AC-LGAD FY24 R&D Proposal

- Optimized sensor design and final prototypes that meet ePIC requirements, including timing and spatial resolution, irradiation tolerance, and reasonably large size for module assembly
- Prototypes of interposer for mechanical/electrical connections between strip sensor and ASIC
- Prototypes of light-weight module mechanical structures for forward TOF
- Prototypes of frontend ASICs
- Functional and full size low-mass Kapton PCB
- Low-cost interconnect for sensor-ASIC hybridization
- Service hybrid prototype

eRD112 (414k$)

- Sensor R&D (346k$)
  - BNL, HPK/FBK productions
  - TCAD, lab/beam/irradiation tests
- Sensor/ASIC integration (15k$)
  - Interposer
- Mechanical structure ($53k)
  - Light-weight structure w. cooling

eRD109 (435k$)

- Frontend ASICs
  - EICROC (85k$)
  - FCFD (40k$)
  - 3rd Party ASICs (45k$)
- Frontend electronics
  - Low-mass Kapton PCB (30k$)
  - Low-cost sensor-ASIC hybrid. (15k)
  - Service hybrid (220k)

EPIC Simulation

- Geometry model, digitization and reconstruction
- Requirements on spatial, timing resolutions, and material budget

Project Engineering Design

- Engineering design for pre-TDR
- Integration & services

Sensor **Electronics** **Sensor-ASIC integration** **Mechanics**

eRD109 FY24 Proposal

- EICROC by IJCLab/Omega (85k)
  - EICROC0 characterization
  - EIRCRO0_v1 design and submission in FY24 Q2 (submission cost covered by FY23 funds)
  - EICROC1 design and submission in FY24 Q4
- FCFD by FNAL (40k)
  - FCFDv1 characterization
  - FCFDv2 design and submission in FY24 Q4
- 3rd party ASICs by UCSC (45k)
  - ASROC, FAST3, HPSoC
- Functional full-size low-mass Kapton PCB + low-cost interconnect for sensor-ASIC hybridization (45k) by ORNL
- Service hybrid (220k)
  - BNL (137k) demonstrate the initial readout chain and contribute to the development of the full RDO Prototype
  - Rice (49k) contribute to the development of the full RDO prototype, with a focus on the end cap-specific designs
  - UIC (34k) contribute to the development of the full RDO prototype, with a focus on the barrel TOF
  - ORNL communicate with BNL, Rice and UIC and make and test a flex PCB prototype that connects a readout ASIC and sensor assembly to a RDO prototype from BNL/Rice/UIC, using external or ORNL services.

eRD109 FY24 Proposal

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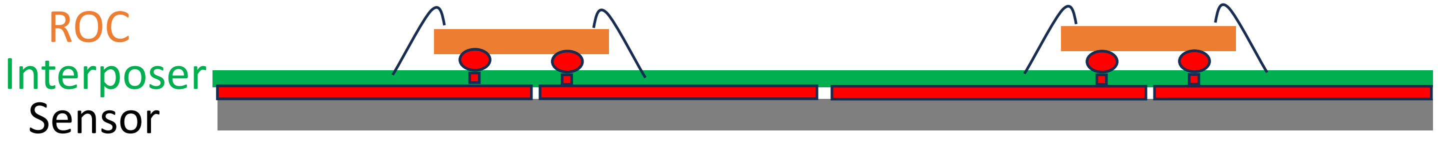
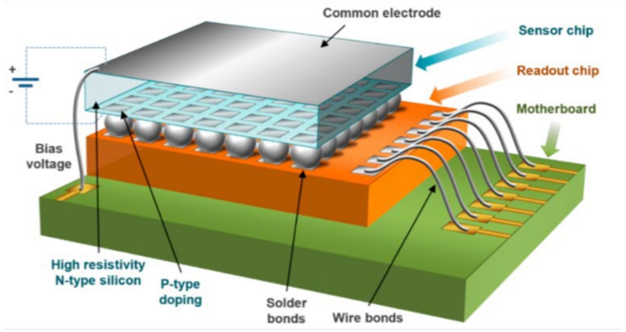
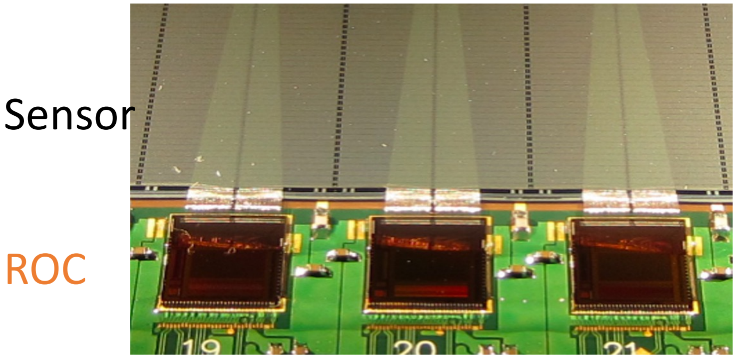
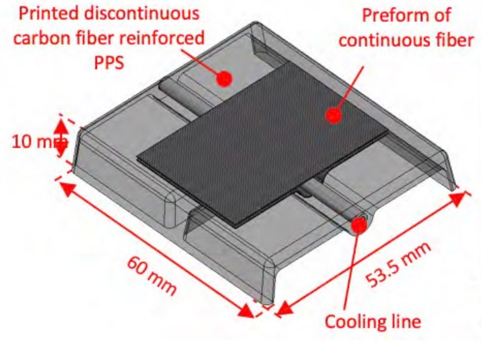
eRD112 FY24 Proposal

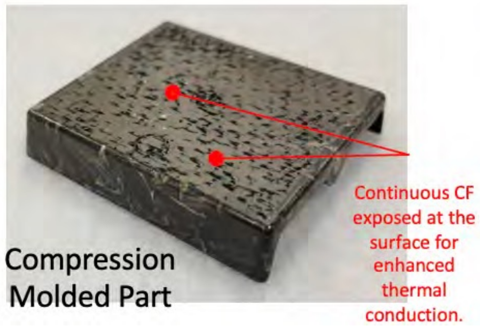
- Sensor further optimize sensor design, determine final size and yield, verify radiation tolerance
  - TCAD simulation and sensor irradiation test (20k)
  - Sensor production and characterization: BNL IO (75k+46k), HPK (80k+40k), FBK (70k+15k)
- Sensor/ASIC integration (15k)
  - Interposer to connect pixelated ASICs with strip sensors, or pixel sensors with various pitch
- Mechanical structure (53k)
  - Light-weight structure made from CF composite materials using compression or injection molding for FTOF











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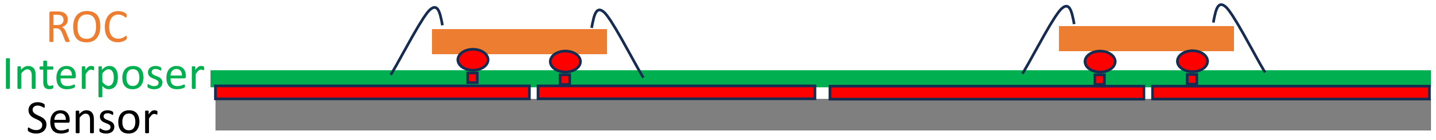

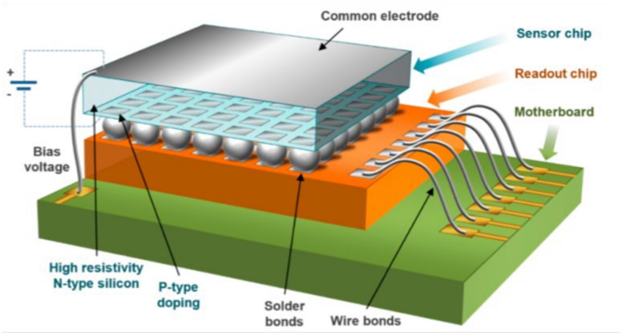

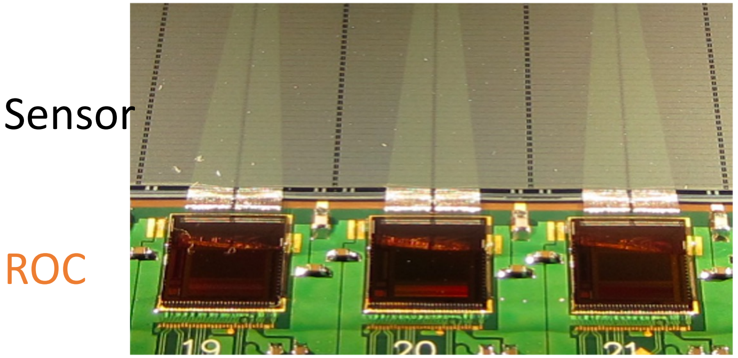

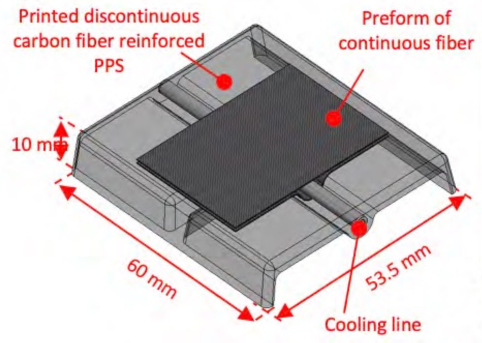

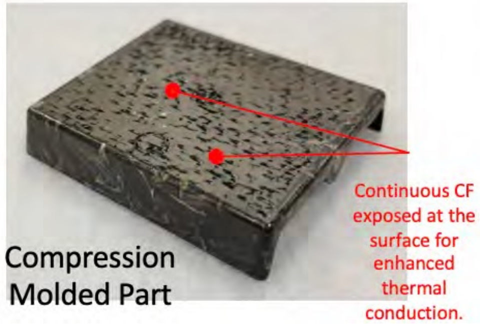

AC-LGAD FY24 R&D Proposal

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eRD112 (414k->286k$)

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    - ~~Light-weight structure w. cooling~~

eRD109 (435k->390k$)

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- Engineering design for pre-TDR
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Sensor **Electronics** **Sensor-ASIC integration** **Mechanics**

EIC AC-LGAD R&D FY23 Report and FY24 Proposal

eRD112 (this talk)

Brookhaven National Laboratory: E.C. Aschenauer, G. Giacomini, A. Jentsch, A. Kiselev, A. Tricolli
Fermi National Accelerator Laboratory: A. Apresyan, I. Dutta, C. Madrid, C. Pena, S. Xie
Los Alamos National Laboratory: X. Li, E. Renner
National Cheng Kung University/Academia Sinica (Taiwan): W.-C. Chang, P.-J. Lin, Y. Yang
Purdue University: S. Karmarkar, A. Jung
University of California, Santa Cruz: M. Gignac, S. Mazza, J. Ott, A. Seiden, S.H. Sadrozinski, B. Schumm
University of Illinois at Chicago: O. Evdokimov, S. Nanda, D. Shekar, Z. Ye

eRD109 (Fernando's talk)

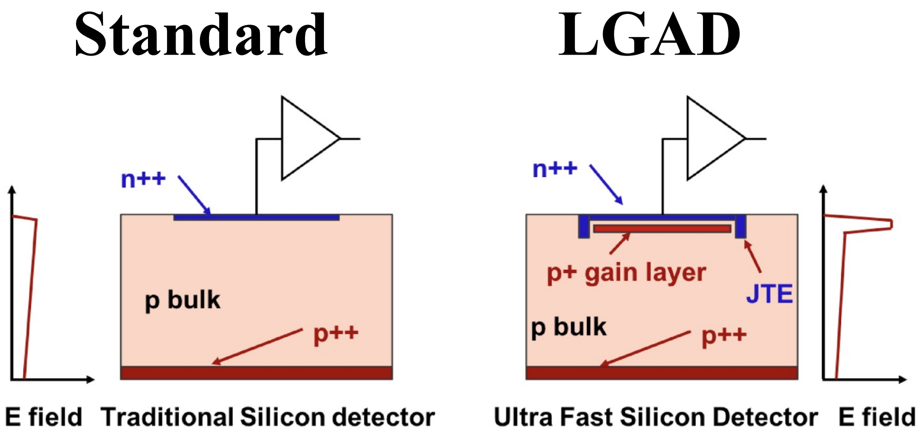
Brookhaven National Laboratory: P. Shanmuganathan, P. Tribedy, T. Ljubicic, Z. Xu
Fermi National Accelerator Laboratory: A. Apresyan, I. Dutta, C. Madrid, C. Pena, S. Xie, T. Zimmerman
IJCLAB/OEMGA/CEA-Irfu (France): A. Ba, J.-J. Dormard, B.Y Ky, D. Marchand, C. Munoz Camacho, E. Rauly, L. Serin, A.-S. Torrento, P.-K. Wang, P. Dinaucourt, N. Seguin-Moreau, C. de La Taille, M. Morenas, F. Bouyjou
Oak Ridge National Laboratory: M. Benoit, O. Hartbrich, K. F. Read, N. Schmidt
Rice University: F. Geurts, W. Li
University of California, Santa Cruz: M. Gignac, S. Mazza, J. Ott, A. Seiden, S.H. Sadrozinski, B. Schumm
University of Illinois at Chicago: O. Evdokimov, S. Nanda, D. Shekar, Z. Ye

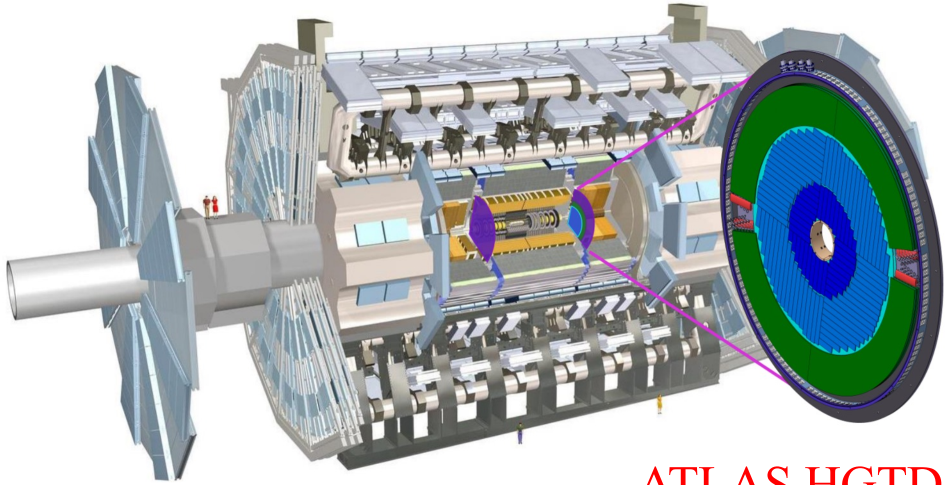
Institutions seeking external resources:

University of Science and Technology of China (China), National Institute of Sci. Edu. and Research (India)
Hiroshima University (Japan), Nara Women's University (Japan), RIKEN (Japan), Univ of Tokyo (Japan)

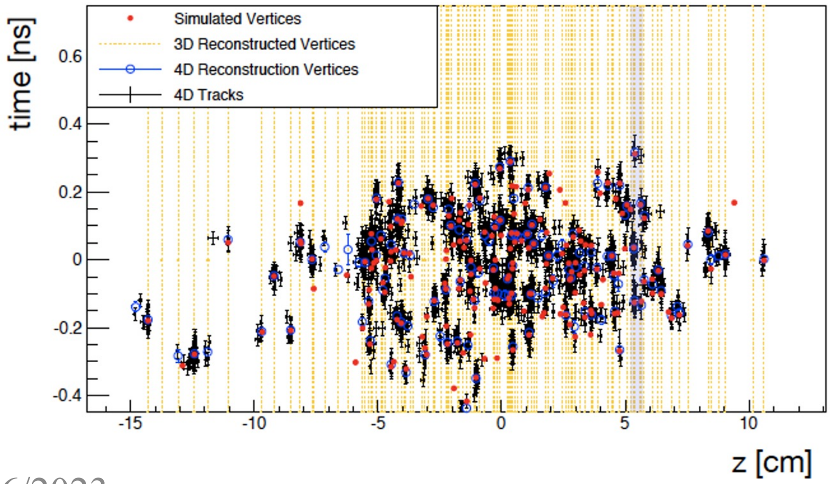
Low Gain Avalanche Diode

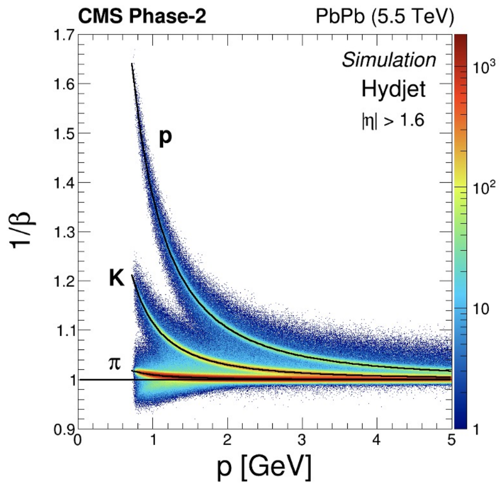
- Utilizing synergies to LGAD detectors at ATLAS (6 m^2) and CMS (14 m^2) for HL-LHC.

