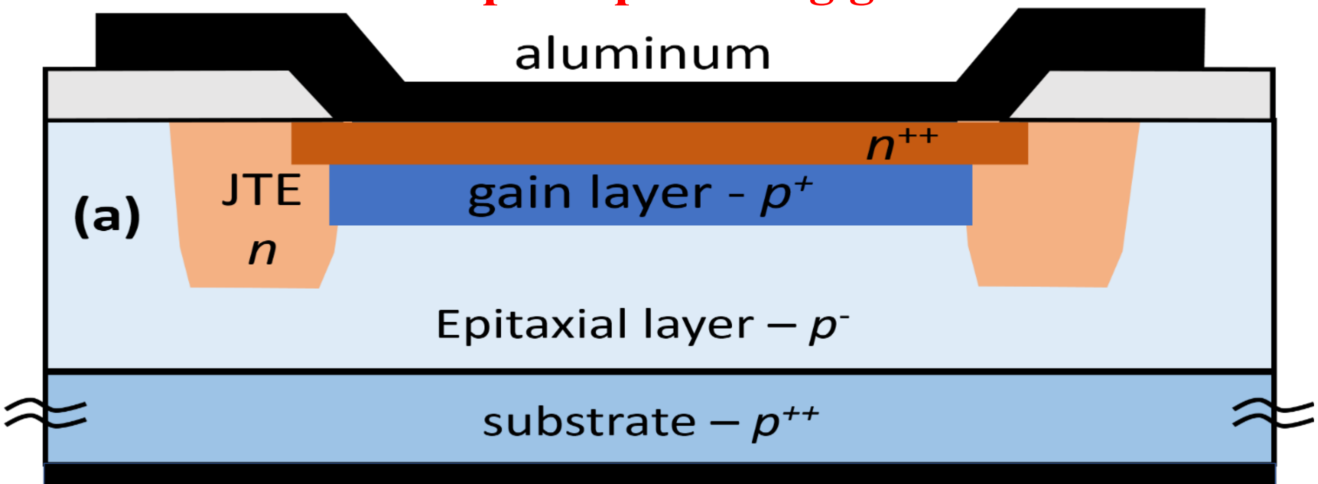
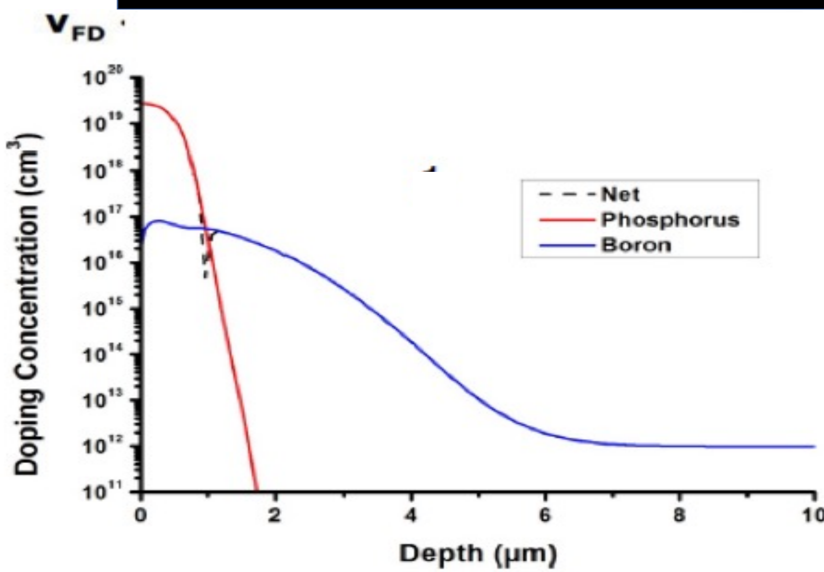
Toward Large Scale 4-D Tracking

Topics:

- What is an LGAD?
- What is an AC-LGAD (also called RSD for resistive silicon detector)?
- Role of sensor pad geometry and signal rise-time. Formulas for estimating the resolution.
- Measured spatial and temporal resolution versus hit position.
- Use of strips for fewer channels.
- Possible novel geometries.
- Use of thinner sensors to improve timing resolution.
- Possibilities for radiation hardening the detectors.

LGAD (Low Gain Avalanche Detector): Silicon detector with extra p+ implant providing gain.





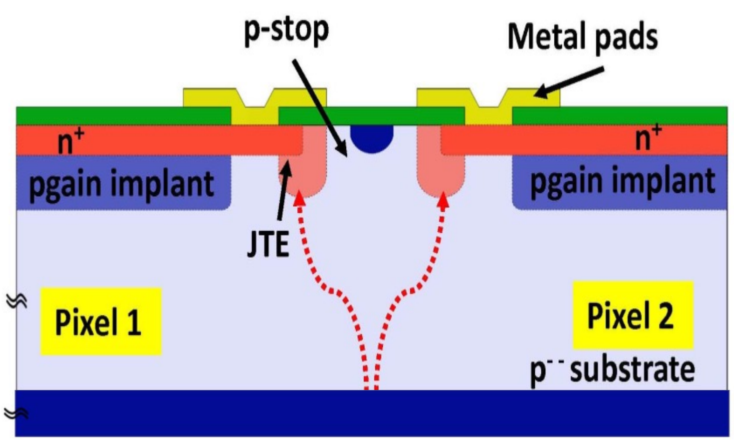
Goal: Gain field ~ 300 kV/cm over ~ 1 μm near junction. Bulk field in rest of sensor ~ 20 kV/cm, gives a saturated electron drift velocity ~ 10^7cm/sec. Want to have gain for electrons but not holes, leads to gain ~ 20. Sensor thickness choice for HL-LHC is 50 μm resulting in 30 psec timing resolution.

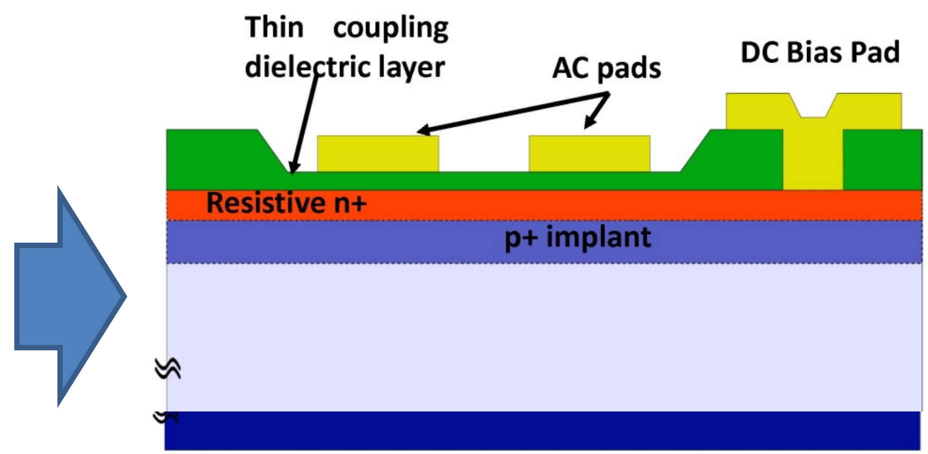
First application: HL-LHC upgrade – forward charged particle detectors. Many square meters of detectors to be built made of individual modules 2cmx4cm bump bonded to two 2cmx2cm readout chips. Each LGAD pad is 1.3x1.3 mm so position resolution is modest.

From LGAD to AC-LGAD

To go from LGAD on the left to AC-LGAD on the right have to remove physical pixellization of LGAD:

- Make n++-implant at the junction more resistive and extend it as a continuous sheet over the gain layer across the entire sensor.
- Add dielectric layer for isolation and AC-coupling into readout pads, which are connected to the electronics. Results in 100% fill factor.
- Simplification of design and production (no p-stop, JTE, inter-pad gap).

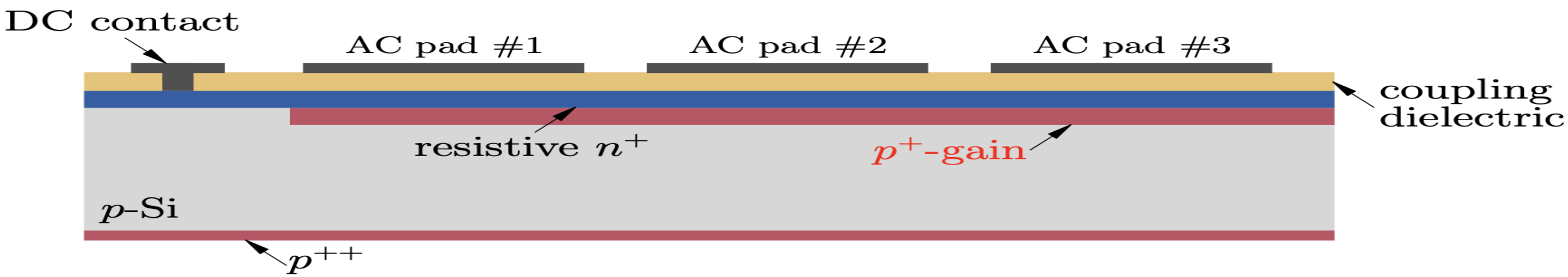




Result:

- Can use sparse readout with pulse sharing between ~ 4 pads for precision spatial resolution. Sparse metallization results in lower capacitance, and lowered power by limiting channel count. The signal (defined by peak height) summed over the pads is very close to constant independent of hit location and can be made large because of the LGAD gain.

