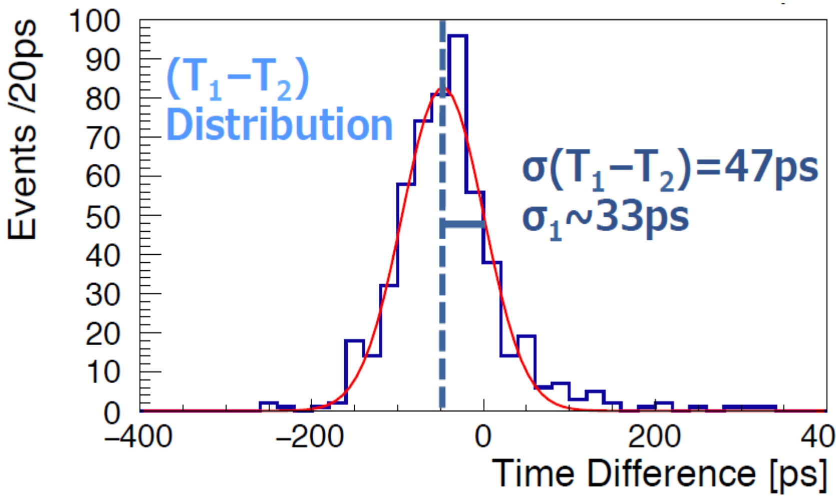
beam

Measure time difference



Signal drivers : **Gain Holes**

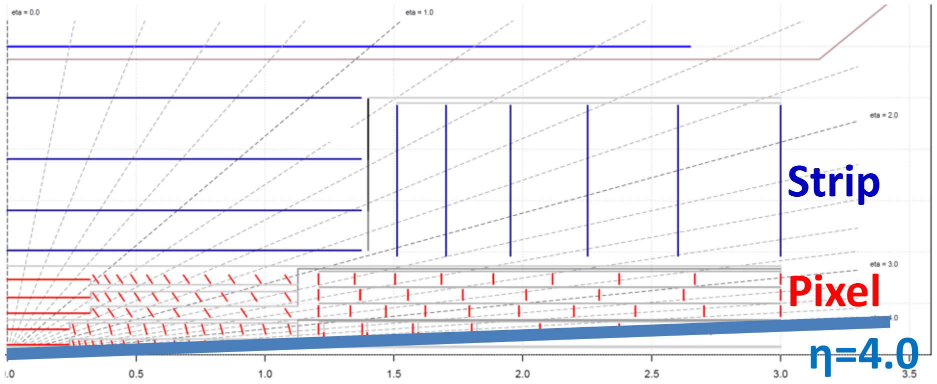




# What we need for Hadron Collider?

- High Luminosity LHC detector

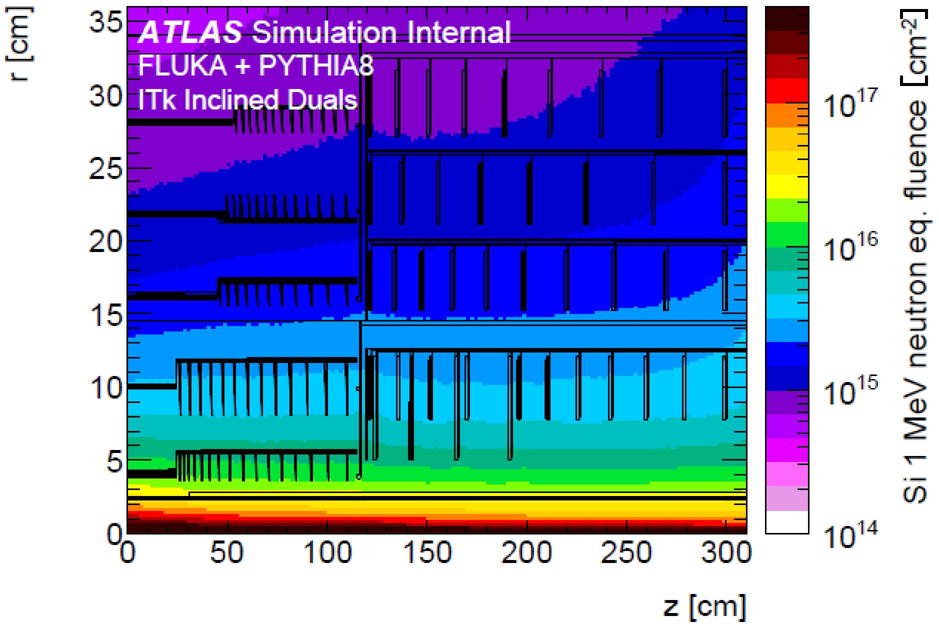
**ITK upgrade detector**



- Strip : ~75.5um pitch
- Pixel : 50um x 50um pitch

**Is this granularity possible?**

- Expected radiation level for 4000fb$^{-1}$
  - Non Ionizing Energy Loss (NIEL):
    - 3rd layer: 2.8x$10^{15}$ $n_{eq}$ /cm$^2$   1st layer : 2.6x$10^{16}$neq/cm$^2$
  - Total Ionizing Dose (TID) :
    - 3rd layer : 1.6MGy  1st layer : 19.8MGy



**Could replace detector at the middle of runs.**

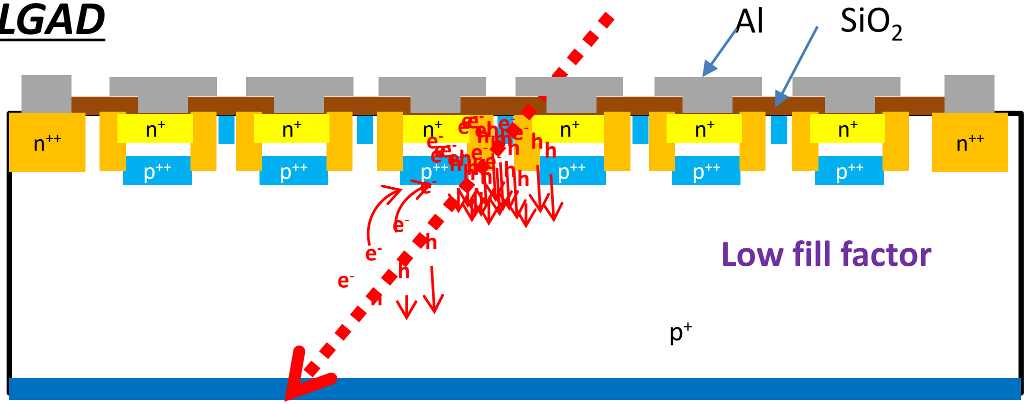
**Survive upto 1e16neq/cm$^2$?**

**If we have LGAD sensor with this granularity and radiation tolerance, all tracker can be replaced by LGAD!**

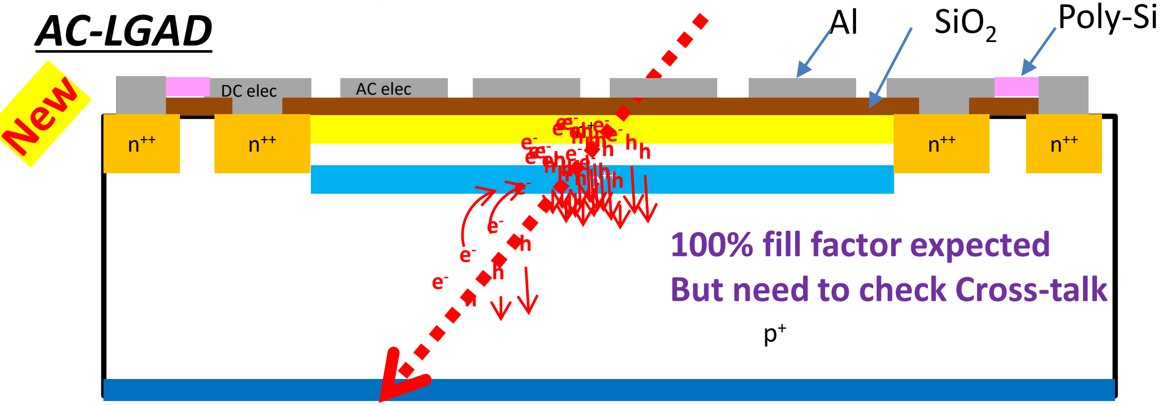
# 高い位置分解能と時間分解能を併せ持つには

- 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**

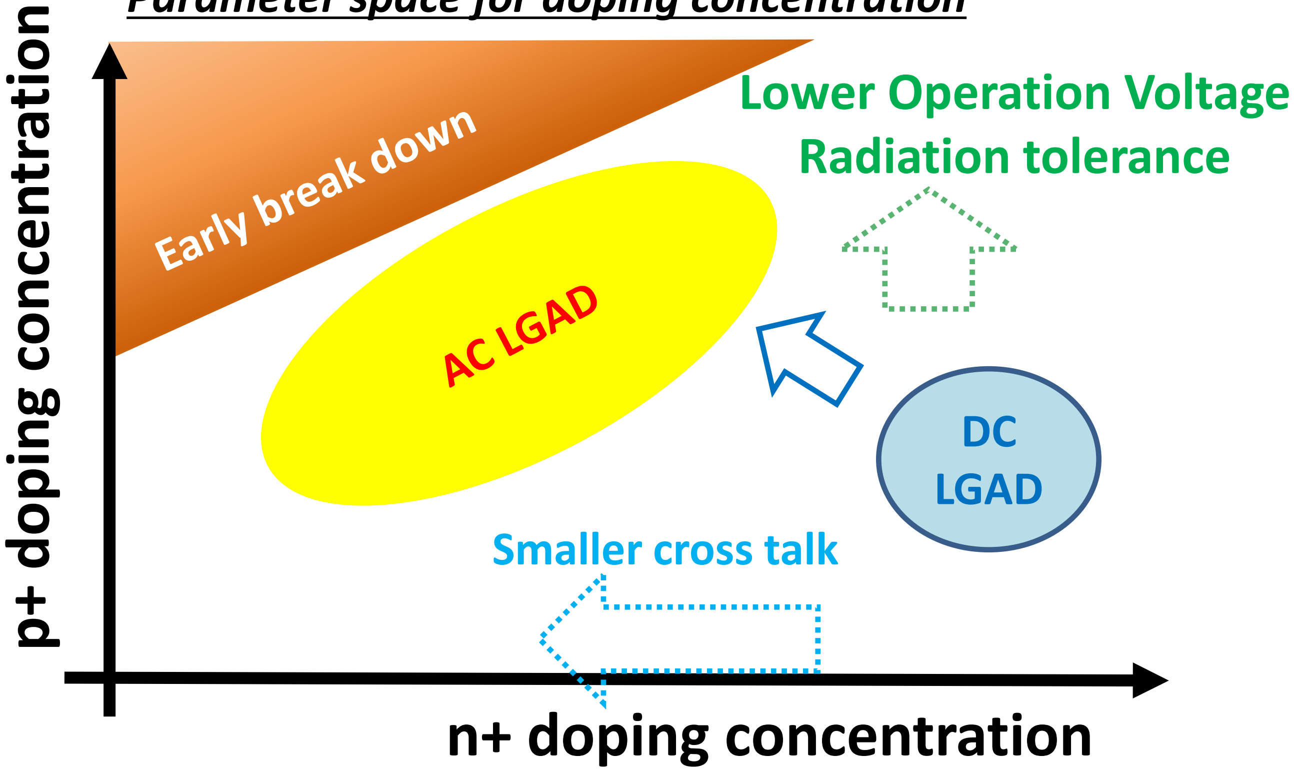
***DC-LGAD***



***AC-LGAD***

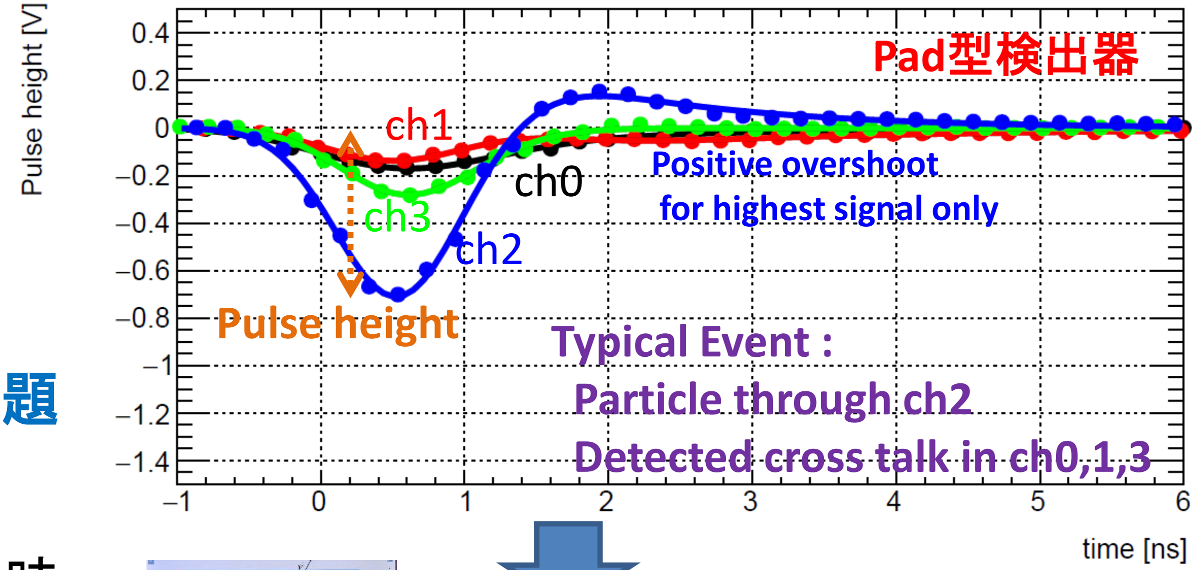


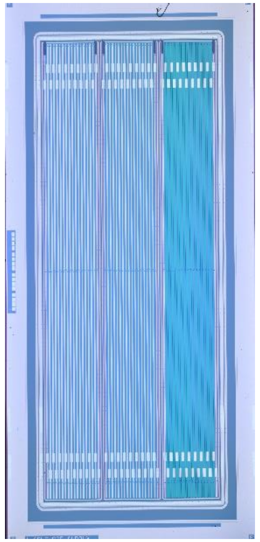
***Parameter space for doping concentration***



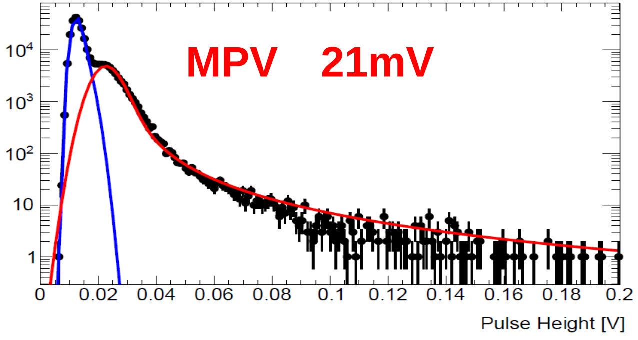
# LGAD検出器の課題と応用

- コライダー用の飛跡検出器
  - ***電極の細分化***
    - 80umピッチのストリップ型
    - 50x50umピッチのピクセル型
    - 信号の大きさとクロストークを抑えることが課題
  - ***放射線耐性*** →**高エネルギー実験用**
    - 5e15 1MeV中性子/cm2程度の放射線照射で時間分解能が30ps->50psほどに悪化する。
- 他分野への応用
  - **MIP粒子に対して30psの時間分解能の検出器の高エネルギー実験以外の応用？**
  - 可視光に対しても応答のある検出器に改良





