LGAD Detectors at Electron Ion Collider

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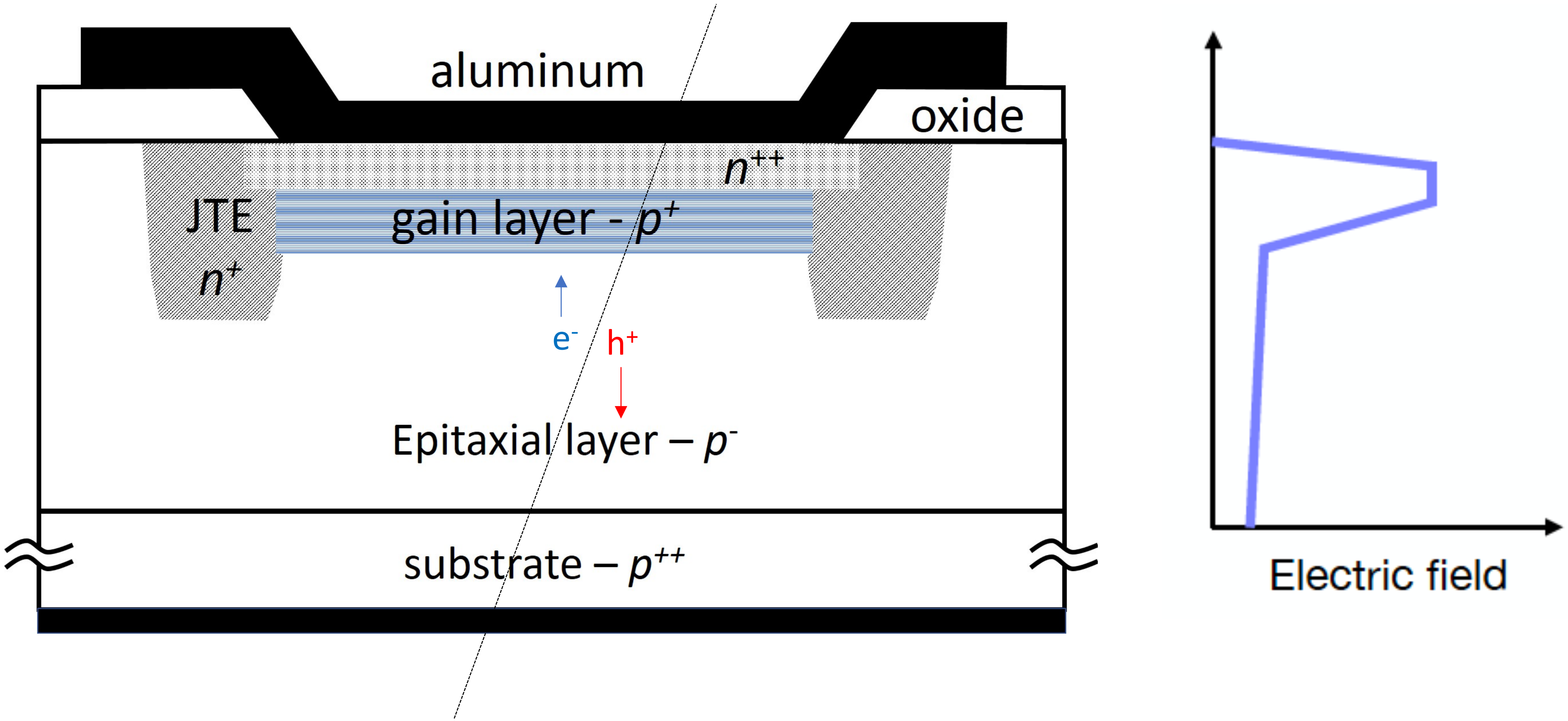
Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY Jefferson Lab U.S. DEPARTMENT OF ENERGY Office of Science

Low Gain Avalanche Diode (LGAD)



Ultra-fast silicon detectors with a highly doped p+ gain layer
Moderate internal gain : 10-30

LGAD for CMS Phase-2 Upgrade

Trigger/HLT/DAQ &

- Track information in L1-Trigger
- L1-Trigger: 12.5 ms latency – output 750 kHz
- HLT output 7.5 kHz

Barrel ECAL/HCAL

- Replace FE/BE electronics
- Lower ECAL operating temp. (8 °C)

Muon Systems

- Replace DT & CSC FE/BE Electronics
- Complete RPC coverage in region $1.5<h<2.4$
- Muon tagging $2.4<h<3$

New Endcap Calorimeters

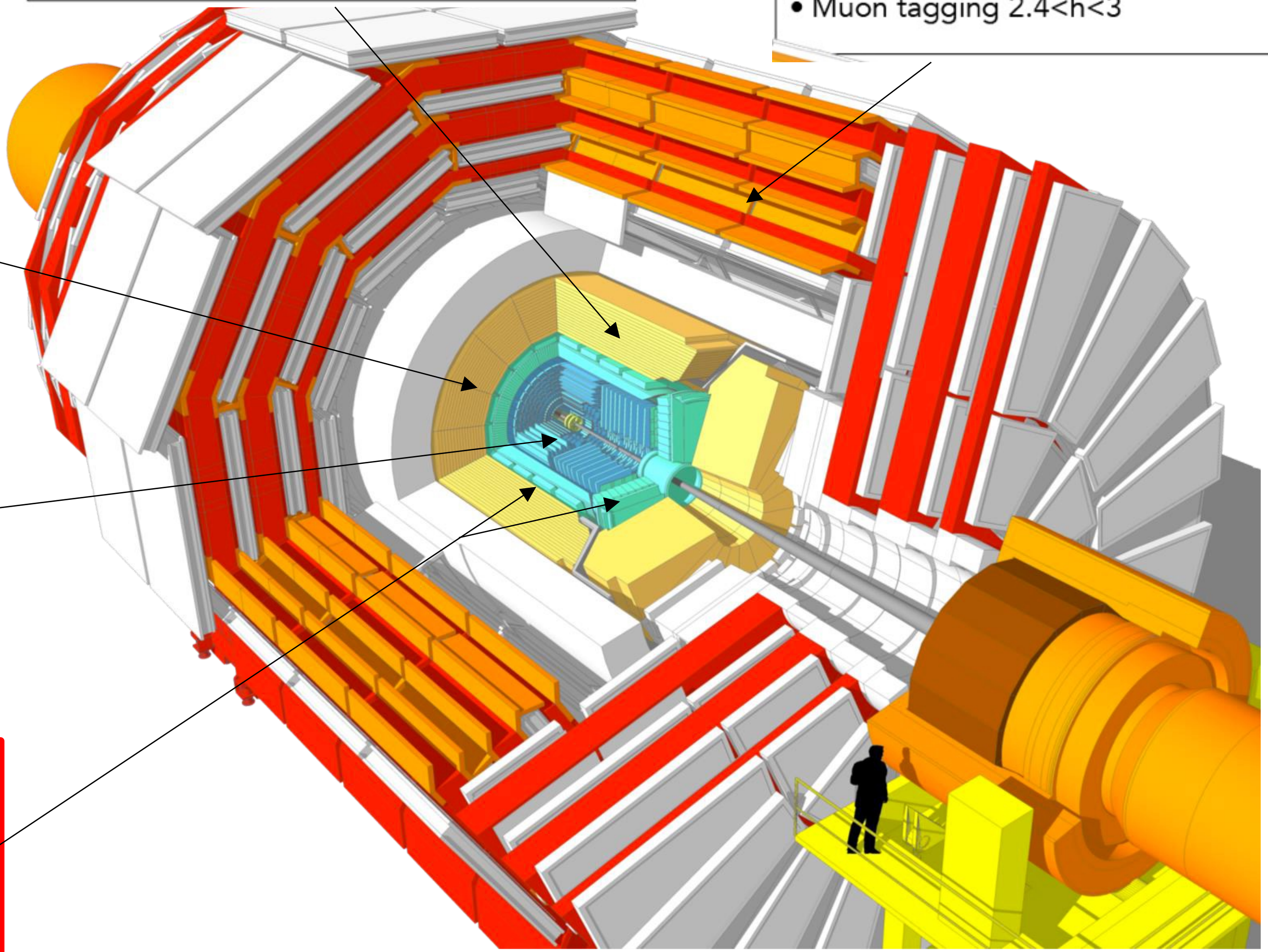
- Rad. tolerant – high granularity
- 3D capable

