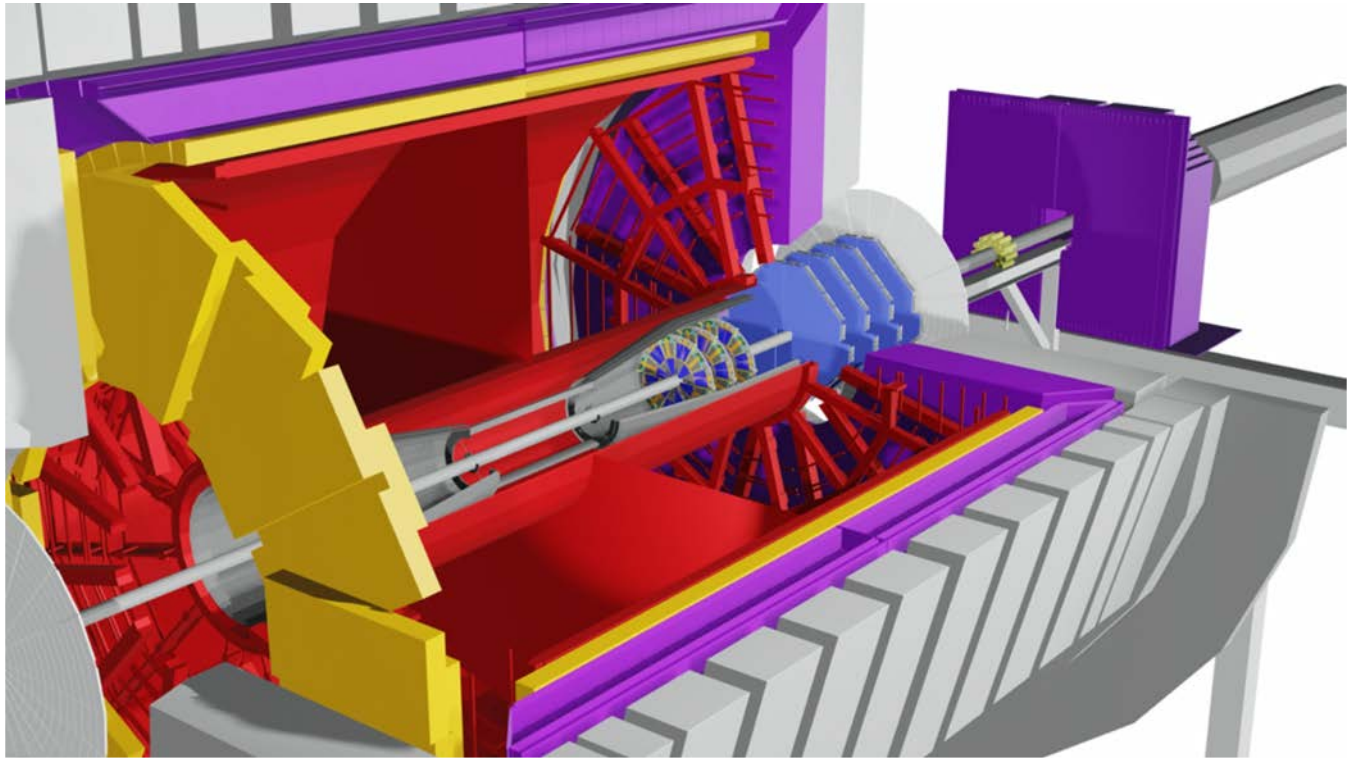
STAR Forward Silicon Tracker

Zhenyu Ye

August 13, 2021



BROOKHAVEN NATIONAL LABORATORY
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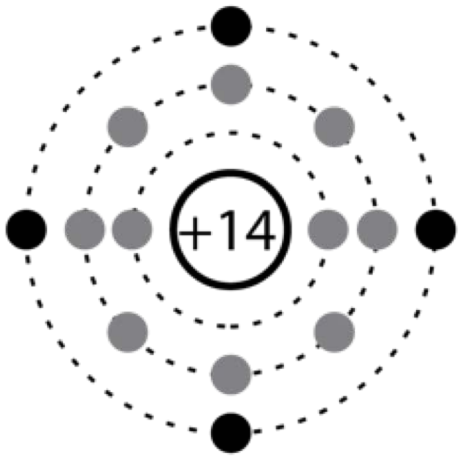
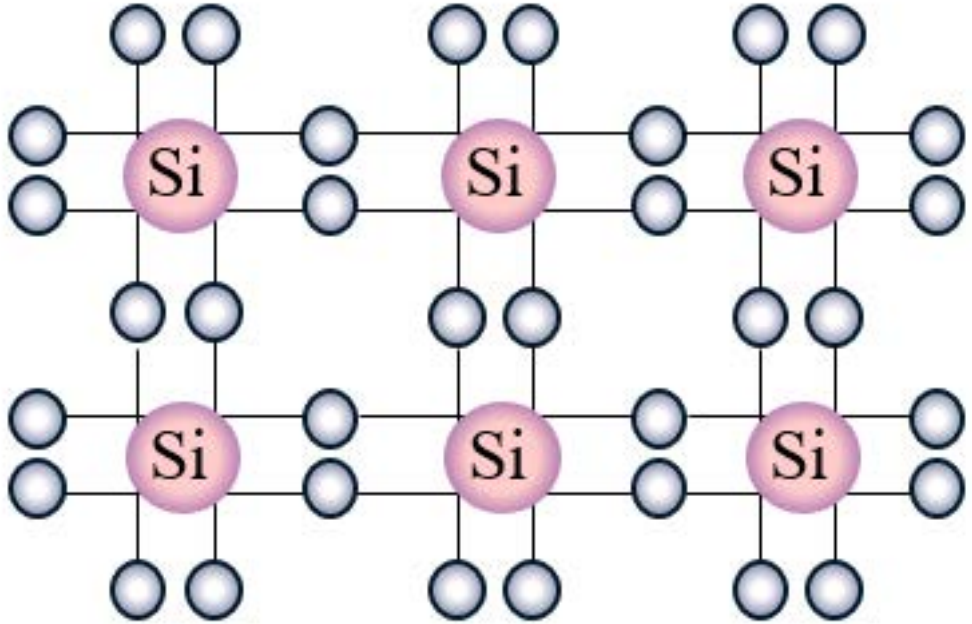
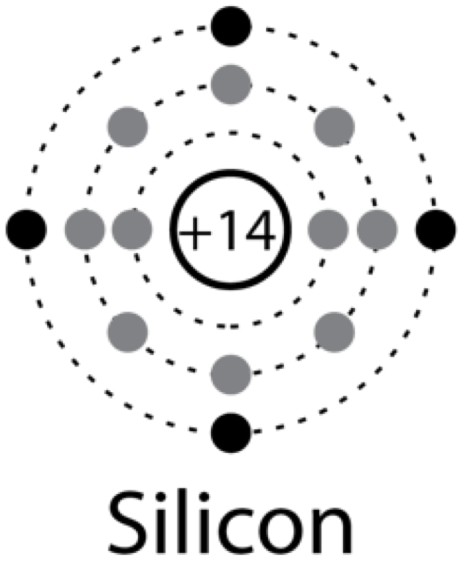
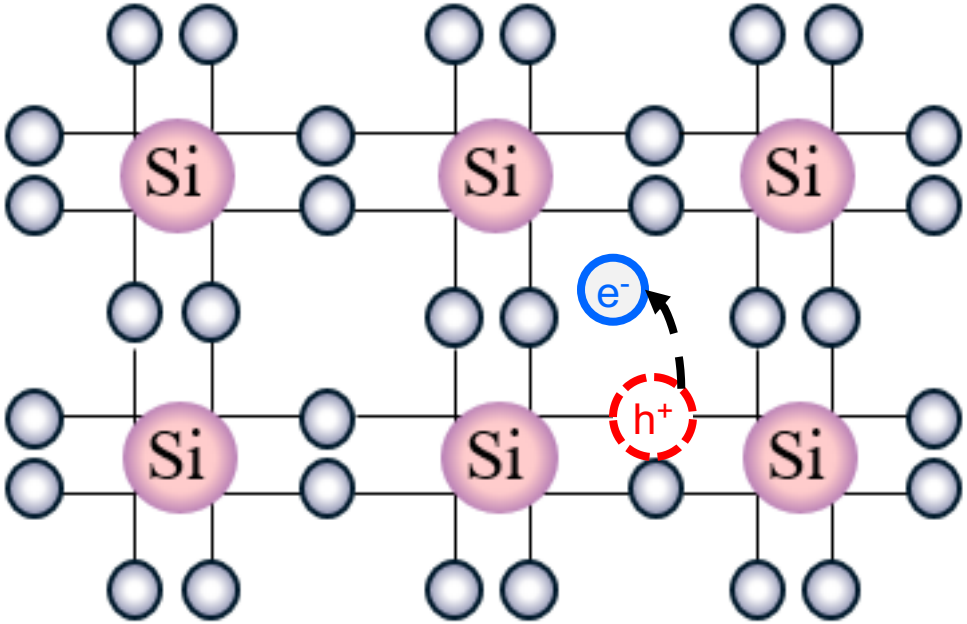
NATIONAL CHENG KUNG UNIVERSITY 1931
山东大学 SHANDONG UNIVERSITY
UIC UNIVERSITY OF ILLINOIS AT CHICAGO

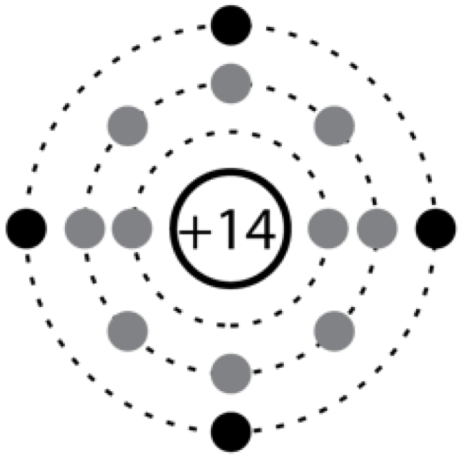


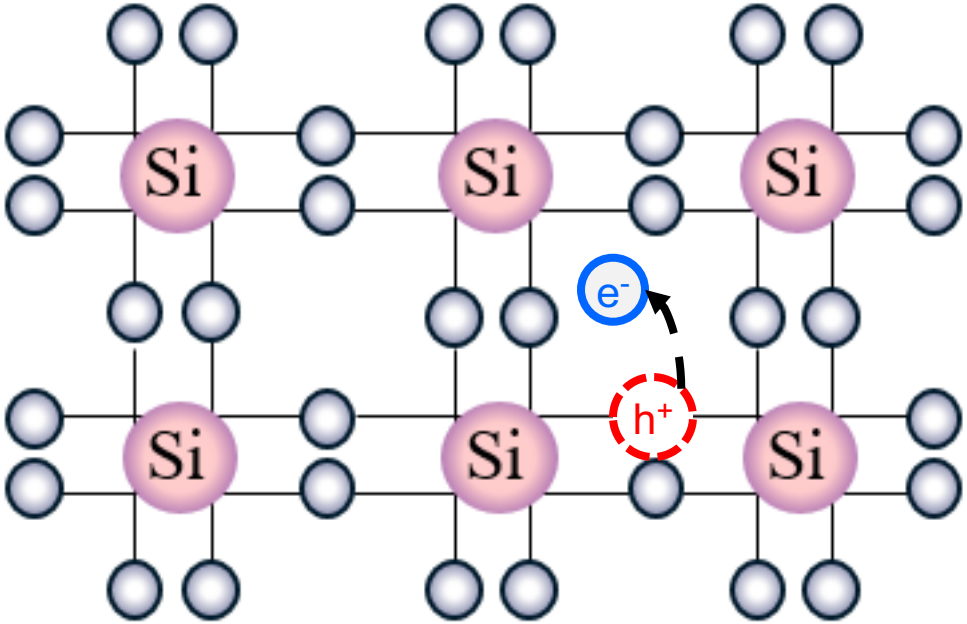
Silicon



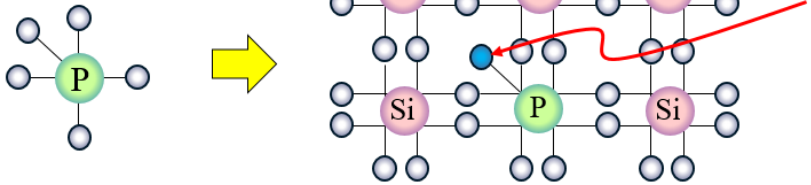

+14
Silicon


Si
Si
Si
Si
Si
Si
e-
h+

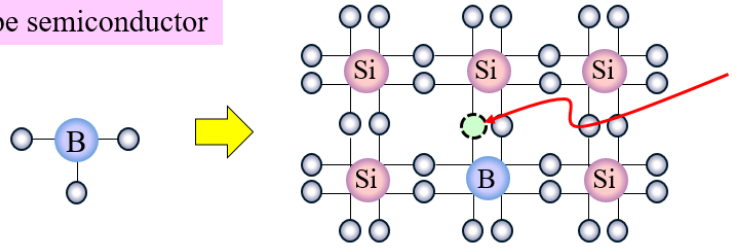




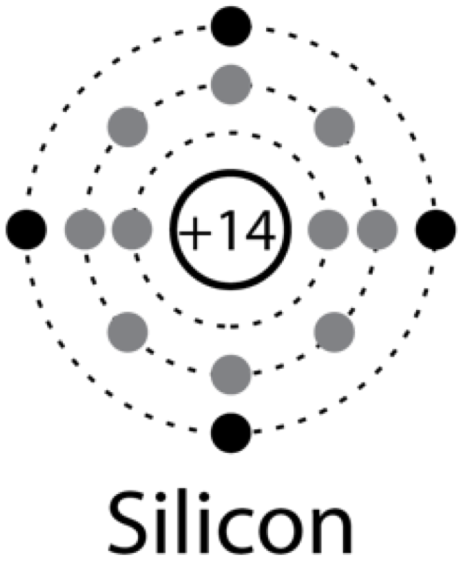
n-type semiconductor

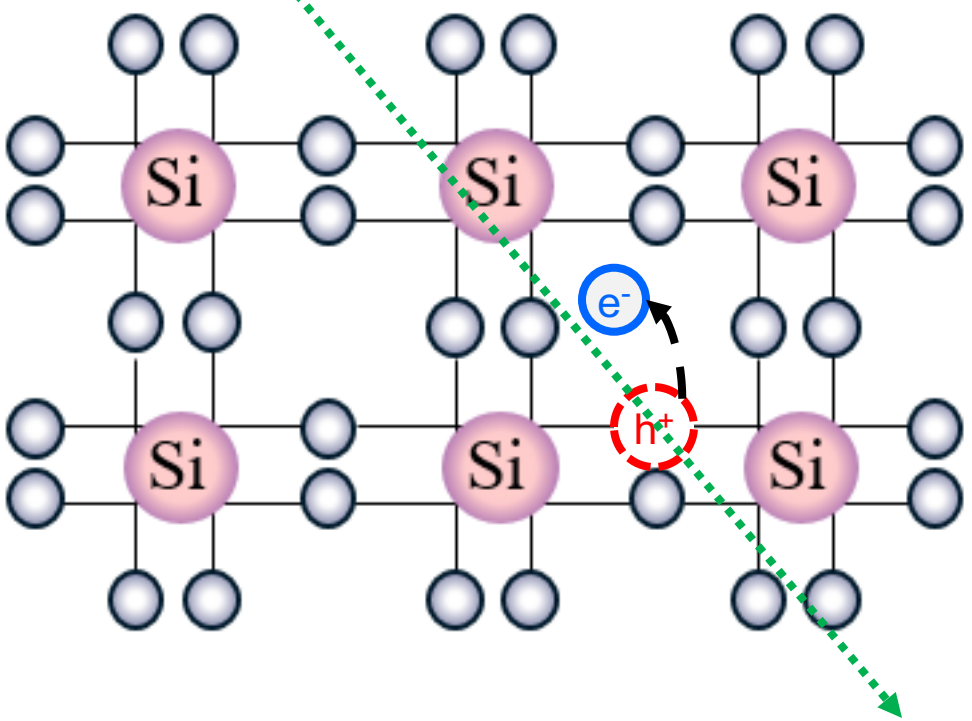


p-type semiconductor



Review of Particle Physics, 2021 – Section 34&35





- Modern integrated circuit technology allows the formation of high-density micron-scale electrodes on large (15–20 cm diameter) wafers, providing **excellent position resolution**.
- The density of silicon and the small ionization energy yield adequate signals with active layers of only 100–300 μm thick, so the **signals can be very fast**.
- About 3.6 eV of energy is needed to create an electron-hole pair in Si. This is much smaller than other detector materials and thus provide **good intrinsic energy resolution**.

