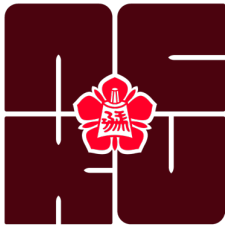
Mechanical Structure for EPIC TOF

6th April 2023

2nd half	**Andreas Jung**	Purdue University
	Po-Ju Lin	Academia Sinica, Institute of Physics
1st half	**Yi Yang**	National Cheng Kung University



AS-NCKU-Purdue Team

- Wen-Chen Chang, Po-Ju Lin (AS) & Yi Yang (NCKU)
  - Excellent machine shop
  - Experiences with the AMS-02 UTTPS radiator and lead the project of the mechanical structure of STAR FST



- Andreas Jung (Purdue)
  - Experienced in R&D for low mass support structures.
  - Working on the light-weight composite tracker support structures for CMS.

PURDUE UNIVERSITY

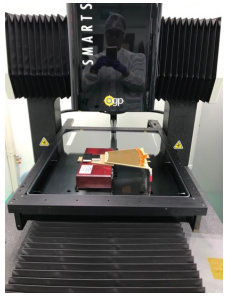
PUEDUE & NCKU

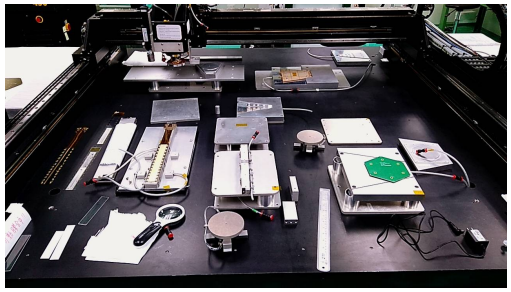
- NCKU and Purdue has excellent relationship since 1950s
- We already had dual degree program in the engineering department, and are establishing the program between Colleges of Science (departments of physics) now

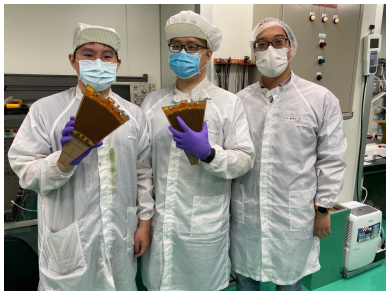
Resource from Taiwan

More details please see RS's talk!

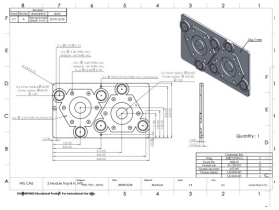
- **Taiwan Instrumentation and Detector Consortium (TIDC):**
  - https://tidc.phys.ntu.edu.tw/WordPress/
  - Sophisticated machines for detector assembly



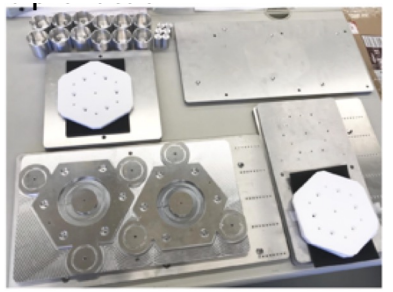




- **NCKU:**
  - Strong mechanical engineering department
  - Good relationship with **A**erospace **I**ndustrial **D**evelopment **C**orporation (AIDC)
    ➔expert on composite material



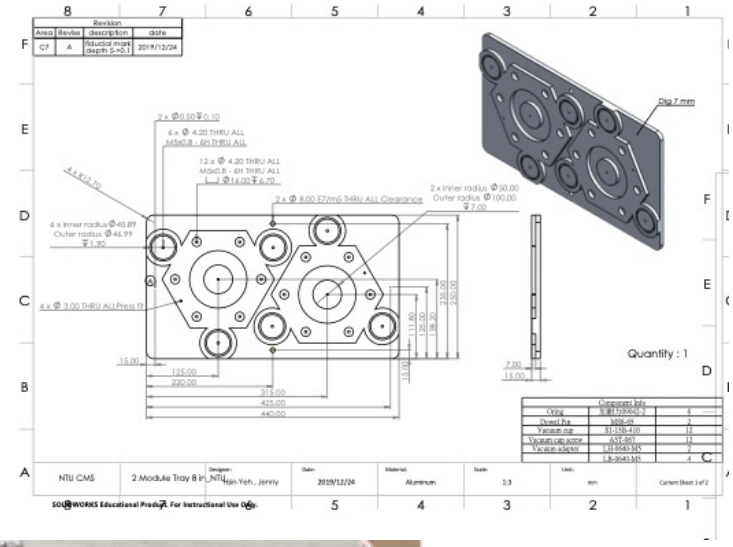
- **AS IoP:**
  - High precision machine shop
  - Experienced engineers, effective production

