Improvement of timing resolution and radiation tolerance for finely segmented AC-LGAD sensors

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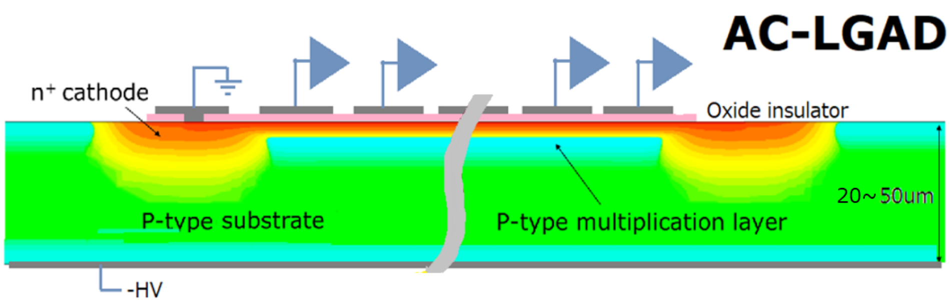
FJPPL (France Japan Particle Physics Laboratory)

AC-LGAD : parameters to optimize

High granularity achieved by AC electrodes achieving uniform LGAD gain



Hamamatsu Photonics:

n⁺ implant resistivity(Ω/sq)

Ccp (pF/mm²)	40	130	400	800	1600
80	✔	✔	✔	✔	
120			✔	✔	✔
240			✔		✔
600			✔		✔

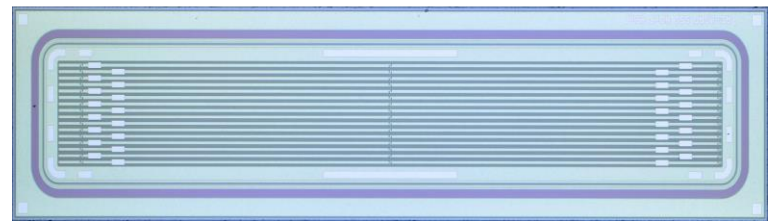
- p+ implantation adjusted to V_{gain}<160~190V (50um^t)
- active thickness : 50um, 20um

$$Q = \frac{R_{\mathrm{imp}}}{\sqrt{1/(2\pi f C_{\mathrm{cp}})^2 + R_{\mathrm{imp}}^2}} \times Q_0$$

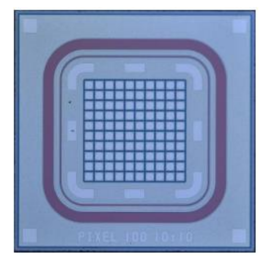
- *Q* larger for larger *Ccp, Rimp*
- large *Rimp* to suppress X-talk

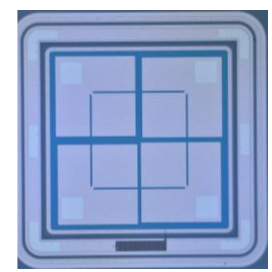
- *Performance evaluated of three sensor types*

Strip (80um pitch x 1cm)



Pixel (1x1mm active: 50,100,150,200um☐)





4ch Pad (2x2 500um☐)

- w/ slits for laser

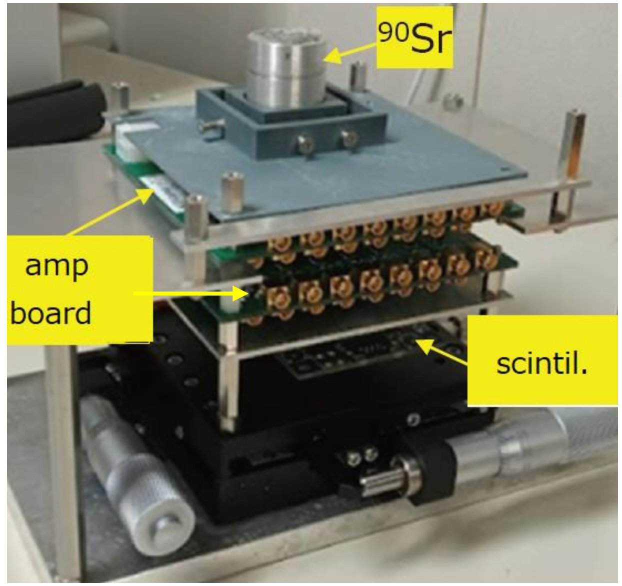
- electrode gap varied slightly

Measurement system@ bench (20℃)

16-ch amp

(2-stage GALI-S66+, BW~3GHz)

- *Beta-ray*

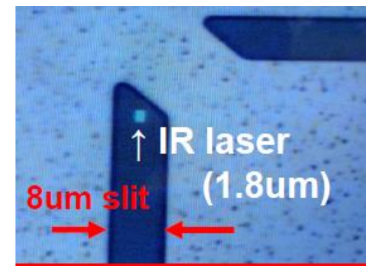


2 sensors aligned for timing resolution study

- *IR laser*

KATANA10

(1064nm, 35ps PW, Jitter ~ 5 ps)



collimated

- *Time reference* or

Photek PMT240

(40mmϕ,Jitter<10ps)

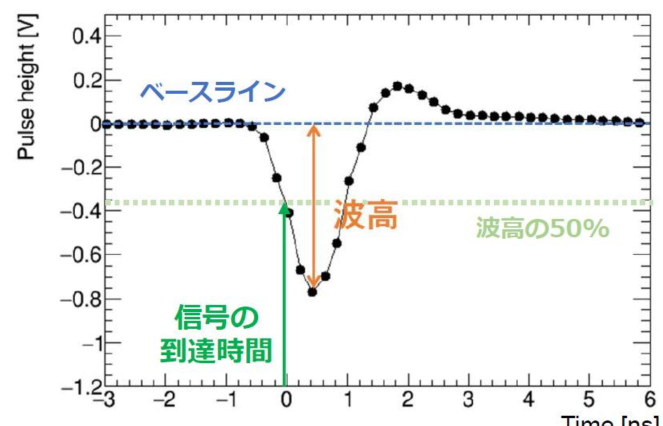
- *DAQ*

DT5742(16ch,5GS/s)

or

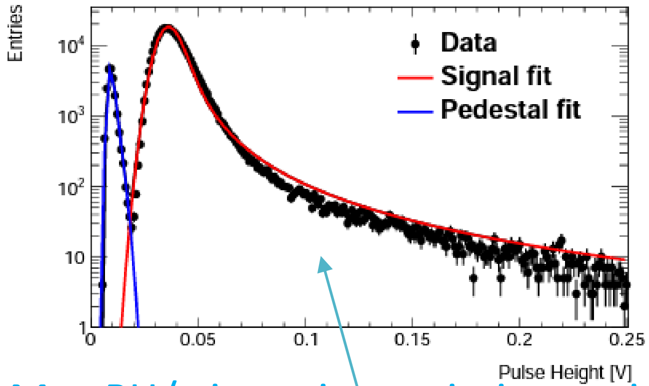
Waverunner8208HD

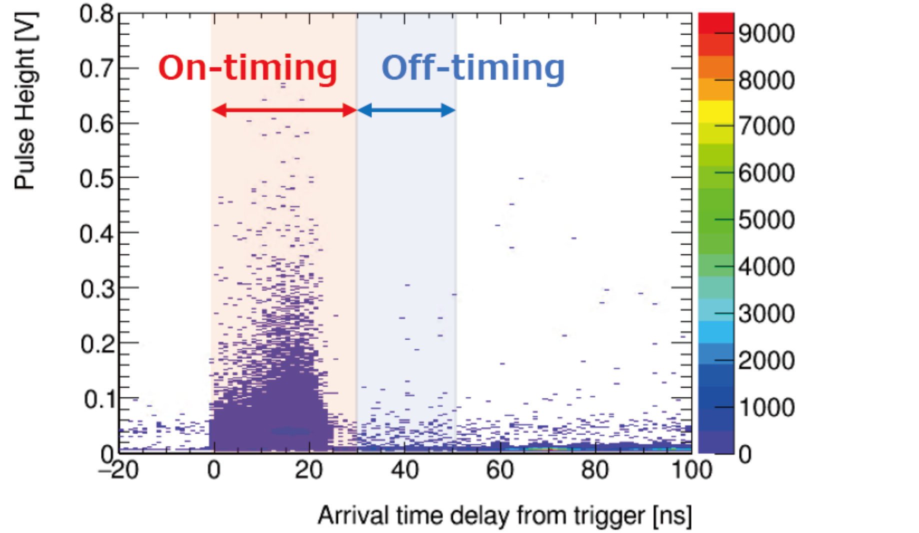
(2GHz, 8ch,10GS/s)



