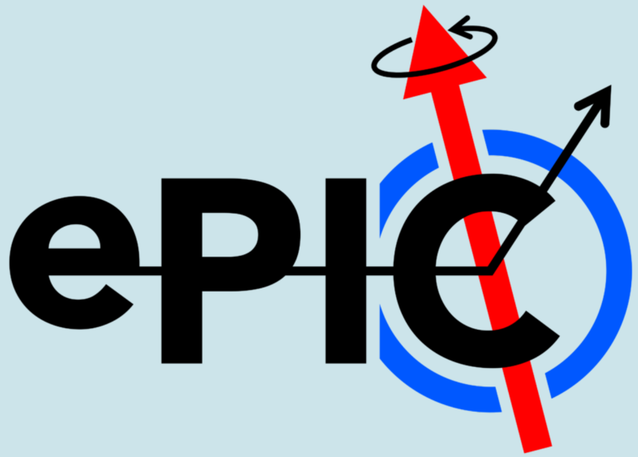


AC-LGAD Workfest Report

Satoshi Yano (Hiroshima University)

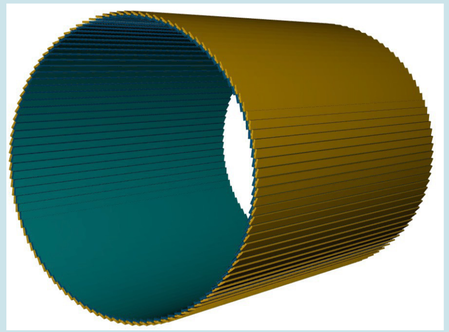
ePIC Collaboration meeting @ Lehigh University

07/27/2024

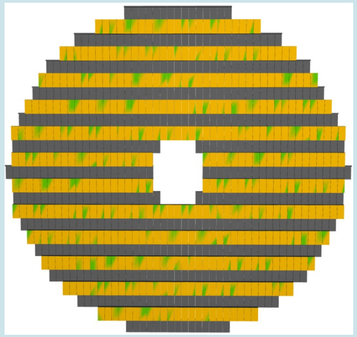
Overview

- Description: Discussion and coordination of detectors using AC-LGAD sensor, BTOF, FTOF, and FF detectors

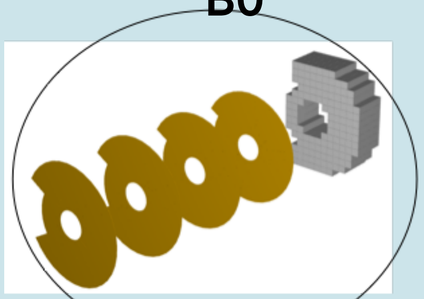
BTOF



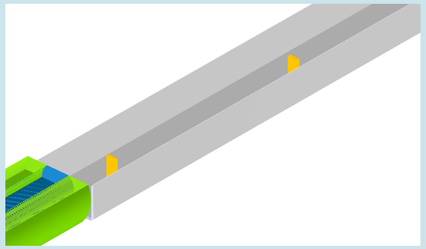
FTOF



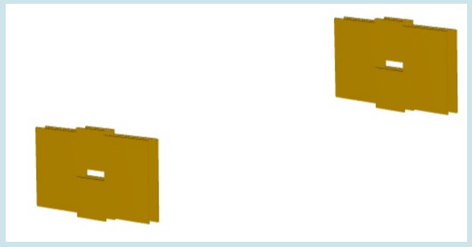
B0



OMD



Roman Pots

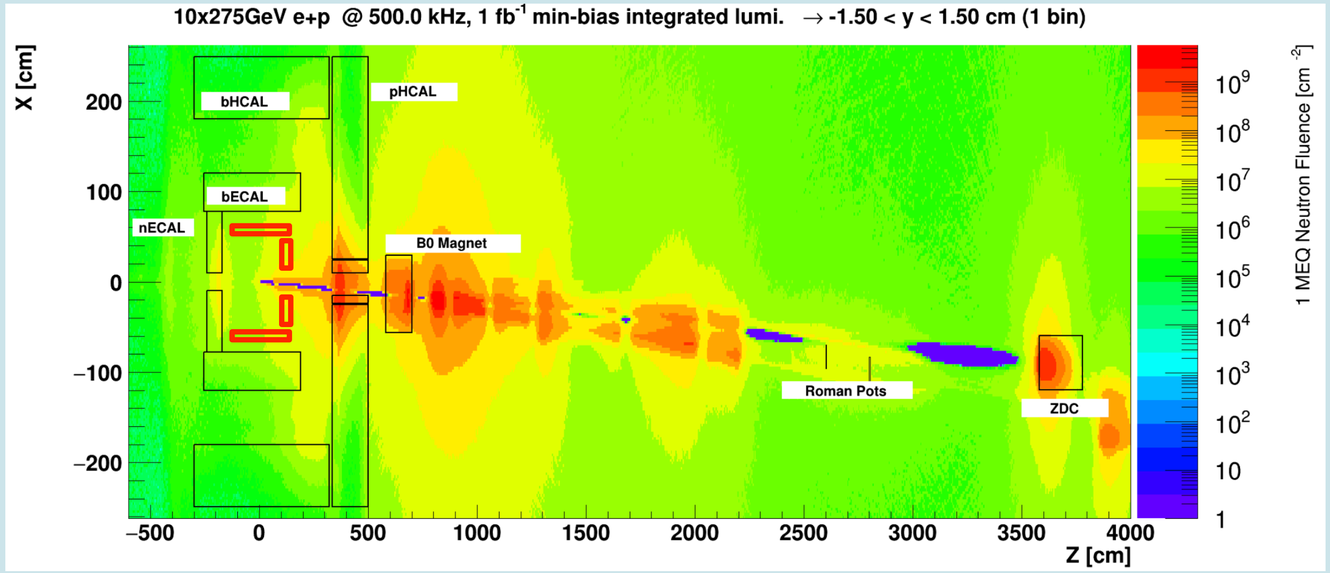


Print | PDF | Full screen | Detailed view | Filter

13:00	**Introduction**	*Zhangbu Xu*
	Rm 85, Rauch Business Center	13:00 - 13:10
	Barrel TOF	*Satoshi Yano*
	Rm 85, Rauch Business Center	13:10 - 13:25
	Forward TOF	*Prof. Wei Li*
	Rm 85, Rauch Business Center	13:25 - 13:40
	FF AC-LGAD detectors	*Alexander Jentsch*
	Rm 85, Rauch Business Center	13:40 - 14:05
14:00	**Luminosity Tracker**	
	Rm 85, Rauch Business Center	14:05 - 14:06
	eRD112	*Alexander Jentsch et al.*
	Rm 85, Rauch Business Center	14:20 - 14:45
	Coffee Break	
15:00	*Rm 85, Rauch Business Center*	14:45 - 15:15
	FCFD	*Artur Apresyan et al.*
	Rm 85, Rauch Business Center	15:15 - 15:30
	EICROC	*Christophe de la Taille*
	Rm 85, Rauch Business Center	15:30 - 15:45
	Electronics	*Prof. Wei Li*
16:00	*Rm 85, Rauch Business Center*	15:45 - 16:05
	Support structure & PCB & Cooling	*Oskar Hartbrich*
	Rm 85, Rauch Business Center	16:05 - 16:25
	Digitization	*Prithwish Tribedy*
	Rm 85, Rauch Business Center	16:25 - 16:45
	Discussion	
17:00	*Rm 85, Rauch Business Center*	16:45 - 17:05

Requirements for AC-LGAD

	Area (m^2)	channel size (mm^2)	# of channels	Timing reso.	Spatial reso.	Material budget
BTOF	12	0.5x10	2.4M	35 ps	30 μm in r⋅ ϕ	0.01 X_0
FTOF	1.4	0.5x0.5	5.6M	25 ps	30 μm in x⋅y	0.025 X_0
B0	0.07	0.5x0.5	0.28M	30 ps	20 μm in x⋅y	0.05 X_0
RPs/OMD	0.14/0.08	0.5x0.5	0.56M/0.32M	30 ps	140 μm in x⋅y	no strict req.



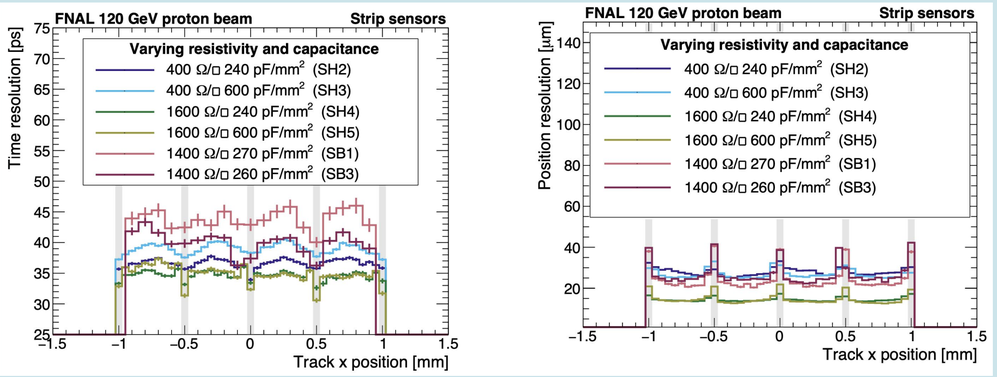
https://wiki.bnl.gov/EPIC/index.php?title=Radiation_Doses

- BTOF uses strip-type and FTOF/FF use pixel-type sensors
- Cooling strategy and support structure of FF is different from BTOF/FTOF due to spatial limitation
- Doses are ~1e2 smaller than LHC levels for the ePIC environment

AC-LGAD performance

- eRD112 presented FY24 report and FY25 plan
- Previous test beam campaign has been finalized
  - Timing resolution of 35 ~ 45 ps, and spatial resolution of 15 ~ 30 μm are achieved by BNL and HPK prototypes
  - The results are under control and the next prototype will be improved

Beam test @ FNAL results



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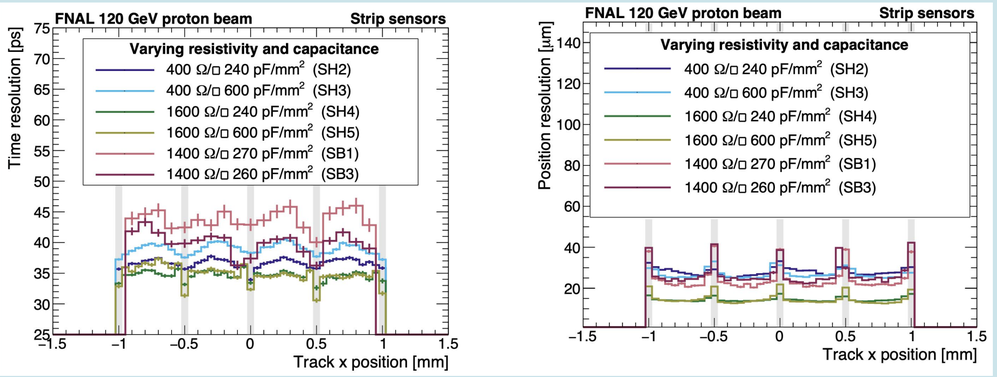
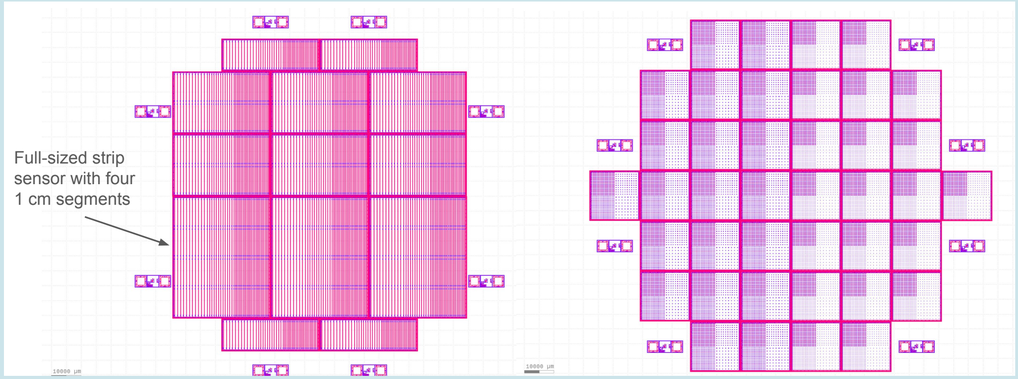


Next prototype scheme



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- Readout board from SCIPP will be used to characterization these sensors

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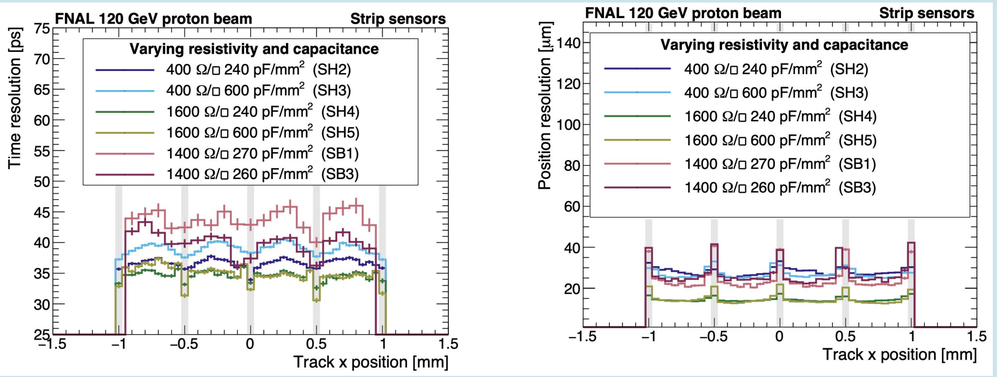

