ATAR Sensors

Jennifer Ott on behalf of the SCIPP PIONEER team

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*jeott@ucsc.edu

Outline

- **AC-LGAD strips**
- **Double-sided strip sensors**
- **Thicker sensors**
- **Trench-insulated LGADs**
- **Gain suppression in LGADs**
- **Measurements with x-rays**

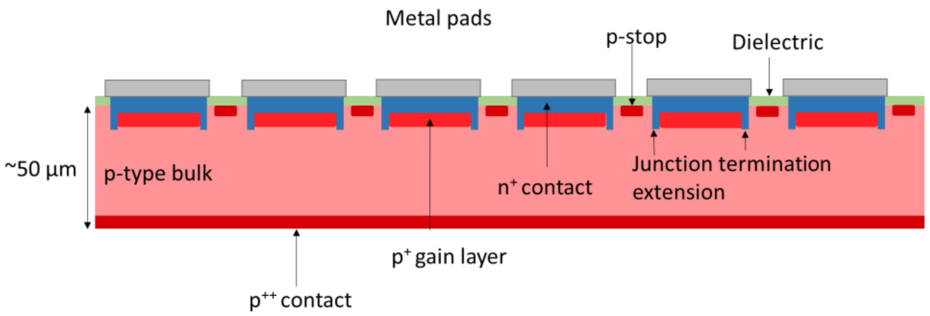
AC-LGAD strip sensors

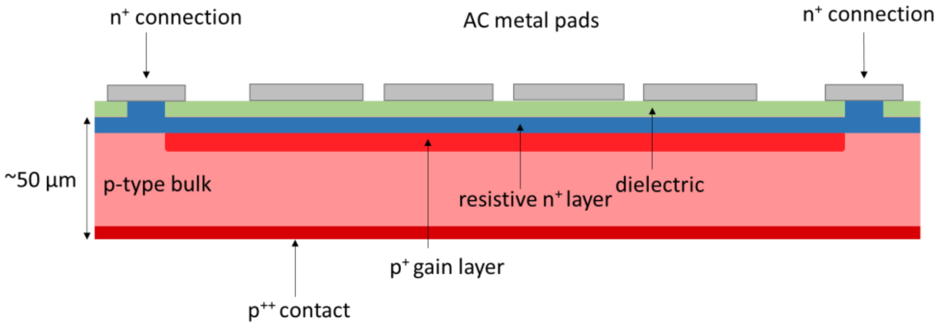
Low gain avalanche diodes

Silicon low-gain avalanche diodes (LGADs) are studied by the CMS and ATLAS experiments for their endcap timing detector upgrades

- Thin sensors, typical thickness 50 µm
- Low to moderate gain (5-50) provided by p^+ multiplication layer
- ➢ Timing resolution down to ca. 20 ps
- ➢ Good radiation hardness up to 10^{15} n_{eq}/cm^2

A more recent development: AC-coupled LGAD





H. F.-W. Sadrozinski et al, *4D tracking with ultra-fast silicon detectors*, Reports on Progress in Physics 2018, 81, 026101
CMS Collaboration, *A MIP Timing Detector for the CMS Phase-2 Upgrade*, CERN-LHCC-2019-003, 2019
ATLAS Collaboration, *A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade*, CERN-LHCC-2018-023, 2018

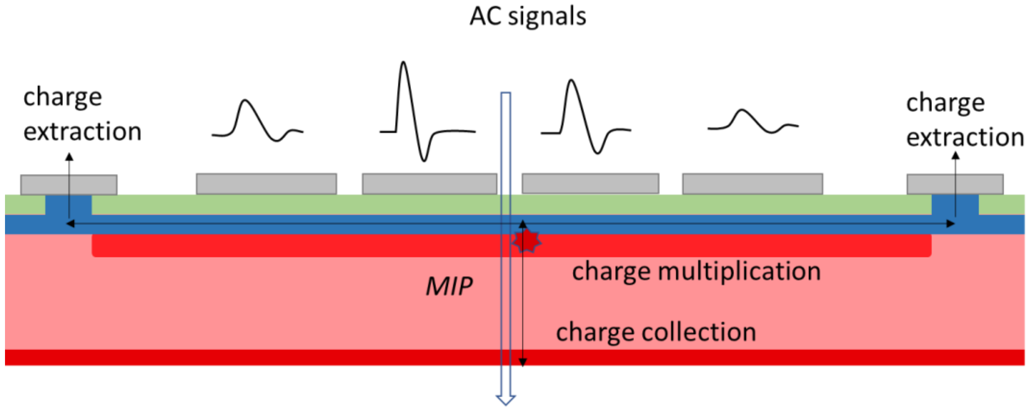
AC-coupled low gain avalanche diodes

In AC-coupled LGADs, also referred to as Resistive Silicon Detectors (RSD), the multiplication layer and n^+ contact are continuous, only the metal is patterned:

- The signal is read out from metal pads on top of a continuous layer of dielectric
- The underlying resistive n^+ implant is contacted only by a separate grounding contact
- No junction termination extension: fill factor ~100

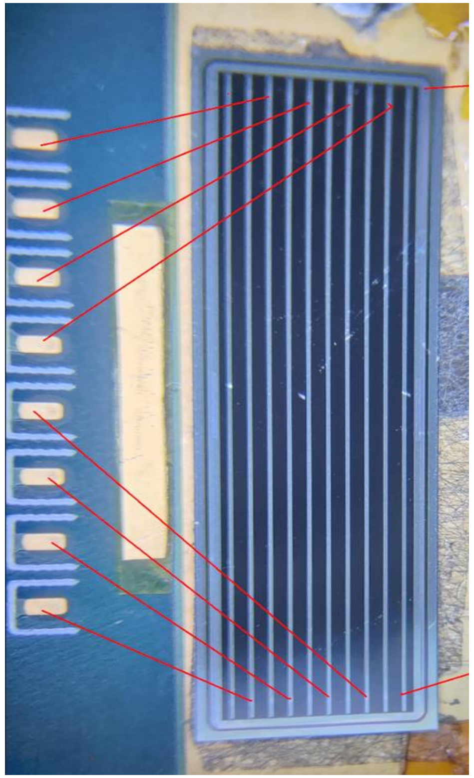
The continuous n^+ layer is resistive, i.e. extraction of charges is not direct

- Mirroring of charge at the n^+ layer on the metal pads: AC-coupling
- Strong sharing of charge between metal pads
- **Extrapolation of position based on signal sharing – finer position resolution for larger pitch, also allowing for more sparse readout channels**

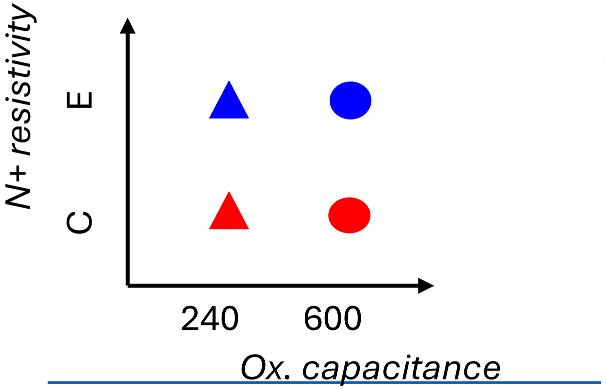


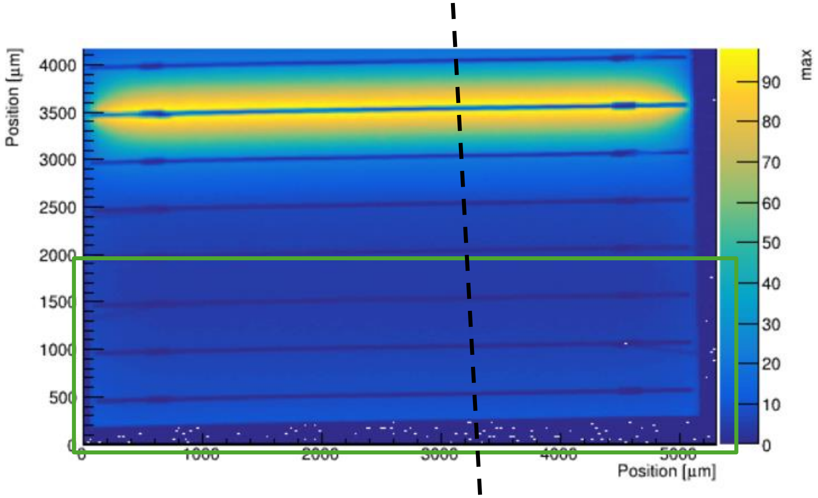
G. Giacomini *et al.*, Fabrication and performance of AC-coupled LGADs, *JINST* **2019**, 14, P09004
A. Apresyan *et al.*, Measurements of an AC-LGAD strip sensor with a 120 GeV proton beam**,** *JINST* **2020**, 15, P09038
S. M. Mazza, An LGAD-Based Full Active Target for the PIONEER Experiment, *Instruments* **2021**, *5*(4), 40

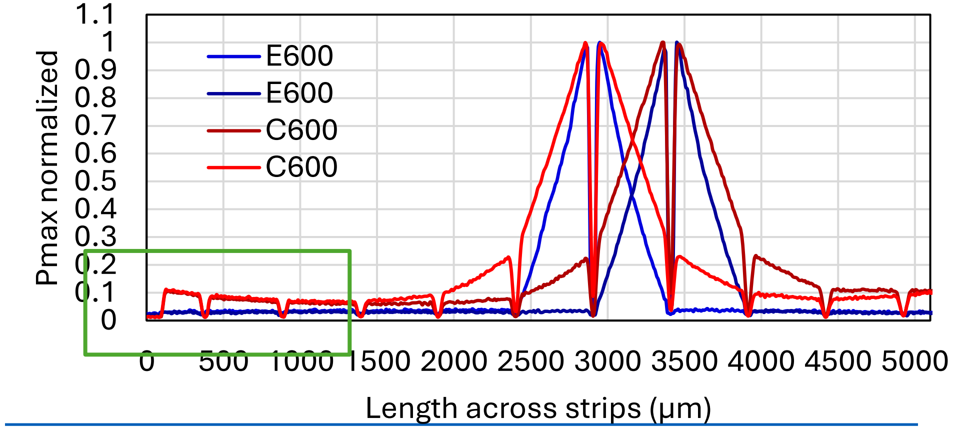
AC-LGAD strips



- **HPK fabricated AC-LGAD sensor prototypes for the Electron-Ion Collider time-of-flight particle ID detectors**
- **Thoroughly studied charge sharing in different splits: sensor thickness, metal width, n+ layer resistivity, oxide capacitance**
  - Presentation and article by Hartmut et al, senior thesis from Casey Bishop soon to come
- **Production included 2 cm AC-LGAD strips: very useful prototypes for the ATAR**
  - More (too much) charge sharing in C-type strips – E-type performs well!