The Review of Particle Physics (2021), Ch35. Particle Detectors at Accelerators

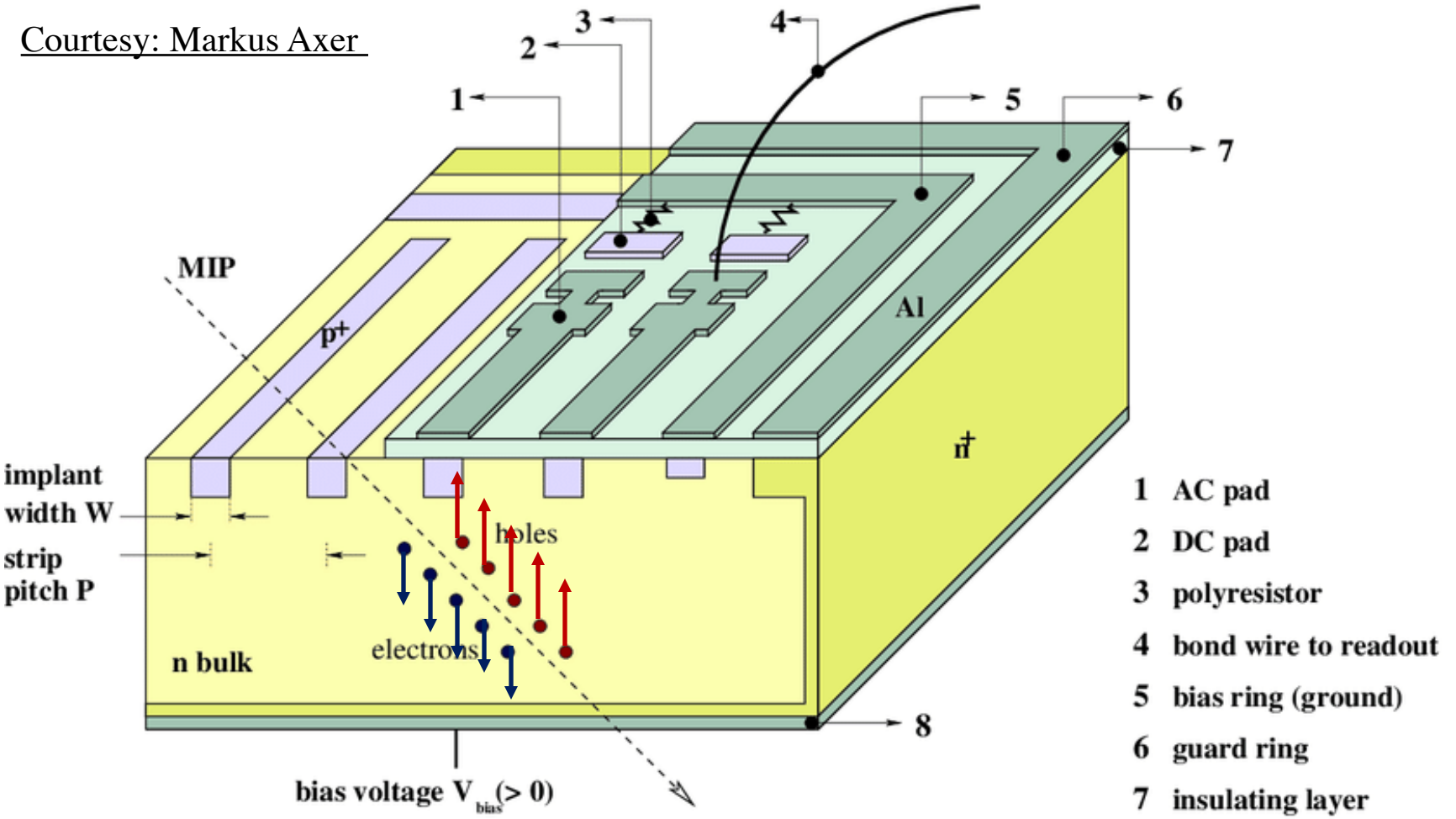
Detector Type	Intrinsinc Spatial Resolution (rms)	Time Resolution	Dead Time
Resistive plate chamber	$\lesssim$ 10 mm	1 ns (50 ps*)	—
Streamer chamber	300 μm†	2 μs	100 ms
Liquid argon drift [7]	~175–450 μm	~ 200 ns	~ 2 μs
Scintillation tracker	~100 μm	100 ps/n‡	10 ns
Bubble chamber	10–150 μm	1 ms	50 ms§
Proportional chamber	50–100 μm¶	2 ns	20-200 ns
Drift chamber	50–100 μm	2 ns‖	20-100 ns
Micro-pattern gas detect.	30–40 μm	< 10 ns	10-100 ns
Silicon strip	pitch/(3 to 7)**	few ns††	$\lesssim$ 50 ns††
Silicon pixel	$\lesssim$ 10 μm	few ns††	$\lesssim$ 50 ns††
Emulsion	1 μm	—	—

∗For multiple-gap RPCs

††Limited by the readout electronics

Introduction to Silicon Strip Detector

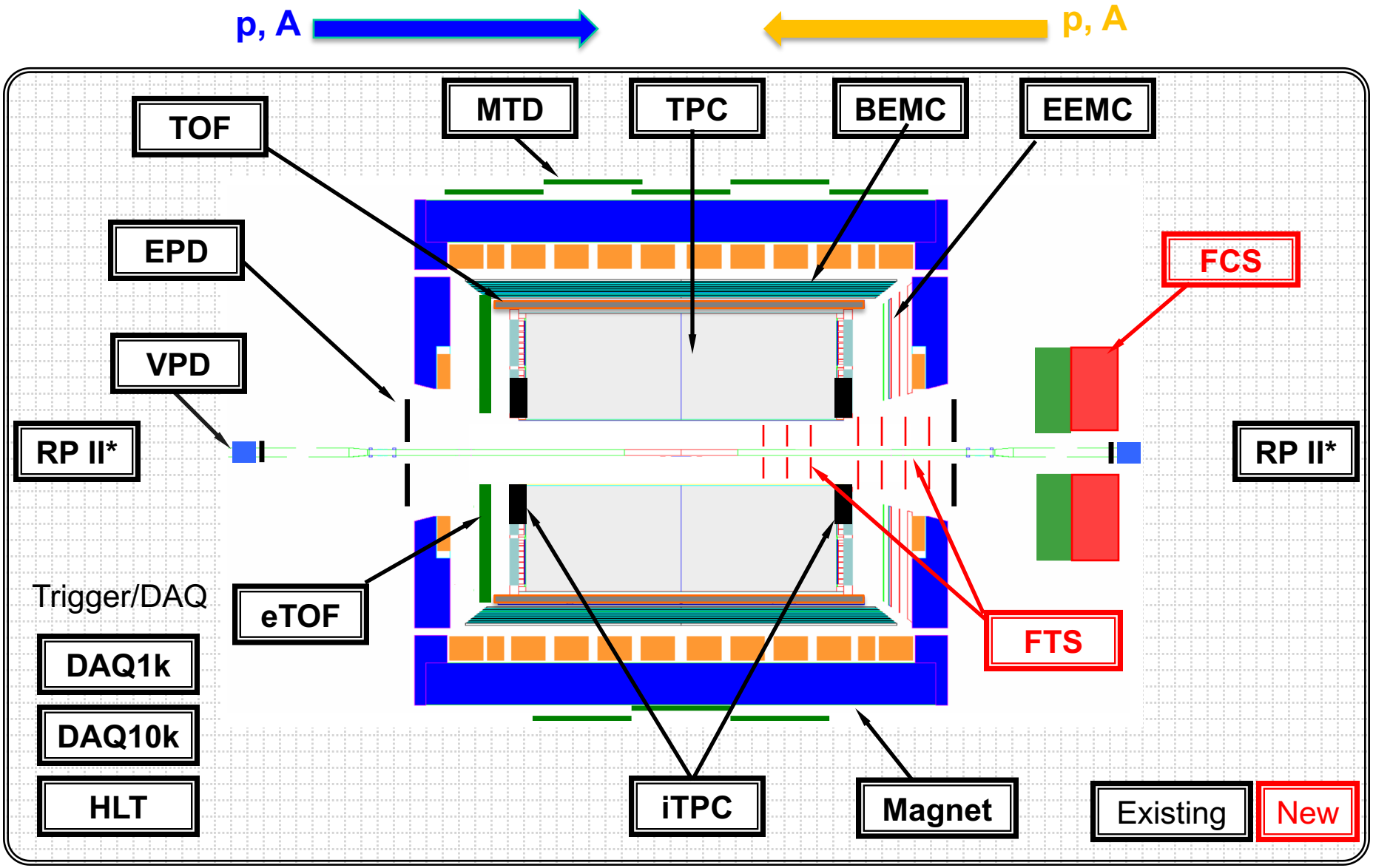
Courtesy: Markus Axer



AC-coupled p-in-n Si strip sensor

- reverse bias of p-n diodes to deplete free charges and reduce leakage current
- signal: proportional to thickness, 22,000 e^- in 300 μm Si
- noise: linearly dependent on sensor input capacitance, typical level ~1000 e^-

STAR Experiment in 2021+

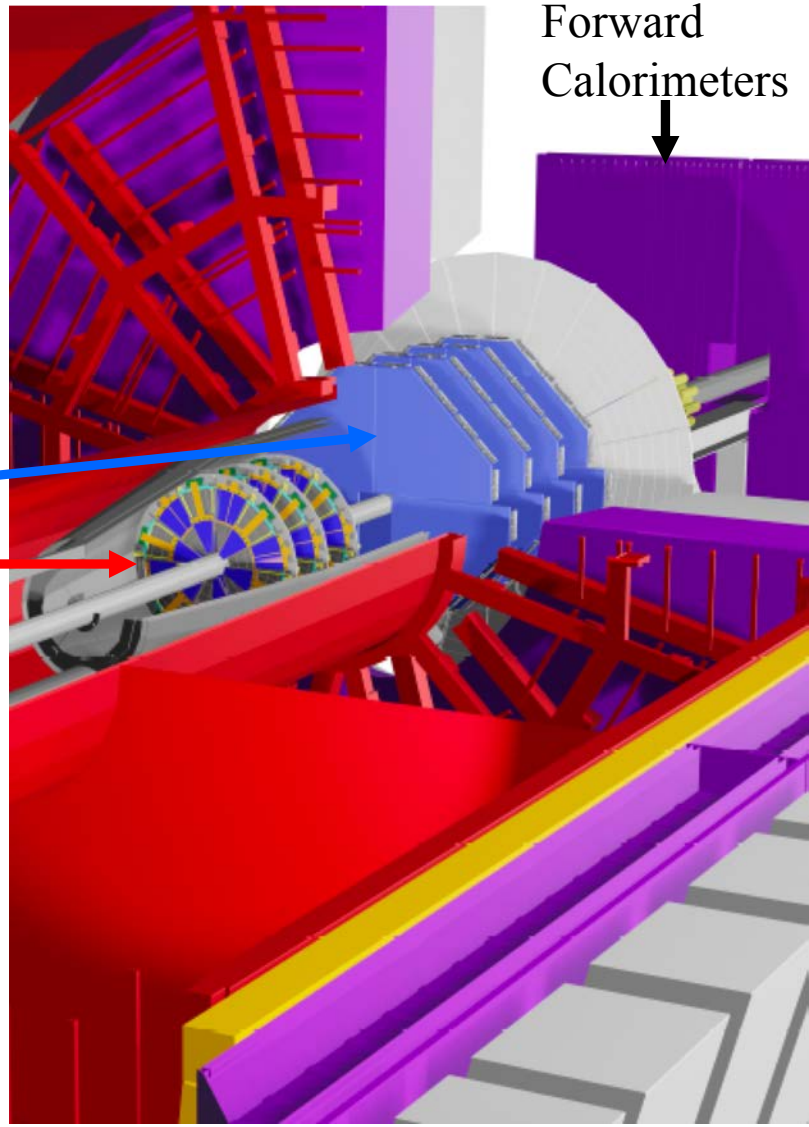


STAR Forward Upgrade (2021+)

- **STAR Forward Physics Program**
  - p+p: proton spin structure, …
  - p+A: gluon saturation at small-x, …
  - A+A: initial state conditions, …

  with new tracking and calorimeter detectors in the forward direction ($2.5 < \eta < 4$)
- **Forward Tracking System** includes
  - 4 layers of **small Thin Gap Chambers**
  - 3 layers of **silicon strip detectors**

  inside 0.5T solenoidal magnet to provide
  - high tracking efficiency
  - charge separation
  - $\delta p_T/p_T \sim 20-30\%$ for $0.2<p_T<2$ GeV/c



STAR Public Note 0648: The STAR Forward Calorimeter System and Forward Tracking System beyond BES-II

- **STAR Forward Physics Program**
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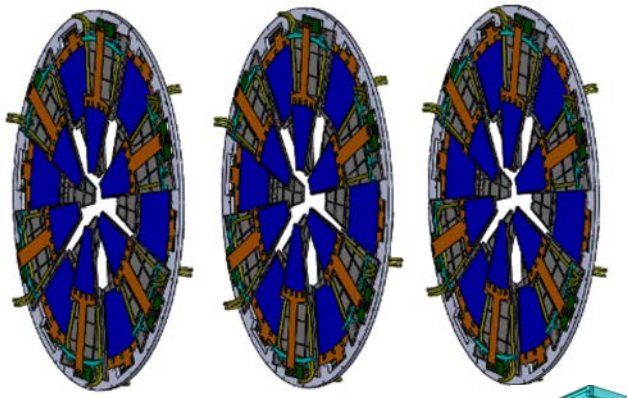

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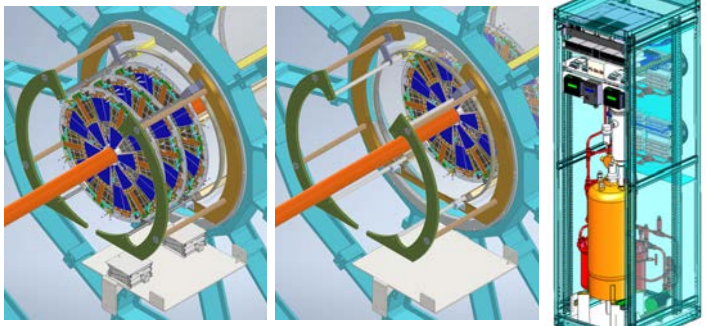
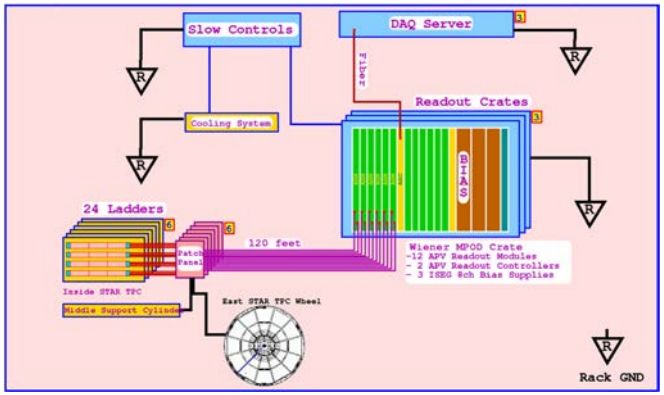


- **Forward Silicon Tracker**
  - 3 disks each with 12 wedge-shaped modules
  - fine ϕ segmentation and coarse in r
  - low material budget
  - cost effective - reuse IST cooling/DAQ



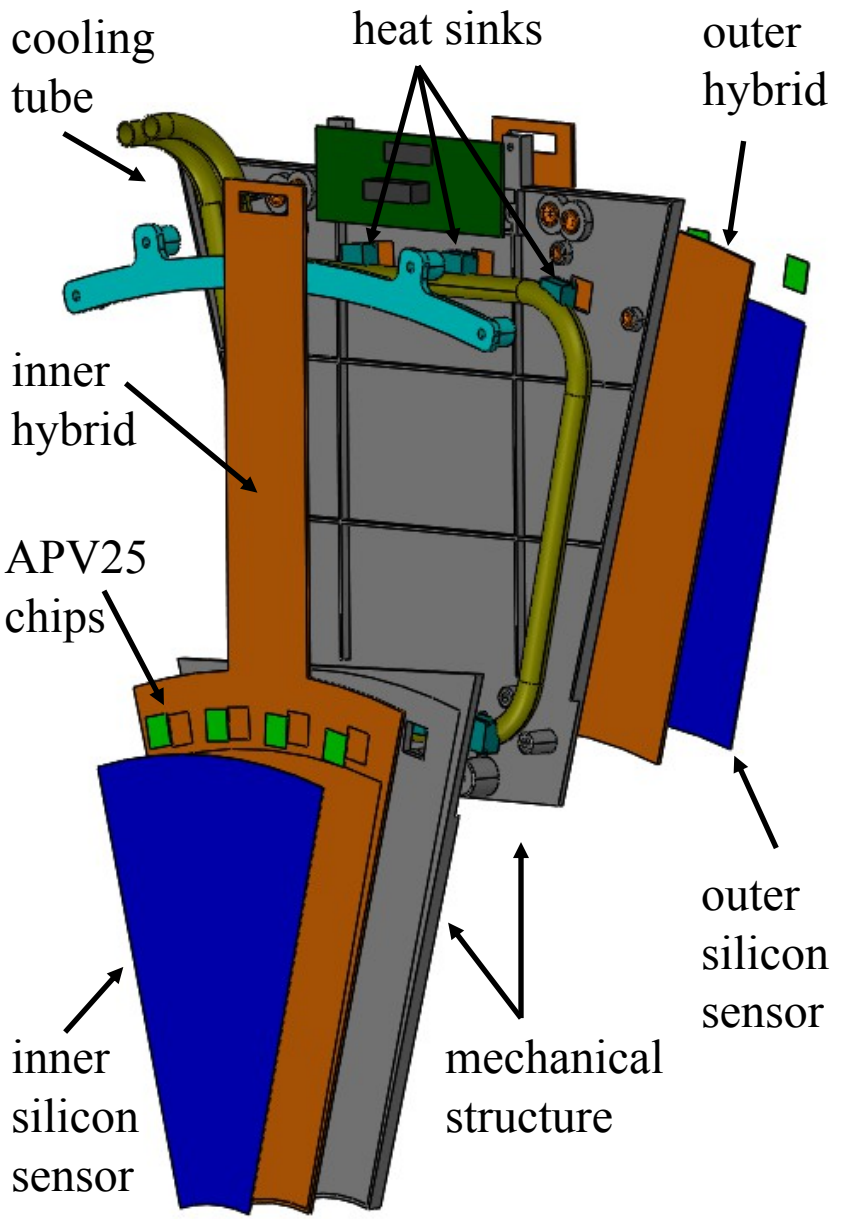
STAR Public Note 0648: The STAR Forward Calorimeter System and Forward Tracking System beyond BES-II