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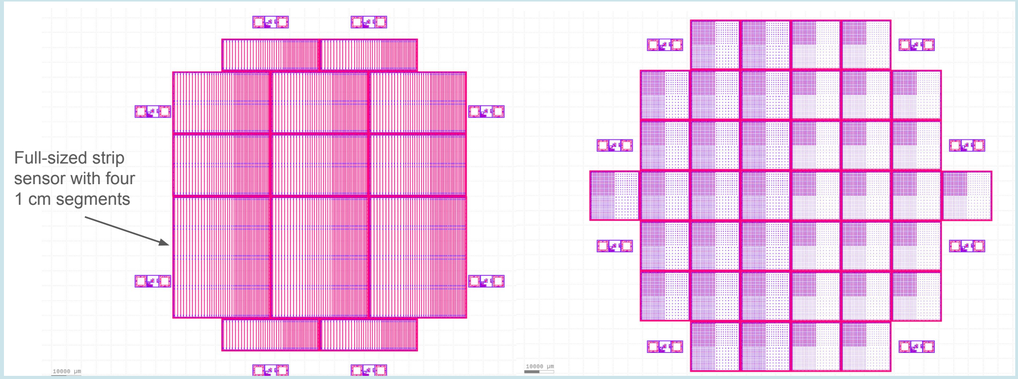
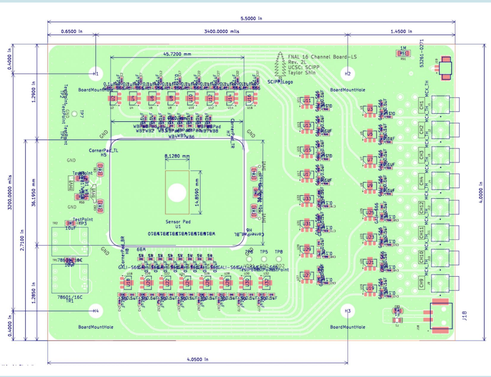


SCIPP RDO blueprint



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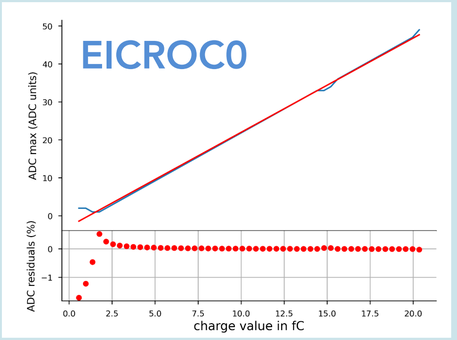
Charge v.s. ADC



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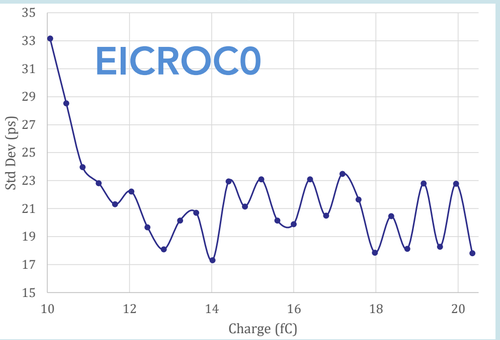

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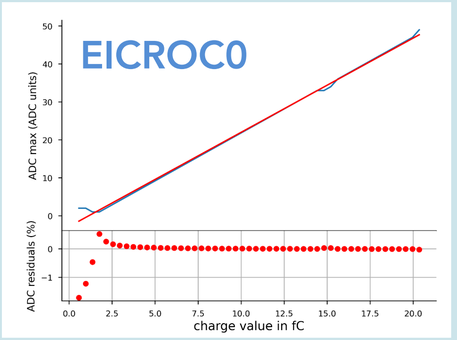

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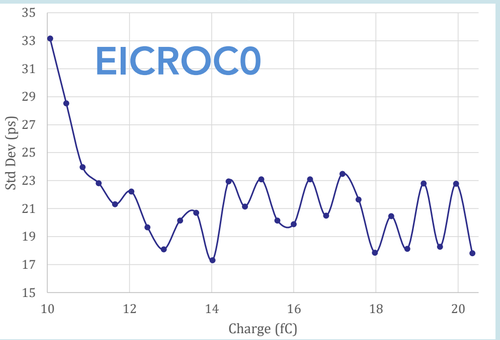

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  - The timing resolution of the FCFD + sensor is 55 ps without corrections has been reported
  - The performance is affected by the AC-LGAD larger input capacitance than expected
    - After matching the input capacitance, 35 ps timing resolution is expected

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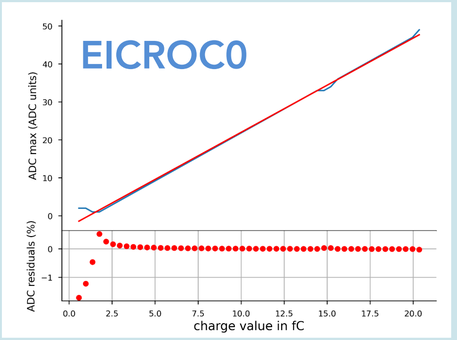

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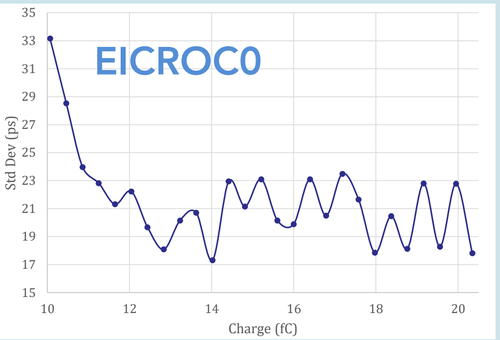
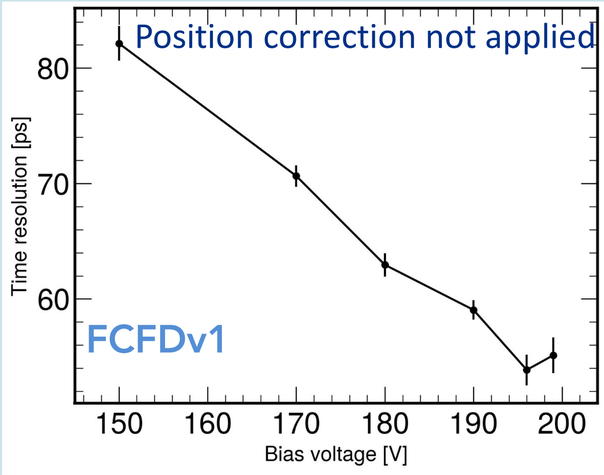


Timing reso. w/ AC-LGAD



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- FCFDv2 with a digital block full-size prototype will be obtained @ end of 2025

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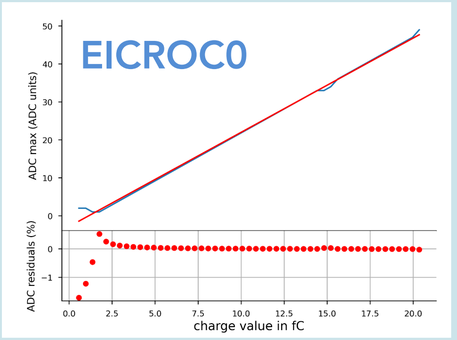

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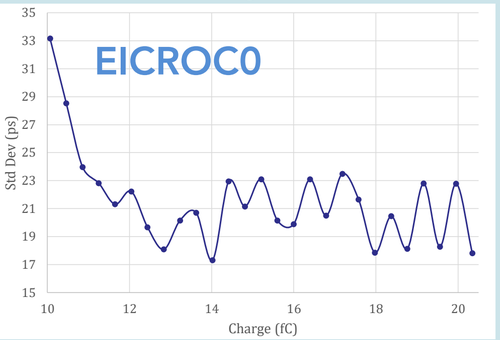

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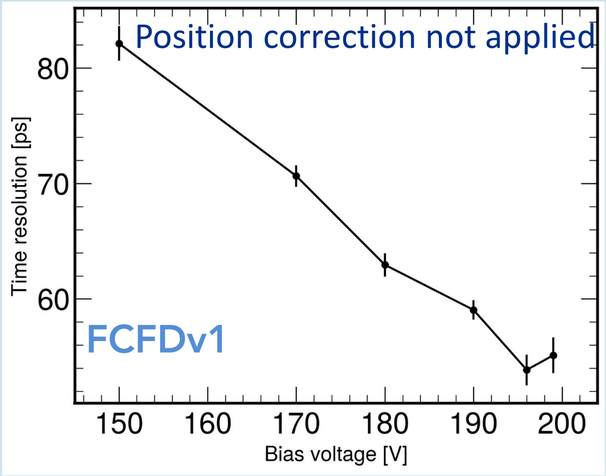
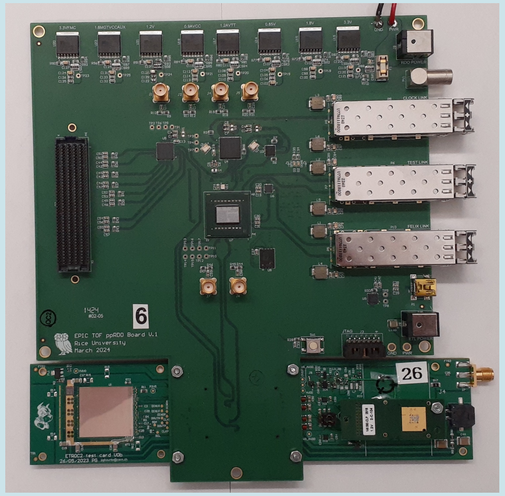


Front-end electronics

- Pre-prototype readout board (ppRDO) has been made with ETROC2 ASIC
  - 6 boards are available
- Several tests are ongoing
  - FPGA firmware development
  - Readout test with ETROC2
  - Evaluation of power consumption

ppRDO



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- Power board (PB) design is ongoing
  - PB supplies 5 different voltages
    - ASIC: 1.2 V (EICROC case)
    - FPGA: 1.8, 1.2, 0.9, 0.85 V
    - SFP+: 3.3 V
  - Several options for DC-DC converters are being tested

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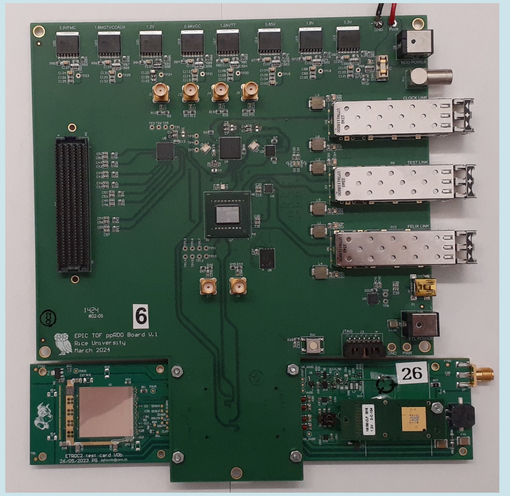
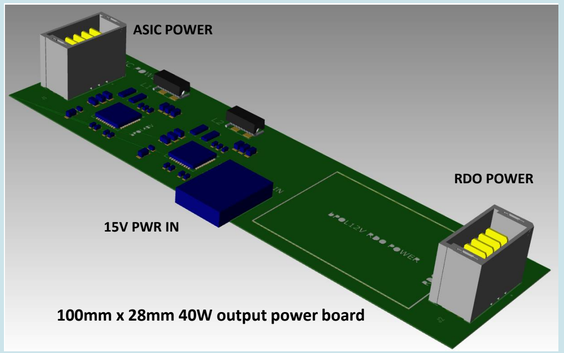
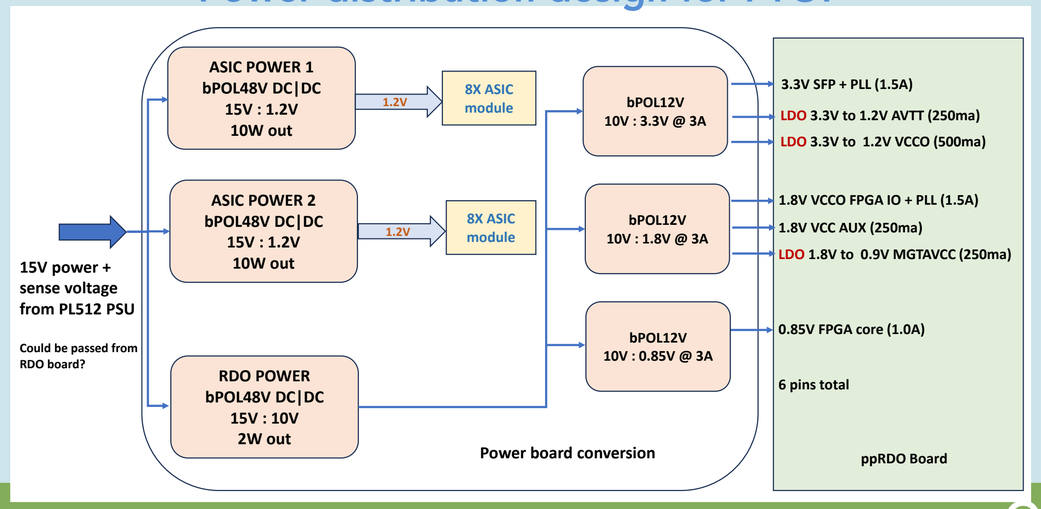


PB design



Power distribution design for FTOF



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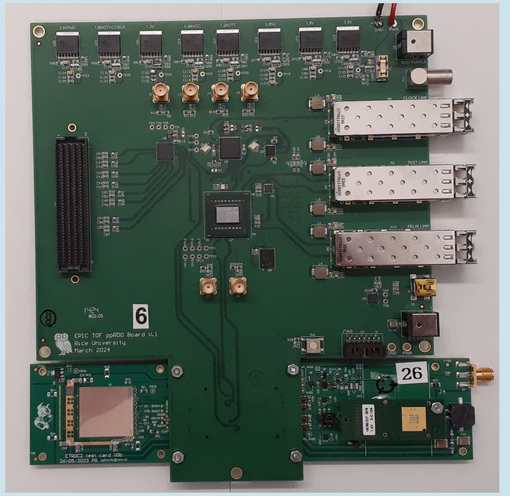
Roadmap and timeline of SH development

2024: **Prototype v0** (pre-prototype): establish all essential functionalities and readout chain.