ストリップタイプの波高分布



信号の大きさが小さい…

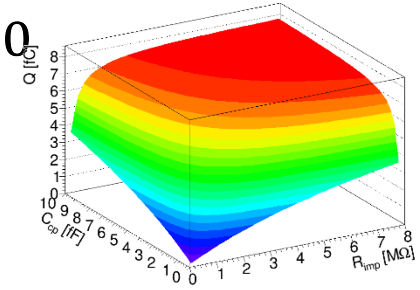
# 細密電極 ：信号の大きさの理解と改善

JFY2019サンプル

- Crosstalk and Readout charge

Assuming $Z_{cbulk}$>>$Z_{Ccp}$…

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



  - Generated charge $Q_0$
  - Readout charge Q

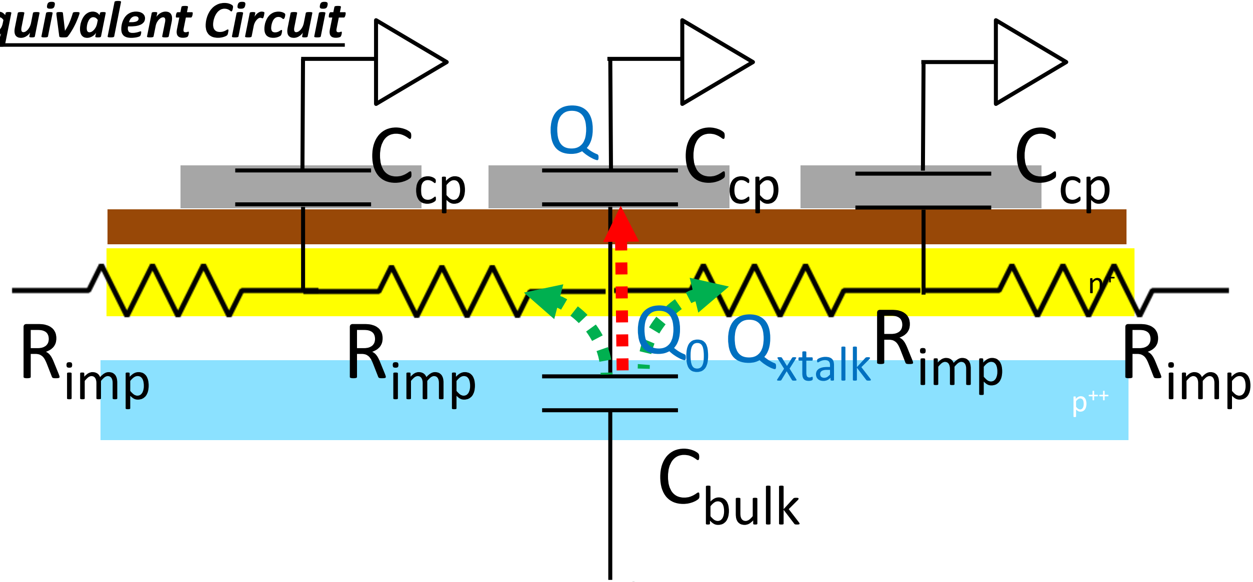
**To have larger signal**

**Larger $C_{cp}$**

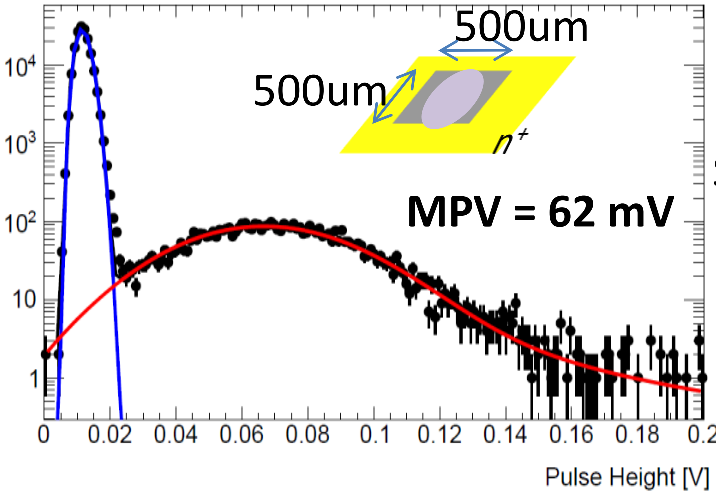
**Larger $R_{imp}$**

*JPS : 12aT3-7 Sayuka Kita (Tsukuba)*

***Equivalent Circuit***



***Pad type***

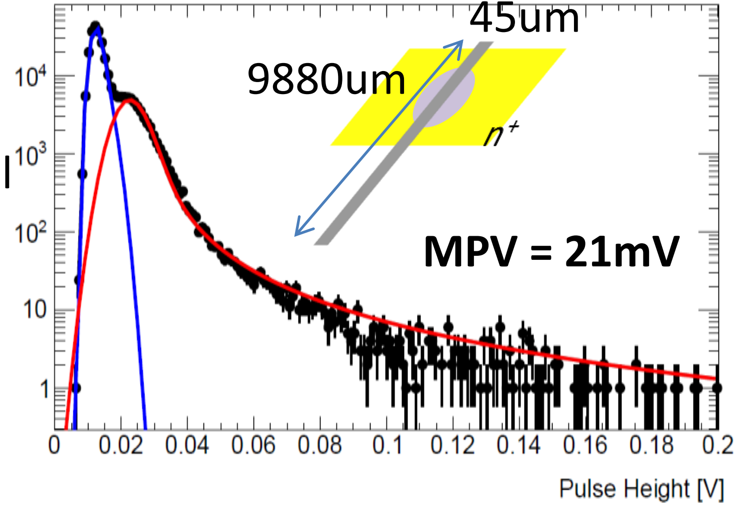


**MPV = 62 mV**

Signal

**x3**

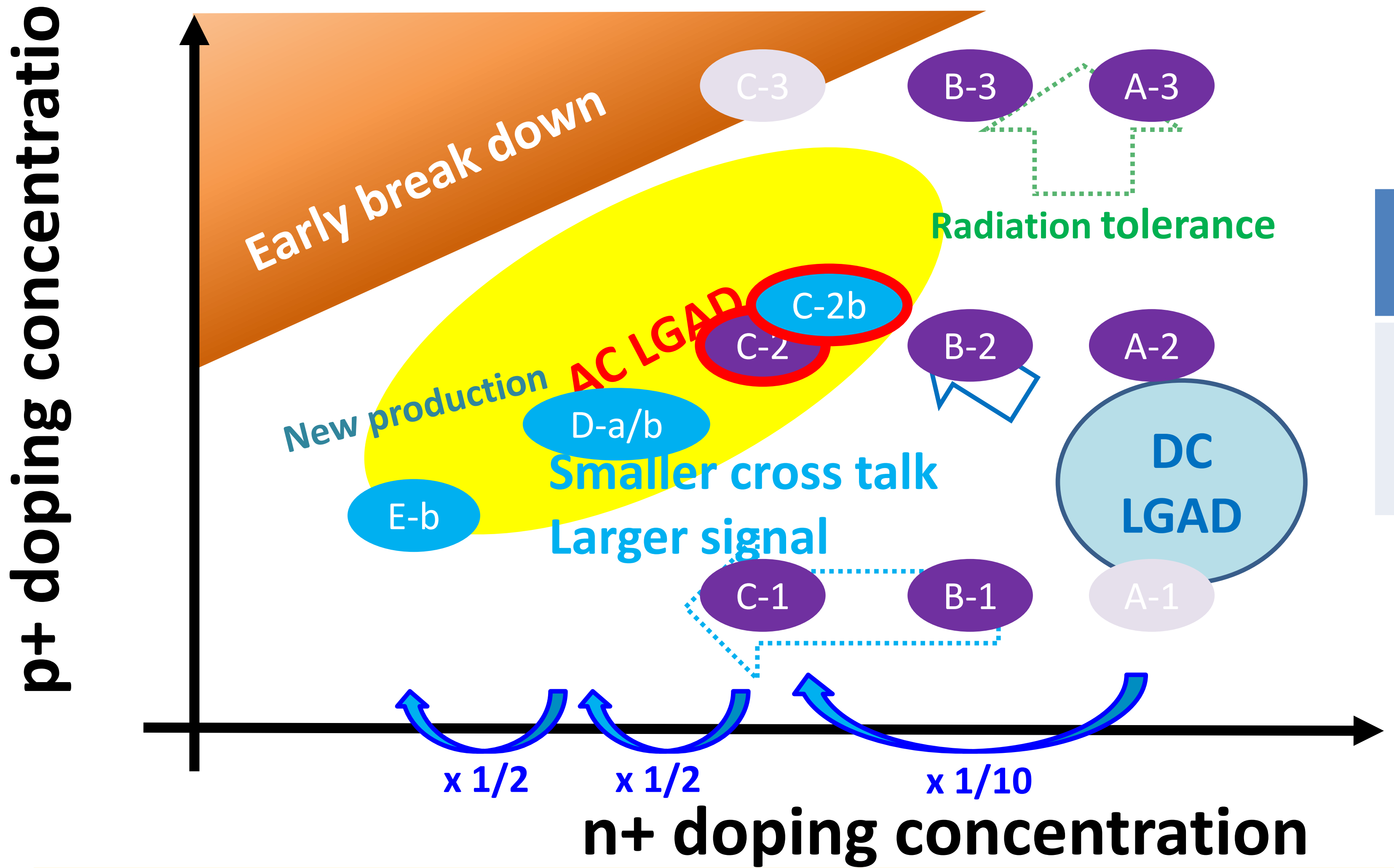
***Strip type***



**MPV = 21mV**

# New samples (4 types of sensors)

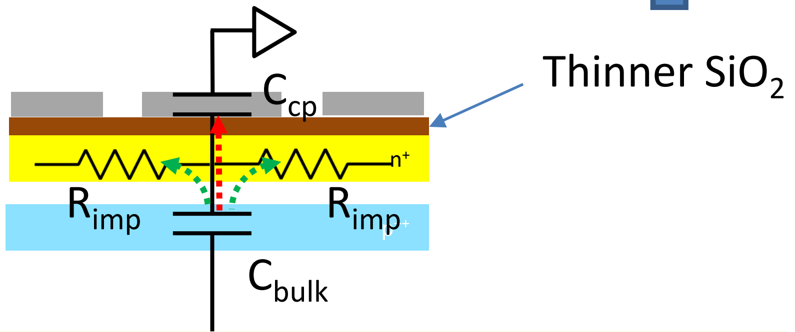
***Parameter space for doping concentration***



🟣 **JFY2019 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 |



# 細密電極　：信号の大きさの理解と改善

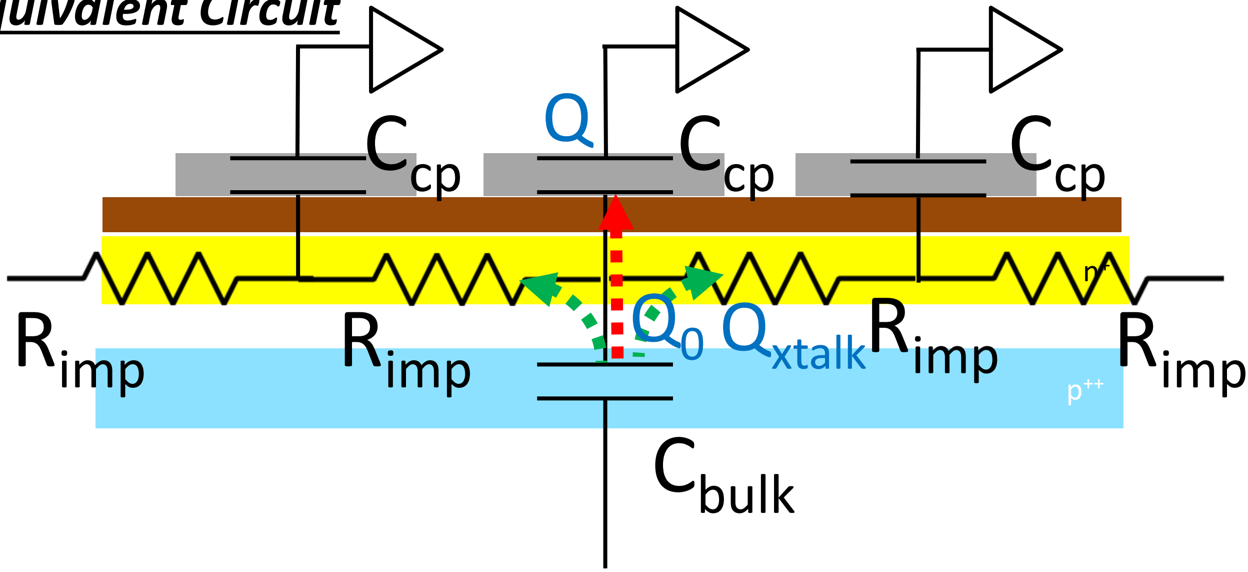
- Crosstalk and Readout charge

Assuming $Z_{cbulk}$>>$Z_{Ccp}$…

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

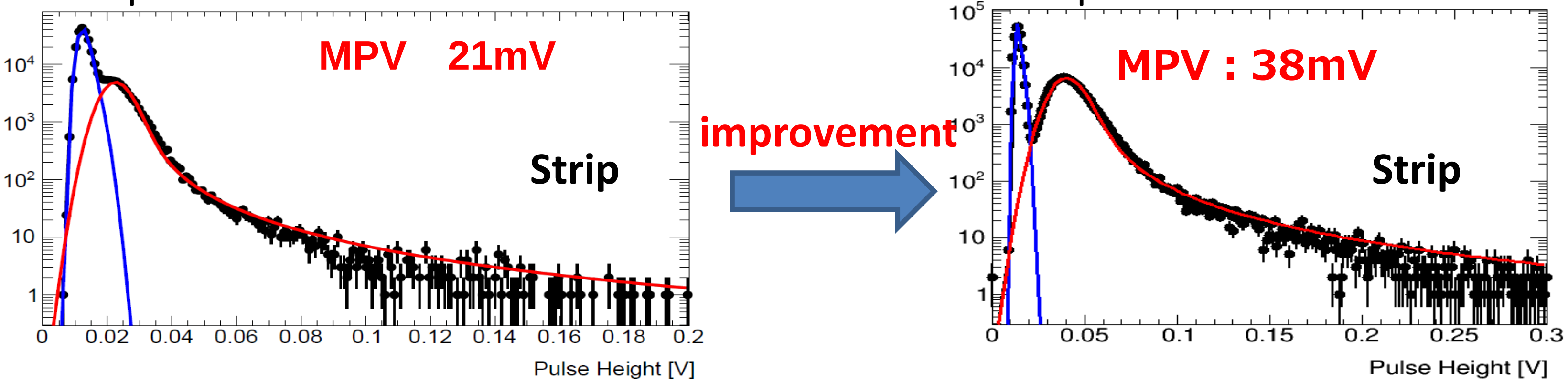
- New strip prototype with :
  - 4x higher n+ resistivity
  - 1.5x larger coupling capacitance

***Equivalent Circuit***



Sample in JFY2019

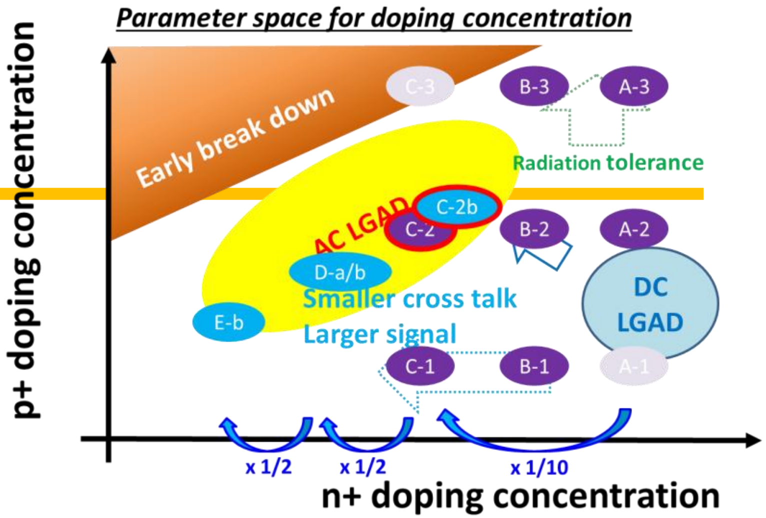
Sample in JFY2020



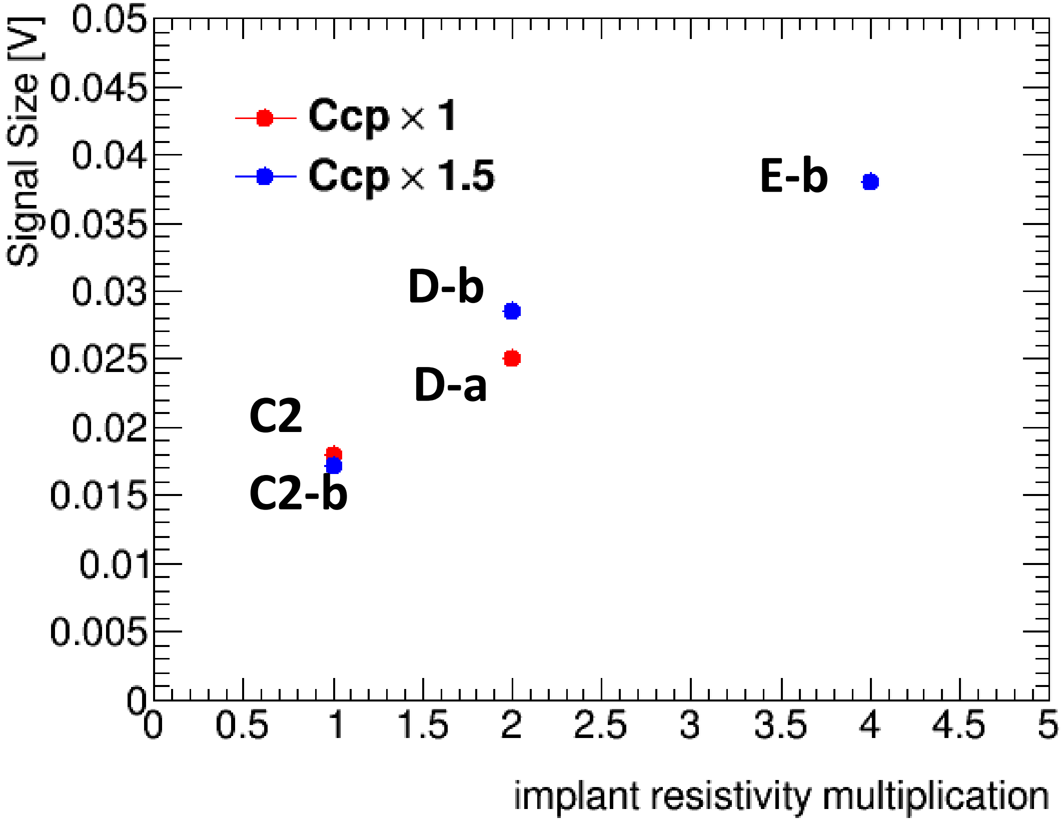
1. **Set a threshold with 99% efficiency, noise rate is less than 1e-3.**
2. **Cross talk distance is 87.4um ~ 1 strip.**

