Los Alamos NATIONAL LABORATORY

Silicon detector R&D for the future Electron-Ion Collider

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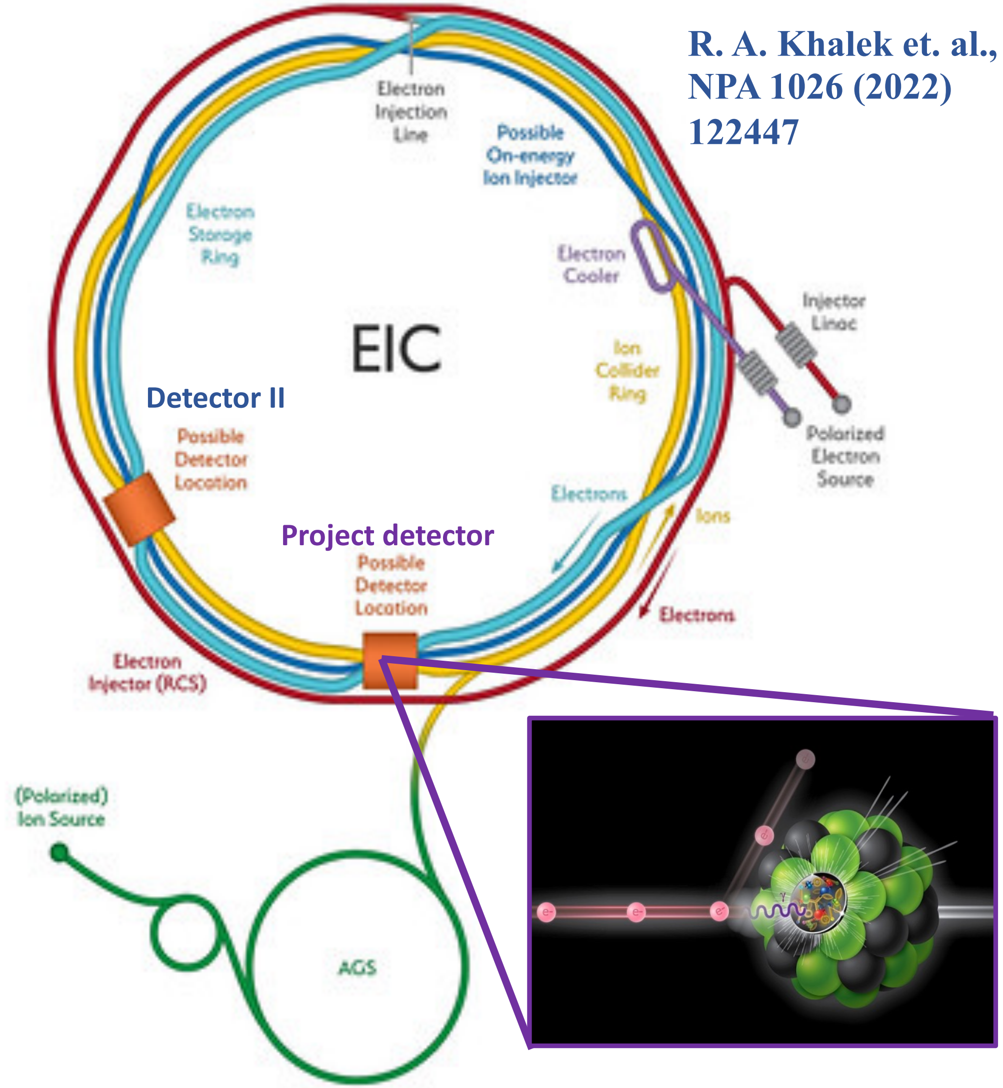
Outline

- Introduction to the Electron-Ion Collider (EIC) and the EIC detector.
- The Silicon vertex and tracking detector design and performance.
- MAPS and AC-LGAD R&D progress for the EIC silicon detector.
- Summary and Outlook.

Introduction to the future Electron-Ion Collider (EIC)

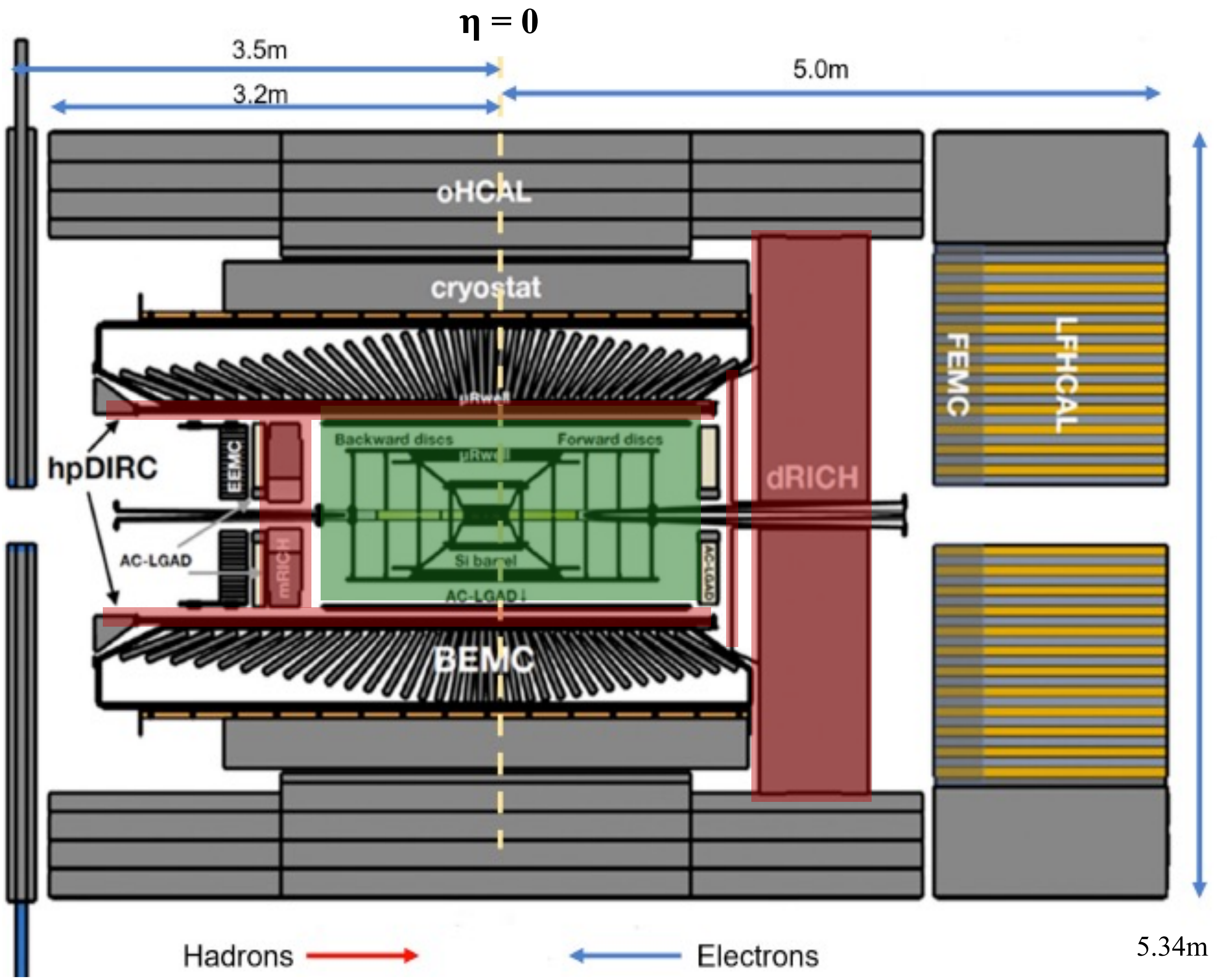
- The future Electron-Ion Collider (EIC) will utilize high-luminosity high-energy e+p and e+A collisions to solve several fundamental questions in the nuclear physics field.
- The EIC project has received CD1 approval from the US DOE in 2021 and will be built at BNL.
- The future EIC will operate:
  - (Polarized) p and nucleus (A=2-238) beams at 41, 100-275 GeV.
  - (Polarized) e beam at 2.5-18 GeV.
  - Instant luminosity L_{int} ~ 10^{33-34} $cm^{-2}sec^{-1}$. A factor of ~1000 higher than HERA.
  - Bunch crossing rate: ~10 ns.



R. A. Khalek et. al., NPA 1026 (2022) 122447

Current EIC project detector design by the EPIC collaboration

- The EPIC collaboration is leading the EIC project detector geometry optimization and technical design preparation for EIC CD2/3A approval (scheduled in 2024).

