eRD112 Report – March 2024

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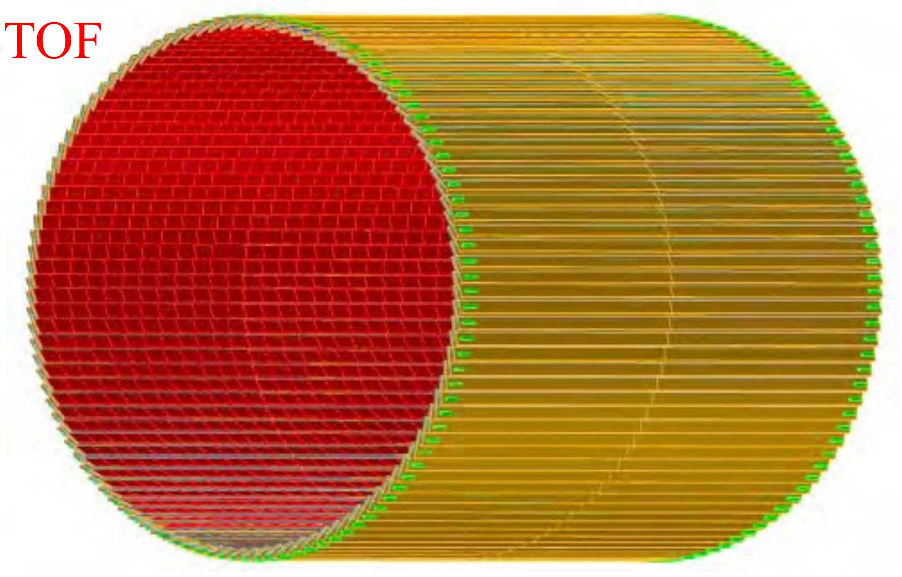
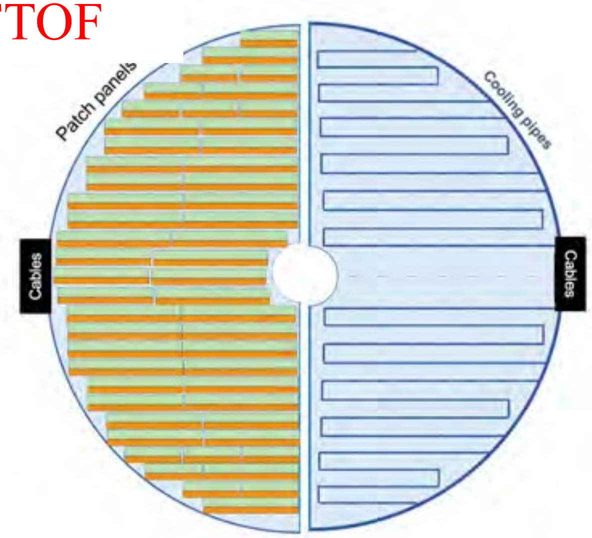
ePIC AC-LGAD Detector Specifications

BTOF



FTOF



Roman Pots

	Area (m^2)	Channel size (mm^2)	# of Channels	Timing Resolution	Spatial resolution	Material budget
Barrel TOF	12	0.5*10	2.4M	35 ps	30 μm in $r \cdot \varphi$	0.01 X_0
Forward TOF	1.1	0.5*0.5	4.5M	25 ps	30 μm in x and y	0.05 X_0
B0 tracker	0.07	0.5*0.5	0.28M	30 ps	20 μm in x and y	0.05 X_0
RPs/OMD	0.14/0.08	0.5*0.5	0.56M/0.32M	30 ps	140 μm in x and y	no strict req.
LUMI Tracker	0.32	0.5*10	64k	35 ps	30 μm in x or y	0.01 X_0

Requirements on timing and spatial resolutions and material budget are still being evaluated and are subject to change as the design matures, and we will continue to explore common designs for these detectors where possible to reduce cost and risk.

Key Components for AC-LGAD Detectors

- **AC-LGAD sensor:**
  - Goal: large area sensors that meet timing/spatial resolution requirements with minimal # channels
  - Approach: utilize BNL IO to optimize the sensor design (pitch, electrode width, n-layer doping density, active volume thickness); engage commercial vendors HPK/FBK to verify sensor quality and production cost/yield
- **Sensor/ASIC integration:**
  - Goal: cost-effective way to establish reliable electrical and mechanical connections between sensor and ASIC
  - Approach: bump-bonding, wire-bonding, interposer
- **Light-weight mechanical structure with cooling for BTOF:**
  - Goal: light-weight structure with cooling that meet the material budget, thermal and mechanical requirements
  - Approach: finite element analysis and prototyping with carbon-fiber composite and/or PEEK materials
- **Frontend ASIC:**
  - Goal: low jitter (<15 ps) and low power (~1 mW/channel), streaming readout with TDC and ADC outputs
  - Approach: custom-designed EICROC and FCFD, ASICs from 3rd party institutions
- **Frontend readout electronics:**
  - Goal: low jitter clock (<5 ps), low X_0 flexible module PCB, service hybrid (readout and power board)
  - Approach: design a precise clock distribution system in concert with EPIC DAQ group, design and prototype flexible PCB that meet the requirements; design and prototype service hybrid

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Grey: in eRD109

Updates since August 2023

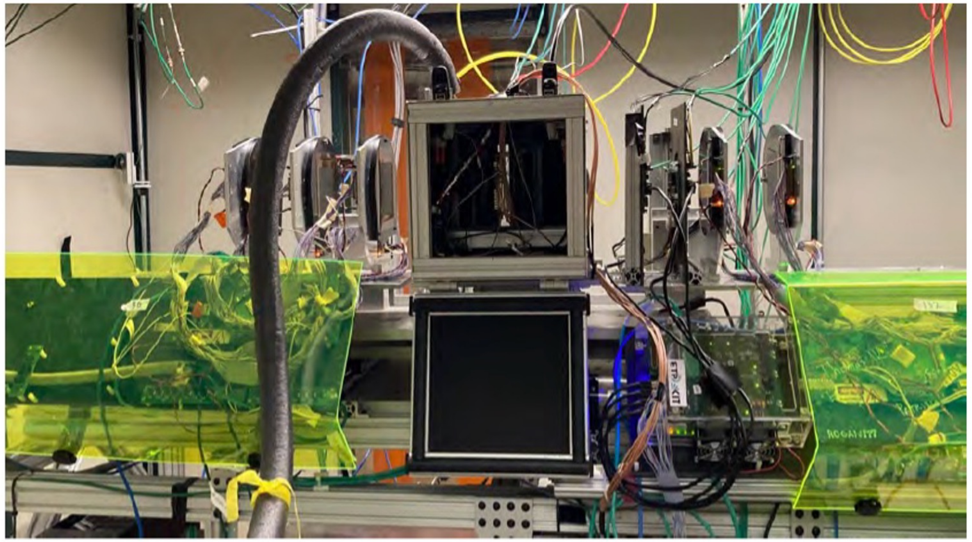
- **AC-LGAD sensor:**
  - Updates:
    - Finalized timing and spatial performance studies for the 1st HPK prototype production sensors
    - Preparation for radiation tests of the 1st HPK prototype production sensors
    - Finalized sensor design for the 2nd HPK prototype production
    - Preparation for performance studies for the 2nd HPK prototype production sensors
- **Sensor/ASIC integration (interposer):**
  - Updates:
    - waiting for funds
- **Light-weight mechanical structure with cooling for BTOF:**
  - Updates:
    - First prototyping efforts well underway and promising
    - Deformations in the staves are well understood and will be minimized
    - Thermal simulation and preparation for tests are underway

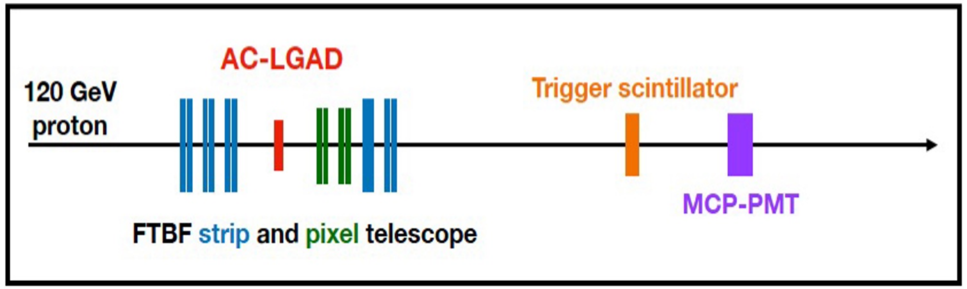
FY23 Deliverables – Sensor (August 2023)

- **Sensor**
  - Sensors with different configurations produced by BNL-IO and Hamamatsu, and tested with 120GeV protons
  - Prototype strip sensors with ~34 ps time resolution and 12-15 um spatial resolution for BToF.
  - Prototype pixel sensors with ~20 ps time resolution and ~20* um spatial resolution for FToF, B0, RPs/OMD.