Forward Silicon Tracker – Module Design

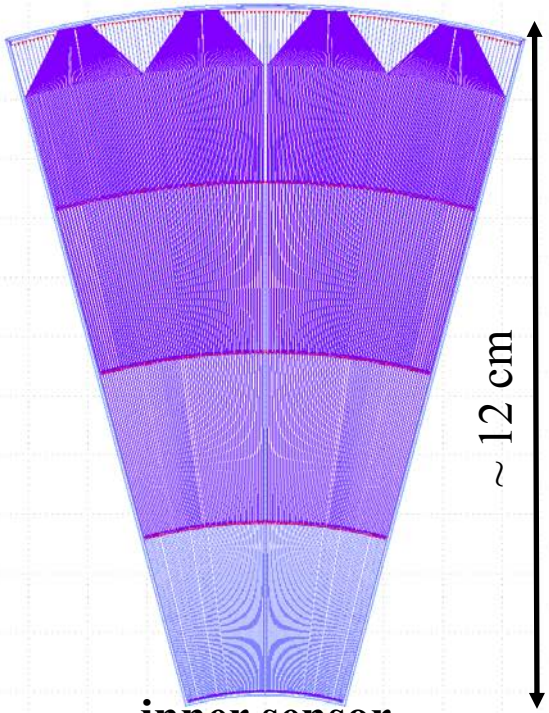
- Each FST module has two regions
  - Inner-radius region: 5<R<16.5 cm
    - 1 Kapton flexible PCB
    - 1 Si sensor: 128 × 4 (ϕ×R) strips
    - 4 APV chips
  - Outer-radius region: 16.5<R<28 cm
    - 1 Kapton flexible PCB
    - 2 Si sensors: 128 × 4 (ϕ×R) strips
    - 4 APV chips

- Mechanical structure is made of
  - PEEK (main structure, tube holder)
  - Stainless steel (cooling tube)
  - Aluminum (heat sinks)

- Module assembly is done at two sites
  - TiDC (Taiwan): gluing inner/outer hybrids and mechanical structures together
  - FNAL: mount/wire-bond AVPs and Silicon sensors on hybrids

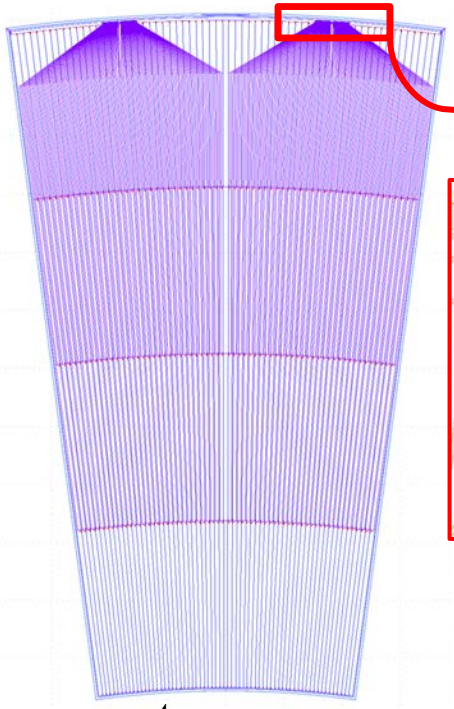


Forward Silicon Tracker – Silicon Sensor (UIC/BNL)

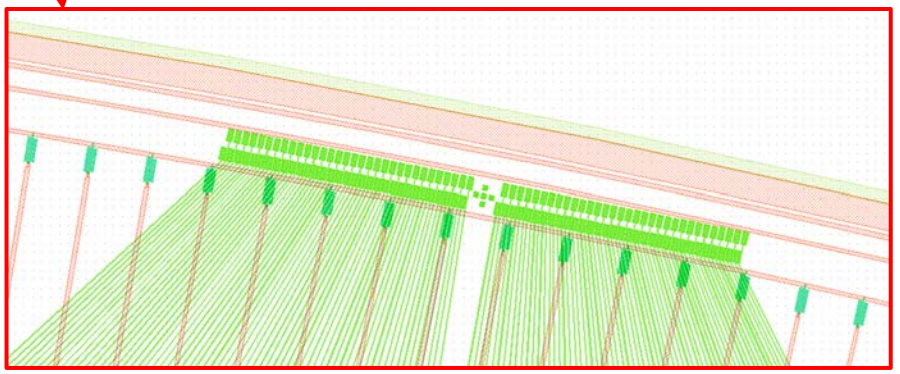


inner sensor

~ 12 cm



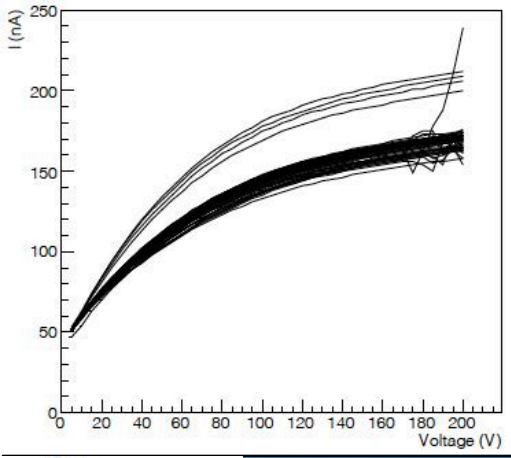
outer sensor



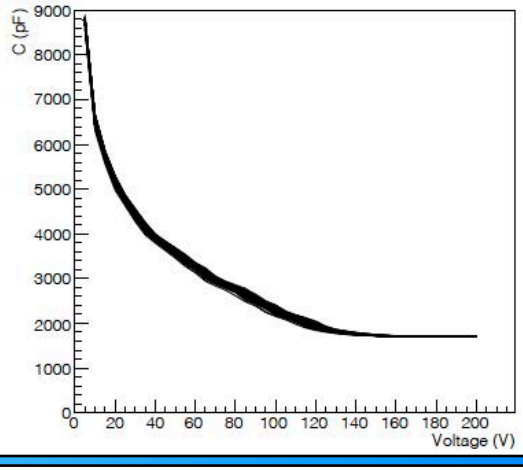
wire-bonding pads

Hamamatsu, Japan

sensor VI



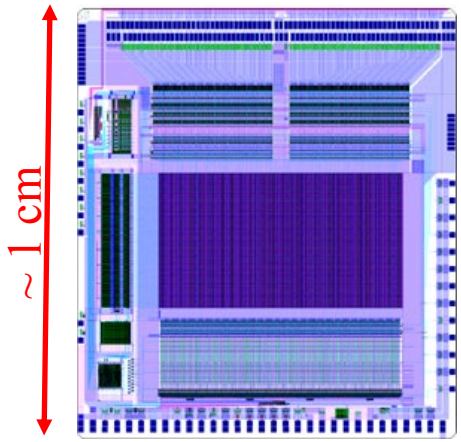
sensor VC



	Inner	Outer
Radial (cm)	5-16.5	16.5-28
Angle (degree)	30	15
# of strips (R*ϕ)	4*128	4*64
Thickness (μm)	320	

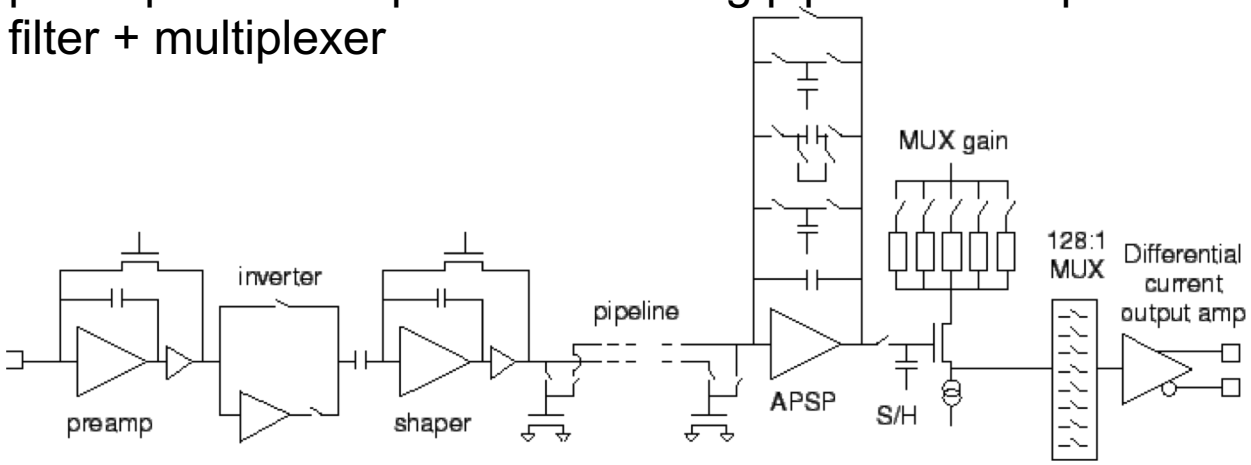
STAR Forward Silicon Tracker - APV25 Chip (UIC)

128 front-end input pads

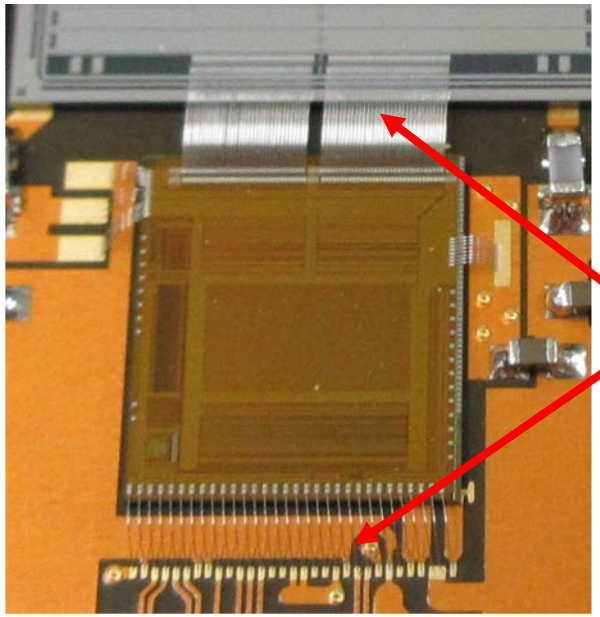


control and output pads

preamplifier + shaper + 192 analog pipelines + capacitor filter + multiplexer

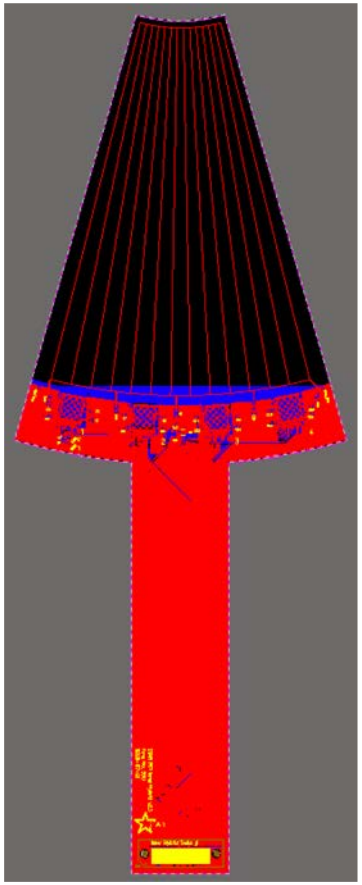


Power: ~360 mW/chip generated heat need to be removed



Aluminum wire-bonds between Silicon sensor and APV, and between APV and flexible PCB (hybrid – see next slide)

Forward Silicon Tracker – Hybrid (SDU)



inner hybrid (v3)

- Phi angle: 32°
- Inner radius: 49 mm
- Outer radius: 185 mm
- Tail length: 126 mm
- Thickness: ~0.35mm

outer hybrid (v3)

- Phi angle: 32°
- Inner radius: 164mm
- Outer radius: 300 mm
- Tail length: 20 mm
- Thickness: ~0.35mm

Base material: Kapton with 3 copper layers

layer	um			
	25	25um cvl PI	25um cvl PI	25um cvl PI
	35	35um cvl AD	35um cvl AD	35um cvl AD
1	35	35um (18+plating) copper	35um (18+plating) copper	35um (18+plating) copper
	50	50um polyimide	50um polyimide	50um polyimide
	20	25um AD	25um AD	25um AD
2	18	18 um copper	18 um copper	18 um copper
	75	75um polyimide	75um polyimide	75um polyimide
3	35	35um (18+plating) copper	35um (18+plating) copper	35um (18+plating) copper
	35	35um cvl AD	35um cvl AD	35um cvl AD
	25	25um cvl PI	25um cvl PI	25um cvl PI
	flex thickness=0.35±0.05mm			

FastPrint, China

Bring in power, clock, control signals to APV and Si sensor, and bring out APV readout signals

Forward Silicon Tracker – Mechanical Structure (NCKU)

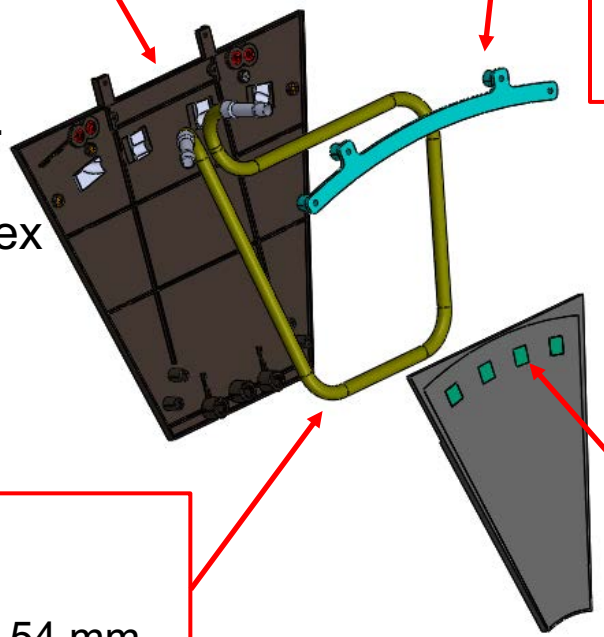
Main structure:
- ❑ Material: PEEK
- ❑ Thermal Conductivity: 0.24 W/m/K

Tube fixture:
- ❑ Material: PEEK

Thermal grease:
- ❑ Material: Thermalrigh TF8 2G

Main structure made by injection molding method.

Challenges:
thin + large area + complex structure with many components embedded



Glue (inner MS + outer MS):
- ❑ Material: Loctite EA 9359.3 AERO

Glue (hybrid + MS):
- ❑ Material: Araldite 2011

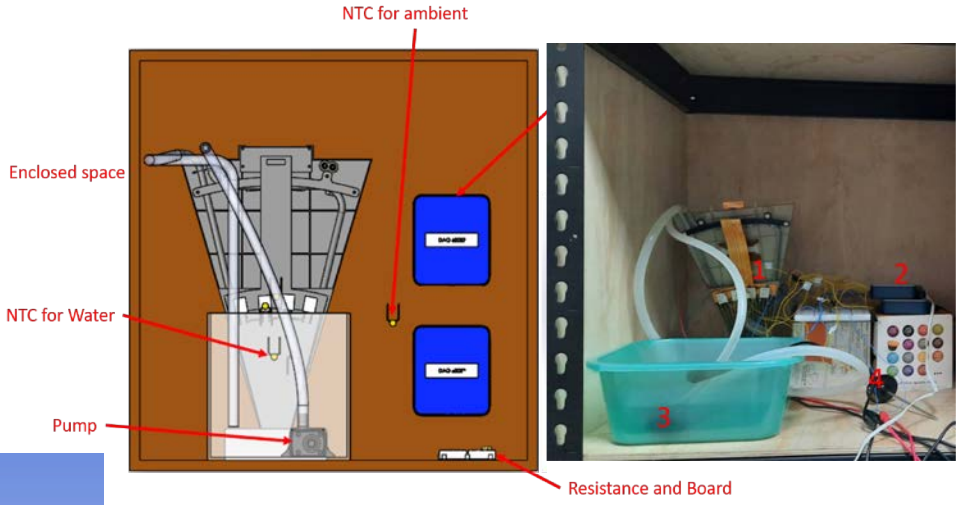
Tube:
- ❑ Material: Stainless 316
- ❑ Size: OD 6.35 mm, ID 5.54 mm
- ❑ Thermal Conductivity: 14 W/m/K

