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High granularity fast silicon sensors for the PIONEER Active TARget detector

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Overview

- Criteria for ATAR sensors
- Silicon sensor candidates for the ATAR
  - Standard LGAD
  - AC-LGAD
  - TI-LGAD
  - AC/DC –readout LGAD
  - *Planar silicon – in presentation by Xin Qian*
- Signal readout with flexes
- Investigation of gain suppression with beta and alpha particles
- Summary, Outlook

ATAR sensor criteria and motivation

- Spatial resolution
  - Separation of tracks – π , e and μ
  - (Location of decay vertex)
  - Position resolution of < 200 μm
- Area
  - 2x2 cm^2 for each plane, as little inactive material as possible: not convenient to divide this into multiple sensors or have bump-bonded pixels

→ Strip sensors, every other plane rotated 90°

- Granularity in z:
  - Thin sensor to provide granularity in z as well as fast rise time
  - Sufficiently thick to not require inactive support material
- Timing resolution
  - Rise time: precision timing of hits within < 100 ps
  - **Fall time**: recovery of baseline to register subsequent hits with 1-2 ns temporal separation

→ Signal multiplication needed: LGAD

- Efficiency
  - Fill-factor (fraction of active vs inactive area) should be as high as possible

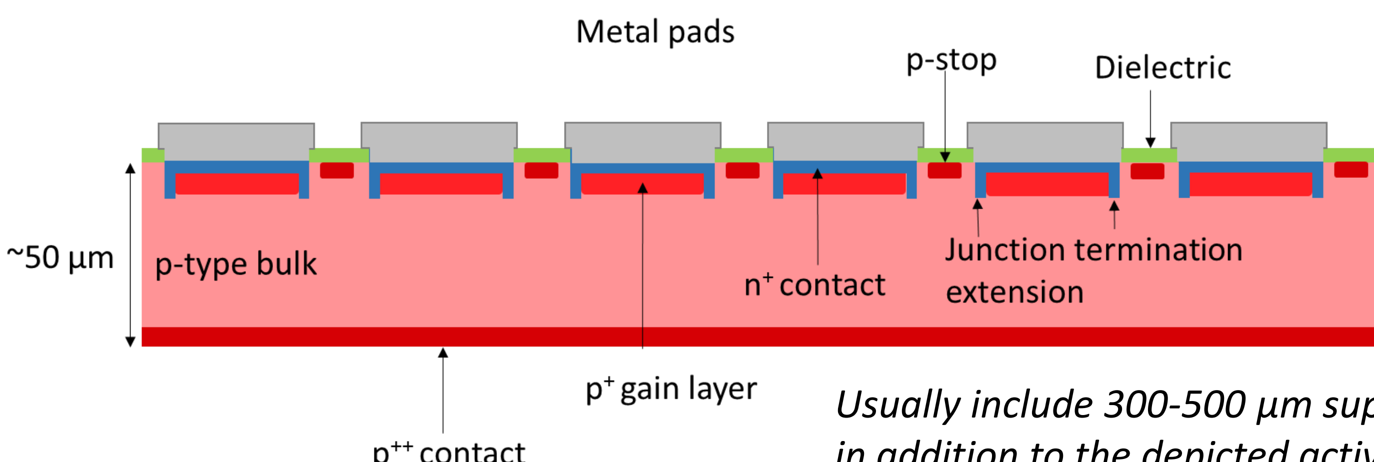
→ Conventional LGAD likely not feasible

  - High-energy event deposits in addition to MIPs: cross-talk over adjacent segments cannot be too large

→ Challenge!

Recap: Low Gain Avalanche Diodes

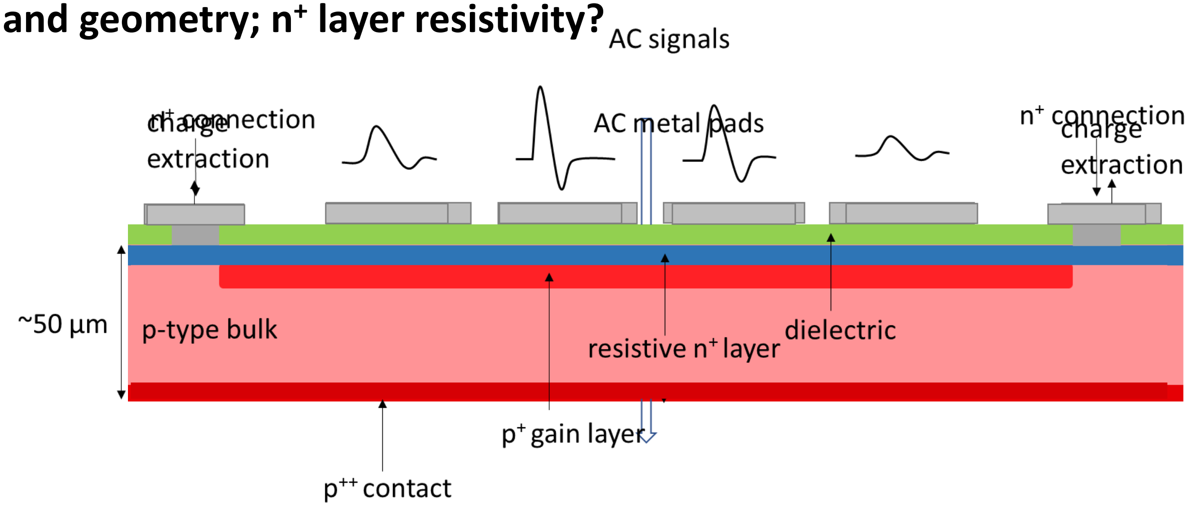
- Developed in the past 5-7 years for high-energy physics, primarily in the scope of the CMS and ATLAS endcap timing detector upgrades
  - Ultrafast timing and 4D tracking essential in future HEP experiments to mitigate effects of higher luminosity and pile-up
- LGAD key characteristics
  - Thin sensors, typical thickness 50 µm (on top of mechanical support wafer)
  - 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
  - ➢ **High-field region of the gain layer needs to be terminated between neighbouring pads: limited downscaling of this technology**



Usually include 300-500 µm support wafer in addition to the depicted active region!