2025: **Prototype v1**: first prototype with realistic dimensions, and meeting requirements/constraints for FTOF and BTOF, and other AC-LGADs subsystems.
- Focusing on FTOF first

2026: **Prototype v2**: final prototype

ppRDO



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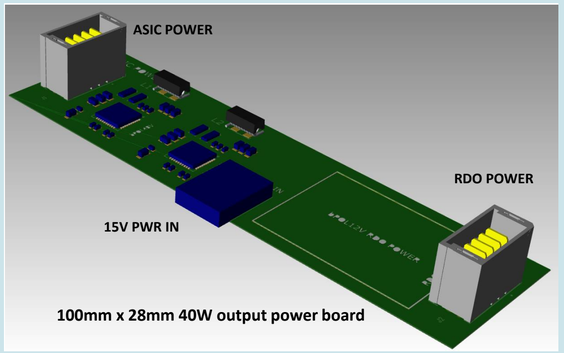

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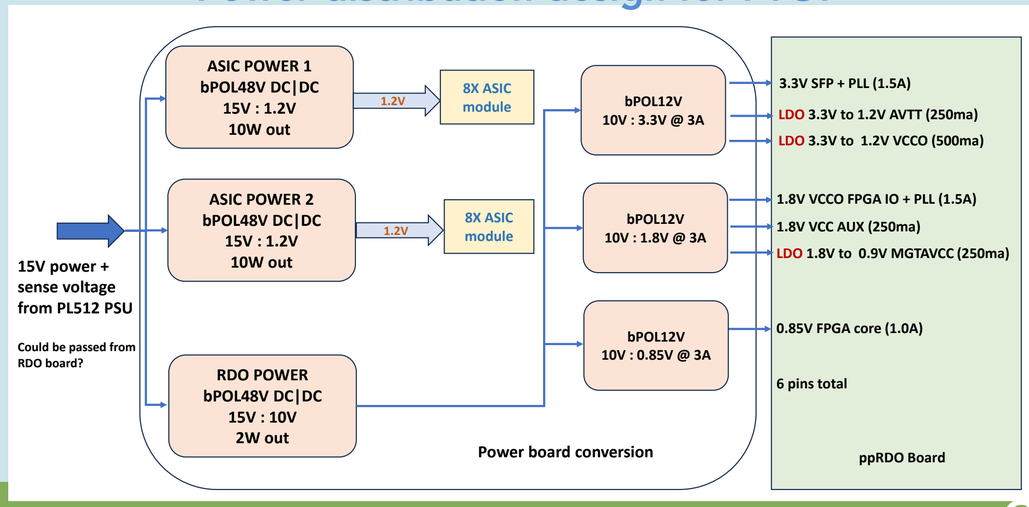
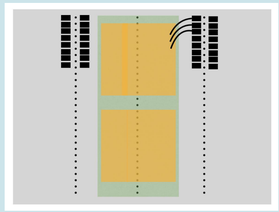
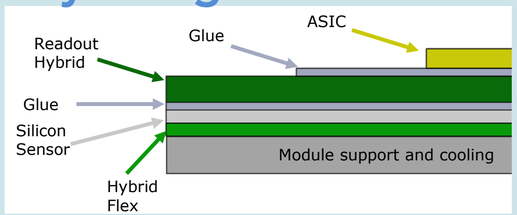


Mechanics, cooling, and FPC

- The idea of BTOF module assembly has matured
  - Wire length is uniform, but worse cooling power due to many layers between ASIC and cooling pipe (support structure)

Module assembly design





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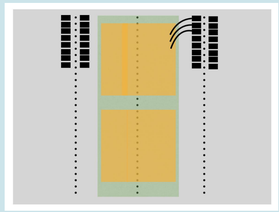
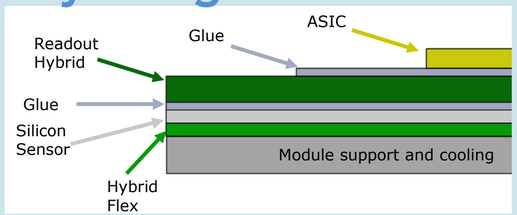
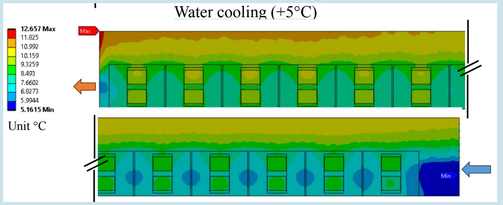




Temperature gradient



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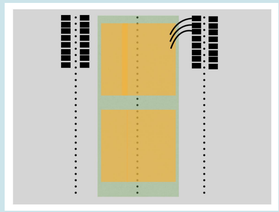

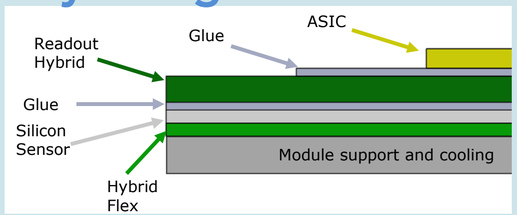

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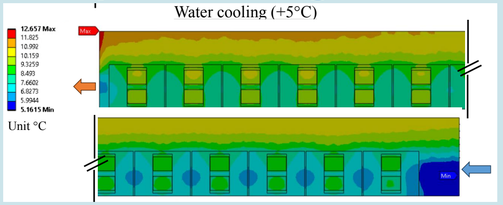
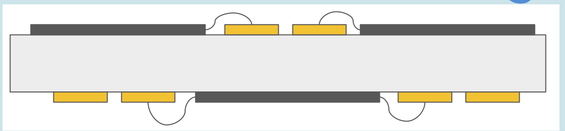


Double side stave design



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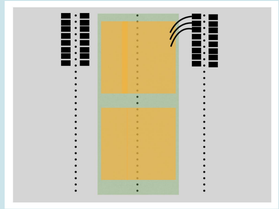
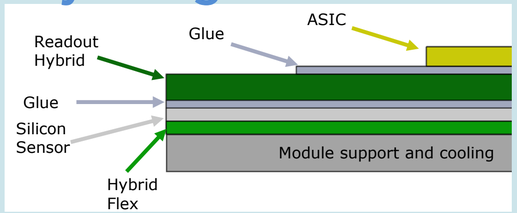
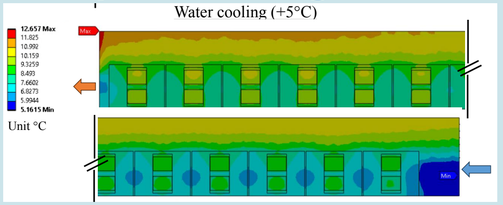
- Support structure production process has been shown
  - Bonding and curing process

Module assembly design

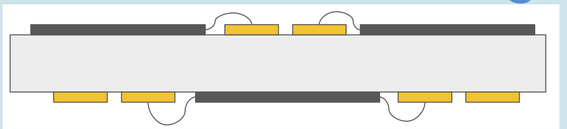




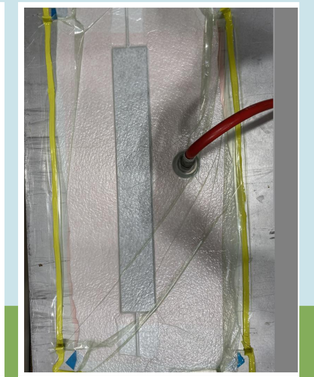
Temperature gradient

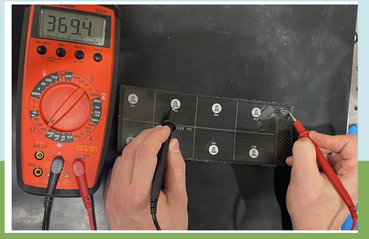


Double side stave design



Support structure production process





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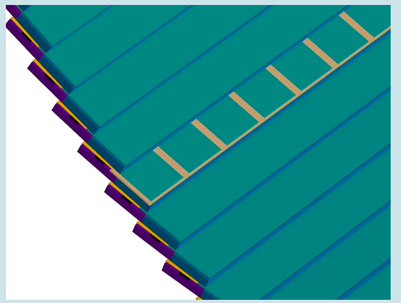
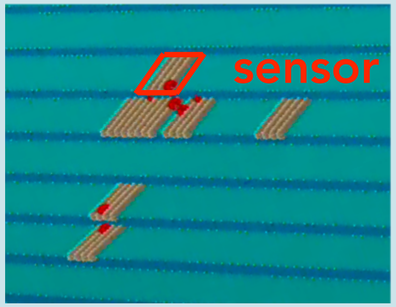
New segment



Strip visualization



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  - The signal strength and charge-sharing profile come from real sensor result

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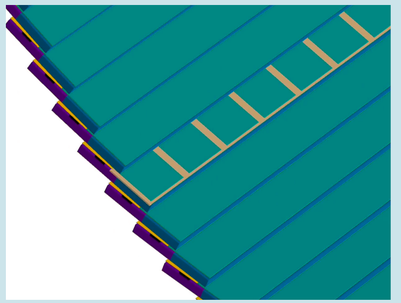

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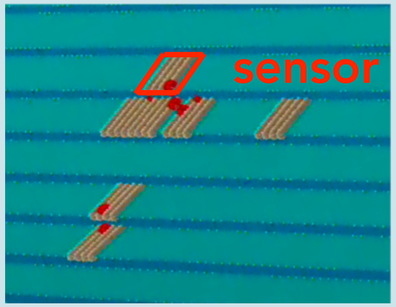
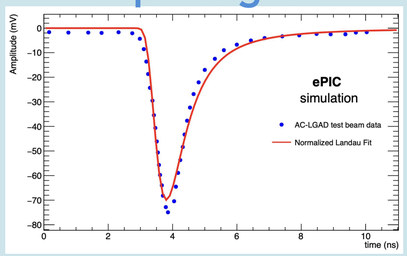
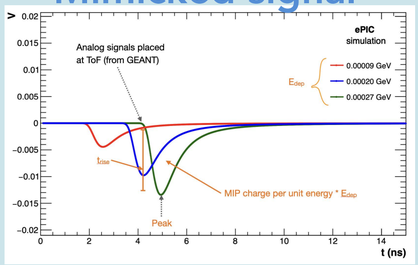


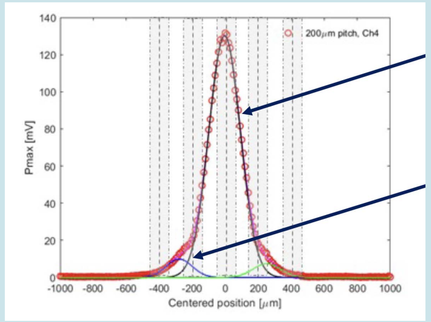
Input signal



Mimicked signal



Input charge dist.



