Overview of timing detector development produced by BNL&HPK

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Introduction

- LGAD is now quite mature technology and developing to build detector for HL-LHC experiments.

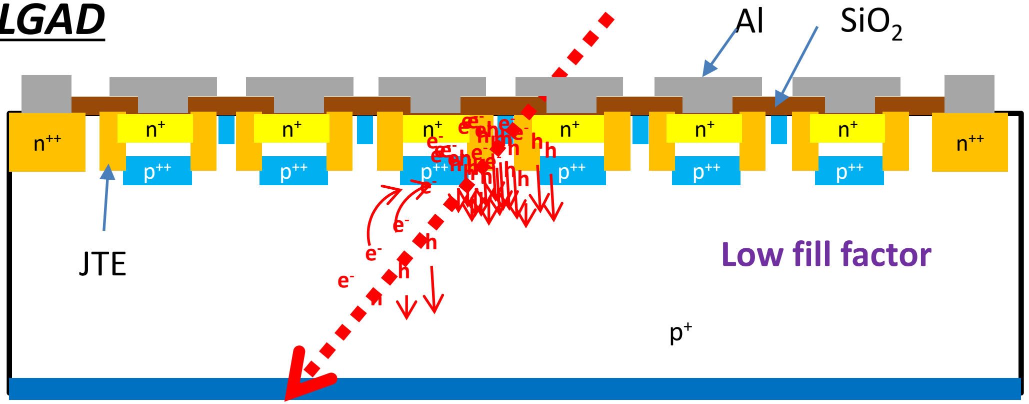
- Spatial resolution will become more important to use the timing information in inner tracking detector in a collider detector.

- BNL and KEK/Tsukuba is developing AC-LGAD technology.
  - Collaborating to Fermilab to test the devices in the high energy proton beam.

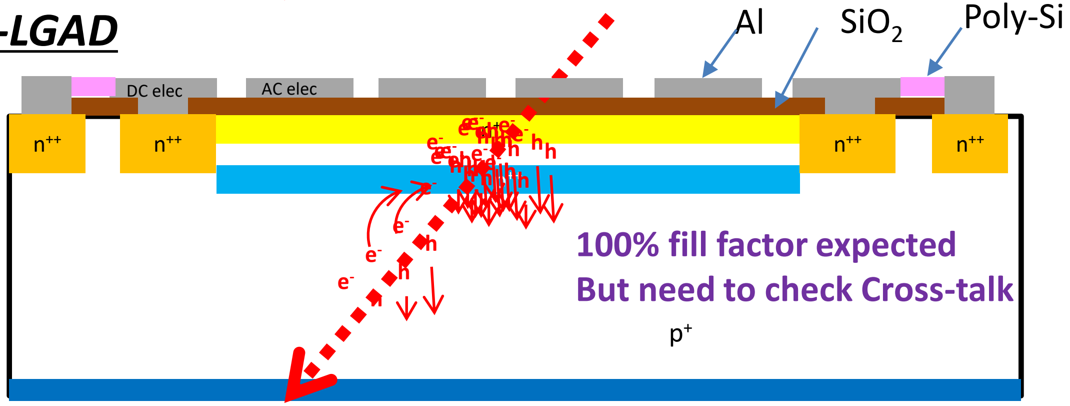
AC-LGAD detector

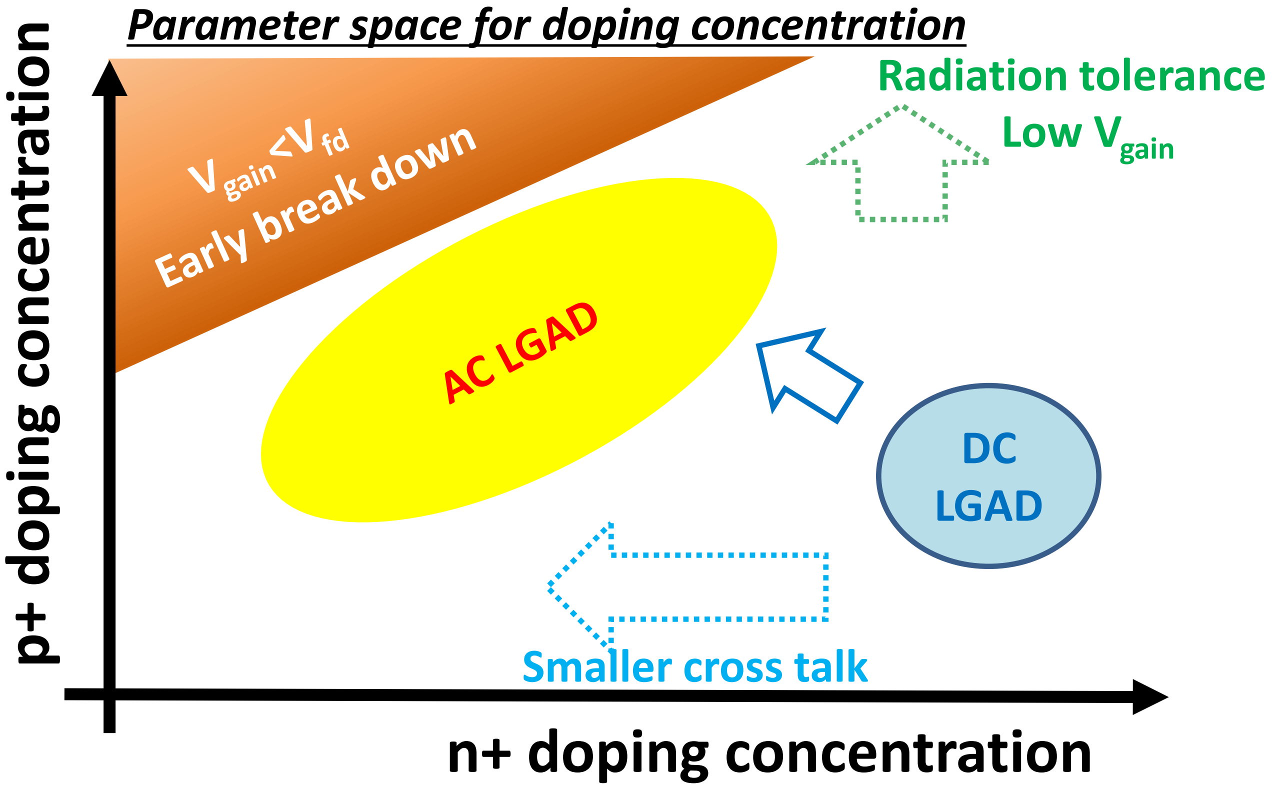
- Limits of LGAD :
  - Need JTE and p-stop structure to have individual gain layer →**Low fill factor (20% for 80um strip)**
- AC-LGAD :
  - **Uniform gain layer with AC-Coupled electrode. 100% fill factor. Signal shared on neighboring electrodes.**

DC-LGAD



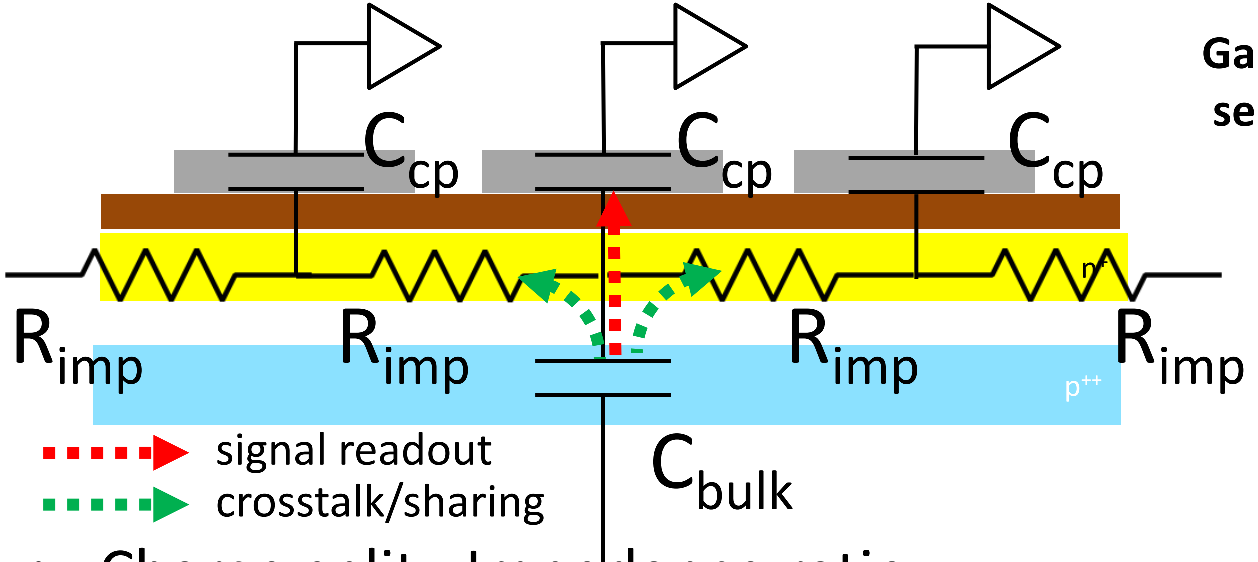
AC-LGAD



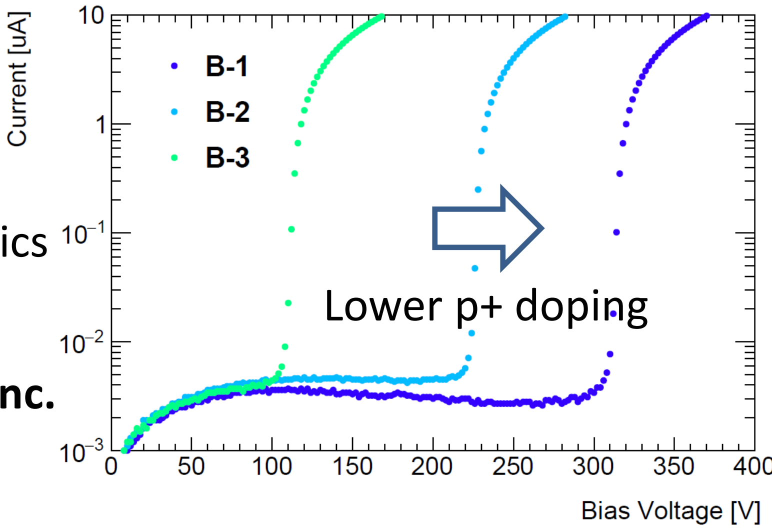


AC-LGAD detector

- **Read out principle of AC-LGAD**



I-V characteristics

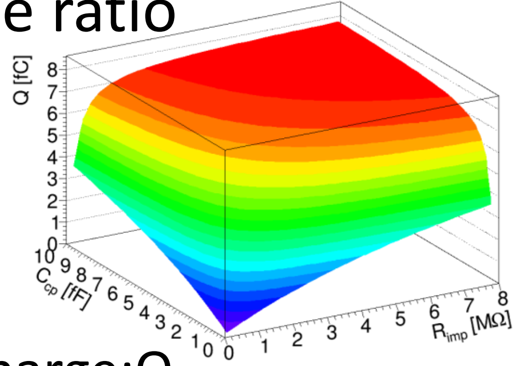


Gain Voltage (V_{gain}) is quite sensitive to the p+ doping conc.

- Charge split : Impedance ratio

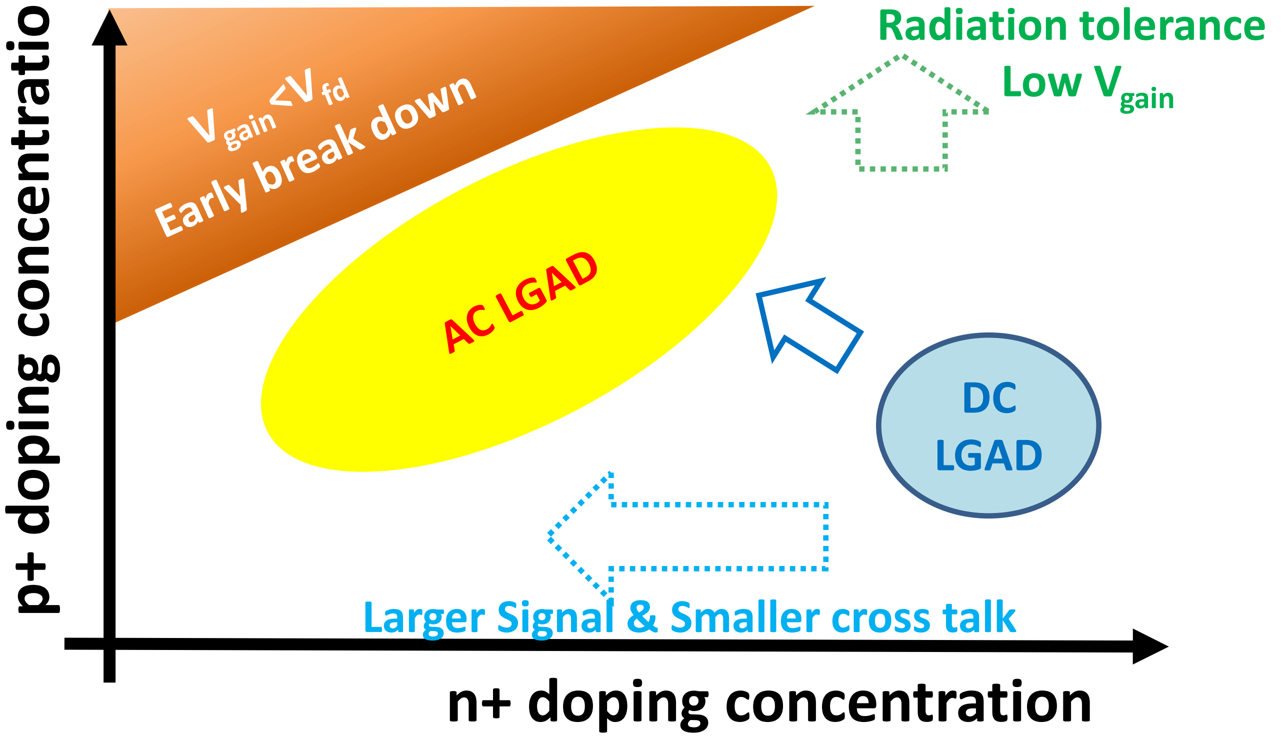
Assuming Z_{Cbulk}>>Z_{Ccp}…

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



  - Amount of produced charge:Q_0
  - Readout Charge :Q

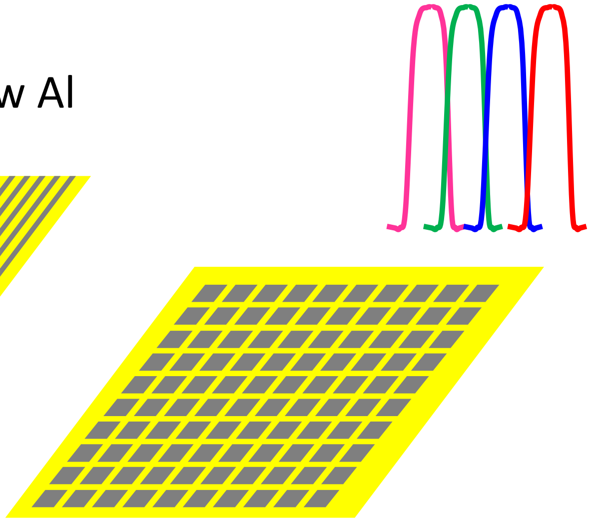
Parameter space for doping concentration