AC-coupled low gain avalanche diodes

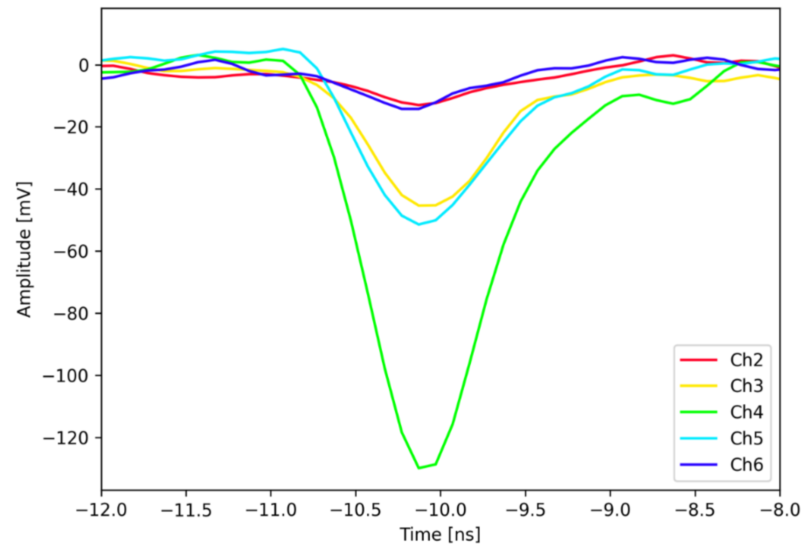
- In AC-coupled LGADs, also referred to as Resistive Silicon Detectors (RSD), the multiplication layer and n^+ contact are continuous, only the metal is patterned:
  - Signal is read out from metal pads on top of a continuous layer of dielectric
  - The underlying resistive n^+ implant is contacted only by a separate grounding contact
- 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
  - **Impact on signal sharing by segment pitch, metal width, distance; electrode shape and geometry; n^+ layer resistivity?**

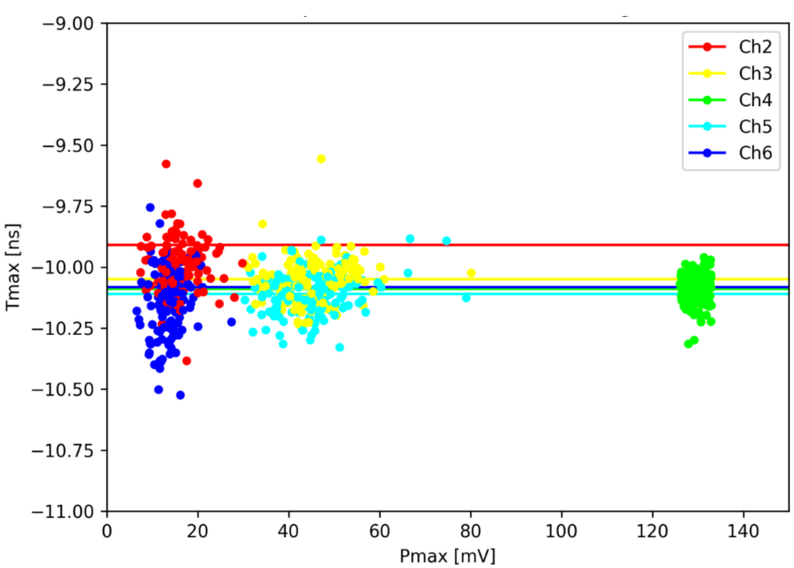


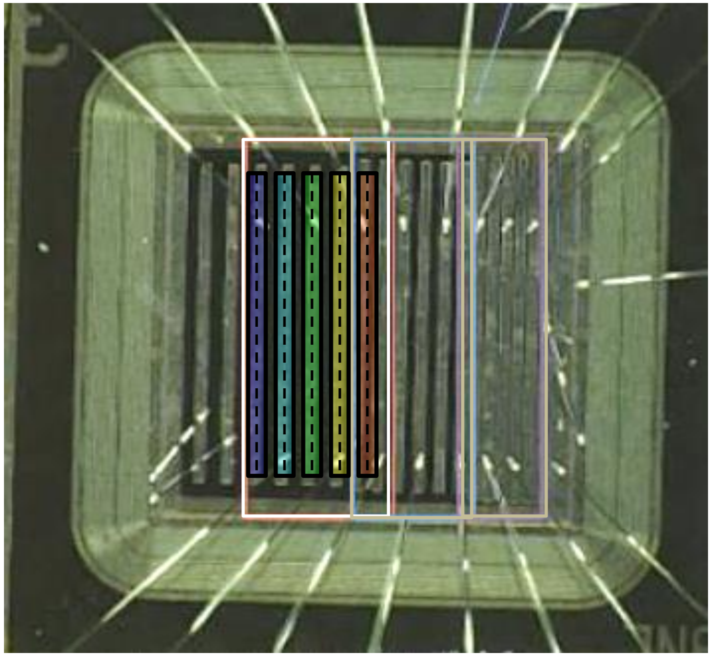
G. Giacomini *et al.,* Fabrication and performance of AC-coupled LGADs, *JINST* **2019**, 14, P09004
A. Apresyan *et al.,* Measurements of an AC-LGAD strip sensor with a 120 GeV proton beam**,** *JINST* **2020**, 15, P09038
S. M. Mazza, An LGAD-Based Full Active Target for the PIONEER Experiment, *Instruments*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

Signal pulse shapes

- Signal in first and second neighbors is observed, but with lower amplitude and wider spread in maximum amplitude and peak time, respectively
  - ➢ Slower rise time: impact on jitter → timing resolution



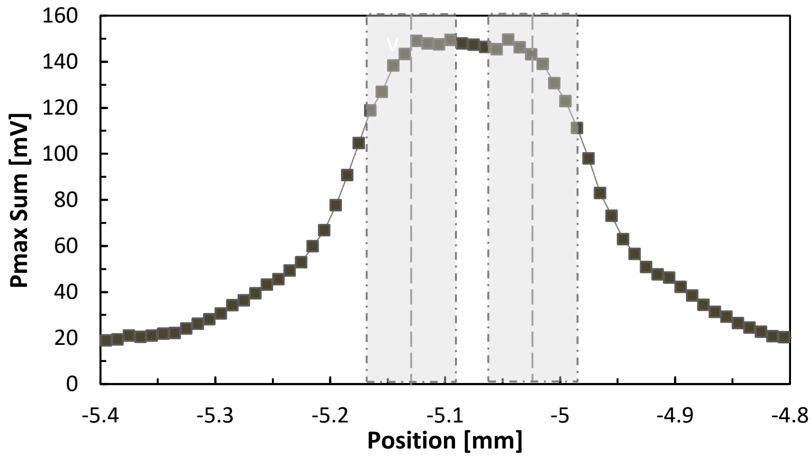




Pulse fraction and position resolution

Case of two adjacent strips

- The pmax sum ist not constant under the strip metal, but fairly constant between strip centers