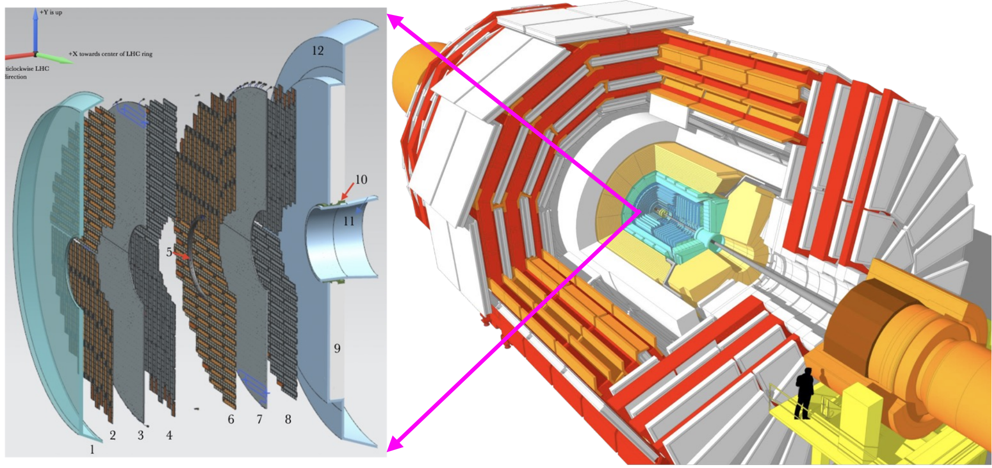




ATLAS HGTD







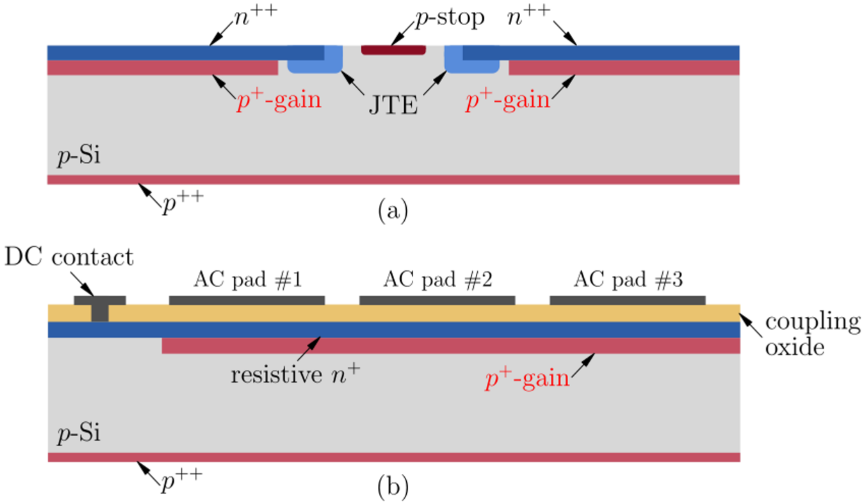
CMS ETL

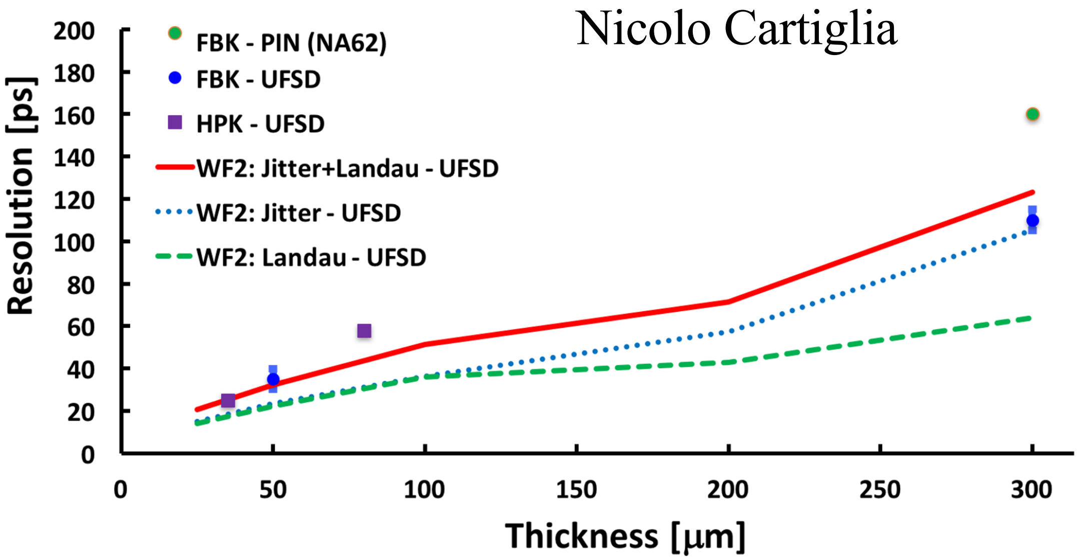
AC-coupled LGAD

- AC-LGAD provides not only precise timing resolution, but also ~100% fill factor and much better spatial resolution than DC-LGAD.

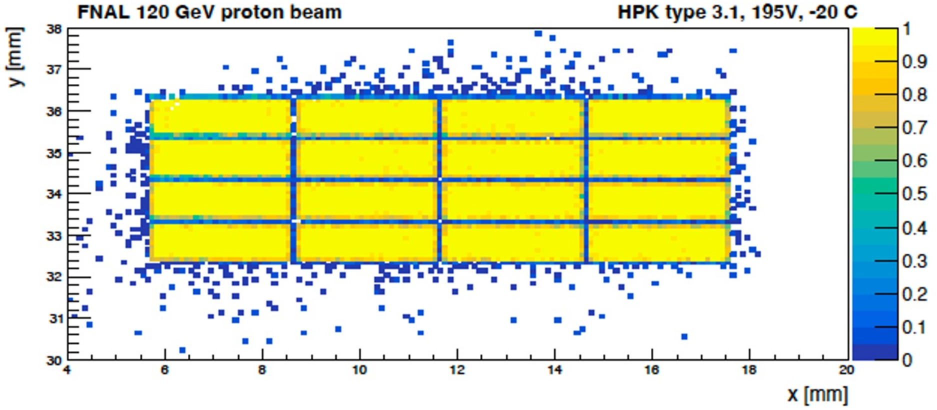
(DC-)LGAD

AC-LGAD

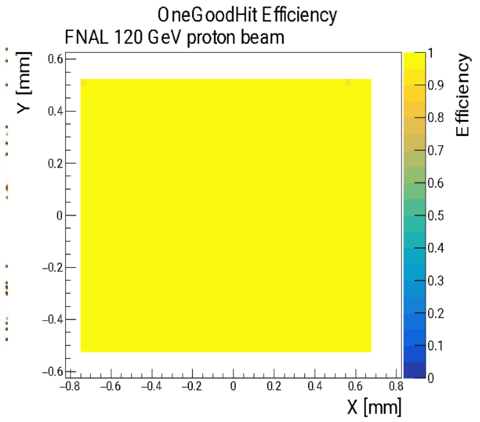




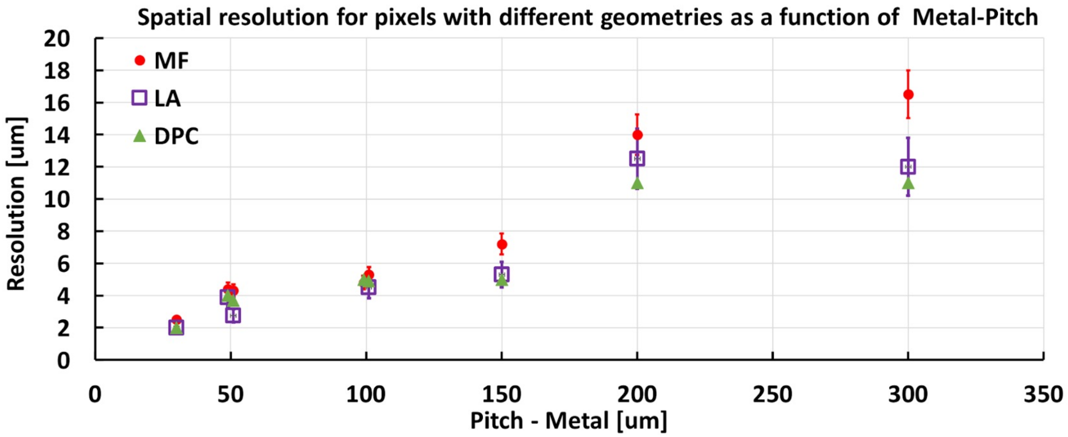
Nicolo Cartiglia



DC-LGAD

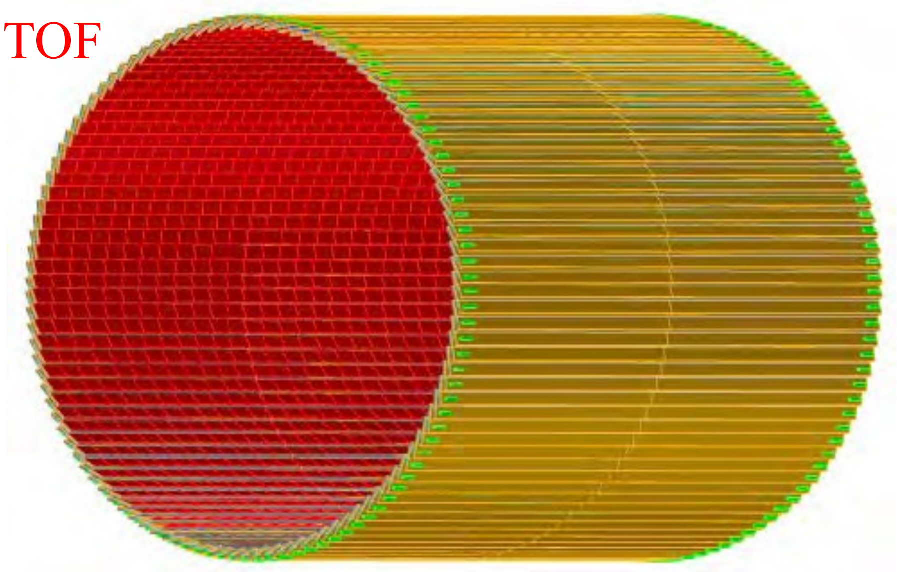


AC-LGAD

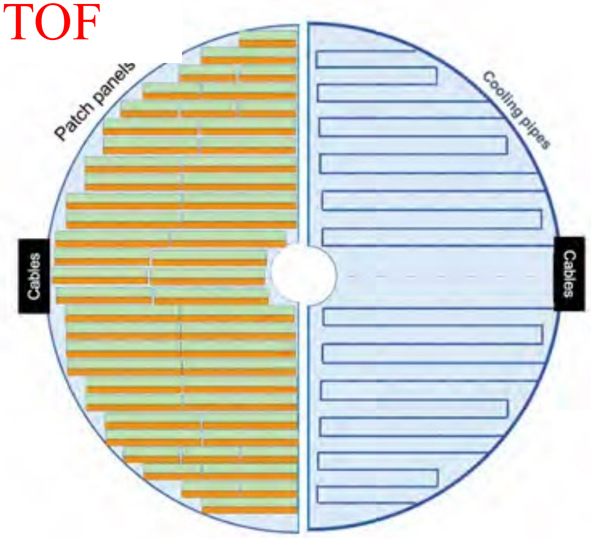


ePIC AC-LGAD Detector Requirements (Last Year)

BTOF



FTOF



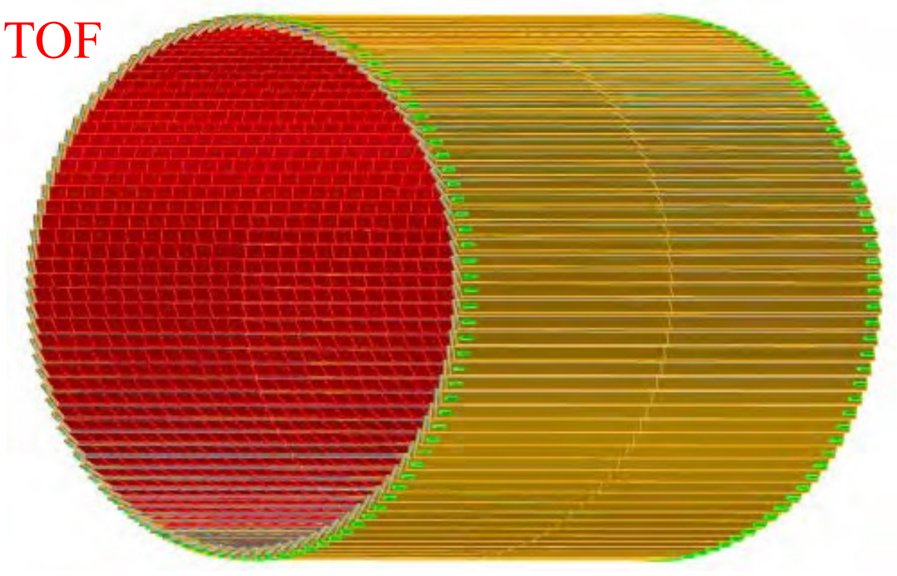
Roman Pots

	Area (m^2)	Channel size (mm^2)	# of Channels	Timing Resolution	Spatial resolution	Material budget
Barrel TOF	10	0.5*10	2.4M	30 ps	30 μm in $r \cdot \varphi$	0.01 X_0
Forward TOF	1.4	0.5*0.5	5.6M	25 ps	30 μm in x and y	0.08 X_0
B0 tracker	0.07	0.5*0.5	0.28M	30 ps	20 μm in x and y	0.01 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.

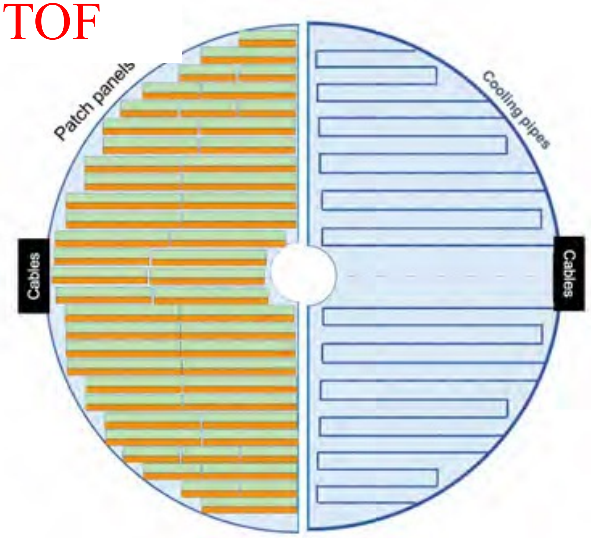
Requirements on timing and spatial resolutions and material budget are still being evaluated and are subject to change as the design matures, and we will continue to explore common designs for these detectors where possible to reduce cost and risk.

ePIC AC-LGAD Detector Requirements (Current)

BTOF



FTOF



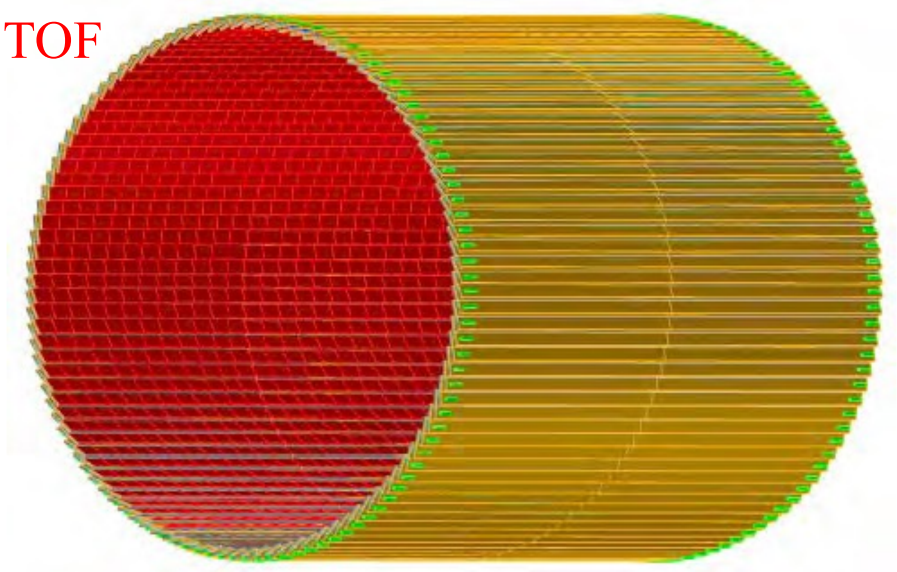
Roman Pots

	Area (m^2)	Channel size (mm^2)	# of Channels	Timing Resolution	Spatial resolution	Material budget
Barrel TOF	10	0.5*10	2.4M	30 → 35 ps	30 μm in $r \cdot \varphi$	0.01 X_0
Forward TOF	1.4	0.5*0.5	5.6M	25 ps	30 μm in x and y	0.08 → 0.025 X_0
B0 tracker	0.07	0.5*0.5	0.28M	30 ps	20 μm in x and y	0.01 → 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.