Two approaches to have good spatial resolution

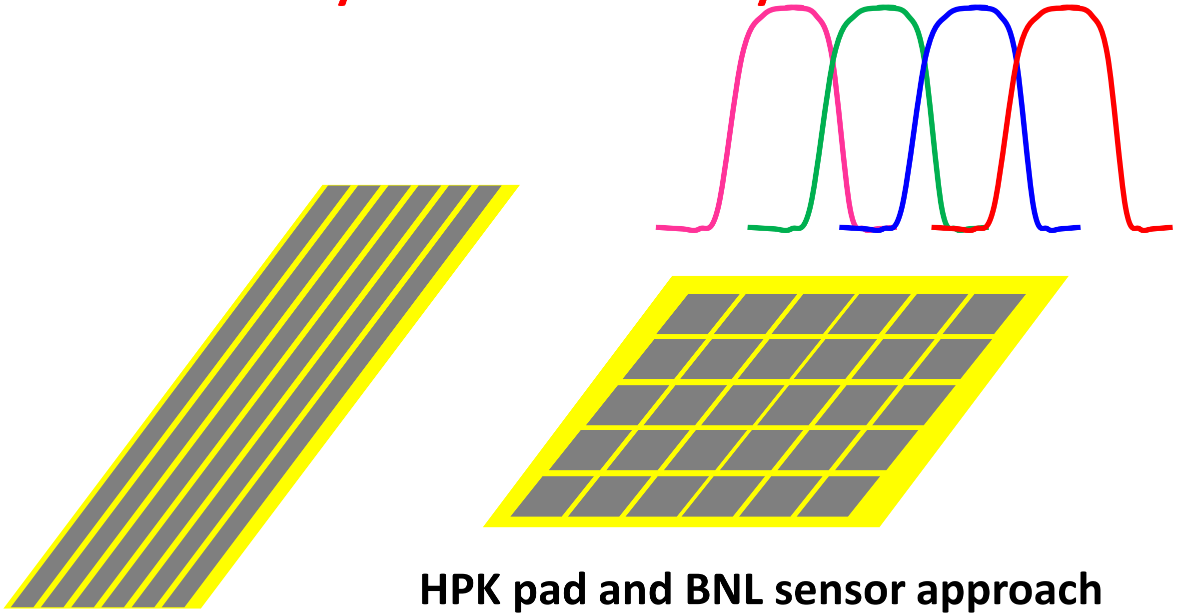
- ***Fine pitch electrode approach***
  - **For High occupancy experiment like hadron collider.**
  - Reduce crosstalk (charge sharing)
    - High n+ implant resistivity
  - **Pros. : smaller occupancy and smaller data size like digital readout**
  - **Cons. : May have limitation of spatial resolution by electrode size.**

Fine pitch strip with narrow Al (to reduce inter strip cap.)



HPK strip/pixel approach

- ***Charge sharing approach***
  - **For lepton collider or other low occupancy colliders.**
  - Reconstruct particle position using charge sharing (charge fraction to next channels)
    - Relatively low n+ implant resistivity
  - **Pros. : Very good spatial resolution if high resolution ADC used.**
  - **Cons. : May have Limitation by readout data size.**



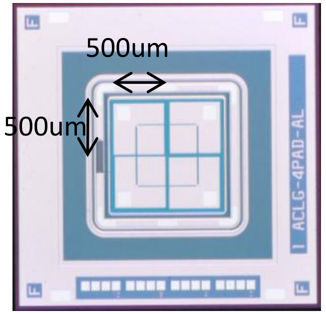
HPK pad and BNL sensor approach

HPK prototype samples

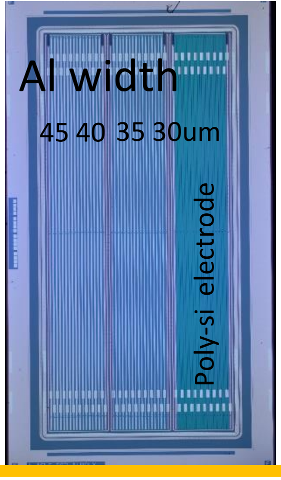
- Samples produced in JFY 2019 & JFY 2020
  - 50um active thickness, V_{fd}~50V
  - n+ and p+ doping concentrations (A-E, 1-3)
  - Oxide thickness of AC-elec. (C_b=1.5xC_a)
- Electrode types
  - Pad type : 500um☐ 4pad/sensor
  - **Strip type : 80um pitch, 9.88mm long**
  - Pixel type : 50um☐ 14x14 array

First goal

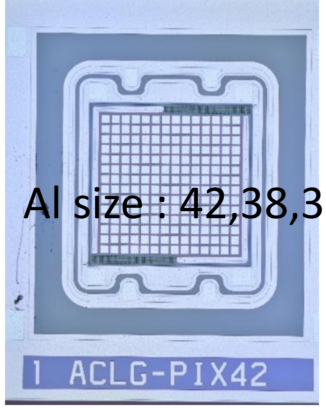
Pad type



Strip type



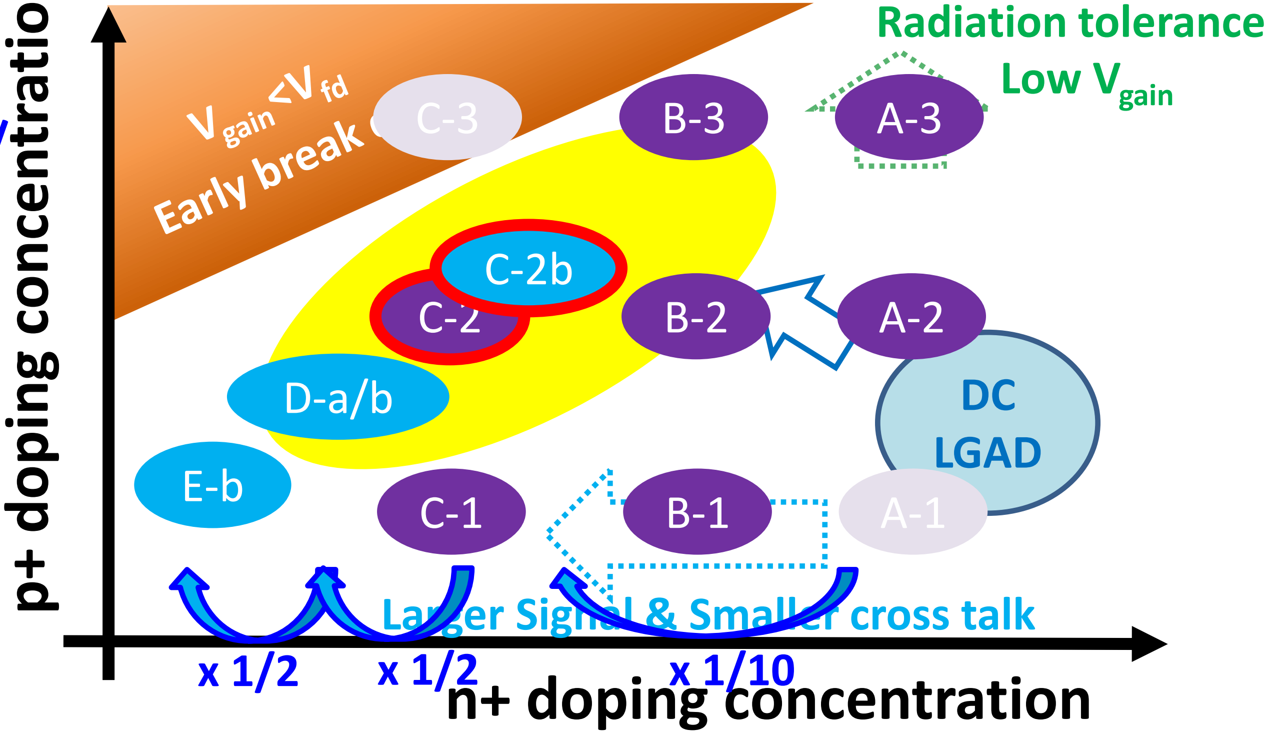
Pixel type



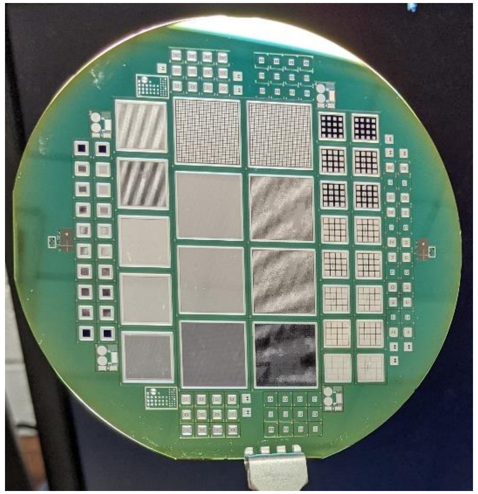
● **JFY2019 Samples**

● **JFY 2020 Samples**

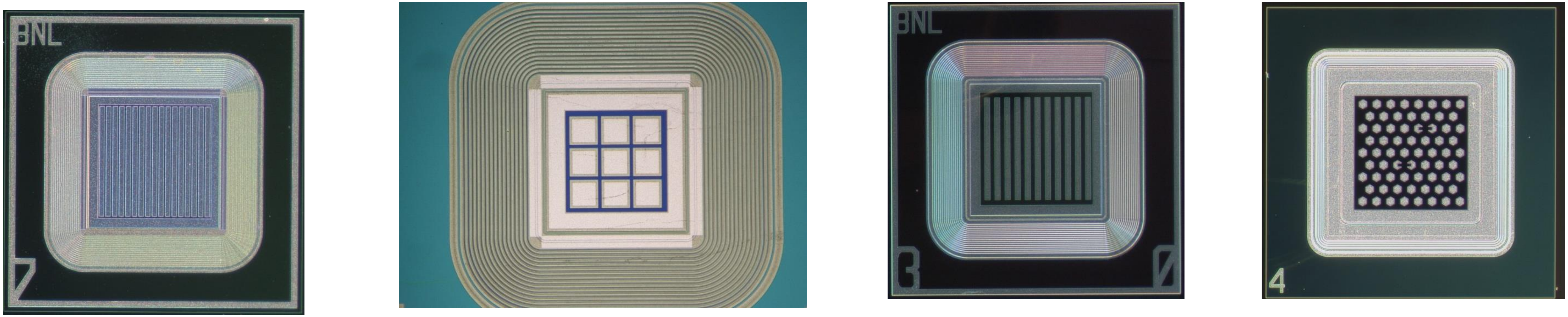
Parameter space for doping concentration



BNL samples



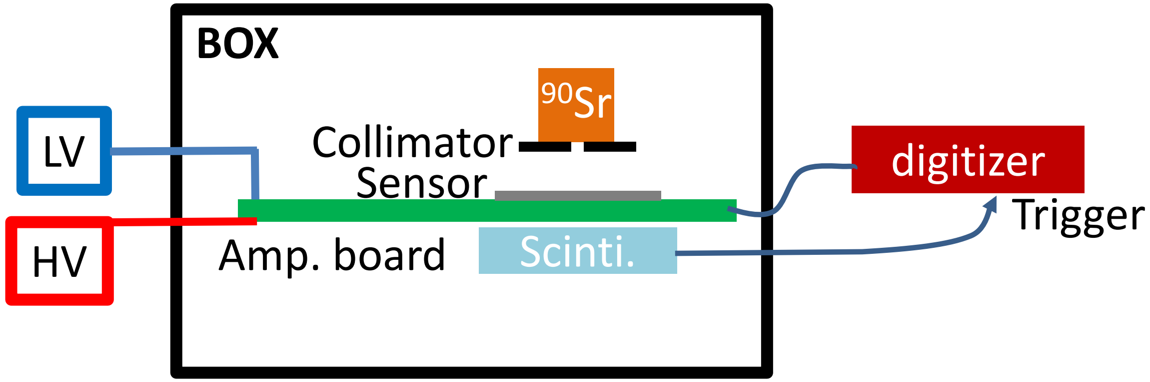
- Samples produced starting from 2018, full 4’ wafers dedicated.
- Wafers are (p-type) epitaxial, 50um thick, V_{fd}~120V.
- Modification of termination regions (Guard Ring, JTE) in last batches.
- Strips/pad/pixels total area 3x3mm^2, different pitch-width-shape.
  - E.g. for TCT measurement.
    - Lateral strip pitch 100um Al gap 44um, 2mm long strips.
- (mainly) one n+ doping concentration : 1/50 of the DC-LGAD dose.
- V_{gain} tuned to be ~200V



Measurement at lab

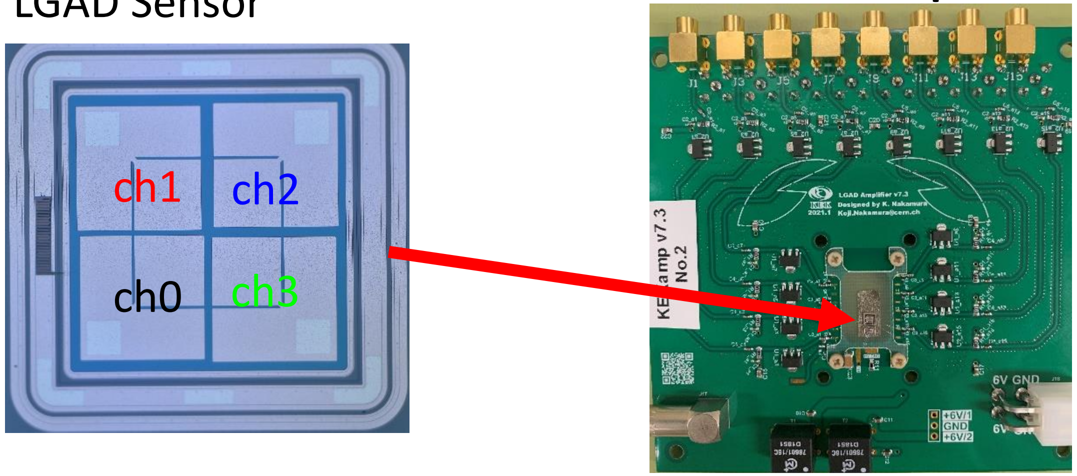
Measurement setup @ KEK/Tsukuba

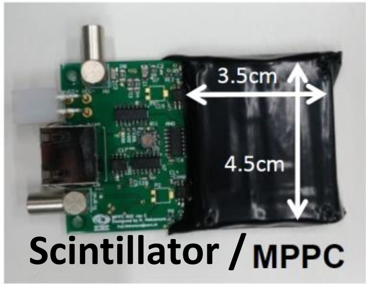
- Lab setup @ KEK/Tsukuba



LGAD Sensor

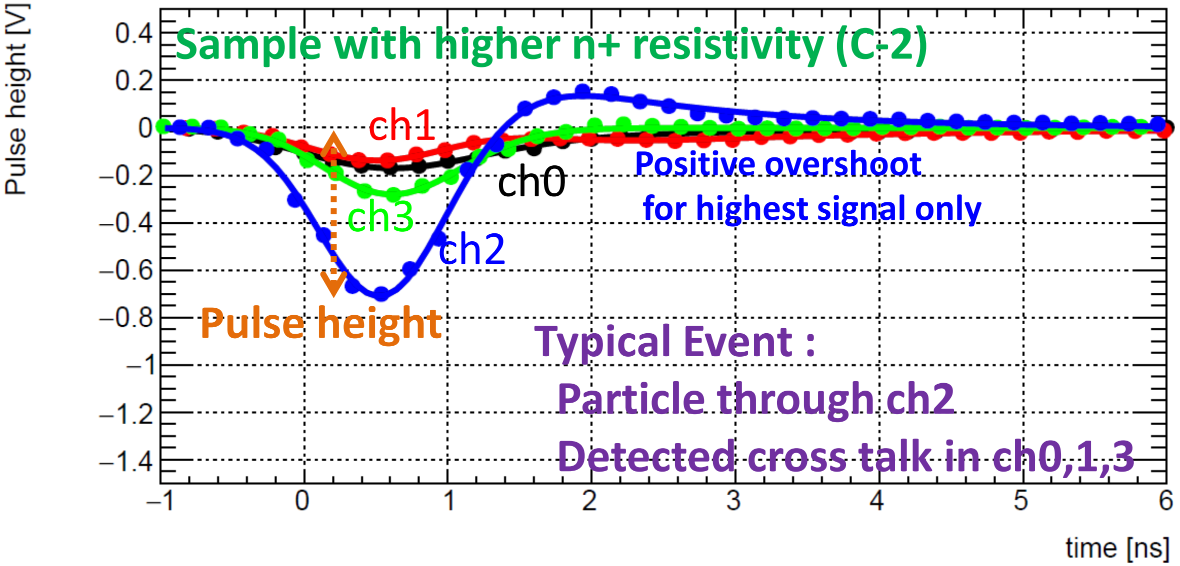
KEK 16 ch Discrete Amp.





