VERTEX 2020 Virtual !
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筑波大学
University of Tsukuba

KEK

First prototype of finely segmented HPK AC-LGAD detectors

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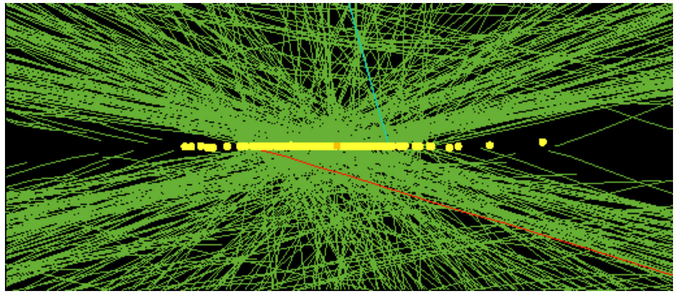
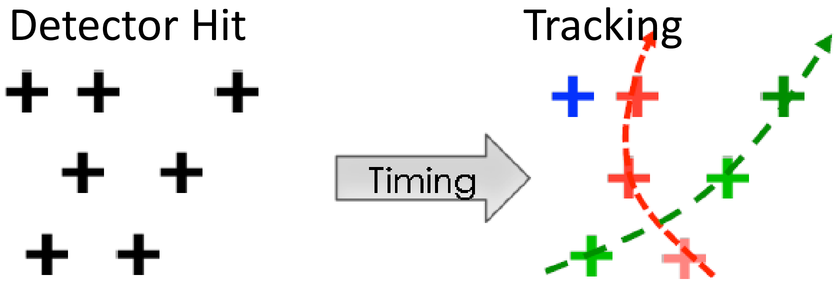
Hamamatsu Photonics K.K.

Introduction

- Most serious issue in the future hadron collider should be a number of **multiple interactions** per bunch crossing.
  - About 140-200 at the HL-LHC and 1400 (FCC) in future colliders.
  - Idea to solve the issue?
    1. ***Pixel size*** : Construct smaller pixel size detector and make better vertices separation →**May be hard to improve 10 times…**
    2. ***Time resolution*** : If we could use timing information for the hit in the track, may have better track finding using the information. →If the timing resolution is less than 1cm/*c* = **30ps** it should help a lot.

To do this, detector should have both spatial and timing resolution





4D Detector??

Introduction

- **Low Gain Avalanche Diode (LGAD) Detector is getting mature technology as precise timing detector (~30ps resolution) for MIP particle detection.**

- **30ps (~1cm by speed of light) resolution**, there are a lot of application possibilities to the interdisciplinary worlds.
  - Biology, Medical and Industry area

- To apply this technology to High Energy collider inner tracking detector to improve physics performance :
  - **Need ~o(10)um spatial resolution.** ⇐ **Main topic in this presentation**
  - **Need ~o(10^{16})n_{eq}/cm^2 radiation tolerance (in case of hadron collider)**
  - **Need small/Front-end readout electronics (i.e. ASIC with high speed Amplifier)**

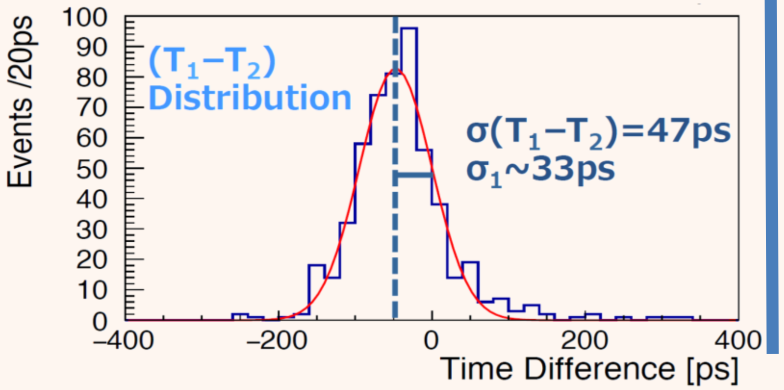
History of HPK LGAD detector development

First LGAD detector by HPK in 2015

S.Wada et.al. NIMA Volume 924, Pages 380-386 doi:10.1016/j.nima.2018.09.143

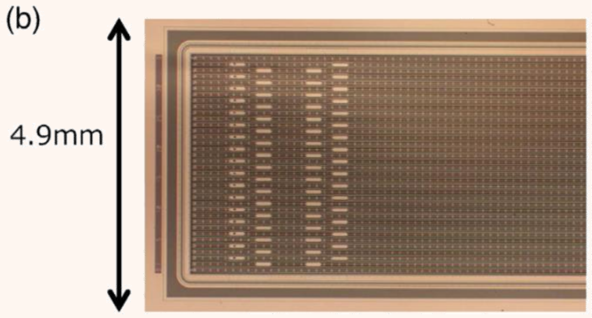
K.Onaru et.al. NIMA Volume 985, 164664 doi:10.1016/j.nima.2020.164664

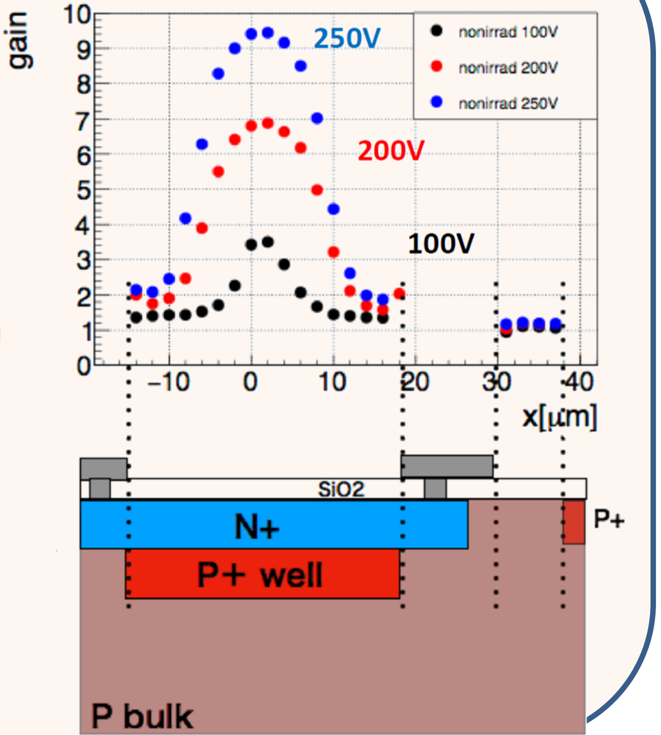
First PAD detector worked and evaluated 33ps timing resolution !!



First Strip detector had gain un-uniformity

80um pitch strip detector :
only 20um region (25%) have gain





Second LGAD detector by HPK in 2018

R. Padilla et. al. 2020_JINST_15_P10003 doi:10.1088/1748-0221/15/10/P10003

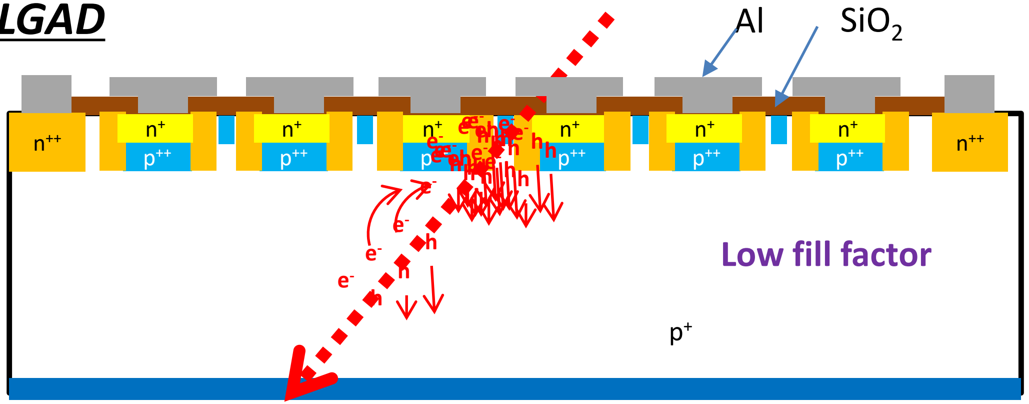
ATLAS/CMS run for HL-LHC timing detector

Optimization of process/doping profile/active thickness etc. by ATLAS/CMS collaboration

Idea of AC-LGAD detector

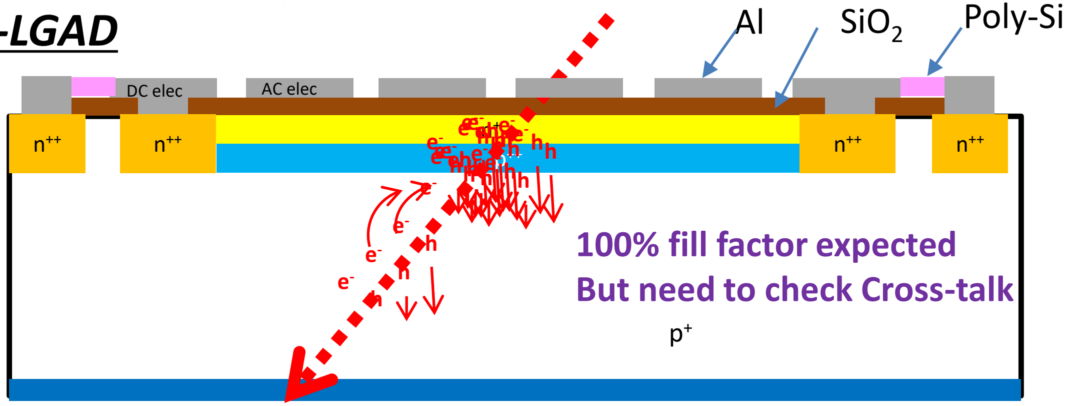
- Original segmented LGAD detector has a quite low fill factor (25%) due to separated gain layers.
- Single gain layer with AC-coupled electrodes may solve the issue.
  - **Lower n+ doping concentration (= higher resistivity) to reduce cross talk. How much lower?**