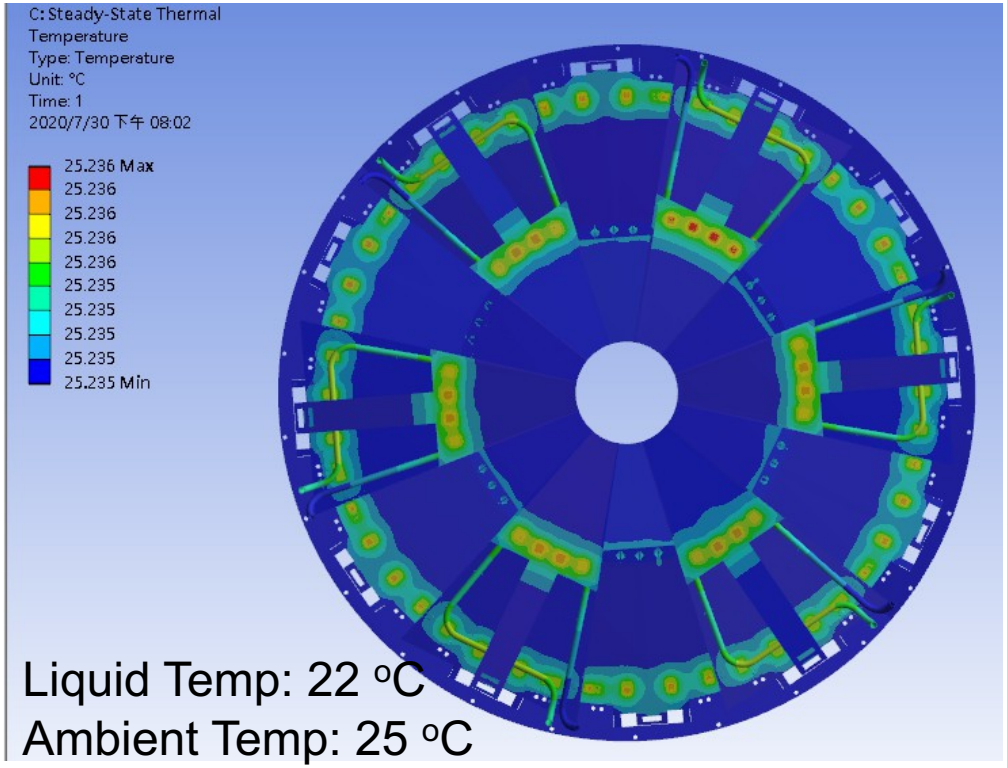
Heat sink:
- ❑ Material: Al 6061
- ❑ Size: ~8.2 x 8.0 x 3 mm^2

AIDC/EASTON, Taiwan

Forward Silicon Tracker – Thermal Analysis (NCKU)

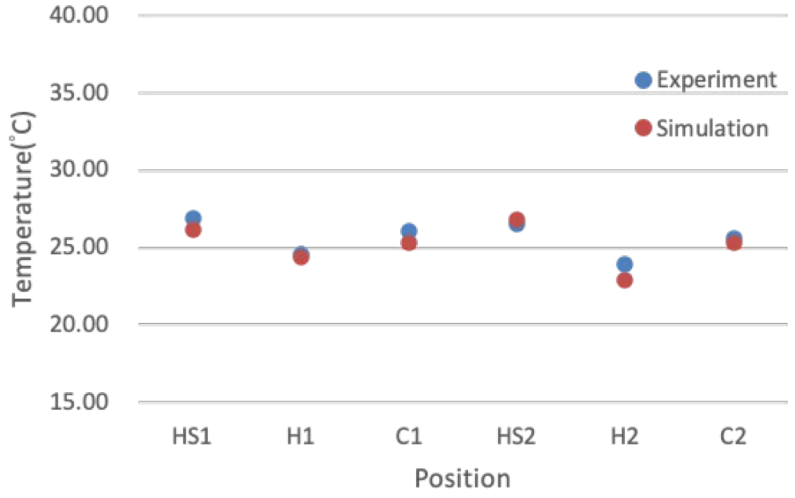
- Careful thermal analysis is performed by using single module with water cooling
- **Temperature at thermal equilibrium is less than 26 °C**





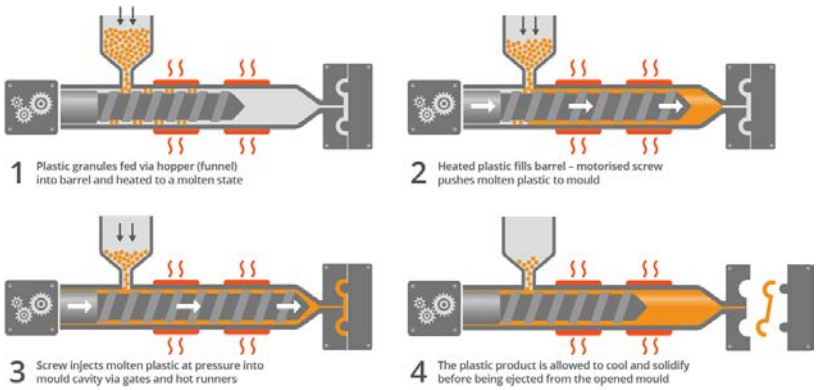
Liquid Temp: 22 °C
Ambient Temp: 25 °C

Consistent results between experiments and simulation



Mechanical Structure - Injection Molding

- **Very challenging:**
  thin + large + complex structure
  many components embedded
- Using injection molding method
  acceptable maximum deformation 250 μm



Moving Half (Core Side)

Fixed Half (Cavity Side)

Forward Silicon Tracker – Module Assembly

1) Assemble hybrids, inner and outer mechanical structures (NCKU@TiDC)

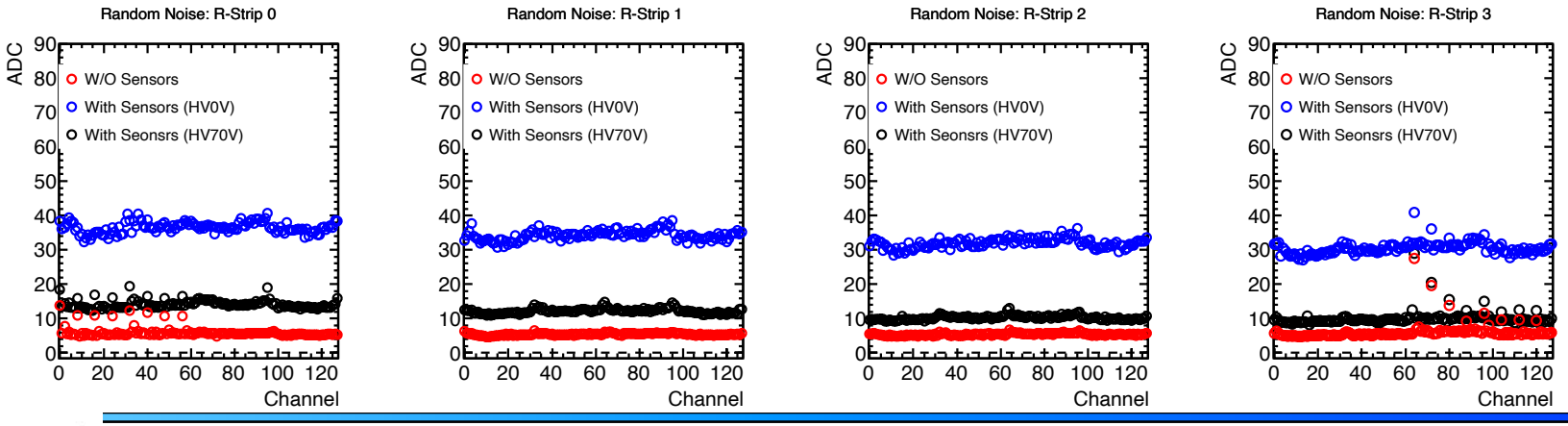
- Solder connectors onto the hybrids by an external company. QC by visual and electrical tests
- Use a robotic machine at **Taiwan instrumentation Detector Consortium** (TiDC) to assemble
  - Hybrid PCBs onto inner and outer mechanical structures
  - Inner wedge and outer wedge together
  - QC by using an OGP to measure the surface flatness and relative positions of the hybrids
- Solder passive components manually onto Hybrids. QC by visual and electrical tests

2) Assemble APV and Silicon sensors onto hybrids (FNAL/UIC)

- Glue and wire-bond APVs onto the hybrids. QC by read out APVs to get pedestal/noise.
- Glue, wire-bond and survey Silicon sensors. QC by read out APVs to get pedestal/noise.
- Encapsulate wire-bonds. QC by read out APVs to get pedestal/noise.
- QC by sample testing (e.g. 1/6th) of modules with cosmic ray

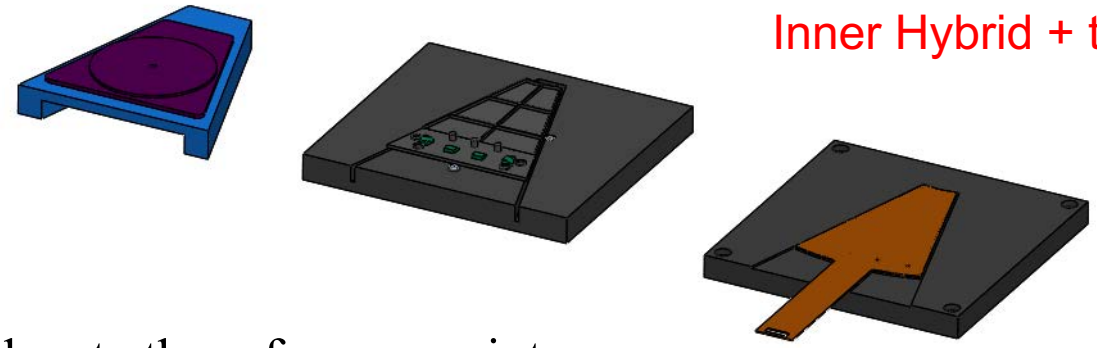
3) Shipping assembled modules to BNL. QC by read out APVs to get pedestal/noise.

4) Mount modules onto support structure at BNL. QC by read out APVs to get pedestal/noise.

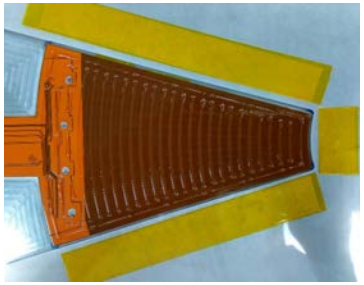


Module Assembly – Inner Wedge

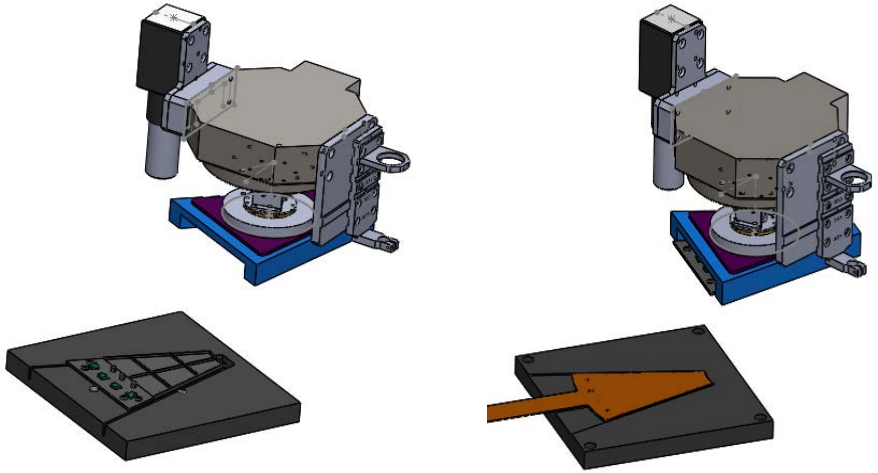
1) Place pickup tool, inner MS + tray, inner Hybrid + tray on table



2) Use camera to locate the reference points

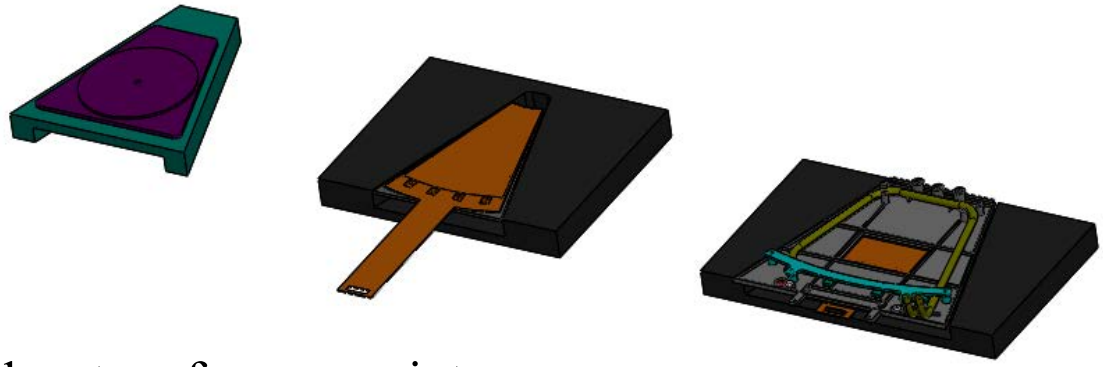


3) Pick up inner mechanical structure and glue it on the inner hybrid



Module Assembly – Outer + Inner

1) Place pickup tool, inner wedge + tray, outer wedge + tray on table



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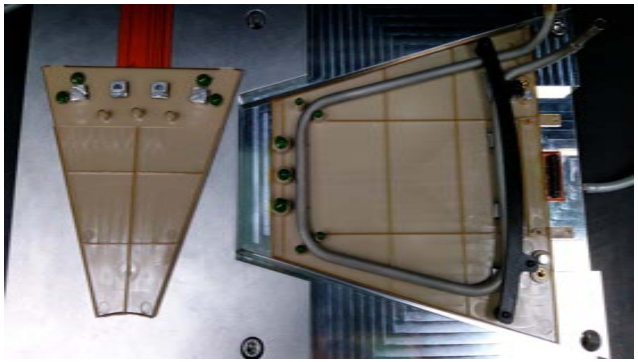
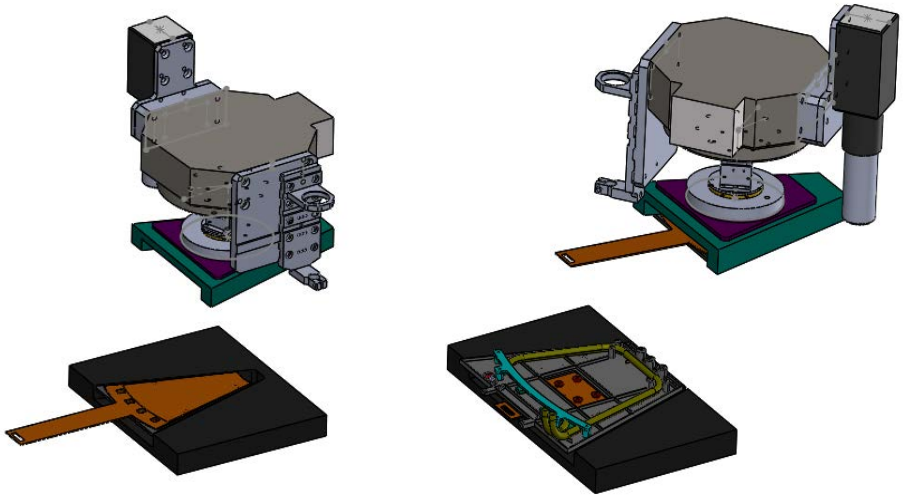
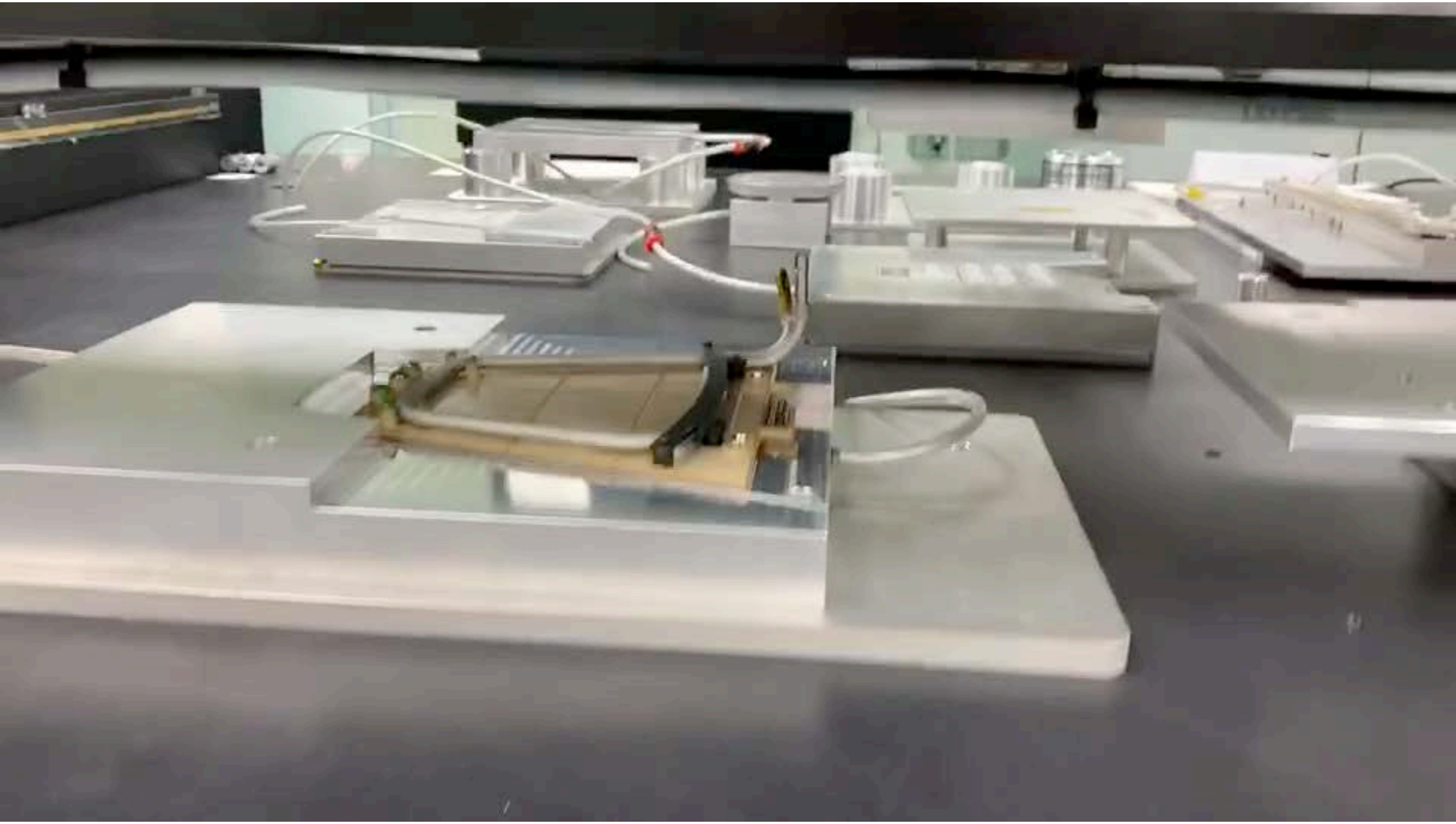