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

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

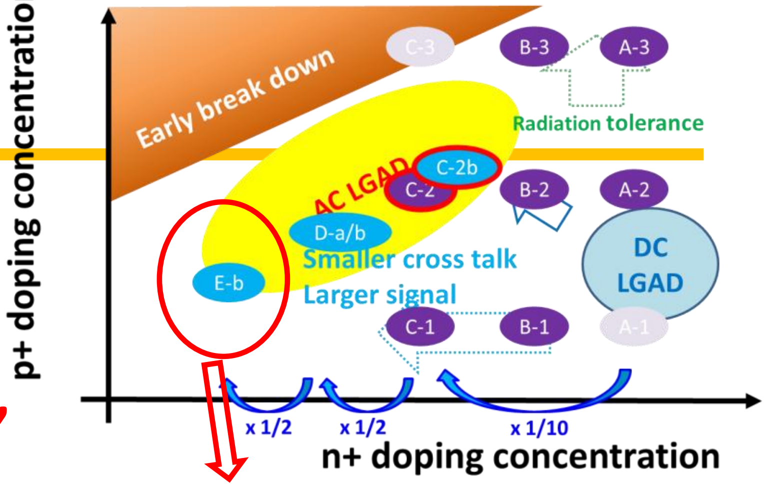


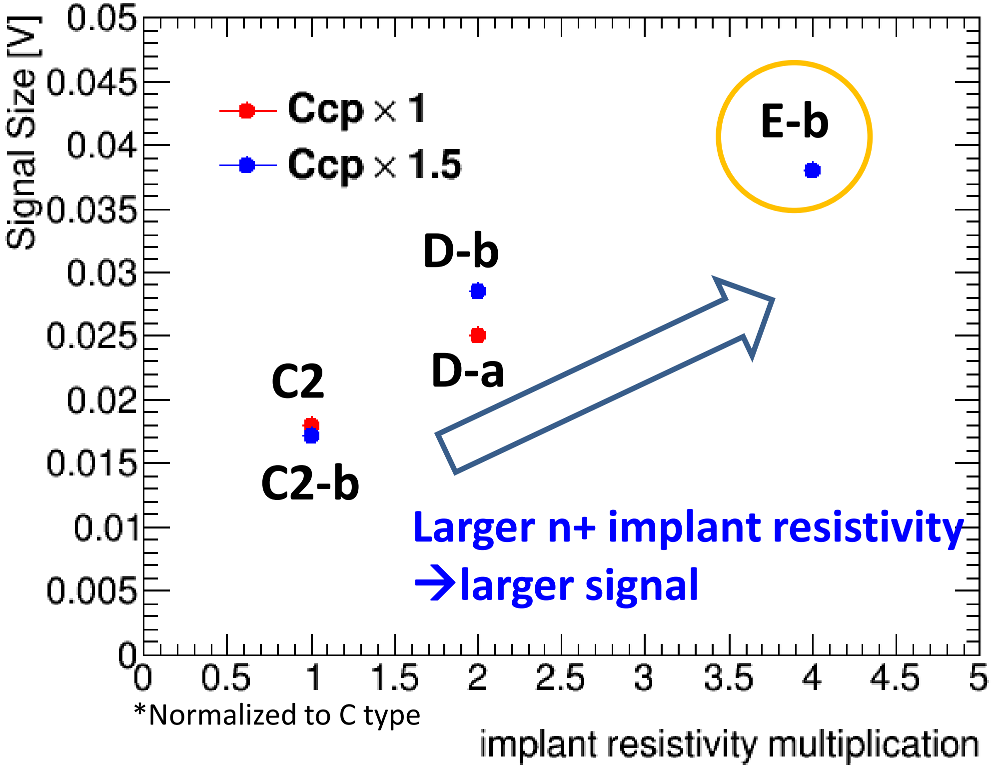
Typical Event :
Particle through ch2
Detected cross talk in ch0,1,3

Signal size and crosstalk

- Compared various parameters for signal size and crosstalk
  - Signal size and crosstalk has been measured by strip sensor.
  - Significant dependence of n+ implant resistivity observed
  - **Larger n+ resistivity have “larger signal” & “Smaller crosstalk”**

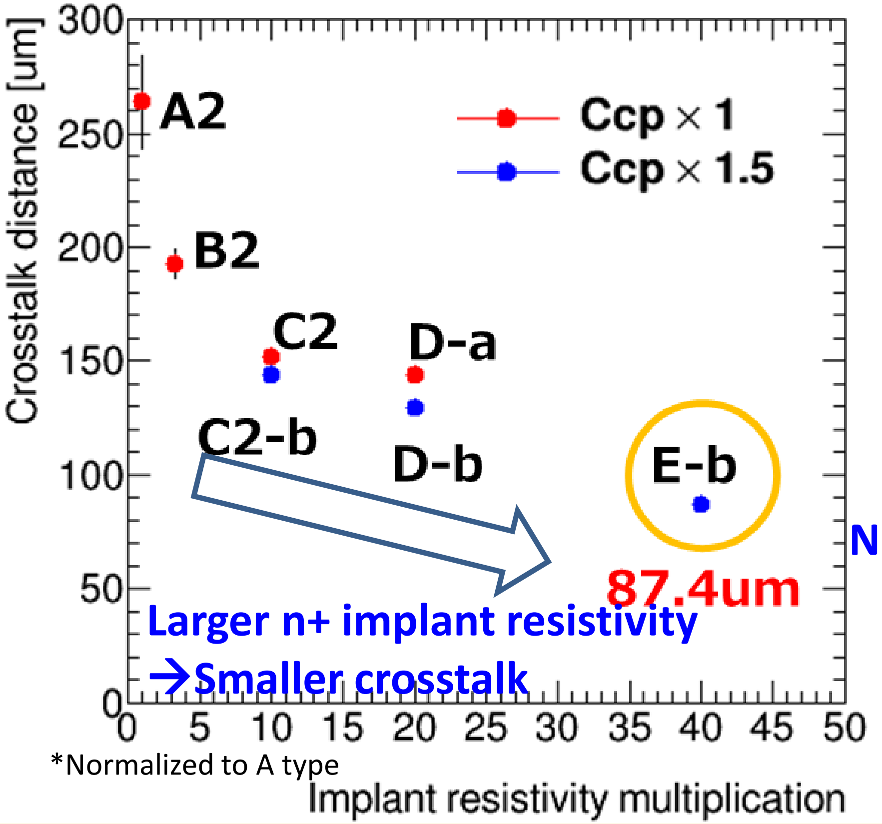
Parameter space for doping concentration





Larger n+ implant resistivity →larger signal

*Normalized to C type

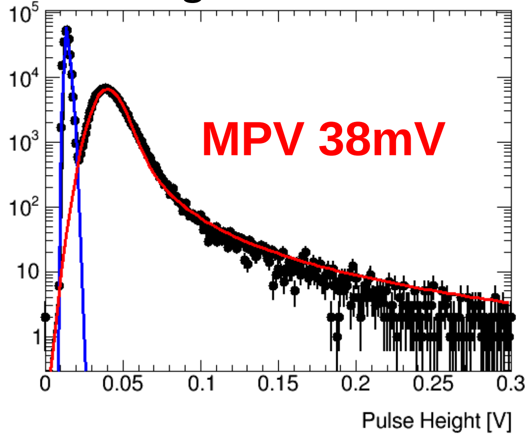


87.4um

Larger n+ implant resistivity →Smaller crosstalk

*Normalized to A type

Pulse height



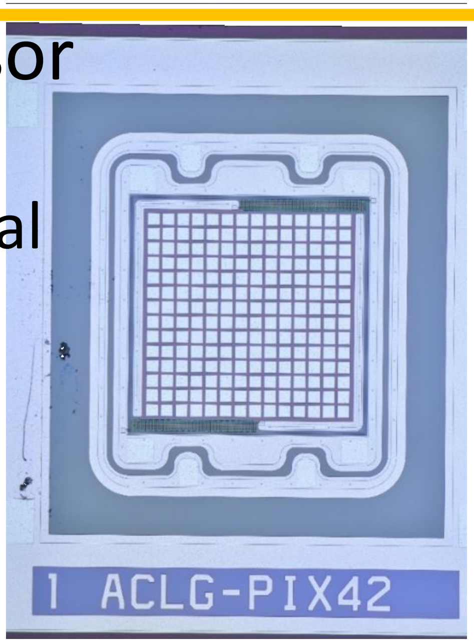
MPV 38mV

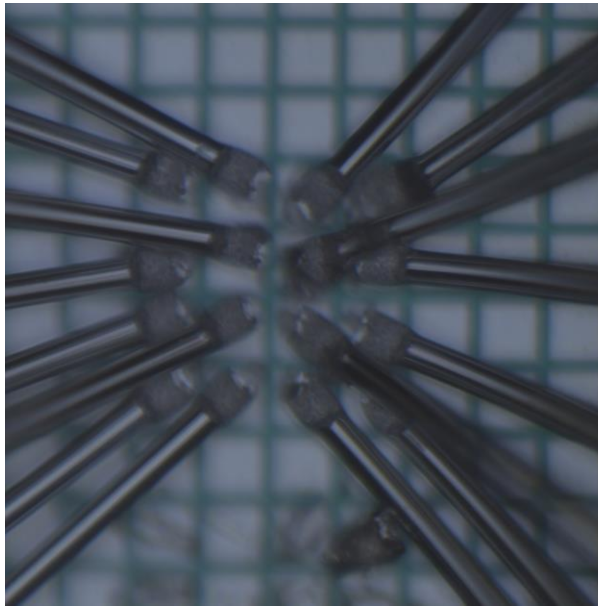
Noise fake rate :10^{-3} @ 99% Effi.

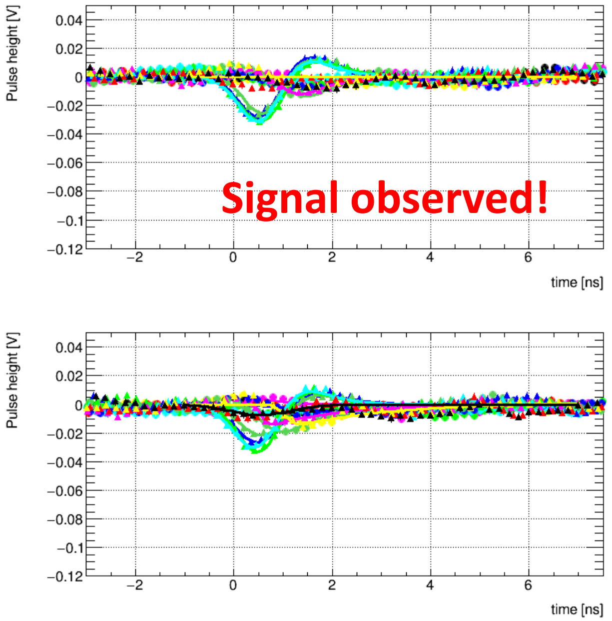
Good S/N ratio
Usable AC-LGAD detector
with 80um strip electrode.

Challenge : Pixel detector

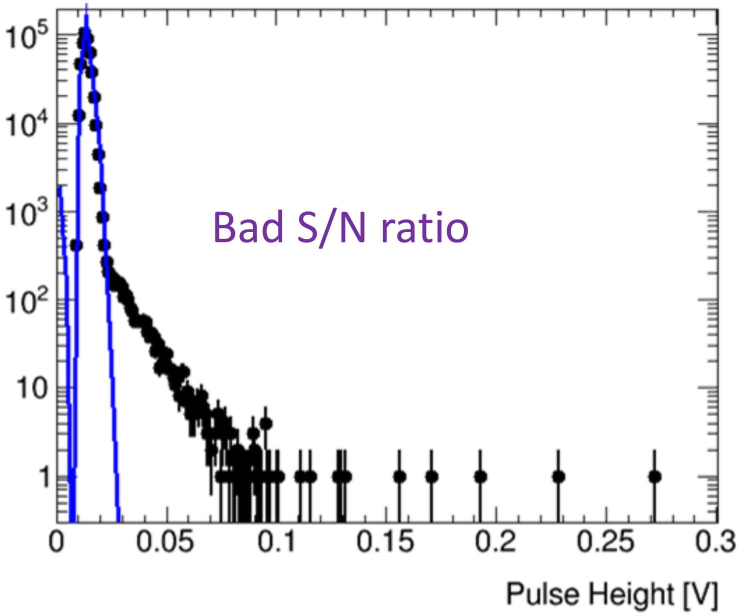
- Prototype of 50um x 50um pitch pixel sensor
  - Wirebonded only 4x4 array at the center.
  - First observation of AC-LGAD pixel sensor signal
    - Smaller signal and larger cross talk observed
    - **S/N ratio is not enough and need improvement.**







