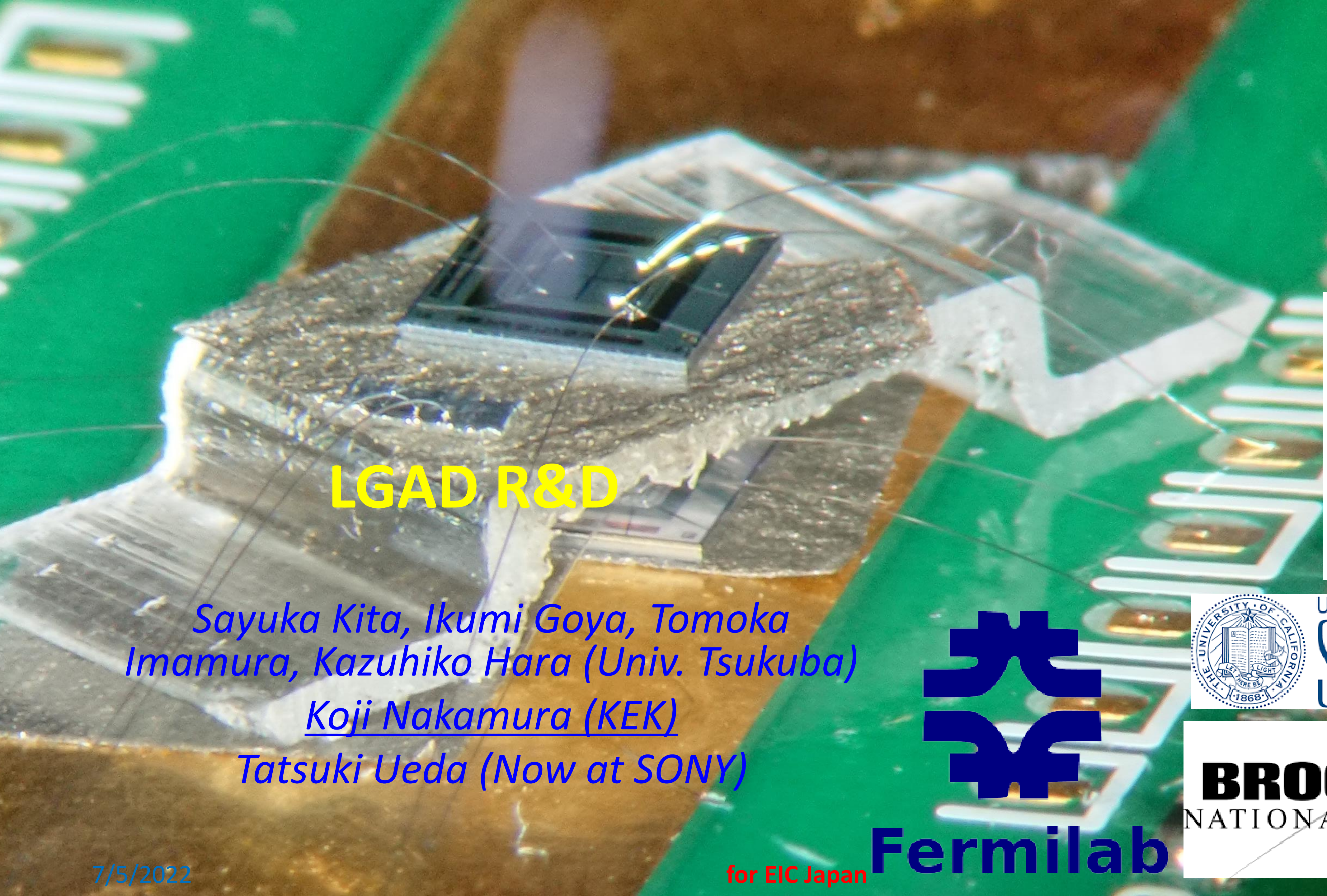


LGAD R&D

Sayuka Kita, Ikumi Goya, Tomoka Imamura, Kazuhiko Hara (Univ. Tsukuba)
Koji Nakamura (KEK)
Tatsuki Ueda (Now at SONY)

Next generation of Collider experiment

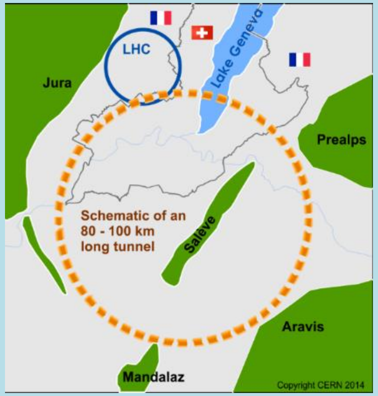
- Need "Higher Luminosity" and/or "Higher Energy"
  - *High Luminosity LHC (HL-LHC)*
    - 20 times more data (~3000-4000fb^{-1}) at **14TeV**
    - Plan : Start at 2029

    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

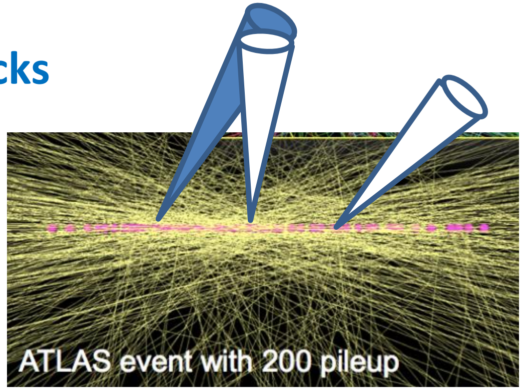
    Final decision soon



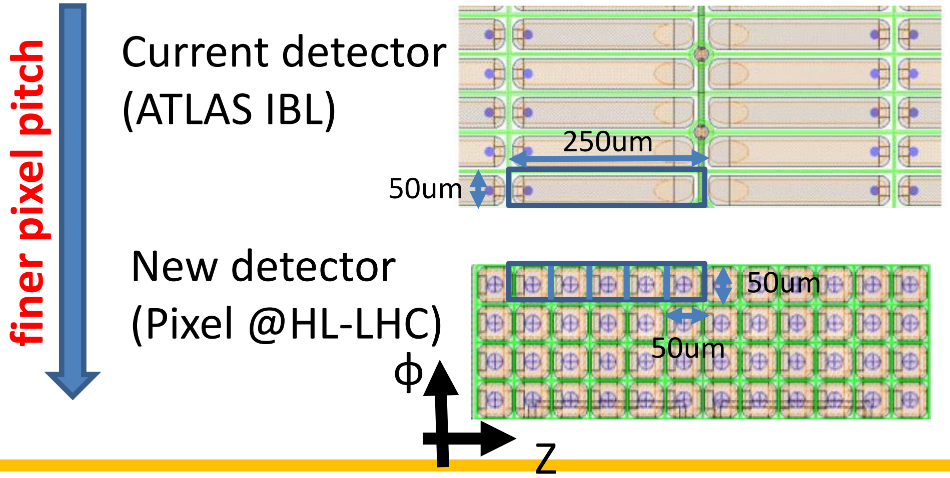
Inner Tracking system

Very high density tracks

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



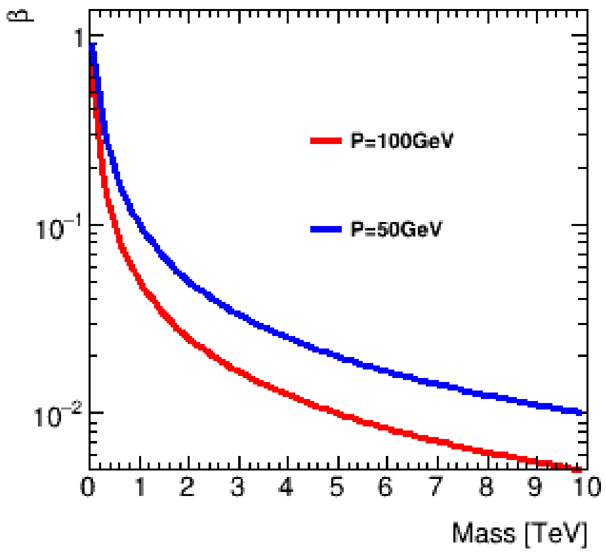
Only way to solve this so far…



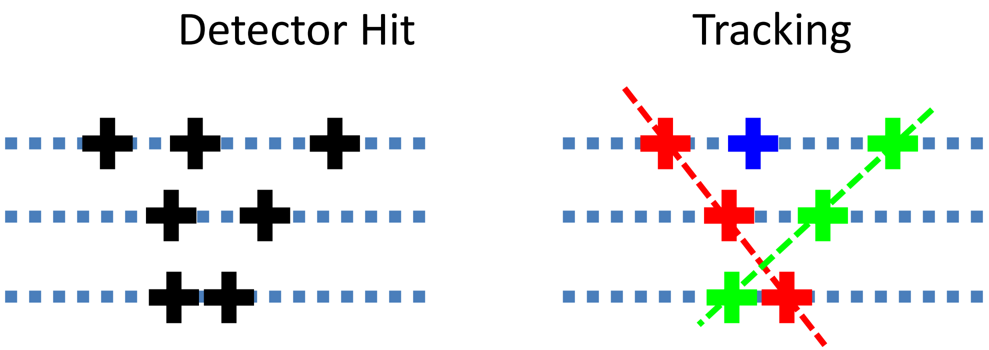
Future Semi-conductor Tracking Detectors

- **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**

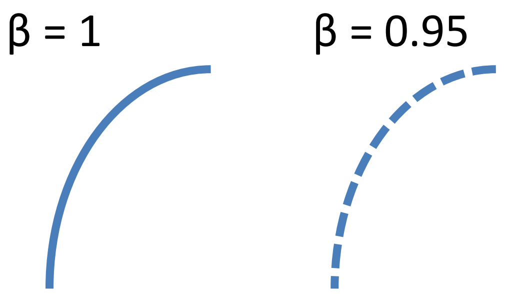
Mass spectrum for new particle



4D tracking !



Particle identification



150ps difference at R=1m

β measurement to obtain mass

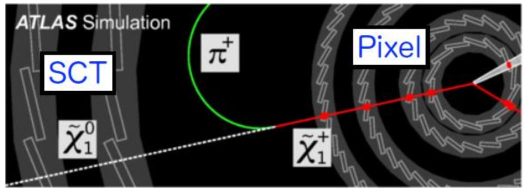
Solve pileup hits in an event

K+ π+ separation

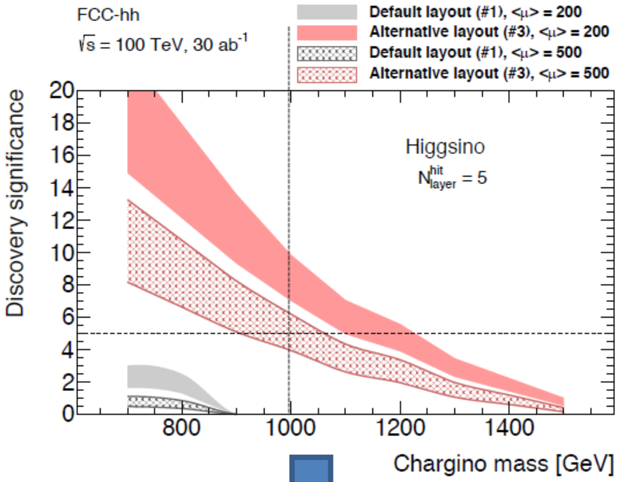
e.g. Mass measurement for Long lived chargeno

Physics impact of timing detector

Higgsino production by using disappearing track

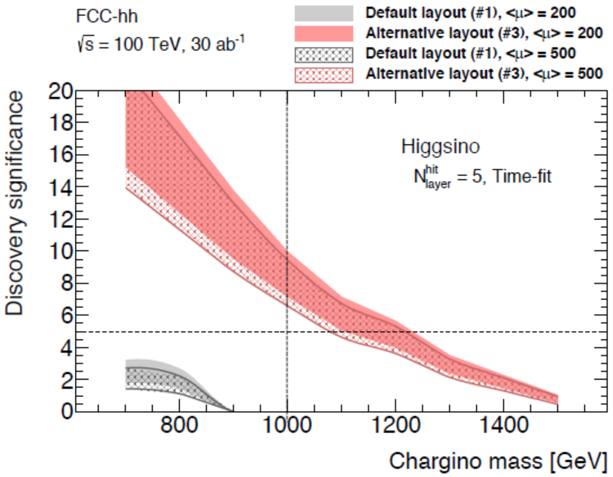


LSP: higgsino
Δm($\tilde{\chi}^{\pm}$,$\tilde{\chi}^{0}$)~300MeV
τ $_{\tilde{\chi}\pm}$ ~0.04ns (cτ~12mm)

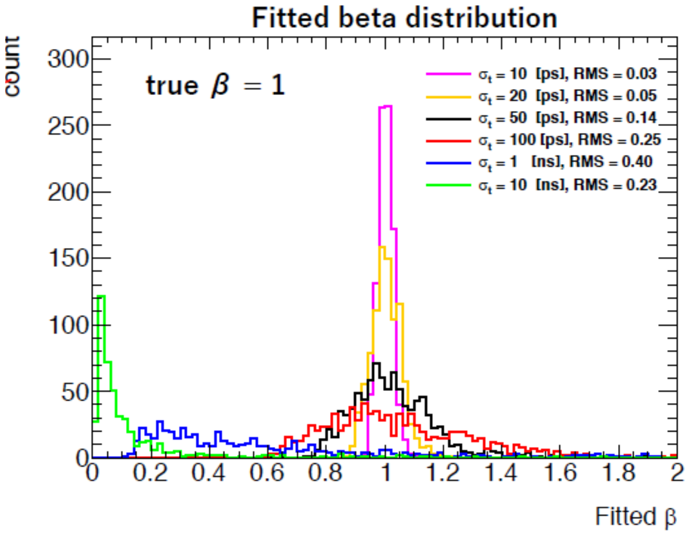


Used timing information only for pileup removal

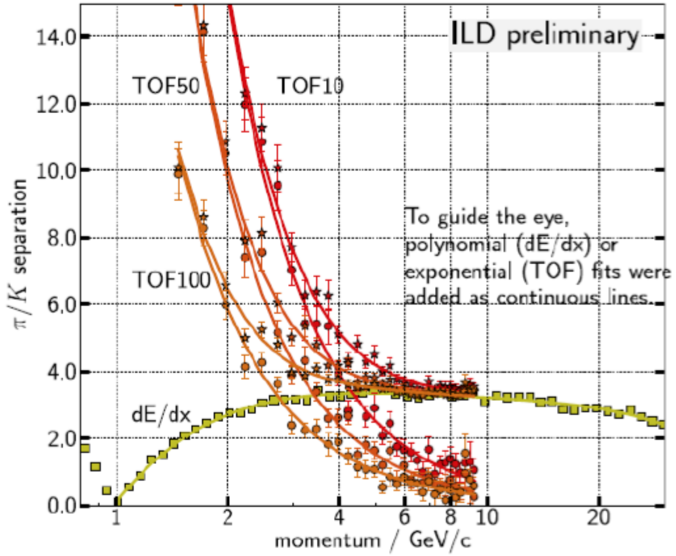
50ps timing information



β measurement in FCC detector



ILC K/π separation



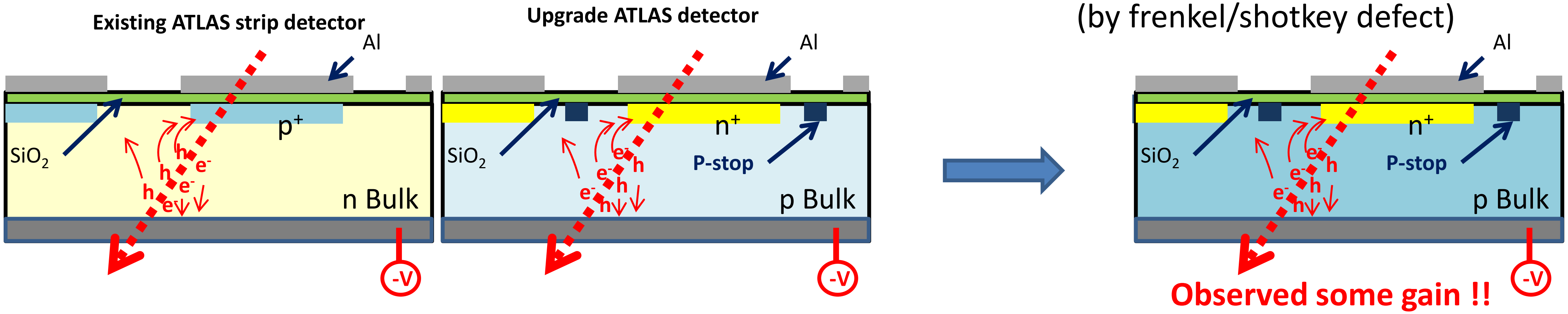
- See more information in timing detector workshop in 2018: https://indico.cern.ch/event/747424/timetable/#20181208

How LGAD development started?

Silicon detector with High resistivity bulk

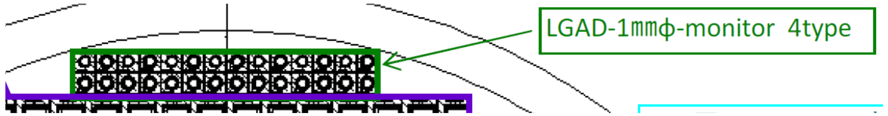
~2005 **2005-**

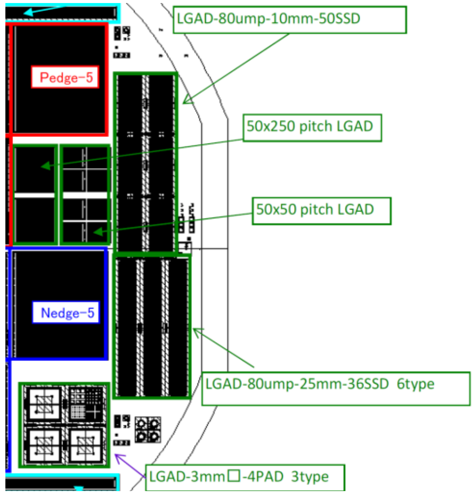
After proton/neutron irradiation :
higher p+ like doping potential
(by frenkel/shotkey defect)



2015-

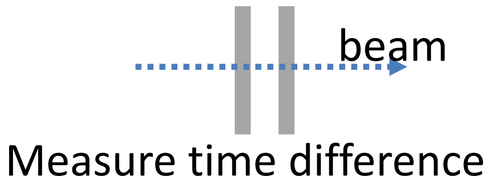
- In 2015, **first LGAD detector build with HPK.**
  - Although this is the same technology to the Avalanche photo diode(APD) since 1970s…
- First detector is 1mm monitor diode.