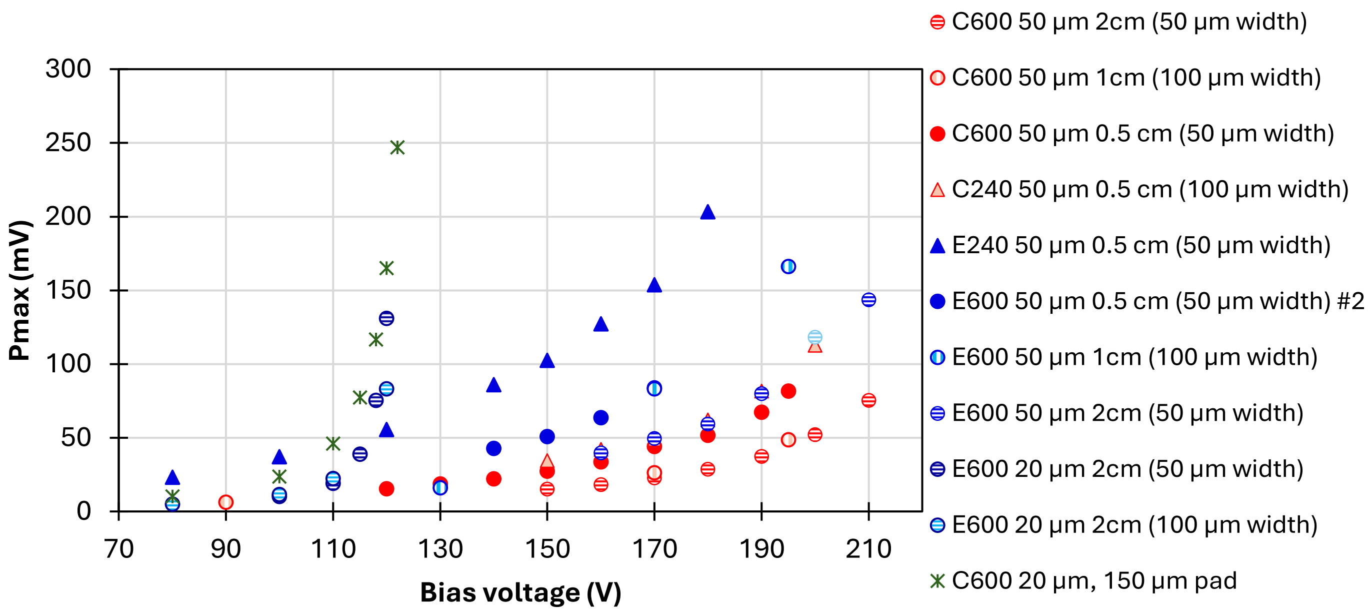


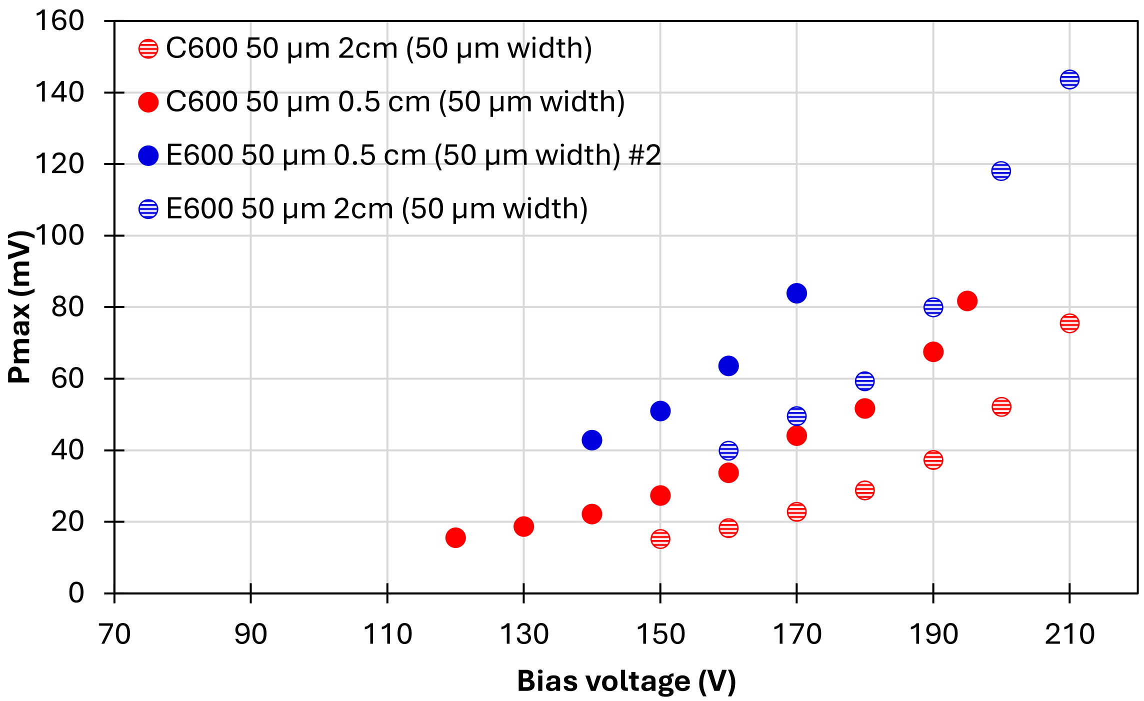




AC-LGAD strips

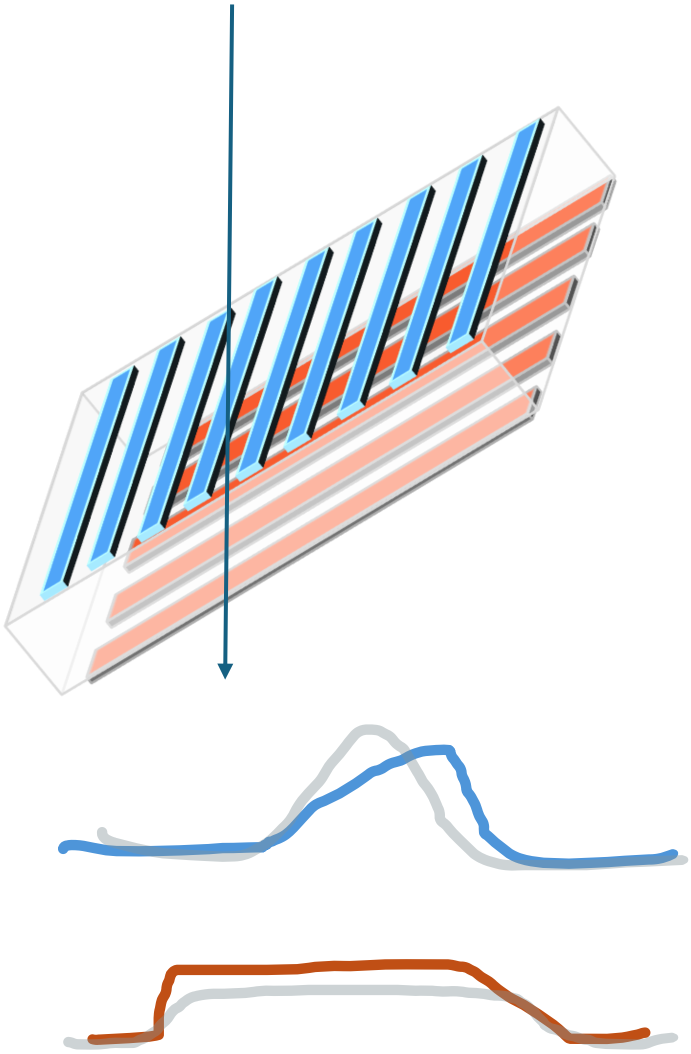
- **Maximum signal amplitude is lower in longer strips – but can well reach SNR of > 30 when operated at appropriate bias voltage**
  - These are 20-50 µm thick sensors!
  - Important to reach sufficiently high bias voltage and gain in thicker sensors before breakdown





AC-LGAD strips

- Ongoing: position reconstruction in AC-LGAD strips with classical methods and ML, utilizing spatial and timing information
- **Next measurement series: test angular dependence of charge sharing and position reconstruction!**
  - All previous studies have focused on basic characterization of sensors, with normal incidence of laser or particle beam
  - Especially in the PIONEER ATAR tracks might graze strips at a large angle!
  - Barrel strip modules in EIC are also planned to be tilted by 18 degrees
- **Waited (waiting) for rotational stage and mounts for the laser setup – can get started soon**

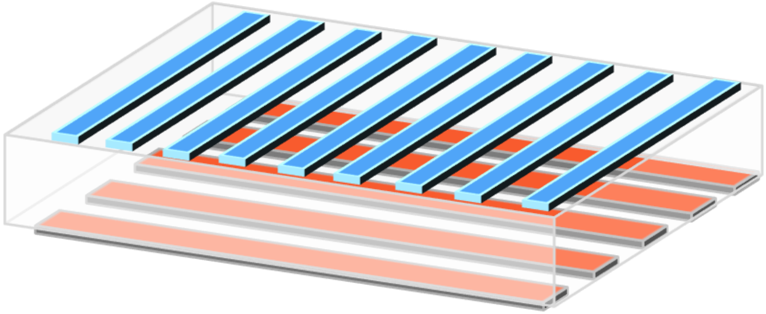


Double-sided sensors

Combined AC and DC readout

Suggested: adaptation of AC-LGAD strips to also include strip pattern and readout on the (DC) back side of the sensor

- Providing resolution in x and y on the same sensor plane, with no dead material between – hit with spatial resolution even for a very large μ/e track angle
- AC side for position resolution (charge sharing)
- DC side for timing resolution (no sharing – faster rise time)
- Even a combined reconstruction?



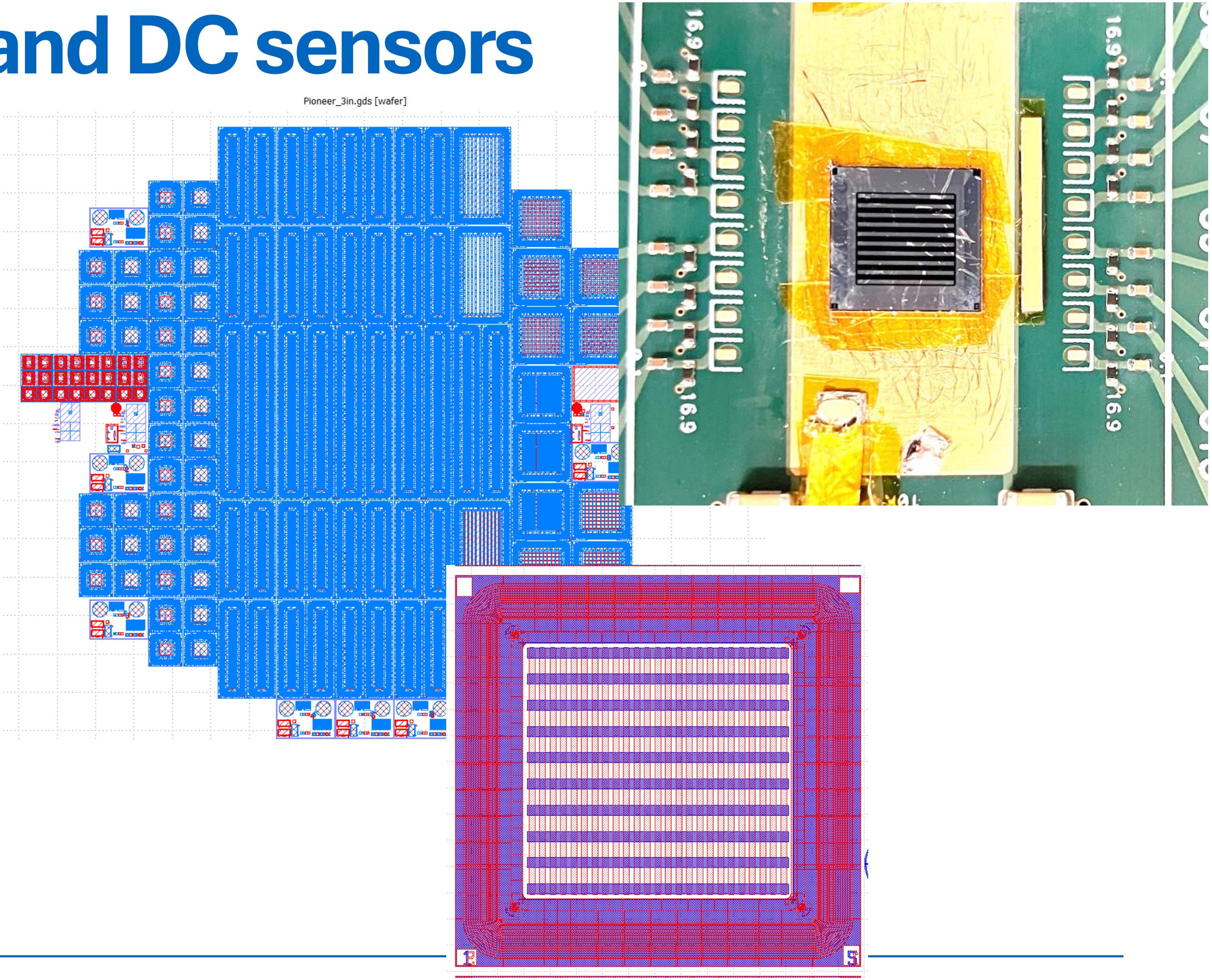
Production by BNL: double-sided, 200 μm active thickness wafers

‘Thick’ LGADs with fully active thickness and no mechanical support wafer!

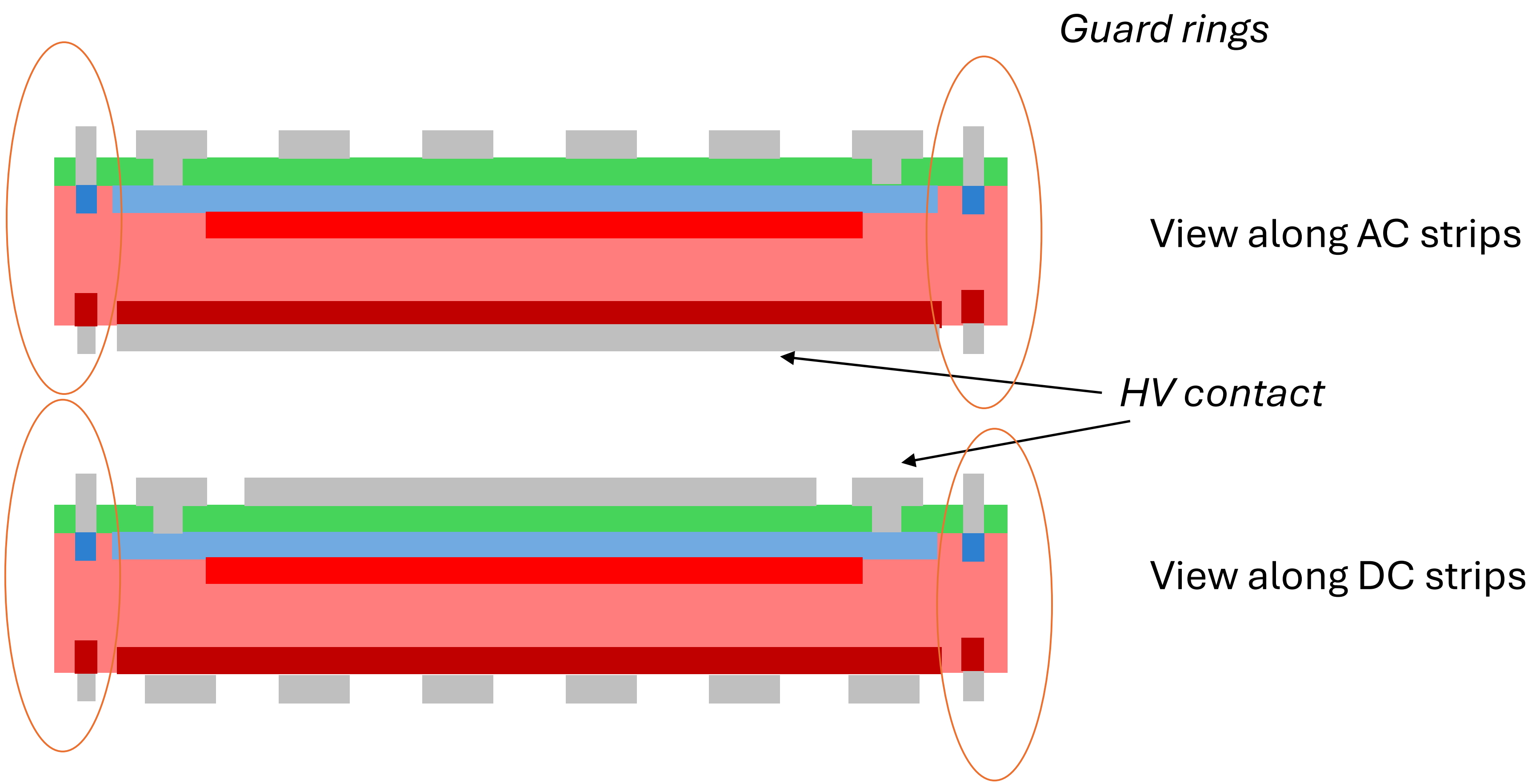
Double-sided AC and DC sensors

- Previously presented (next 3 slides): sensors on the first wafer are functional, but have high leakage currents, do not reach sufficient bias voltage or gain

- **Following wafers were fabricated with different gain layer parameters: improved biasing – to be tested with new boards. Both PIN and LGAD samples need to be tested – signal formation and pick-up are different**



