高い時間分解能と位置分解能を併せ持つ新型LGAD検出器(AC-LGAD)の研究開発

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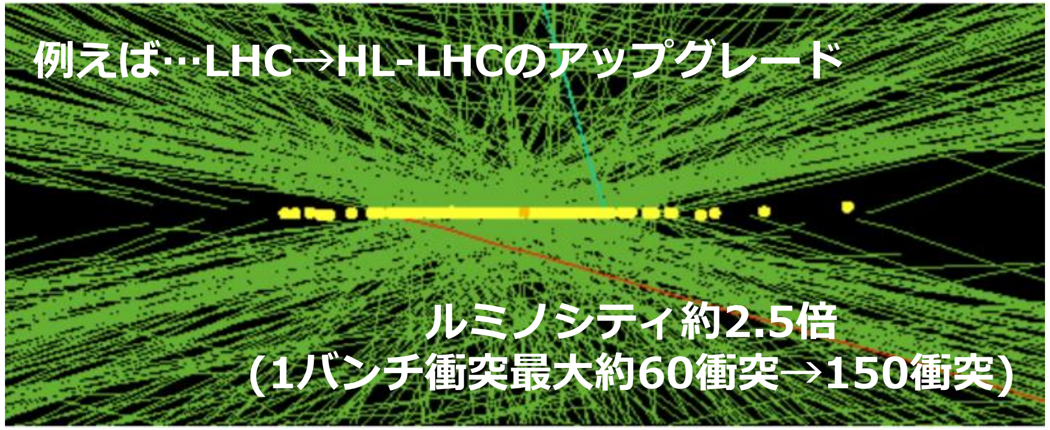
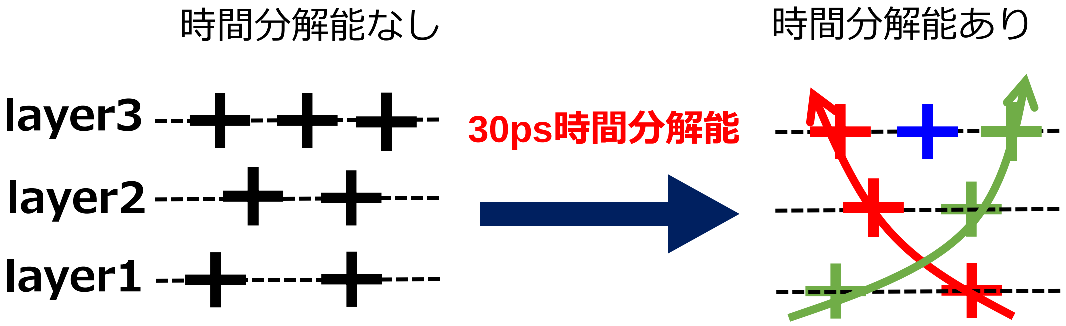
モチベーション

将来の加速器実験：高輝度化


例えば…LHC→HL-LHCのアップグレード

ルミノシティ約2.5倍
(1バンチ衝突最大約60衝突→150衝突)



30psの時間分解能をもつ半導体飛跡検出器
॥
光速の荷電粒子の1cmの区別がつけられる！

30psの時間分解能
- ✓ Fakeトラックを除ける
- ✓ 別衝突点からのトラックを区別できる

＋

O(10um)の高い位置分解能
- ✓ より精密な粒子の
  飛跡再構成＆運動量測定

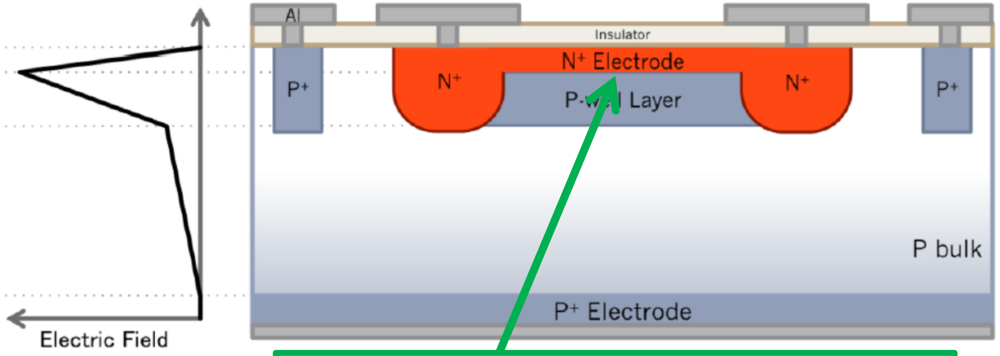
＋

高い放射線耐性
($1\mathrm{x}10^{16}n_{eq}/cm^2$)

❖ **将来の加速器実験には、**
高い時間＋位置分解能＋高い放射線耐性を併せ持つ新型シリコン飛跡検出器が必要！

Low-Gain Avalanche Diode 検出器

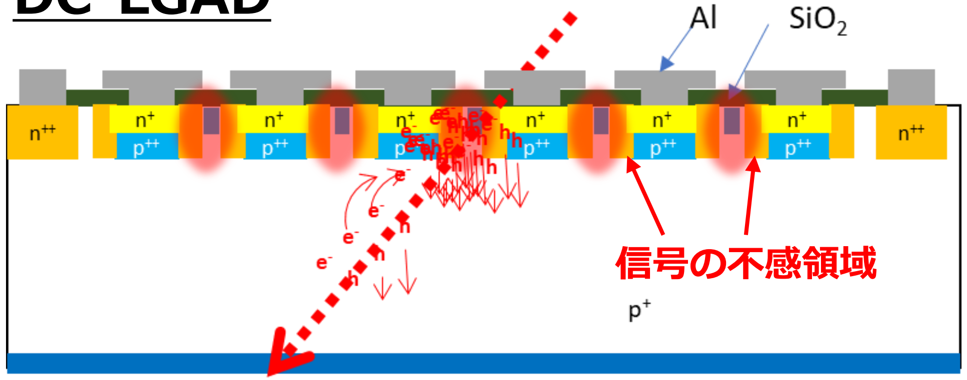
➢基本構造



高電場：電子雪崩
増幅された信号で**高い時間分解能**

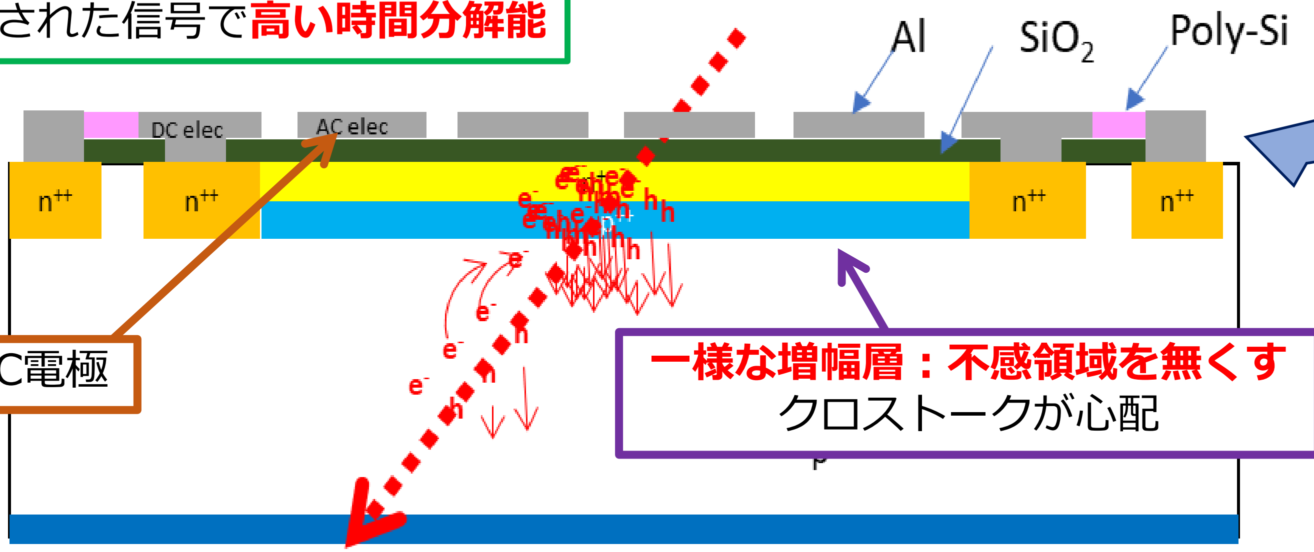
高い位置分解能の
ために電極細密化

DC-LGAD



改良

AC-LGAD

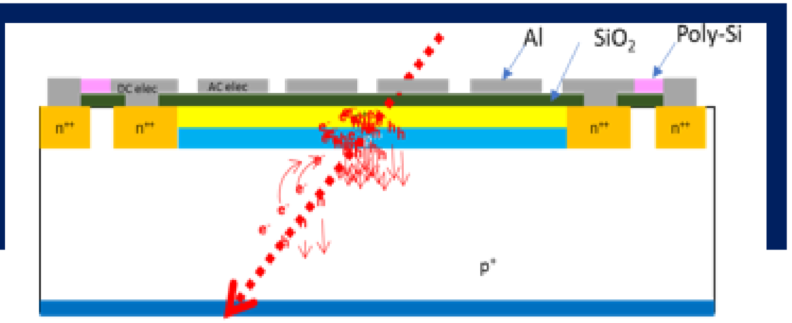


AC電極

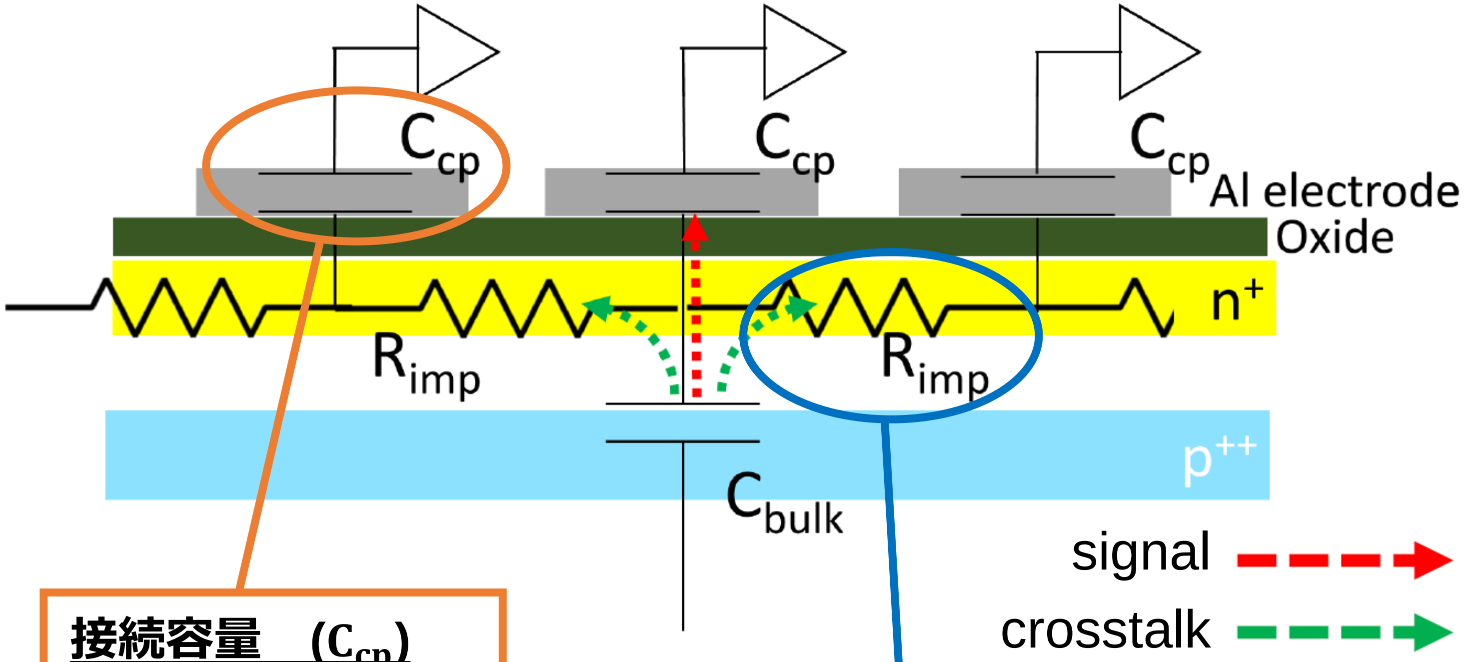
一様な増幅層：不感領域を無くす
クロストークが心配

AC-LGAD検出器は
高い時間分解能と
位置分解能を
併せ持つ検出器

信号の読み出しモデル



センサー表面



接続容量　(C_{cp})
- ✓ 電極の大きさ
- ✓ 酸化膜厚

n+抵抗　(R_{imp})
- ✓ n+ 不純物濃度

信号の大きさとクロストークの量の比
→RimpとCcpのインピーダンスの比

読みだされる電荷

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

バルク内でできた電荷

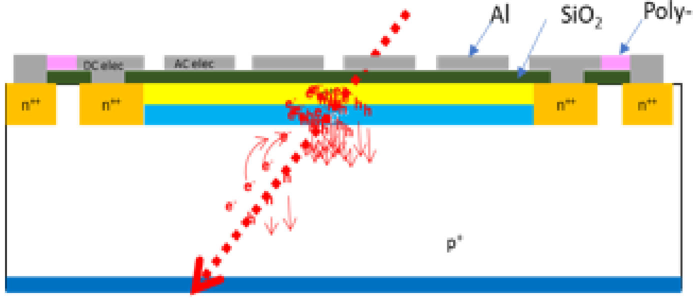
電極を細密化すると…
- ➢ 電極が小さくなる→C_{cp}が小さく
- ➢ Z_{Ccp}が大きくなる
- ➢ 読みだされる電荷Qが小さくなる

→**信号が小さくなる**

(SNをよくするため信号はなるべく大きくしたい)