New Tracker

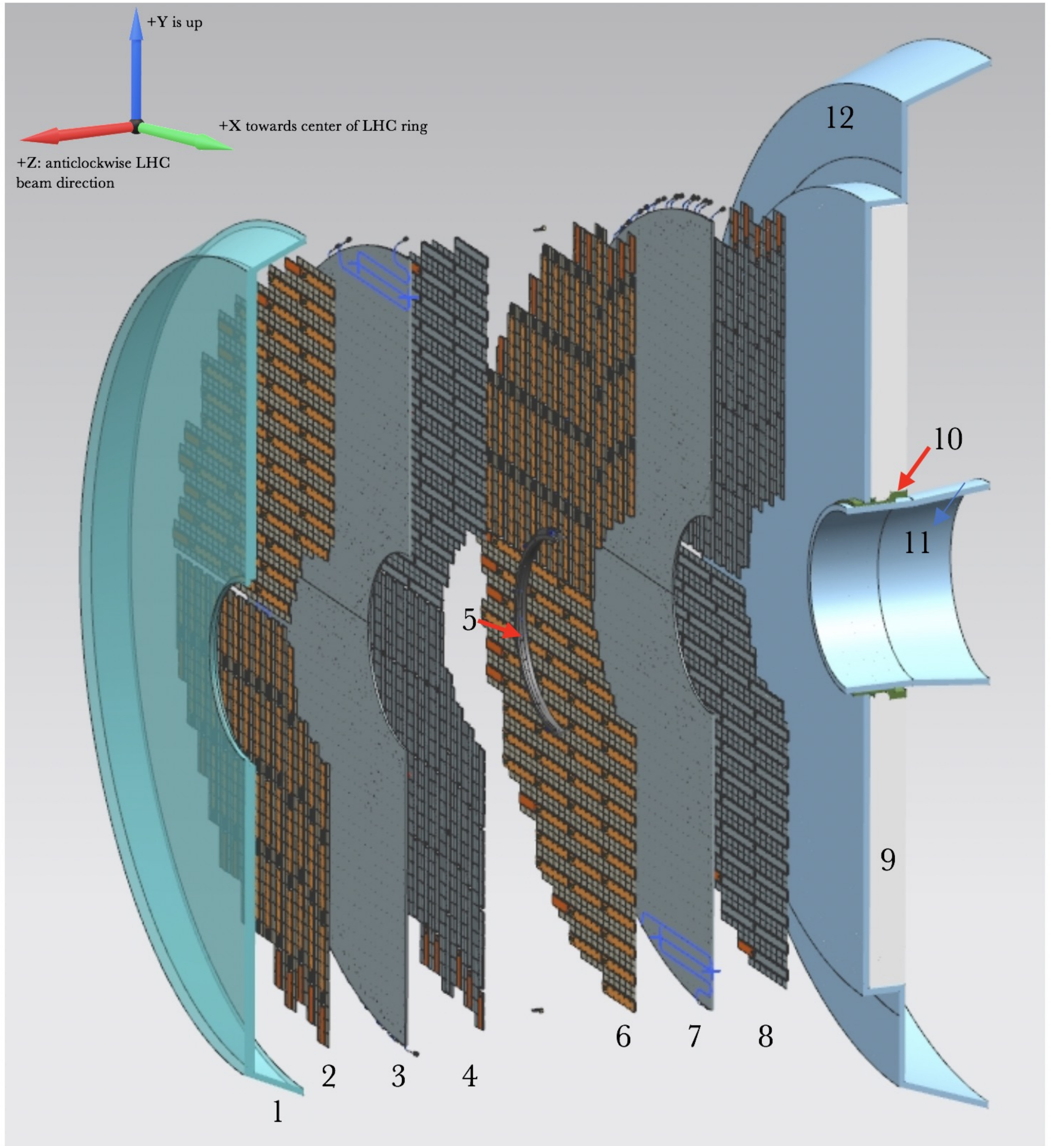
- Rad. tolerant – high granularity – significant less material
- 40 MHz selective readout (pT>2 GeV) in Outer Tracker for L1 -Trigger
- Extended coverage to $h=4$

MIP Precision Timing Detector

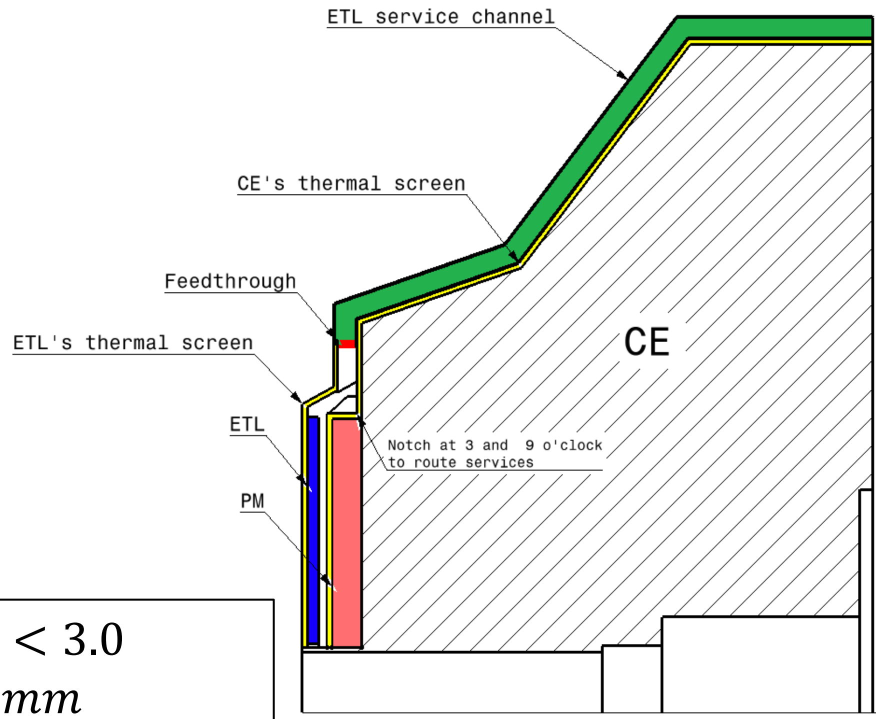
- Barrel: Crystal +SiPM
- Endcap: Low Gain Avalanche Diodes



CMS Endcap Timing Layer (ETL)



1: ETL Thermal Screen
2: Disk 1, Face 1
3: Disk 1 Support Plate
4: Disk 1, Face 2
5: ETL Mounting Bracket
6: Disk 2, Face 1
7: Disk 2 Support Plate
8: Disk 2, Face 2
9: HGCal Neutron Moderator
10: ETL Support Cone
11: Support cone insulation
12: HGCal Thermal Screen

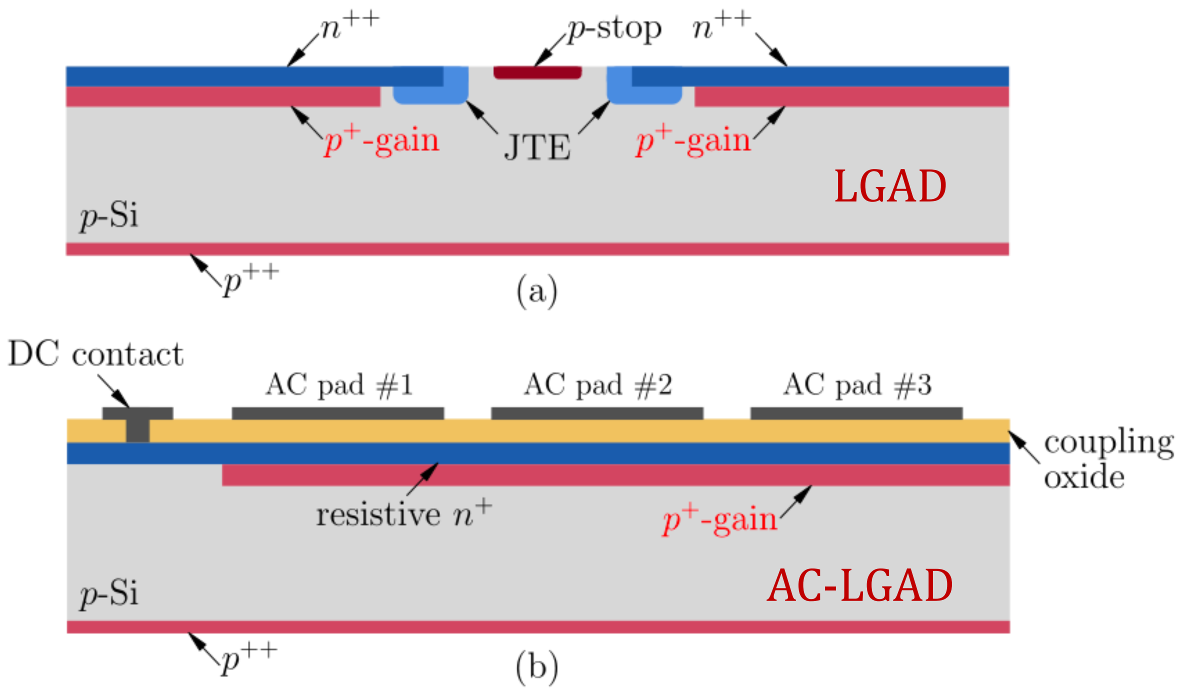


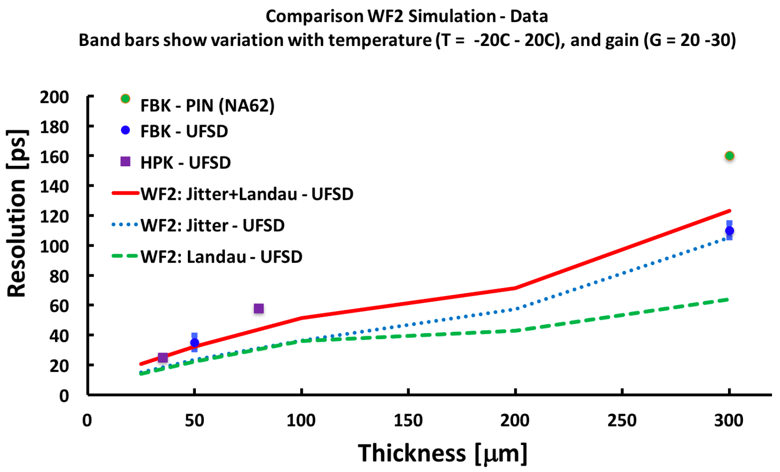
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: $315 < R < 1200\ mm$
- Position in Z: $\pm 3.0\ m$ (45 mm thick)
- Surface ~$15.8\ m^2$; ~8.6M channels
- Weight 282 kg/side; Power: 26kW/side

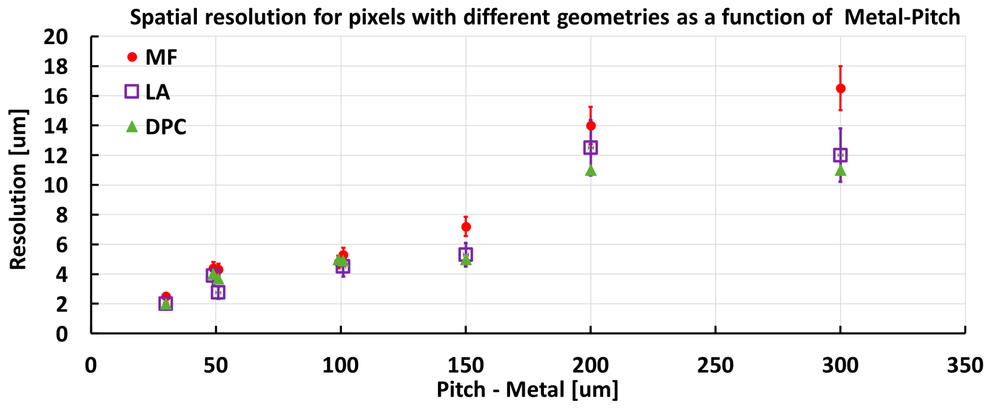
- **Two disks on each side allowing up to 2 time measurements per track**
  - **50 ps per hit → 30 ps per track**
- **Stageable, serviceable, maintainable**