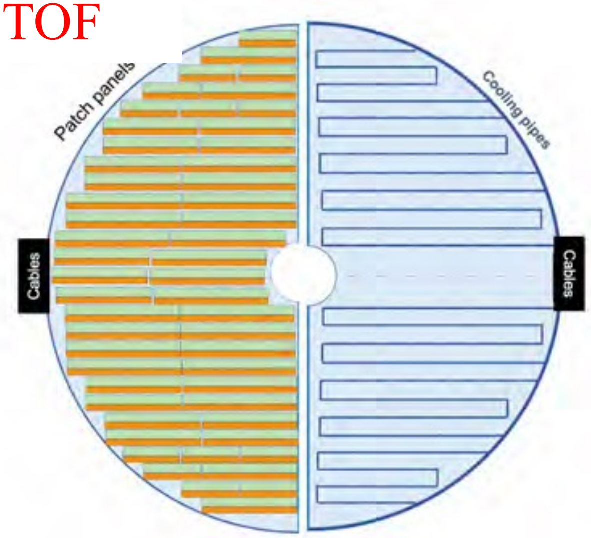
Requirements on timing and spatial resolutions and material budget are still being evaluated and are subject to change as the design matures, and we will continue to explore common designs for these detectors where possible to reduce cost and risk.

ePIC AC-LGAD Detector Module Designs

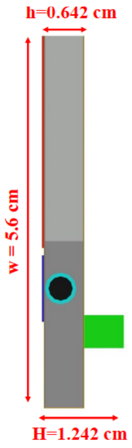
BTOF

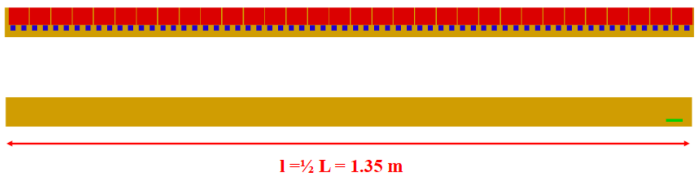


FTOF

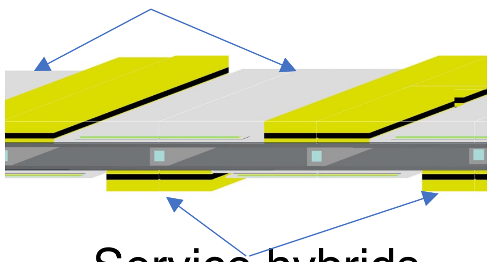


Roman Pots



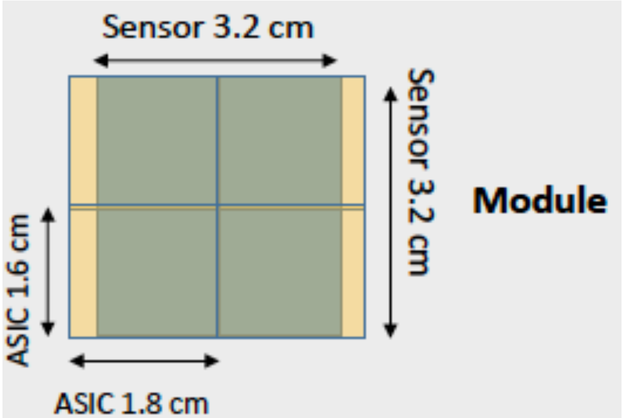


- **32 AC-LGAD sensors**, each 3.2*4 cm² read out by **2 ASICs**
- **Low mass flexible Kapton PCB** distributes power and I/O signals from a low mass connector(s) at the edge
- **Liquid coolant** in **Al cooling tube** takes away heat from the ASICs



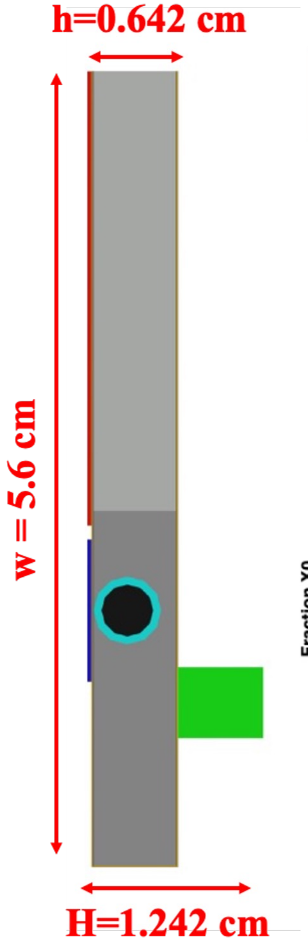
Sensor module

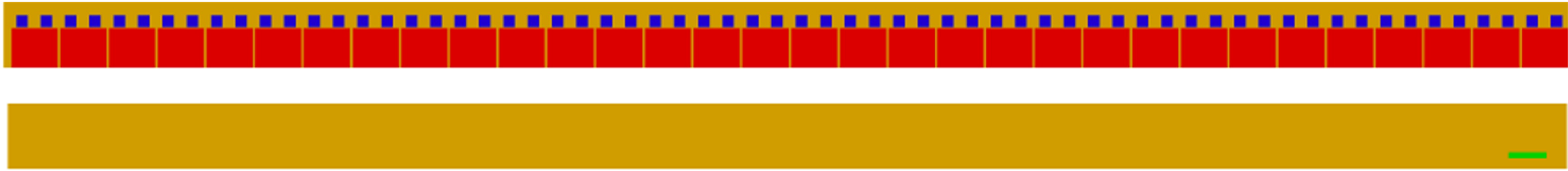
Service hybrids
(readout, power)



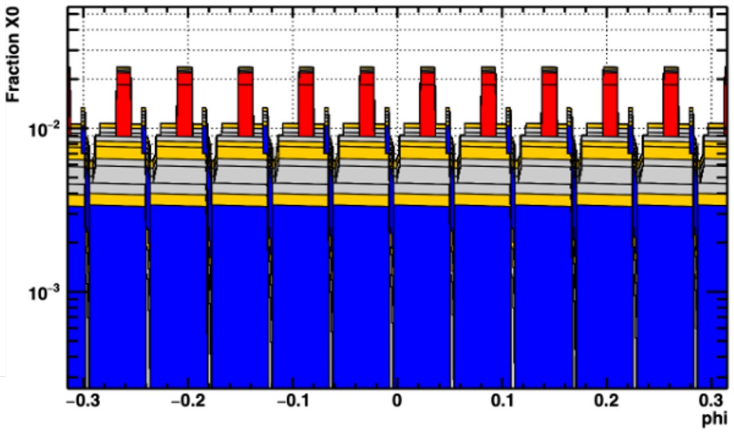
Key components -> detector module -> integration and services

ePIC BTOF Detector Module Conceptual Design





- **64 AC-LGAD strip sensors**, each 3.2*4 cm^2 read out by **2 ASICs**
- **Low mass flexible Kapton PCB** distributes power and I/O signals from connector
- **Liquid coolant** in **Al tube** embedded in CF light-weight structure for heat removal

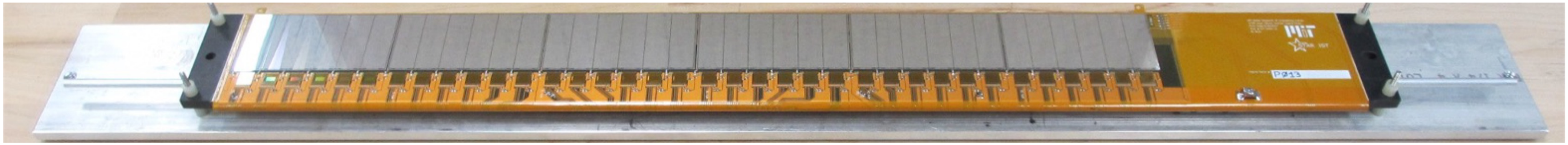


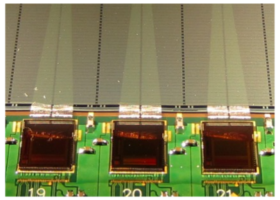
144 modules, each with 2 readout boards with 2 LV+HV cables, 2 DAQ fiber, and 1 cooling line

Power consumption: ~4 kW (2.4kW for ASIC, 1 kW for DC-DC, 0.6kW for sensors+cable)

Total weight: ~70 kG

STAR IST





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 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
- **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/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

eRD112 FY23 Report

$461k requested, $250k approved in 2/2023

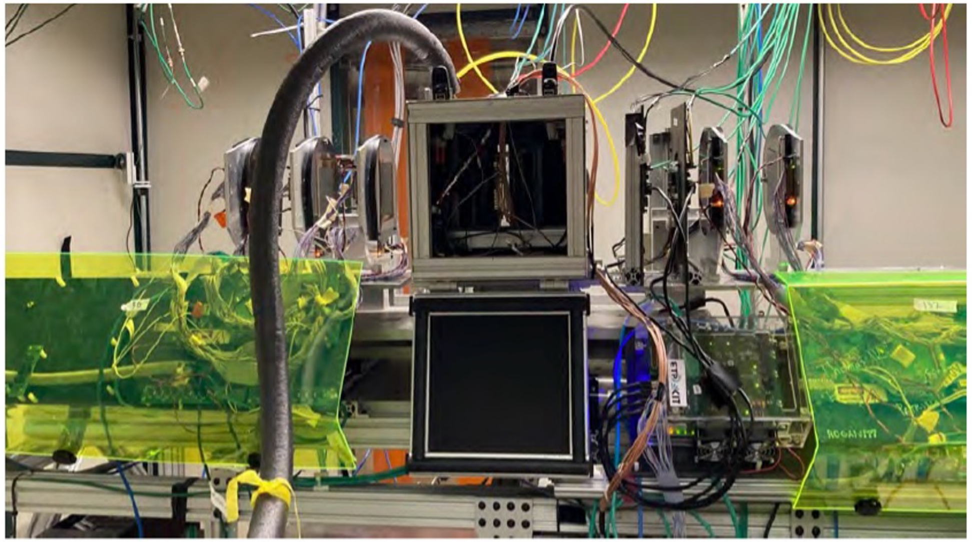
- AC-LGAD Sensor
  - ✓TCAD simulation
  - ✓Productions by BNL IO and HPK~~/FBK~~
  - ✓Sensor characterization in the lab/beam
  - ~~Irradiation test~~
- ~~Sensor/ASIC integration~~
  - ~~Interposer to connect pixelated ASICs with strip sensors, or pixel sensors with various pitch~~
- Mechanical structure
  - ✓Light-weight structure made from carbon-fiber composite materials and/or PEEK

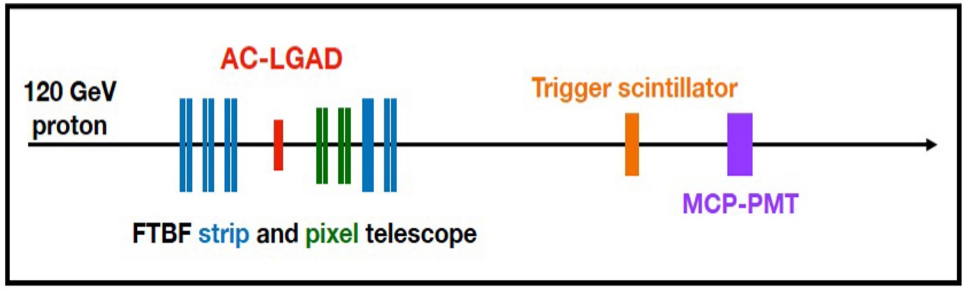
eRD112 FY23 Deliverables - Sensor

- 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.

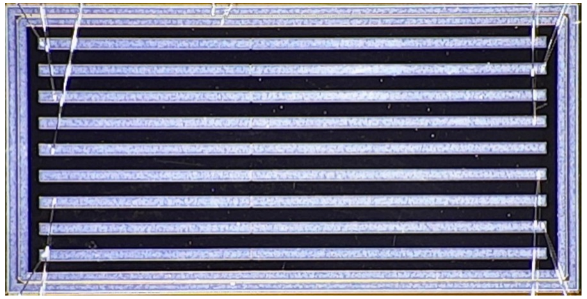
* ~50 um under the metal eletrode. To be improved

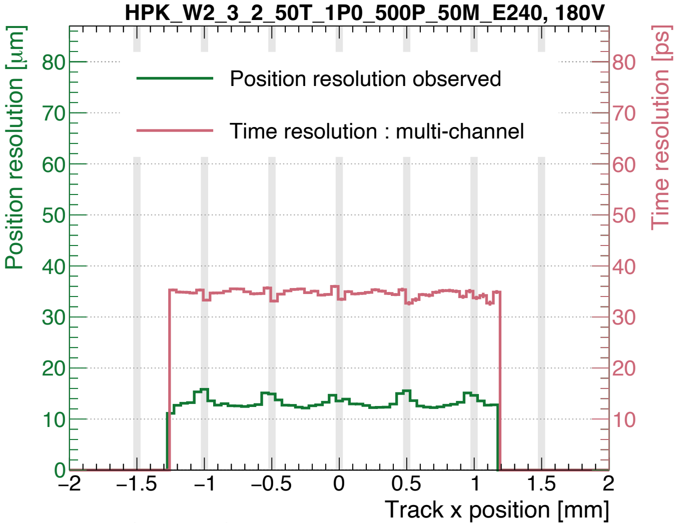
Fermilab Test Beam Setup



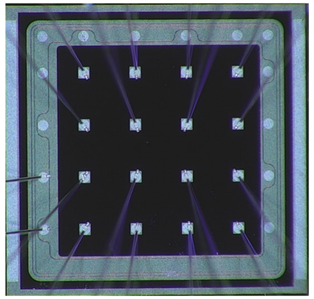


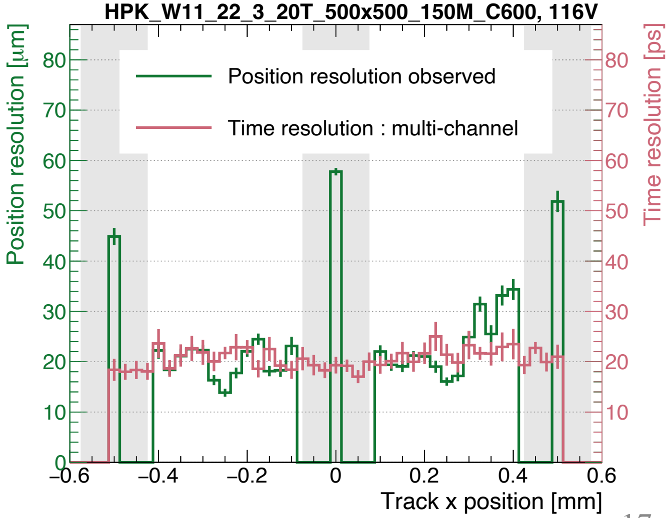
HPK Strip Sensor (4.5x10 mm^2)