Double-sided AC and DC sensors

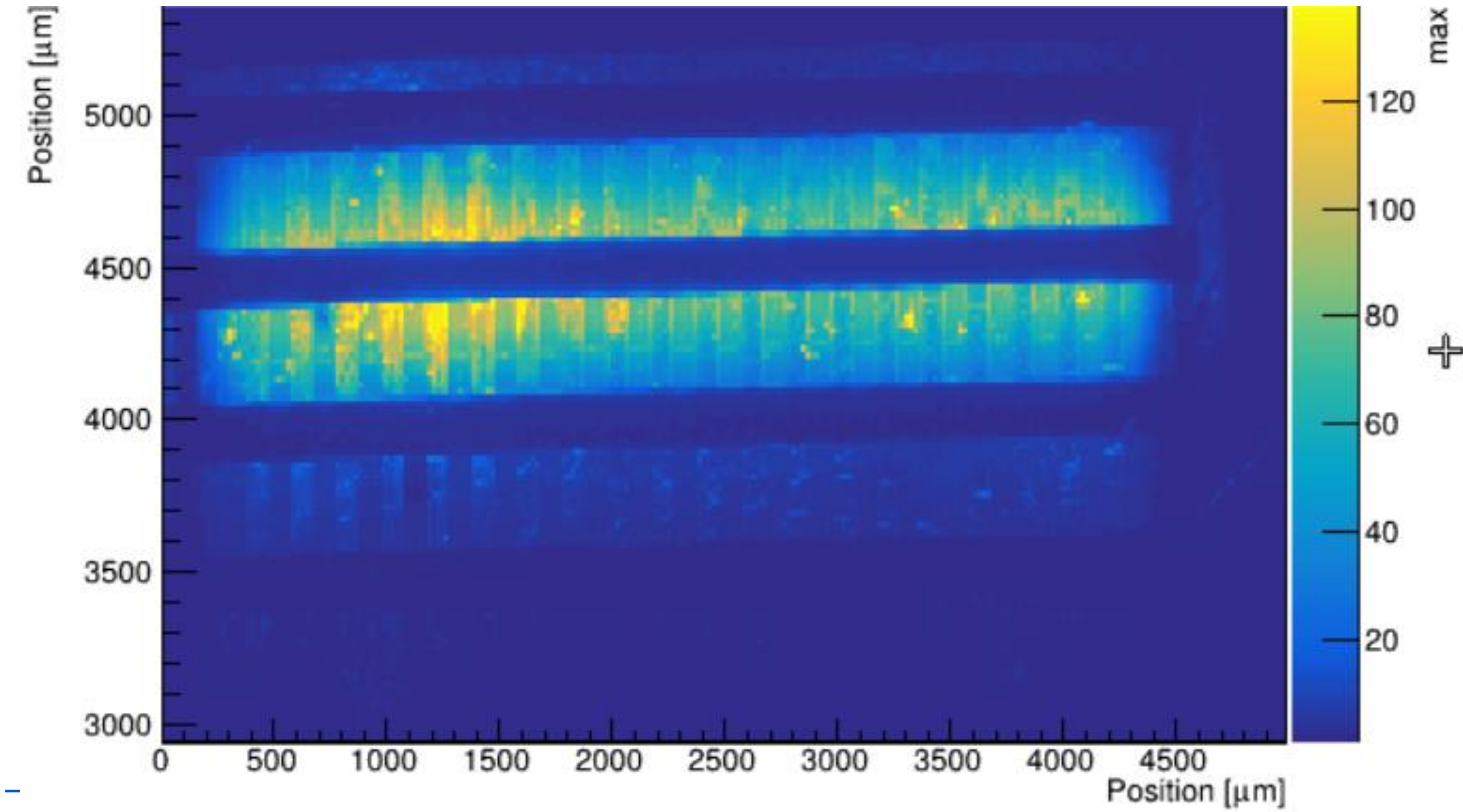


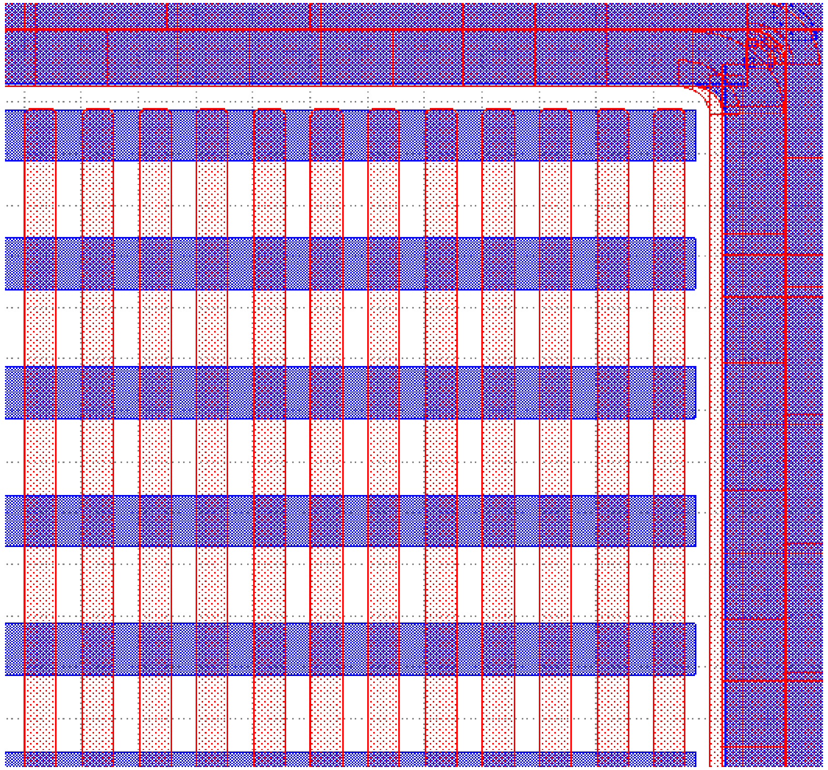
Both sides include a guard ring design that should be shielded from HV: complicated on boards that assume single-side readout

Drawing is conceptual, not to scale, does not include all termination structures

Double-sided AC and DC sensors: laser

- Some nonuniformities, potentially due to reflections from the backplane DC strips and conductive tape used for mounting – also region with nonuniform gain?
- Sensor has high leakage current, cannot be biased to very high voltages
- Response in terms of pmax is okay, not too much sharing to neighboring strips





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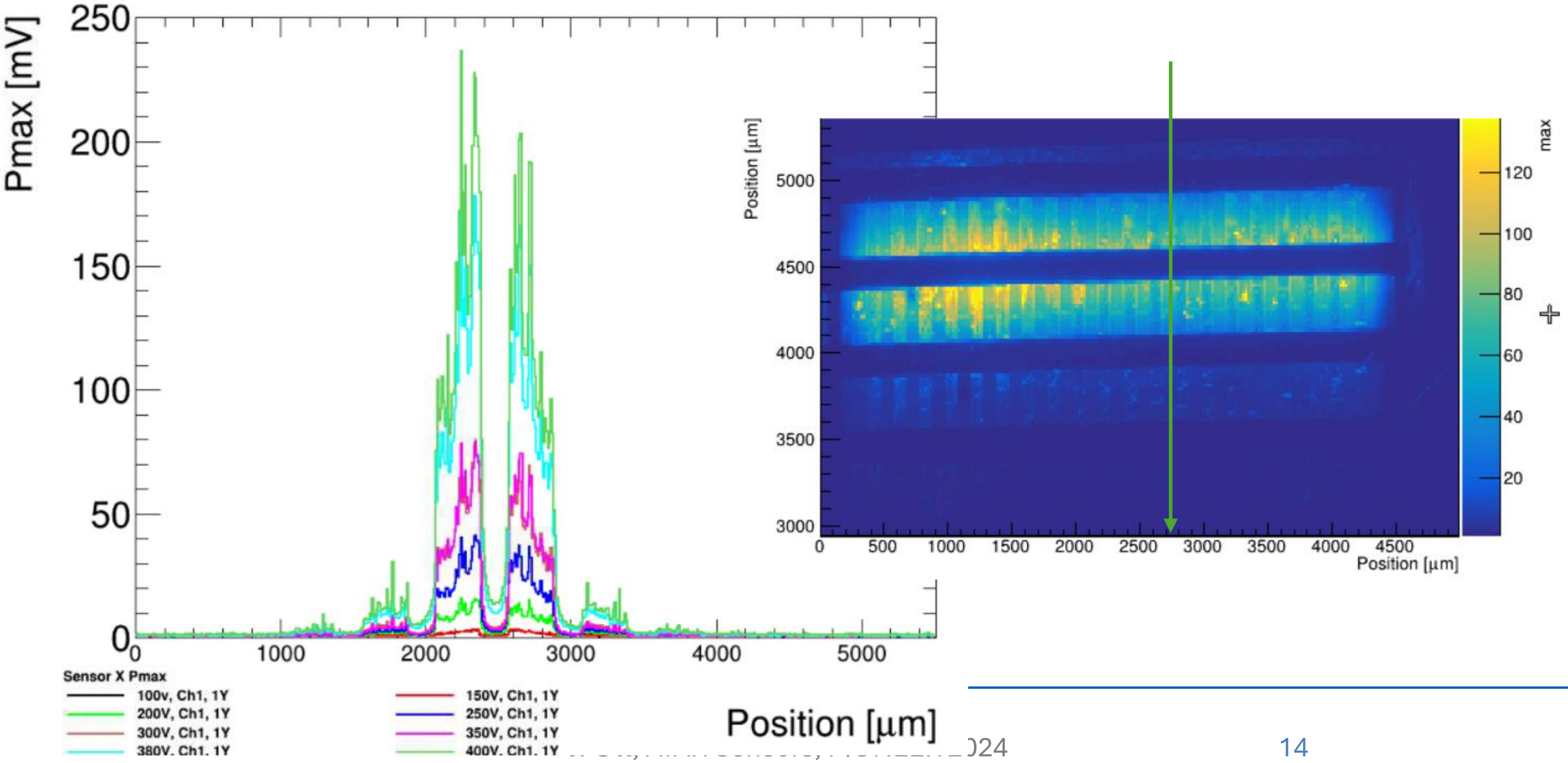
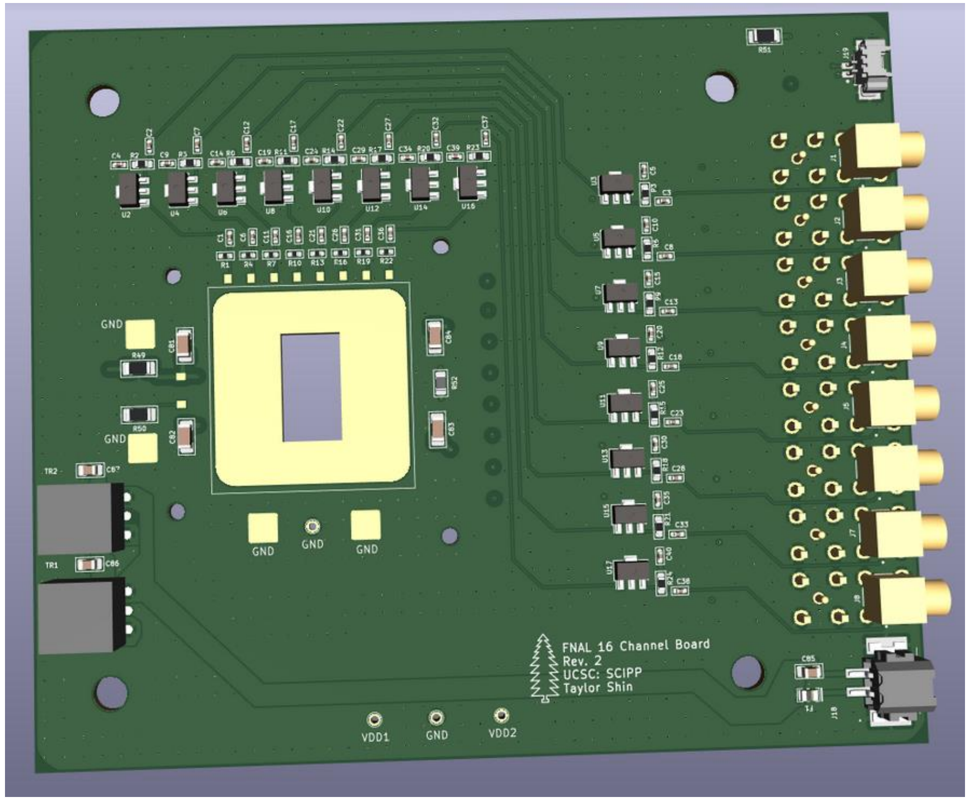
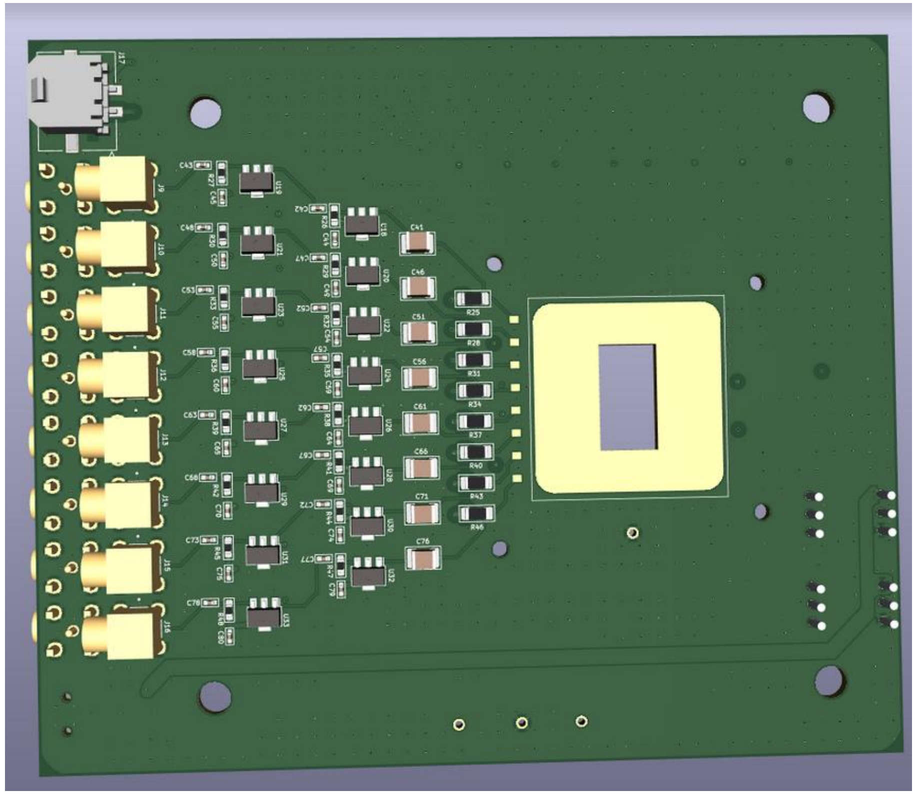


Double-sided sensors readout board

Double-sided readout board designed by Taylor Shin, based on FNAL 16-ch board

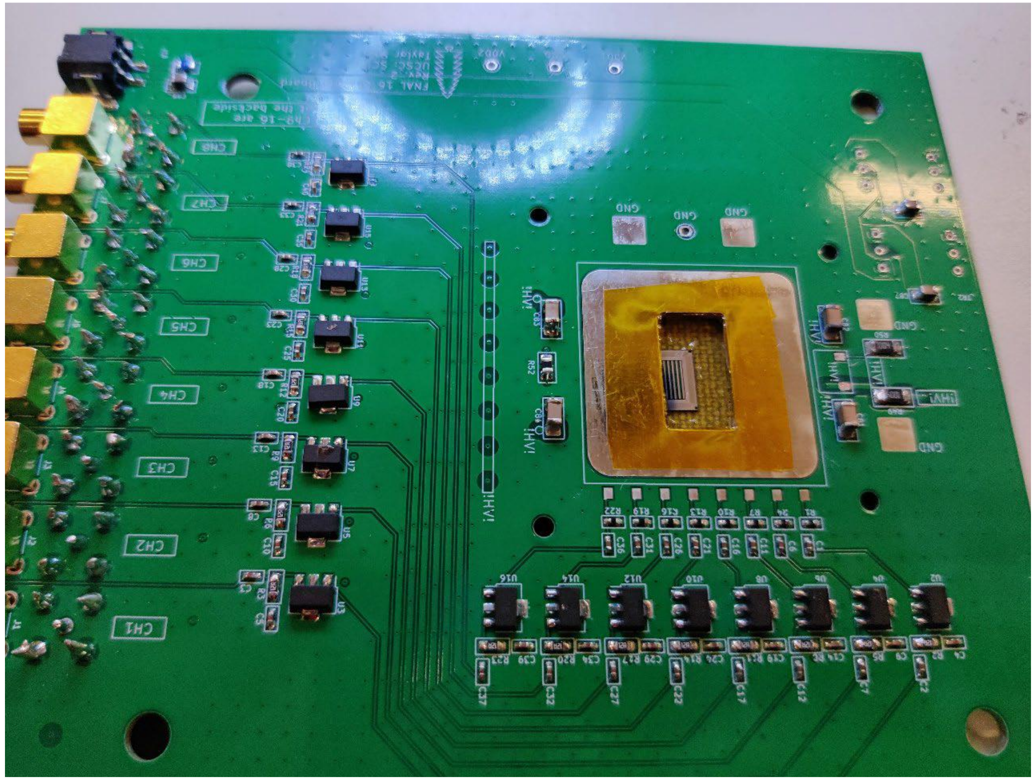
- **8 channels on the front, unchanged**
- **8 channels on the back, capacitively coupled to include biasing**