AC-Coupled LGAD

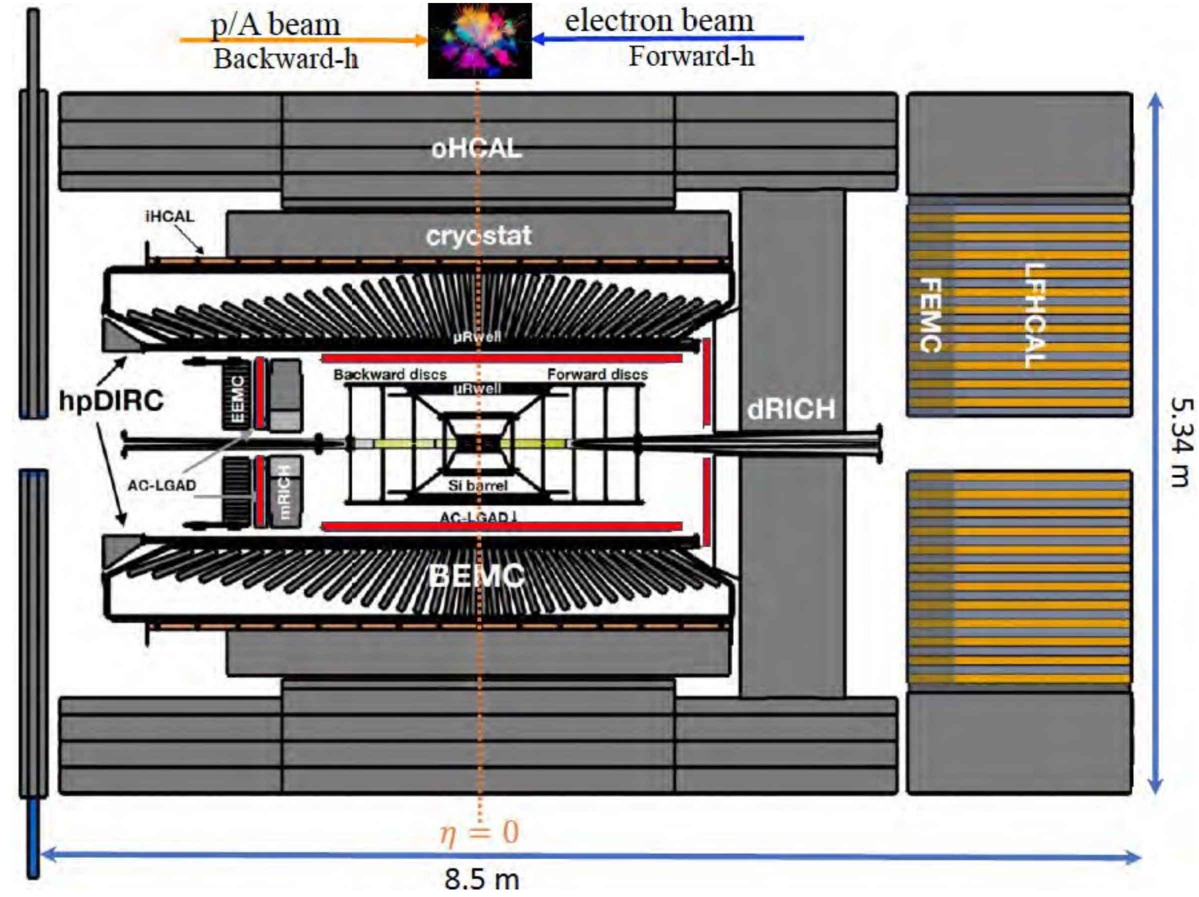
- Due to the presence of JTE and the gap between LGAD cells, 100% fill factor can not be achieved in LGAD. The position resolution is limited to be $\sqrt{1/12}$ of cell size.
- AC-LGAD: replacement of the segmented n^{++} layer by a less doped but continuous n^{+} layer. Electrical signals in the n^{+} layer are AC-coupled to neighboring metal electrodes that are separated from the n^{+} layer by a thin insulator layer.
- AC-LGAD can not only provide a timing resolution of a few tens of picoseconds, but also 100% fill factor and a spatial resolution that are orders of magnitude smaller than the cell size.

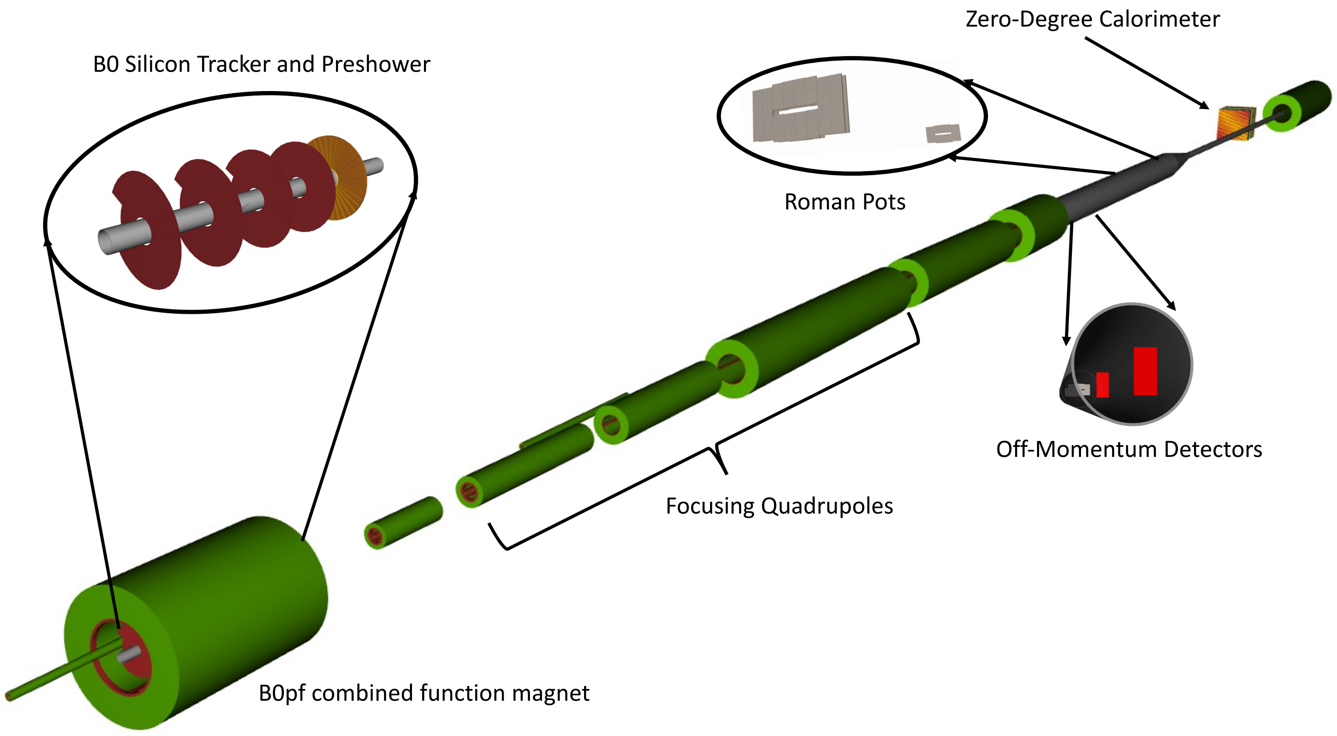






AC-LGAD Detectors for ePIC



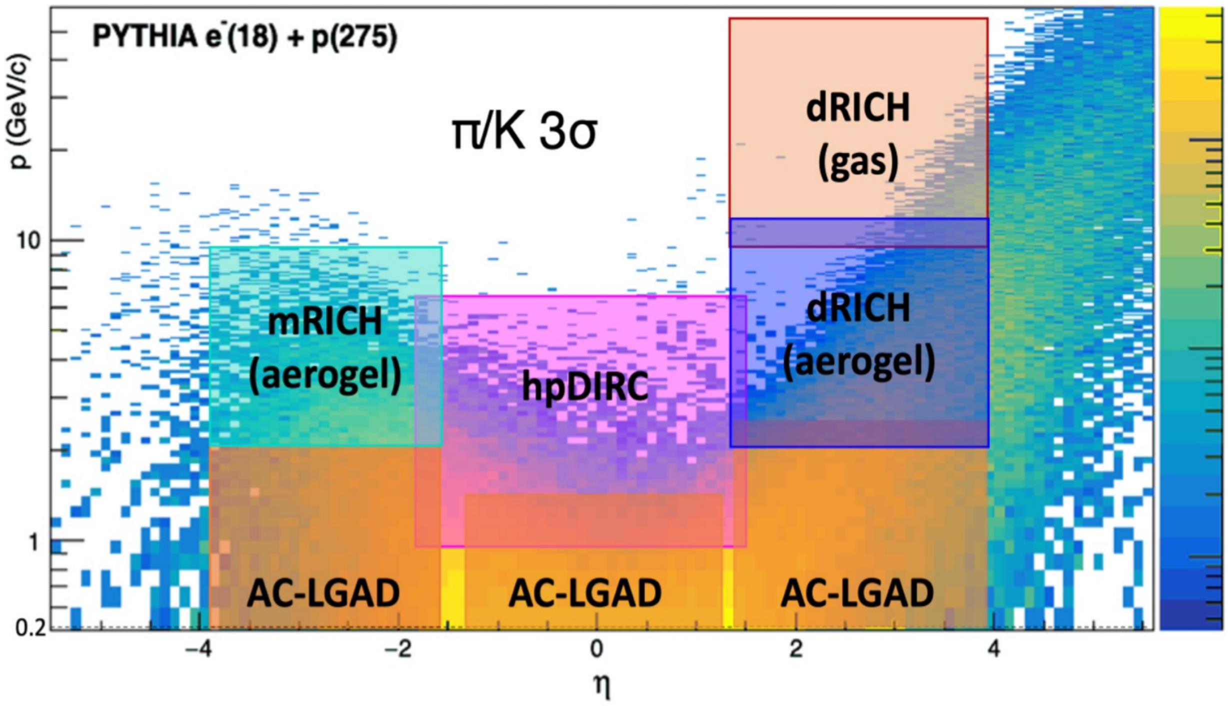


Detector	Angular accept.	p_T coverage
~~Backward ToF~~	~~$-3.7 < \eta < -1.74$~~	~~$0.15 < p < 2.0$ GeV~~
Barrel ToF	$-1.4 < \eta < 1.4$	$0.15 < p_T < 1.5$ GeV
Forward ToF	$1.5 < \eta < 3.5$	$0.15 < p < 2.0$ GeV