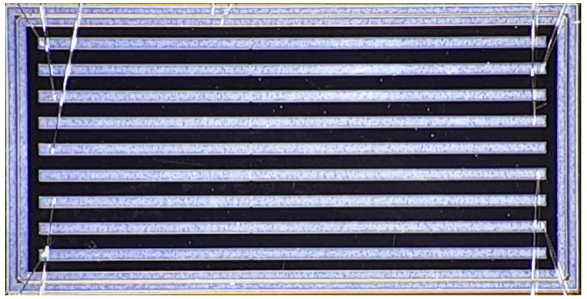
* ~50 um under the metal eletrode. To be improved

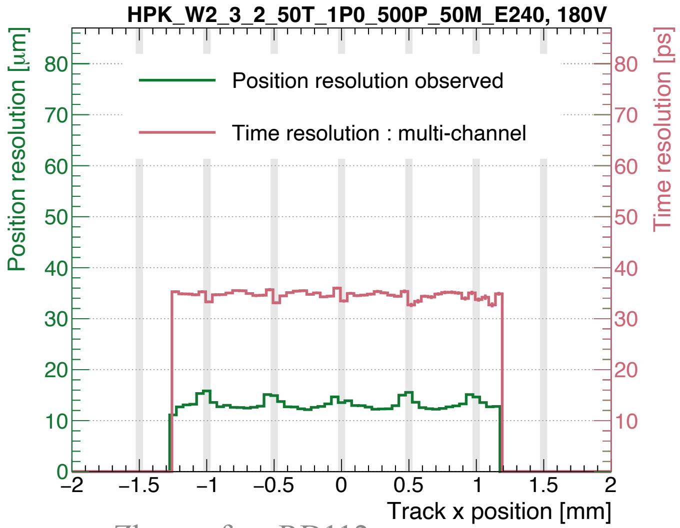
Fermilab Test Beam Setup



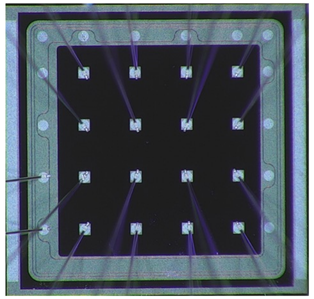


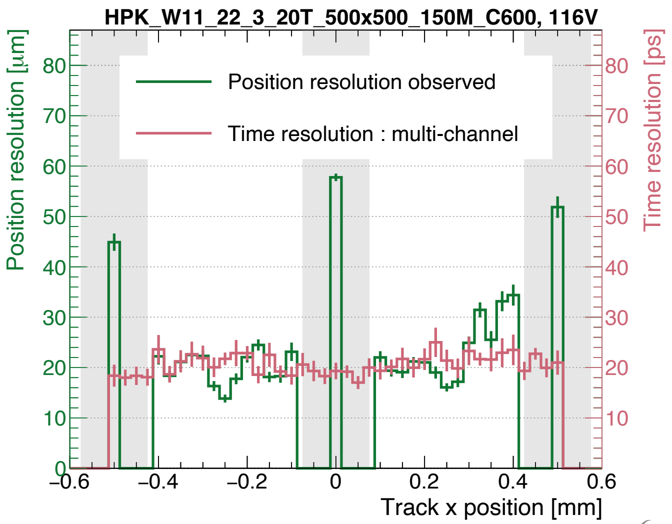
HPK Strip Sensor (4.5x10 mm^2)



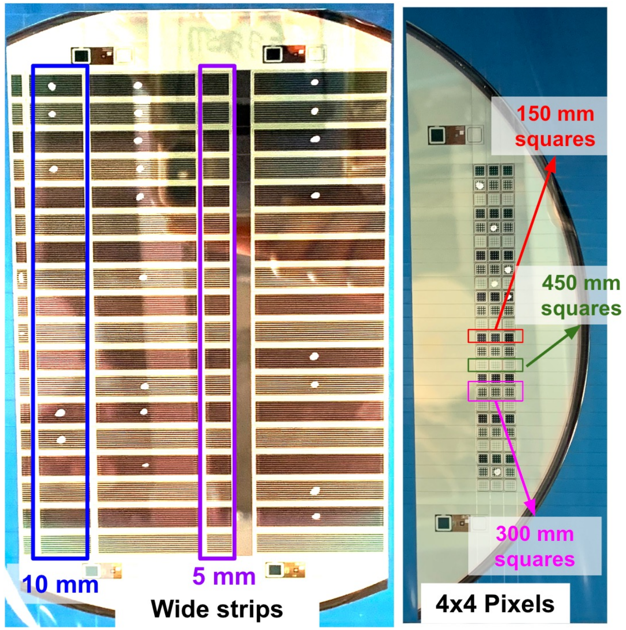


HPK Pixel Sensor (2x2 mm^2)

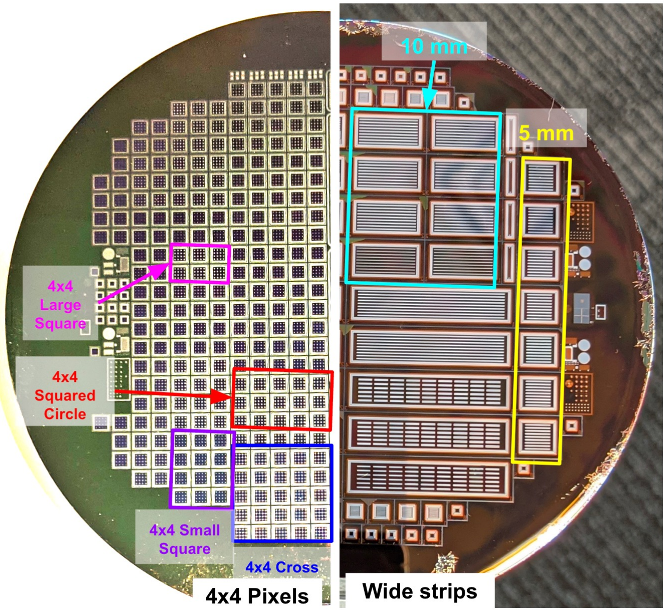




Systematic Study of Sensor Performance

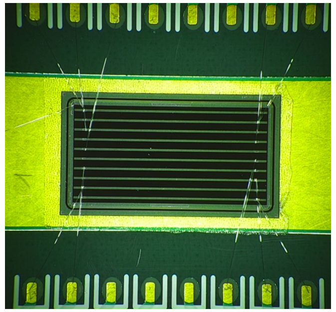


HPK

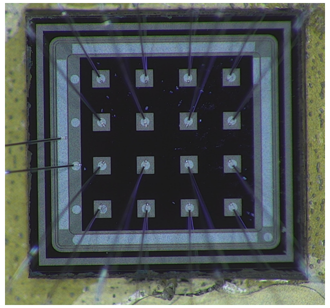


BNL-IO

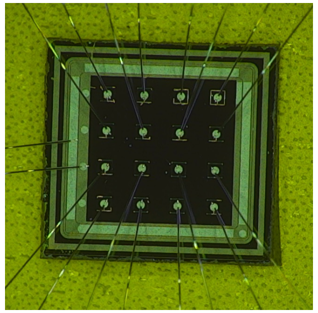
Name	Wafer	Pitch (μm)	Strip length (mm)	Metal width (μm)	Active thickness (μm)	Sheet resistance (Ω/□)	Capacitance (pF/mm^2)	Optimal bias voltage (V)
HPK Wide strip								
SH1	W9				20	1600	600	114
SH2	W4					400	240	204
SH3	W8			50	50		600	200
SH4	W2	500	10			1600	240	180
SH5	W5						600	190
SH6	W9			100	20	1600	600	112
SH7	W8				50	400	600	208
BNL Wide strip								
SB1	WB1			50	50	1400	270	170
SB2	WB1	500	10	100	50	1400	270	160
SB3	WB2			50	50	1400	260	185



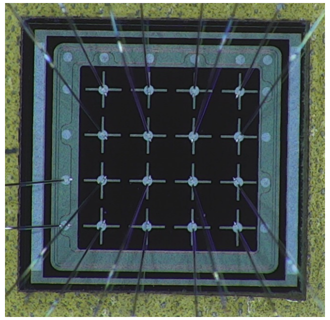
SH7



PB2



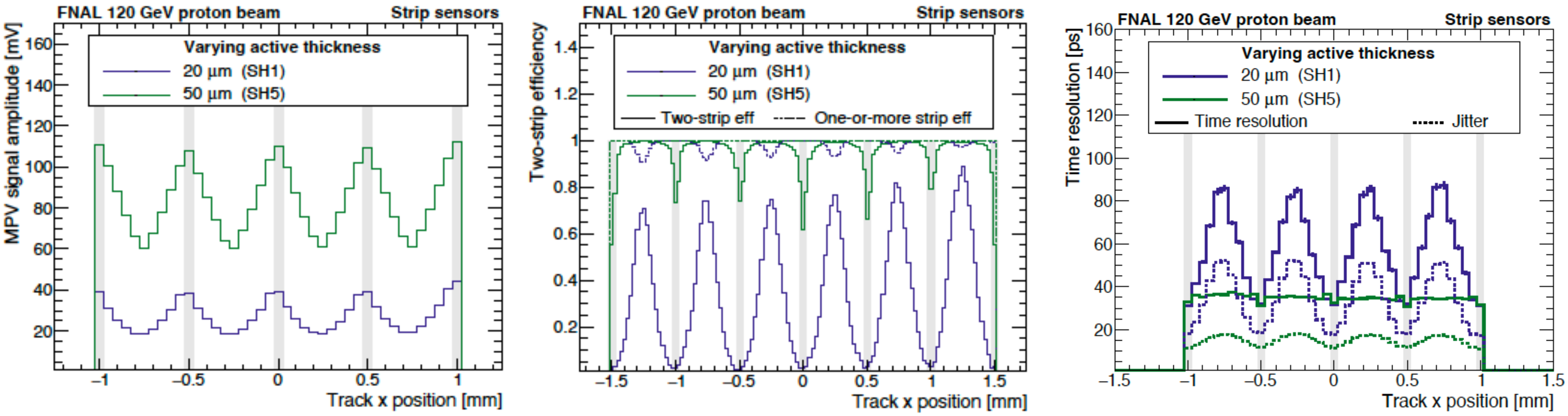
PB3



PB4

Name	Wafer	Pitch (μm)	Metal width (μm)	Active thickness (μm)	Sheet resistance (Ω/□)	Capacitance (pF/mm^2)	Optimal bias voltage (V)
HPK 4 x 4 Square pixel							
PH4	W11			20	400	600	116
PH5	W9		150		1600	600	112
PH6	W8	500		50	400	600	200
PH7	W5				1600	600	185
PH8	W9		300	20	1600	600	112
BNL 4 x 4 Square pixel							
PB1	WP4	500	100	30	1400	695	115
PB2	WP4		200	30	1400	695	115
BNL 4 x 4 Squared Circle pixel							
PB3	WP4	500	110(*)	30	1400	695	110
BNL 4 x 4 Cross pixel							
PB4	WP4	500	400×25(**)	30	1400	695	115