Pulse height distribution



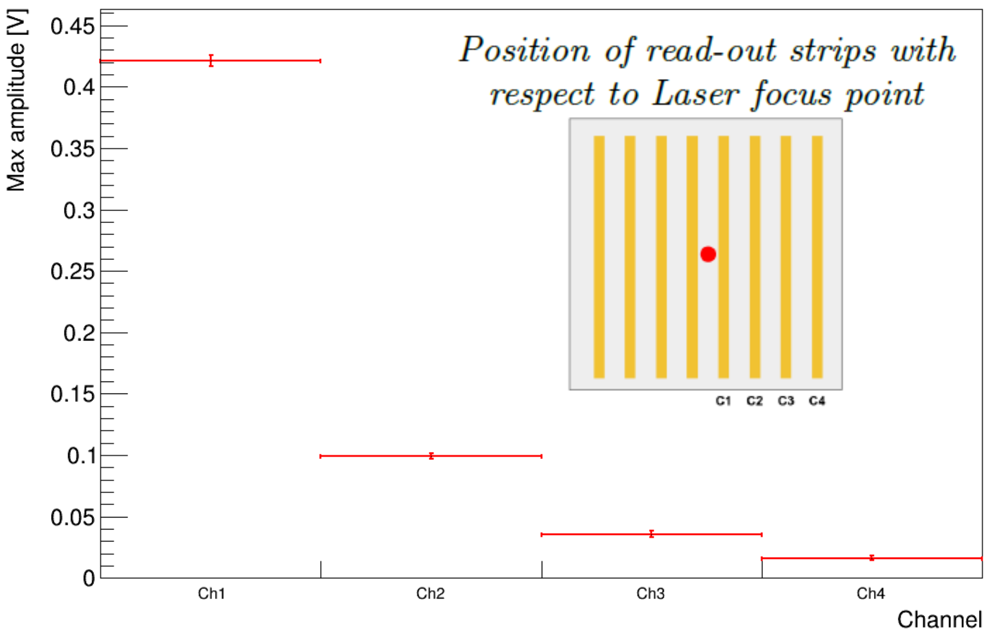
Clearly need improvement

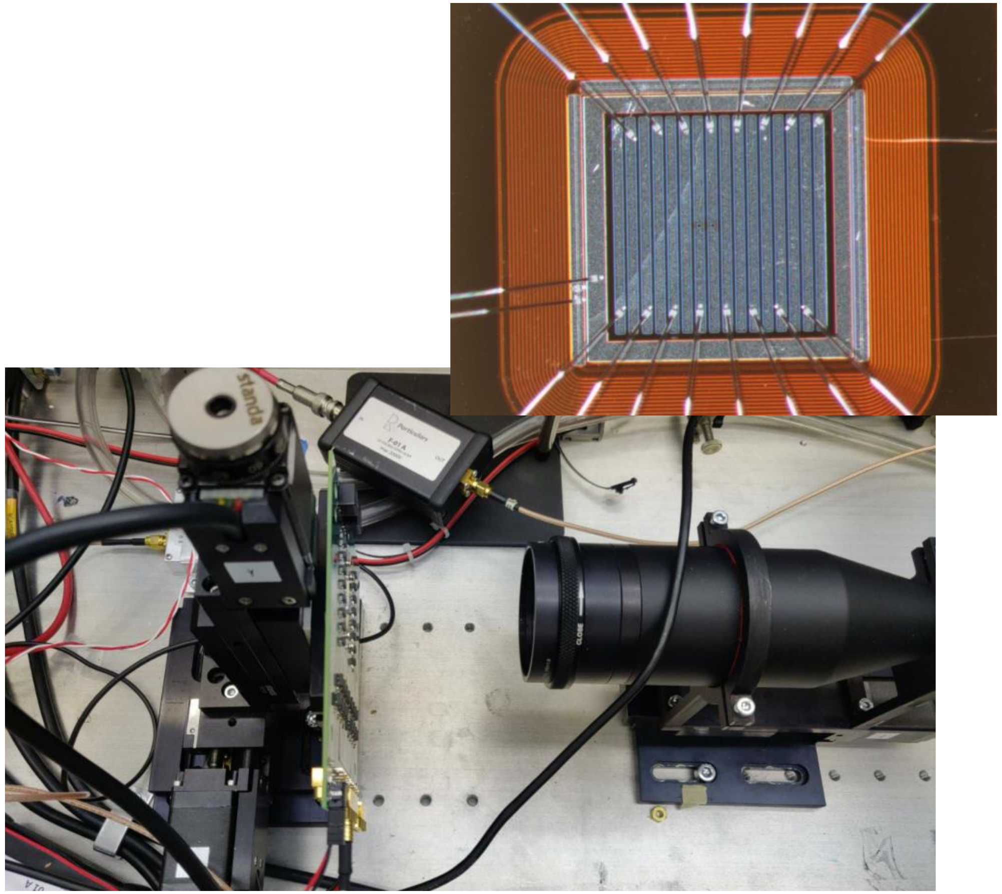
Coupling capacitor Ccp (Effective area?)

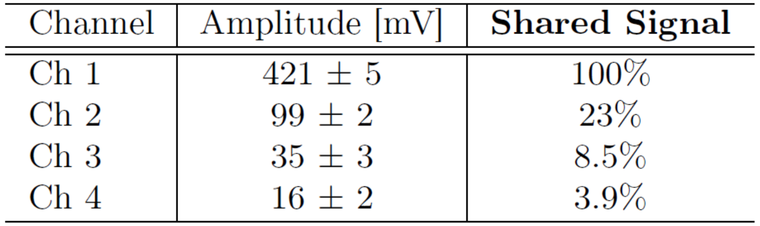
MPV : 100mV 38mV <15mV

Infra Red Laser - TCT setup @ BNL

- Sample :
  - BNL AC-LGAD 16-strips array
  - Lateral strip pitch 100um, 44um Al gap
- 3 MIPs charge injected to center between strips.
  - Check amplitude for 4 strips (ch1-4)
  - **Some charge sharing observed.**



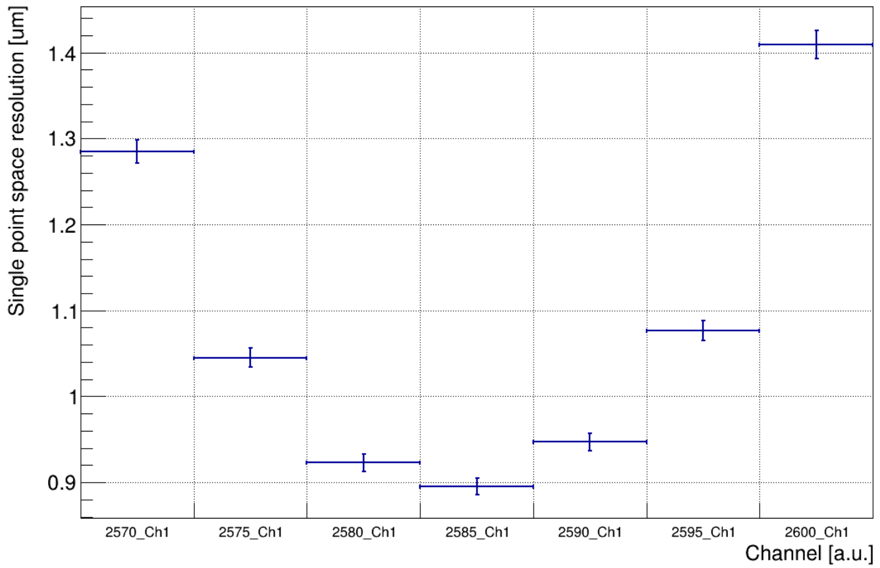


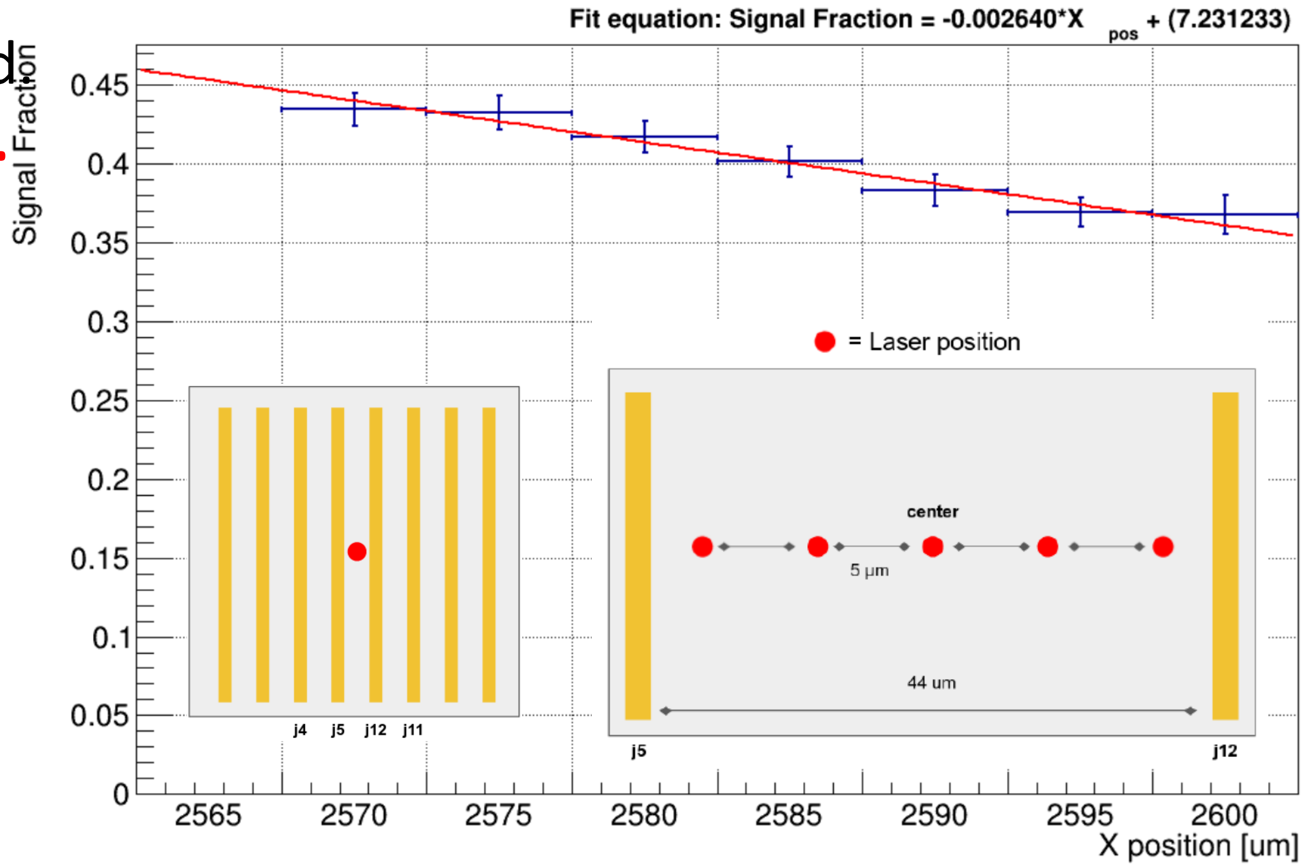


Channel	Amplitude [mV]	**Shared Signal**
Ch 1	421 ± 5	100%
Ch 2	99 ± 2	23%
Ch 3	35 ± 3	8.5%
Ch 4	16 ± 2	3.9%

Spatial resolution

- Scanning Laser position with 5um step and measured signal fraction among neighbor strips.
  - Spatial resolution computed via χ^2 minimization of signal fractions observed.
  - **Spatial resolutions of ~ 1um achievable.**
    - Ideal case with huge signal (>400mV)



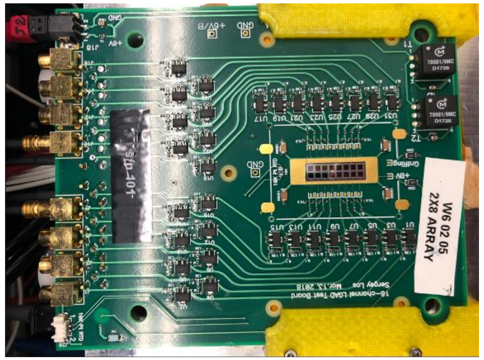


Performance measurement at testbeam

Fermilab testbeam setup

- Permanent setup in FNAL test beam facility (FTBF)
  - 120GeV proton beam
  - Record 100k events per minute.
  - Tracker resolution : ~10um
  - Environmental control : temperature -25^{o}C to 20^{o}C
  - 10ps time reference (MCP)
  - DAQ : high bandwidth scope.
- Simple Readout boards without ASIC

Readout amp board

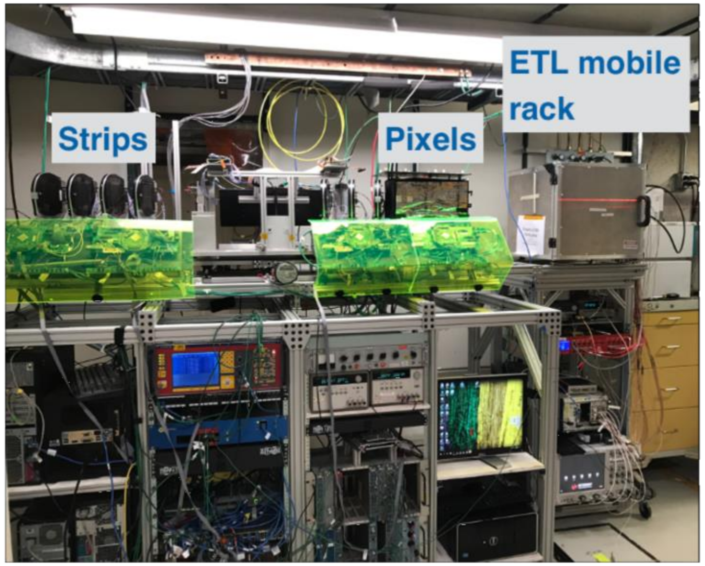


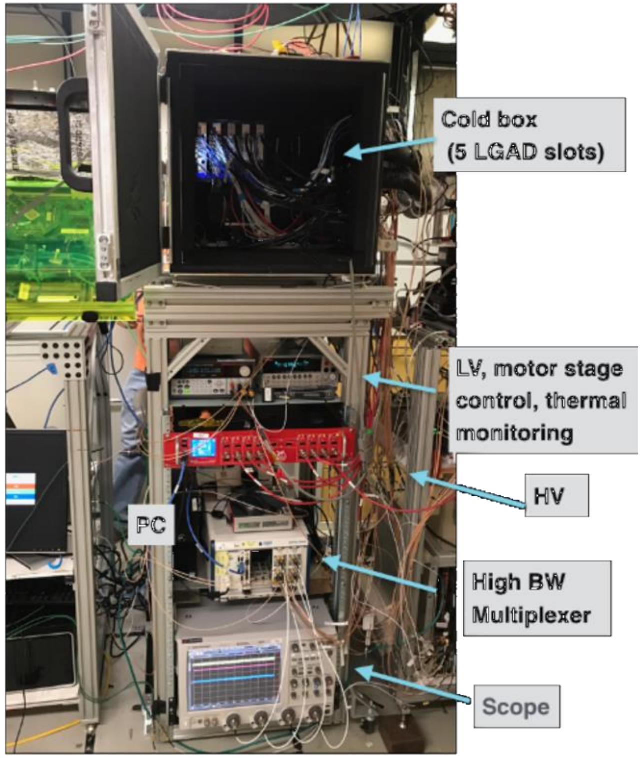
Readout by Oscilloscope

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

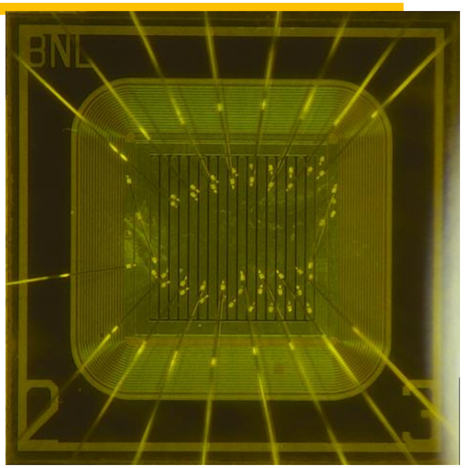
Timing reference Detector

PHOTEK
MCP photomultipliers (PMT140)
450ps FWHM with 5e3 Gain
Multi-photon jitter below 10 ps



