Fermilab Testbeam Results for 500 µm pitch AC-LGADs

Christopher Madrid

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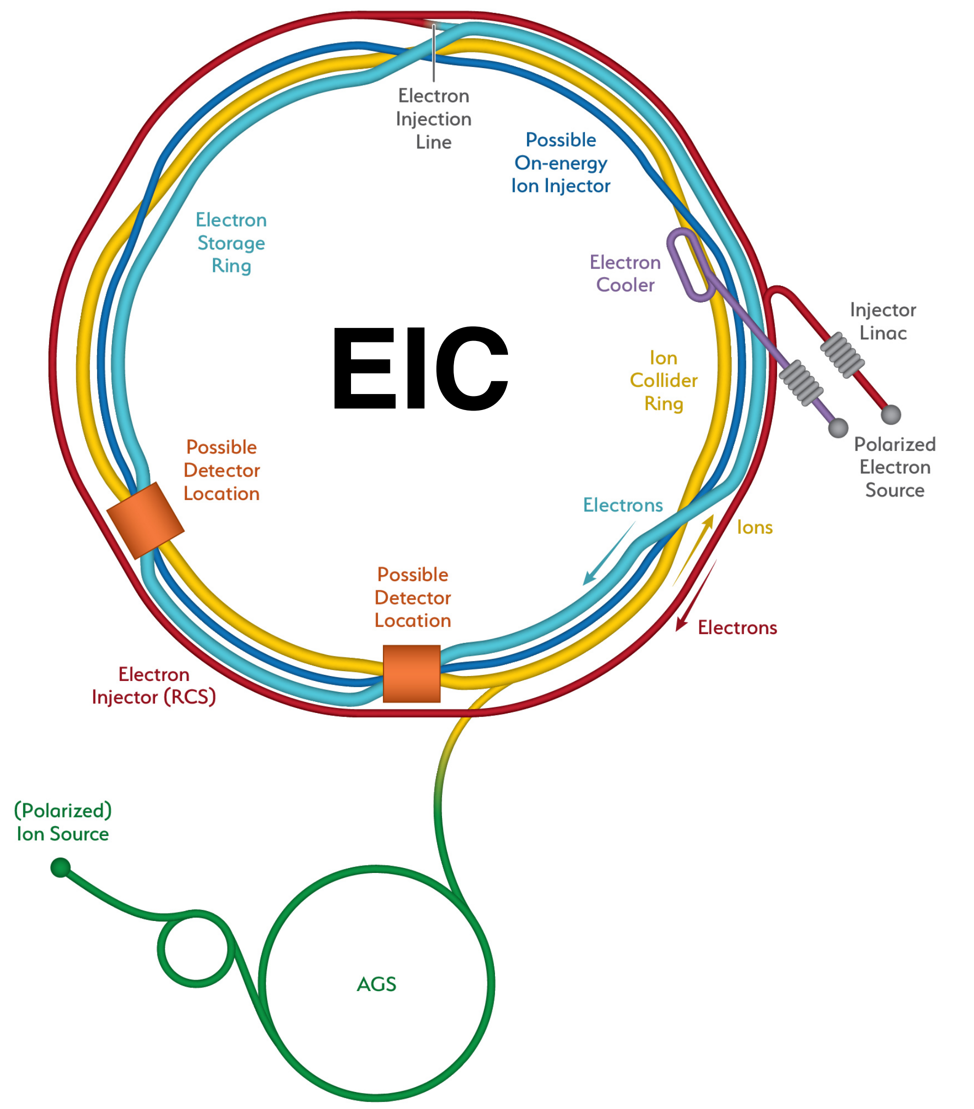
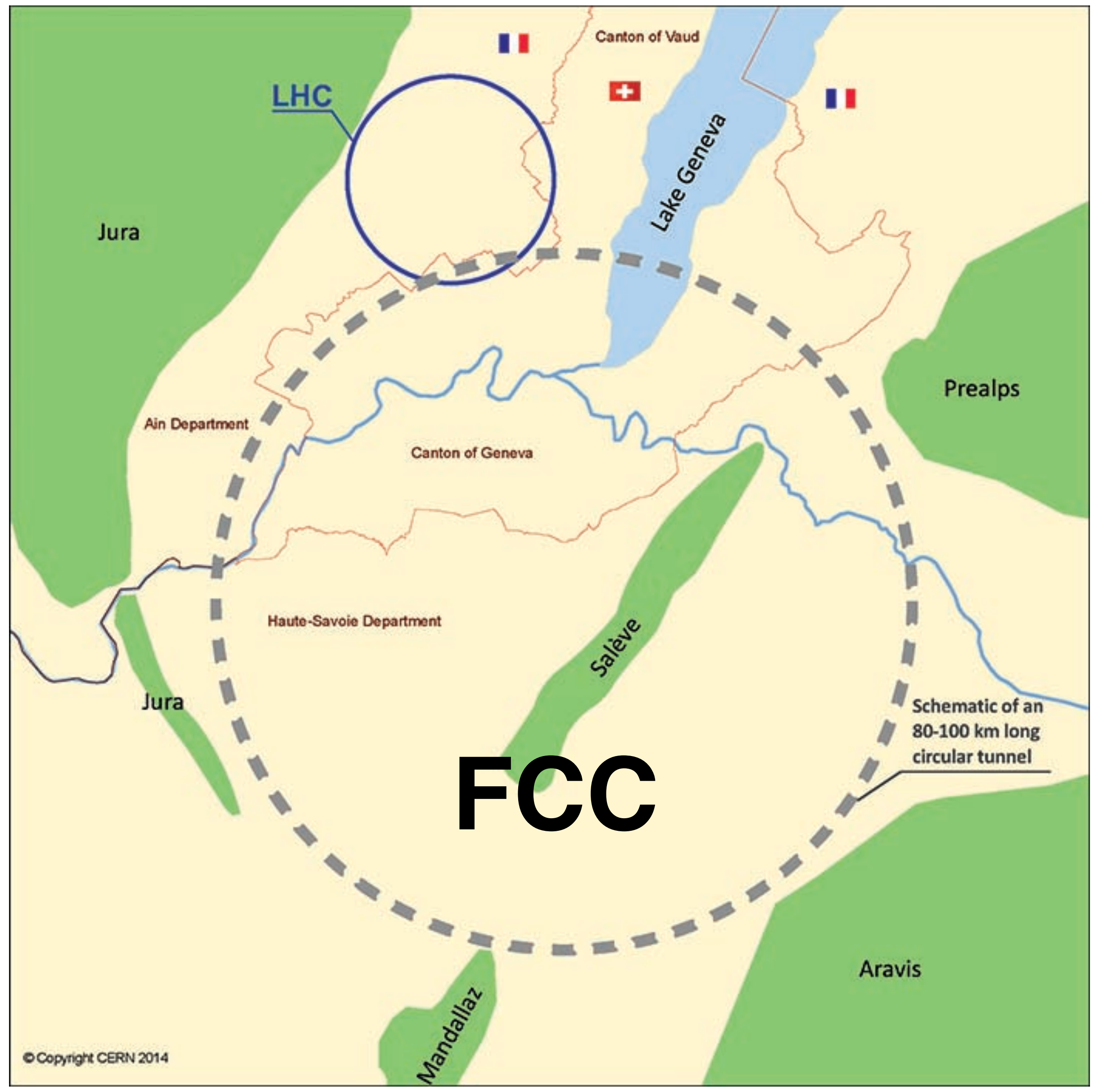
Future trackers will be 4D!

- The 4D-trackers will play a key role at the future machines
  - Reduce backgrounds, track reconstruction, triggering will need precision timing information in addition to precision position
  - Enhanced capabilities: PID and LLP reconstruction
  - All of these pose unique challenges, and opportunities to detector and electronics design, and event reconstruction

Measurement	Technical requirement
Tracking for e^+e^-	Granularity: 25x50 μm^2 pixels
	5 µm single hit resolution
	Per track resolution of 10 ps
Tracking for 100 TeV pp	Generally the same as e^+e^-
	Radiation toleran up to 8×10^{17} n/cm^2
	Per track resolution of 5 ps

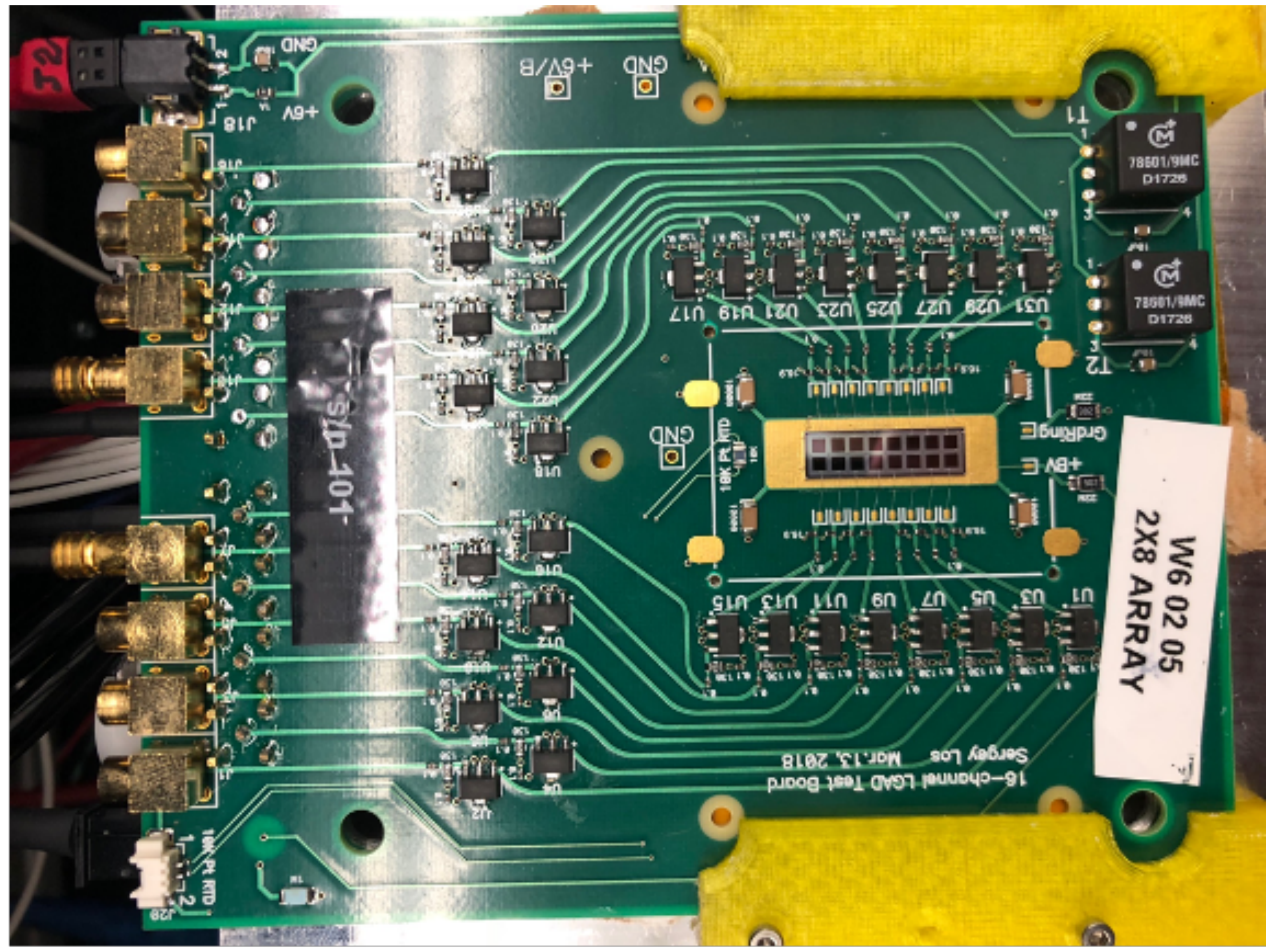
Technical requirements for future trackers: from DOE's HEP BRN