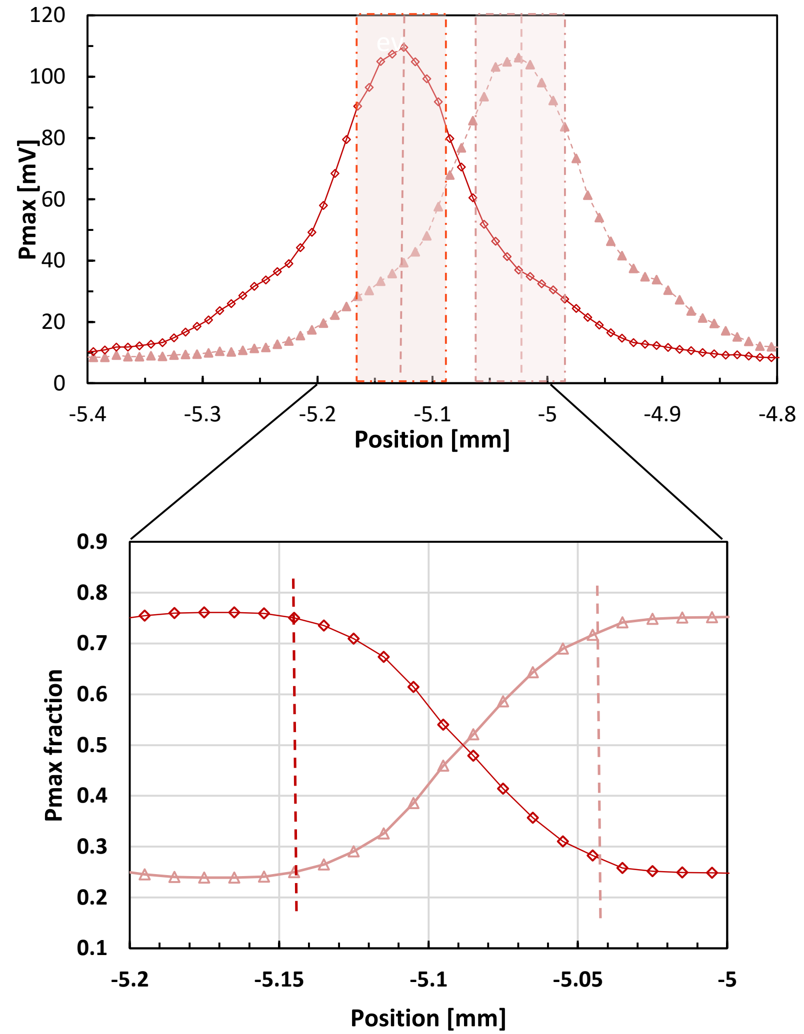


- The pmax fraction of an individual strip is defined as:

$$pmax\ fraction\ (channel) = \frac{pmax\ (channel)}{\sum pmax}$$

- The position resolution can be calculated from the fraction of pmax at a given position (fitted with an error function):

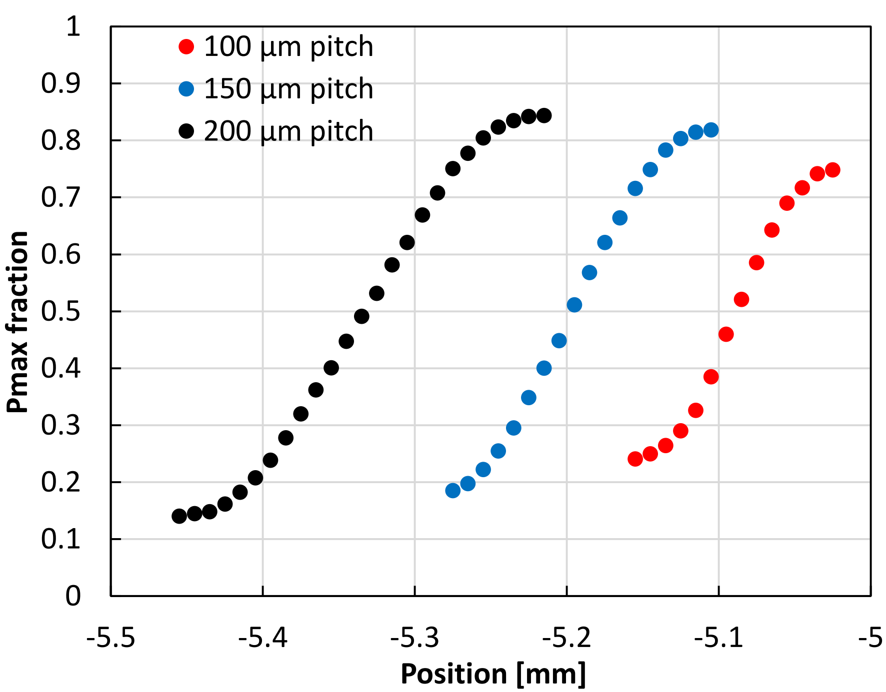
$$position\ resolution\ \sigma_{pos} = \sqrt{2}\,\frac{d(position)}{d(fraction)} / \frac{S}{N}$$