AC-LGAD Goals



Goal is to achieve 4-Dim tracking, with per measurement, for example:
Spatial resolution < 15 microns. Time resolution < 15 picoseconds.

Defining D_{MAX} as the sensor pitch and T_{MAX} as the 10-90% pulse signal rise-time, these are two key dimensional parameters for the spatial and time measurements. Key dimensionless parameter is the signal-noise ratio, SNR, a critical parameter for good performance. Goal: SNR > 30 based on sensor gain ~ 20.

Position resolution ~ D_{MAX}/SNR. It is important to minimize the pad size since the resolution is generally worse for hits under the metal.

Timing Resolution ~ T_{MAX}/SNR, subject to Landau fluctuations. Key for good time resolution: keep detector thin for small T_{MAX} and small Landau fluctuations. Thin detectors do both. Typically have used 50 μm thick detectors, could achieve better time resolution with thinner detectors.

Example of Pads Tested

	RSD1 run at FBK	
	square matrices	
pitch [um2]	**pad size [um2]**	**# of pads**
200x200	100x100	3x3
	150x150	
	190x190	
300x300	150x150	2x2
	200x200	
	290x290	
500x500	200x200	3x3
	300x300	4x4
	490x490	

Indicate sensors via Pitch – Pad size. Find that 500-490 has capacitive cross talk between neighbors ~ 10% and poor position resolution since no sharing. 500 μm pitch with the smaller pads (300 and 200) have negligible cross-talk. Have focused effort on 500-300 and 500-200 since 500 μm pitch is closest to what we might want from the point of view of power limitations in a VLSI readout chip.

Pulse Shapes for Front or Back Laser Irradiated Sensor

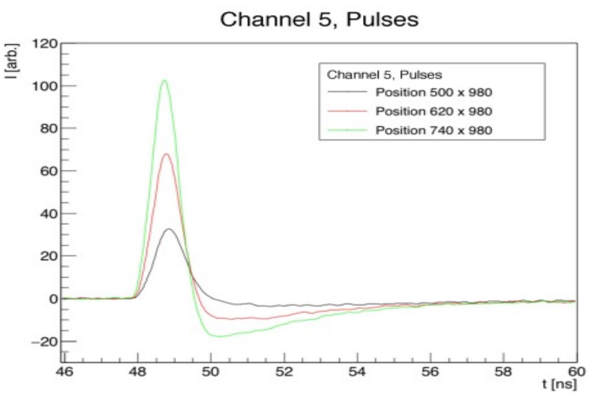
Pixel Pitch = 500µm, Pad Size = 200µm

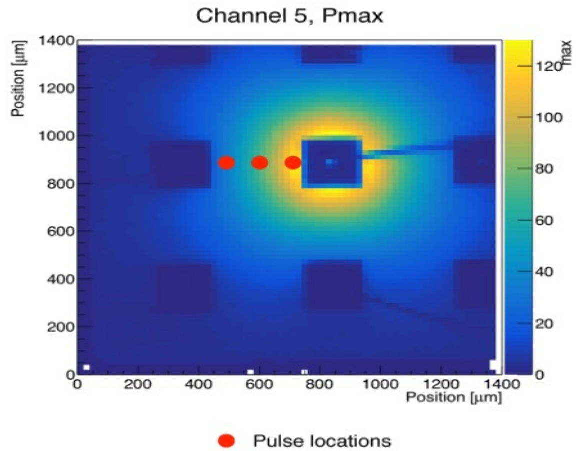
Laser irradiation, locations shown by red dots in figures. Front-side, can't irradiate location of metal pad, backside can explore full detector response**.**

Pulses have very consistent rise and fall times. 10-90% rise-time about 530 psec. Different amplitudes basis of position interpolation.

Frontside Scan: Pulse Comparison

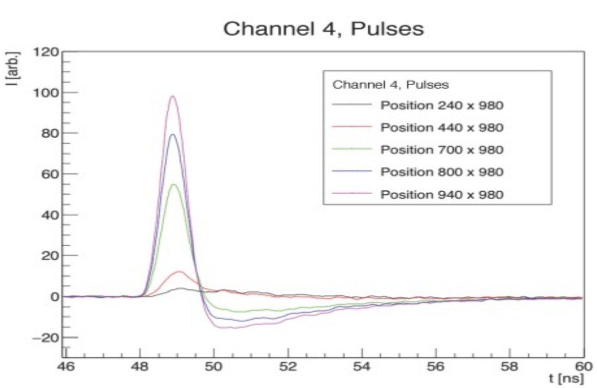
In Between Pad 4 and 5:

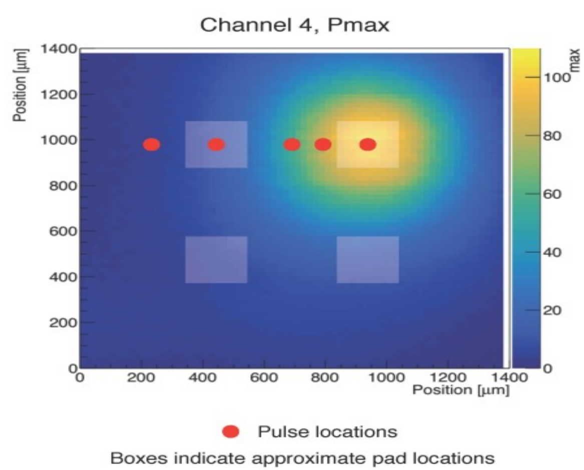




Backside Scan: Pulse Comparison

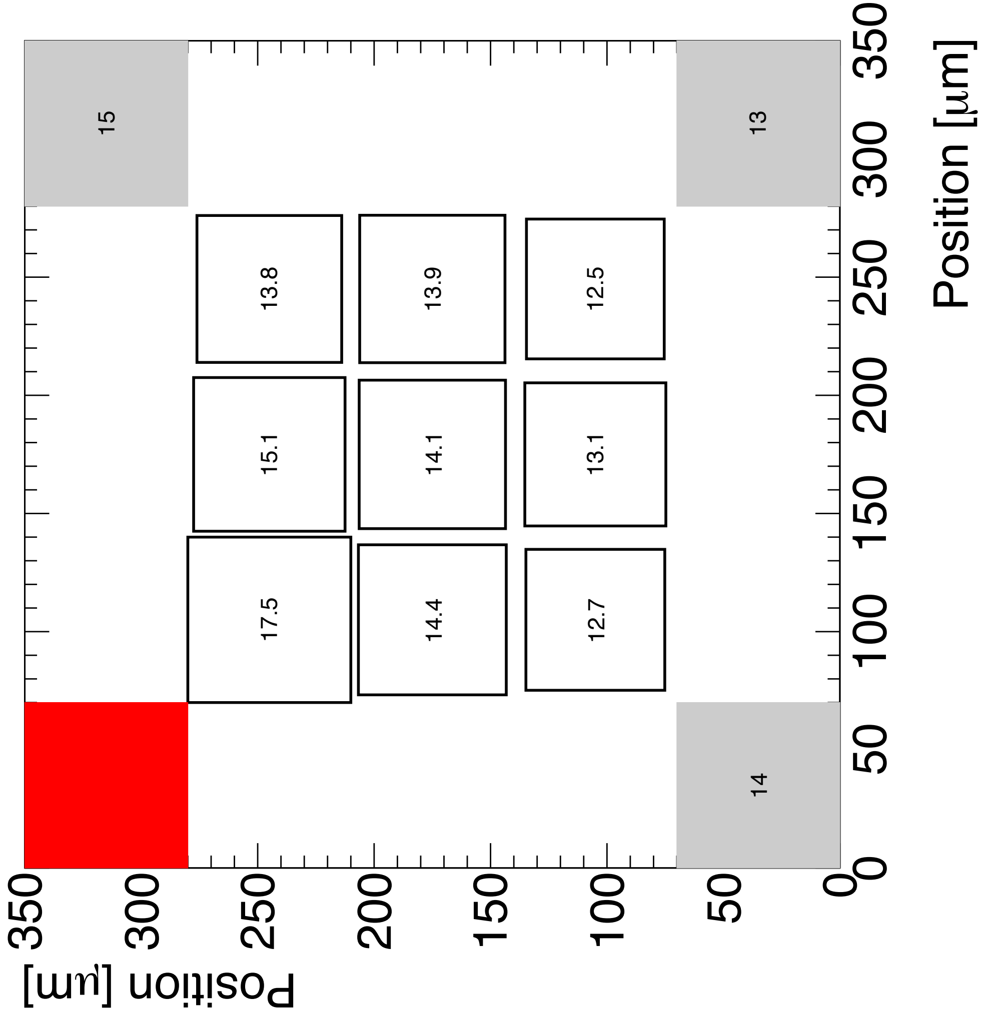
In Between Pad 4 and 5:





Pmax under next neighbor pad: ~ 10% of hit pad.
Pmax beyond next neighbor pad: less than 2%.

