https://indico.bnl.gov/event/17621/

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U.S. DEPARTMENT OF ENERGY

AC-LGAD Sensor Status and Plan

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1/11/2023

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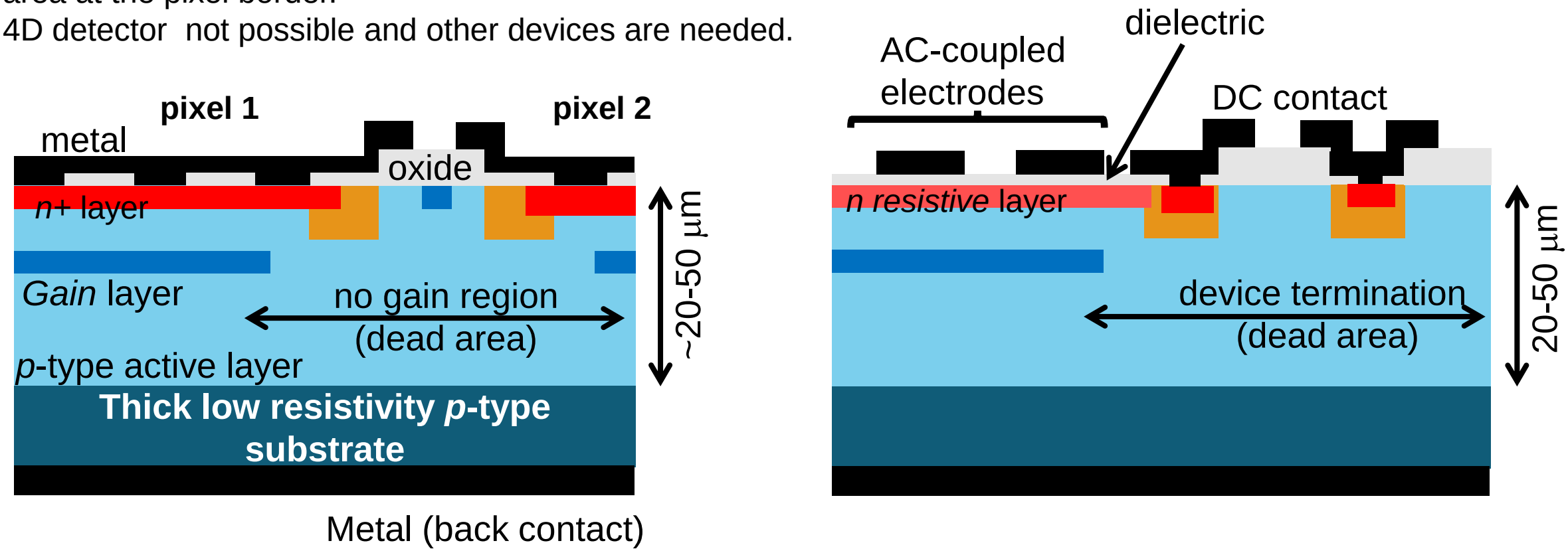
LGAD vs AC-LGAD

Low-Gain Avalanche Diodes show good timing resolution (30ps) but poor spatial resolution, due to large dead area at the pixel border.
4D detector not possible and other devices are needed.



Capacitively-Coupled Low-Gain Avalanche Diodes have large uniform area for 100% fill factor (no dead areas), and potentially same timing resolution. Excellent spatial resolution when signal sharing is used to interpolate hit position.
Process modification needed to pass from LGAD to AC-LGAD but still feasible in standard Clean Room.

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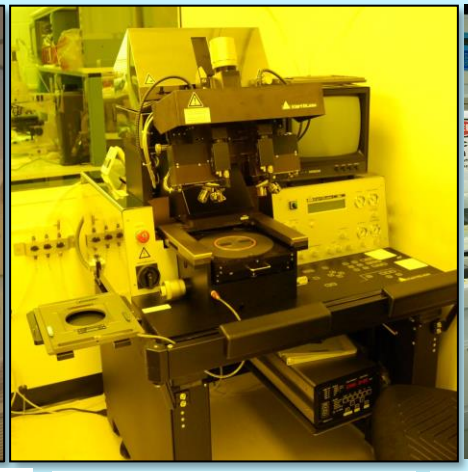
BNL Clean Room for silicon sensors

LGAD and AC-LGAD can be fabricated at BNL, using standard tools.
Ion Implantation is outsourced: paramount importance process step that dictates gain.

All silicon process done in BNL Instrumentation Division Class-100 Clean Room

Furnaces for high-quality SiO_2 growth and annealing



Double-sided mask aligner

Wet bench (HF, RCA I & II, piranha, …)

Sputtering (Al, Al1%Si, Ti)