DC-LGAD



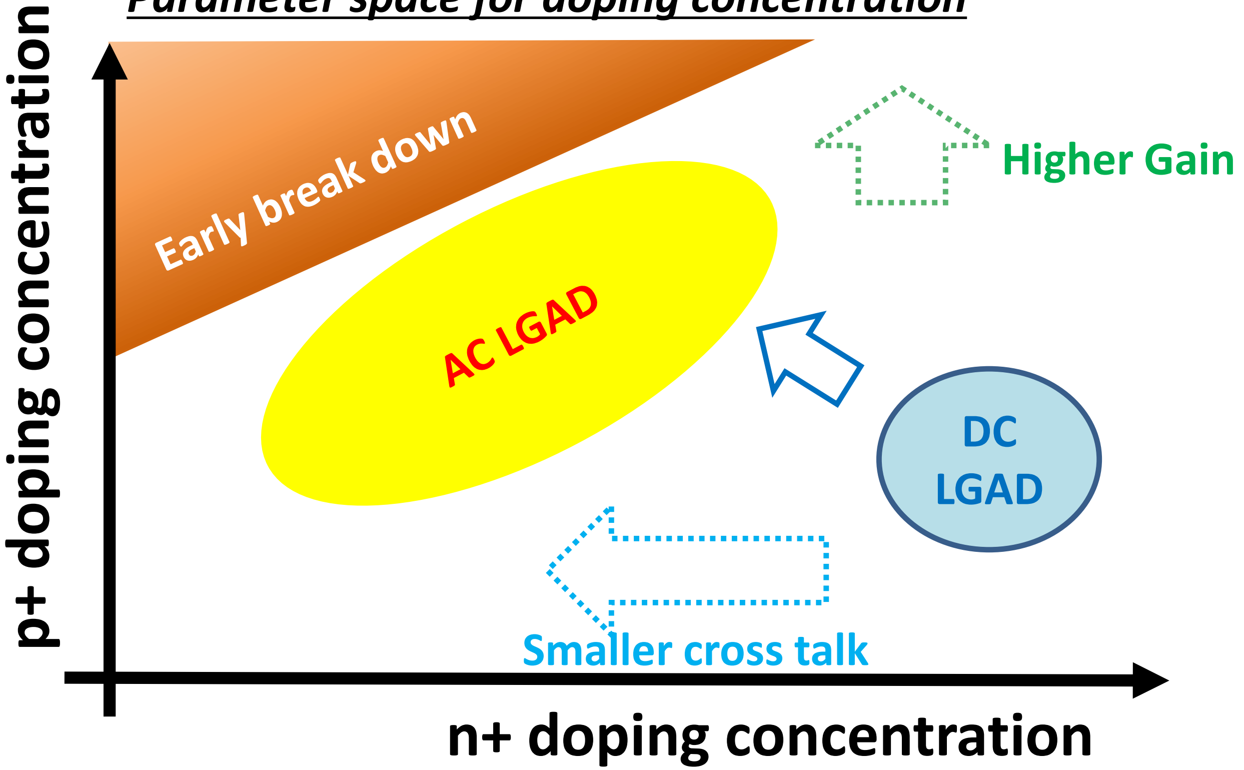
Low fill factor

AC-LGAD



100% fill factor expected
But need to check Cross-talk

Parameter space for doping concentration



Higher Gain

Smaller cross talk

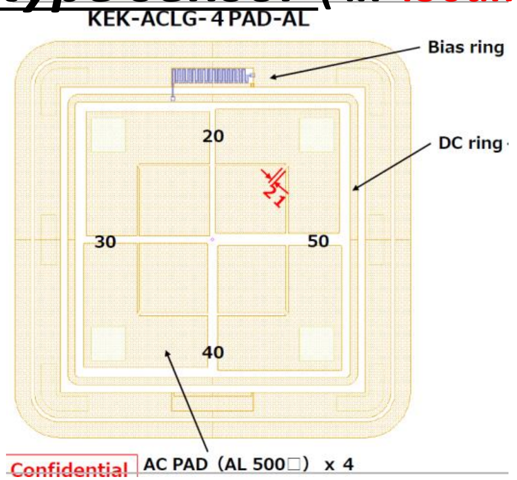
p+ doping concentration

n+ doping concentration

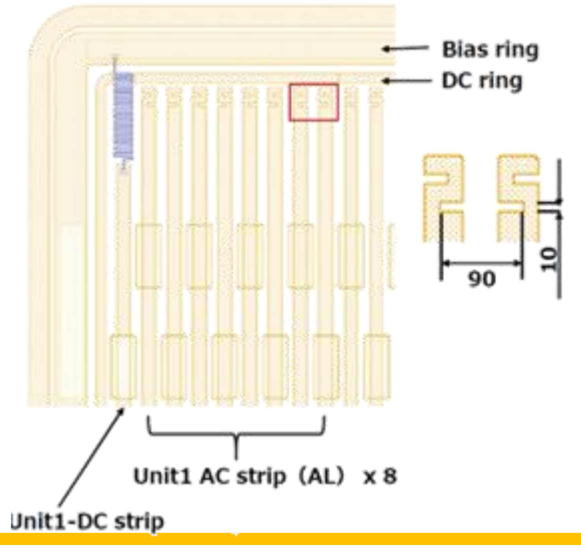
First AC-LGAD mask at HPK

50um Active thickness

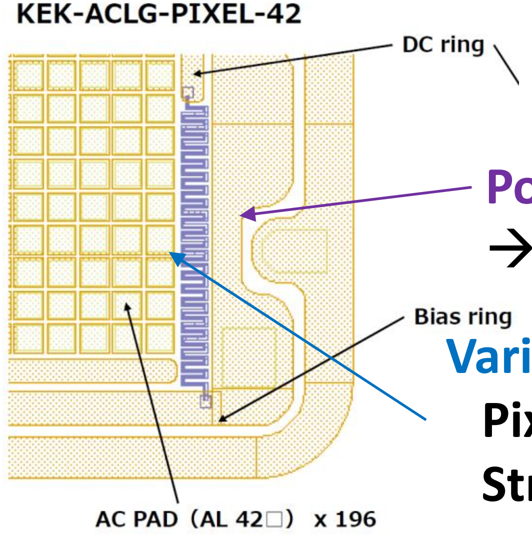
Pad type sensor (4x 450umx450um)



Strip type sensor (16x 80um pitch)



Pixel type sensor (14x14 50umx50um)



Poly-si resistor between DC ring and Bias ring(GND)

→ To free up charge in n+.

Varied Al size (AC coupling capacitance size)

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

Strip : 47/42/37/32 um width

Varied n+ and p+ doping concentration

p+ doping ↑, n+ doping →

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

Electrical Properties – IV curve

Varied n+ and p+ doping concentration

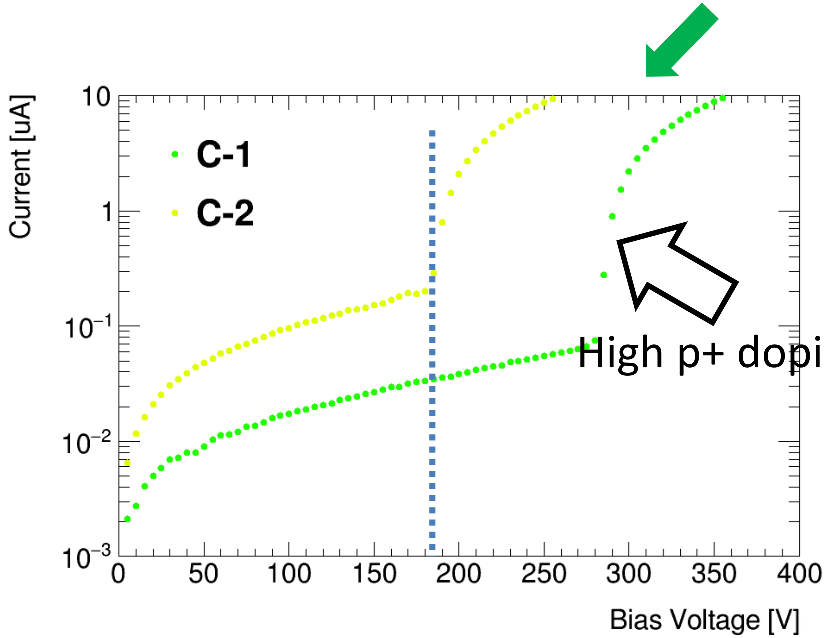
		N+ doping concentration / resistivity		
		C(Ax10 resistivity)	B(Ax3.3 resistivity)	A (~DC-LGAD)
P+ doping concentration	3 (high)		B-3	A-3
	2 (mid)	C-2	B-2	A-2
	1 (low)	C-1	B-1	

