CPAD 2025 at Penn

5D tracking active target development for the PIONEER experiment

Dr. Simone M. Mazza (SCIPP, UC Santa Cruz)

On behalf of PIONEER collaboration

CPAD 2025, Oct. 2025, U. Penn

SCIPP
SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS
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PIONEER

TAR

PIONEER

- **PIONEER** is a next generation rare Pion decay experiment that will run at PSI
  - World-wide collaboration, most of the institutes are in north America
  - https://arxiv.org/abs/2203.01981

- The goal is to **improve the precision of $R_{e/\mu}$** and **$B(\pi^+ \rightarrow \pi^0 e^+ \nu)$** by an order of magnitude
  - **$R_{e/\mu}$** is the ratio of pion decay to electron a muon: precision measurement of **lepton flavor universality. Goal of 0.01%** (current 0.1%)
  - **$B(\pi^+ \rightarrow \pi^0 e^+ \nu)$** is the cleanest measurement of Vud: very important to test **CKM matrix unitarity**
- **Exotic searches:** Heavy neutral leptons, hidden sector…

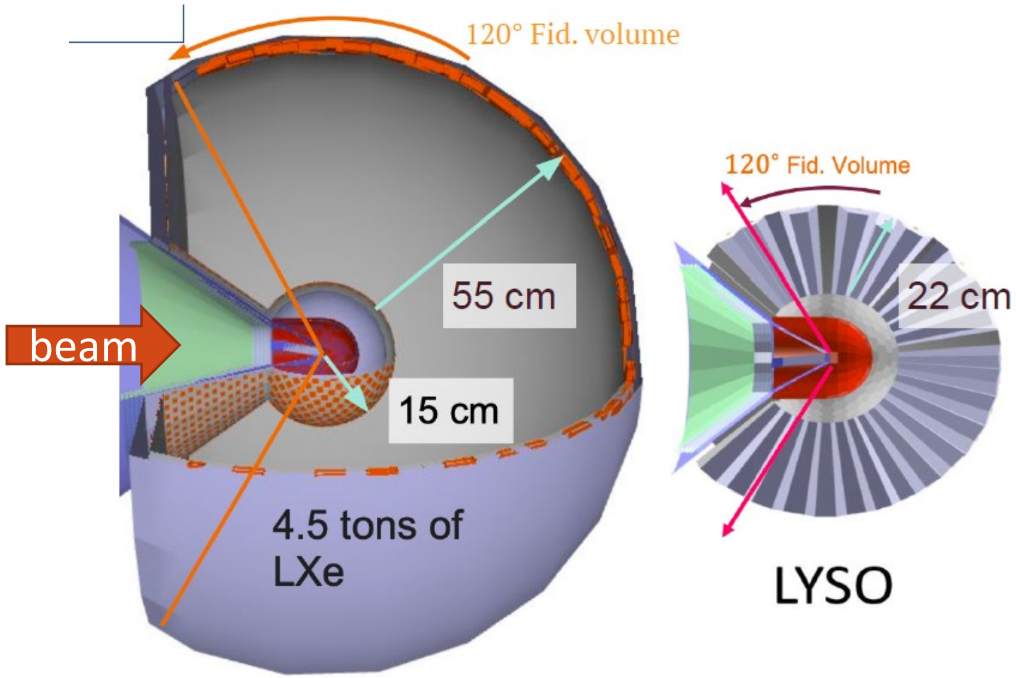
PIONEER goal

$$R_{e/\mu} = \frac{\Gamma(\pi \rightarrow e\nu + \pi \rightarrow e\nu\gamma)}{\Gamma(\pi \rightarrow \mu\nu + \pi \rightarrow \mu\nu\gamma)} : O(\pm 0.01\%)$$

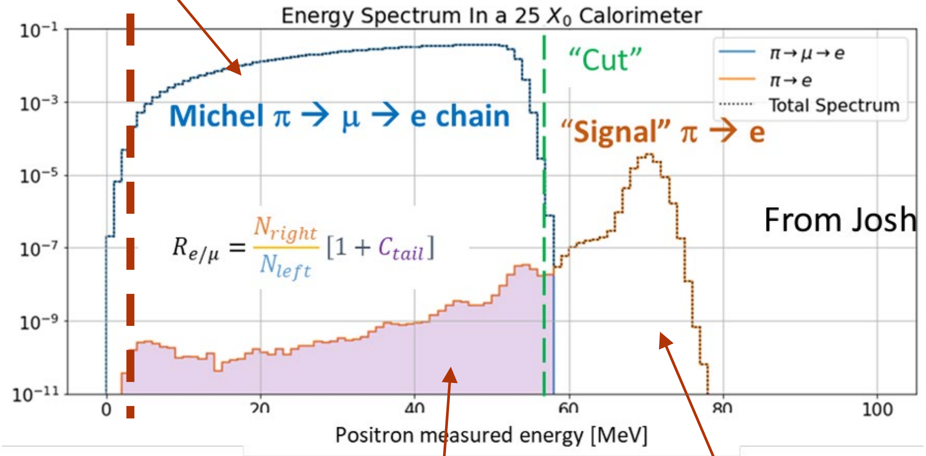
PIONEER experimental design

- Two main detectors:
  - Active TARget, **ATAR** Silicon with fast timing and high segmentation, fully digitized
  - Calorimeter with high energy resolution (liquid Xe or LySO crystals)
- Plus, a tracker in between
- **Goal: Separation of deposited energy spectra of π→eν and π→μν→eνν**

- ATAR uses topology, energy and timing: a 5D tracker!
  - Suppress pile-up from old muons by tracking the positron as coming from the original pion stop location
  - Measure e+ energy loss
  - Separating π→eν and π→μν→eνν decays



Easy: low energy trigger



At some point e+ won't make it to the Calo

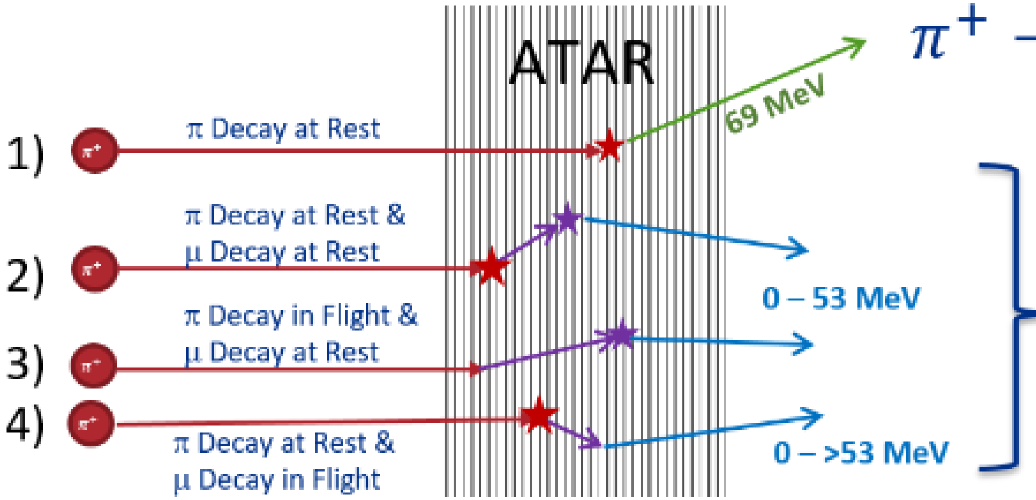
This is the hard part
Tail fraction trigger

Easy: high energy trigger

https://www.mdpi.com/2410-390X/5/4/40 ATAR 1st paper

PIONEERS's ATAR

- Trench insulated LGAD (TI-LGAD) for the ATAR
  - **Why LGADs?** MIP detection with thin bulk, good time-of-arrival determination, charge collection times of 2-3 ns
- ATAR baseline design: 48 layers of 120um thick 2x2 cm LGAD strips (200um pitch)
  - 120 um gives good pion stopping point, 4-7 muon hits, 2-3 ns collection time, thick enough to allow low-gain operation
- 10-15 cm readout flexes carry the un-amplified signal to the ASIC
- **FAST** ASIC does analog amplification and ships the signal to back-end digitizers (**HD-SOC or SAMPIC**)
  - Full digitization allows for (x,y,z,t,E) measurements to reconstruct the event's topology