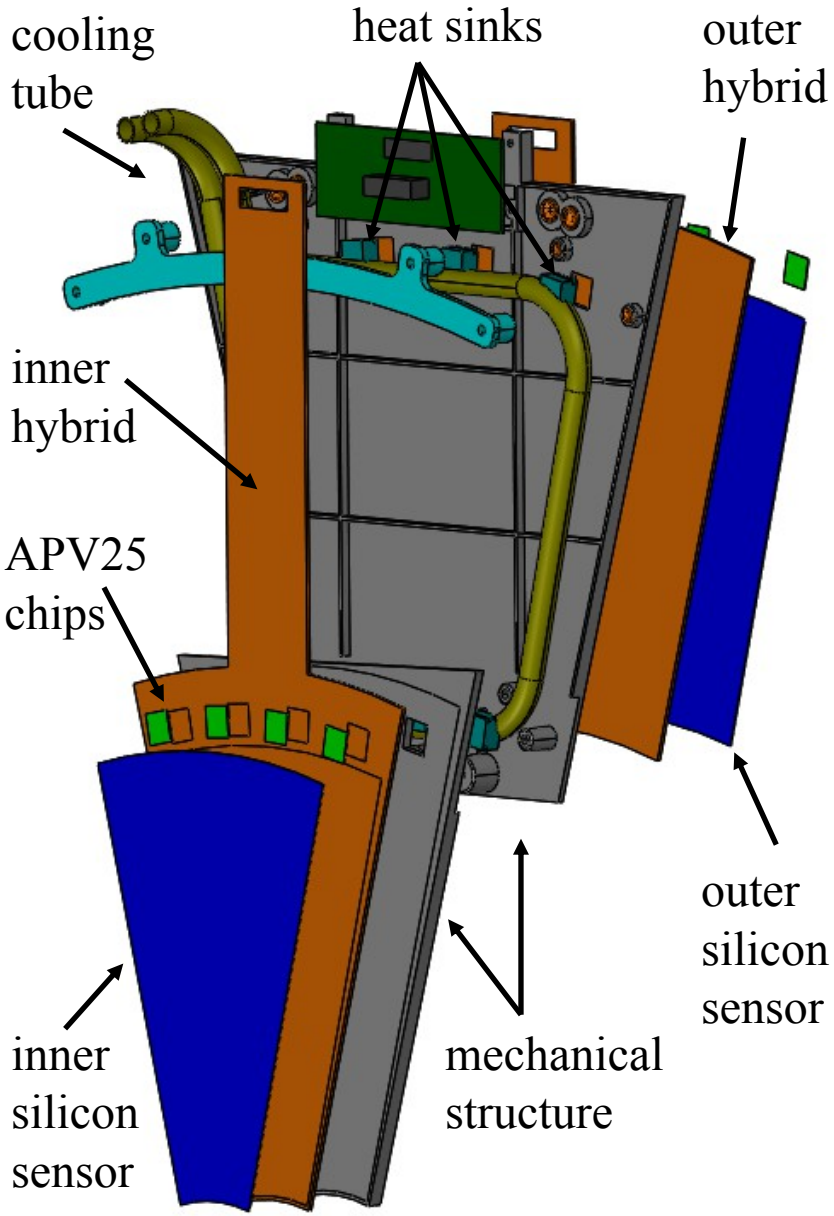
3) Pick up inner wedge and glue onto outer wedge

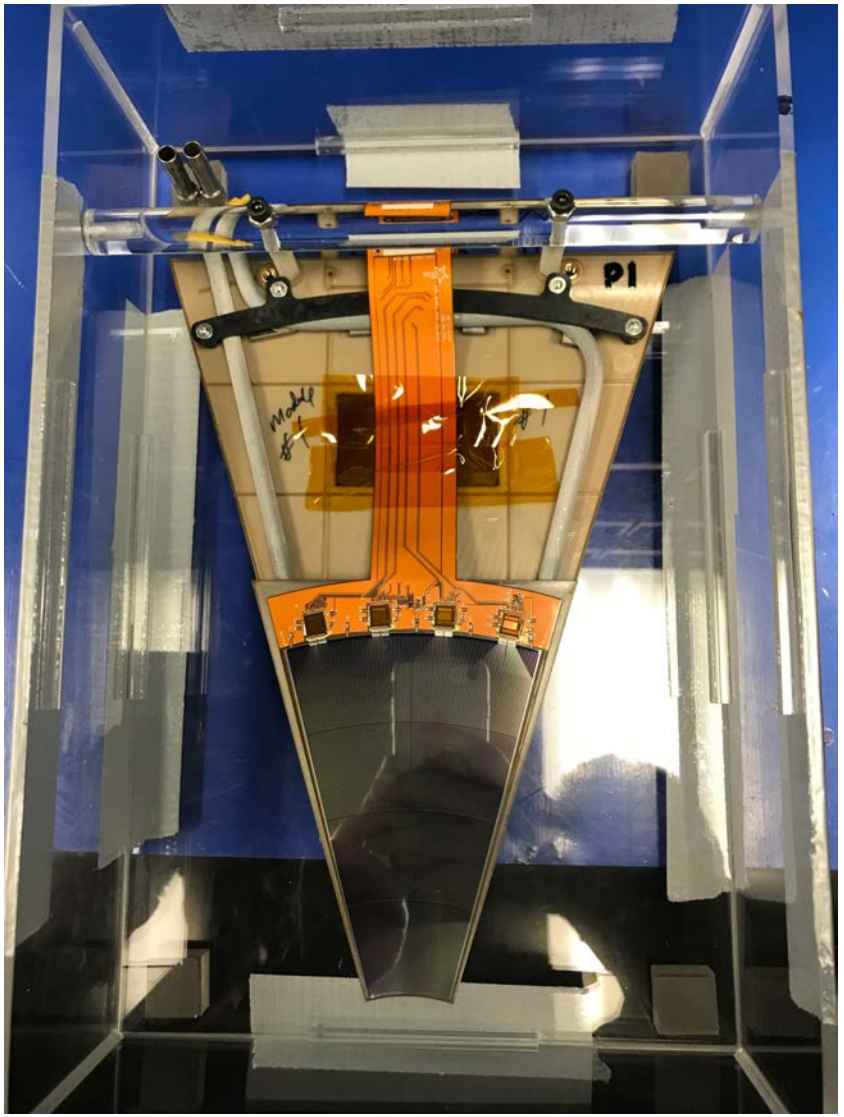


Forward Silicon Tracker – Module Assembly at TiDC

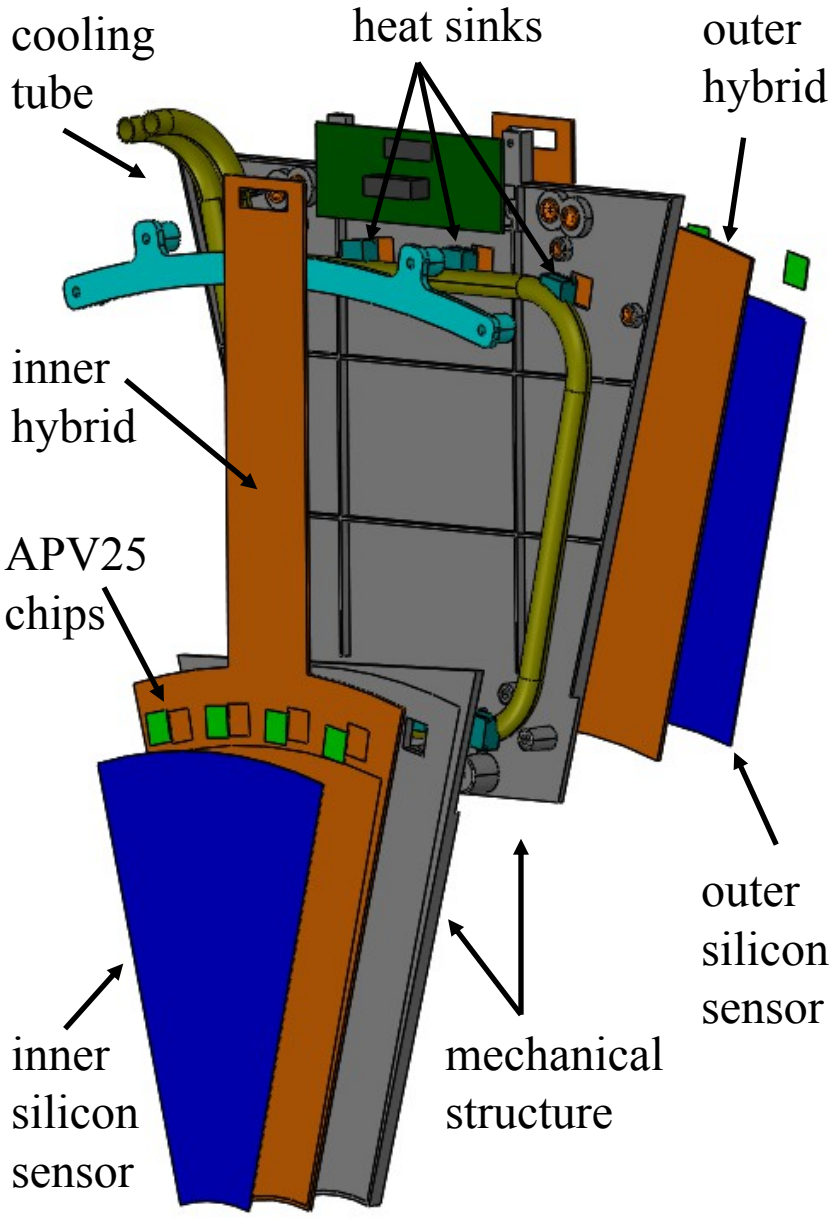


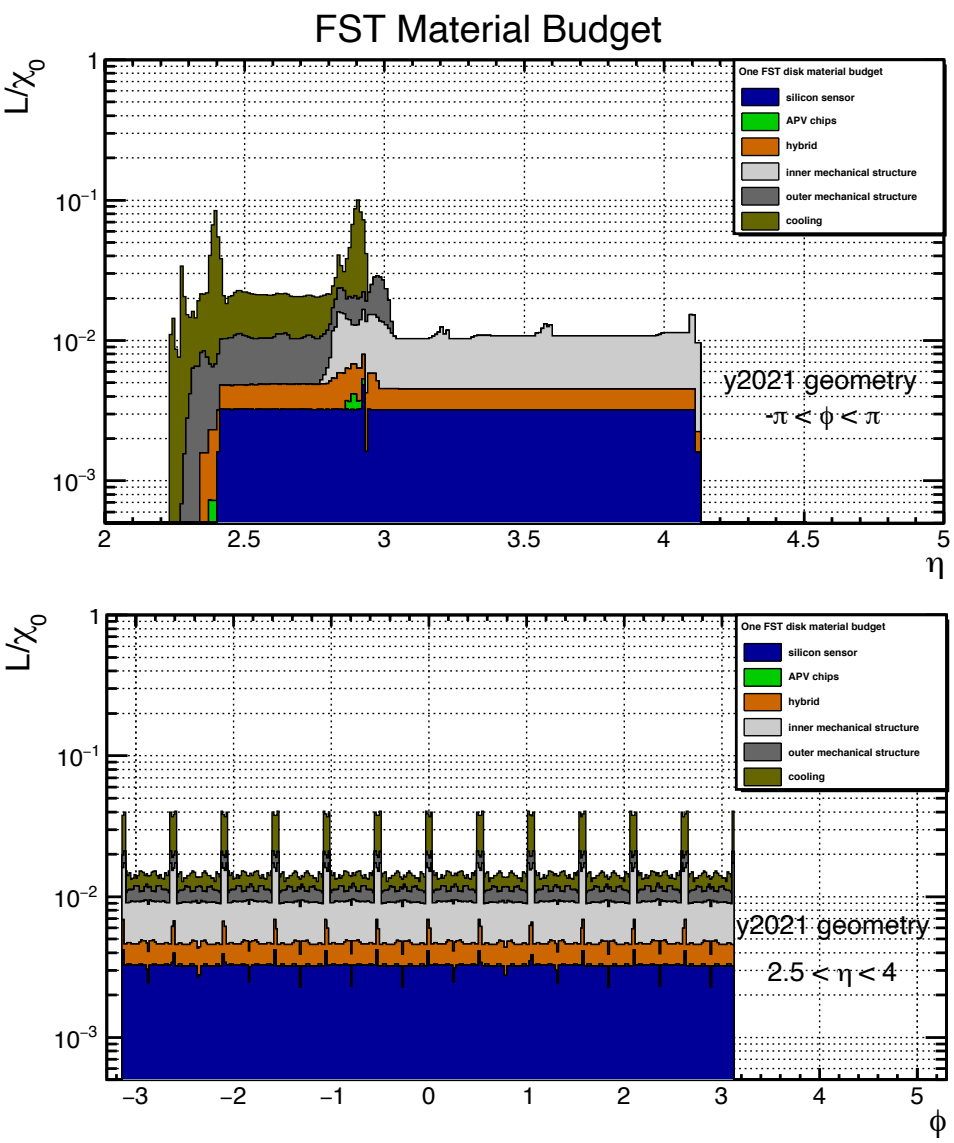
Forward Silicon Tracker – Assembled Module





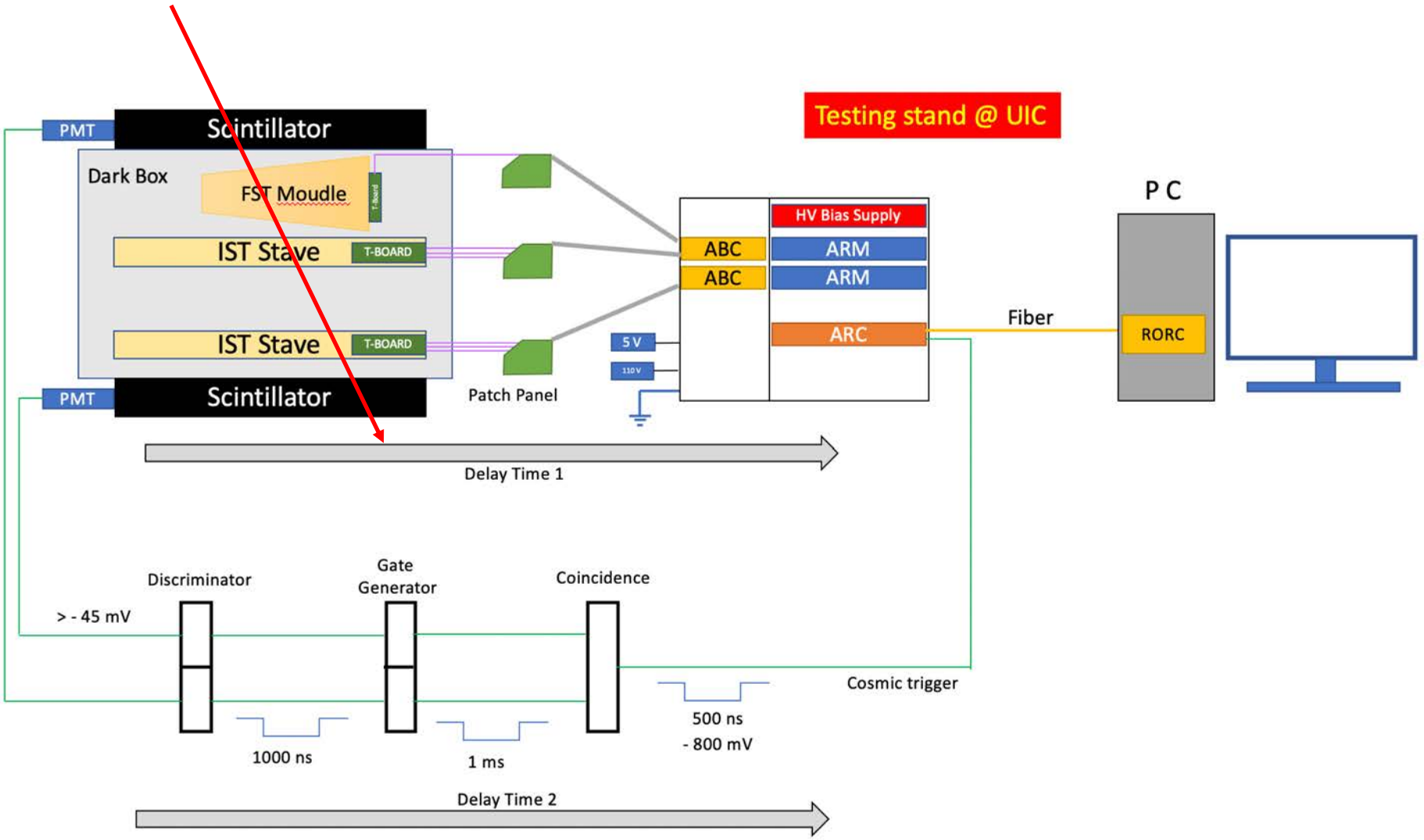
Forward Silicon Tracker – Assembled Module