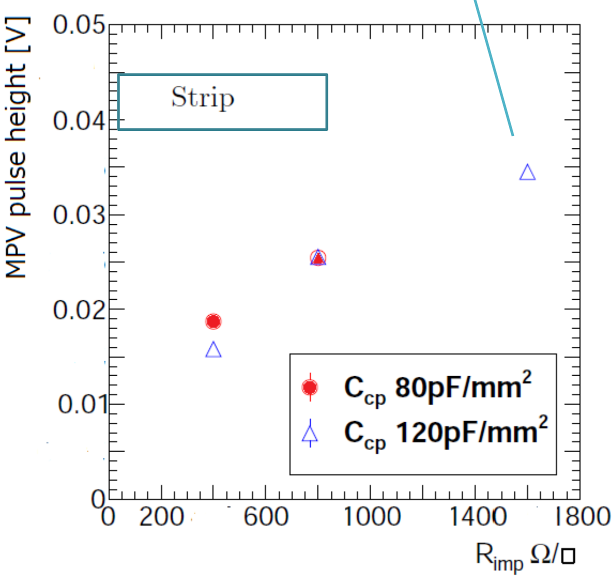
Pulse height

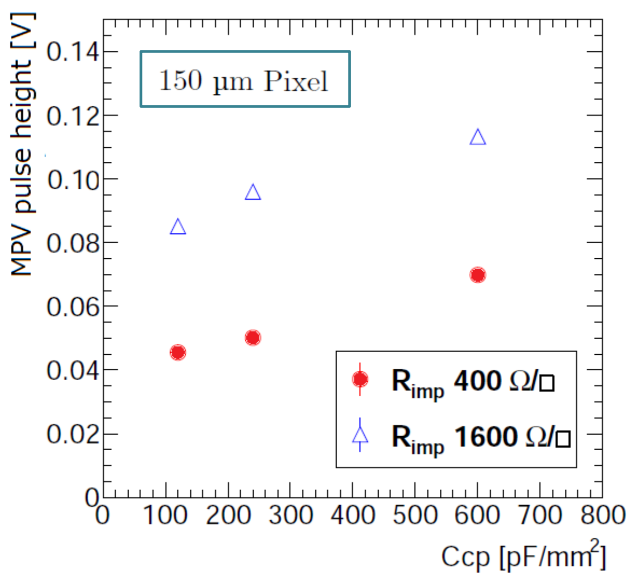
HV@ max V below noise increases

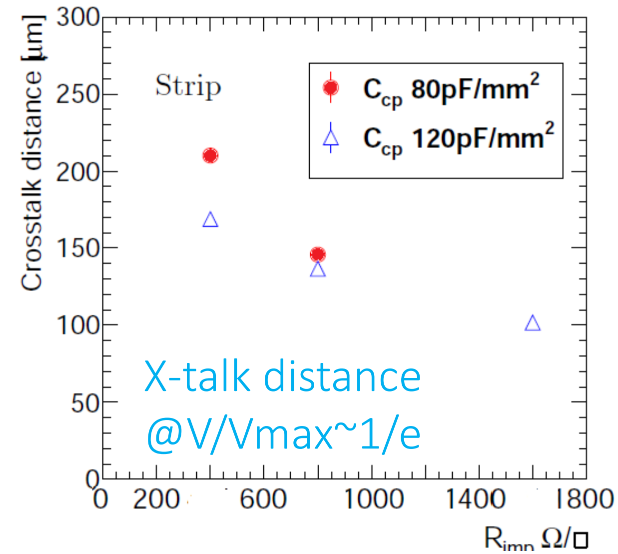




Max PH/trigger in on-timing region







X-talk distance @V/Vmax~1/e

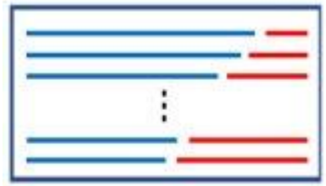
Nice signal, rms noise~1.5-2.0 mV
Q larger for larger Ccp, Rimp
X-talk smaller for larger Rimp
, as expected

but

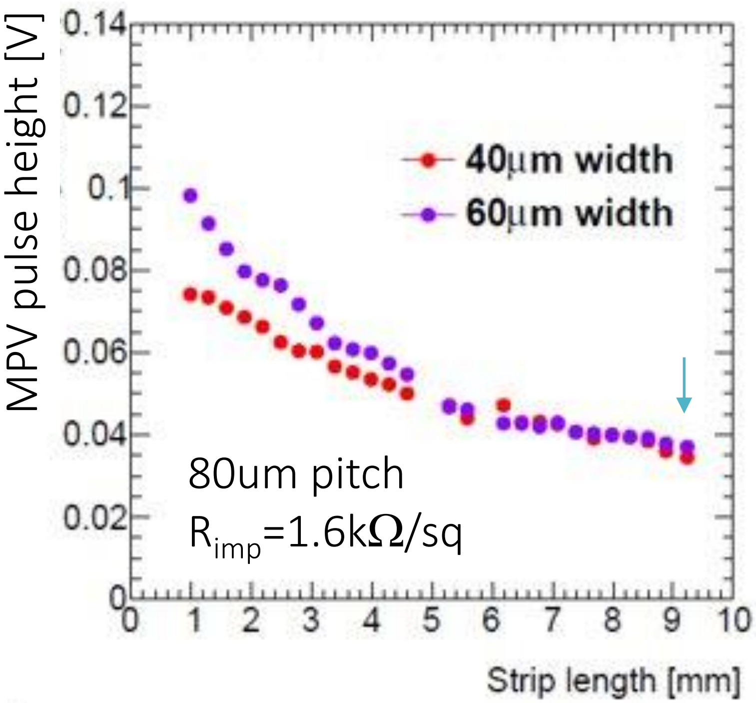
- *PH(strip)<PH(pixel)*
- *weak Ccp(strip) dependence.*