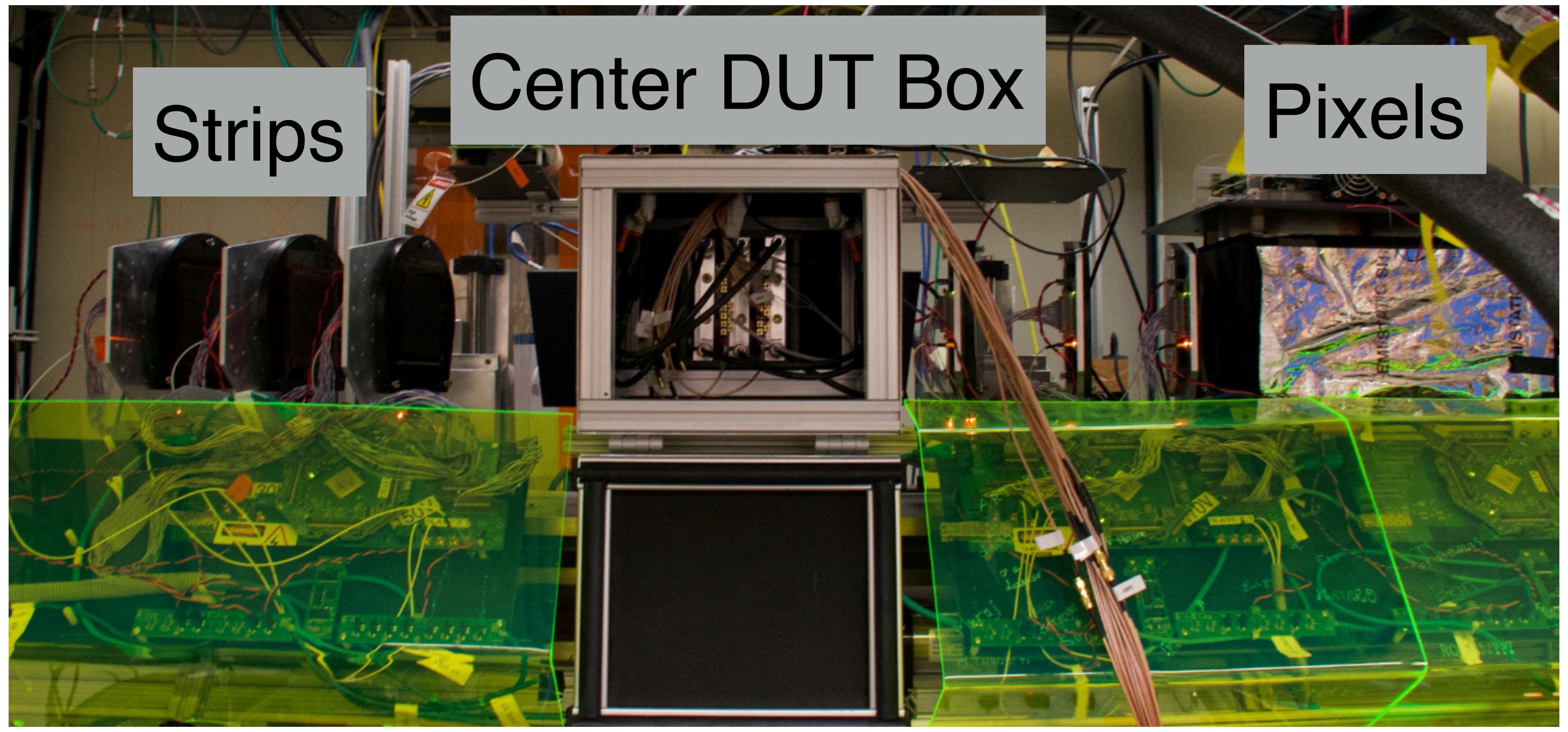


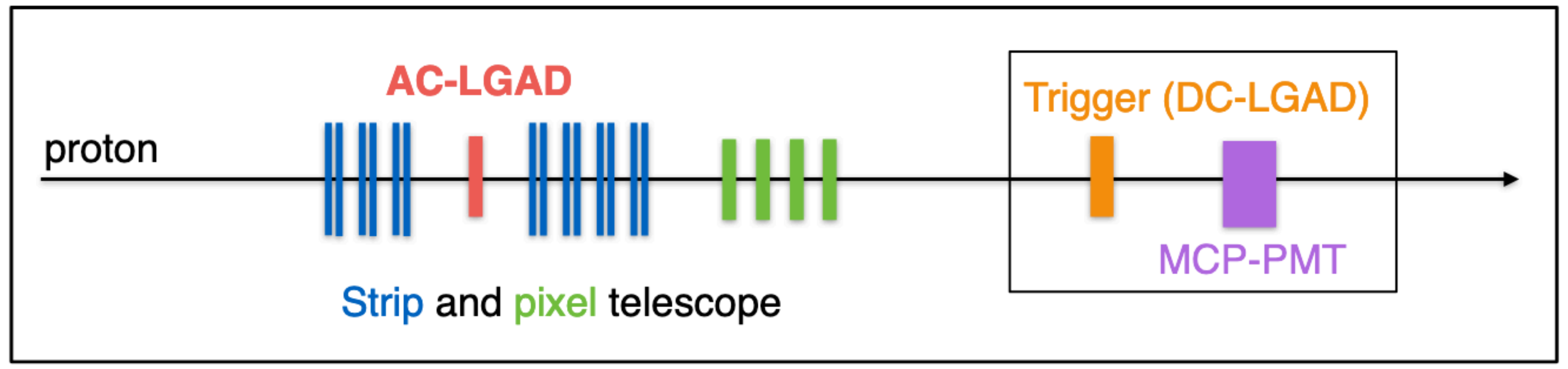


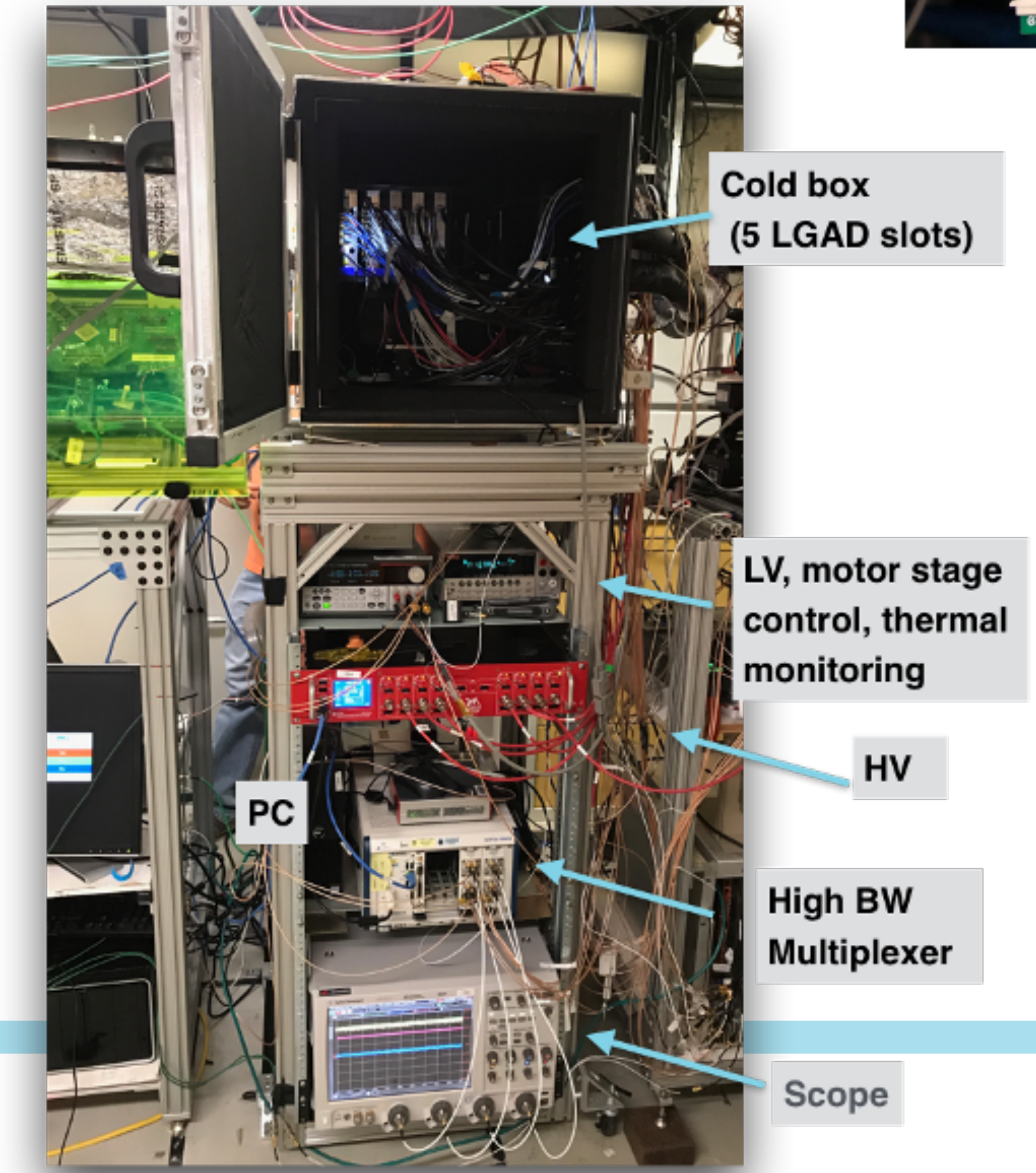
Fermilab 4D-trackers test beam infrastructure

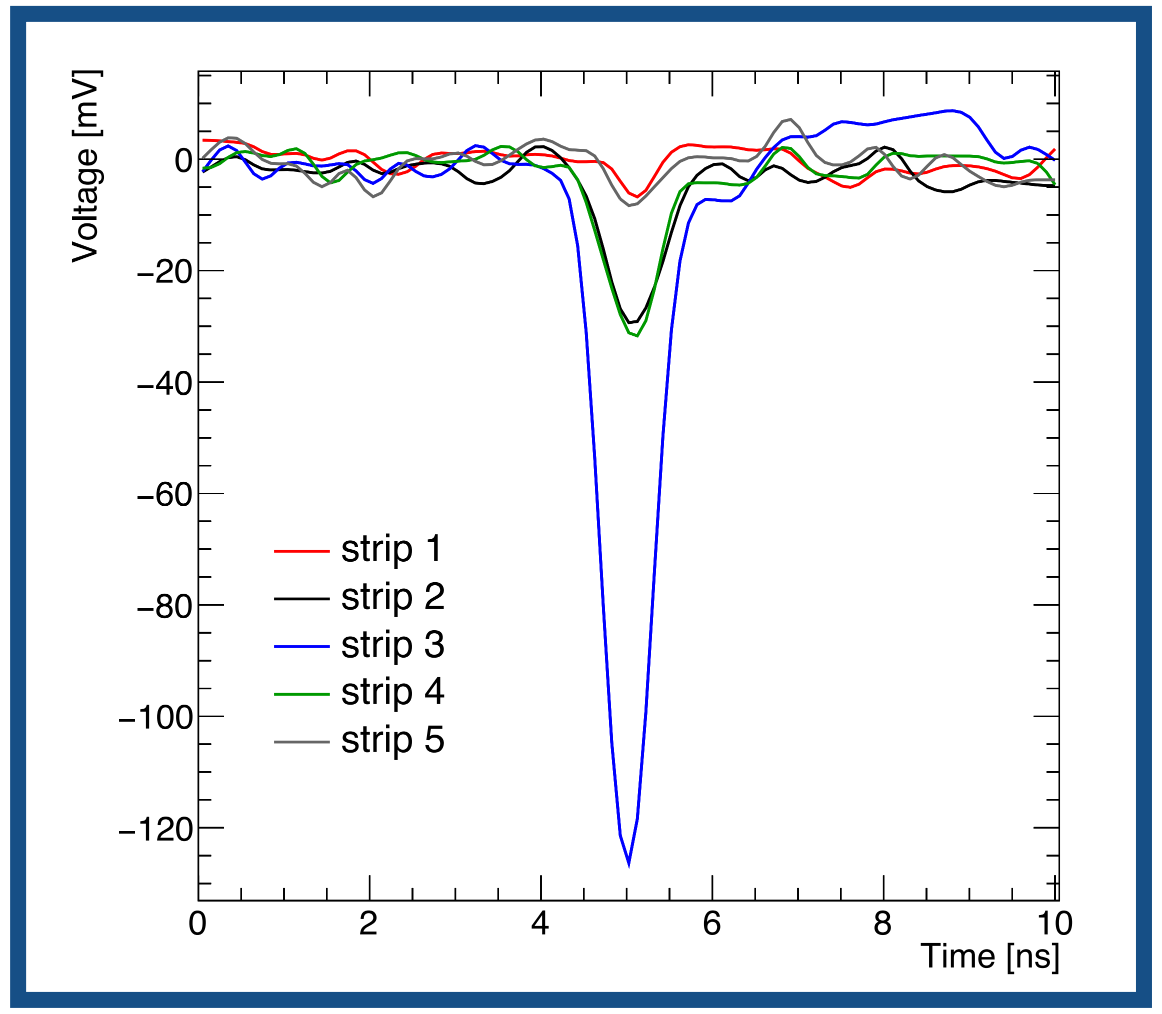
- Permanent setup in FNAL test beam facility (FTBF)
  - Movable: slide in and out of beamline as needed, parasitic use of beam
  - Environmental controls: sensor temperature (-25 C to 20 C), and humidity, monitoring
  - Remote control (stages, HV, LV), logging & reconstruction; σT ~ 10 ps time reference (MCP)
  - Cold operation of up to 10 prototypes at the same time
  - DAQ: high bandwidth, high ADC resolution scope 8-channel scope
  - Record 100k events per minute, tracker with ~5 μm resolution
- Developed readout boards for the characterization of LGADs
  - Without complicated ASIC and DAQ