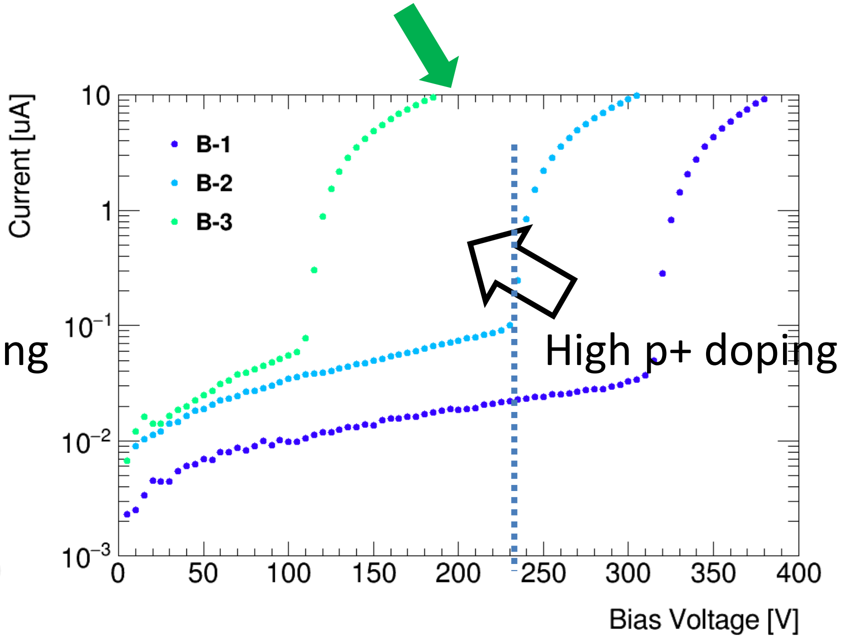
Higher Gain/earlier break in case :

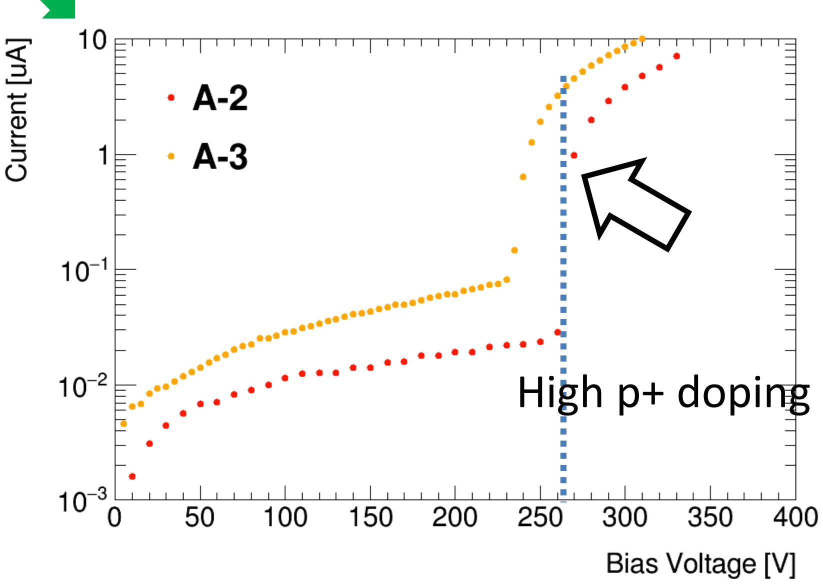
- Higher p+ doping
- Lower n+ doping

C-2 type should be :

- Smaller crosstalk
- Relatively higher gain



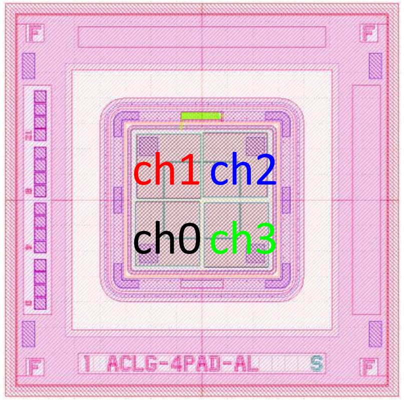




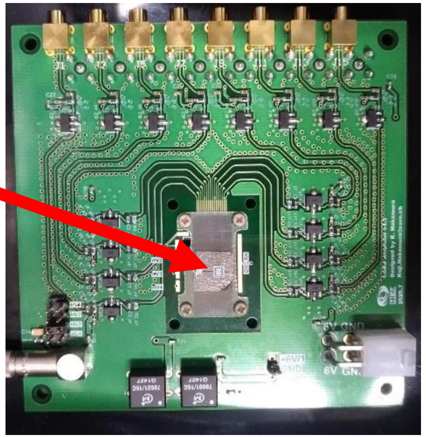
Pulse shape measurement

- To detect signal from AC-LGAD
  - Used ^{90}Sr β source
  - Discrete Amp has been designed by Fermilab and modified/produced at KEK.
  - Pulse detected by CAEN DT5742 digitizer
  - Triggered by Scintillator with MPPC readout

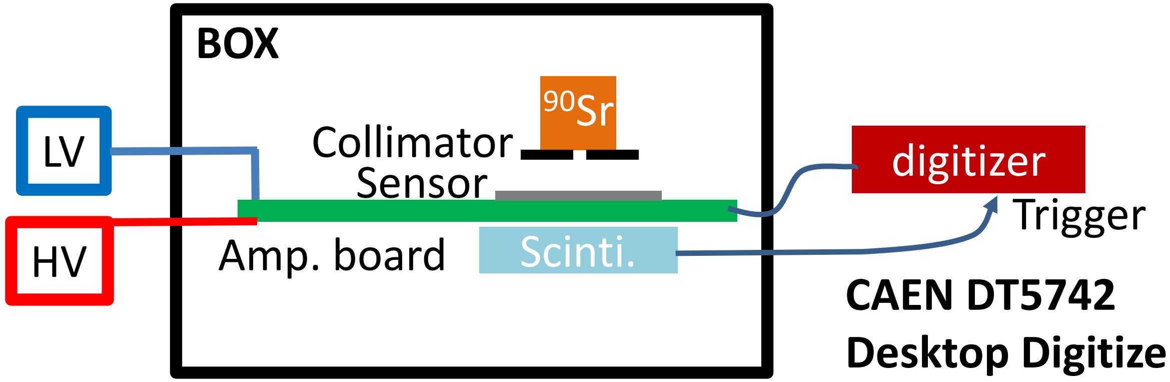
Pad Sensor

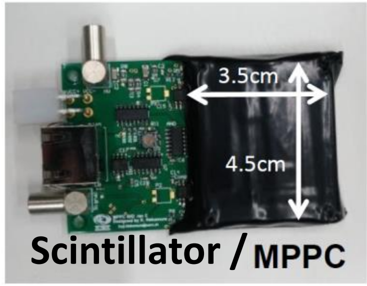


KEK
16 ch Discrete Amp.



Fermilab
16 ch Discrete Amp.