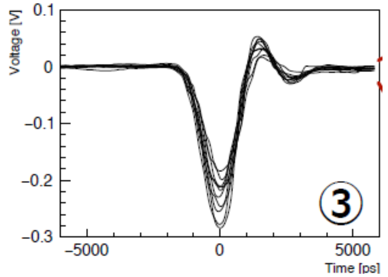


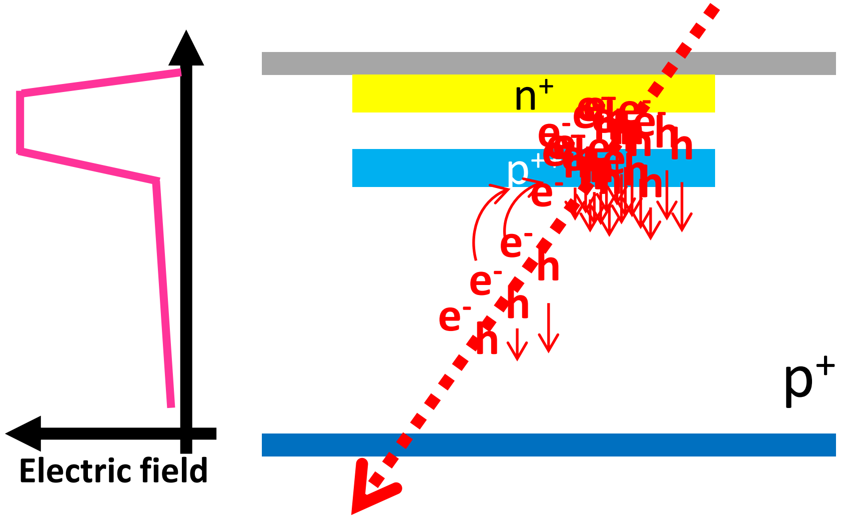


Low gain Avalanche Diode (LGAD)

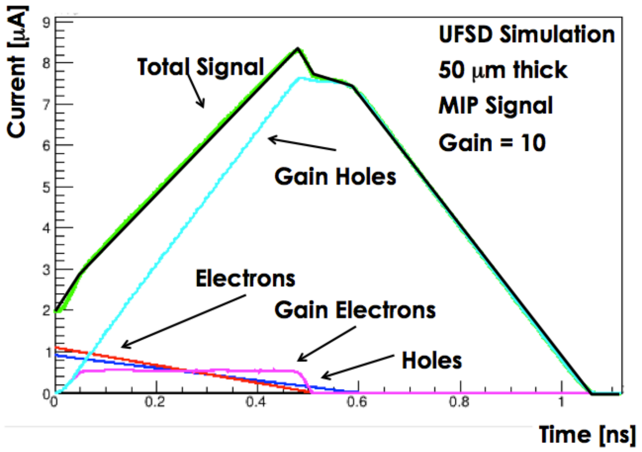
- Low gain Avalanche Diode (LGAD)
  - General *n*⁺-in-*p* type sensor with *p*⁺ gain layer under *n*⁺ implant to make higher Electric Field → Good timing resolution.
  - **30ps timing resolution achieved already in 2015.**
  - Next development
    - **Finer electrode separation for spatial resolution**
    - **Radiation tolerance**

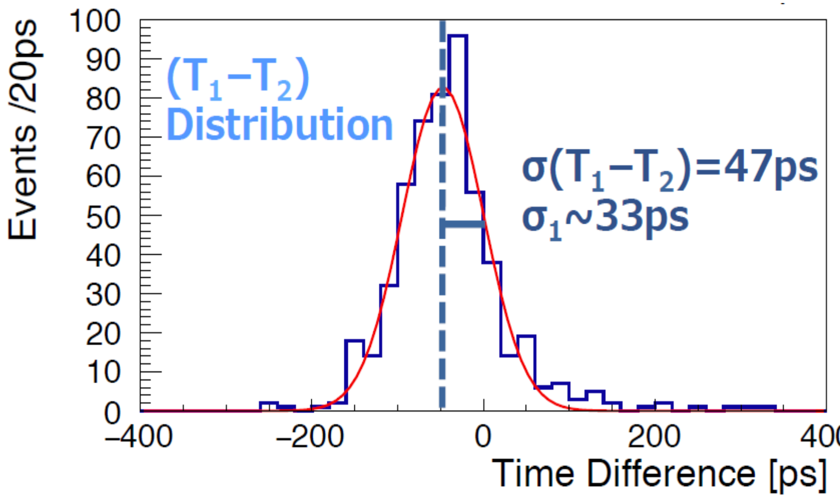






Signal drivers : **Gain Holes**





What drives timing resolution?

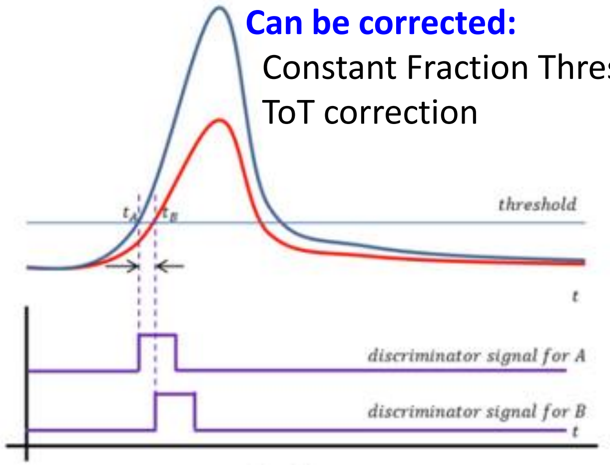
Time Walk

Over-threshold Timing difference due to the size of the signal

Can be corrected:

Constant Fraction Threshold

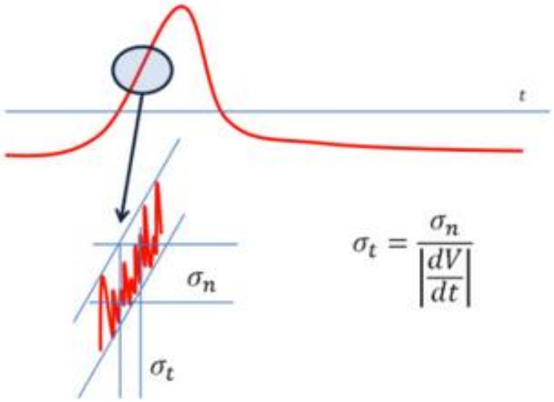
ToT correction



Time walk effect

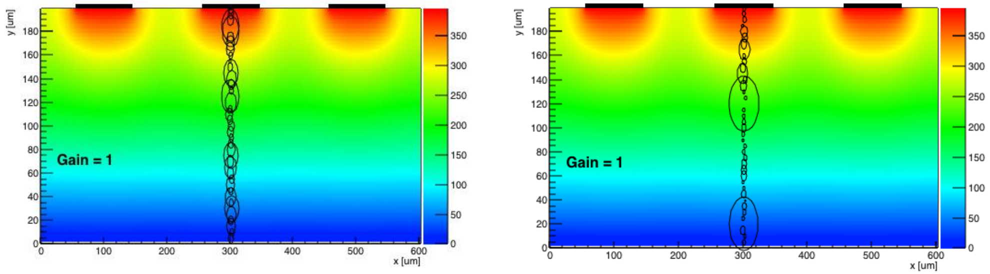
Time Jitter

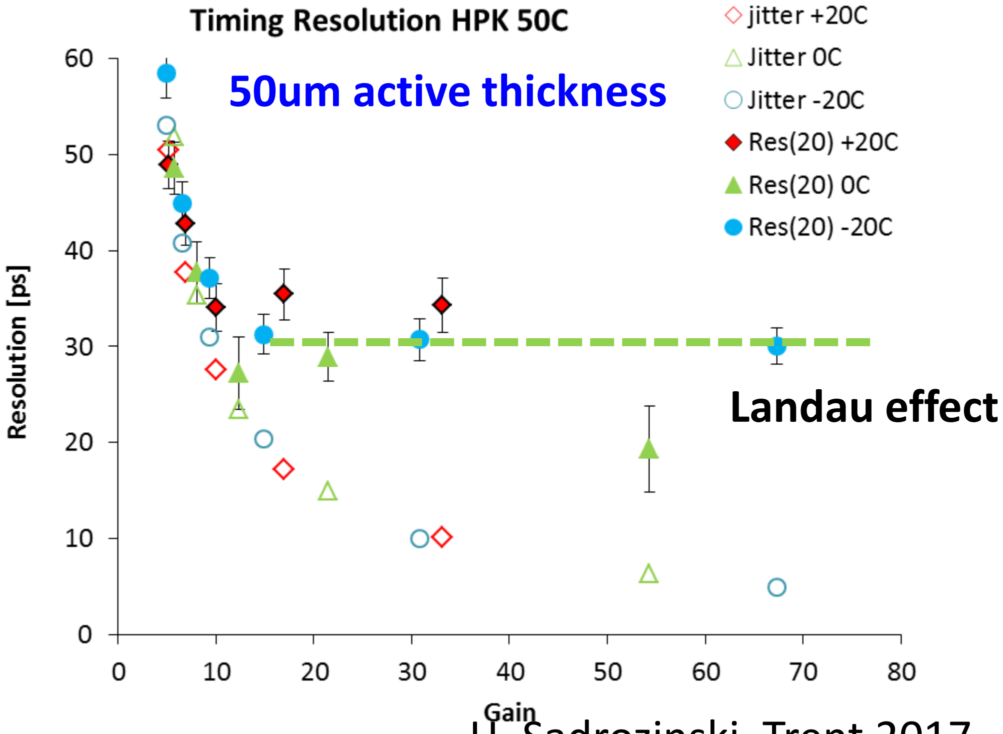
Due to various noise souces



Jitter effect

Landau Effect





H. Sadrozinski, Trent 2017

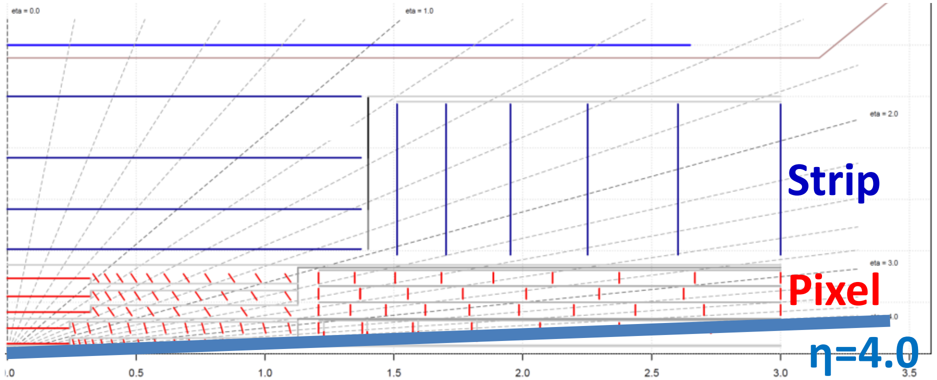
Fast turn on (i.e high dV/dt) should have better timing resolution.

- **Time Jitter can be reduced by higher electric field (i.e. higher gain**
- **Landau Effect** : Non-uniformity of ionization energy drop of MIP
  - Induced Current (I_{ind}) should follow **Shokley-Ramo's theorem**.
  - For LGAD, need charge at Gain layer. **(~30ps with 50um thick sensor)**
    - Drift time can be different in case un-uniform energy drop.
    - **Thinner sensor have better timing resolution. (recently developing 20-30um)**

What we need for Hadron Collider(+ILC)?

- High Luminosity LHC detector

ITK upgrade detector



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

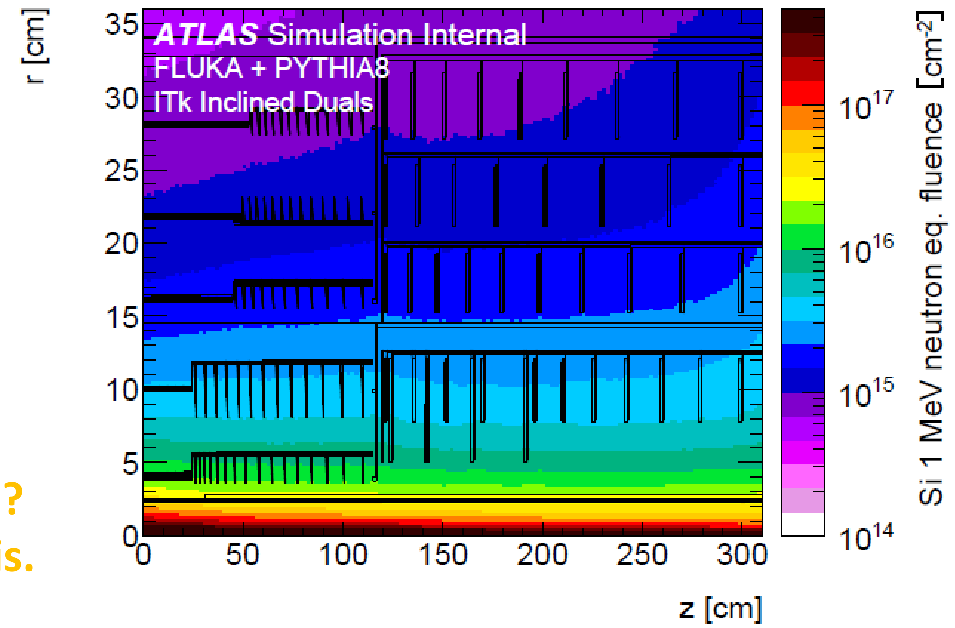
Is this granularity possible?

ILC

Outer tracker layers of ILC are also possibly LGAD?
LGAD for CAL should work with current LGAD as is.
Better timing resolution helps for PID?

- 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.



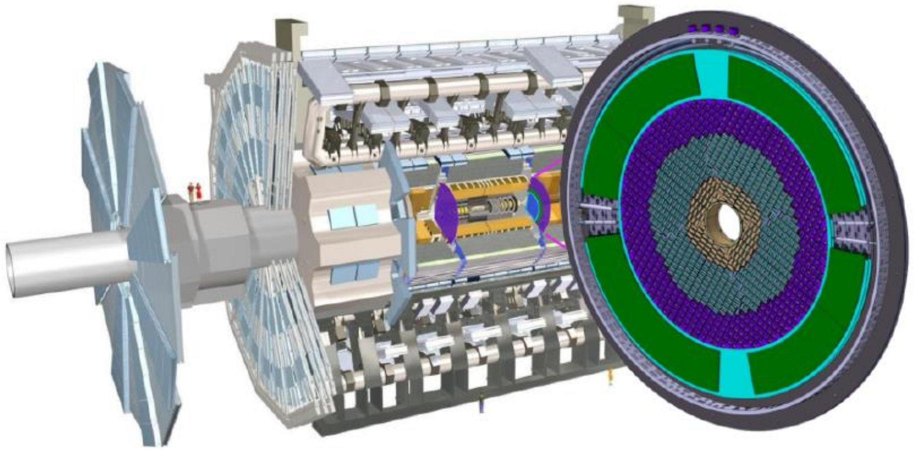
Survive upto 1e16neq/cm^2?

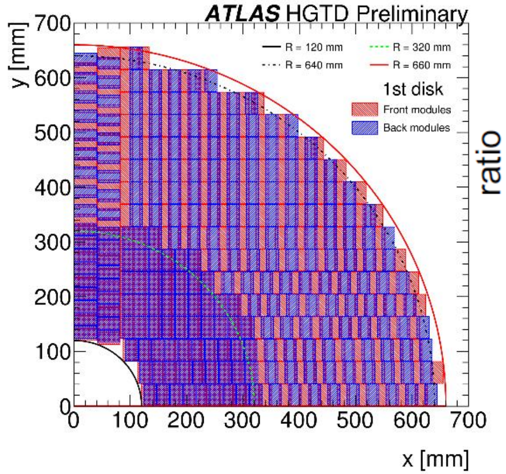
If we have LGAD sensor with these granularity and radiation tolerance, all tracker can be replaced by LGAD!

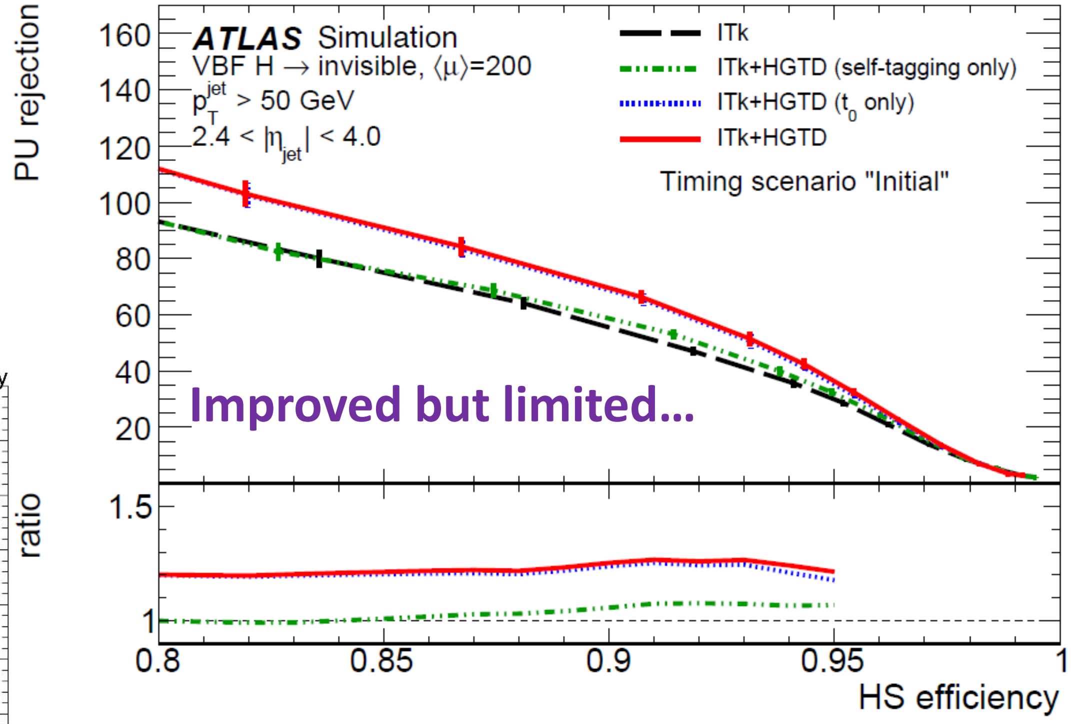
c.f. LGAD detector for HL-LHC

- **Rapid development of LGAD detector ← HL-LHC**
- ATLAS and CMS introduce LGAD detector
  - Only forward and backward region.
  - 2 layer of LGAD detector for each side
  - Electrode size : **1.3mm x 1.3mm**
  - **Not for tracking but add timing information to tracks.**
  - **20% improve of pileup removal.**
- Possible foundry of LGAD detector
  - **HPK**(JP)、**CNM**(Spain)、**FBK**(Italy)、**NDL**(China)
  - **BNL**(USA)、**Teledyne e2v**(UK?)

Hard Scatter (HS) vertex identification and pileup (PU) removal.





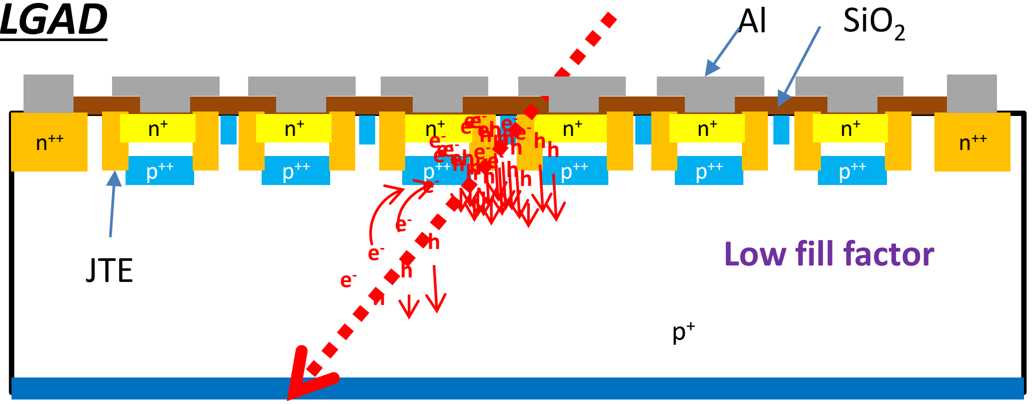


Readout ASIC with fast amplifier
Stable operation of LGAD detector

How LGAD detector get spatial resolution?

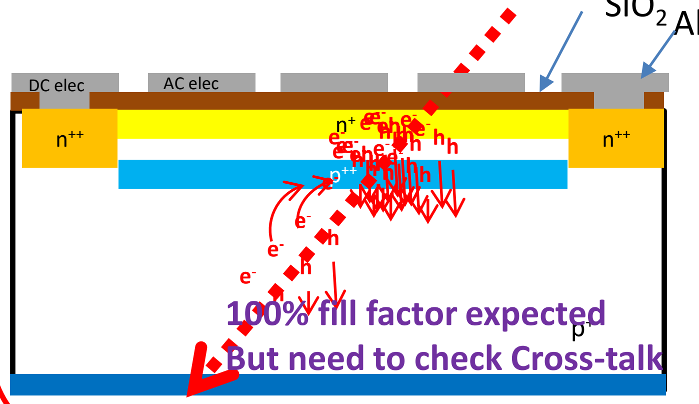
- Segmented electrode
  - Need high n++ dope (Junction Terminating Extension)at the edge of gain region.
  - In-active area at the gap exist→low fillfactor
- Possibility of higher fill factor LGAD
  - Three possibility :

DC-LGAD



AC-LGAD HPK, BNL, FBK etc.

Larger cross talk?



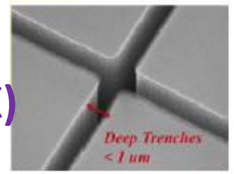
100% fill factor expected

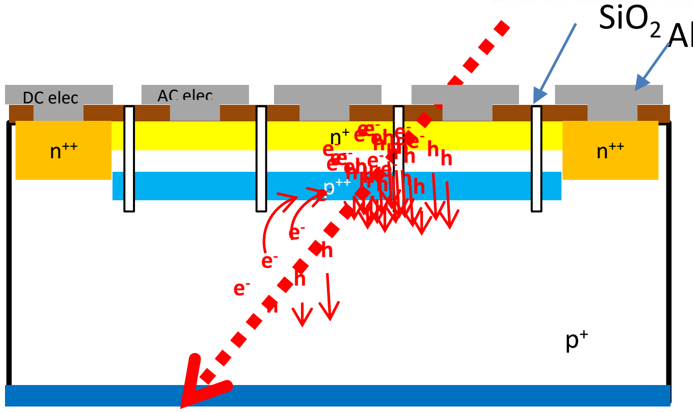
But need to check Cross-talk

Trench Protection CNM, FBK etc..