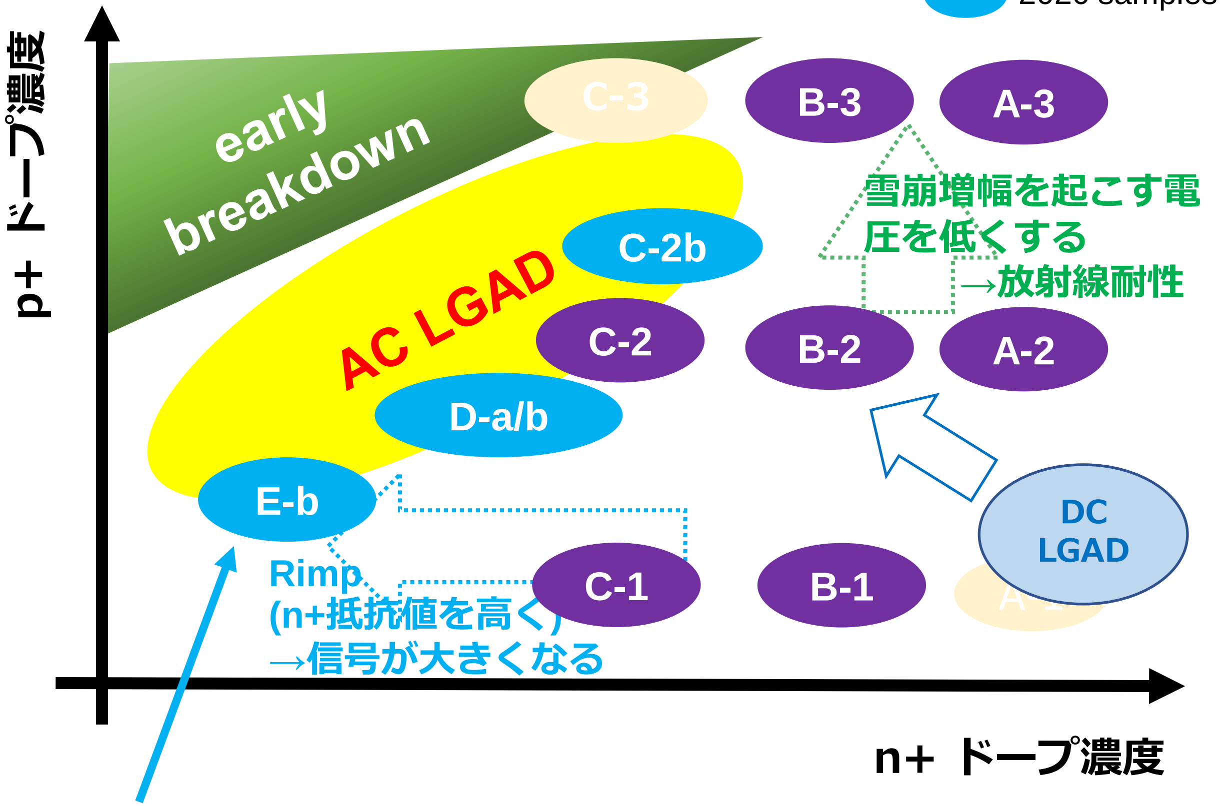
❖ **電極を細密化すると信号が小さくなりクロストークが増える**

最適化が必要な条件と試作サンプル



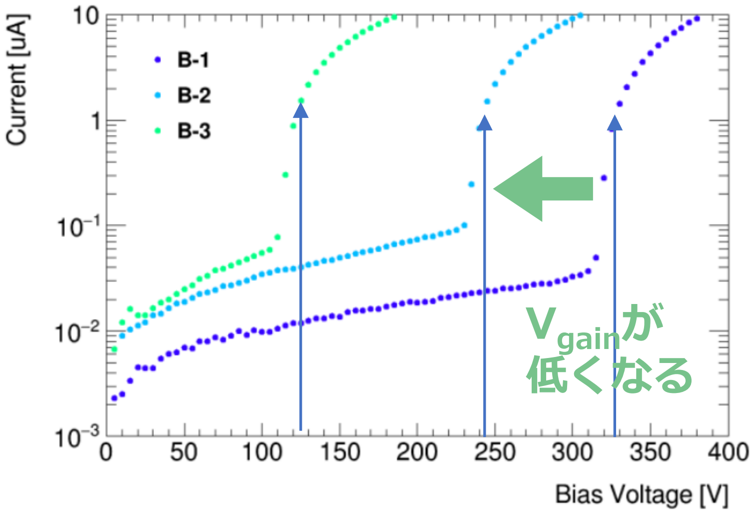
- いくつか条件を変えたサンプルを試作

● 2019 samples
● 2020 samples



雪崩増幅を起こす電圧を低くする
→放射線耐性

Rimp
(n+抵抗値を高く)
→信号が大きくなる



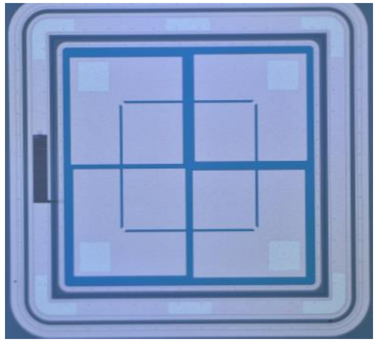
V_{gain}が低すぎると空乏層が作れない
⇕
V_{gain}が高いと放射線耐性がない

→p+濃度はV_{gain}の調整に使う。

n+ドープ濃度を薄く(R_{imp}大)、酸化膜厚を薄く(C_{cp}大)
→電極を細密化しても信号を大きく、クロストークを小さく

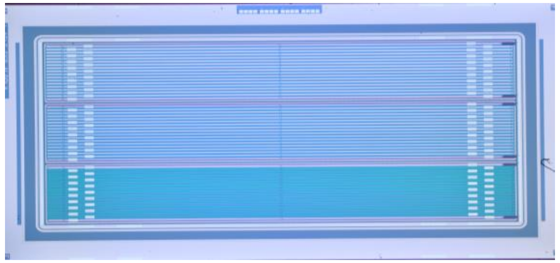
- 電極の形：2種類

Pad sensor
(500um x 500um, 4ch)



Strip sensor
(45, 40um x 9880um, 16ch)

80um pitch

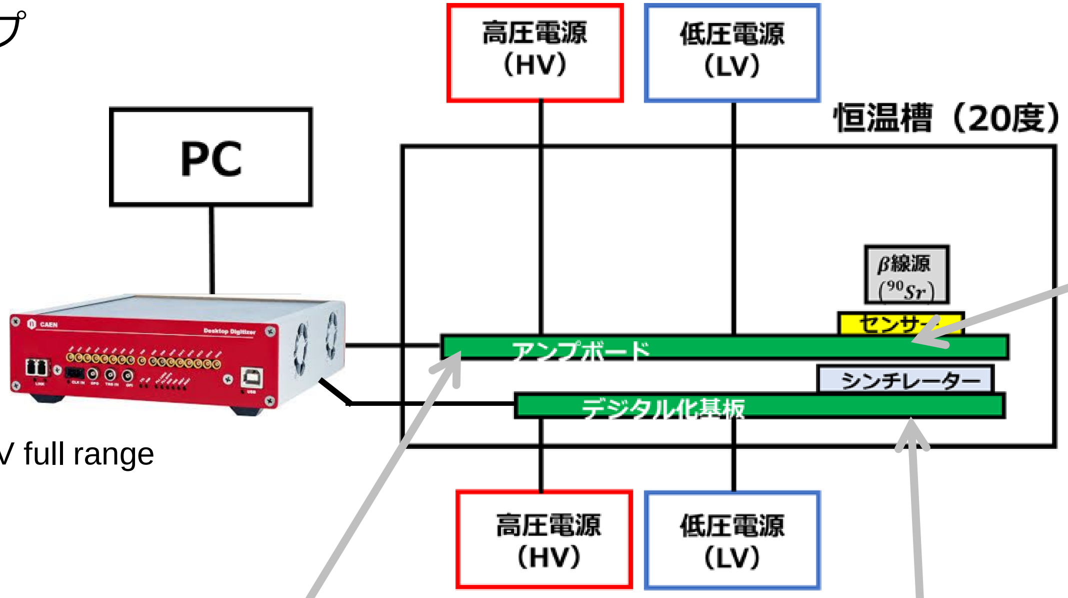


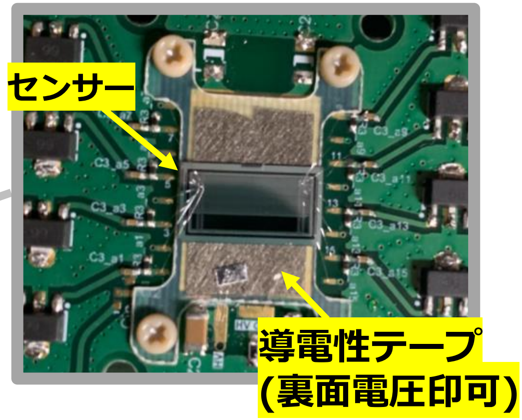
実験室測定セットアップ

- ➢ セットアップ

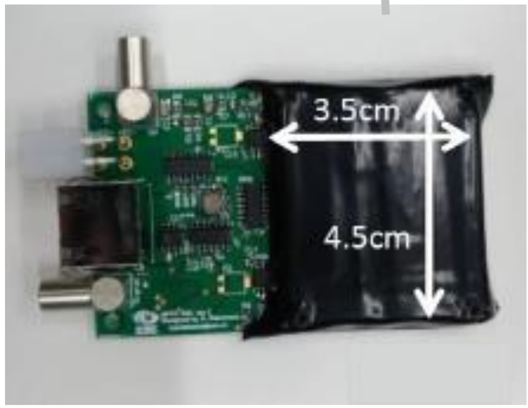
デジタイザー
FlashADC
CAEN DT5742

5GS/s 10bit
12bit ADC 2V full range



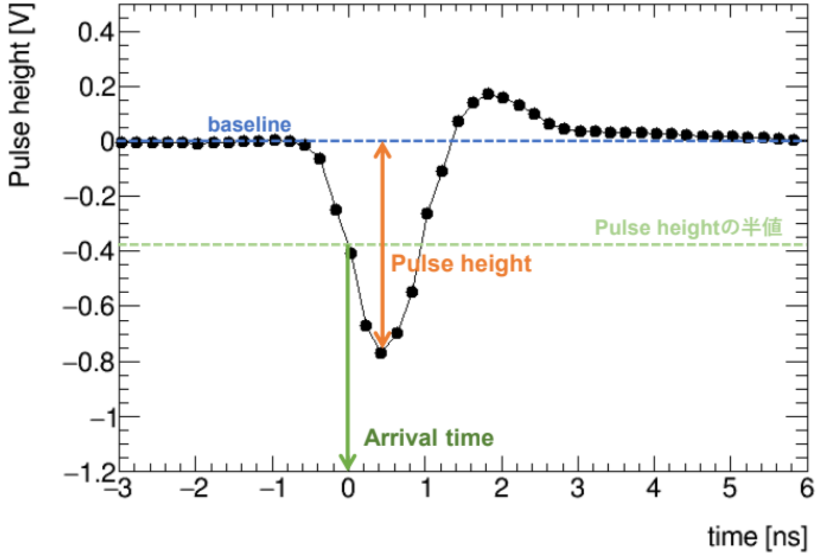


アンプボード：KEK 16ch amp



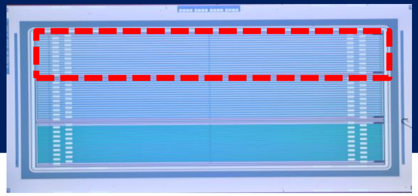
トリガー：シンチレーター（MPPC）

- ➢ 実際の波形

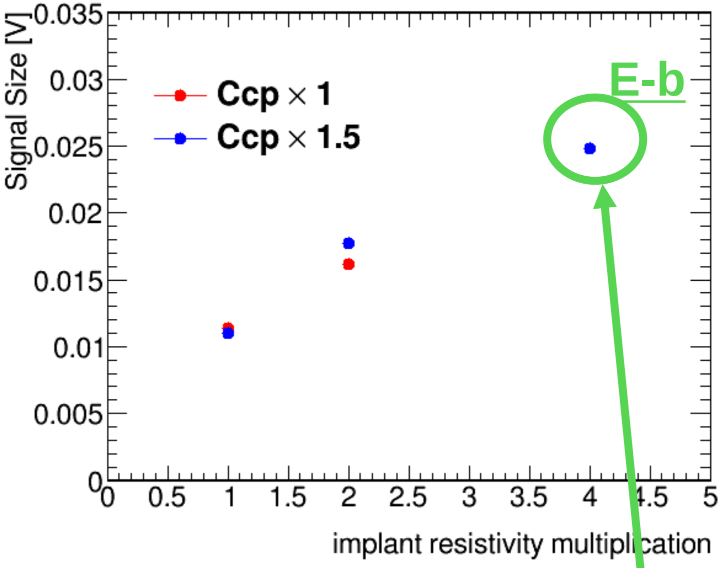


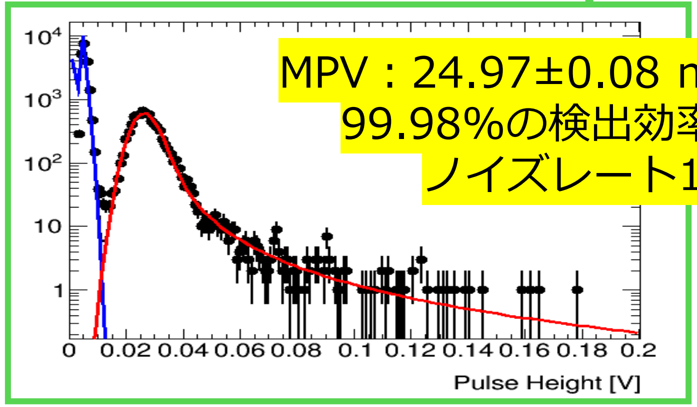
信号の大きさとクロストークの大きさ

Strip sensor



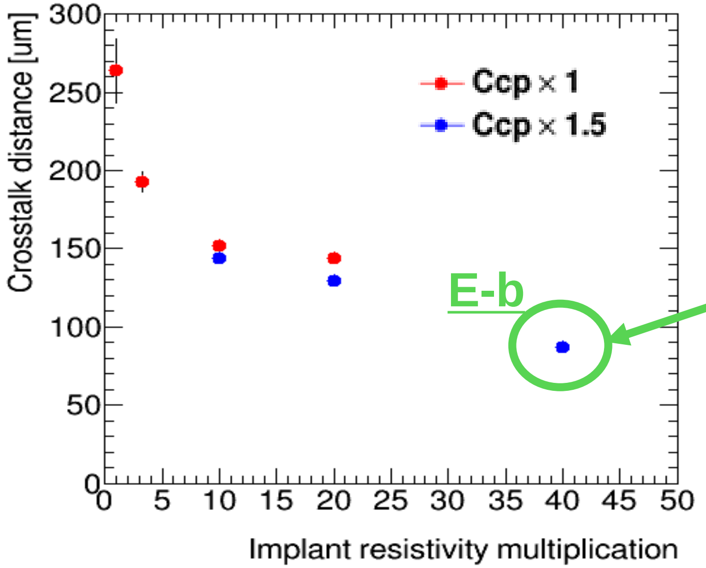
- 信号の大きさ

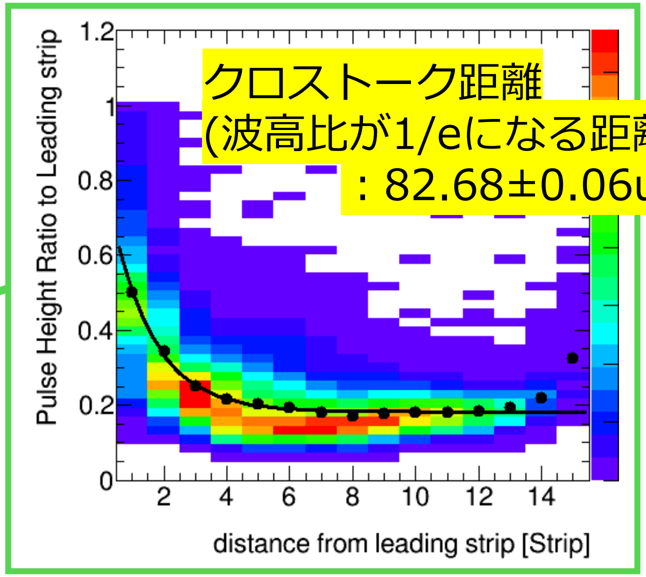




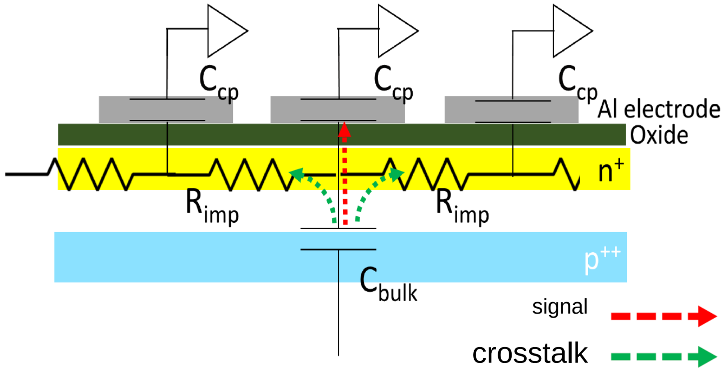
MPV：24.97±0.08 mV
99.98%の検出効率で
ノイズレート10^{-4}