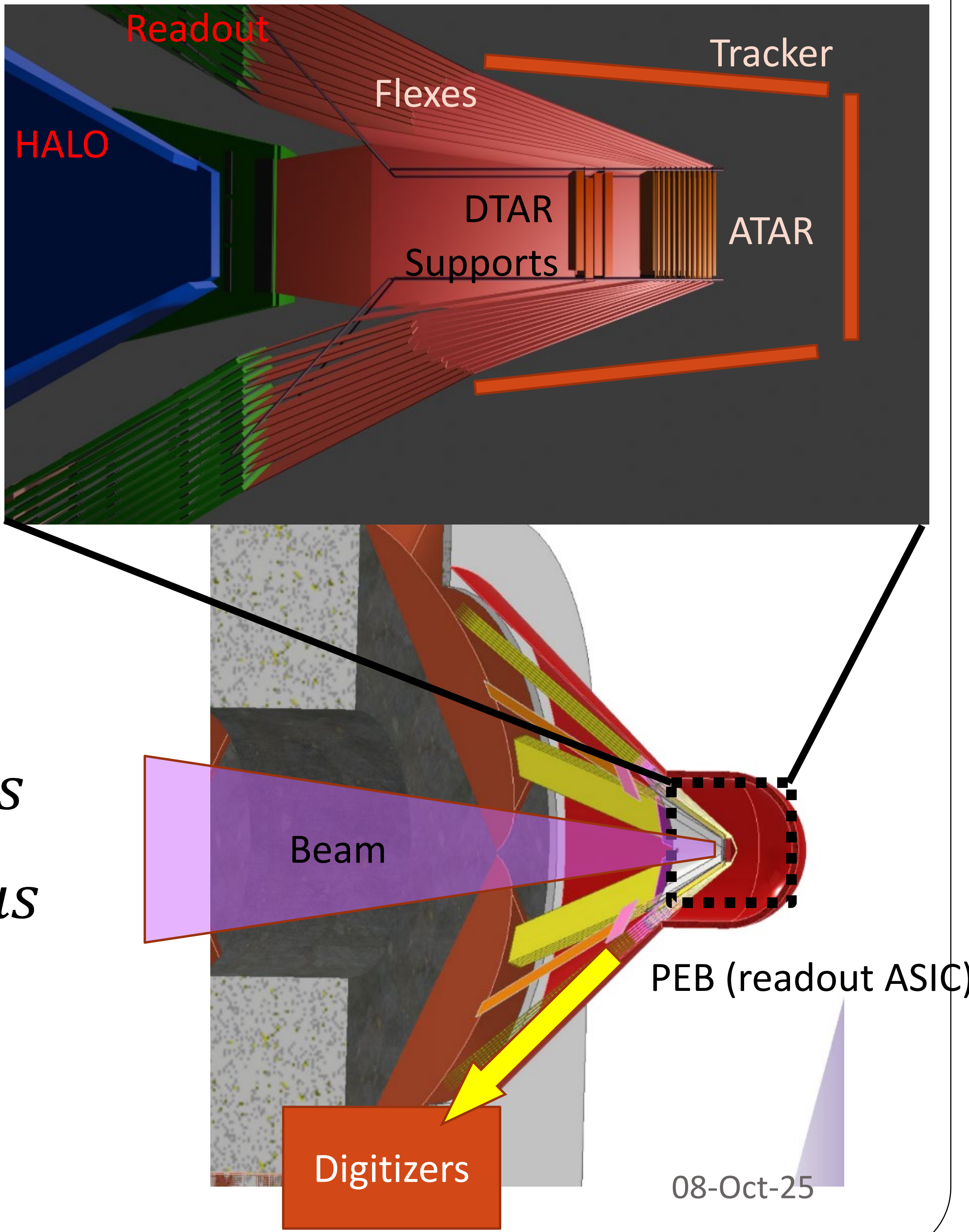


$\pi^+ \to e^+$

$\pi^+ \to \mu^+ \to e^+$

$$\lambda_\pi = \sim 26\, ns$$

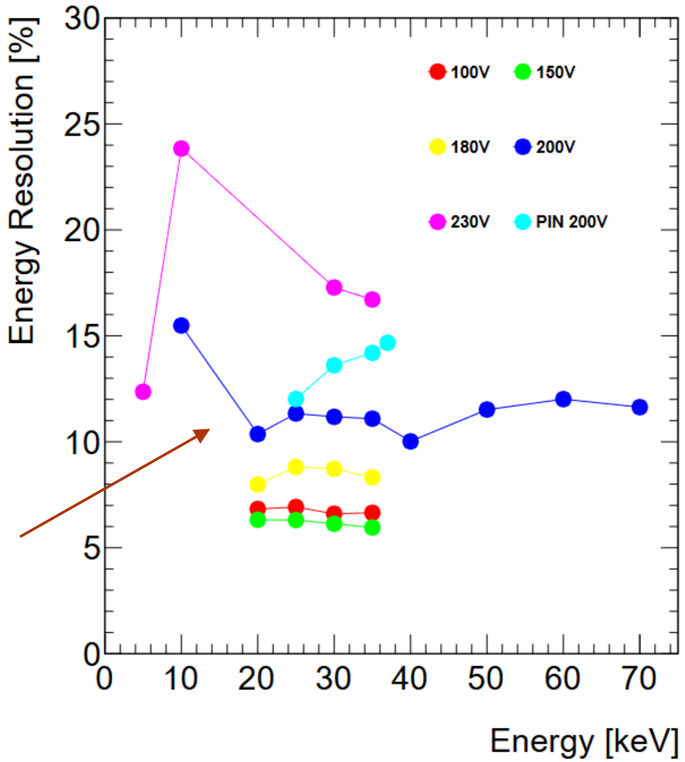
$$\lambda_\mu = \sim 2.2\, \mu s$$

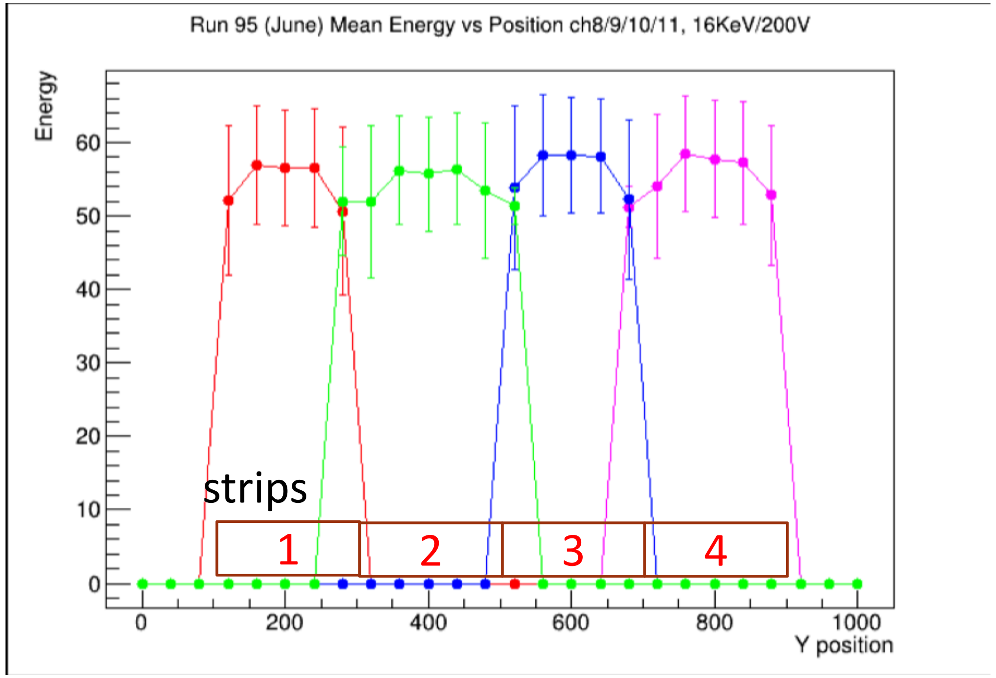


ATAR's ongoing R&D – Sensors energy resolution

- Testing and production of **FBK TI-LGAD prototypes:** Laser TCT studies show a 3% first neighbor cross-talk and "Long range" crosstalk around 1%
- Thicker (100 um) prototype should be ready summer/fall 2025 (part of ongoing FBK production)
- **LGAD energy resolution** measured in the SSRL X-ray fixe energy beam line:
  - 8-15% for MiPs to few MiPs, good linearity tested until 70 KeV X-rays
  - Tested TI-LGAD as well with similar performance with no gap between strips

More or less all running conditions for the tested sensors have 10-20% Energy resolution