Impossible to apply

>600V bias voltage (by HPK)

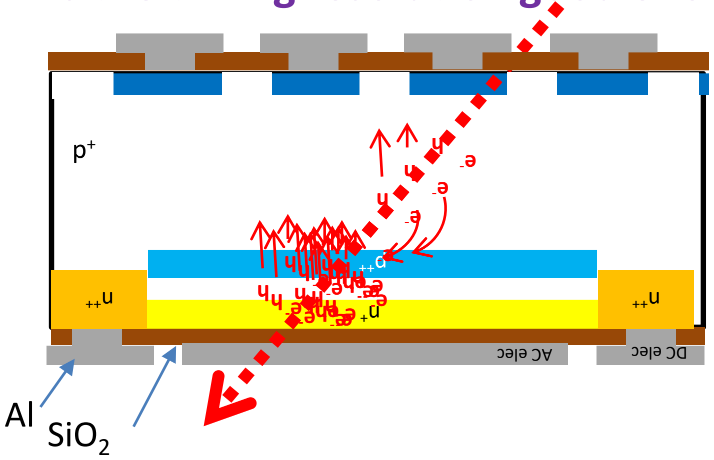




Inverse LGAD CNM etc.

Similar to AC-LGAD?

Is the timing resolution good enough?



We decided to develop AC-LGAD.

US-Japan Collaboration

In 2019

Japan side development

AC-LGAD sensor development
(Hamamatsu Photonics K.K)
Spatial resolution
& radiation tolerance

Fermilab Testbeam Facility

Testbeam

120GeV
Proton beam

Fermilab

US-Japan Collaboration Now

Japan side development

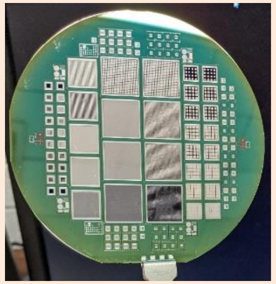
AC-LGAD sensor development
(Hamamatsu Photonics K.K)
Spatial resolution
& radiation tolerance

Comparison

Slightly Different approach
to achieve spatial resolution

BROOKHAVEN NATIONAL LABORATORY

AC-LGAD sensor development
4 inch wafer fabrication
Fast feedback but
No mass production capability



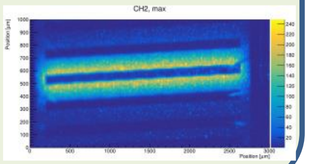
Fast ASIC development

High Speed Bi-CMOS ASIC
Designing for EIC detector

UNIVERSITY OF CALIFORNIA SANTA CRUZ

Laser testing at LAB

Testing experience
Laser testing



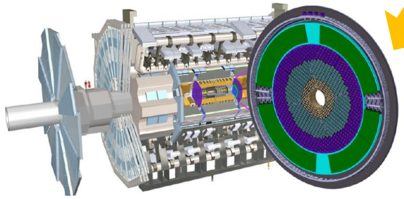
Fermilab Testbeam Facility

Testbeam

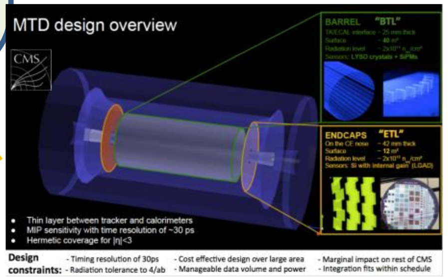
120GeV
Proton beam

Fermilab

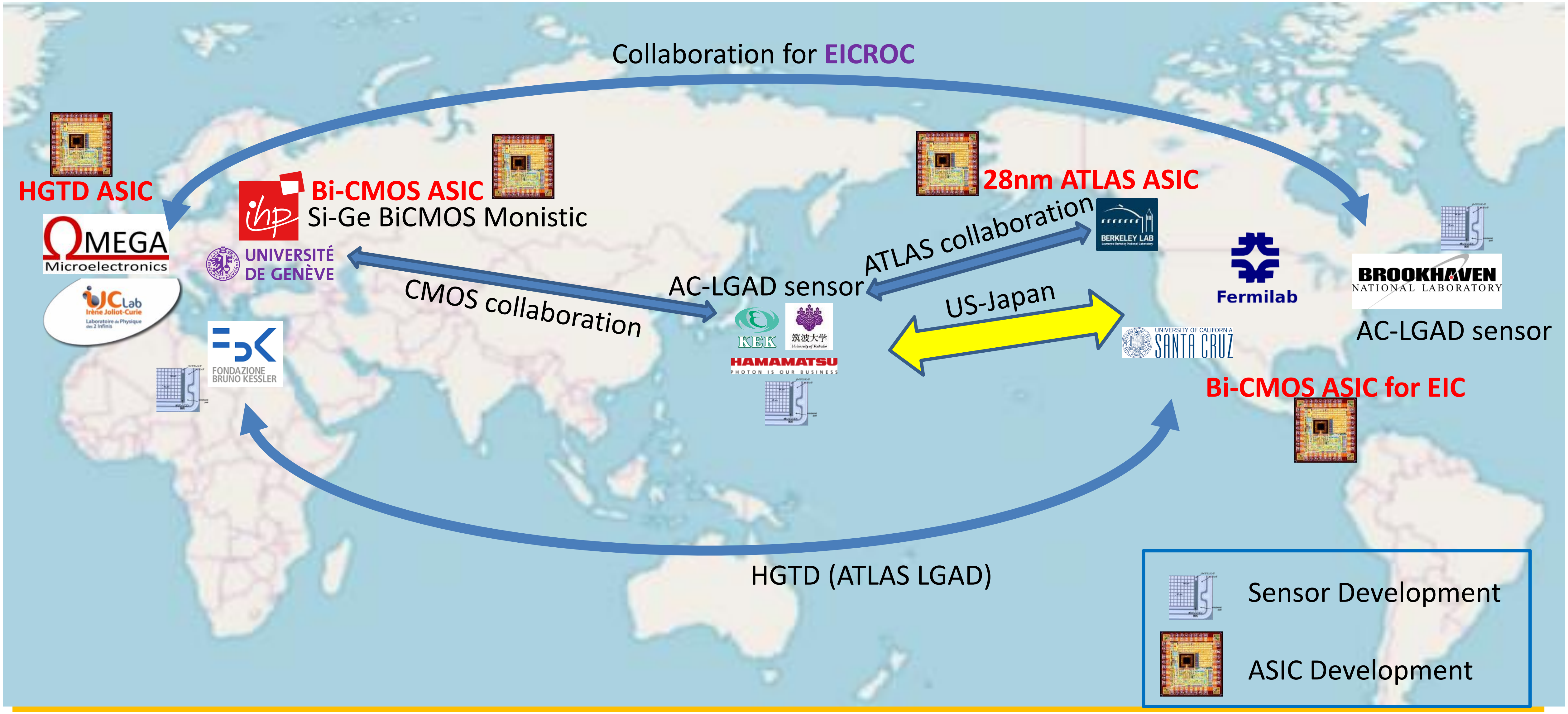
ATLAS HGTD



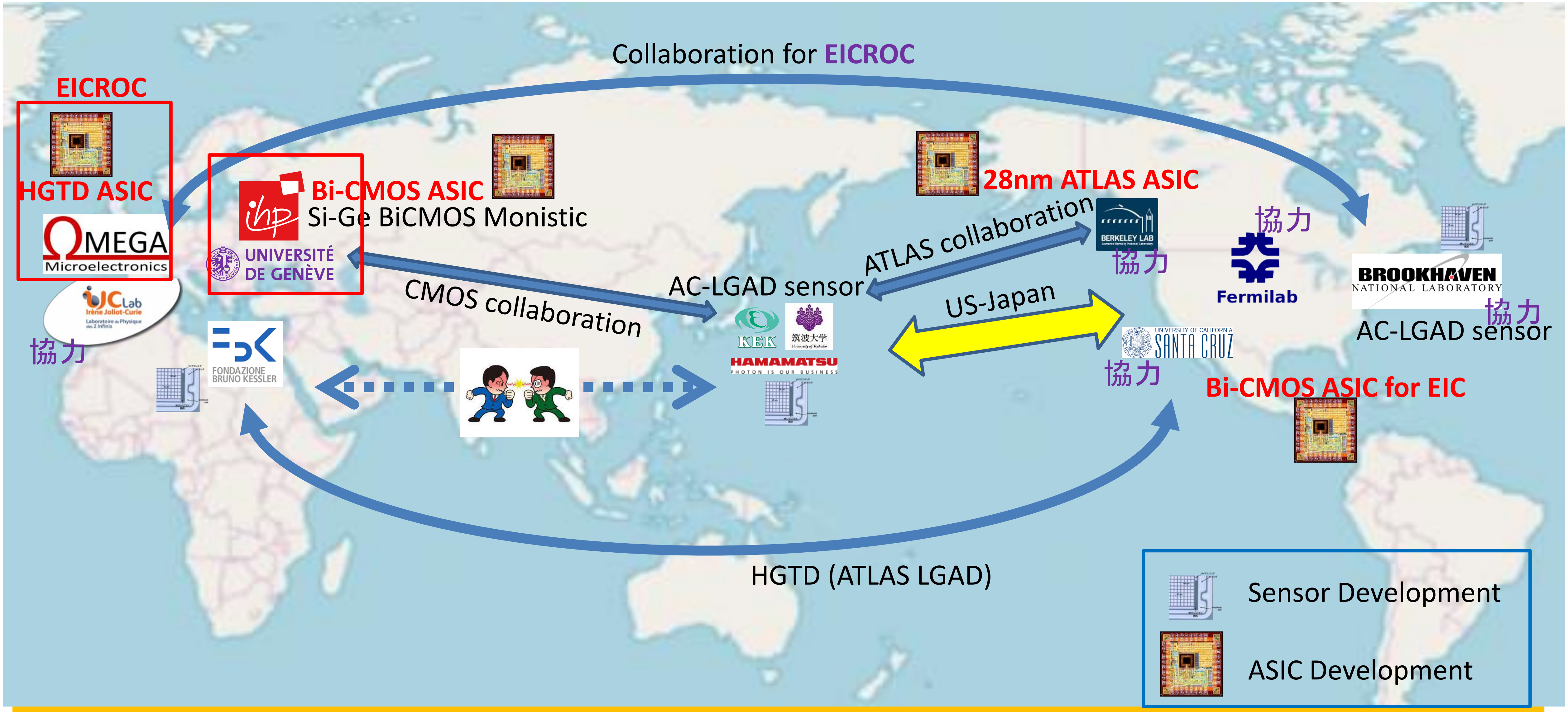
CMS MTD



AC-LGAD development & readout Electronics

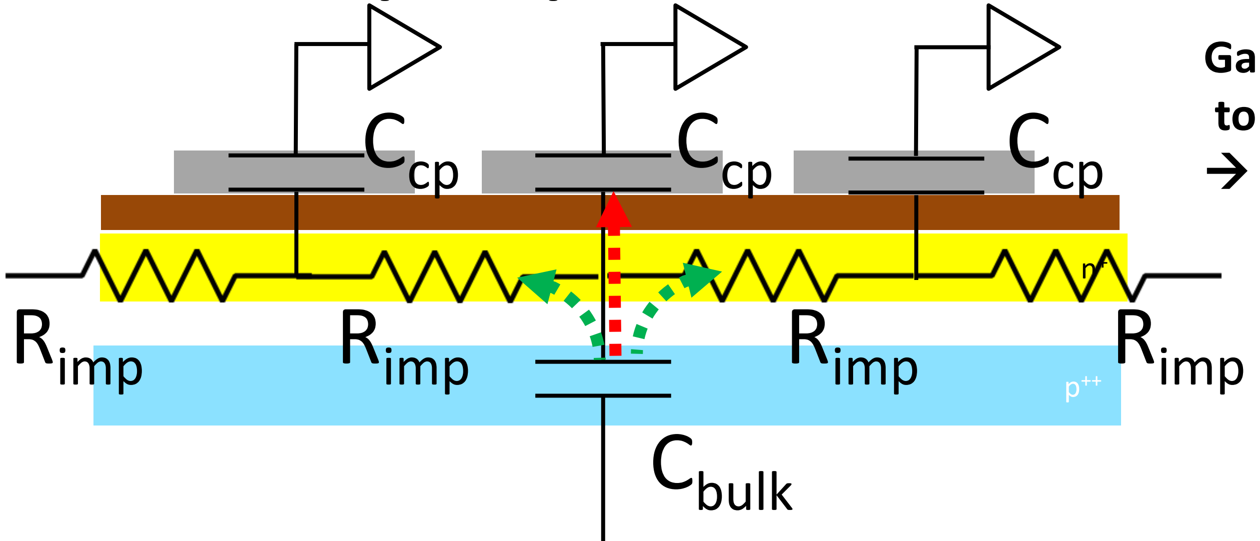


AC-LGAD development & readout Electronics

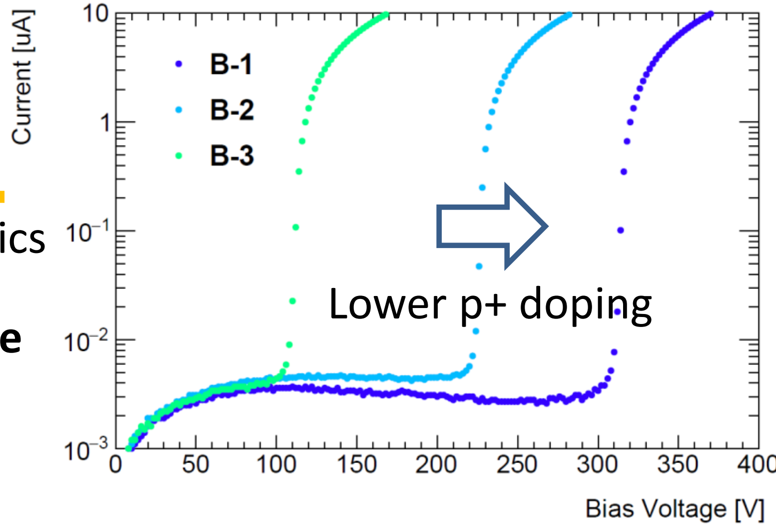


How AC-LGAD works?

- **AC-LGAD principle**



I-V characteristics

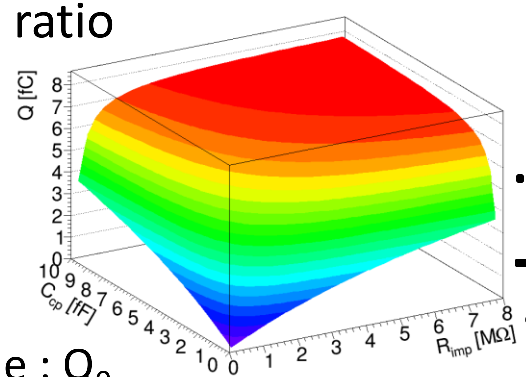


Gain voltage (V_{gain}) is sensitive to p+ doping concentration.
→ Adjust V_{gain} around 150V

- Signal separation : impedance ratio

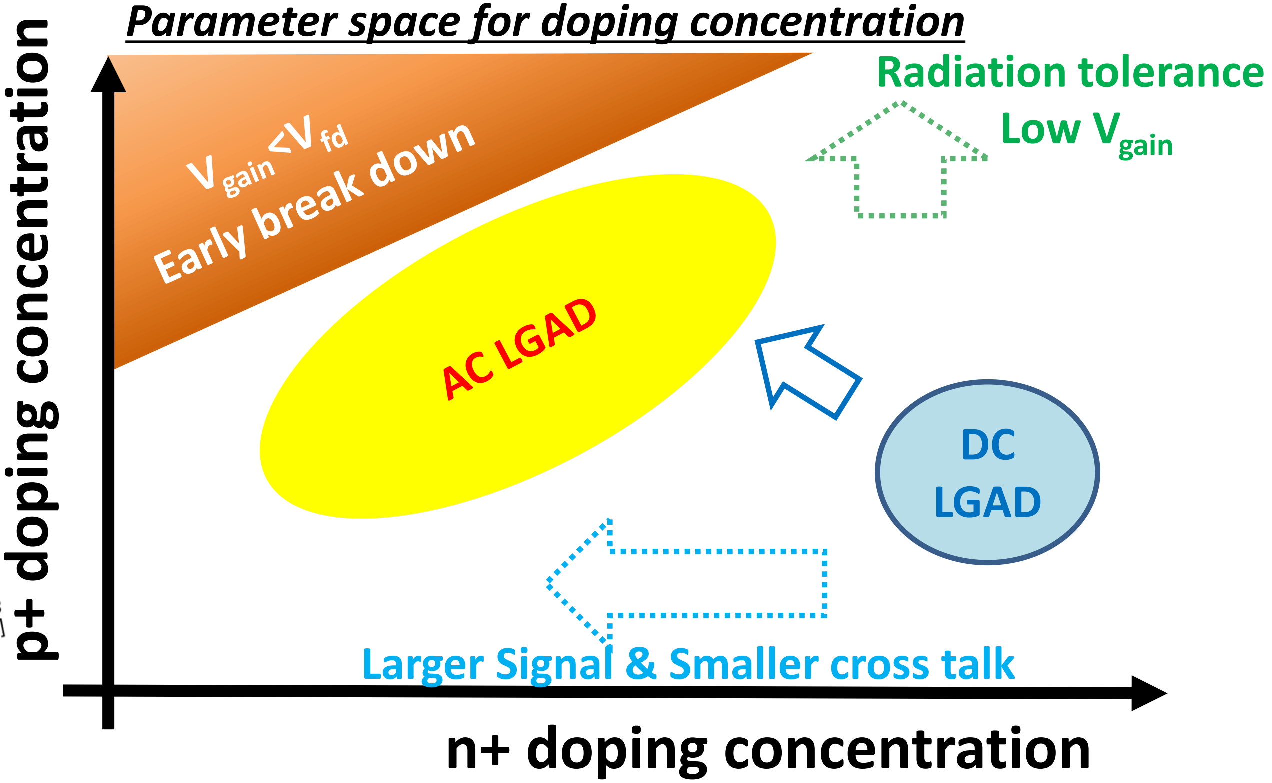
Assuming $Z_{Cbulk} >> Z_{Ccp}$

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



- Produced charge by avalanche : Q_0
- Readout charge from electrode : Q

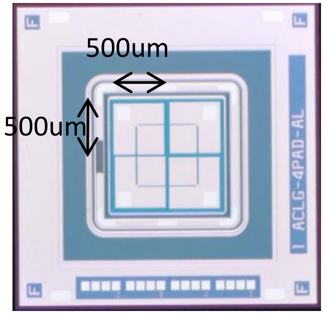
Parameter space for doping concentration



HPK LGAD development

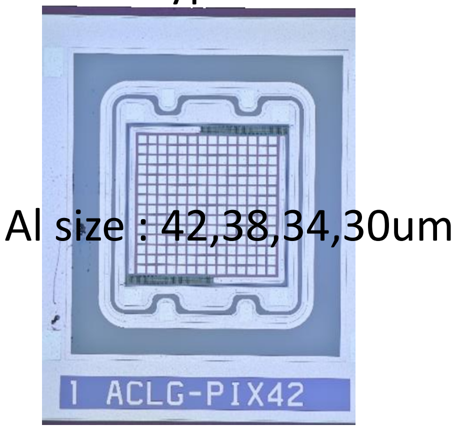
- JFY2015-JFY2018 DC-LGAD
  - **We contributed only first prototype.** HGTD took over.
- JFY2019, JFY2020 AC-LGAD production
  - Vary n+ and p+ dope (A-E, 1-3)
  - Vary thickness of SiO_2 (capacitance : C_b=1.5xC_a)
- Electrode type
  - Pad type: 500um sq. 4pad/sensor
  - **Strip type : 80um pitch** *First goal*
  - Pixel type : 50um sq. 14x14 electrode