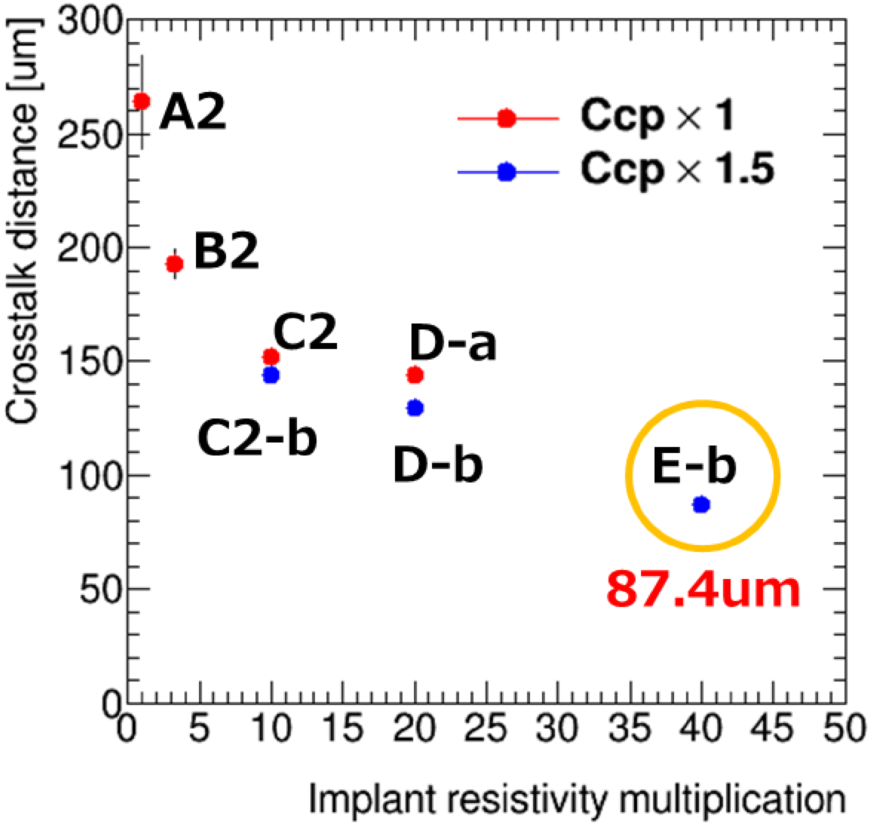
**Signal size & position resolution is good enough for tracking detector.**

# 細密電極　：信号の大きさの理解と改善



- 信号とクロストークの大きさのn+インプラント抵抗値依存性を確認
  - **n+インプラント抵抗が大→信号が大、クロストークが小**

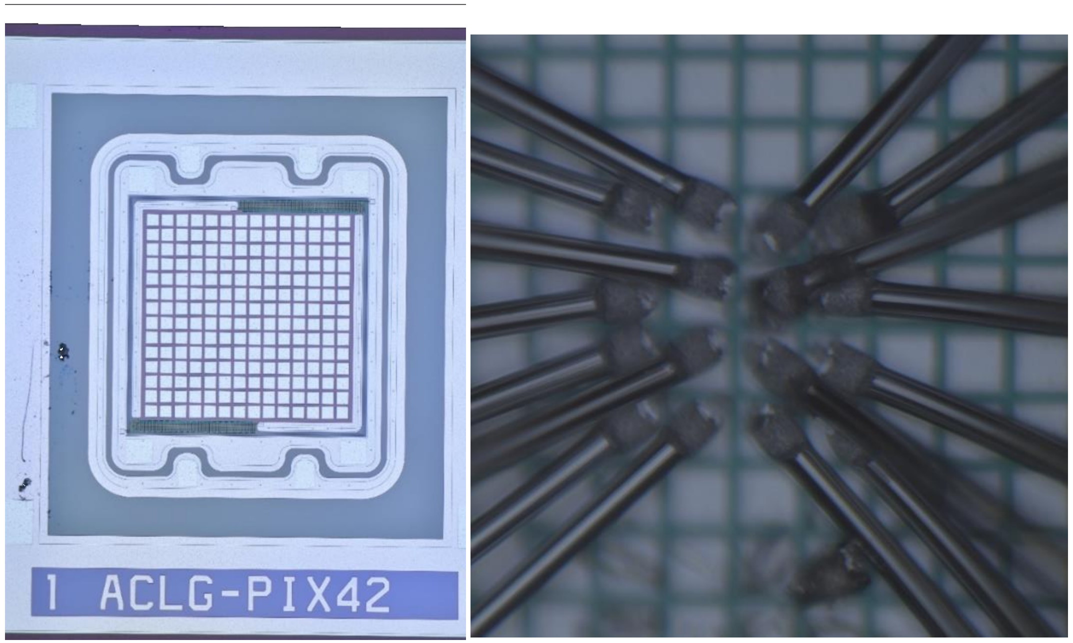


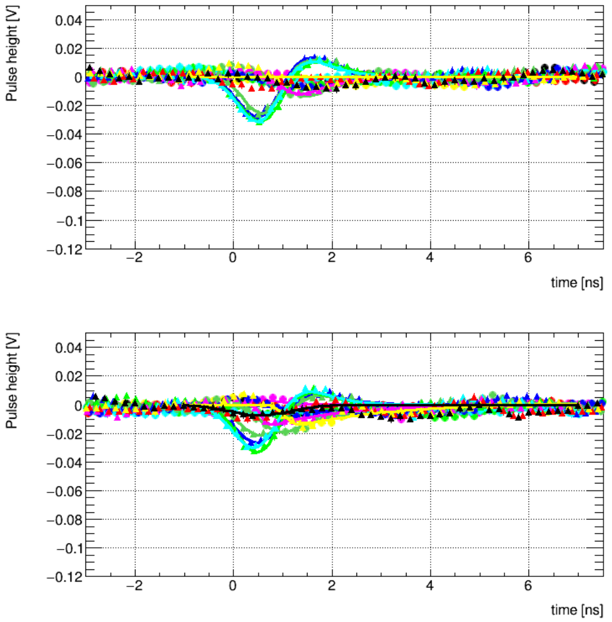


# New challenge！ Pixel detector

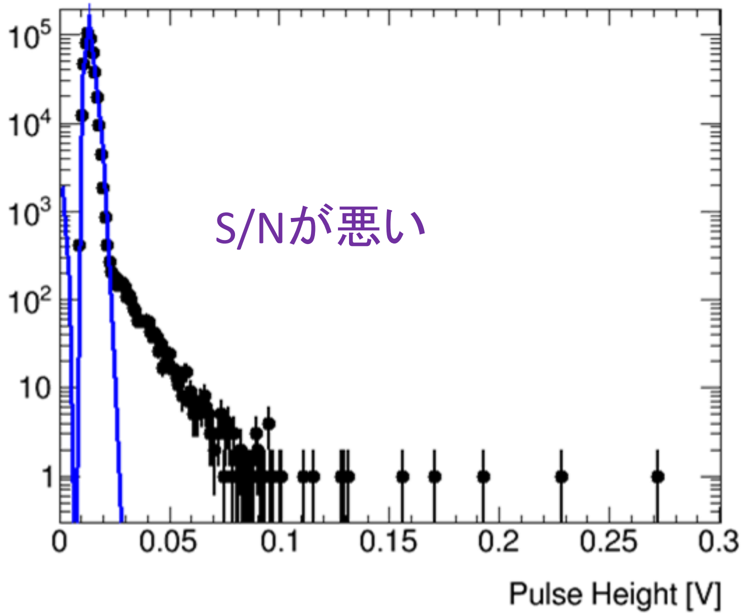
- 50um x 50um pitchのピクセルセンサーを制作
  - ワイヤーボンドして4x4ピクセルだけ読み出し
  - AC-LGAD pixelセンサーの信号を初めて観測
    - 大きなクロストーク(or ワイヤーボンドのショート？)
    - **ただし、信号の大きさが小さく、S/Nが不十分**

**明らかに改善が必要**





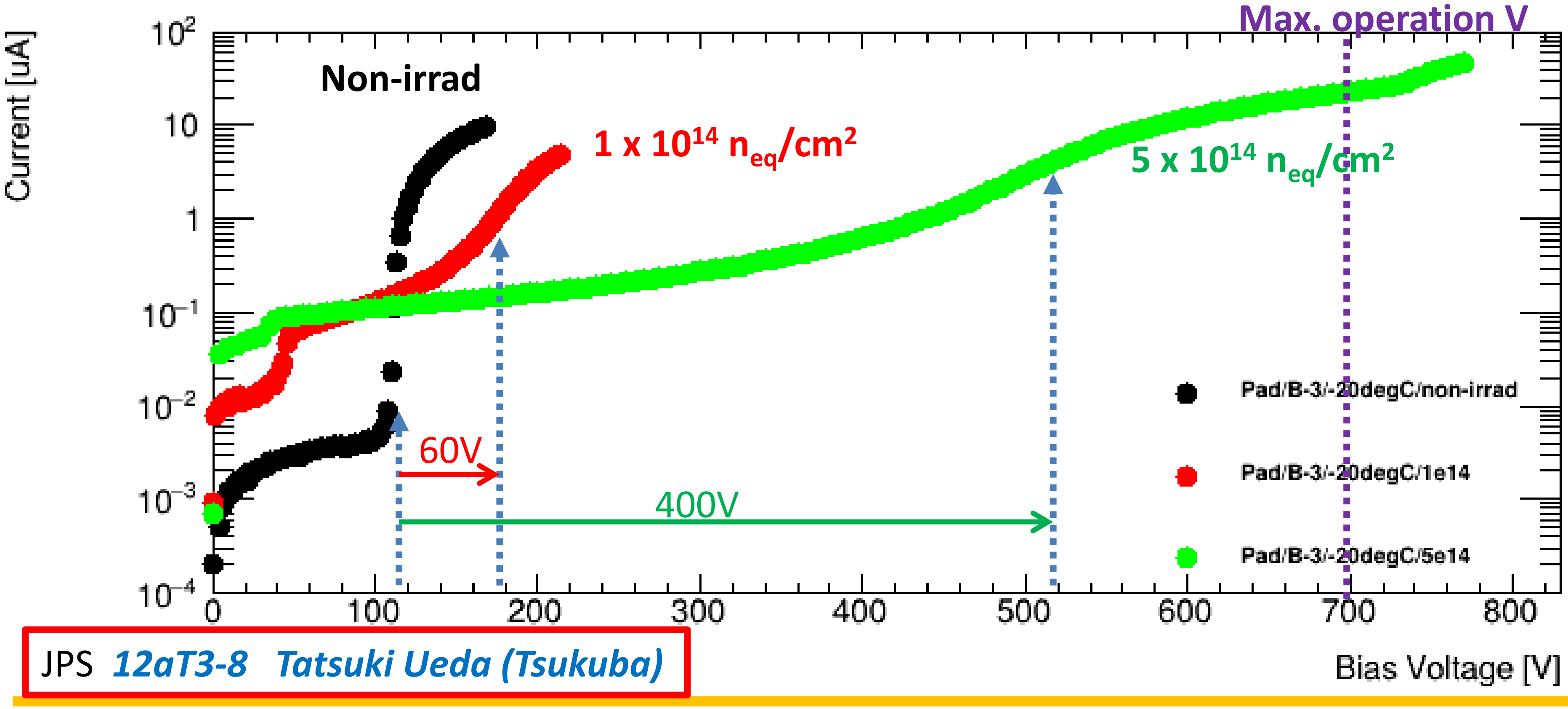
波高分布



S/Nが悪い

# 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 1x10$^{15}$n$_{eq}$/cm$^{2}$ fluence or more.**



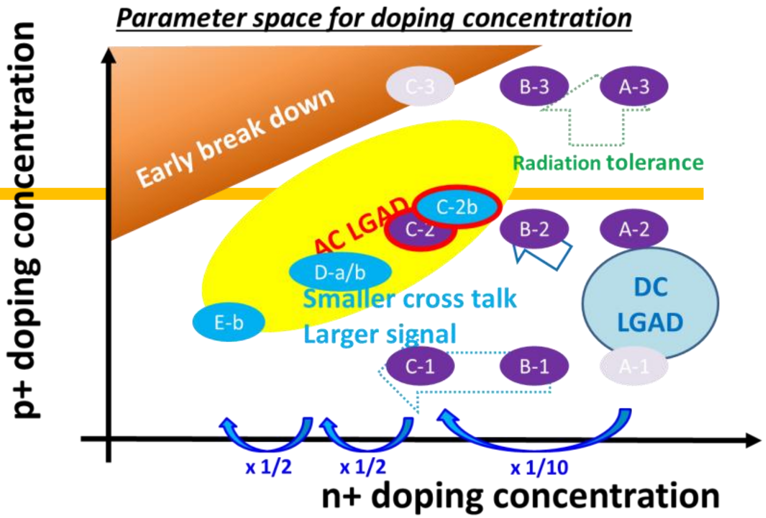
JPS *12aT3-8 Tatsuki Ueda (Tsukuba)*

**Signal Size**

| Fluence | Signal MPV |
|---|---|
| Non-irrad | 35±2 mV |
| 1x10$^{14}$n$_{eq}$/cm$^{2}$ | 39±1 mV |
| 5x10$^{14}$n$_{eq}$/cm$^{2}$ | 30±2 mV |

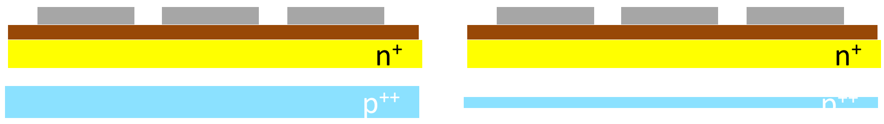
**5x10$^{14}$n$_{eq}$/cm$^{2}$ may have slight decrease of signal (But keep at least ~75%)**

# 放射線耐性の改善



- **P+ドープ量が高いほど放射線耐性に優れている**
  - P+ドープ量が小さいほどGain Voltageが高い。
  - 陽子線照射によってP+層のアクセプタリムーバルで見かけのドープ量が小さくなりGain Voltageが上がる。
  - 耐圧を超えたときに寿命を迎える
- **P+ドープ量が高すぎると(特にn+濃度が低い場合)**
  - 放射線損傷前のセンサーでGain Voltageが低すぎる(全空乏化電圧近くでbreak)

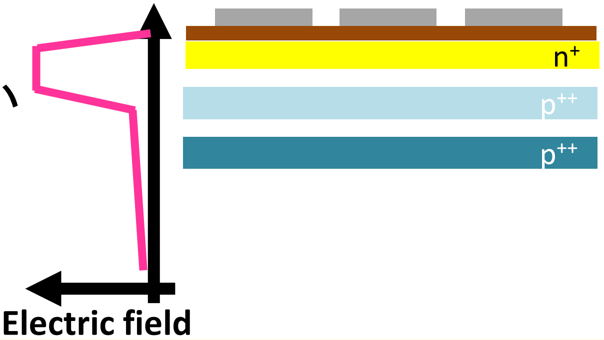
深さ方向の広がりを小さくする



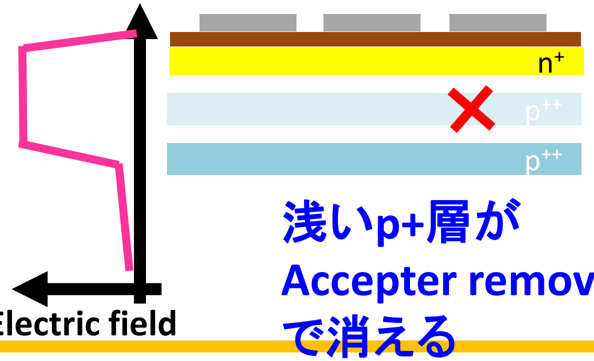
改善のアイデア
- ➢ P+ドープの深さ方向の広がりを小さくする
- ➢ P+ドープのプロファイルを変えて解決できないか
  - ➢ 例えば二層構造