Strip Pulse Height

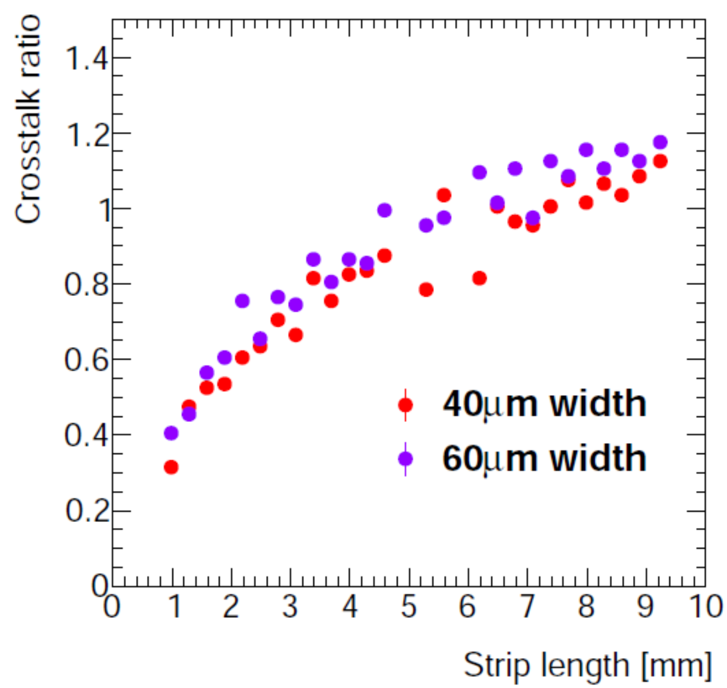
- *PH(strip)<PH(pixel)*
- *weak Ccp(strip) dependence*



PH dependence on strip length studied w/ a dedicated sample

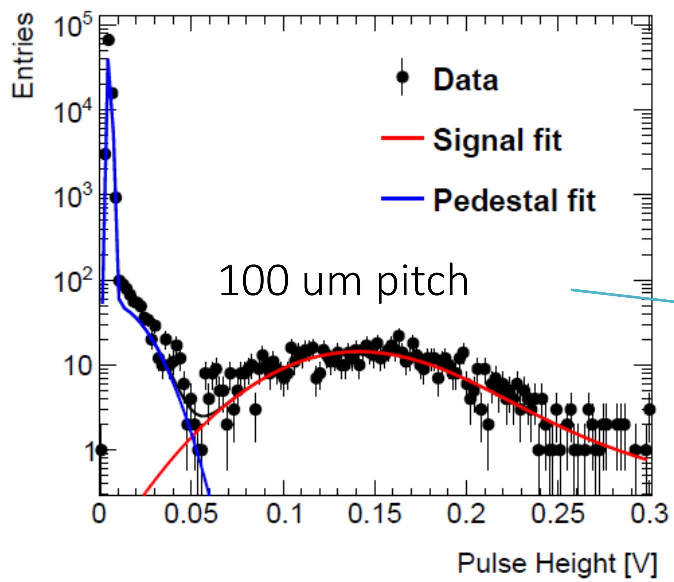


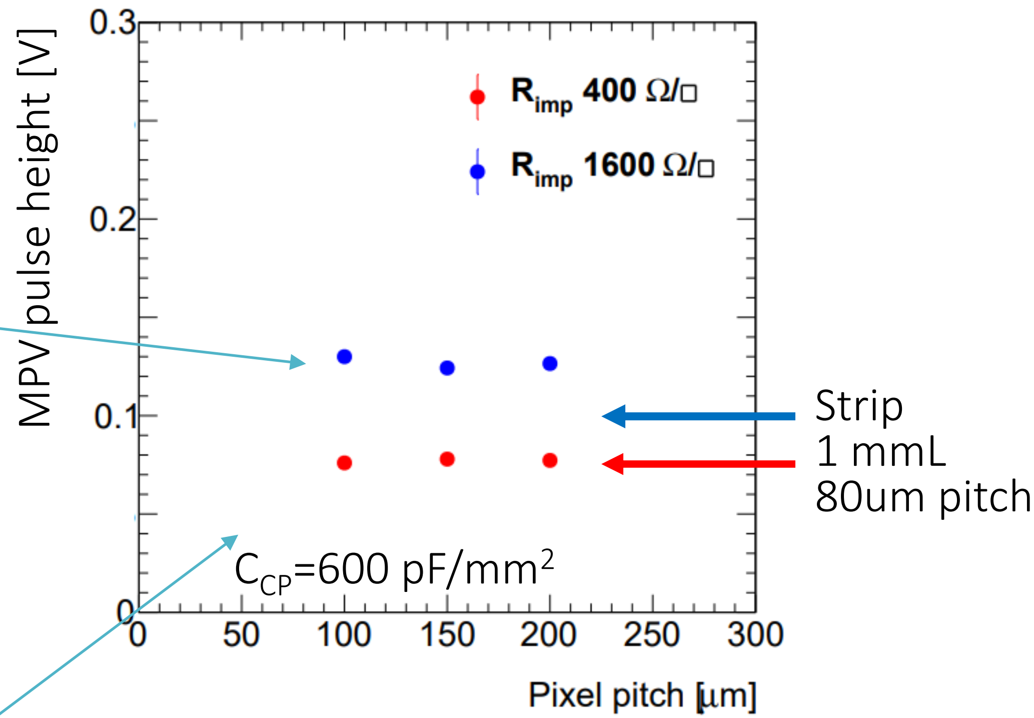
X-talk ratio =$(P_{-1}+P_{+1})/P_0$

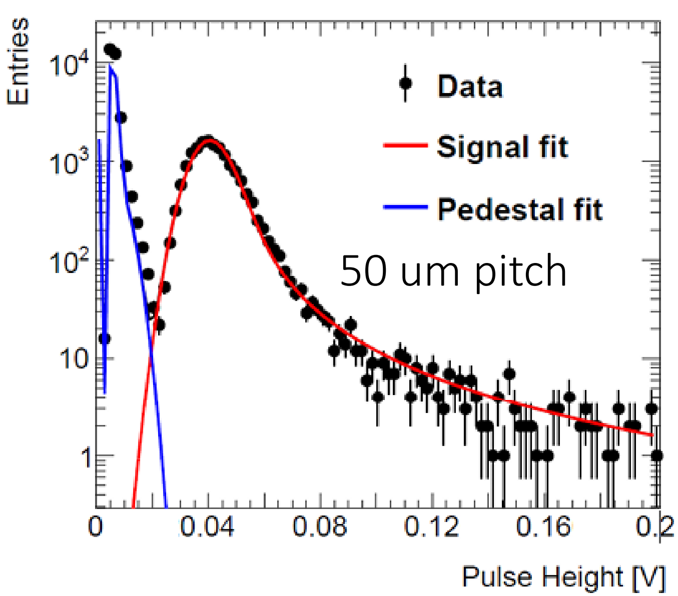


- *PH reduced by 60% by inter-strip capacitance at 10 mm, dominating over Ccp dependence*
- *X-talk increase with length*