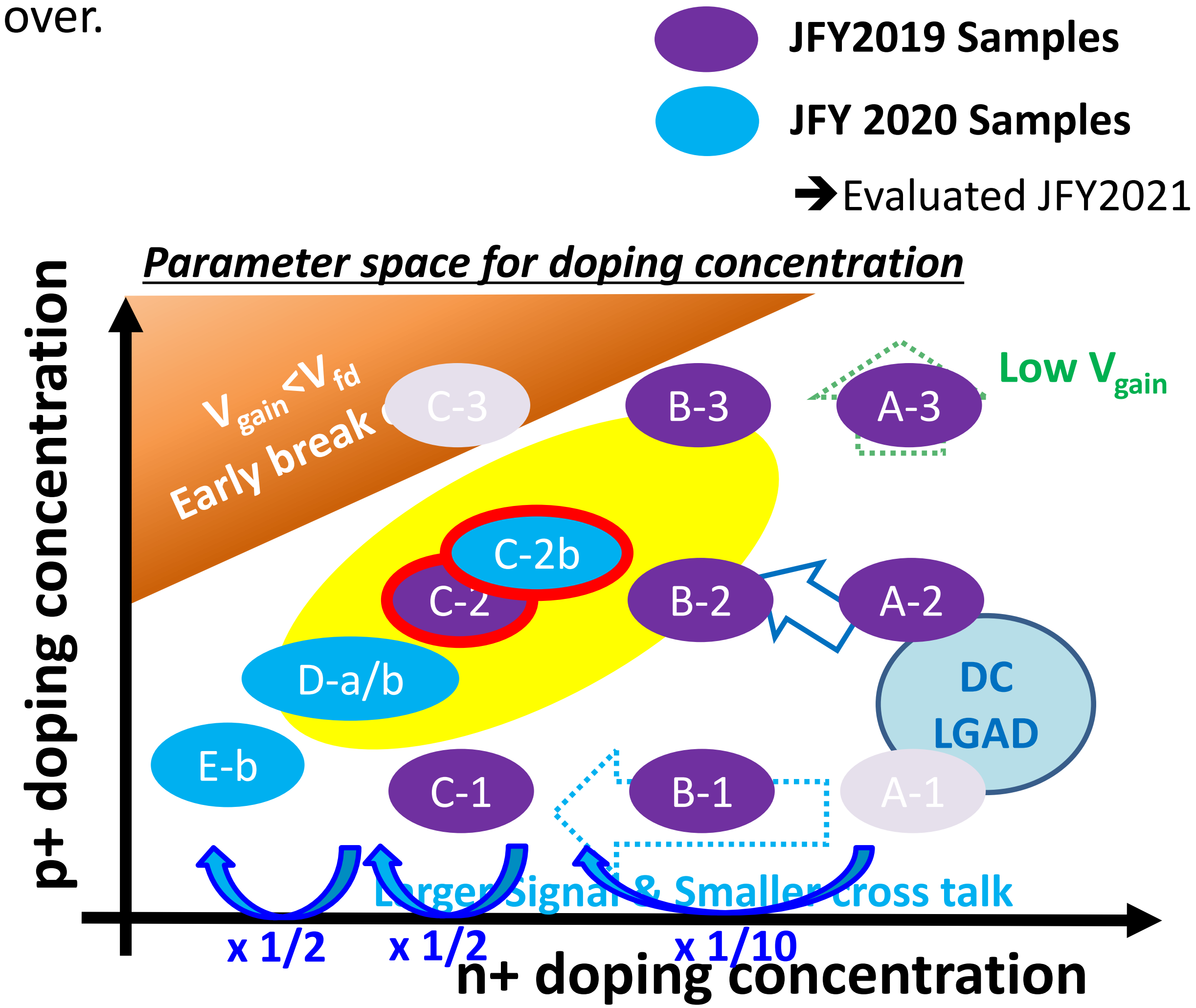
Pad type



Strip type

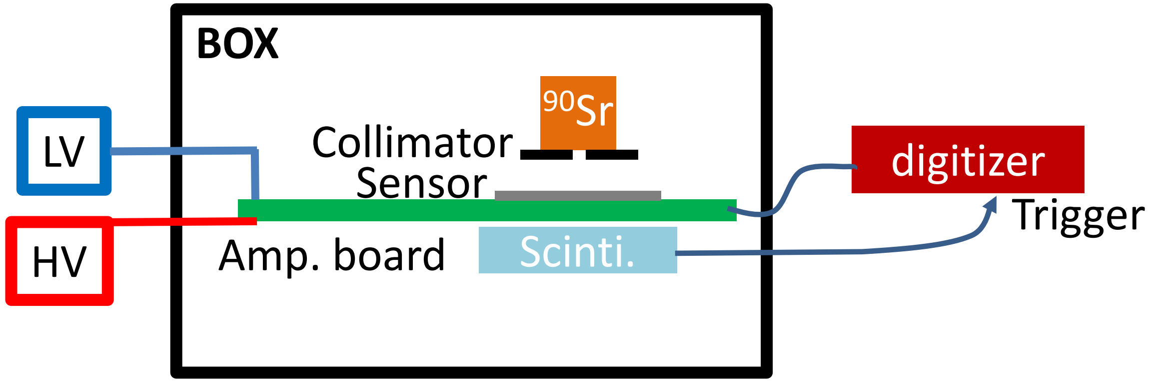
Pixel type



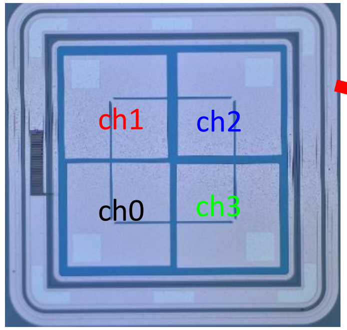


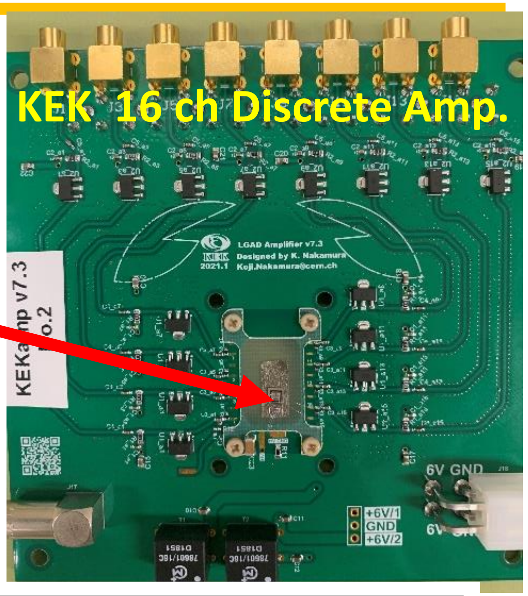
Measurement setup and signal observation

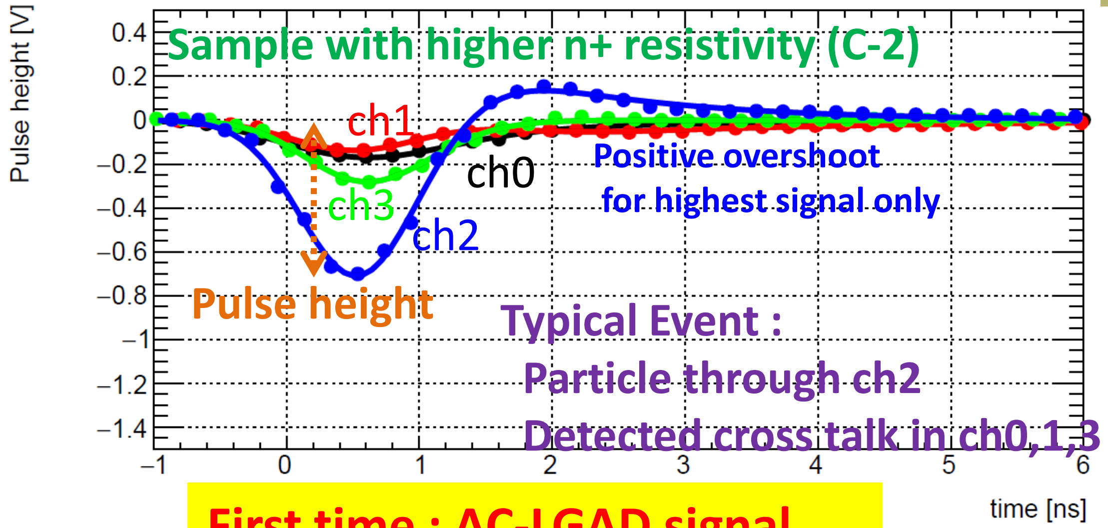
- Lab setup
  - Designed high speed amplifier board.
- Signal recorded by CAEN DT5742 digitizer or LeCroy WR8208HD scope
  - ^{90}Sr β lay source
  - Triggered by Scintillator (MPPC readout)

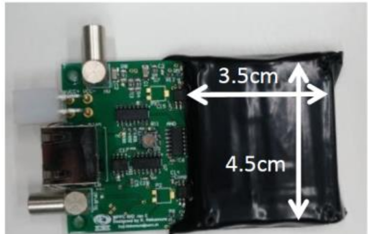


Pad Sensor









Scintillator / MPPC

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

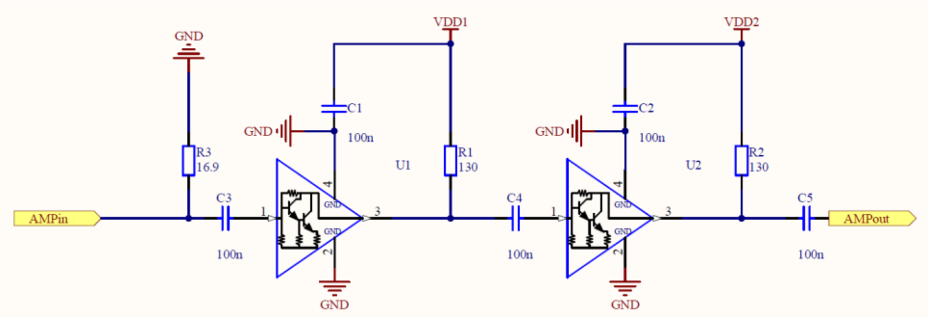
CAEN DT5742
Desktop Digitizer
5GS/s 10bit
12bit ADC 2V full range

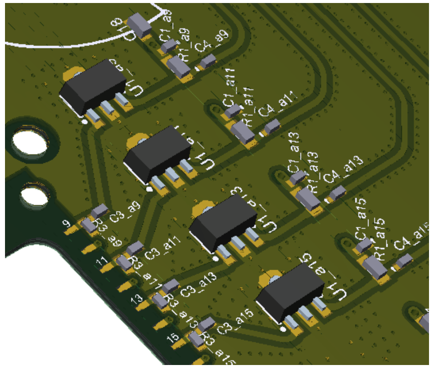
First time : AC-LGAD signal observed with small crosstalk

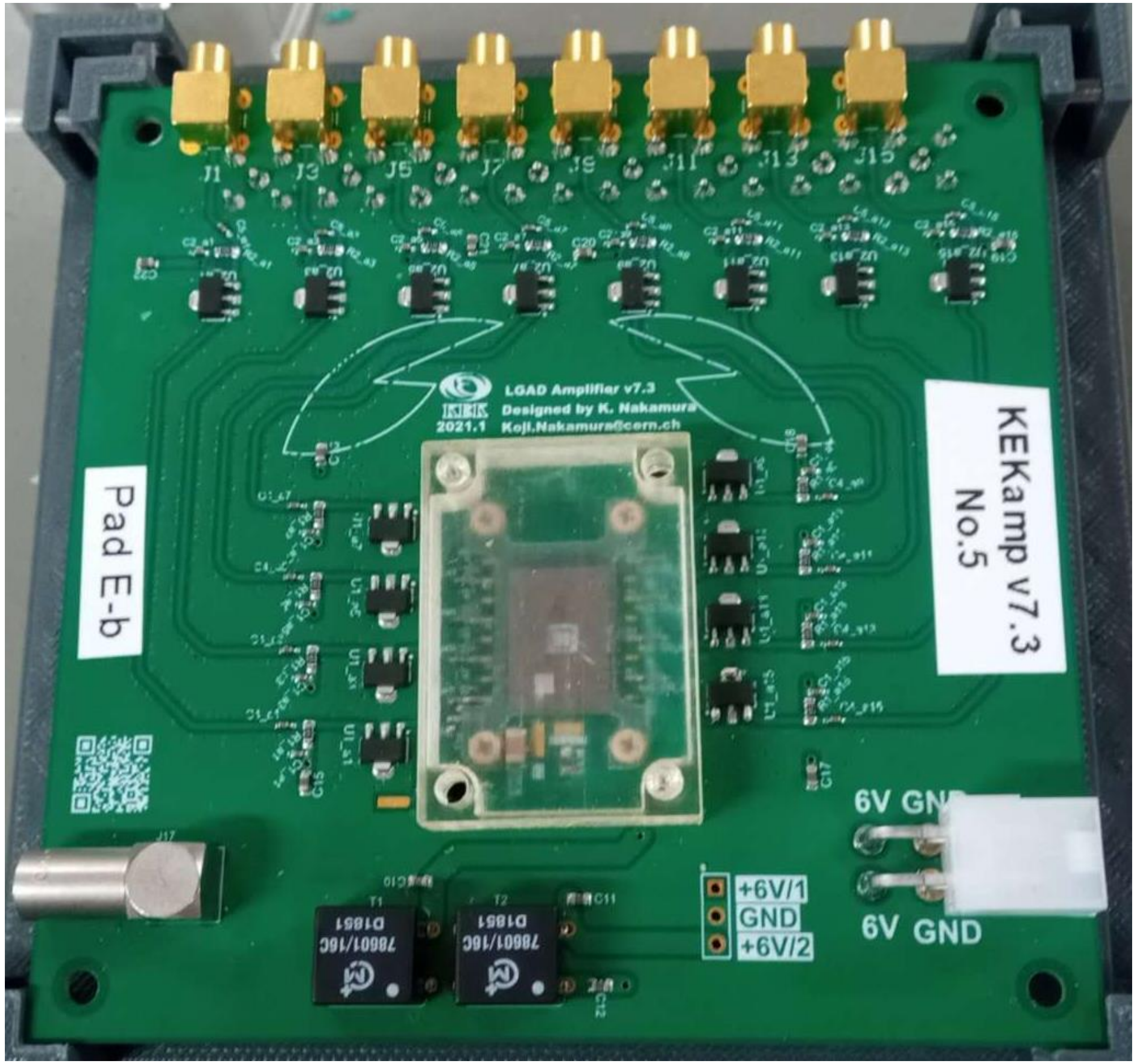
Development of Amplifier board

- Ultra high speed discrete amplifier board.
  - AMP : GALI-S66+ :
    - SMT Low Noise Amplifier, DC - 3000 MHz, 50Ω

Due to my lack of experience of ultra high speed analog circuit…

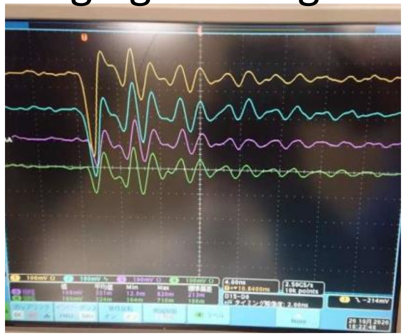




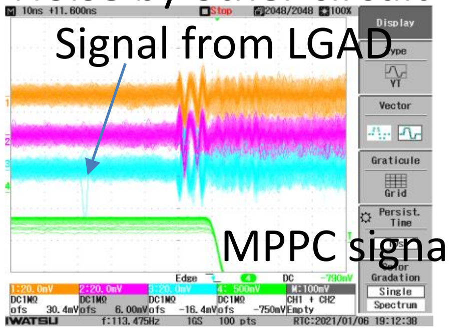


Simply high noise

Ringing after signal



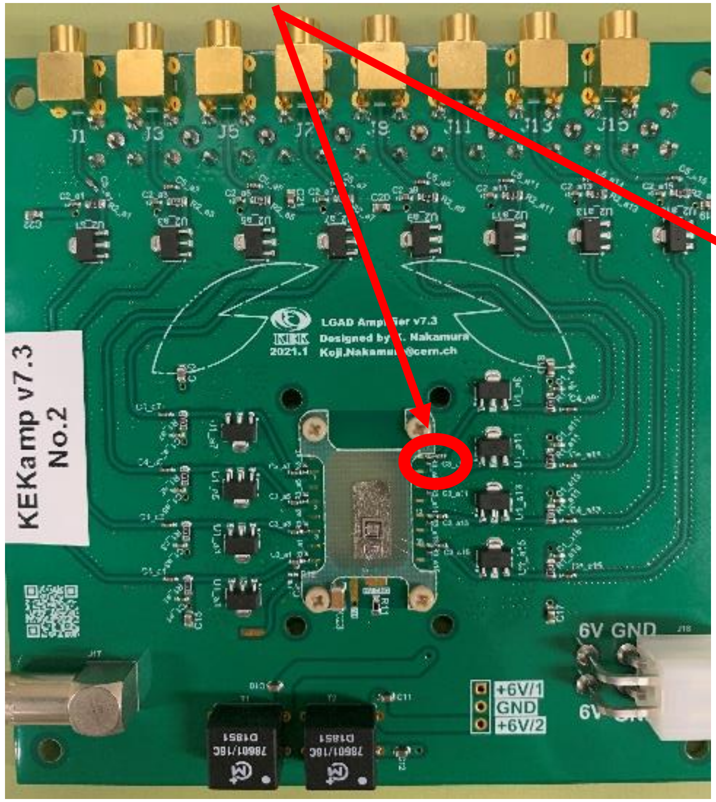
Noise by other circuit

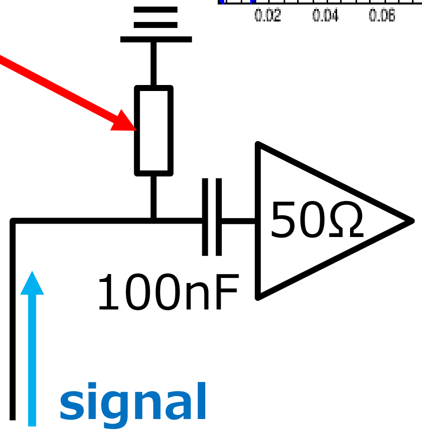


Improvement of Amplifier board

Improvement of impedance matching

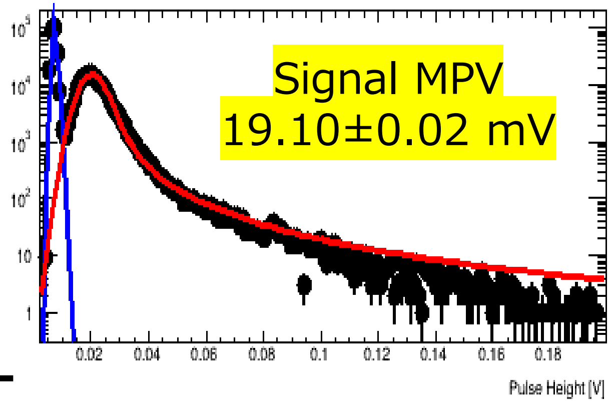
Changed input resistance 25Ohm→1kOhm

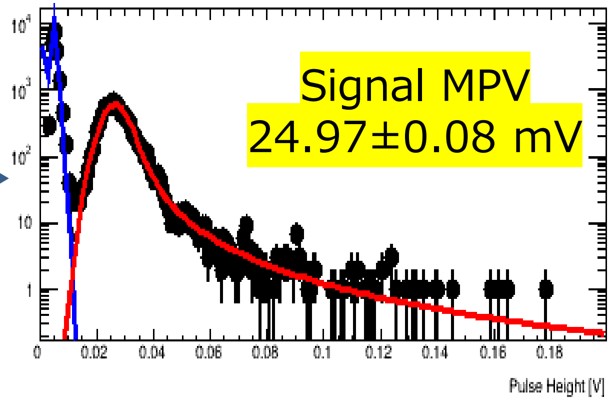


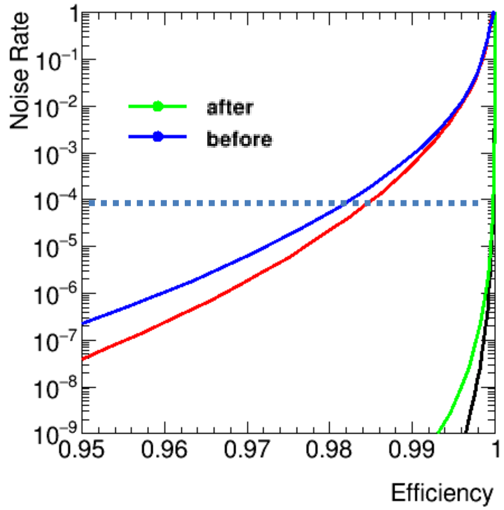


In summary,
larger resistance
better matching

- Improvement of pulse height (StripE-b type)





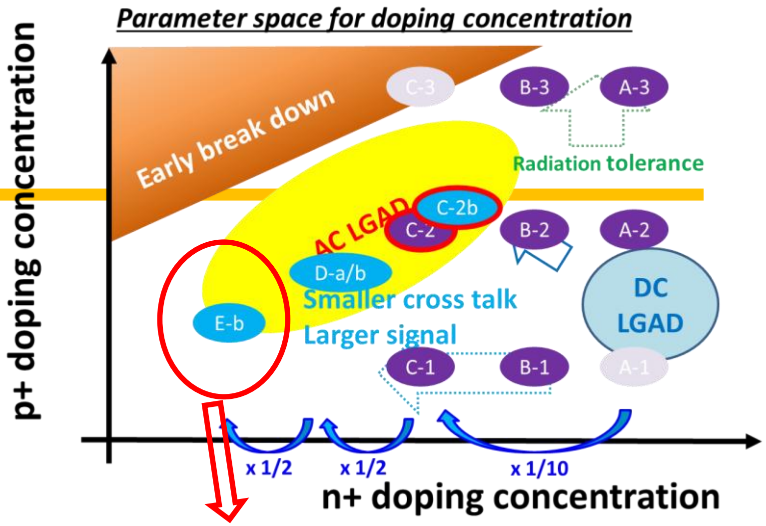


signal efficiency
@ 1e-4 noise rate
before : 98.12%
after : 99.98%

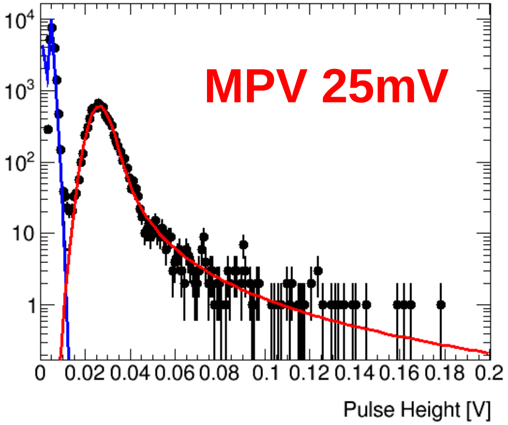
SN ratio improved!