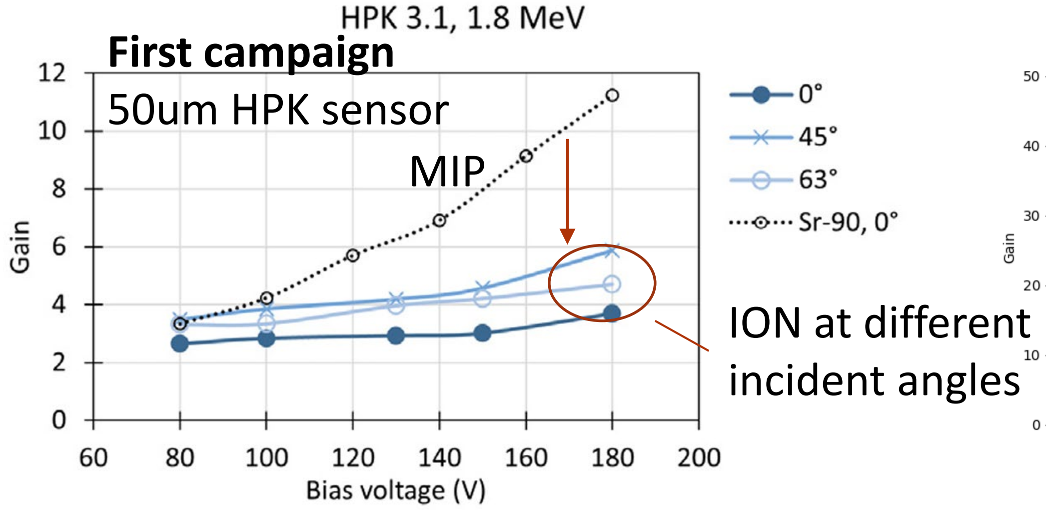


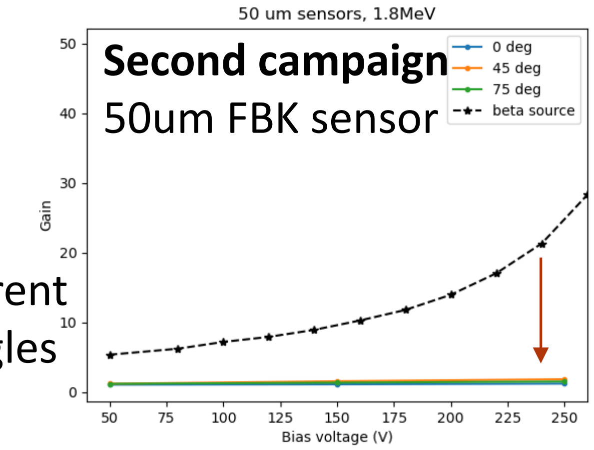
08-Oct-25

https://dx.doi.org/10.1088/1748-0221/18/10/P10006 https://iopscience.iop.org/article/10.1088/1748-0221/20/07/C07044

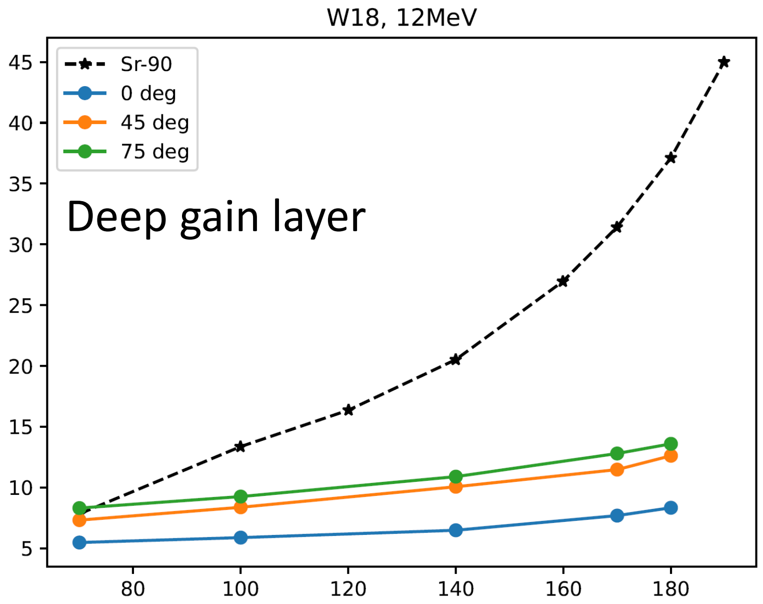
ATAR’s ongoing R&D – Sensors energy linearity

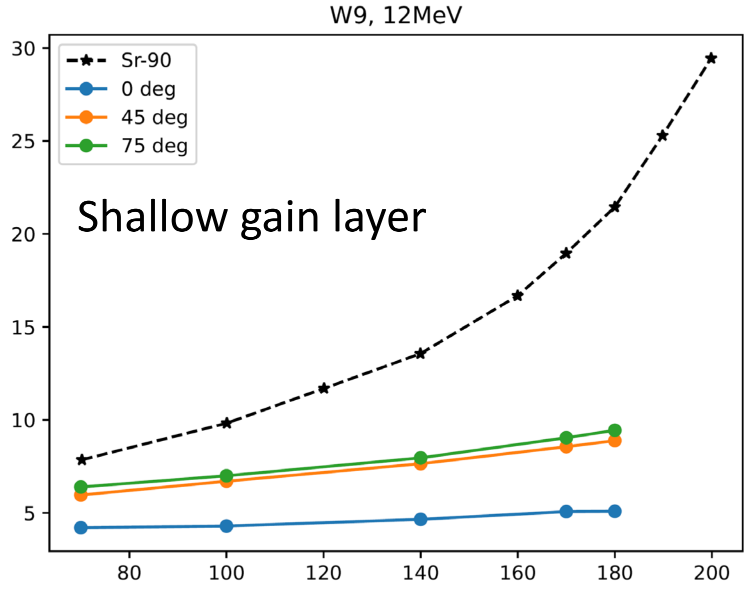
- **Studying the gain saturation of LGADs** with ions at the CENPA Tandem accelerator to identify the design with the most linear behavior
  - Three tests for now: HPK 50um detectors, FBK 50, 100, 150um detectors with shallow gain layer, FBK detectors with shallow and deep gain layer
- Gain saturation is evident in all cases
  - Different sensors vendor showed higher gain suppression, could be an effect on the gain layer doping profile (deep vs shallow)
  - Deeper gain layer seem to retain gain better, but effect is small
- **Important input for final production:** LGAD energy response (resolution and saturation) is a big challenge!





Third campaign (new, unpublished), Energy deposit similar to PIONEER



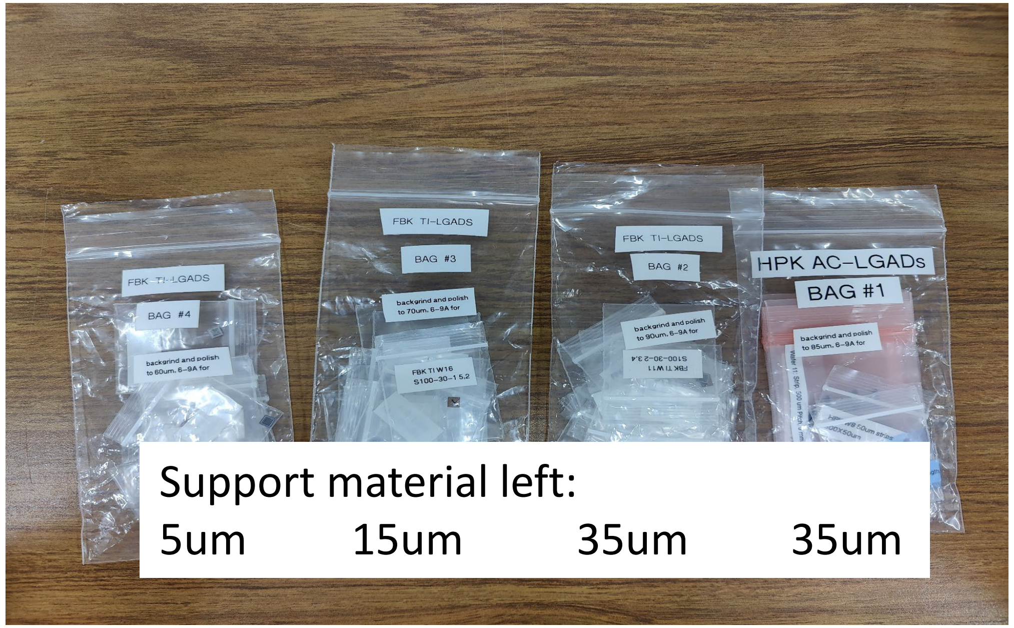


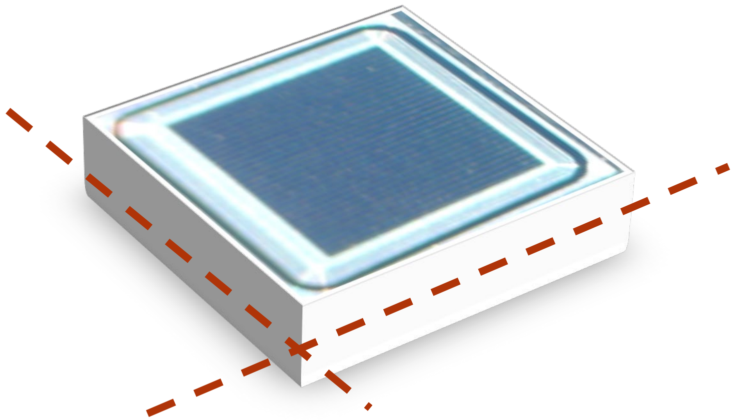
https://doi.org/10.1016/j.nima.2024.169395
https://iopscience.iop.org/article/10.1088/1748-0221/20/08/C08028

Sensor thinning procedure

- All LGAD devices available have 20-50um of active region and a 200-500um inactive support wafer
- The ATAR a fully active sensor is needed, develop a thinning procedure to reduce the support wafer
- Procedure tried twice, second one was more aggressive
- Sensor thinning of AC-LGADs and TI-LGADs
  - Sensors thinned at different levels to test process yield
  - TI-LGADs down to 5um of support left (60um total)