- クロストーク





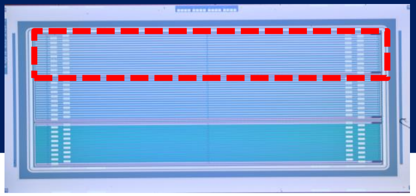
クロストーク距離
(波高比が1/eになる距離)
：82.68±0.06um



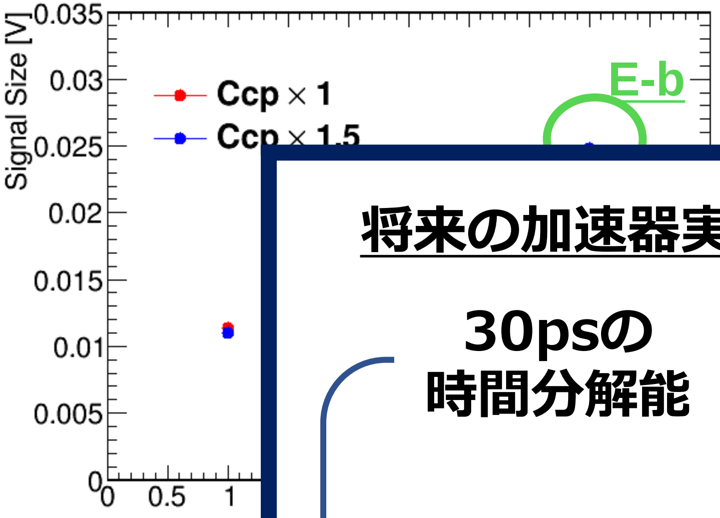
❖ **電極を細密化したE-bタイプ**
(Rimp、Ccp大サンプル)
→十分に信号大、
クロストーク小

信号の大きさとクロストークの大きさ

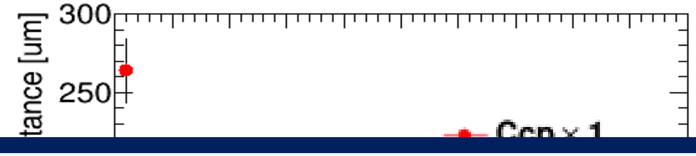
Strip sensor

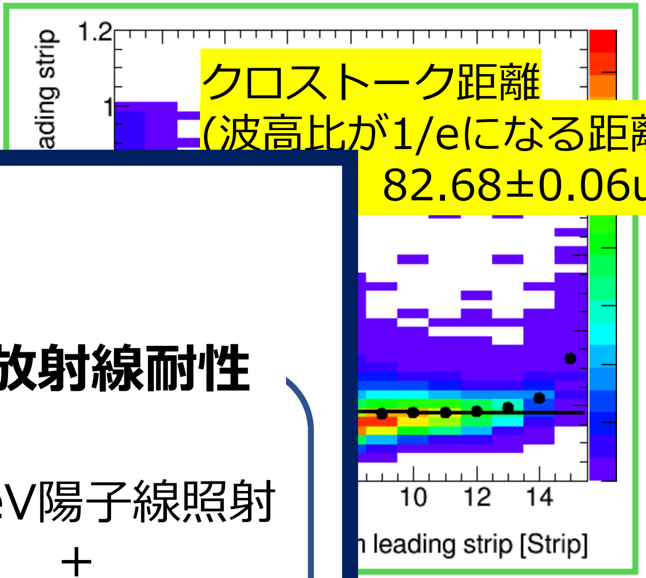


- 信号の大きさ



- クロストーク





クロストーク距離
(波高比が1/eになる距離)
82.68±0.06um

将来の加速器実験に必要な内部飛跡検出器の特徴

30psの
時間分解能

ベータ線による測定

+

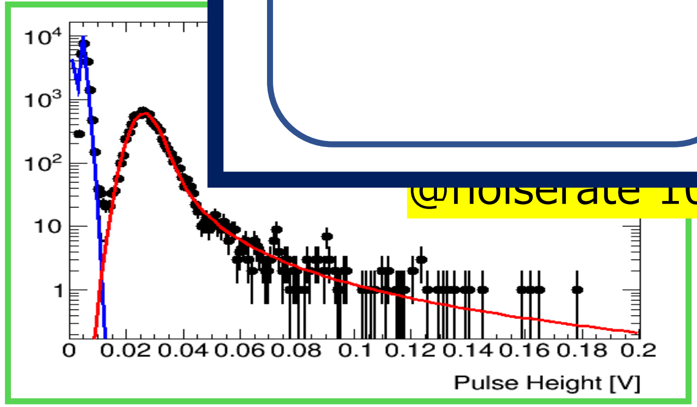
O(10um)の
高い位置分解能

テストビーム
(800MeV電子)
による測定

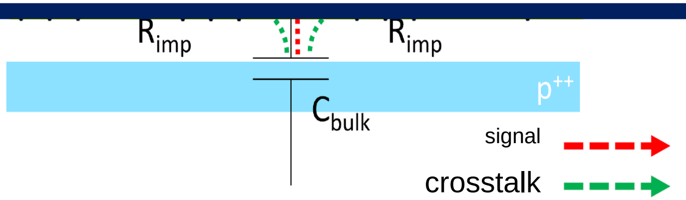
+

高い放射線耐性

70MeV陽子線照射
+
ガンマ線照射

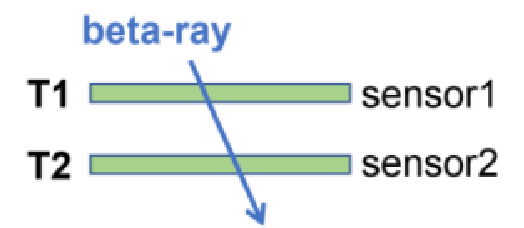


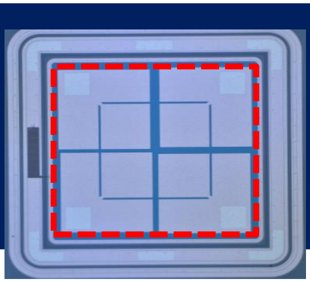
@noiserate 10-4



したE-bタイプ
大サンプル)
→十分に信号大、
クロストーク小

時間分解能測定

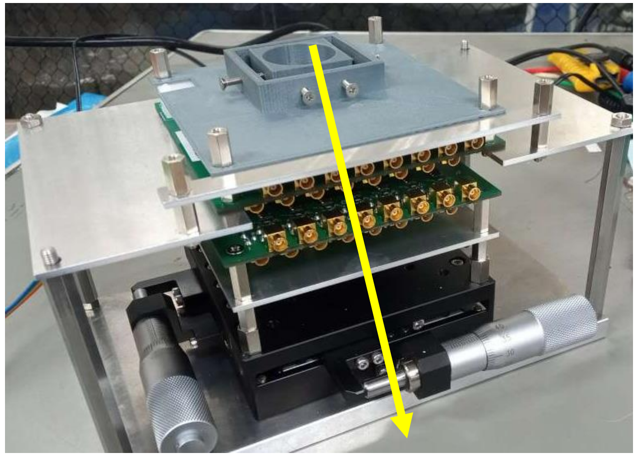




Pad sensor

PadE-bタイプ(信号大、クロストーク小)とPadC2タイプで時間分解能を算出

- 方法：2枚のセンサーの信号の時間差から求める



アンプボードを2枚重ねた

2枚のセンサーが同じなら

$$\sigma(T_1 - T_2) = \sqrt{(\sigma_1)^2 + (\sigma_2)^2}$$

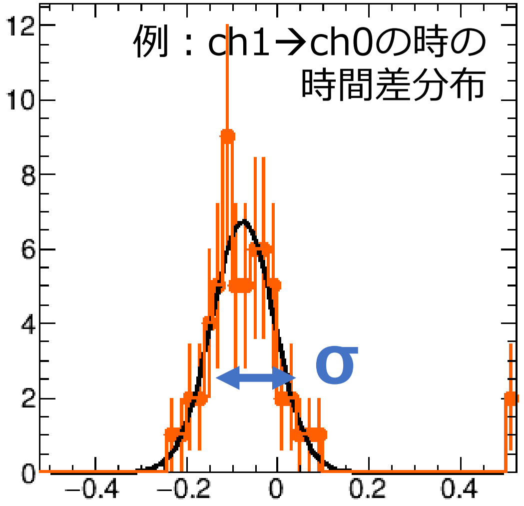
時間分解能

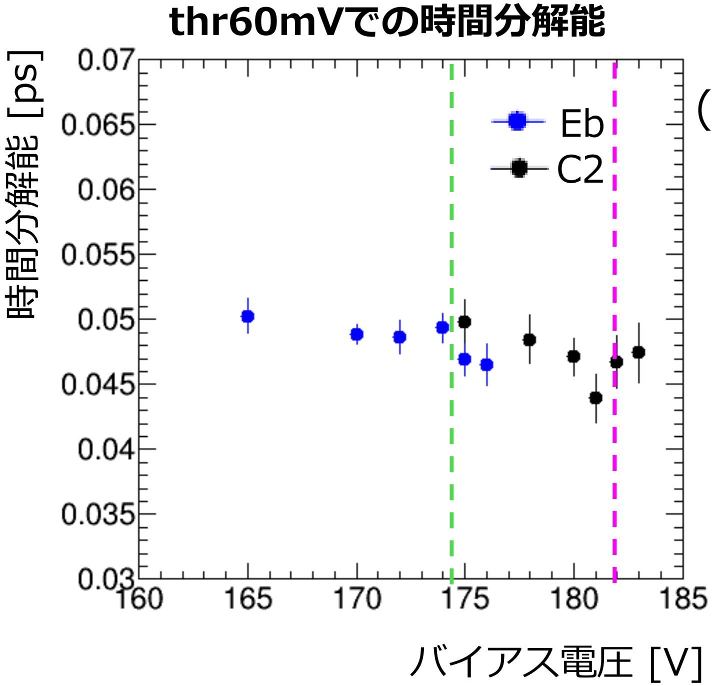
$$\boldsymbol{\sigma_t = \sigma(T_1 - T_2)/\sqrt{2}}$$

WaveRunner 8208HD

2GHz, 8ch, 10GS/s, 12bit

各チャンネルの組み合わせごとに時間差分布を作成、重みづけして全体の時間分解能とした





時間分解能
(signal efficiency>95%
@noise rate 10^{-4})

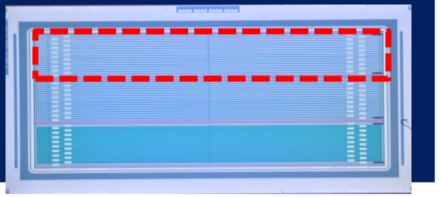
C2　38.2+-2.0ps
(182V)
E-b　49.3+-1.1ps
(174V)

30psに到達していない
ベータ線だから？
(調査中)

- **C2タイプでもEbタイプでも50ps以下の高い時間分解能を確認**

位置分解能測定(テストビーム)

Strip sensor

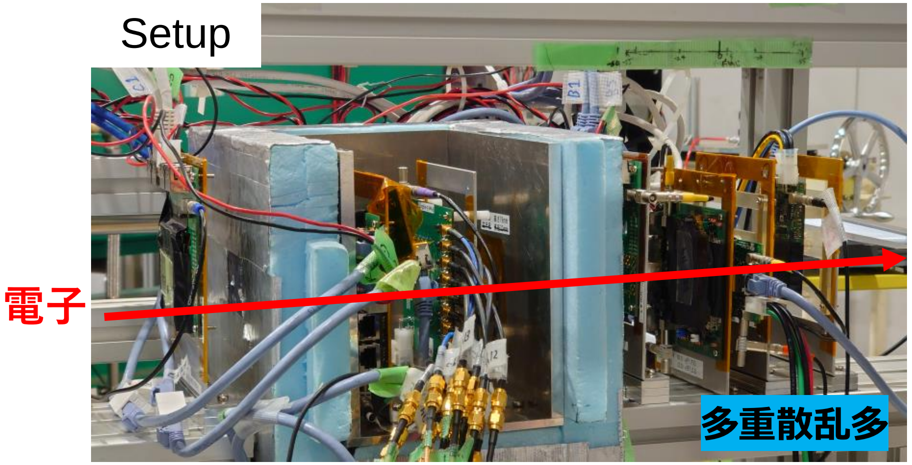


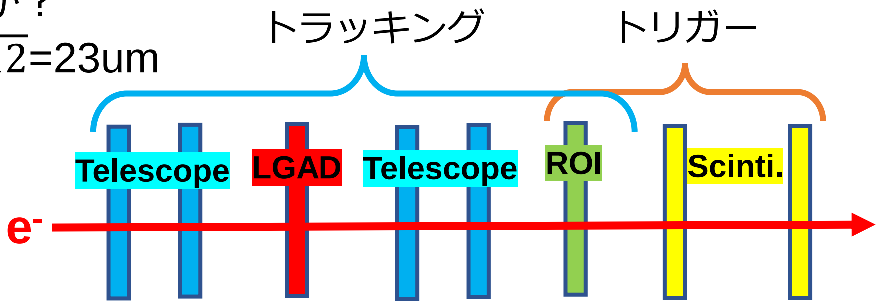
バイナリー読み出しで位置分解能がちゃんと出るか？

- ELPHテストビーム@東北大

80um÷$\sqrt{12}$=23um

Setup





🟦 Pixel sensor (25x500um)

🟩 Pixel sensor (50x250um) Specify region

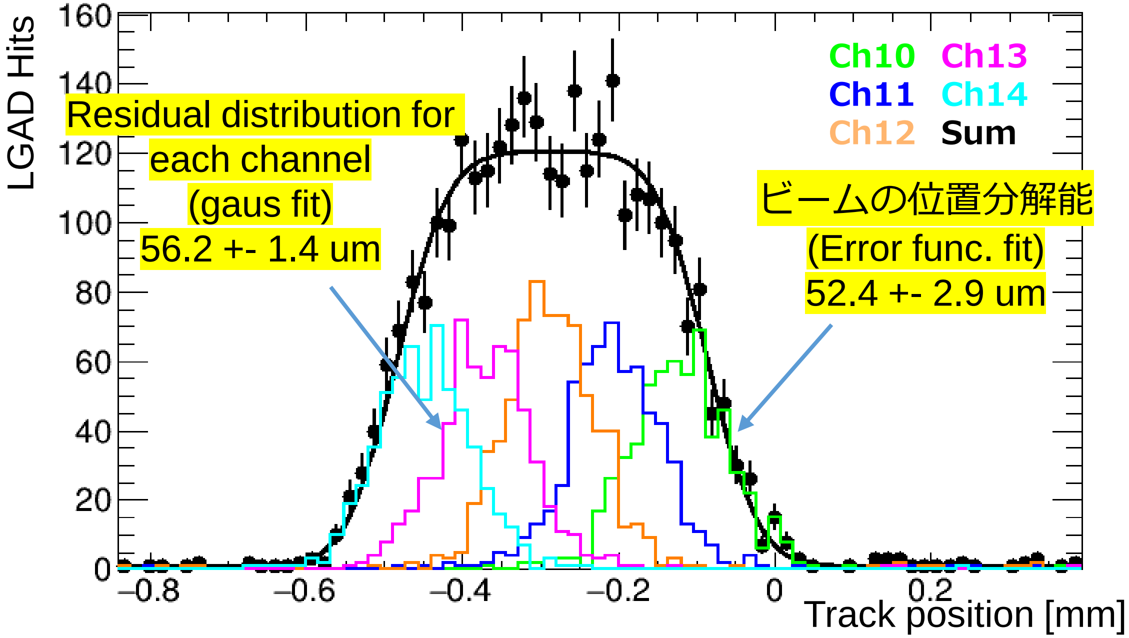
解析

- ✓ Good tracks
  - : 全てのtelescopeとROIにヒット
  - : χ^2/NDF : < 18 (x,y)
- ✓ LGAD hit : > 14mV (95%efficiency)

- ✓ 800MeV電子ビーム
- ✓ beam rate : 200 ~ 400 Hz
- ✓ beam current : 14.38mA
- ✓ センサー : Strip E-b (信号大)
- ✓ Number of events : 600,000
- ✓ Bias voltage : 170V