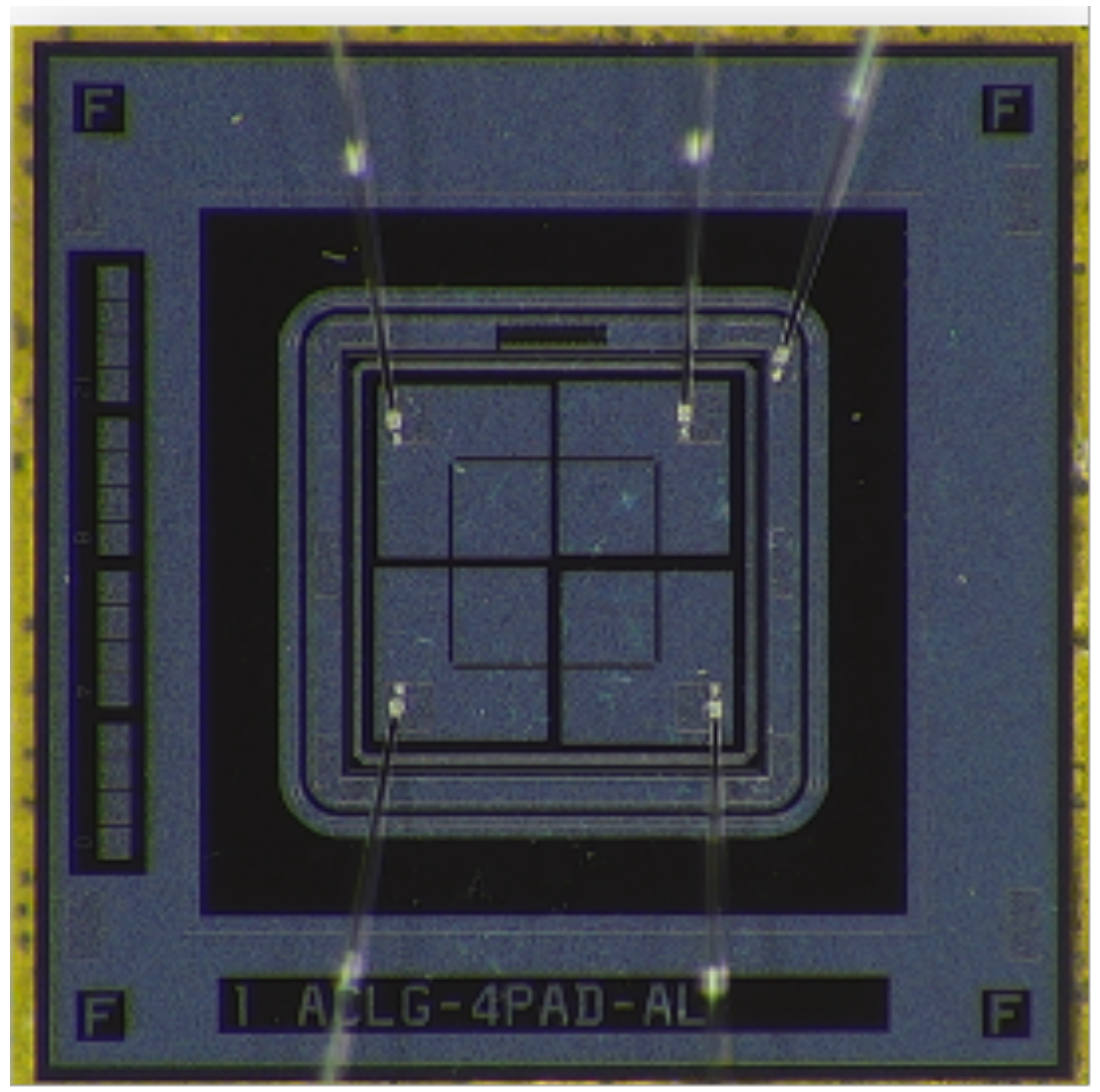
Testbeam Sensors Overview

- Showing results for sensors that could meet EIC requirements
  - Only showing a small fraction of the sensors tested at both testbeam campaigns
- **Pixels**
  - Studied 2x2 4-channel 500x500 μm² pixels manufactured by HPK with 50 μm thickness of active volume
  - Mostly covered in metal
  - Results detailed in a **paper** published early this year based on 2021 testbeam data
  - Further sensor design optimizations planned for future productions, e.g. changing metal size and resistive layer
- **Long Strips**
  - Studied 3 strip length variation (5, 10, and 25 mm) manufactured by BNL with 50 μm thickness of active volume
  - Constant pitch (500 μm) and metal width (200 μm)
  - Preliminary results based on testbeam data from March 2022
    - Main goal is to study impact of large geometry on AC-LGAD performance
    - **Paper with detailed results coming soon**