RTA for sintering

Laser dicing

Design + TCAD + process flow: all in house

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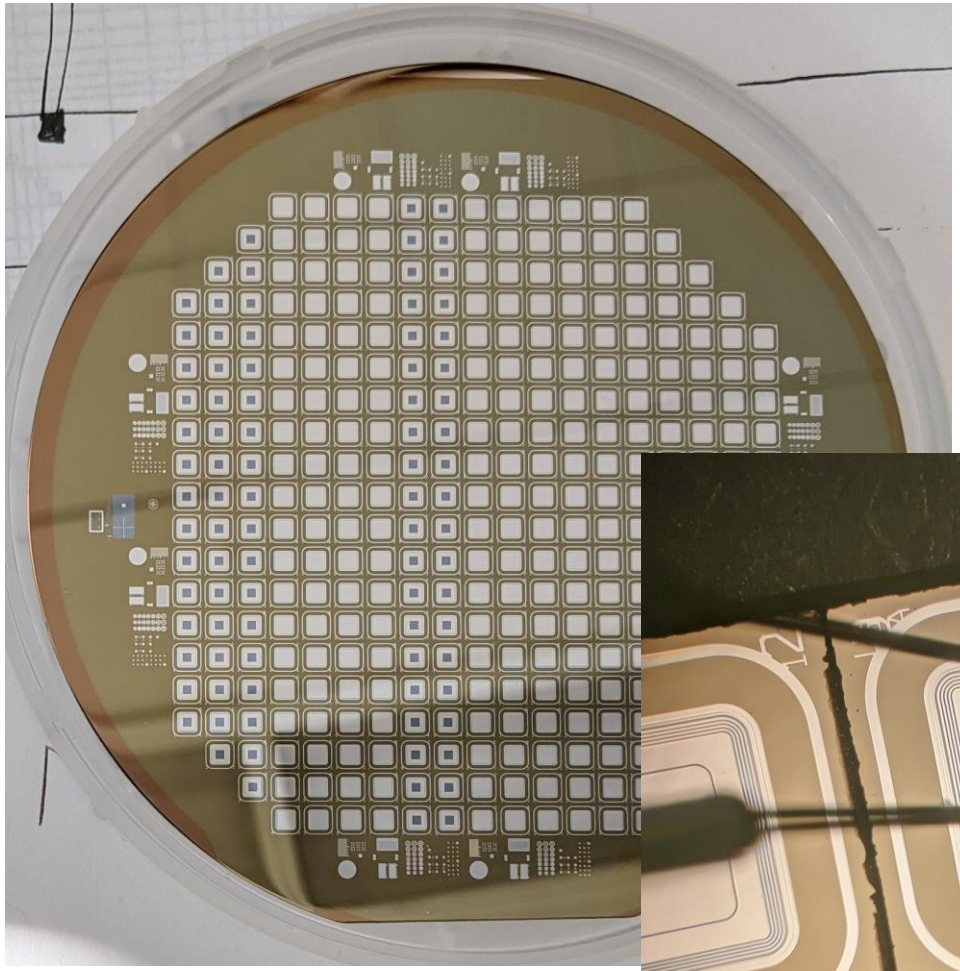
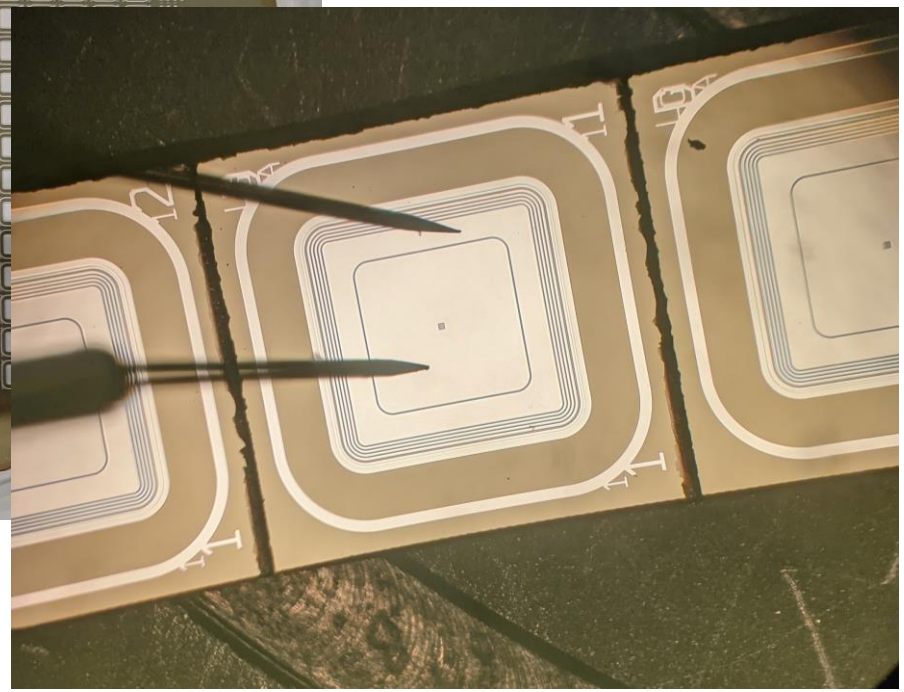
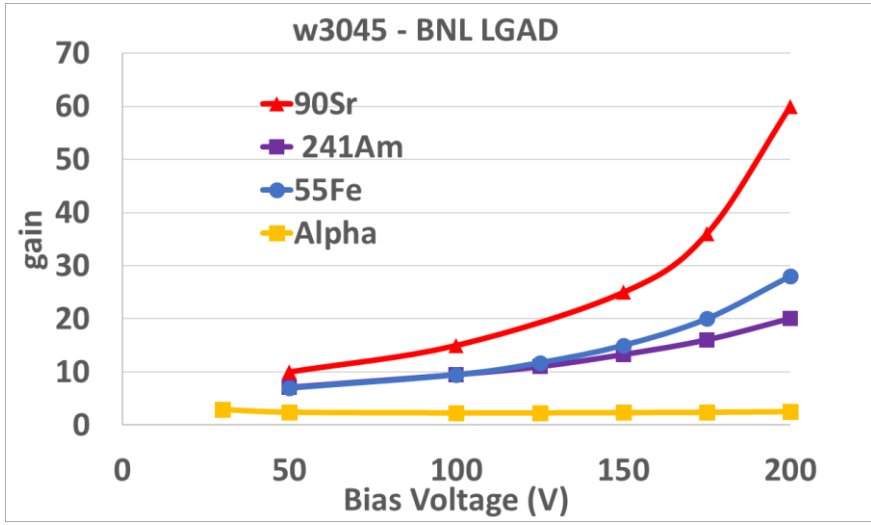
LGAD



- Single channel LGADs
- 1.3 mm x1.3mm
- 20, 30, 50 um thick
- Fabricated for:
  - testing purposes (some solution brought to AC-LGADs)
  - Processed in parallel
  - Training of students and new hires
- Easier to test than AC-LGADs.