WaveRunner 8208HD

2GHz, 8ch, 10GS/s, 12bit



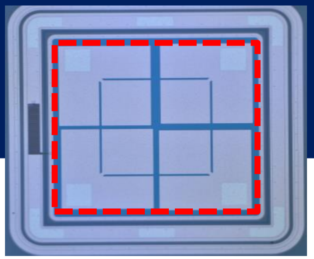
Residual distribution for each channel (gaus fit) 56.2 +- 1.4 um

ビームの位置分解能 (Error func. fit) 52.4 +- 2.9 um

位置分解能：20.3+- 3.2um → 期待したよい位置分解能

放射線耐性

Pad sensor



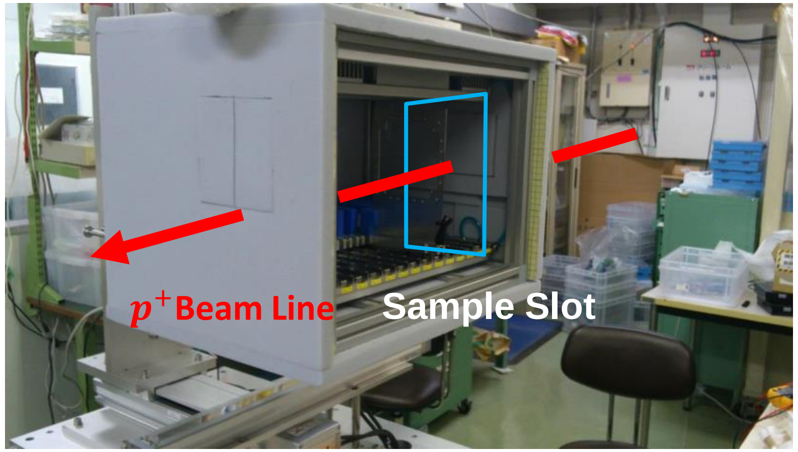
放射線ダメージ

- ✓ TID : 表面損傷 → ガンマ線照射
- ✓ NIEL : バルク損傷
- ✓ acceptor removal (p+濃度の減少)

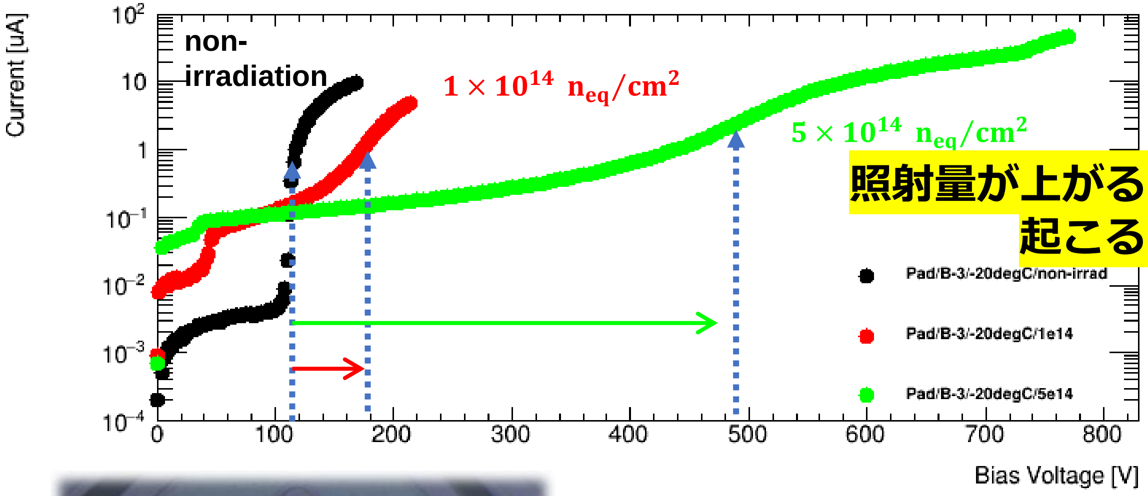
} **陽子線照射**

陽子線照射@CYRIC(東北大)

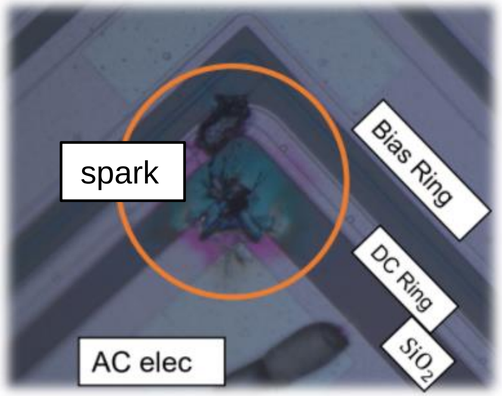
- ✓ 70MeV陽子
  $1\mathrm{x}10^{14}\ \mathrm{n_{eq}/cm^2}$, $5\mathrm{x}10^{14}\ \mathrm{n_{eq}/cm^2}$
- ✓ センサー：Pad B3



IV curve



照射量が上がると電子雪崩の起こる電圧が上がる



700V以上をかけるとスパーク

- ✓ 照射量の増加でp+濃度の減少 →運転電圧の上昇
- ✓ 高電圧によりスパーク
- ✓ 照射量が増加しても運転電圧が上がらないような工夫が必要…

内部飛跡検出器として使うには放射線耐性の改良が必要

まとめ

高い空間・時間分解能を併せ持つ検出器である**LGAD検出器**の開発をしている

信号の不感領域のない新型の**AC-LGAD**を試作した。

30psの
時間分解能

ベータ線による測定

38.2+-2.0ps
(C2Pad)
49.3+-1.1ps
(E-bPad)

+

O(10um)の
高い位置分解能

テストビーム
(800MeV電子)
による測定

20.3+- 3.2um
(E-bStrip)

+

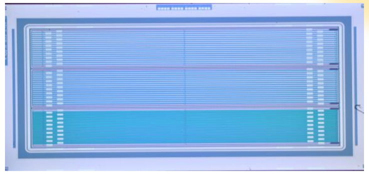
高い放射線耐性

改良が必要

70MeV陽子線照射
+
(ガンマ線照射)

$1x10^{15}$ n_{eq}/cm^2程度の
照射量でセンサーが
耐圧を超える

E-bタイプ
Stripセンサー



e^+e^- collider / hadoron colliderの外層飛跡検出器ならすでに実用化可能！！

→大型検出器の試作を予定

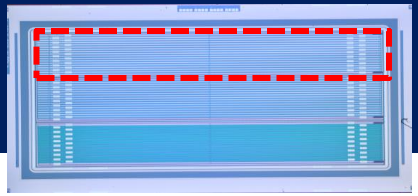
高放射線環境下の内部飛跡検出器として使うには…

- ✓ 放射線耐性：放射線を浴びても運転電圧が上がらない(p+ドープ濃度が減らないよう)内部構造に何か工夫
- ✓ pixel化：50um pitchのセンサー

backup

Signal size and crosstalk measurement

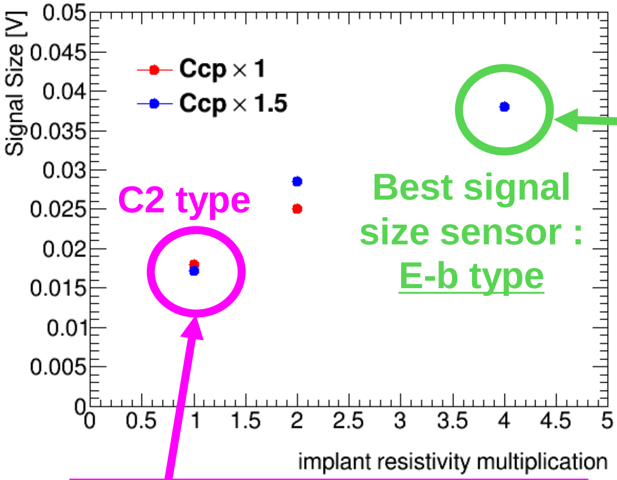
Strip sensor



To check new prototypes → Tested using ^{90}Sr beta-ray source

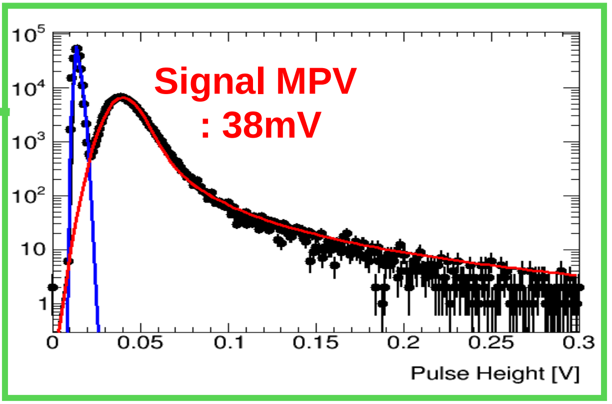
➢ Signal size measurement

Signal size : MPV of pulse height distribution in the highest signal channel.



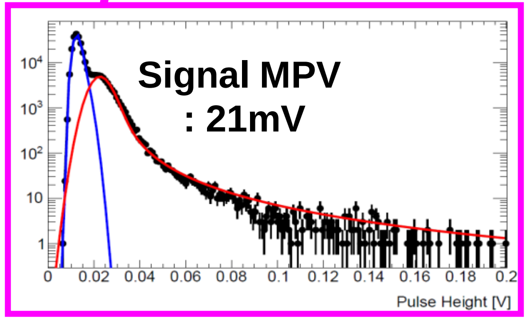
C2 type

Best signal size sensor : E-b type



Signal MPV : 38mV

Signal clearly separated from noise !!!



Signal MPV : 21mV

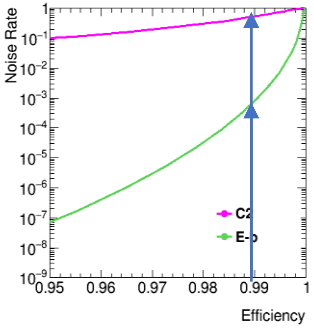
Signal **not** clearly separated from noise …

Noise efficiency at 99% of signal efficiency

0.6 (C2)

R_{imp} x 4
C_{cp} x 1.5

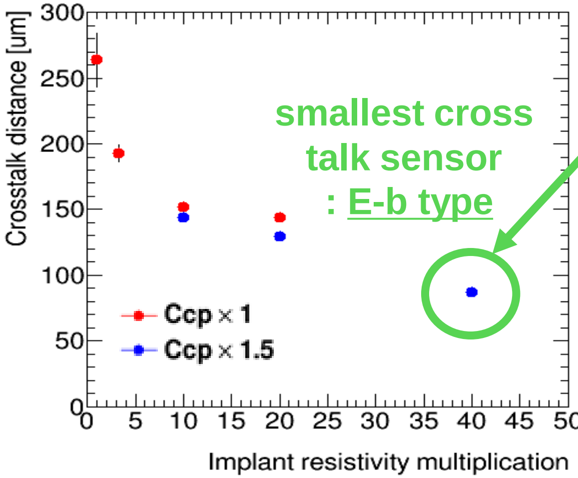
10^{-3} (E-b)



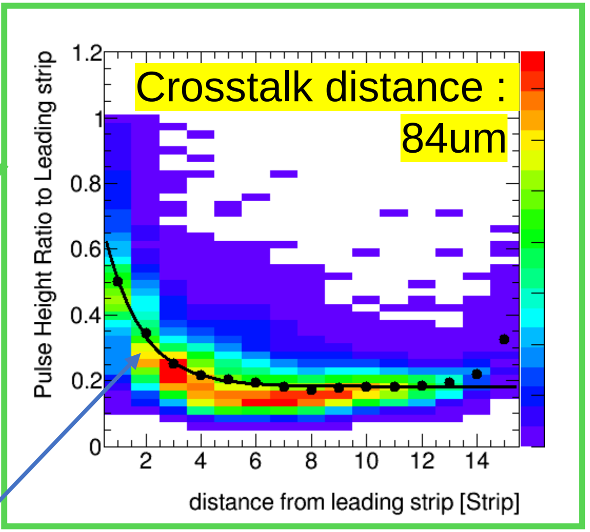
➢ Crosstalk measurement

Compare crosstalk size : "crosstalk distance"

Distance of 1/e pulse height from leading strip



smallest cross talk sensor : E-b type



Crosstalk distance : 84um

Fit with function :

$$y = A\exp\left(-\frac{x}{\tau}\right) + B$$

crosstalk distance

50% of crosstalk to next strip

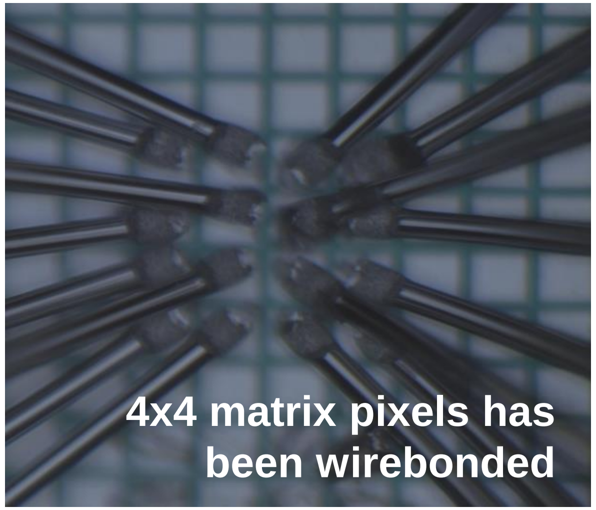
Largest R_{imp} and C_{cp} sample (E-b type) is the best sensor type
- ✓ Signal size → clearly separated from noise
- ✓ Crosstalk → suppressed enough

Pixel sensor measurement

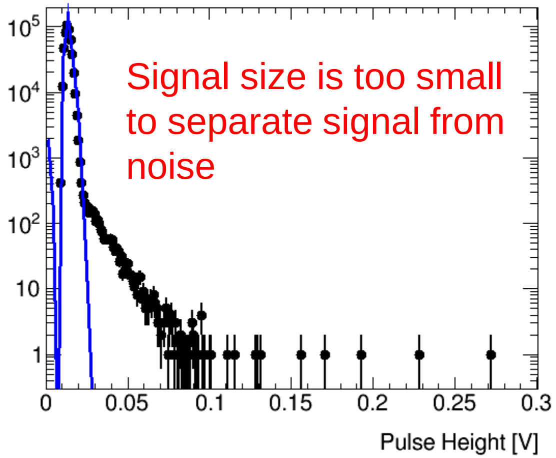
To reduce pile up effect, developing pixel sensor !

- E-b type (high resistivity, high coupling capacitance)

50um pitch pixel sensor
(42 um x 42 um)


4x4 matrix pixels has been wirebonded

Signal size distribution

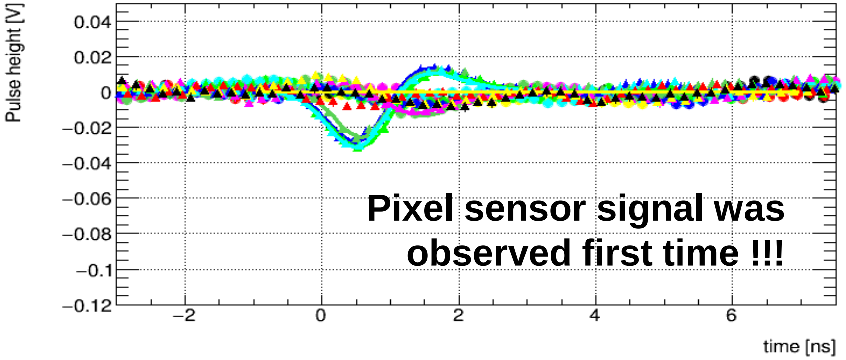


Signal size is too small to separate signal from noise

Need further improvement for pixel sensors

→ Make signal size larger
(or, allow larger pixel size and take charge division for better spatial resolution)

Pulse shape



Pixel sensor signal was observed first time !!!