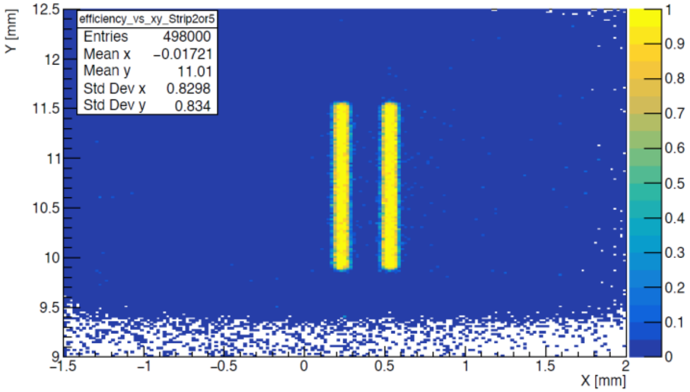


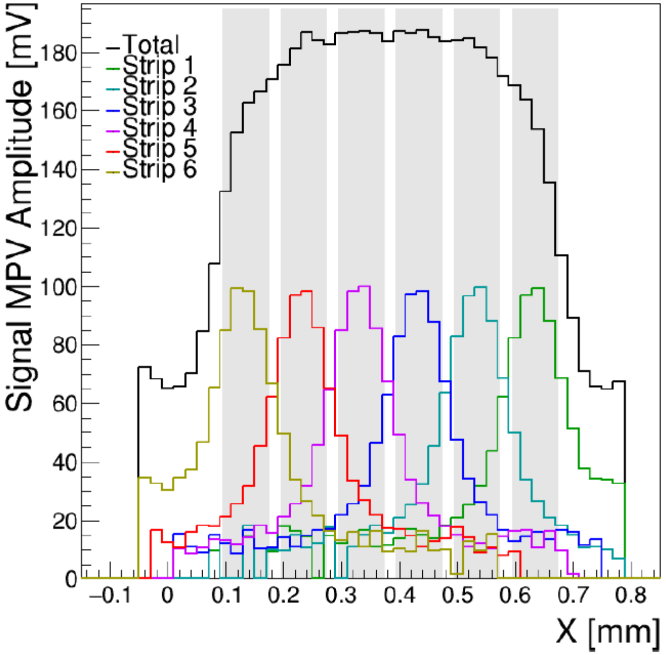
Results in BNL 2020 strips

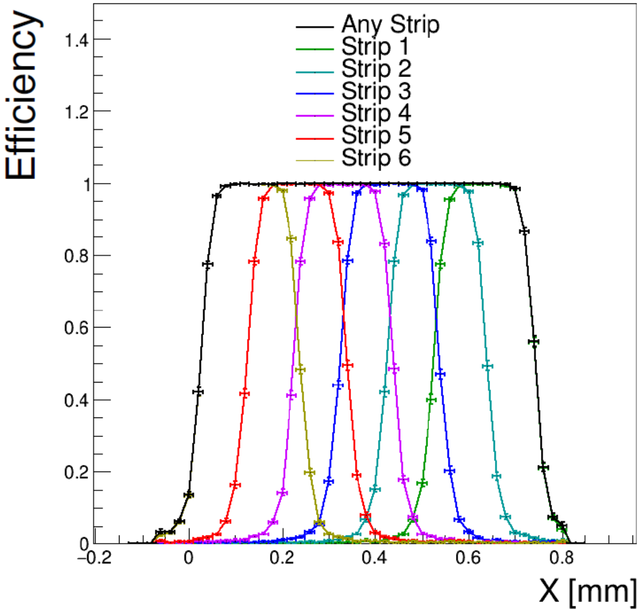


- 100um pitch with 20micron gaps
- Read out 6 interior strip + DC ring + MCP timing reference
- Selected events with proton in inner 4 readout strips to see performance.
- Charge sharing between strops has be seen.
  - **Each strips have amplitude peaks at around 100mV. (180mV in total)**
  - **100% efficiency across all strips.**

Efficiency for 2nd and 5th strips



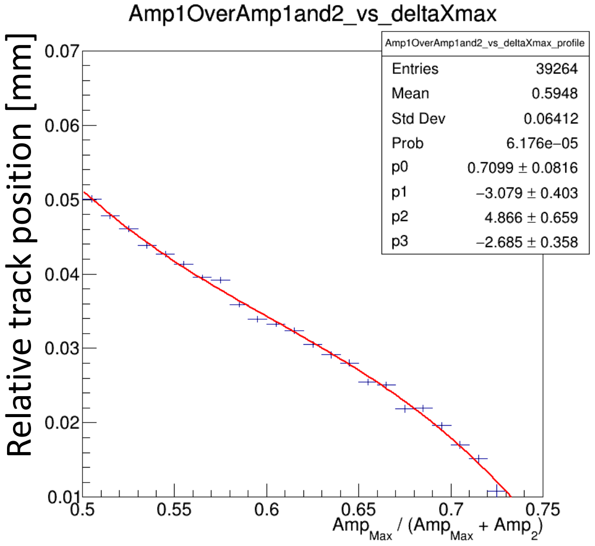


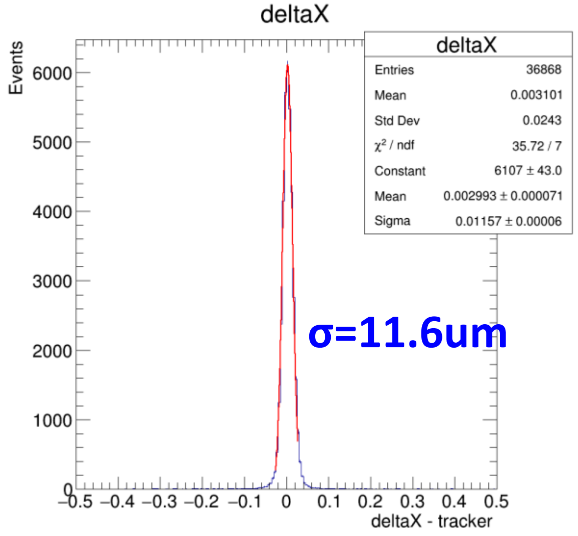


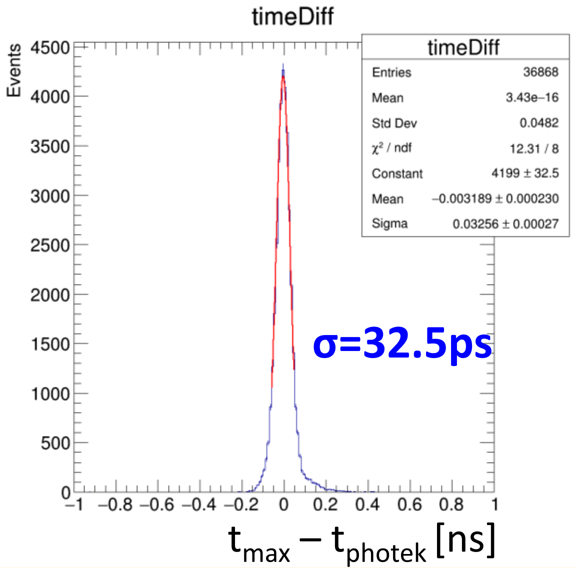
30 mV Threshold

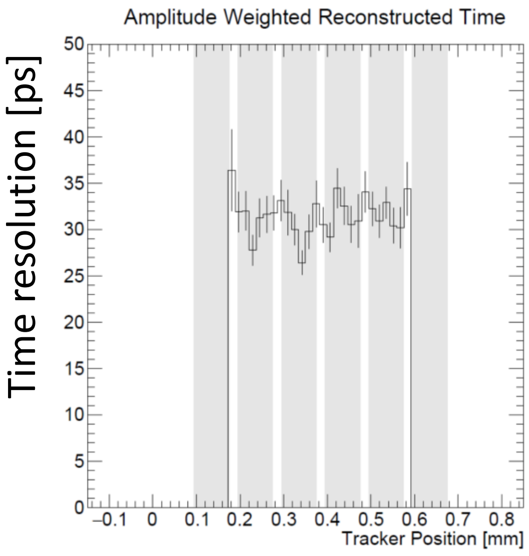
Results in BNL 2020 strips

- Position Reconstruction
  - Reconstruct the location of proton hit using the primary strip and secondary strip relative amplitude.
  - Use max amplitude (A_{max}) and second highest amplitude (A_2) strip and parametrize $A_{max}/(A_{max}+A_2)$ as a function of location
  - **Observed ~5um position resolution after subtracting tracker resolution (~10um).**
- Time Reconstruction
  - Calculated time difference of max amplitude arrival time (t_{max}) and MCP (t_{photek})
  - **Observed 32.5ps timing resolution.**
  - **Timing resolution has also be calculated as a function of particle position.**



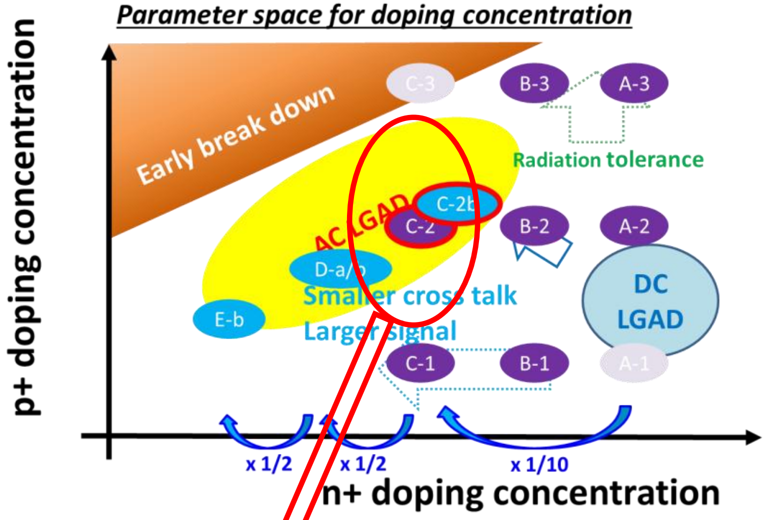




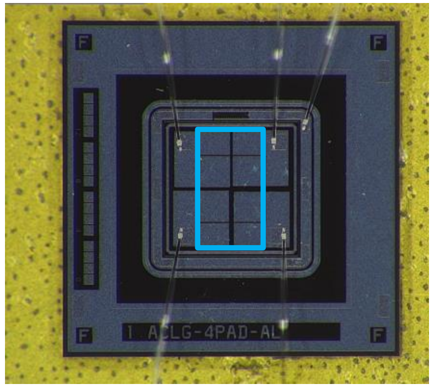


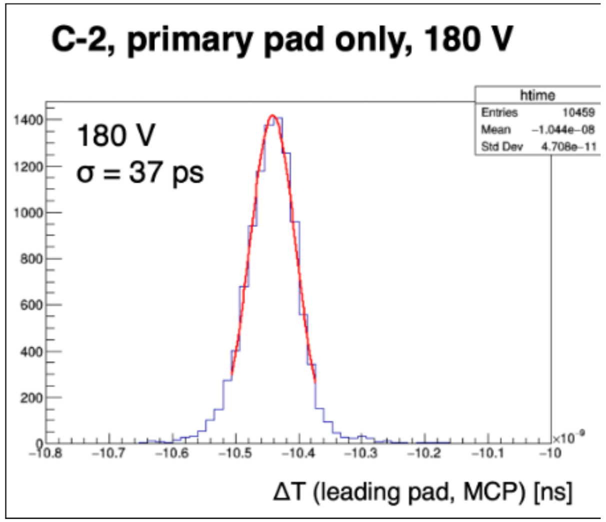
HPK pad sensor with charge sharing

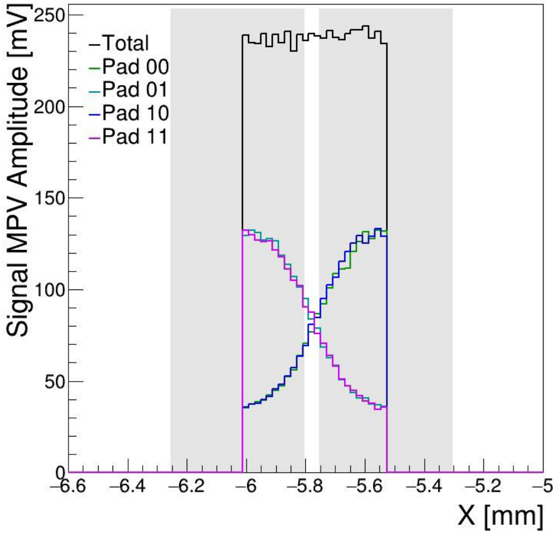
- **Charge Sharing information can be used to have position even pad sensor**
  - Fermilab testbeam at Feb 2021, HPK ACLGAD (Pad type)
  - 500um□ pad sensor with C-2 type instead of best type E-b
  - **Timing resolution 37ps**
  - **Position resolution in middle 500um area : 15um resolution including tracker resolution.**

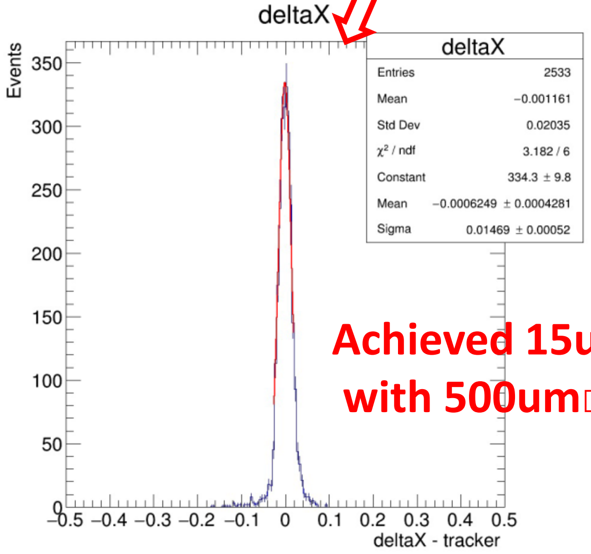


HPK AC-LGAD Pad (C-2 type)



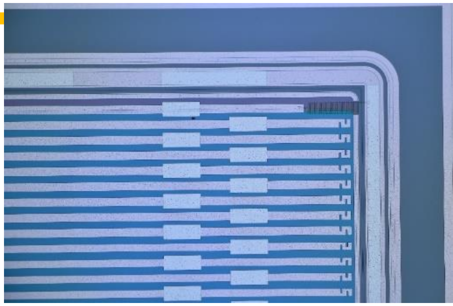






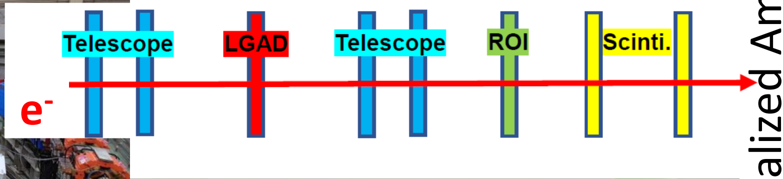
Achieved 15um resolution with 500um□ pad sensor