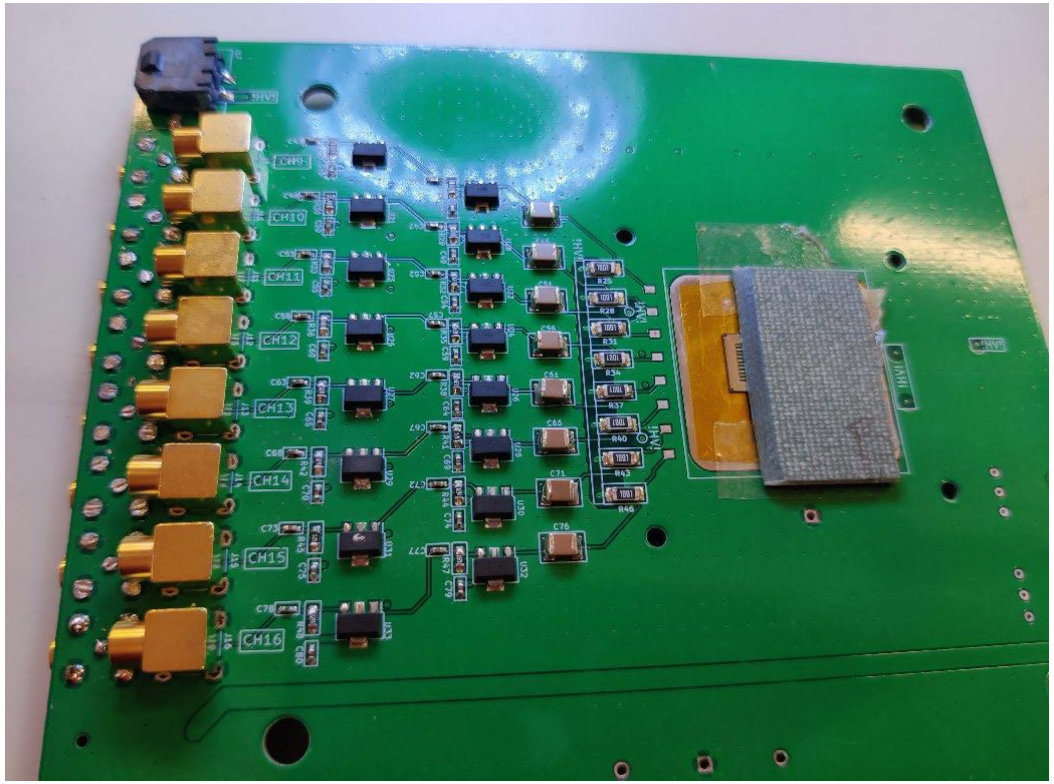




Double-sided sensors readout board

- Some non-idealities with excess noise/ringing, bondable surface not specified – had to solder gold pads, traces overetched – but boards work





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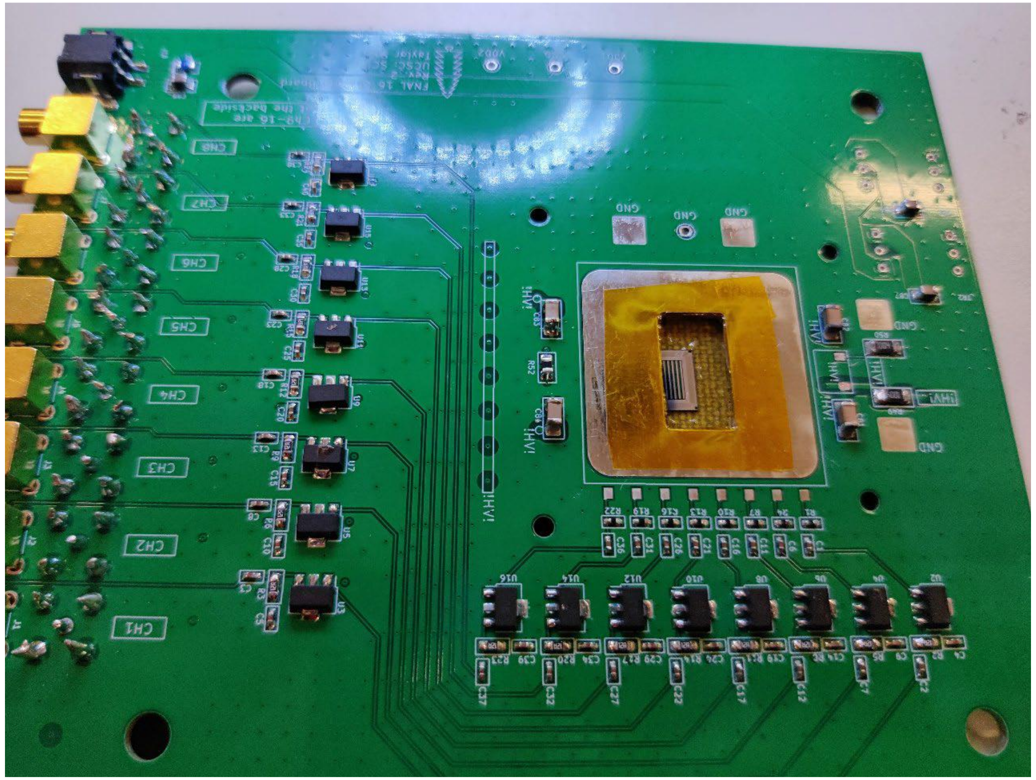
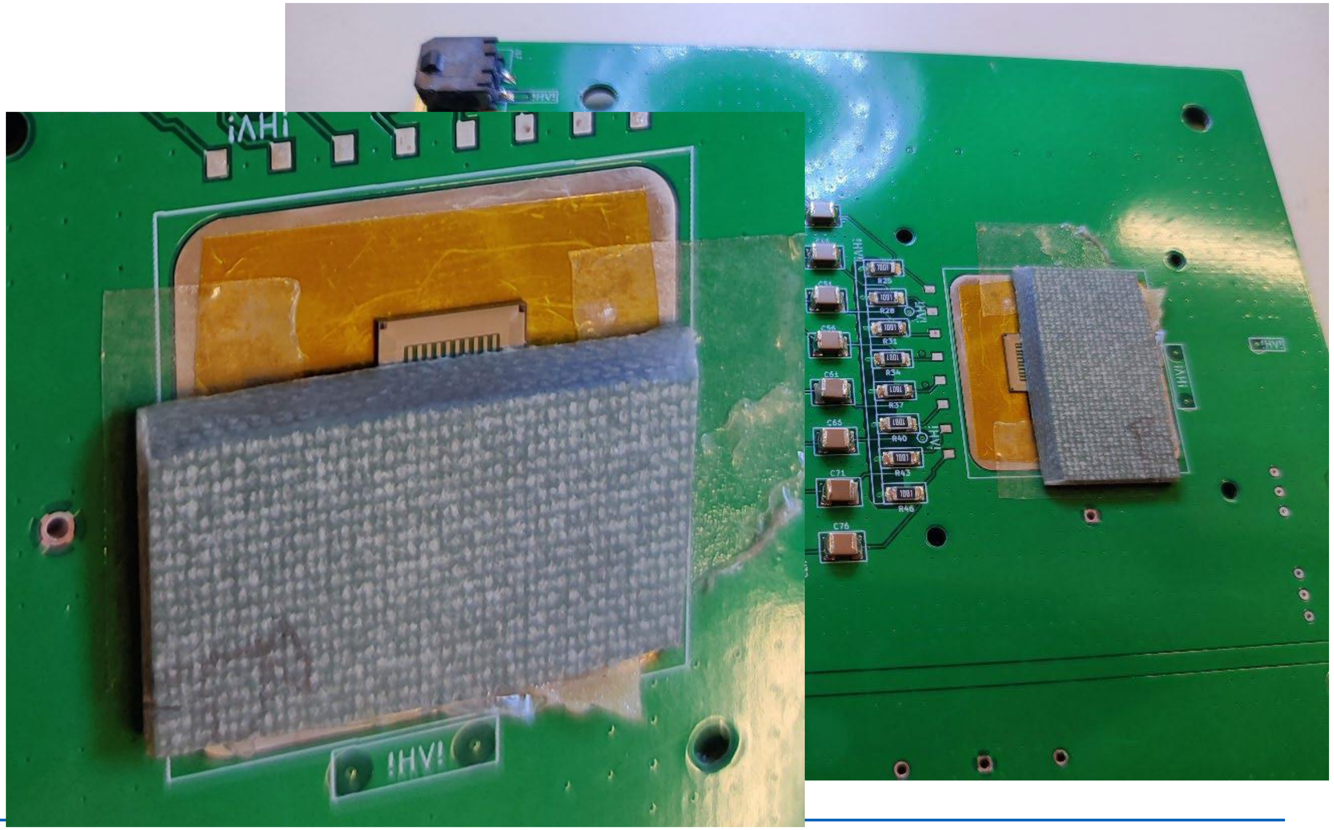
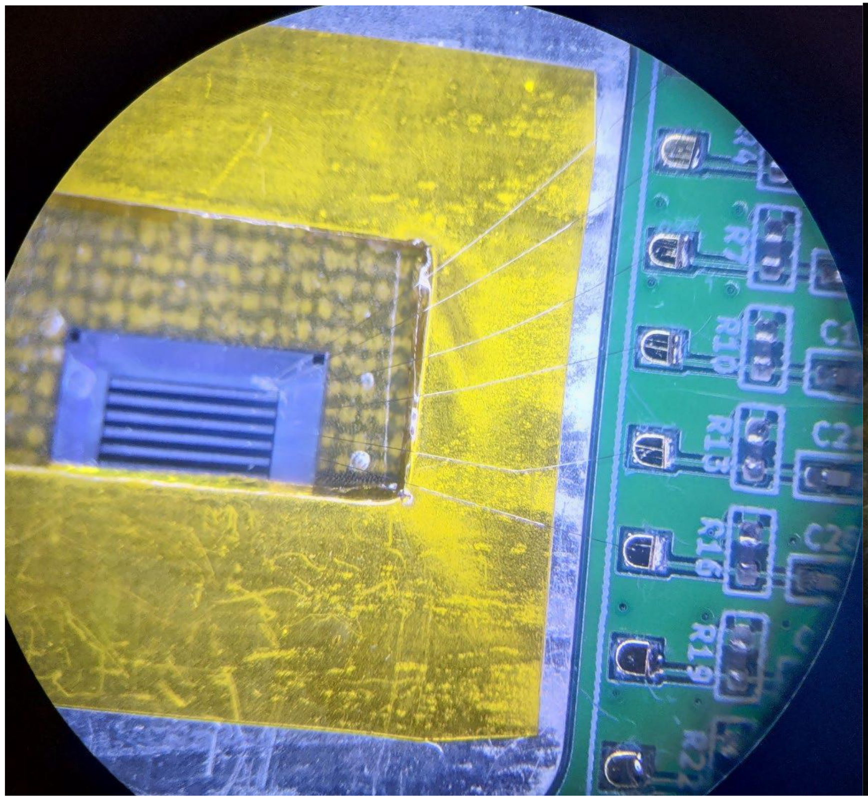
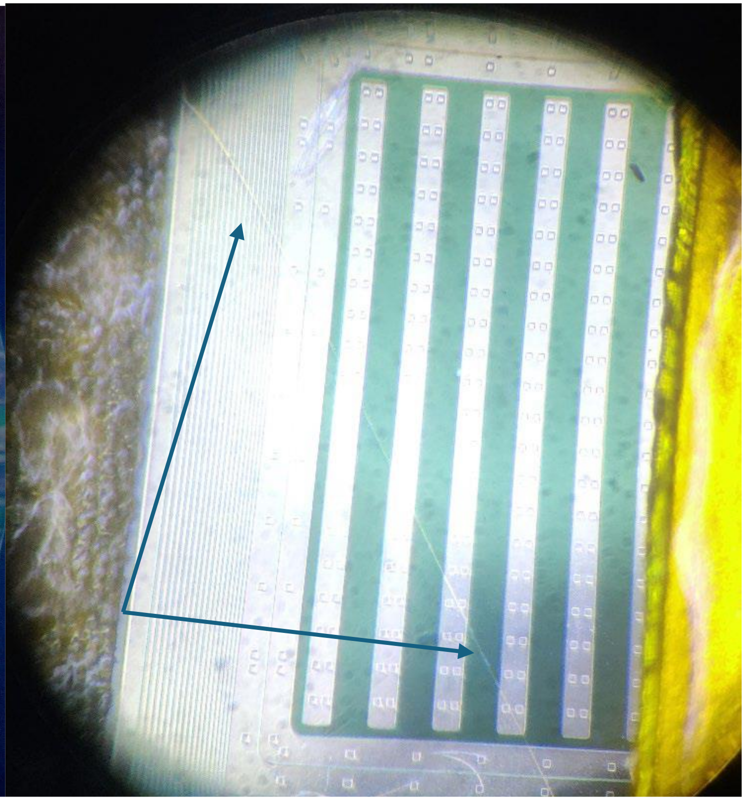