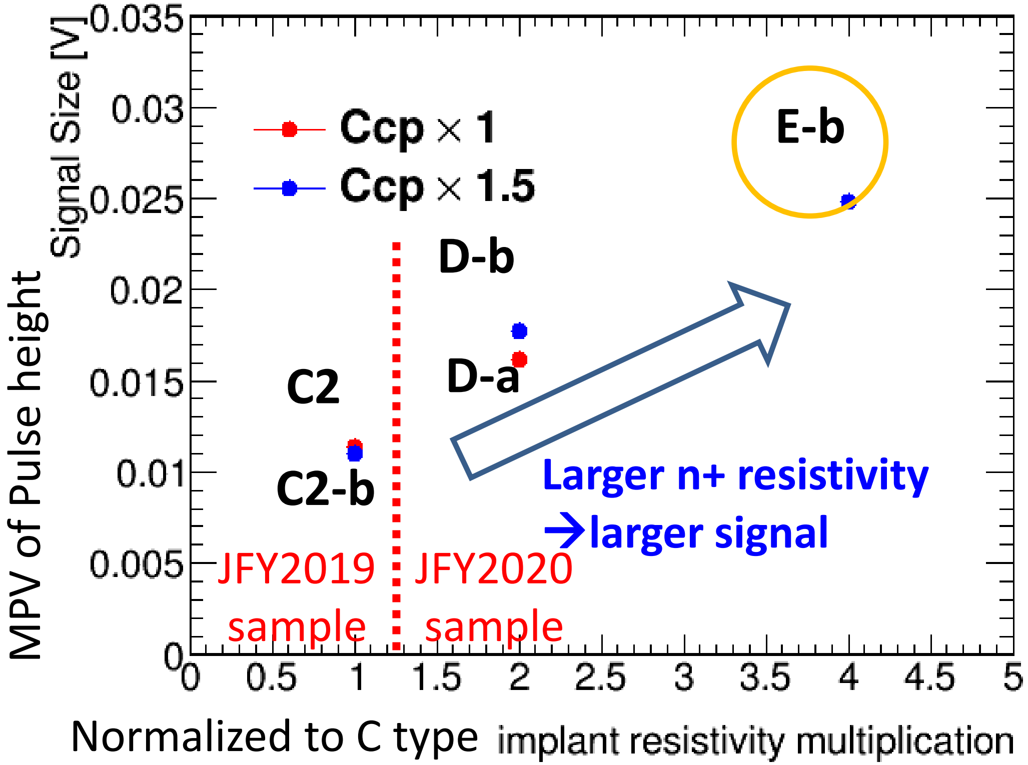
Signal size and crosstalk

- **Strip type :** Signal size and Crosstalk
  - n+ resistivity dependence of signal size and crosstalk.
  - **Large n+ resistivity →Large signal & Smaller crosstalk**

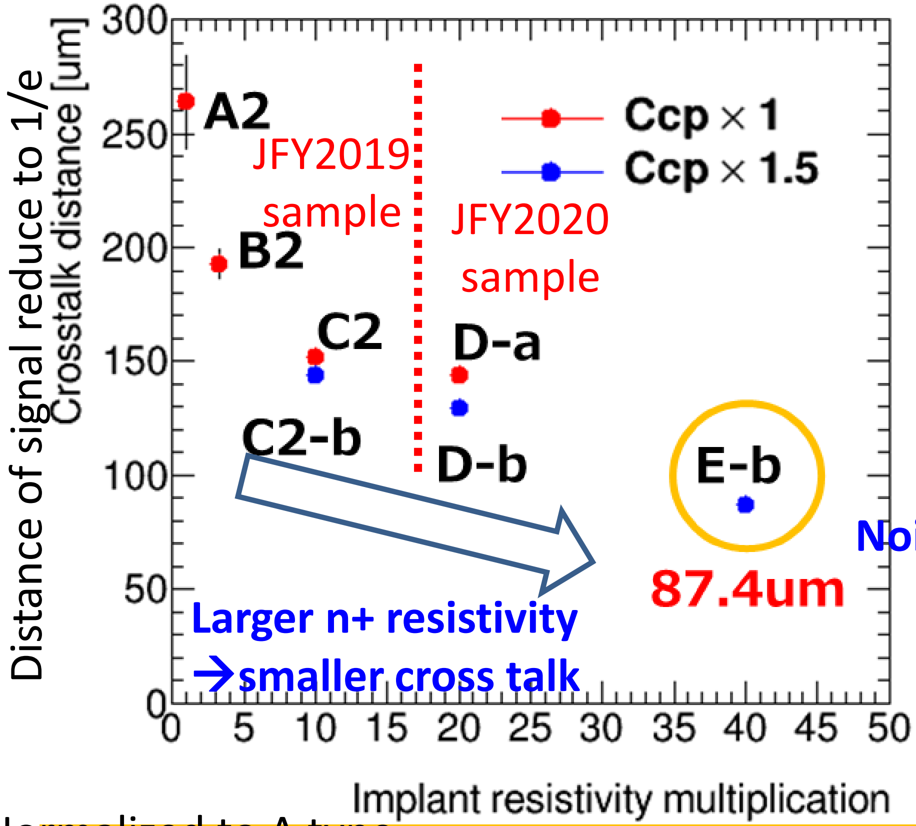


Pulse height





Normalized to C type

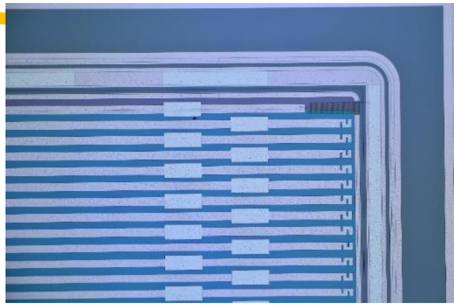


Normalized to A type

Noise rate 10^{-4} Efficiency 99.98%

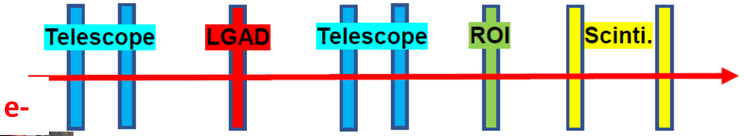
Successfully developed Good S/N strip detector!

Spatial resolution measurement at ELPH TB



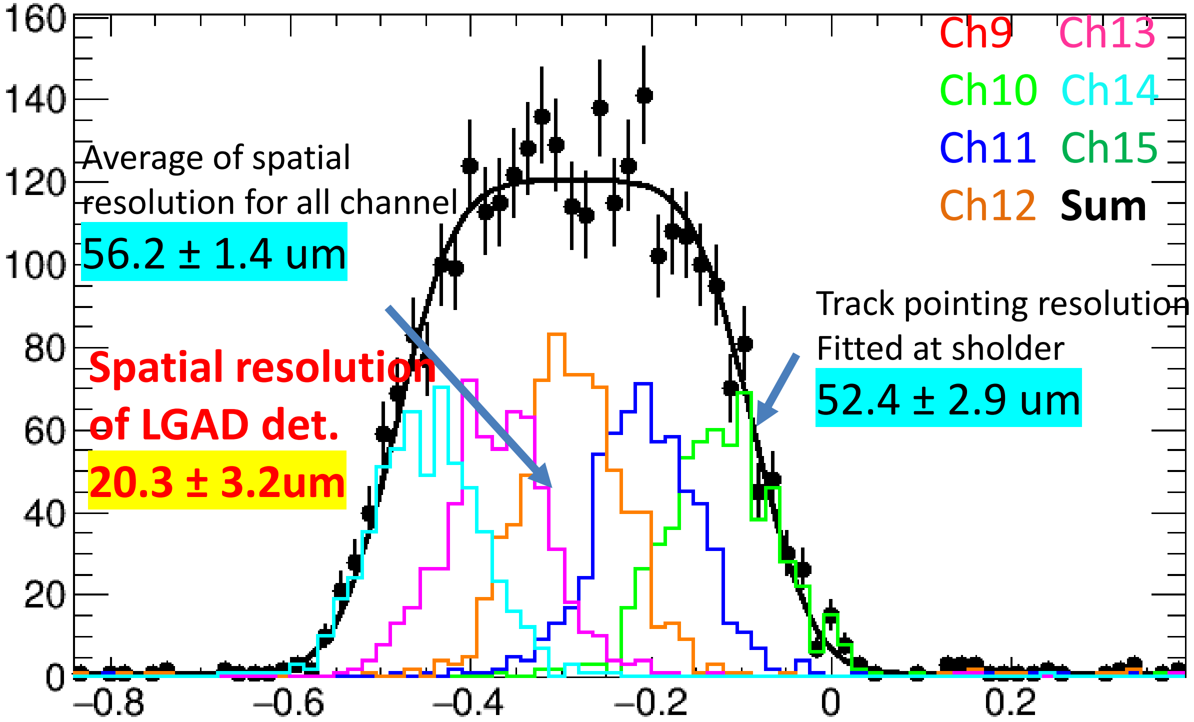
- In principle, no dead area and small crosstalk
  - At least 23um($80um/\sqrt{12}$) resolution by binary readout
- ELPH testbeam at Tohoku Univ. (8-9 July 2021)
  - 800MeV electron beam
  - Trigger rate 200-400Hz
  - Strip E-b type 170V @ 20°C

Huge Multiple-Scattering



5 layer of Telescope
2 upstr. + 3 downstr.
(25um x 500um pixel)
Scintillator + MPPC trigger
Region of interest (ROI)

Residual distribution
of hit position and reconstructed position by tracking.

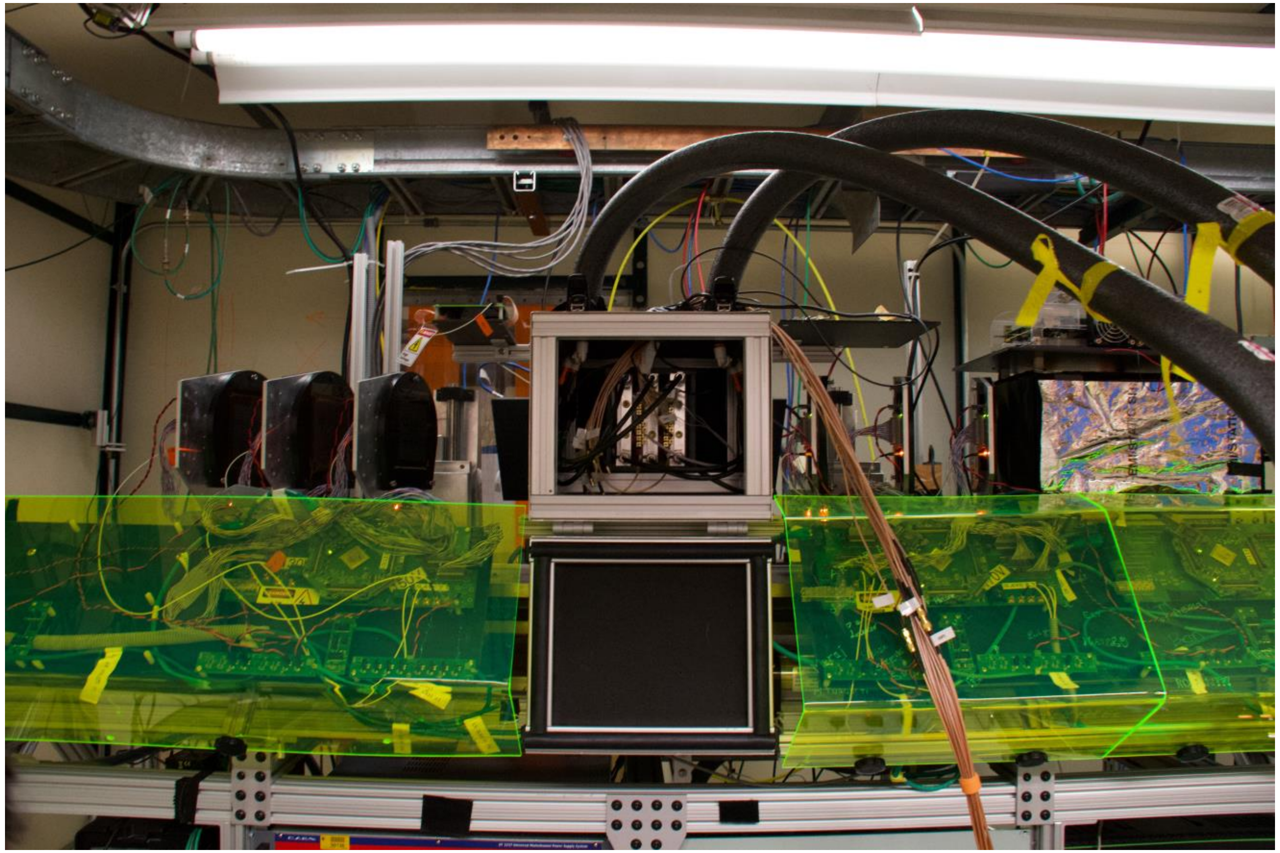


Timing resolution for AC-LGAD detector

Fermilab Test Beam Facility (FTBF)

120GeV proton beam

Strip Detector based Telescope : ~15um pointing resolution



Timing reference Detector

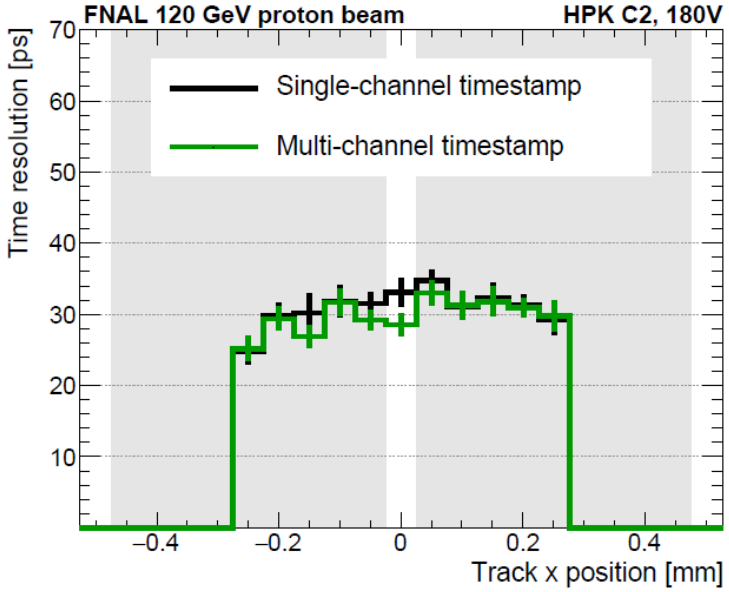
PHOTEK MCP photomultipliers (PMT140)

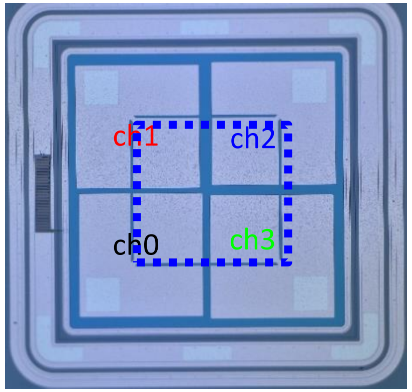
450ps FWHM with 5e3 Gain

~5ps timing resolution

(SPEC: Multi-photon jitter below 10 ps)

Position dependent Timing resolution

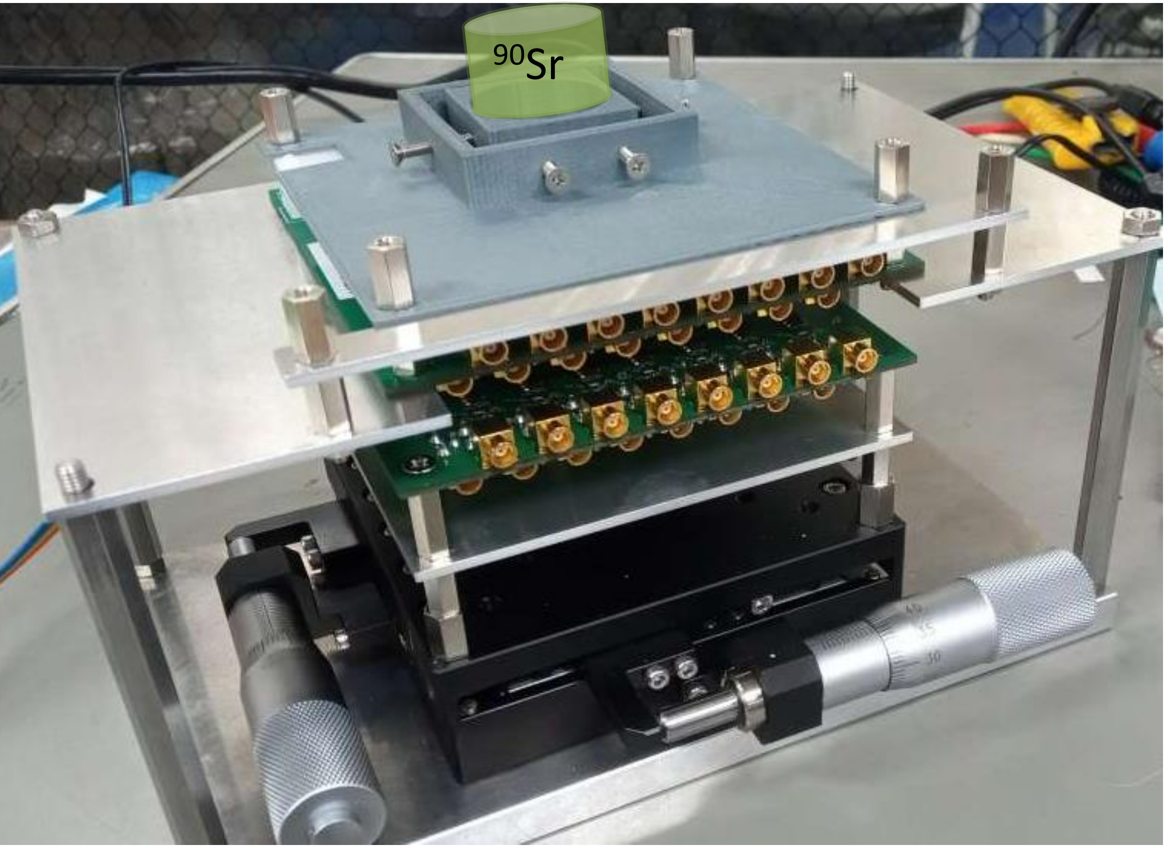


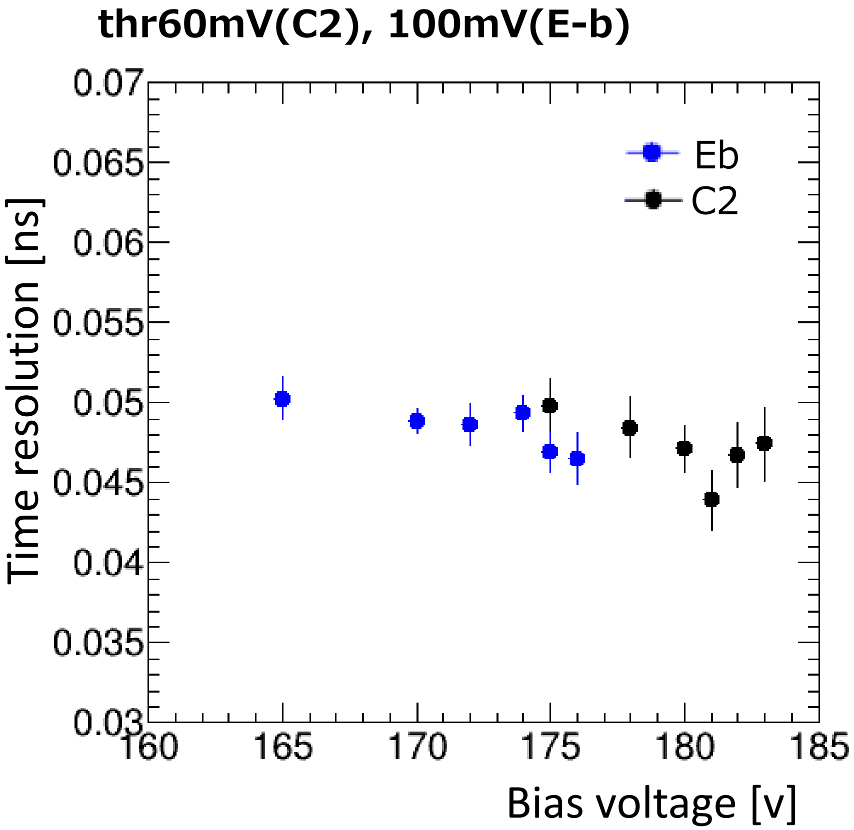


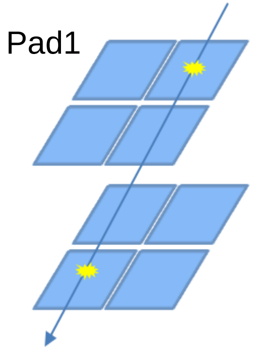
- **25-35 ps timing resolution uniformly!**

Can we measure time resolution at the lab?