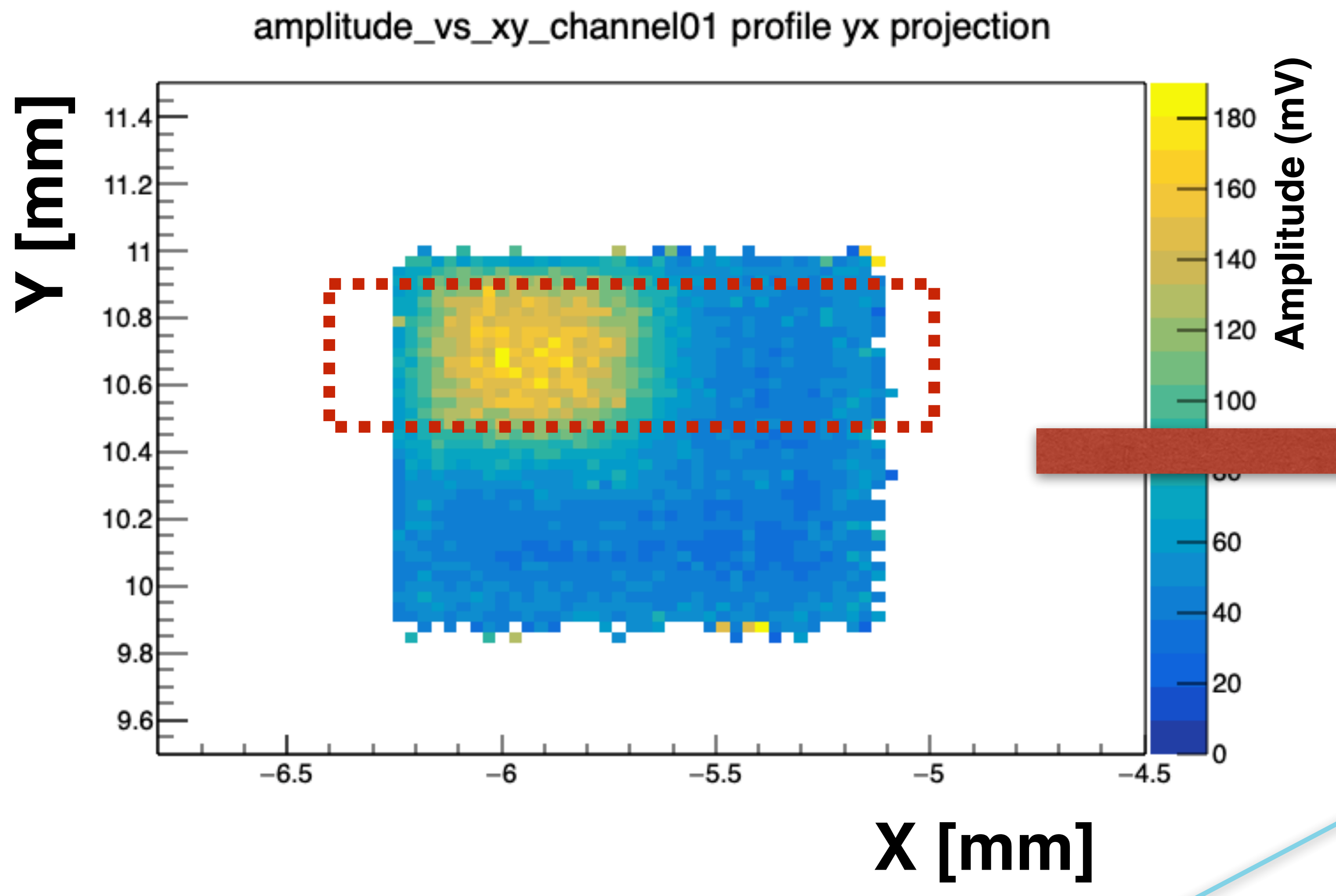
Test beam results: HPK Pixels

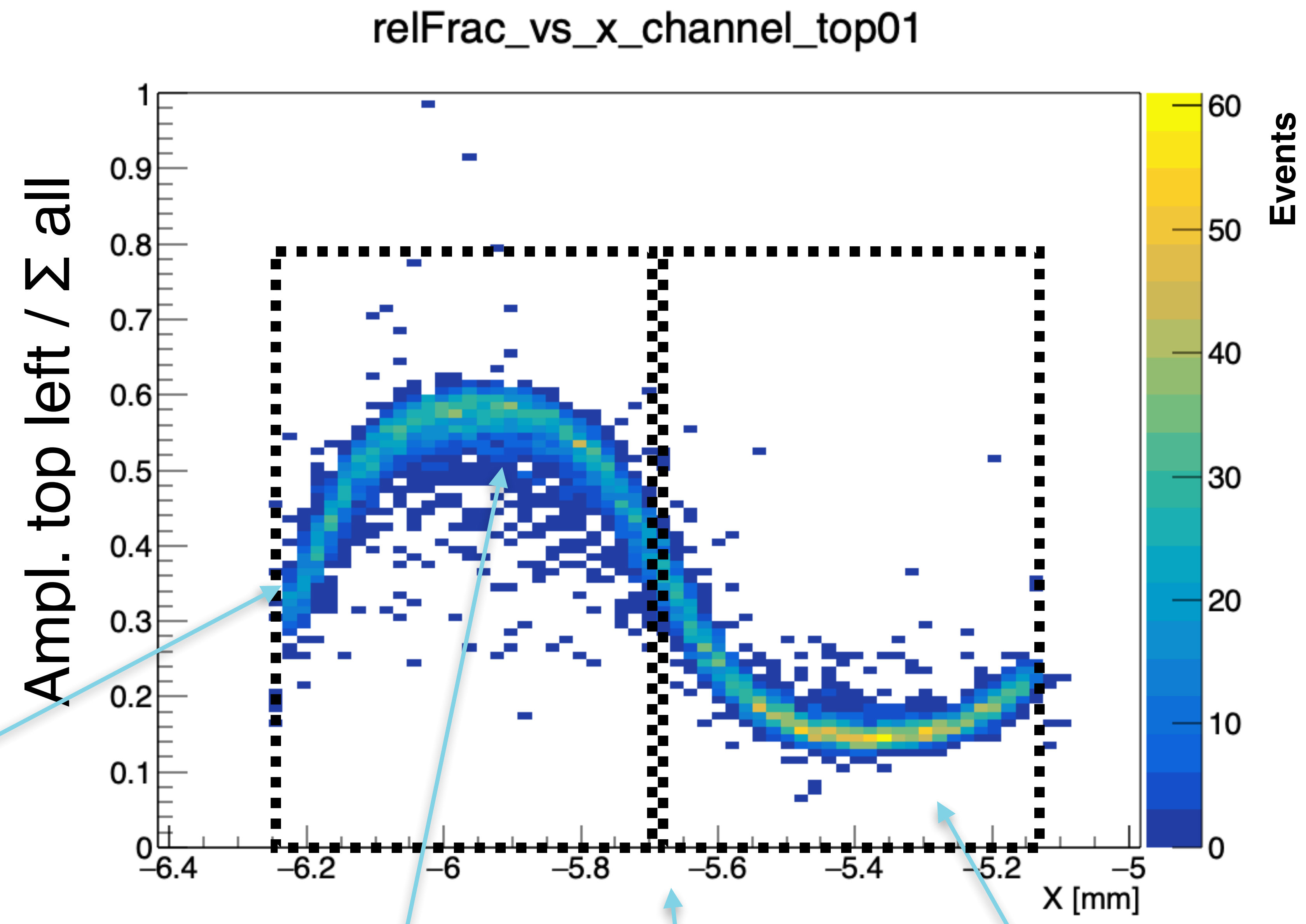
- We have sensors from KEK and U. of Tsukuba that are fabricated at HPK
- Here we have a 2x2 pad sensor with 500 µm size pads
- **The overall performance we observe is great:**
  - 100% efficient, primary signal size are large (~128 mV), and signal sharing extends well into neighboring channel
- **Show effects of signal sharing in 2 dimensions by looking at the signal size for hits to the top left pad**

arxiv:2201.07772



HPK 2x2, 500 µm pad size





Decreased coupling near pad edge

Signal fraction flat at center

300 micron linear region!

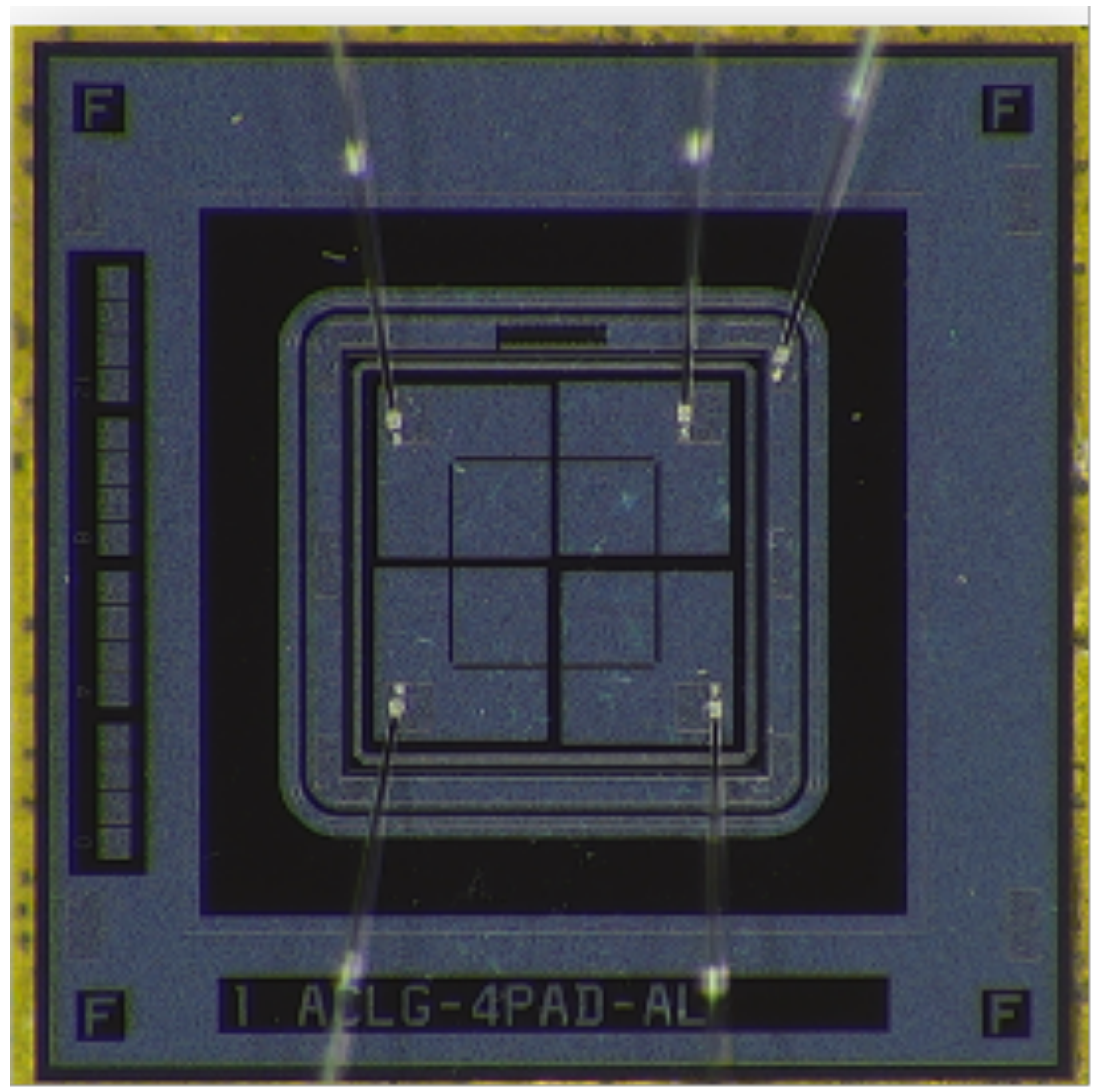
Constant distant coupling.