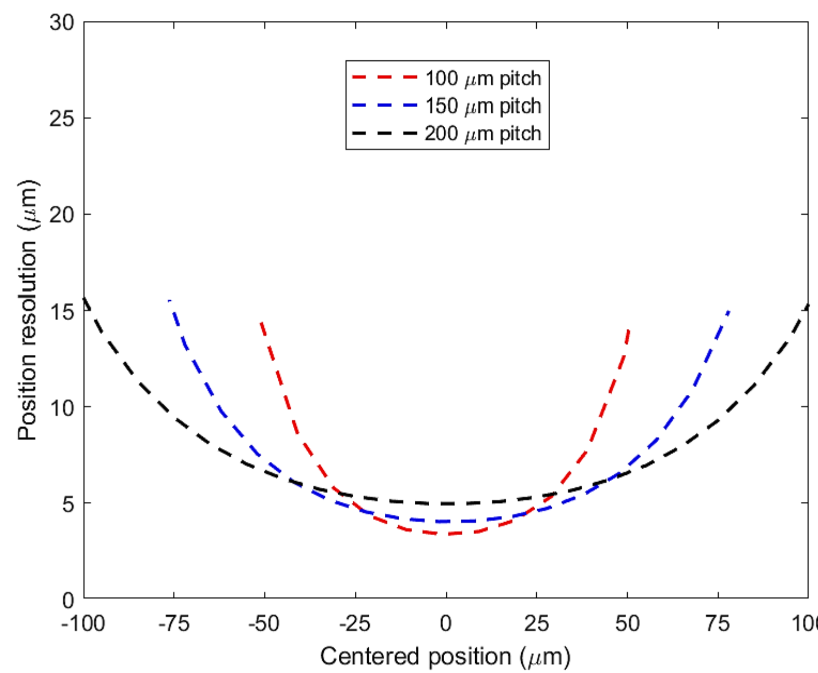


Signal-to-noise ratio is favourable in (AC-)LGADs due to their internal gain

Position resolution in BNL 2021 strips

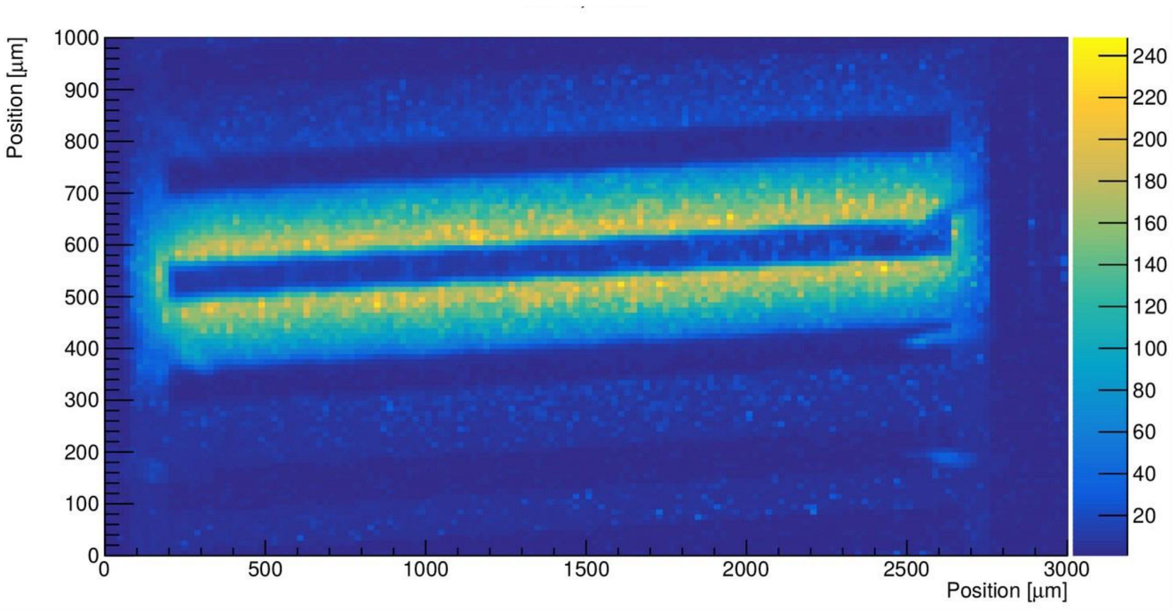
- Strip pitch is expected to - and appears to - have a large impact on charge sharing as seen in the pmax fraction profile …
- … position resolution of ca. 15 µm at the respective strip metal centers (end of the data points in the plot): **in fact very similar for all three pitches**
- Between strips, a position resolution of ~6 µm or less is reached; slightly better for smaller pitch
  - **At best, < 1/20 of the pitch**





Charge sharing in long strips

- Charge sharing over wide distances is observed, in particular for wide and long strips
- Sharing is increased with strip length, with a difference visible already between 0.5 and 1.0 cm



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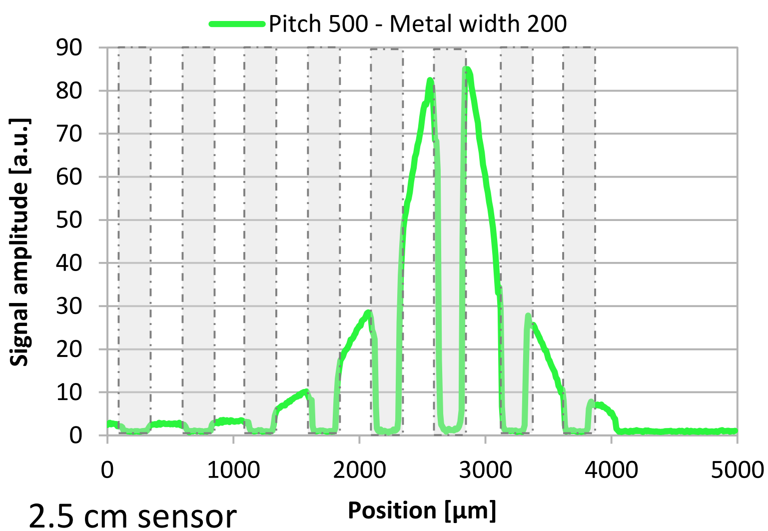
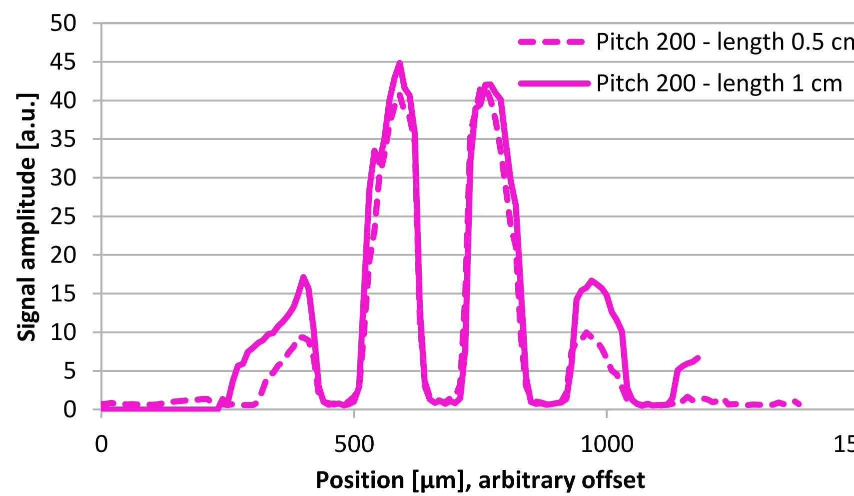
➢ Adjustment of (inter)strip capacitance, (inter)strip resistance through the metal size and n^+ resistivity is going to be of central importance