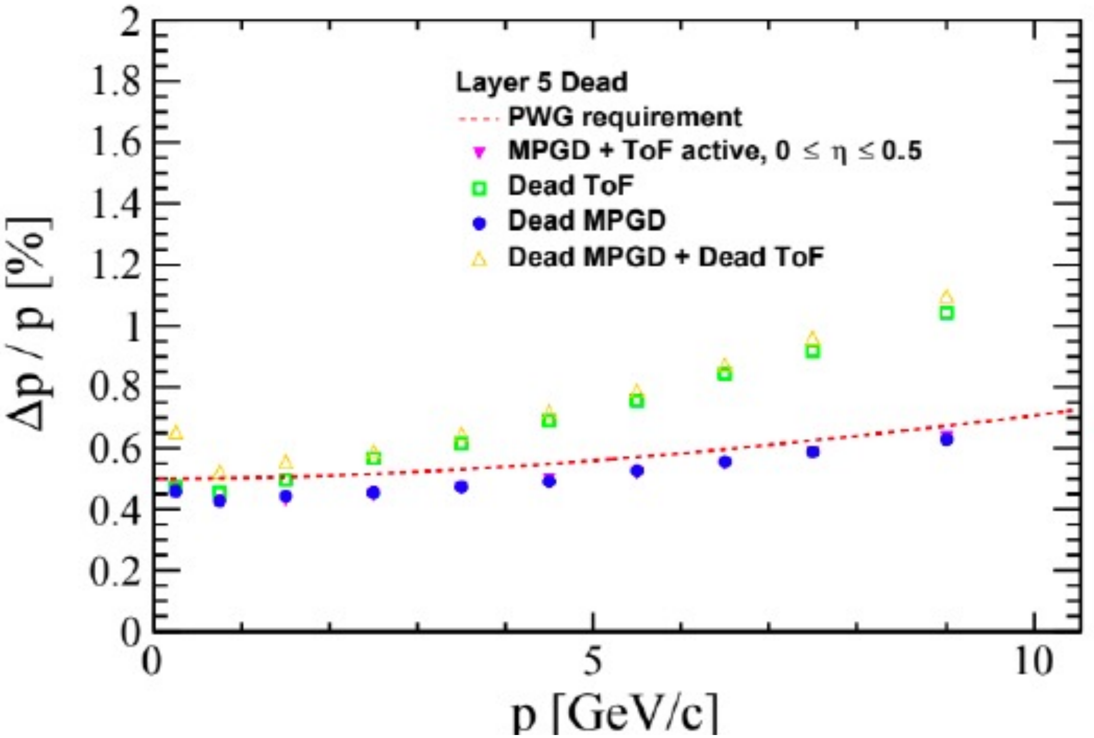
Detector	Angular accept.	p_T coverage
B0 Detector	$4.6 < \eta < 5.9$	Higher p_T
Roman Pots	$\eta > 6$	Low p_T cut-off from beam optics
Off-Momentum	$\eta > 6$	Low-rigidity from nucl. breakups

AC-LGAD for Central Detector: TOF PID + Tracking

- **Time-of-flight for e/π/K/p identification** at low-to-intermediate momentum range
- Provide a **high spatial resolution point for tracking**



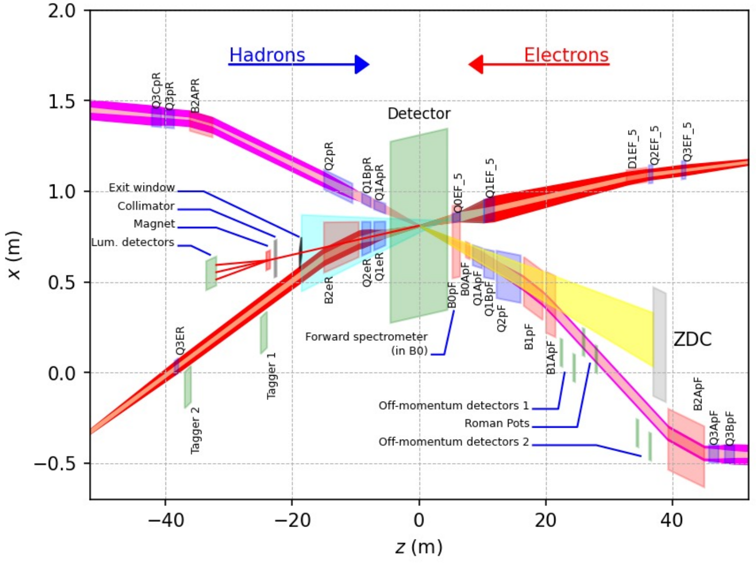
Missing hit in outer Si layer

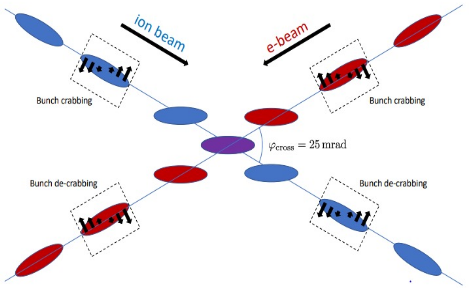


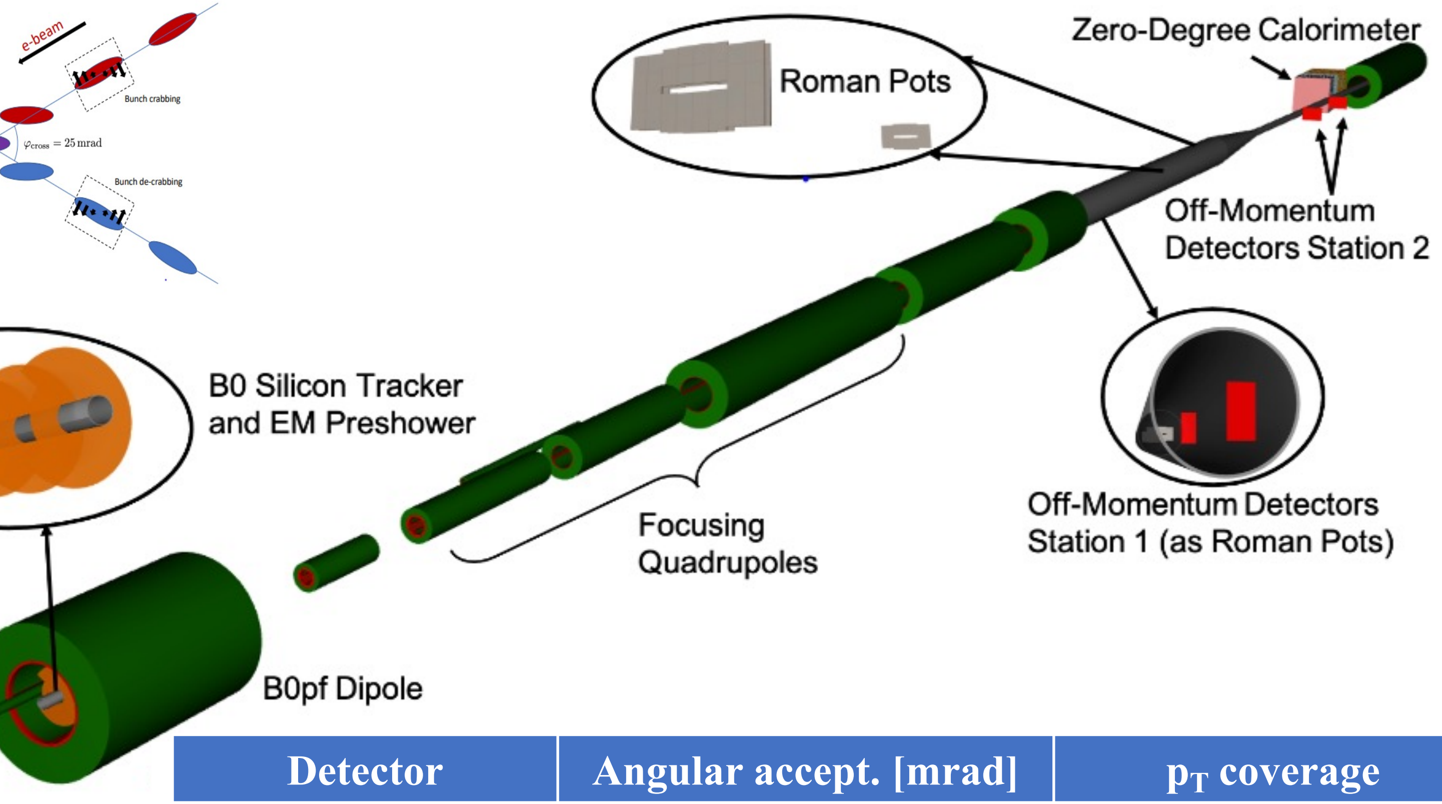
Need more than one technology to cover the entire momentum ranges at different rapidity

Rapidity	π/K/p and π0/γ	e/h	Min pT (E)
-3.5 – -1.0	7 GeV/c	18 GeV/c	100 MeV/c
-1.0 – 1.0	8-10 GeV/c	8 GeV/c	100 MeV/c
1.0 – 3.5	50 GeV/c	20 GeV/c	100 MeV/c

AC-LGADs at Far-Forward: Timing + Tracking

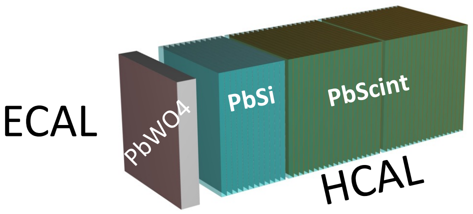






Technologies defined

- Silicon: AC-LGAD & MAPS
- ZDC:
  - ECAL (PbWO4)
  - HCAL (PbSi + PbScint)