Fine pitch approach



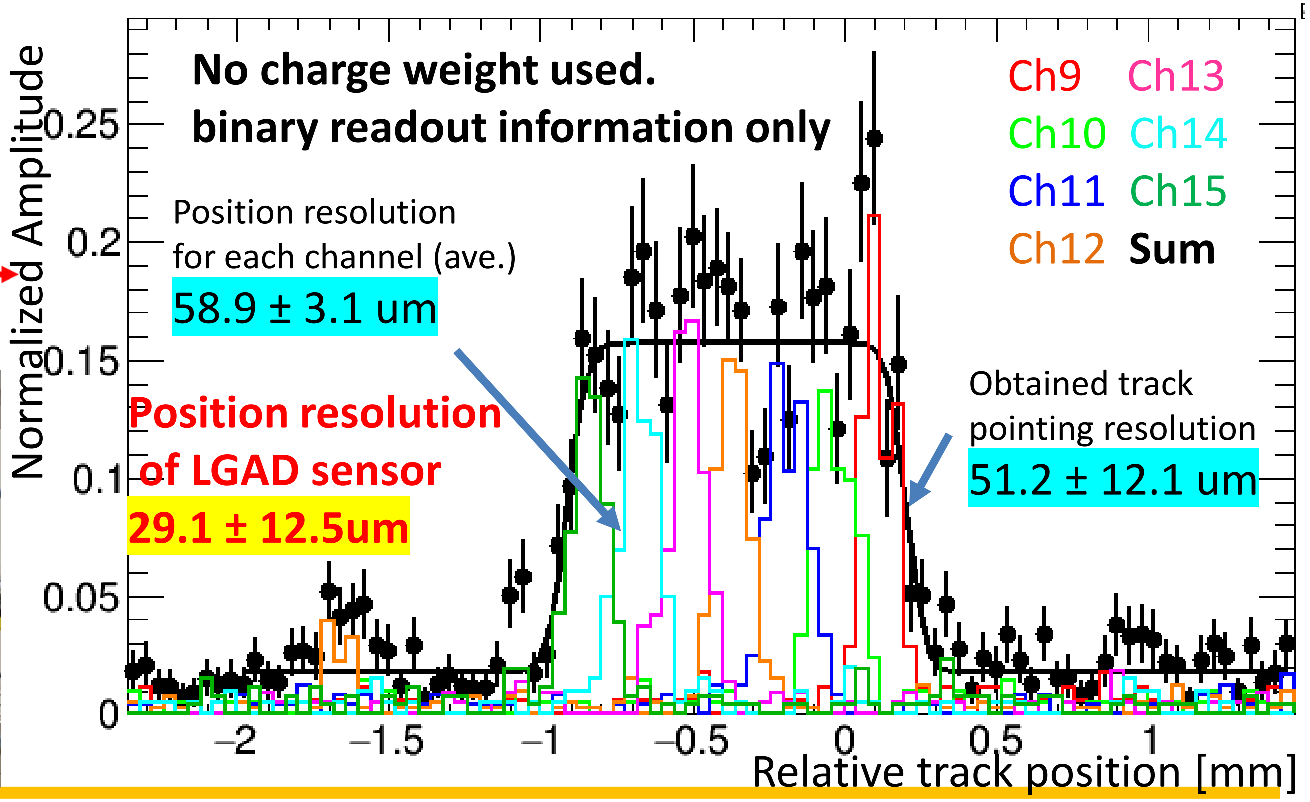
- HPK 80um pitch strip sensor with highest implant resistivity (E-b type)
  - Position resolution : 23um(80um/$\sqrt{12}$) is expected in case of binary readout
- Testbeam @ Tohoku University (ELPH)
  - 800MeV electron beam
  - Trigger rate : 200-400Hz
  - Strip E-b type 170V @ 20°C

High Multiple-Scattering effct



4 layer of Telescope
(25um x 500um pixel)
Trigger by scintilator
Specify region (ROI)

Amplitude distribution with residual



No charge weight used.
binary readout information only

Position resolution for each channel (ave.)
58.9 ± 3.1 um

Position resolution of LGAD sensor
29.1 ± 12.5um

Obtained track pointing resolution
51.2 ± 12.1 um

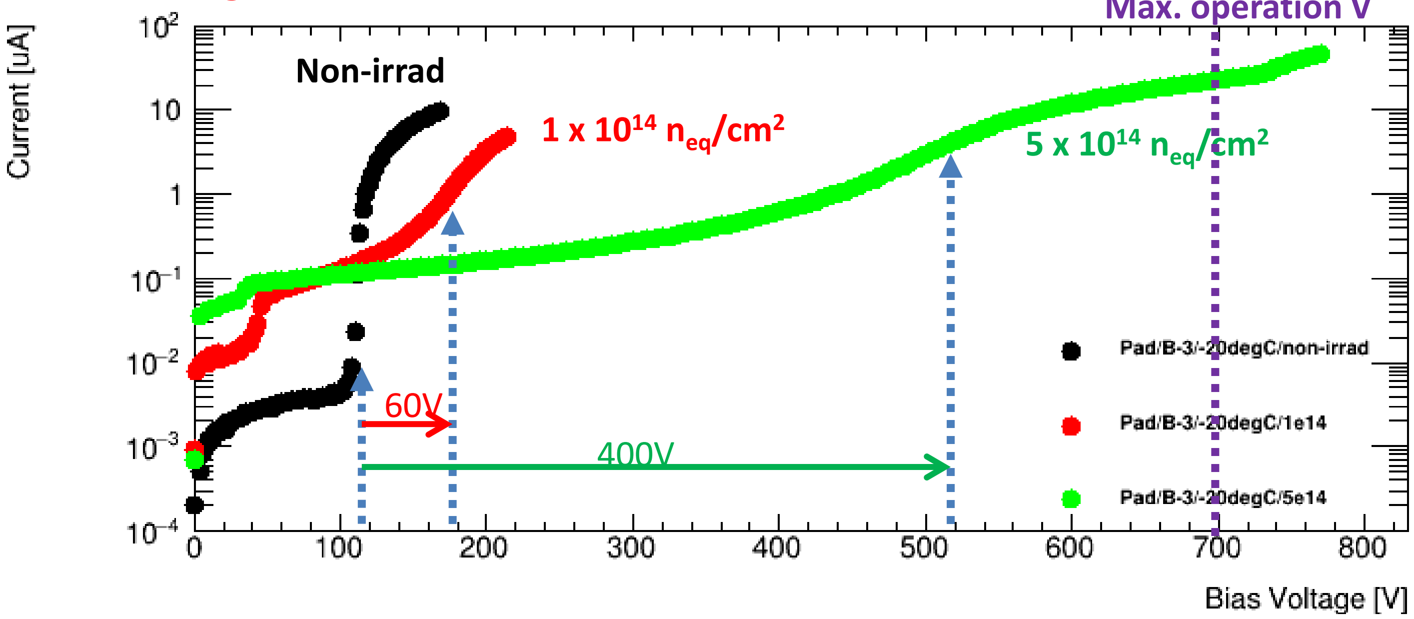
Radiation tolerance

Radiation Tolerance

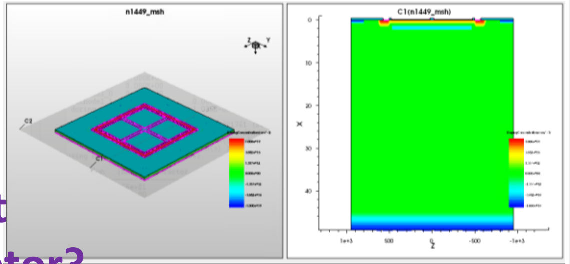
- As like normal n+-in-p type silicon sensor
  - Bulk damage (NIEL) : Si lattice
  - Surface damage(TID) : positive charge @SiO_2-Si
- + **”Acceptor Removal”**
  - Acceptor in *p*+ gain layer is reduced.

How serious effect by reducing acceptor?

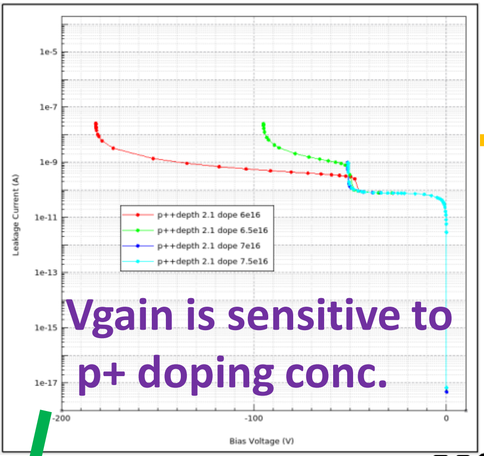
Issue : V_{gain} become higher due to acceptor removal



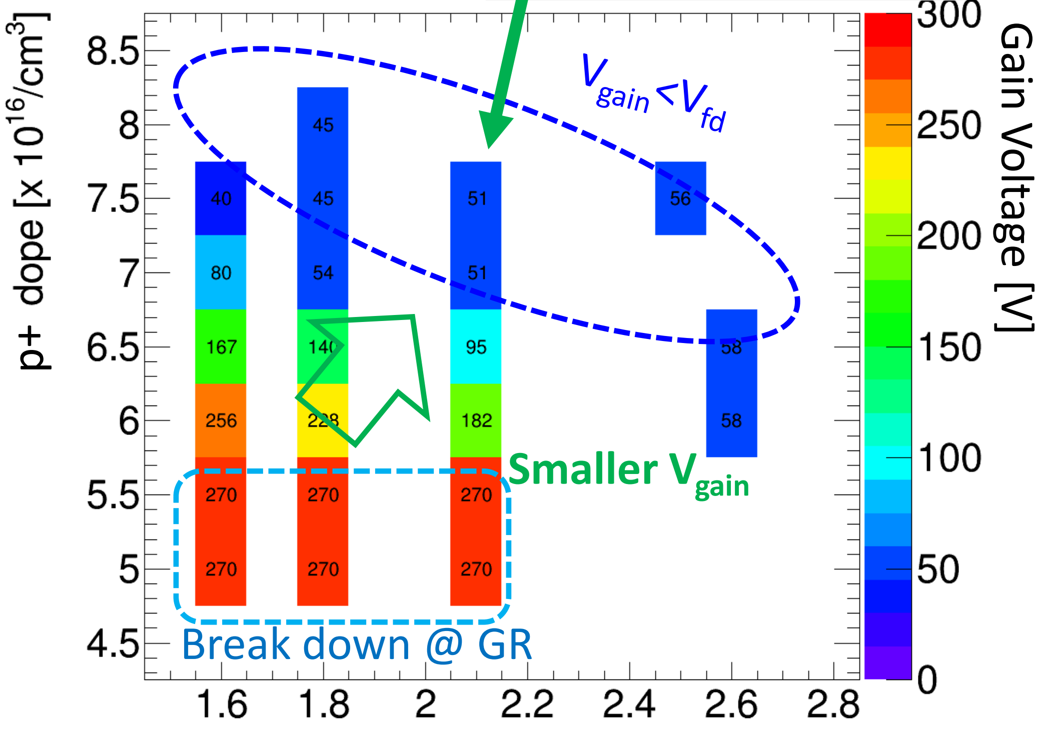
3D TCAD simulation



p++ dope changed 6e16 – 7.5e16



Vgain is sensitive to p+ doping conc.



Smaller V_{gain}

Break down @ GR

20% of acceptor removal may critical

Similar behavior to normal LGAD and will survive upto ~$10^{15}n_{eq}/cm^2$

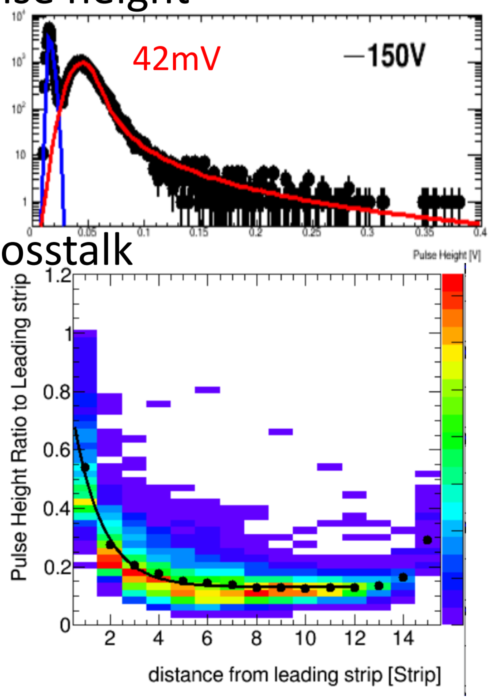
TID effect on AC-LGAD sensor

- To test TID damage effect ^{60}Co irradiation has been done in Japan
- Positive surface charge affect to :
  - **Increase signal size.**
  - **Reduce signal crosstalk**
  - **Efficiency will be checked at testbeam.**

Improve performance?

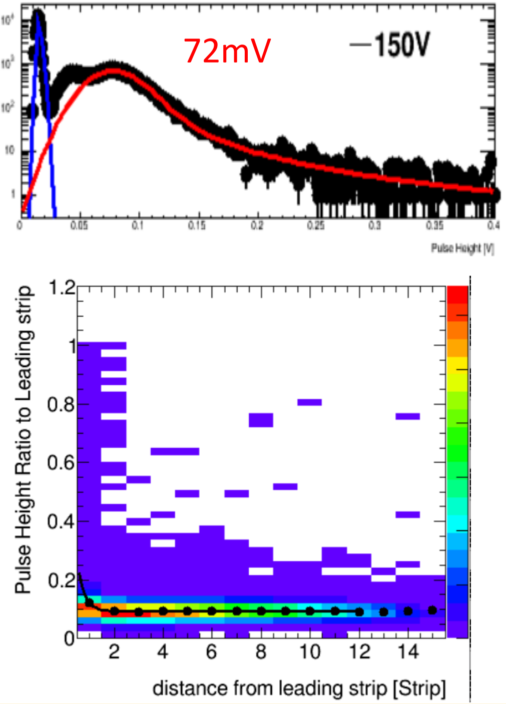
Pulse height

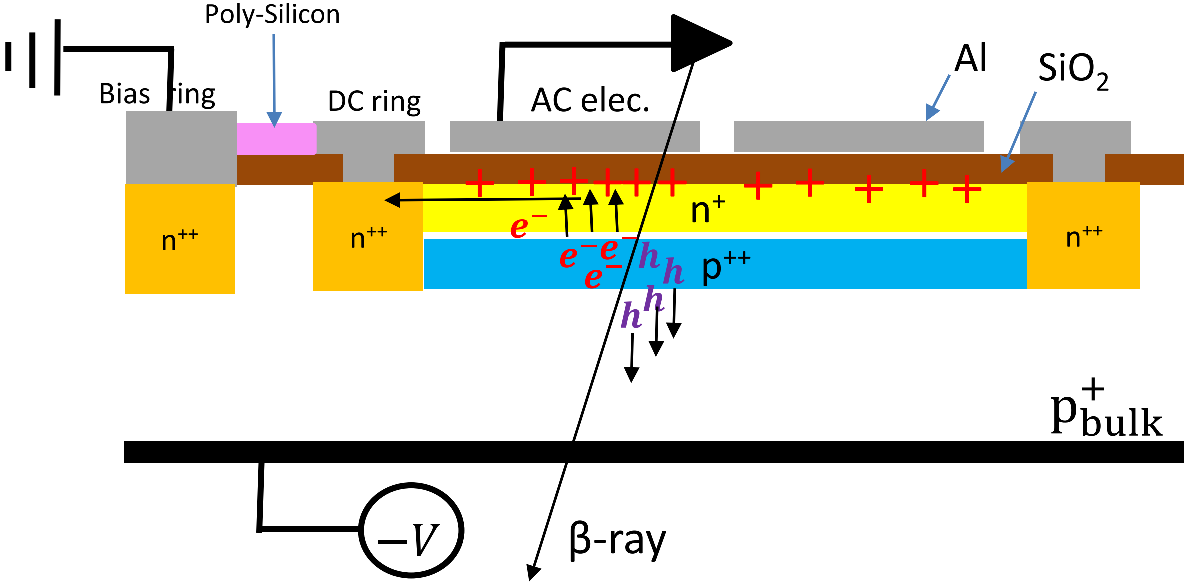
Crosstalk

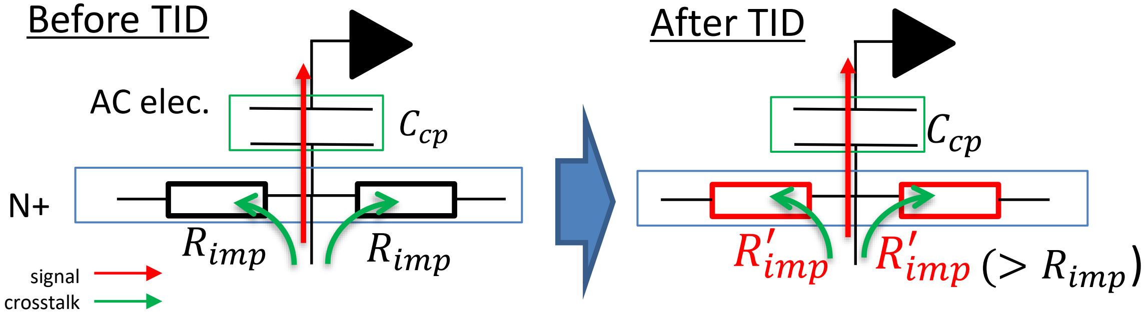


^{60}Co γ-ray

1MGy







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

Conclusion

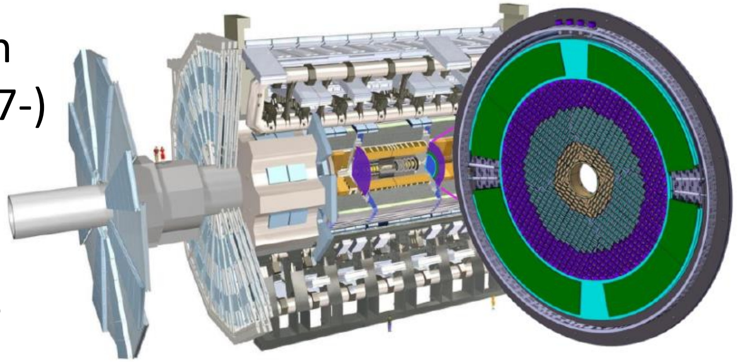
2015-

Low Gain Avalanche Diode Technology

30ps timing resolution for MIP particle!