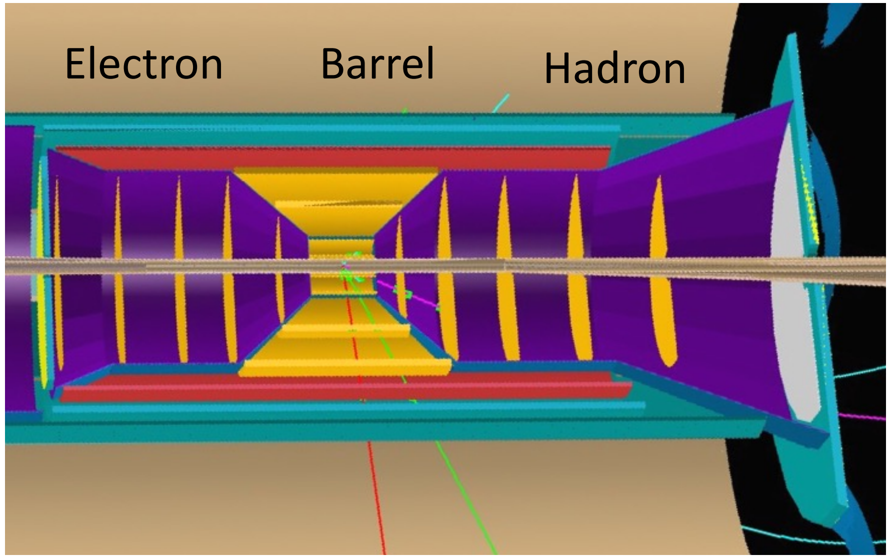


- The EPIC detector design consists of optimized tracking, PID and calorimeter subsystems and will utilize a new 1.7 T magnet.
- The high granularity and low material budget EPIC vertex and tracking detector includes the 65 nm Monolithic Active Pixel Sensor (MAPS) detector in the barrel, hadron endcap and electron endcap regions. AC coupled Low Gain Avalanche Diode (AC-LGAD) layer/plane serves as the outer tracker.

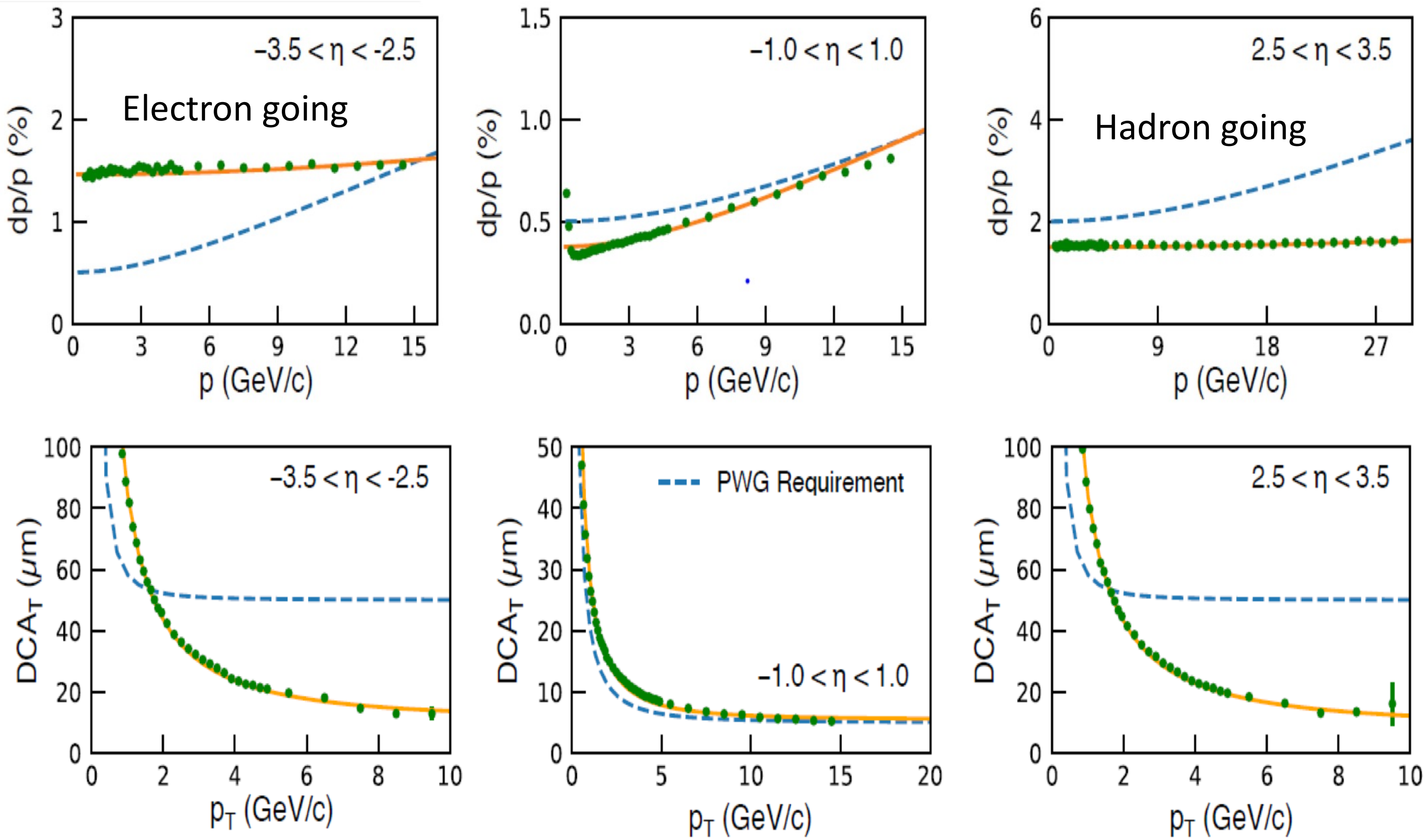
Tracking performance of the EIC project detector

- Tracking momentum resolution and transverse Distance of Closest Approach (DCA_{2D}) resolution of the current EPIC detector design meet the EIC yellow report detector requirements in most kinematic regions.

Updated EPIC vertex and tracking detector geometry in GEANT4 simulation



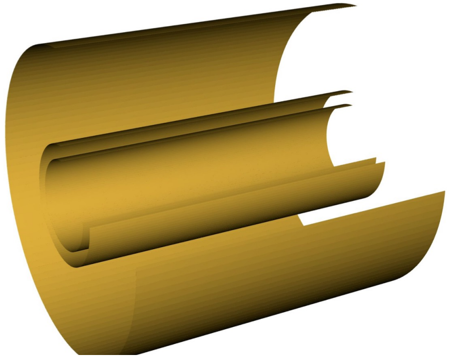
Barrel: 5 MAPS layers and 1 AC-LGAD layer.
Hadron endcap: 5 MAPS disks and 1 AC-LGAD plane.
Electron endcap: 5 MAPS disks.



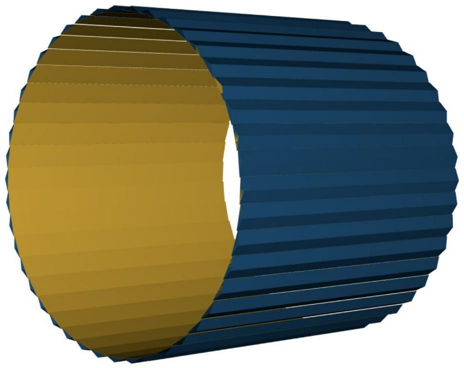
Ongoing EIC project detector R&D for the MAPS detector (I)

- The recommended 65 nm MAPS technology for the EIC silicon vertex and tracking detector is under design and early R&D. Utilizing the current ALICE ITS3 prototype sensor for the related silicon detector mechanical design.
- Other components such as sensor design for the sagitta layers and disks, readout architecture, detector mechanical structure, powering, cooling and integration are under developments.