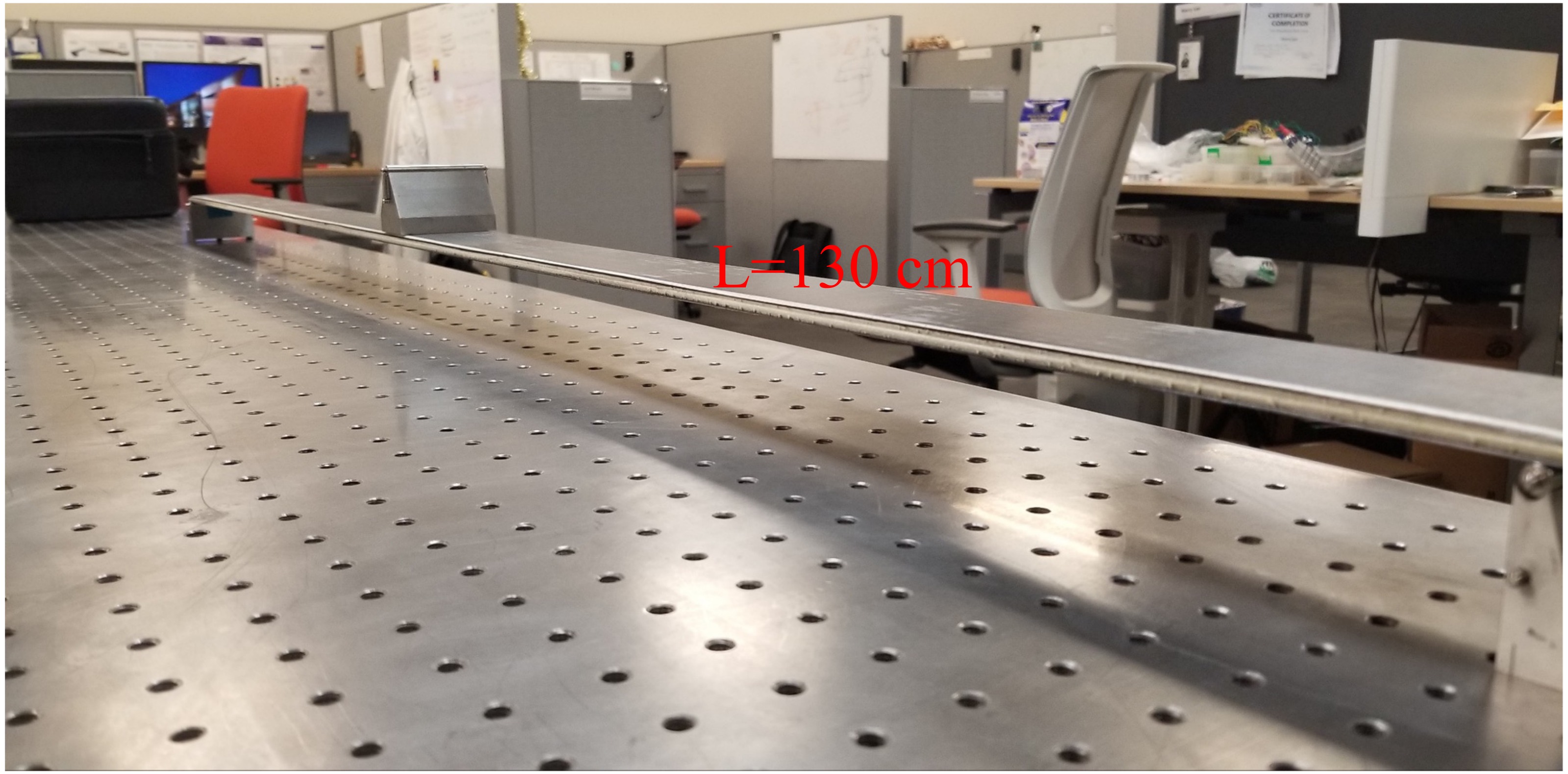
HPK Pixel Sensor (2x2 mm^2)





eRD112 FY23 Deliverables - Mechanical Structure

- **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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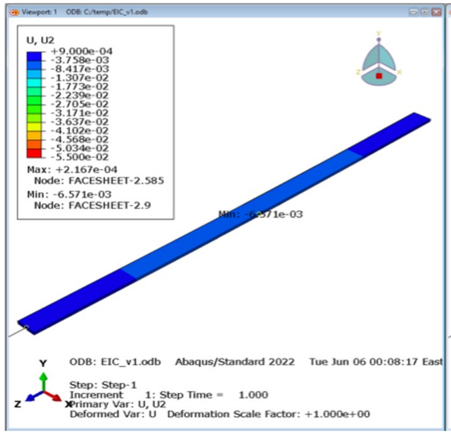

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 -3.171e-02
 -3.637e-02
 -4.102e-02
 -4.568e-02
 -5.034e-02
 -5.500e-02
Max: +2.167e-04
  Node: FACESHEET-2.585
Min: -6.571e-03
  Node: FACESHEET-2.9

Min: -6.571e-03

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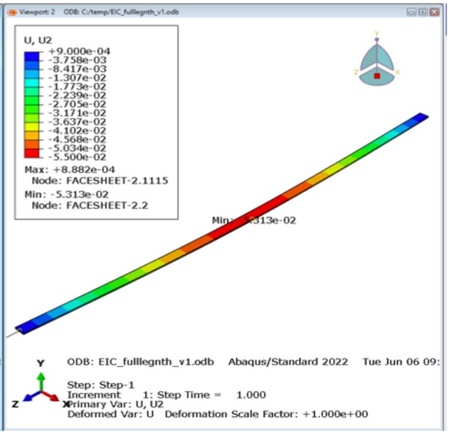

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 -3.637e-02
 -4.102e-02
 -4.568e-02
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 -5.500e-02
Max: +8.882e-04
  Node: FACESHEET-2.1115
Min: -5.313e-02
  Node: FACESHEET-2.2

Min: -5.313e-02

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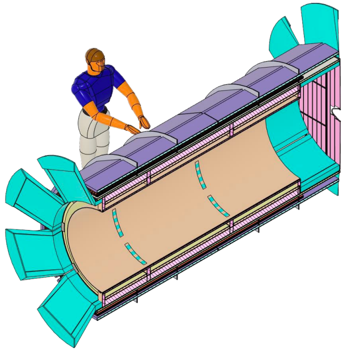
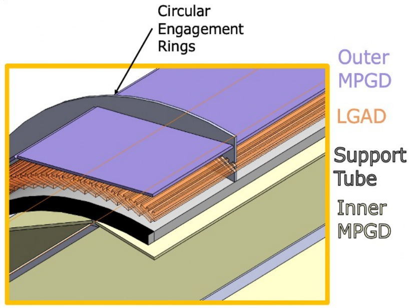




eRD112 FY24 Proposal

- AC-LGAD Sensor
  - Productions by BNL IO, HPK and FBK
  - Sensor characterization in the lab/beam
  - TCAD simulation
  - Irradiation test

Further optimize sensor design and produce prototypes that meet ePIC requirements, including timing and spatial resolution, irradiation tolerance, and reasonably large size for module assembly

- Sensor/ASIC integration
  - Interposer to connect pixelated ASICs with strip sensors, or pixel sensors with various pitch

Investigate reliable and cost-effective mechanical and electrical sensor-ASIC connections with interposer

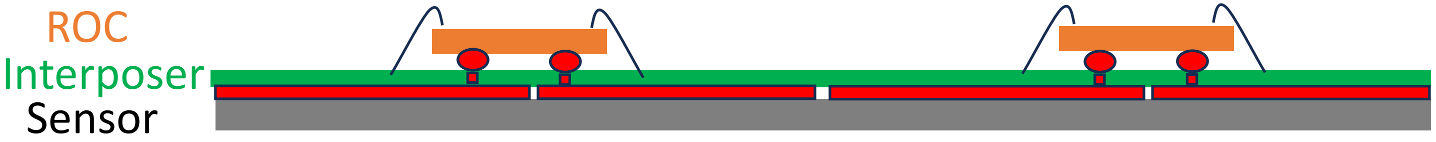
- Mechanical structure
  - Light-weight structure for FTOF

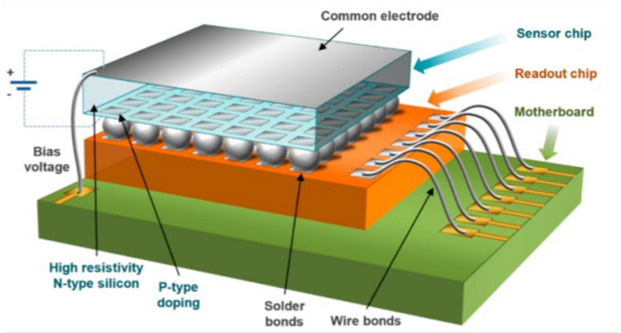
Develop light-weight mechanical structures for FTOF

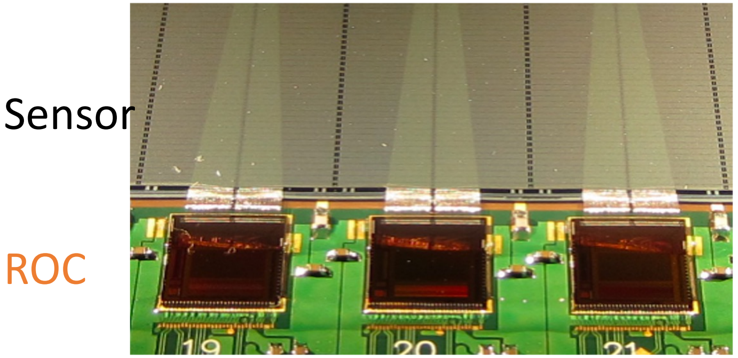
Sensor + ASIC demonstrator (prototype module) for EIC and testing with particle beam

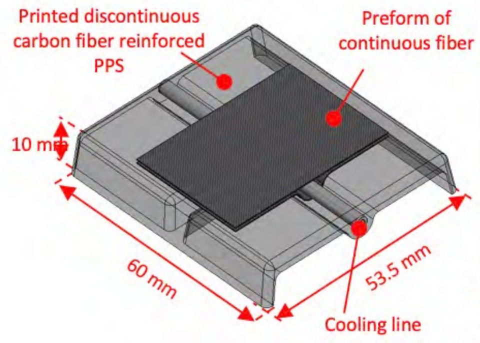
eRD112 FY24 Proposal

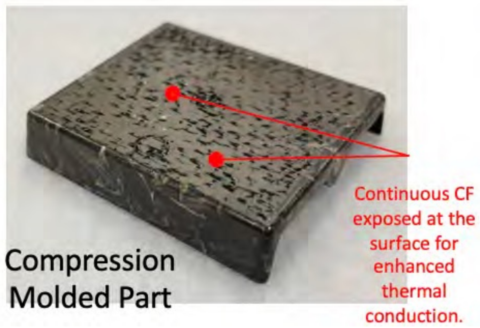
- Sensor (346k) further optimize sensor design, determine final size and yield, verify radiation tolerance
  - TCAD simulation and sensor irradiation test (20k)
  - Sensor production and characterization: BNL IO (75k+46k), HPK (80k+40k), FBK (70k+15k)
- Sensor/ASIC integration (15k)
  - Interposer to connect pixelated ASICs with strip sensors, or pixel sensors with various pitch
- Mechanical structure (53k)
  - Light-weight structure made from CF composite materials using compression or injection molding for FTOF











eRD112 FY24 Deliverables

- Optimized sensor design and final prototypes that meet ePIC requirements, including timing and spatial resolution, irradiation tolerance, and reasonably large size for module assembly
- Prototypes of interposer for mechanical/electrical connections between strip sensor and ASIC
- Prototypes of light-weight module mechanical structures for both barrel and forward TOF
- Sensor + ASIC demonstrator for EIC applications and testing with particle beam.

eRD112 (414k)

- Sensor R&D (346k$)
  - BNL, HPK/FBK productions
  - TCAD, lab/beam/irradiation tests
- Sensor/ASIC integration (15k$)
  - Interposer
- Mechanical structure ($53k)
  - Light-weight structure with cooling

eRD109 (Fernando's talk)

- Frontend ASICs
  - EICROC, FCFD
- Frontend electronics
  - Low Jitter Clock
  - Low-mass flexible PCB
  - Service hybrid

EPIC Simulation

- Geometry model, digitization and reconstruction
- Requirements on spatial, timing resolutions, and material budget

Project Engineering Design

- Engineering design for pre-TDR
- Integration & services

Sensor **ASIC** **Sensor-ASIC integration** **Services** **Prototype Module**

Summary

FY23 Report:

- AC-LGAD requirements have evolved with improved knowledge from ePIC simulation.
- Prototype HPK sensors are promising to meet the timing/spatial resolution requirements
- Development of light-weight mechanical structures for Barrel TOF staves has started

FY24 Proposal:

- Continue sensor development to further optimize and finalize design and specifications
- Develop interposer for sensor-ASIC integration
- Develop light-weight mechanical structures for Forward TOF

AC-LGAD Detectors for ePIC

Tracking and Vertexing:

- MAPS
- **AC-LGAD (30 µm)**
- MPGD

PID:

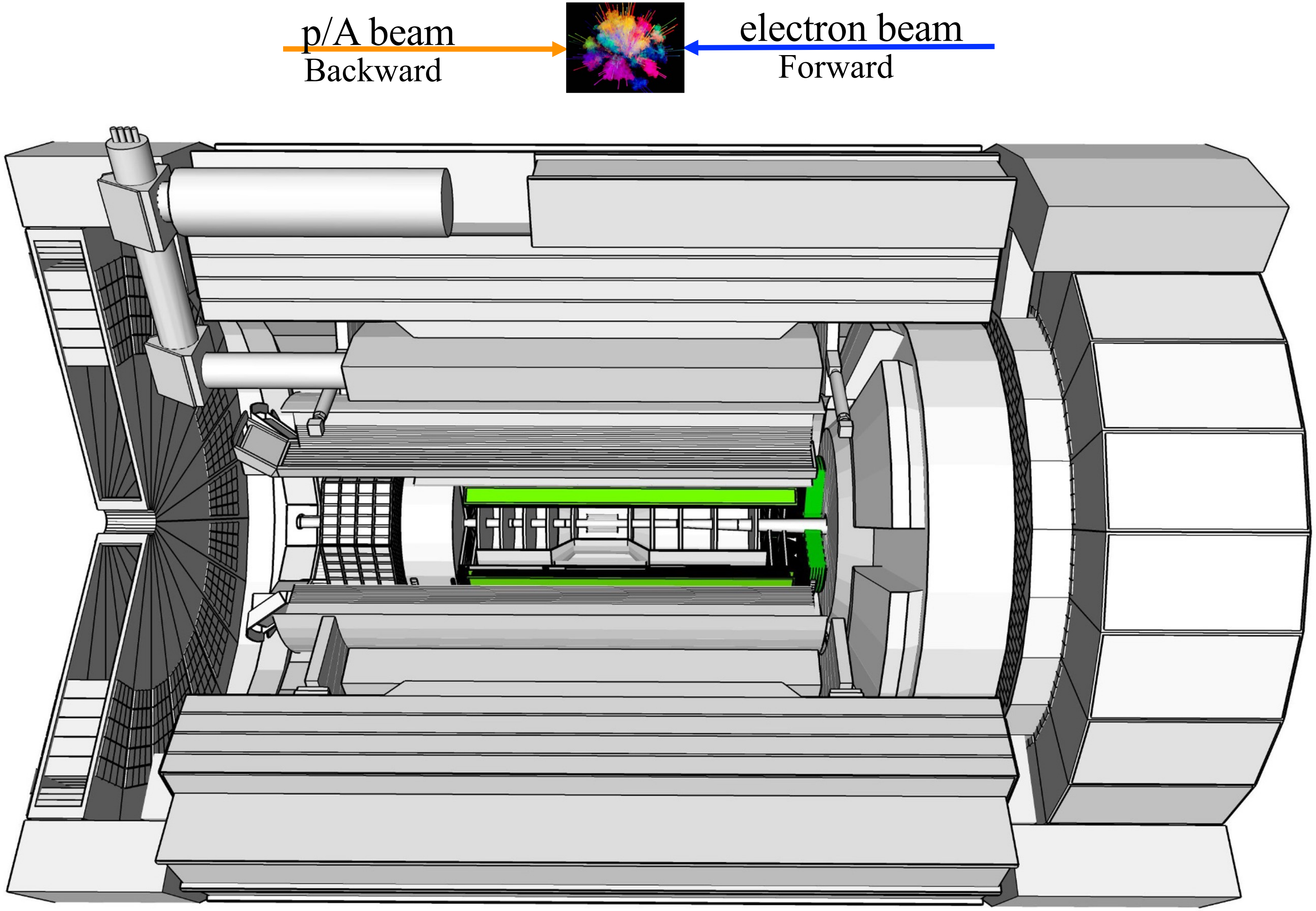
- hpDIRC
- pfRICH
- dRICH
- **AC-LGAD TOF (25/35 ps)**