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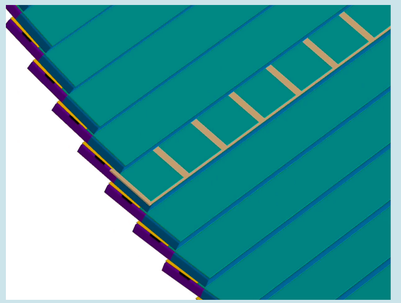
- The positional resolution depends on where the particles were incident relative to the position of the readout metal
  - Charge is not shared enough when a particle hits the corner of the sensor → worse spatial resolution
  - Possibly the required charge-sharing profile for finding the best spatial resolution can be extracted

New segment



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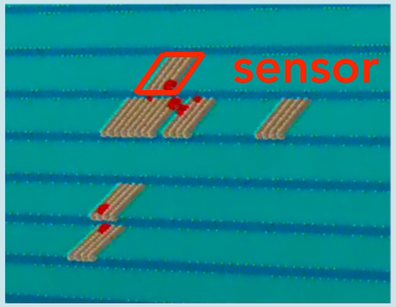

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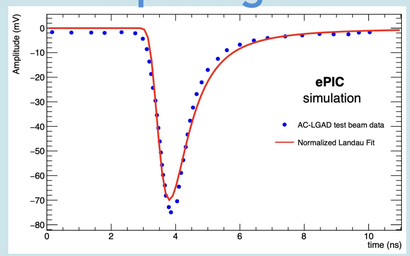
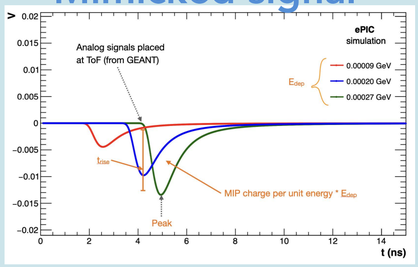
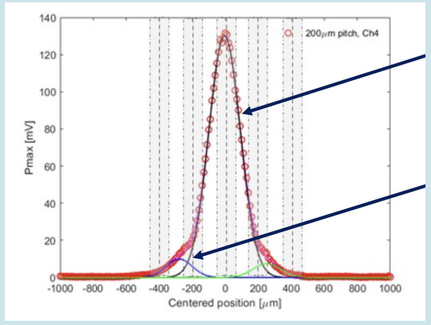


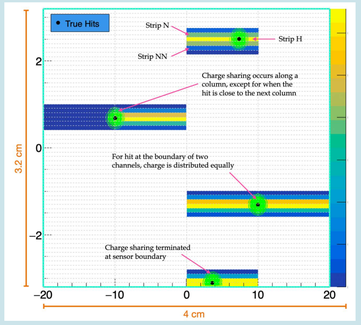
Mimicked signal



Input charge dist.



Mimicked charge dist.



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- New functions, realistic segmentation, digitization, and charge-sharing, have been implemented in the simulation
  - The best charge-sharing property can be measured by the new function

What was discussed

- We need ASICs with a digital block for the strip-type sensors
  - We are making steady progress toward strip-type sensor ASIC choice, but the inter-dependence on the ASIC makes it difficult to finalize FEE, FPC, and other components at this moment.
  - We need reference ideas for all designs (FCFD with digit. block will be received end of 2025)
  - HGCROC3 is one of the candidates, but modification is necessary
    - Large power consumption: HGCROC3 ~ 15 mW/ch, FCFD ~ 2 mW/ch, and EICROC ~ 1 mW/ch
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- Long (135 cm) and low material (1% X/X_0) stave design is a key point in demonstrating the true ability of AC-LGAD
  - Temperature control (cooling system) design is one of the most important elements for BTOF
    - AC-LGAD sensor performance strongly depends on temperature
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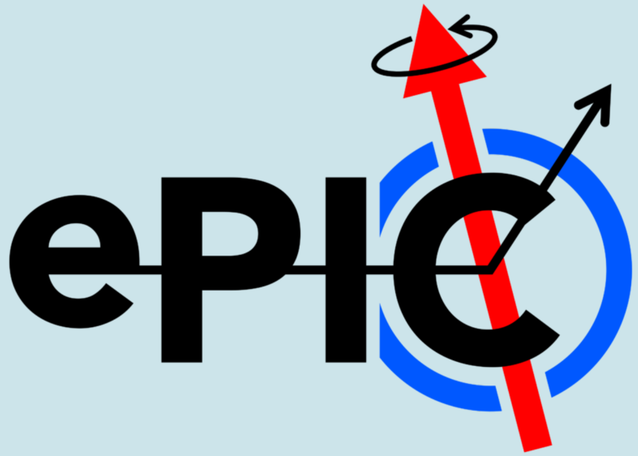
  - **It is necessary to continue to understand and optimize the material budget (1% BTOF and 5% FTOF) and its impacts on the design of FPC and cooling integration**

Backup slides



AC-LGAD TOF

Satoshi Yano (Hiroshima University)

ePIC Collaboration meeting @ Lehigh University

07/25/2024

Role of the TOF in the ePIC project

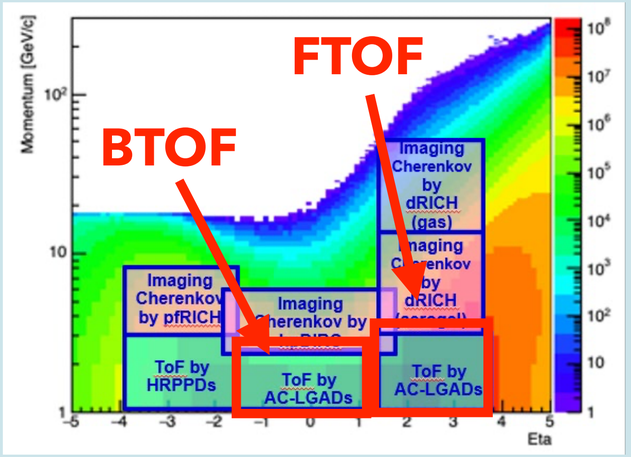
- BTOF covers midrapidity and FTOF covers forward rapidity
  - BTOF and FTOF cover -1.42<η<1.77 and 1.86<η<3.85, respectively

- TOF has been assigned many important roles
  - Low *p* region PID at $p < 1.5$ GeV/*c* and $p < 2.5$ GeV/*c* for BTOF and FTOF, respectively with excellent timing information
  - Tracking with excellent spatial resolution
  - Machine-induced background rejection

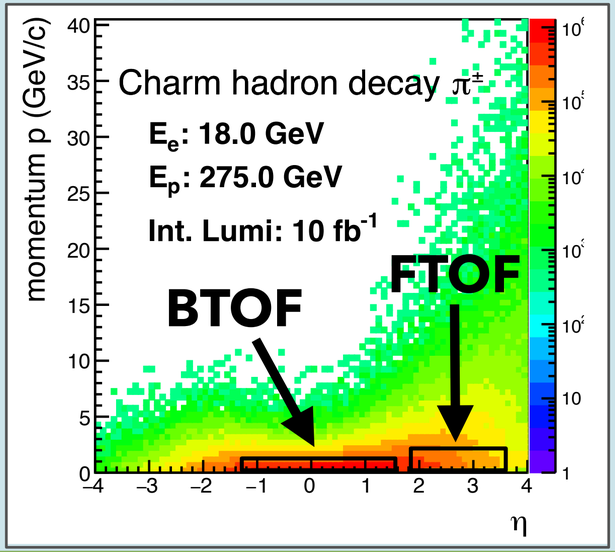
- AC-LGAD is the most promising technology for TOF
  - High-timing resolution σ_t = ~30ps
  - High-spatial resolution σ_{xy} = ~30 μm
  - Space-saving design ΔD < 10cm
  - **but… no experiments have been used so far…**

TOF is one of the most important detectors for ePIC and also the most challenging detector

Detectors for PID

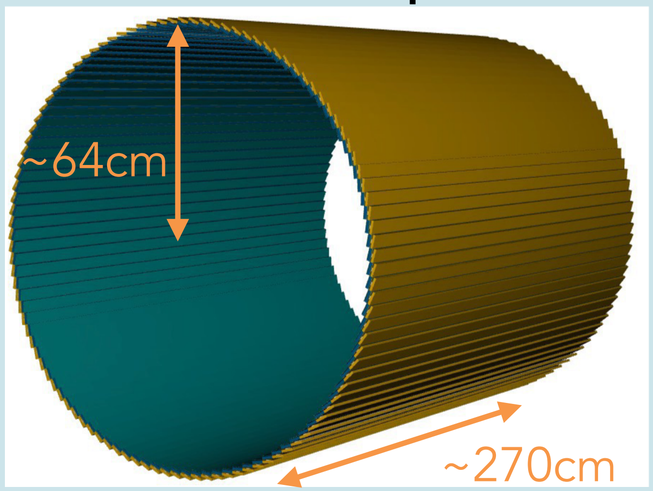


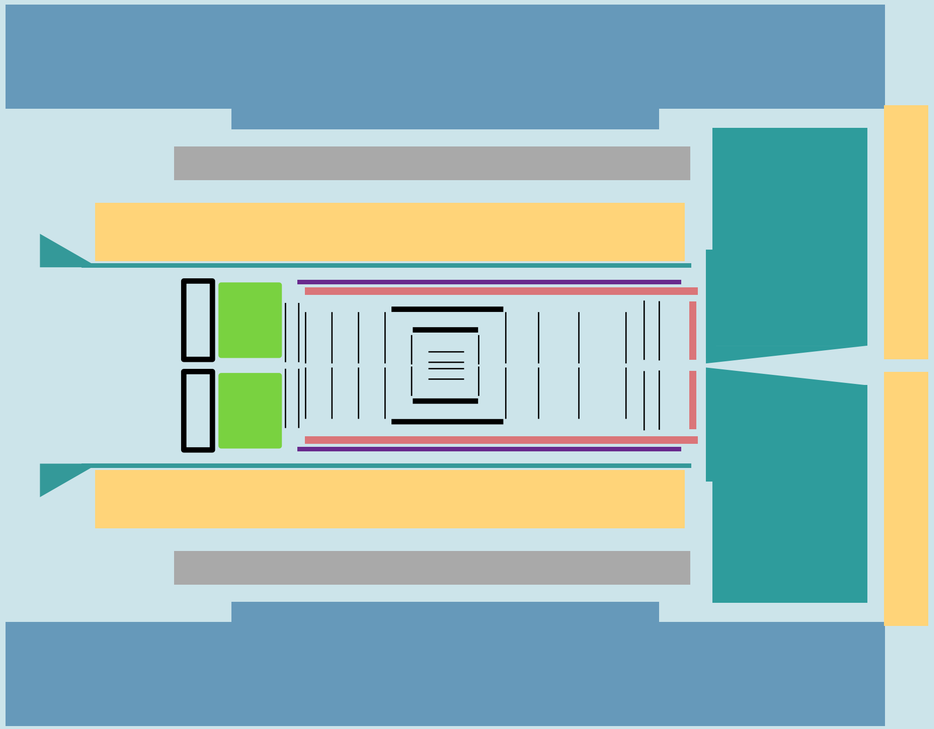
Decay particle kinematics



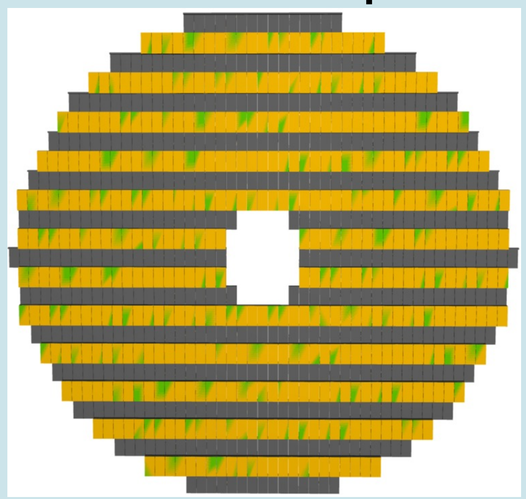
Recap of BTOF and FTOF

BTOF shape

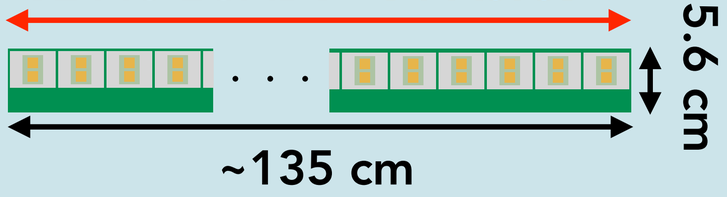




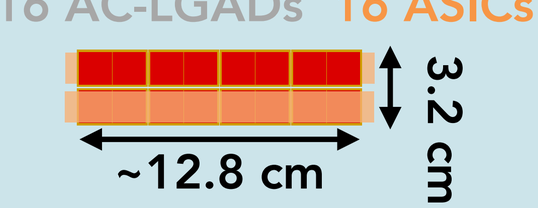
FTOF shape



BTOF half Stave



FTOF Module

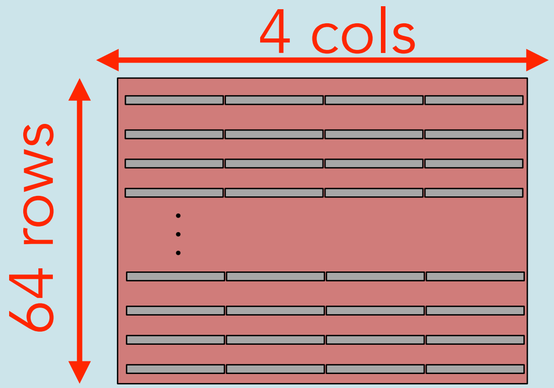


- Strip-type and pixel-type AC-LGAD are used for BTOF and FTOF, respectively
- Different ASICs are used for BTOF and FTOF due to different sensor properties