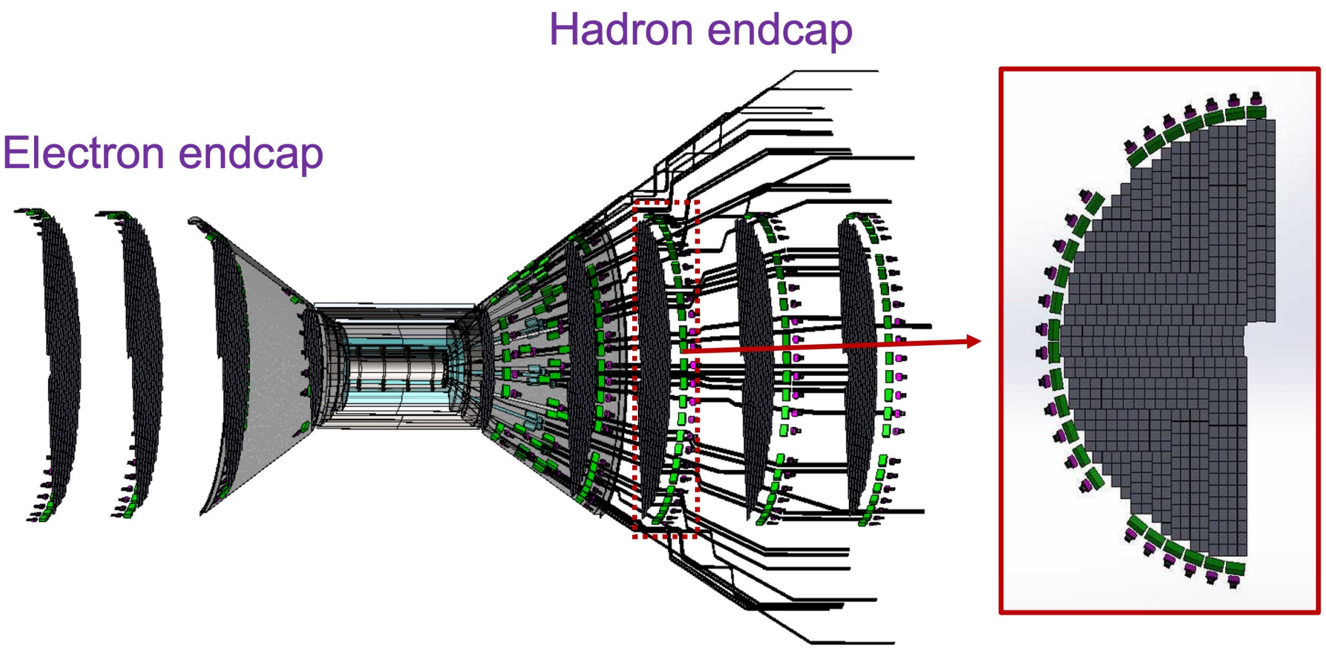
MAPS barrel vertex detector geometry



MAPS barrel sagitta detector geometry



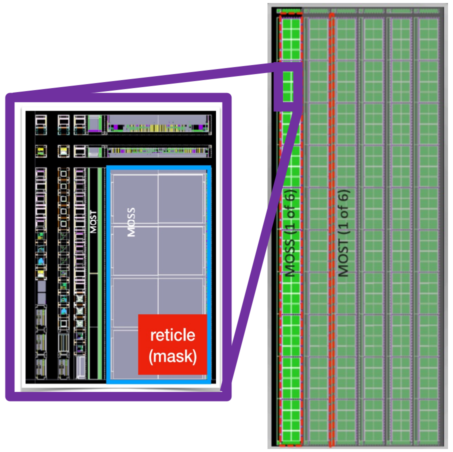
EIC MAPS tracker conceptual mechanical design



Ongoing EIC project detector R&D for the MAPS detector (II)

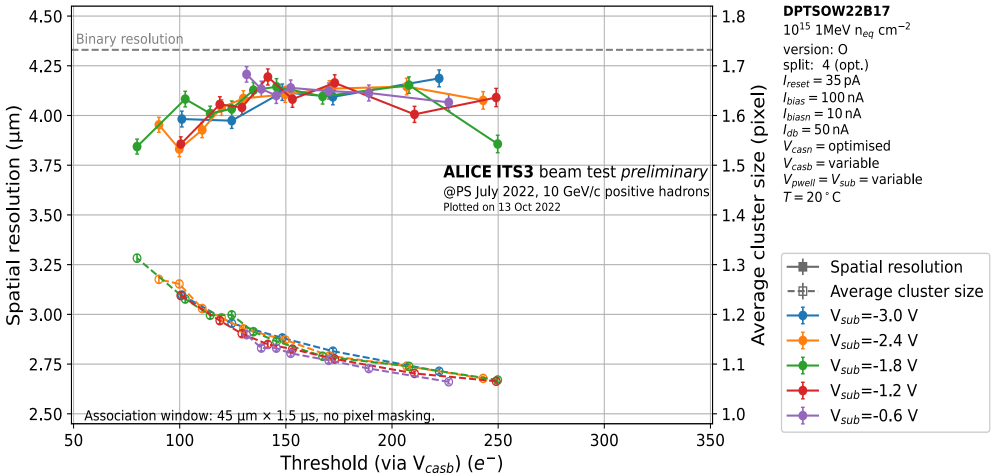
- Technology candidate for EPIC silicon vertex layers: ITS3-like MAPS bent sensor with
  - pixel size around $10\mu m$,
  - 0.05% X/X0 radiation length per layer,
  - Time resolution at O(100ns),
  - Fake-hit rate $<10^{-7}$,
  - radiation tolerance at around 10^{15} 1MeV n_{eq}/cm^2 at 20 ℃.
- Technology candidates for the middle sagitta layers and endcap disks: flat MAPS sensors with similar features of the ALICE ITS3 technology and the detector will consist of stitched sensor staves. This prototype sensor is under design.
- Parallel detector R&D with the ALICE ITS3 project.

ALICE ITS3 ER1 design



ALICE ITS3 vertex layer test assembly

Spatial resolution of ALICE DPTS in DESY beam tests with irradiation dose at 10^{15} 1MeV n_{eq} cm^{-2}

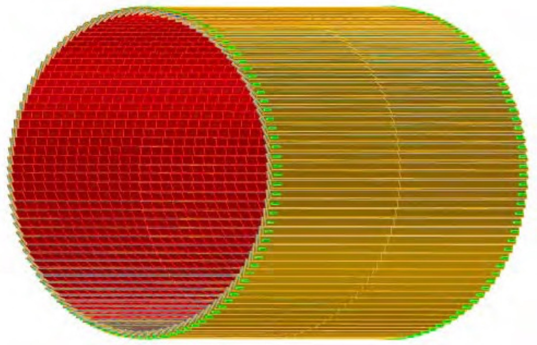


Ongoing EIC project detector R&D for the AC-LGAD detector

- Detailed detector geometry of the barrel and hadron endcap AC-LGAD tracker (ToF) has been developed.
- New prototype sensors have been produced at BNL and HPK.
- New AC-LGAD strip design prototype sensors have been characterized with beam tests at FNAL. Around 30 μm spatial resolution and better than 30 ps timing resolution per hit can be achieved.

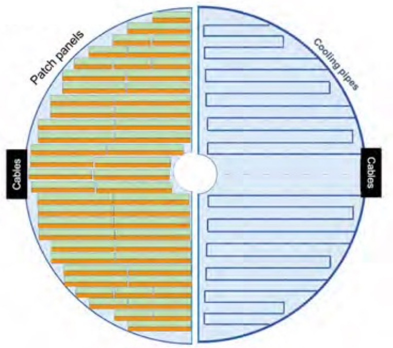
Barrel AC-LGAD tracker (ToF):

Pixel size 0.5mm by 1.0mm. 10.9 m^2 active area.

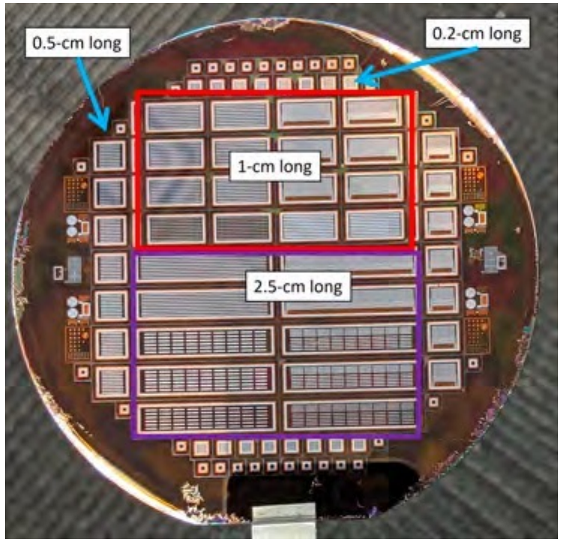


Hadron endcap AC-LGAD tracker (ToF):

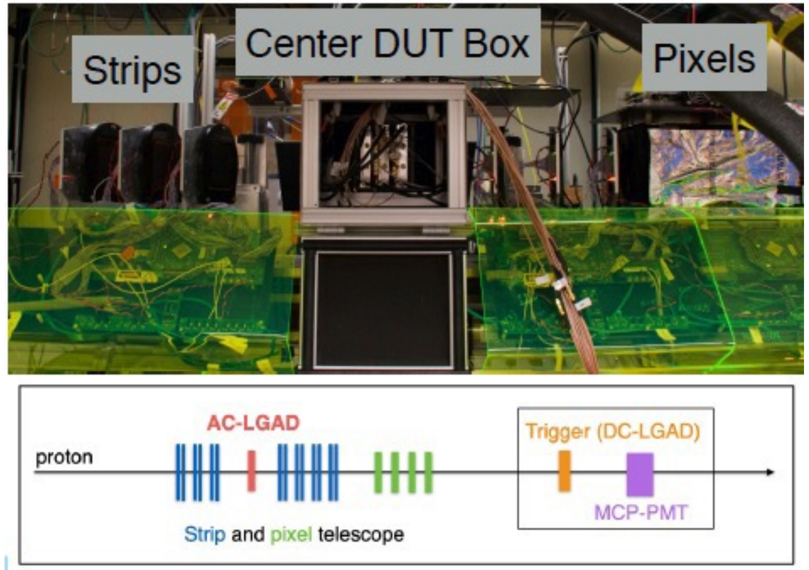
Pixel size 0.5mm by 0.5mm. 2.22 m^2 active area.



AC-LGAD prototype sensor



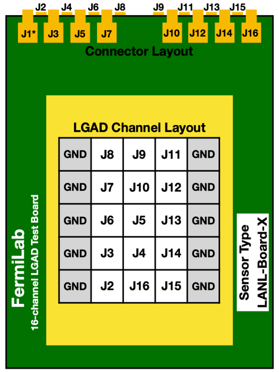
AC-LGAD FNAL beam test setup



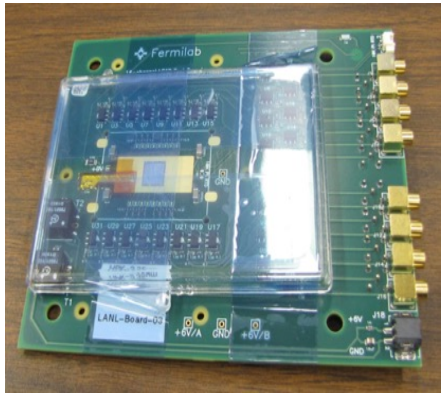
Other silicon technology candidates for the EIC silicon tracker

- Several advanced silicon prototype sensors are under characterization at LANL.