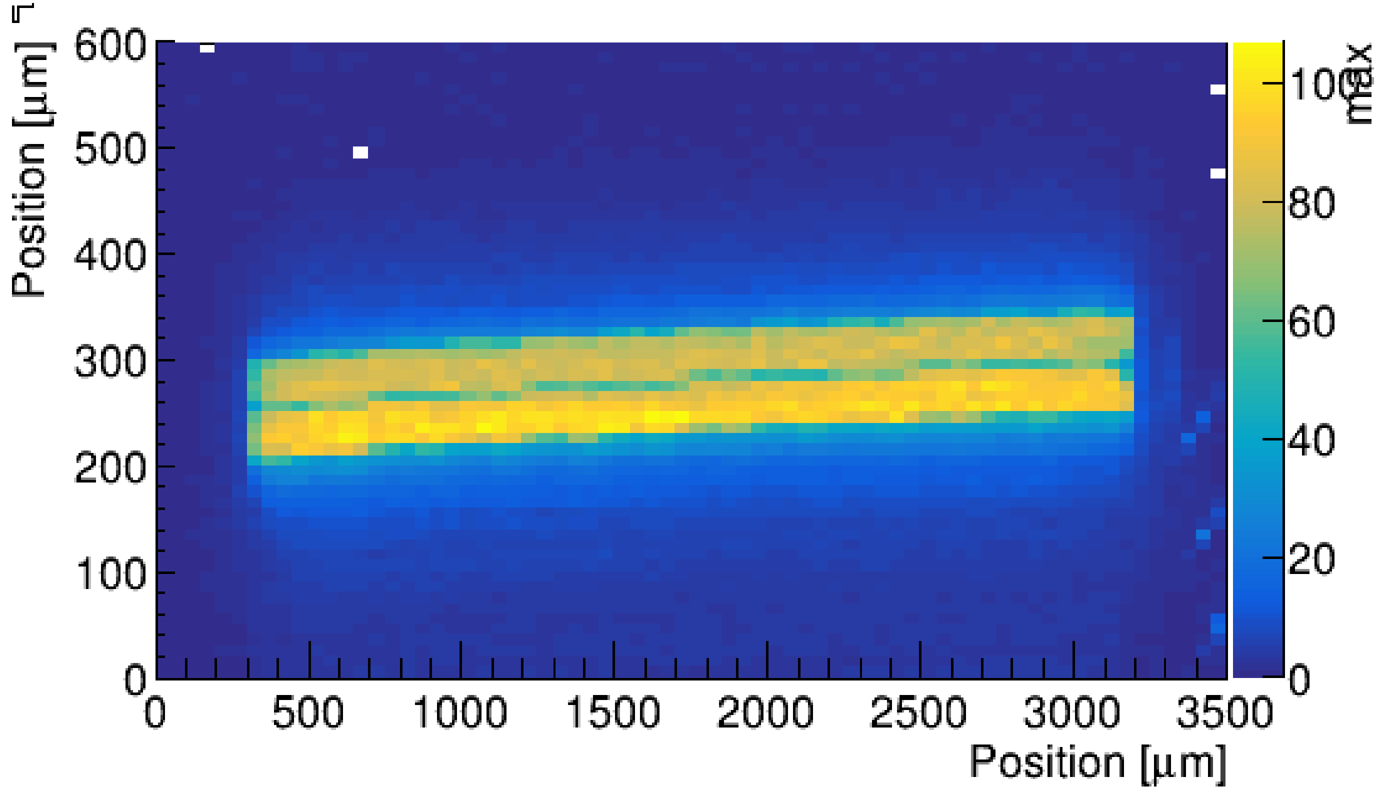
- All sensors (50) worked after the procedure
  - → 100% yield!
  - Will try a more aggressive approach next

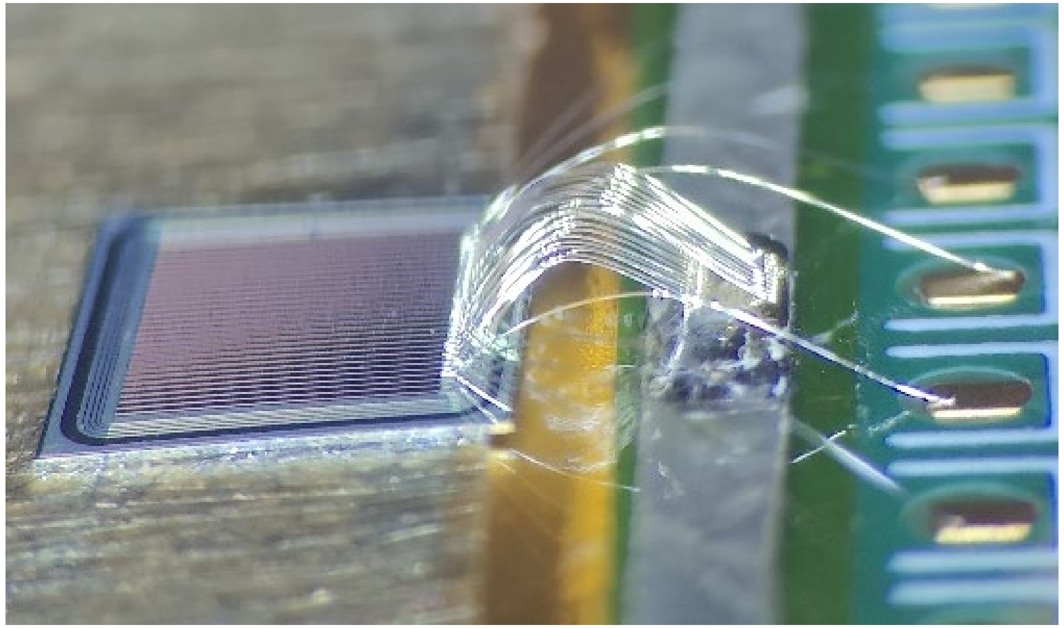




60um TI-LGAD

- Laser TCT scan using red laser, IR laser is not good because of backside reflection with no attenuation (due to lack of support wafer)
- The sensor works, shows gain and has good strip insulation!

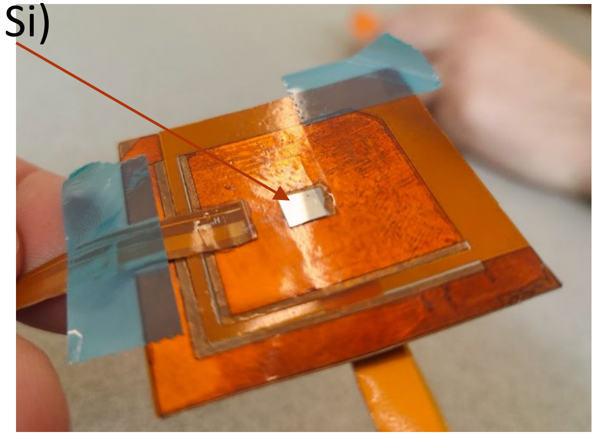


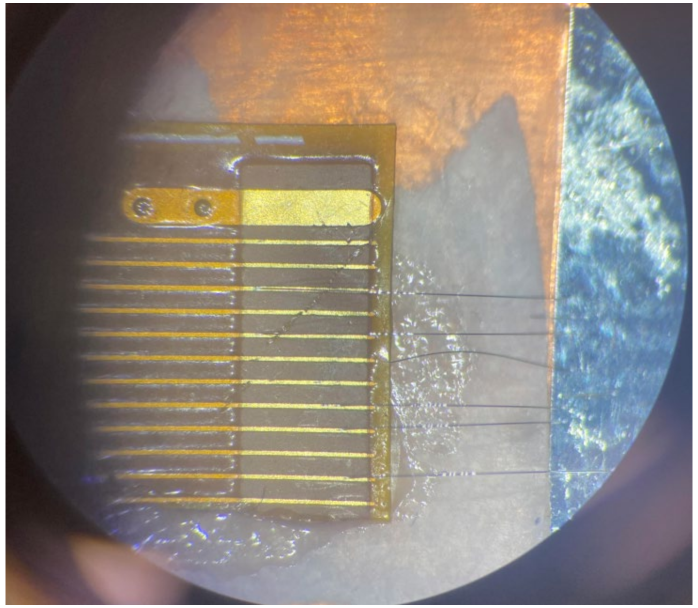


Sensor assembly

- Assemble thinned sensor stacks using thin metal and Kapton shims
- Sandwich the sensor and component to have a larger frame to put flex or boards in place and provide HV return path
- Double-sided wire bond assembly requires a specialized jig to avoid damage to the sensors

Dummy sensor (200um Si)