Production & operation in HL-LHC detector (2027-)

Will accumulate operation experience



2021 **LGAD sensor with Spatial resolution**

Achieved o(10)um resolution using AC-LGAD!!

Expected various applications

- Outer layer of hadron colliders
- Lepton colliders or heavy ion colliders
- Other medical and imaging fields

→ **Large size prototype**

To do

LGAD sensor with Radiation tolerance?

Upto o($1x10^{15}$)n_{eq}/cm^2 so far

How to avoid Acceptor removal?

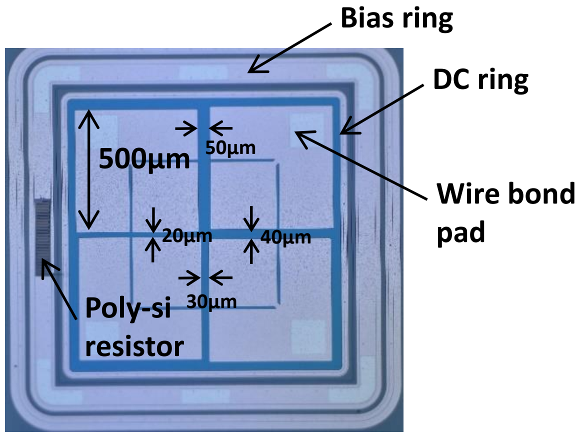
→If survive upto $1x10^{16}n_{eq}/cm^2$:

All hadron collider tracker can be replaced to LGAD sensor.

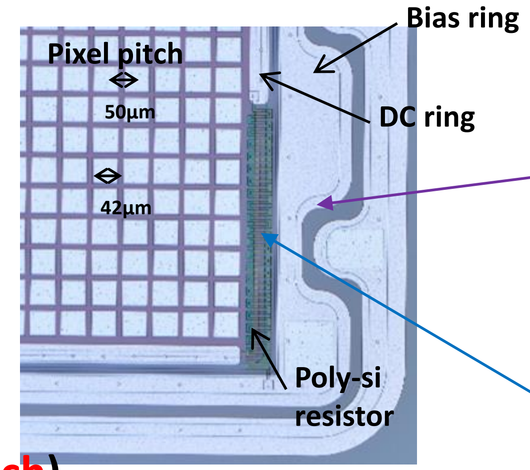
backup

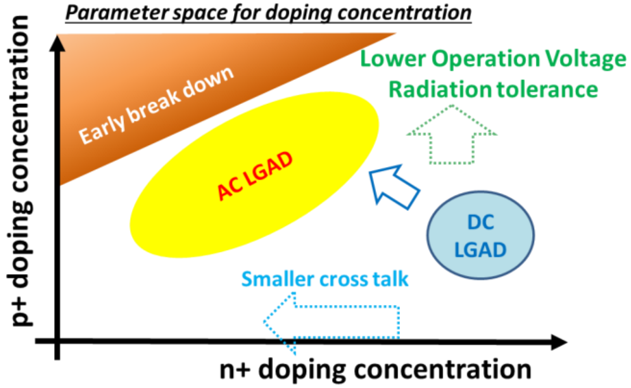
First AC-LGAD by HPK

Pad type sensor (4x 500umx500um)



Pixel type sensor (14x14 50umx50um)





GNDed DC ring via Poly-si

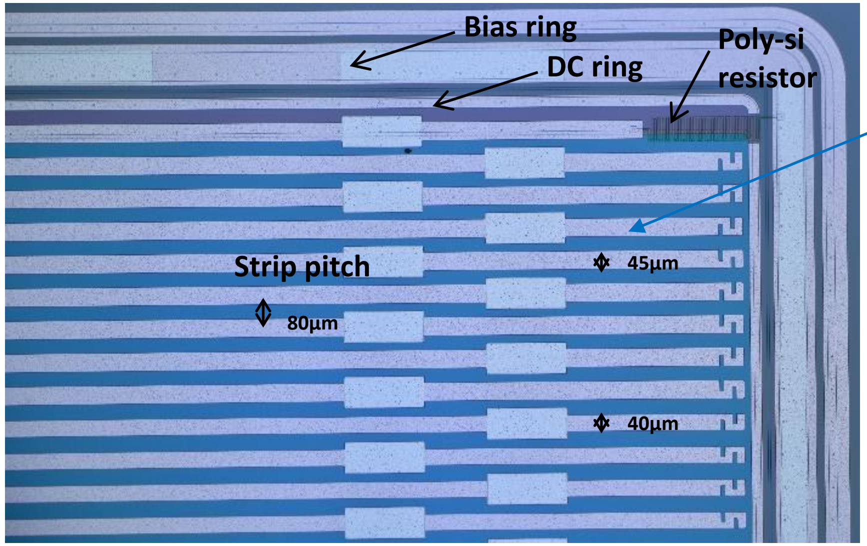
→ To remove charge in n+

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)



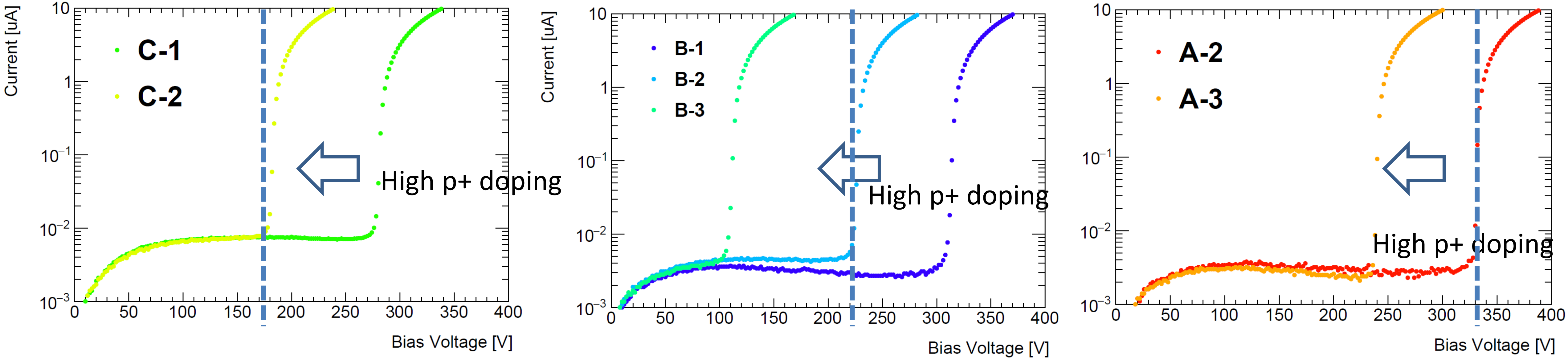
n+ and p+ doping concentration

		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

Leakage current vs Bias voltage



Break down (gain) voltage get lower

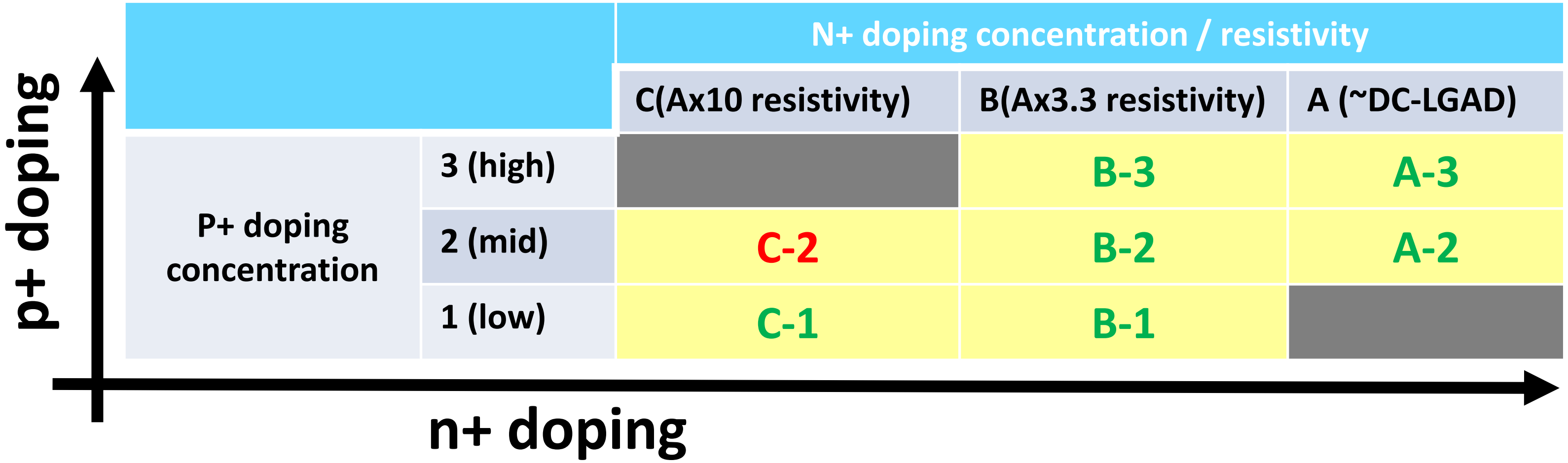
- **Higher P+ dope**
- **Lower N+ dope**

→ Radiation trelance

C-2 type :

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

Variation of p+ and n+ doping concentration

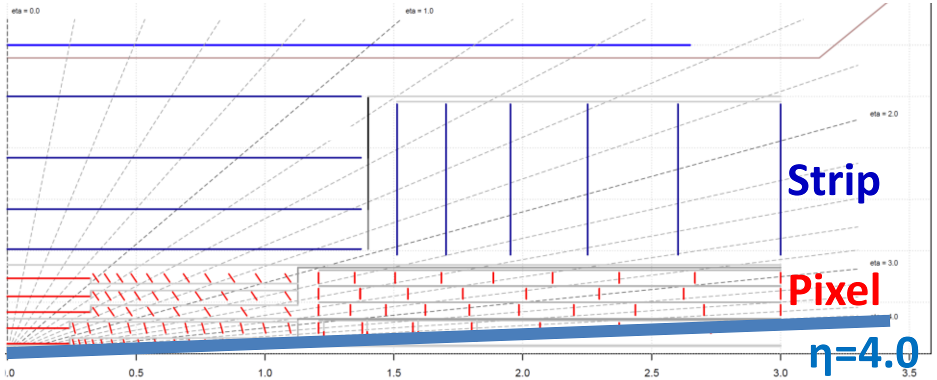


		N+ doping concentration / resistivity		
		C(Ax10 resistivity)	B(Ax3.3 resistivity)	A (~DC-LGAD)
P+ doping concentration	3 (high)		B-3	A-3
	2 (mid)	C-2	B-2	A-2
	1 (low)	C-1	B-1	

What we need for Hadron Collider?

- High Luminosity LHC detector

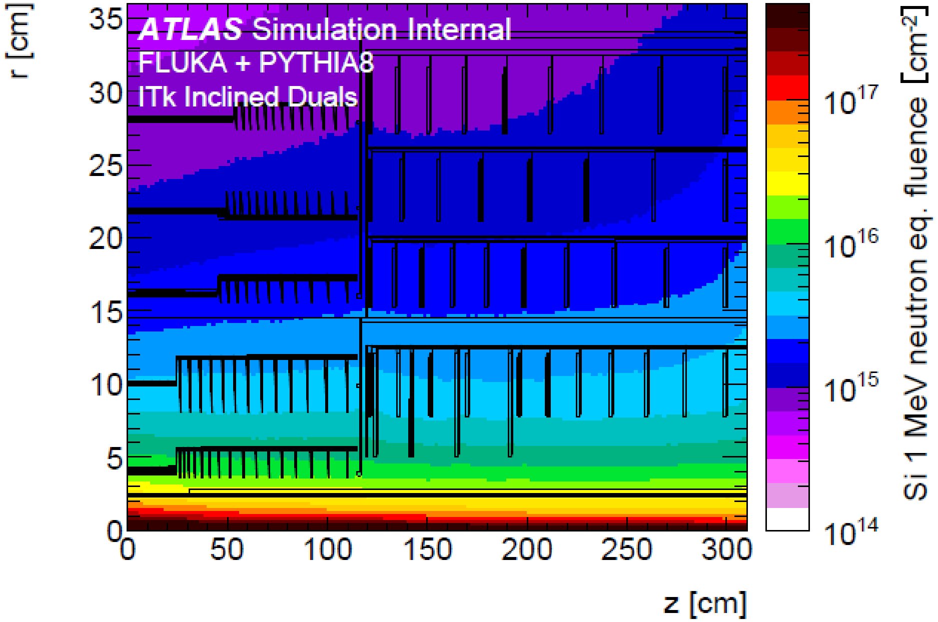
ITK upgrade detector



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

Is this granularity possible?