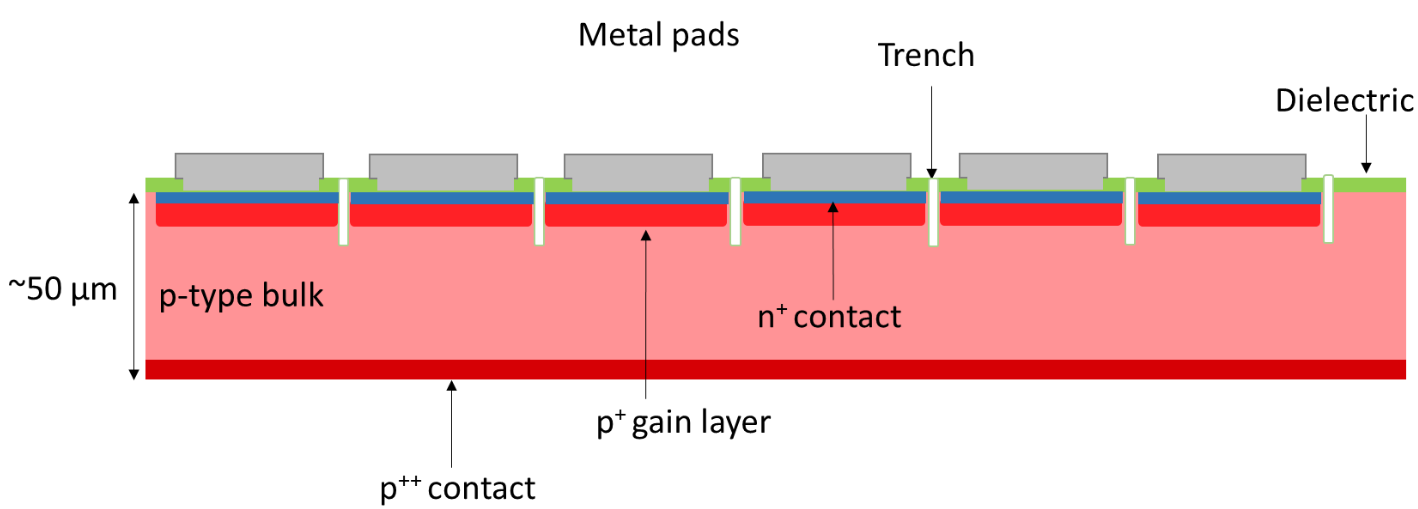
2.5 cm sensor



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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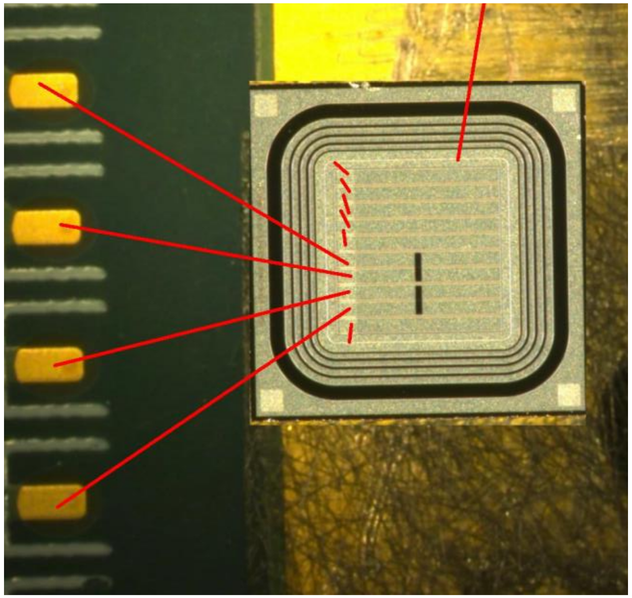
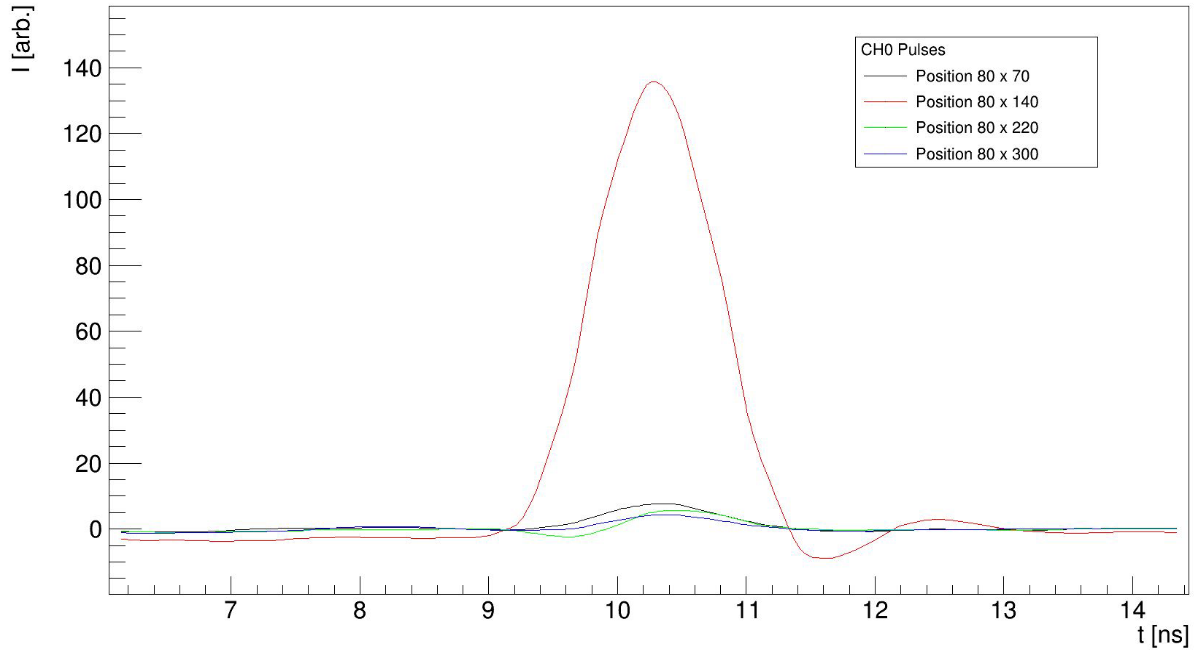
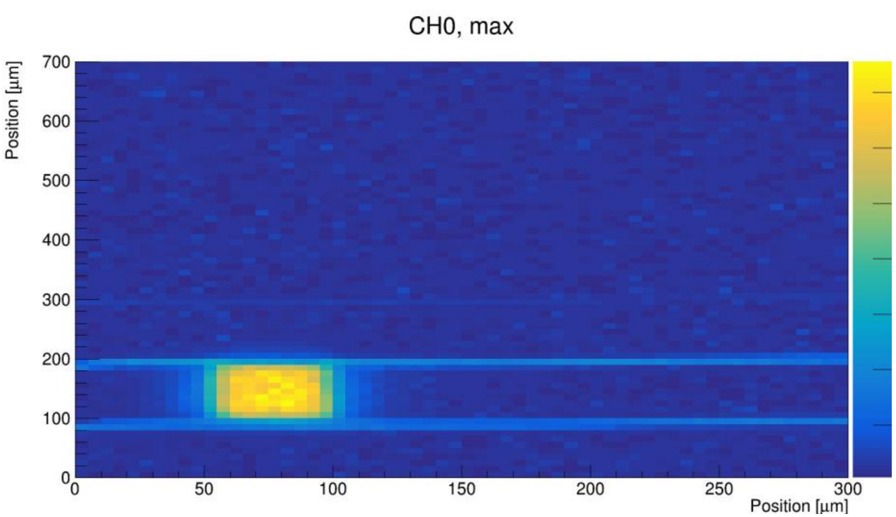
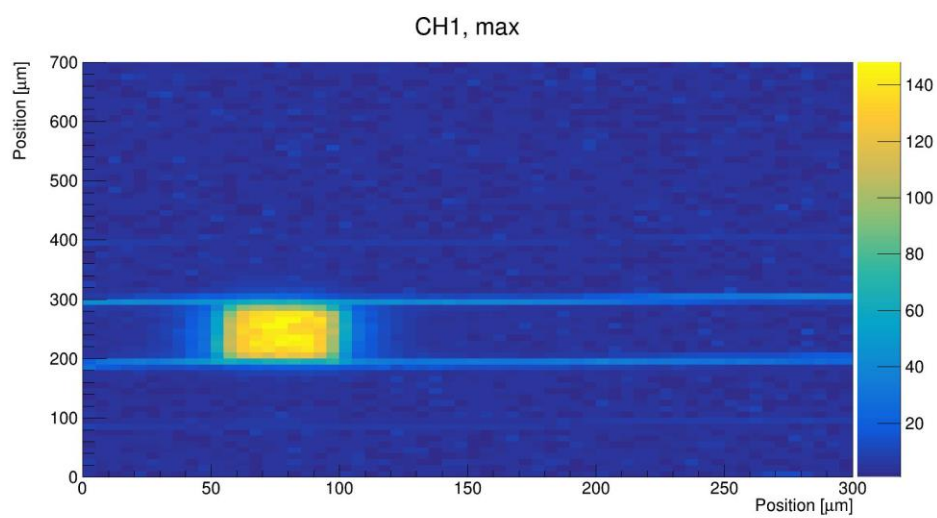