With present technology:
max gain = 60 for mips



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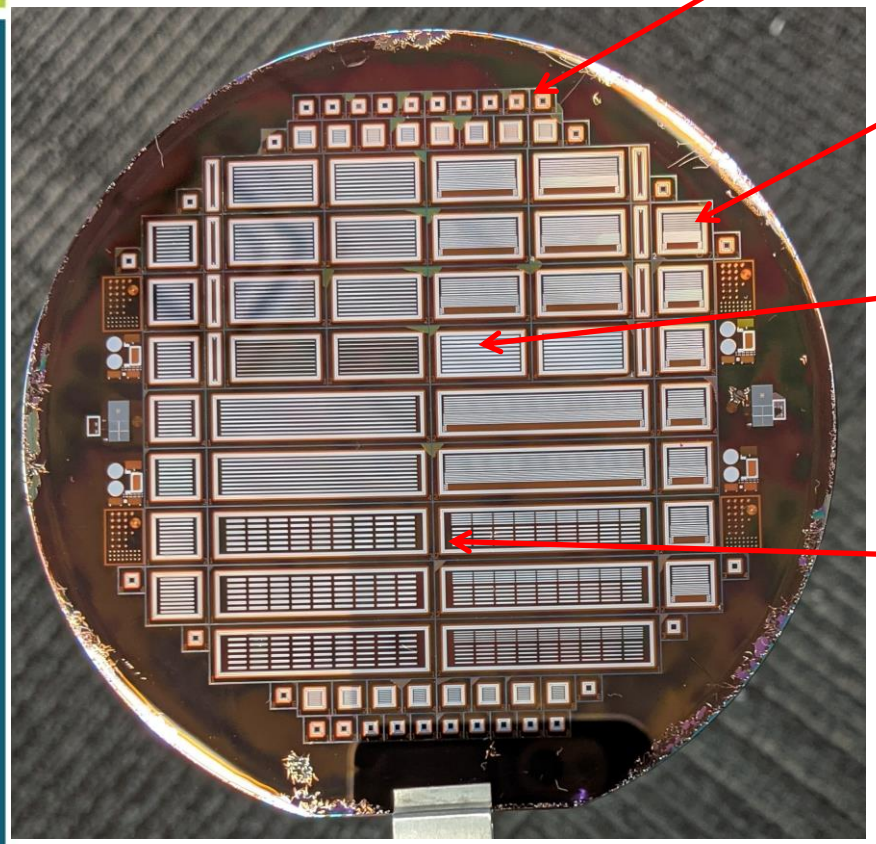
AC LGAD strip
layout # 1



4 wafers fabricated
(2 50um + 2 20um)

Layout #1

	2x2 mm2		
	pitch	gap	
7x	200	100	
	5x5 mm2		
	pitch	gap	
7x	500	300	
7x	300,200,100	150,100,50	multipitch
	5x10mm2		
	pitch	gap	
6x	500	300	
6x	300,200,100	150,100,50	multipitch
2x	500	400	
2x	500	200	
	5x25mm2		
	pitch	gap	
2x	500	300	
2x	300,200,100	150,100,50	multipitch
2x	700	350	2.5mm long pixels
1x	700	450	2.5mm long pixels
1x	500,300	350,200	2.5mm long pixels, multipitch
2x	500,300	250,150	2.5mm long pixels, multipitch

Pitch usually 500um
but smaller pitches used for test

Variations on the metal width

Variations on strip lengths

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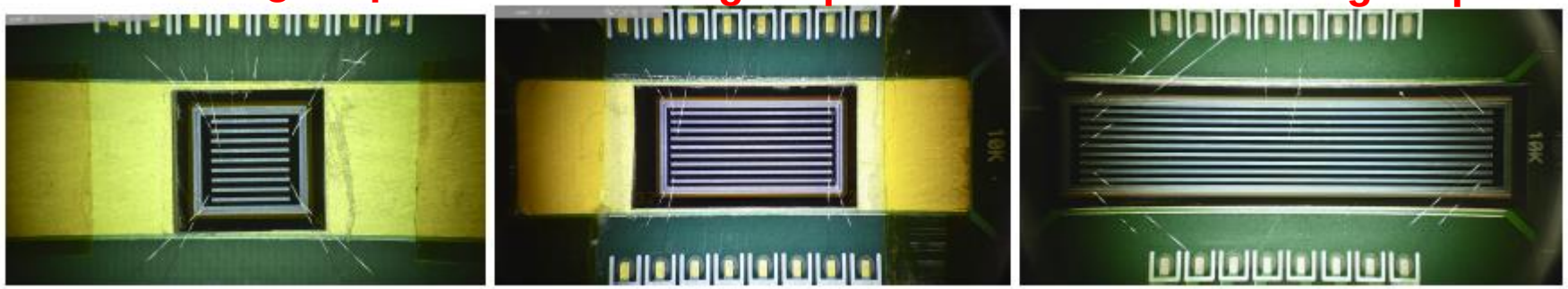
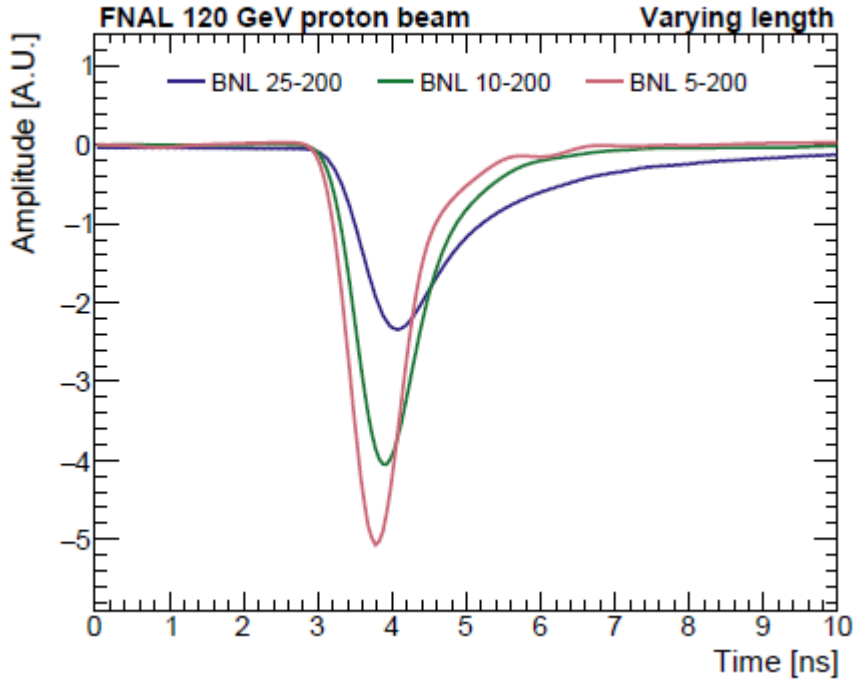
120GeV proton test beam @ FNAL