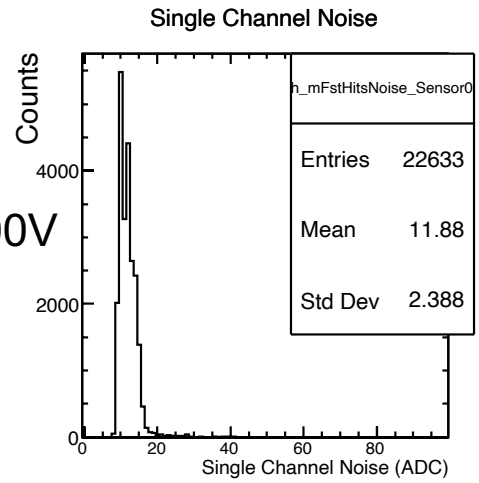
material budget: ~1% X_0 per disk in most areas

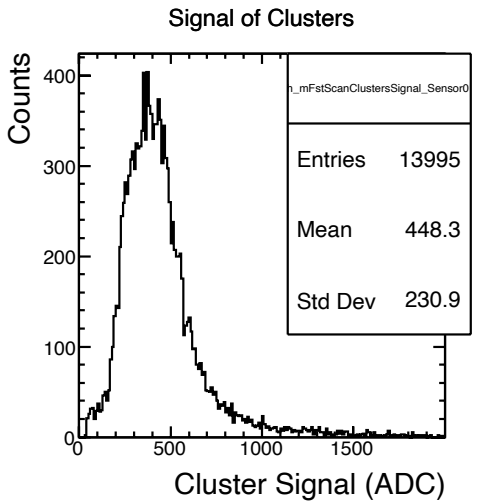
Forward Silicon Tracker – Cosmic Ray Test

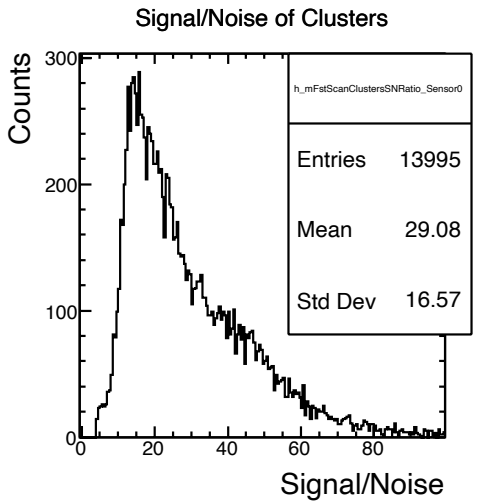


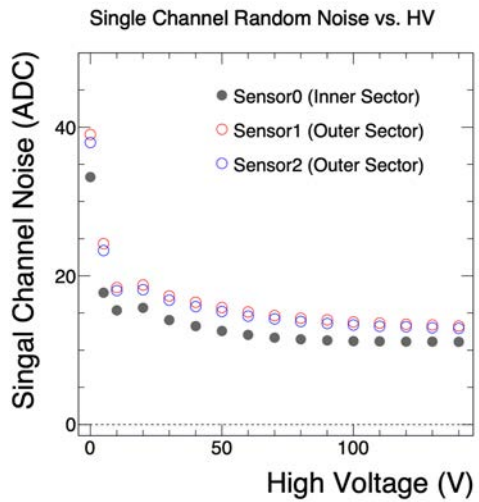
Forward Silicon Tracker – Prototype Performance

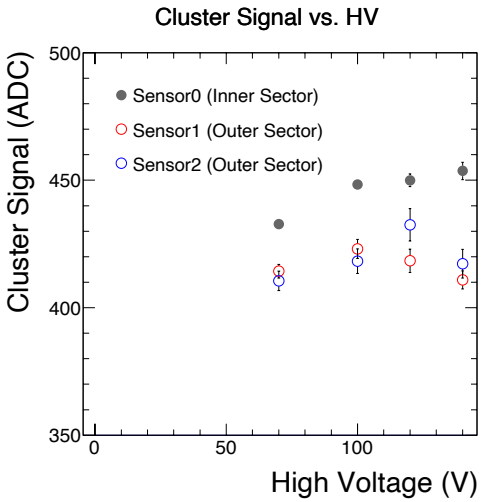
HV100V

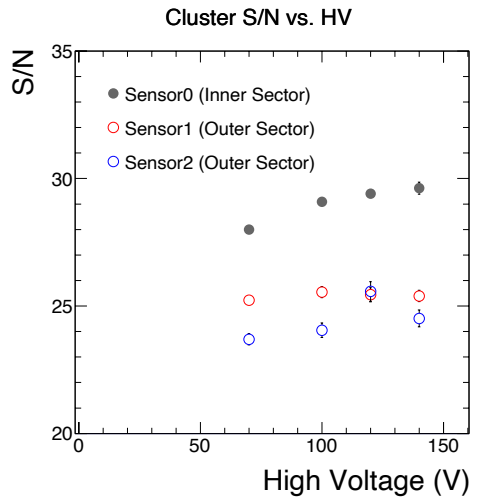




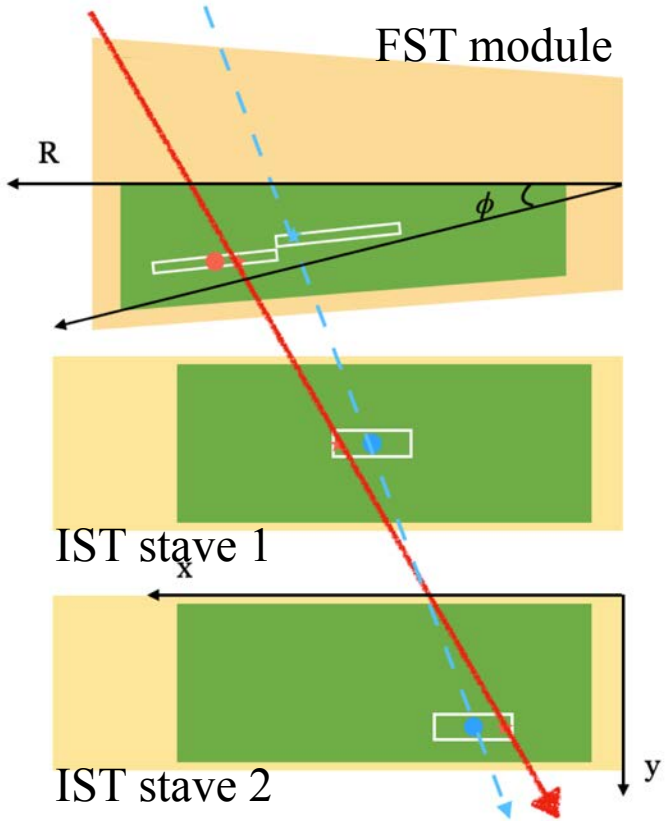


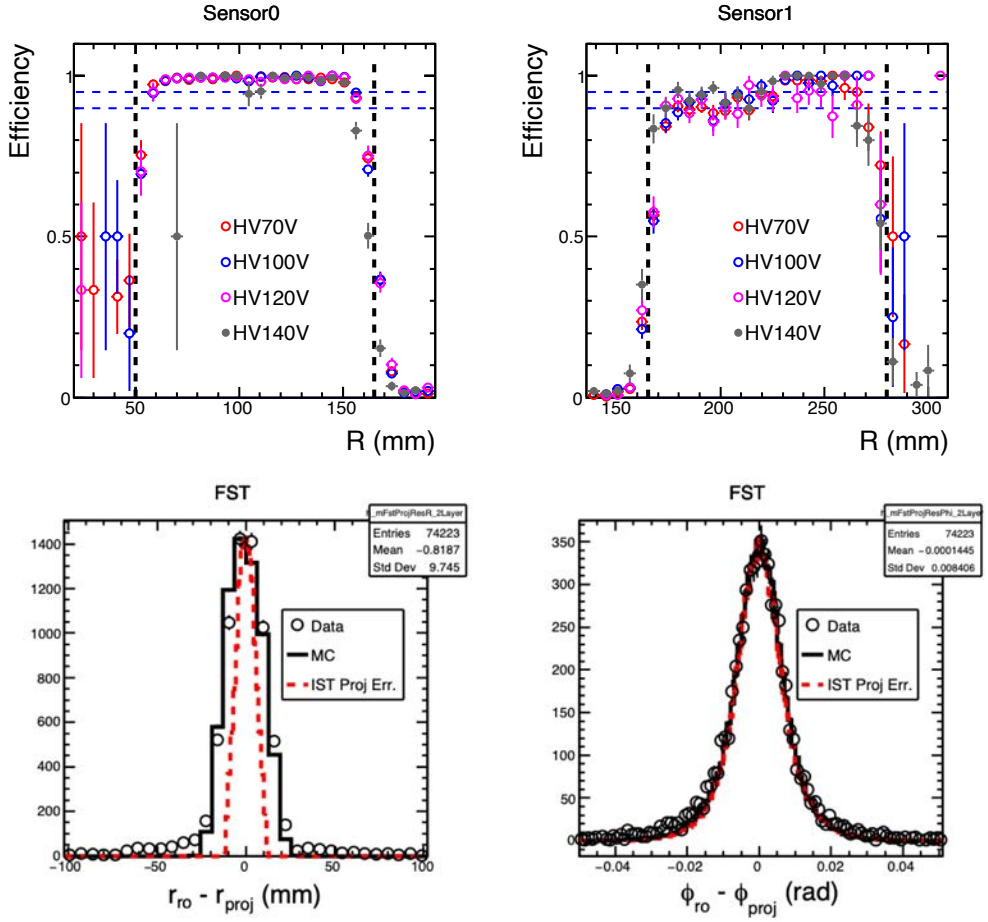






Forward Silicon Tracker – Prototype Performance





FST clustering algorithm

- Seed hit: >4*noise in 2 time bin.
- Recovery hit: >2.5*noise in 2 time bin
  OR >3.5*noise in 1 time bin.

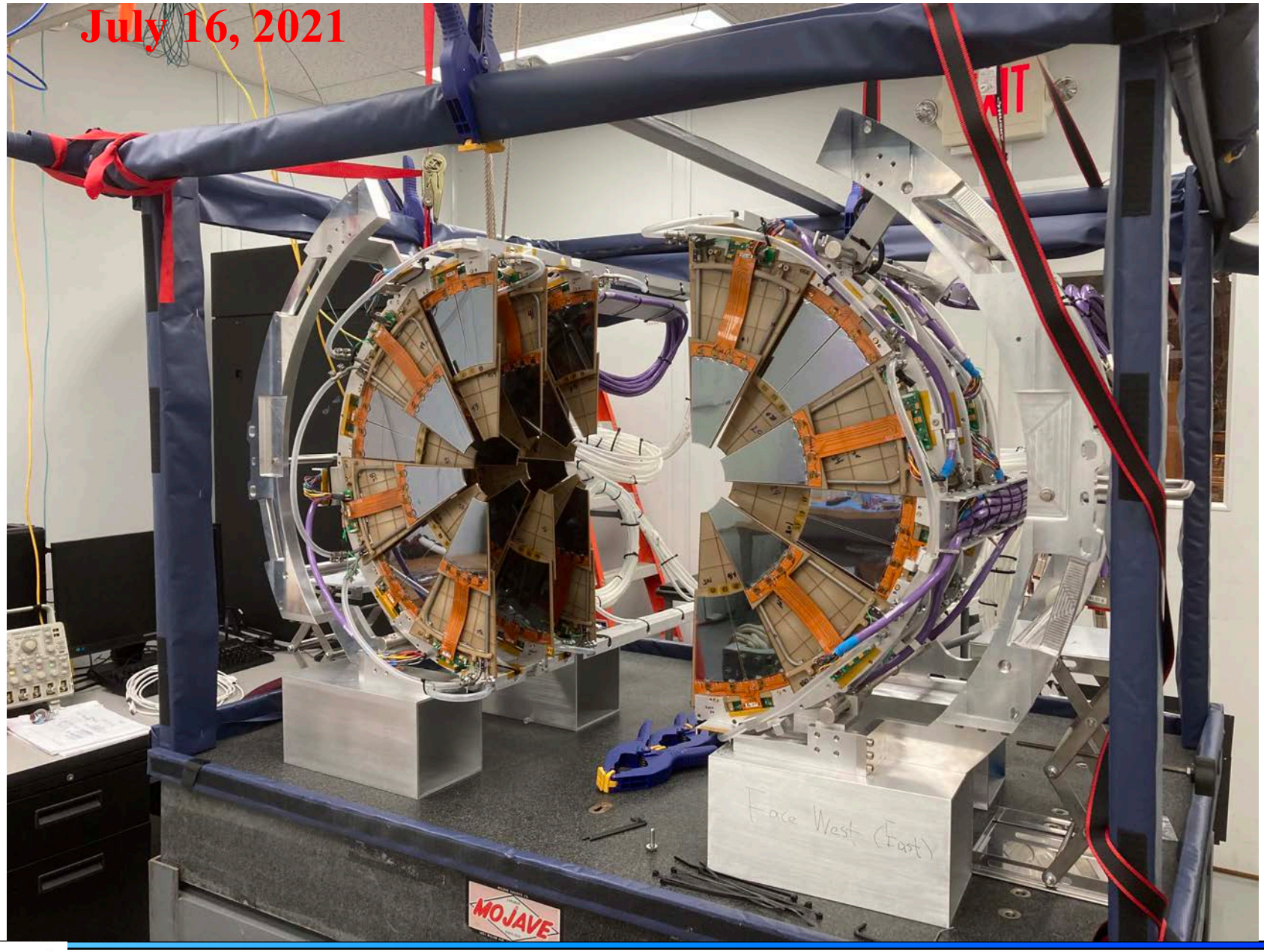
Performance of two fully assembled prototype modules evaluated with cosmic ray:

- All channels can be read out (**KPP: > 85%**)
- Efficiency higher than 90% (**KPP: > 90%**)

STAR Forward Silicon Tracker – Milestones

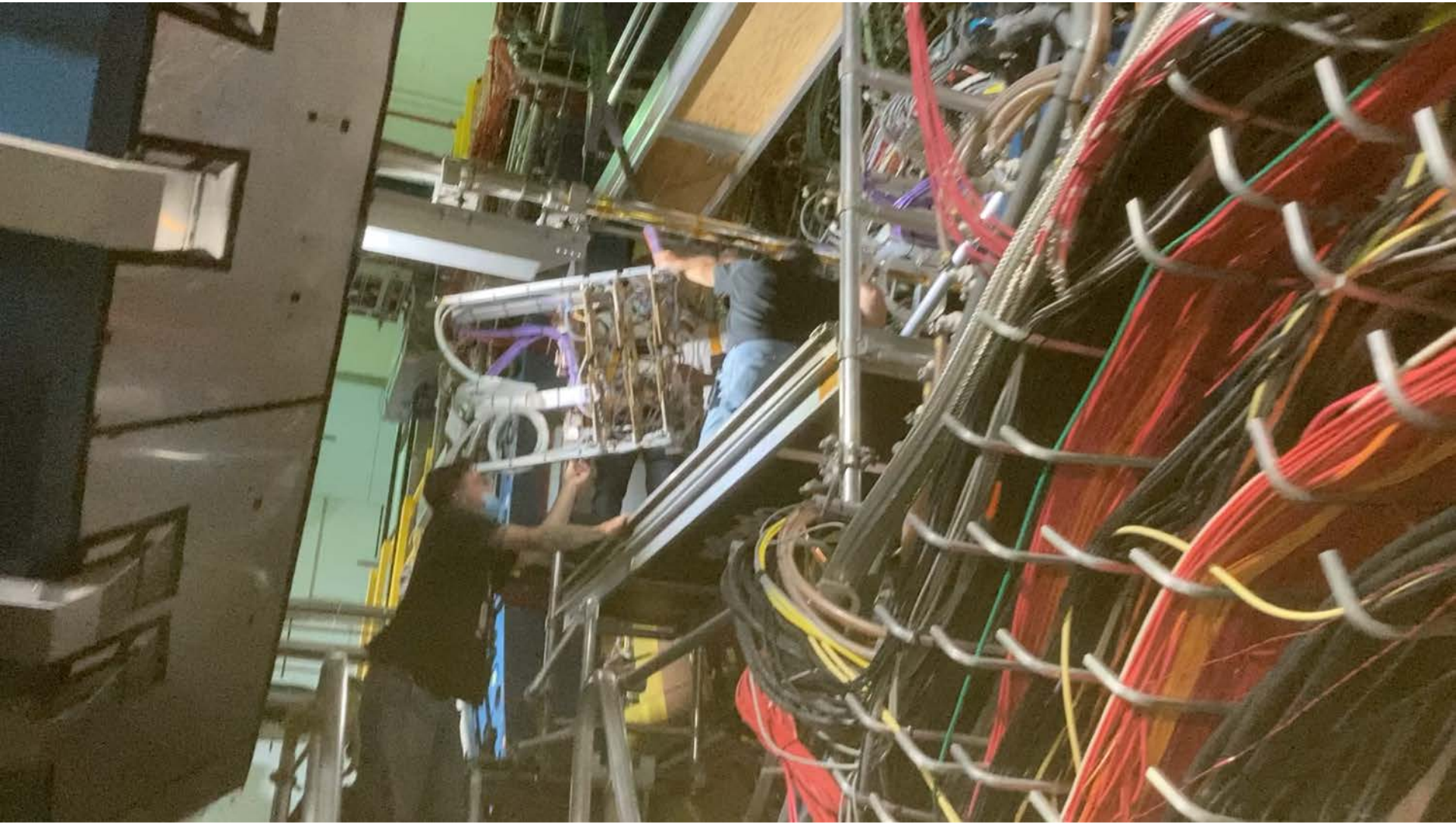
	Aug 2020
• **Detector Module Prototype**	
• Silicon sensor:	**08/23/2019**
• Flexible hybrid:	**12/26/2019**
• Inner signal cable:	**02/05/2020**
• Mechanical structure:	**06/19/2020**
• Detector module assembly:	**07/27/2020**
• Detector module testing:	**08/15/2020**
• **Detector Module Production**	
• Flexible hybrid:	09/21/2020
• Mechanical structure:	01/15/2021
• Silicon sensors:	02/15/2021
• Detector module assembly (complete):	06/30/2021
• **Supporting Structure and Cooling System**	
• Design and Fabrication	11/30/2020
• **DAQ System**	
• T-boards and inner signal cables:	12/01/2020
• **Installation**	
• Installed onto supporting structure:	07/31/2021
• Installed into STAR:	08/20/2021