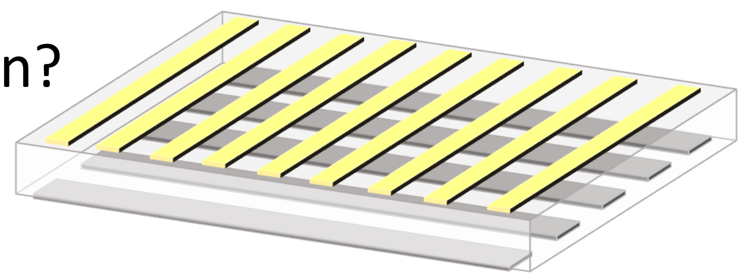






Combined AC-LGAD and DC readout

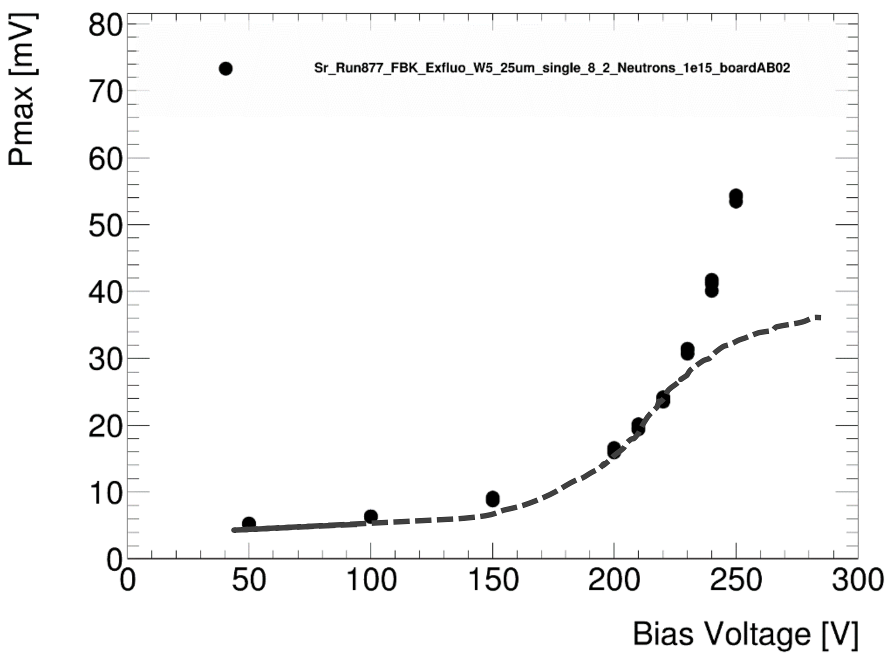
- More recently suggested by BNL: adaptation of AC-LGAD strips to also include strip pattern and readout on the (DC) back side of the sensor
  - AC side for position resolution (charge sharing)
  - DC side for timing resolution (no sharing – faster rise time)
  - Even a combined reconstruction?



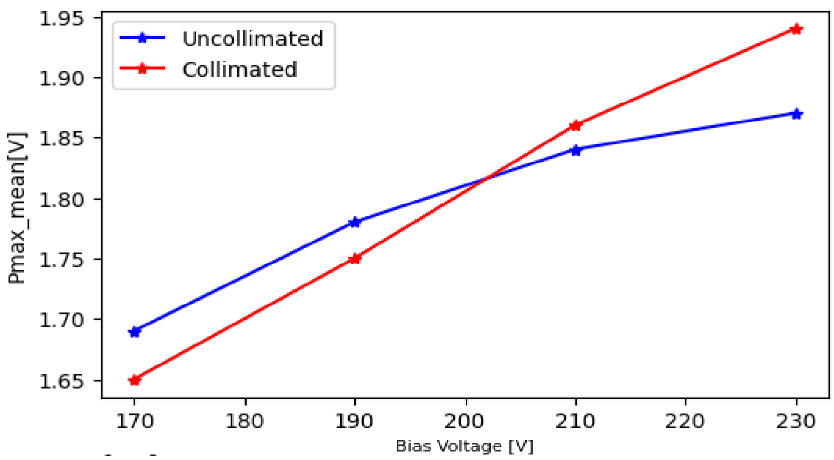
- Structure still requires simulation effort: no prototypes fabricated yet
- Adds complexity to the readout, since strips on both sides would need to be read out

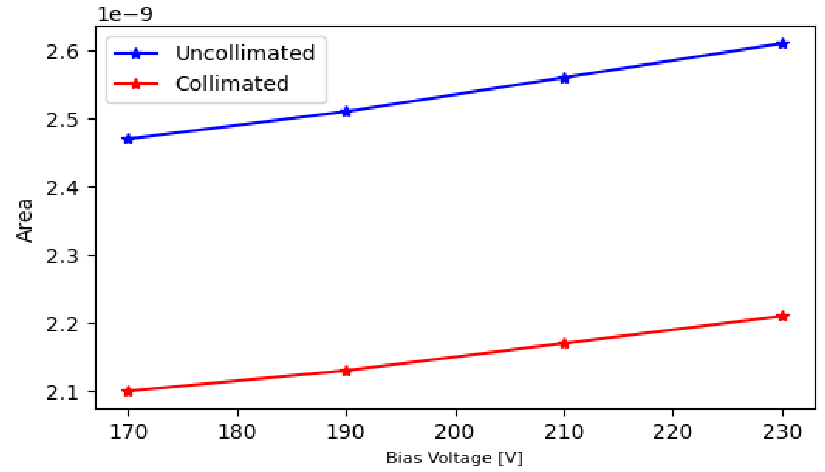
Studies of gain suppression

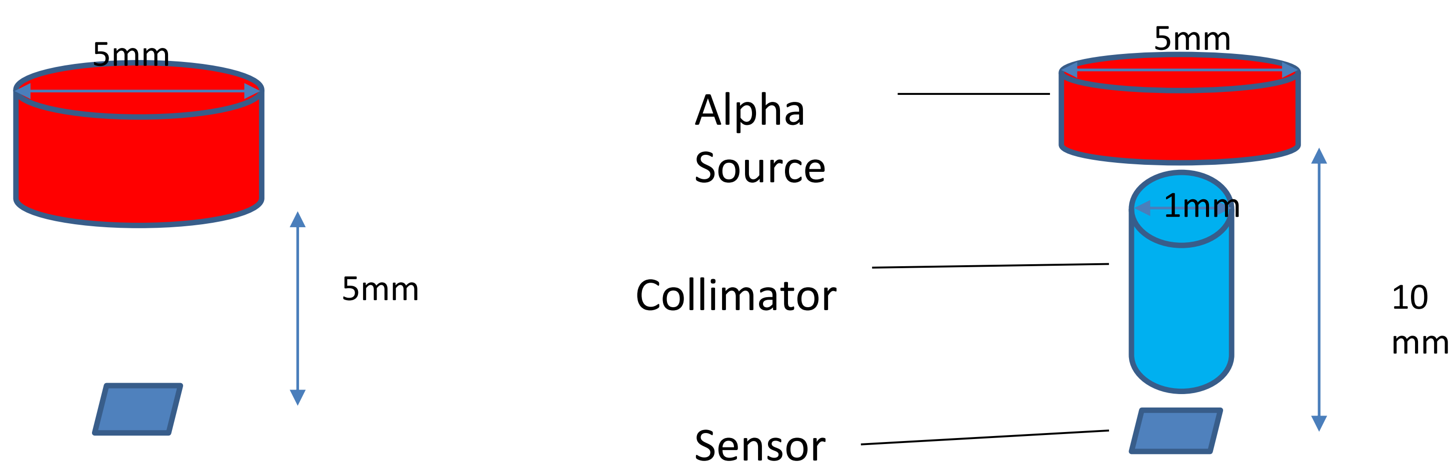
- Gain can be suppressed if a very large amount of charge carriers is present around the gain layer: absorption of high-mass particles in the surface layers of the Si sensor
  - Development of an alpha particle testing station at SCIPP
  - Comparison of alphas vs minimum-ionizing beta particles, in resemblance of charged pion and e/μ events