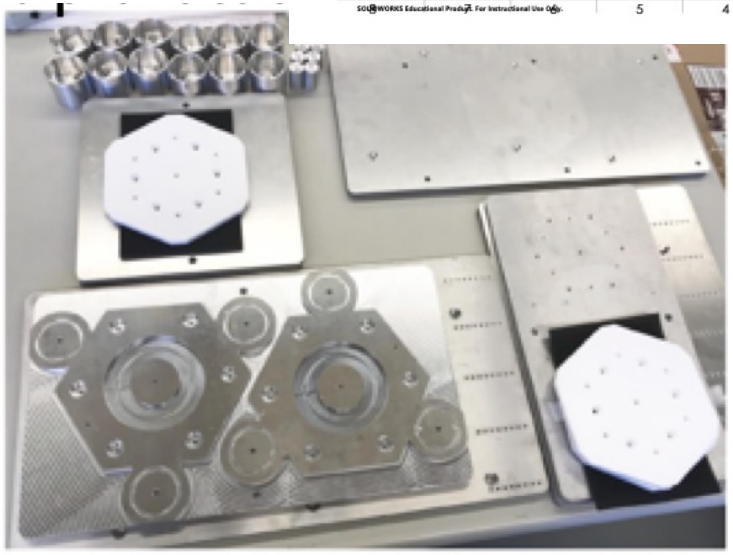


- **Three mechanical engineers from AS, NCKU and TIDC**

TIDC: High Precision Machine Shop

- Experienced engineers, effective production @ AS





STAR Forward Silicon Tracker

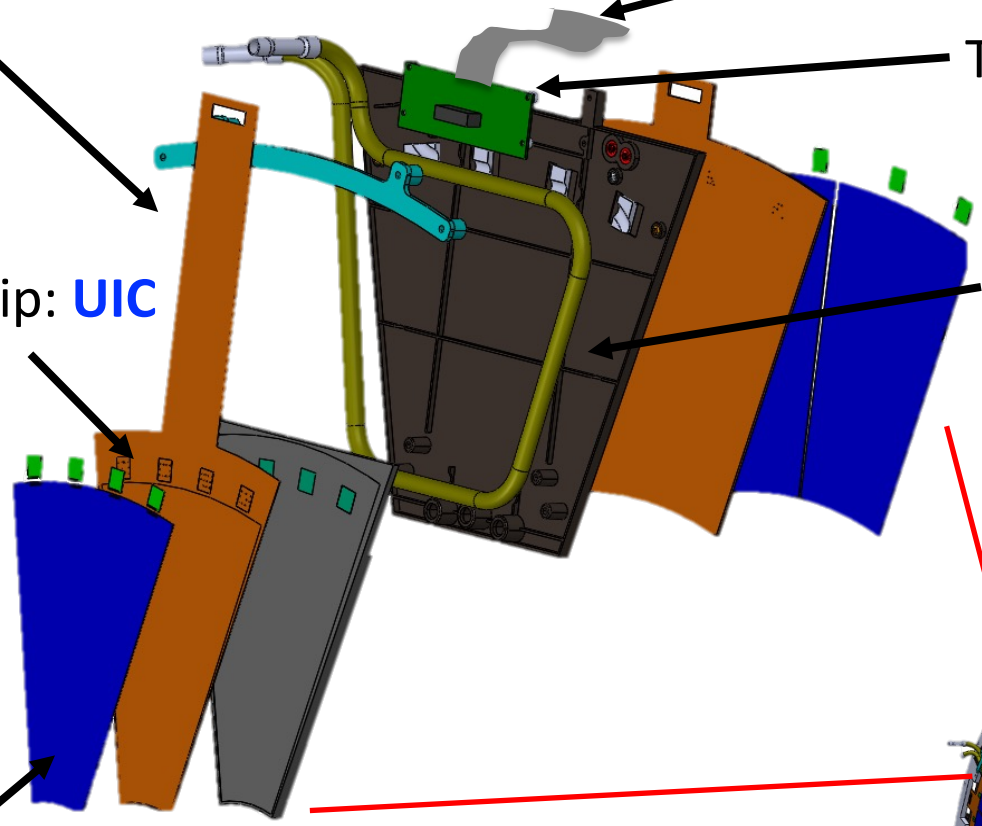
Flexible hybrid PCB: **SDU/IU**

Inner Signal Cable: **BNL/IU**

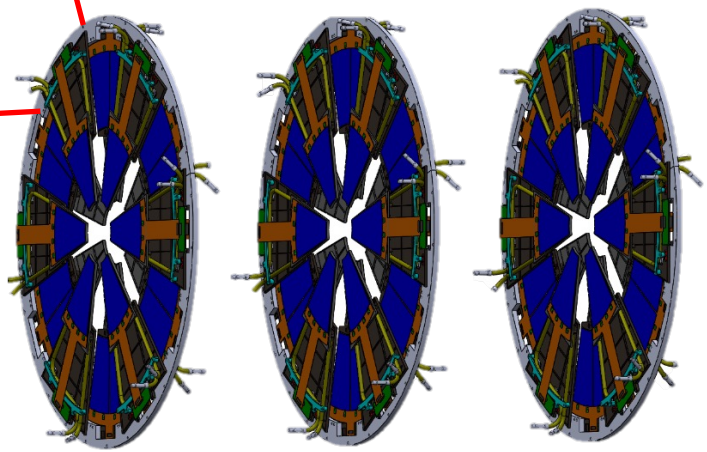
T-Board: **SDU/IU**

APV25 Chip: **UIC**

Mechanical Structure
(+ cooling pipe): **NCKU/AIDC**



Supporting Structure &
Integration: **BNL**



Silicon sensor: **UIC/BNL**

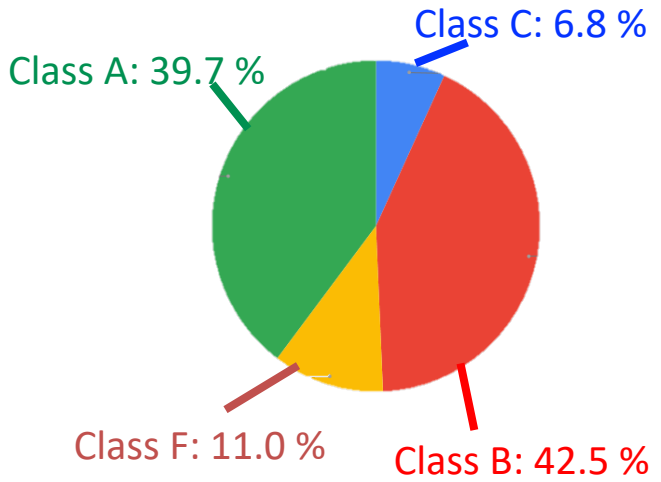
Cooling: **BNL/NCKU**

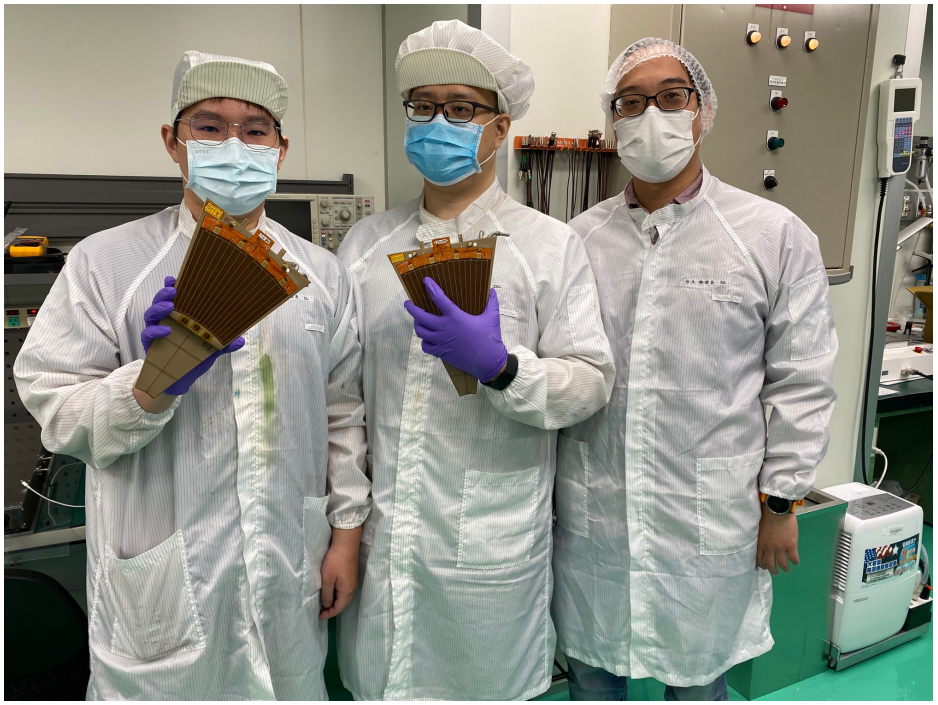
Simulation: **UIC/BNL/IISER/NCKU**

Experience from NCKU: STAR FST

- Total 73 modules (48 needed) are produced

  → **Successful rate ~89%**

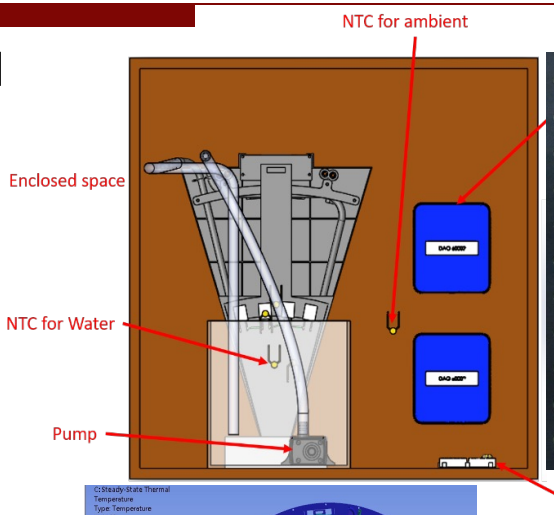