Time Resolution Using 3 Pads (red Pad Not Read out)



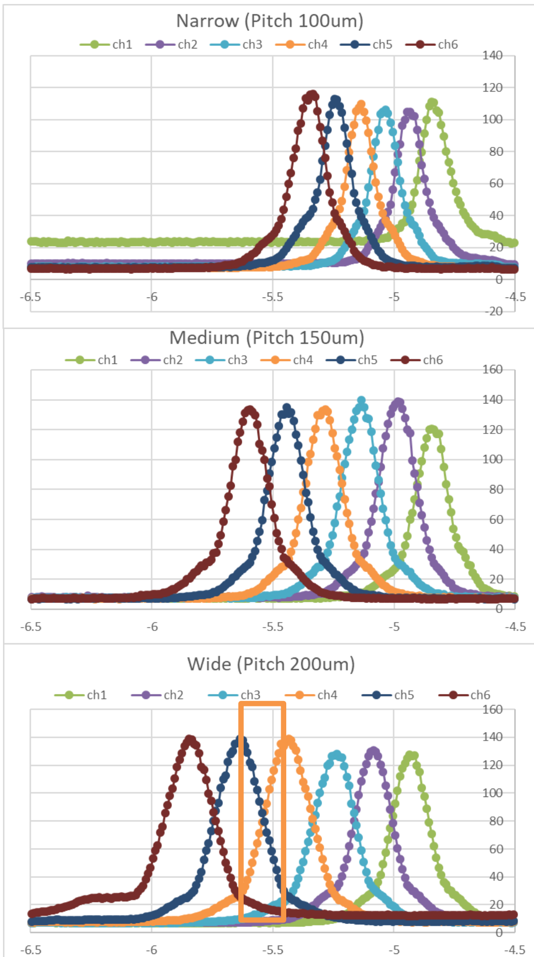
Box indicates center for laser irradiation, number in box is the jitter in picoseconds using 3 pads. Irradiations explore region of maximal sharing.

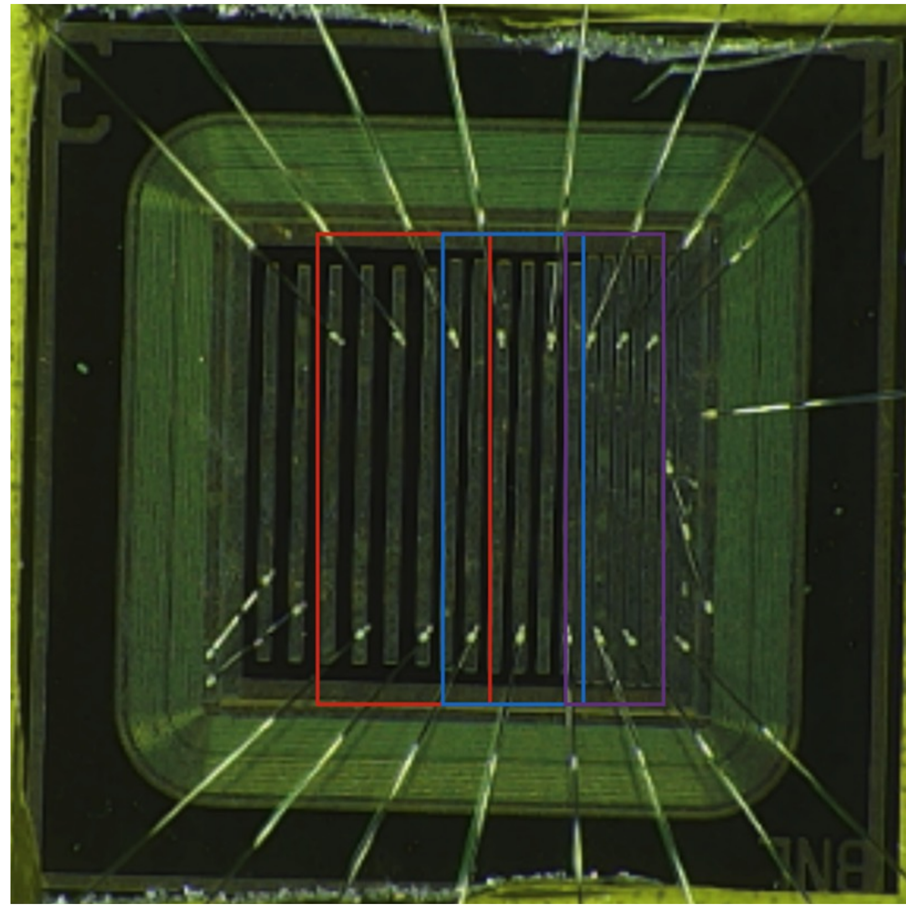
Potential for Novel Geometries

Because the metal is not tied to the internal detector structure the readout geometry can be chosen in innovative ways. Strips have been looked at in some detail and can provide very good performance for one coordinate (resolution of a few microns) and the time measurement. Has fewer channels than pads, which results in less power from electronics. For a tracker in a solenoidal B-field the resolution in z does not have to be as good as in r-phi, away from the vertex region, making strips a good choice.

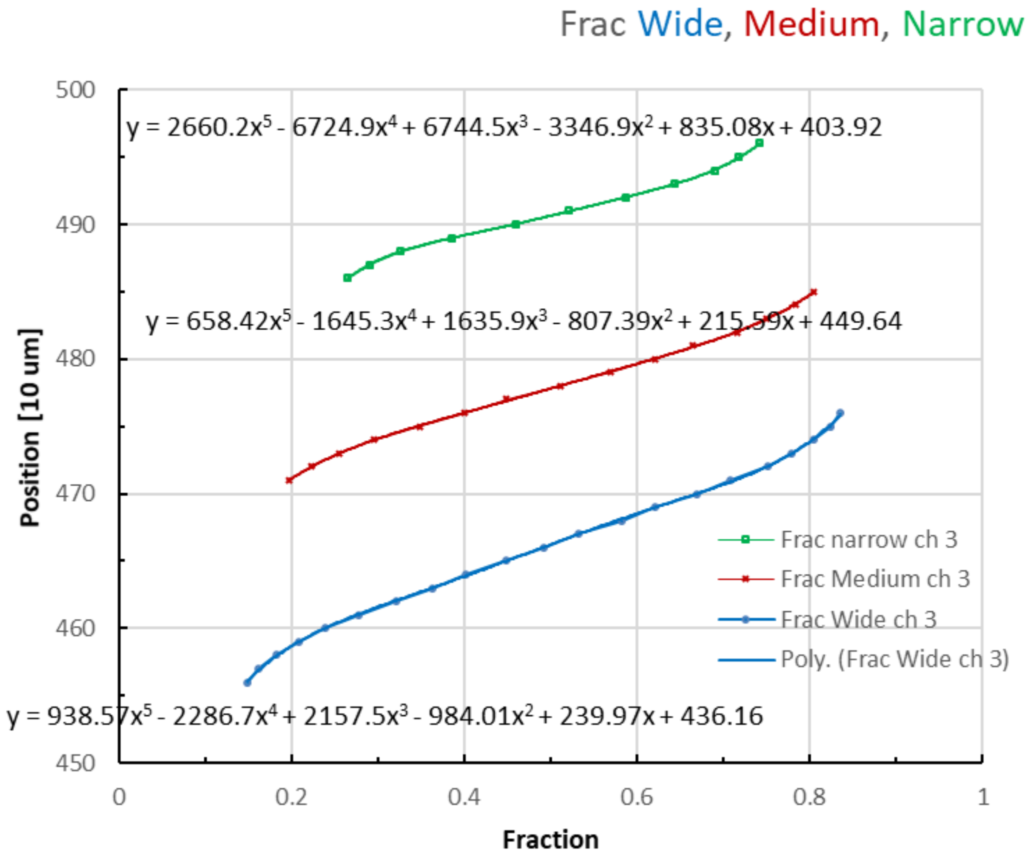
Positions in Narrow, Medium, Wide Strip Sensor fabricated by BNL