- If we need testbeam to measure time resolution, it's critical for the development… → want to measure at the lab.







C2 43.9+-1.9ps (181V)

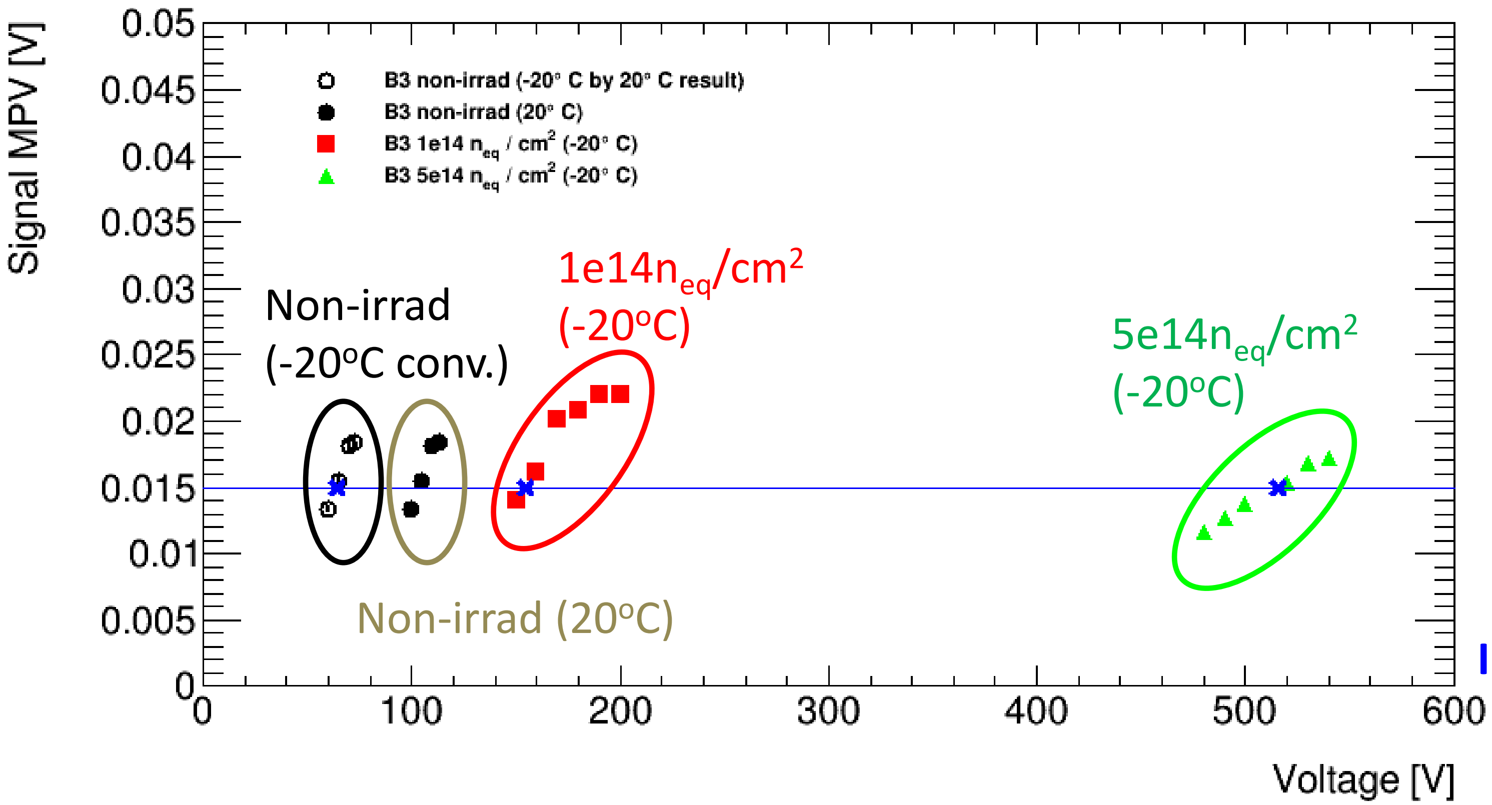
E-b 44.2±1.5ps (176V)

Still need to investigate ~10ps worse than TB

In principle, it works → Accelerate R&D !!

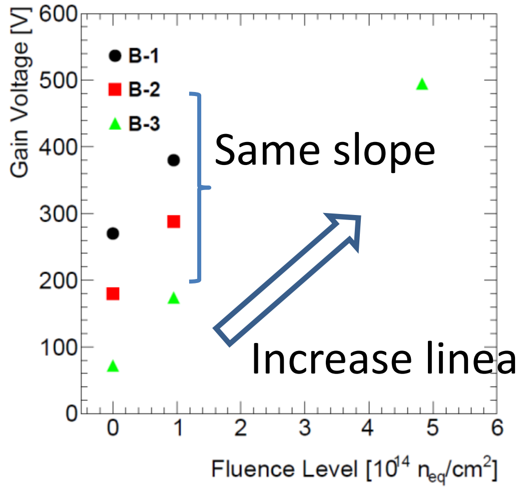
Radiation tolerance (NIEL, accepter removal)

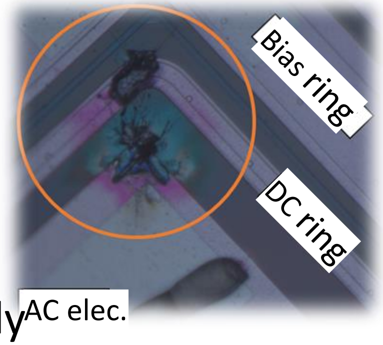
- Sensor irradiated at CYRIC and tested signal size after irradiation
  - Getting higher gain voltage (V_{gain}) after irradiation.
    - Effective p+ dope in gain layer is reduced by **acceptor removal**.



Define V_{gain} as Signal MPV=15mV

Radiation Fluence dependence of V_{gain}





Spark >700V

ΔV_{gain}=93.57±0.03V / 1e14n_{eq}/cm^2

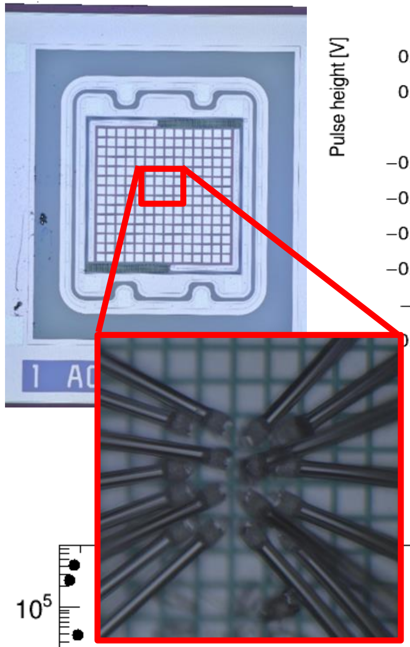
Increase of V_{gain} independent from intrinsic P+ dope

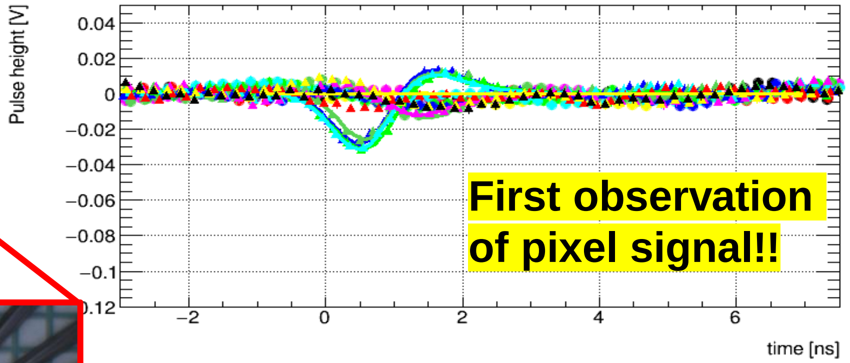
Survive upto 0.7x10^{15}neq/cm^2

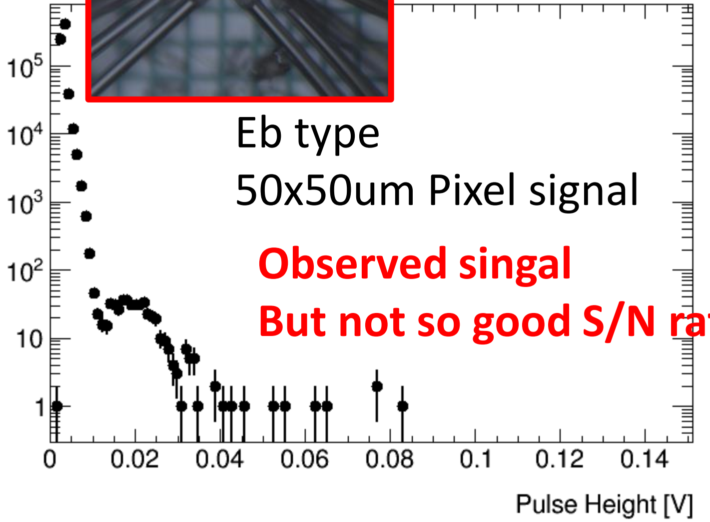
Fluence at outer traker region at HL-LHC

Challenge to Pixel detector?

- How far to make pixelated AC-LGAD?





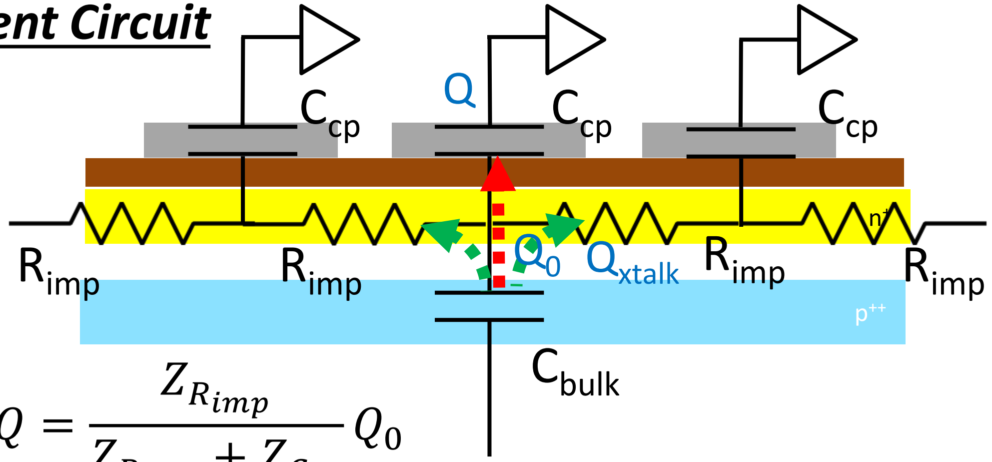


Eb type
50x50um Pixel signal

Observed singal
But not so good S/N ratio

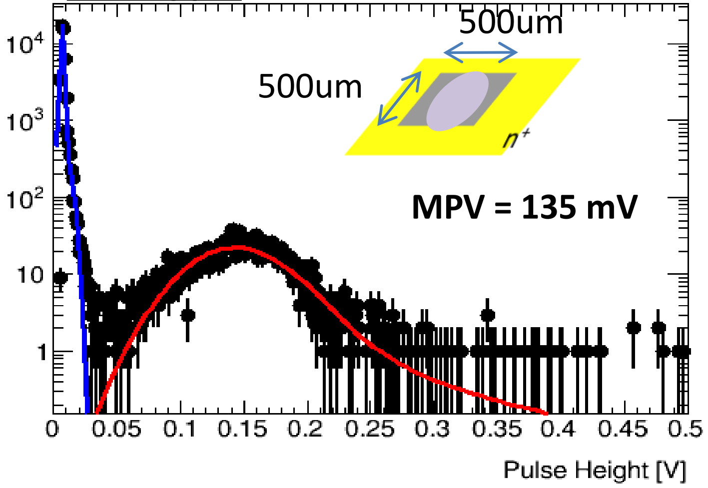
- Why signal is so small?

Equivalent Circuit



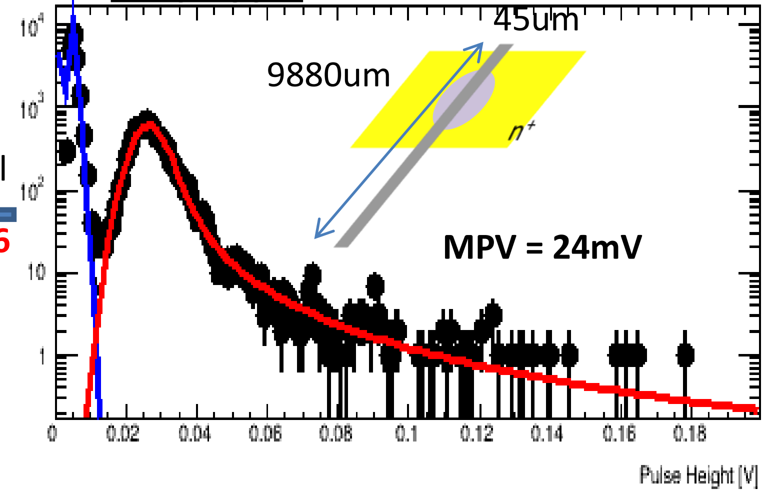
$$Q = \frac{Z_{R_{imp}}}{Z_{R_{imp}} + Z_{C_{cp}}} Q_0$$

Pad type



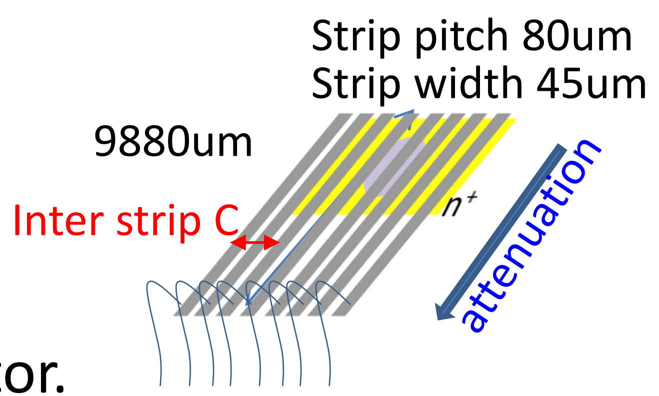
Signal
x5.6

Strip type



What should be understood and what's next?

- ***Understand Strip detector***
  - Why so small signal?
  - **How much effect of interstrip capacitance?**
    - Significantly smaller signal compared with pad type detector.
  - **How much signal attenuation in the strip?**
    - This might affect to the signal size un-uniformity and delay of signal readout.

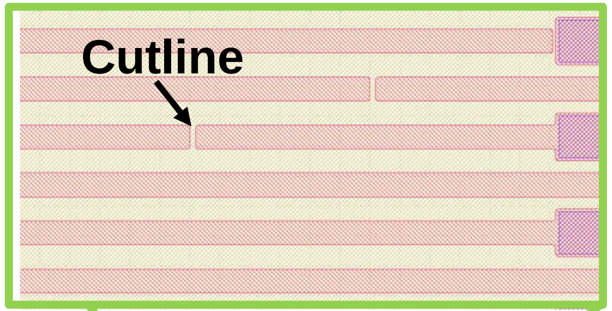


- **Certainly we want to develop pixel type detector.**
  - **First 50um x 50um pixel sensor does not have enough signal size.**
  - **What is the minimum pixel size we can see good S/N signal?**
  - **What is the effective area for electrode capacitance ?**

New sample (2021 sample) : received in April 2022

Used thinner di-electric layer (Oxide layer)

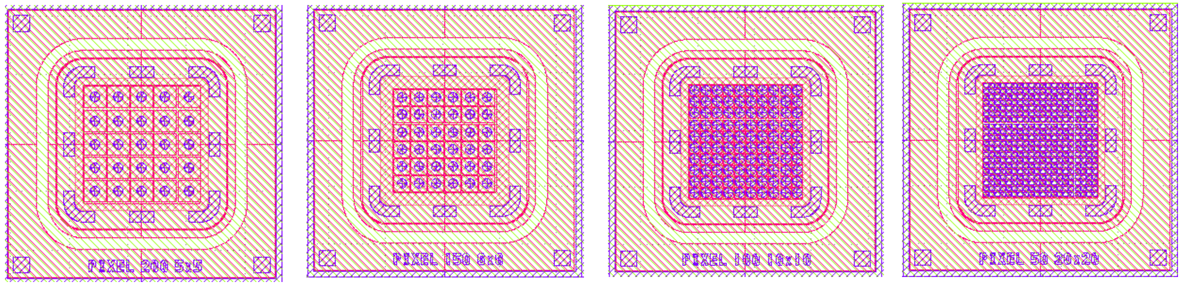
→ **Basic electrode capacitance increased by factor of 5 !!**



Pixel sensor

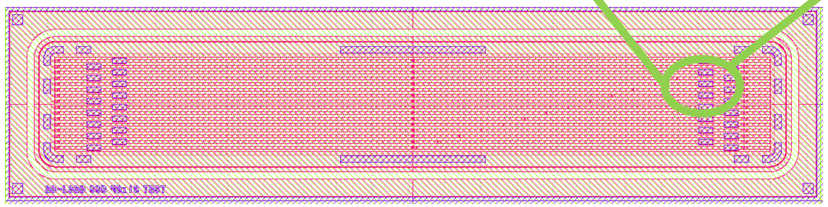
- 5 times larger Ccp compared with E-b (2020)
  type : E-600
- Various of pitch