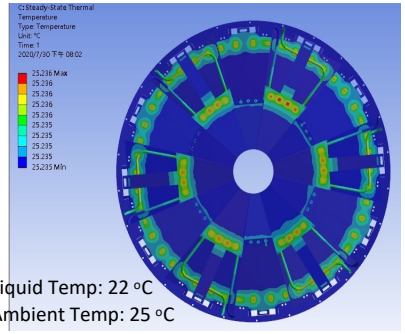


Experience from NCKU: STAR FST

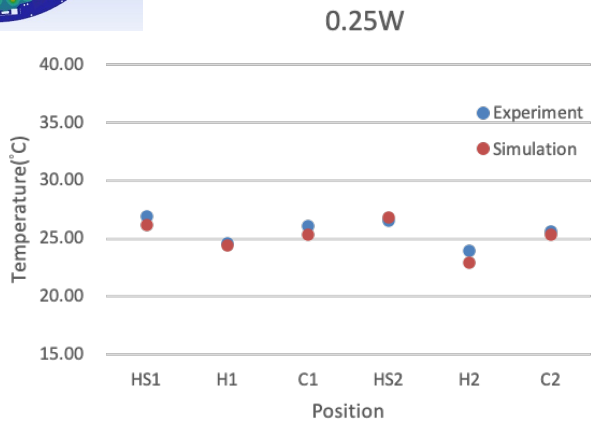
- Careful thermal analysis is performed by using single module with water cooling
- **Temperature at thermal equilibrium is less than 26 °C**
- Cooling test on FST-04

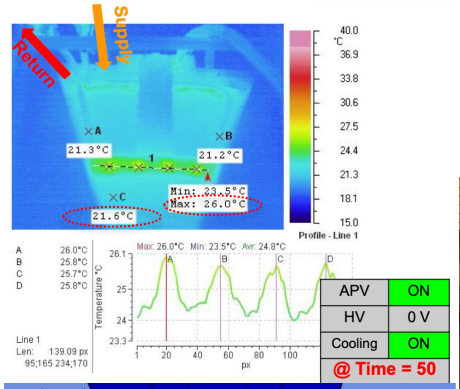
  (Dec. 21, 2020@BNL)
  - Ambient T: 19.8 °C
  - Coolant T: 22.2 °C

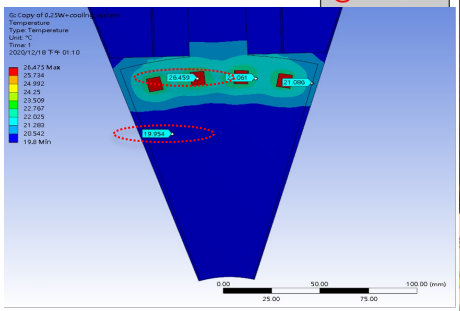


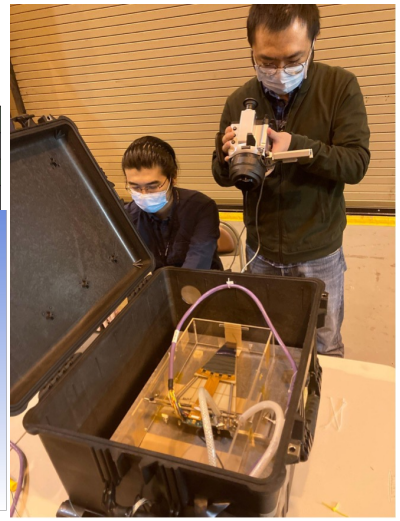


Consistent results between experiments and simulation





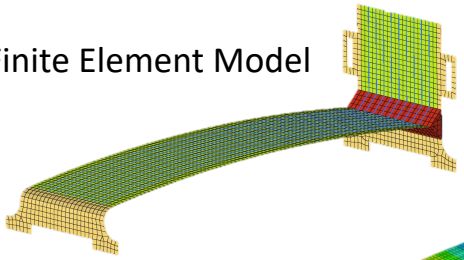




AMS-02 PDS Radiator in Taiwan

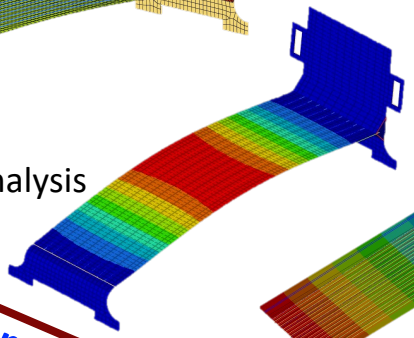
Structural design and analysis

Finite Element Model

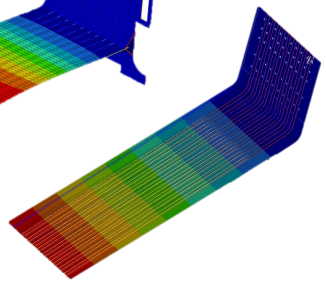


Component	Material	Weight
Heat Pipe	6063-T5	23.057 lb
Inner/Outer Skin	2024-T81	13.296 lb
Rohacell-51WF	--	3.445 lb