Test Beam Results on 1-cm Long Strip Sensors



$$\sigma_t^2 = \sigma_{\text{ionization}}^2 + \sigma_{\text{jitter}}^2 + \sigma_{\text{TDC}}^2 + \sigma_{\text{clock}}^2$$

- $\sigma_{ionization}$: Landau term, depending on sensor thickness
- σ_{jitter}: jitter term, depending on the S/N ratio

- 50 um sensor = higher signal amplitude = more hits from 2+ strips = better spatial resolution than 20 um
- 50 um sensor = higher signal amplitude = smaller jitter = better timing resolution than 20 um where jitter dominant
- New HPK strip sensor production will include both 30 um and 50 um sensor thickness

Test Beam Results on 1-cm Long Strip Sensors

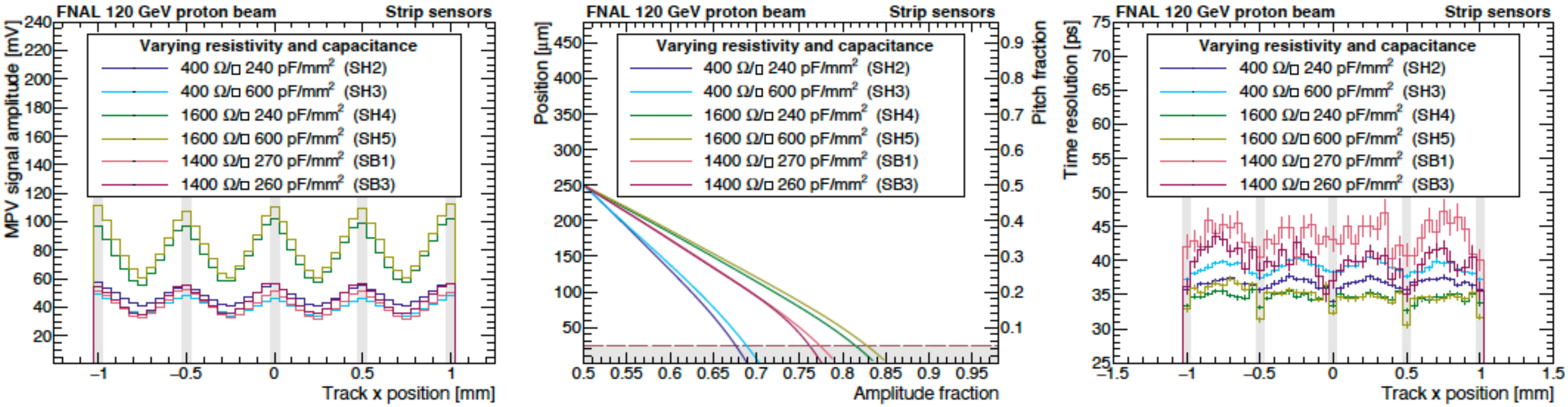


Figure 6: Amplitude vs x positions (left), position reconstruction fits (center), and time resolution vs x position (right) for HPK and BNL strip sensors of different coupling capacitance and sheet resistance values. The sensors presented here have a 50 µm active thickness and a 50 µm strip width.

- Higher n+ resistivity = less charge sharing = higher signal amplitude = less jitter = better timing resolution
- Higher AC-coupling capacitance = less charge sharing = higher signal amplitude
- Signal amplitude and timing resolution of HPK sensors are much better than BNL-IO sensors

Test Beam Results on 1-cm Long Strip Sensors

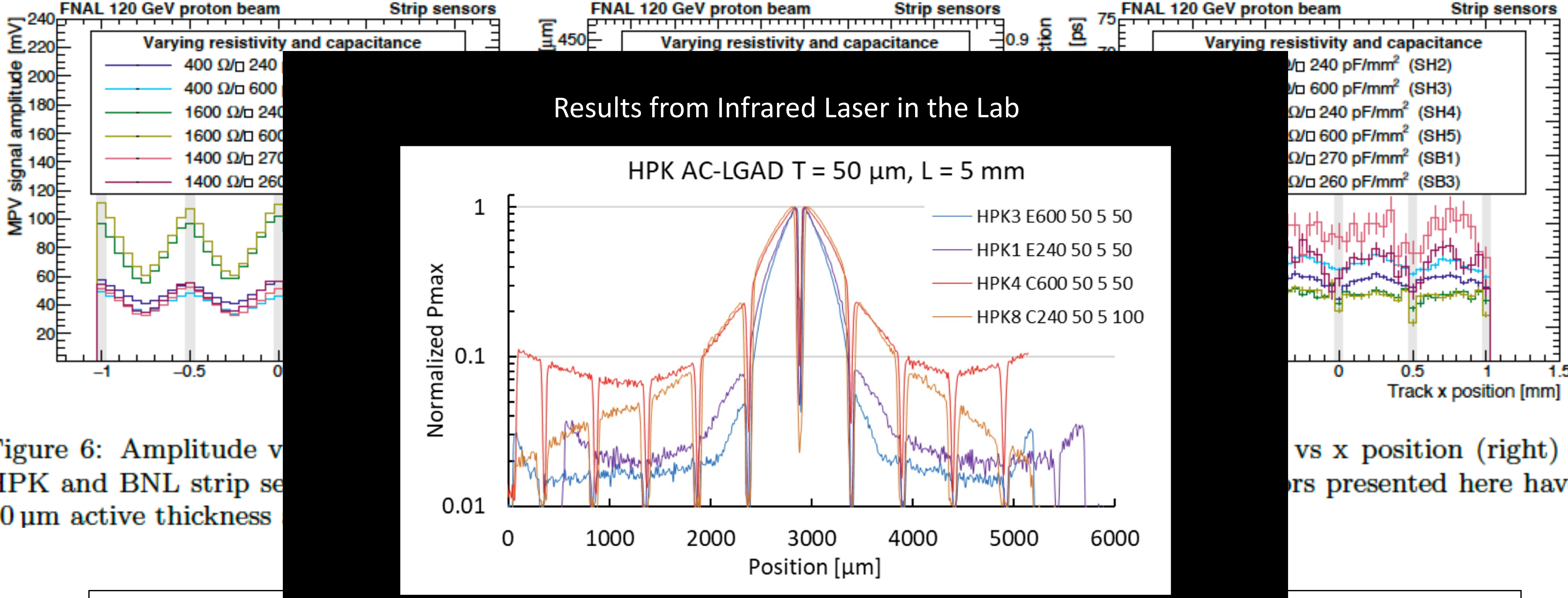


Figure 6: Amplitude v … vs x position (right) for HPK and BNL strip se … rs presented here have a 50 µm active thickness …

- Higher n+ r … ng resolution
- Higher AC- …
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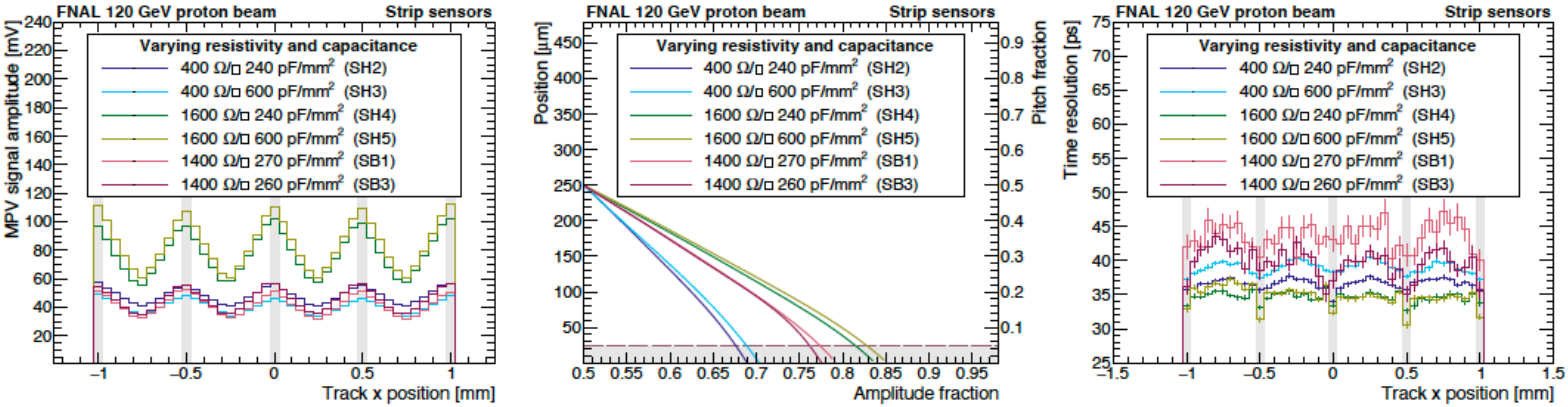
Test Beam Results on 1-cm Long Strip Sensors