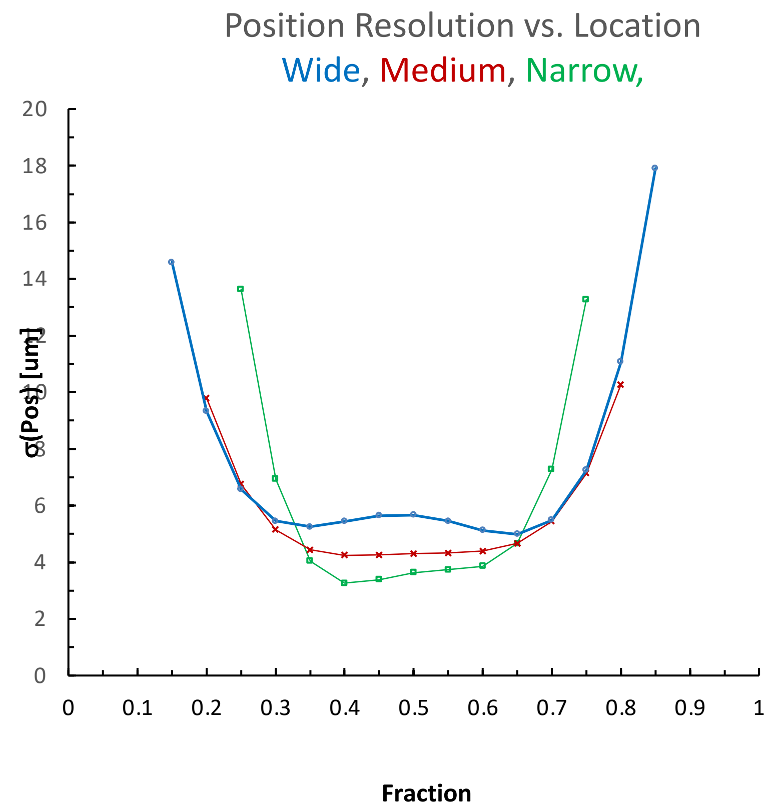
Sensor has strips with pitch 100, 150, or 200 microns, strip metal width always 80 microns. Signals on collection of strips as we move across sensor in space. Data from Fermilab beam test. Position given by tracking telescope.





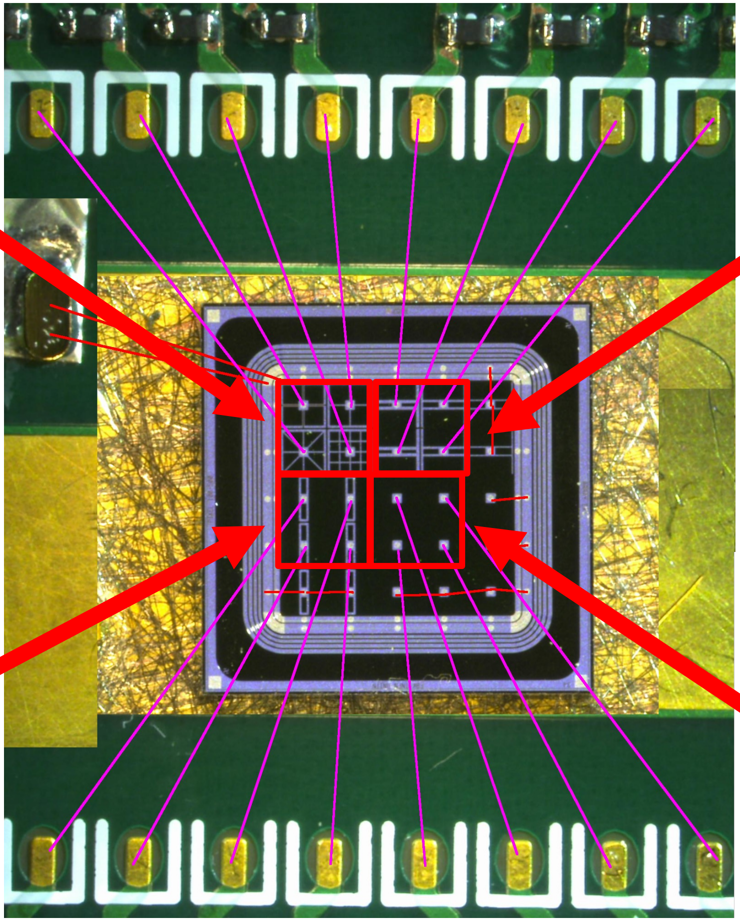
Signal Sharing between neighbors versus location, 5^{th} order polynomial fits, and resulting position resolution





FBK RSD2 pad sensor, with different structures, 500um pitch

“cages
”



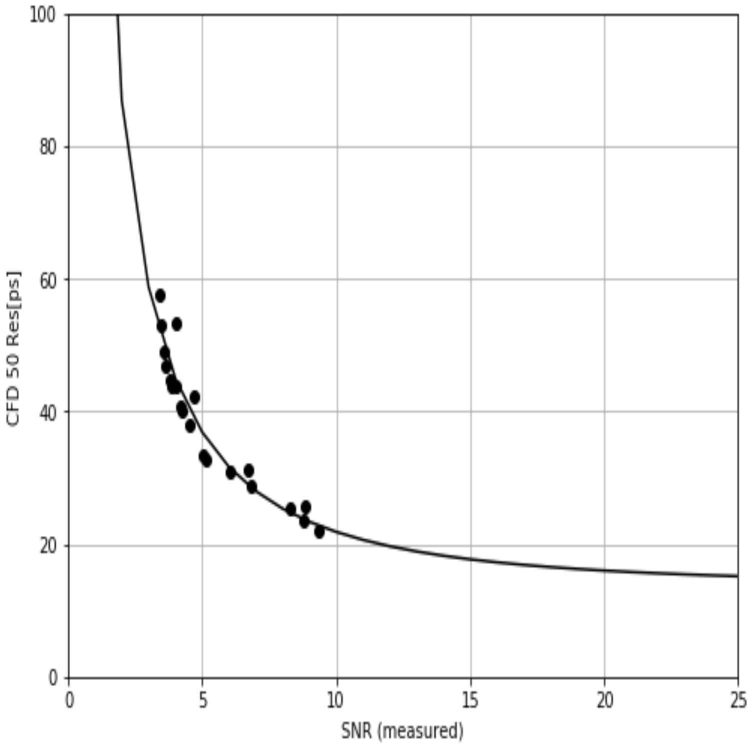
“H pads”

“micro-
strips”

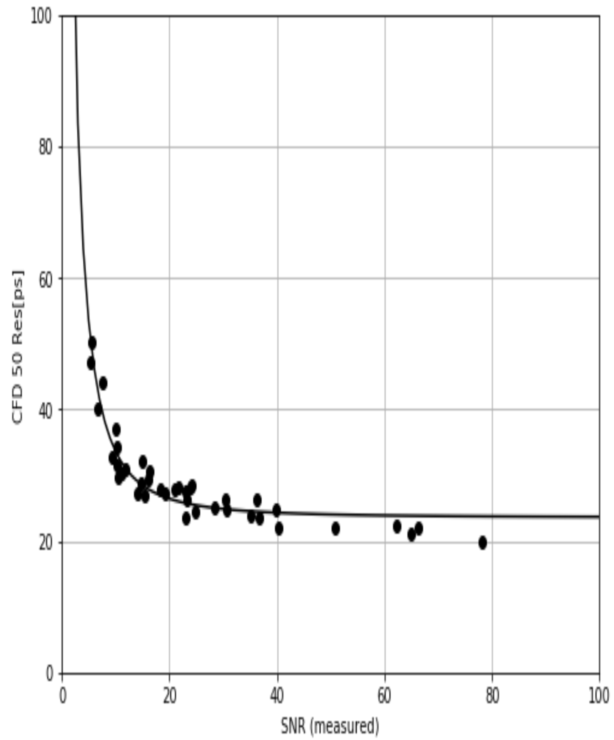
“pads” (500um-
100um)

Measured time resolution versus signal-to-noise ratio for thin detectors

20 micron thick sensor



35 micron thick sensor



Time resolution for minimum ionizing particles measured for thin detectors versus the signal-to-noise ratio. Signal is defined as the peak height and can be adjusted by changing the detector voltage (and gain). Left: for 20 micron thick detector. Right: for 35 micron thick detector. Note the modest value of signal-to-noise required to get to about 20 picosecond time resolution for the 20 micron thick sensor.