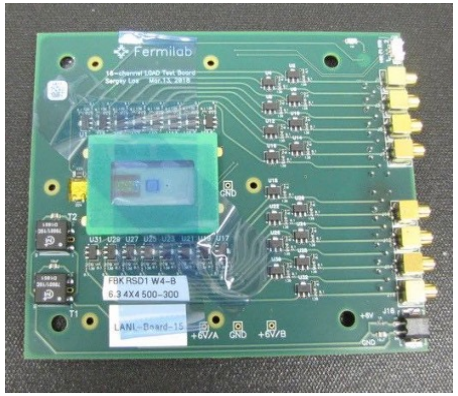
LGAD pixel map 3X5 Matrix



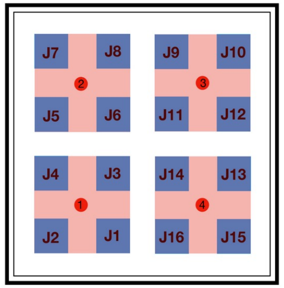
LGAD Carrier Board



AC-LGAD Carrier Board



AC-LGAD pixel map 4X4 Matrix



Supported by the LANL 20200022DR project

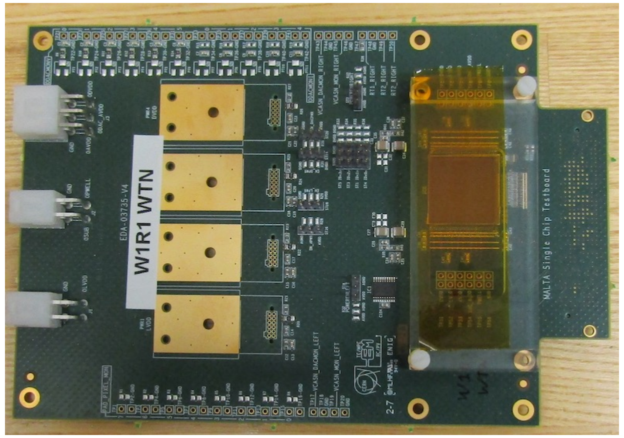
Low Gain Avalanche Detector (LGAD) and AC-Coupled LGAD (AC-LGAD)

Pixel size: 0.5 to 1.3 mm

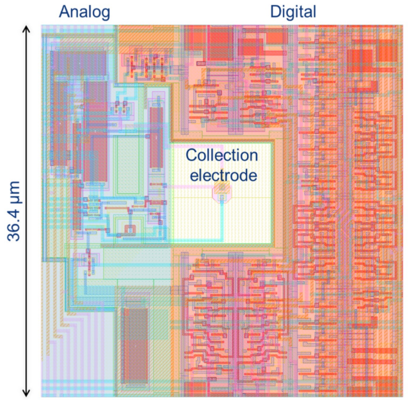
Spatial resolution: ~30 μm

Time resolution: <30 ps

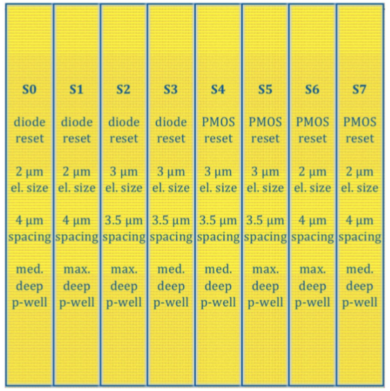
MALTA Carrier Board



MALTA Pixel diagram



MALTA sensor diagram 512X512 Matrix



Depleted Monolithic Active Pixel Sensor (e.g., MALTA)

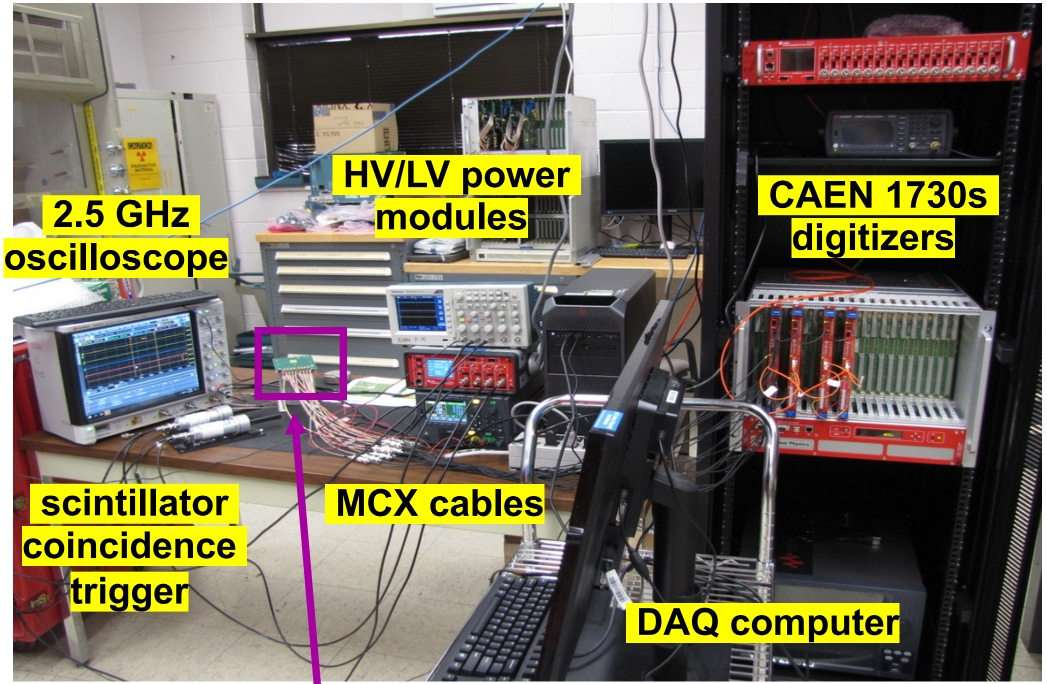
Pixel size: 36.4 μm

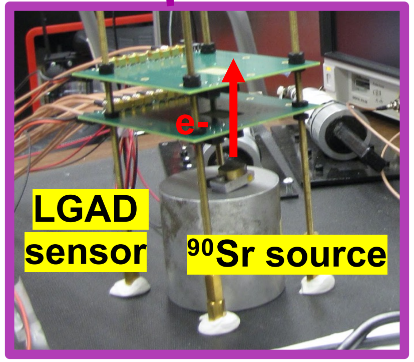
Spatial resolution: ~7 μm

Time resolution: ~2 ns

Advanced silicon technology R&D setup for EIC silicon tracker

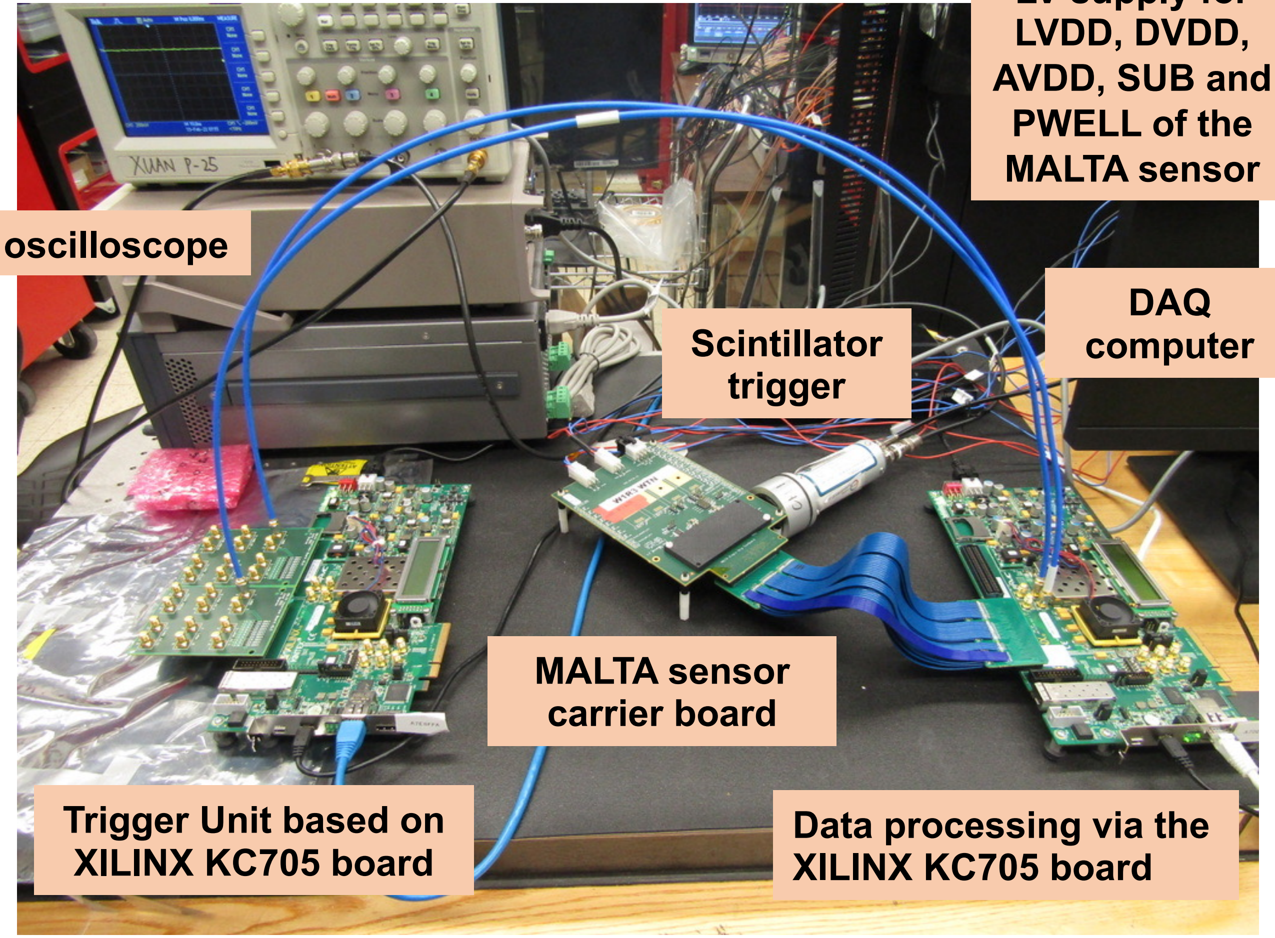
LGAD (AC-LGAD) sensor characterization with the ^{90}Sr source test