**シミュレーションで検証予定**

放射線損傷前



放射線損傷後

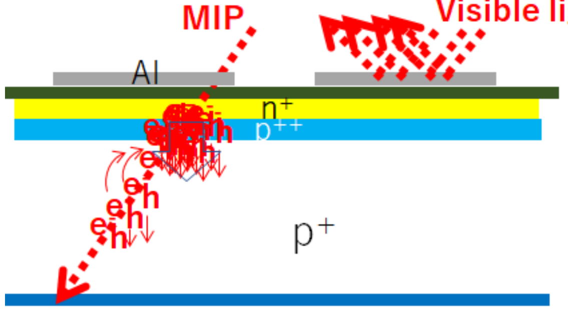


**浅いp+層が Accepter removal で消える**

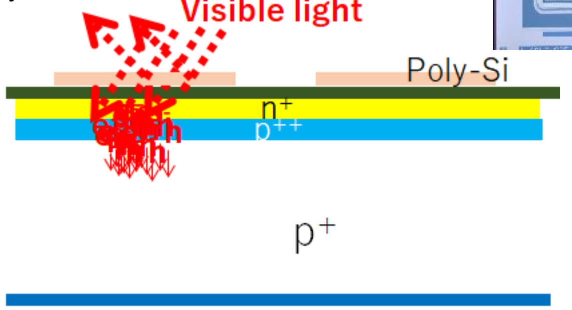
# Poly電極AC-LGAD

- AC電極をAlではなくPoly-si(300um)にすると可視光の約50%が透過(TBC)
- 可視光の検出が可能
  - 異分野への応用の幅がひろがる
- パッド検出器とストリップ検出器でPoly-si電極のセンサーを製造済み
- **最初のサンプルを測定 (とりあえずベータ線)**

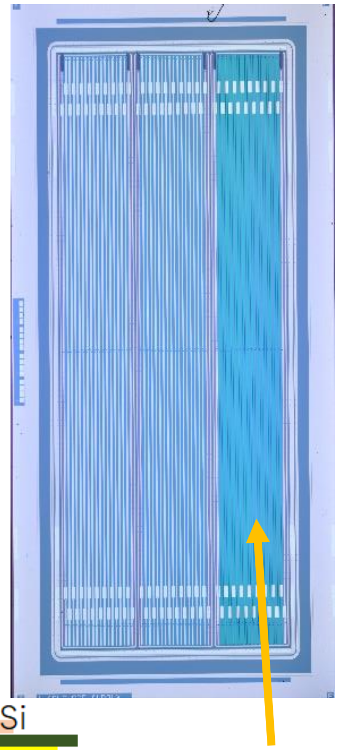
通常のAl電極 AC-LGAD



Poly-si 電極 AC-LGAD

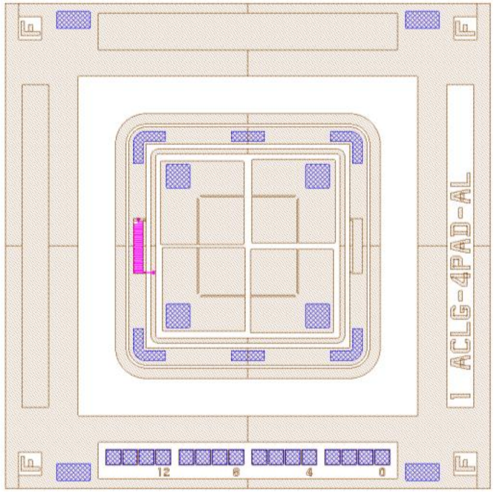


ストリップ型

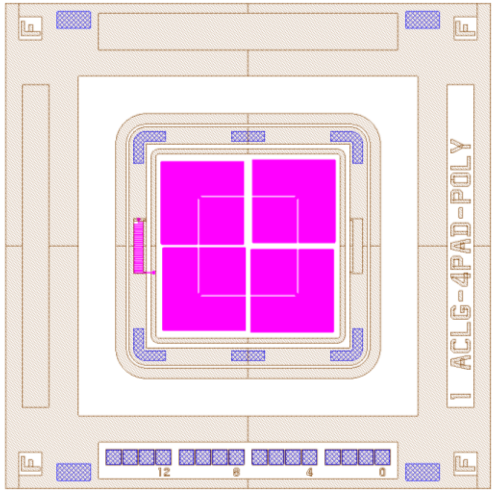


Poly-si

通常のAC-LGAD



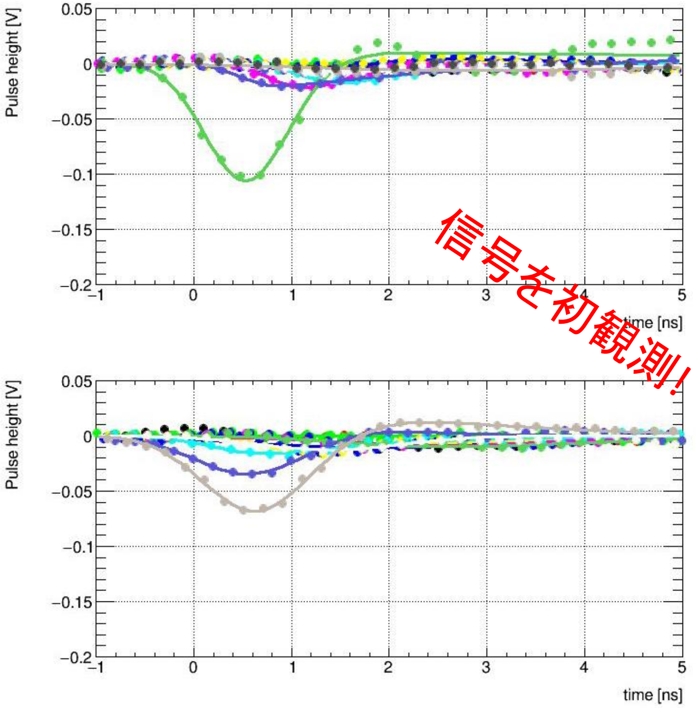
Poly-Si電極 AC-LGAD



# Poly-si電極AC-LGAD ベータ線試験

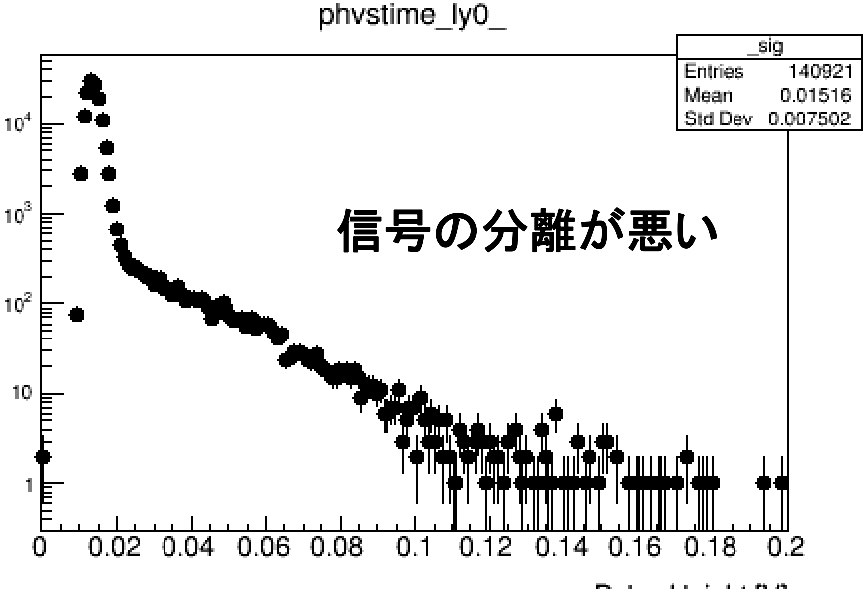
Preliminary

- ストリップセンサー(80umピッチ)の信号とクロストークを評価
  - Al電極と比較するためベータ線で信号を観測
    - 信号の大きさはAl 電極と比較して同程度
    - クロストークはAl電極と比較して小さく見える。(次ページ)



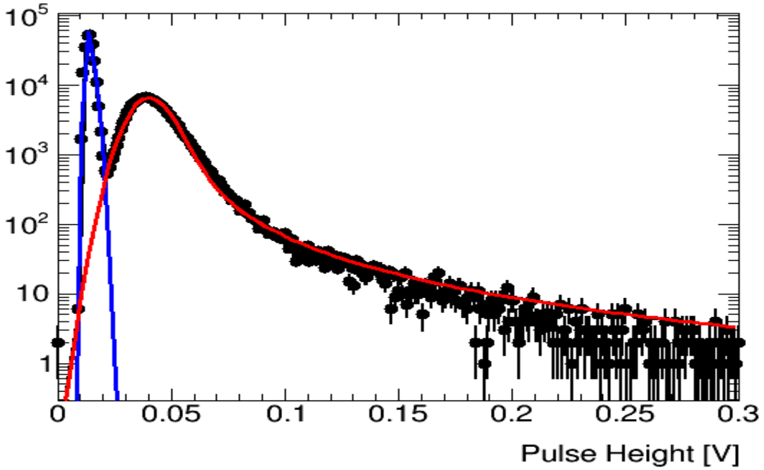
信号を初観測!

Poly-Si電極



信号の分離が悪い

Al電極

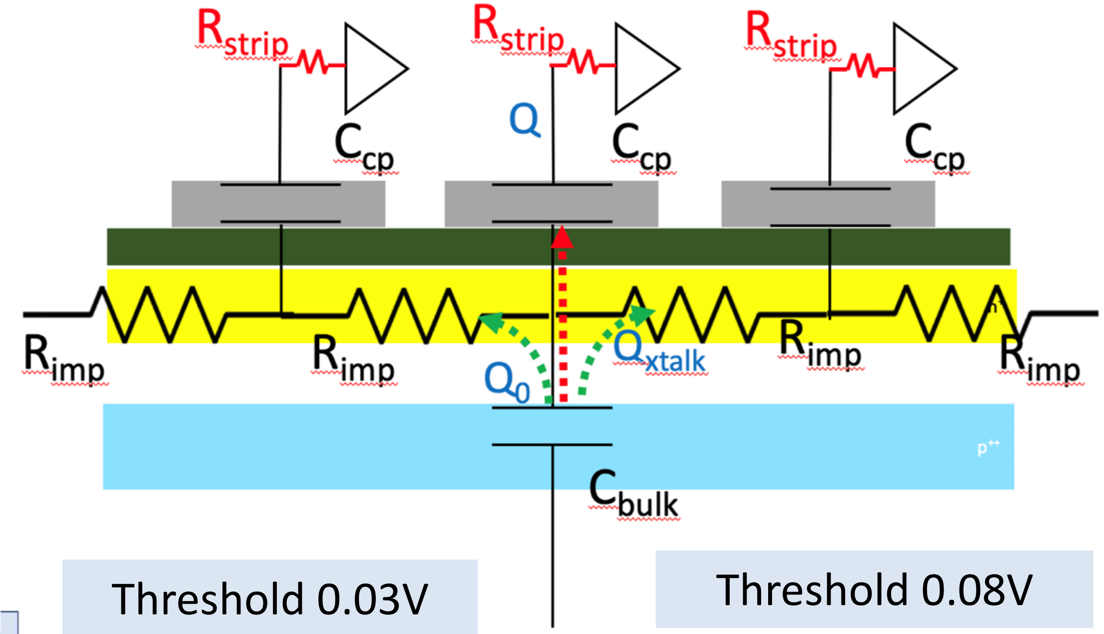


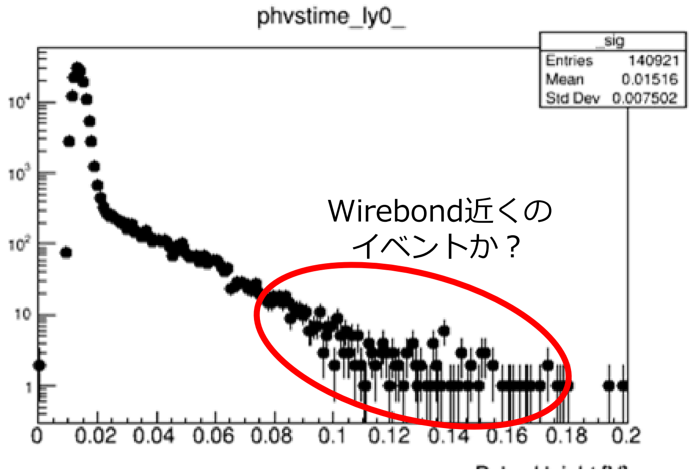
# Poly-si電極AC-LGAD ベータ線試験

- Crosstalk and Readout charge

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

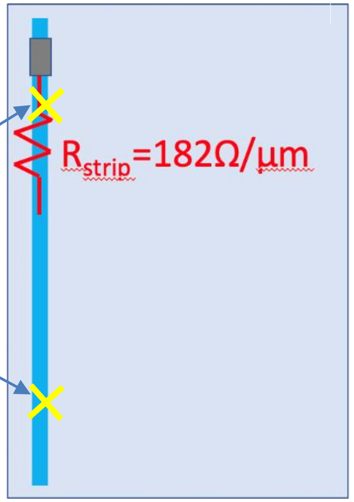
- $Z_{R_{strip}}$ はワイヤーボンドパッドからの距離に比例 (182Ω/um)