Modal analysis

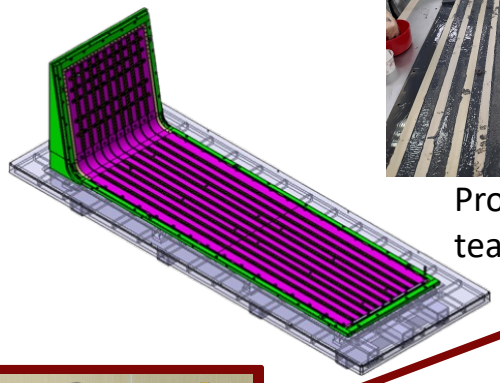


Deformation and stress



Manufacture

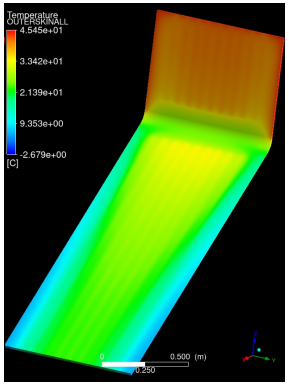
Jig design, manufacture procedure

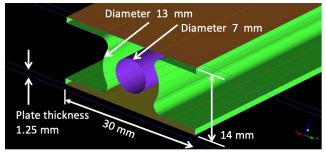


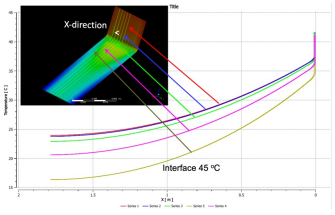
Professional assembly team

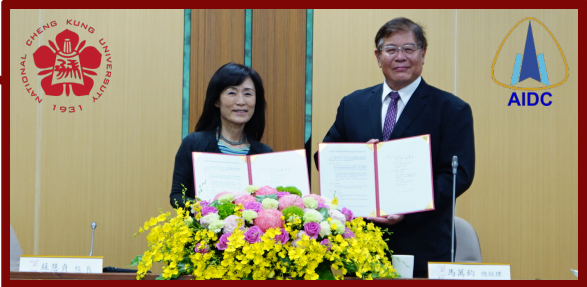
Thermal analysis

Experts and Profs. from AIDC and ME department of NCKU









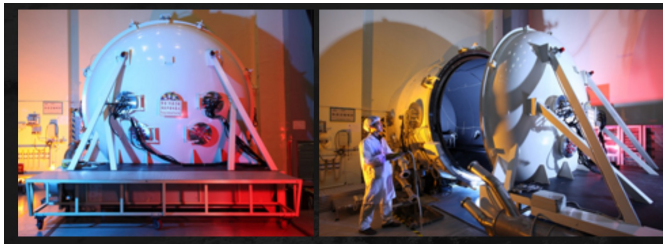
NCKU and AIDC signed the agreement on PDS radiator design and manufacture (March 28, 2022)

- NCKU: management, design, fund
- AIDC: design, manufacture

> 1 M USD allocated to this project

Tests

Giant thermal vacuum chamber at Taiwan Space Agency (TASA)

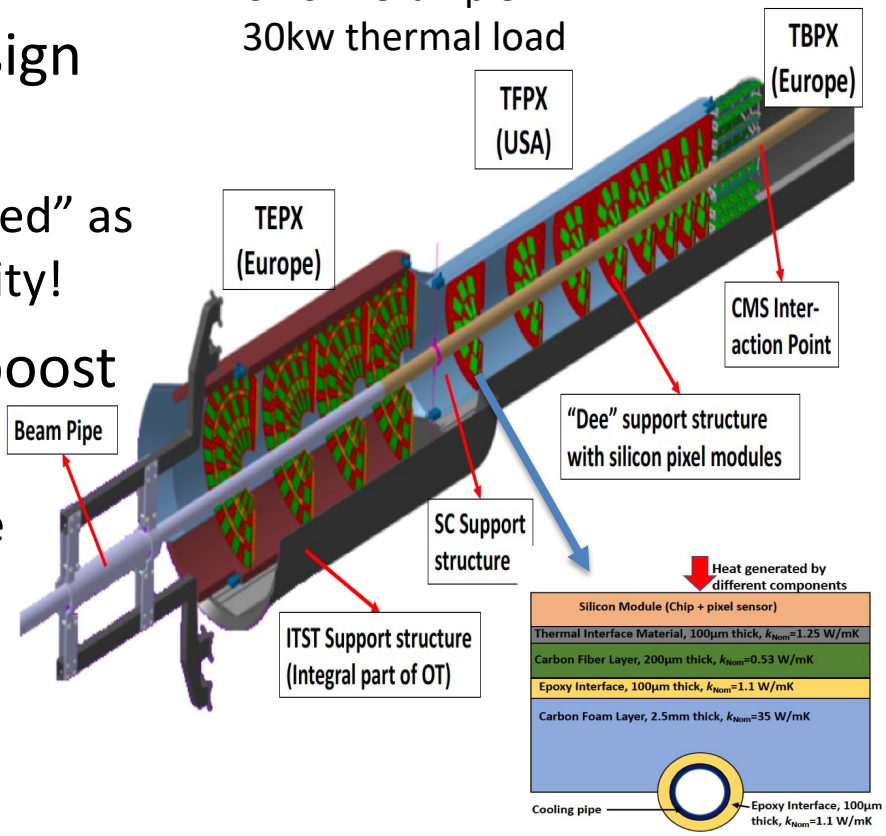


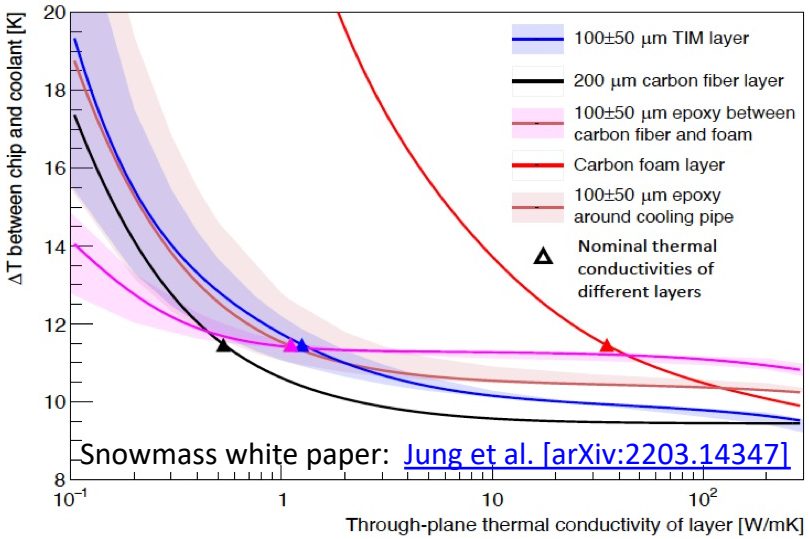
Operation volume: 3 meters (diameter) x 3.5 meters (length)
Ultimate pressure: 10 –7 mbar
Temperature range: 77 ° K ~ 400 ° K
Air–pumping rate: 10 –5 mbar in 4 Hours
Maximum temperature adjustment rate: 1 K/min