2-layer LGAD telescope

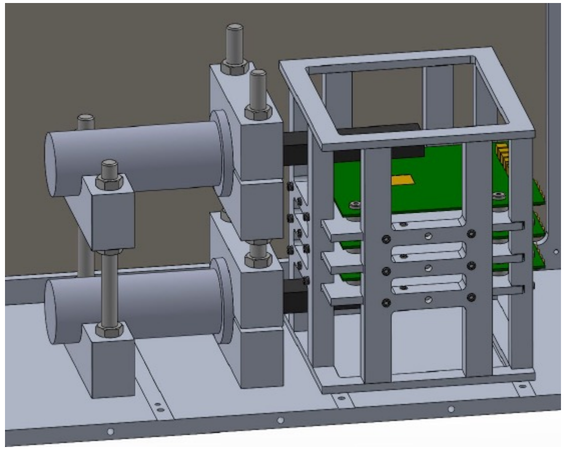
MALTA sensor characterization test bench



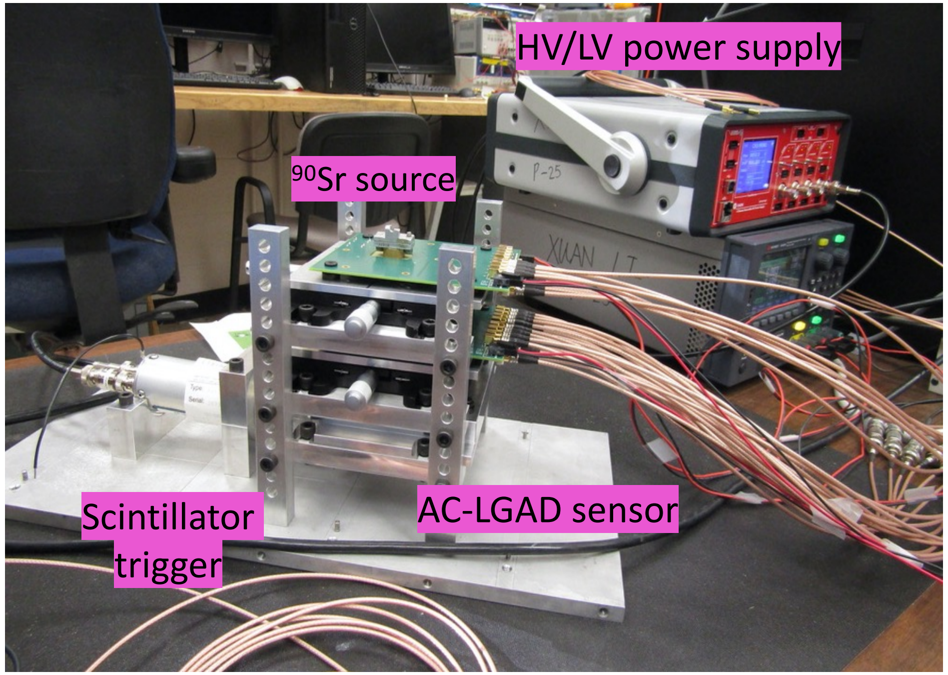
LGAD and AC-LGAD R&D test results

- Feasibility tests of a two-layer AC-LGAD telescope using a ^{90}Sr source.

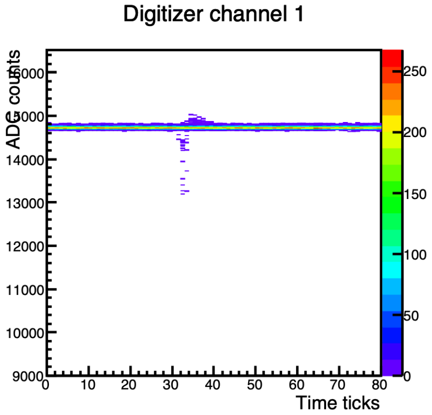
Mechanical design of 3-layer LGAD (AC-LGAD) telescope



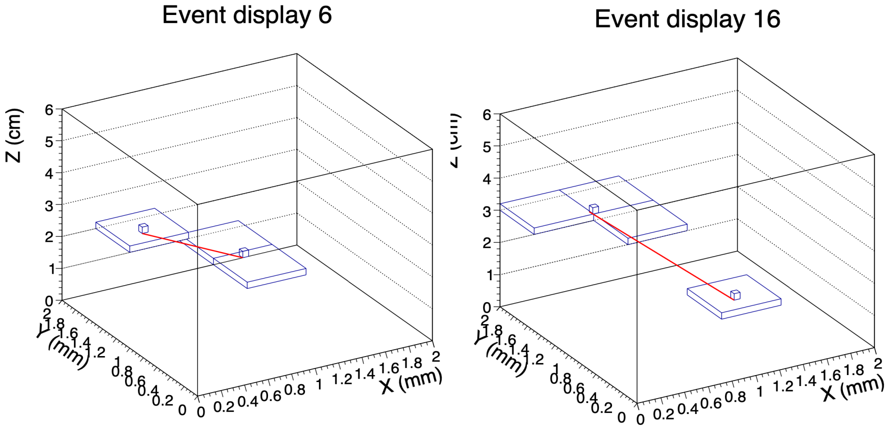
3-layer AC-LGAD telescope ^{90}Sr test setup with 2 sensors connected to the readout



Digitized pulse shape VS time tick (2ns) for individual pixel of AC-LGAD sensor from the ^{90}Sr source tests.



Event display of reconstructed electron tracks

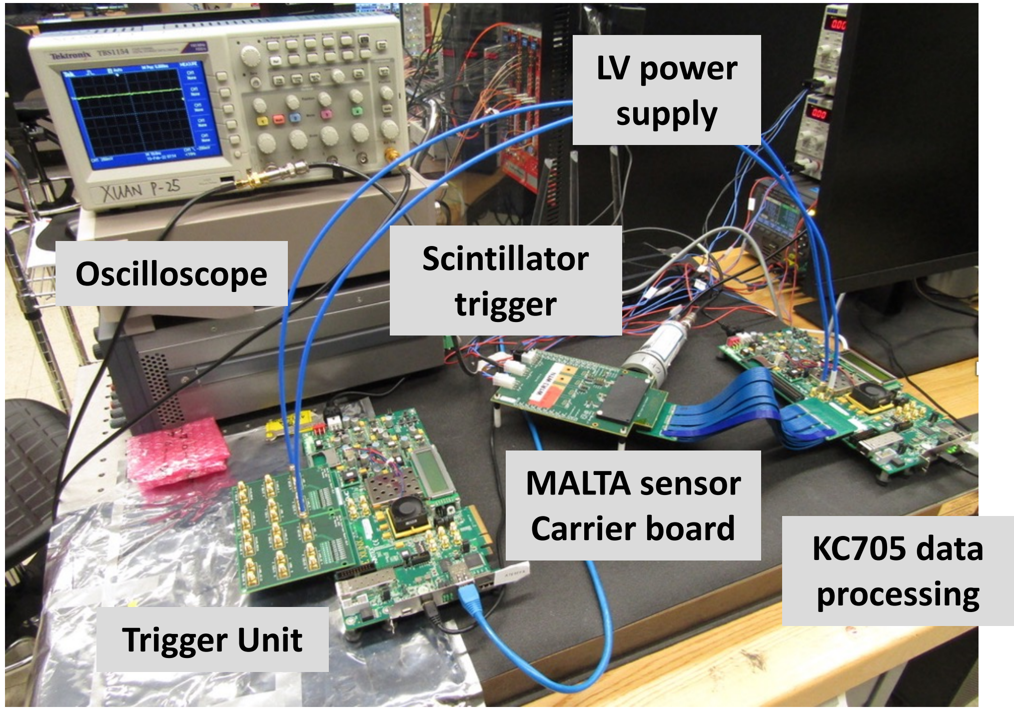


- Tracking performances such as efficiency, spatial and temporal resolutions are under study with the 3-layer telescope configuration.