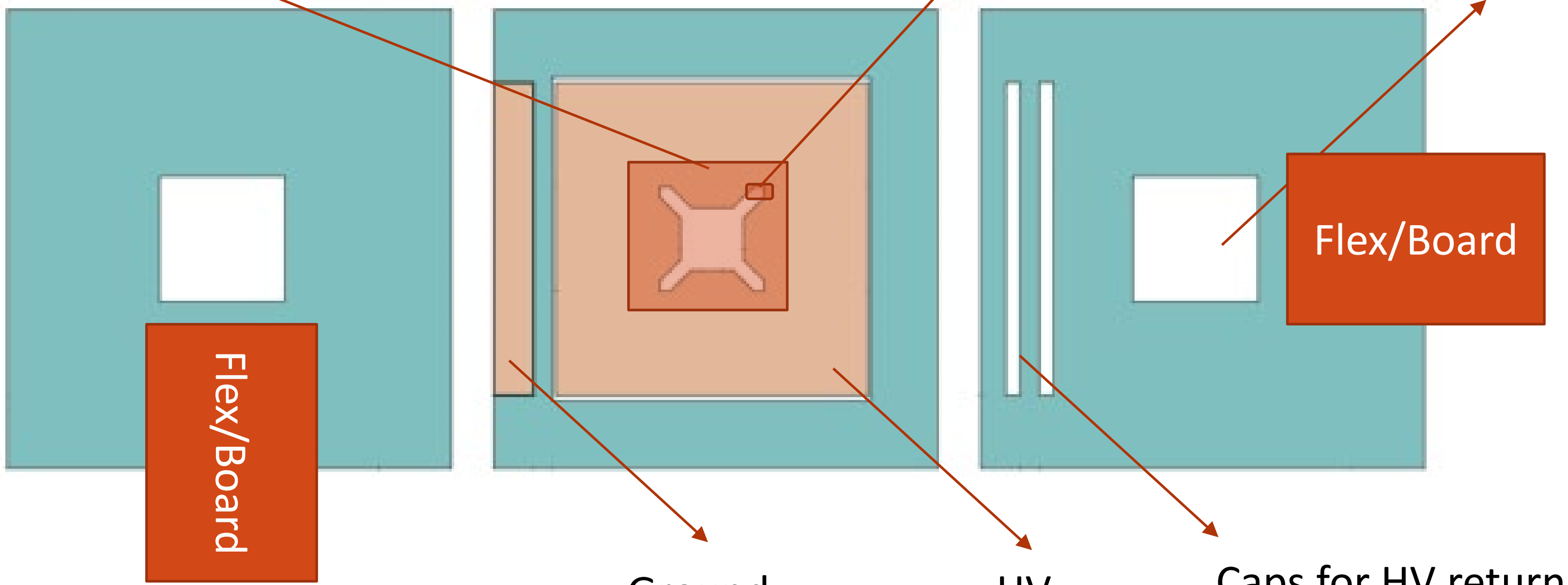




Sensors (on both sides)

Glue slots to keep it flush

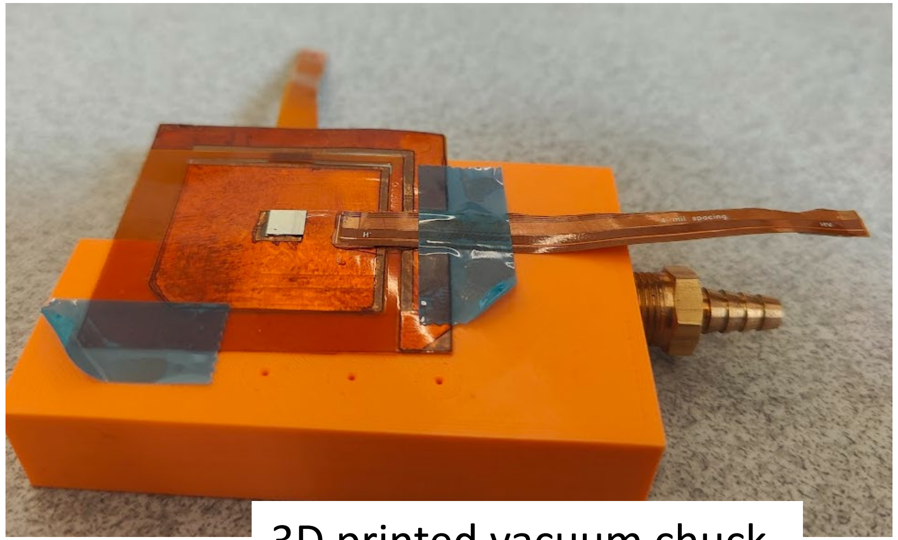
Opening for sensor



Ground

HV

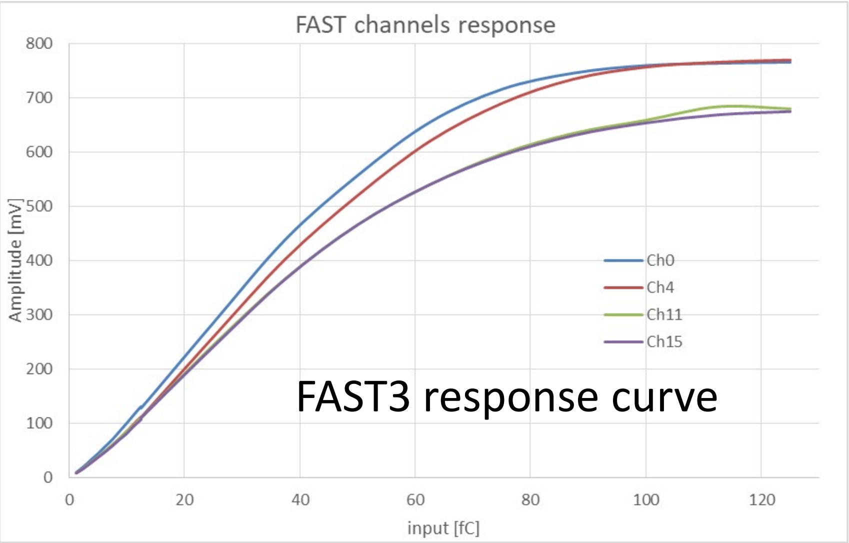
Caps for HV return



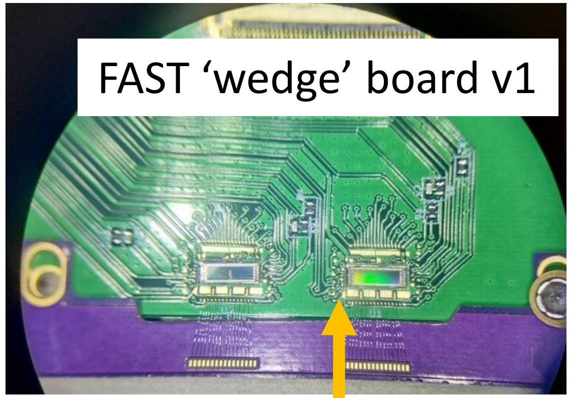
3D printed vacuum chuck
For double-sided bonding

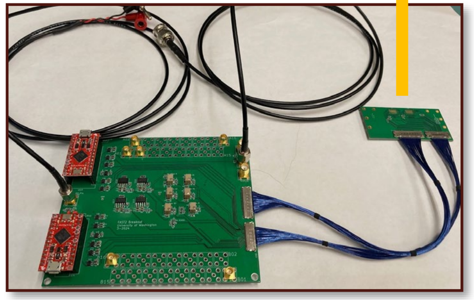
ATAR's ongoing R&D - Electronics

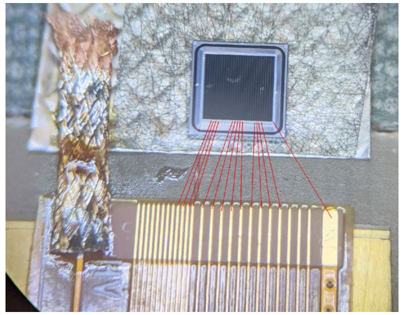
- Testing amplifier chip (FAST3) with 16 channels
  - Bandwidth ~1GHz, Noise ~1 mV, dynamic range up to ~700 mV
  - Packaged version of FAST3 expected end of 2025
  - Updated production foreseen in 2026-2027 with 20 channels and minor fixes on the layout
- Peripheral wedge boards with 2x FAST chips fabricated and under testing

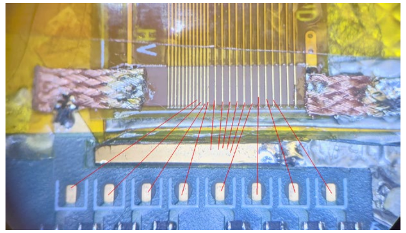


- Flexes prototype for high bandwidth signal transmission
  - Cross talk with first neighbor ~10%
  - Long range cross talk is minimal ~1.5%
  - Newer version seems to have better performance