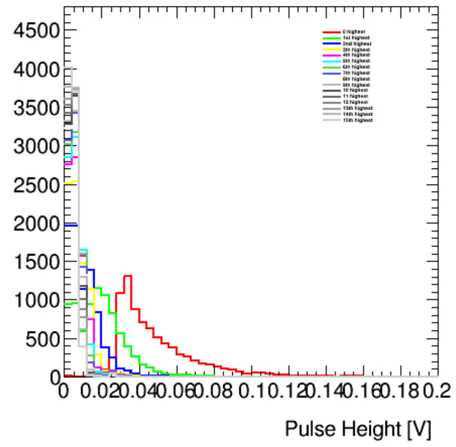


ワイヤーボンド
パッドに近い
信号大
クロストーク小

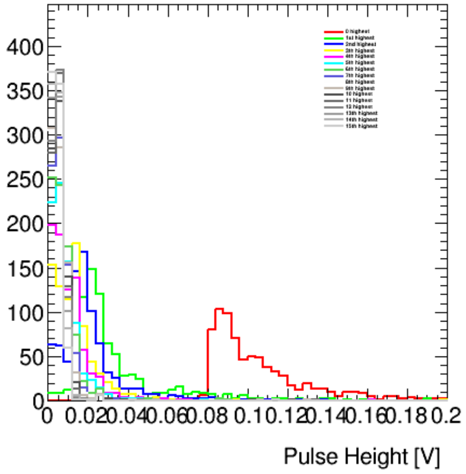
ワイヤーボンド
パッドから遠い
信号小
クロストーク大



Threshold 0.03V



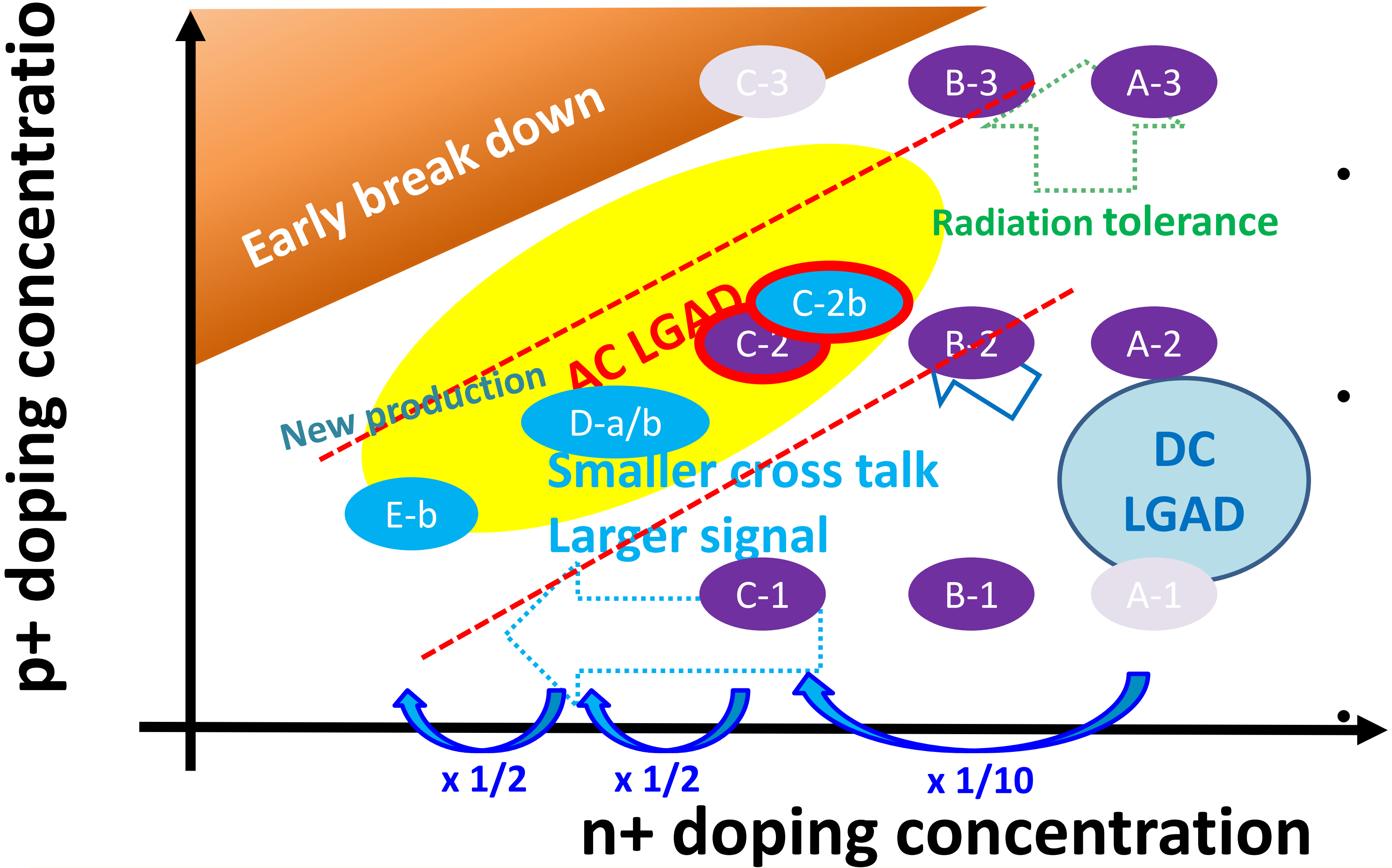
Threshold 0.08V



**ポリシリの抵抗値を下げる必要がある。**

# まとめ

***Parameter space for doping concentration***



● **JFY2019 Samples**

● **New Samples (26th Mar)**

- ***電極の細密化***
  - **E-b typeがベスト**
  - **S/Nの良いストリップ検出器が完成**
  - ピクセル検出器は改善が必要
- ***放射線耐性***
  - **B-3がベスト。(ただしクロストーク大)**
  - p+ドープ量が多いほどよい。(照射後も$V_{op}$がさほど高くならない)
  - **C-2タイプでは5e14くらいまで。**
  - DやEタイプはさらに耐性が弱いか…
- ***ポリシリ電極(他分野応用)***
  - PAD型はAl電極と同様に動作
  - Strip型は抵抗値を下げる必要がある

# backup

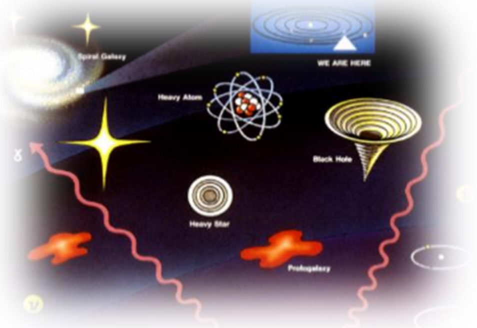
# Motivation

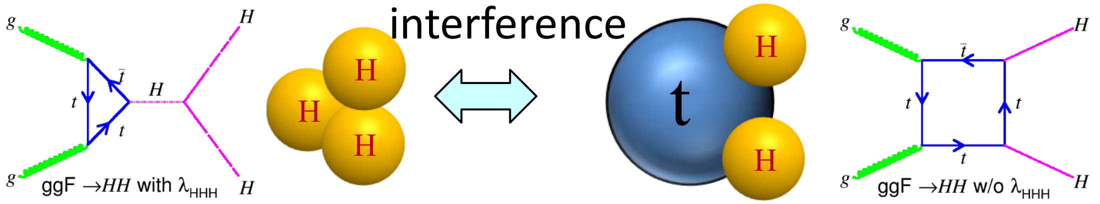
## Higgs discovery and measurement by LHC experiment

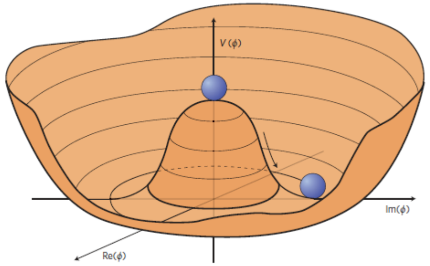
**New era!**

- ***“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.

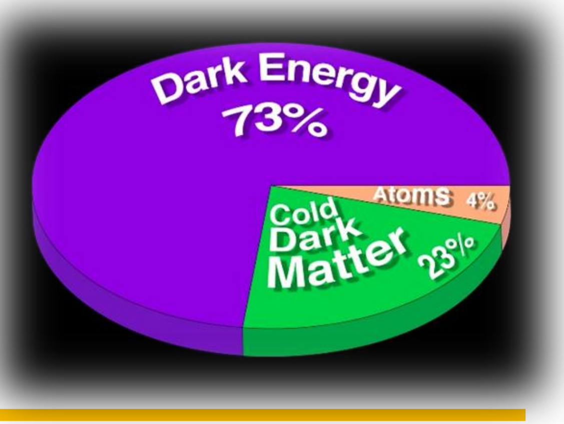
  →Observe/measure “Higgs self coupling”.







- ***“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)***
    - 20 times more data (~3000-4000fb$^{-1}$) at **14TeV**
    - Plan : Start at 2027

**Coming soon**

  - ***High Energy LHC (HE-LHC)***
    - Use Super Conducting Magnet with Higher Magnetic field(16T)
    - **28TeV** collider in the same tunnel as LHC.

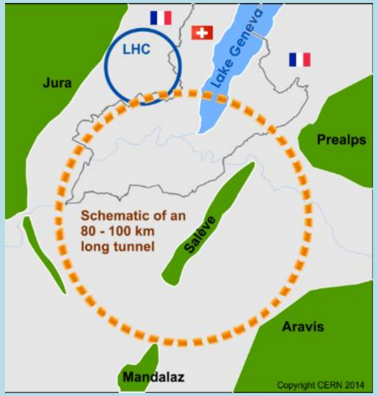
**Discussion Started**

  - ***Future Circular Collider (FCC-hh)***
    - Use Super Conducting Magnet with Higher Magnetic field(16T)
    - **100TeV** collider with 100km tunnel at CERN.

**Discussion Started**

  - ***International Linear Collider (ILC)***
    - 250GeV e+ e- collider in Japan

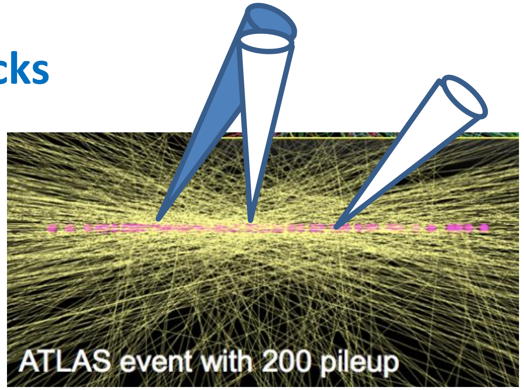
**Final decision soon**



## Inner Tracking system

**Very high density tracks**

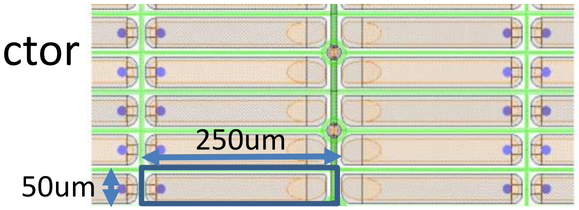
**140 pileup @ HL-LHC**
**1500 pileup @ FCC-hh**



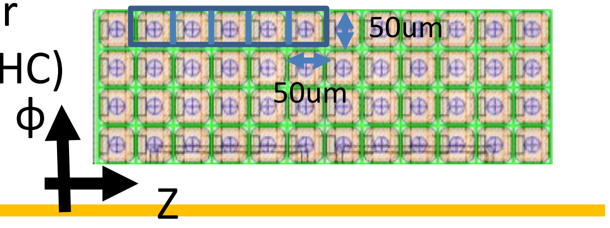
**Only way to solve this so far…**

**finer pixel pitch**

Current detector
(ATLAS IBL)



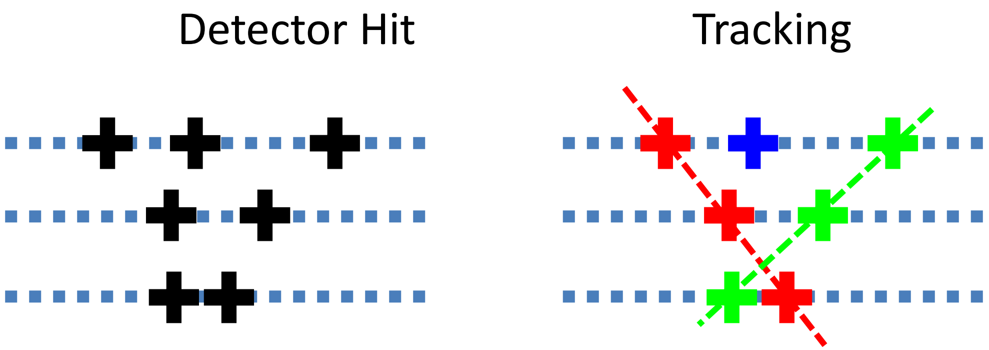
New detector
(Pixel @HL-LHC)



# Future Semi-conductor Tracking Detectors

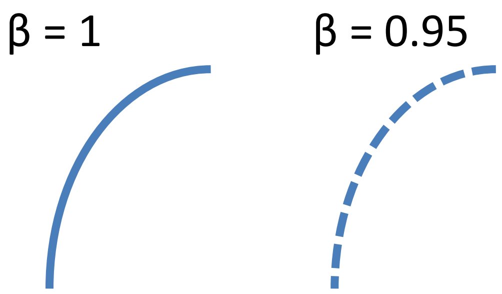
- **Further finer pitch pixel detector → Limited by front end Electronics (min : $50x50um^2$)**
  - In addition to spatial resolution, **Timing resolution helps!**
  - **→New generation of Tracking detector should have timing information for all hits!**
- **Tentative Requirement**
  - **30ps timing resolution**
  - **~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**

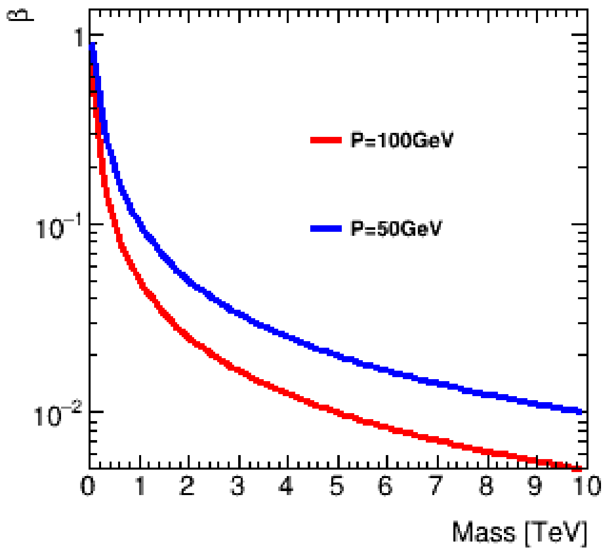
**Particle identification**



**150ps difference at R=1m**

**K+ π+ separation**

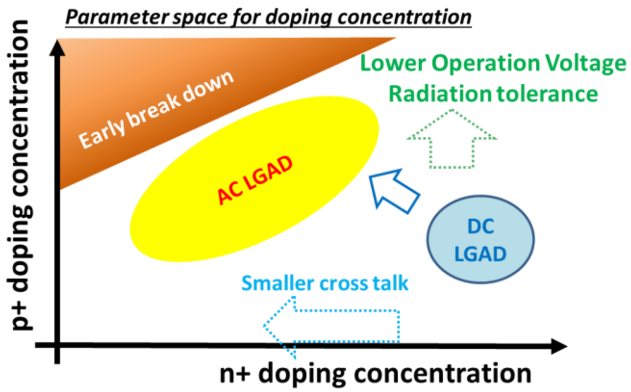
**Mass spectrum for new particle**



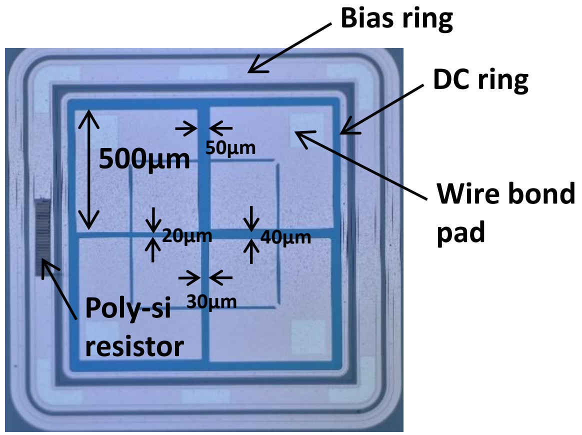
**β measurement to obtain mass**

**e.g. Mass measurement for Long lived chargeno**

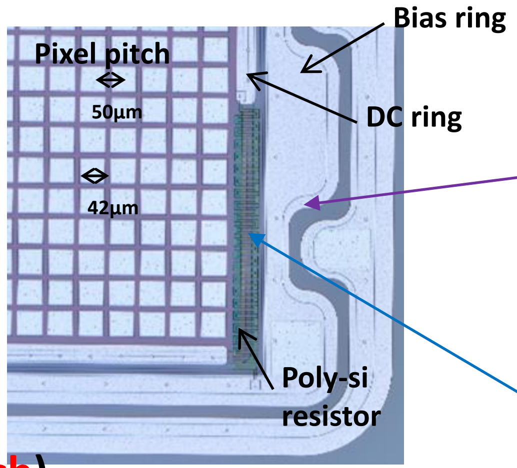
# First AC-LGAD by HPK



## *Pad type sensor* (4x 500umx500um)



## *Pixel type sensor* (14x14 50umx50um)



**GNDed DC ring via Poly-si**

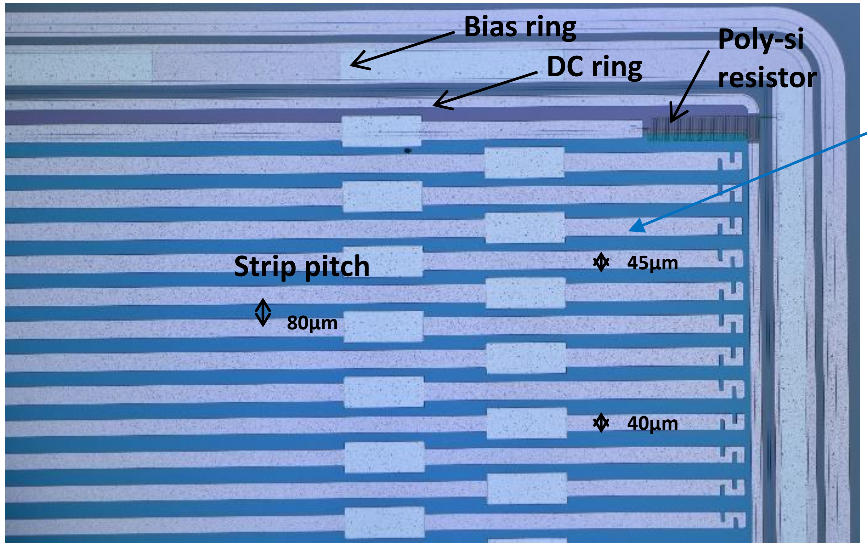
→ To remove charge in n+

**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**

| | | 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 | |

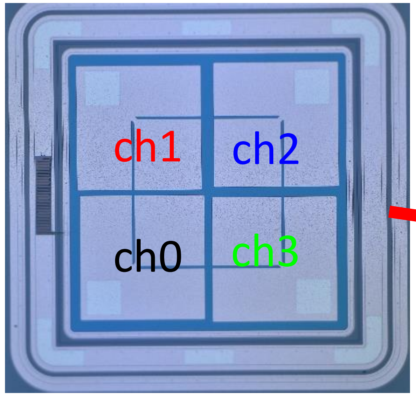
p+ doping

n+ doping

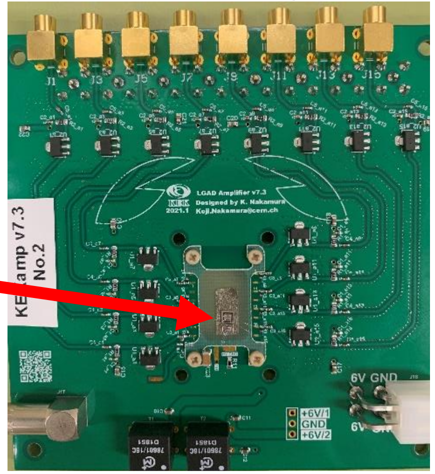
# Measurement setup and signal observation