0.5cm long strips **1cm long strips** **2.5 cm long strips**



~ 15 devices mounted on FNAL 16 ch RF boards and tested at FNAL



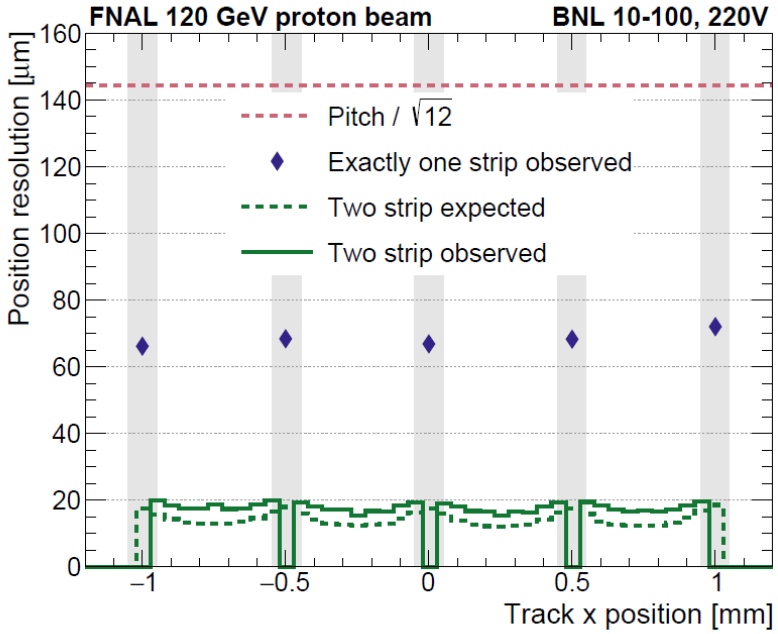
Average waveforms for different strip lengths (same strip width to help comparison).
Rise time significantly depends on strip length – possibly due to larger capacitance at the RF-amp inputs.

Not significant difference for different metal widths

C. Madrid et al. "First survey of centimeter-scale AC-LGAD strip sensors with a 120 GeV proton beam," https://arxiv.org/abs/2211.09698

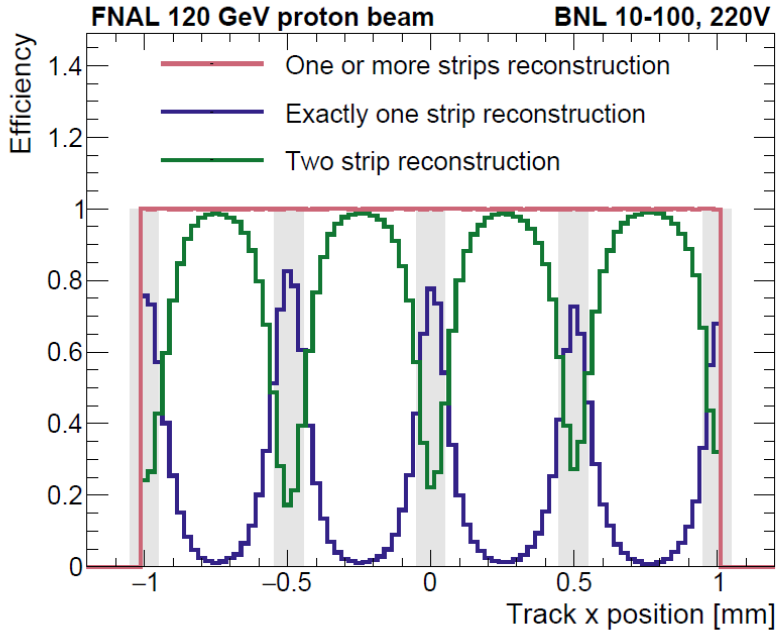
FNAL Test Beam Results - 1

Position resolution



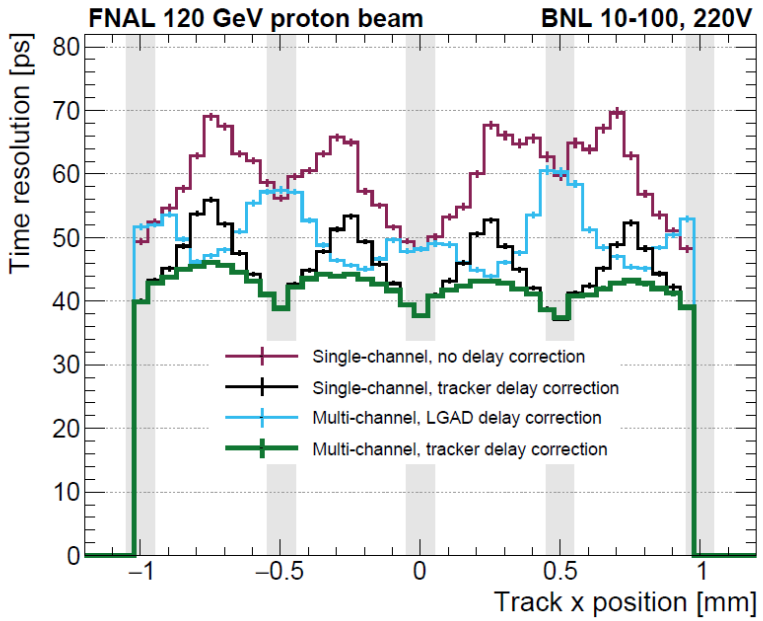
Interpolation from more strips brings the spatial resolution down to > P/20