Radiation Hardness

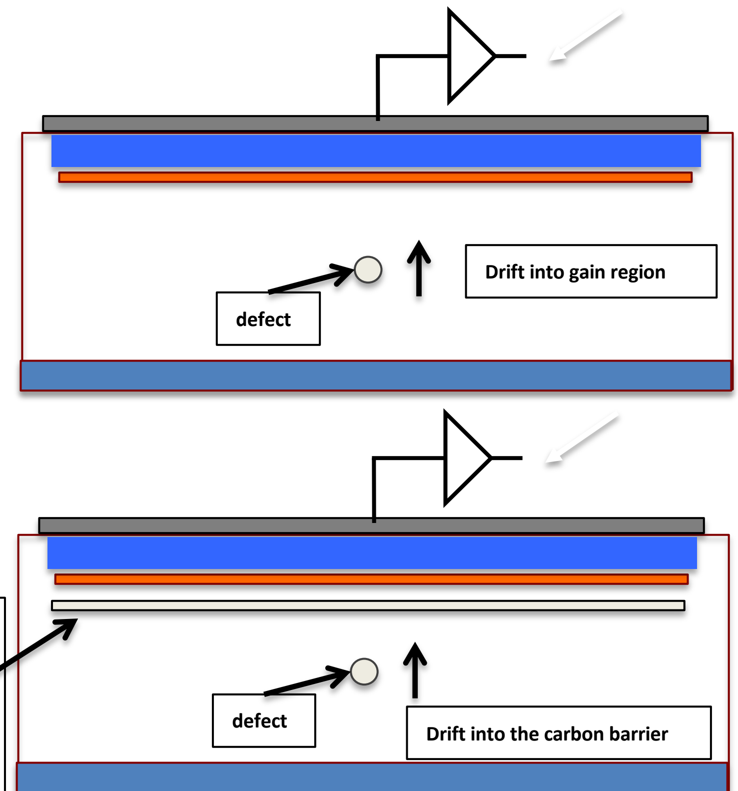
- The fact that an LGAD is thin reduces dramatically the trapping of drifting charge after irradiation compared to a standard 300 micron thick silicon detector.
- Unfortunately the p+ gain layer is subject to deactivation after irradiation. This can be compensated up to a point by raising the voltage on the detector. Some improvement is possible by making the gain layer thin and especially the addition of carbon in the gain layer. The carbon captures the harmful defects more readily than the gain layer material.
- However, the LGADs are sufficiently radiation hard for many applications without any special measures such as the addition of carbon. Examples: the detectors planned for the Electron Ion Collider or the active target for the PIONEER experiment to be run at PSI toward the end of this decade.
- For the HL-LHC, the CMS timing detector should be sufficiently radiation hard to last the full lifetime of the experiment, the ATLAS device will likely require a replacement during the lifetime since it suffers a larger fluence.
- For a possible future very high energy hadron collider, improvements in radiation hardness will extend the radial region over which LGADs can be used. Several ideas will be explored in the near future.

Carbon Shield

Carbon implantation in the gain layer has been shown to improve radiation hardness by a factor of a few to about $3\times10^{15}\ n_{eq}/cm^2$.

Assumption: defects have high mobility, so they drift from the bulk into the gain implant, deactivate boron implant.

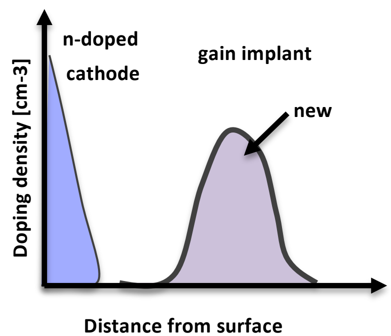
Solution: add a carbon barrier to capture more defects.



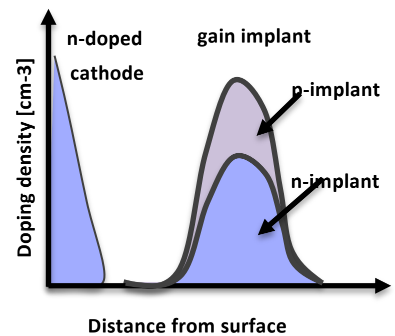
Deep carbon implant acting as absorber of defects drifting into the gain layer

Another idea: Compensated gain implant

New sensors



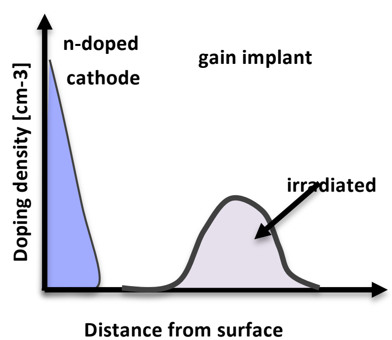
Present LGAD design



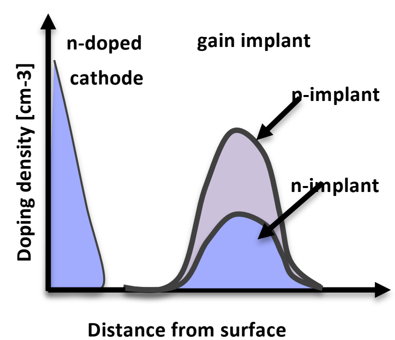
Compensated LGAD design

Design the gain implant as the difference between a p-doped and an n-doped implants

Irradiated sensors



Present LGAD design



Compensated LGAD design

The p-n difference is more stable than a single p-implant

Conclusions

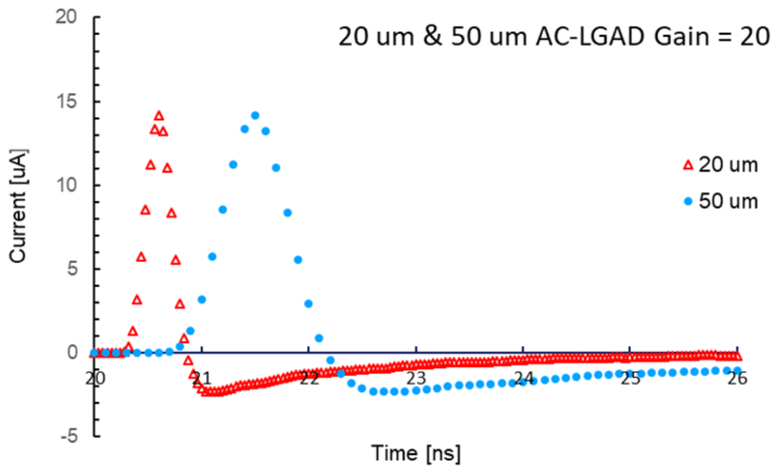
- LGADs with a gain of ~ 20 allow a much increased signal to noise compared to a standard silicon sensor. By making them thin, for example 50 microns, can achieve a very good timing resolution, for example ~ 30 psec.
- AC-LGADs are a relatively new type of silicon sensor. We are learning much more about them now.
- They combine the advantages of gain from the LGAD with signal-sharing to allow very good time resolution and position resolution. Allows sparse readout to minimize overall power.
- To achieve better timing resolution requires a thinner sensor than 50 microns to minimize Landau fluctuations.
- Development of an appropriate amplifier to make use of the fast signals from an AC-LGAD and power minimization is required. A few efforts are underway. The possibility for low capacitance for small metal structures is helpful for the amplifier development.

Backup Slides

Specification for Fast LGAD Read-out

The development work of LGAD sensors was/is based on high-speed readout boards with discrete components introduced by SCIPP.
The crucial characteristics of LGAD signals were mapped out.

Measured Pulse shapes of AC-LGAD



LGAD Characteristics	50 um	20 um
Rise Time (10-90%) [ps]	455	182
Input Charge (G = 20) [fC]	11	4.6
I_{MPV} Input Current [uA]	15	15

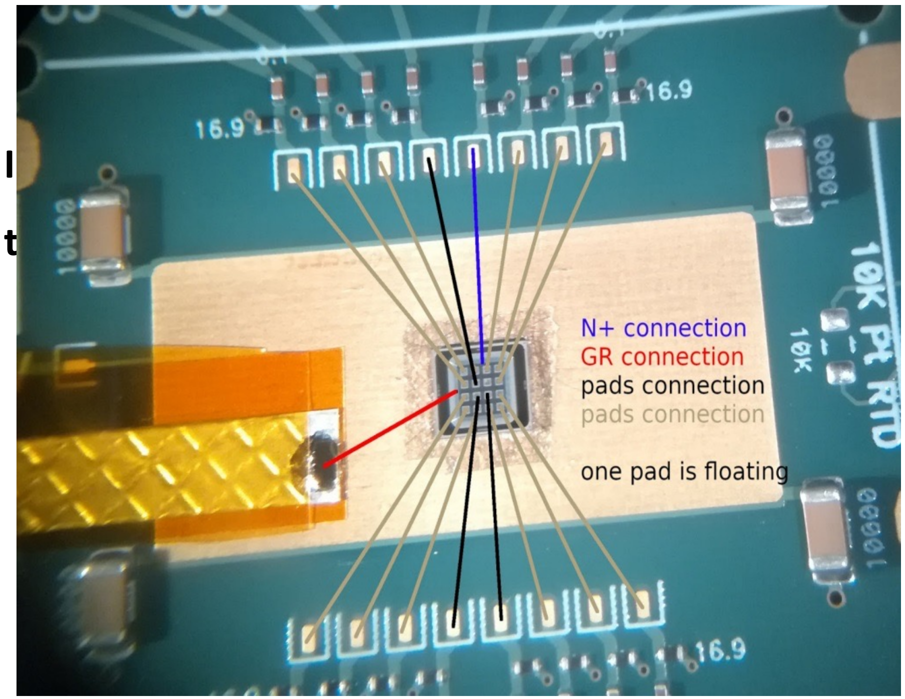
It allowed to come up with specifications for different applications in terms of temporal and spatial resolution and the double pulse capability and translate them into required performance parameters for ASICs ("Design Goals").