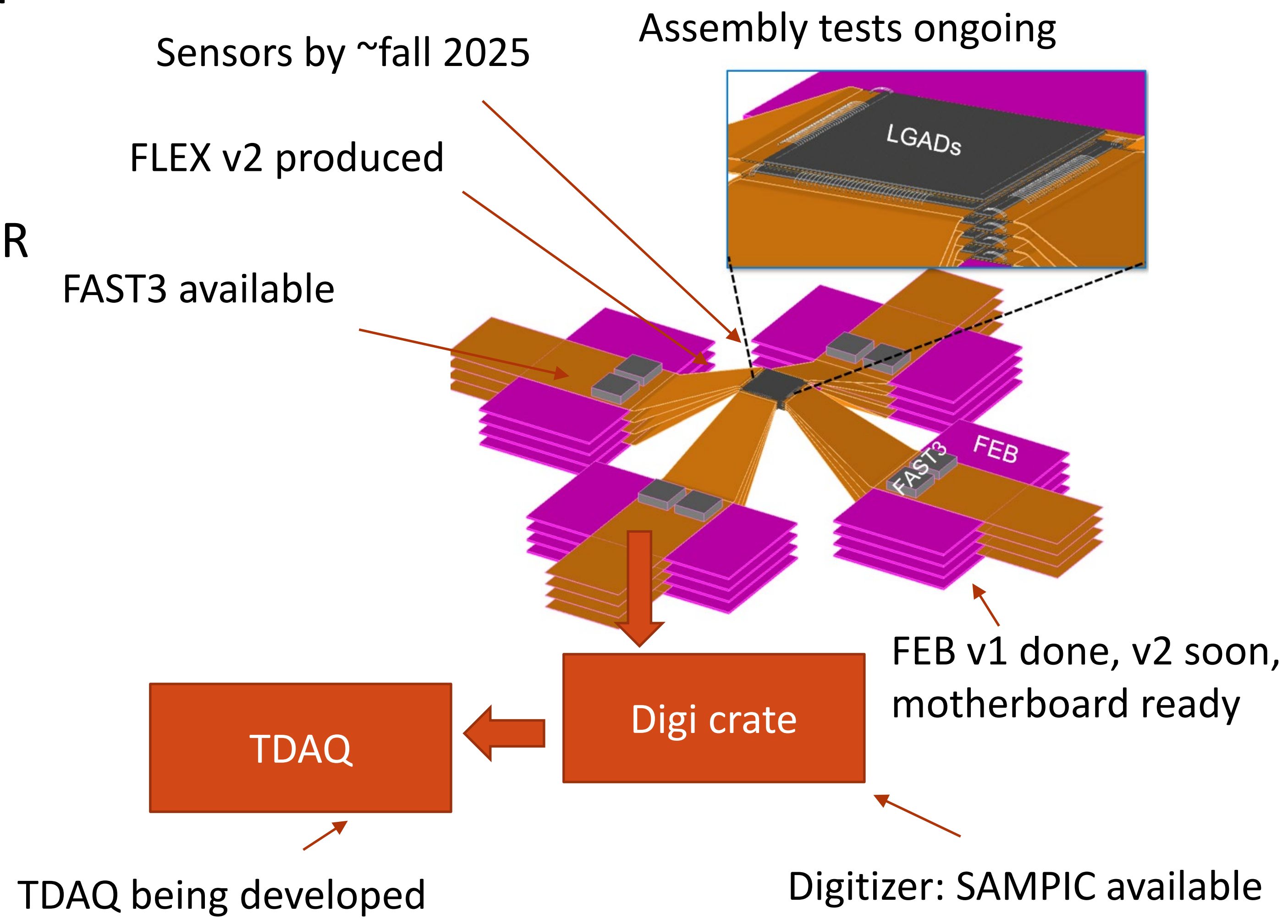
Flex prototype characterization

- Digitizer chips: HD-SOC or SAMPIC
  - https://www.naluscientific.com/technology/
  - https://indico.cern.ch/event/1040996/contributions/4402547/

ATAR’s Demonstrator

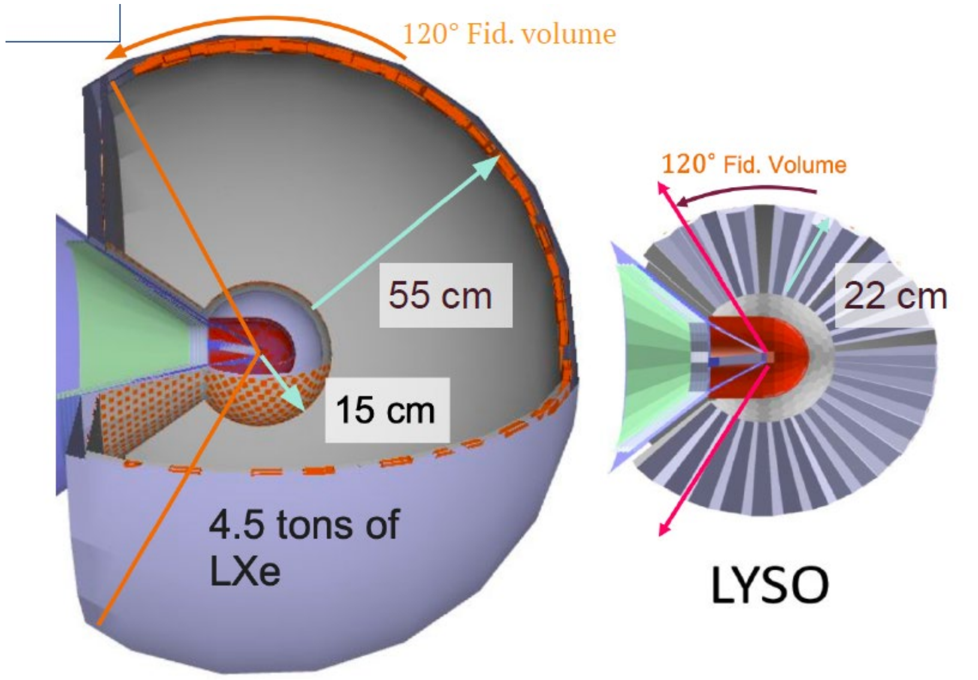
- **Pre-demonstrator**: 2-4 planes of detector, run at TRIUMF in December 2025
- **Demonstrator**: a multi-layer device with 16 layers
  - Goal: verify reconstruction capabilities of the ATAR
  - Run planned at PSI and TRIUMF

- Layers are 100um thick strip devices, size is 1cmx1cm or 0.5x0.5cm (~10-20% channels of final ATAR)
  - Sensors are thinned to remove dead material
- Readout is wedge boards with 2-3x FAST 3 chips per board
- Sensors are ‘stacked’ in layers of 2-4, directly connected to PEB or with short flex
- One SAMPIC crate available for digitization



Conclusions

- **PIONEER** is a next generation rare Pion decay experiment to measure $R_{e/\mu}$ and Pion beta decay branching fraction with **unprecedented precision**
  - Three main detector: ATAR, CALO and tracker
- PIONEER's active target (ATAR) **is a very ambitious detector**
  - Many challenges still need to be solved
  - R&D is steadily advancing
- First test at TRIUMF in December 2025, 2-4 planes to make a zero-mass tracker for low energy muons in a pion lifetime experiment
- Plans to have a working PIONEER Demonstrator tested first at PSI in and then at TRIUMF



Thanks for the attention

Many thanks to the SCIPP group students and technicians!

In particular to A. Molnar and A. Tiernan

Thanks to FBK for fabricating sensors for this study

This work was supported by the United States Department of Energy, grants DE-SC0010107 and DE-SC0020255.

Backup

PIONEER main physics goals ($R_{e/\mu}$)

- **Charged lepton flavor universality ($R_{e/\mu}$)**
  - SM theory calculation is precise to O(10E-4)
  - But current experimental measurement is still one order of magnitude away from theory calculation

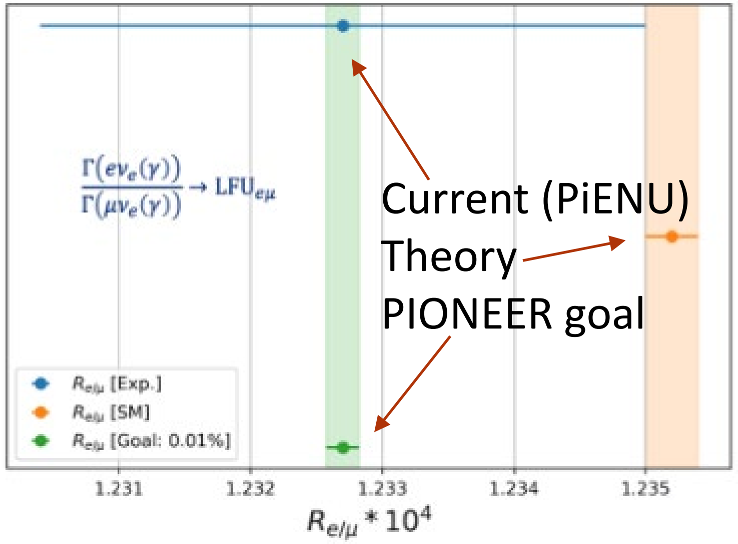
$$R^{theory}_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = (1.2352 \pm 0.0002)\, x10^{-4}$$

Current Result (PDG): $R^{exp}_{e/\mu} = 1.2327 \pm 0.0023 x10^{-4}$ $(\pm 0.19\%)$

$$\frac{g_e}{g_\mu} = 0.9989 \pm 0.0009 \quad (\pm 0.09\%)$$

PEN, PIENU goals ($R^{exp}_{e/\mu} \leq \pm 0.1\%$)

PIONEER goal $R_{e/\mu} = \dfrac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)} : O(\pm 0.01\%)$