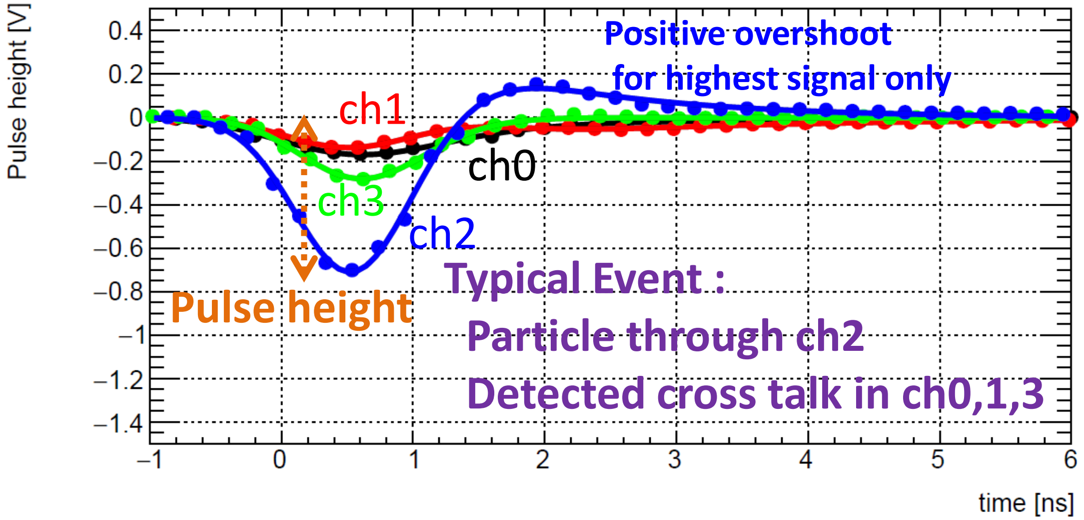




Scintillator / MPPC

CAEN DT5742
Desktop Digitizer

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

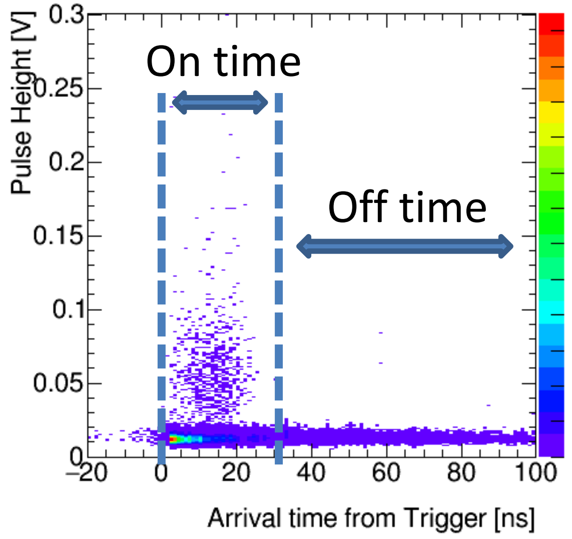


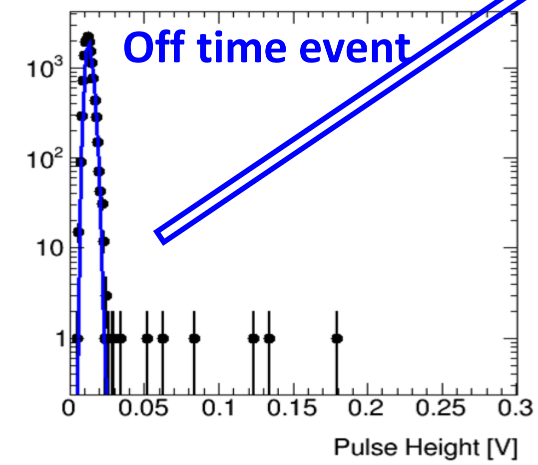
Positive overshoot for highest signal only

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

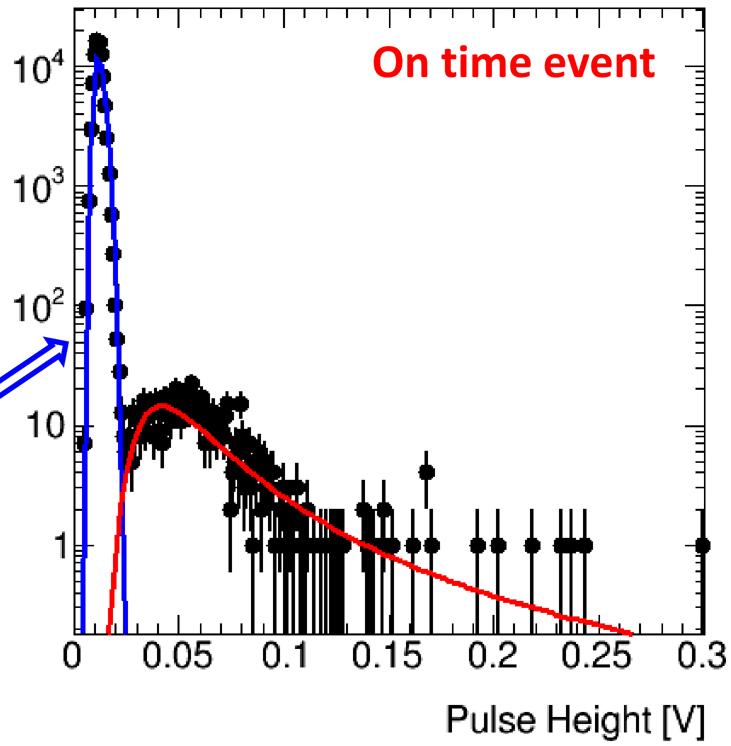
Pulse Height and Bias Voltage dependence

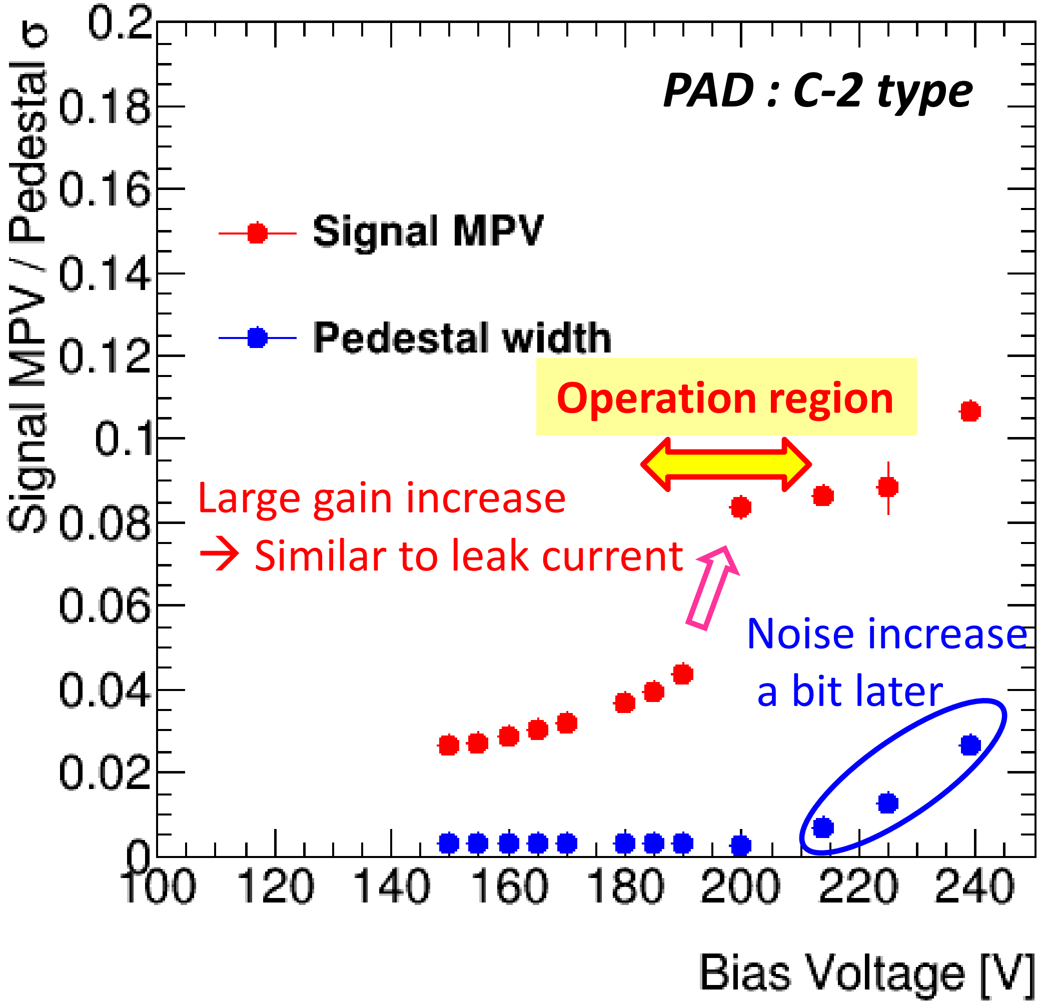
Pedestal distribution is evaluated from off timing region