To make larger signal size : larger R_{imp} and C_{cp}

- ✓ R_{imp} : not possible to make higher (limitation of Foundry process)
- ✓ C_{cp} : possible to make larger

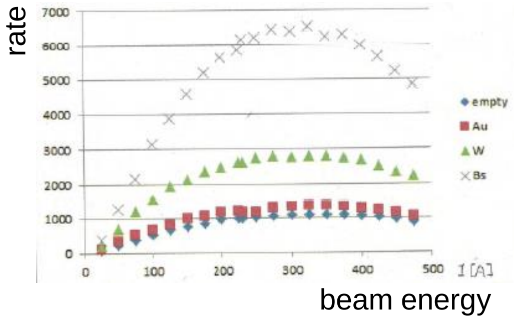
→ Next prototype

Make oxide thickness thinner (make Ccp larger)

Testbeam at ELPH

- Purpose
  - ✓ evaluate **efficiency** and **timing resolution**
  - ✓ check position resolution (and crosstalk)
- Research center for **EL**ectron **PH**oton science in Tohoku university (July 5th-9th)

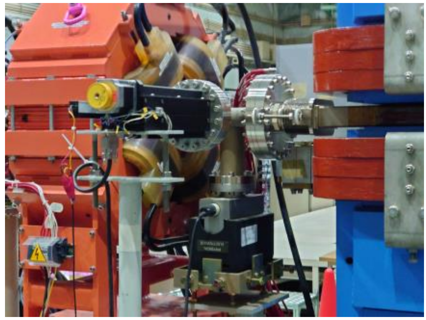
beam energy vs rate of Au, W, brass and empty target



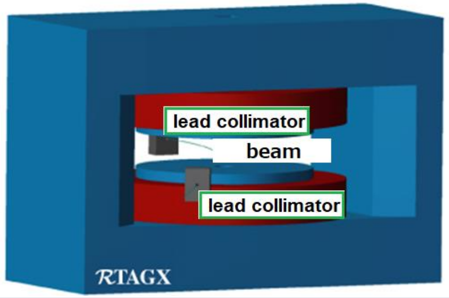
Metal foil : Brass

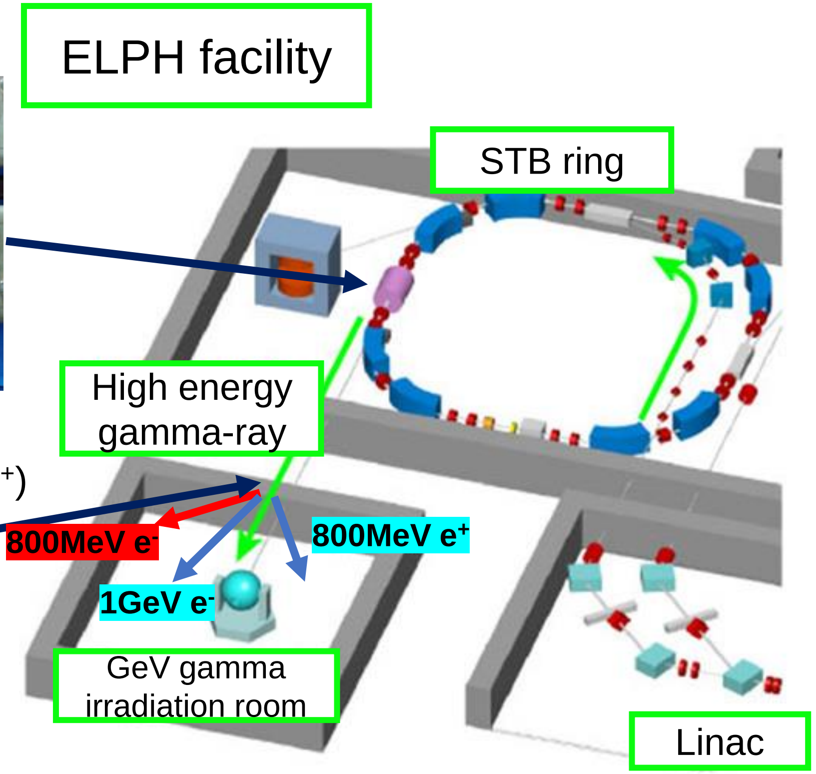
- ✓ radiation length = 0.6 X_0
- ✓ highest beam rate but various energies

C target
(convert e^- to gamma-ray)



Metal foil target
(convert gamma to e^- and e^+)



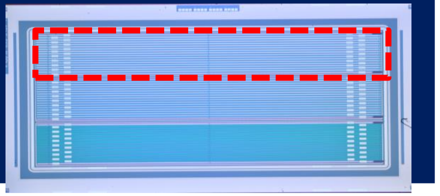


STB ring
(accelerate to 1.3GeV)

Linac
(accelerate to 90MeV)

Efficiency (testbeam)

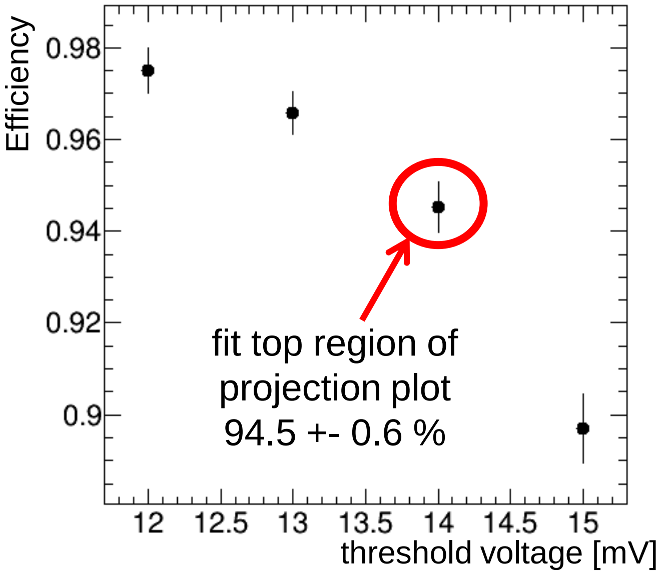
Strip sensor



To check expected 100% of efficiency

- ➢ Testbeam at ELPH (Tohoku University)
  - ✓ Sensor : Strip E-b
  - ✓ Bias voltage : 170V
  - ✓ channel : 9~15ch

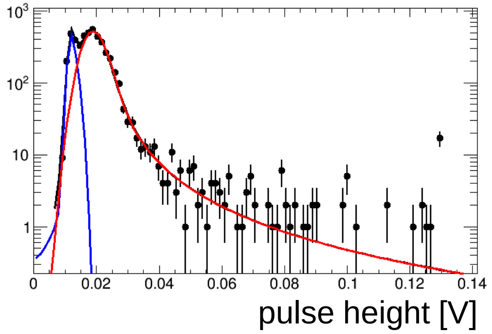
Efficiency vs threshold

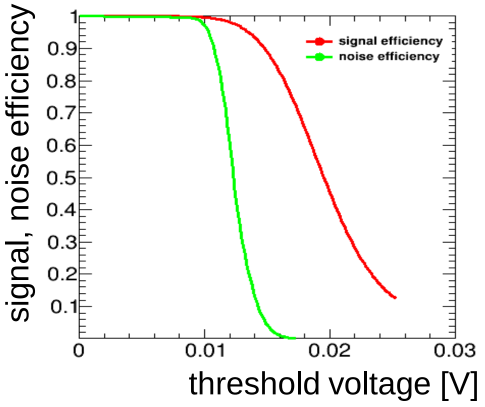


fit top region of projection plot 94.5 +- 0.6 %

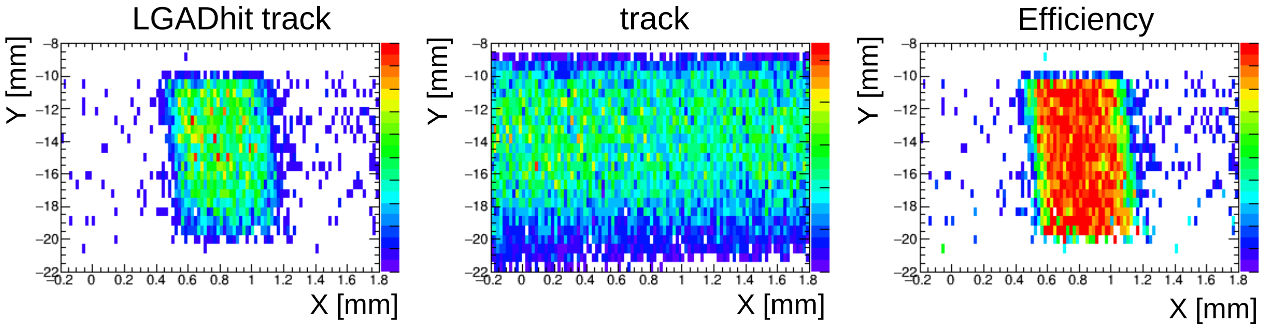
consistent to estimation from pulse height distribution

Efficiency estimation from pulse height distribution

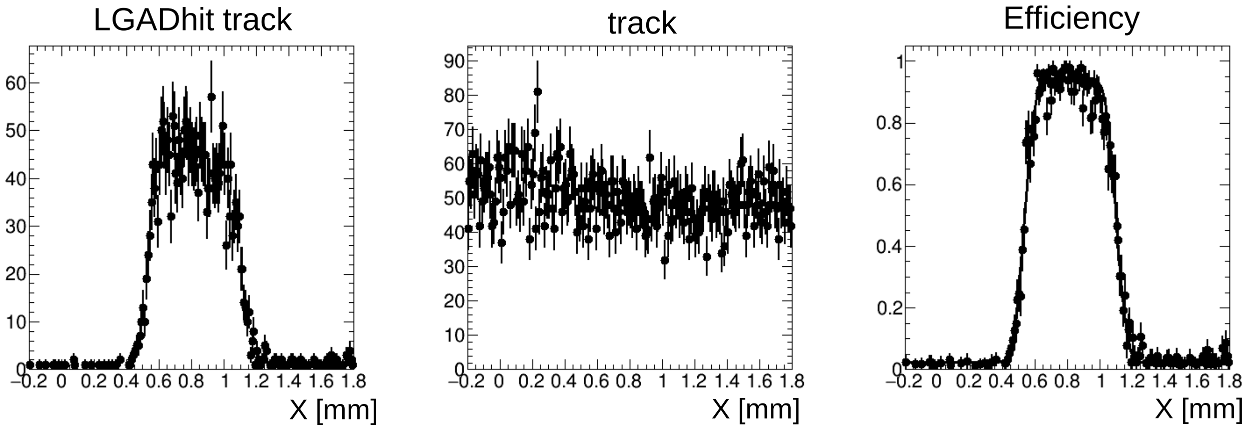




- ➢ threshold 14mV
  - ✓ 2D track map



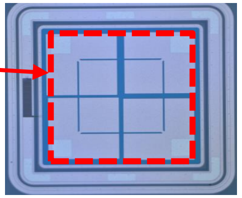
- ✓ projection X (y=-12~-17 mm)



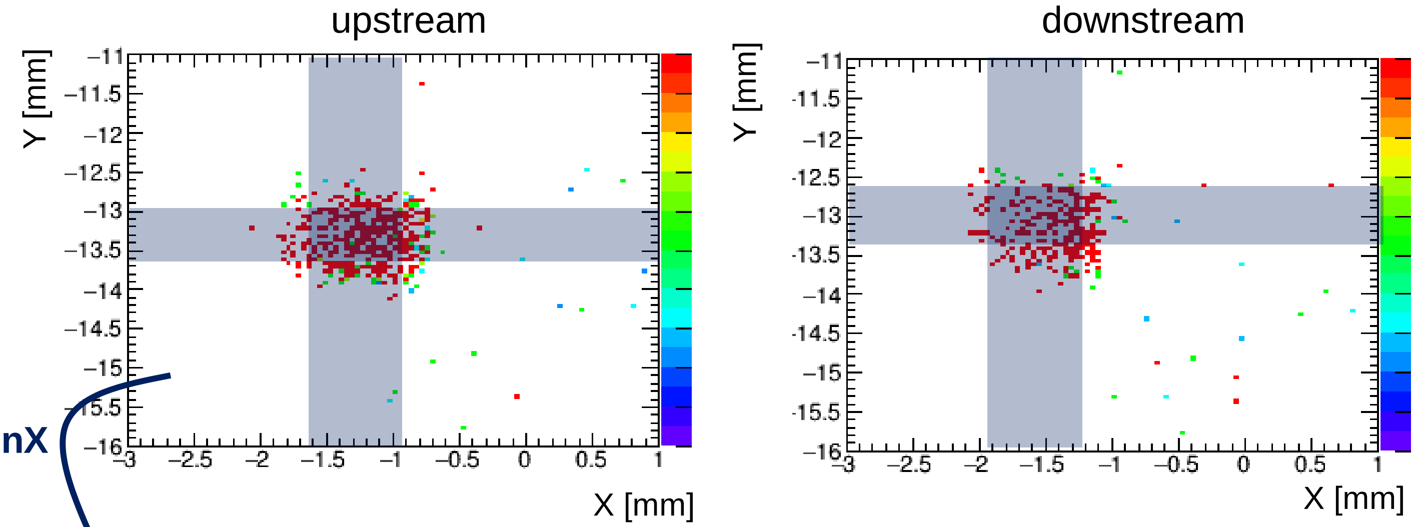
Efficiency was 94.5+-0.6% at 14mV threshold

Efficiency (Pad E-b type)

- Efficiency
  - ✓ Bias voltage : 140~170V
  - ✓ ch0~3 (2layers)
  - ✓ Event : ~240,000
  - ✓ Event selection
    - ✓ Good tracks
      - ✓ have hits for all tel and ROI
      - ✓ χ^2/NDF : < 18 (x,y)
    - ✓ LGAD hit : > 18mV

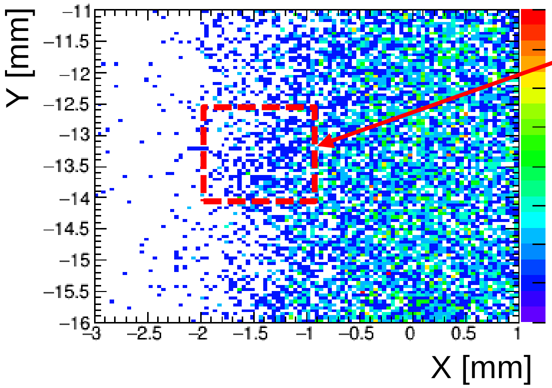


Efficiency map



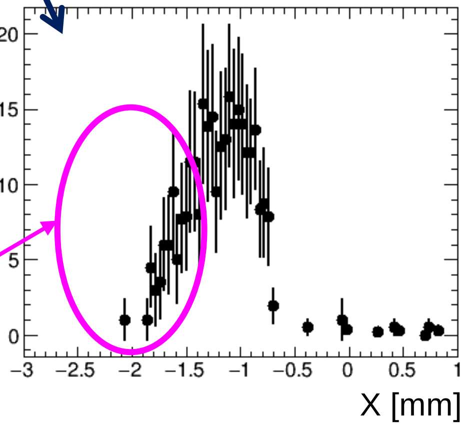
projectionX

Trackmap at LGAD Z position



LGAD region

LGAD dector is located at the edge of ROI region



less event in left side of sensor

LGAD region

: center of 1mm region by projection X/Y plot – 3 sigma of pointing resolution of beam

Efficiency : Efficiency average in LGAD region

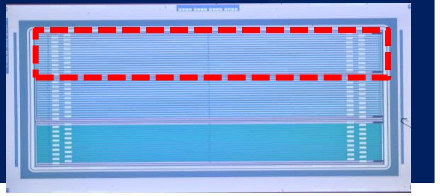
→ **97.9 +- 0.9 %**

(up and down stream conbined)