Efficiency



100% fill factor: no dead area (except at the periphery)

Timing

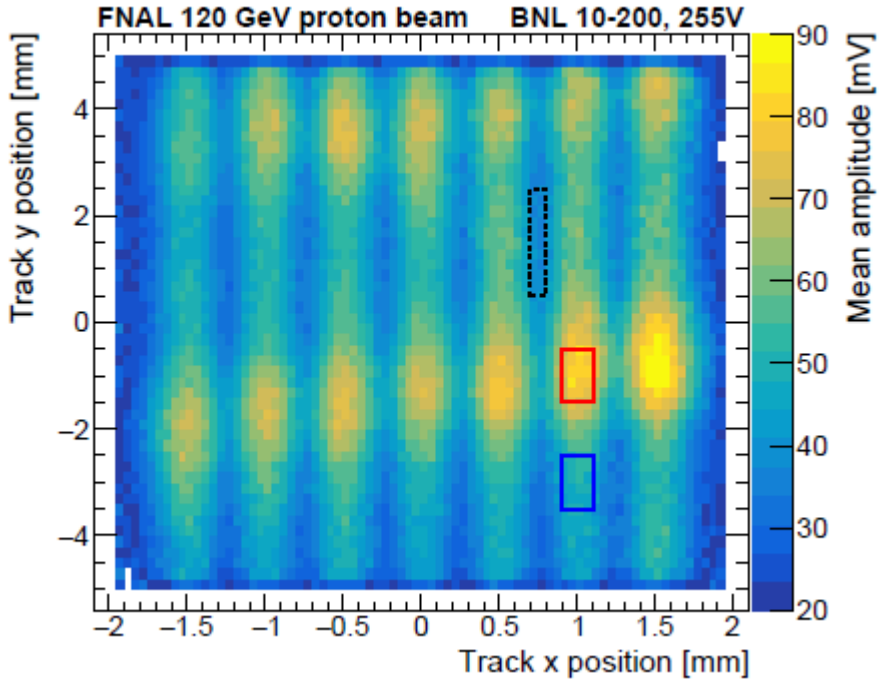


Time from 2+ channels, with correction for the propagation time to the RF input (via tracker)

C. Madrid et al. "First survey of centimeter-scale AC-LGAD strip sensors with a 120 GeV proton beam," https://arxiv.org/abs/2211.09698

FNAL Test Beam Results- 2

Issue of non uniformity: high- gain spots aligned on some tracks.
Pointing to gain implant non-uniformity (1% difference makes a big difference)



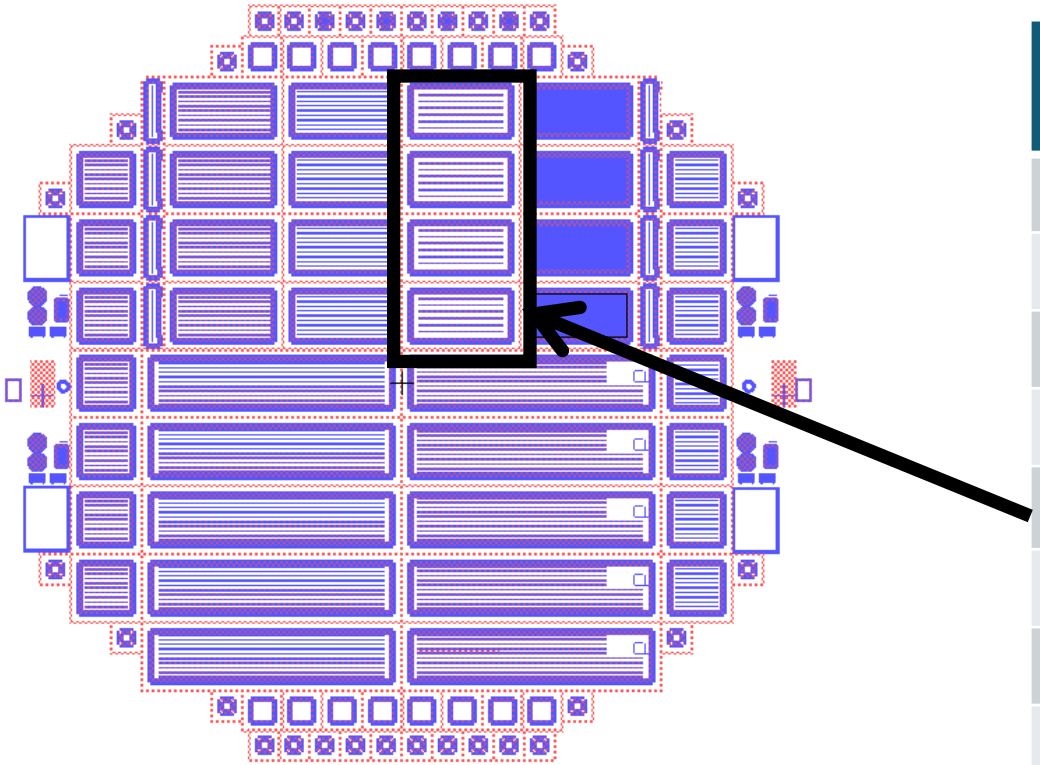
Considering hot spots only, timing and spatial resolution are better.
These vales are to be expected in a uniform gain sensor.