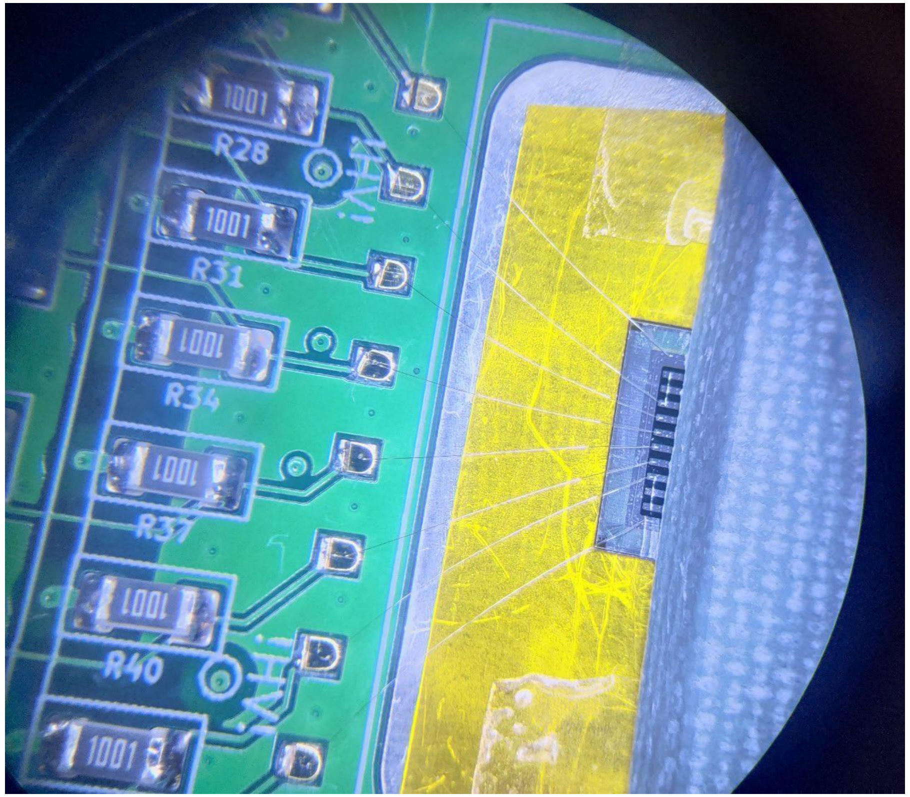


Double-sided sensors readout board

- Mounting of sensors and supporting during wirebonding challenging, needs to be revised – two strip sensors were broken
- First sensor showed cleave boundary, but was still functional





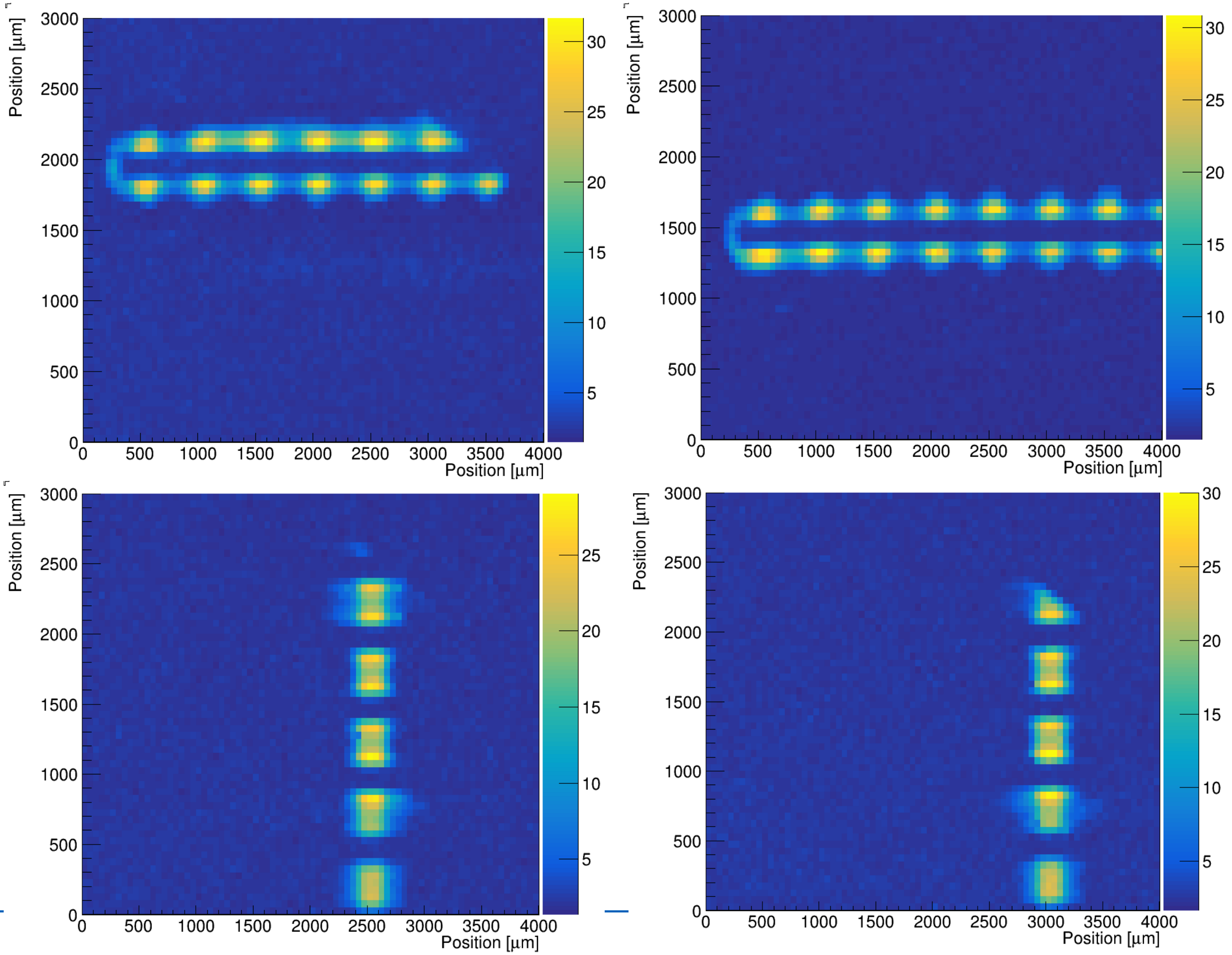


Double-sided sensors readout board

Top: AC-coupled front side strips

Bottom: DC backside strips

With IR laser ~ uniform injection throughout the bulk: similar signal amplitude; light blocking from front strips (backside) and reflection from backside strips (top) are visible – as expected



Full details in ATAR meeting update: https://pioneer.npl.washington.edu/cgi-bin/private/ShowDocument?docid=252

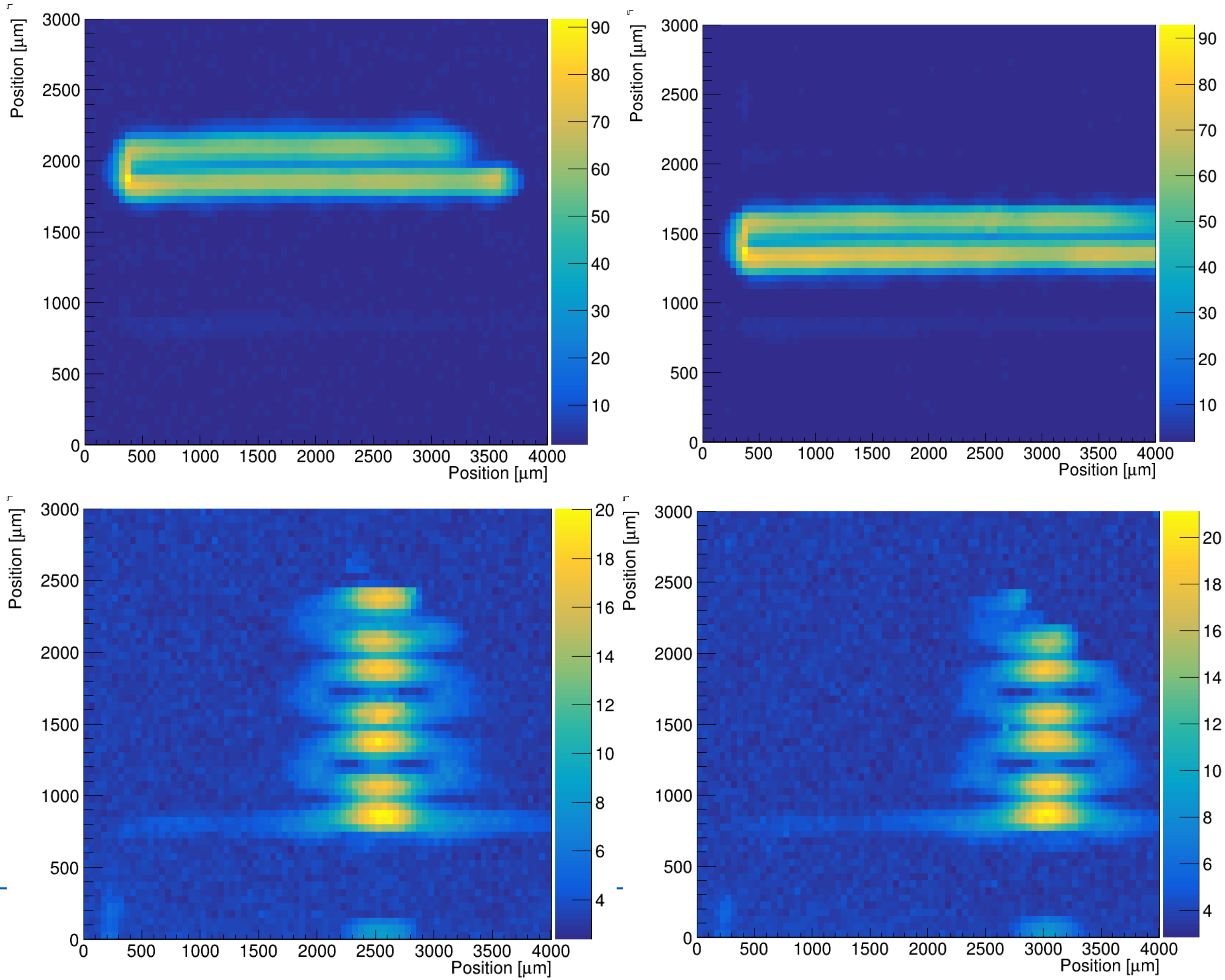
Double-sided sensors readout board

Top: AC-coupled front side strips

Bottom: DC backside strips

With red laser = injection only close to top surface: no reflections from backside (as expected), overall smaller signal on the back side

- ➢ **Affected by weighting field of the strip electrodes?**



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LGAD thickness series

FBK DC-LGAD thickness series

Single-pad DC sensors from FBK – as presented by Matteo Centis Vignali in last year's meeting

- Test samples for space applications

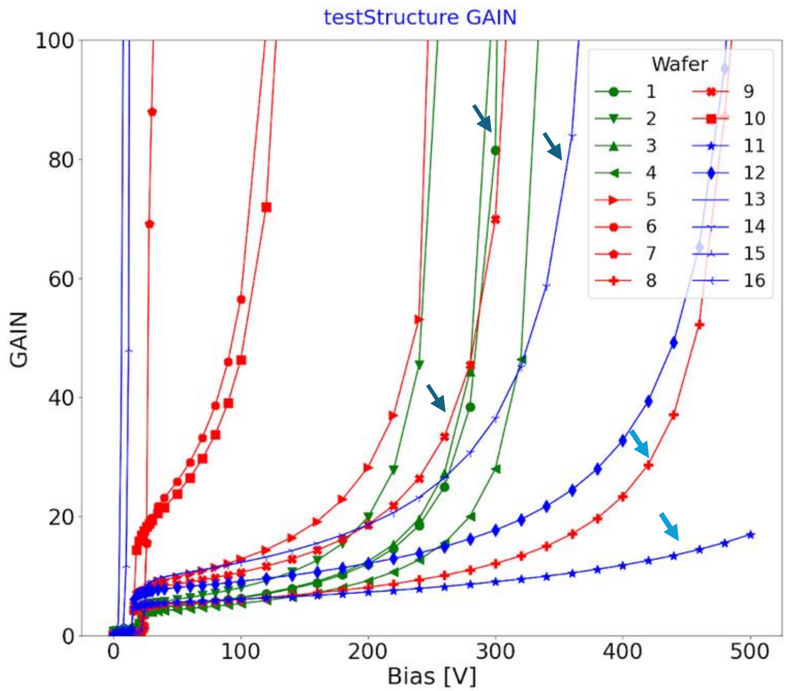
Different gain layer doping splits: some with more moderate gain, allowing for higher bias voltage before breakdown

Different thicknesses: 50, 100, 150 µm

- Standard LGAD reference thickness 50 µm
- 100 and 150 µm around the thickness targeted by the ATAR

➢ Very useful to compare and verify performance of thicker sensors in a 'pure' way, without involving AC-coupling or double-sided readout

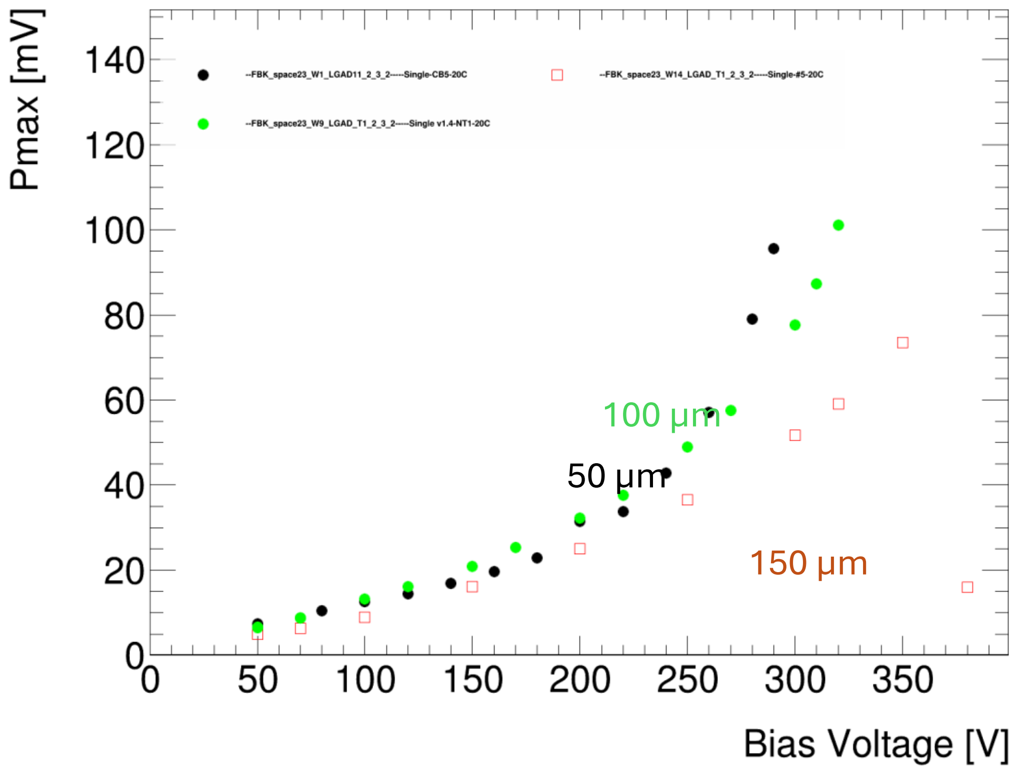
➢ Later received also sensors from W8 and W11 with higher breakdown voltages – to be tested in detail