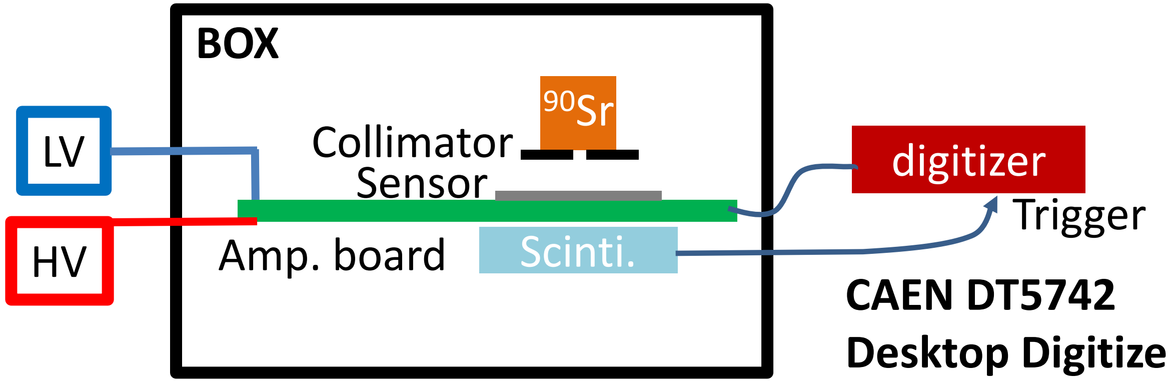
- Lab setup
  - Designed high speed amplifier board.
  - Signal recorded by CAEN DT5742 digitizer
  - $^{90}$Sr β lay source
  - Triggered by Scintillator (MPPC readout)

Pad Sensor

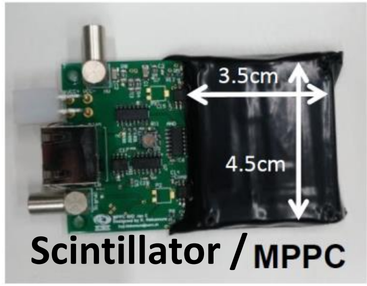


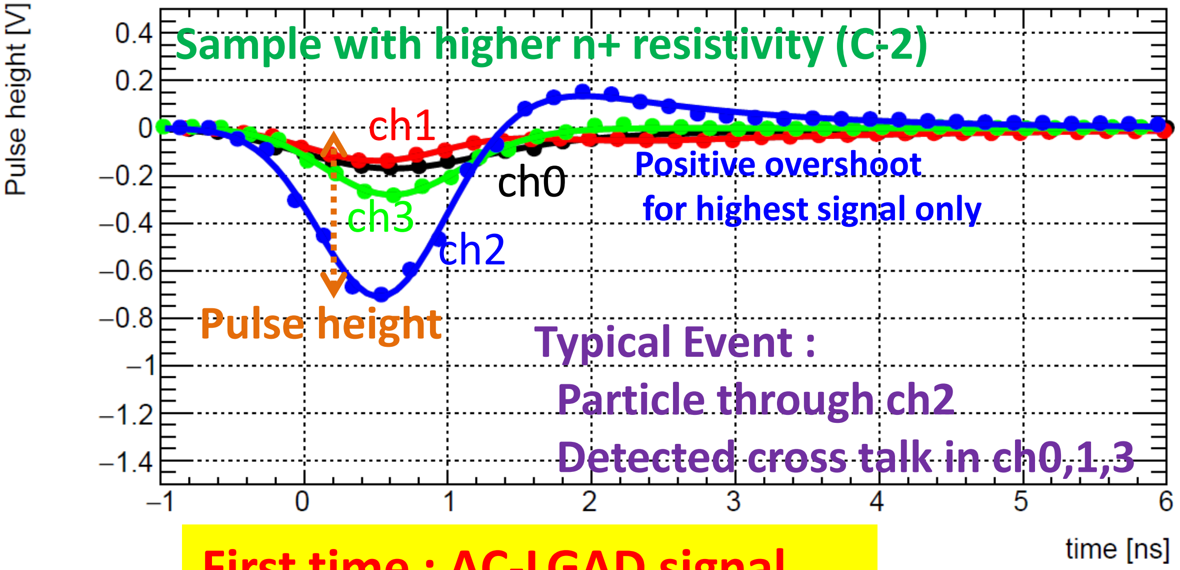
**KEK 16 ch Discrete Amp.**





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



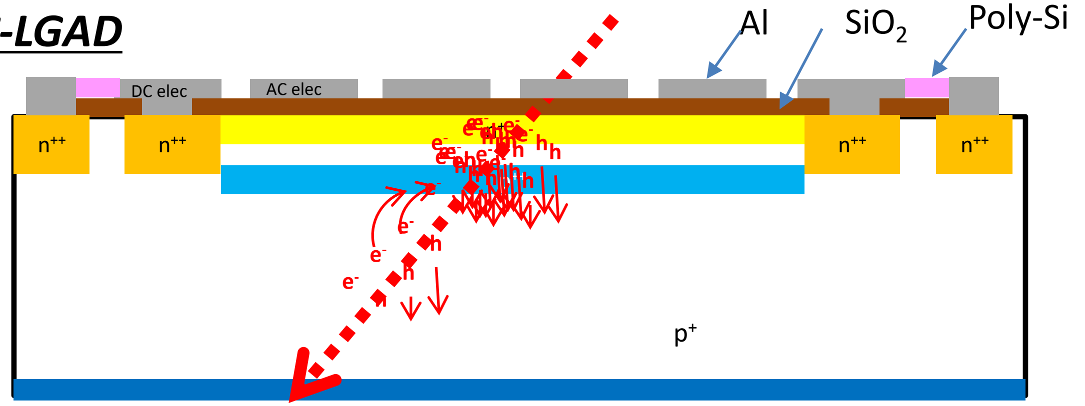


**First time : AC-LGAD signal observed with small crosstalk**

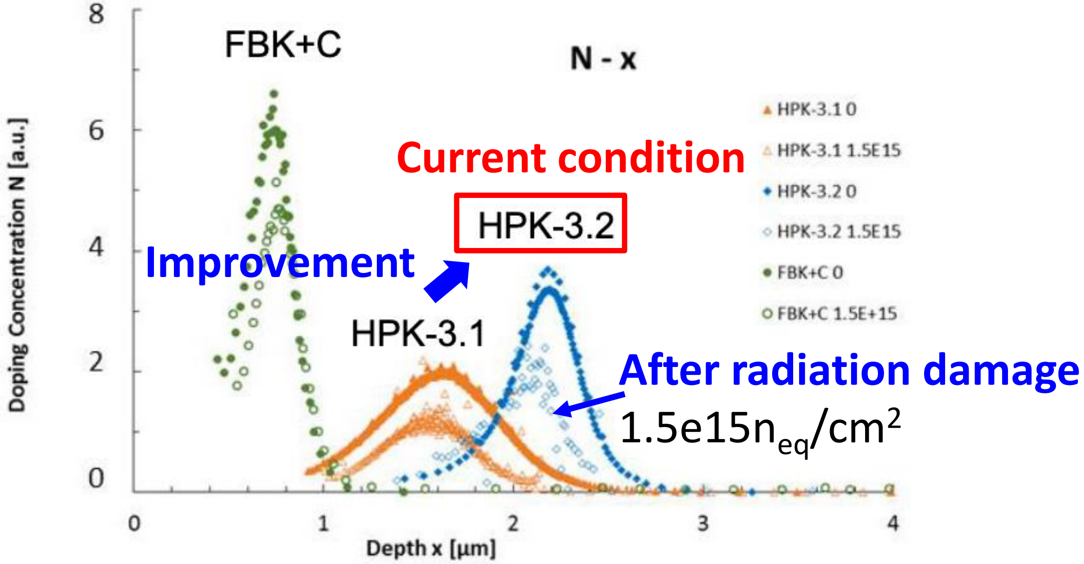
# Radiation Effect in LGAD sensor

- 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***

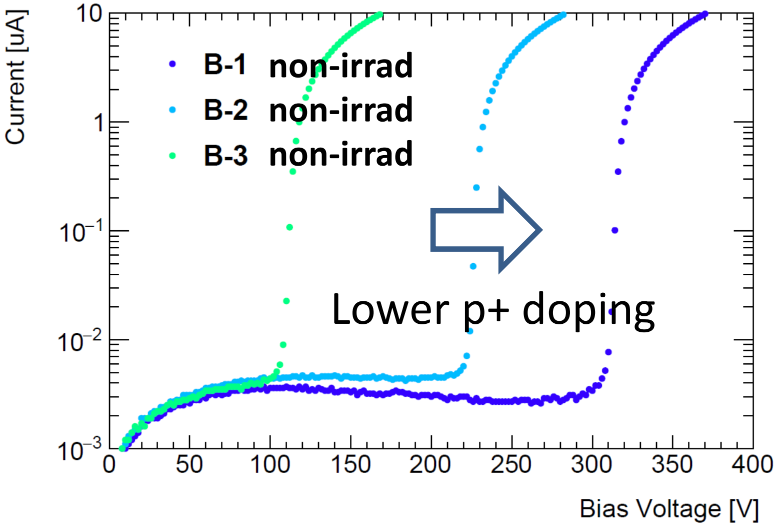


**Current condition**

**Improvement**

**After radiation damage**
$1.5e15n_{eq}/cm^2$

***What happened if p+ dope reduced by accepter removal?***



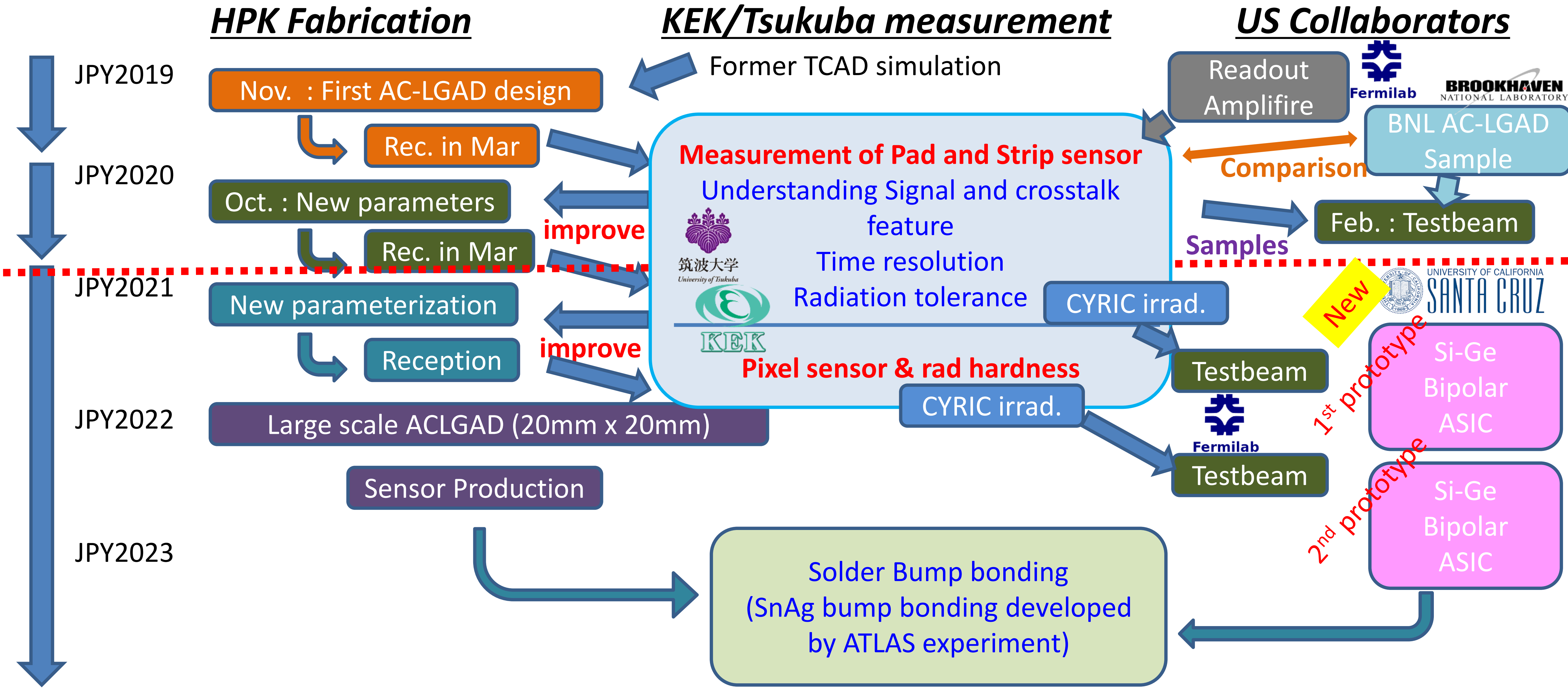
**Reduce p+ doping concentration**

**Higher Gain (operation) Voltage**

**Operation Voltage > Max voltage (~700V)**

**End of life**

# Summary and plan



***HPK Fabrication***

***KEK/Tsukuba measurement***

***US Collaborators***

JPY2019

JPY2020

JPY2021

JPY2022

JPY2023

Nov.  : First AC-LGAD design

Former TCAD simulation

Rec. in Mar

Oct. : New parameters

**improve**

Rec. in Mar

New parameterization

**improve**

Reception

Large scale ACLGAD (20mm x 20mm)

Sensor Production

**Measurement of Pad and Strip sensor**

Understanding Signal and crosstalk feature

Time resolution

Radiation tolerance

CYRIC irrad.

**Pixel sensor & rad hardness**

CYRIC irrad.