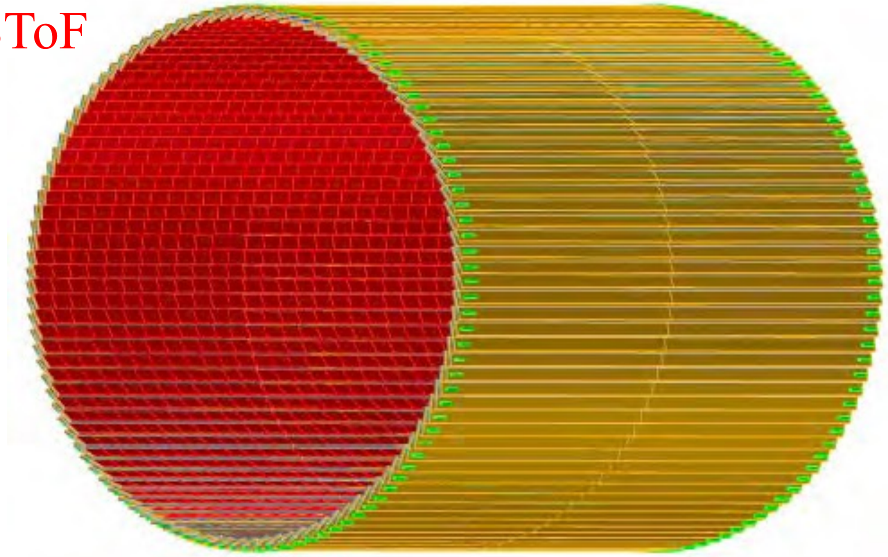


Detector	Angular accept. [mrad]	p_T coverage
ZDC @ ~30m	θ<5.5 ($\eta > 6$)	p_T<1.3 GeV
Roman Pots	0*<θ<5.0 ($\eta > 6$)	*Low p_T(t) cutoff (beam optics)
Off-Momentum Detectors	0.< θ < 5.0 ($\eta > 6$)	Low-rigidity particles from nuclear breakups
B0 forward spectrometer	$5.5 < \theta < 20.0$ ($4.6 < \eta < 5.9$)	High p_T(t)

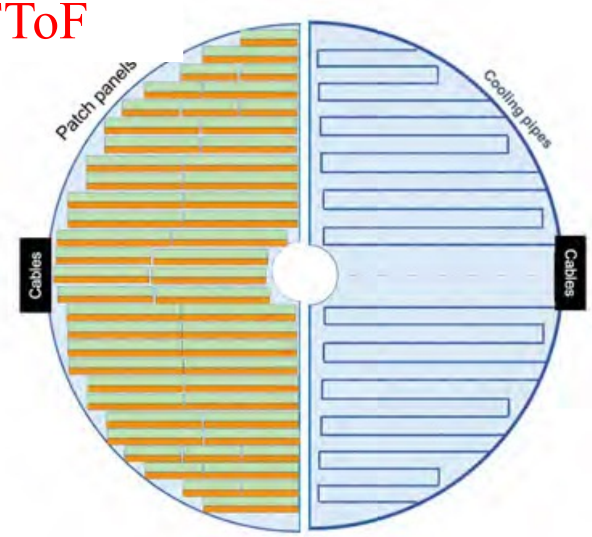
Specifications of ePIC AC-LGAD Detectors

- High-level strawman layout design and requirements for sub-systems using AC LGADs.

BToF



FToF



Roman Pots

	Area (m^2)	Channel size (mm^2)	# of Channels	Timing Resolution	Spatial resolution	Material budget
Barrel TOF	10.9	0.5*10	2.4M	30 ps	30 μm in $r \cdot \varphi$	0.01 X0
Forward TOF	2.22	0.5*0.5	8.8M	25 ps	30 μm in x and y	0.08 X0
B0 tracker	0.07	0.5*0.5	0.28M	30 ps	20 μm in x and y	0.05 X0
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.

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.

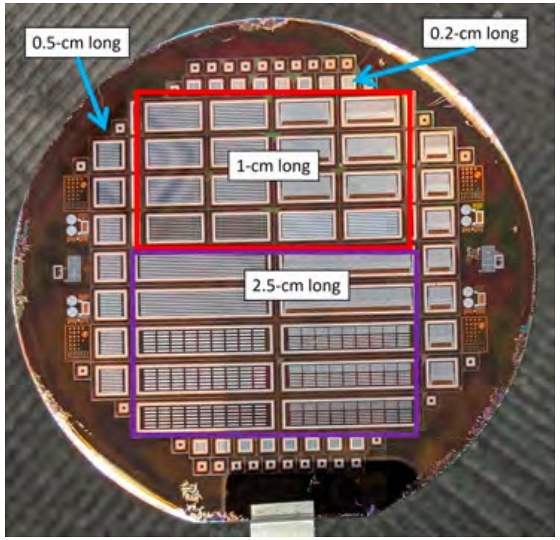
Questions to be Addressed

- **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 to verify sensor quality and production cost/yield
- **Frontend readout ASIC:**
  - Goal: low jitter (15-20ps) and low power (~1 mW/channel), streaming readout with TDC and ADC outputs
  - Approach: custom-designed EICROC and FCFD, ASICs from 3rd party institutions
- **Sensor/ASIC integration**
  - Goal: reliable and cost-effective way to establish connections between AC-LGAD sensor and frontend ASIC
  - Approach: bump-bonding, wire-bonding, interposer
- **Mechanical structure with cooling:**
  - 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 PEEK materials
- **Flex and frontend electronics:**
  - Goal: low jitter clock to frontend ASICs (<5 ps), low X_0 flexible PCB to route power/signal to sensor/ASIC
  - Approach: design a precise clock distribution system in concert with EPIC DAQ group, design and prototype flexible PCB that meet the requirements; work with EPIC DAQ to define the streaming readout scheme

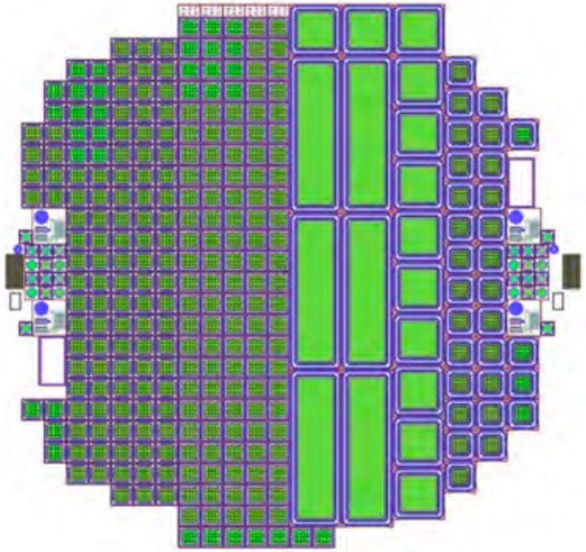
AC-LGAD Sensor R&D

- Production of medium/large area sensors with different doping concentration, pitch and gap sizes between electrodes to optimize performance by BNL IO.
- Start production of sensors of small thickness (20 and 30 microns) for ToF applications with time resolution 20 ps.
  - 1st BNL IO (11/2021): 5-25 mm strips with 500 μm pitch, 100-300 μm electrode width, 50 μm active Si
  - 2nd BNL IO (12/2022): 5-25 mm strips with 500-700 μm pitch, 50-100 um electrode width, 20-50 μm Si
  - 3rd BNL IO (03/2023): pixels with 500 μm pitch, 20-50 μm Si
  - Joint HPK production with KEK (4/2023): strip and pixel sensors with different pitch, electrode width, active Si thickness and n^+-layer doping

1st/2nd BNL Production



3rd BNL Production



Joint HPK Production

AC-LGAD Sensor R&D

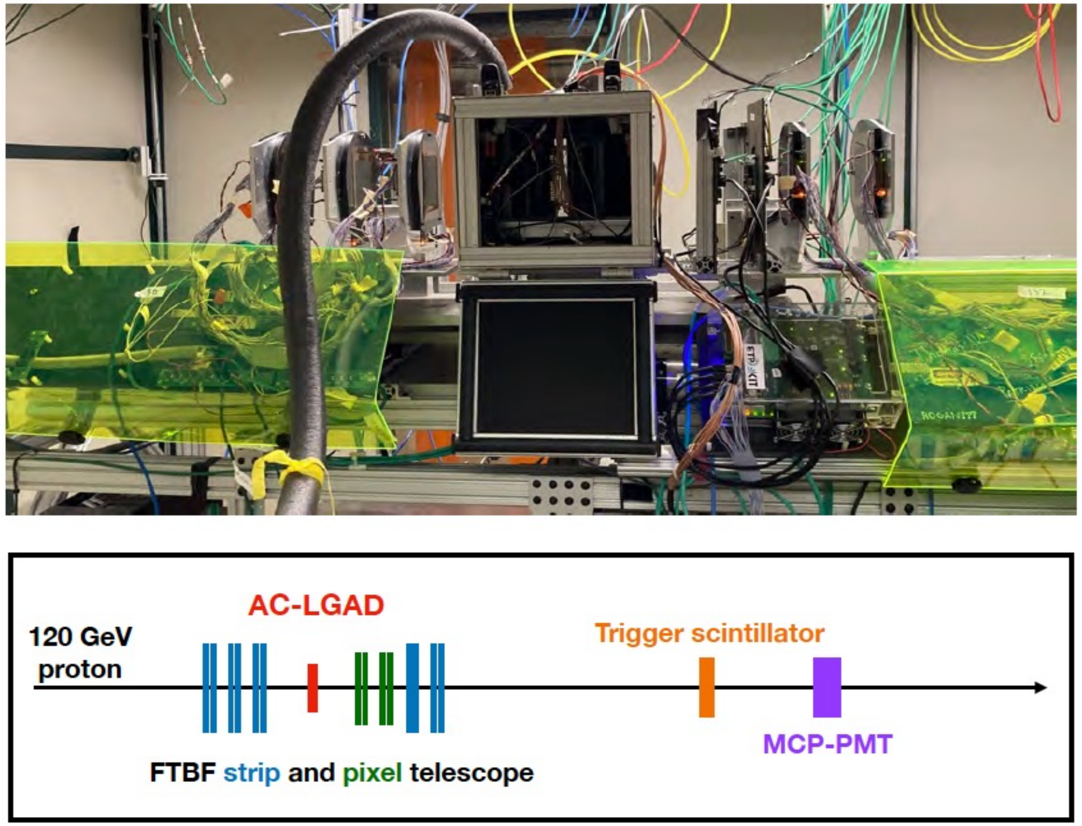


Figure 7: Picture (top) and diagram (bottom) of the FTBF silicon telescope and reference instruments used to characterize AC-LGAD performance. The telescope comprises five pairs of orthogonal strip layers and two pairs of pixel layers, for a total of up to 14 hits per track.