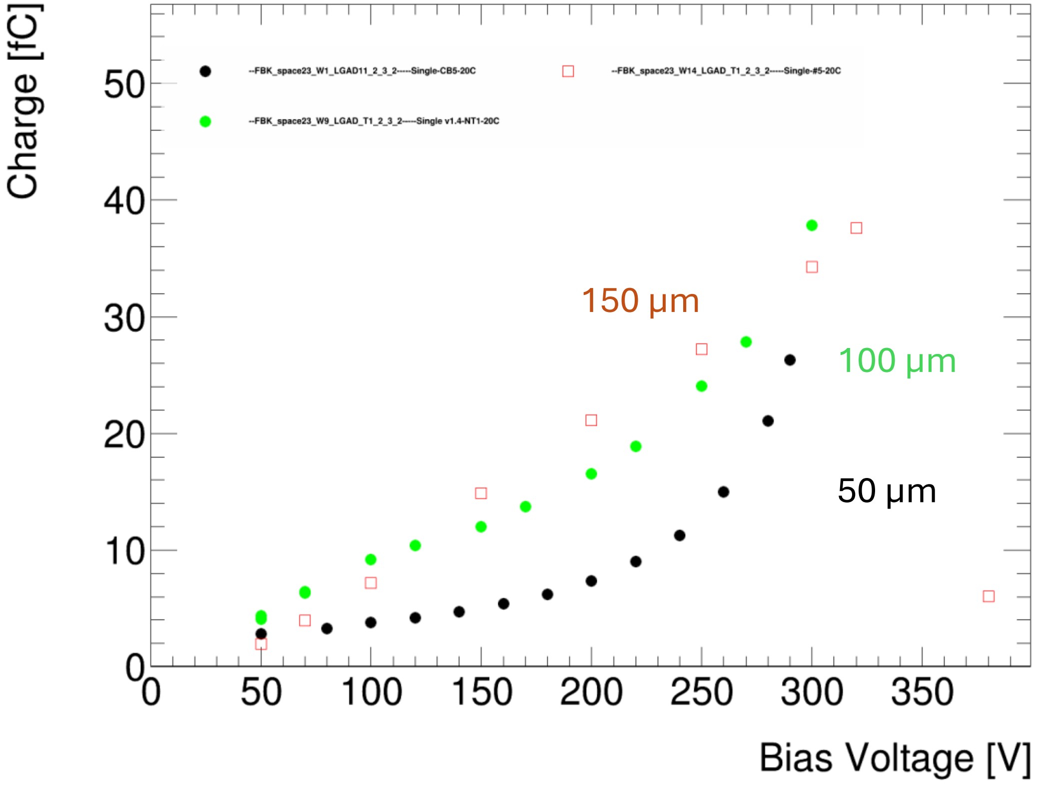


Thickness (µm)	Wafer	n^+ dose	Gain dose	Gain energy
50	1	1	0.98	1
	2	1	1	1
	3	3	1	1
	4	3	0.98	1
100	5	1	1.04	1
	6	1	1.08	1
	7	1	1.12	1
	8	1	1.4	0.5
	9	1	1.46	0.5
	10	1	1.52	0.5
150	11	1	1.4	0.5
	12	1	1.46	0.5
	13	1	1.52	0.5
	14	1	1.04	1
	15	1	1.08	1
	16	1	1.12	1

FBK DC-LGAD thickness series

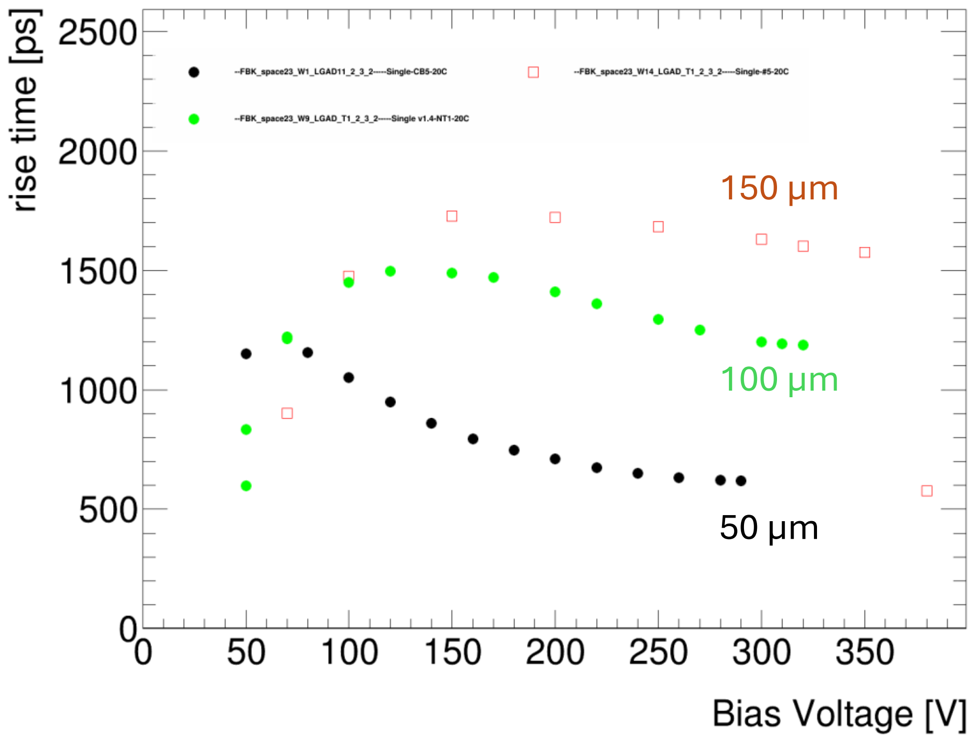
- Signal amplitude is similar: weighting field compensates decreased thickness
- Collected charge not quite scaling with thickness, shape of exponential is different especially for 150 μm sensor

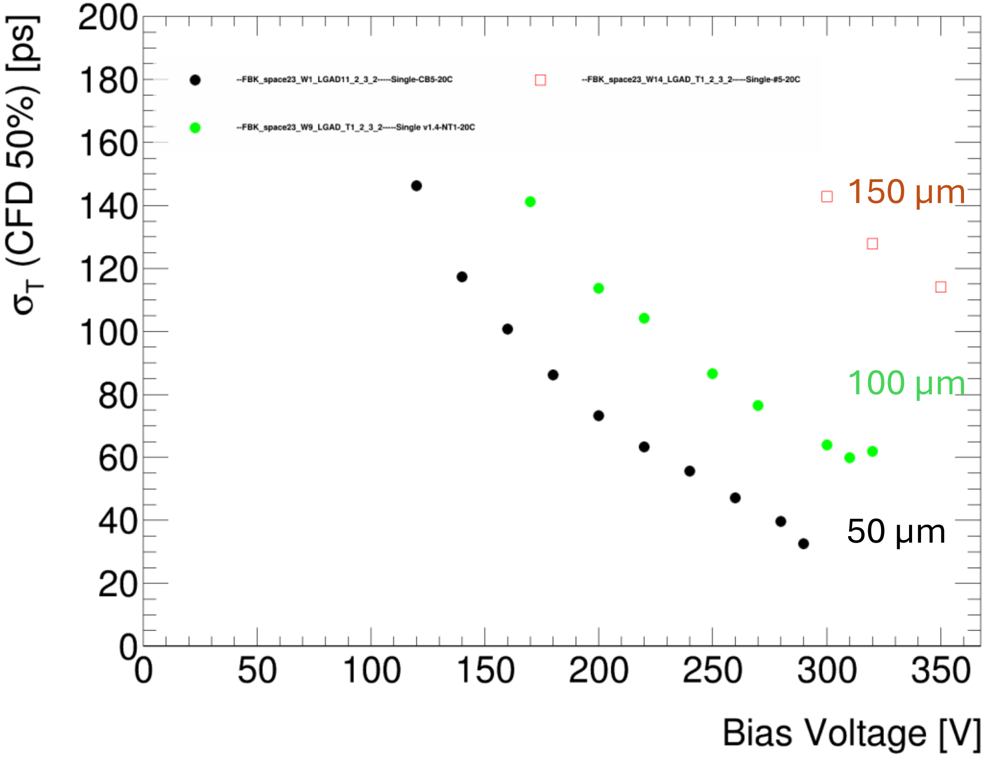




FBK DC-LGAD thickness series

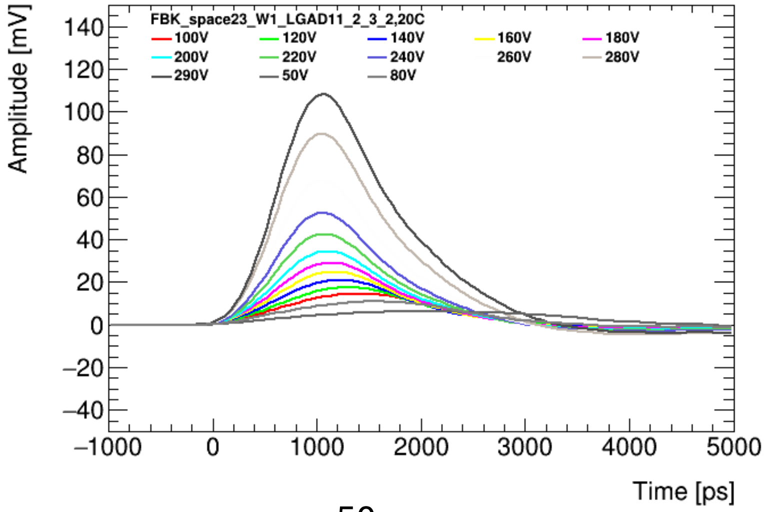
- Rise time and timing resolution scale with thickness: as expected
- ➢ 120 μm can be scaled between 100 and 150 μm – ca. 1.4 ns rise time, time resolution ca. 80-100 ps



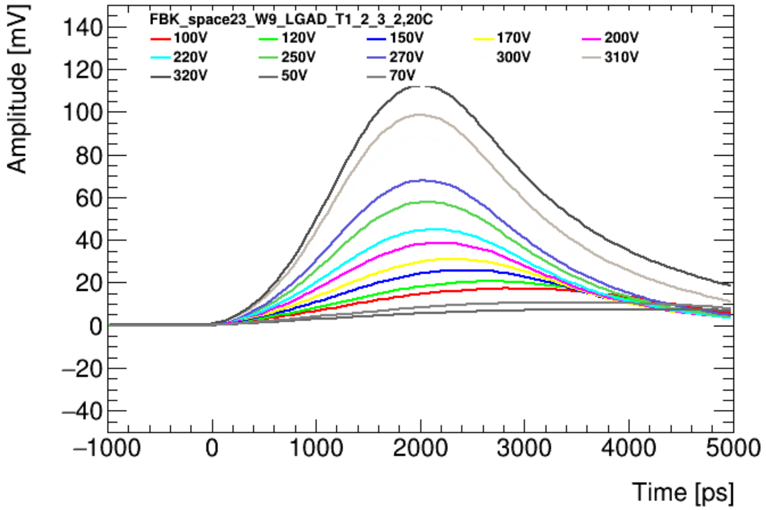


FBK DC-LGAD thickness series

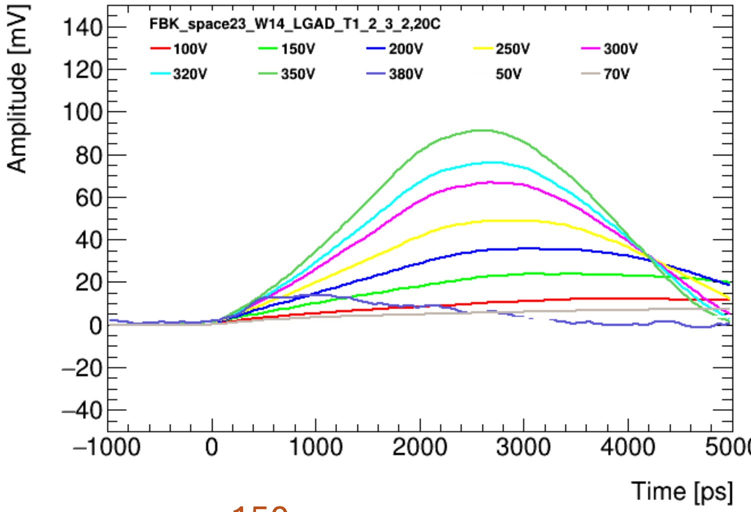
- Lower electric field and drift velocity are apparent in average signal waveforms as well – scale with thickness
  - Full signal barely contained within 5 ns for 100-150 µm sensors
  - (Perhaps these are not the fastest sensors to begin with: duration in 50 µm also 3 ns)



50 µm



100 µm



150 µm

Trench-insulated LGADs

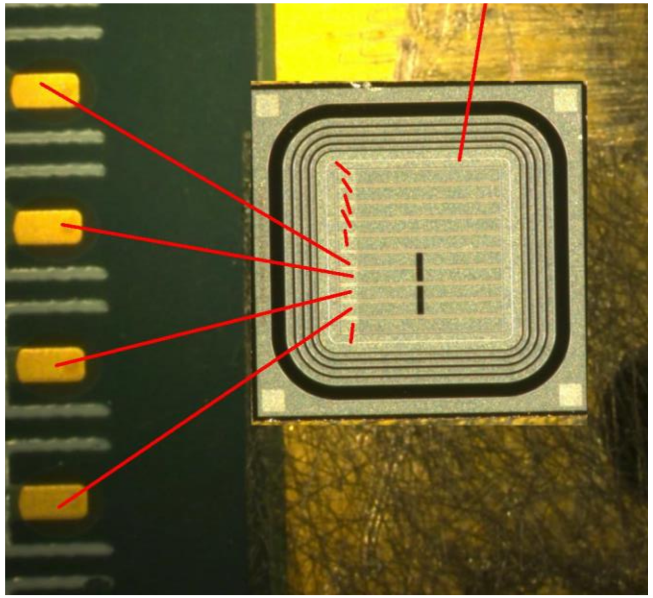
Trench-insulated LGADs

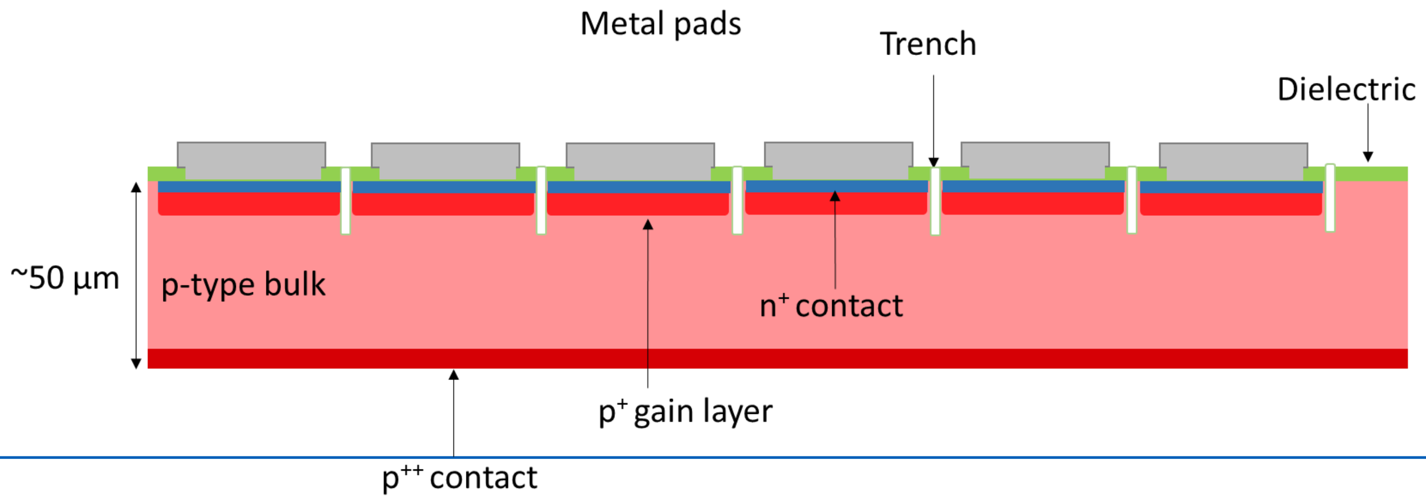
Rely on direct readout from metal pads and segmented gain layer in the same way as standard LGADs