Mechanical Support Design

- Mechanical support structure design impacts detector performance
  - At times detector mechanics is “solved” as an after-thought – missed opportunity!
- Optimal materials & budget can boost a detectors physics performance
  - Needs timely action, well in advance

CMS IT example:
30kw thermal load





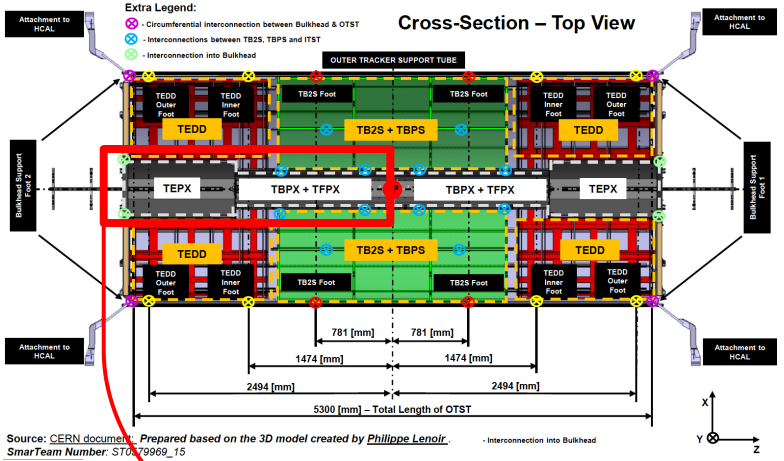
Snowmass white paper: Jung et al. [arXiv:2203.14347]

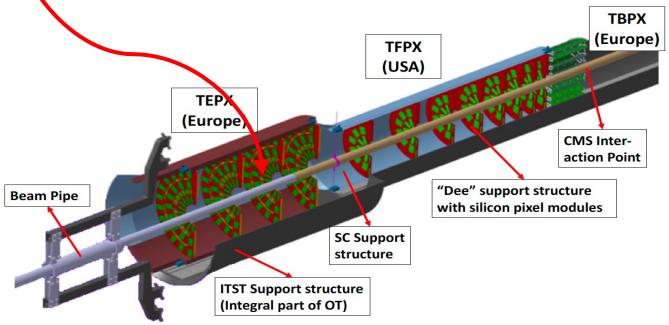
“Sandwich” supports pixel module:

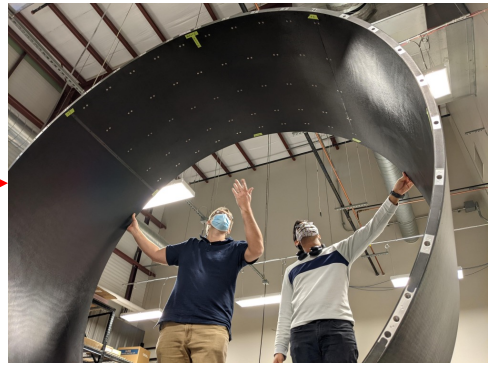
- State-of-the art for multiple systems (inner & outer tracker, timing layers)
- Select materials depending on thermal performance needs
- Applicable to variety of detectors

Experience from Purdue

- CMS upgrade relies on Purdue for design & manufacturing of mechanical support structures
  - Service Cylinder housing the Inner Tracker (IT)
    - 4+2 half cylinder structures with a length of 2.9m and transition region between small & large radii
    - Barrel, Forward, and Extended Pixel Detectors
  - Components for Inner Tracker pixel
    - Sandwich structures to mount pixel modules (Dee's) for the forward pixel (US project)
    - CFRP structures for the barrel pixel (European led)
  - Inner Tracker Support Tube (ITST)
    - Supports the 4 IT Service Cylinders, separates Inner Tracker and Outer Tracker volumes
    - Longitudinal stiffness for the entire Outer Tracker
  - Components for Outer Tracker (OT) modules
    - CFRP stiffeners (~3000ft^2) for the OT modules assembly
  - Barrel Timing Layer Tracker Support Tube
    - Supports the entire IT + OT + Timing Layer of CMS

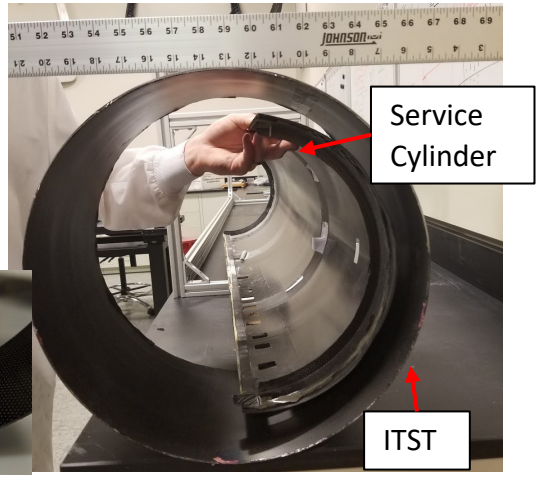


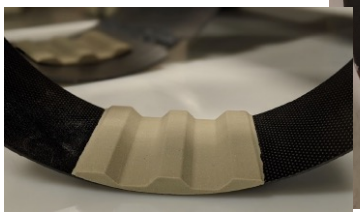


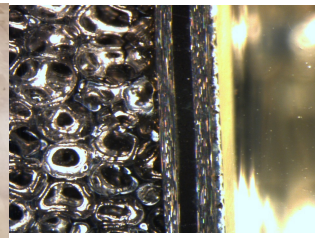


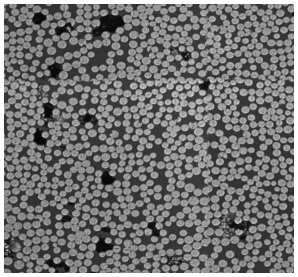
Experience from Purdue

- Prototyping & Manufacturing related to ITST, SC, Dee's
  - Prototypes confronted with FEA predictions, multiple iterations
  - Prototyping and Development of additional structures for IT pixel
    - Cartridges, Portcard holders, all extensively studied for high thermal performance
    - Accompanied by irradiation campaigns: sample prep, characterization, etc.
    - Dedicated measurement of thermal conductivities
    - High thermally conductive materials for 3D printed parts