200um 150um 100um 50um

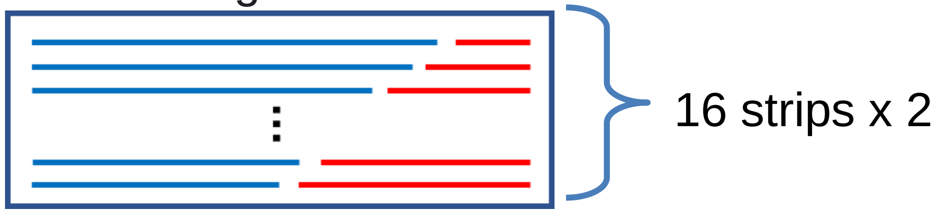


Strip sensor

- Strip sensor which has different electrode length

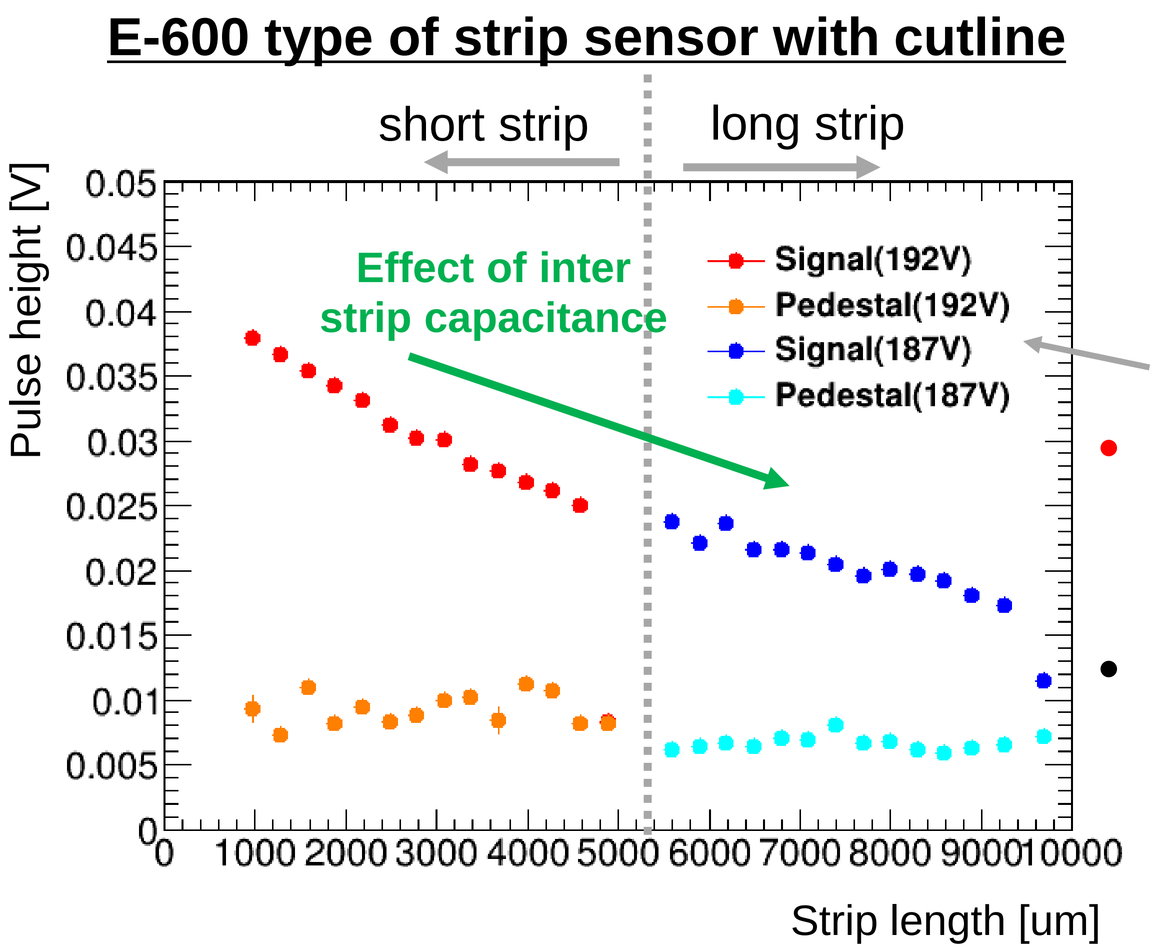


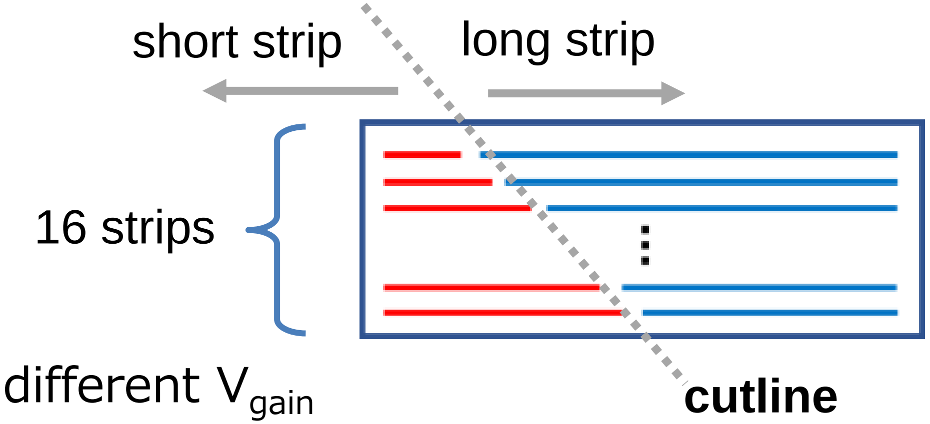
Pattern diagram



Preliminary results : Strip type electrode

To evaluate the effect of signal attenuation and inter strip capacitance :





Due to different V_{gain}

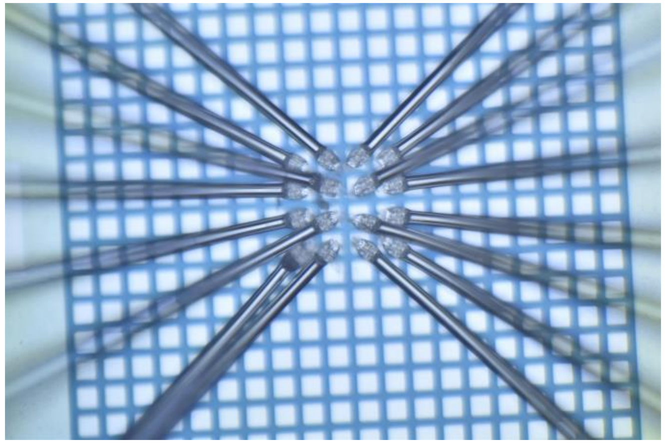
- **Signal reduced by 60% in ~10mm**
  - **Because of inter strip capacitance?**
  - **Because of signal attenuation?**
- We will test smaller gap sample. (the same pitch)
  - Current gap 40um → 20um
  - **Smaller gap have larger inter strip capacitance and smaller attenuation**

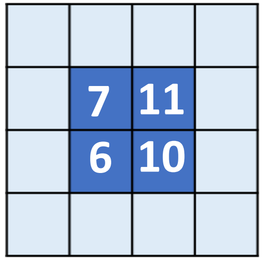
Preliminary results : Pixel type electrode

What is the minimum pixel size we can see good S/N signal?

E-600 type of pixel sensor

4x4 pixels are wirebonded.

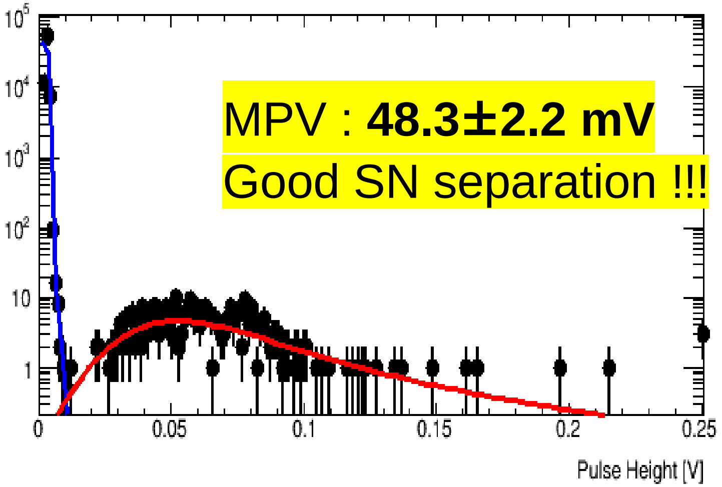




Analysis
Only center 2x2 channels was used.
(To avoid crosstalk effect)

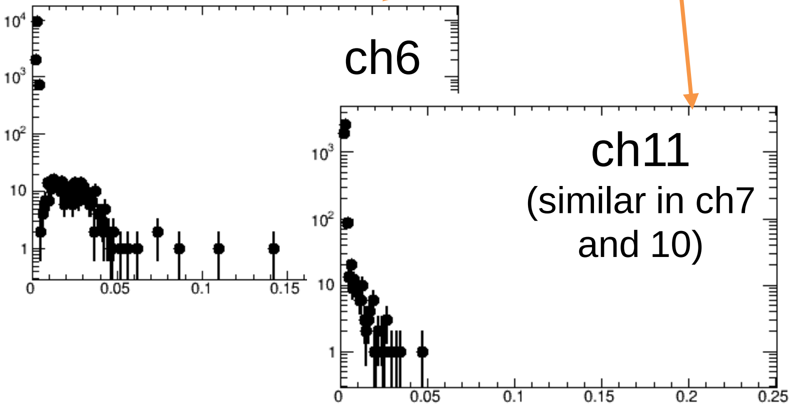
Pulse height distribution

100um pitch



4 electrodes in the middle observed different pulse height MPV for ch6 and the other

50um pitch



Electrode short in ch6 ?

under investigation …

First Pixelated AC-LGAD in the World! (100um x 100um)

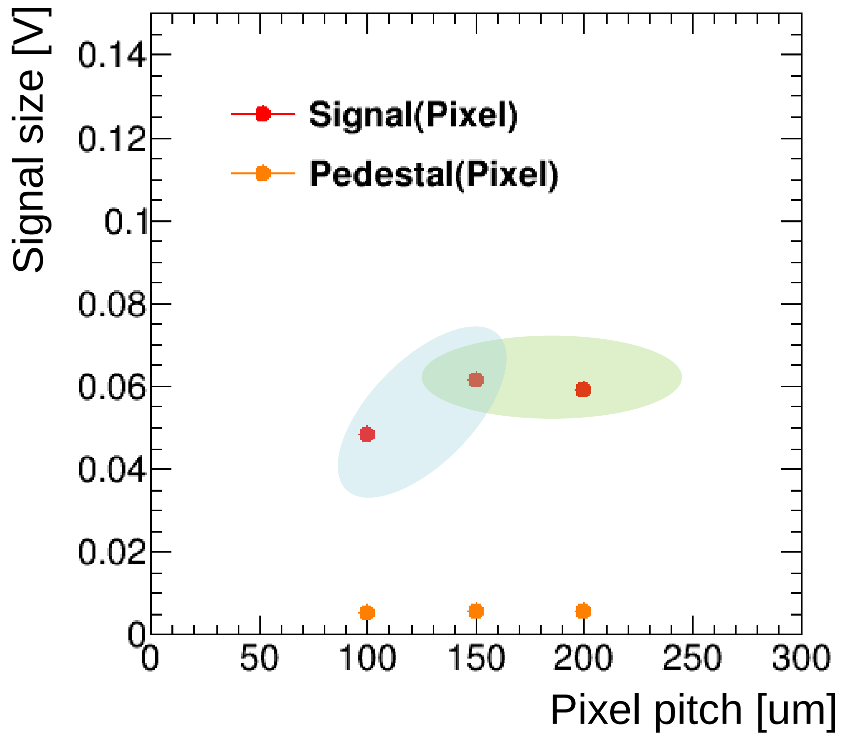
We need to understand the 50um x 50um pixel

Preliminary results : Pixel type electrode

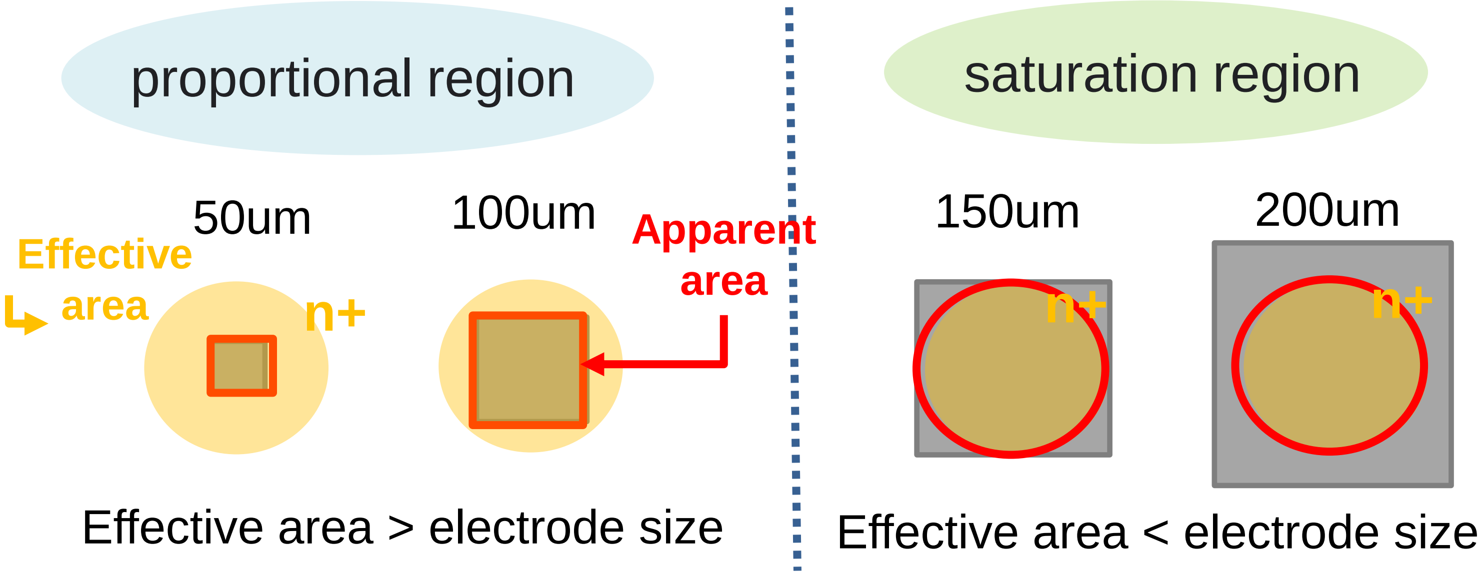
What is the effective area for electrode capacitance ?

E-600 type of pixel sensor

(all suppried 190V)

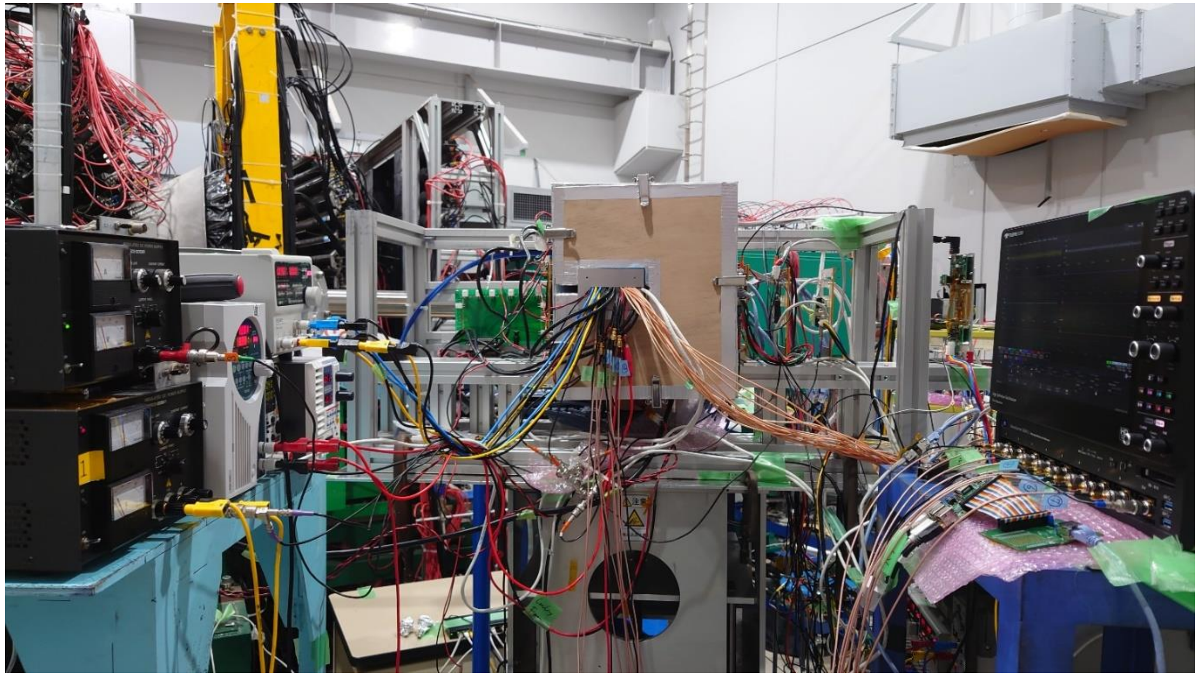


Tested various size of pixel sensor to see the saturation of signal size



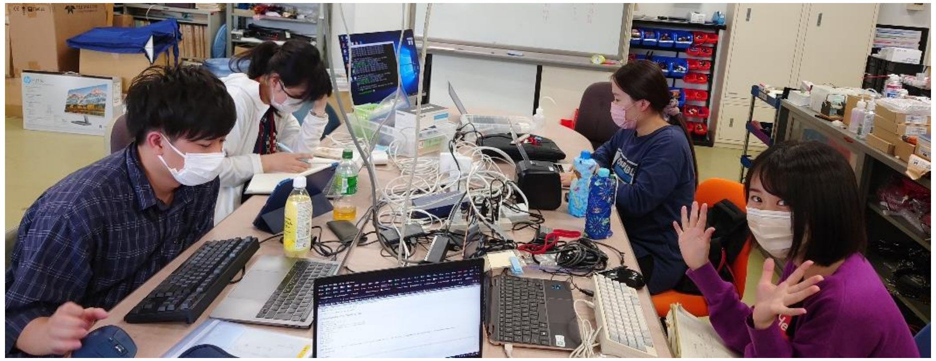
- **Signal seems like saturated at ~150um**
  - It makes sense small signal of 50um x 50um sample
  - **Will test smaller n+ resistivity sample**
    - Expected larger effective area.

Snap shot from ELPH testbeam in June

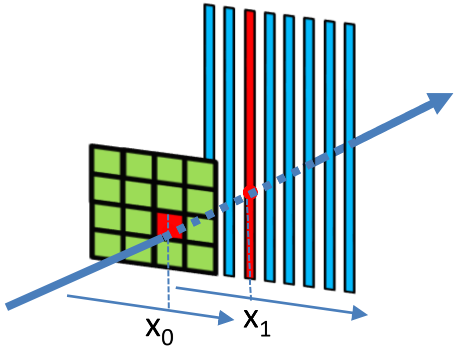


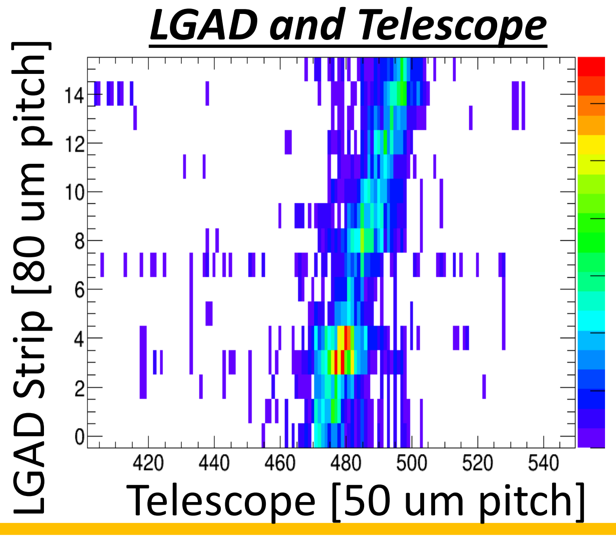
- ELPH testbeam (6/17-24)
  - 800MeV electron beam
- Took huge set of data
  - Pad/Strip/Pixel sensors
  - Combined run with 100um pixel and 80um strip sensor

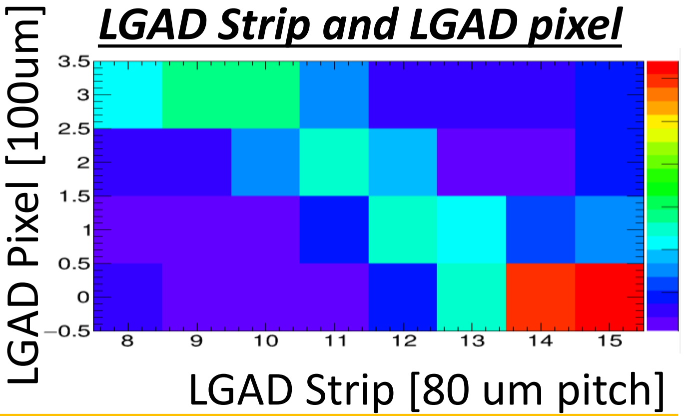
    →First LGAD tracker!!