Pixel Pulse Height



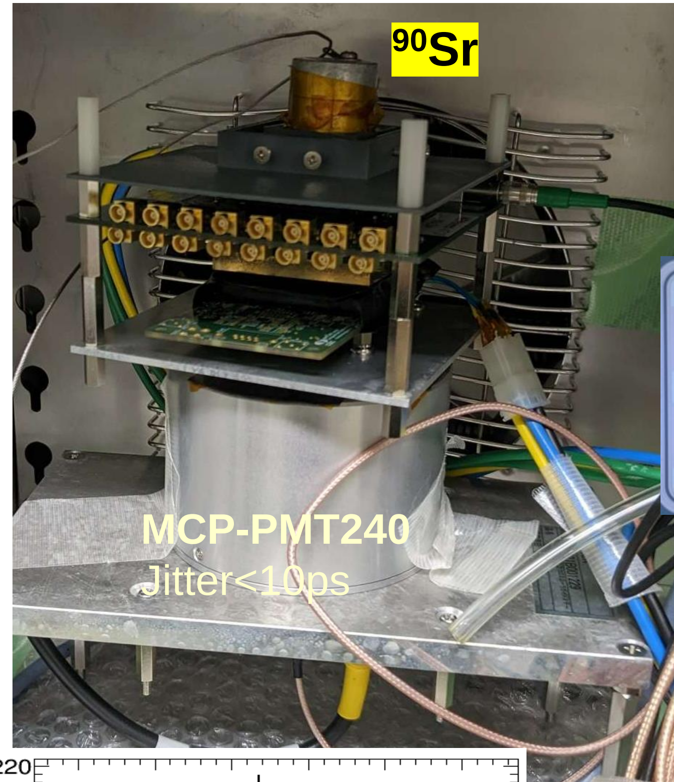




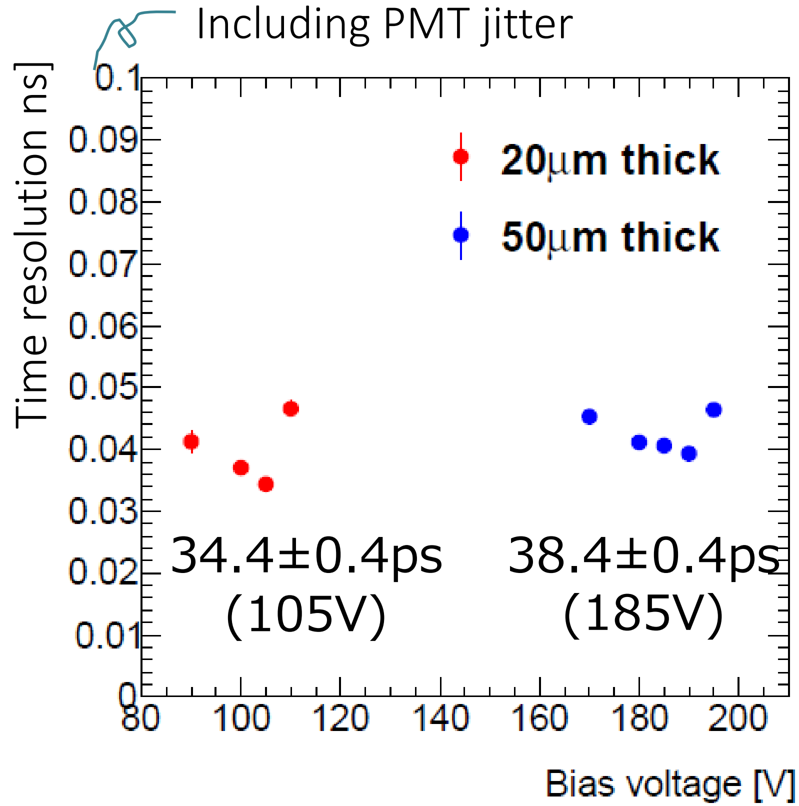
- *PH weakly depends on the pitch*
- *Signal seen also for 50um pitch pixel*

(as wirebonds are at 100um pitch, readout is not similar to the others; we expect larger signal from TCAD)

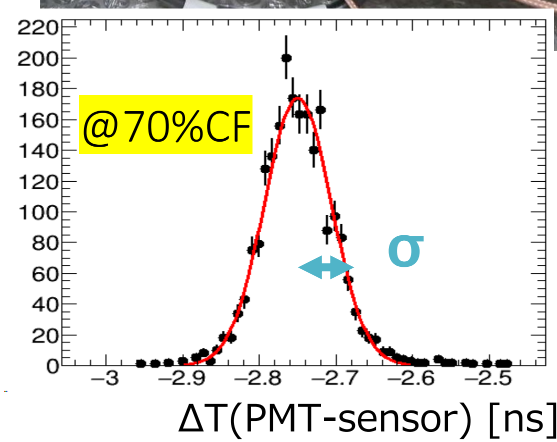
Time Resolution (β)

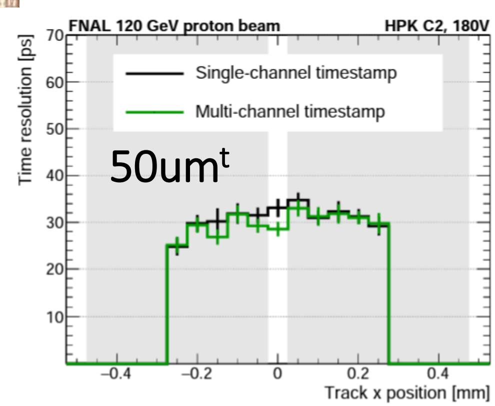


2x2 pad



- *Time resolution is (slightly) better w/ 20um*
- *Not as good as FTBF measurement*





Instrumentation? Beam?

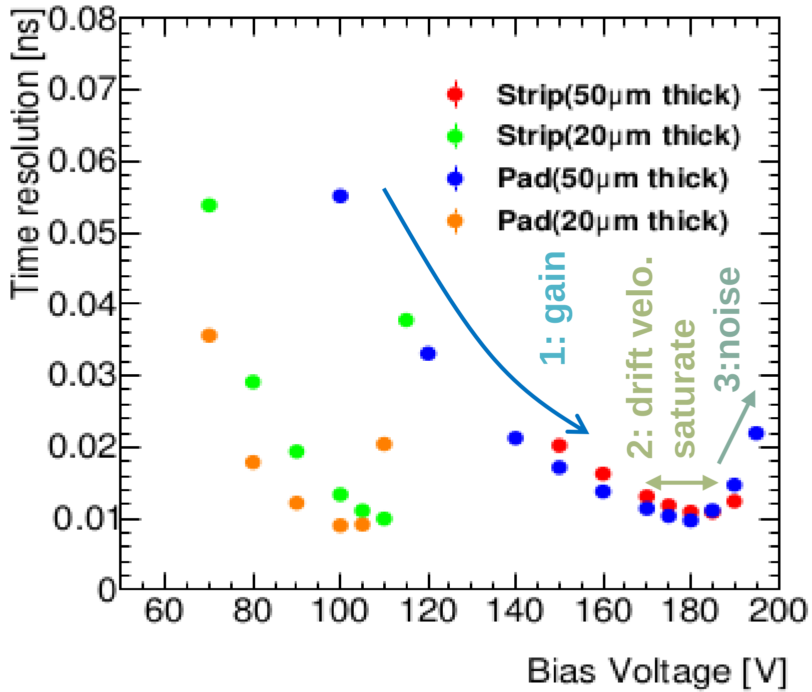
⇒ *Currently testing @ FTBF*

R. Heller et. al., JINST 17 P05001, 2022

Timing resolution (laser)

IR laser: free from Landau effect as charge deposit is uniform along depth

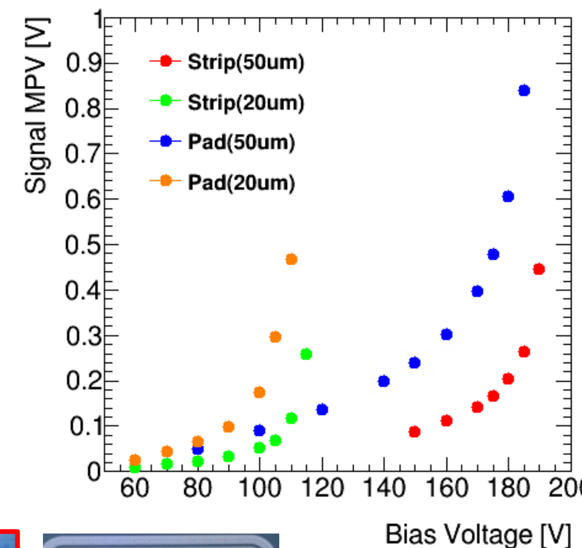
Laser jitter included



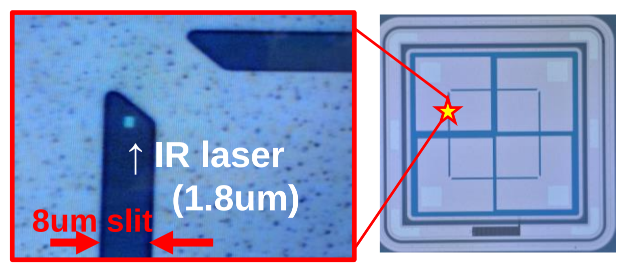
$$\sigma_t^2 = \sigma_{tw}^2 + \sigma_j^2 + \sigma_L^2$$