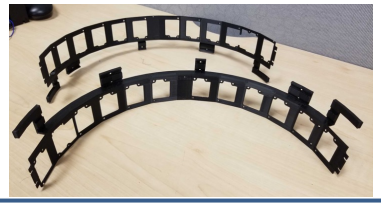


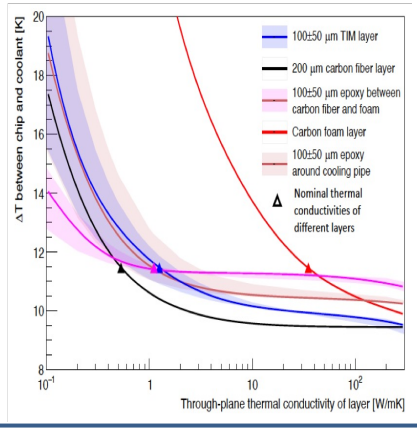


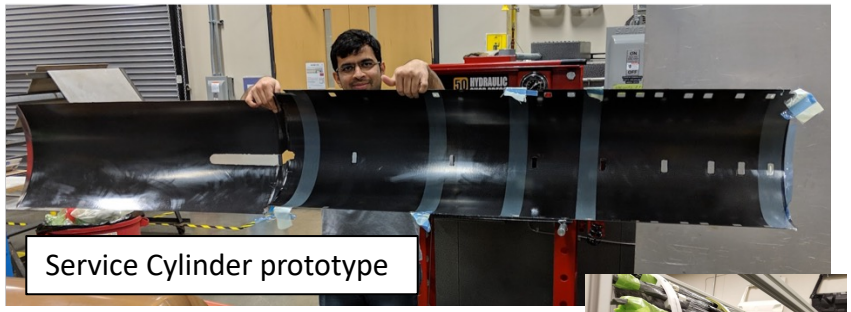


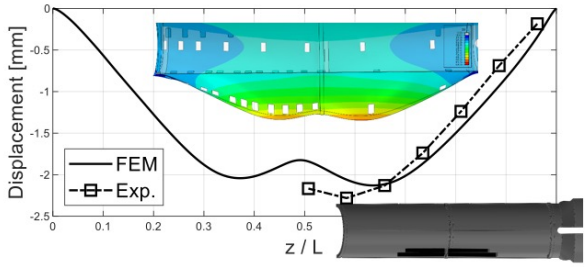


- Forward pixel dee prototype
- Co-cured samples
- Microscopies
- 3D printed mechanical supports
- Critical interfaces via FEA







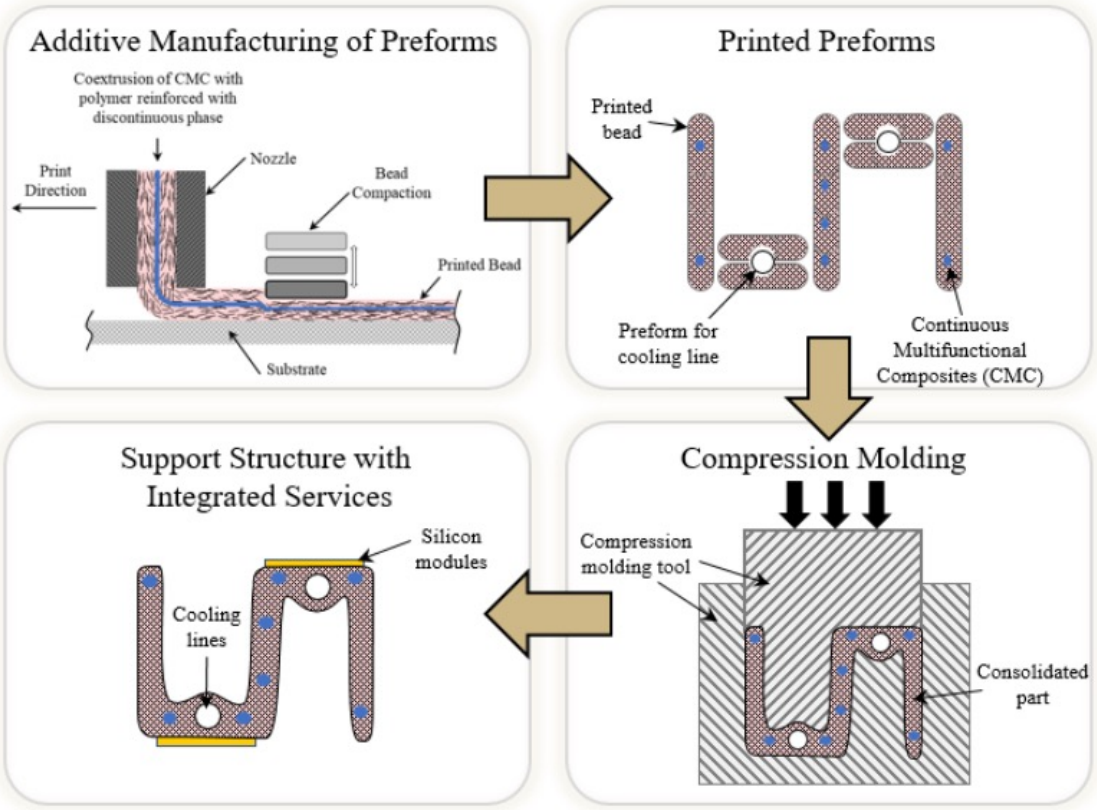


R&D TOF Barrel mechanics

- **Budget**
  - 2022 – 2023: 30K (include material and cost of processing)
    - 2023 – 2024: 30K (include material and cost of processing)
    - 2024 – 2025: 30K (include material and cost of processing)
  - Early Deliverable: One 1.35m “plank” prototype until Sept 2023
    - Lots of relevant experience to draw from and apply to benefit of EIC
    - Budget: 10% FTE eng. ~15k$ + low S&E $$ (Purdue)
      - Materials: cost-effective by using non-final materials and usage of FEA
    - Budget: 10k$ for eng. (NCKU)
      - Thermal analysis based on prototypes
- Goals:
  - Integrated cooling and mechanical support structures
  - Average material budget 1% X_0 or smaller
  - Cooling capable of dealing with multi-kW power dissipation
- Deliverables: 1-3 “stave” structures, but no larger system aspects.
- Latest Updates:
  - Paperwork / SOW submitted
    - Purdue to BNL (late, on 31st March)
    - NCKU to JLAB (done)