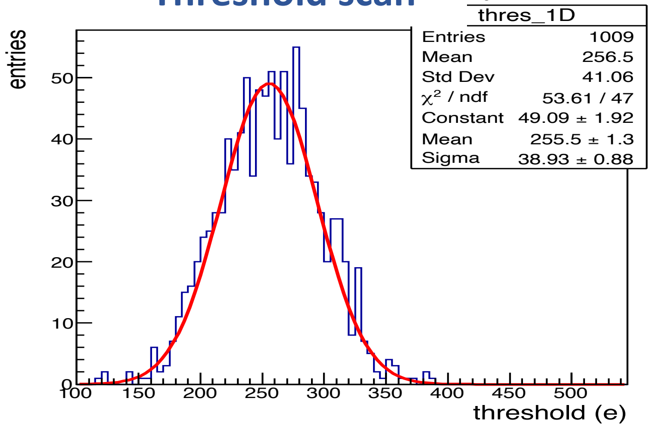
MALTA sensor R&D test results

- Threshold and noise scan has been performed.
- Successfully suppressing the noise hits with optimized DAC configuration and the hit occupancy has been studied with the ^{90}Sr source tests.

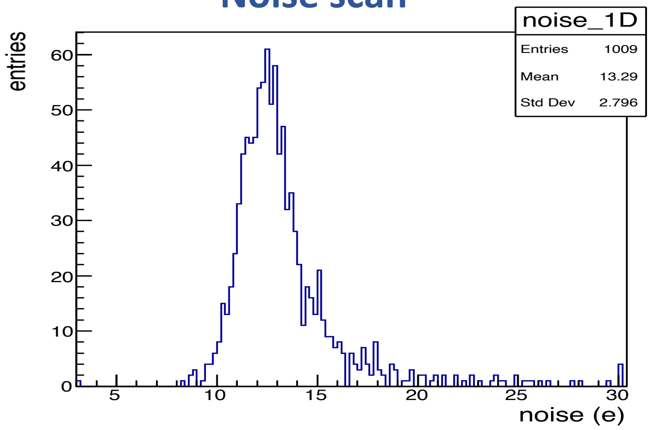
MALTA prototype sensor test setup



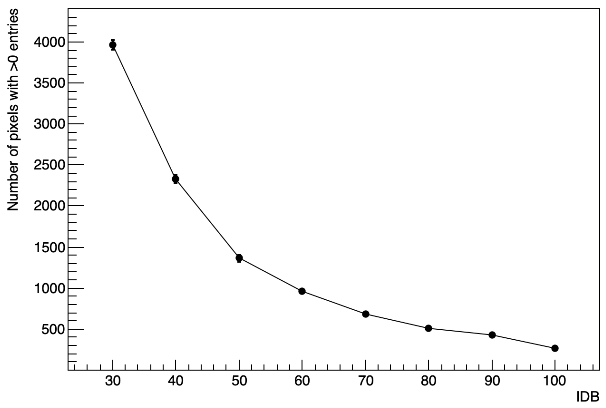
Threshold scan



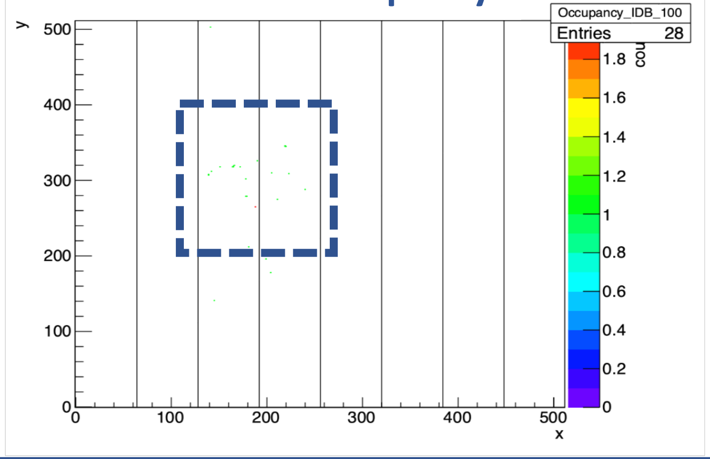
Noise scan



Noisy pixel rate VS IDB value



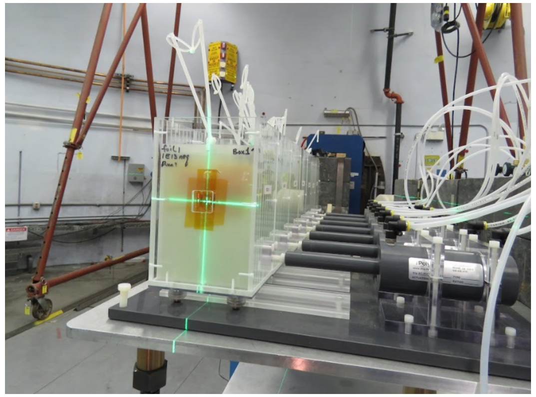
^{90}Sr source hit occupancy



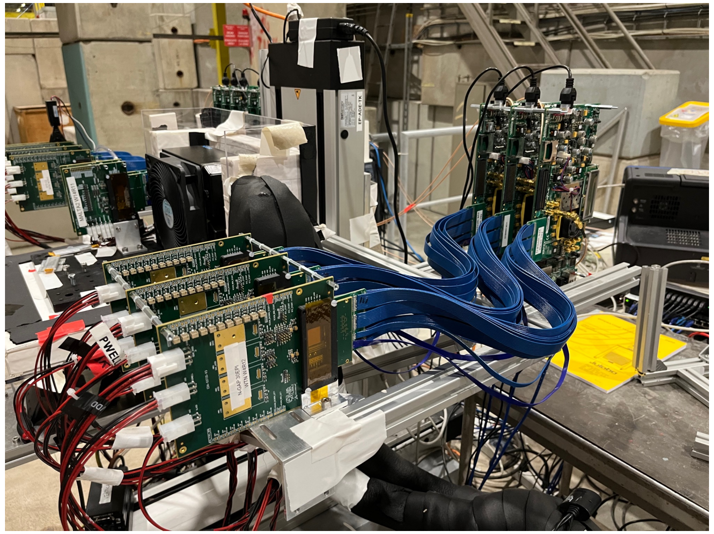
EIC silicon detector irradiation tests and path forward

- Irradiation tests performed with the LANL LANSCE facility 500 MeV proton beams to test the radiation hardness of LGAD and AC-LGAD prototype sensors with 10^{13}-10^{16} $n_{eq}cm^{-2}$ doses. Irradiative sensor characterization is underway.
- Work towards the EIC project detector technical design are carried out by the newly formed EPIC collaboration with scheduled CD2/3A approval in 2024.
- The EIC project and general detector programs have been formed. Dedicated EIC R&D for MAPS and AC-LGAD technologies have been supported by eRD104, eRD111, eRD113 and eRD112 project starting from 2022.

LGAD and AC-LGAD irradiation tests at LANSCE

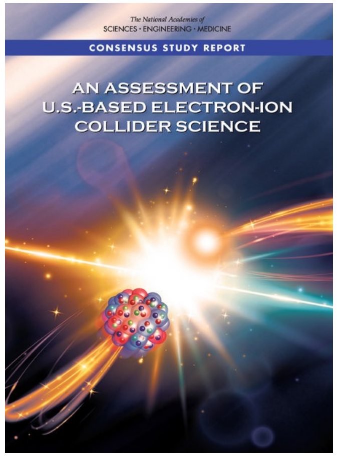


MALTA telescope beam tests at CERN SPS

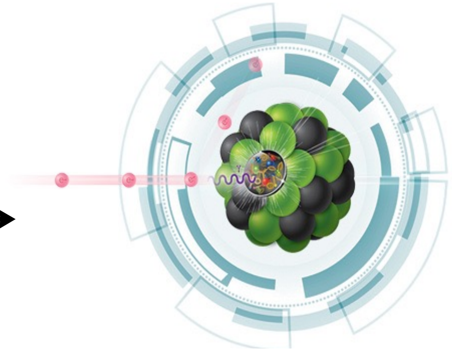


Summary and Outlook

- The optimized EIC project detector design led by the newly formed EPIC collaboration has achieved better tracking performance than the EIC yellow report requirements.
- Great progresses have been achieved for the EIC MAPS and AC-LGAD silicon detector R&D, design and associated performance validation.
- As we are moving towards the EIC CD2/3 approval, we look forward to work with more collaborators for the EIC detector/experiment realization.