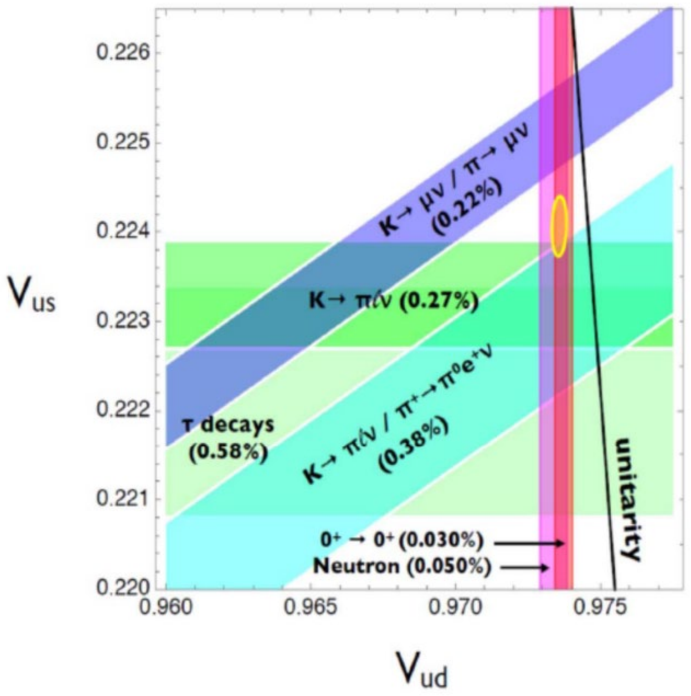
- **The goal of PIONEER is to reach the same precision as the theory calculation**
- **Process of π→eν** is helicity suppressed and **very sensitive to pseudo-scalar and scalar couplings that are absent in SM**
  - A disagreement between theory and experimental value for $R_{e/\mu}$ would be a clear indication of BSM
  - E.g. Charged Higgs BSM coupling (to 3000 TeV)
  - But many others!

PIONEER main physics goals ($R_{\pi\beta}$)

- **Pion beta decay branching fraction $R_{\pi\beta}$:** $B(\pi^+ \rightarrow \pi^0 e^+ \nu)$
  - Important to test CKM unitarity
  - It is a **clean Vud measurement**
  - New constrain in the (Vus – Vud) plane
- Current precision 0.64 % (PIBETA)
  - PIONEER precision goal: 0.2-0.05 % (Phase II-III)

- **Additional physics searches** are also foreseen
  - Such as Axion Like Particles (ALPs), Majorons and massive neutrino searches

Measure $R_{\pi\beta} = \dfrac{\Gamma(\pi^+ \to \pi^0 e^+ \nu)}{\Gamma(\pi^+ \to all)}$: $O(\pm 0.2\% \to \pm 0.05\%)$



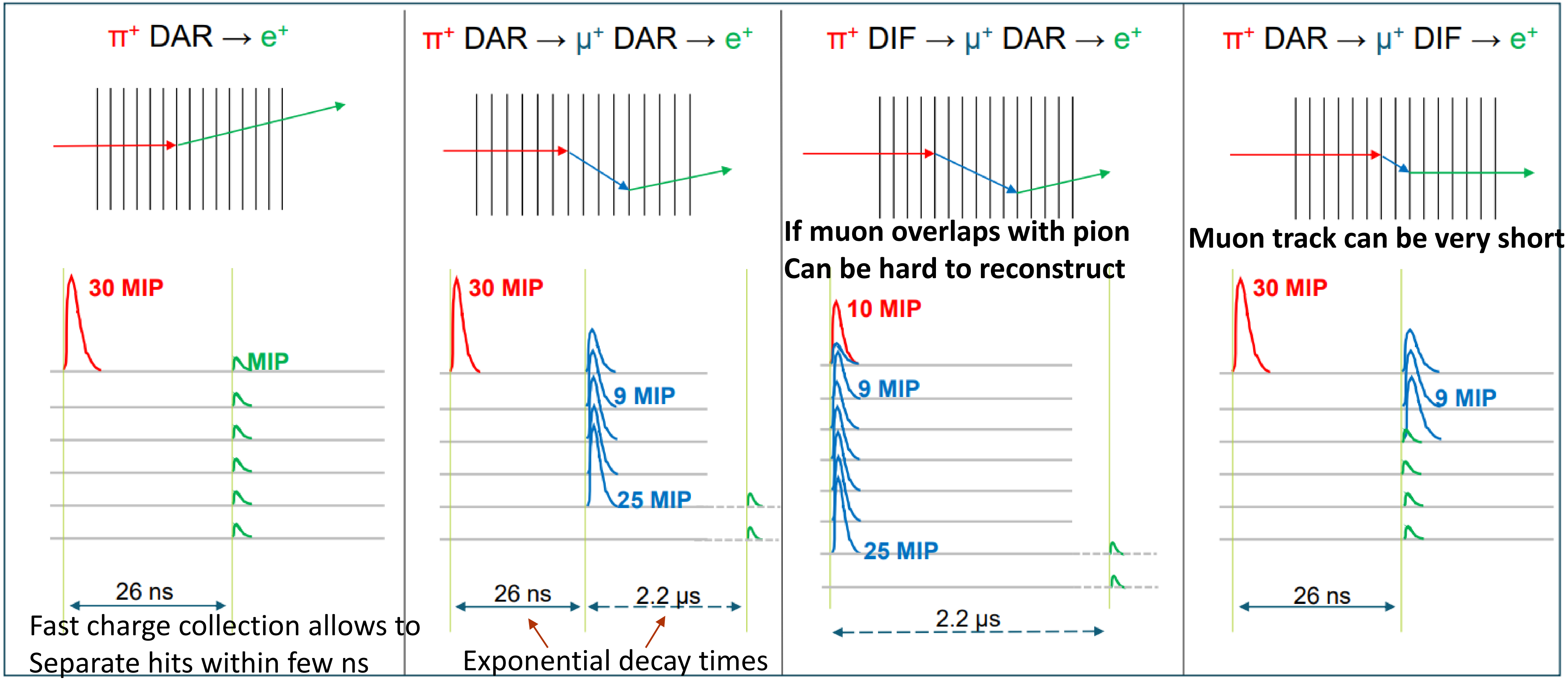
Improve search sensitivities by an order of magnitude

e.g. $\pi \to e\nu_H; \pi \to \mu\nu_H; \pi \to e/\mu\nu\nu\bar{\nu}; \pi \to e/\mu\nu X$

Event Reconstruction

- Complex event reconstruction to detect all types of pion decays
- Reconstruction techniques using machine learning
- Expertise from BNL on LArTPC event reconstruction

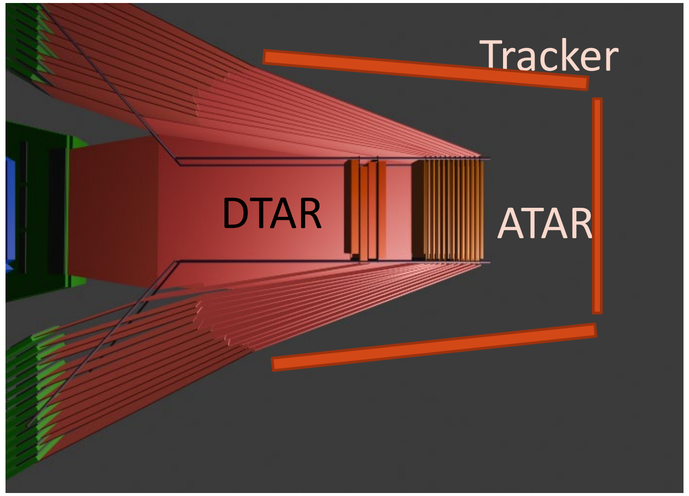
Reminder: to reach the target level of precision for PIONEER it is crucial to recognize π→e from π→μ→e events when final e⁺ energy is the same!



https://indico.cern.ch/event/1175216/contributions/5064176/
https://indico.cern.ch/event/1175216/contributions/5064175/

PIONEER’s Tracker role

- Detect and identify beam particles that miss ATAR
- Pileup identification and Bhabha events (2 simultaneous hits)
- Help with ‘charged’ Albedo (backsplashes electrons/positrons)
  - Duration of 1-2 ns, that’s the needed time resolution
- Helpful in defining the fiducial volume
  - Especially where ATAR has less tracking power (around 90 degrees)
- Seeding trigger or early in the trigger chain