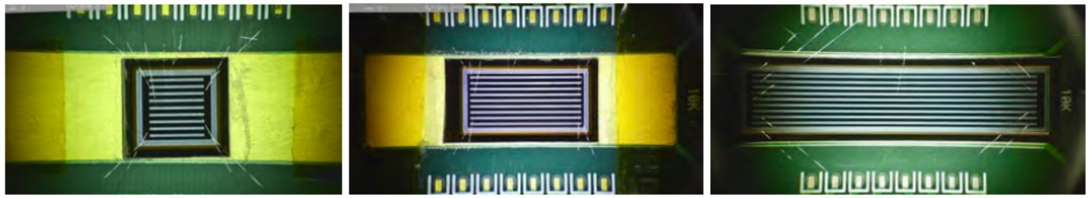
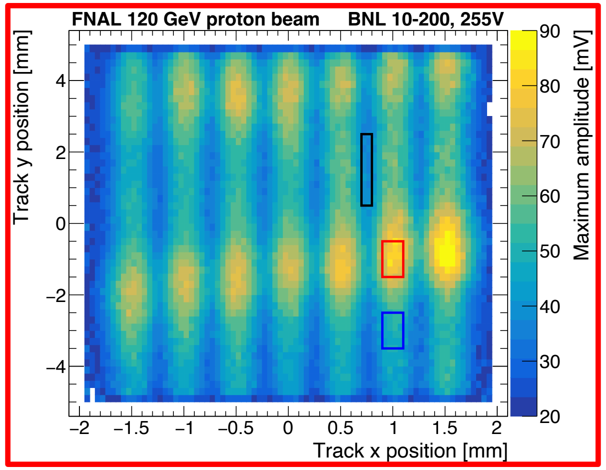
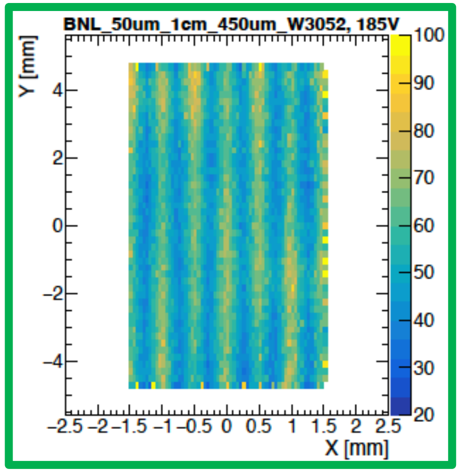


Figure 8: Three AC-LGAD strip sensors wire-bonded on Fermilab test board and tested at FTBF: BNL 5-200 (left), BNL 10-200 (middle) and BNL 25-200 (right). See text for details.





Name	Time resolution		Exactly one strip		Two strip	
	Overall	Hot region	Resolution	Fraction	Resolution	Fraction
Unit	ps	ps	μm	-	μm	-
BNL 5–200	35 ± 1	30 ± 1	52 ± 1	35%	12 ± 1	65%
BNL 10–100	42 ± 1	35 ± 1	28 ± 1	23%	19 ± 1	77%
BNL 10–200	42 ± 1	32 ± 1	55 ± 1	43%	18 ± 1	57%
BNL 10–300	40 ± 1	36 ± 1	78 ± 1	51%	16 ± 1	49%
BNL 25–200	72 ± 1	51 ± 1	71 ± 1	82%	31 ± 1	18%

Table 4: Test beam results of AC-LGAD strip sensors from the first batch of BNL production.

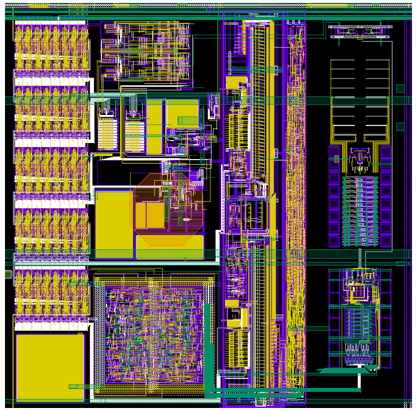
- Timing and spatial resolutions of 1 cm long strip sensors from 1st BNL production are comparable to those of 500x500 μm^2 pixel sensors from HPK (~30 ps, 25 μm), making strip sensors a promising candidate for EIC applications.
- Non-uniform gain in 1st BNL production sensors has been greatly improved in 2nd BNL production.

Frontend ASIC R&D

A first ASIC prototype that is compatible with EIC Roman Pot requirements and can read out an AC-LGAD with 500 micron pitch and 20 ps time resolution.

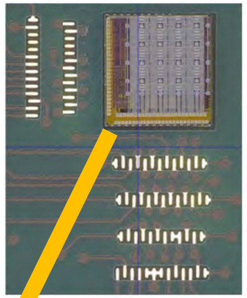
EICROC0 (submitted in 3/2022, received in 7/2022) by OMEGA/CEA-Irfu/AGH/IJCLab

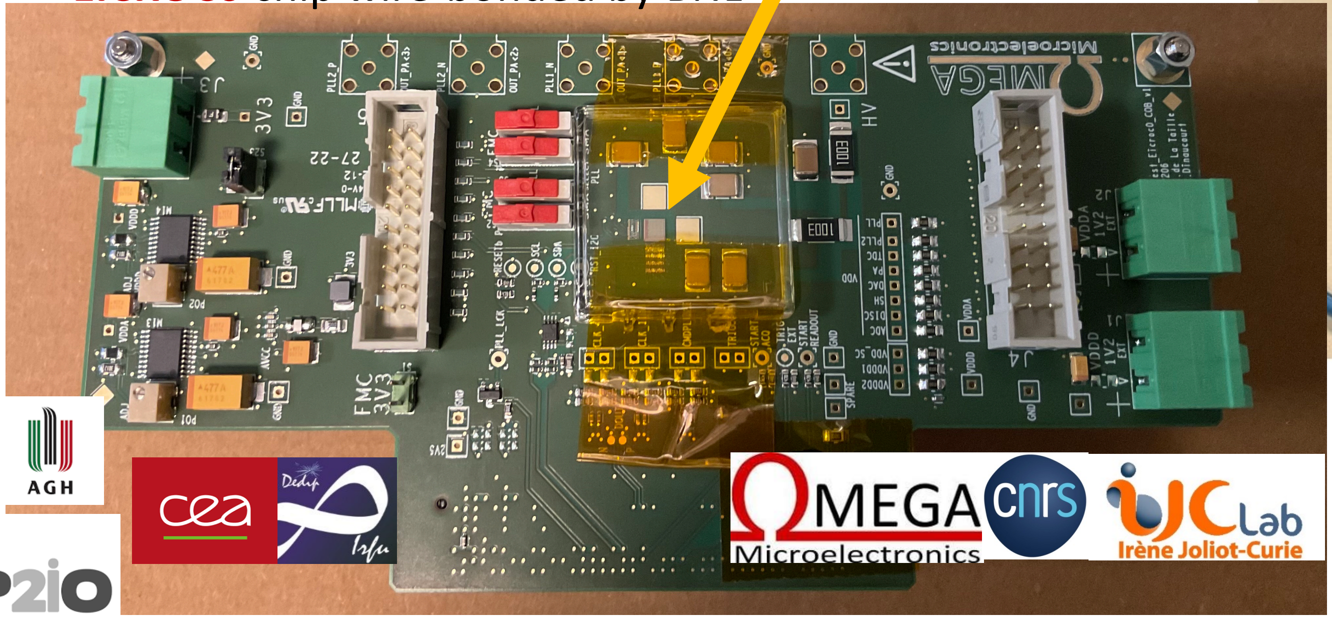
- 4 x 4 channels with 500x500 um^2 pitch
- Preamp, discri. taken from ATLAS ALTIROC
- I2C slow control taken from CMS HGCROC
- TDC (TOA) adapted by CEA-Saclay/Irfu
- ADC (40 MHz) adapted to 8bits by AGH Krakow
- Digital readout: FIFO depth8 (200 ns)