Calorimetry:

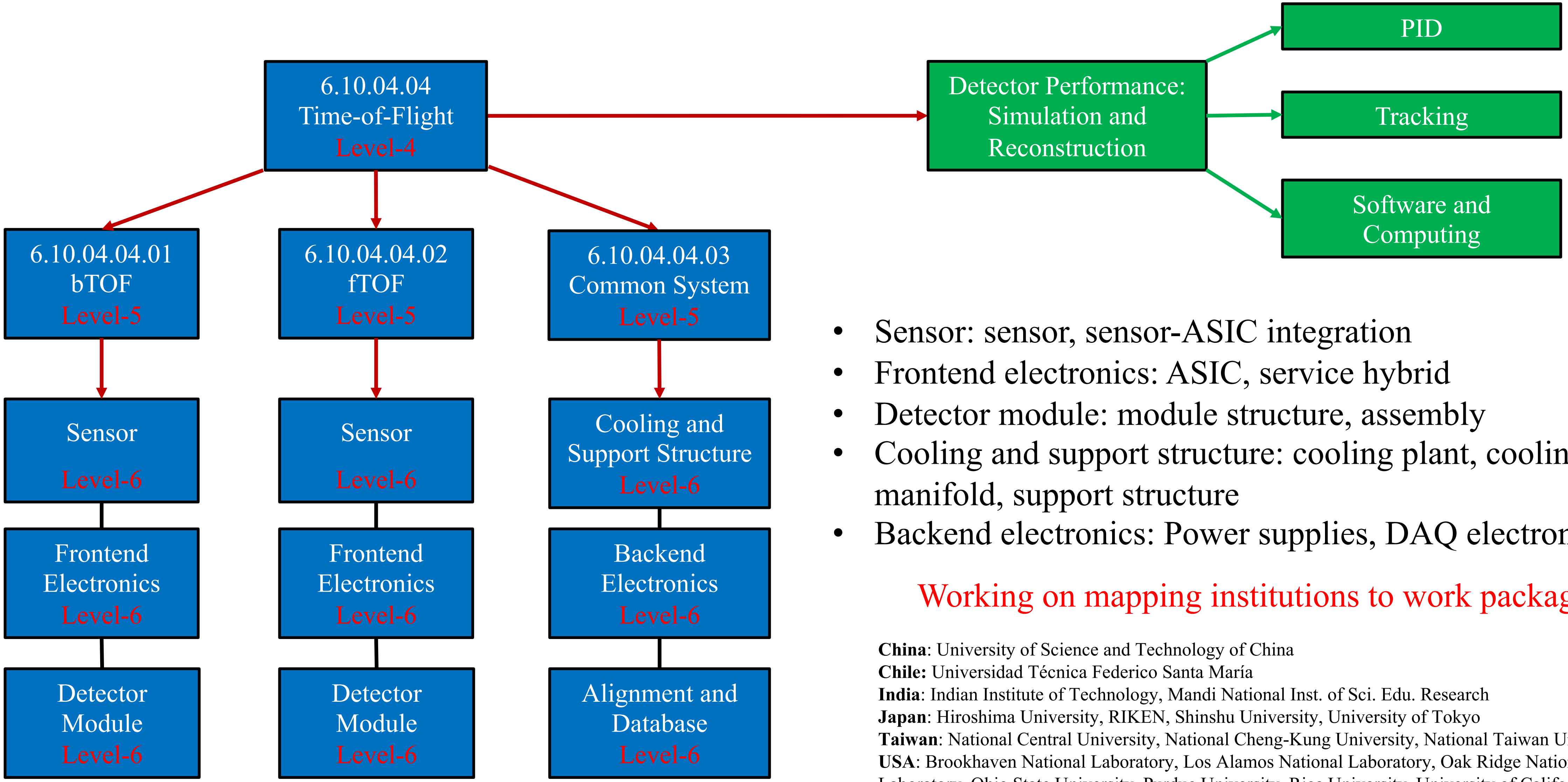
- PbWO EEMCal
- Fe/Sc Backward HCAL
- Pb/SciFi Barrel EMCal with Imaging
- Barrel HCal (sPHENIX re-use)
- W/SciFi FEMC
- Fe/Sc&W/Sc LFHCAL

Far-Forward/Backward

- Roman Pots
- B0 Tracker
- ZDC



Proposed Working Package Structure



6.10.04.04
Time-of-Flight
Level-4

Detector Performance: Simulation and Reconstruction

PID

Tracking

Software and Computing

6.10.04.04.01
bTOF
Level-5

Sensor
Level-6

Frontend Electronics
Level-6

Detector Module
Level-6

6.10.04.04.02
fTOF
Level-5

Sensor
Level-6

Frontend Electronics
Level-6

Detector Module
Level-6

6.10.04.04.03
Common System
Level-5

Cooling and Support Structure
Level-6

Backend Electronics
Level-6

Alignment and Database
Level-6

- Sensor: sensor, sensor-ASIC integration
- Frontend electronics: ASIC, service hybrid
- Detector module: module structure, assembly
- Cooling and support structure: cooling plant, cooling manifold, support structure
- Backend electronics: Power supplies, DAQ electronics

Working on mapping institutions to work packages

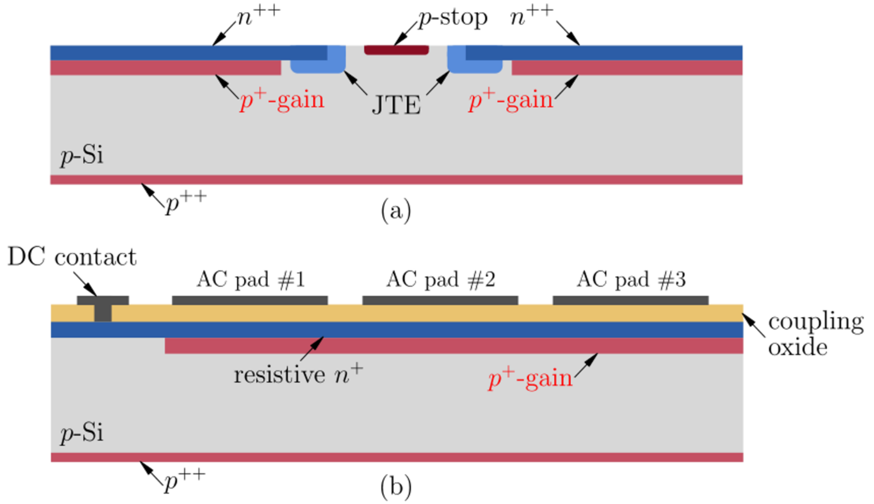
China: University of Science and Technology of China
Chile: Universidad Técnica Federico Santa María
India: Indian Institute of Technology, Mandi National Inst. of Sci. Edu. Research
Japan: Hiroshima University, RIKEN, Shinshu University, University of Tokyo
Taiwan: National Central University, National Cheng-Kung University, National Taiwan University
USA: Brookhaven National Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Ohio State University, Purdue University, Rice University, University of California - Santa Cruz, University of Illinois at Chicago

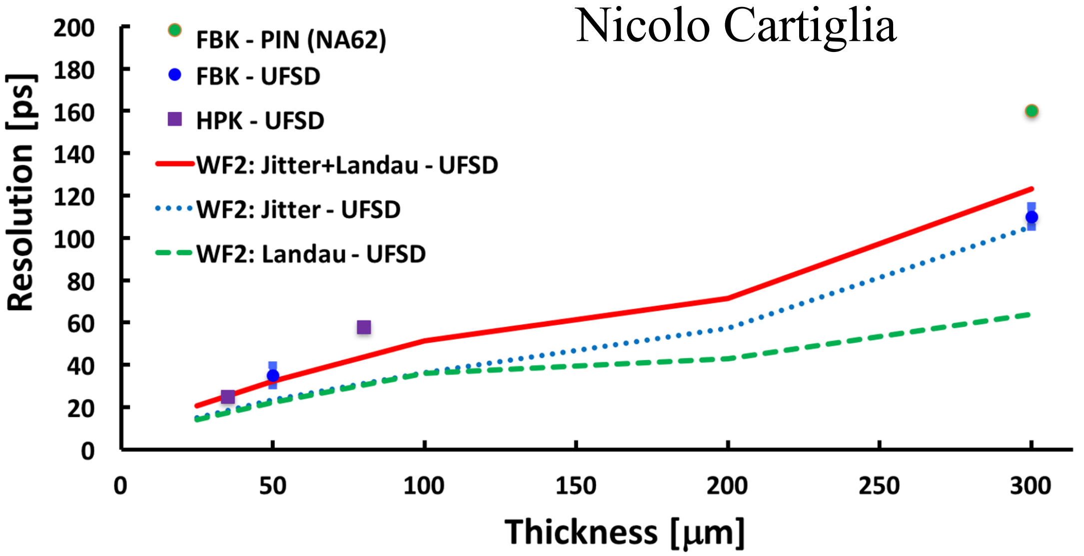
AC-coupled LGAD

- AC-LGAD provides not only precise timing resolution, but also ~100% fill factor and much better spatial resolution than DC-LGAD.