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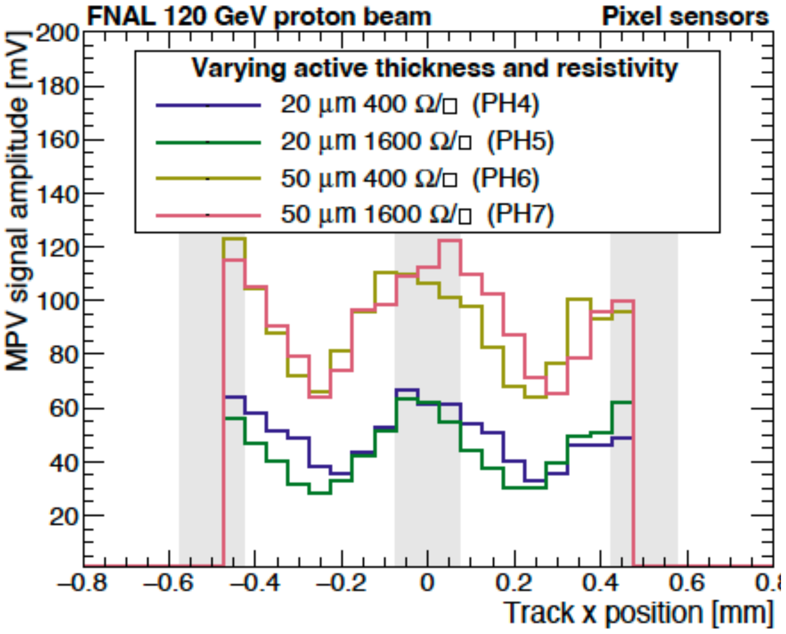
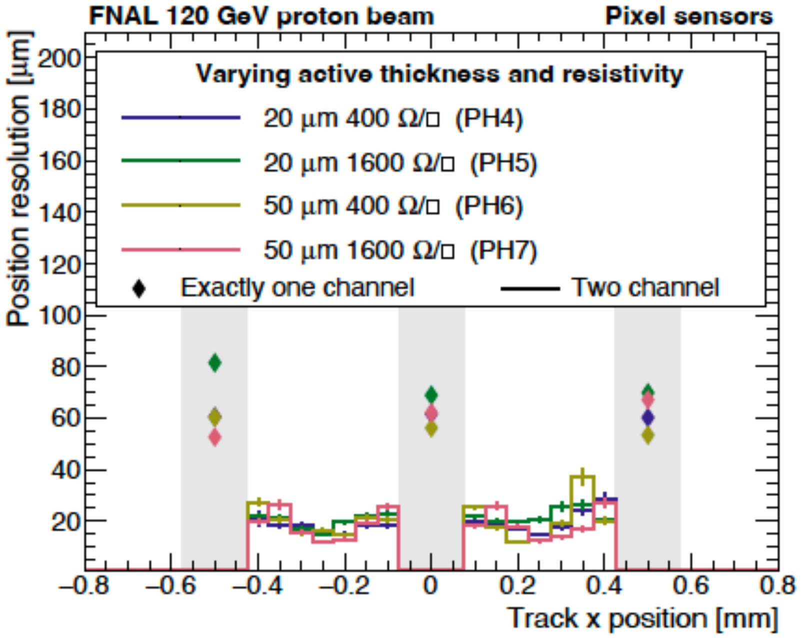
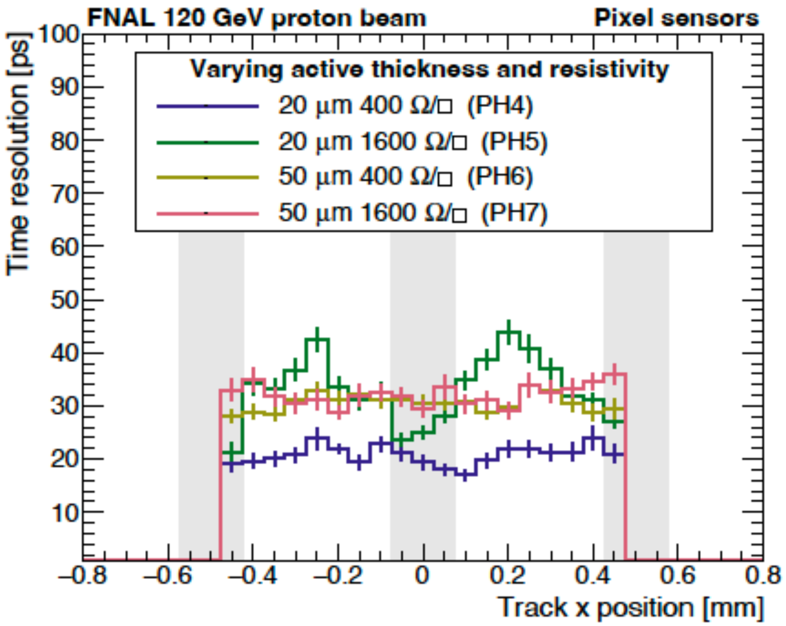
- Higher n+ resistivity = less charge sharing = higher signal amplitude = less jitter = better timing resolution
- Higher AC-coupling capacitance = less charge sharing = higher signal amplitude
- Signal amplitude and timing resolution of HPK sensors are much better than BNL-IO sensors
- New HPK strip sensor production will use highest n+ resistivity and highest AC-coupling capacitance

Test Beam Results on Pixel Sensors







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- $\sigma_{ionization}$: Landau term, depending on sensor thickness
- σ_{jitter}: jitter term, depending on the S/N ratio

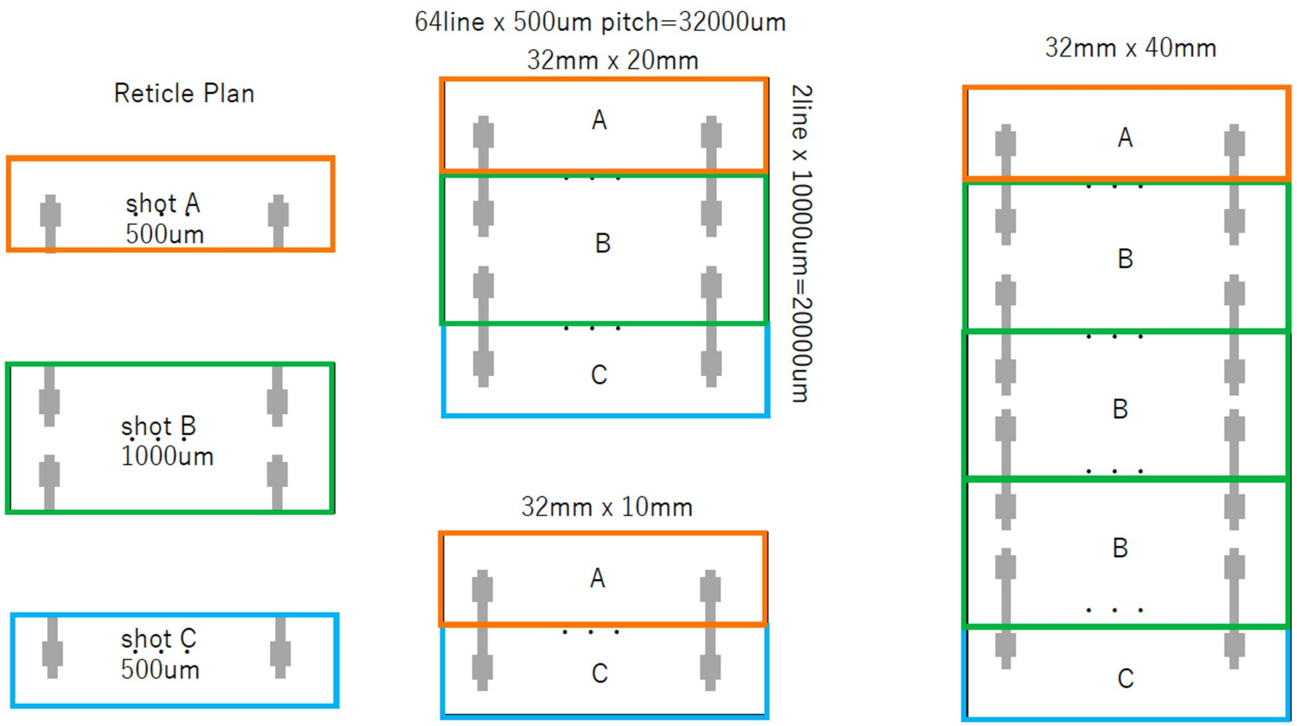
- 20 and 50 um sensors have similar spatial resolution
- 20 um sensor have better timing resolution than 50 um due to lower Landau term
- New HPK pixel sensor production will have 20 um and 30 um thickness, and with highest AC-coupling capacitance, and lower n+ resistivity (for better charge sharing and radiation hardness)

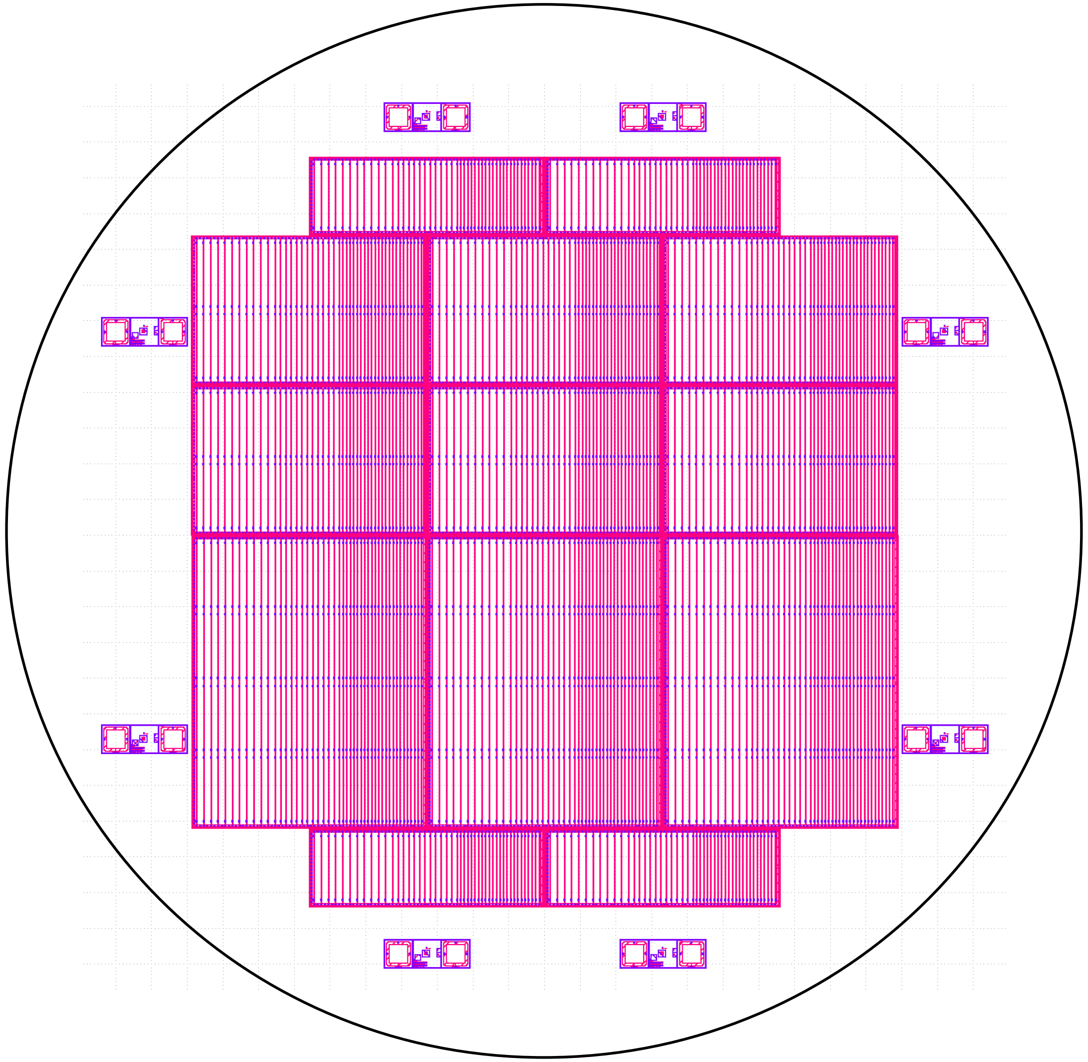
New (2nd) HPK Strip Sensor Production

Requested for quote from HPK for

- 30 um thick E-type 600pF/cm2 two wafers
- 50 um thick E-type 600pF/cm2 two wafers