筑波大学
University of Tsukuba

KEK

Readout Amplifire

Fermilab

BROOKHAVEN NATIONAL LABORATORY

BNL AC-LGAD Sample

**Comparison**

Feb. : Testbeam

**Samples**

Testbeam

Fermilab

Testbeam

New

UNIVERSITY OF CALIFORNIA SANTA CRUZ

1st prototype

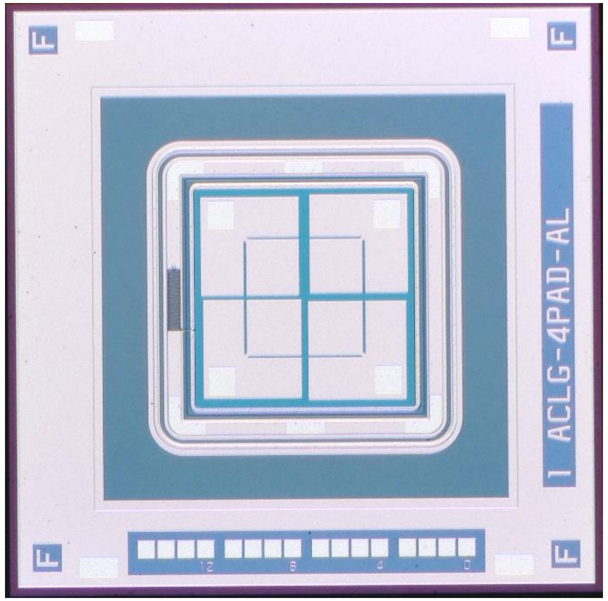
Si-Ge Bipolar ASIC

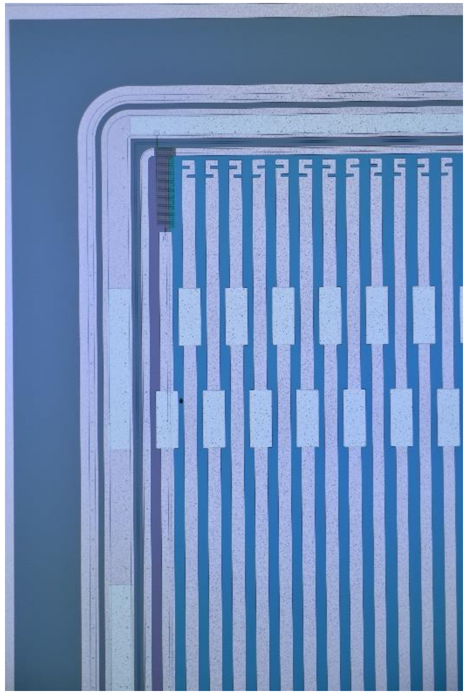
2nd prototype

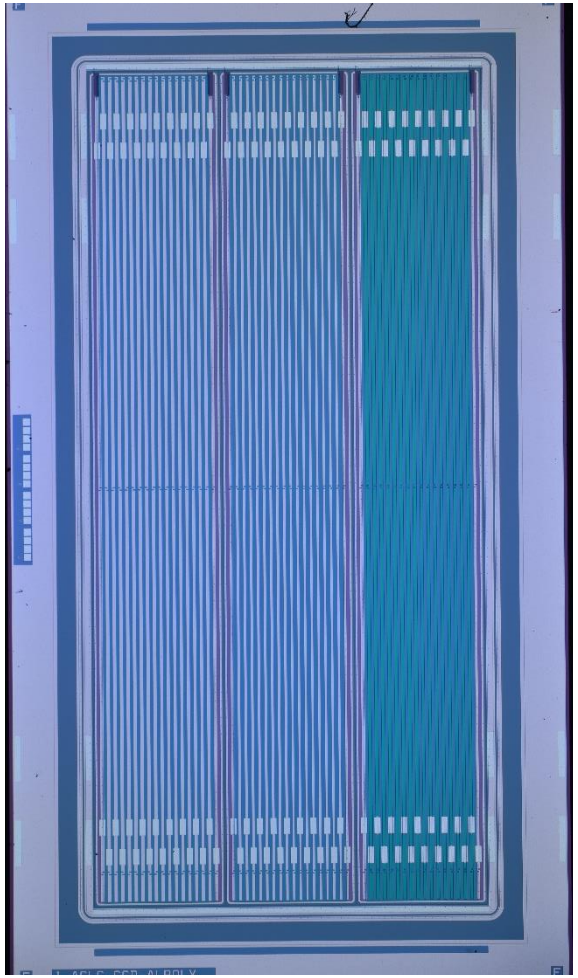
Si-Ge Bipolar ASIC

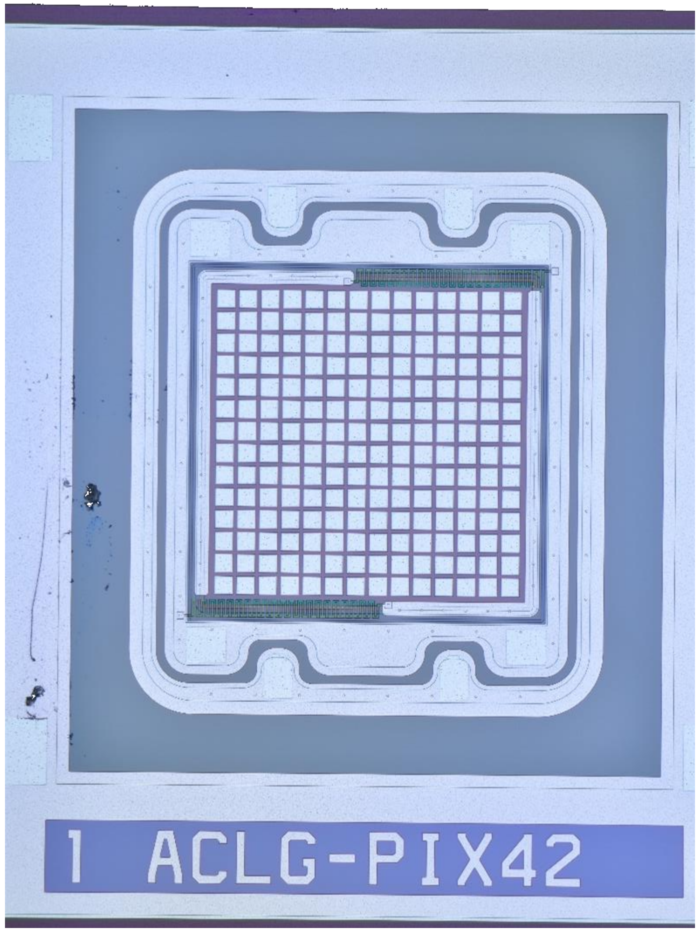
Solder Bump bonding
(SnAg bump bonding developed by ATLAS experiment)

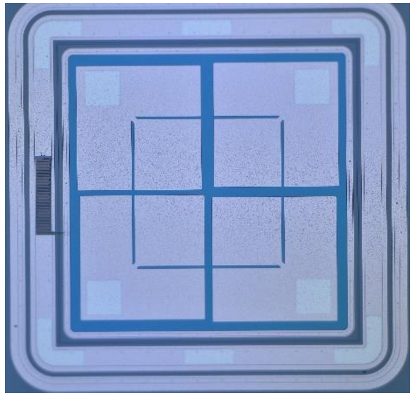
# Photo



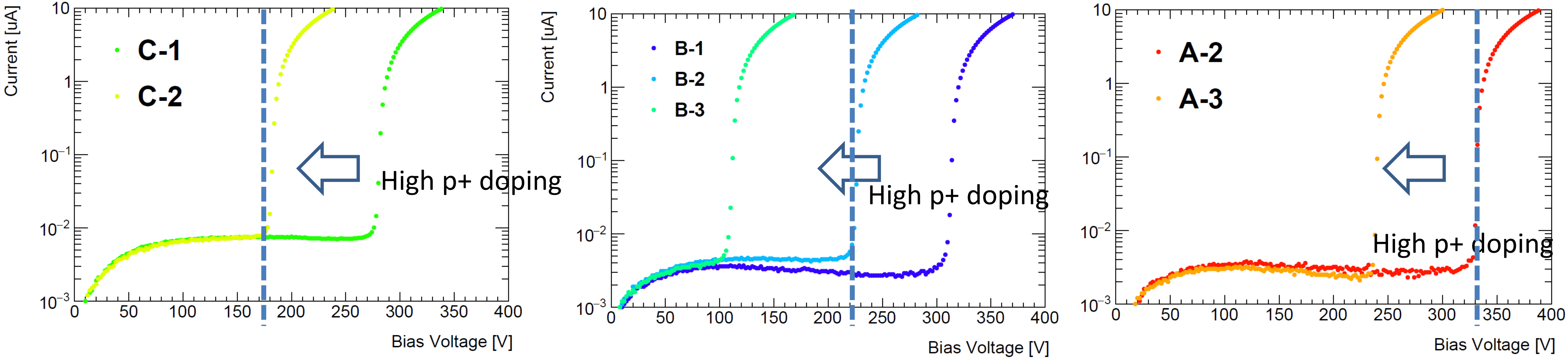








# Leakage current vs Bias voltage



**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**

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

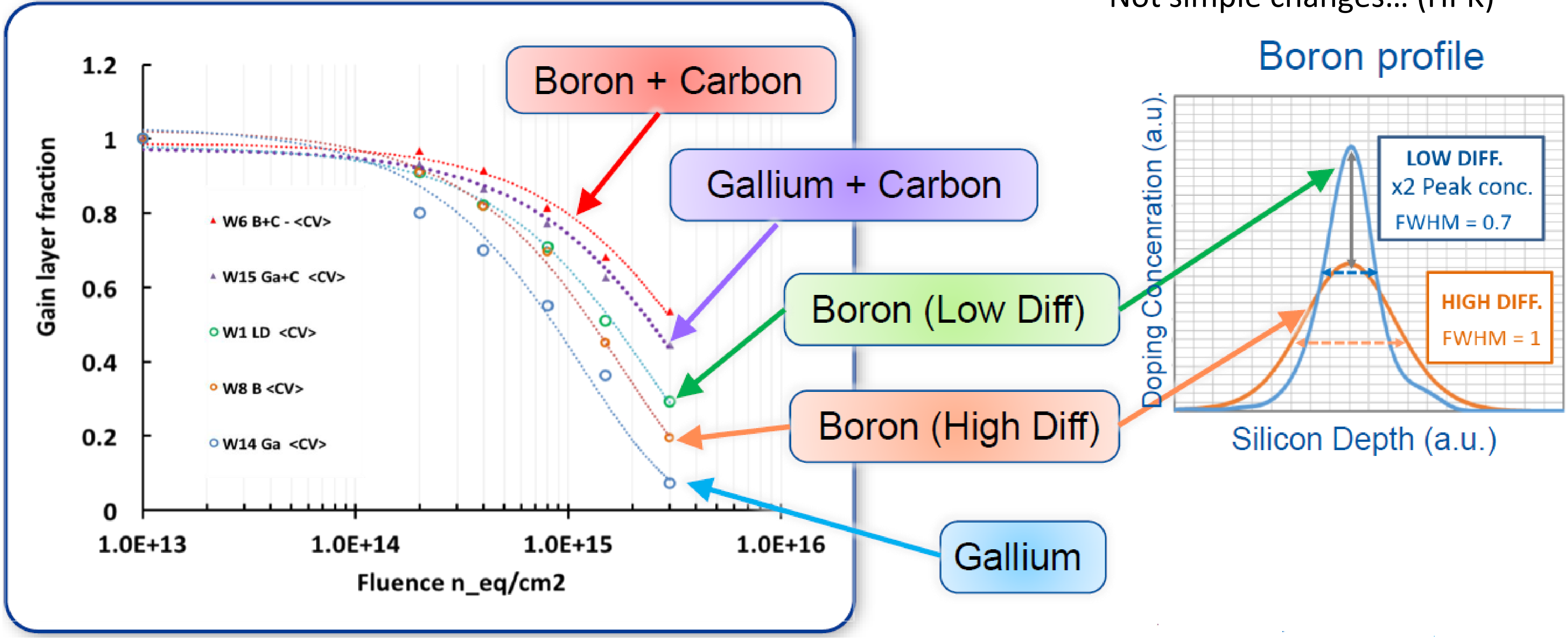
# How to reduce “Accepter Removal” effect?

- 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)



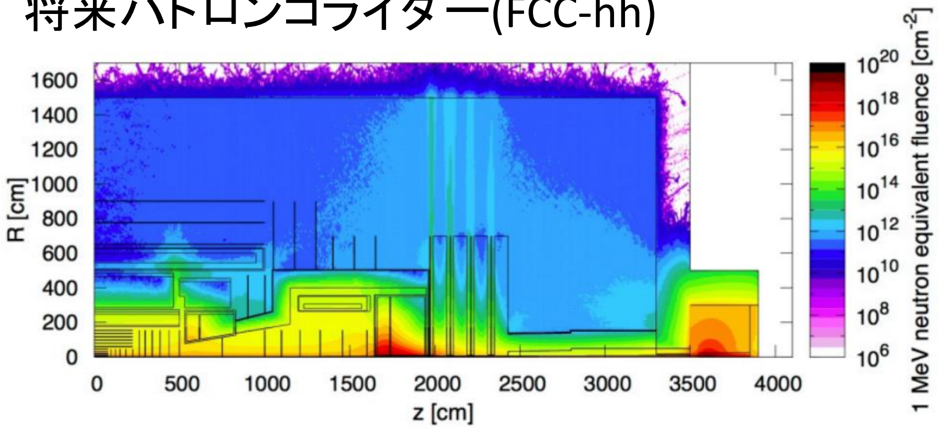
# Radiation Tolerance

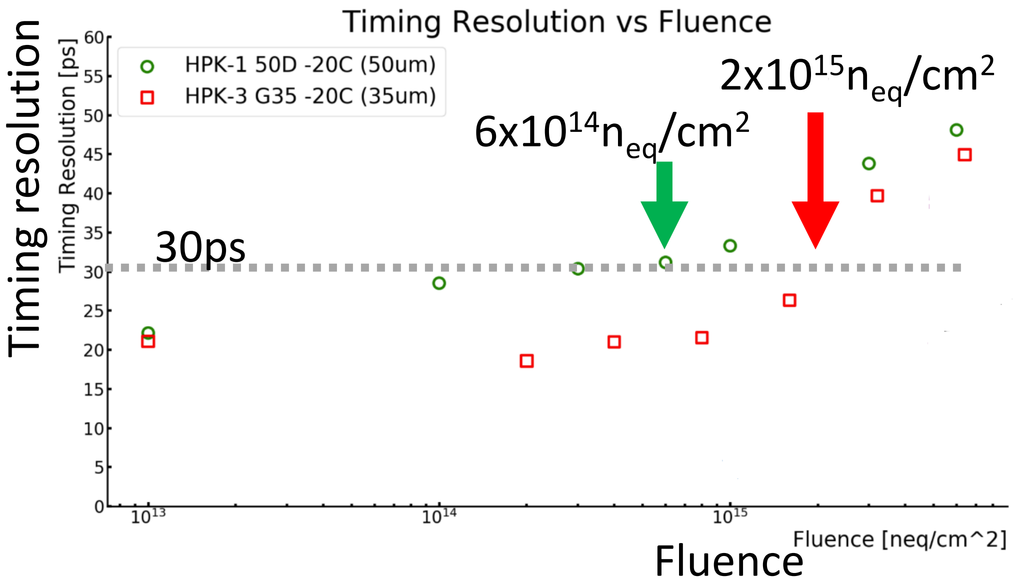
- ***Radiation Tolerance***

  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)