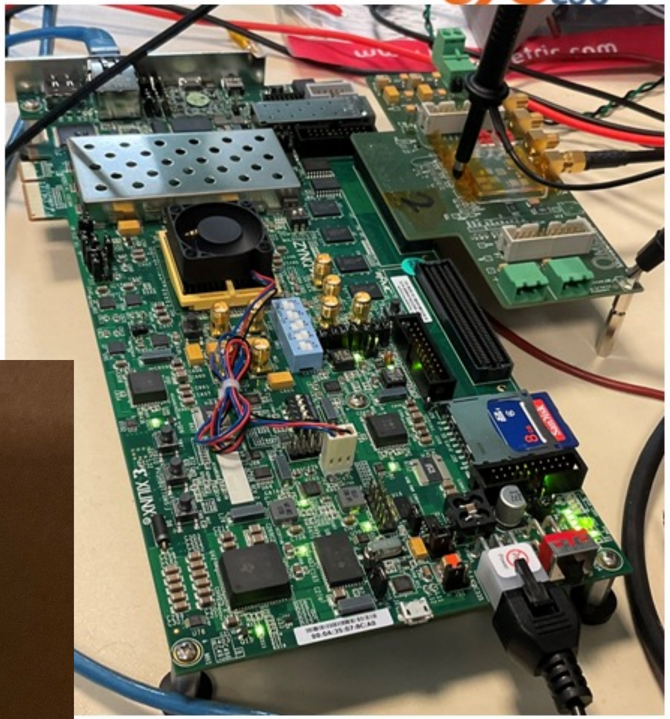
EICROC0, *1 channel implantation*

EICROC0 chip wire-bonded by BNL





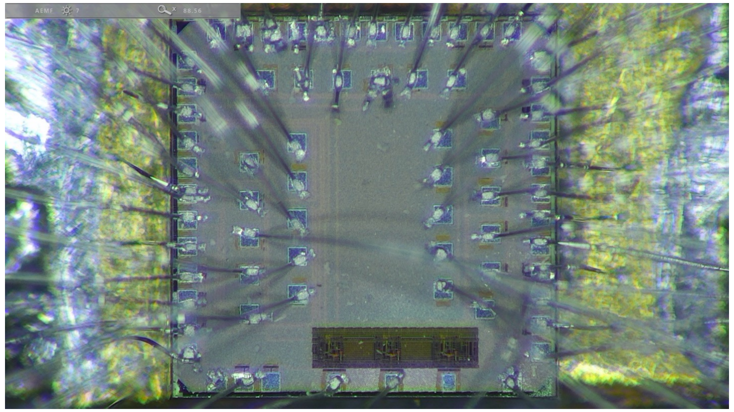
EICROC0 Test bench at IJCLab



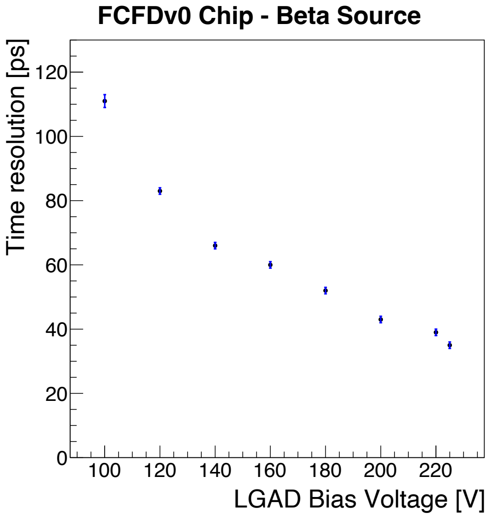
Frontend ASIC R&D

FCFDv0 (Fermilab CFD v0)

- Adapt the Constant Fraction Discriminator (CFD) principle in a pixel when a CFD is paired with a TDC, one time measurement gives the final answer.
- Charge injection and beta source tests consistent with expectation. Tests with beam are planned

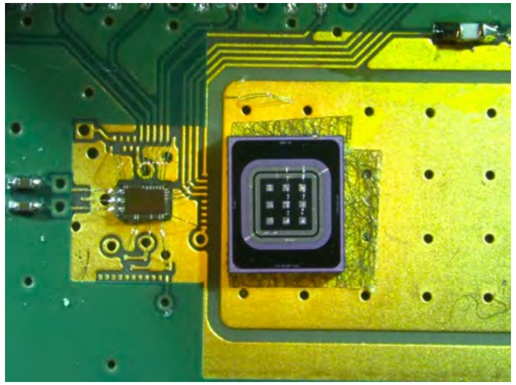


FCFD0

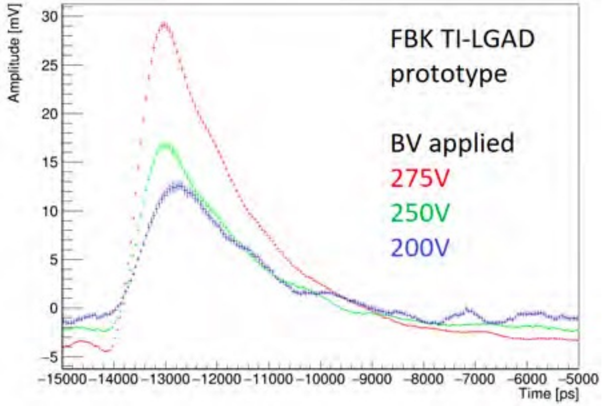


ASIC Efforts at UC Santa Cruz

Institution		Technology	Output	# of Chan	Funding	Specific Goals	Status
INFN Torino	FAST	110 nm CMOS	Discrim. & TDC	20	INFN	Large Capacitance TDC	Testing
NALU Scientific	HPSoC	65 nm CMOS	Waveform	5 (Prototype) > 81 (Final)	DoE SBIR	Digital back-end	Testing
Anadyne Inc	ASROC	Si-Ge BiCMOS	Discrim.	16	DoE SBIR	Low Power	Simulations, final Layout, Board design



HPSoC



Funded R&D Activties in FY23

- AC-LGAD Sensor (eRD112)
  - Productions by BNL IO and HPK
  - TCAD simulation, sensor characterization in the lab/beam
- Frontend readout ASIC (eRD109)
  - EICROC0 lab/beam test, EICROC1 submission
  - FCFD0 beam test, FCFD1 submission
  - Characterization of ASICs from 3rd party institutions
- Frontend electronics (eRD109)
  - Low-density flexible PCB
- Mechanical structure (eRD112)
  - Light-weight structure made from carbon-fiber composite materials and/or PEEK

FY23 Deliverables

- Sensor prototype with 30 ps time and space resolution match RPs and Tracker; Sensor prototype with 20 ps time resolution for ToF.
- 1st sensor + ASIC demonstrator for EIC applications and testing with particle beam.
- 2nd ASIC prototype submissions with better performance and extended features.
- Design and prototype of flexes, interconnects and off-detector electronics.
- Design and prototype of light-weight structure with embedded cooling tubes.

On-going Work

[1] https://wiki.bnl.gov/conferences/index.php/ProjectRandDFY23
[2] https://wiki.bnl.gov/EPIC/index.php?title=TOFPID
[3] https://www.overleaf.com/read/vftxyvjtjrvp

R&D [1]

- Sensor
  - BNL, HPK/FBK productions
  - Lab/beam test, Irradiation
- Mechanical structure
  - Low-density mechanical structure
- ASIC:
  - EICROC1, FCFD1, SCIPP
- Frontend electronics
  - Low-mass service hybrid

Simulation [2]

- DD4HEP geometry, digitization, reconstruction
- Timing resolution requirement
- Spatial resolution requirement
- Material budget requirement

Project Engineering and Design (PED) [3]

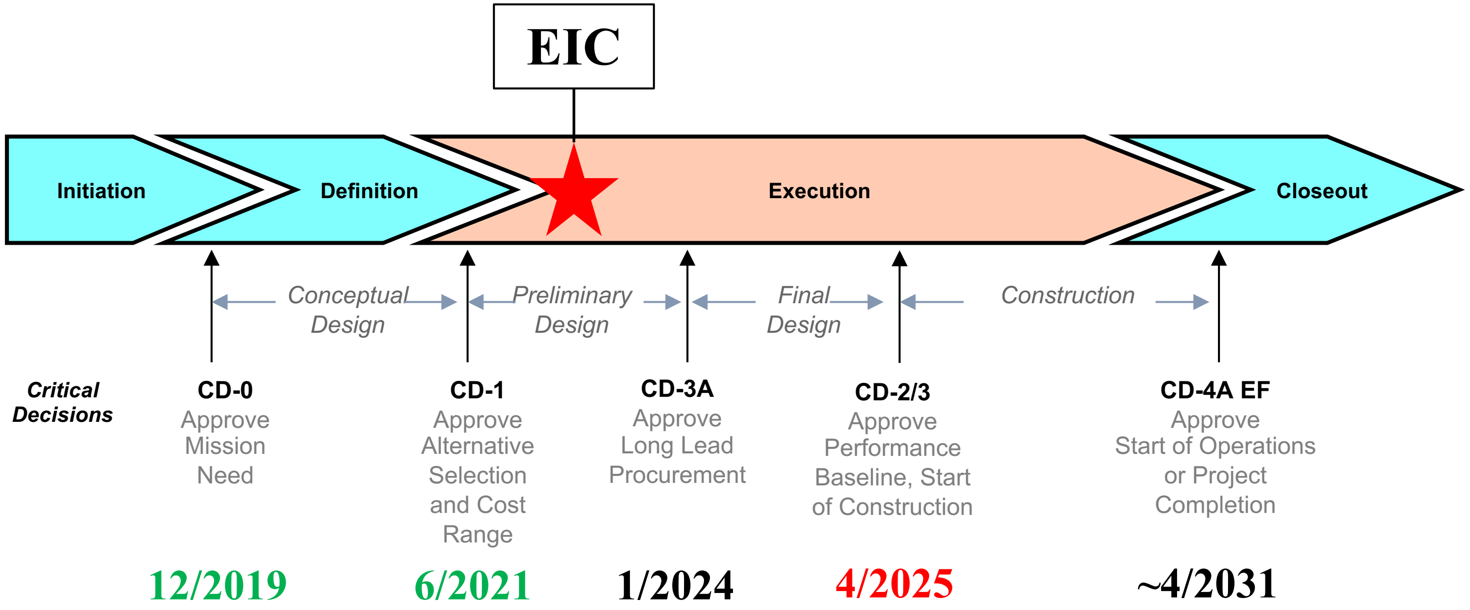
- Mechanical engineering
  - Support structure
  - Cooling system
- Electric engineering – DAQ PED
  - Precision clock distribution (<5 ps)
  - Timing chips and streaming readout
  - Prototype readout board, cables