Design Goals

ASIC Parameter	50 um Sensor	20 um Sensor	Comment
Rise time (10 – 90%) [ps]	455	182	Rise time (electronics) = Rise time (sensor signal)
Jitter [ps]	10	5	< 30 % of the predicted "Landau" Noise
S/N	> 50	> 40	S/N = Rise Time / Jitter
Voltage signal [mV]	70	70	$V_{MPV}=R_{FB}*I_{MPV,}$ [R_{FB} = 5 kΩ]
Noise RMS [mV]	1.4	1.8	N = S/(S/N)
Internal Sensor Gain	> 20	> 20	

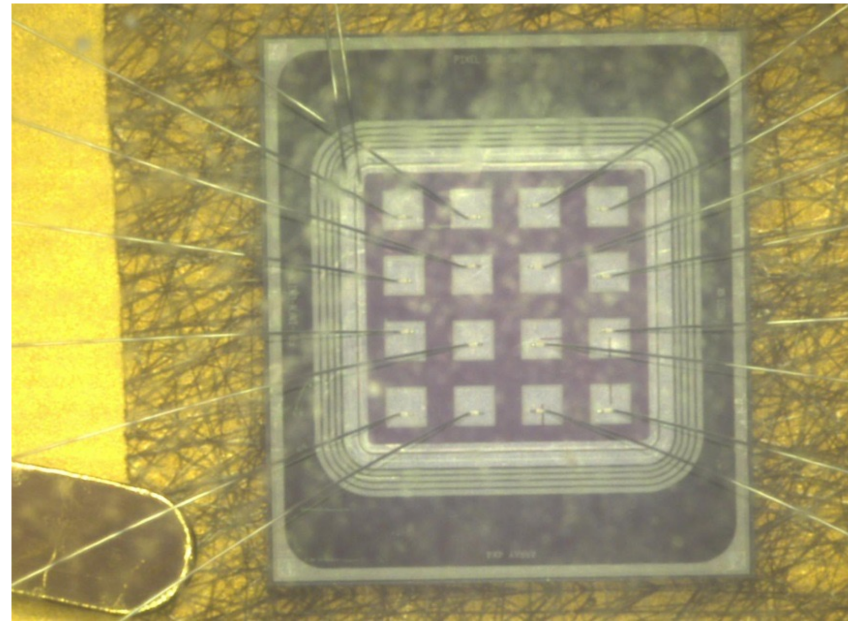
AC-LGAD Setup for IR Laser Scan

16 channel board courtesy of FNAL



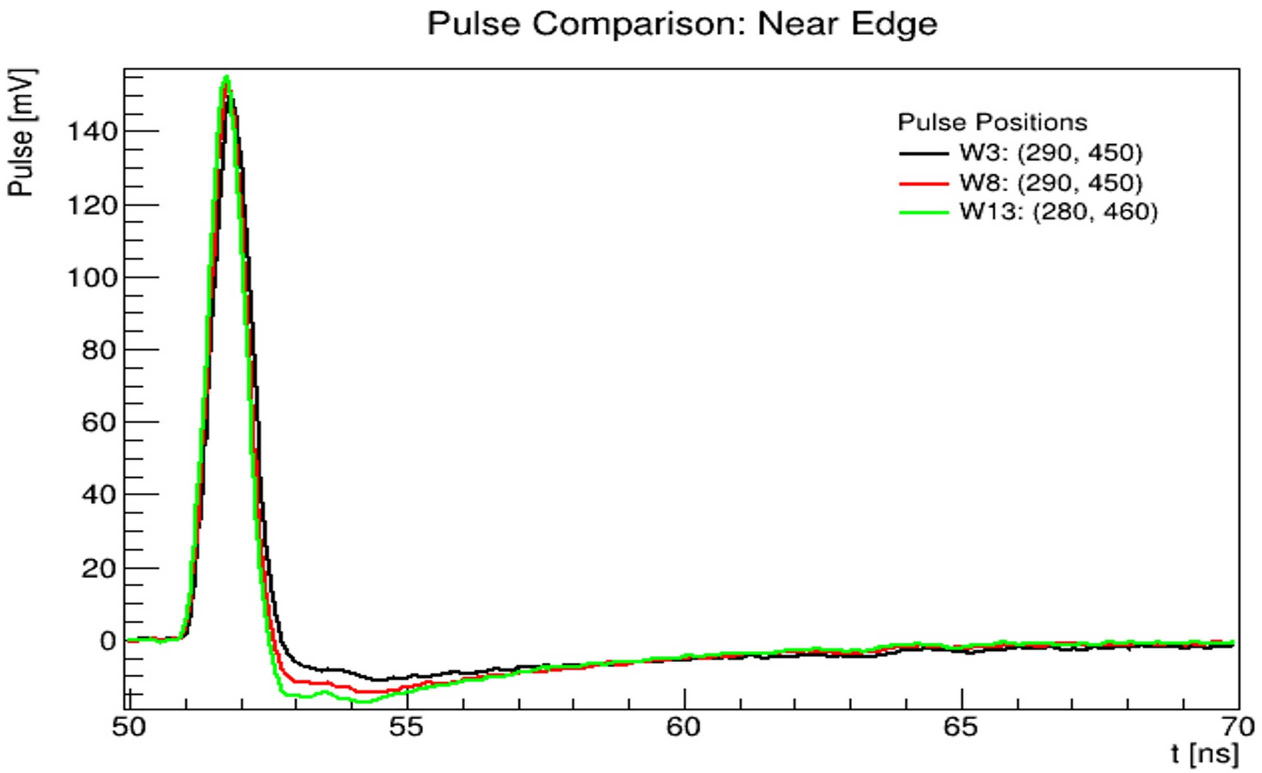
16 Channel AC-LGAD

All AC-LGAD pad detectors provided by FBK



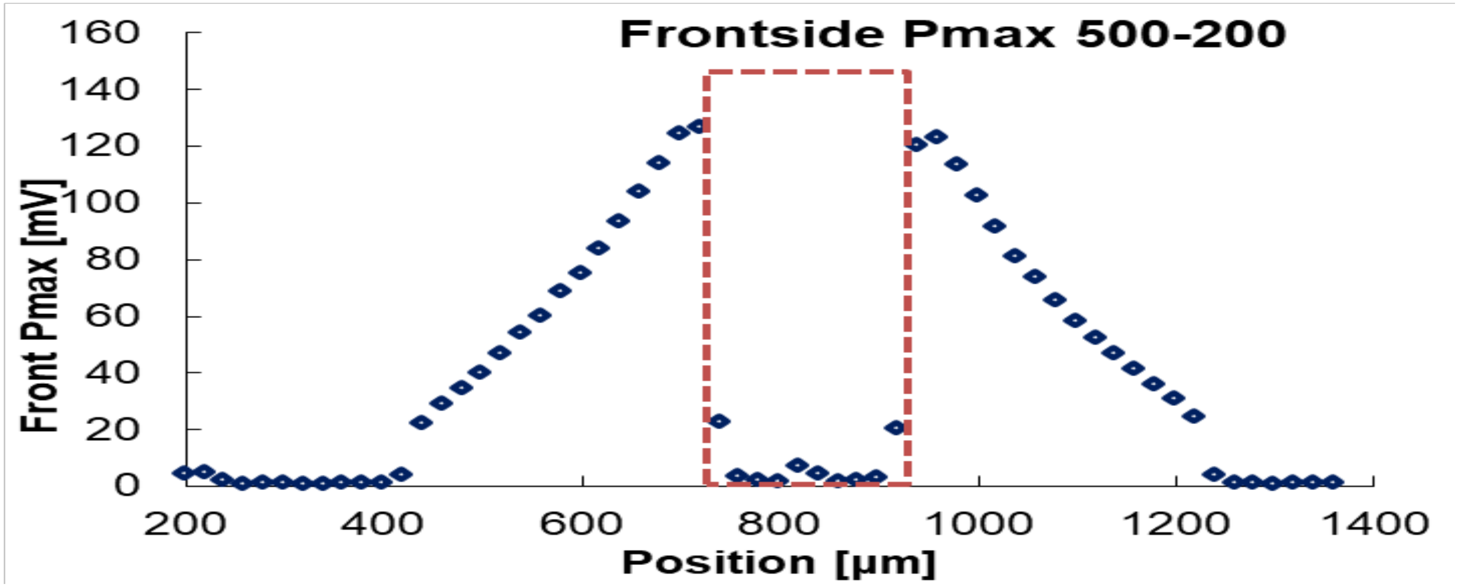
Laser scans were performed to measure sensor signals for ~ mip equivalent energy deposit. Sensors 55 micron thick, gain ~ 20. Signals saved using storage scope. Time reference provided by laser. Laser spot size ~ 20 microns.
Most scans from front, in some cases the backside metal was removed and scans from the backside were performed.