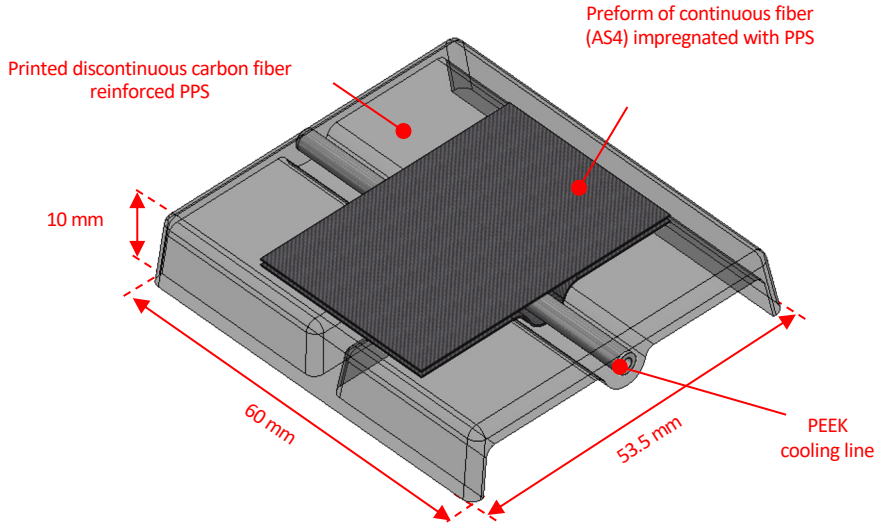
R&D for irreducible sturctres…

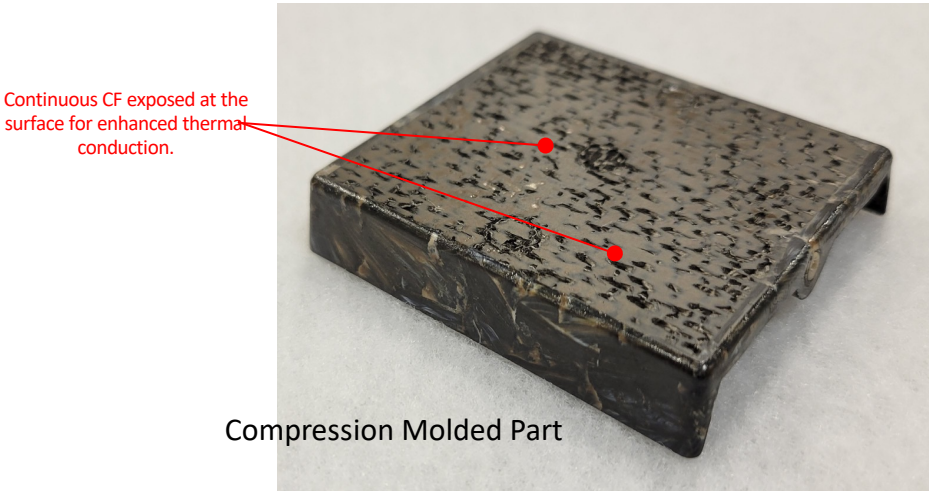
- Identified by DOE BRN effort & CPAD
  - Scaling of low-mass detector system towards irreducible support structures with integrated services. Includes: integrated services, power management, cooling, data flow, and multiplexing.
  - Purdue proposed mechanics R&D to solve detector challenges at future colliders