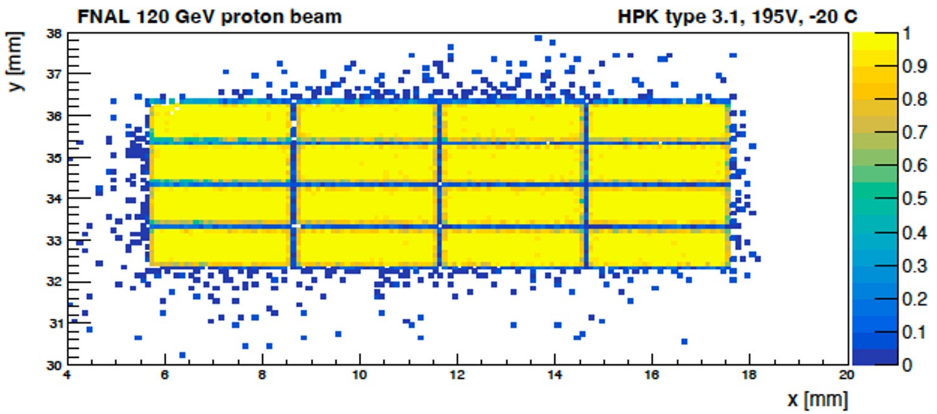
(DC-)LGAD

AC-LGAD

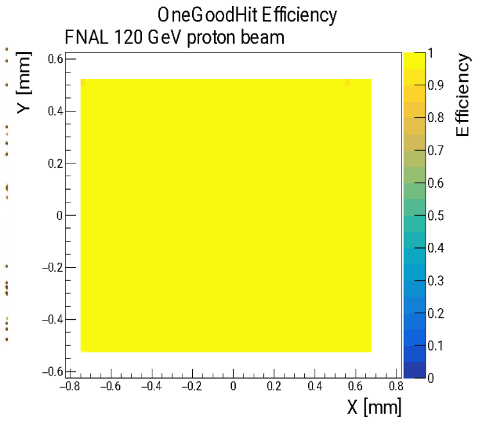




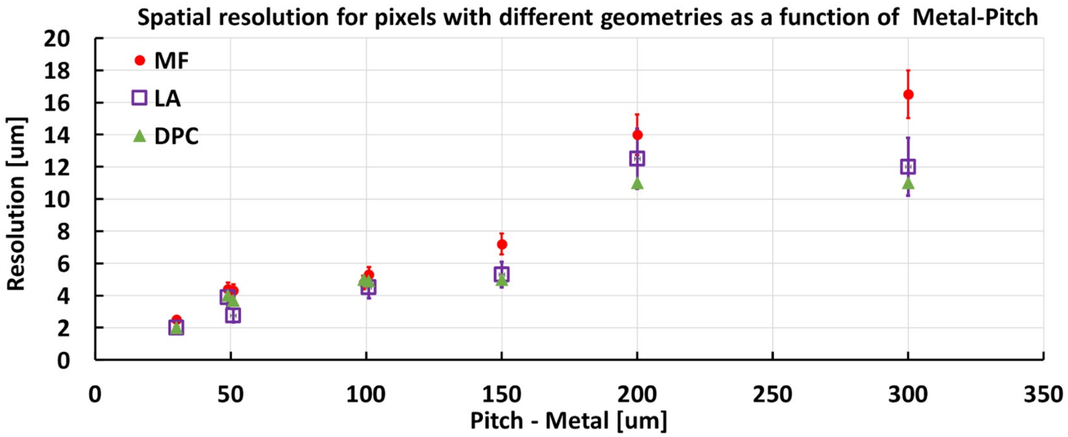
Nicolo Cartiglia



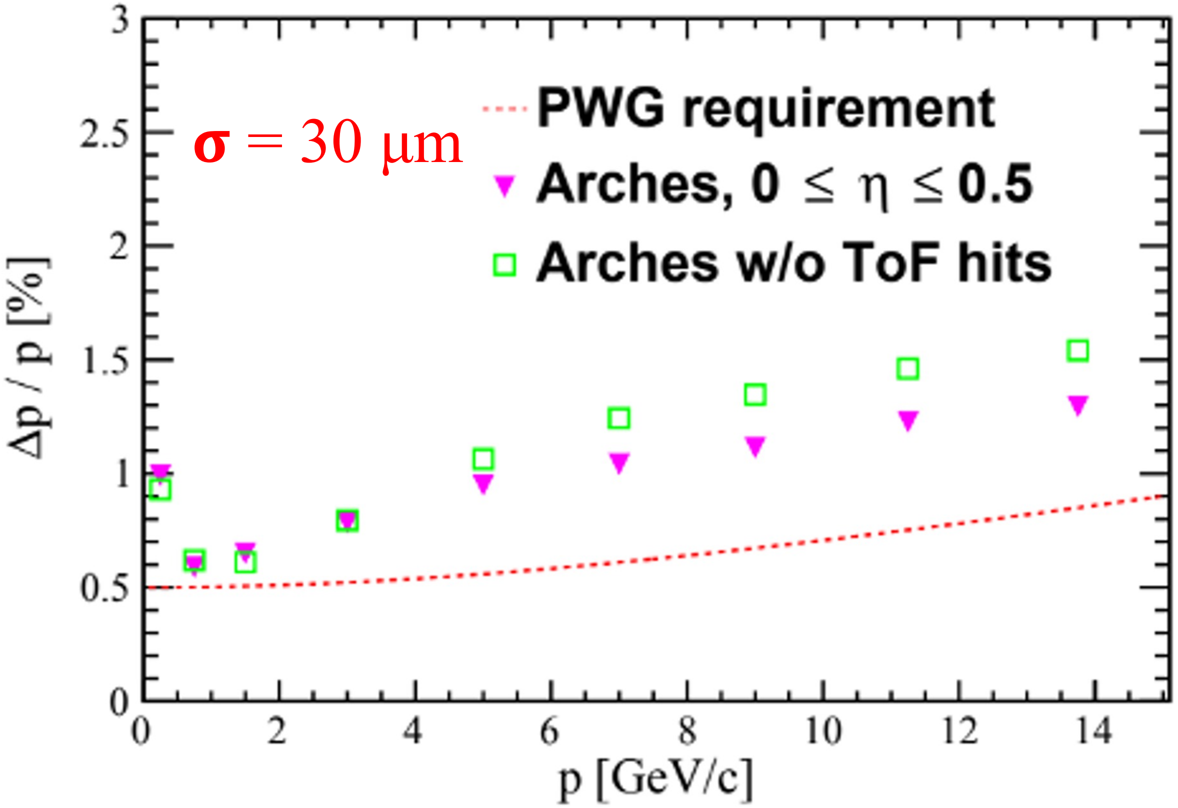
DC-LGAD

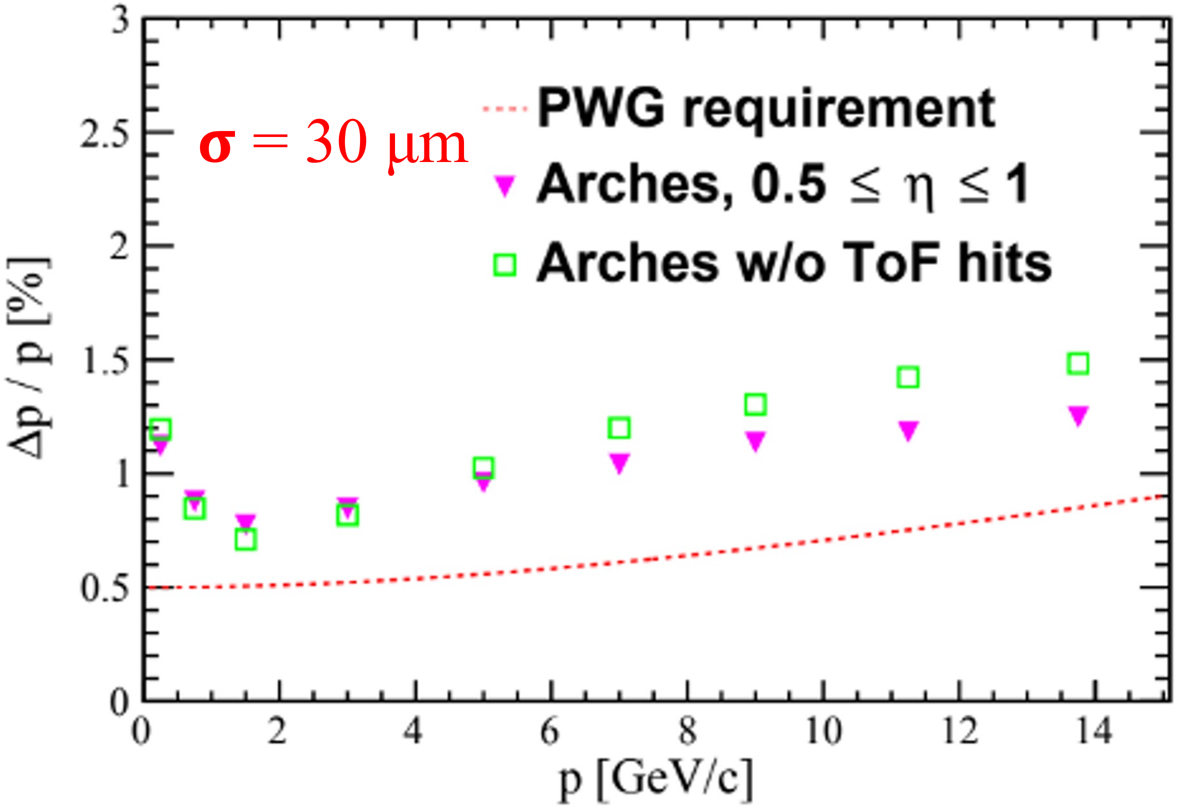


AC-LGAD



AC-LGAD TOF for Tracking in ePIC Simulation

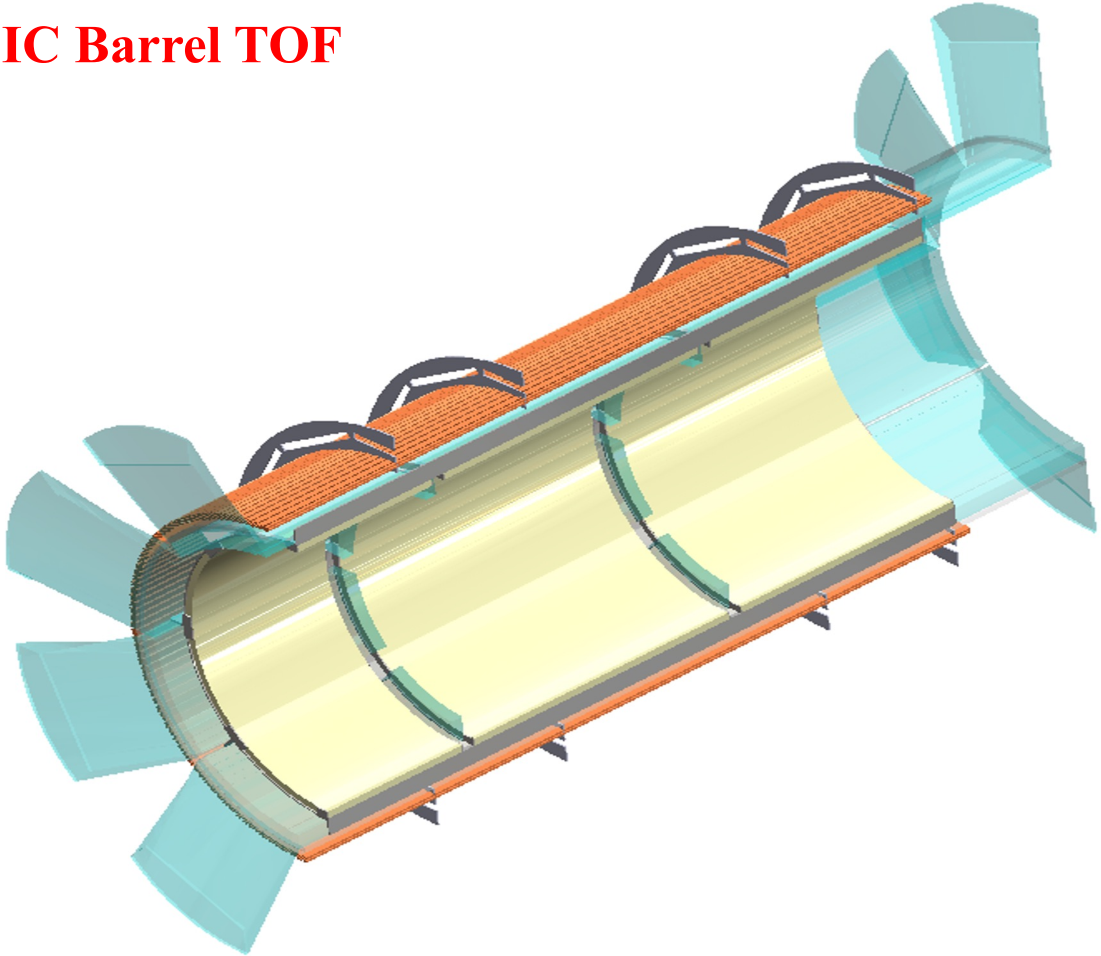




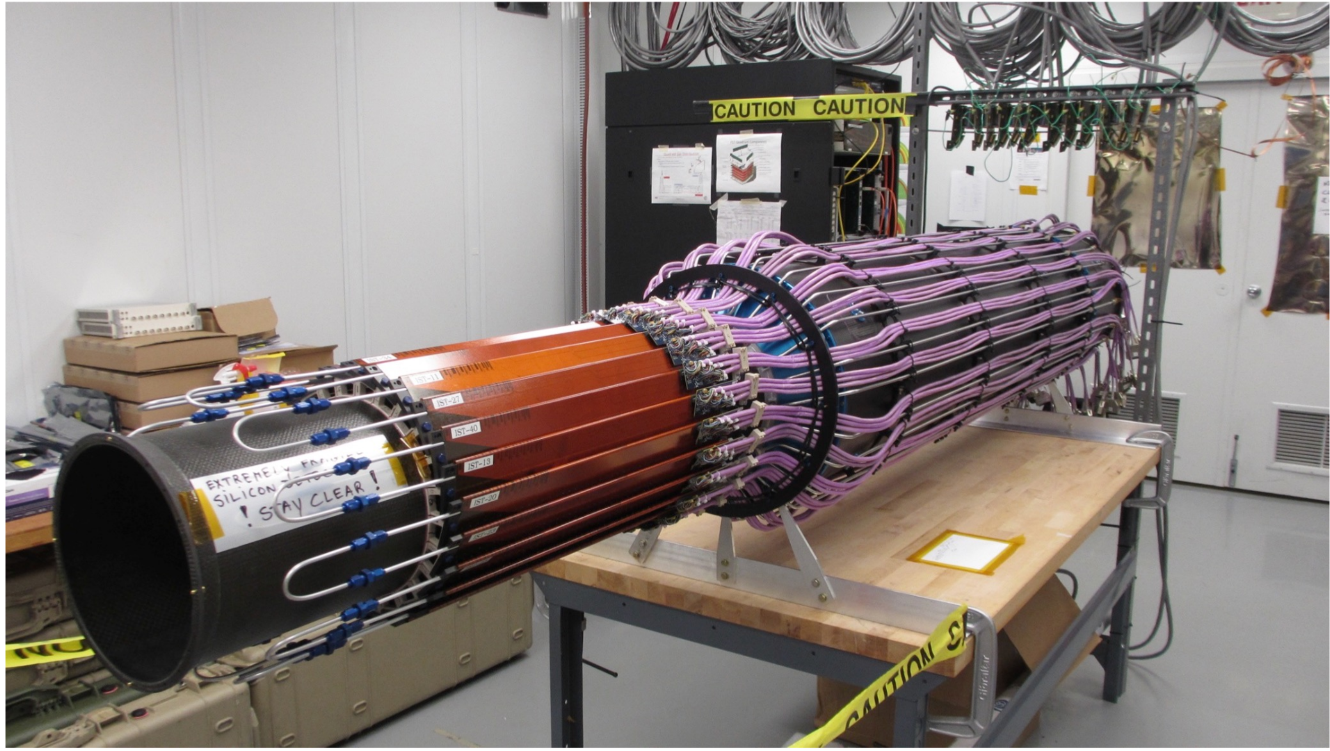
- TOF with a spatial resolution of 30 μm improves momentum resolution at high p_T
- TOF helps track reconstruction by rejecting beam background and pileup hits in Si-MAPSs

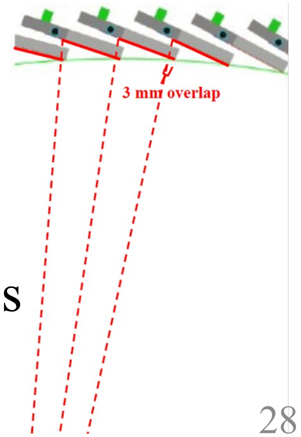
BTOF Detector Layout

ePIC Barrel TOF



STAR Intermediate Silicon Tracker

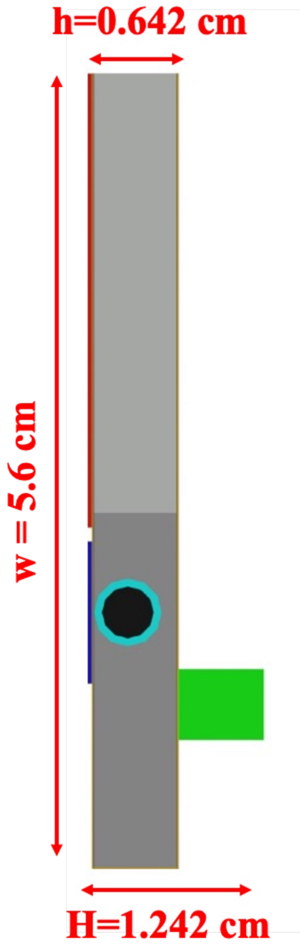


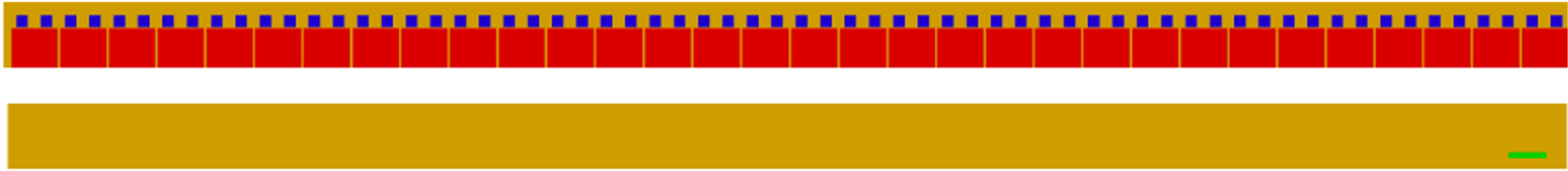


ePIC BTOF follows cylindrical silicon tracker design (e.g. STAR IST)

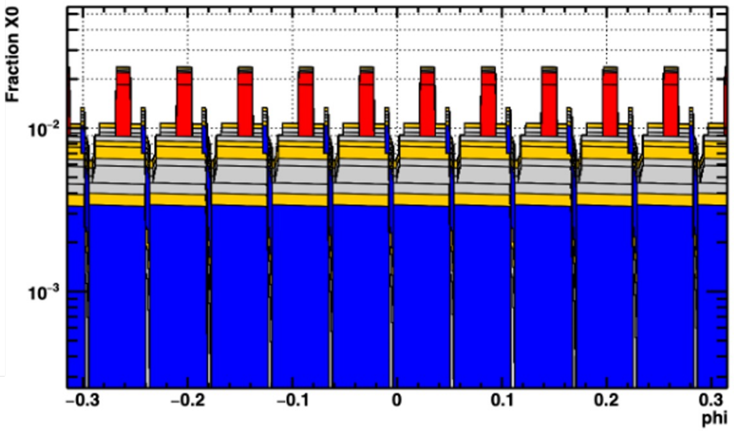
- Tilted stave modules overlap in phi to fully cover the azimuthal 2**π** angle
- Readout boards connected to the end of staves are outside of the BTOF acceptance Cooling tubes with liquid coolant at room temperature to take the heat generated by frontend ASIC

BTOF Detector Module Conceptual Design





- **64 AC-LGAD strip sensors**, each 3.2*4 cm^2 read out by **2 ASICs**
- **Low mass flexible Kapton PCB** distributes power and I/O signals from connector
- **Liquid coolant** in **Al tube** embedded in CF light-weight structure for heat removal

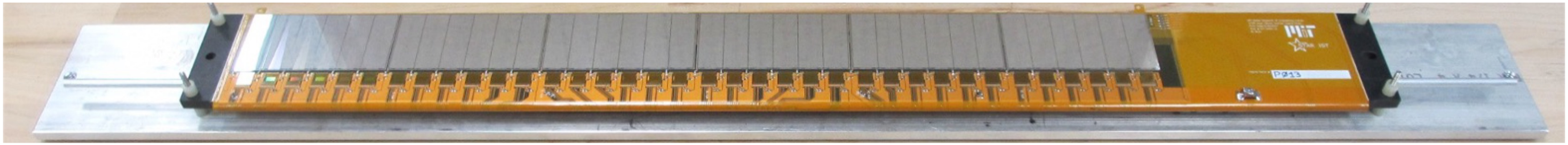


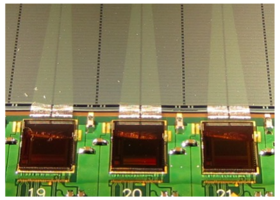
144 modules, each with 2 readout boards with 2 LV+HV cables, 2 DAQ fiber, and 1 cooling line

Power consumption: ~4 kW (2.4kW for ASIC, 1 kW for DC-DC, 0.6kW for sensors+cable)