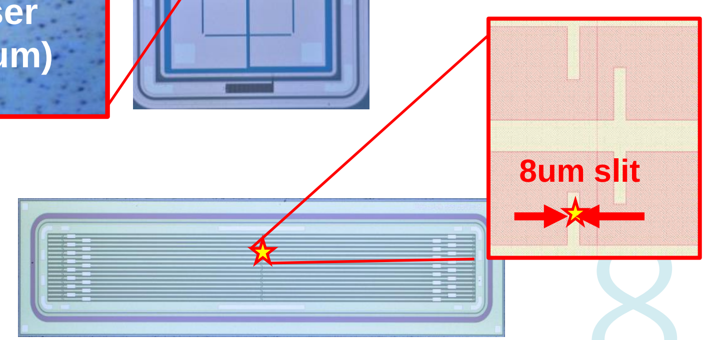
Time-walk is small for larger signal and CFD method…

cf: PH=50mV for β w/ strip (50um) at 180V



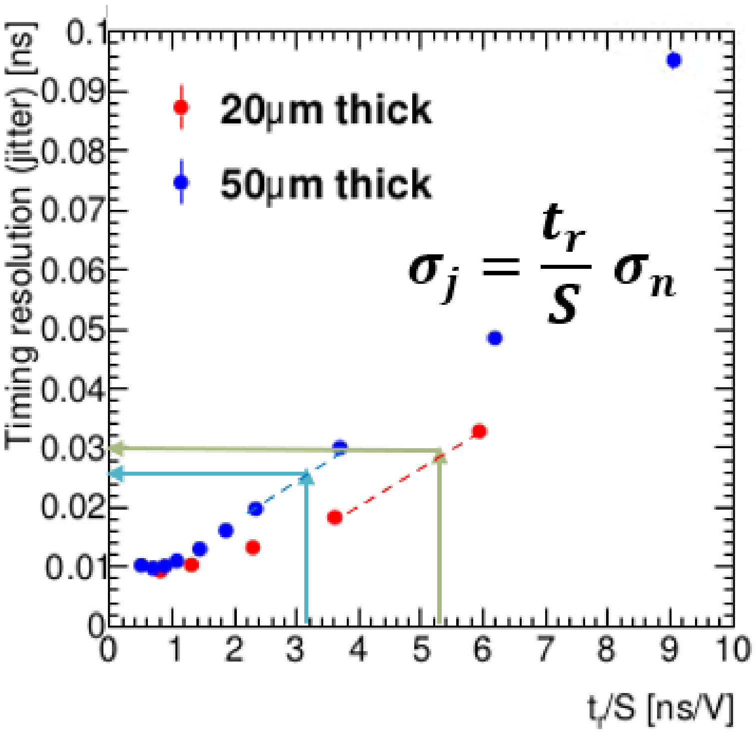
20um→80% CF
50um→60% CF
@ best time resolution





	4chPad	Strip
20um	8.54±0.03ps @105V	10.69±0.03ps @110V
50um	9.81±0.03ps @180V	10.83±0.03ps @185V

Timing resolution contributions in β



Time resolution w/ laser for varied HV

t_r/S calculated for t_r=20%-80% of S

$$\sigma_t^2 = \sigma_{tw}^2 + \sigma_j^2 + \sigma_L^2$$

	50um[t]	20um[t]
σ_t	38.4ps	34.4ps
σ_j	26.8ps	30.7ps
σ_L	**27.1 ps**	**15.5 ps**

σ_t: measured w/ beta (p7)

σ_j: measured t_r/S translated to σ_j

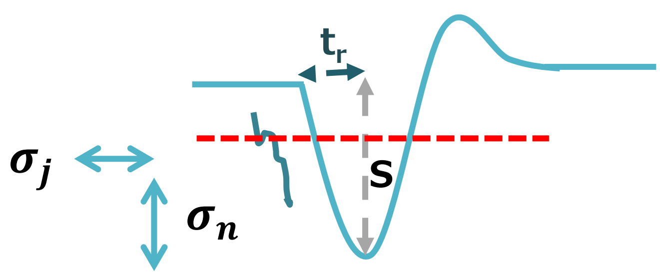
σ_L: subtraction of above

Timing resolution deterioration due to Landau effect is smaller for 20 um thick sensor

Dependence as expected as

$$\sigma_j = \frac{t_r}{S}\,\sigma_n$$

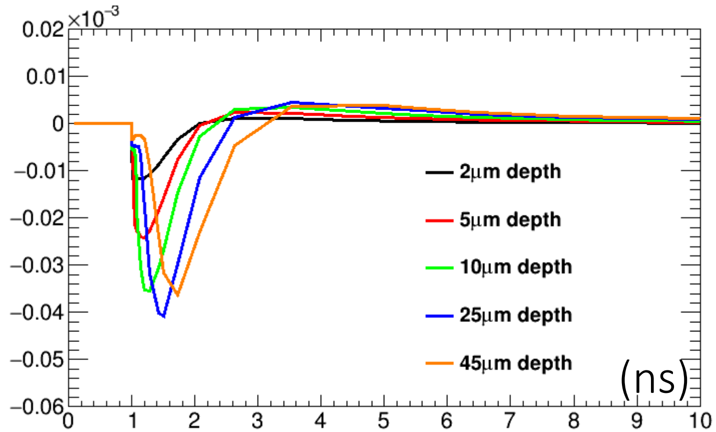
(T_{jitter}) (V_{noise})



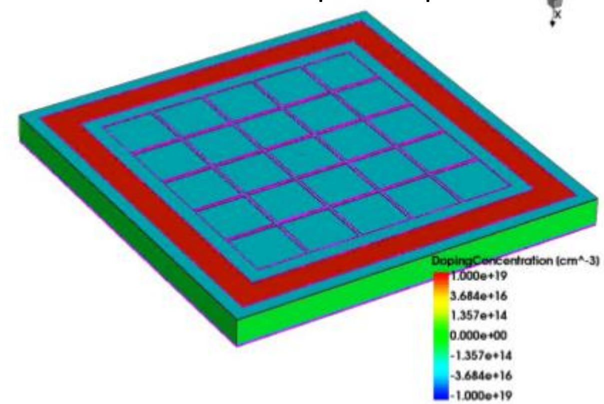
3D TCAD - signal dependence on depth

- ✓ 20 um thickness has smaller Landau contribution than 50 um

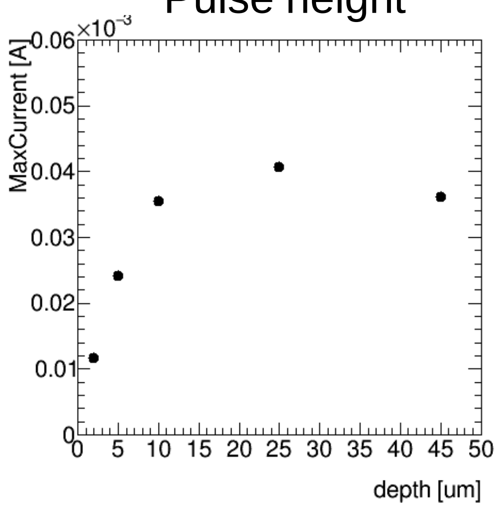
Signal shapes for charges created at specific depths (D = 2 to 45 um)