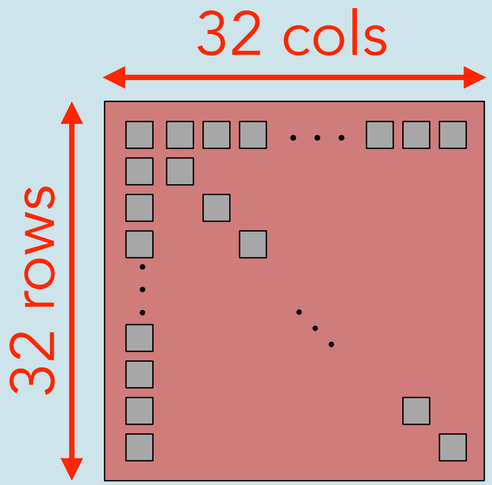
AC-LGAD for BTOF and FTOF

- **Strip-type** sensor, 3.2 x 4 cm^2 sensor size with 0.05 x 1 cm^2 metals, is used in **BTOF**
- The readout metal geometry is 64 x 4 and 256 channels in total each
- 2 ASICs are attached to each sensor with wire bonding

- **Pixel-type** AC-LGAD sensor, 1.6 x 1.6 cm^2 sensor size with 0.05 x 0.05 cm^2 metals, is used in **FTOF**
- The readout metal geometry is 32 x 32 and 1024 channels in total each
- 1 ASIC (2D 32x32) is attached to the one sensor



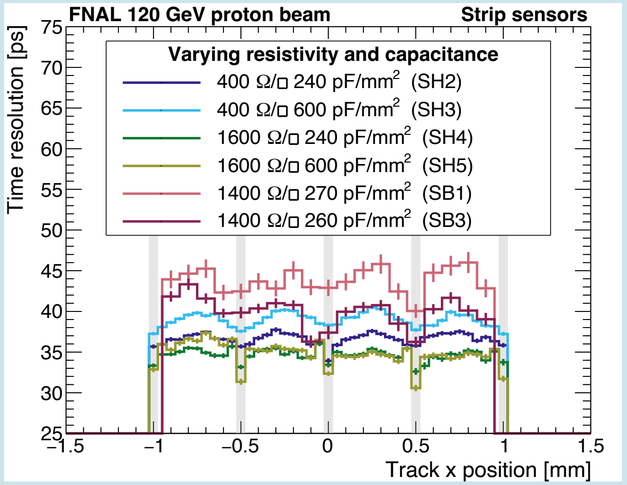
- BTOF strip sensor
  - **9216 sensors**
  - **10 m^2**
  - **2.4 M readout channels**

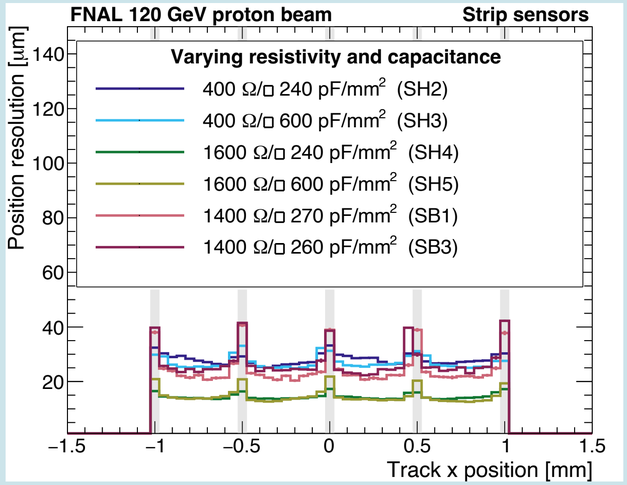


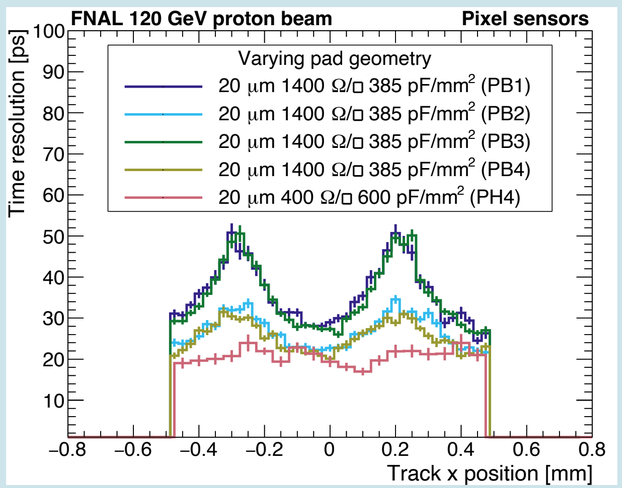
- FTOF pixel sensor
  - **3632 sensors**
  - **1.4 m^2**
  - **3.6 M readout channels**

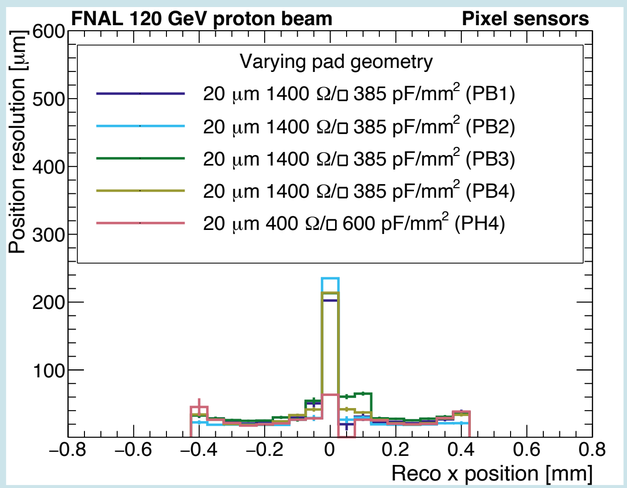
Latest sensor performance

Beam test result at FNAL (from FY24 report by FNAL, LBNL and UIC)









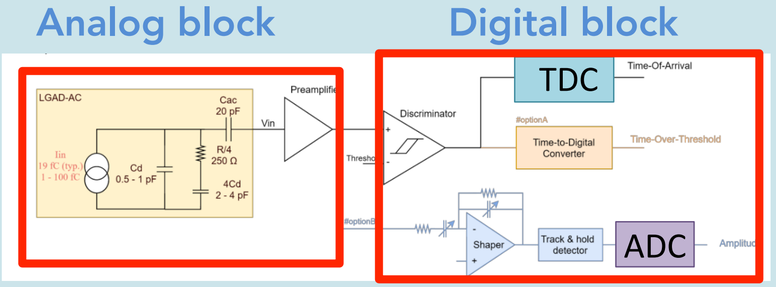
- HPK and BNL sensors show reasonable results in both strip and pixel types with the “BEST” bias voltage
  - Performance redundancy should be considered
- The performances are under control and the next prototypes will have higher performance
- The sensors are still smaller than the sensors used in the experiment
- The full-size sensors will be shipped in a few months and gain uniformity will be checked
- Sensor temperature dependence study is mandatory and ongoing

TOF ASIC

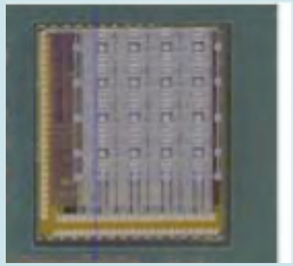
- EICROC (32x32 = 1024ch) is one of the common ASICs used in ePIC
  - Design suits to pixel-type AC-LGAD readout (for low input capacitance)
  - 10-bit TDC and 8-bit ADC is now available (EICROC0)

- We have several options for the strip-type AC-LGAD readout
  - The strip type has a large input capacitance of ~10 pF
    - "Standard" EICROC should be modified if it is used for the strip type
  - FCFD, HGCROC, and "Modified"-EICROC are the candidates
    - FCFDv1 with the analog block is available and FCFDv2 with digital block will be available beginning of next year
    - HGCROC has been developed for CMS Calorimeter and is ready
    - EICROC tuned for a larger input capacitance is being considered

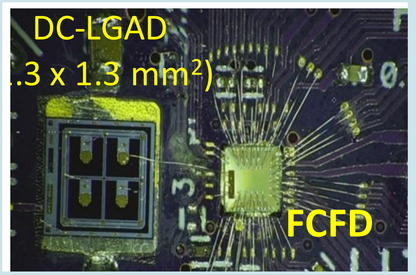
- The possibility of third-party ASICs has begun to be discussed
  - ASROC and HPSoC are one of the options



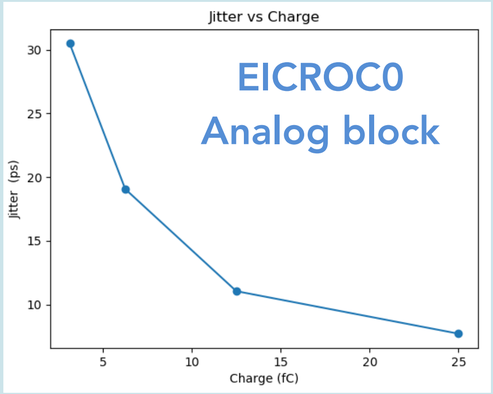
EICROC0

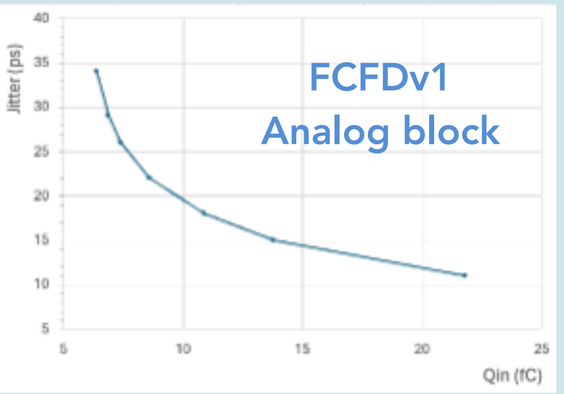


FCFDv1



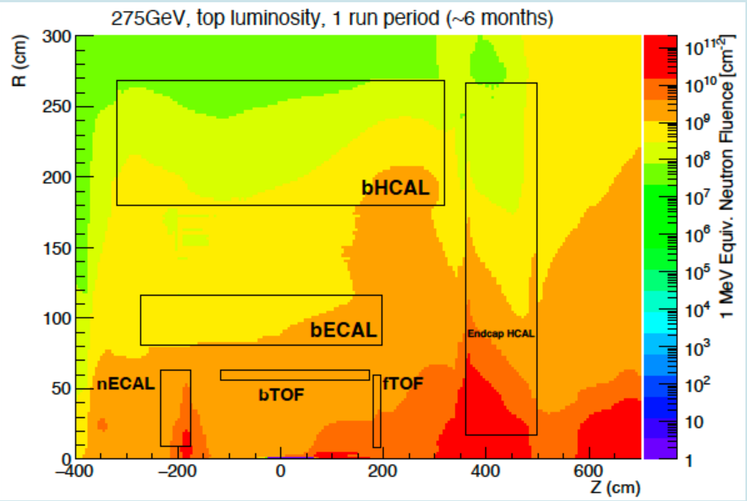
HGCROC3

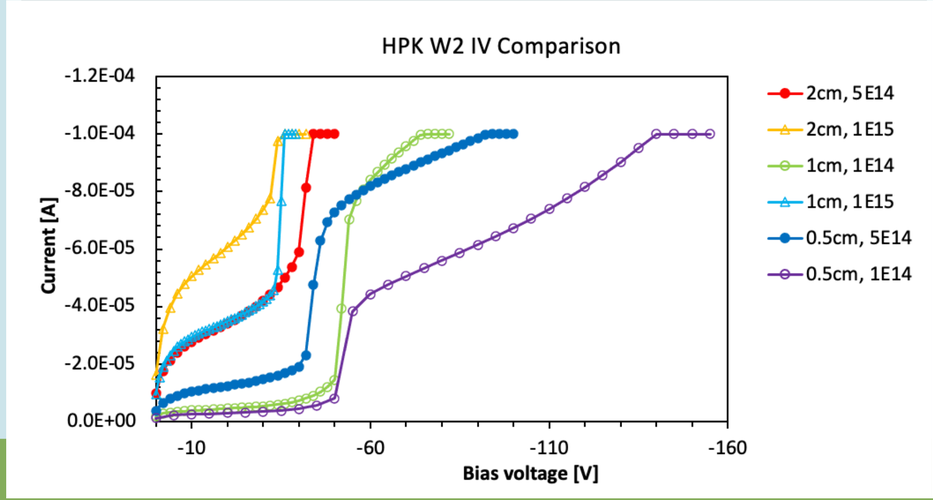


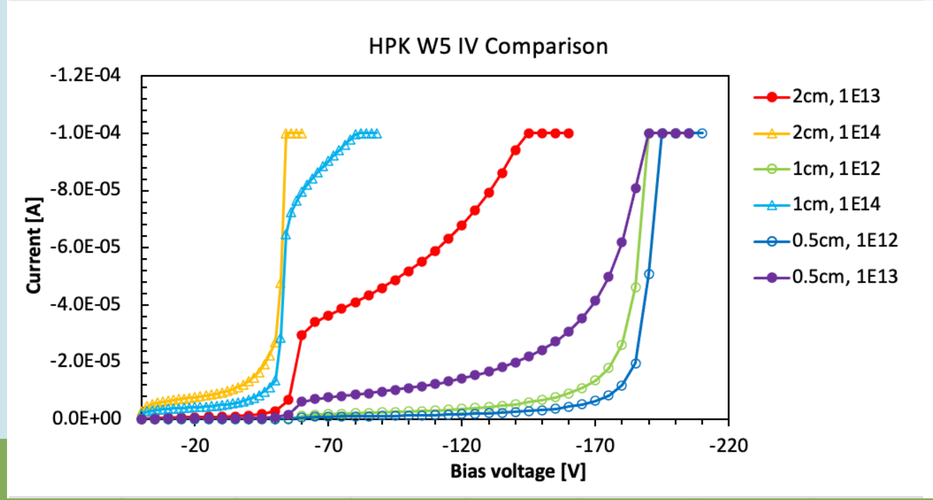


Sensor irradiation test

- Not very large radiation is expected at both BTOF and FTOF ($10^{9\text{-}10} n_{eq}/cm^2$)
- Irradiation test of strip sensor has been done at IJS with 1 MeV neutron
- All devices were annealed for 80 min at 60°C to avoid rapid change in sensor behavior
- Testing done at room temperature with a probe station, the current is higher for high irradiation devices
- The irradiation effects should be corrected in the experiment