Fermilab

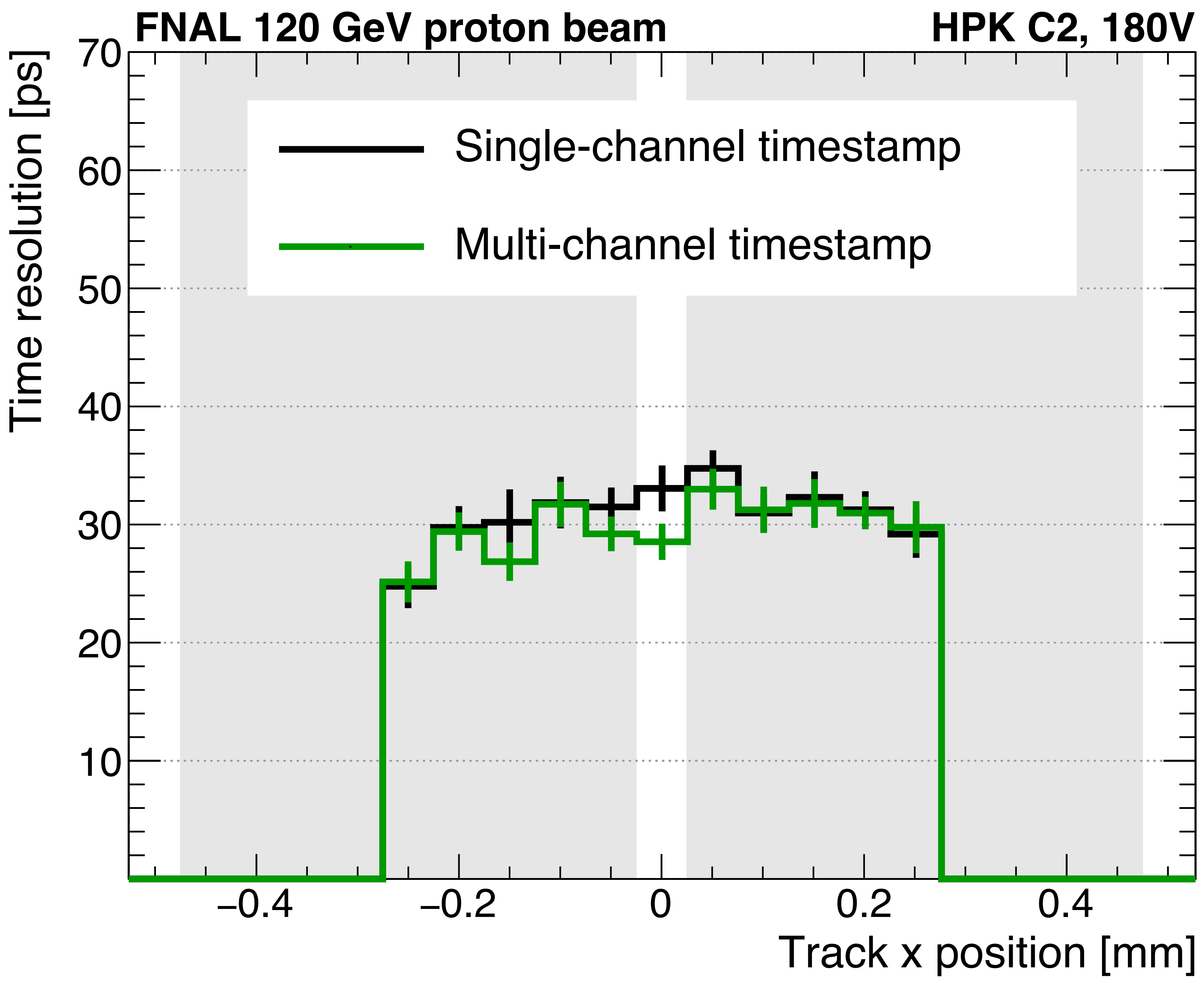
Test beam results: HPK Pixels

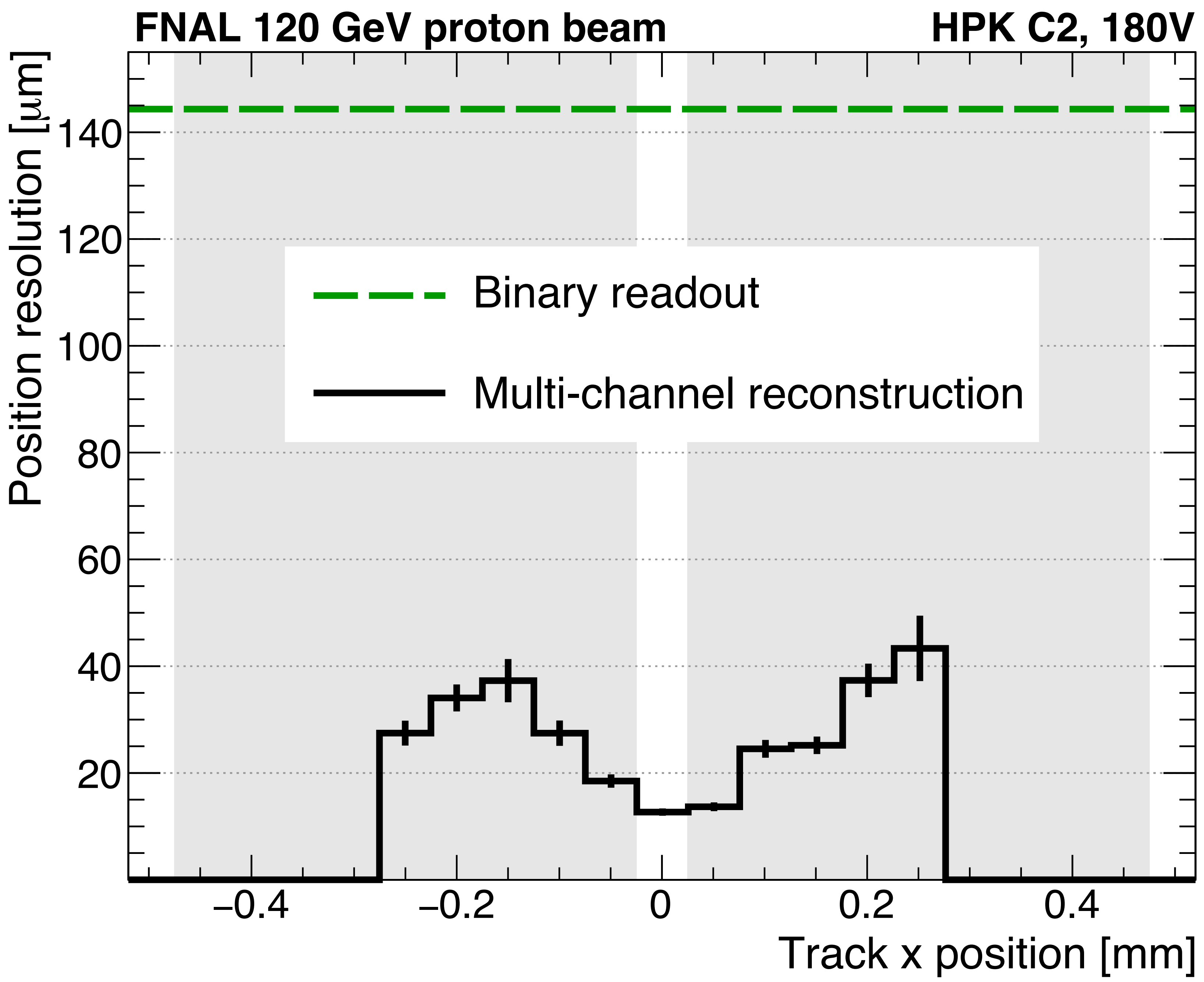
- **Time resolution measured to be 30 ± 1 ps and uniform over sensor**
- **Position resolution ranges from 15 - 40 μm depending on location**
  - **Overall is measured to be 22 ± 1 μm**
- Future productions optimizing metal and increasing the number of channels is planned

[arxiv:2201.07772](https://arxiv.org/abs/2201.07772)