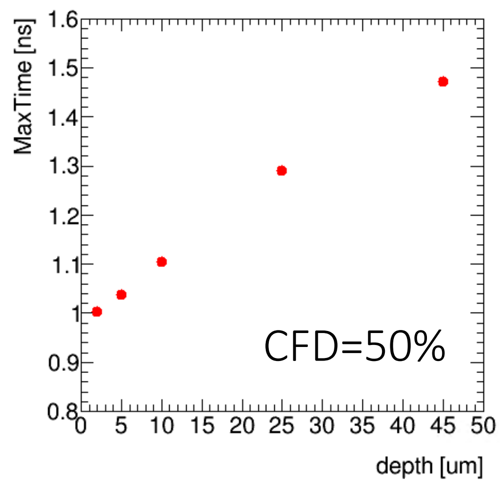
5x5 100um pitch pixels



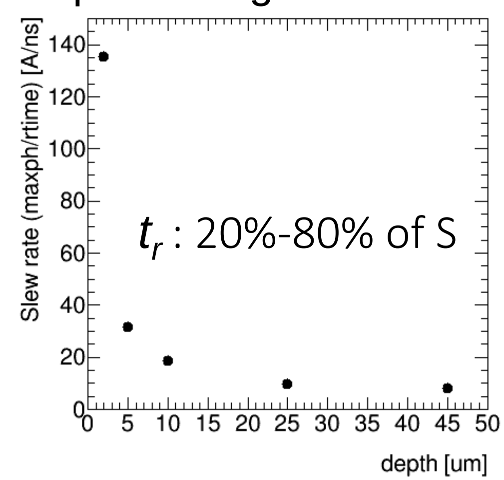
Pulse height



Arrival time



pulse height / rise time



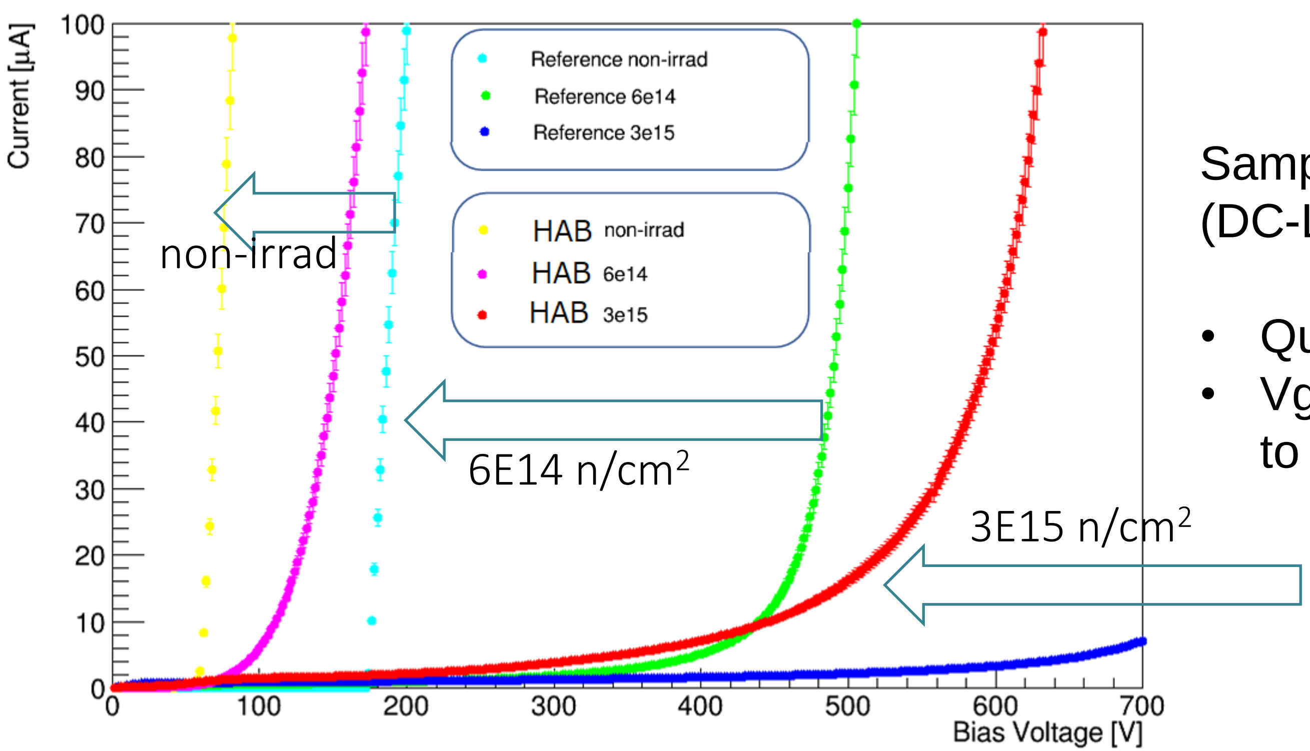
- ✓ PH almost saturated for D>20 um
- ✓ Landau fluctuation⇒signal shape deteriorated by late arrival time for D>20um

Radiation tolerance improvement – trial1

HPK is investigating to improve their (poor) radiation hardness !

<u>HAB = Half Activated Boron</u>

dope Boron more than required -> insufficient annealing process
->Borons not in Si lattice work to suppress "acceptor removal" e.g. capture O



Samples: HGTD prototype (DC-LGAD)

- Quite promising results
- Vgain at non-irrad needs to tune higher

Radiation tolerance improvement – trial2

Compensation

Result not promising….

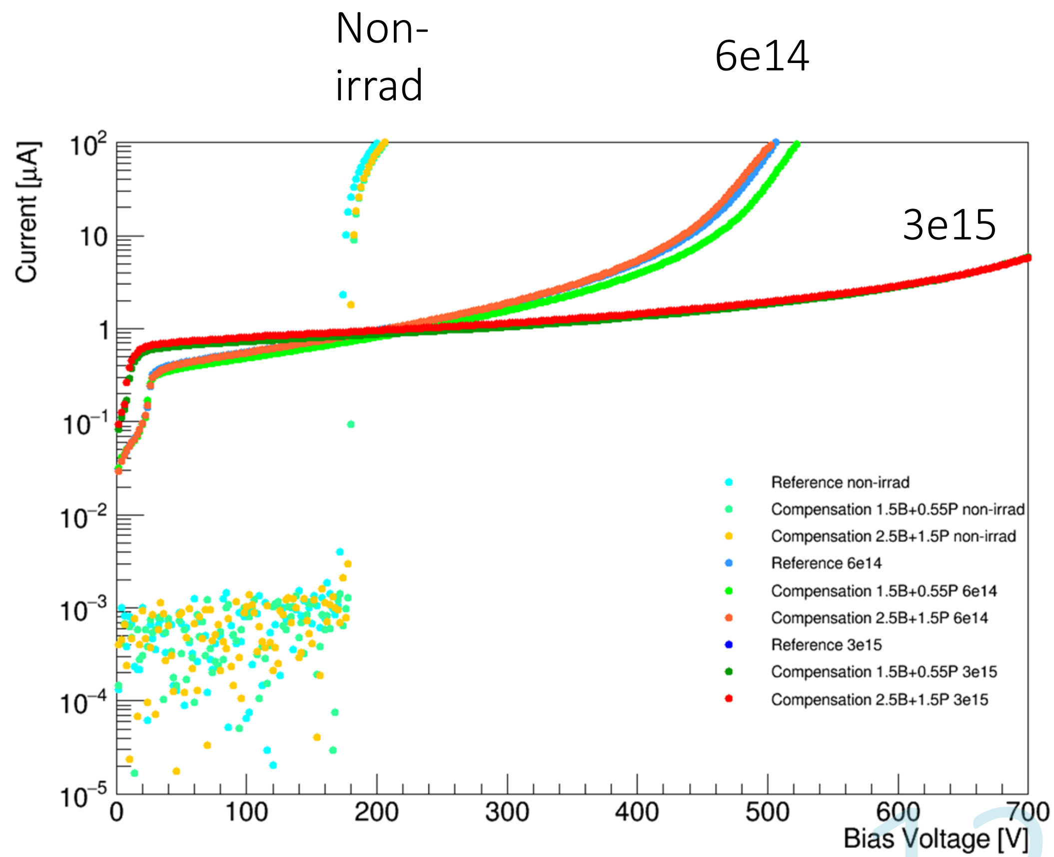
Not much change by two different compensation parameters