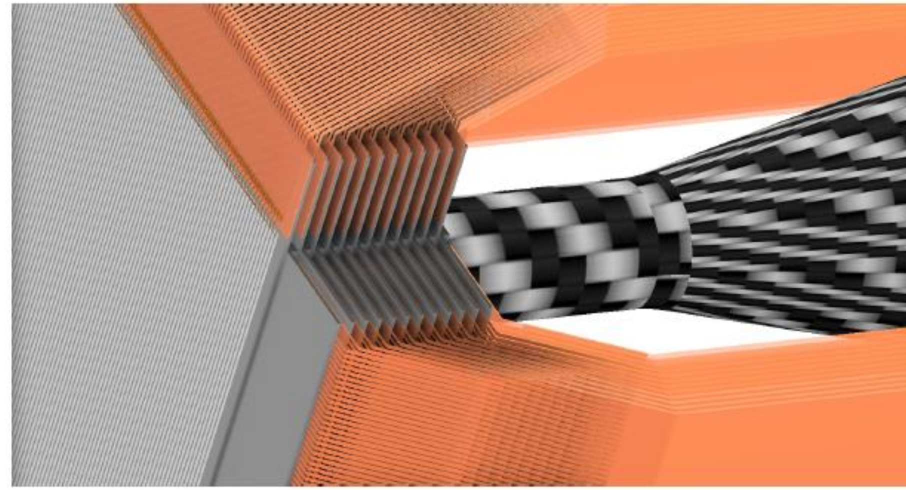
Gain suppression in the alpha station



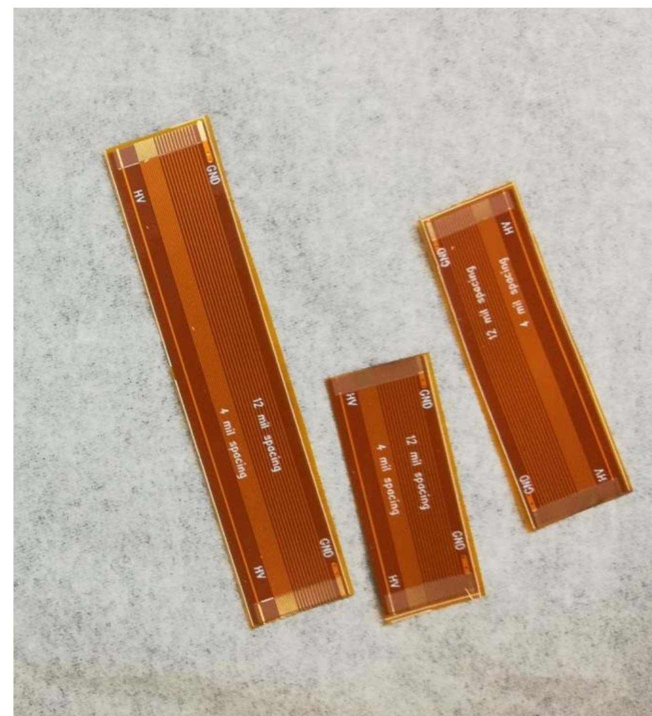




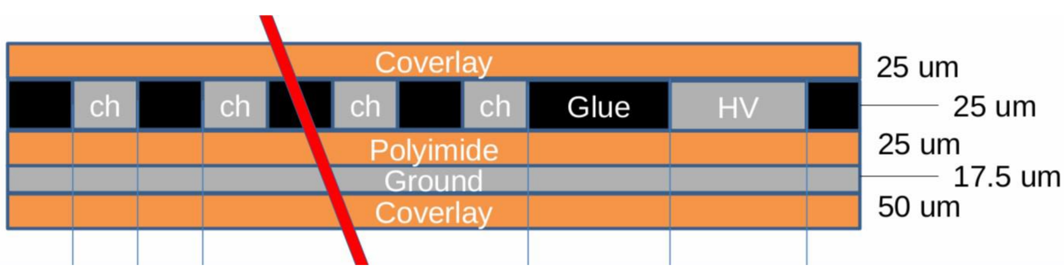
Flex readout



- Transfer of raw signals from the ATAR sensors by flex cable: readout chips do not need to be positioned in the beam or path of the decay products