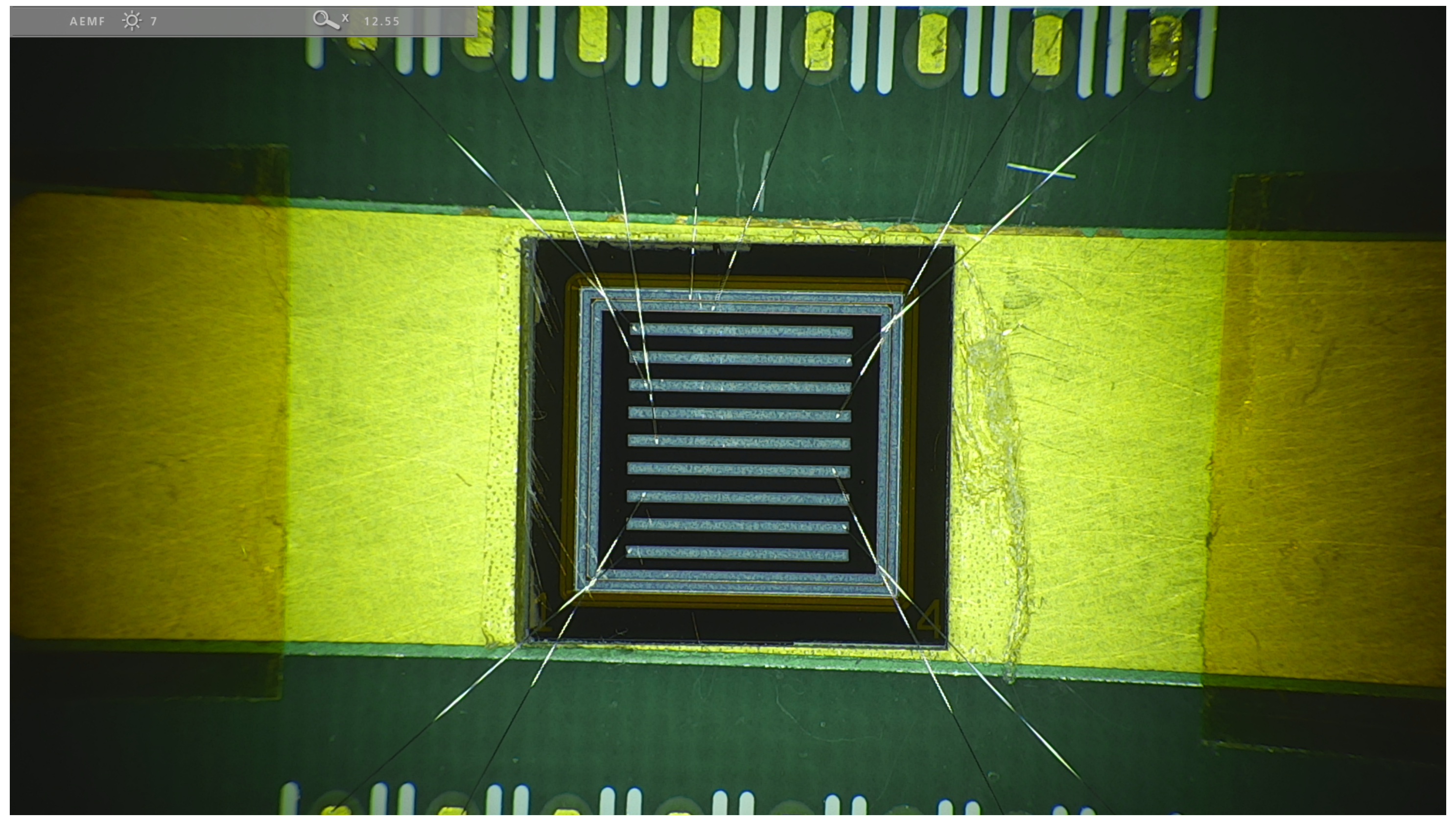


HPK 2x2, 500 μm pad size

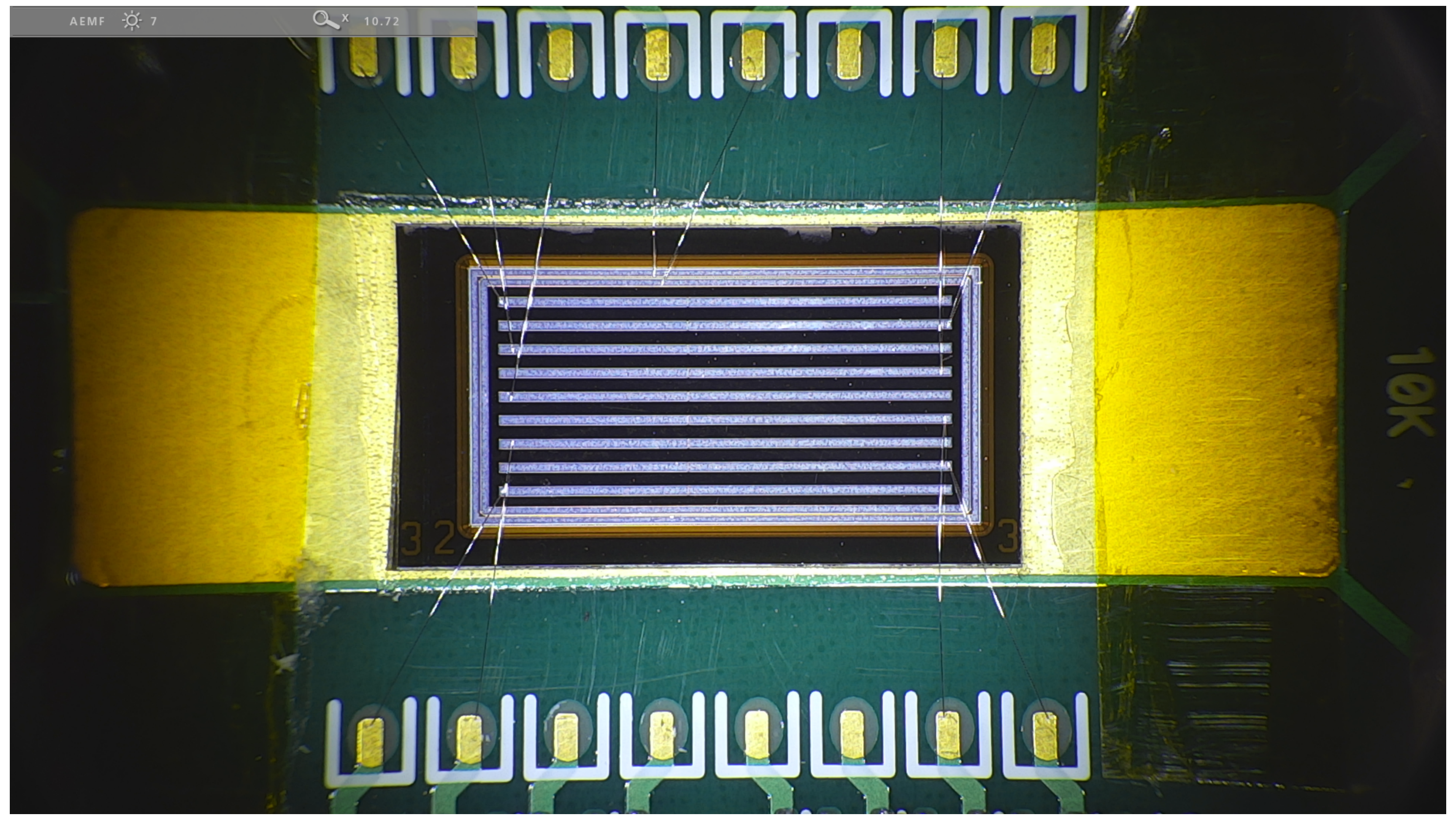




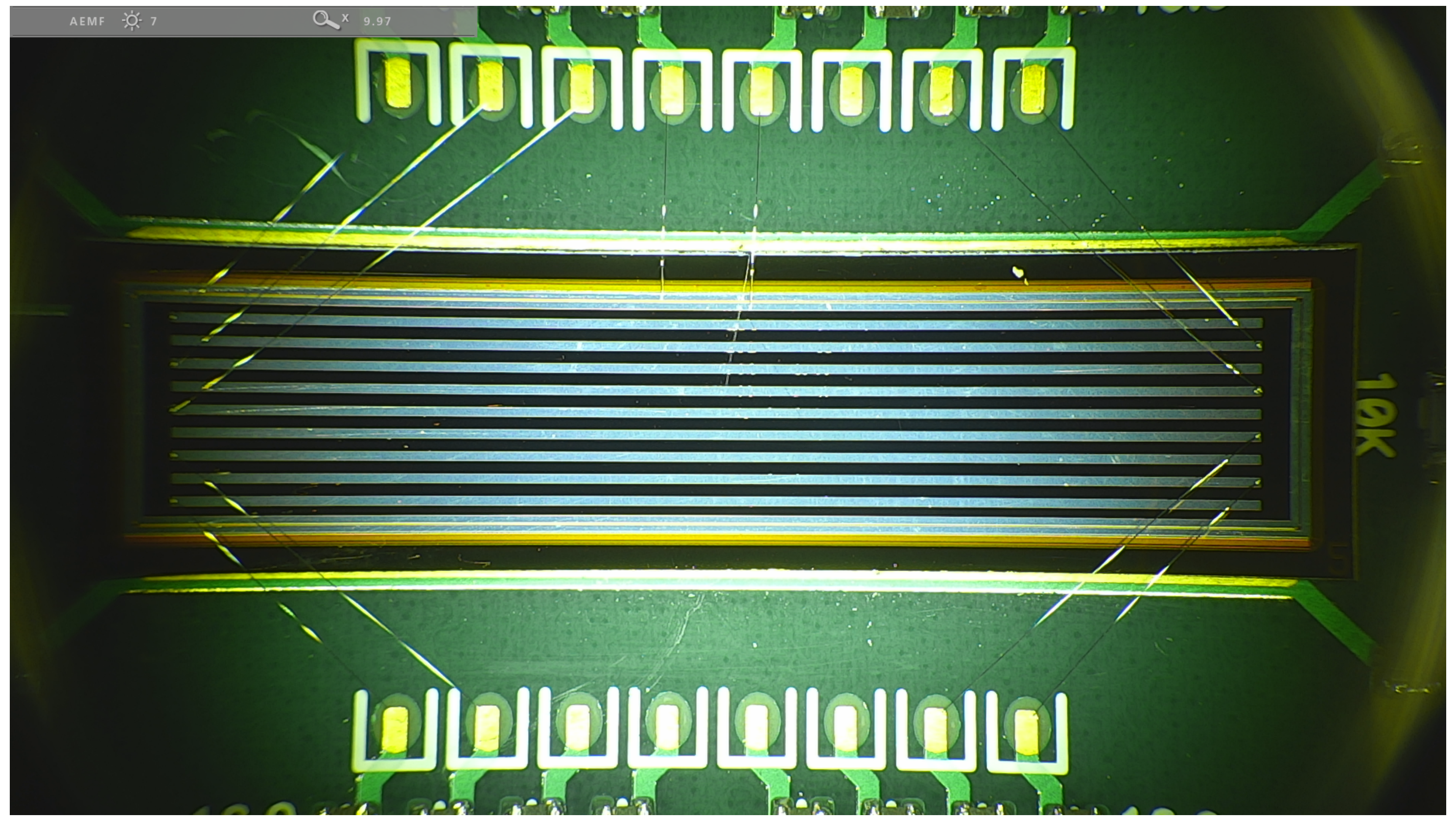
Testbeam Results: BNL Long Strips



5 mm



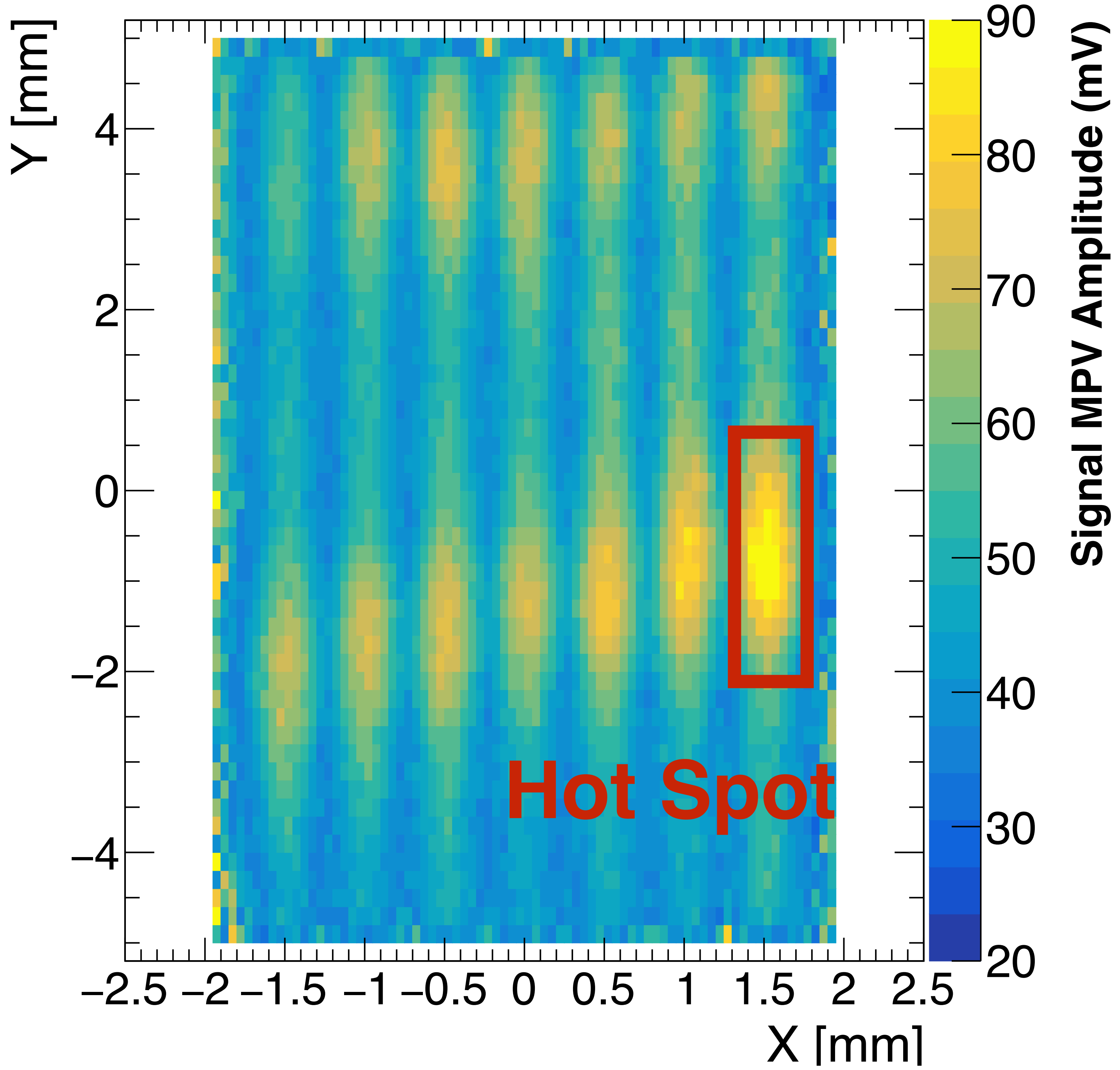
10 mm

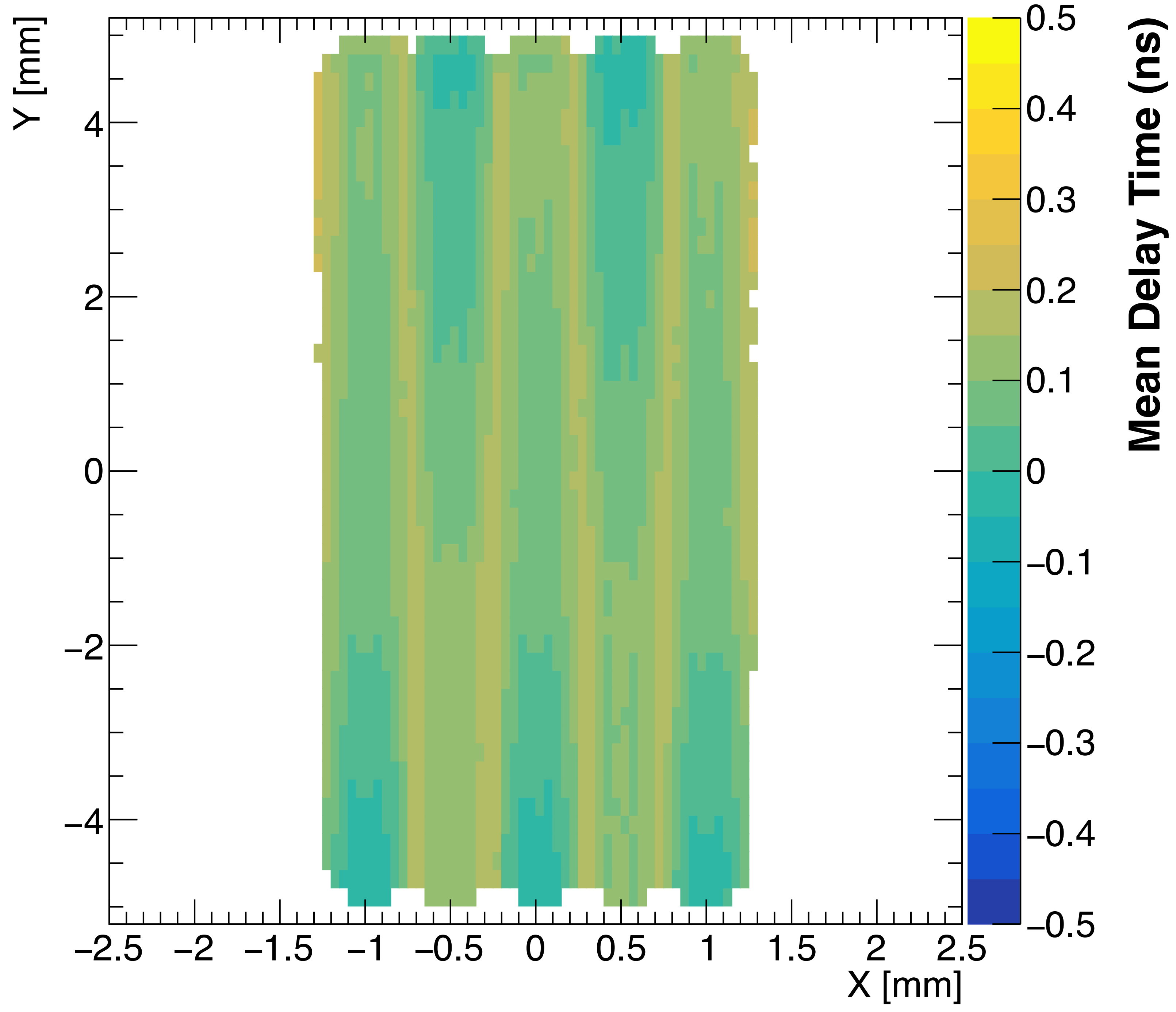


25 mm

- Studied impact of sensor length on AC-LGAD performance
  - **Realistic channel size**
  - Expect sensor capacitance to increase and impact performance
- Readout 7 channels at a time
- **Wirebonded alternating left and right ends of strips**
  - Expect to help mitigate propagation time delay impact on performance