2.5B+1.5P

1.5B+0.55P

Initial comensation works perfect

What does this mean?



How should we understand the results?

$$N_A(\emptyset) - N_D(\emptyset) = N_A(0) \cdot e^{-C_A \emptyset} - N_D(0) \cdot e^{-C_D \emptyset}$$

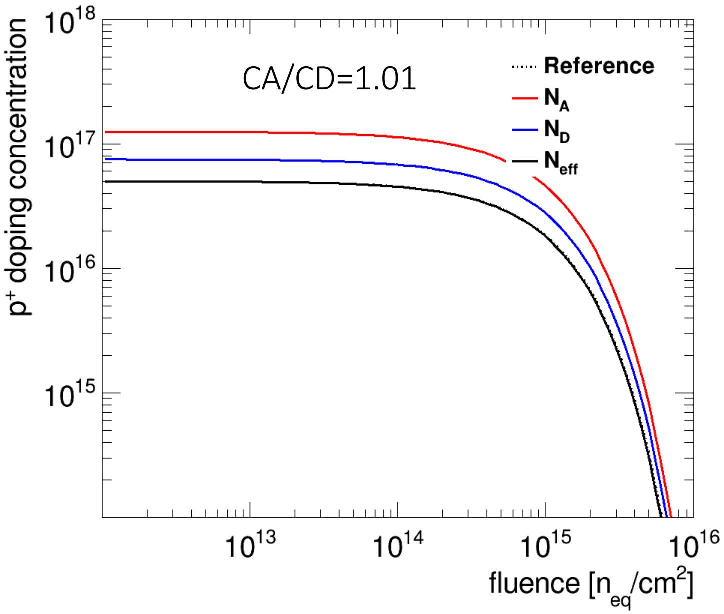
If $C_A = C_D$

$$N_A(\emptyset) - N_D(\emptyset) = (N_A(0) - N_D(0)) \cdot e^{-C_A \emptyset}$$

reference

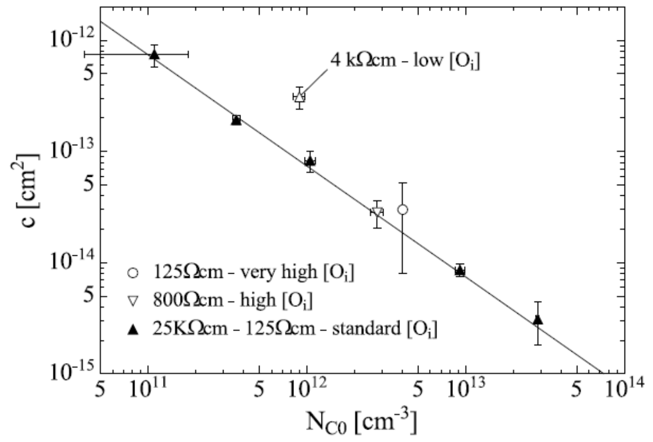
$$N_A(\emptyset) = N_A(0) \cdot e^{-C_A \emptyset}$$

Reduction of effective p+ must be the same as non-compensated case

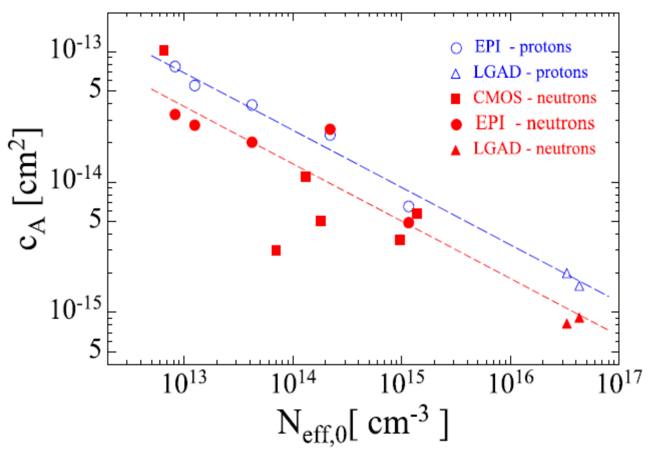


Previous data

Donor removal



Acceptor removal



Conclusion

- AC-LGAD sensor parameters are tuned: β signals observed for
  strip sensor of 80 um pitch
  pixel sensors down to 50 um pitch

- Time resolution evaluated w/ β
  - time resolution obtained w/ IR laser is used to decompose σ_{Landau} and σ_{jitter}
  20um thick sensor has smaller σ_{Landau}
  more reliable estimate will be soon available from FTBF

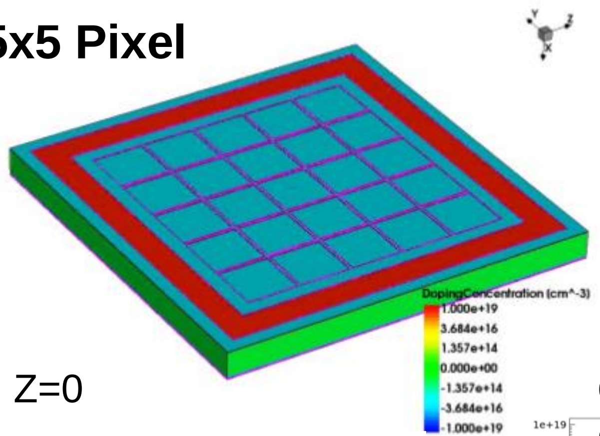
- 3D TCAD is ready for qualitative evaluation on time resolution

- HPK is investigating radiation tolerant LGAD: half-activated boron is promising : initial trial of compensation was not promising