Example : 190V Bias Voltage



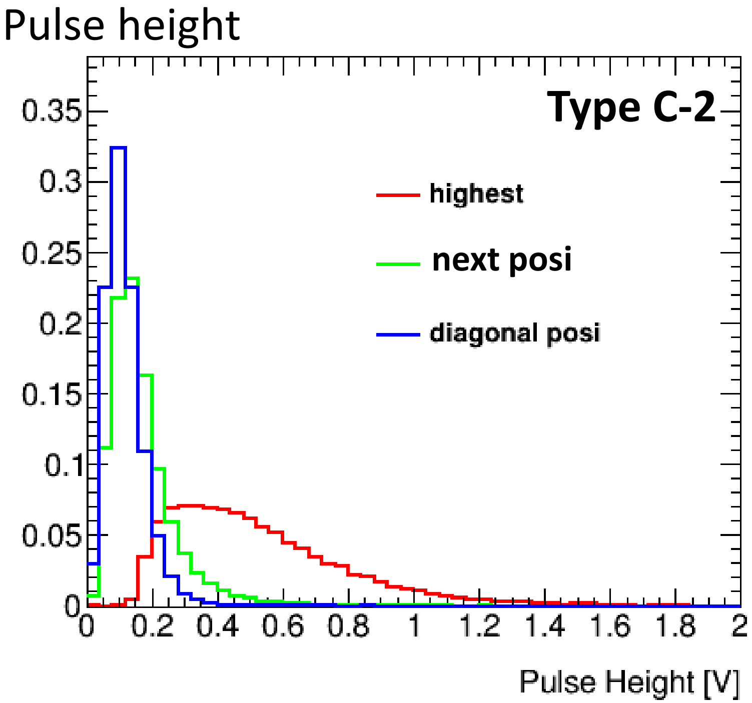


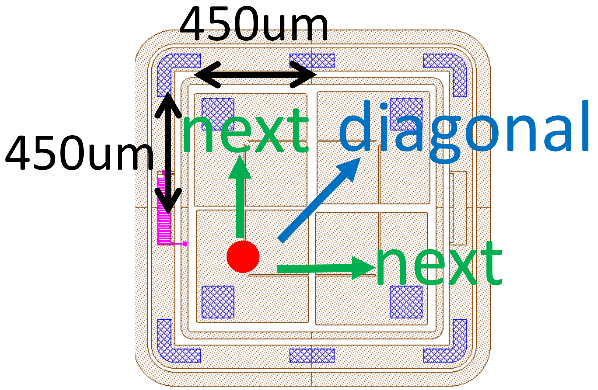
Operation region

Large gain increase
→ Similar to leak current

Noise increase
a bit later

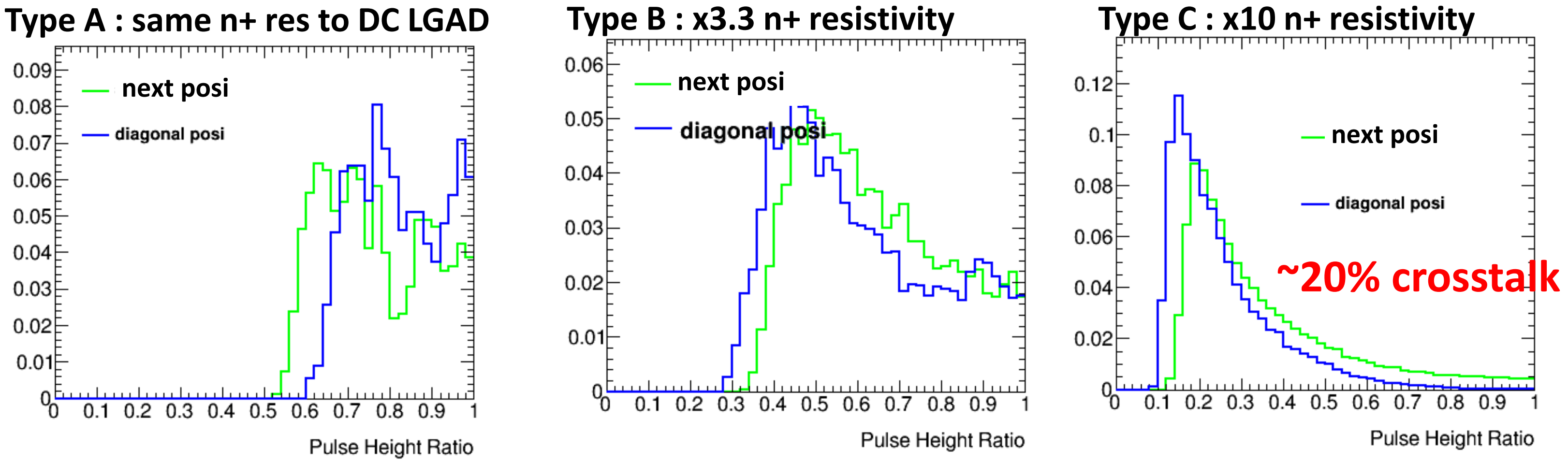
Pulse height distribution and Crosstalk





- ***Pulse height distribution***
  - type C-2 (x10 n+ resistivity) show good separation of signal and crosstalk.
- ***Cross talk depends on n+ resistivity***
  - Higher resistivity have smaller crosstalk
  - **~20% crosstalk for type C (x10 n+ resistivity)**

Pulse height ratio to the Leading pulse height



Type A : same n+ res to DC LGAD

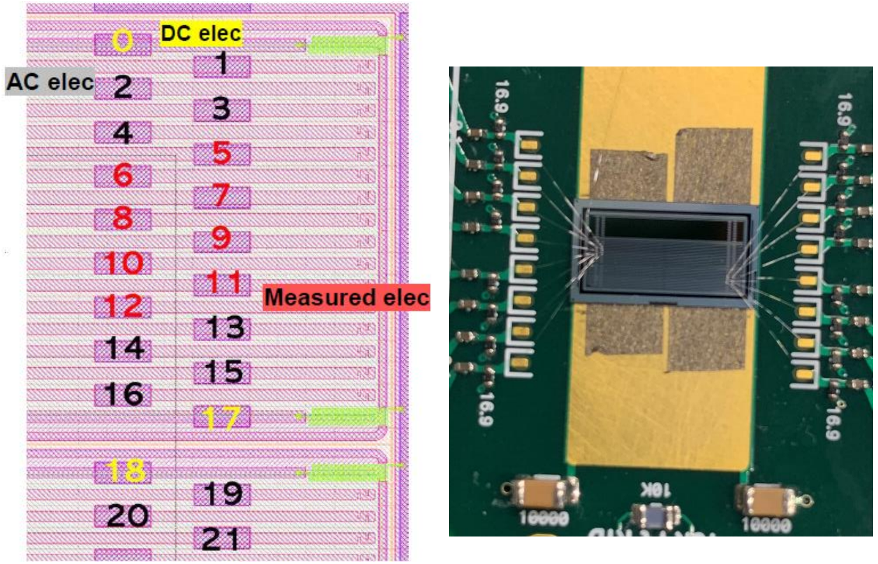
Type B : x3.3 n+ resistivity

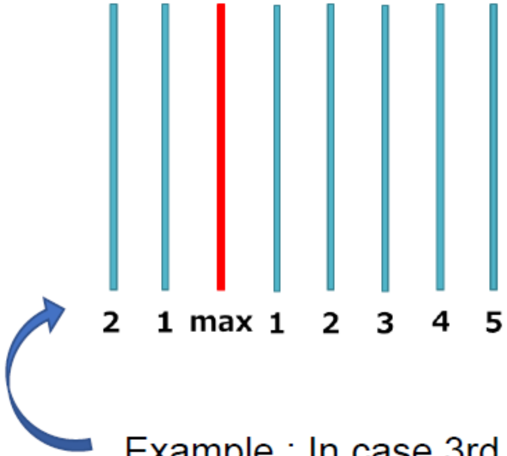
Type C : x10 n+ resistivity

Distance dependence of Crosstalk

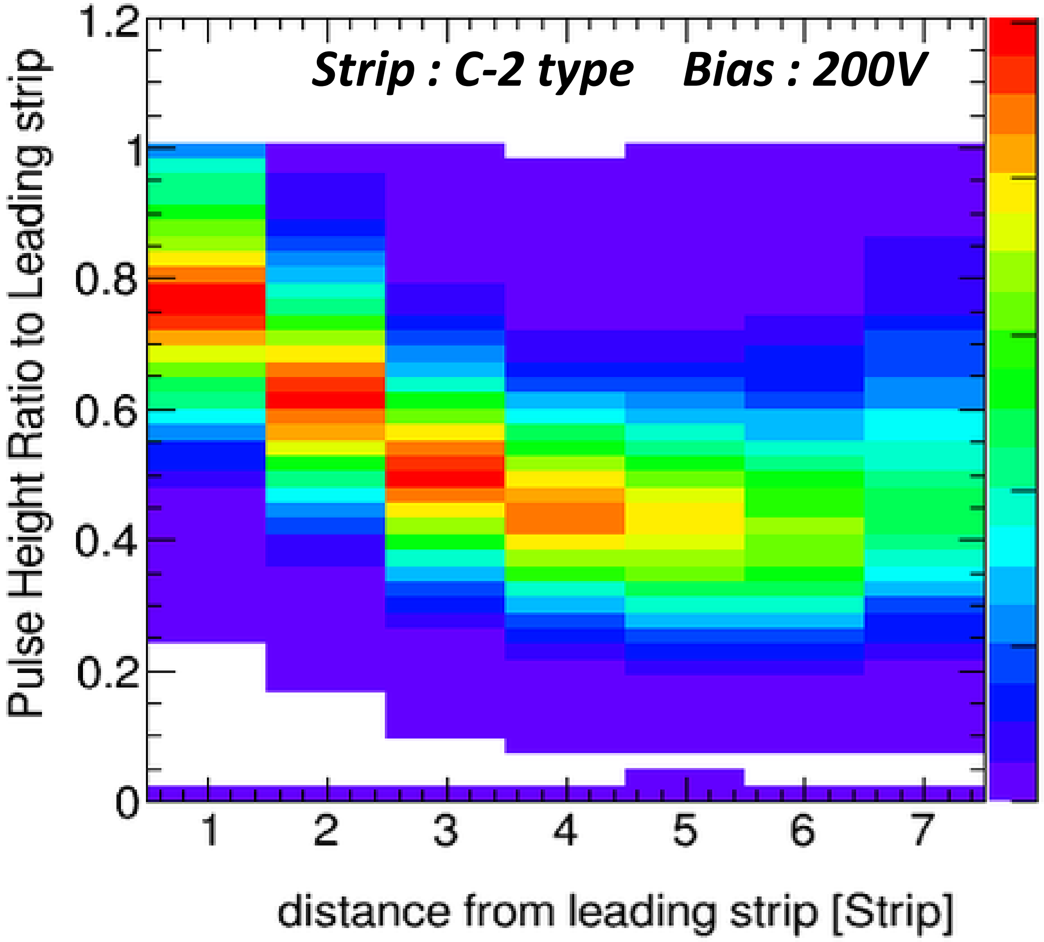
- Crosstalk should depend on distance of electrode.
  - To check the dependence, **strip sensor** (80um pitch) is used
  - Pulse height ratio to leading strip is plotted as a function of distance (unit of strips)
  - **~75% @ 80um, ~62% @ 160um distance.**
  - **The strip where particle passed can be identified, but better to have smaller crosstalk.** → will test higher n+ resistivity