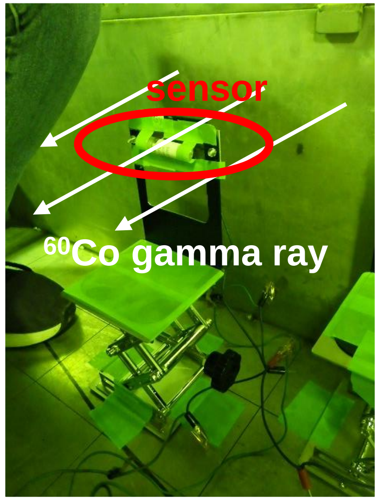
Efficiency of pad sensor was expected value

Radiation tolerance (TID)

Strip sensor

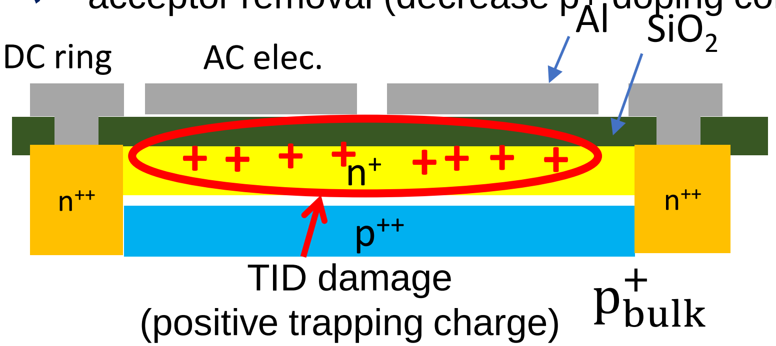


- Irradiation at facility in Takasaki

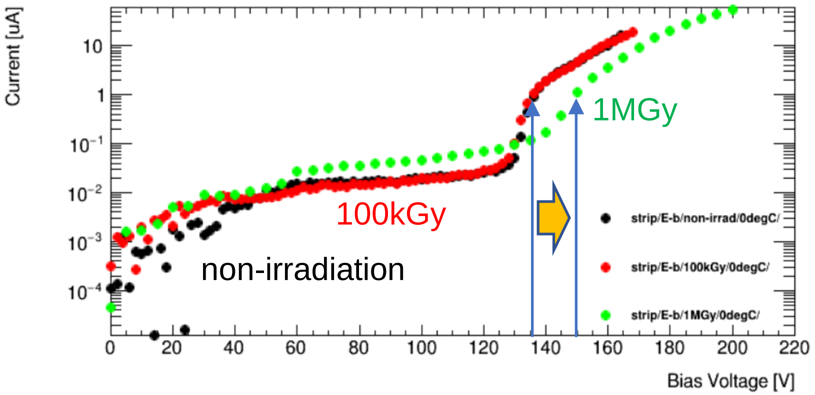


Radiation damage

- ✓ NIEL : Bulk damage
- ✓ TID : Surface damage ← Gamma irradiation
- ✓ acceptor removal (decrease p+ doping conc)

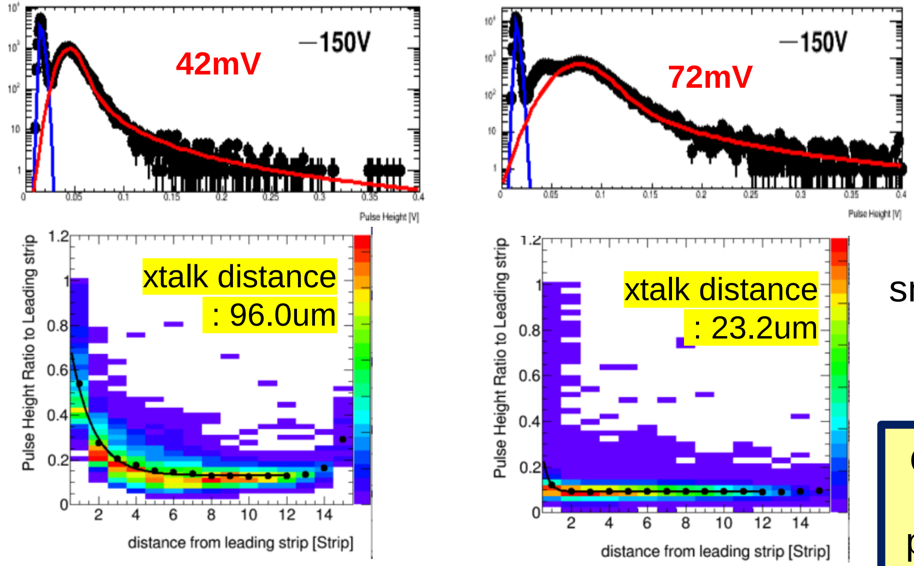


- IV curve of E-b strip @ 0degC



gain voltage getting higher in radiation level (not big issue)

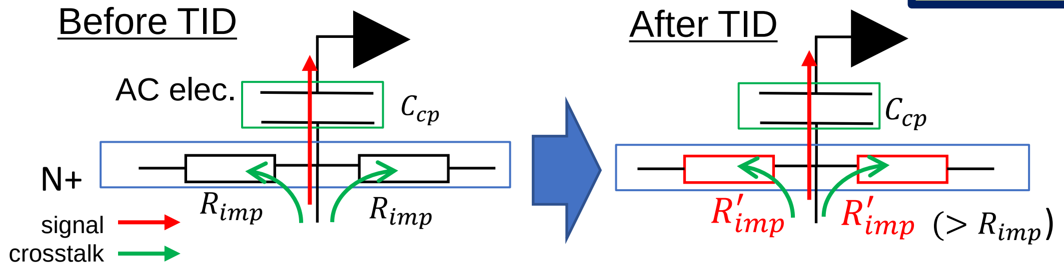
- Signal size and crosstalk
  - ✓ non-irradiation
  - ✓ 1MGy



signal size larger in irradiated sample

crosstalk smaller by radiation level

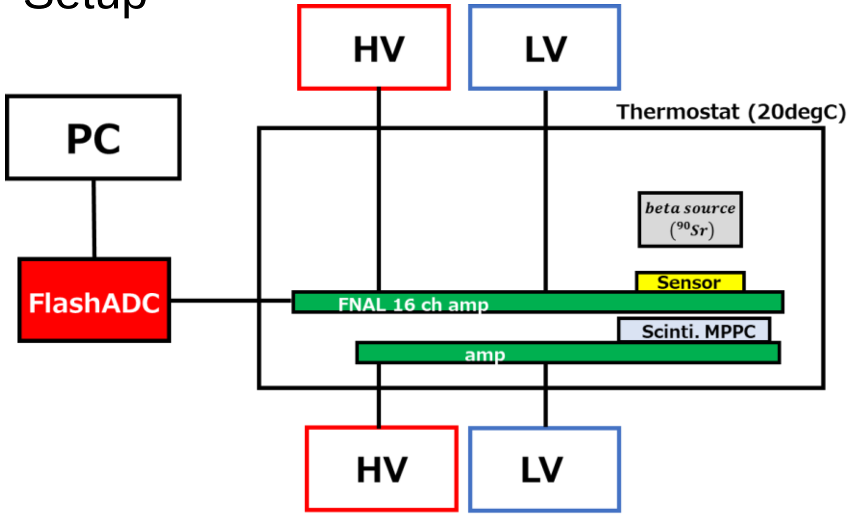
Gamma irradiation makes sensor performance better



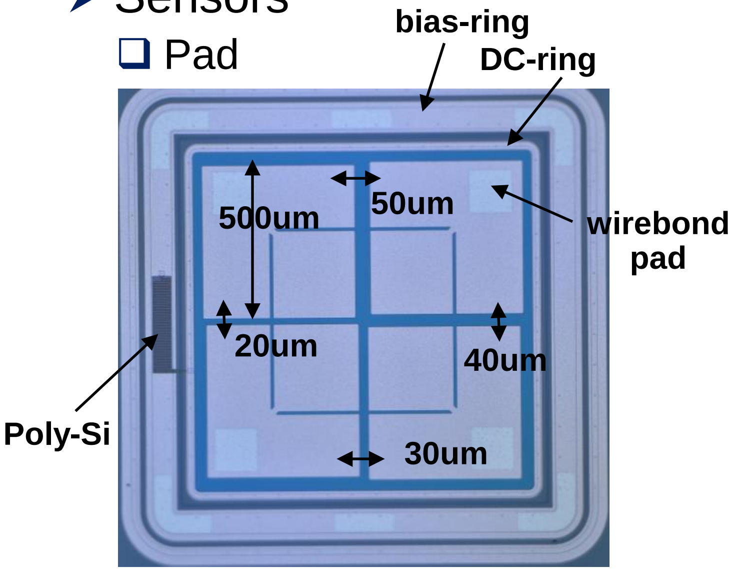
$$Q = \frac{Z_{R_{imp}}}{Z_{C_{cp}} + Z_{R_{imp}}} Q_0 \quad < \quad Q' = \frac{Z_{R'_{imp}}}{Z_{C_{cp}} + Z_{R'_{imp}}} Q_0$$

Lab measurement setup and sensors

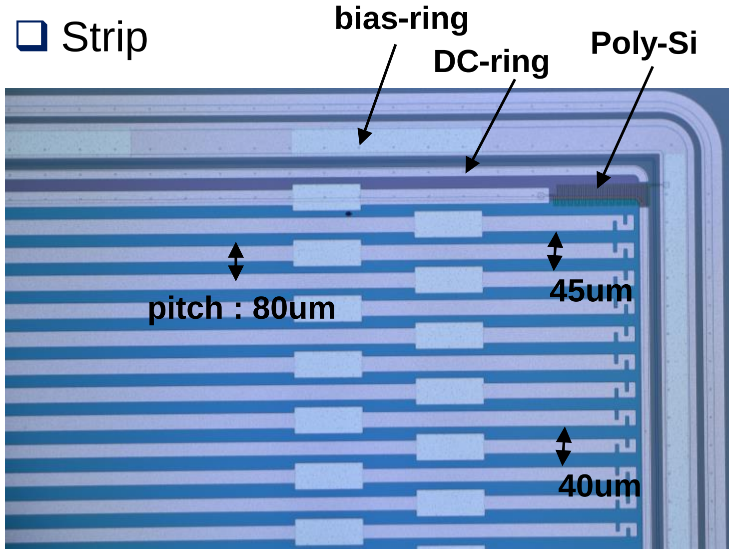
- Setup



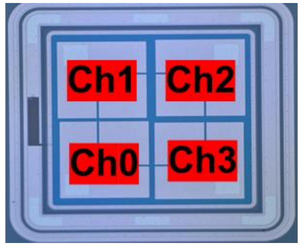
- Sensors
  - ☐ Pad



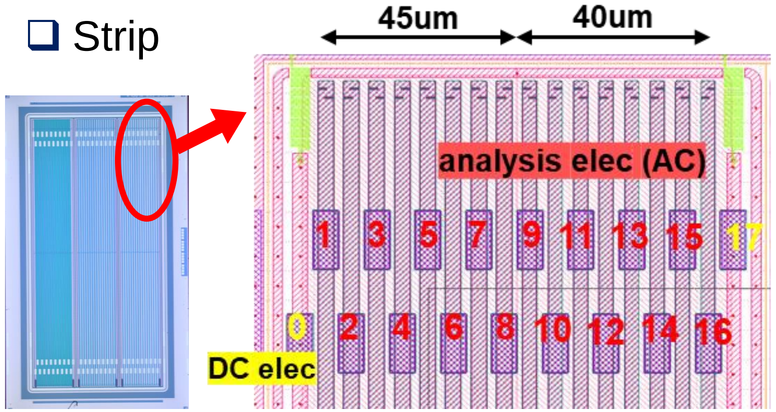
  - ☐ Strip

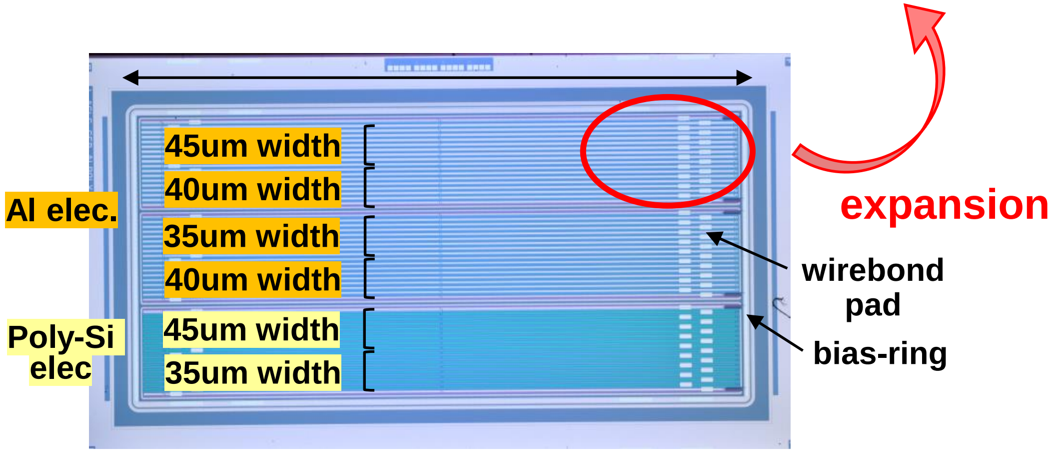


- Wirebond channel
  - ☐ Pad



  - ☐ Strip

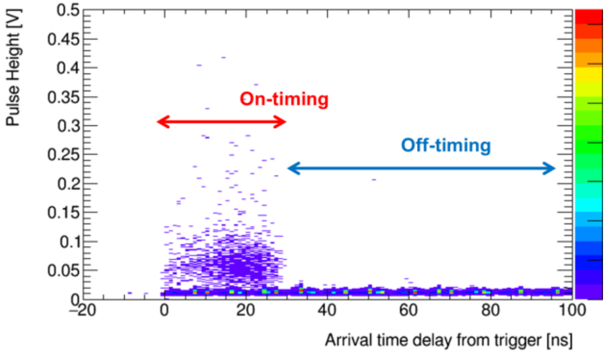




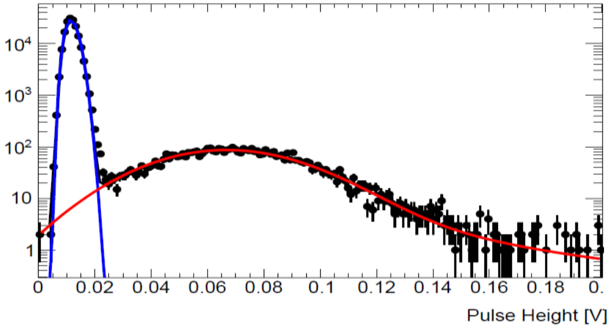
Signal size analysis

- Analysis
  - ☐ Noise
    - ✓ Fit Off-timing pulse distribution by asymmetric gaussian function
  - ☐ Signal
    - ✓ Fit On-timing pulse height distribution by Gaussian convoluted Landau function plus function of noise
    - ✓ **Signal MPV will be used to compare the signal pulse height size.**