Each with four 3.2x1 cm², six 3.2x2 cm² and three 3.2x4 cm² sensors (stitching reticles)



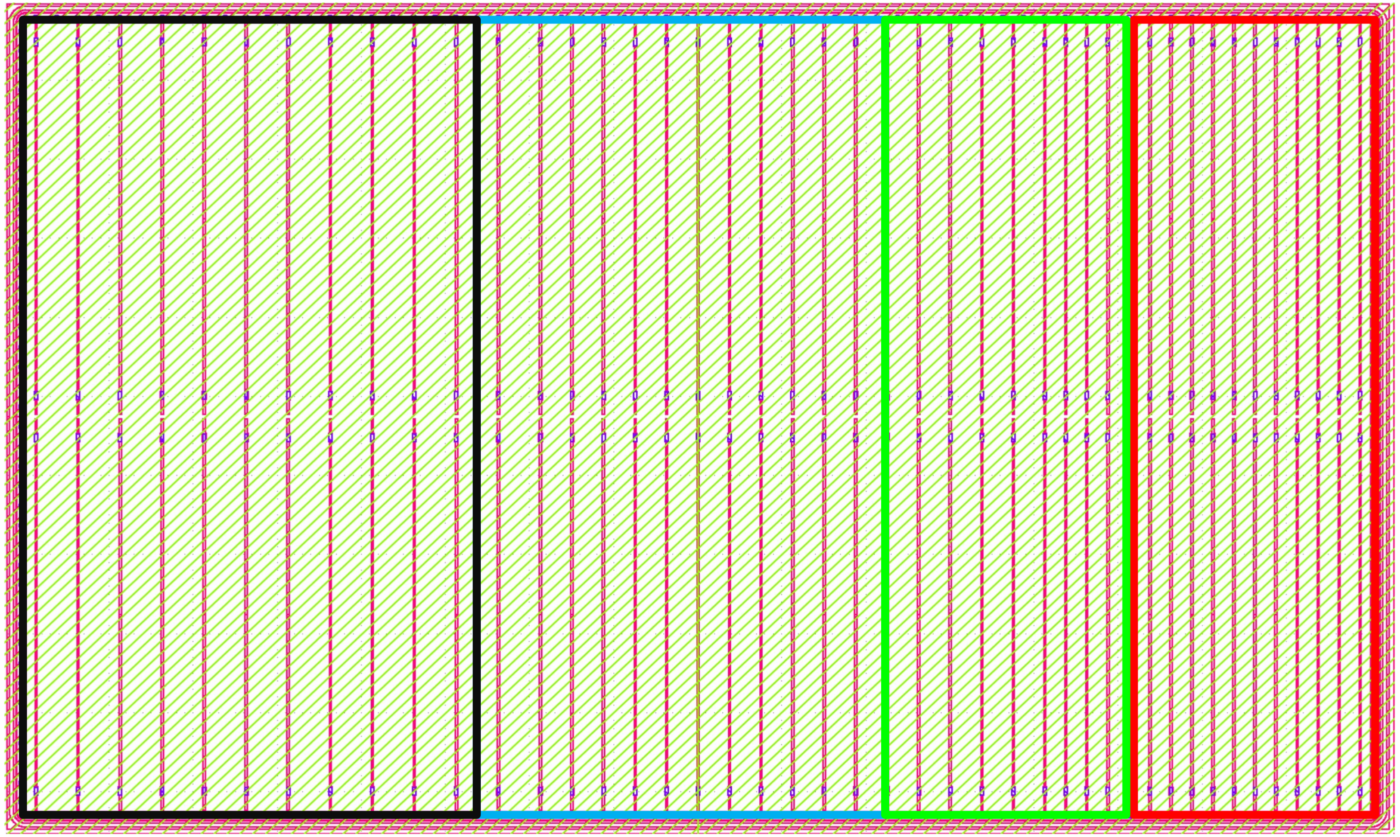


New (2nd) HPK Strip Sensor Production

Requested for quote from HPK for

- 30 um thick E-type 600pF/cm2 two wafers
- 50 um thick E-type 600pF/cm2 two wafers

Each with four 3.2x1 cm², six 3.2x2 cm² and three 3.2x4 cm² sensors (stitching reticles)



Each sensors will have (N=1, 2, 4)

- 12xN strips with 500 um pitch, 1 cm length, 40 um width
- 12xN strips with 500 um pitch, 1 cm length, 50 um width
- 12xN strips with 750 um pitch, 1 cm length, 50 um width
- 12xN strips with 1000 um pitch, 1 cm length, 50 um width

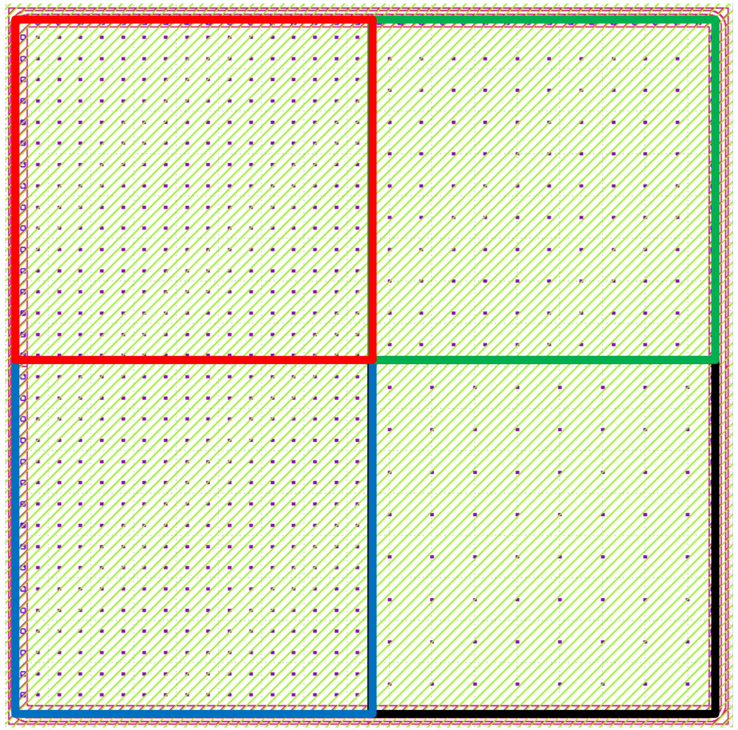
to examine impact of strip pitch, width and length