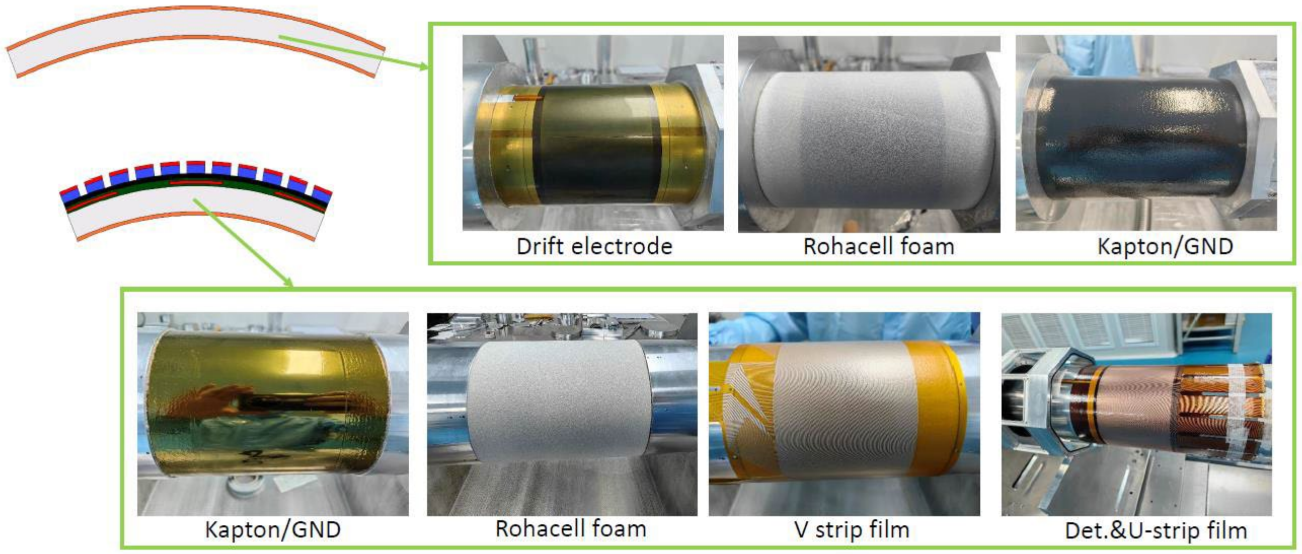


- Possible negative effects that need to be explored
  - Degrade energy resolution of positrons
  - Create a source of annihilation that will be hard to track/model
  - Might be a major challenge to make it uniform in material thickness vs polar angle (might need acceptance correction)

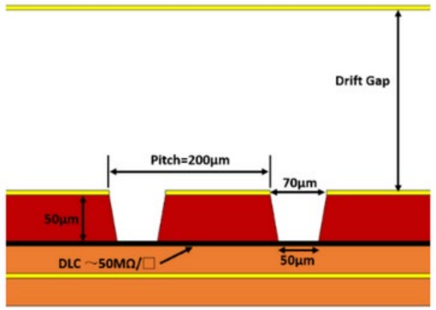
Dr. Simone M. Mazza - University of California Santa Cruz

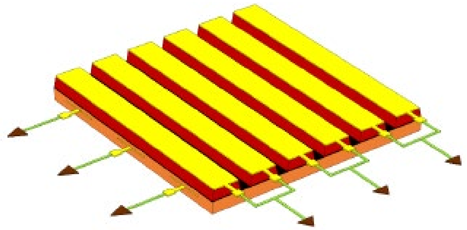
Tracker technologies

- **Looking into 2 different technologies for the tracker**
- **Micro-Resistive Groove (Stony Brook)**
  - Micro Resistive Groove or µRGroove is a member of the Micro Pattern Gas Detector (MPGD) family
  - Proven CERN development of bent µRGroove with 0.23% X0
  - Energy resolution around 25% at 8 keV
  - Position resolution ~100um
  - Time resolution >5ns
  - Plan to build the full size tracker if NSF gets funded

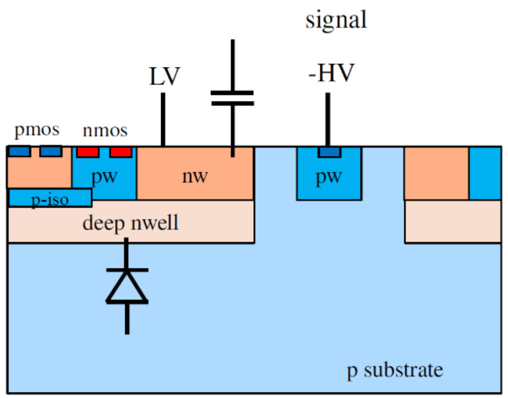


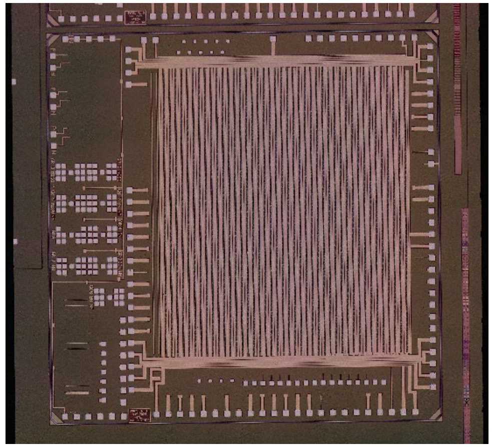
✓ Total material budget: ~0.23%X_0





- **MAPSI chip (PSI group)**
  - The MAPSI chip arrived,1st chip submitted in this technology
    - Testing will start once the test system is ready
  - Position resolution ~50um
  - Time resolution <1ns
  - Geometric structure challenging
    - Currently working on technical drawings on a possible geometry with the aim to have a realistic model to include into the simulation.
  - Power management is key task in order to keep the material budget as low as possible

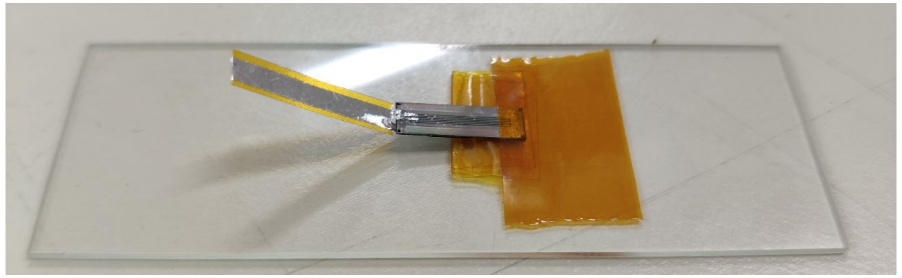


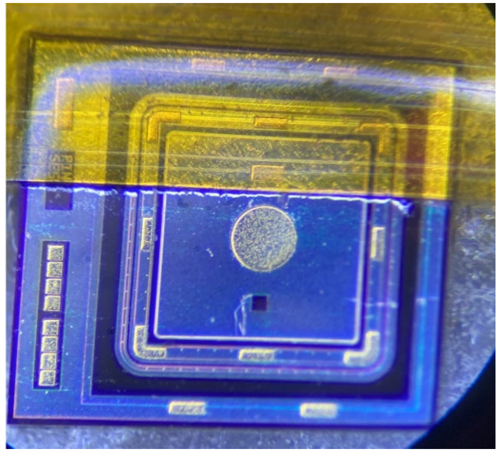


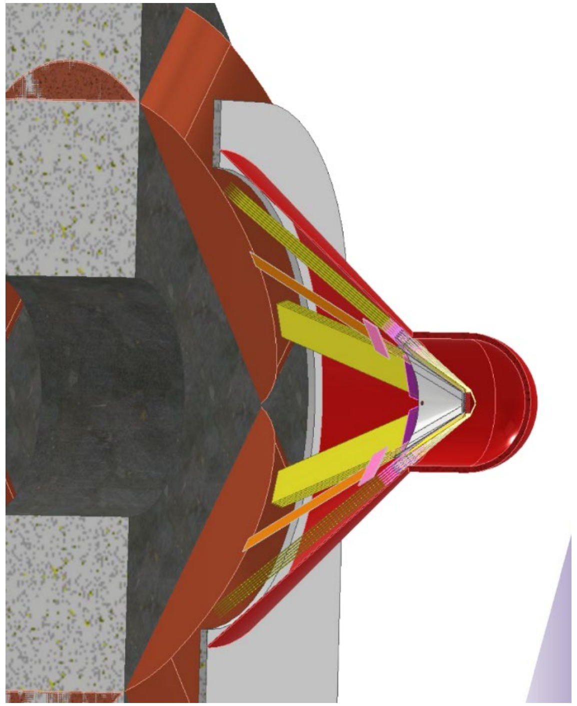
ATAR's ongoing R&D - Mechanics

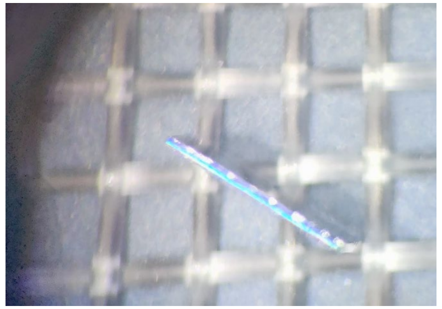
- Dead material removal from LGAD devices
  - Thin down support on 50um, 100um and 150um active thickness sensors.
  - Afterward, all were still working. Remaining support ~30um.
- Demonstration of mechanical connection of two sensors with Anisotropic Conductive Paste and stud bonds
  - 20-30um (or less) gap observed
- Parylene (type N) tests to insulate sensors areas when assembled in tight stacks
- spTAB connection trials on strip sensors
  - Allow for tighter packaging than wire bonds

- Development of concept support structure for the ATAR/tracker de-coupled from Calorimeter
  - Cooling via air draft or active liquid cooling for the FEBs
  - FEBs in split 8 direction from the ATAR


spTAB connection to strip sensor (both front and back connection)


LGAD with Parylene coating


Conical support structure drawing


LGAD thinned down to 60-90um