Testbeam Results: BNL Long Strips

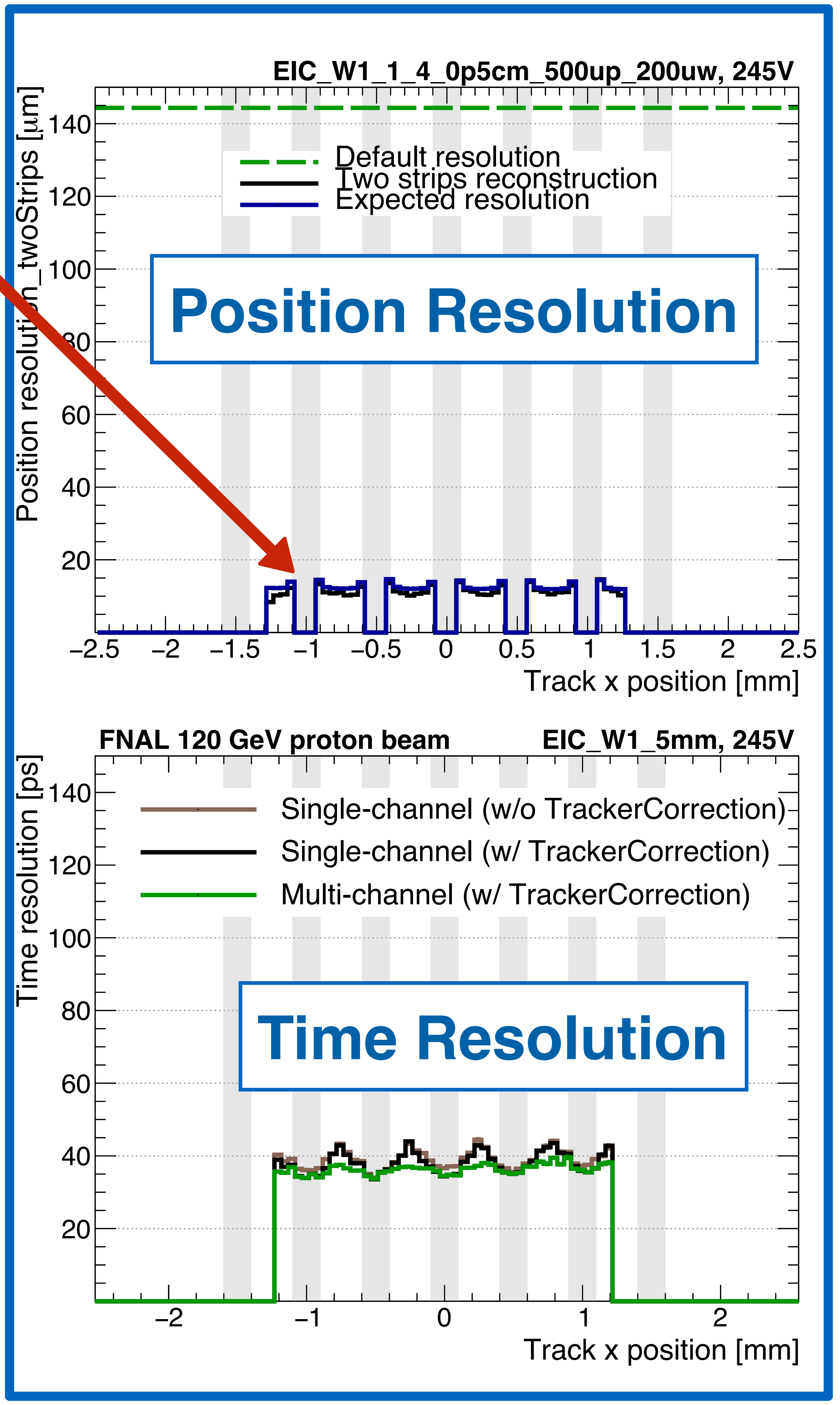




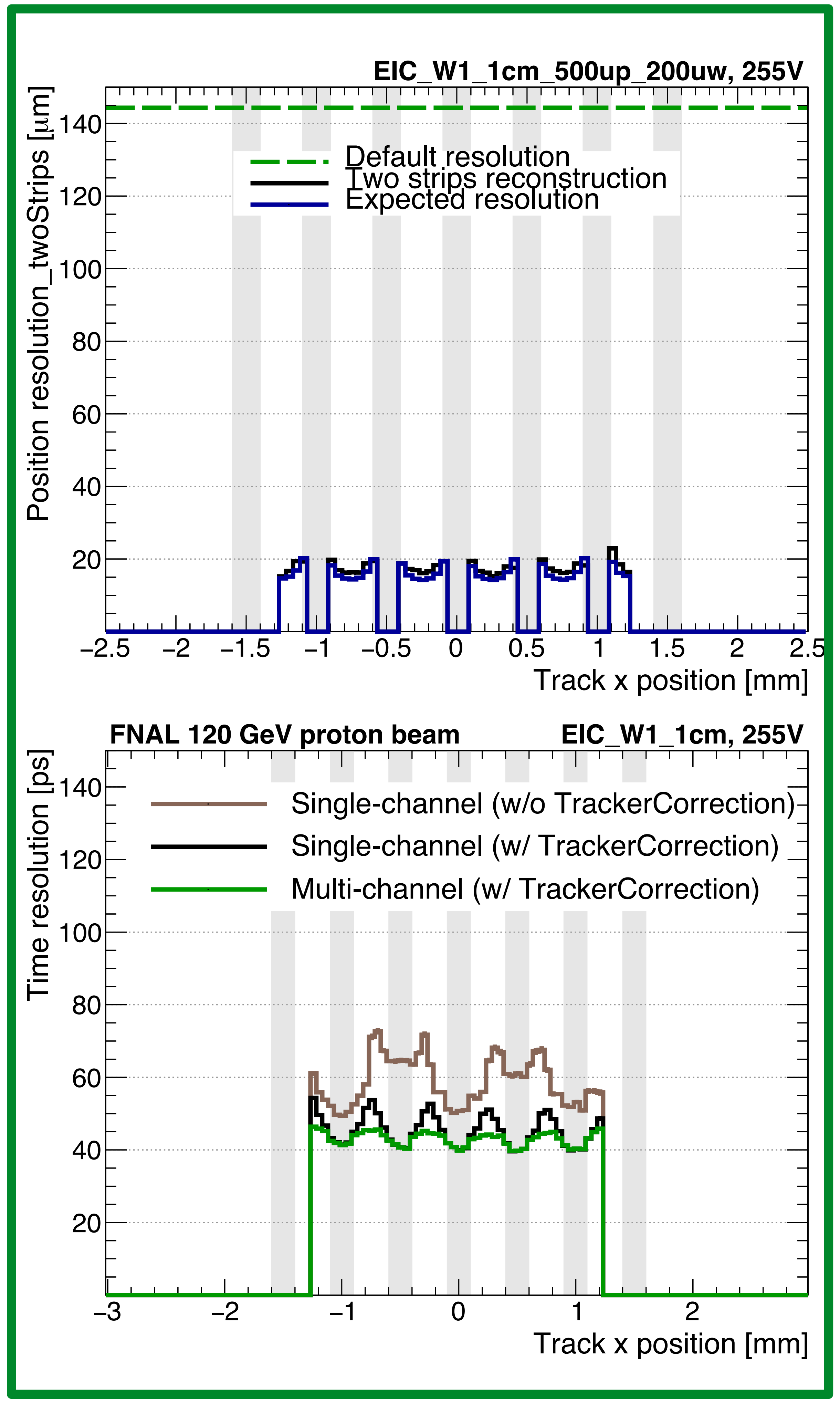
- BNL sensors suffered from gain non-uniformity
  - **Known issue for BNL production and solution understood for next production**
    - We do not see the same issue with the HPK sensors so this is not a long term problem for LGADs
  - **Makes getting a single time resolution value difficult (Measure hot spot)**
  - Position reconstruction measurement not directly impacted (amplitude ratio method)
- **Length of strips introduce significant time delay as a function of hit position**
  - Calibration needed to account of delay (Track information)

Testbeam Results: BNL Long Strips

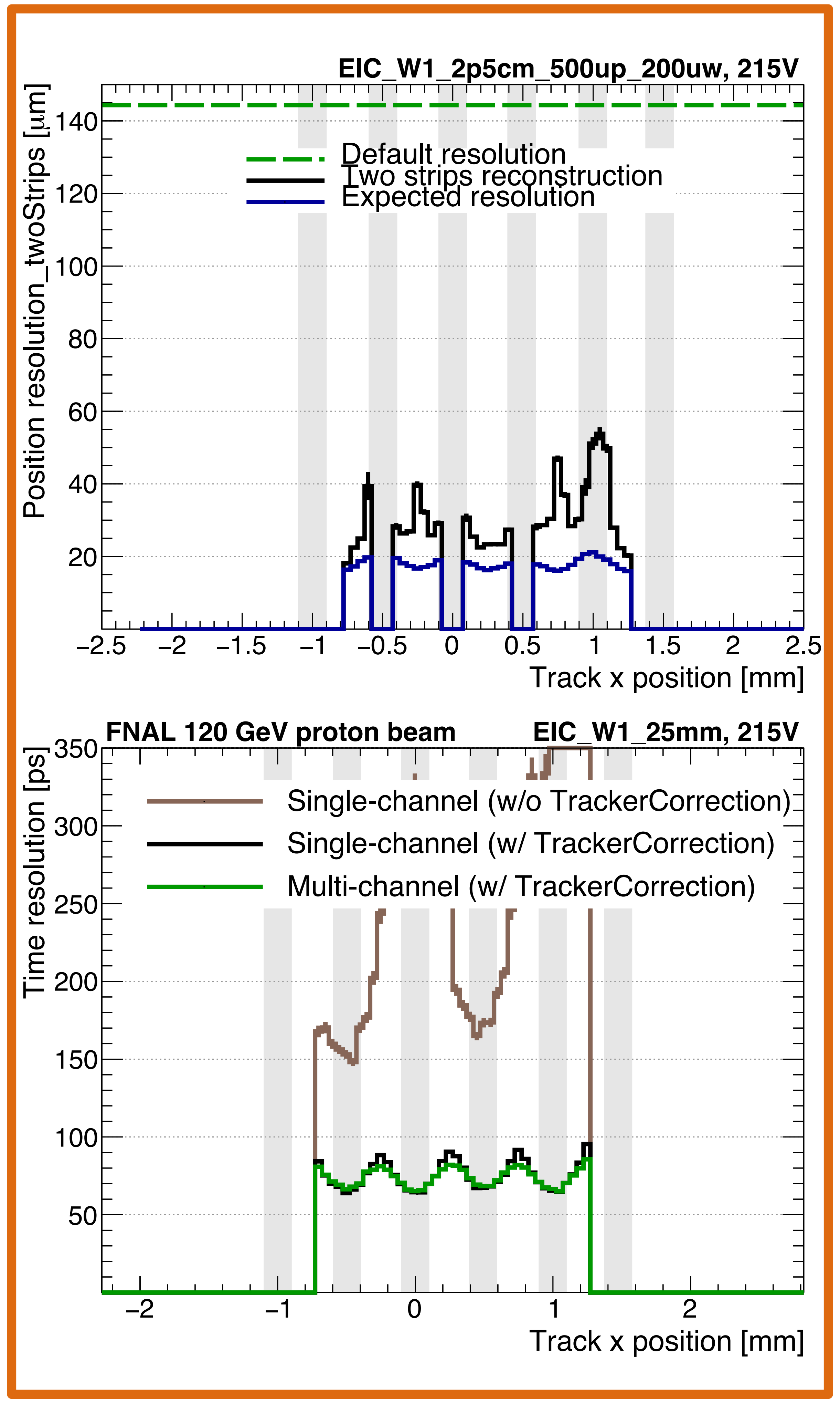
- **2-strip reconstruction not 100% outside of metal**
- **Can be mitigated with smaller metal**
  - Resolution on metal is metal size / sqrt(12)
  - Metal size of ~80 µm recovers uniform performance
- **Position resolution factor of 10 better than binary readout**
- **Using time delay tracking info can recover good timing resolution**