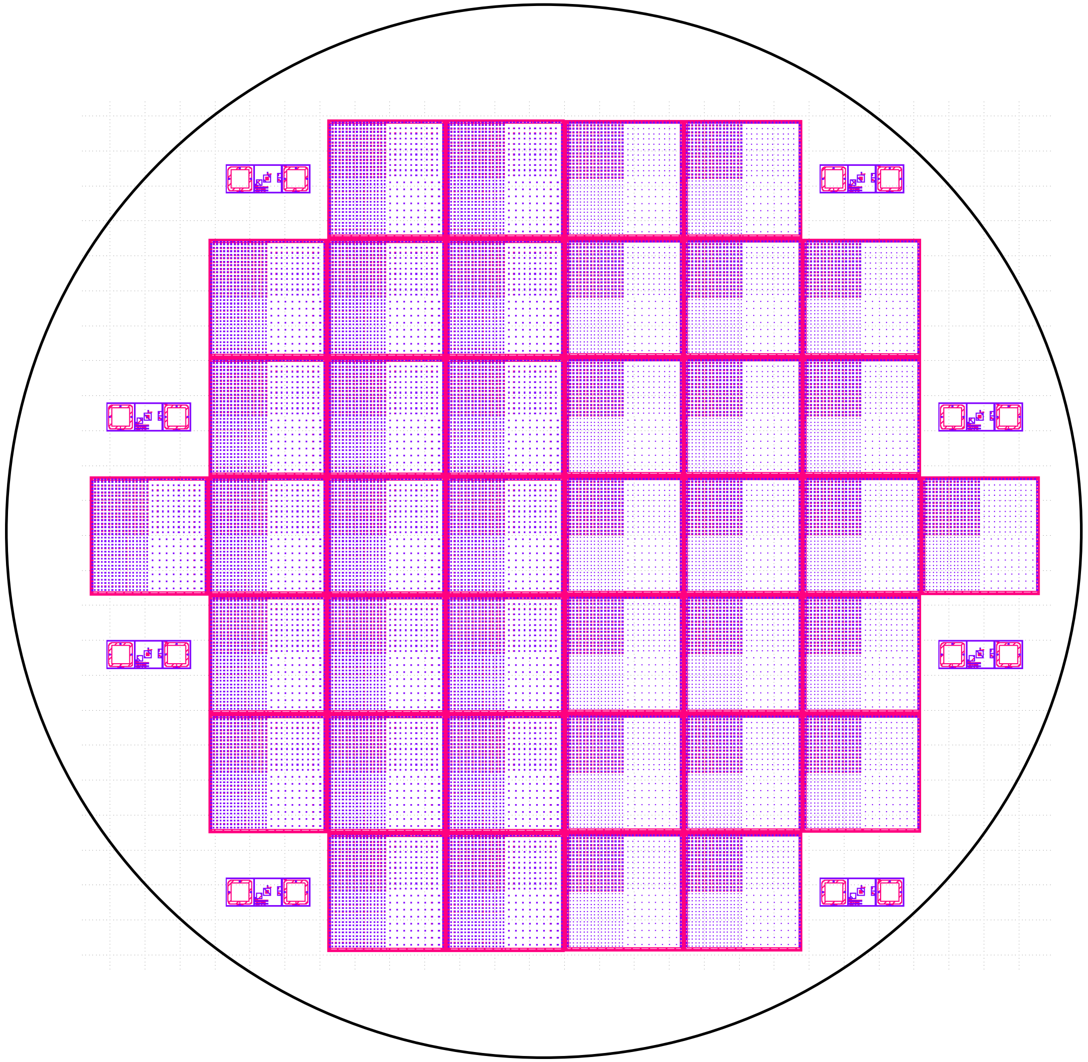
New (2nd) HPK Pixel Sensor Production

Requested for quote from HPK for

- 20 um thick E-type 600pF/cm2 two wafers
- 30 um thick E-type 600pF/cm2 two wafers

Each with twenty 1.6x1.6 cm^2 sensors





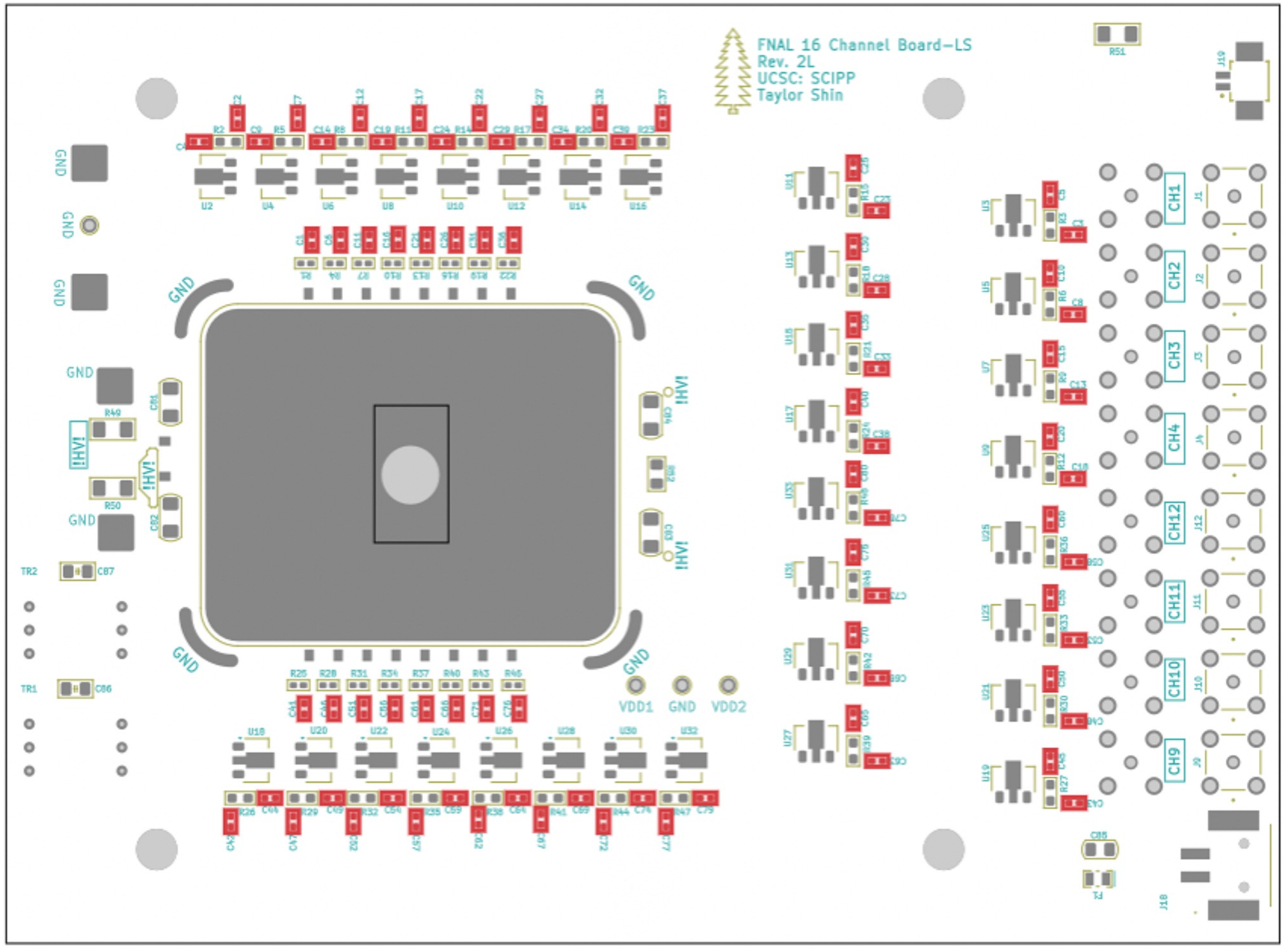
Each sensor will have four regions to examine different pitch (500-1000 um) and electrode width (40-150 um)

Getting Ready for New (2nd) HPK Sensors

Work has been completed at UCSC on the redesign of the FNAL board

- Increased sensor pad size to accommodate full-sized sensors (4.5x3.6 cm2) expected from HPK production this year
- Added half-moon GND pads at sensor edge to ease wire-bonding ground connections to n+ layer
- Rounded traces to limit trace length and reduce noise further

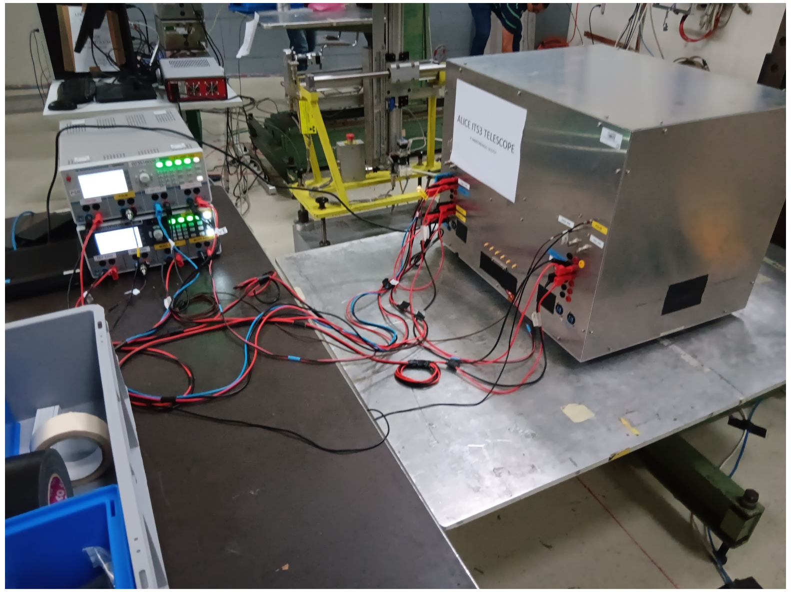
Board submission planned before the end of March 2024, with boards expected by end of April; followed by loading, expected distribution by middle of May.



Beam Test Plans

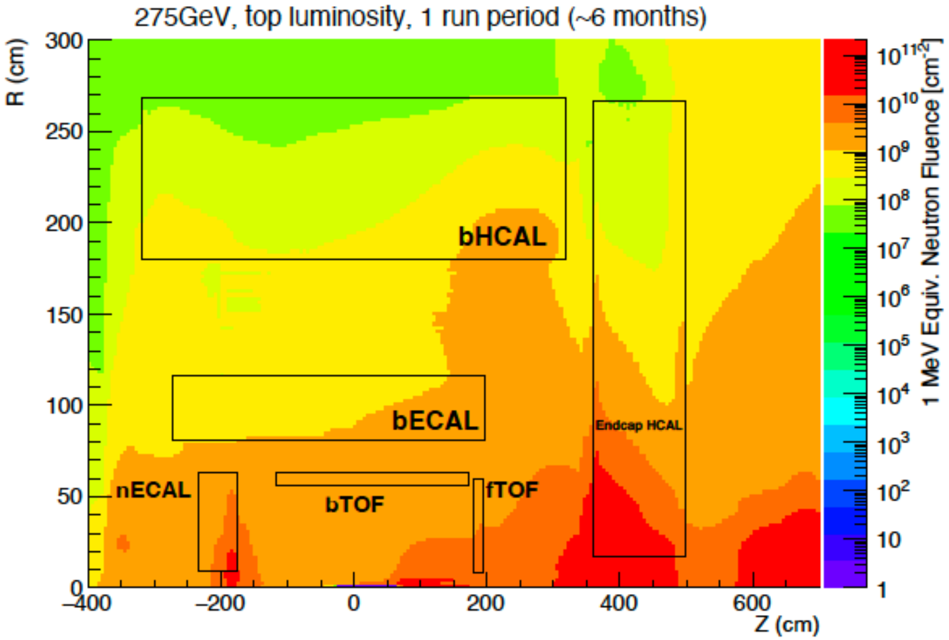
Test beam for sensor (and ASIC) performance

- **Plan to assemble own beam telescope using MAPS+LGAD**
- 1 week of beam time (TBC) at FNAL during May 1-June 5 (July12), 2024
- 2 weeks of beam time at DESY in June 10-23, 2024
- Investigate test beam possibility at Jlab in Fall 2024