Pulse Comparison: 3 Different n+ doping concentrations.



Doping of n+ layer for sensor indicated as W8 in figure is ~1/10 of standard DC-coupled LGAD. W3 is ½ as doped, W13 twice as doped. Small changes observed, with under shoot dependent on doping choice. Other parameters such as rise-time vary by ~ 5%.

Position Measurement for 500-200



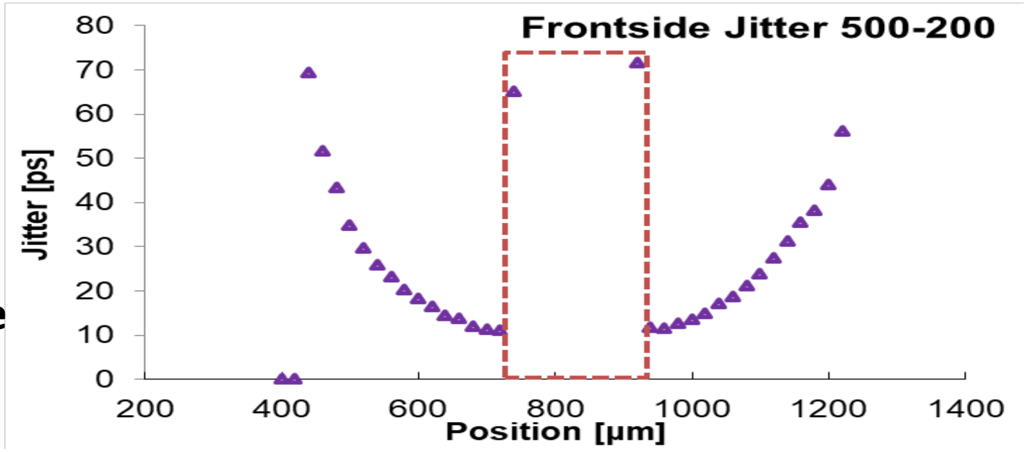
Pulse maximum decreases nearly linearly as we move away from a pad. A measurement of the coordinate along the direction we are scanning, referenced to the center between the pads, is therefore approximately: x = (P1 – P2)/(P1+P2) where P1 is shown above and P2 is pulse height for neighbor (not shown). (P1 + P2) is nearly constant independent of location in x. From this one can calculate the expected error on x in terms of the uncorrelated variation on the pulse heights from electronics noise. The linear approximation gives for the error on x:

σ_x = [Interpad Spacing/ signal-to-noise ratio] f

The signal-to-noise ratio is the electronics noise (assumed to be the same for each pad) divided by (P1+P2) and f is a factor near 1 given by: [0.5/(maximum value of (P1-P2)/(P1+P2)] sqrt $(P1^2 + P2^2)/(P1+P2)$. The position resolution varies only a little with x.

Time Measurement for 500-200

500-200: Jitter = 11 ps near pad (note no Landau contribution for Laser). Further away use several time measurements.

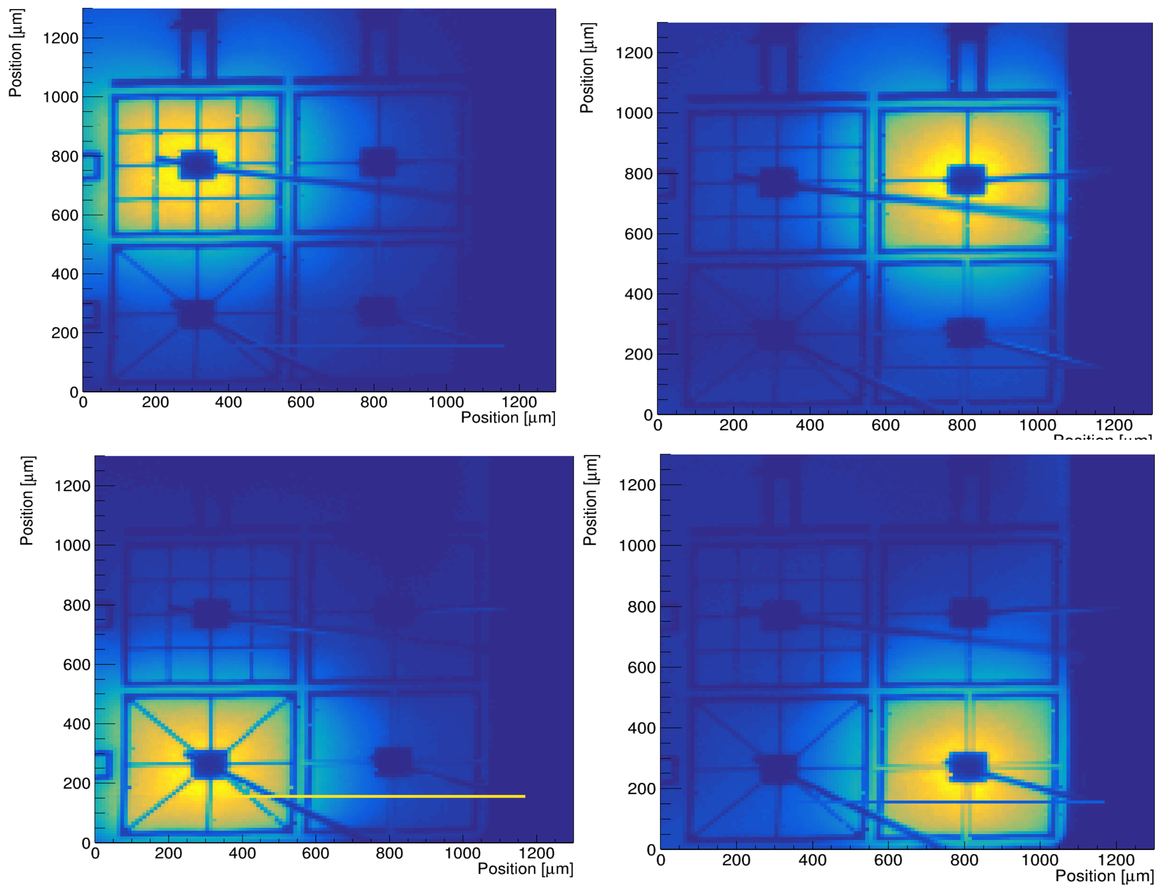


We have a collection of times measured on several pads and need to combine for a best value and error estimate. Assume any systematics have been corrected and we have times t_i for the various pads (usually 3 or 4). The jitter for each (where jitter is the contribution from the electronics system, assume Landau fluctuations are in common) is then estimated to be $T_{MAX}/(P_i/\sigma_{NOISE})$. Here T_{MAX} is the 10-90% rise-time of the signal, σ_{NOISE} is the electronics noise, and P_i is the maximum pulse height. Assuming that T_{MAX} and σ_{NOISE} are the same for all signals, we can then calculate that the best estimate for the time and its error, which are;