5 mm



10 mm



25 mm

Summary

- Showing results for a handful of tested sensors
  - Paper detailing all long strip results and further design optimization coming soon
- **Current AC-LGAD designs approaching EIC requirements**
- Next productions of sensors will address the remaining optimization
  - BNL gain uniformity
    - Solution understood
  - Optimizing signal sharing
    - Changing metal size
  - Realistic size
  - Thinner active volume

https://wiki.bnl.gov/conferences/index.php/ProjectRandDFY22

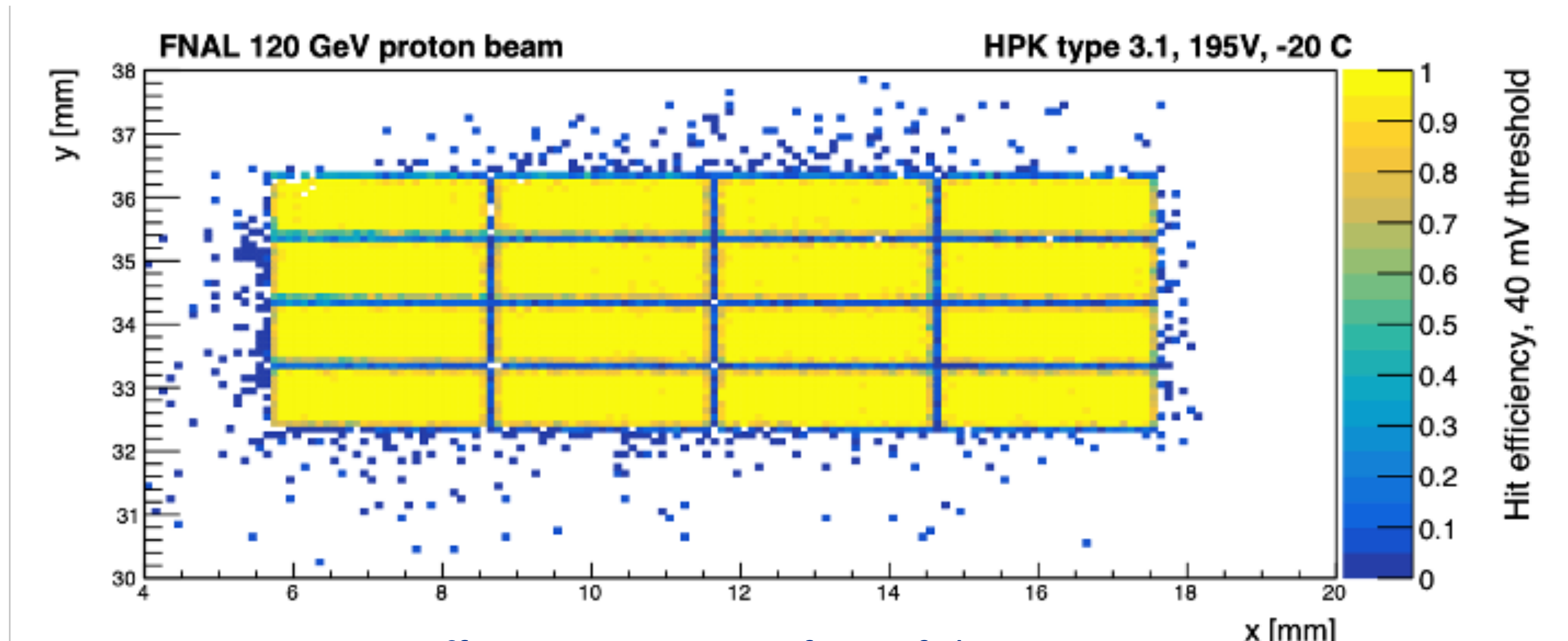
	Time resolution / hit	Position resolution / hit	Material budget / layer
Barrel ToF (Tracker)	<30 ps	(3-30 μm for Tracker)	$< 0.01\ X_0$
Endcap ToF (Tracker)	<25 ps	(30-50 μm for Tracker)	e-direction $< 0.05X_0$ h-direction $< 0.15X_0$
Roman Pots	<50 ps	$< 500/\sqrt{12}\ \mu m$	N/A
B0	<50 ps	$O(50)\ \mu m$	$< 0.01\ X_0$

Preliminary Results	Time Resolution / hit	Position Resolution / hit
HPK-C2 Pixels 500 x 500 µm²	30 ± 1 ps	22 ± 1 µm
BNL Strips 500 µm x 5 mm	~ 30 ps (Hot spots)	< 15 µm
BNL Strips 500 µm x 10 mm	~ 32 ps (Hot spots)	< 20 µm
BNL Strips 500 µm x 25 mm	~ 53 ps (Hot spots)	< 40 µm

Backup

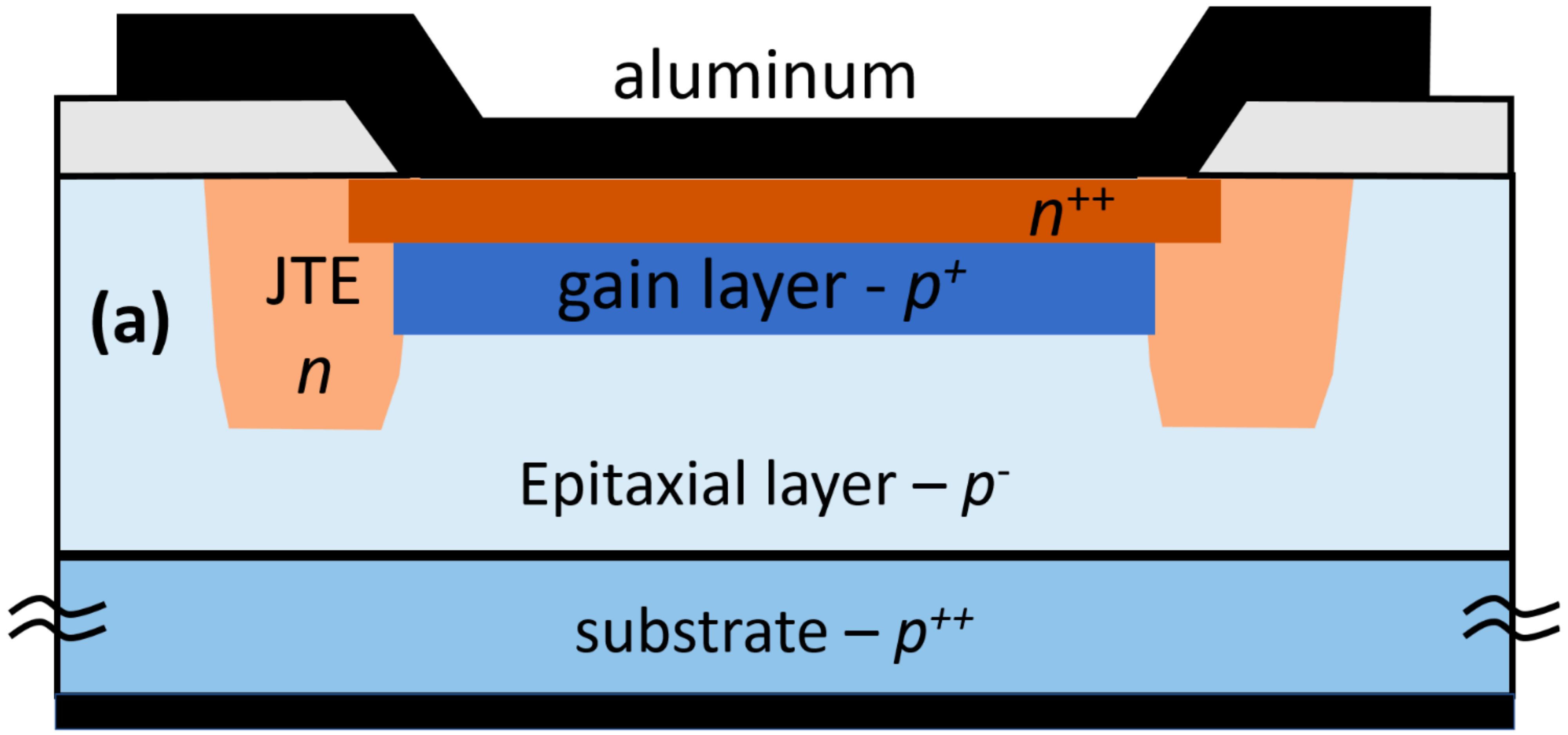
AC-coupled LGADs

- DC-LGADs are a promising sensor for timing detectors
  - Although, they have an issue with their fill factor when pixels are small enough for a realistic tracker

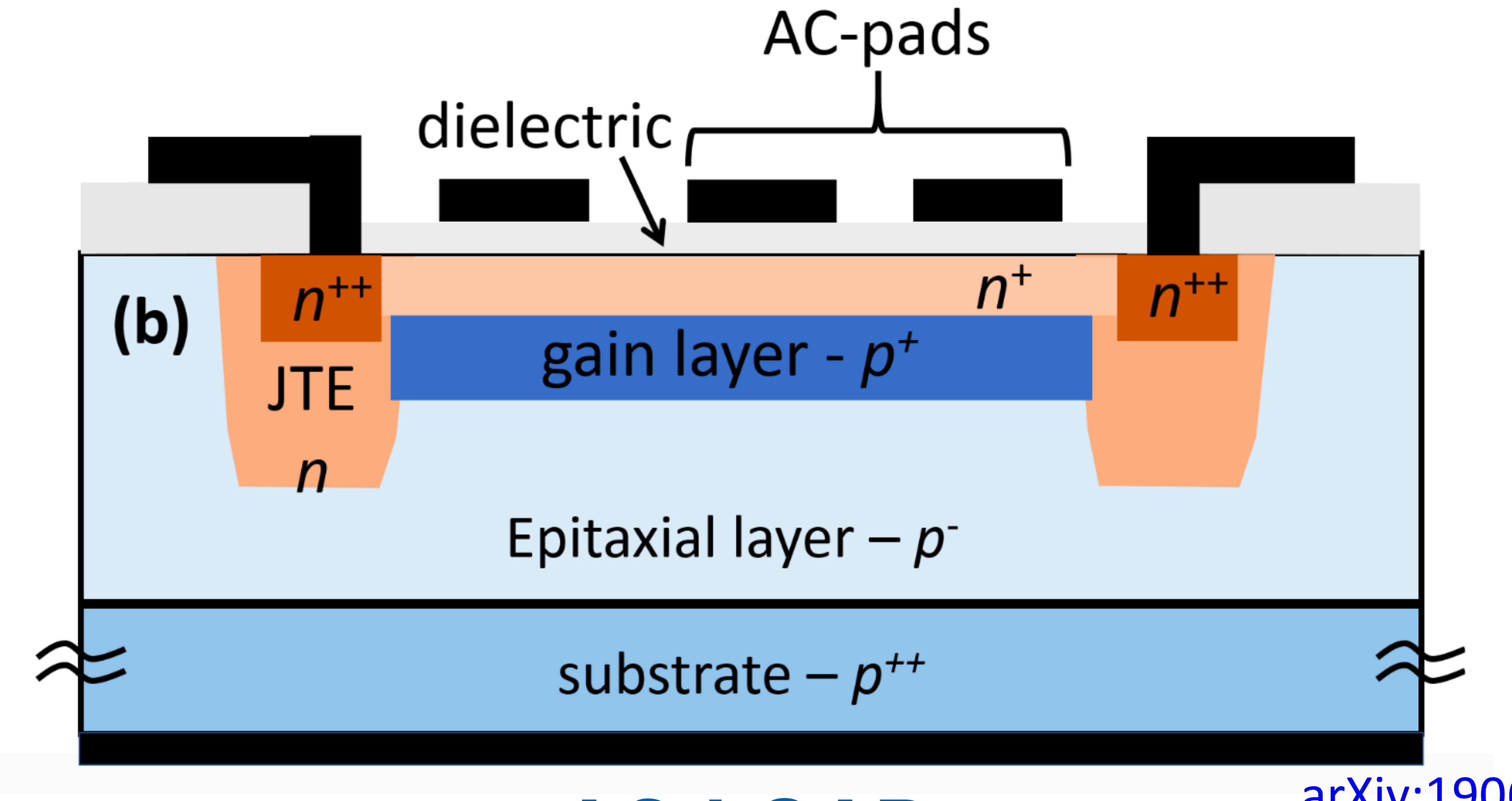


Hit efficiency across surface of the 4x4 sensor

- AC-LGADs can solve this issue
  - 100% fill factor, and fast timing information at a per-pixel level
  - Electrons collect at the resistive n+ and then slowly flow to an ohmic contact at the edge.
    - Simultaneously improve position resolution via charge



DC-LGAD



AC-LGAD

arXiv:1906.11542