Correlation of x position of two planes







Candidate ASICs

ASIC	Comment	Designer	Foundry	# of Channel	pitch	Status
ALTILOC	For ATLAS HGTD	OMEGA		5x5	1.3mm x1.3mm	V0,V1 available
EICLOC	For EIC	OMEGA		4x4	500um x 500um	V0 available
BiCMOS?	For TOF-PET/Faser	Uni. Geneva	IHP (130nm)	10x10	100um x 100um	Available
FAST	Discrim. & TDC.	INFN Torino	??(110nm)	20		Available / testing
HPSoC	Waveform digitizer	NALU Scientific	?? (65nm)	5 → 81		Available / testing
ASROC	Si-GeBiCMOS for EIC	UCSC	Anadyne	16		Simulation / design

Technology choice :

- Bi-CMOS vs CMOS ?
  - Issue is Power Consumption and Bi-CMOS have benefit.
- Finer pitch or

For our development,

- Started to collaborate with Uni. Geneva
- Started testing Bi-CMOS 100um pitch ASIC

Conclusion and plan

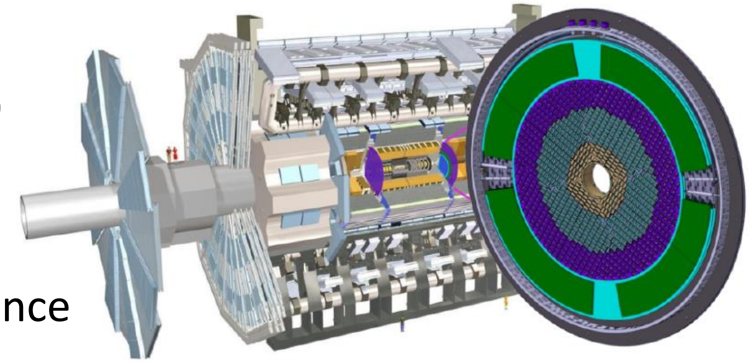
2015-

LGAD semiconductor technology

Achieved 30ps timing resolution for MIP

First experience in
actual collider (2029-)

Important
for operation experience



2021

LGAD with both timing and spatial resolution

AC-LGAD achieved O(10um) spatial resolution

Application of the device to various detector :

- Outer tracking detector of Hadron collider
- Lepton collider and Ion collider
- Application to imaging detector (Transparent electrode)

➔ **Larger size prototype**

Home work

LGAD detector with Radiation tolerance

Currently up to $1.0 \times 10^{15} n_{eq}/cm^2$

Need to think how to reduce Acceptor removal effect…

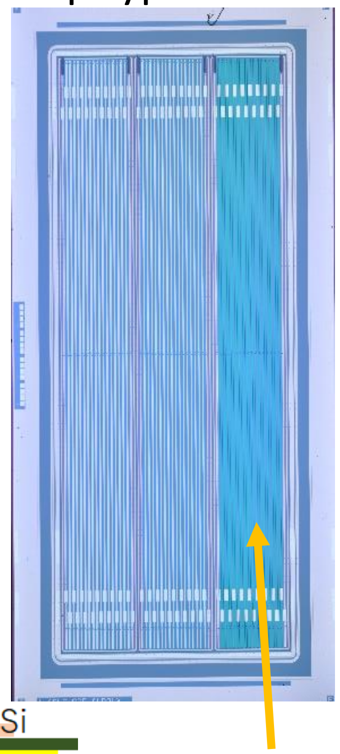
➔ $1 \times 10^{16} n_{eq}/cm^2$ NIEL radiation tolerance is necessary to **use this detector for inner part of hadron collider.**

backup

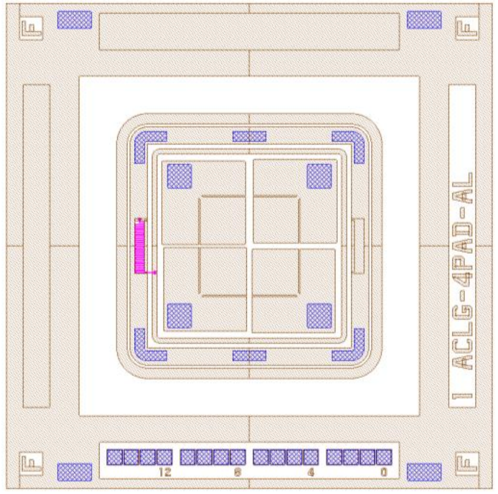
Possible application of AC-LGAD

- For **molecular imaging, medical and industry application** of the AC-LGAD detector, we have discussing how the detector make photo-detector (especially visible and Infra-red light).
- Electrode is Aluminum so 100% of visible light and infra-red light reflected…
- **Poly-si(300um) electrode possibly transparent at least certain fraction of light ??**
- If this is true : we can detect visible light an infra-red light.
  - More application possible to the other field if the timing resolution still good.
- Both pad and strip detector with poly-si electrode prototyped.

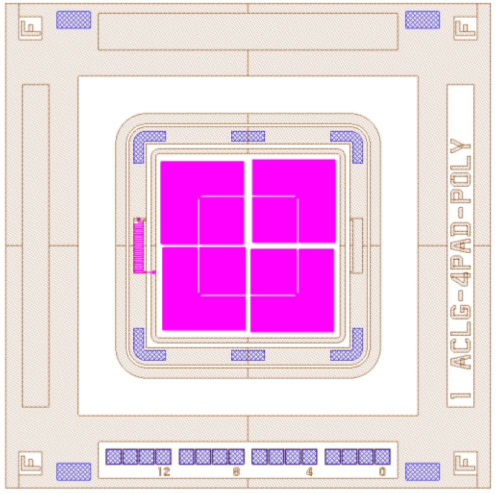
Strip type



Normal AC-LGAD

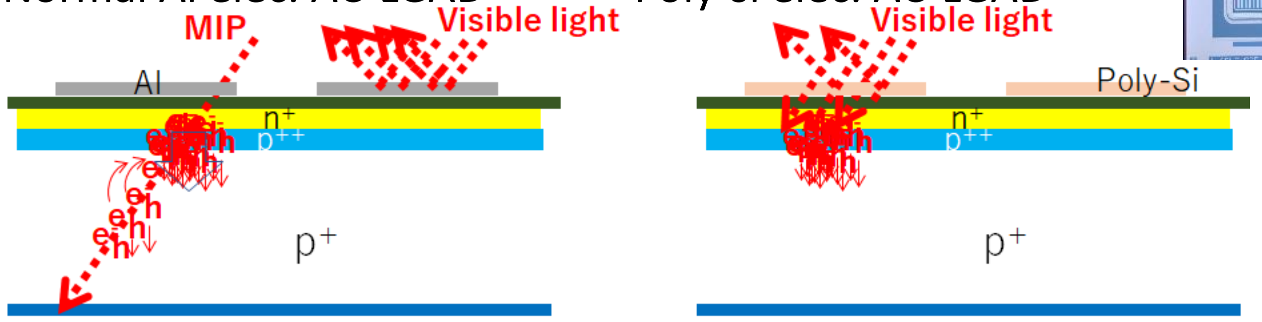


Poly-Si AC-LGAD



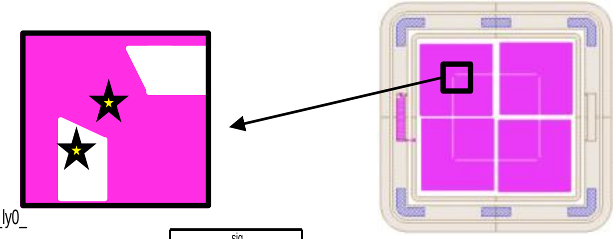
Normal Al elec. AC-LGAD

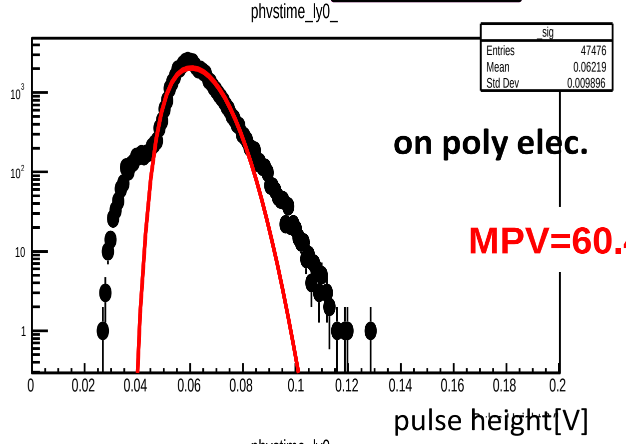
Poly-si elec. AC-LGAD

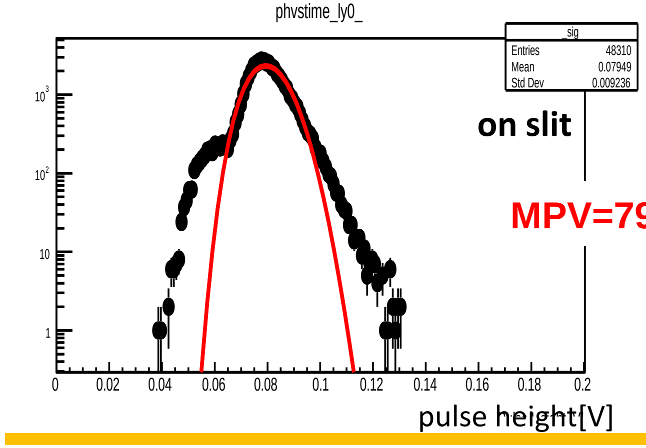


Possible application of AC-LGAD

Transmittance measurement @ red laser

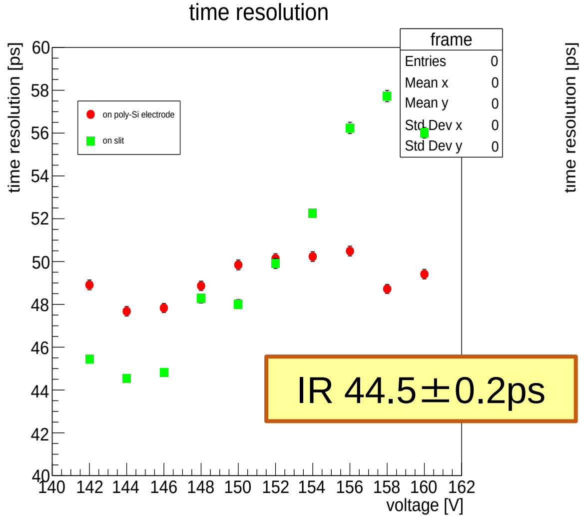


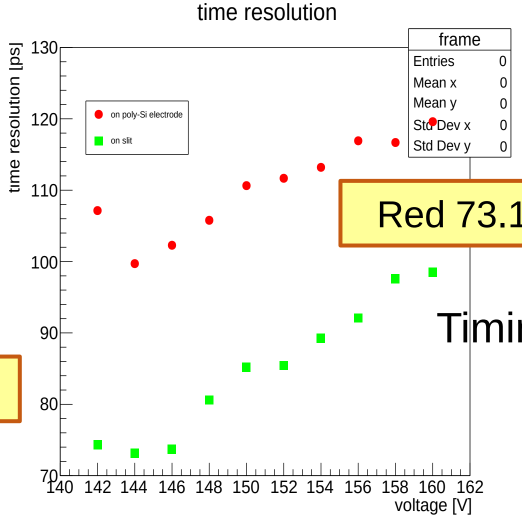




Transmittance (red laser) 76.16±0.15 %

Timing resolution measurement





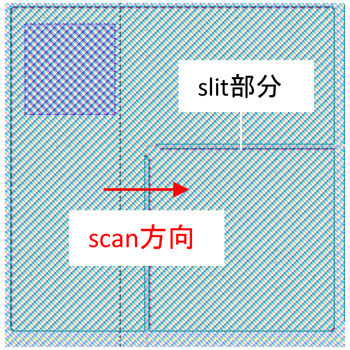
Timing resolution
Red > IR
On elec. > slit

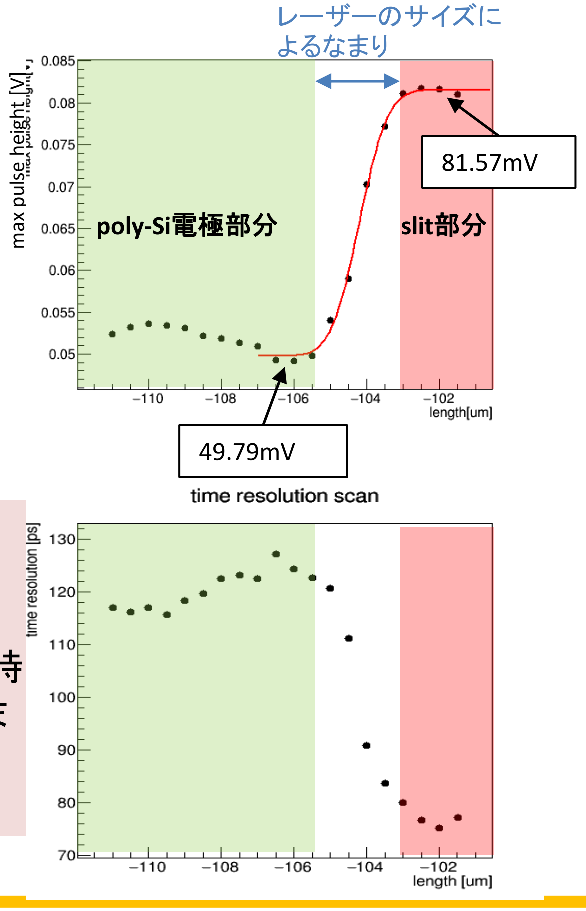
- Just started evaluation of poly-si electrode AC-LGAD
  - Transmittance by red light : 76% (not bad)
  - Timing resolution by is similar to MIP, getting worse for red light. → need to check
- A lot of thing need to think :
  - What Quantum Efficiency for photon?
  - Is there wave length dependence?
  - What is the effect of resistivity of poly-si elec. ?

poly-Si電極サンプルの透過率と時間分解能

- pad型E-bタイプに赤色レーザー(波長634nm)と赤外線レーザー(波長1064.25nm)を入射
  - ✓ 透過率：poly-Si電極上に入射した時の信号の大きさとslit部分(電極のない部分)に入射した時の信号の大きさから求めた
  - ✓ 時間分解能：trigger信号と読み出し信号の時間差をgauss fitし、そのσを時間分解能とする

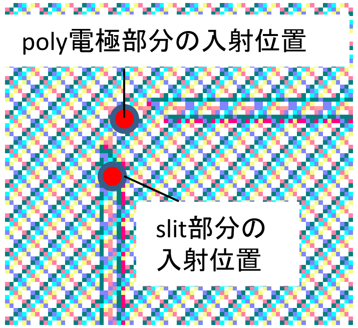
赤色レーザー



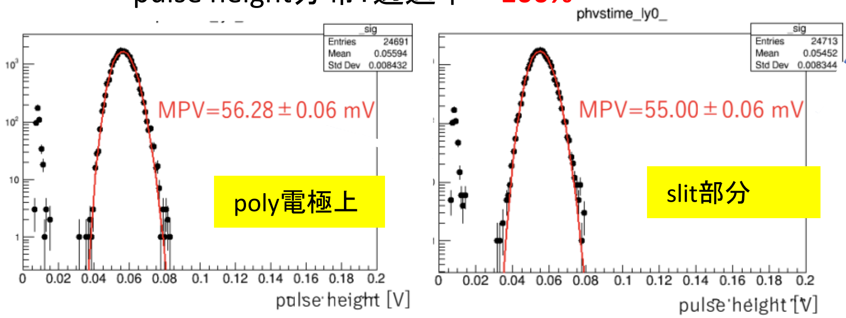


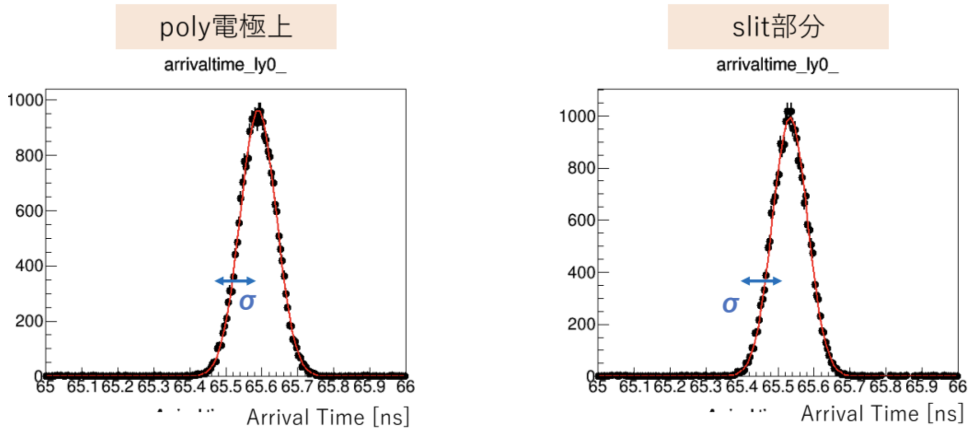
- 透過率
  61.04±0.07%
- 時間分解能
  poly電極上に入射すると時間分解能が悪くなってしまうことがわかった
  ⇨原因を調査中

赤外線レーザー



pulse height分布：透過率**～100%**





時間分解能　σ=50.3±0.2 ps

時間分解能　σ=48.6±0.2 ps

poly-Si電極サンプルの透過率と時間分解能

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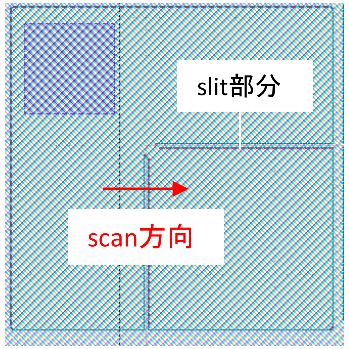
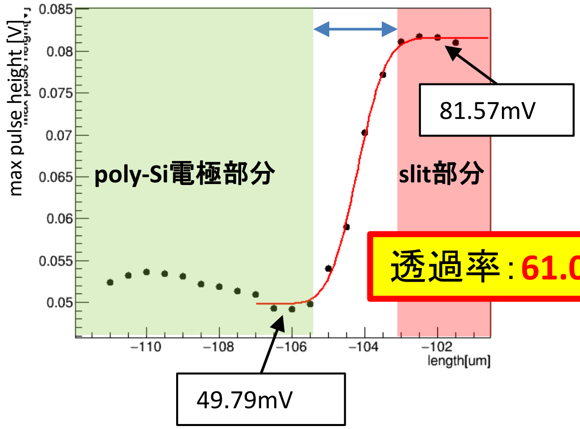
赤色レーザー

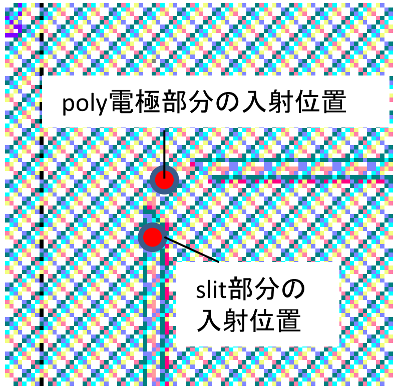


レーザーのサイズによるなまり

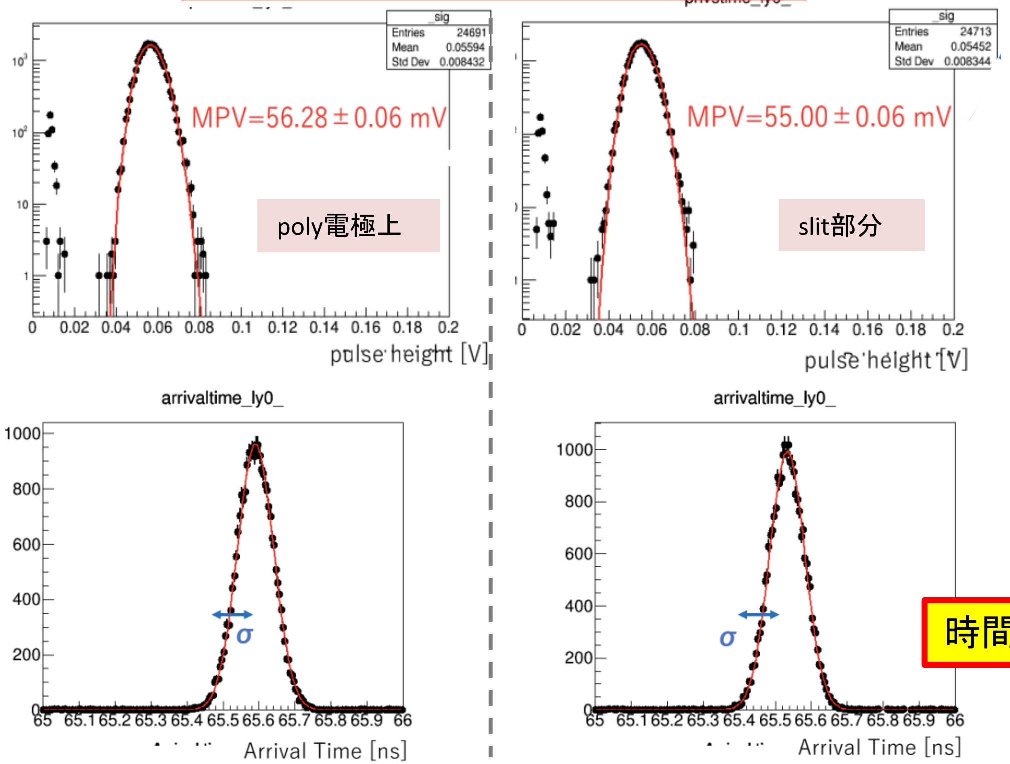


透過率：**61.04±0.07%**

赤外線レーザー



pulse height分布：透過率**～100%**



時間分解能　σ=50.3±0.2 ps

時間分解能　σ=48.6±0.2 ps

時間分解能：約50ps