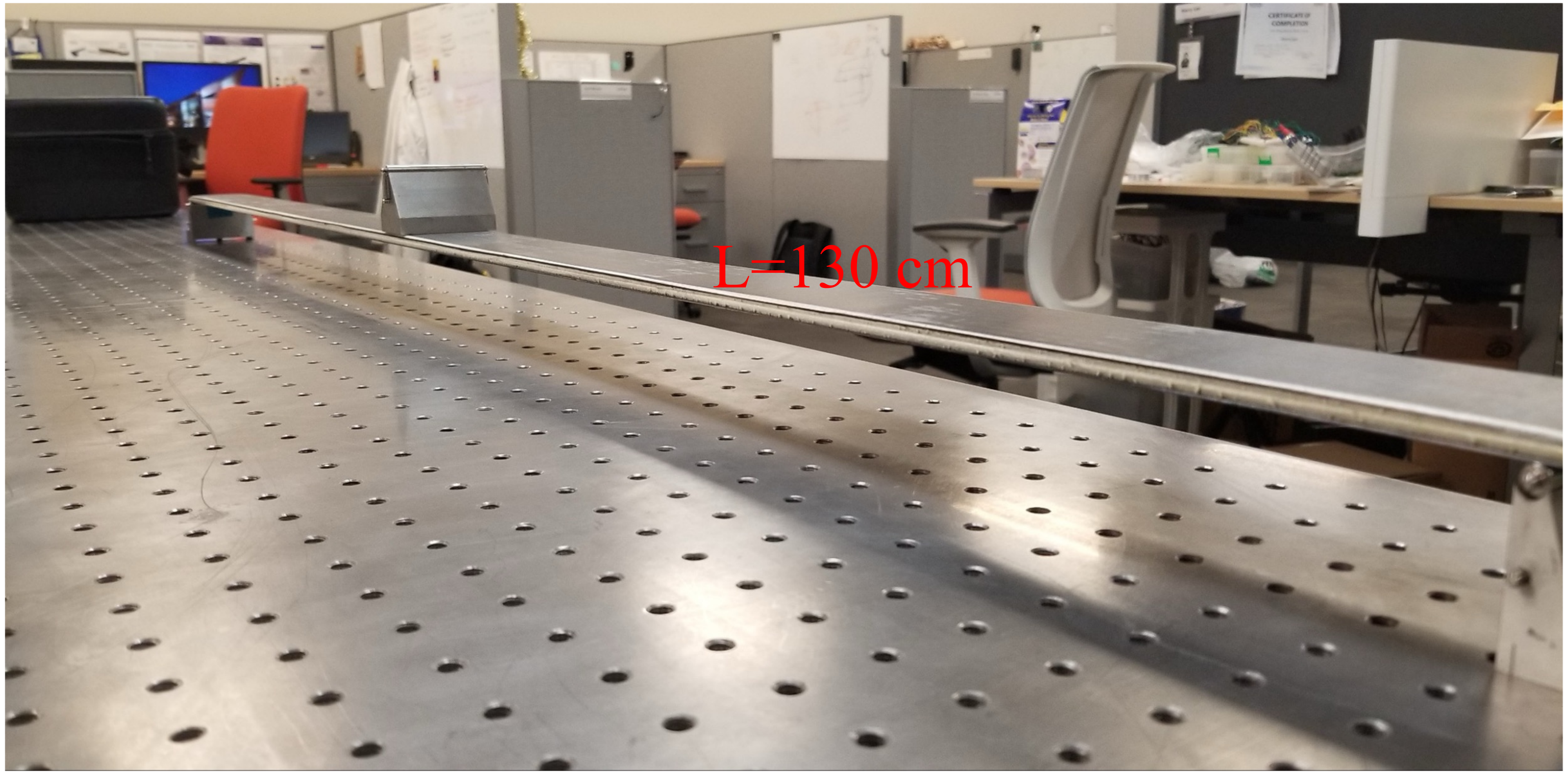
Test beam for sensor irradiation tolerance

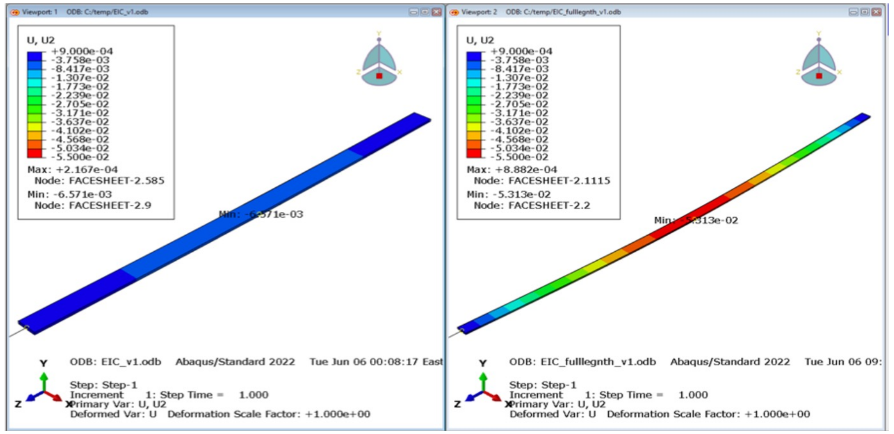
- **Don't expect radiation damage at $10^{11\text{-}12}$ 1MeV n_{eq}/cm^2 would be an issue but will verify**
- Fermilab ITA with high energy protons
- IJS Ljubljana TRIGA reactor: neutrons
- LBL BASE: protons/neutrons/heavy ions

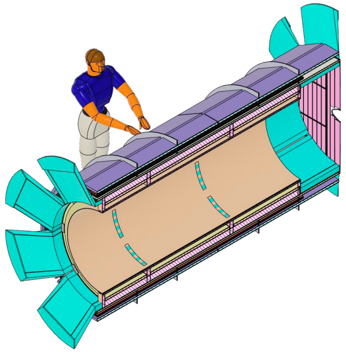


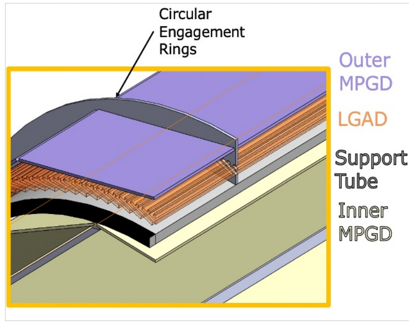
FY23 Deliverables - Mechanical Structure (Aug 2023)

- **Mechanical structure:**
  - Prototype of light-weight module structure for BTOF made with Carbon-Fiber foam/sheets by Purdue.
  - In the process of producing a few more prototypes with embedded cooling tube by the end of 2023