STAR Forward Silicon Tracker – Integration



STAR Forward Silicon Tracker – Installation

August 10, 2021

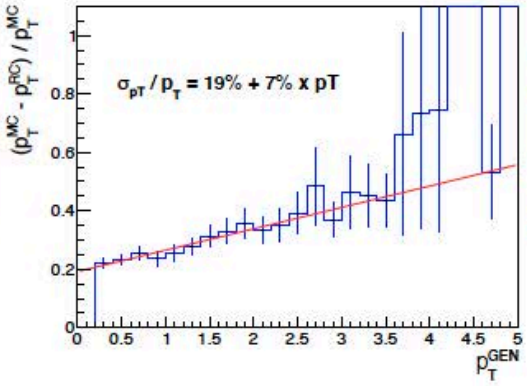


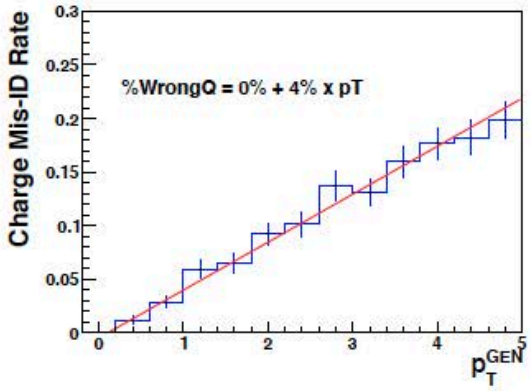
STAR Forward Silicon Tracker – Milestones

	Aug 2020	Aug 2021
Detector Module Prototype		
Silicon sensor:	**08/23/2019**	
Flexible hybrid:	**12/26/2019**	
Inner signal cable:	**02/05/2020**	
Mechanical structure:	**06/19/2020**	
Detector module assembly:	**07/27/2020**	
Detector module testing:	**08/15/2020**	
Detector Module Production		
Flexible hybrid:	09/21/2020	-> **10/21/2021**
Mechanical structure:	01/15/2021	-> **03/23/2021**
Silicon sensors:	02/15/2021	-> **02/08/2021**
Detector module assembly (complete):	06/30/2021	-> **06/09/2021**
Supporting Structure and Cooling System		
Design and Fabrication	11/30/2020	-> **02/08/2021**
DAQ System		
T-boards and inner signal cables:	12/01/2020	-> **07/10/2021**
Installation		
Installed onto supporting structure:	07/31/2021	-> **07/16/2021**
Installed into STAR:	08/20/2021	-> **08/20/2021**

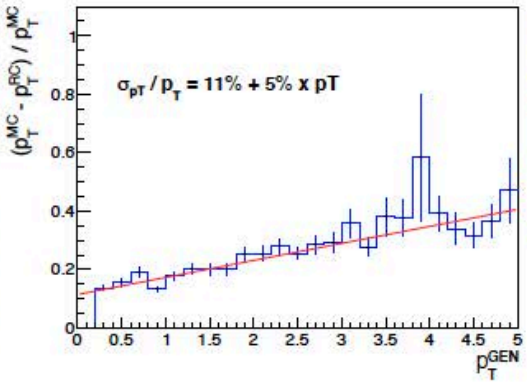
Track Fitting and performance

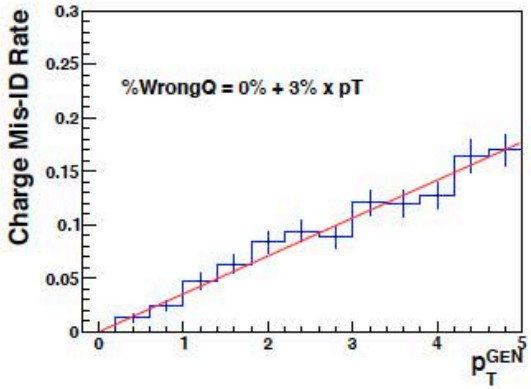
sTGC + PV





Refit 3 Silicon hits





1. Fit with sTGC and primary vertex
2. Project tracks to Si disks and search for hits along track
3. Refit tracks with PV + sTGC + Si

Primary Vertex $\sigma_{XY} = 500\ \mu m$

- Beamline constraint should provide $\sigma_{XY} = 500\ \mu$m or better

- Refit with Si provides significantly improved momentum resolution (x2) + charge identification (especially at higher pT)

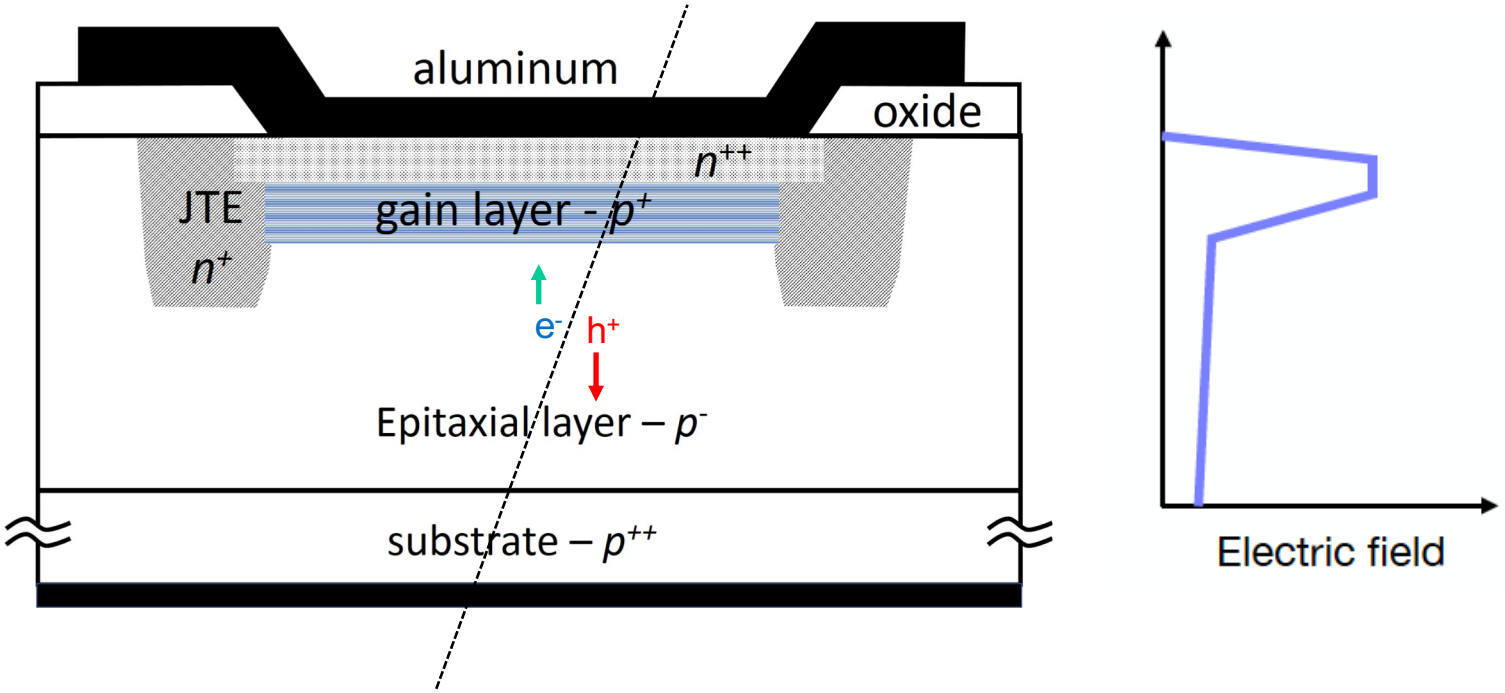
8/12/21 Daniel Brandenburg | BNL 40

STAR Forward Silicon Tracker – Summary

- A 3-layer forward tracking detector based on the Silicon microstrip detector technology is designed for STAR Forward upgrade.

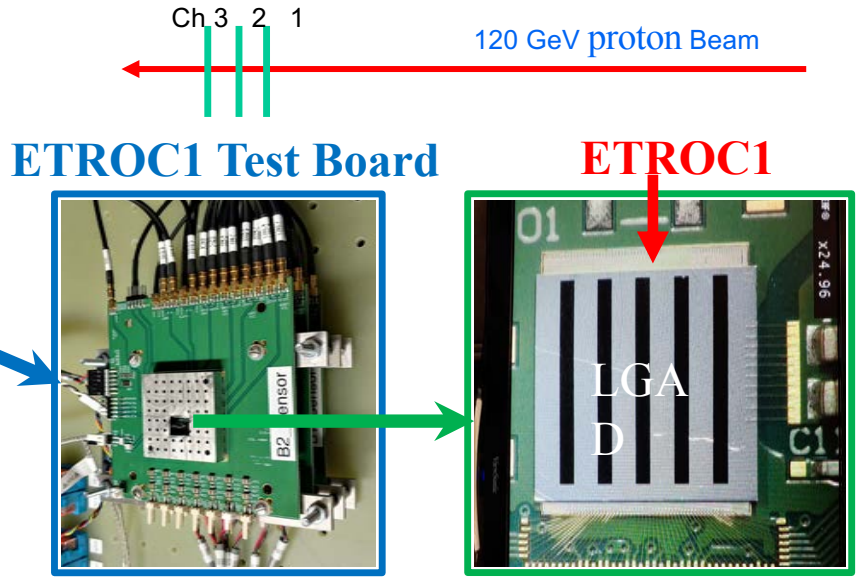
- The FST utilizes the successful experience and infrastructure of the previous STAR Intermediate Silicon Tracker, in order to reduce cost and risk.

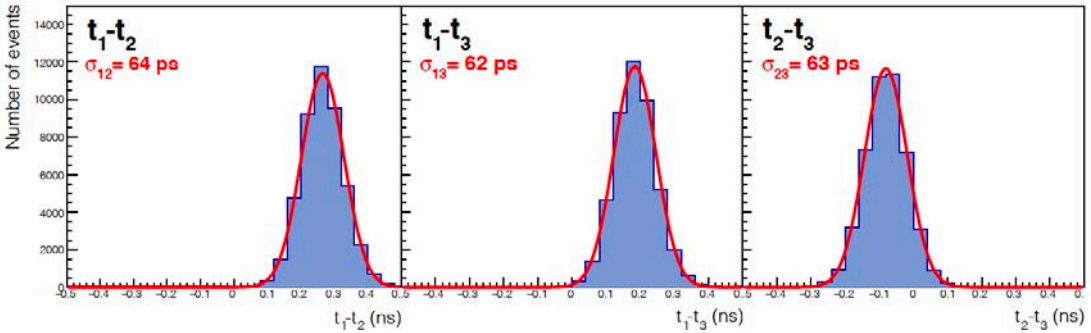
- The detector has been produced and is being installed into STAR, and will be ready for STAR forward physics program starting in 2022.



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

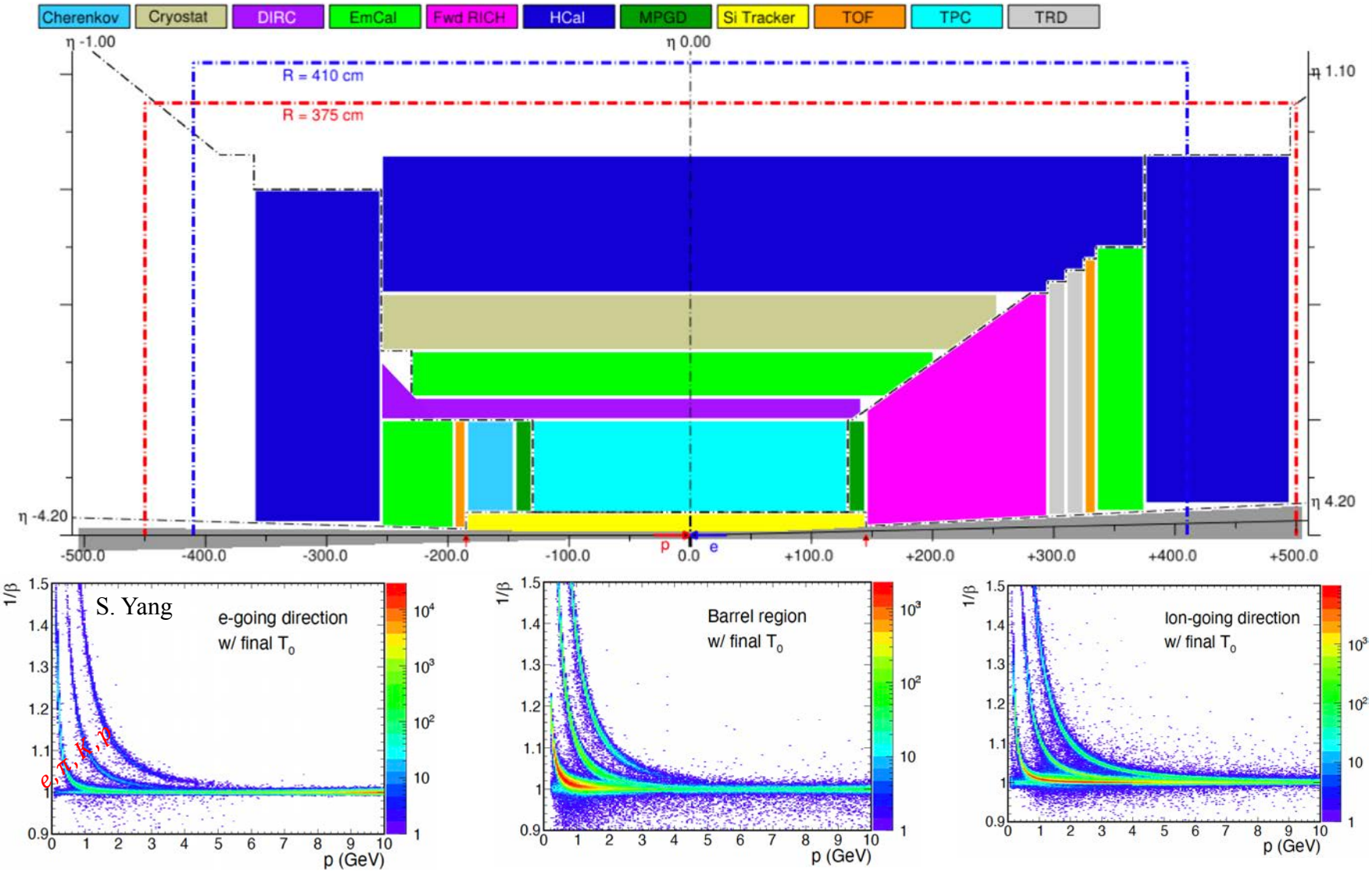
UFSD for CMS – Preliminary Test Beam Results





From preliminary analysis of the data from ongoing beam test at FNAL, the resolution of single LGAD+ETROC1 devices with large signal amplitude is 42-46 ps.

$$\sigma_i = \sqrt{0.5 \cdot \left(\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2\right)}$$