Support structure and temperature control

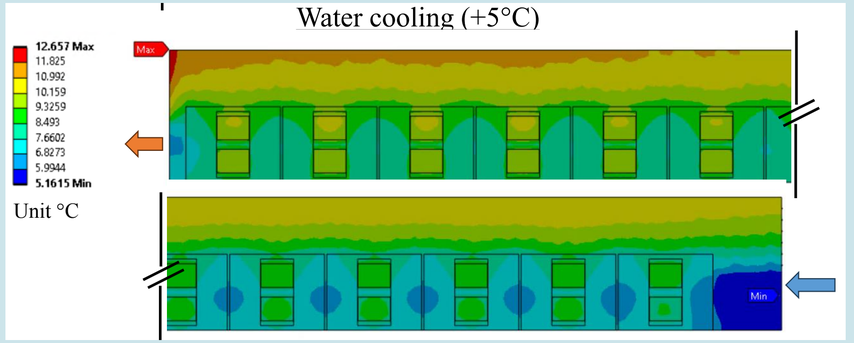
- BTOF consists of long staves with a lower material support structure than ever before

- Low material (1% X/X_0) long FPC design requires a high-level technology and imposes significant limitations on functionality
  - sPHENIX INTT team has the experience of making such a long FPC

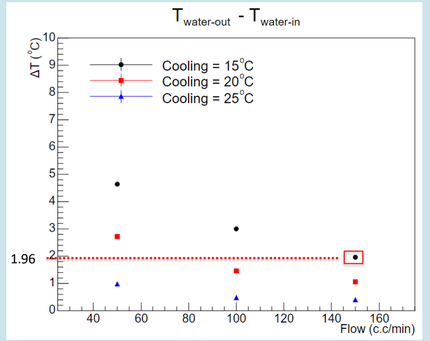
- The thermal conductivity of the stave is under investigation
  - Full-size stave (270 cm) thermal conductivity is being studied with simulation
  - Mini-size support structure (30 cm) thermal conductivity is being studied under several conditions
  - Middle-size support structure (100 cm) is available now and the results will be out soon

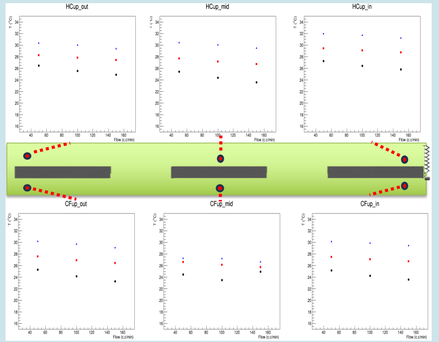
sPHENIX INTT FPC

Full-size stave test with simulation



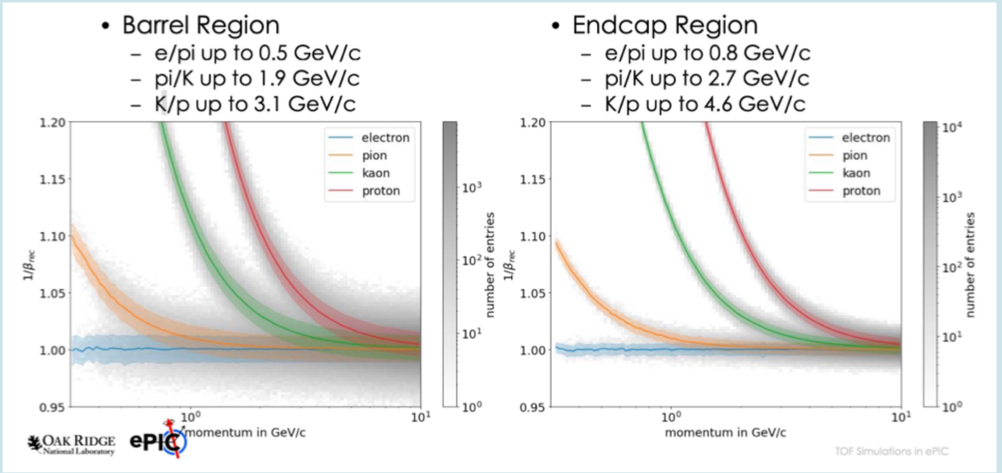
Mini-size stave test results



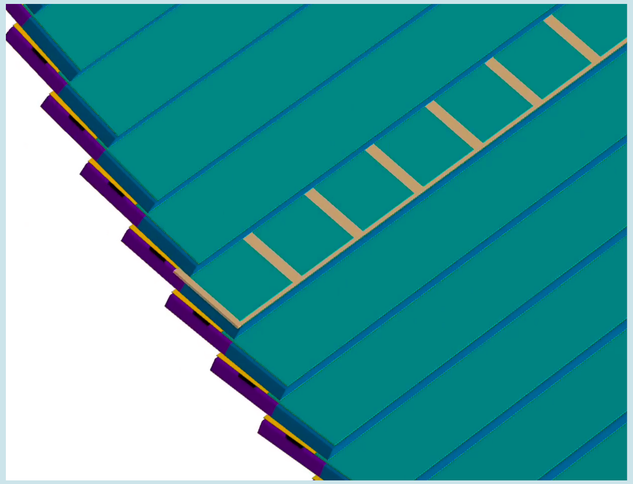


Simulation development

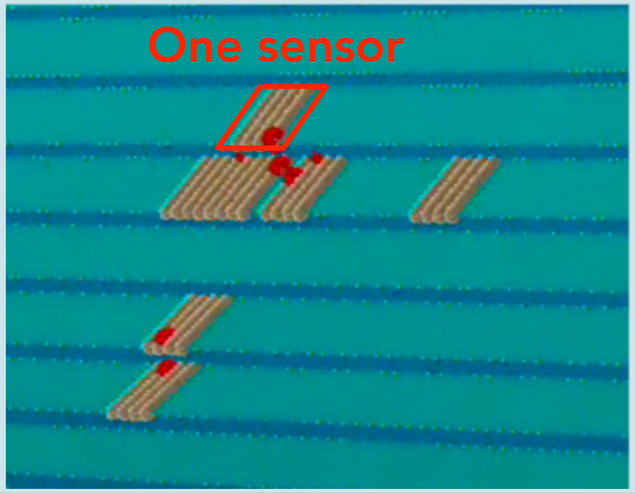
- The LUT PID has been implemented into the official simulation
- More realistic sensor segmentation is being implemented in the simulation
- Digitization mimicking charge sharing has been implemented in the simulation
- Material budget effect on the outer detectors by BTOF is under evaluation



Sensor segment



Readout metal visualization



RawTrackerHitCollection

- Energy deposited
- Time of Flight
- Cell ID

rawhits

Analog signal generation

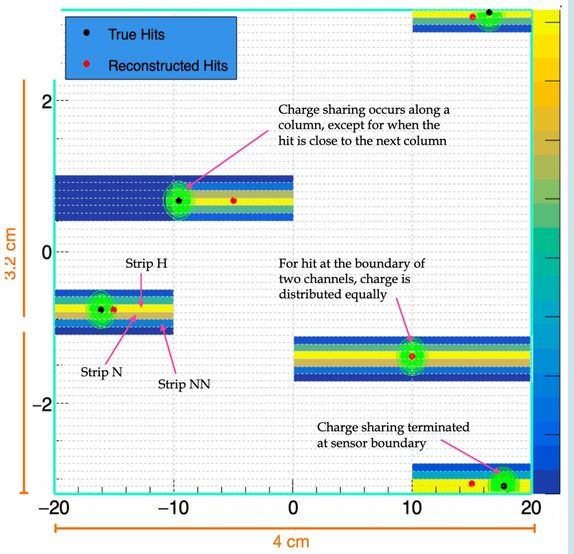
Reference clock
Delay cells
Threshold voltages

BTOFHitDigi (*on git but not main branch*)

Resides in EICrecon/src/detectors/BTOF

- ADC (8-bit)
- TDC (10-bit)
- Cell ID
- Sensor ID

digi

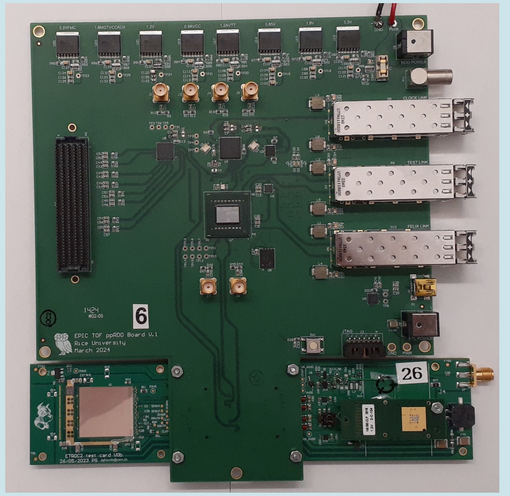


Front-end electronics

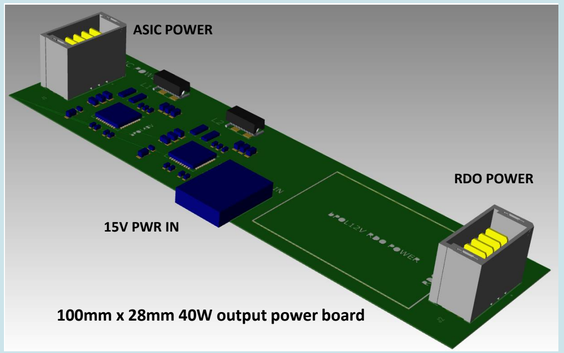
- Pre-prototype readout board (ppRDO) has been made with ETROC2 ASIC
  - 6 boards are available
- Several tests are ongoing
  - FPGA firmware development
  - Readout test with ETROC2
  - Evaluation of power consumption

- Power board (PB) design is ongoing
  - PB supplies 5 different voltages
    - ASIC: 1.2 V (EICROC case)
    - FPGA: 1.8, 1.2, 0.9, 0.85 V
    - SFP+: 3.3 V
  - Several options for DC-DC converters are being tested

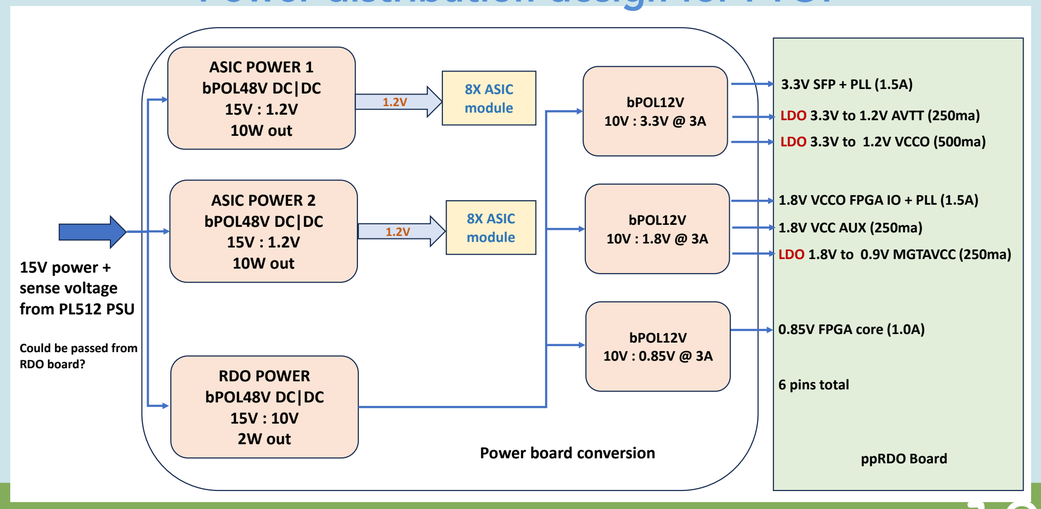
ppRDO



PB design



Power distribution design for FTOF



Summary

- AC-LGAD TOF is the key detector in the ePIC project for the PID at low *p* region and background rejection

- Prototypes of BNL and HPK fulfill the requirements, but it is under the BEST environment
  - Breakdown voltage is expected to depend on the temperature strongly
  - Performance redundancy should be considered
  - The first irradiation test with strip sensors has been done

- ASIC analog part performance of EICROC and FCFD meet the requirement
  - Not only ASIC but also AC-LGAD sensor + ASIC performance must be evaluated in the coming year

- Support structure thermal properties are being investigated with a 30 cm-long prototype
  - The first 100 cm prototype will be tested soon

- The prototype RDO is available and being tested with ETROC2

TOF project is making steady progress!