	Time resolution	Spatial resolution			
		Exactly one strip		Two strip	
Name	High gain	Resolution	Eff.	Resolution	Eff.
Unit	ps	μm	-	μm	-
BNL 5–200	30 ± 1	61 ± 1	35%	12 ± 1	65%
BNL 10–100	35 ± 1	69 ± 1	23%	19 ± 1	77%
BNL 10–200	32 ± 1	82 ± 1	43%	18 ± 1	57%
BNL 10–300	36 ± 1	83 ± 1	51%	16 ± 1	49%
BNL 25–200	51 ± 1	128 ± 1	82%	31 ± 1	18%

C. Madrid et al. "First survey of centimeter-scale AC-LGAD strip sensors with a 120 GeV proton beam," https://arxiv.org/abs/2211.09698

AC LGAD strip
layout # 2

- Improve uniformity of gain
- Narrow strips for lower capacitance and to reduce single-strip events



multiplicity	mm x mm	Pitch (um)	Gap (um)
7	5x5	500	400
7	5x5	500	450
4	5x10	500	400
4	5x10	500	450
4	**5x10**	**700**	**600**
4	5x10	Zig Zag	
5	5x25	500	400/450
5	5x25	500	400 (l=2 or 2.5cm)

2+2 wafers fabricated
(2 50um + 2 20um)

Test beam on-going @ FNAL

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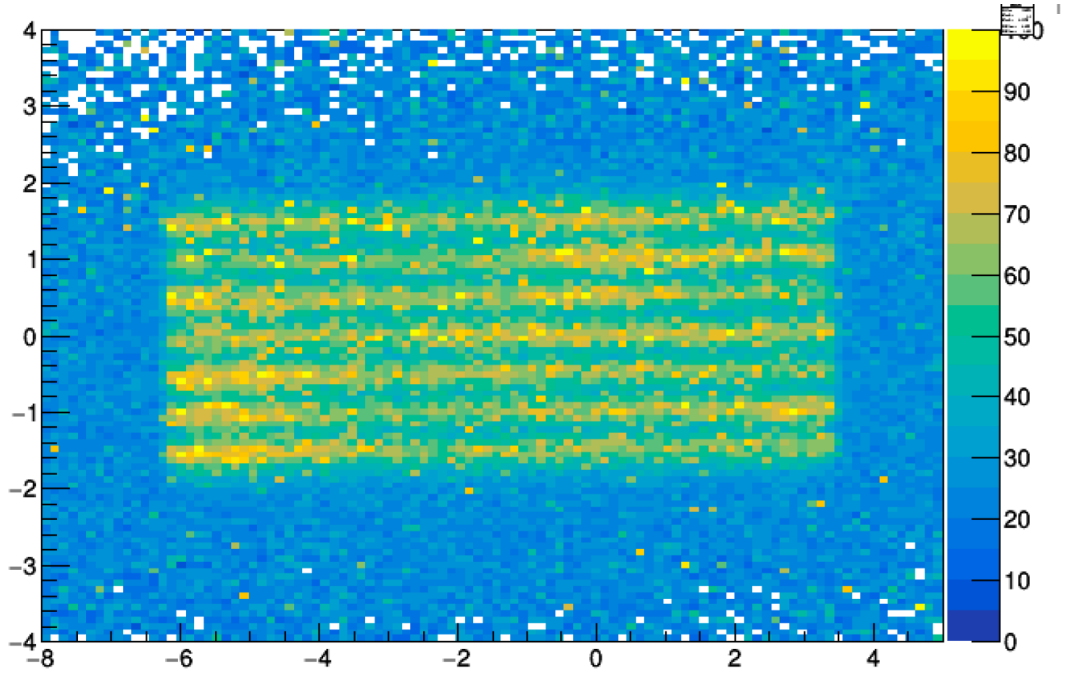
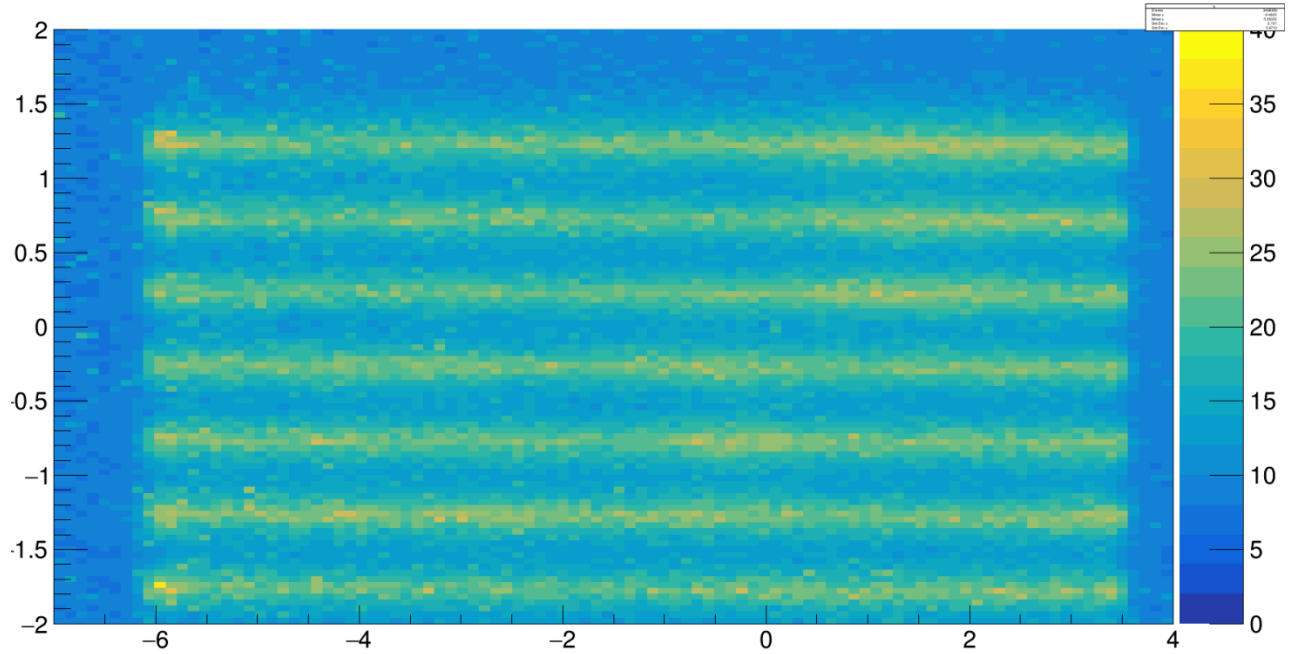
Some Very Preliminary Test Beam Results – January 2023