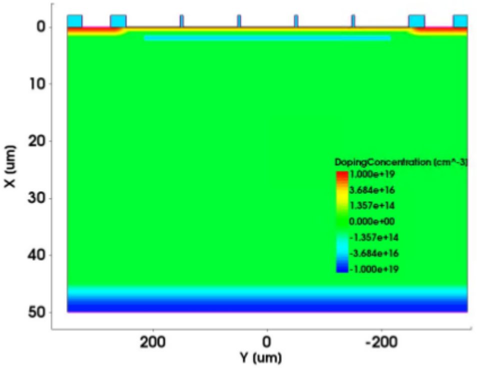
backup

TCAD3D model

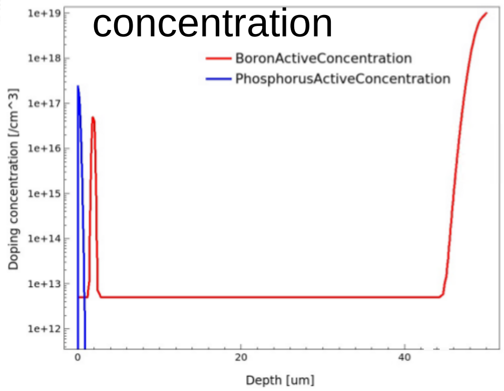
5x5 Pixel



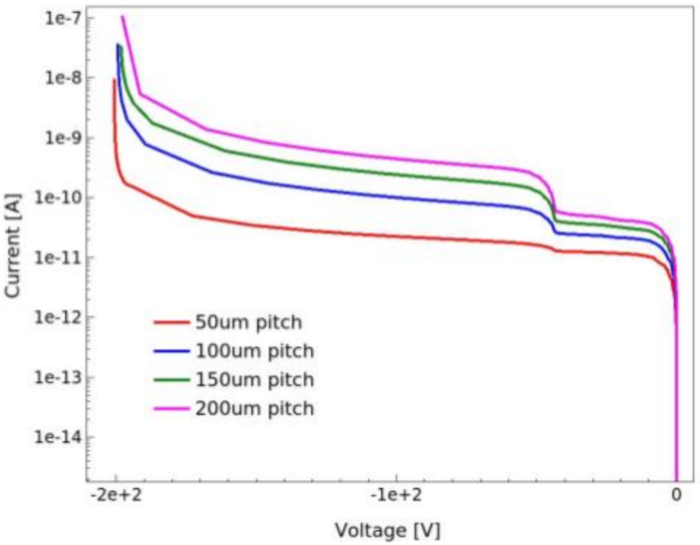
Z=0



doping concentration



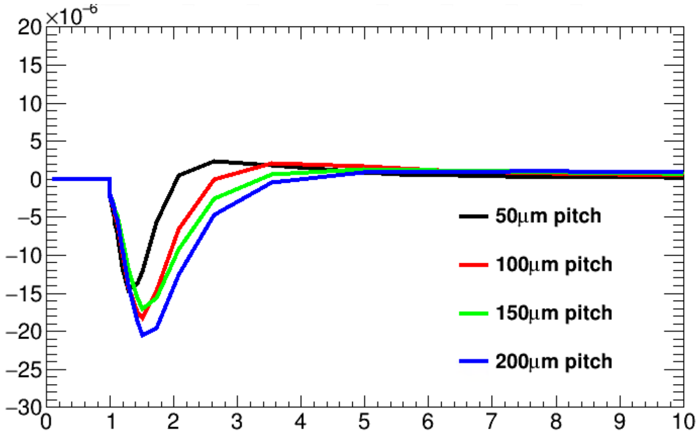
IV simulation @ -20degC



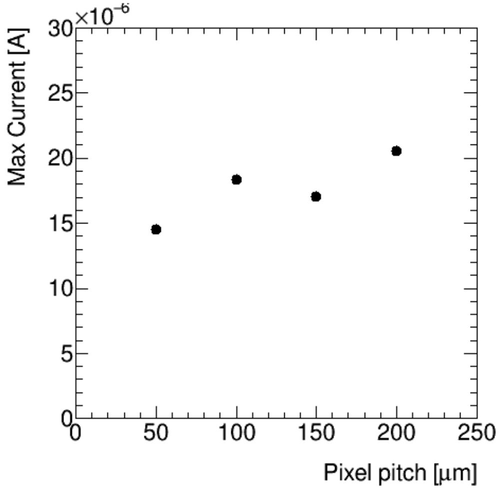
Signal size pitch dependence

Compared different pitch (50, 100, 150, 200um)

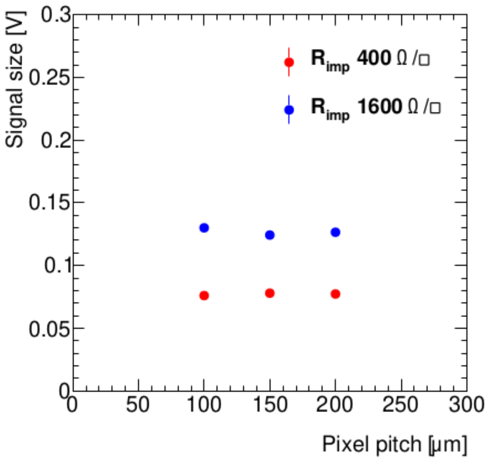
Pulse shape



simulation



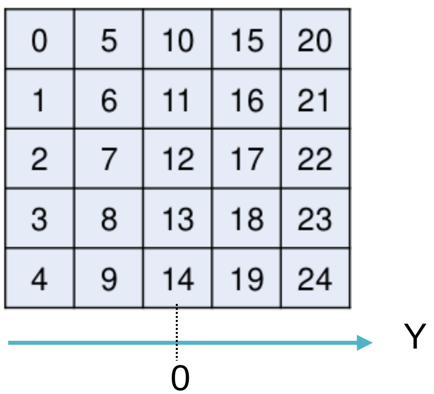
measurement

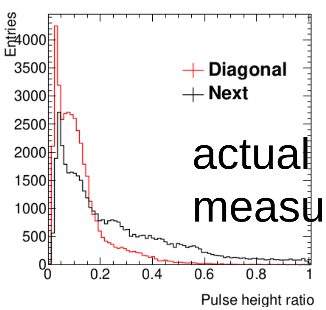


- ✓ signal size is similar to each pitches.
- ✓ simulation and measurement are consistent
- ✓ signal size of 50um pitch may be ~90mV?

Pixel crosstalk

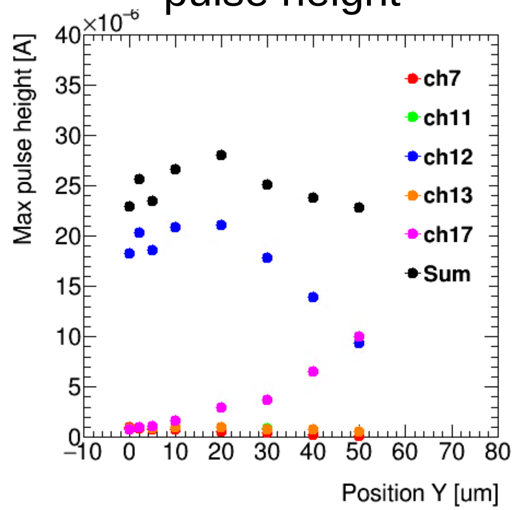
Change MIP injection point to y axis



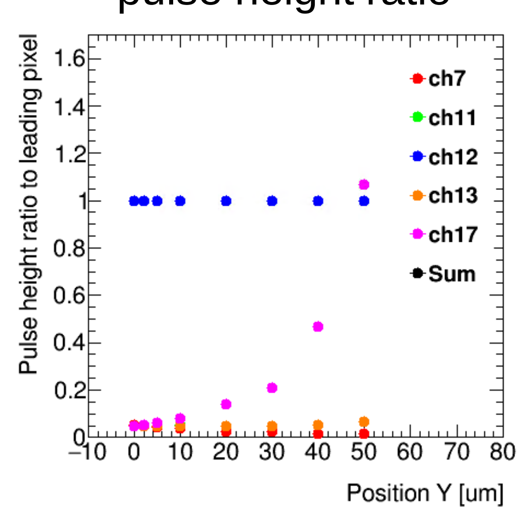


actual measurement

pulse height



pulse height ratio



- ✓ pulse height ratio is 1 between two electrode
- ✓ ±30um area is <30% of xtalk