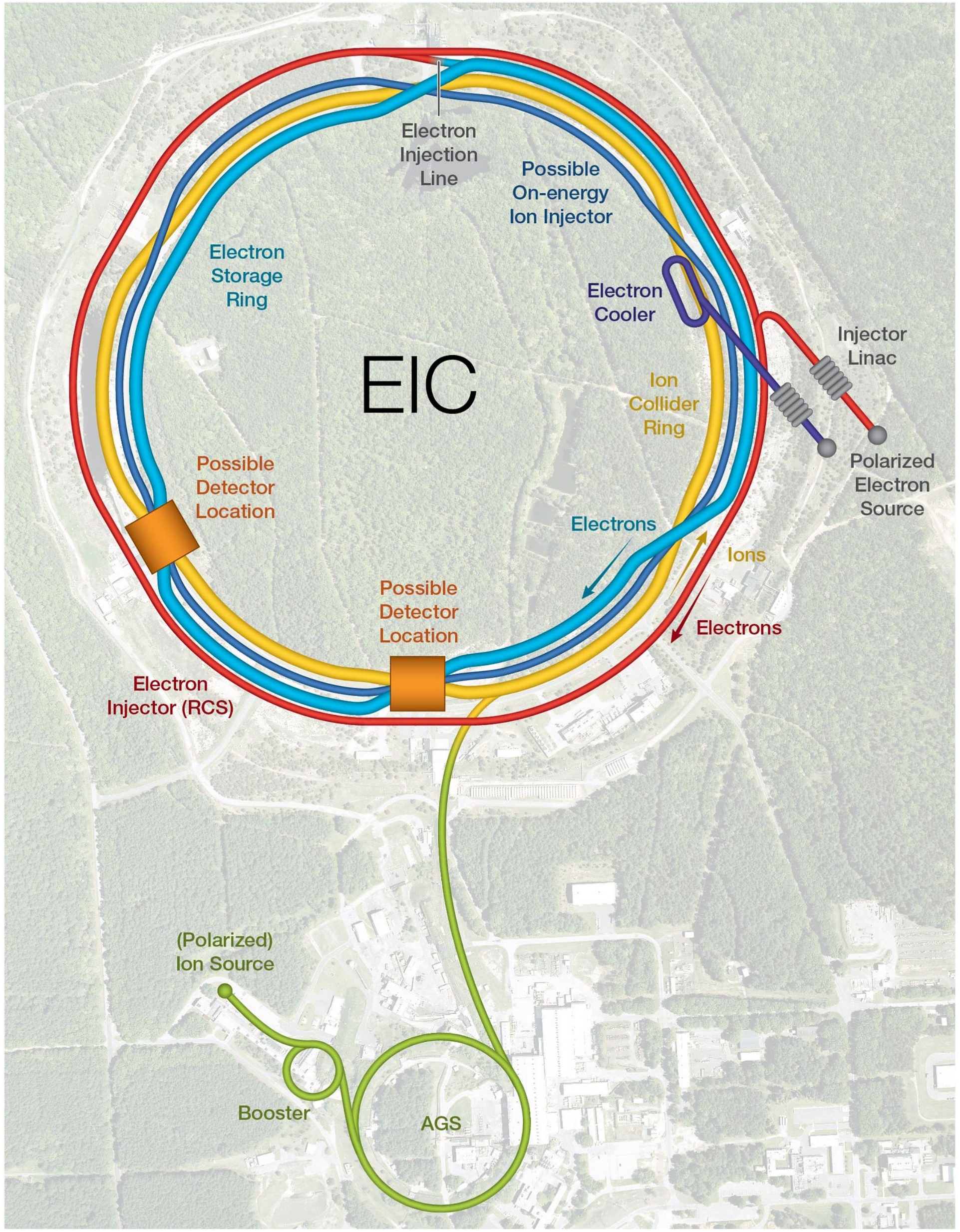
Summary and Outlook

[4] EIC CDR

AC-LGAD is selected by EIC Detector-1 for timing and tracking in central and far-forward detectors.

- Work on-going for detector simulation, R&D and engineering design
- Great opportunity to contribute to the advancement of a 4D tracker technology for future high energy experiments and its first realization at EIC





Electron Beam: 5-18 GeV Ion: 40, 100-275 GeV

References

[1] Electron Ion Collider: The Next QCD Frontier - Understanding the glue that binds us all (2012), arXiv:1212.1701

[2] Reaching for the Horizon: The 2015 Long Range Plan for Nuclear Science (2015), link

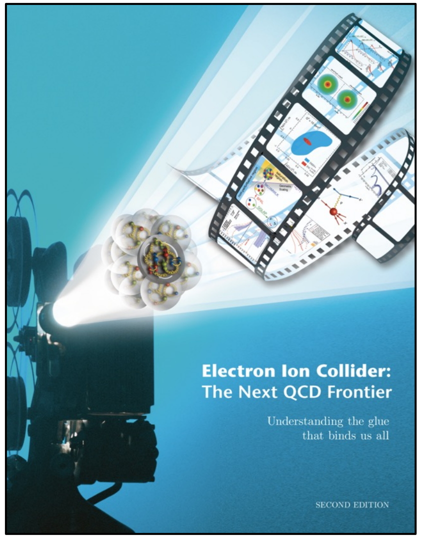
[3] An Assessment of U.S.-based Electron-Ion Collider Science (2018), link

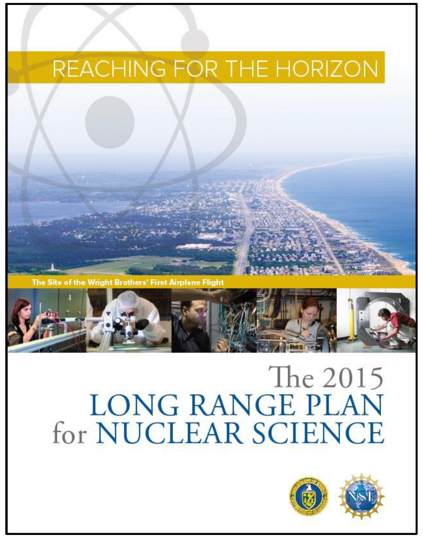
[4] Electron Ion Collider Conceptual Design Report (2021), link

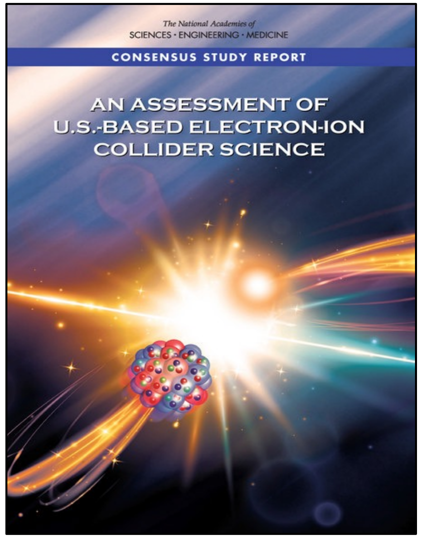
[5] Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report, arXiv:2103.05419

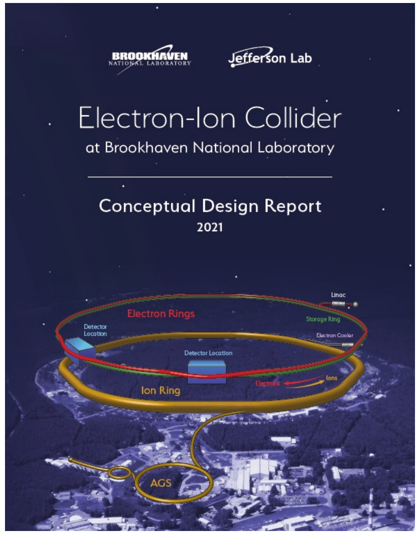
[6] EIC Detector Proposals and Advisory Panel Report (2022), link

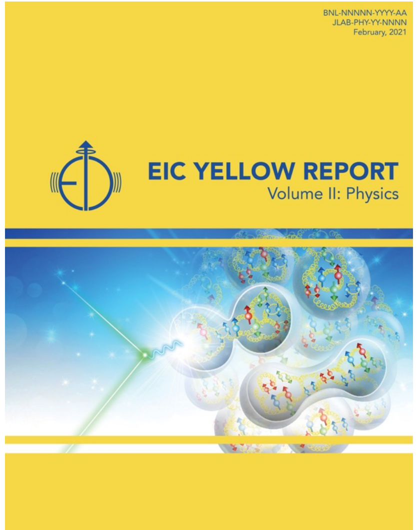
[7] eRD112: EIC AC LGAD R&D Proposal (2022), link

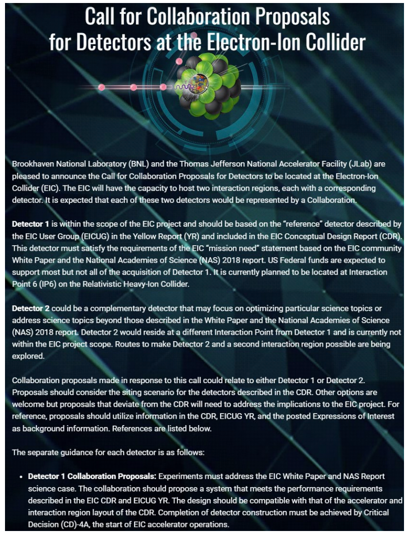











Call for Collaboration Proposals
for Detectors at the Electron-Ion Collider

Brookhaven National Laboratory (BNL) and the Thomas Jefferson National Accelerator Facility (JLab) are pleased to announce the Call for Collaboration Proposals for Detectors to be located at the Electron-Ion Collider (EIC). The EIC will have the capacity to host two interaction regions, each with a corresponding detector. It is expected that each of these two detectors would be represented by a Collaboration.

Detector 1 is within the scope of the EIC project and should be based on the "reference" detector described by the EIC User Group (EICUG) in the Yellow Report (YR) and included in the EIC Conceptual Design Report (CDR). This detector must satisfy the requirements of the EIC "mission need" statement based on the EIC community White Paper and the National Academies of Science (NAS) 2018 report. US Federal funds are expected to support most but not all of the acquisition of Detector 1. It is currently planned to be located at Interaction Point 6 (IP6) on the Relativistic Heavy-Ion Collider.

Detector 2 could be a complementary detector that may focus on optimizing particular science topics or address science topics beyond those described in the White Paper and the National Academies of Science (NAS) 2018 report. Detector 2 would reside at a different Interaction Point from Detector 1 and is currently not within the EIC project scope. Routes to make Detector 2 and a second interaction region possible are being explored.

Collaboration proposals made in response to this call could relate to either Detector 1 or Detector 2. Proposals should consider the siting scenario for the detectors described in the CDR. Other options are welcome but proposals that deviate from the CDR will need to address the implications to the EIC project. For reference, proposals should utilize information in the CDR, EICUG YR, and the posted Expressions of Interest as background information. References are listed below.

The separate guidance for each detector is as follows:

- **Detector 1 Collaboration Proposals:** Experiments must address the EIC White Paper and NAS Report science case. The collaboration should propose a system that meets the performance requirements described in the EIC CDR and EICUG YR. The design should be compatible with that of the accelerator and interaction region layout of the CDR. Completion of detector construction must be achieved by Critical Decision (CD)-4A, the start of EIC accelerator operations.