1-cm long strips, pitch = 500um, strip width = 50 um

50um thick epi layer



20um thick epi layer



- Gain uniformity greatly improved
- Signal in 20um thick epi layer within expectation
- Improvement of the gain would be beneficial

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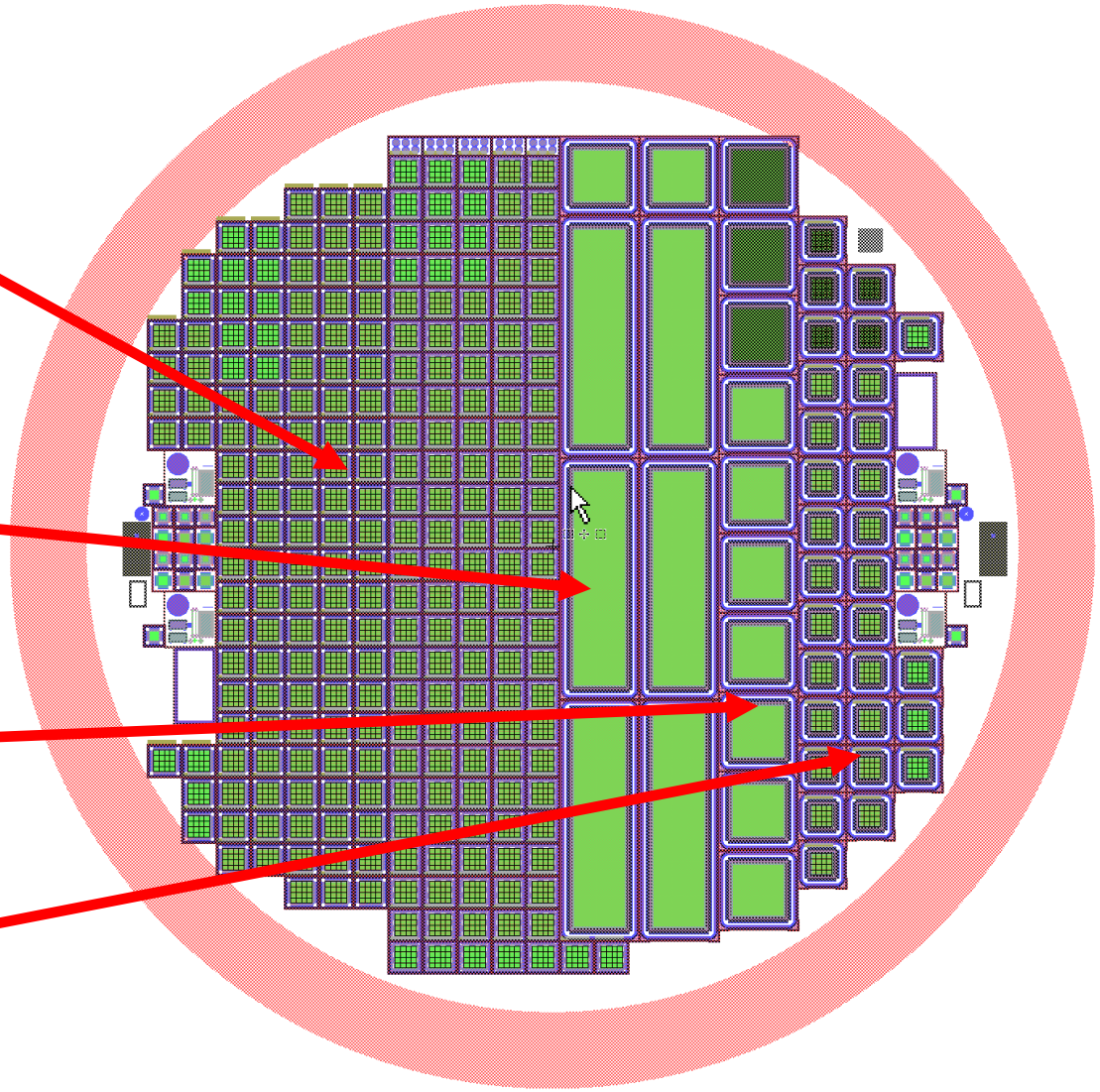
EICROC

Starting wafers: 50, 30, 20 um thick substrates

EICROC bump-bond compatible

All implants done,
Metal not ordered yet,
but designed.
New ideas can be implemented!!!

<u>A fabrication at Hamamatsu (HPK) is also on-going.
Variation of some process parameters.</u>



2cm x 0.5cm

0.5cm x 0.5cm

0.2cm x 0.2cm
Compatible with EICROC

Wafers out begin of February 2023.