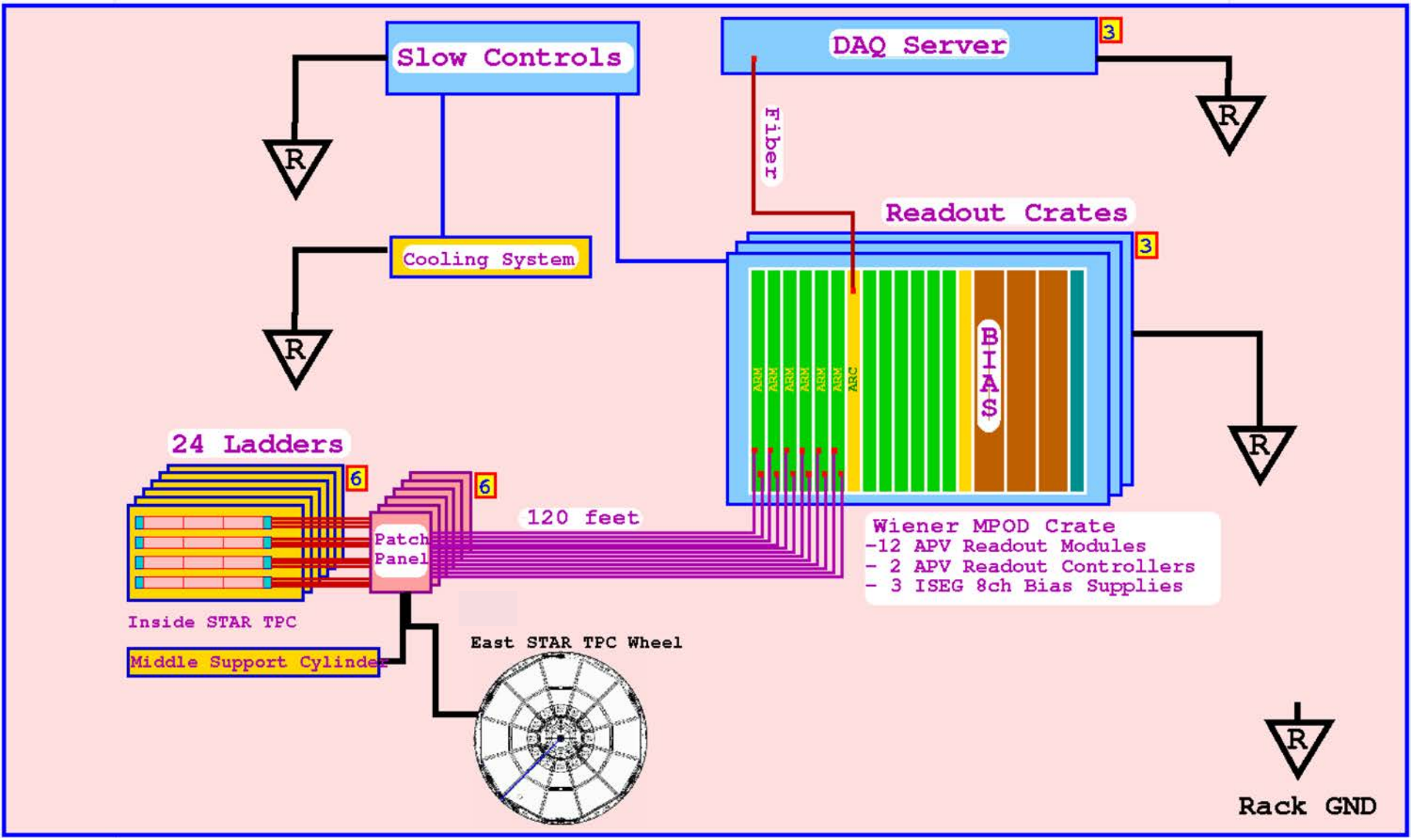
UFSD can provide both precising timing for particle identification and position for tracking at EIC experiments

1. Read Section 35.7 Semiconductor Detectors in Review of Particle Physics 2021

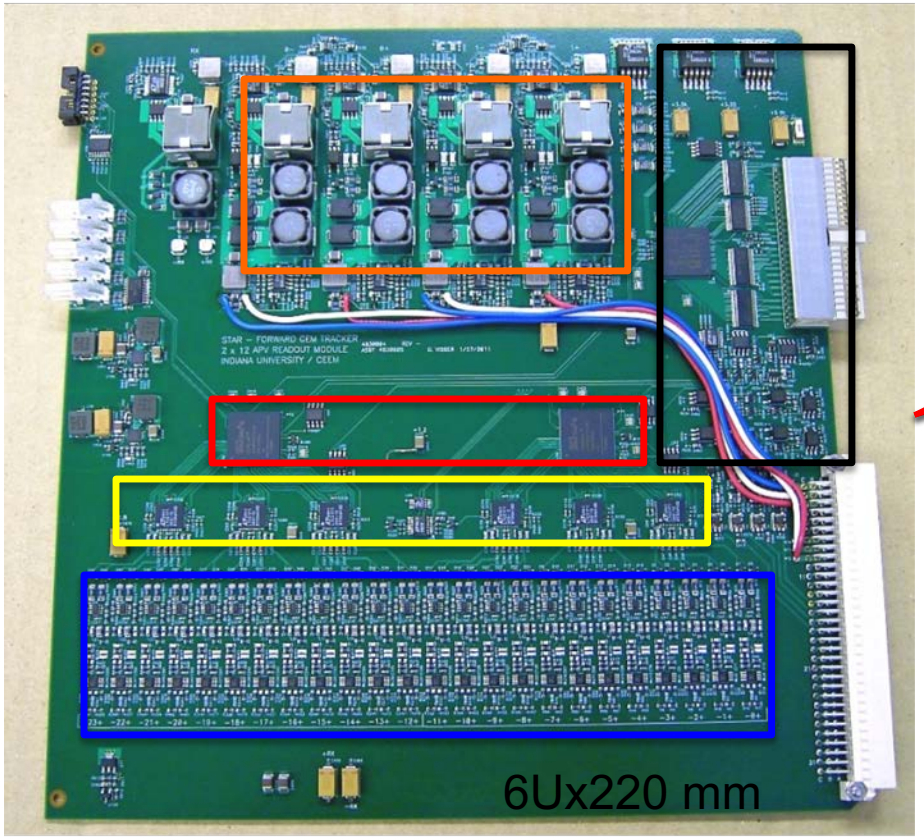
https://pdg.lbl.gov/2021/web/viewer.html?file=%2F2021/reviews/rpp2020-rev-particle-detectors-accel.pdf

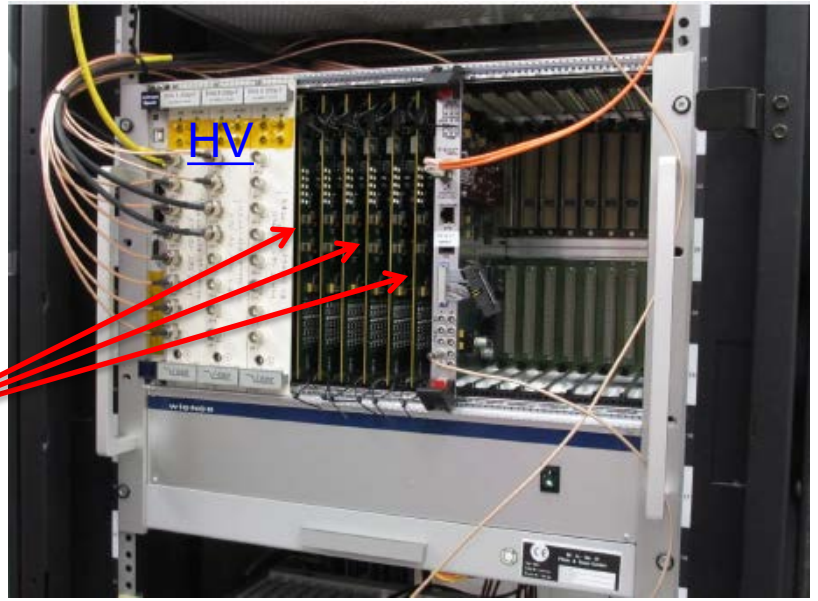
2. A uniform magnetic field (B=0.5T) is along the z-axis. A charged particle travels at a relativistic velocity in the X-Y plane with the initial speed along the X-axis. You can measure the position of the particle at t=0 and T=10 cm/c (c is the speed of light in vacuum). Assume you have a perfect knowledge of the position of the particle along the X-axis. Determine how well the position resolution in the Y-direction in order to achieve a 1% relative resolution to determine the particle's momentum.

Forward Silicon Tracker – DAQ System (IU)



Forward Silicon Tracker – APV Readout Module (IU)





Custom-designed DAQ system in a WIENER MPOD HV-cPCI mainframe

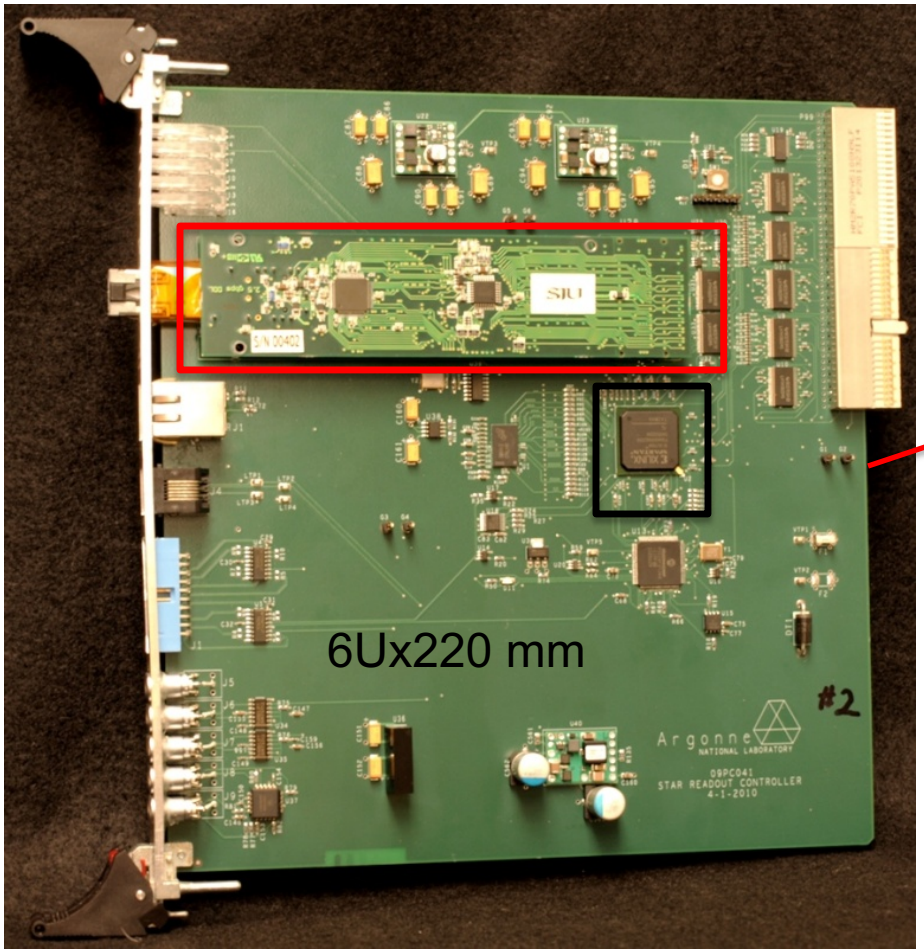
APV/ADC clock 37.532 MHz

4 1.75V Front-end Power Suppliers
2 FPGA
6 Quad ADC (12-bit)
24 analog receivers (= 2 sections on a ladder)

Trigger, Clock, I^2C interface

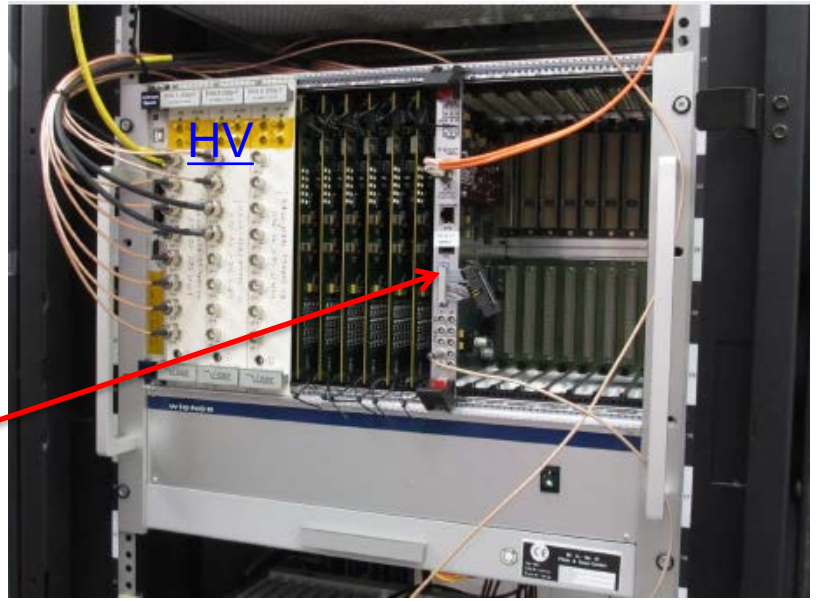
3 crates, 6 ARCII, 18 ARM

Forward Silicon Tracker – APV Readout Controller (IU)



DDL Optical Data Link to DAQ-PC

FPGA

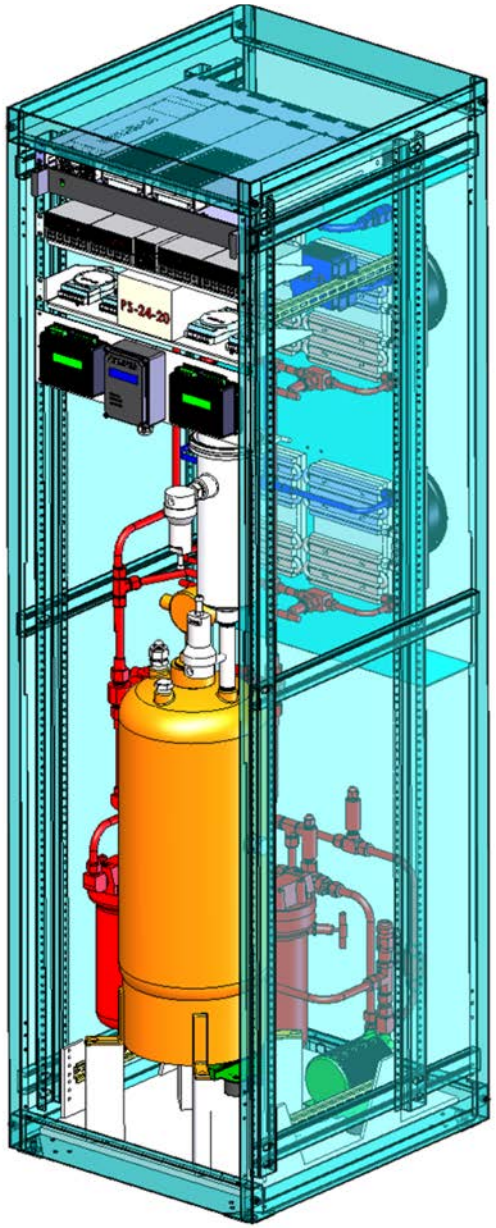


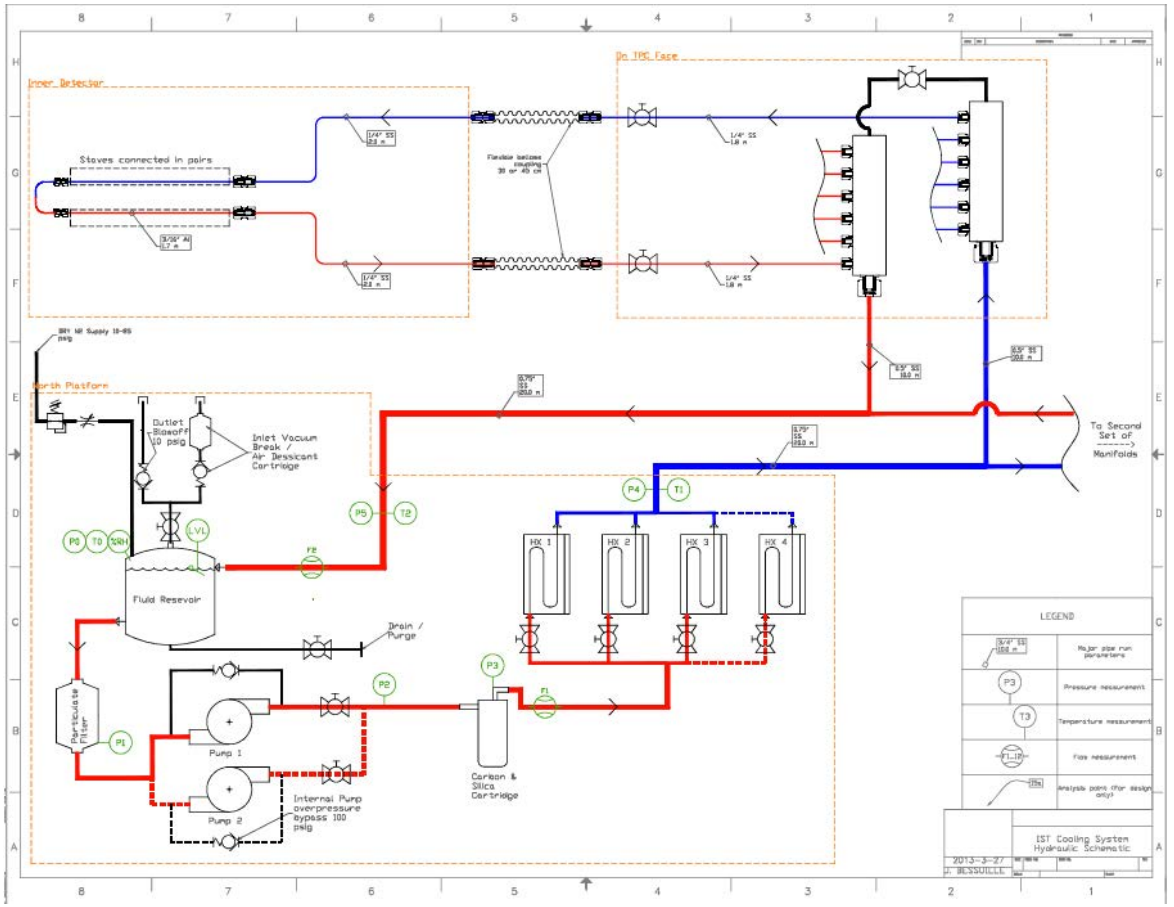
Custom-designed DAQ system in a WIENER MPOD HV-cPCI mainframe

Readout clock 33 MHz

3 crates, 6 ARCII, 18 ARM

STAR Forward Silicon Tracker – Cooling System (BNL)





Heat load ~ 100W

Coolant: 3M^{TM} Novec^{TM} 7200 ($\mathbf{C_4F_9OC_2H_5}$)