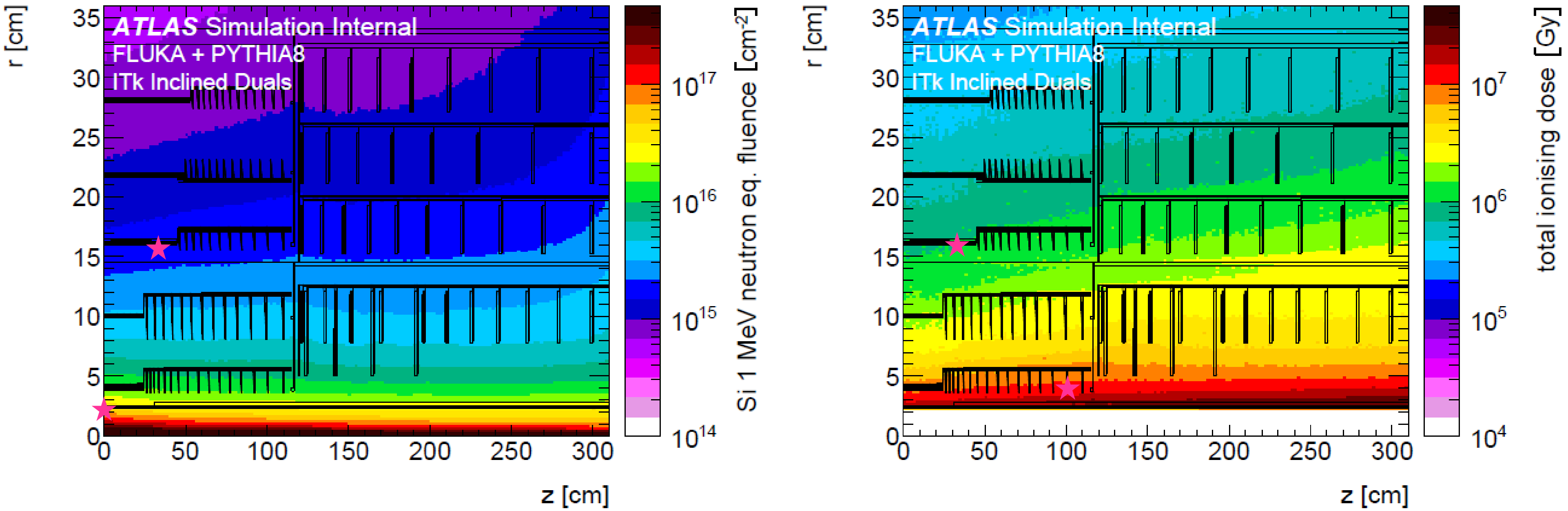
**Idea for improvement?**

**Thinner active thickness and optimized p+ doping**

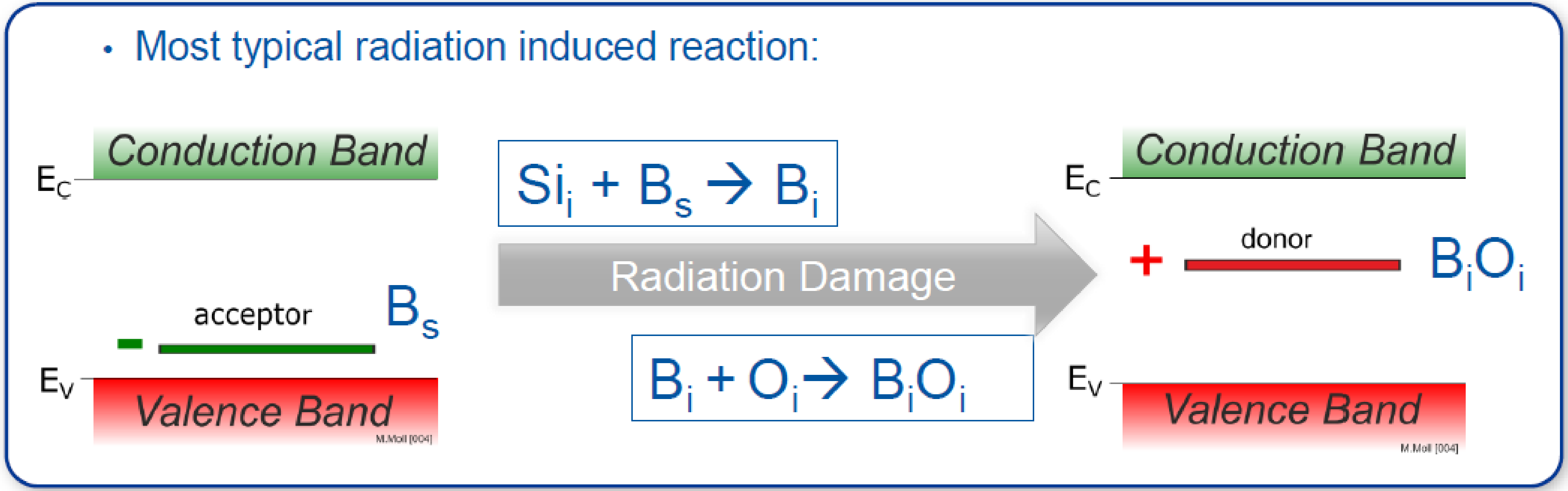
# Radiation environment

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

**Could replace detector at the middle of runs.**



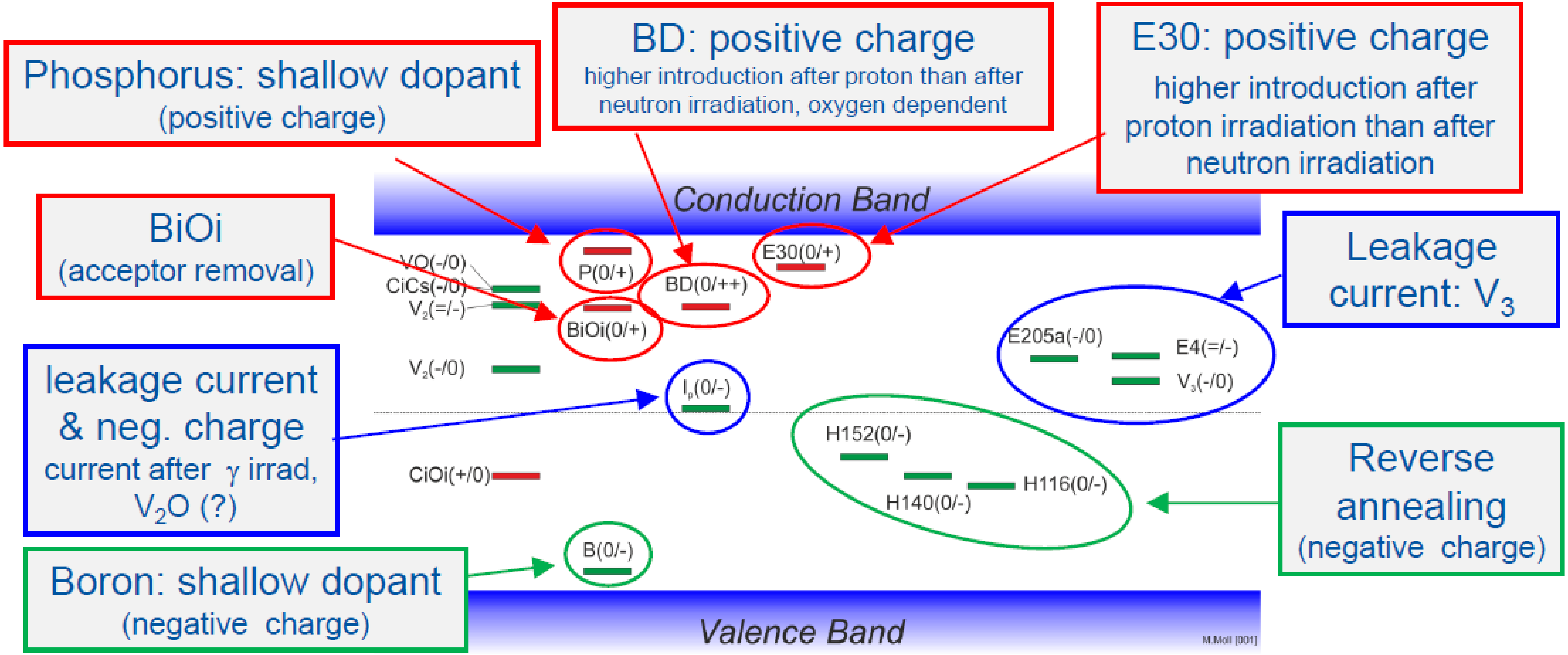
# Accepter removal



- 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)

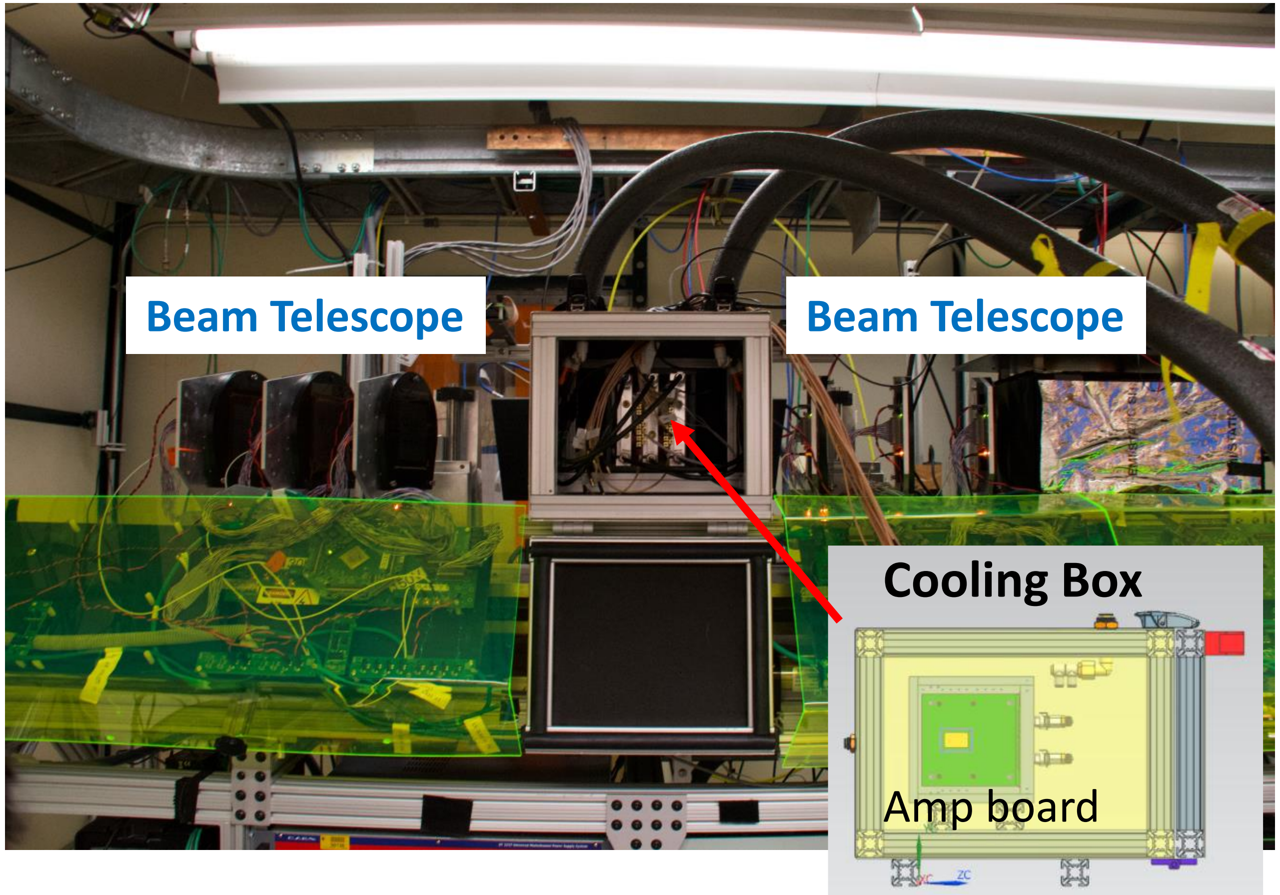
# Test beam in Feb 2021 @ Fermilab

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

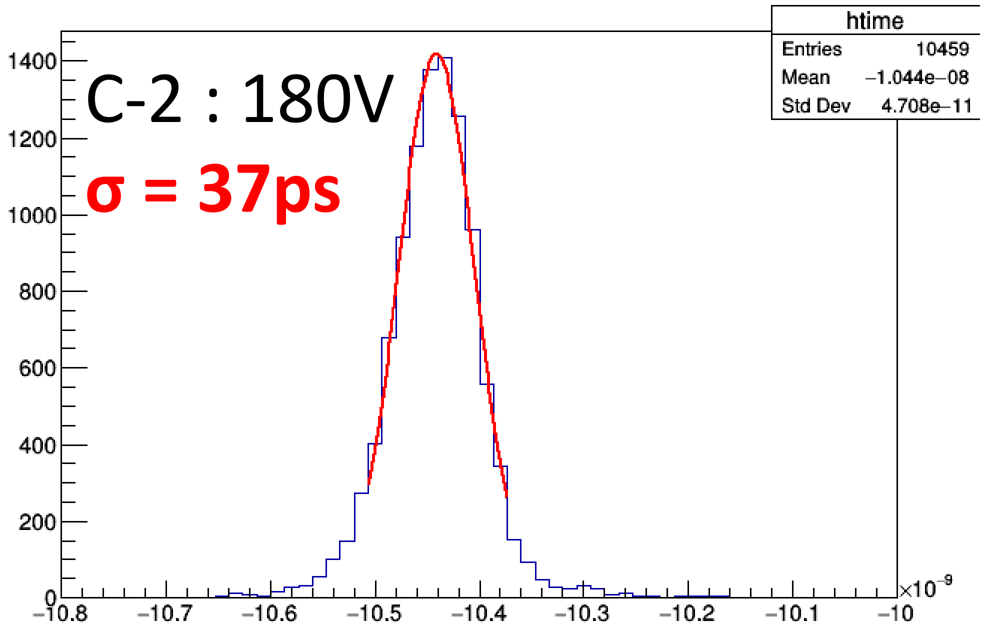
## Timing reference Detector

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

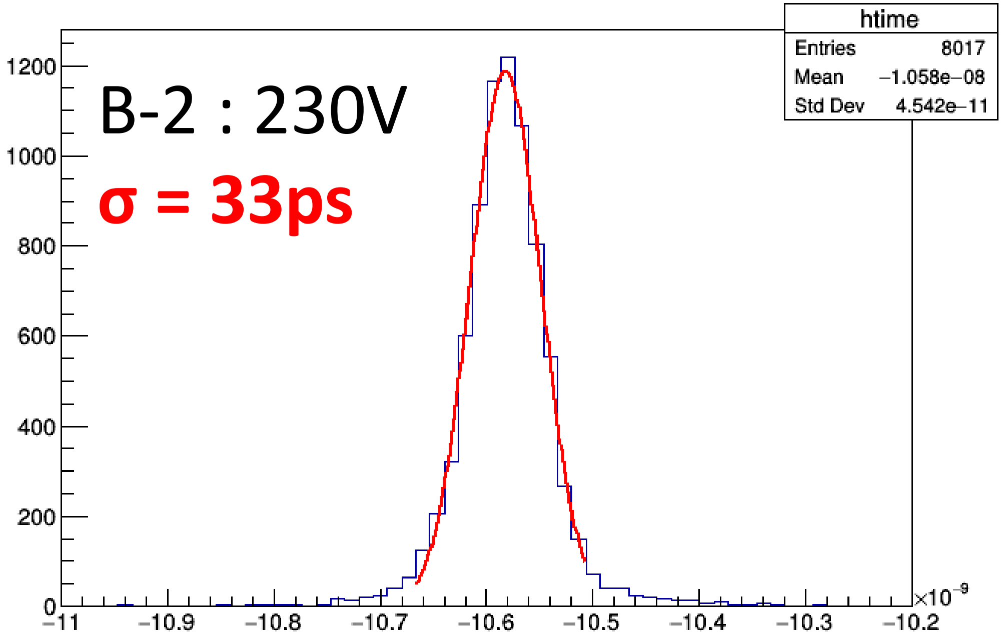
# Time resolution measurement @ testbeam

- 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

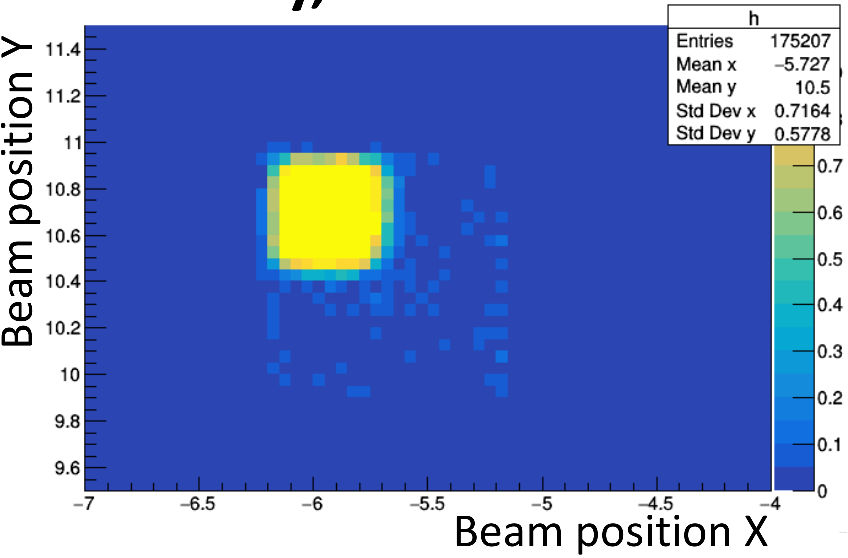
**σ = 37ps**


B-2 : 230V

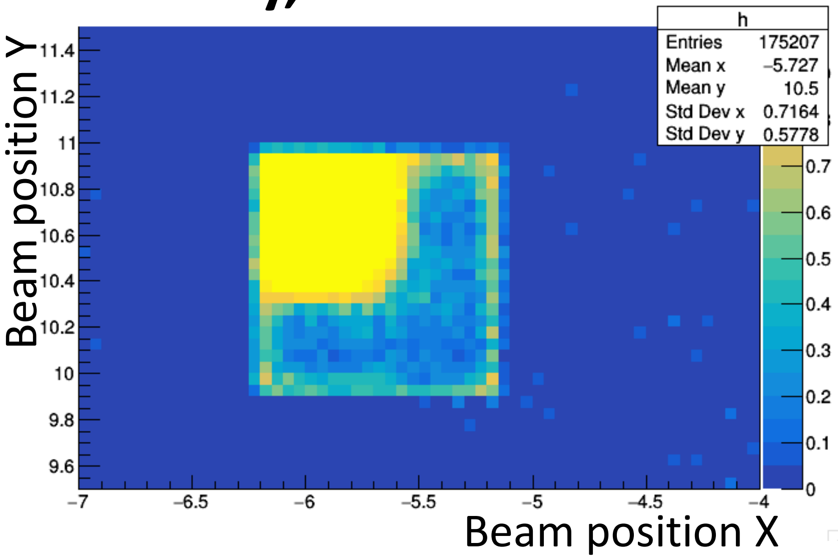
**σ = 33ps**

# Efficiency and signal sharing @ testbeam

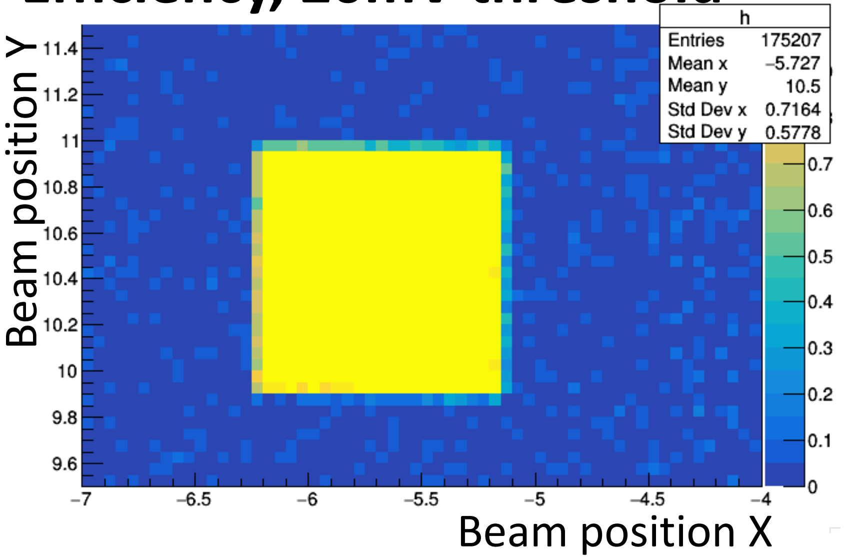
**Efficiency, 90mV threshold**



**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?)**