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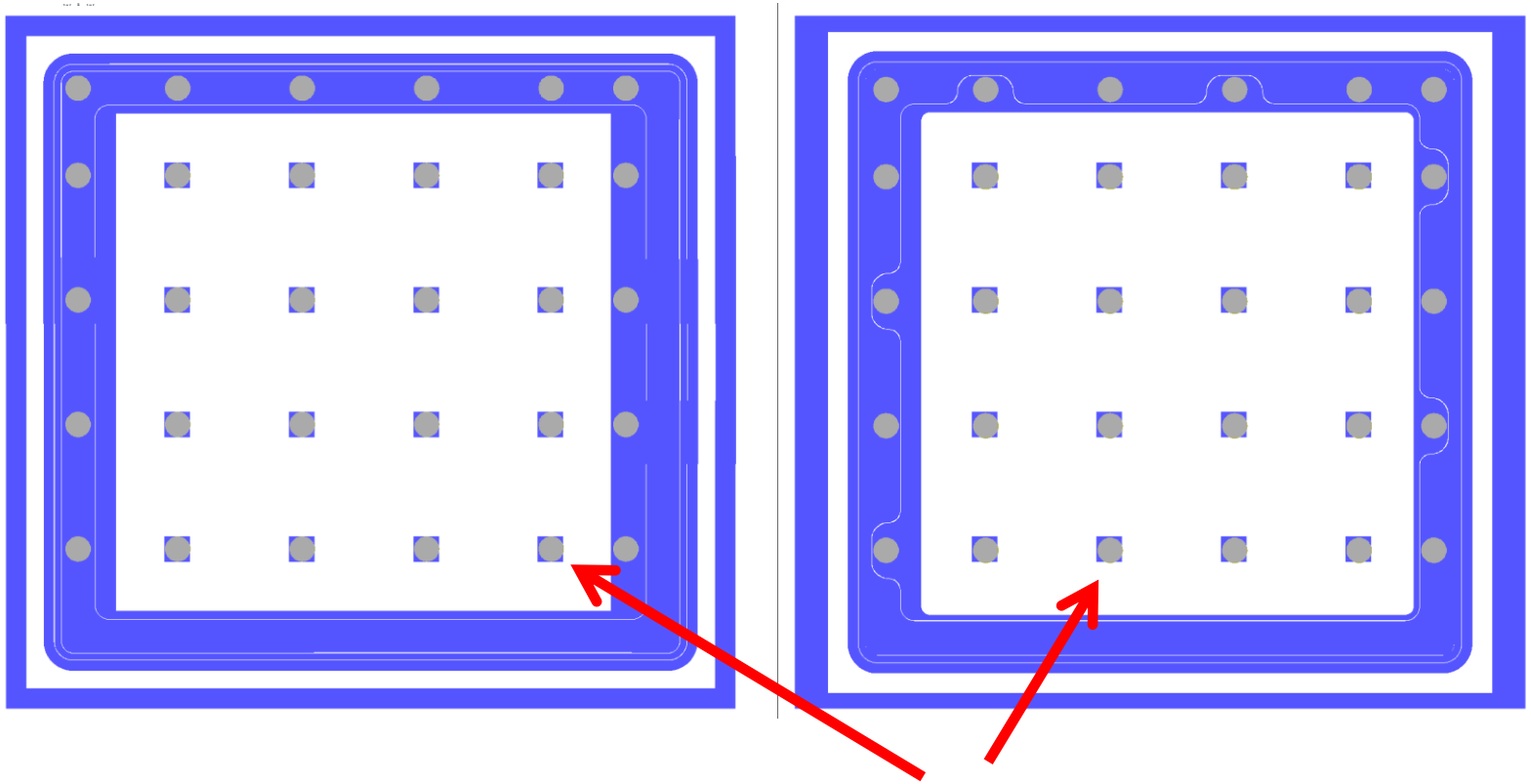
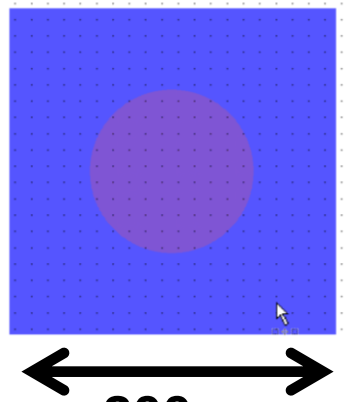
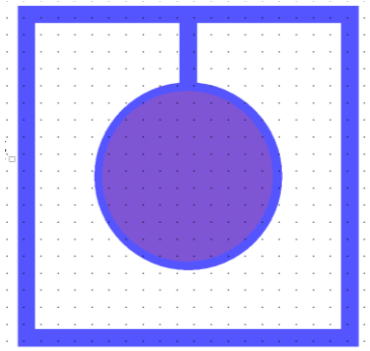
EICROC bump-bond compatible AC-LGAD

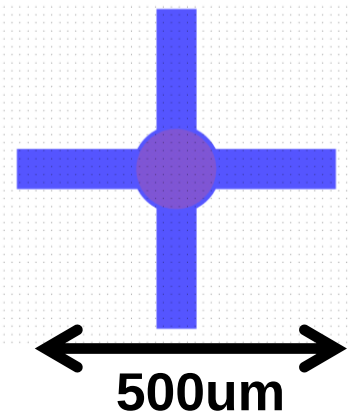
4x4 pixel, 500um pitch.
>10 pads for grounding (Guard Ring + *n*-resistive layer)
Different terminations.
Large number of devices allows a few variations of design (terminations and pixel shapes/dimensions)





Other pixel shapes, for test





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Summary

BNL is engaged in the development of AC-LGADs:

- AC-LGAD strips
- EICROC compatible

AC-LGAD technology features 100% Fill Factor, σ_x < P/20 and σ_t ~30ps (50um thick epi)

Some flaws corrected, but still room for improvements to be addressed in next batches:

- Larger gain
- Larger areas

HPK is also involved in prototyping for EPIC.

Active testing activity with test beams and in labs.