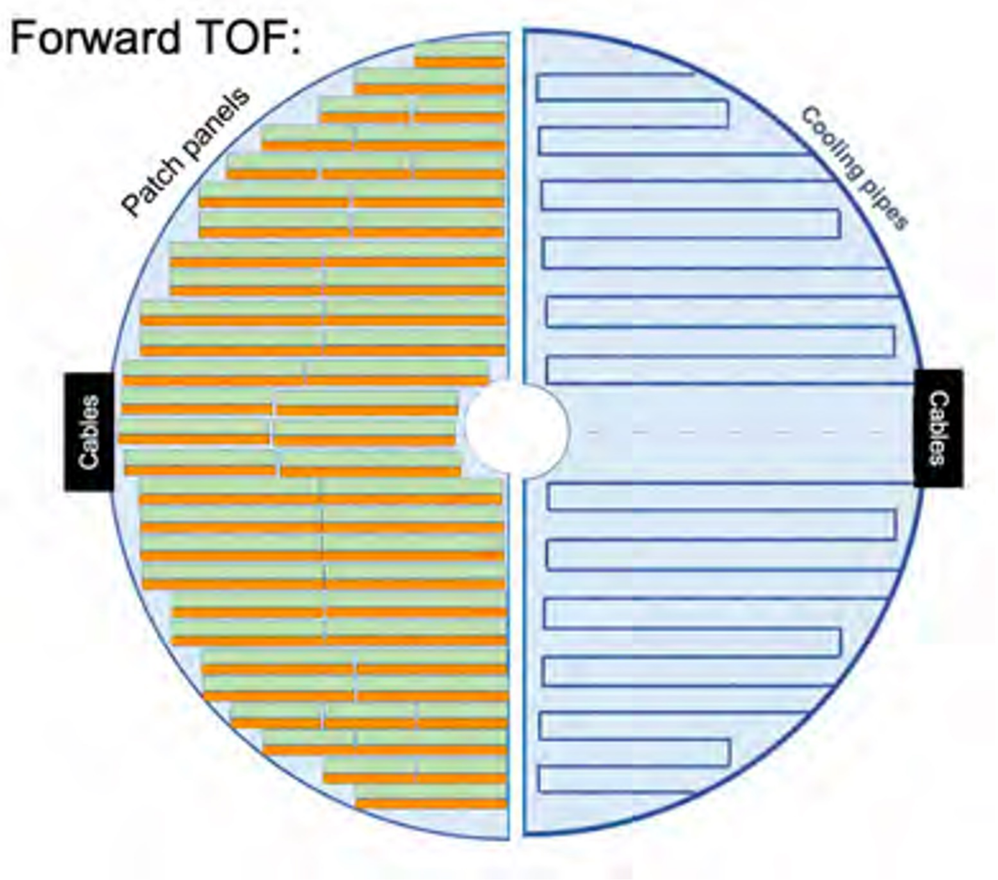
Total weight: ~70 kG

STAR IST

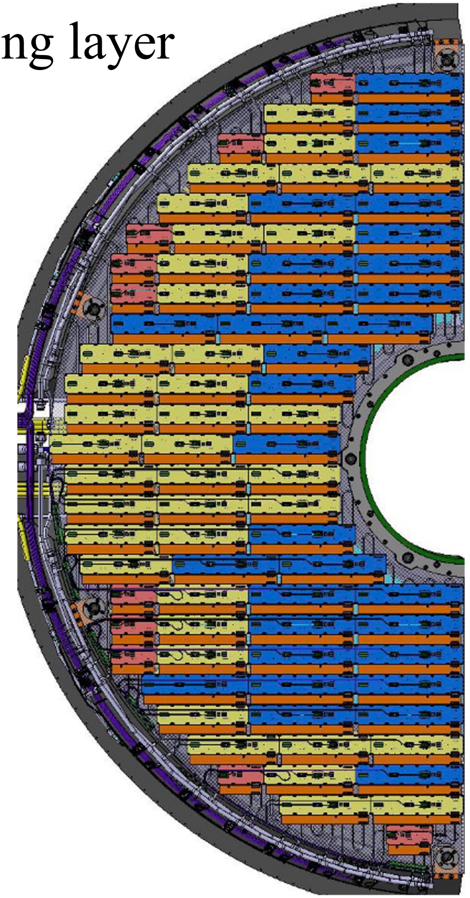




FTOF Detector Layout



CMS endcap timing layer



Forward TOF layout, based on the CMS ETL design:

- Two halves DEEs made of light-weight (carbon fiber) support structure, tiled by rectangular modules of three types with different lengths
- Cooling tubes with coolant at room temperature to take the heat generated by frontend ASICs and other electronic elements

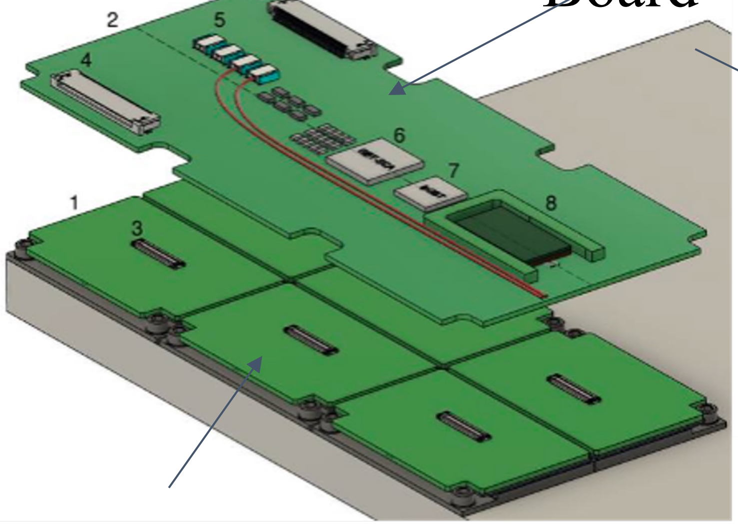
FTOF Detector Module Conceptual Design

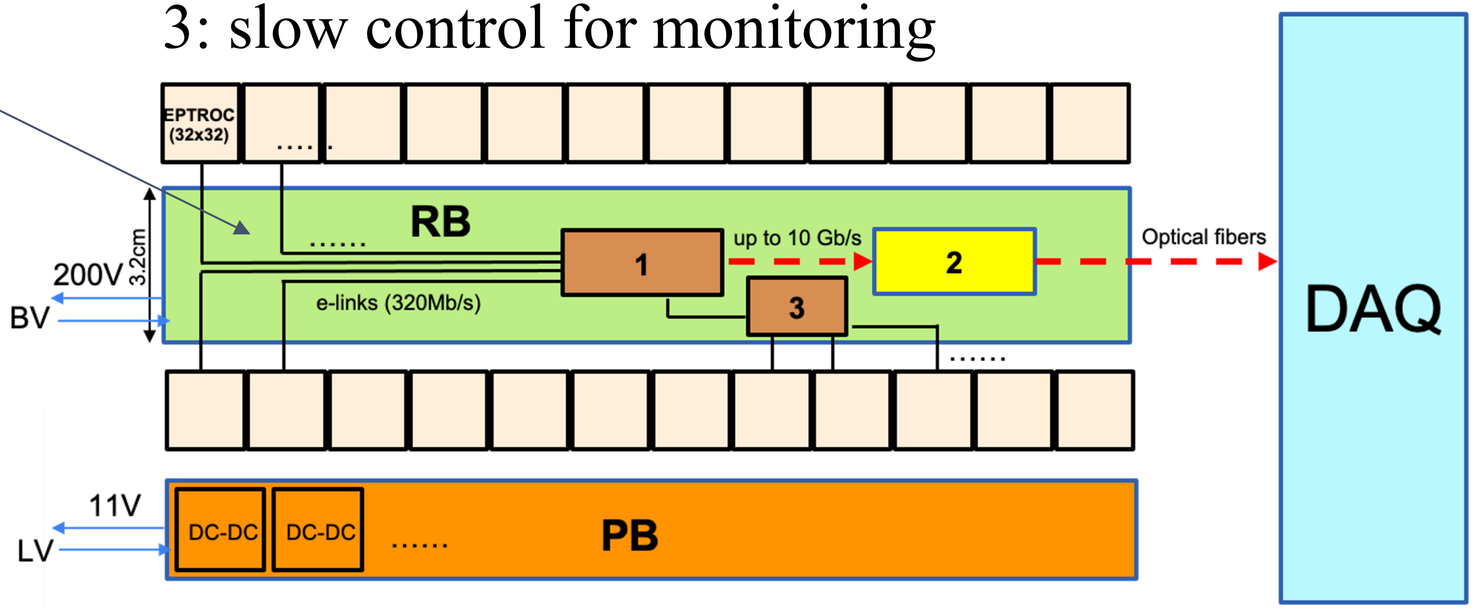
Readout Board

1: data transceiver FPGA chip

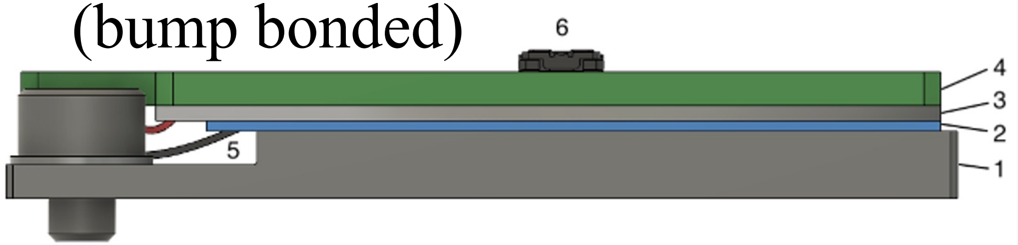
2: optical link module (e.g., CERN VTRx+)

3: slow control for monitoring





LGADs+EICROC (bump bonded)

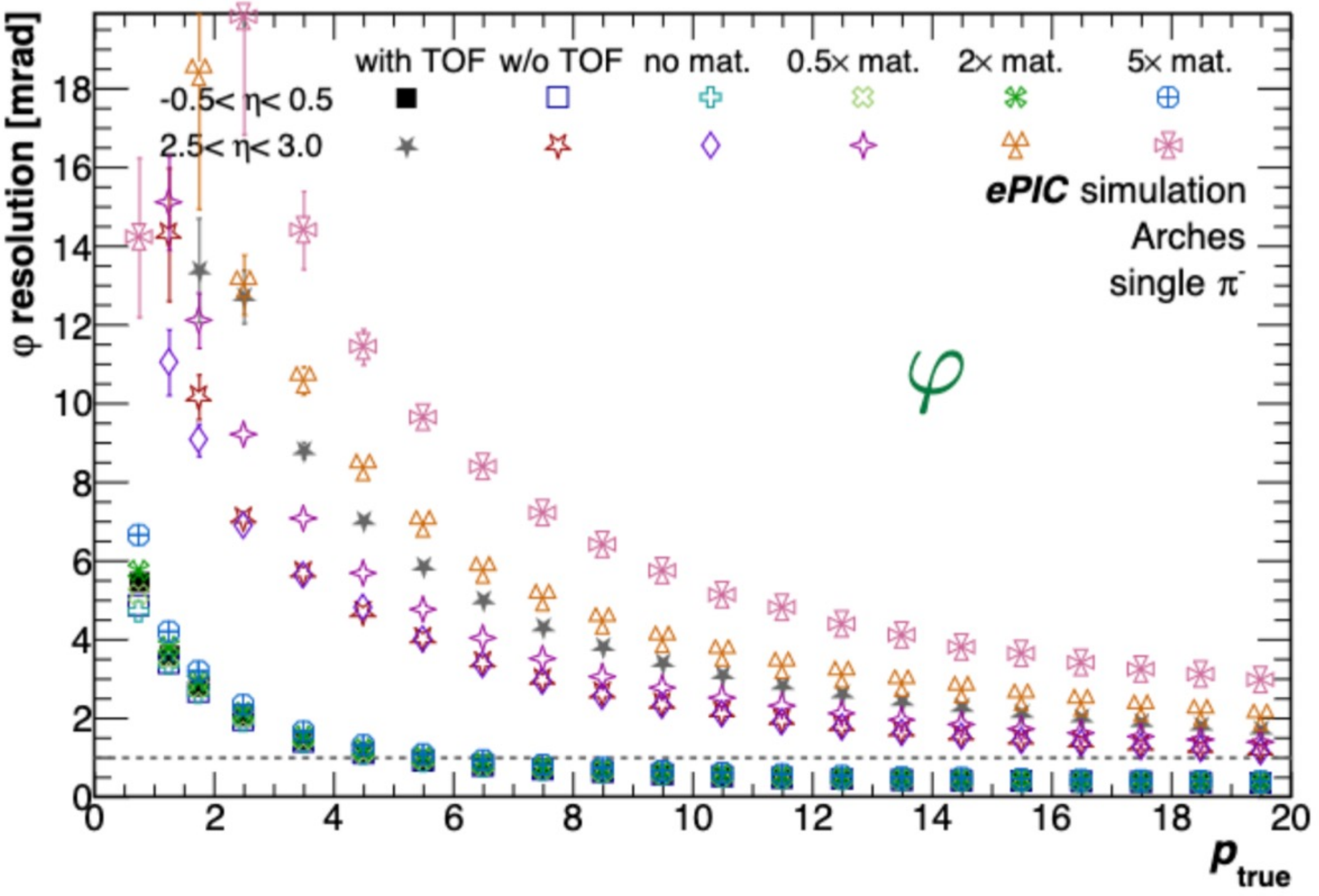


212 readout boards, each has: 1 fiber to DAQ, 2 LV cables (1 supply, 1 return) and 2 BV cables (1 supply, 1 return)

Power consumption: ~13 kW (8.5kW for ASIC, 3.5 kW for DC-DC, 1kW for sensors+cable)

- Considering 0.7x0.7 mm^2 sensor design, which reduces the power budget by ~50%

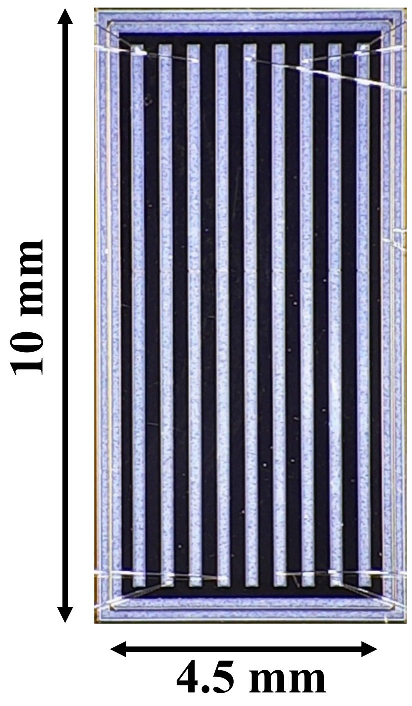
Impact of TOF Material on Angular Resolution

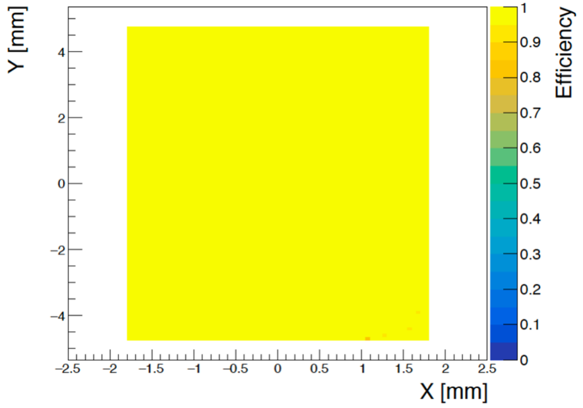


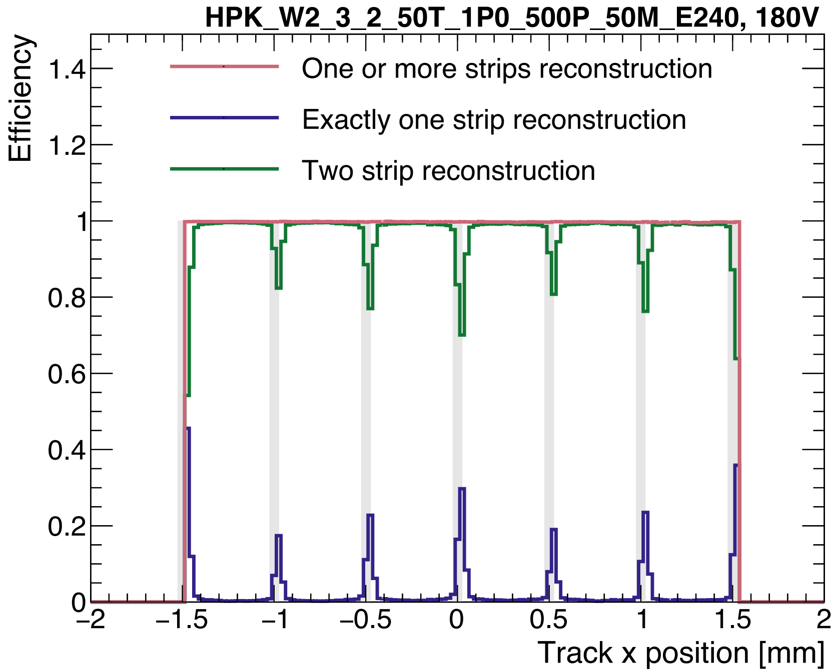
1x mat. = 1%. X_0 for BTOF
5 %. X_0 for FTOF

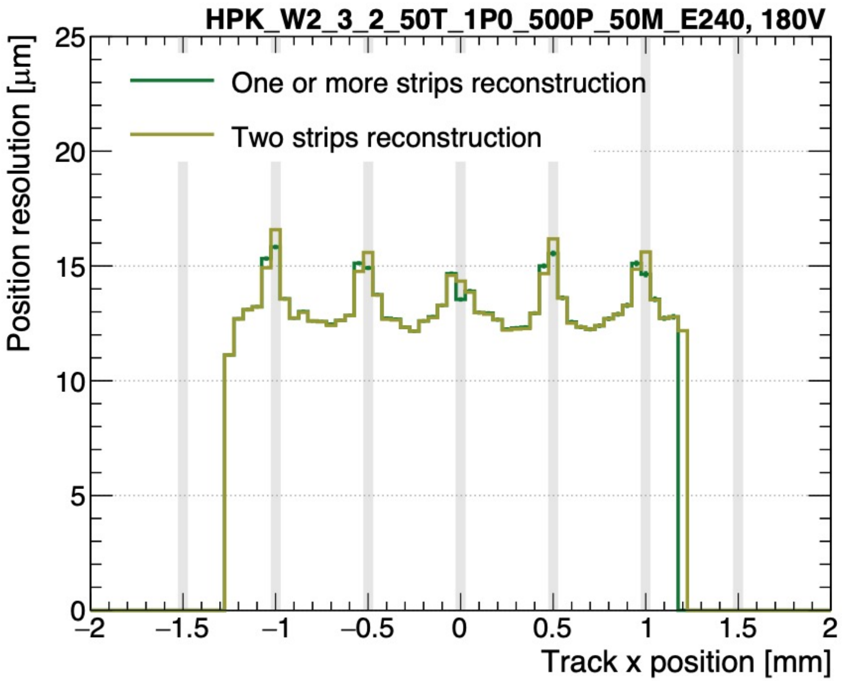
Efficiency and Spatial Resolution of HPK Sensors