- Prototypes: 3 – 7 cm flexes
- 100 and 300 µm trace pitch



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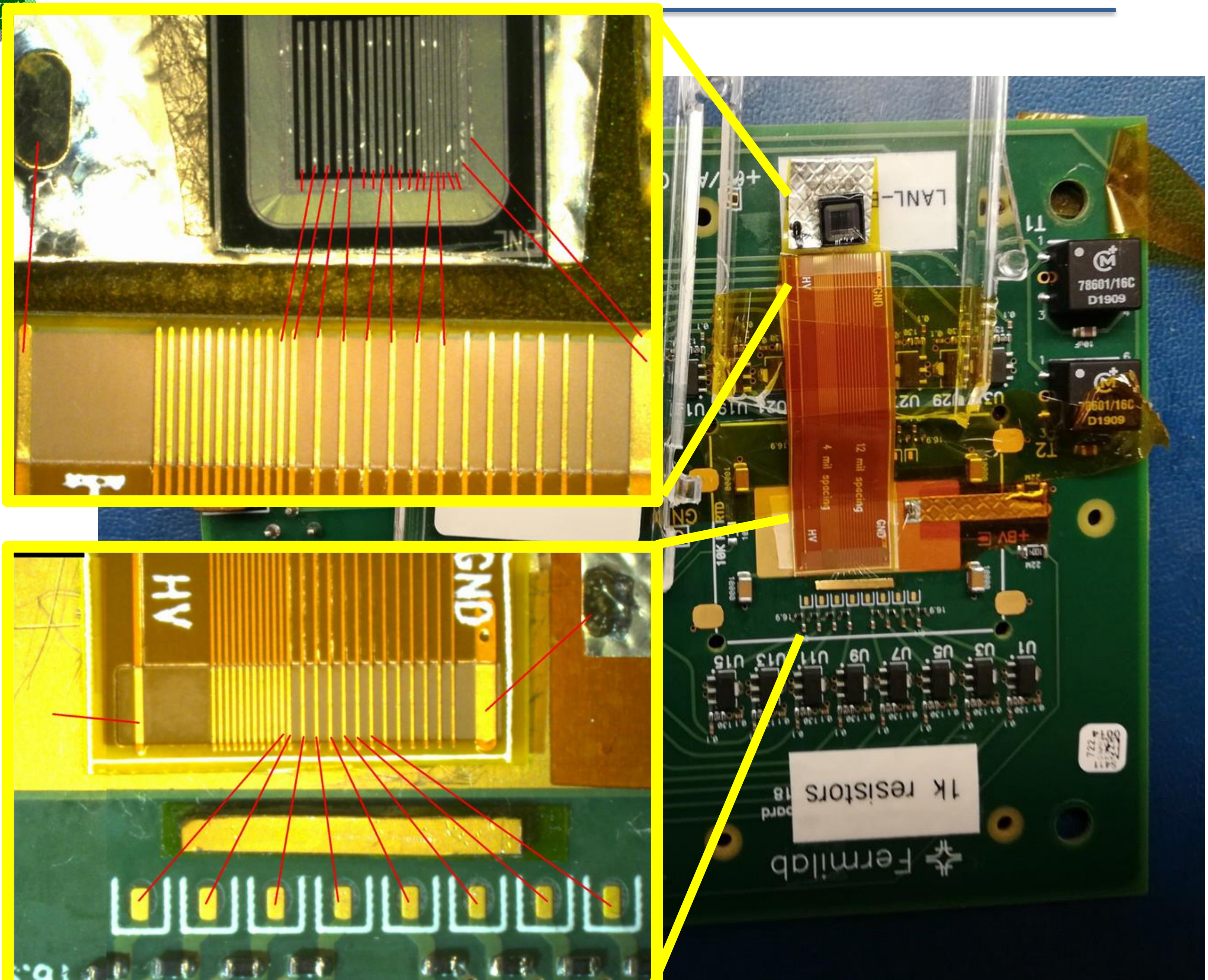
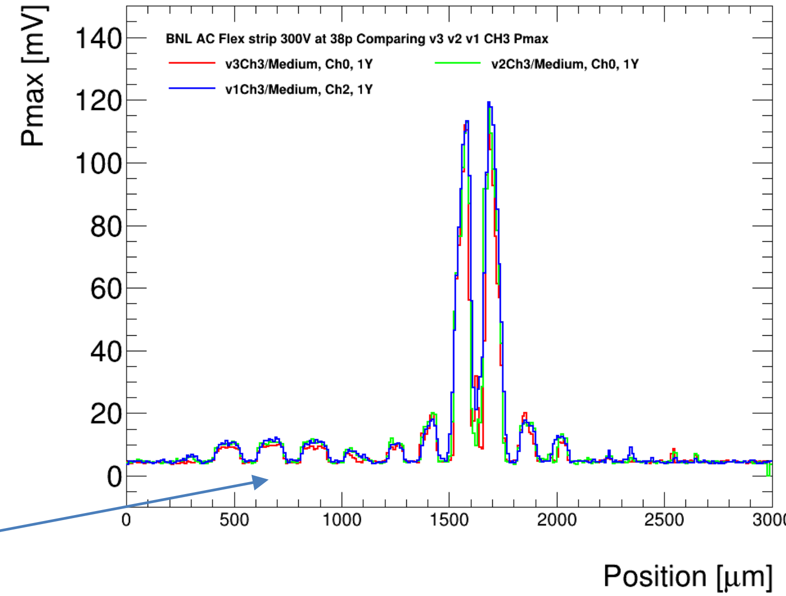
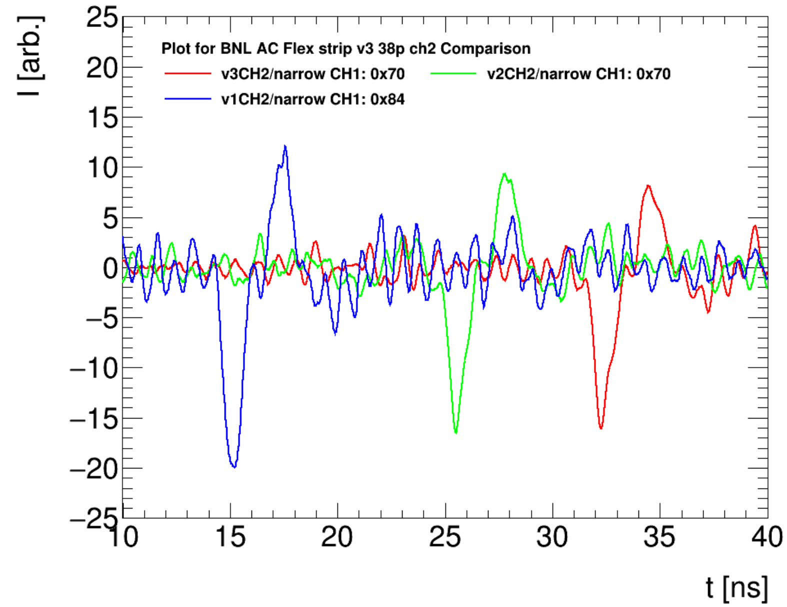


Flex readout

- Bonding of a sensor to the flex cable is mechanically challenging
- Charge sharing with neighboring strip, and baseline noise of channels are increased when connected to the flex
- Strong long-range pick-up from wide strip traces is observed
  - Attempts to reduce this by spacing connections further apart, grounding traces in between: slight improvement, but not solved
  - Very recently, started to study the flex separately from the sensor with a dedicated probe and pulse generator





Summary and Outlook

- ATAR: extensive lists of requirements and aspects to consider in terms of temporal and spatial resolution, electrical performance, readout, mechanical considerations, …
- However, for many of these requirements the precise target or range is not yet known:
  - ➢ ***Input from sensor simulation needed!***
  - ➢ ***Input from detector simulation needed!***

- AC-LGADs are the baseline technology, but other types of silicon sensor are still worth considering and investigating
  - Continued investigation of charge sharing and gain suppression at higher particle energies
  - Analysis of PSI beam test data!

- Detector performance is significantly influenced by readout electronics
  - Routing of signals via flex is nontrivial
  - Different types of particles require a large dynamic range of the front-end


Thank you!

BACKUP

Comparison of sensor technologies

Sensor	Fill factor	Spatial resolution	Timing resolution	Charge sharing	Production -ready	No. of channels to reach 20 µm pos.res.
LGAD	+	--	+++	-	++	N/A*
AC-LGAD	+++	+++	++	+++/--	++	++
TI-LGAD	++	++	+++	-	+	+
DC/AC-LGAD	+++	++	-	++	-	++ ?
Planar Si	++	-	--	+	+++	+

* Position resolution limited to ca. 1 mm/$\sqrt{12}$