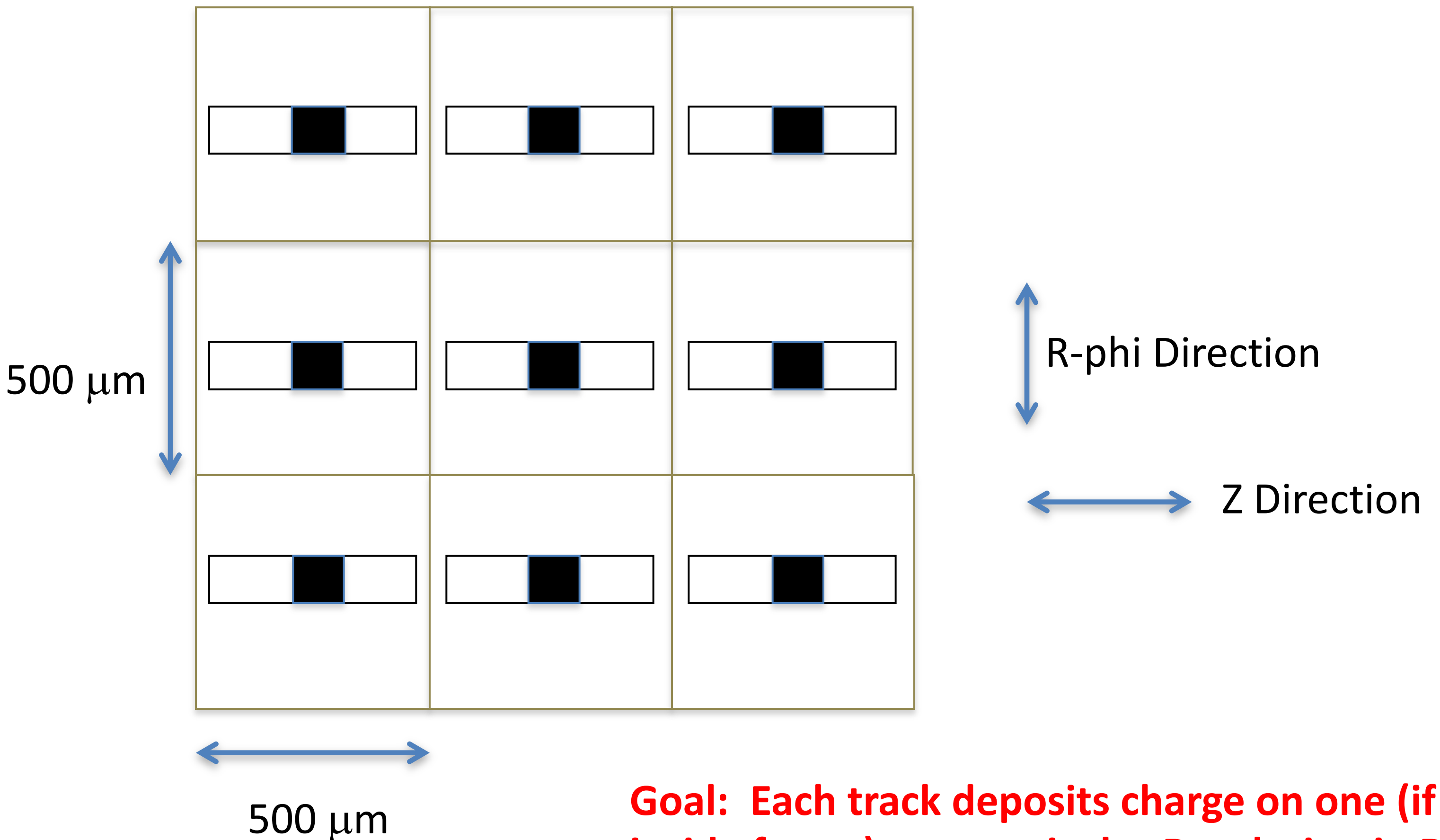
$$t = \Sigma\, t_i\, P_i^2 / \Sigma P_i^2 \quad \text{with} \quad \sigma_t = T_{MAX} / [\mathrm{sqrt}\,(\Sigma P_i^2) / \sigma_{NOISE}]$$

Data above for one pad follow expectation that resolution is inversely proportional to the pulse height.

- Other geometries FBK RSD2 pads, “cages”

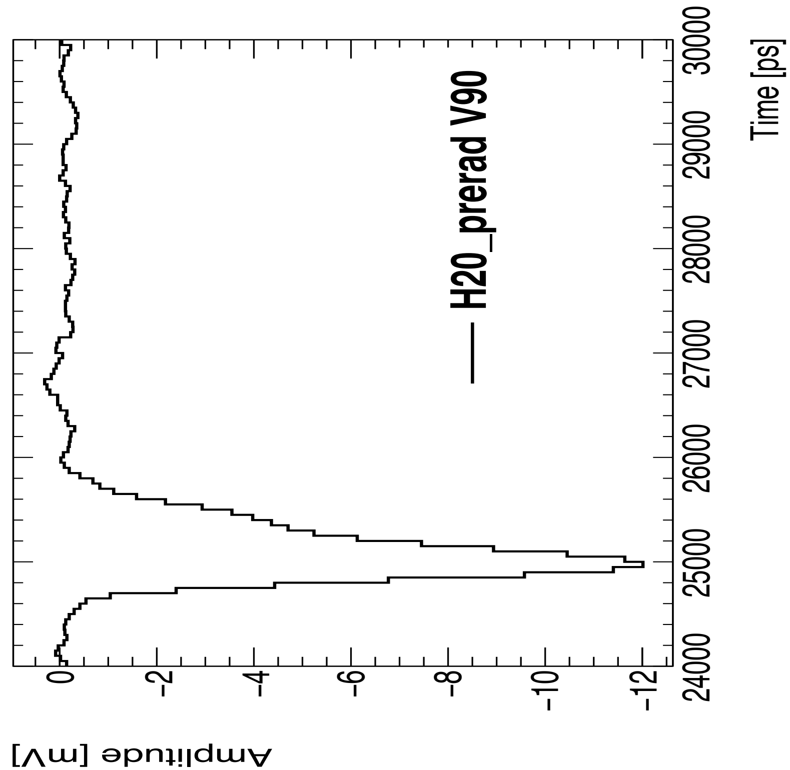


Pixel Pattern on Sensor: 50 μm pad in middle of each pixel for bump bonding with connected thin metal frame (to minimize capacitance) running to edge of each pixel in the Z direction.



Goal: Each track deposits charge on one (if hit is inside frame) or two pixels. Resolution in R-phi is 15 μm, in Z it is 150 μm. Hits outside frame use interpolation for arriving at R-phi position

Thinner detectors offer potential for even better timing resolution. So far measurements only exist for DC-coupled LGADs, example shown below.



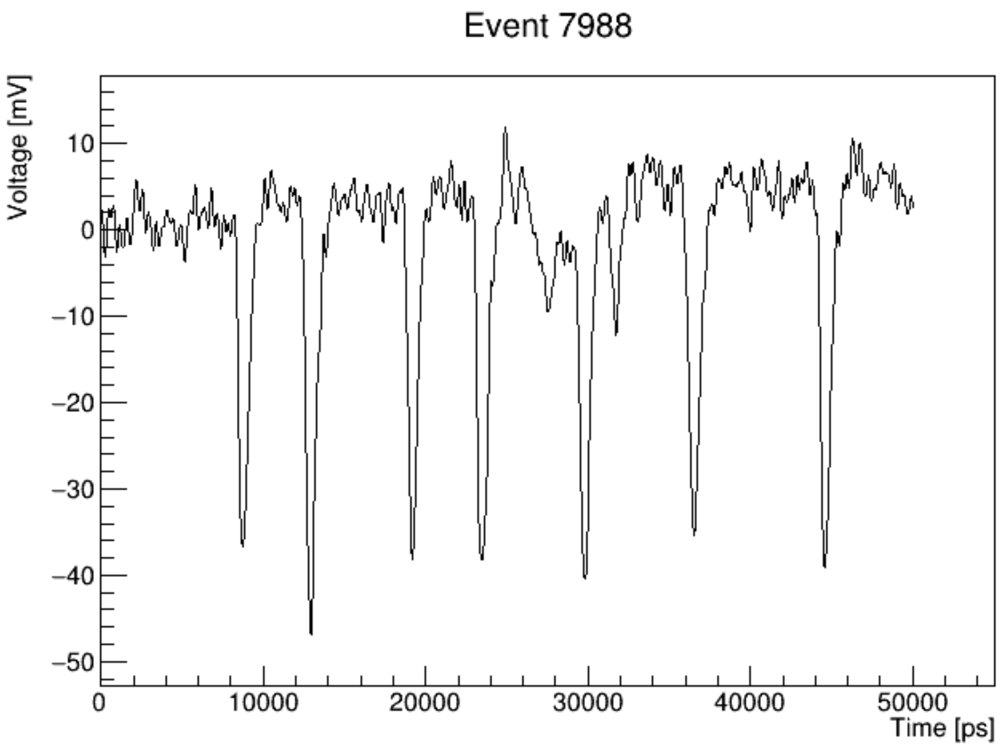
Pulse for 20 micron thick LGAD. Gain ~ 8. Sensors fabricated by HPK in Japan.

Rise-time (10-90%) about 170 picoseconds compared to about 430 picoseconds for 50 micron thick sensors. Contribution to the time resolution from Landau fluctuations is proportional to the detector thickness so smaller for thinner detectors (expected to be less than 15 picoseconds for the 20 micron thick sensor). Have not yet quantified effect of detector thickness on pulse sharing between pads for AC-LGAD.

Power in Electronics

- For a large area tracker the power in the electronics presents an important constraint on the design.
- For example the AC-LGAD pad results shown were for 500 μm pitch. The power question has motivated our focus on 500 μm pitch.
- The number of channels for a 2cmx2cm chip would be 1600 for 500 μm pitch pads. A goal of ~1 watt/chip would put this in a comparable range to other large silicon detectors built or planned.
- The 500 μm pitch also provides a reasonable amount of space for each electronics channel assumed to be bump bonded to the sensor.
- For 500 μm pitch strips with 5 mm length the reduction in the number of channels would be another factor of 10.

Excellent Rate Capability for LGADs: Signals in an 8 keV X-Ray Beam



2 nsec between closest signals – this is beam bunch structure.