Backup slides

Institutes in TOF tasks (official)

- Brookhaven National Laboratory (USA)
- Fermi National Accelerator Laboratory (USA)
- Rice University (USA)
- Oak Ridge National Laboratory (USA)
- Ohio State University (USA)
- Purdue University (USA)
- University of California Santa Cruz (USA)
- University of Illinois at Chicago (USA)
- Hiroshima University (JP)
- RIKEN (JP)
- Shinshu University (JP)
- Nara Woman University (JP)
- National Chen-Kung University (TW)
- National Taiwan University (TW)
- IJCLab, OMEGA, CEA-Saclay (FR)

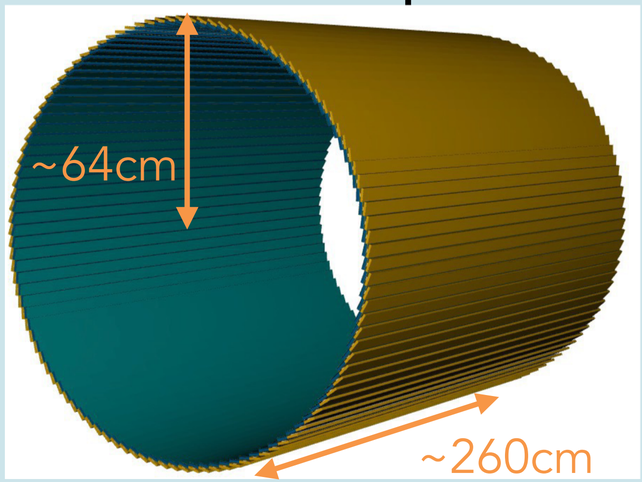
Tasks in BTOF

- **AC-LGAD sensor**
  - BNL
  - ORNL
  - Univ. of California, Santa Cruz
  - Univ. of Illinois, Chicago
  - Hiroshima University
  - Shinshu University
- **Frontend ASIC**
  - Fermilab
  - Rice University
  - ORNL
  - Hiroshima University
  - National Taiwan University
  - IJCLab/OMEGA/CEA-Saclay
- **Sensor-ASIC integration**
  - BNL
  - ORNL
  - Univ. of California, Santa Cruz
  - Univ. of Illinois, Chicago
  - National Taiwan University
- **Module structure**
  - Purdue University
  - National Cheng-Kung University
- **Module assembly**
  - BNL
  - ORNL
  - Ohio State University
  - Univ. of California, Santa Cruz
  - Hiroshima University
  - RIKEN
  - Nara Woman University
  - National Taiwan University
- **Flex PCB**
  - ORNL
  - Nara Woman University
- **Service Hybrid**
  - Rice University
- **Backend electronics**
  - BNL

Detector Layout of BTOF

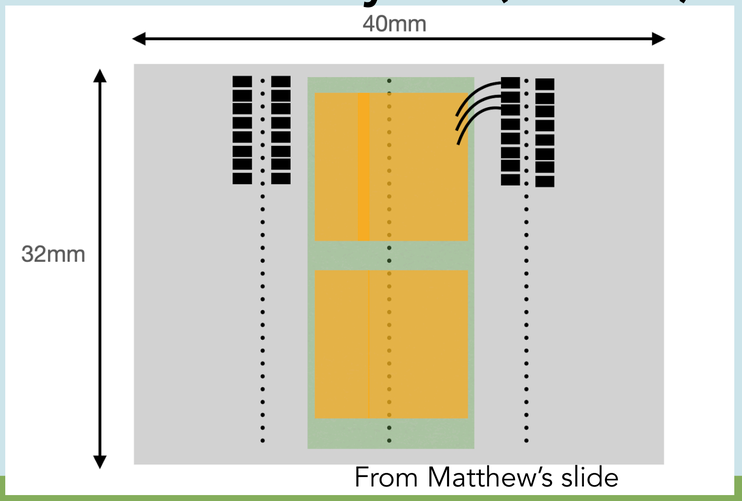
- BTOF is composed of 288 (2x144) staves to form a cylindrical shape
- 32 AC-LGAD **strip-type** sensors are attached to one stave
  - Two ASICs are placed just above one sensor
- Radius is 63 - 66 cm from the beam pipe covering -1.42<η<1.77
- Total material budget in acceptance is ~0.01 X/X_0

BTOF shape

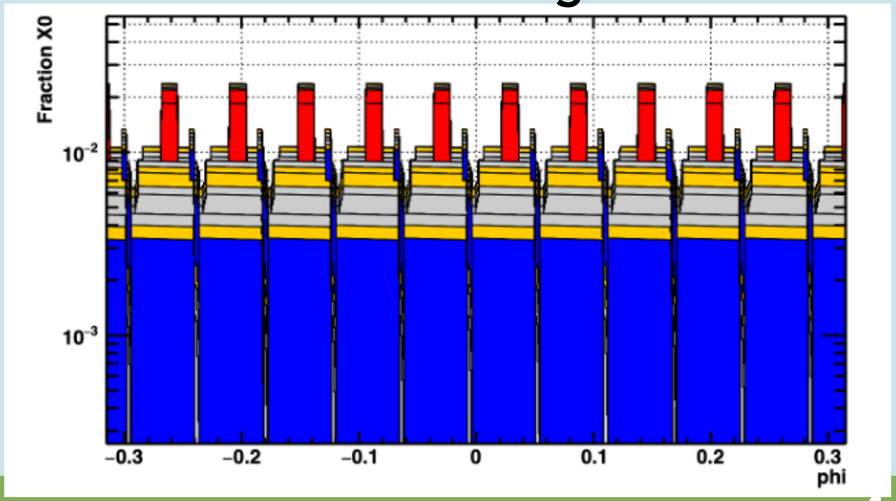


BTOF Stave

Sensor-ASIC hybrid (module)



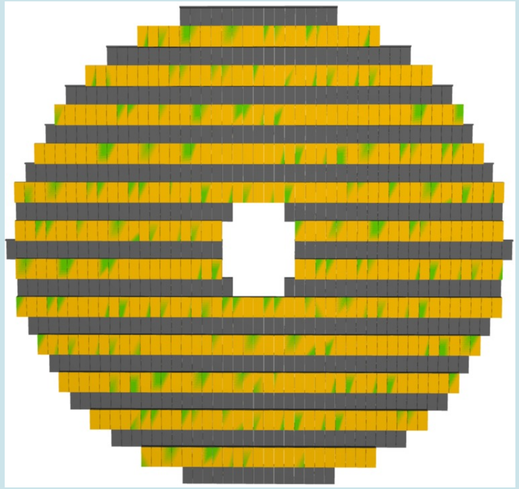
Material budget

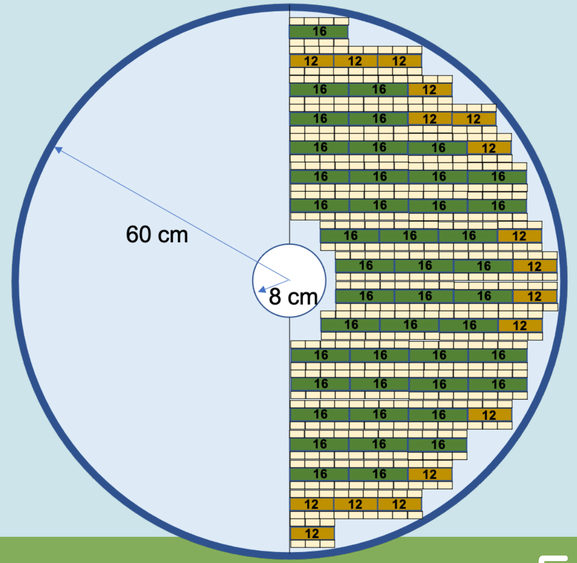


Detector Layout of FTOF

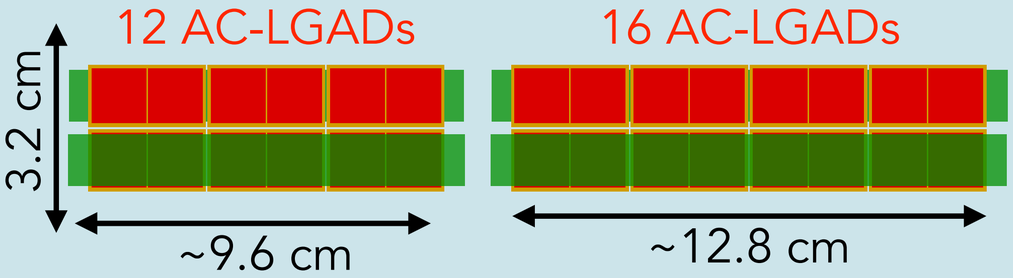
- FTOF is composed of 1816 modules to make a disk
- 12 or 16 AC-LGAD **pixel-type** sensors are attached to one module
  - One ASIC is used for one sensor
- Radius is 10.5 - 60 cm from the beam pipe covering $1.86<\eta<3.85$
- Service hybrid, readout board + power board, is placed in the acceptance
- Total material budget in acceptance is ~0.05 X/X_0

FTOF shape

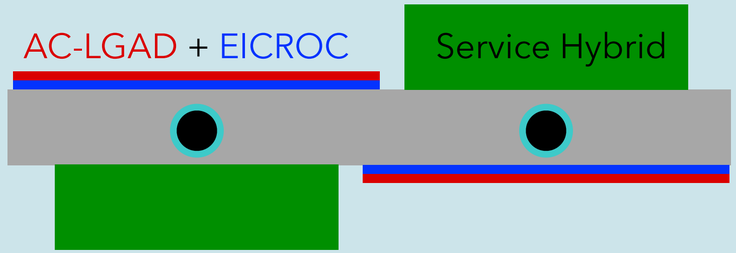




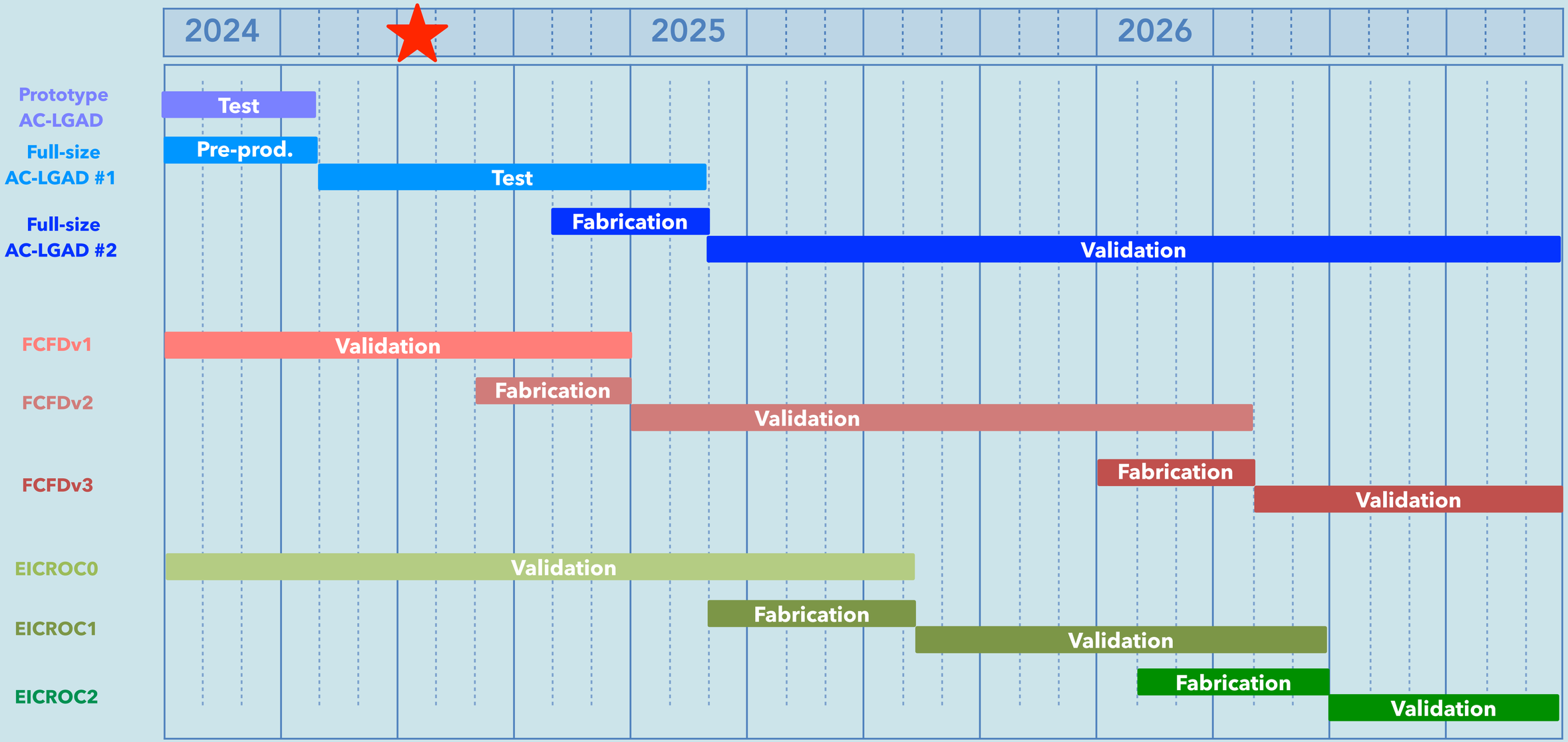
Module top view



Module cross section



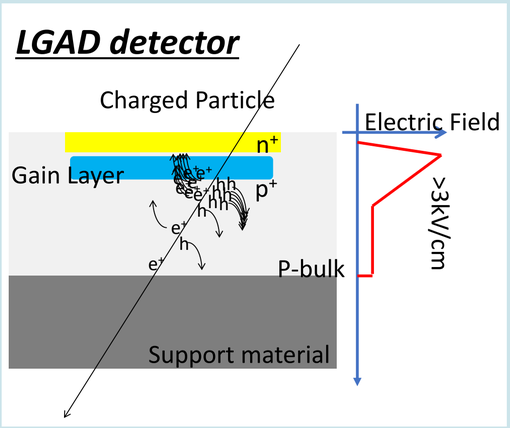
Original schedule of sensor + ASIC (Jan. 2024)