Strip Sensor



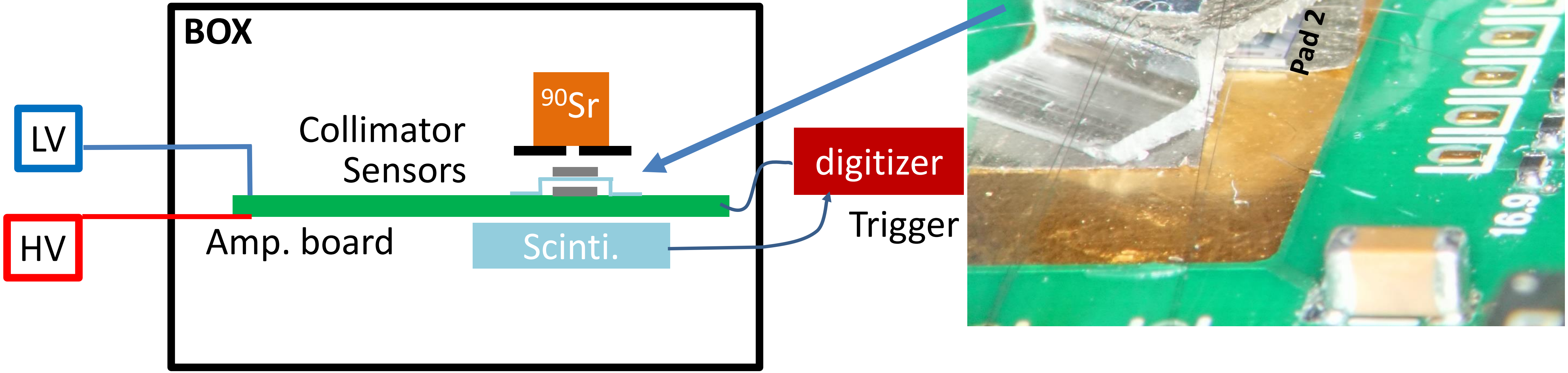


Example : In case 3rd left strip has highest pulse height



Time resolution

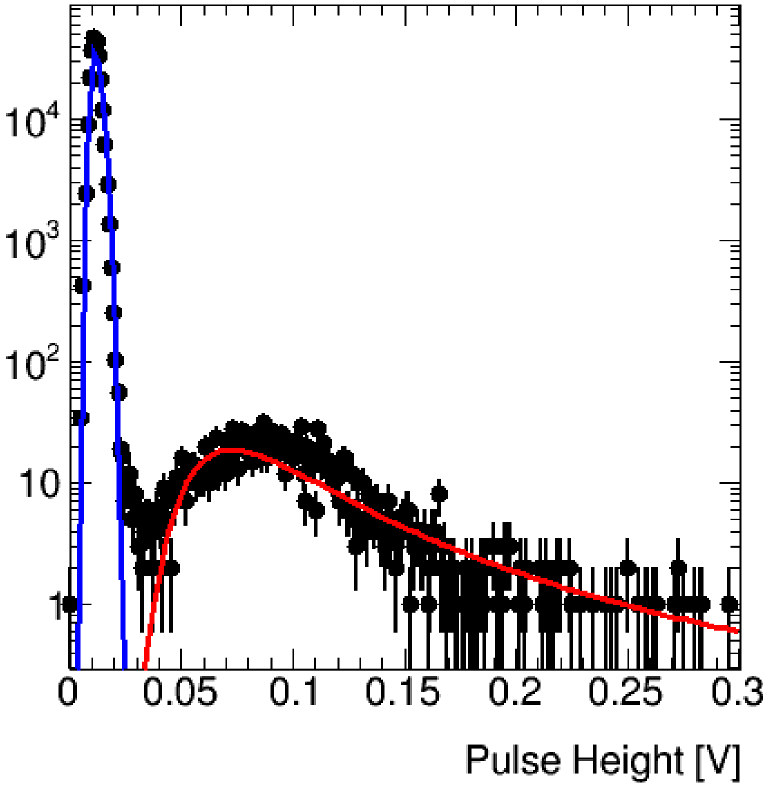
- To evaluate timing resolution, two same type of pad sensors are stacked interleaved by using plastic piece.
  - Sigma of time difference : $\sigma(T_1\text{-}T_2)=\sqrt{(\sigma_1)^2+(\sigma_2)^2}$
  - In case two same type sensors : $\sigma_t = \sigma(T_1\text{-}T_2)/\sqrt{2}$



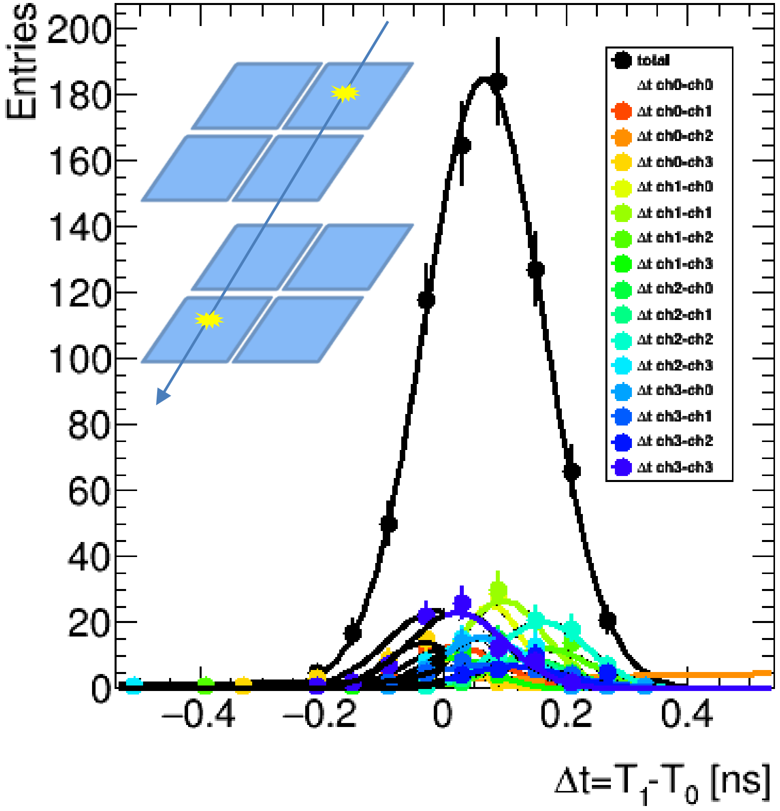
Time resolution

- Time difference has been calculated separately for all combination of channels in top and bottom channel then combined.
- **Evaluated ~45ps time resolution at 200V.**