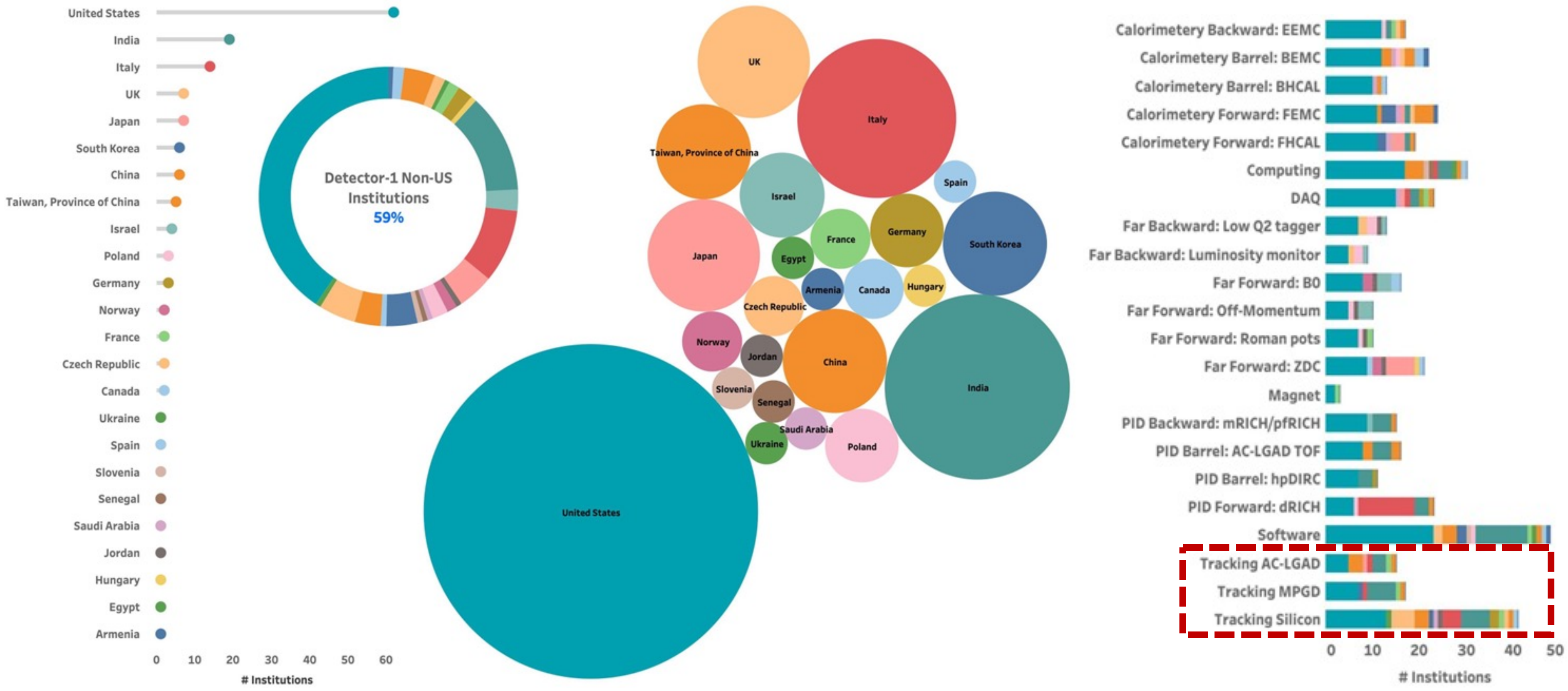
NAS review	EIC CD0	EIC CD1	EIC CD2	EIC CD3	EIC CD-4a	EIC CD-4
2018	2020	2021	2023	2024	2030	2033



Backup

EPIC collaboration and detector developments

- New EIC collaboration: EPIC has been formed in July 2022 to work on the project detector design optimization.
- The EPIC collaboration consists of 500+ participants from 160+ institutions in nearly 30 countries.



Current EPIC vertex/tracking detector geometry

- The EPIC MAPS vertex and tracking detector geometry:

Barrel index	R (cm)	z_{min} (cm)	z_{max} (cm)	Material budget (X/X0)
1	3.6	-13.5	13.5	0.05%
2	4.8	-13.5	13.5	0.05%
3	12.0	-13.5	13.5	0.05%
4	27.0	-27	27	0.25%
5	42.0	-42	42	0.55%

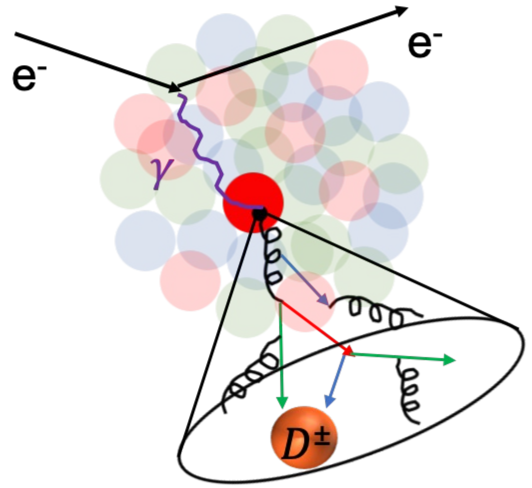
H-endcap index	z (cm)	r_{in} (mm)	r_{out} (mm)	Material budget (X/X0)
1	25	36.76	230	0.24%
2	45	36.76	430	0.24%
3	70	38.42	430	0.24%
4	100	54.43	430	0.24%
5	135	70.14	430	0.24%

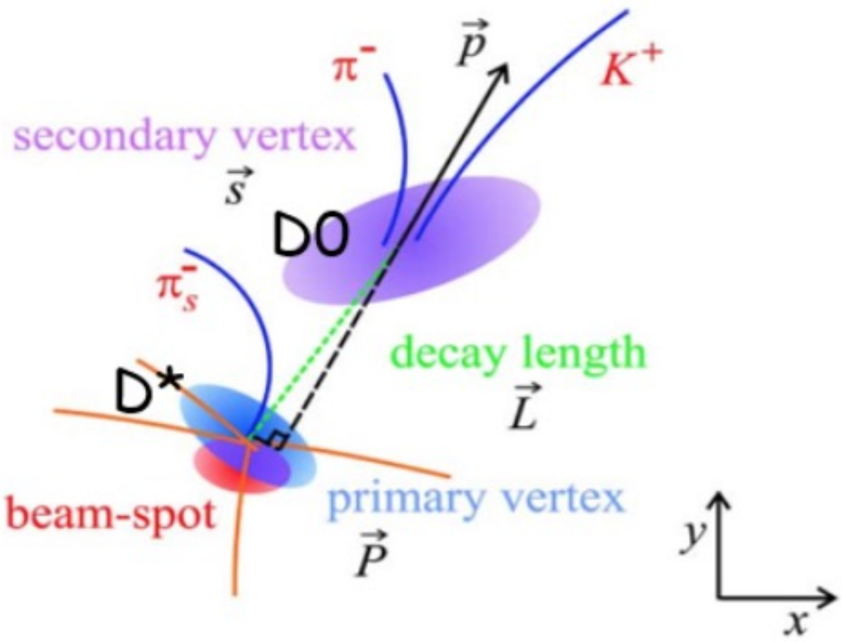
e-endcap index	z (cm)	r_{in} (mm)	r_{out} (mm)	Material budget (X/X0)
1	-25	36.76	230	0.24%
2	-45	36.76	430	0.24%
3	-65	36.76	430	0.24%
4	-90	40.06	430	0.24%
5	-115	46.35	430	0.24%

High precision vertex/tracking detector is required to measure HF products

- Heavy flavor hadrons usually have a short lifetime compared to light flavor hadrons. They can be identified by detectors using their unique lifetime and masses.

$e^- + \mathrm{Au} \rightarrow e^- + jet(D^{\pm}) + X$



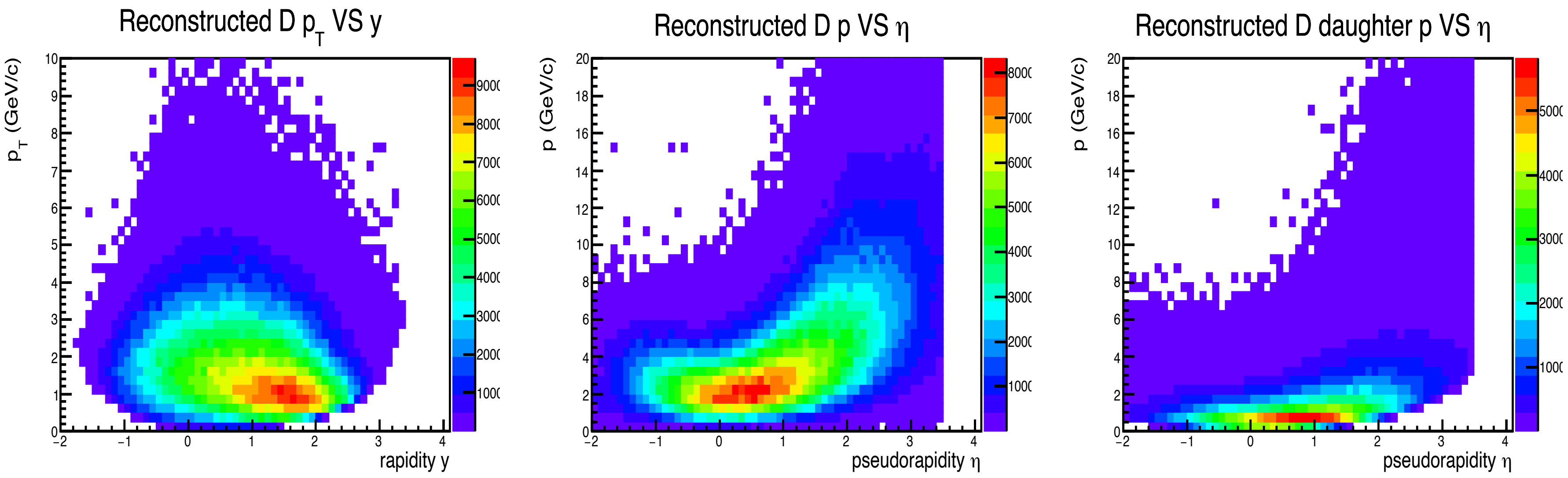


Particle	Mass (GeV/c²)	Average decay length
$D^{\pm}$	1.869	312 micron
D^0	1.864	123 micron
$B^{\pm}$	5.279	491 micron
B^0	5.280	456 micron