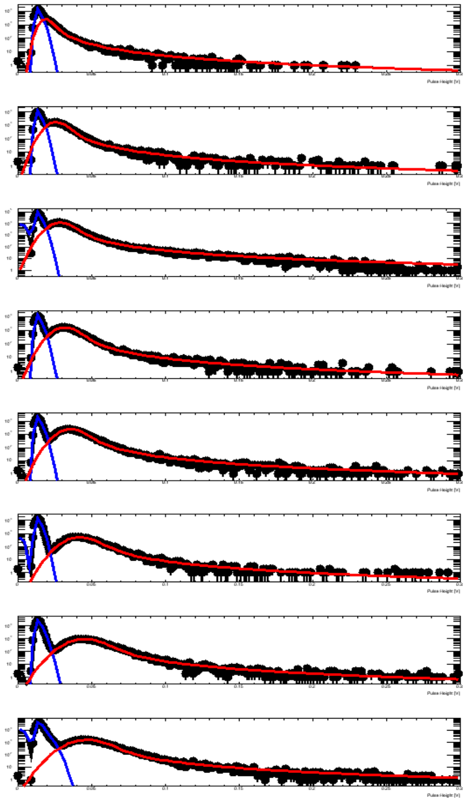
max pulse height channel and arrival time delay from trigger



max pulse height distribution at on-timing

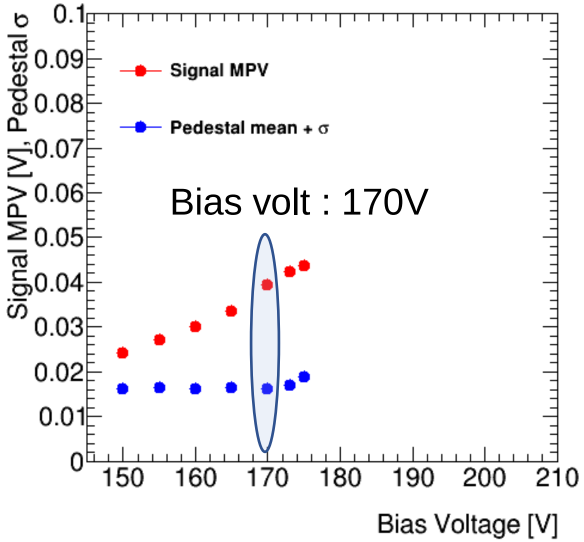


- How to define operation voltage
  - ✓ Example : E-b strip voltage scan

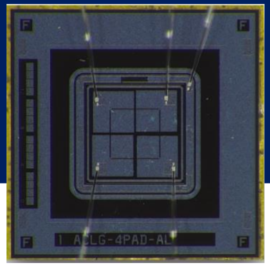


bias voltage

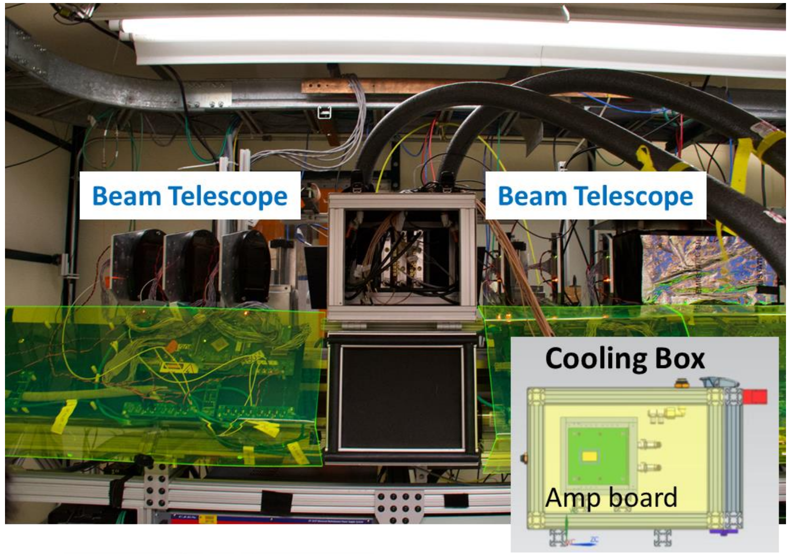
- ✓ larger signal
- ✓ smaller crosstalk



Testbeam @ FNAL

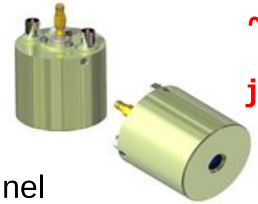


- ➢ Fermilab Test Beam Facility (FTBF)
  : 120GeV proton beam



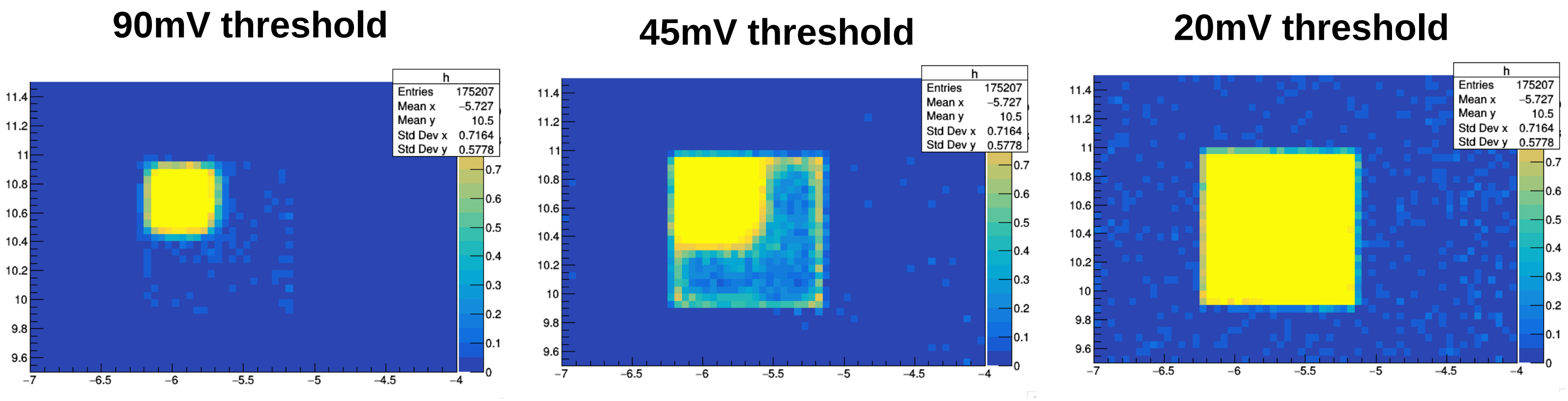
LeCroy
WR8208HD scope
12bit, 10GSa/s, 2GHz 8 channel

PHOTEK
MCP photomultipliers
(PMT140)
450ps FWHM with 5e3 Gain



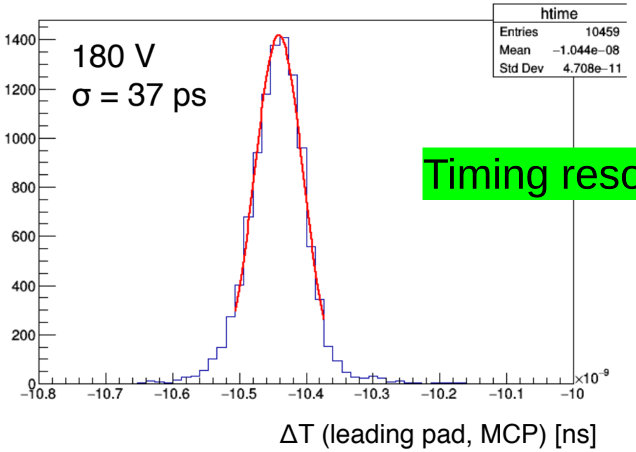
~5ps timing resolution (SPEC: Multi-photon jitter below 10 ps)

- ➢ Efficiency of C2



90mV threshold **45mV threshold** **20mV threshold**

- ➢ timing resolution of C2 pad



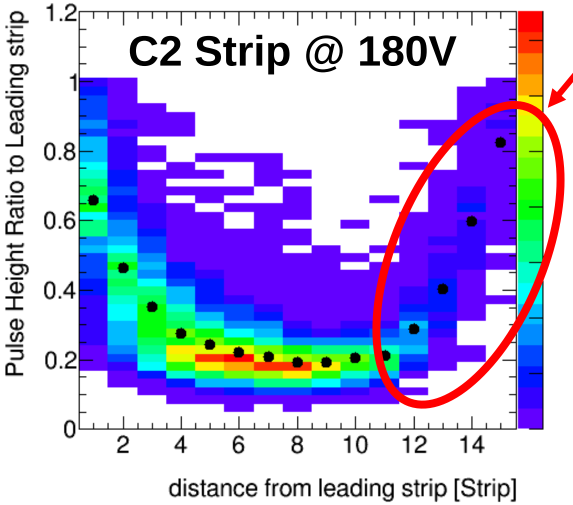
Timing resolution : ~37ps

- ✓ Efficiency : 100%
- ✓ Timing resolution : 37ps

Some issues

- Investigation of bias resister issue (non-irradiation)

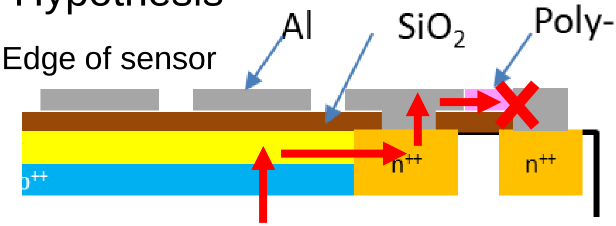
What is the signal leak from the other side of strips?



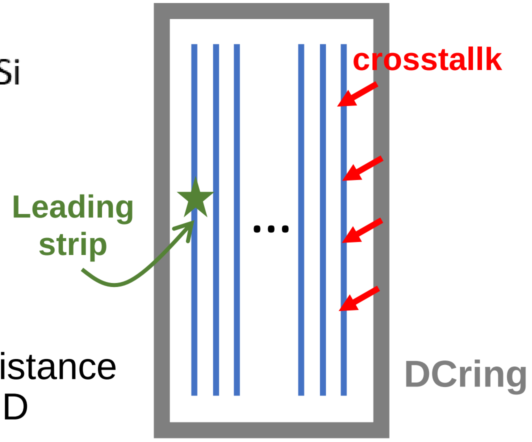
The tail …

- ✓ C2, C2-b, D-a, D-b and E-b (much less pronanced E-b type)
- ✓ Getting smaller by highest resistivity samples

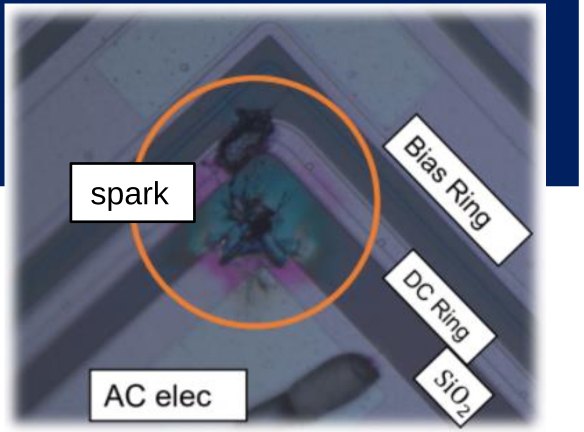
☐ Hypothesis



- ✓ MIP particle inject edge strip
- ✓ Poly silicon resistance > Rimp resistance
  →charge cannot escape to GND

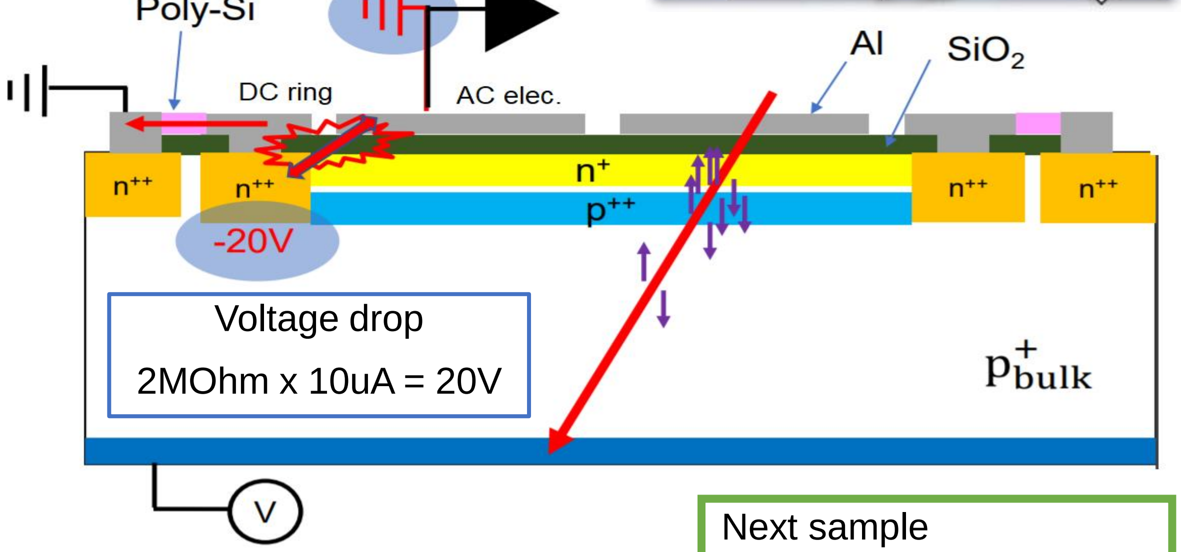


- Sparked sensor (irradiated)



GND(0V)

Poly-Si



Voltage drop

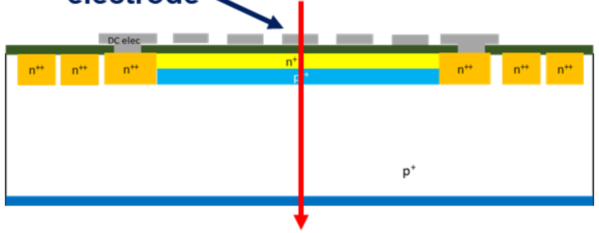
2MOhm x 10uA = 20V

Next sample
: sample with a little far distance between AC elec. and DC ring

Hypothesis

1. High voltage
2. Voltage drop by Poly-Silicon resistivity
3. Voltage difference between AC elec. and n++ ring (DC ring)
   → Spark