Gain layer is not terminated electrically by an implant, but with etched trenches (fabricated e.g. by Reactive Ion Etching)

- Very high fill factor, 99-100%
- No charge sharing

Relatively early stage of prototyping: focused on small pad arrays, no long strip sensor prototypes yet





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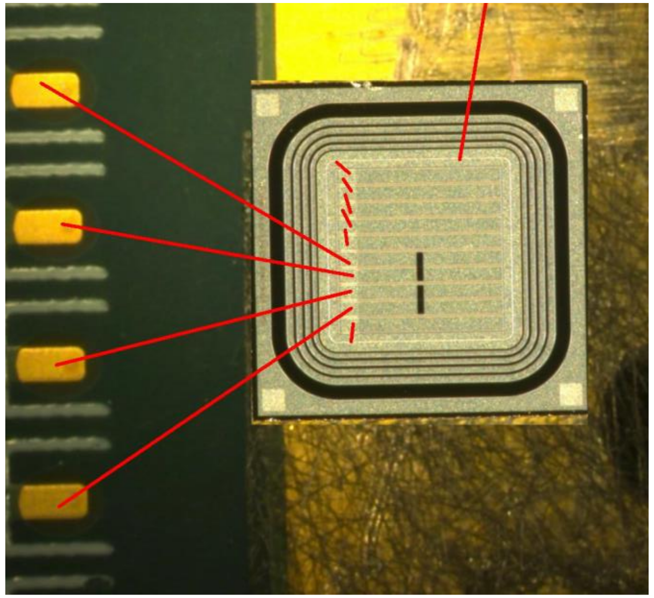
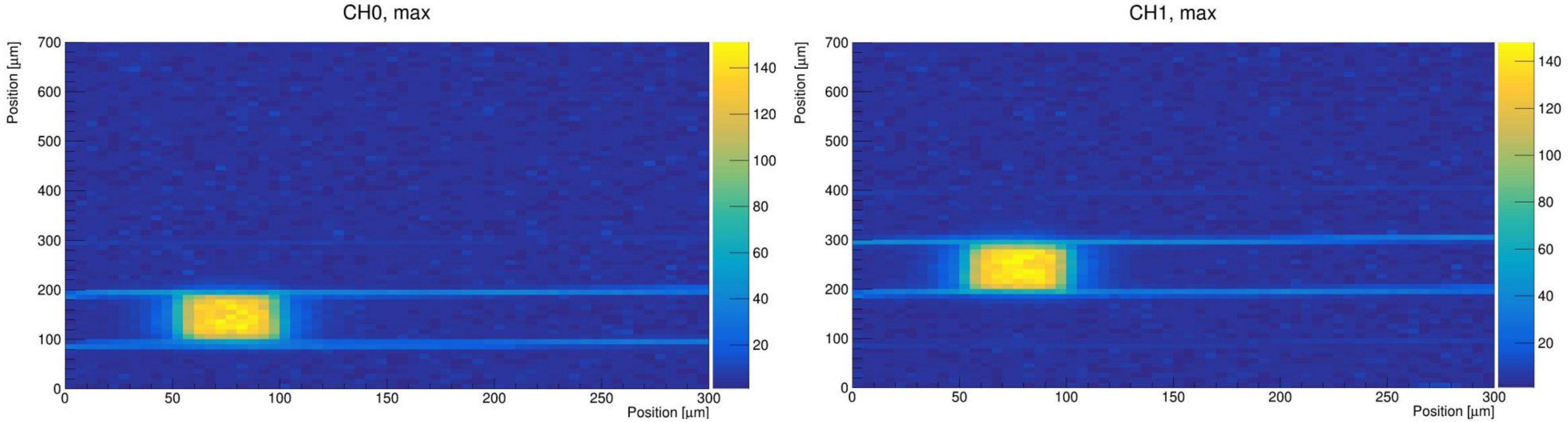
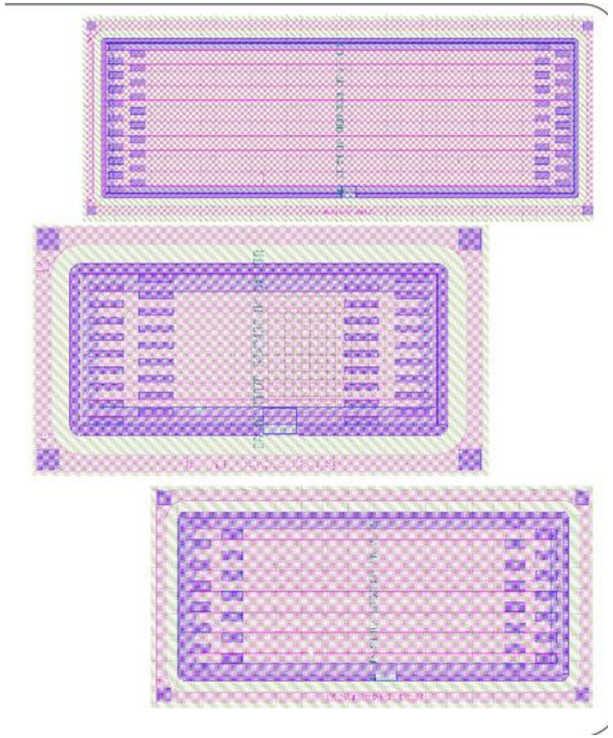




Trench-insulated LGADs



FBK had a European AIDA-INNOVA project on fabrication of TI-LGADs

- 50 μm active thickness
- Devices have been fabricated and are being distributed: we can likely get some samples
- 100um pitch strips with length of 2mm, 3mm, 6mm (both 1TR and 2TR versions)

Joint production of TI-LGAD together with GSI Darmstadt

- 50 μm and 100 μm
- It seems like the production is starting - prototypes in ~1 year if contributing ~10k to the production

Other vendors (Micron) have started fabricating TI-LGADs as well – might open more options for availability

https://indico.cern.ch/event/1402825/contributions/5998478/

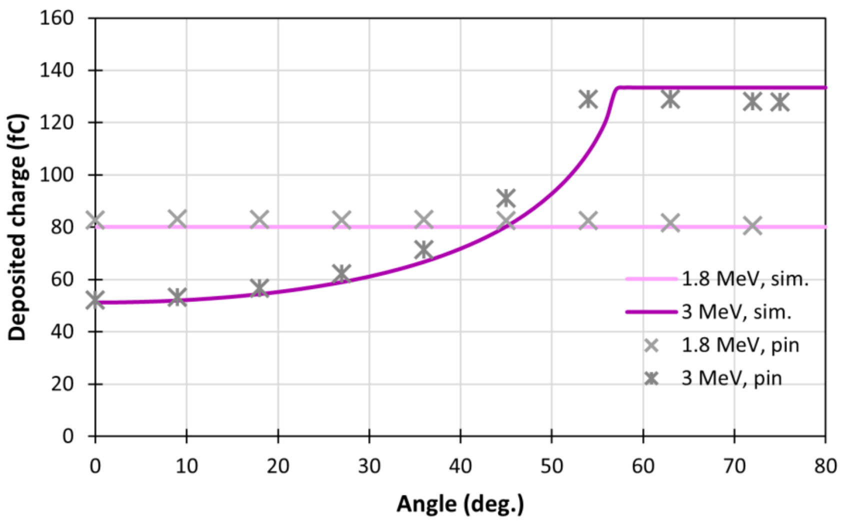
LGAD gain suppression

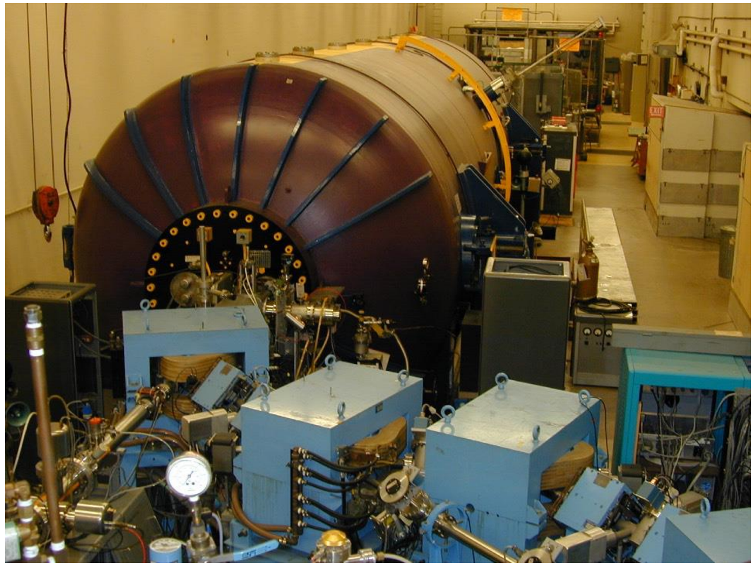
Gain suppression studies at CENPA

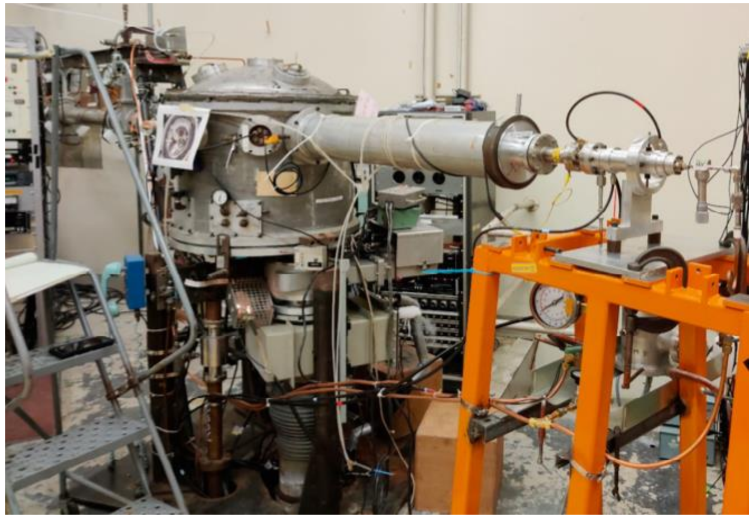
Beam energies of 1.8, 2, 3, 5 MeV

Could go higher

Energies were chosen around the full stopping of proton in 50 µm Si = active thickness of the LGAD







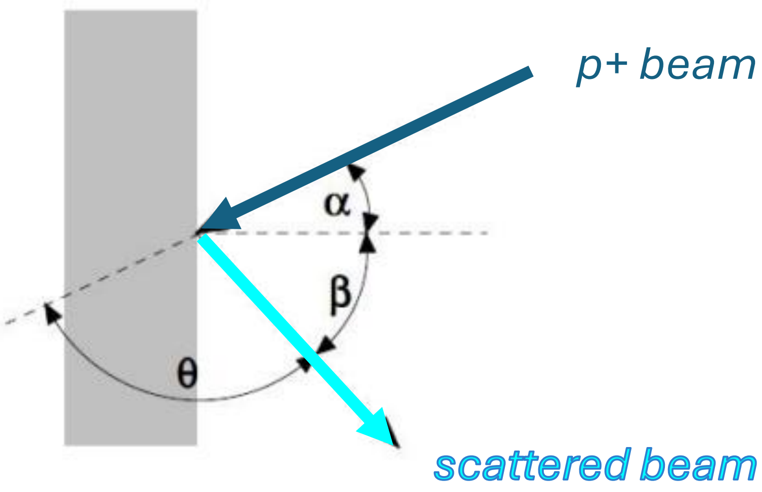
Experimental setup at CENPA

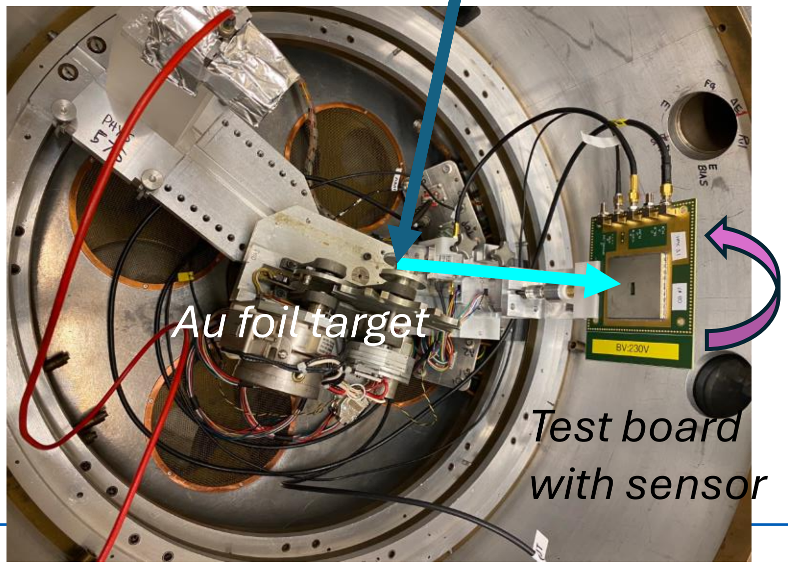
Utilizing Rutherford Backscattering on a gold foil target to avoid direct exposure of the DUT to the beam

- Scattering angle 110°

Test board was mounted on a rotation stepping motor to vary the angle of the sensor with respect to the scattered beam