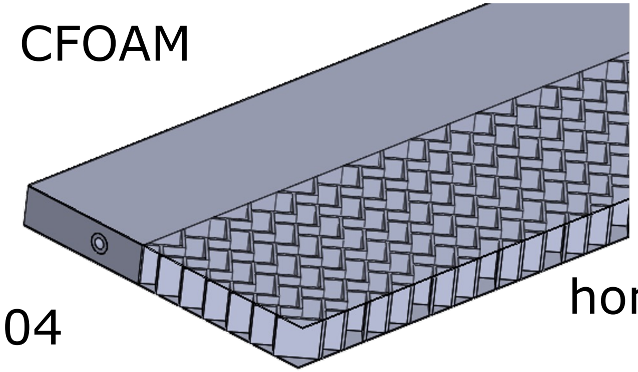




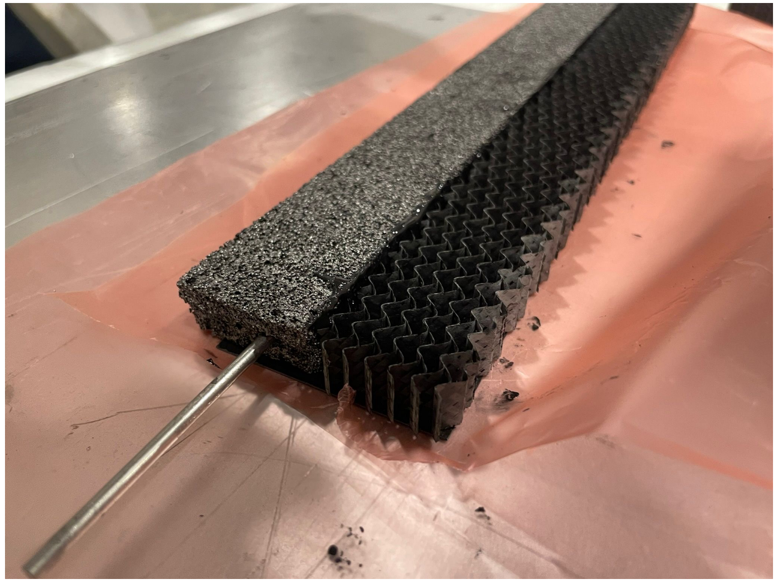


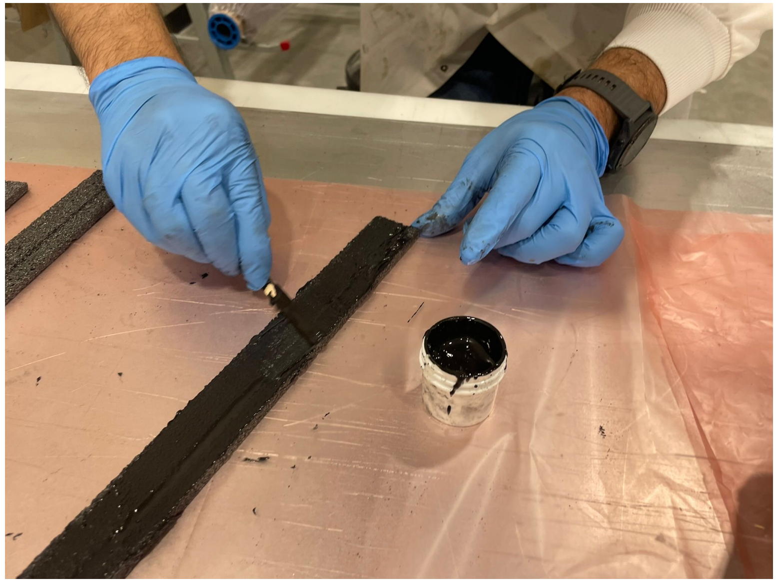
Updates Since August 2023

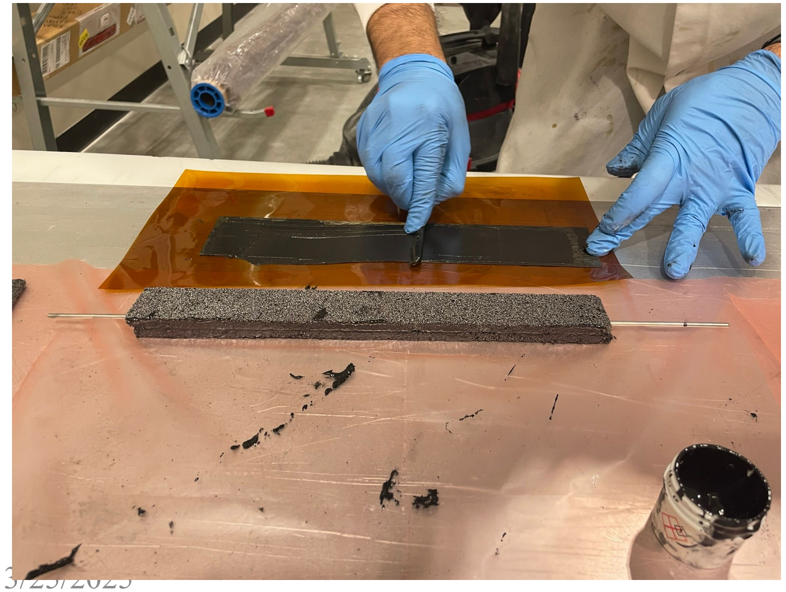
- The first stave prototype manufactured at Purdue in Summer 2023 warped upon curing, which results from internal residual stresses from anisotropic coefficient of thermal expansion mismatch between different materials / structures used in the stave.
- Manufacturing miniSTAVE prototypes with different cure cycles to see which one gives minimum deformation.



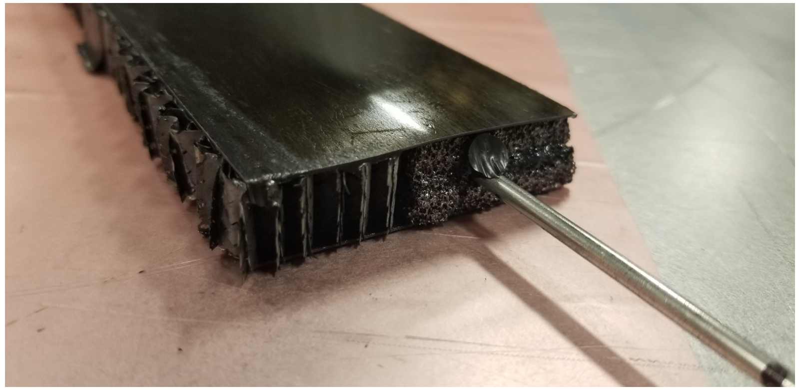
MiniSTAVE Manufacturing Process at Purdue







Prototype Manufacturing Status and Plan at Purdue

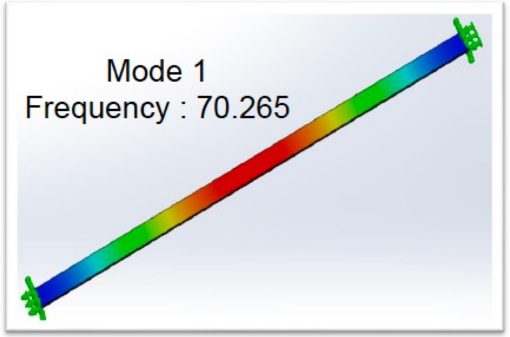


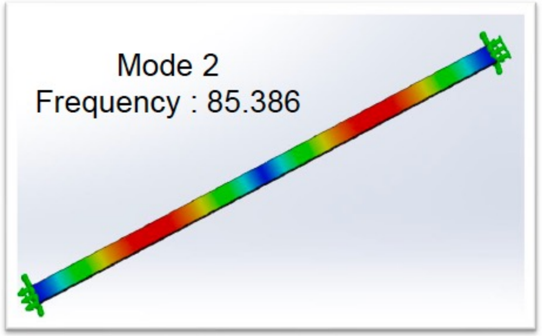
- Manufacture miniSTAVE (x2) – 1 retained at Purdue, 1 shipped to NCKU on March 18
- Manufacture halfSTAVE (x1)
- Heat Transfer Analysis – miniSTAVE, halfSTAVE, fullSTAVE
- Thermal testing of miniSTAVE
- Structural performance FEA and loading tests/validation – miniSTAVE, halfSTAVE

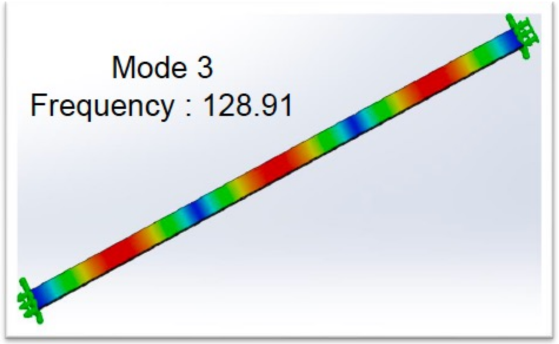
Updates at NCKU

Frequency analysis (FEA simulation):

- Make sure the structure won't be damage because of resonance.
- Decide the position of extra support if necessary

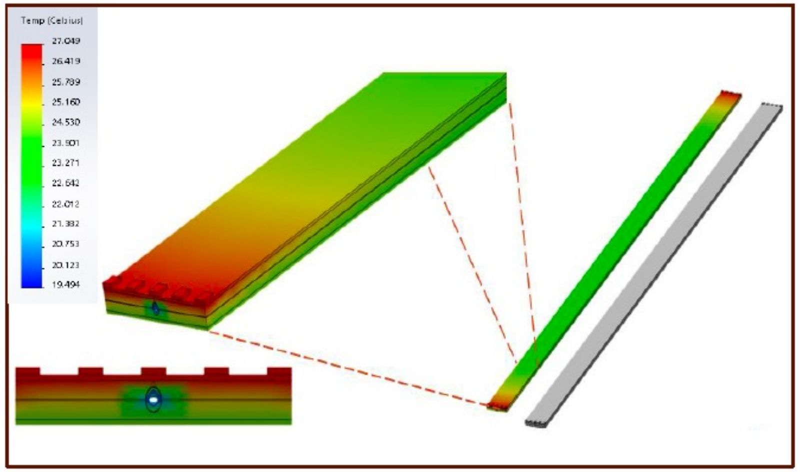


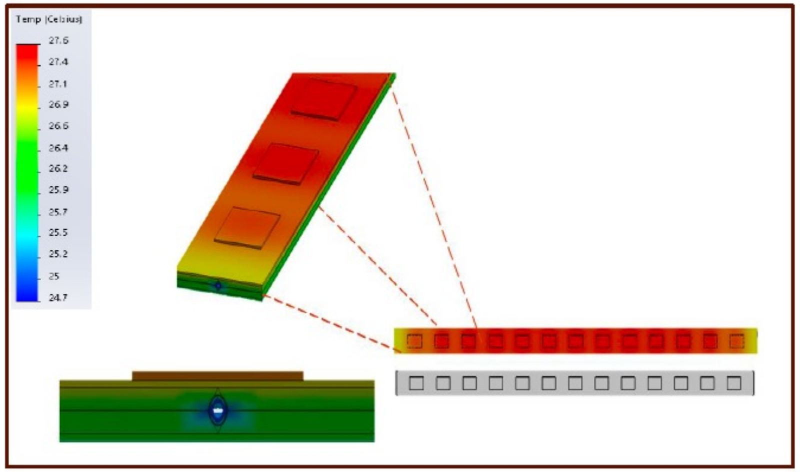




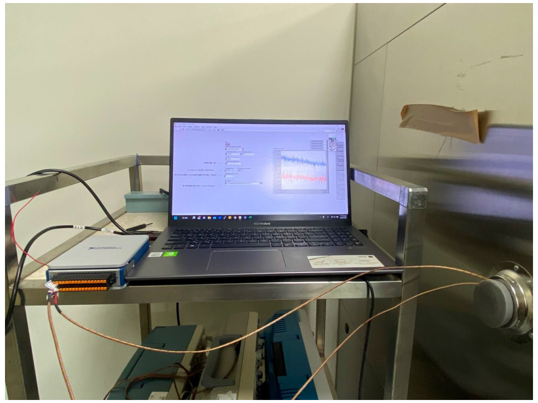
Thermal analysis (FEA simulation):

- Estimate the efficiency of cooling system
- Simulate the temperature distribution of different configure of sensors





Thermocouple and Data Acquisition



Aluminum Tank (covered by styrofoam)

Summary and Outlook

- **AC-LGAD sensor:**
  - 1st HPK prototype sensors: results promising, guiding the new sensor production
  - 2nd HPK prototype sensor: examine optimal sensor thickness, electrode length/pitch/width
    - Design finalized 3/12/2024
    - Sensor procurement and delivery in 3-5 months
    - Preliminary results in 7-9 months
    - Final results in 10-12 months
  - 3rd HPK sensor production in FY25: final prototype production and testing
- **Sensor-ASIC integration**
  - Interposer for strip sensors (e.g. BTOF): waiting for FY24 fund. Will continue in FY25 with new ASIC
- **Light-weight mechanical structure with cooling**
  - 1st prototypes for Barrel TOF stave structures available
  - Detailed analyses and half/full size BTOF stave prototypes in progress
- **Not covered:**
  - eRD109: frontend ASICs, pixel sensor-ASIC bonding, low-mass PCB for BTOF, service hybrid
  - PED: global support structure for BTOF and FTOF (in execution), BTOF/FTOF module prototyping (in prep.)