TCAD Simulation and Actual Measurement



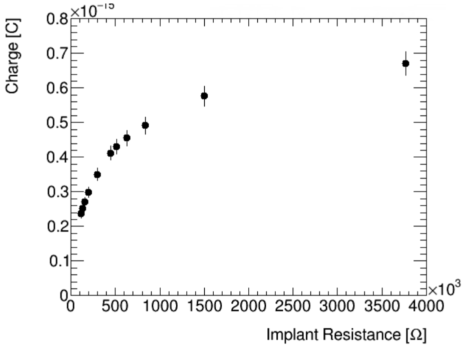
Readout electrode

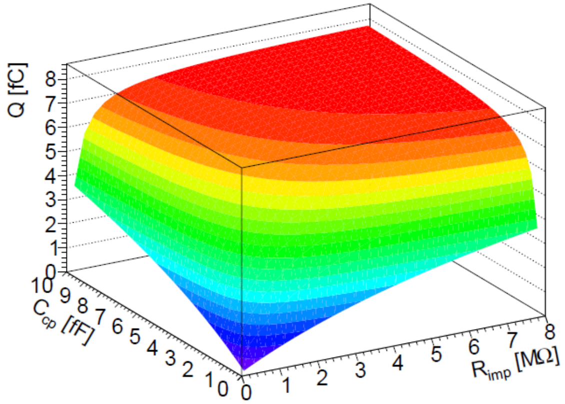
MIP particle

- Signal Size (repost) : Changing Rimp and Ccp

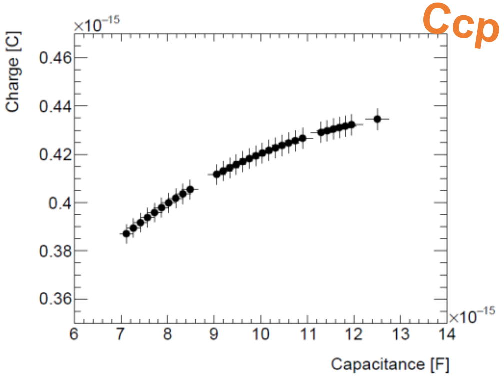
❑ Simulation

Rimp



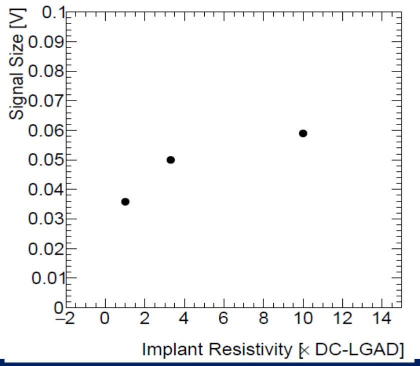


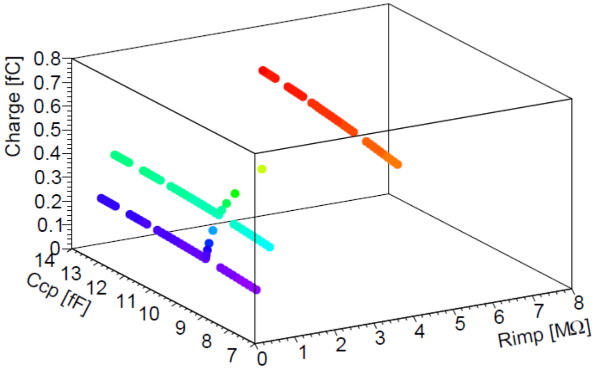
Ccp



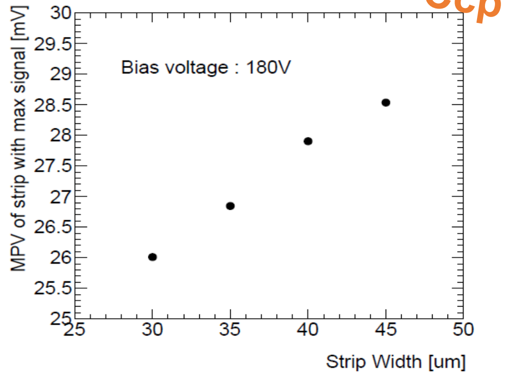
❑ Actual measurement

Rimp

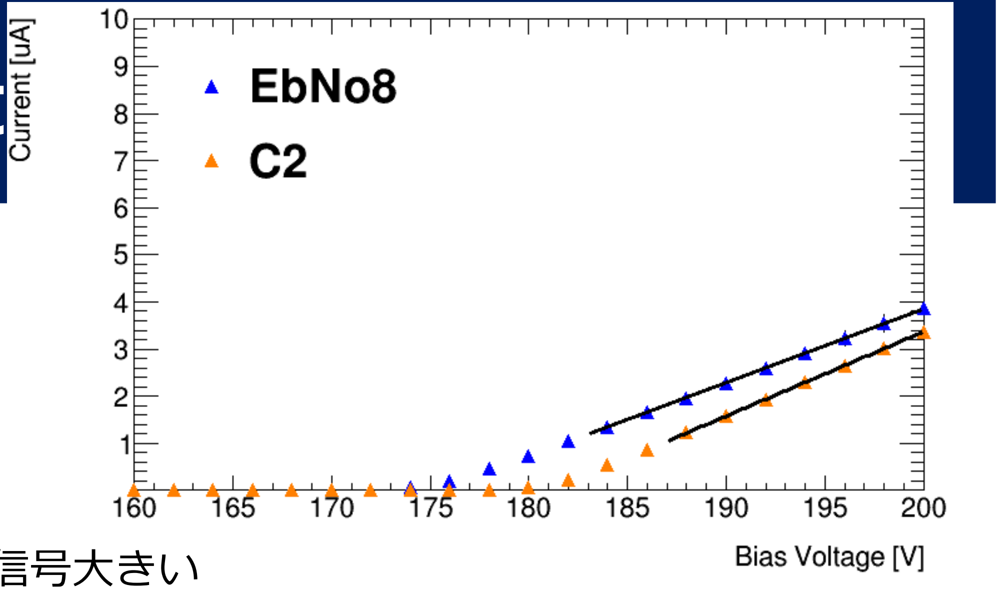




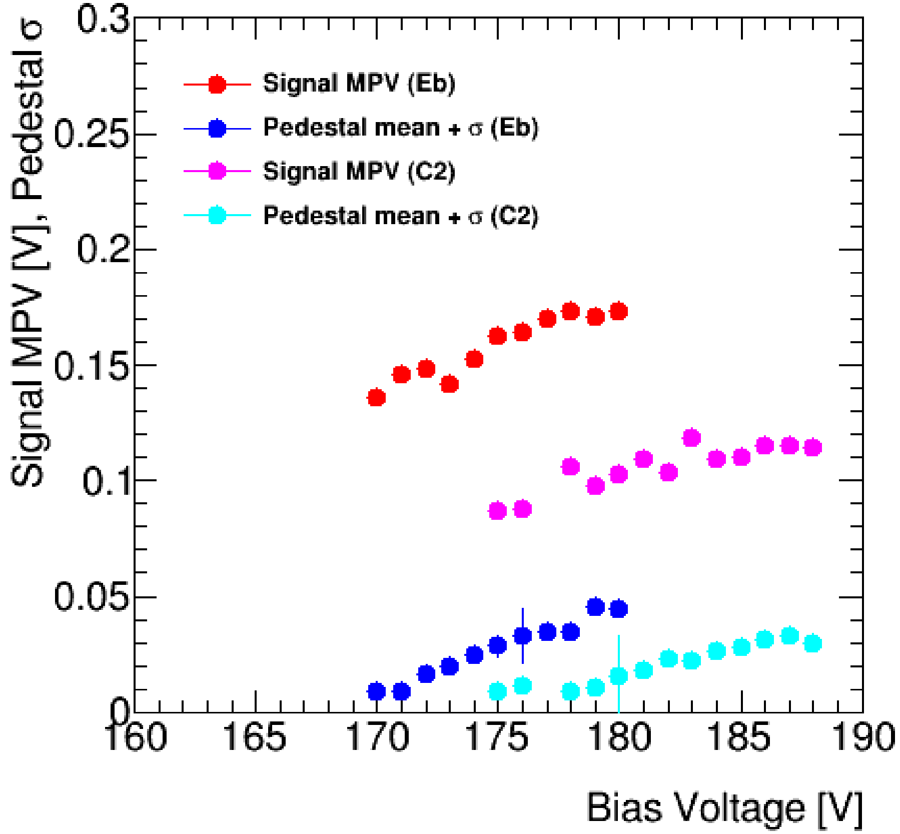
Ccp



totカット後のペデスタルと信号をFit



- うまくFitできた
  - 信号とペデスタル＋σをC2とEbで比較



- C2よりもEbの方が信号大きい

- ペデスタルについて
  - 低電圧：大体同じ(4V差くらい)→IV
    - 表面でブレークしている仮説は違った？
      (表面でブレークしてたらペデスタルの増加が4V差どころじゃなくもっと早いのでは)
  - 高電圧：Ebの方が多そう(4V差で)
    - n+ドープ量が薄いから増幅された熱ノイズがより多く読みだされている

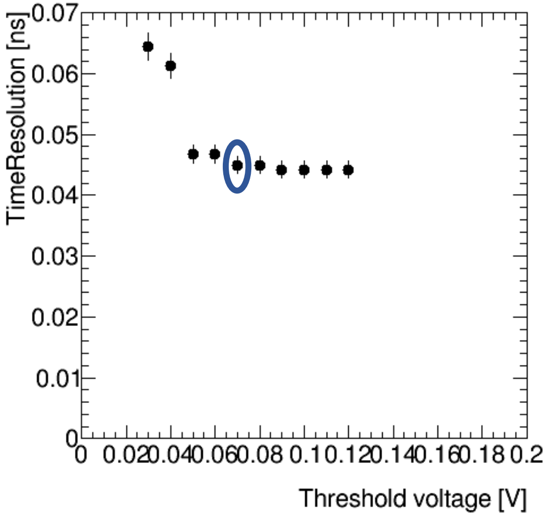
Ebがペデスタルの増幅率が大きいならSN的に時間分解能測定が限界にくるのか？

もう少し高い電圧で見れないかがんばってみる

時間分解能

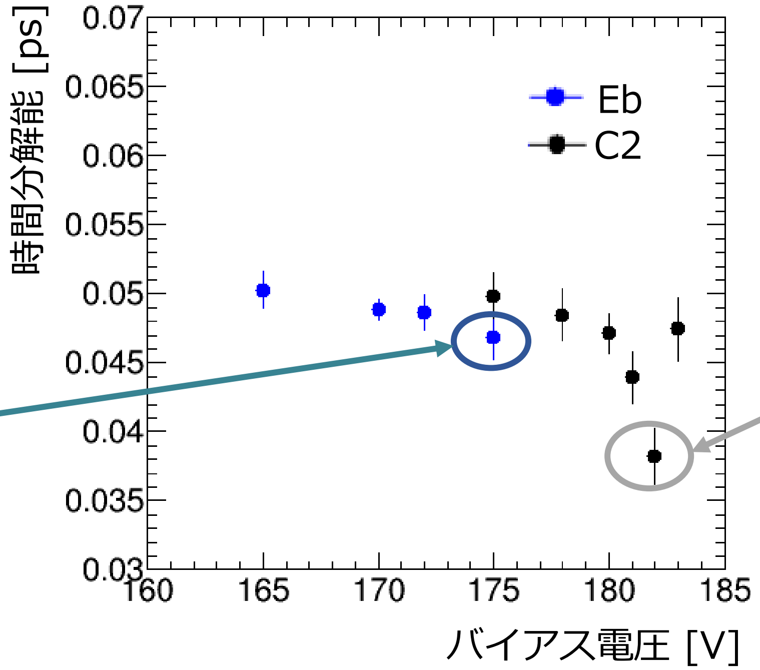
- C2とEbで時間分解能のvoltage scan
  前回：Fitするには少なくとも200run必要だった→100run追加、200run分データをとった

Eb@175V
時間分解能：**46.8+-1.5ps**

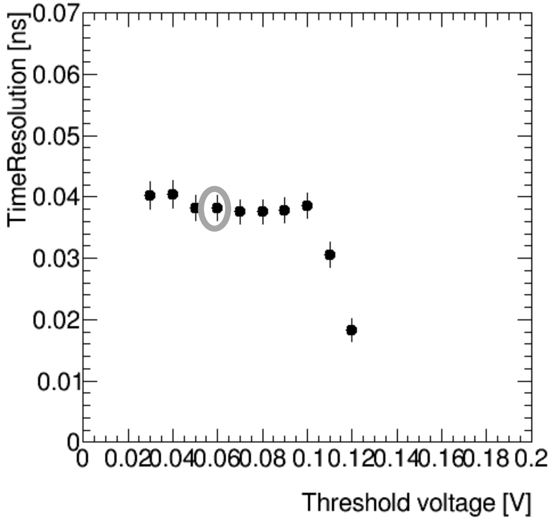


Eb→176Vくらいでびりびり

thr60mVでの時間分解能



C2@182V
時間分解能：**38.2+-2.0ps**

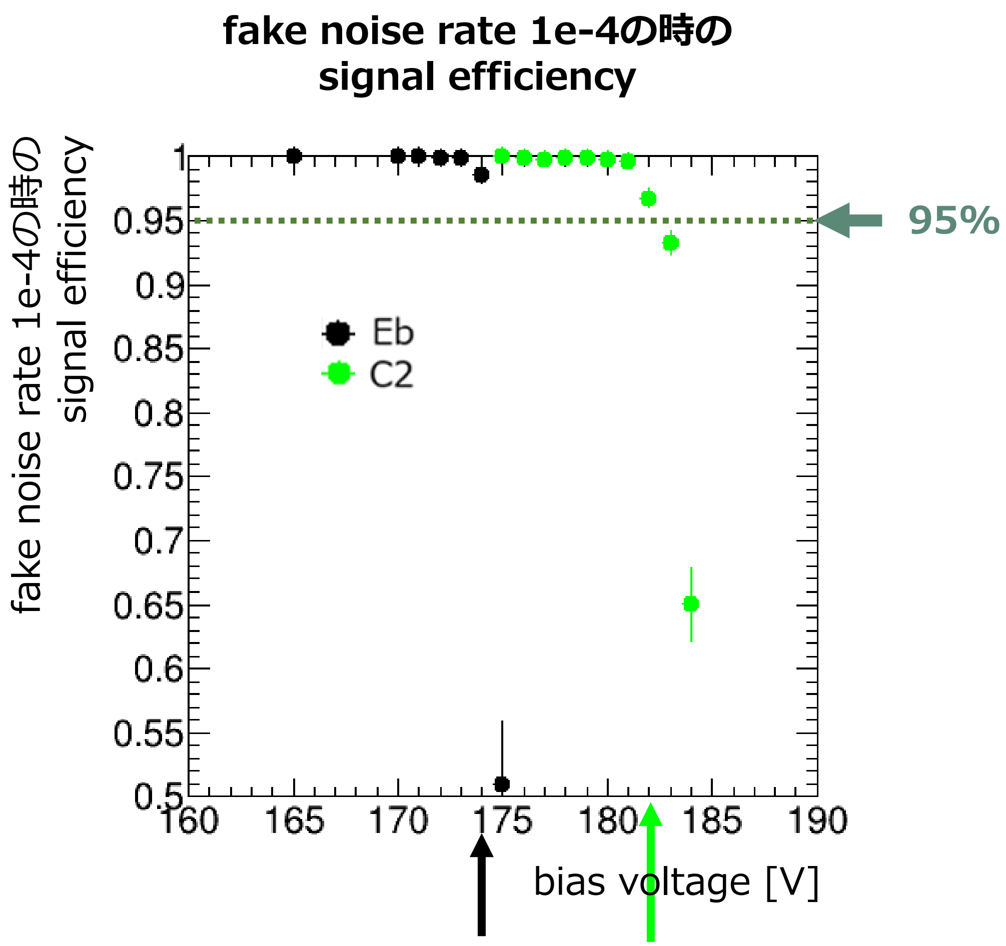


C2→183Vくらいでびりびり

- びりびり限界まで取ると
  - ✓ C2は時間分解能がよくなって悪くなる
  - ✓ Ebは時間分解能がよくなって悪くなる前にびりびり？

びりびりを定量的に定義するために
波高分布のノイズを確認

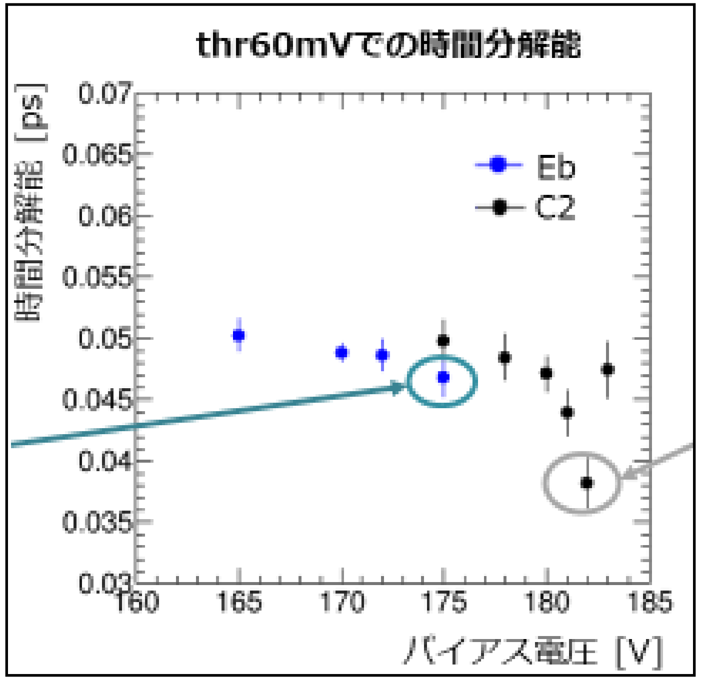
fake noise rateを関数から求めた



fake noise rate 1e-4の時のsignal efficiency95%を切らないようにすると

- ✓ C2：182V
- ✓ Eb：174V

での時間分解能を言えばよい



(論文用) todo

- ✓ Ebを174Vでいっぱいデータとる
- ✓ C2は183Vでいっぱいデータとる
- ✓ このプロットをそれぞれ1e-4の時のthresholdごとの時間分解能にする