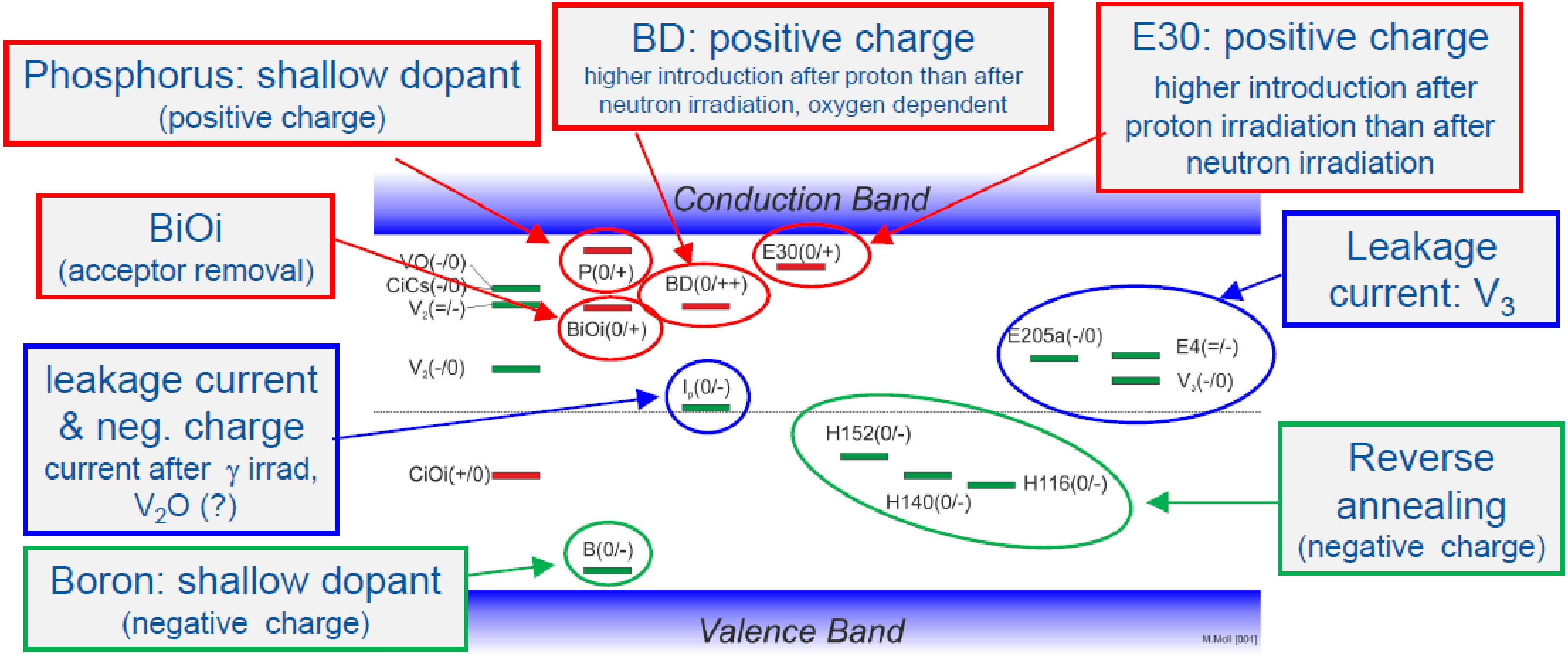
- Expected radiation level for 4000fb^{-1}
  - Non Ionizing Energy Loss (NIEL):
    - 3rd layer: 2.8x10^{15} n$_{eq}$ /cm^2 1st layer : 2.6x10^{16}neq/cm^2
  - Total Ionizing Dose (TID) :
    - 3rd layer : 1.6MGy 1st layer : 19.8MGy



Could replace detector at the middle of runs.

Survive upto 1e16neq/cm^2?

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



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)

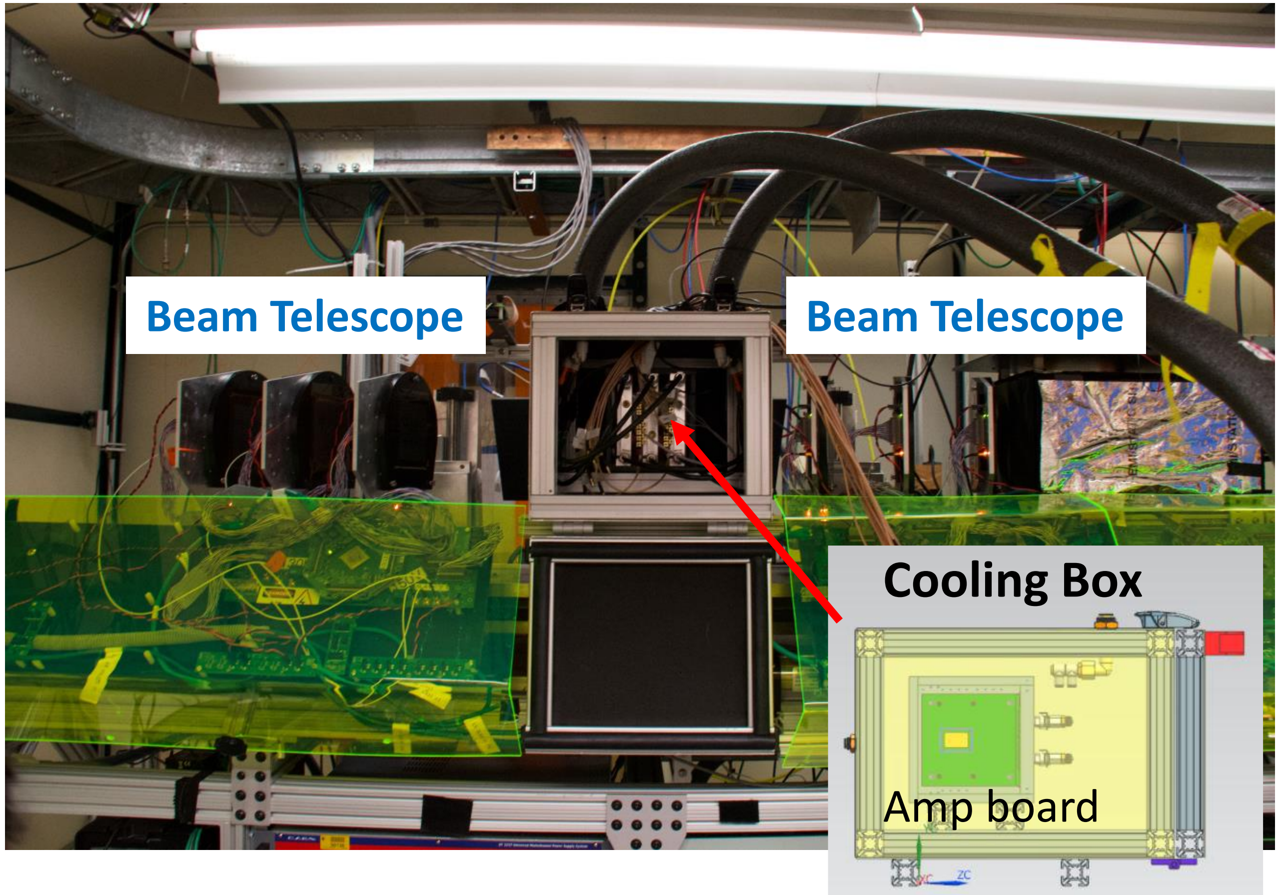
Test beam in Feb 2021 @ Fermilab

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

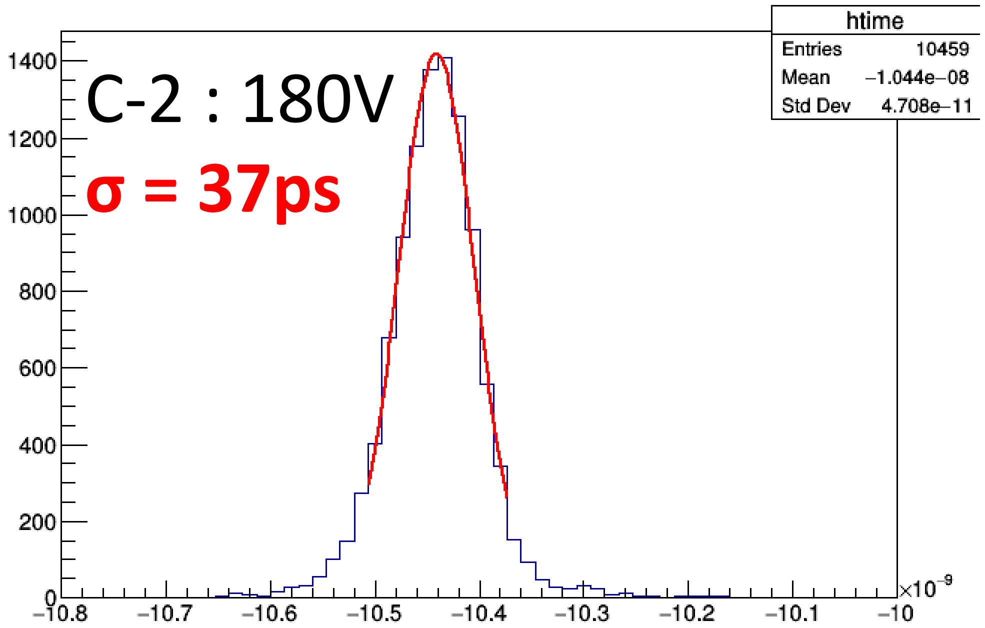
Timing reference Detector

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

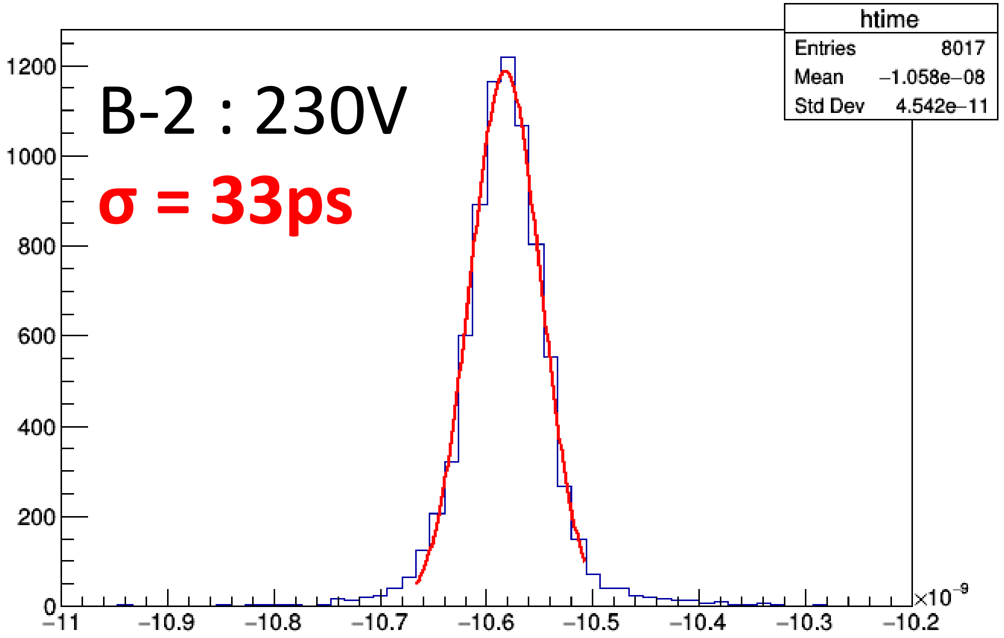
Time resolution measurement @ testbeam

- 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

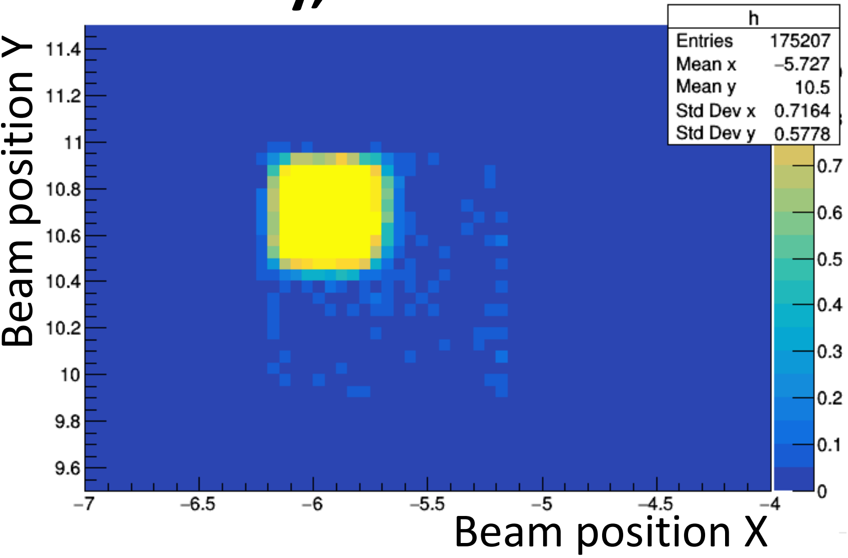
σ = 37ps


B-2 : 230V

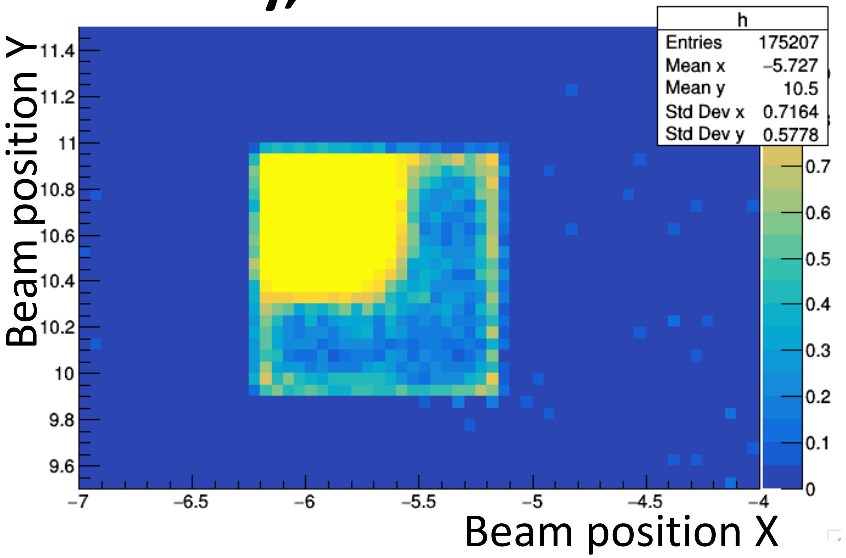
σ = 33ps

Efficiency and signal sharing @ testbeam

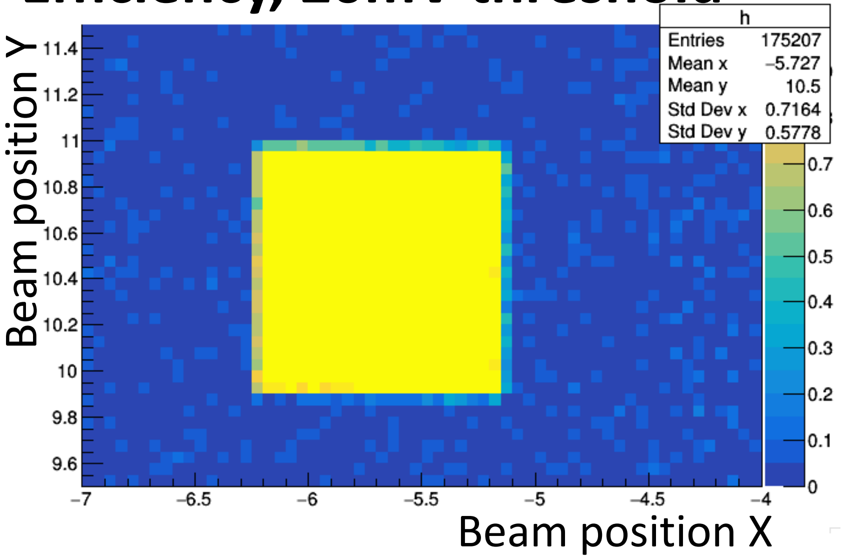
Efficiency, 90mV threshold



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?)**