- **Scanned 0°-75°**



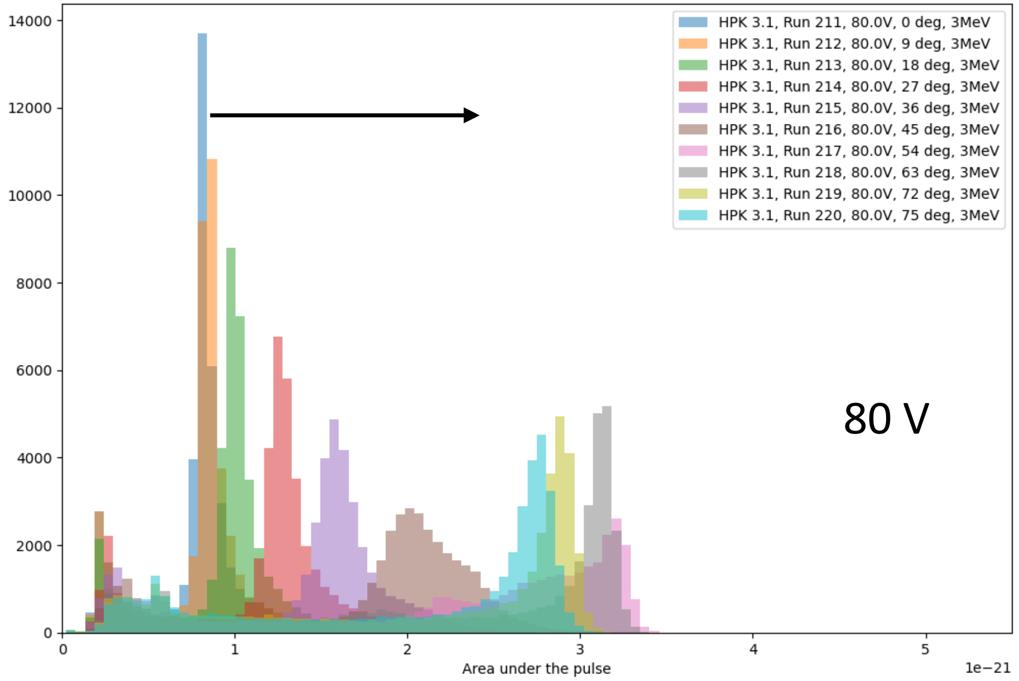


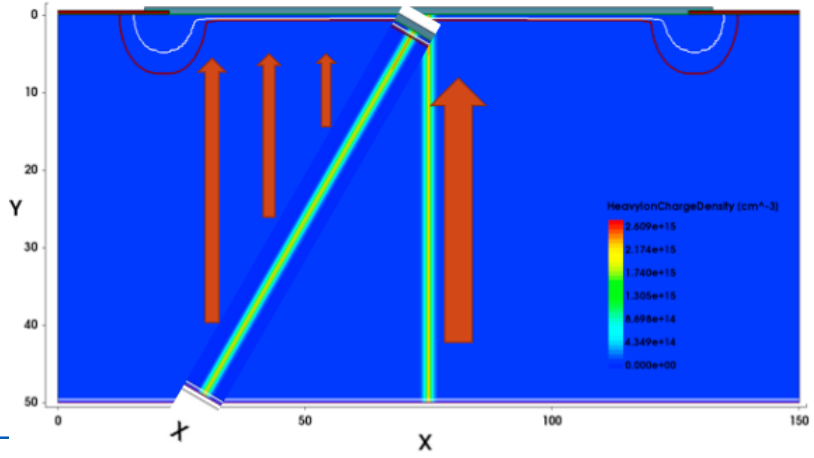
HPK 3.1 LGAD at 3 MeV

Angular dependence of gain

At <10°, energy deposit within the same area: gain suppressed

At increasing incident angles, gain increases as proton energy deposit is spread out over wider depth



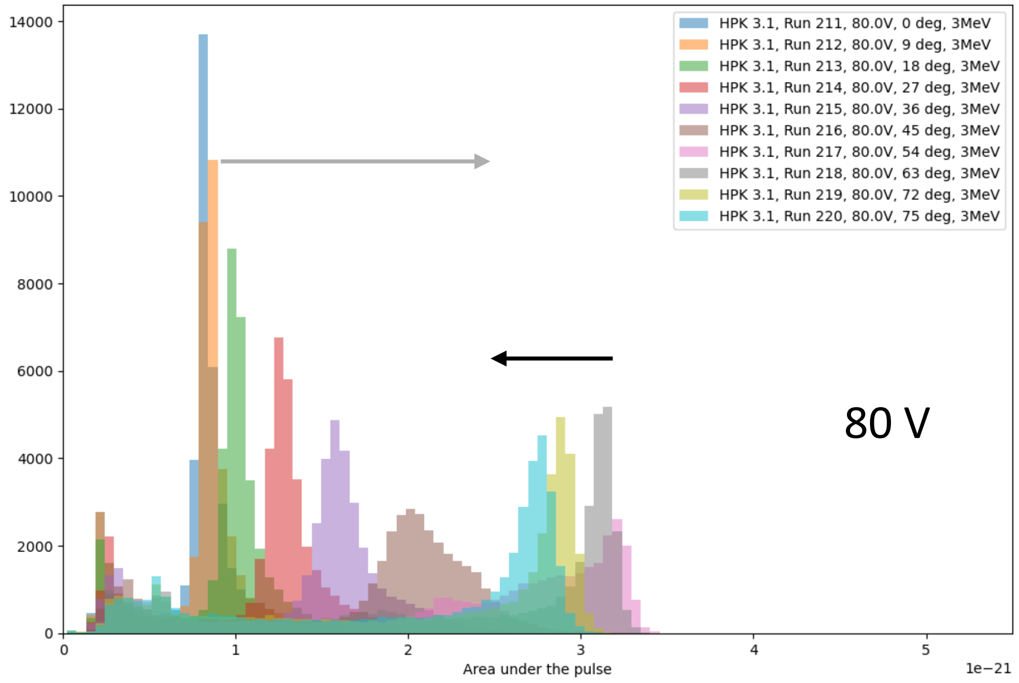


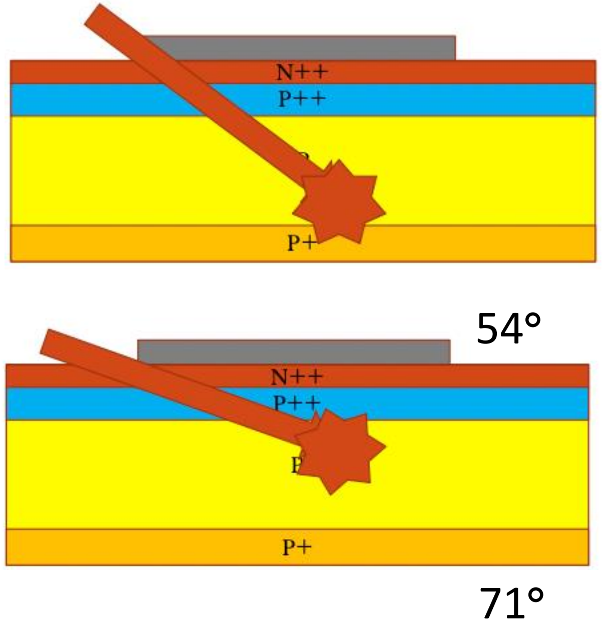
HPK 3.1 LGAD at 3 MeV

Angular dependence of gain

At higher angles (with the proton stopping in the sensor), the gain is suppressed again

- Main energy deposit closer to the gain layer

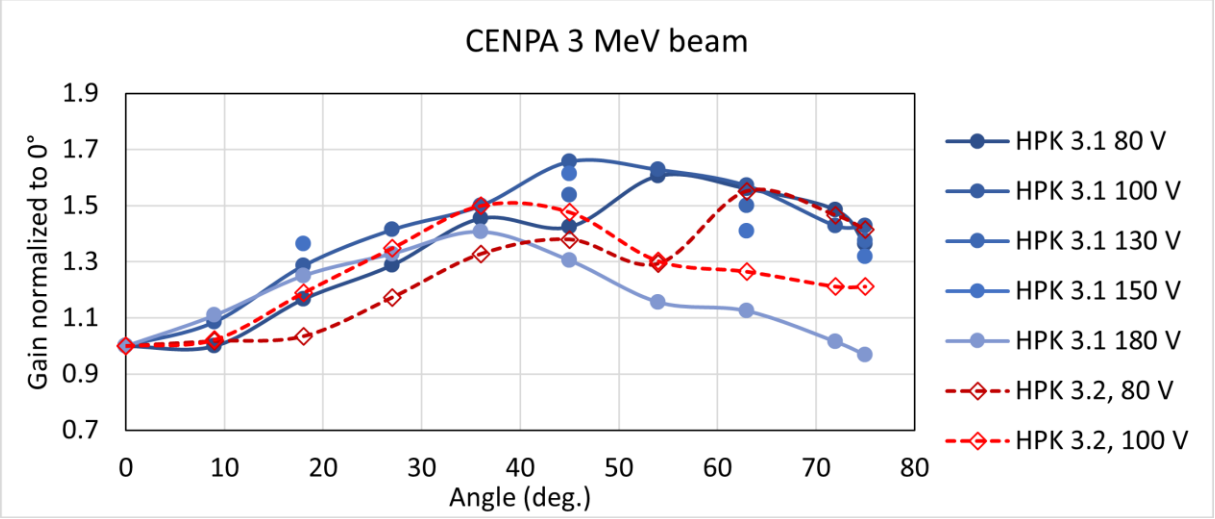


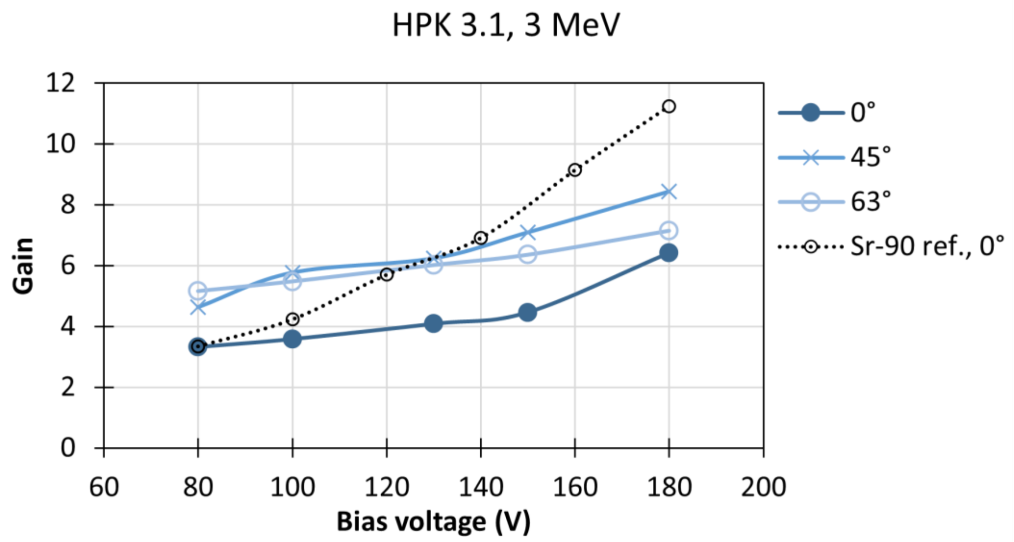


Gain saturation

- Gain: pulse_area(device)/pulse_area(pin) for each angle and each bias voltage; pin at 200 V
- Gain suppression effect as function of incidence angle is stronger for higher bias voltages
- As mentioned before, first increase of gain with increasing angle, then suppression as stopping particle is depositing more energy closer to gain layer

- **Ongoing analysis: energy resolution at different angles**
- **Next beam time at CENPA with thicker sensors and possibly AC-LGADs planned for July 15-25!**





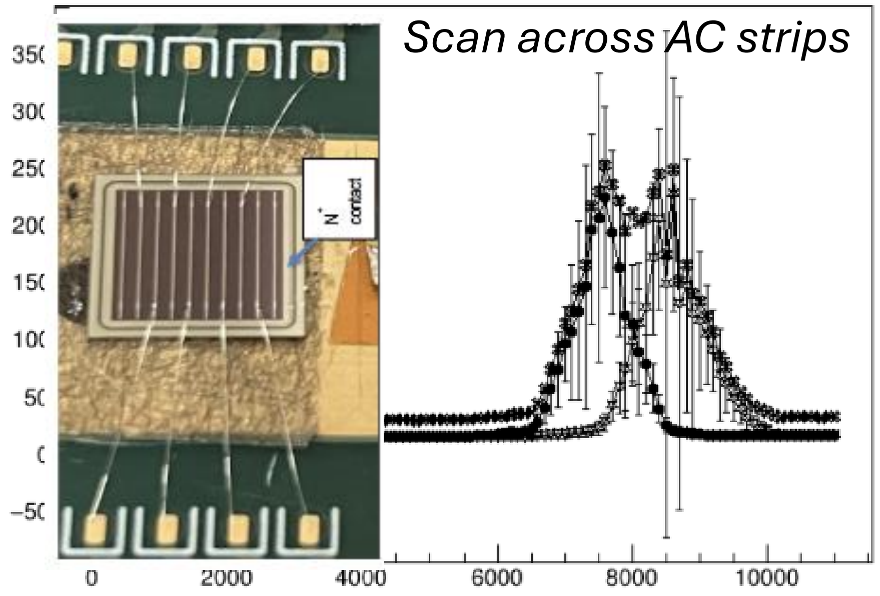
https://indico.cern.ch/event/1184921/contributions/5574780/

Hiroshima Symposium presentation and paper

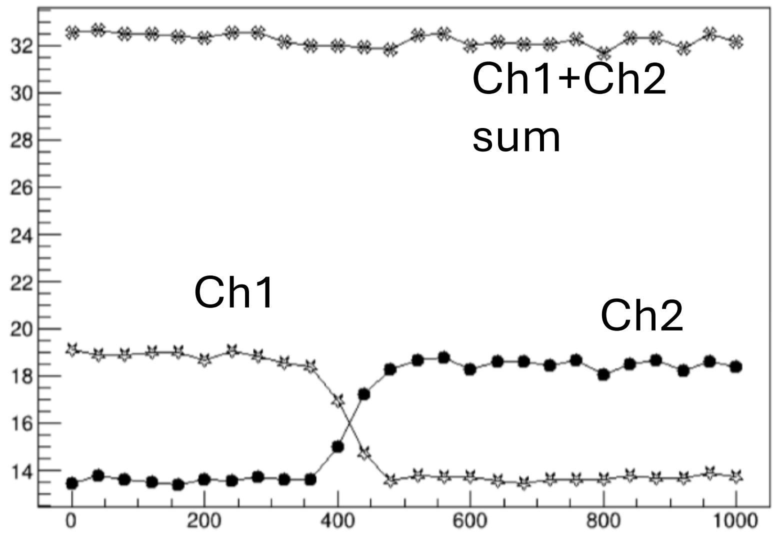
X-ray measurements

Testing LGADs with x-rays

- **After campaign in 2022, next studies conducted at beamline 7-2: focused beam, ca. 30 µm spot size**
- **Beam time at SLAC February 29 – March 4**
- **Tested AC-LGAD strip and pad sensors, single pads, etc**
  - … Ended up only to March 2 due to site-wide power blackout
  - Still managed to complete some very interesting test series
- **Additional beam time June 4-7**
  - Data with LGAD – FAST chip – Nalu HD-SoC!



Scan across TI-LGAD pads



Synchrotron x-ray detection with LGADs (from wider beam): https://dx.doi.org/10.1088/1748-0221/18/10/P10006

Summary

- Ongoing developments on several aspects of the ATAR – and this was only the sensors, more on readout and mechanics in the next talks!
- Fundamental studies: gain suppression, charge sharing in angular distribution, etc

- **Important: get to test sensor prototype in relevant technology (AC? TI? Pin?) and geometry (1+ cm long strips, double-sided, ~120 μm thickness) as multiple layers in charged particle beam, ideally with relevant electronics**

- **Interaction with simulation!**