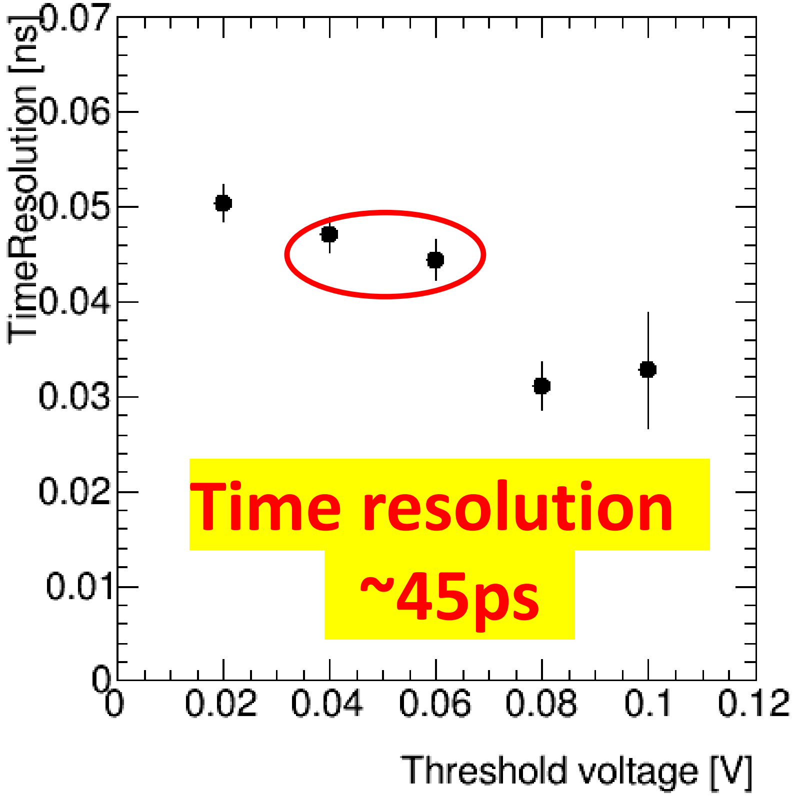
Pulse Height Distribution



Time difference of pad 1 and 2



Timing resolution with certain threshold

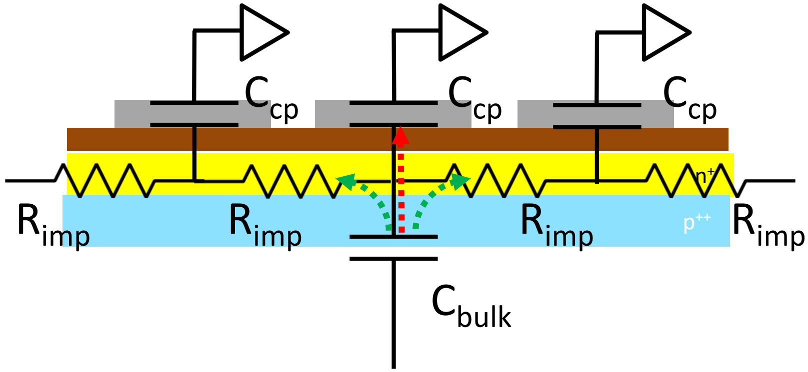


Time resolution ~45ps

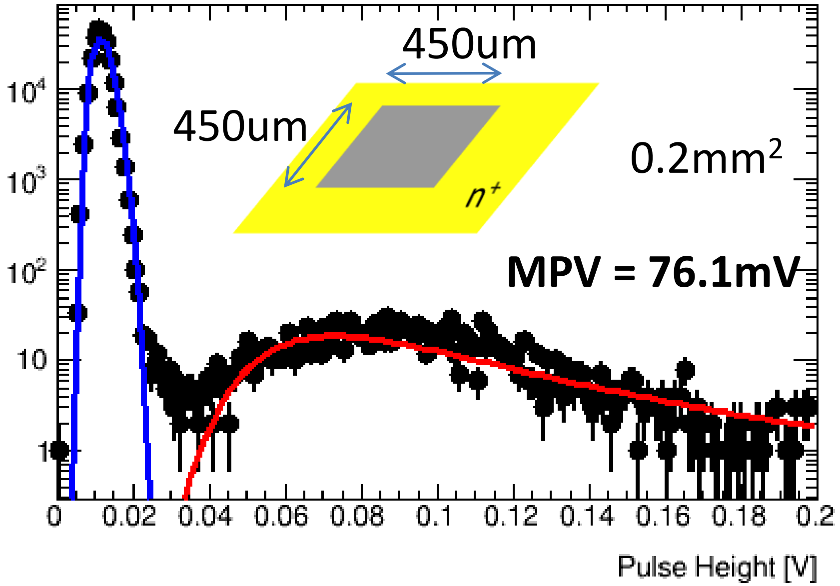
Coupling capacitance and signal size

- Even the same bias voltage (200V), different pulse height signal detected in Pad and Strip detectors.
  - The same n+ and p+ shape for both detector (uniform for all active area). Then signal split to electrode and n+ imp.
  - Smaller Coupling capacitance may attenuation the signal.
    - Large signal difference of strip and pad sensors indicate $1/\omega C_{cp} >> R_{imp}$
      → Larger R_{imp} should help to have larger signal?

Equivalent Circuit



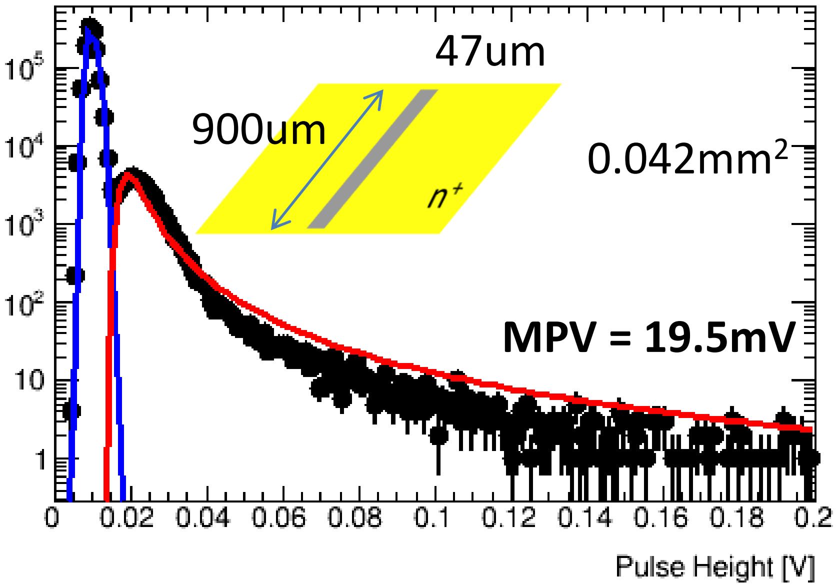
Pad Sensor



Capacitance ← **x4.5**

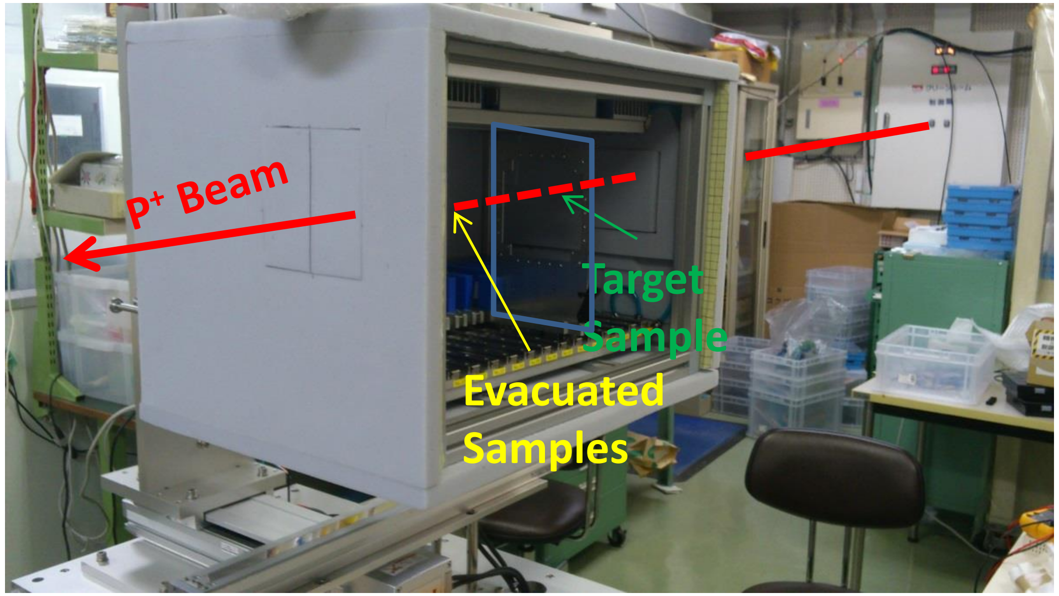
Signal ← **x3.9**

Strip Sensor



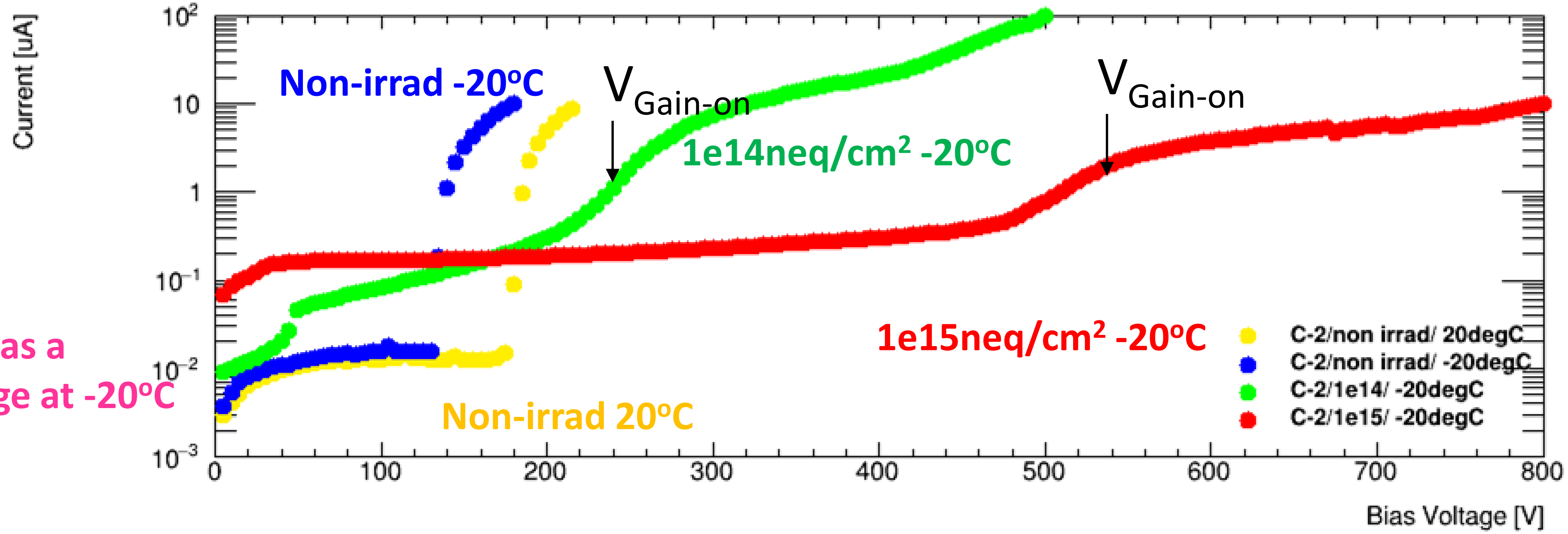
Proton Irradiation Facility in Japan

- CYRIC@Tohoku Univ. is an irradiation facility with 70MeV proton beam (~1μA).
  - This allows irradiation of silicon sensor of 3mm thickness in total (3% E loss).
  - Operated at -15°C temperature with dry N_2 gas.
- Remotely controllable X-Y stage and "push-pull" mechanism are implemented to the machine.
  - Choose to irradiate one or more target samples out of 15 pre-installed samples.
- Scanned over full sensor range during irradiation.
- **Actual Fluence difference relative to the target fluence is within ~10%.**