HPK Strip Sensor



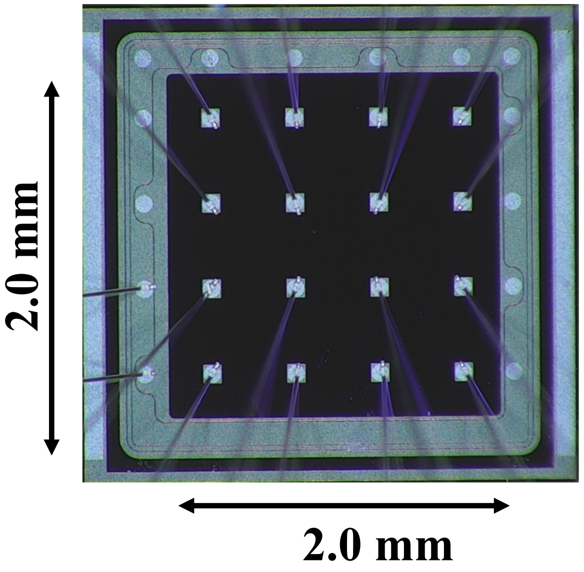


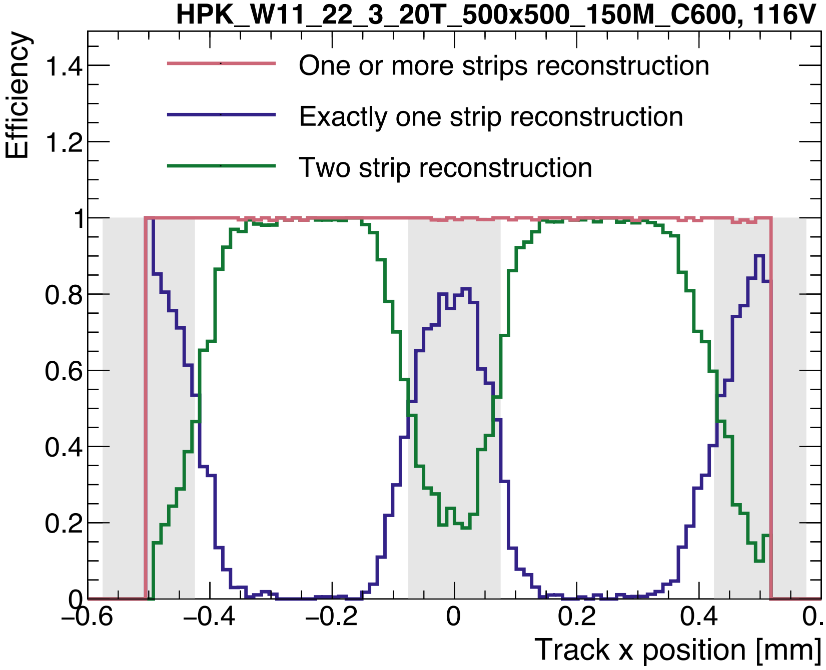


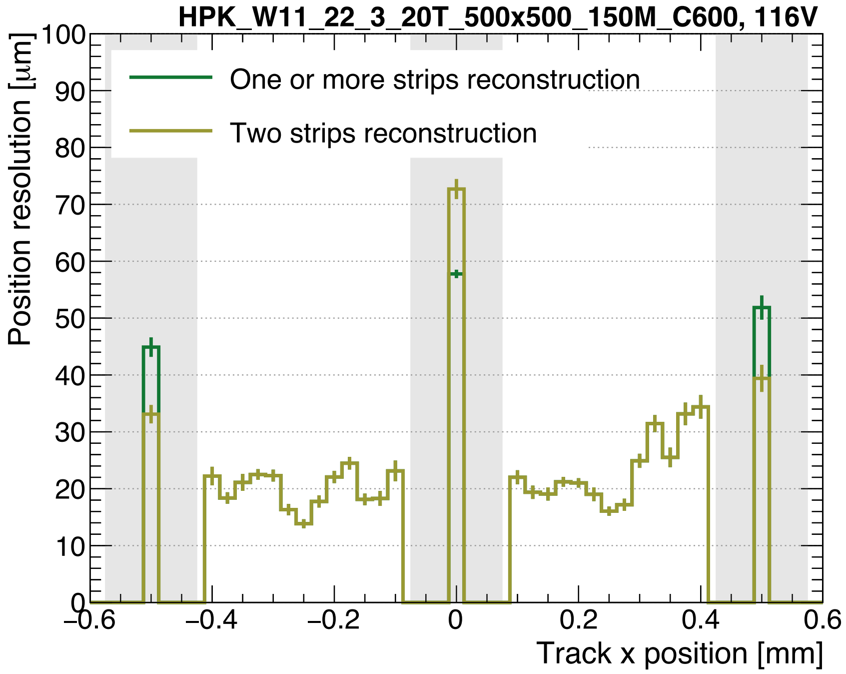


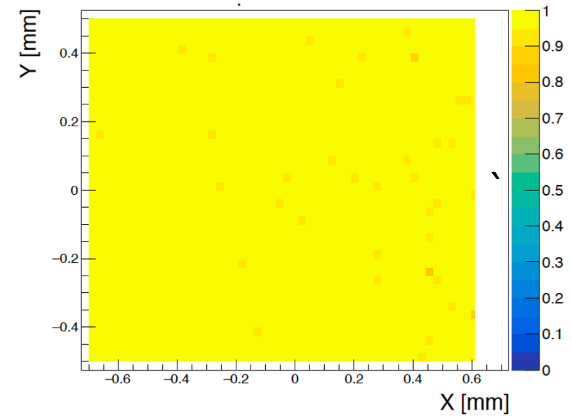
Efficiency and Spatial Resolution of HPK Sensors

HPK Pixel Sensor



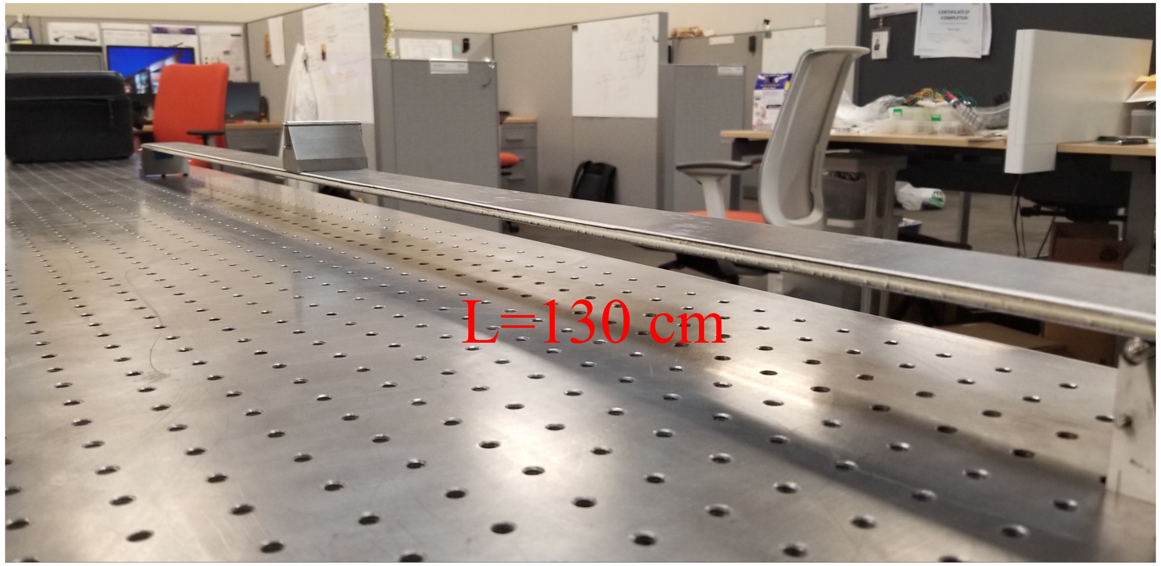


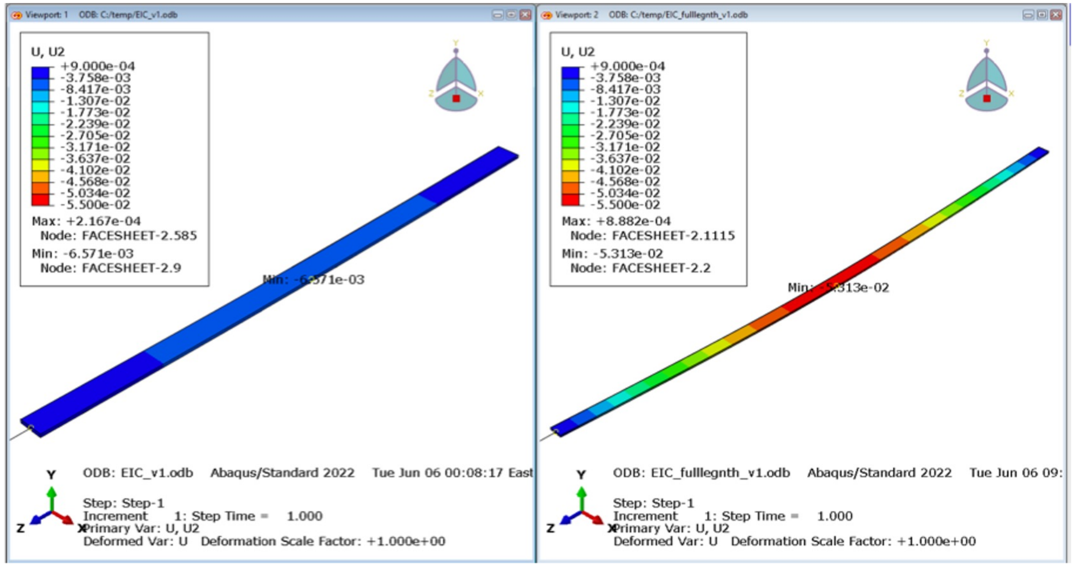




Development Status and Plan

- **AC-LGAD sensor**
  - Goal: large area sensors that meet timing/spatial resolution requirements with minimal # of channels
  - Status: prototype sensors produced by BNL IO and HPK and tested in the lab/beam (next slide)
  - Plan: further optimization for possible better timing and less # of channels, verify sensor size and radiation tolerance
- **Lightweight mechanical structure**
  - Goal: light-weight structure with cooling that meet the material budget, thermal and mechanical requirements
  - Status: first prototype produced with CF sheet+form, detailed analysis and measurement in progress
  - Plan: produce prototypes with cooling tubes, start looking into support structure and cooling system design





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Max: +2.167e-04
 Node: FACESHEET-2.585
Min: -6.571e-03
 Node: FACESHEET-2.9

ODB: EIC_v1.odb    Abaqus/Standard 2022    Tue Jun 06 00:08:17 East

Step: Step-1
Increment     1: Step Time =    1.000
Primary Var: U, U2
Deformed Var: U   Deformation Scale Factor: +1.000e+00
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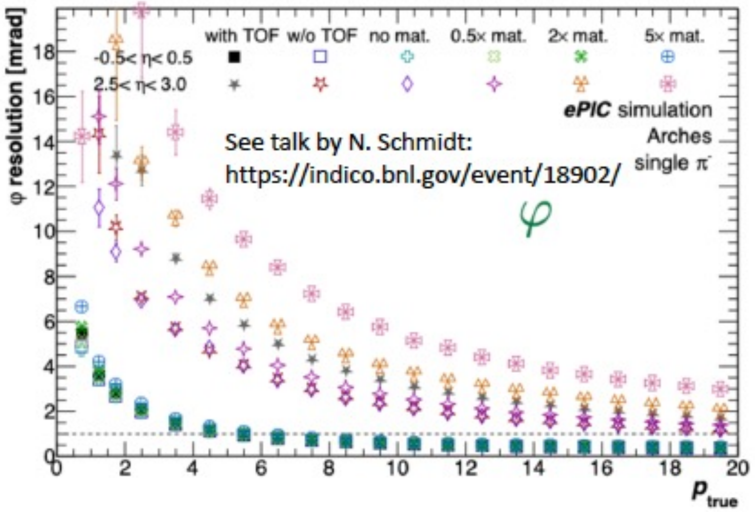
Max: +8.882e-04
 Node: FACESHEET-2.1115
Min: -5.313e-02
 Node: FACESHEET-2.2

ODB: EIC_fulllegnth_v1.odb    Abaqus/Standard 2022    Tue Jun 06 09:

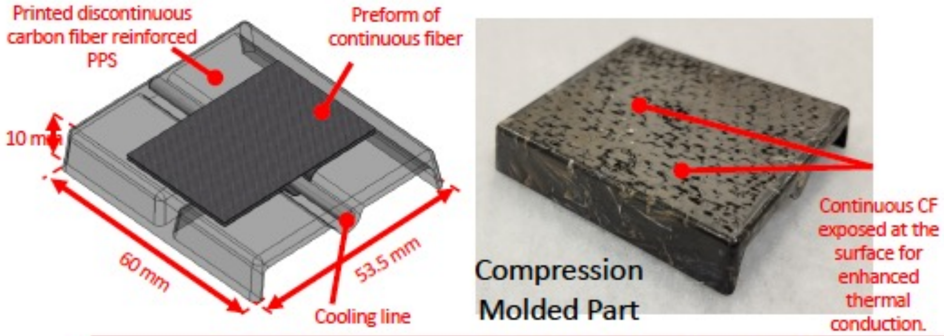
Step: Step-1
Increment     1: Step Time =    1.000
Primary Var: U, U2
Deformed Var: U   Deformation Scale Factor: +1.000e+00
```

Endcap TOF

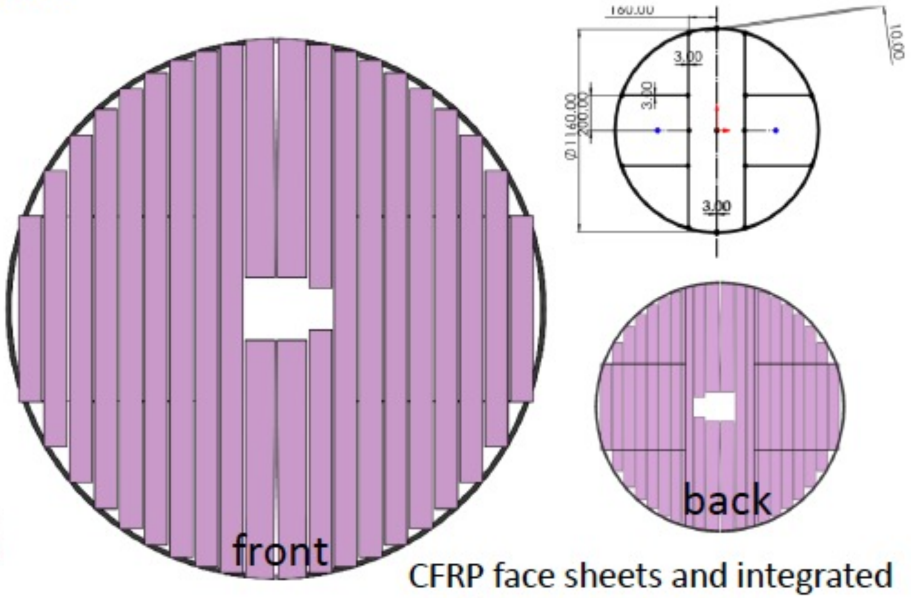
- ○ Material budget critical for performance of dRICH
  - Heat load: 13.6 kW (Aim for 1mW / channel)
  - 5% material budget and possible to reduce to 2.5% w advanced composites
  - Detailed X_0 studies under way
- ○ Following two design choices
  - More “traditional” composite structure with sandwich + metal thin pipes
    - ○ Re-use “staves” or wedges
  - Cutting-edge: “no-pipe” design



See talk by N. Schmidt: https://indico.bnl.gov/event/18902/



Compression Molded Part



CFRP face sheets and integrated cooling stave structure