- Heavy flavor physics-driven detector performance requirements:
  - Fine spatial resolution (<100 μm) for displaced vertex reconstruction.
  - Fast timing resolution to suppress backgrounds from neighboring collisions.
  - Low material budgets to maintain fine hit resolution.

EIC detector requirements for a silicon vertex/tracking detector

- To meet the heavy flavor physics measurements, a silicon vertex/tracking detector with low material budgets and fine spatial resolution is needed.
- Particles produced in the asymmetric electron+proton and electron+nucleus collisions have a higher production rate in the forward pseudorapidity. The EIC detector is required to have large granularity especially in the forward region.

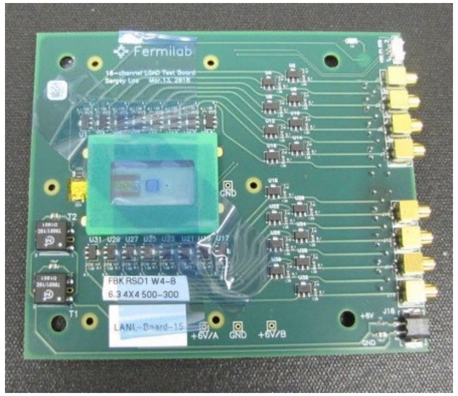


- Fast timing (1-10ns readout) capability allows the separation of different collisions and suppress the beam backgrounds.

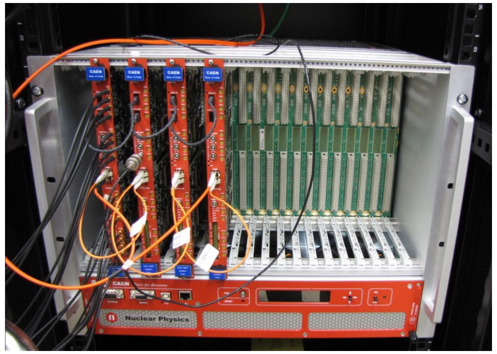
AC-LGAD Sensor Data Processing Flow

- Data flow chart:

AC-LGAD sensor

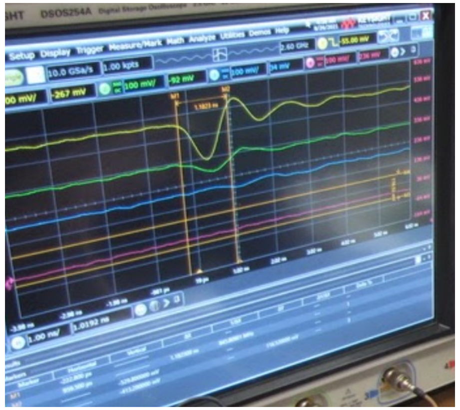


CAEN 1730s digitizer

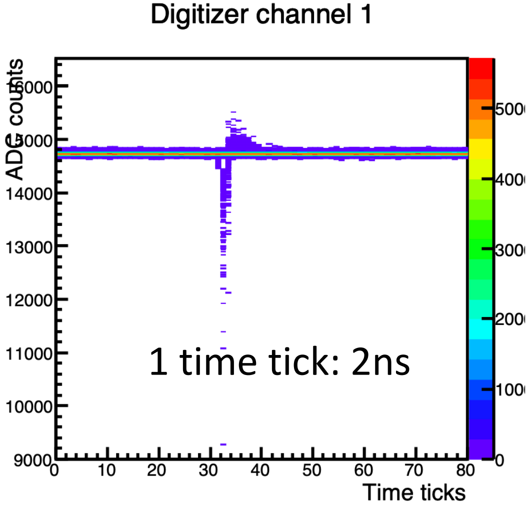


DAQ computer

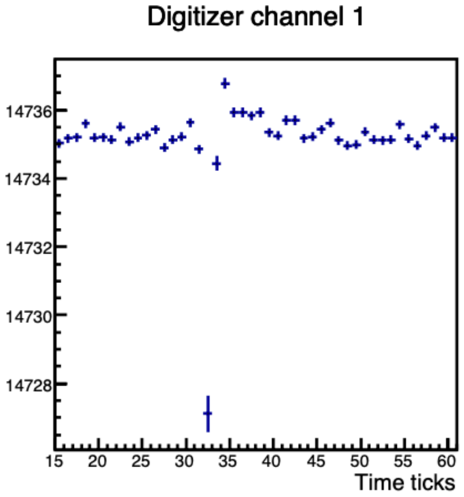
Raw analog signal



Accumulated pulse distribution

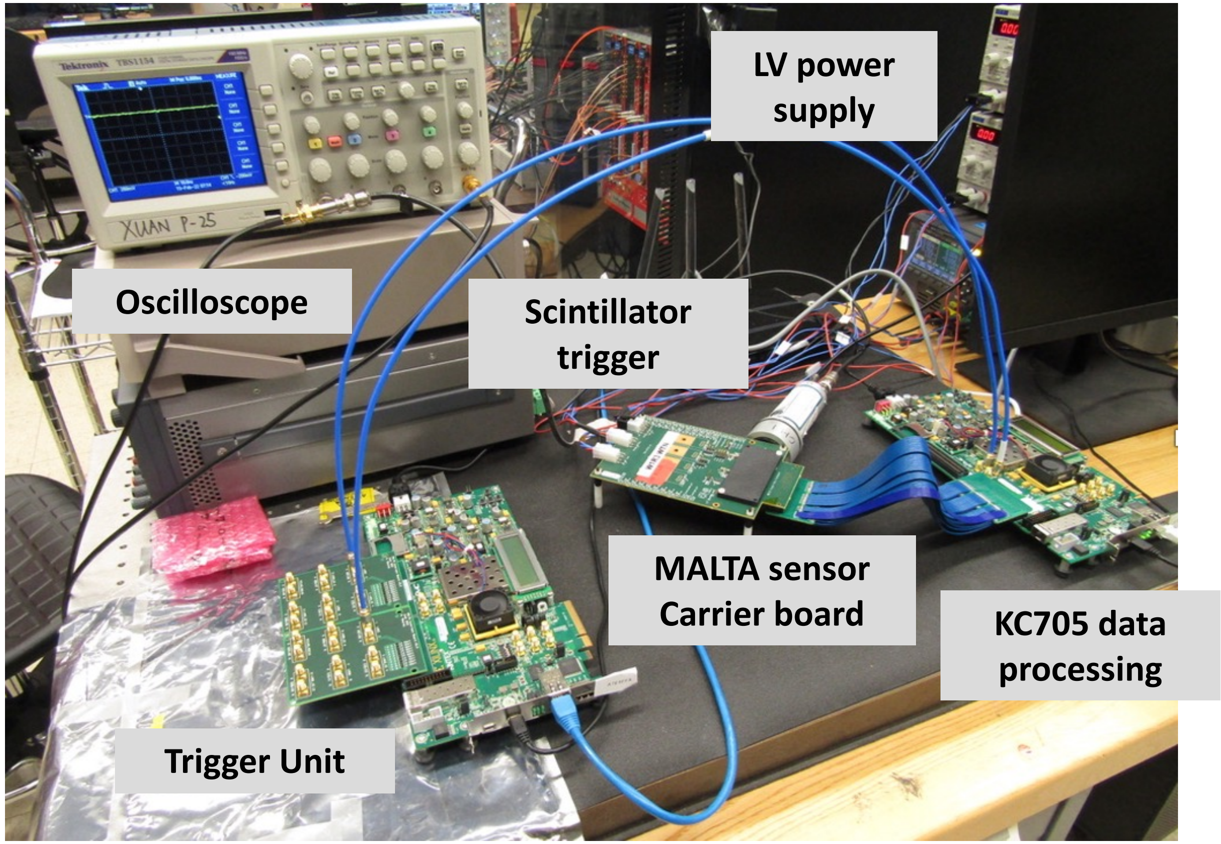


Extracted average pulse shape and charge



MALTA R&D test results

MALTA prototype sensor test setup



MALTA threshold scan in different regions