Electrical test after Irradiation

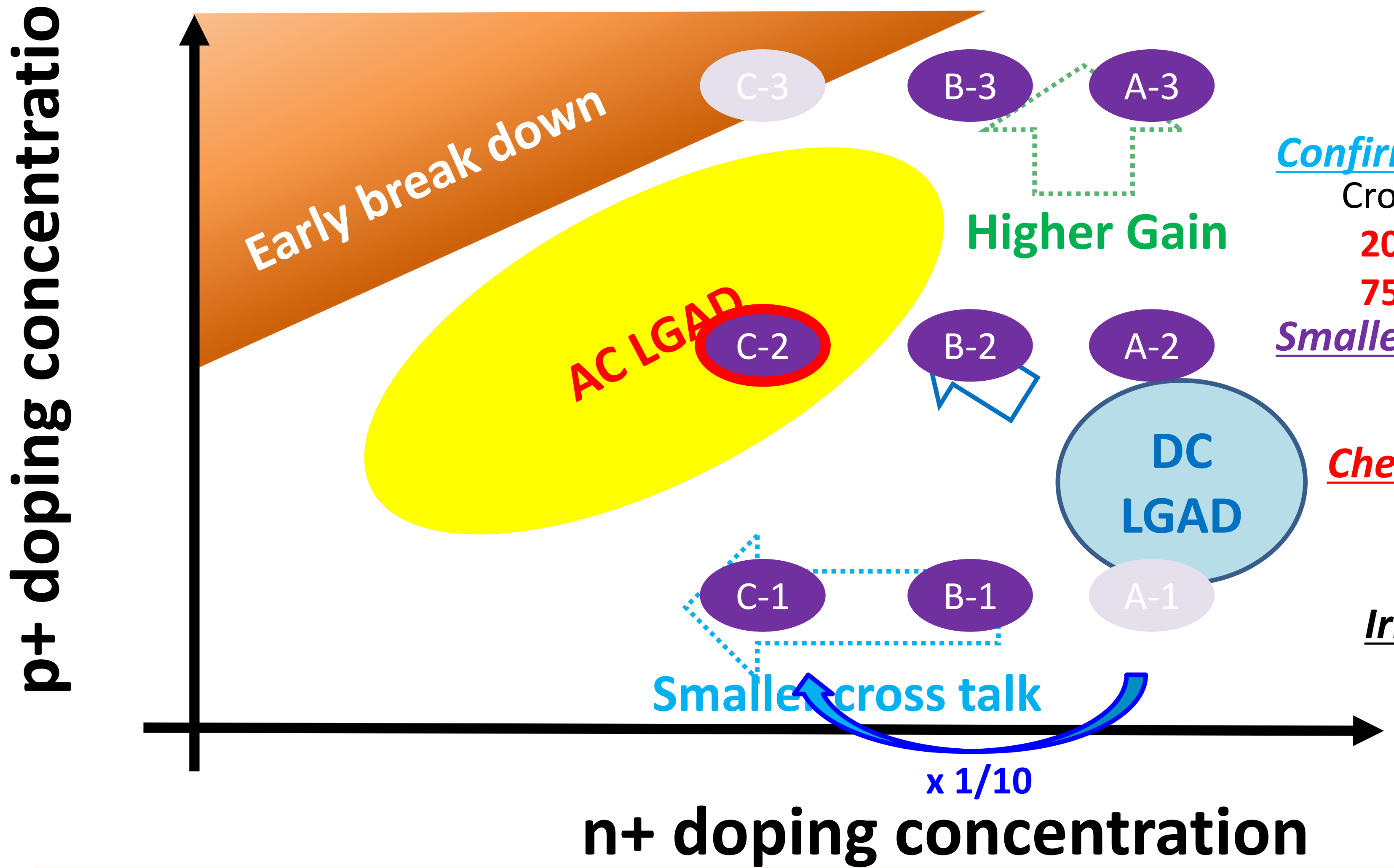
- Irradiated sensors at 1e14neq/cm^2 and 1e15neq/cm^2 and tested I-V performance.
- Gain-on voltage increased to **~220V @ 1e14neq/cm^2** and **550V @ 1e15neq/cm^2** ; they still seem to have gain.



Note: Non-irrad sample has a lower gain-on voltage at -20°C 190V→140V

Conclusion & Plan

Parameter space for doping concentration



● **fabricated at HPK**

Working well as LGAD detector with spatial resolution

Confirmed smaller crosstalk in lower n+ doping

Cross talk : x10 n+ resistivity sample (C-2 type)

20% to next pad

75% (62%) to next (next-next) 80um pitch strip

Smaller Electrode makes smaller signal

Due to smaller Coupling Capacitance

To be improved.

Checked timing resolution for C-2 type pad

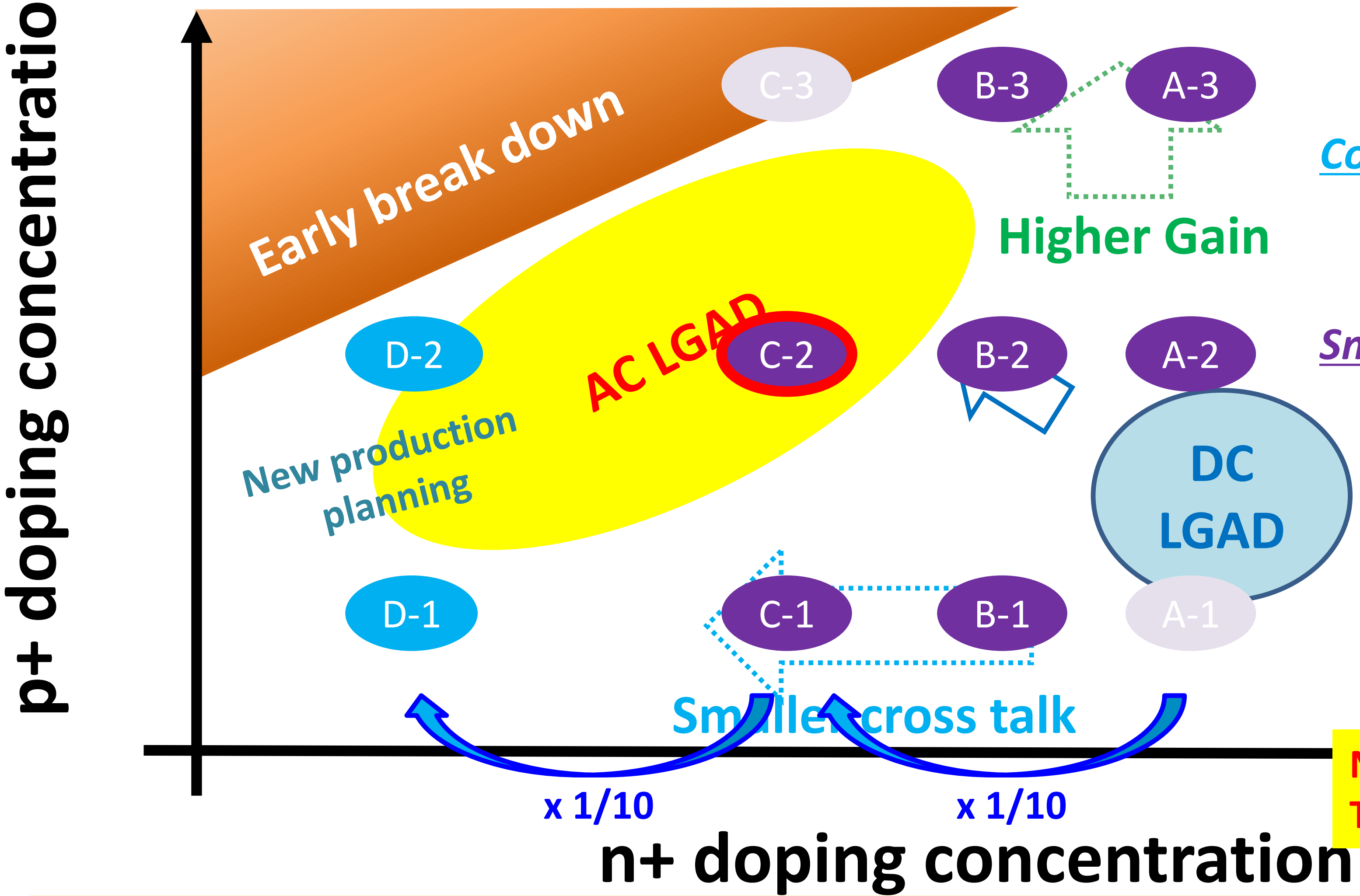
Evaluated **~45ps** timing resolution at 200V bias voltage.

Irradiated sample tested

up to 1e15neq/cm2, and still have gain

Conclusion & Plan

Parameter space for doping concentration



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New production planned further 1/10 n+ doping

Thinner Oxide to make higher Coupling Capacitor

backup

Temperature dependent IV curve

- Changed temperature from -30^{o}C to 24^{o}C