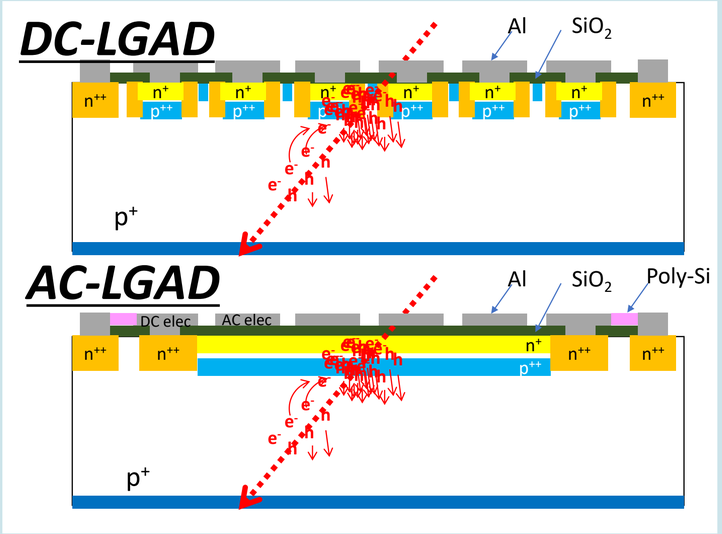


AC-LGAD technology

- Low Gain Avalanche Diode (LGAD)
  - The gain layer (p+ under n+ layer) makes a high electric field inducing electron avalanche → rapid signal raising
  - Standard LGAD (DC-LGAD) has much nonnegligible inactive area in fine segment case
  - CMS and ATLAS adopt DC-LGAD technology at HL-LHC

- AC-coupled LGAD (AC-LGAD)
  - One large gain layer with multiple AC-coupled readout metals on an oxide layer makes possible fine-segment readout keeping high timing resolution
  - High spatial resolution can be achieved with charge sharing even with relatively large pitches
  - EIC can adopt AC-LGAD technology thanks to the low multiplicity environment





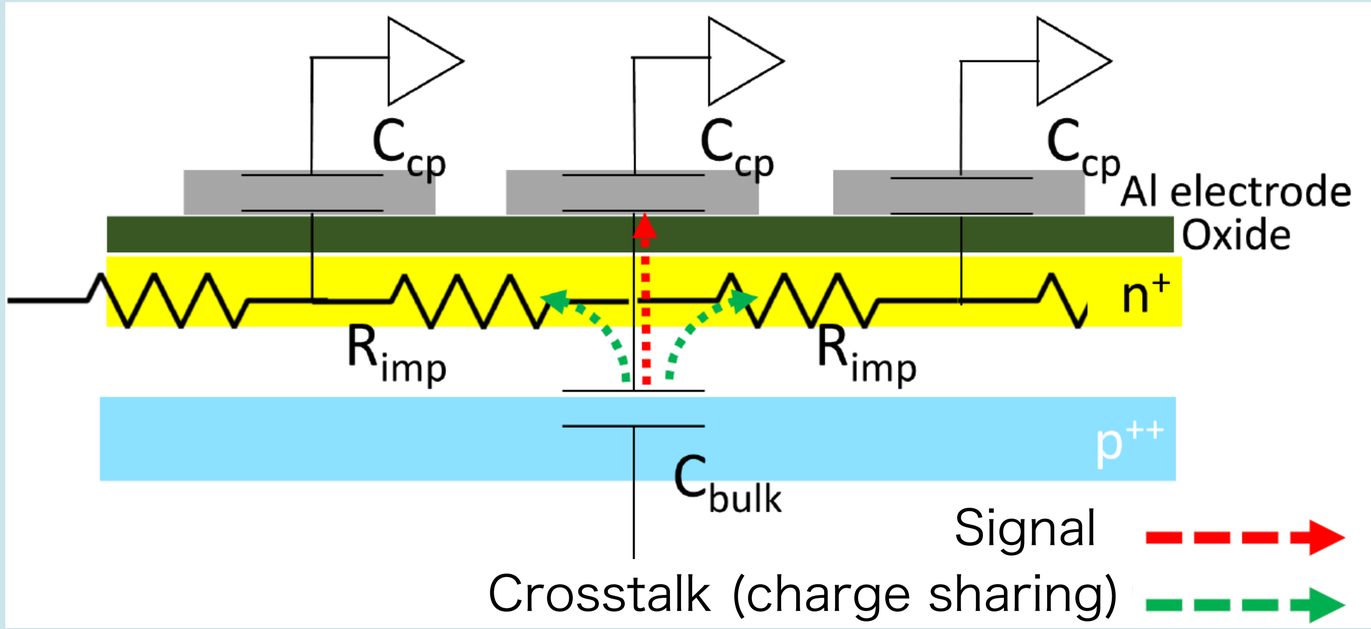
K. Nakamura et al.,
JPS Conf. Proc. 34, 010016 (2021)

R&D elements for AC-LGAD

- Issues of AC-LGAD
  - Crosstalk in n^+ layer
  - Small signal due to AC-coupling
- Signal size Q

$$Q = \frac{Z_{R_{imp}}}{Z_{R_{imp}} + Z_{C_{CP}}} Q_0$$

- Two important parameters
  - R_{imp} → larger is better
    - n^+ doping concentration
  - C_{cp} → larger is better
    - Smaller electrode size → smaller C_{cp}
    - Thinner oxide → larger C_{cp}



K. Nakamura et al., JPS Conf. Proc. 34, 010016 (2021)

Development goal

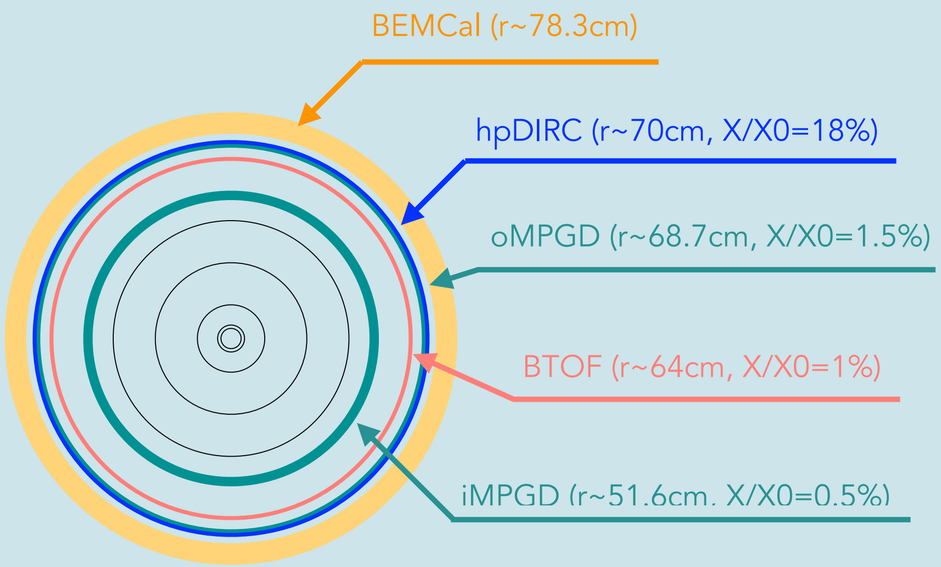
Keep a larger signal and smaller crosstalk with a good time and spatial resolution

Material budget study (Hiroshima)

- **Shunichiro Muraoka** (M2 student) is working on the BTOF material effects on hpDIRC and BEMCal performance

- This study is significant for the stave structure design
  - oMPGD is placed just in front of hpDIRC in the latest design →Not big effects on angular determination resolution by the BTOF material
  - The material budget of hpDIRC in the active area is approximately 18% → Not big effects on the EMCal performance by the BTOF material

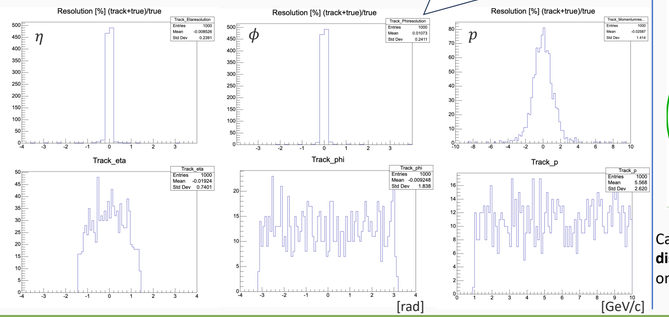
- The study will reveal if the very strict limit of 1% material budget imposed on BTOF is really necessary
  - This will open new options for the stave material selection and 1.3 m FPC design



Current Status — Shunichiro's slide link

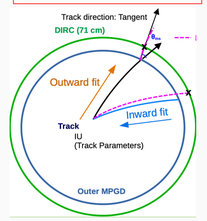
■Track Reconstruction (EICRecon)
- Particle gun : π+ from (0,0,0), 1000event
- Momentum : 1 ≤ p ≤ 10GeV
- Eta : -1.4 ≤ η ≤ 1.4

Reconstruct tracks from each detector hit information using EICRecon official package



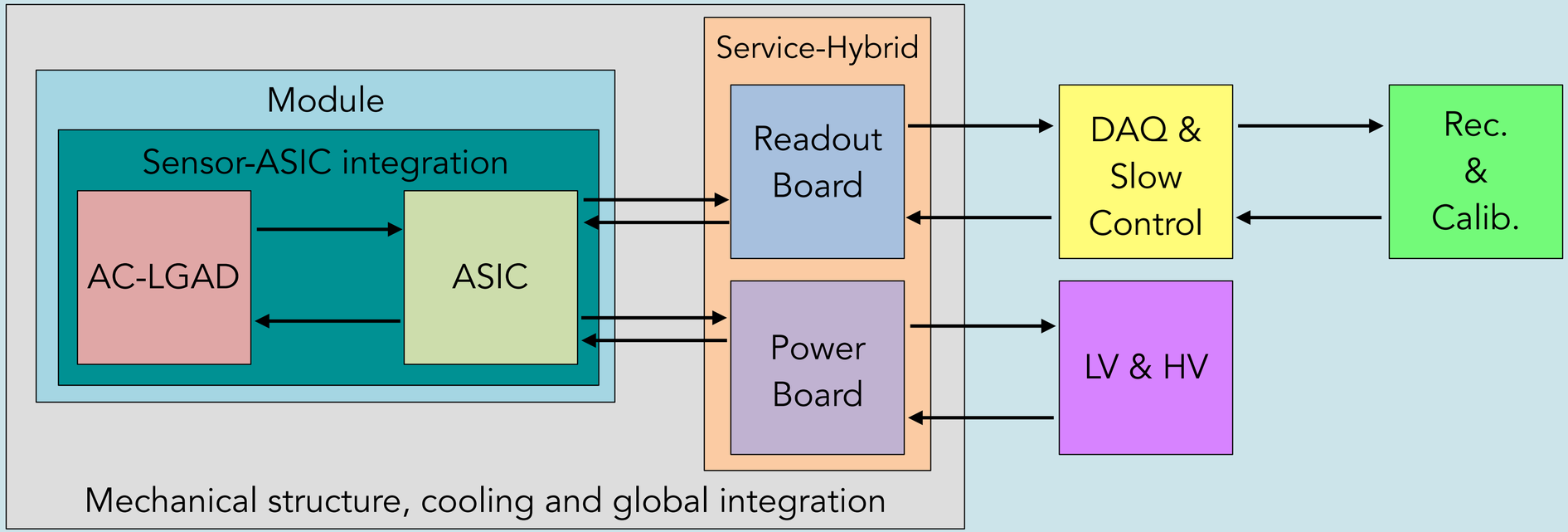
Next plan

Track reconstruction to hpDIRC surface



Calculate the **angular distribution** of incident particles on the hpDIRC surface

TOF structure



- **Barrel-TOF (BTOF)**
  - Strip-type AC-LGAD
  - ASIC (FCFD)
  - Sensor-ASIC integration
  - Module
  - Service-Hybrid
  - Mechanical structure
  - Global integration
- **Forward-TOF (FTOF)**
  - Pixel-type AC-LGAD
  - ASIC (EICROC)
  - Sensor-ASIC integration
  - Module
  - Service-Hybrid
  - Mechanical structure
  - Global integration
- **Common system**
  - DAQ
  - Cooling
  - Software (Rec. & Calib.)
  - HV & LV
  - Slow control

New clean room (100m²) @ HU