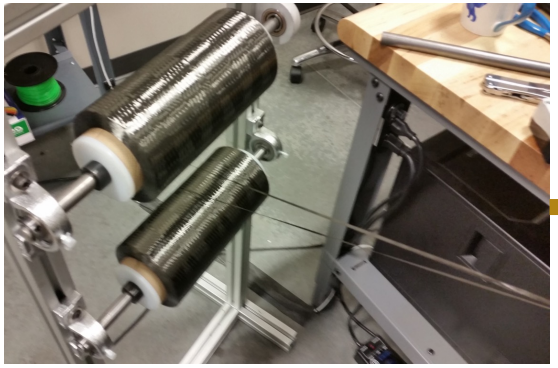
BlueSky R&D at Purdue

- Could be applicable to EIC – recent progress…

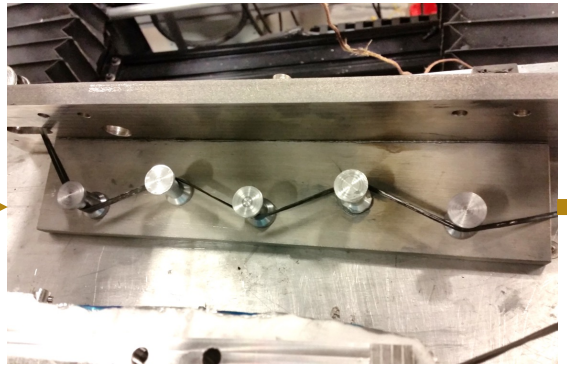




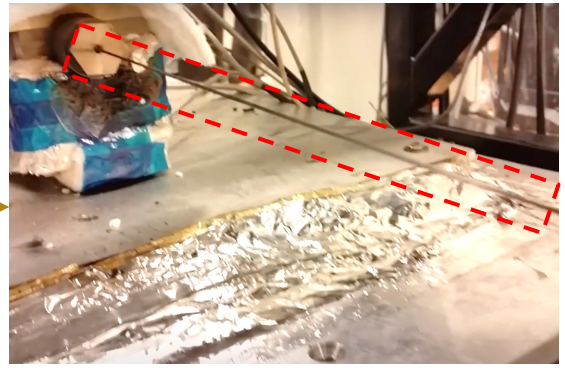
Compression Molded Part



Spools of Carbon Fiber



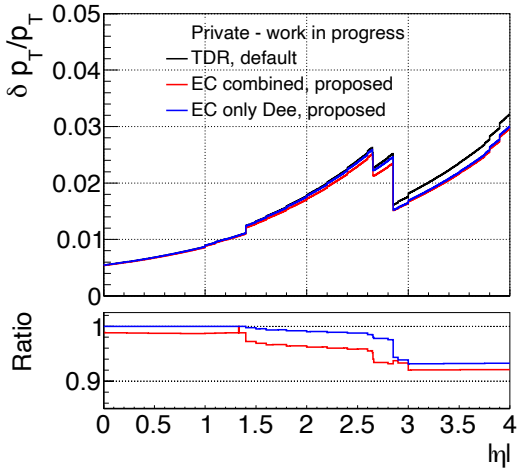
Interior of Impregnation Chamber



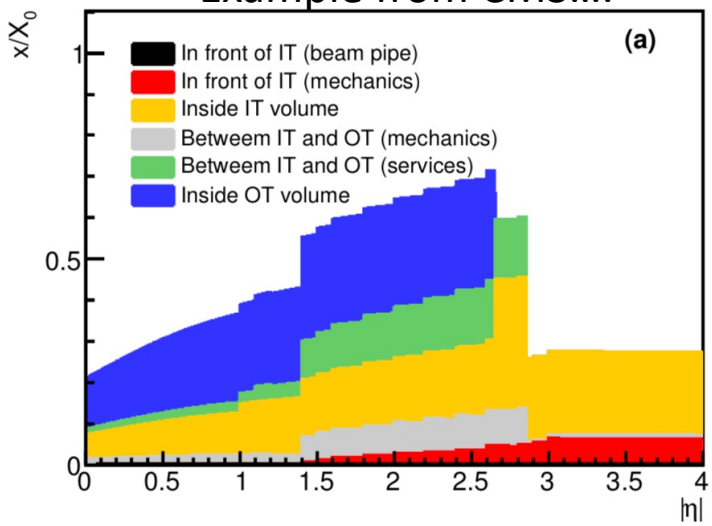
Carbon Fiber Impregnated with PPS

BlueSky R&D at Purdue

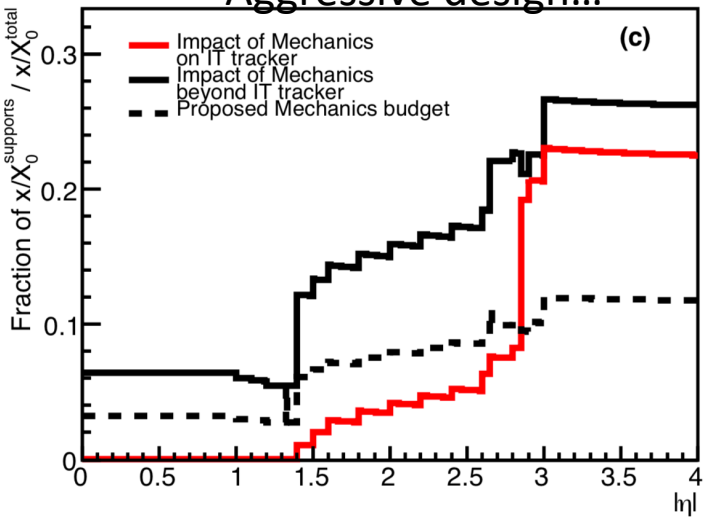
- Radiation length plot more specific to CMS but can be related to EIC conditions
  - First look during R&D phase, PED has to include this
  - Mechanics is often overlooked but impacts detector performance significantly
- These techniques more easy benefit endcap detectors whereas gains are limited in barrel region (harder)
- This seems like an excellent fit to the needs of TOF!



Example from CMS….



Aggressive design…



PED request (Oct '22)

- Integrated cooling and mechanical support structures
- Not presented, no follow-up until now – Goals:
  - First more detailed look at aspect of entire "system" of support structure, interfaces to outside, cooling/services aspects
  - Naturally, also focus on mass optimization and trade-offs
  - Relies on results of stave prototype / R&D activities (Purdue/NCKU), **synergistic** between the R&D and PED
  - Average material budget 1% X_0 or smaller
  - Cooling capable of dealing with multi-kW power dissipation
  - Deliverables:
    - Stave support
    - Interfaces, Services

Resource	FTE (%)	Budget (k$)
Manufacturing Design of pre-production		
Mechanical Engineer + Technician, Purdue	20	60
UG students, Purdue	20	0 (in-kind)
Postdoc, NCKU	20	0 (in-kind)
G/UG students, NCKU	20	0 (in-kind)
Materials and Supplies (staves, etc.)	-	20
Integration aspects / Services		
Mechanical Engineer, Purdue	10	20
Total	-	100

Table 1: Purdue/NCKU budget request on engineering design for barrel TOF in FY23. All entries in thousands of dollars.

PED request (Apr '23)

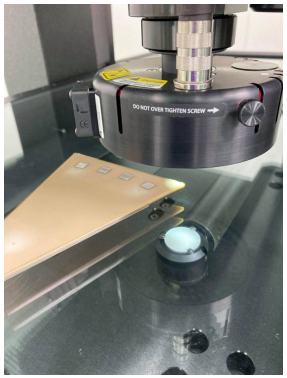
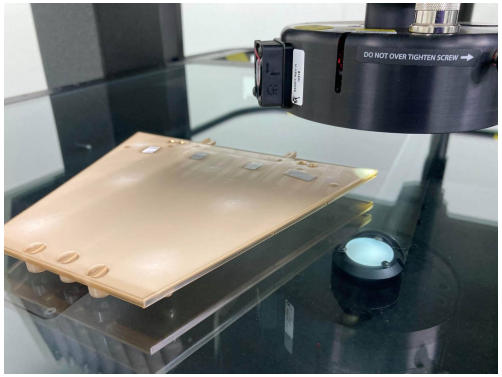
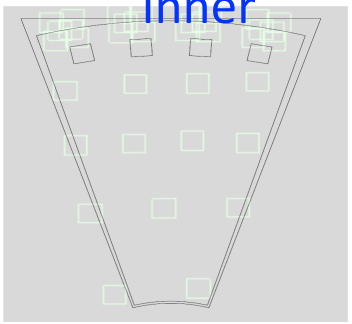
- **Based on recent developments**
  - Purdue/NCKU team in excellent position to design mechanical support structure for **barrel and endcap TOF, high synergies**
  - Use light-weight composite integrated support structure R&D at Purdue
  - Optimize for material budget and thermal performance, consider integration aspects as well, synergistic to submitted R&D SOW
- Updated PED request for a first detailed look at entire TOF mechanical support & optimization (thermal & material)
  - Roughly 250k$ in preparation for DOE CD2/3a
  - Employ Purdue R&D efforts for integrated support structures
  - Based on actual prototyping for CMS structure
    - Service Cylinder (2.6m long, 30cm radius), first rough design, thermal analysis, mechanical FEA + manufacturing design ~180k$
- Welcoming collaboration by other institutes
  - Need to be mindful on efficiency of project

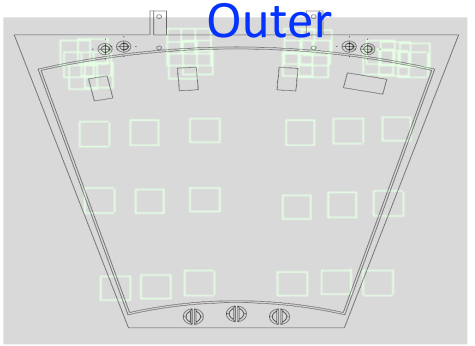
Backups

From Zhenyu's talk
https://indico.bnl.gov/event/16765/

Experience from NCKU: STAR FST

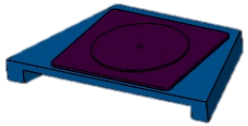
1. Use OGP to measure the flatness

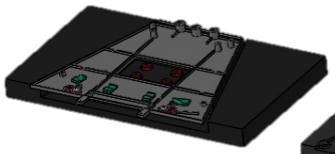


2. Assembly Outer MS with Hybrid PCB using robotic gantry

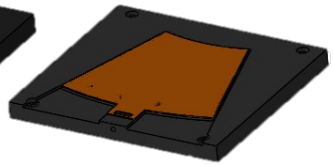
pickup tool

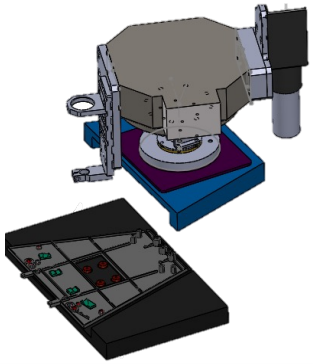
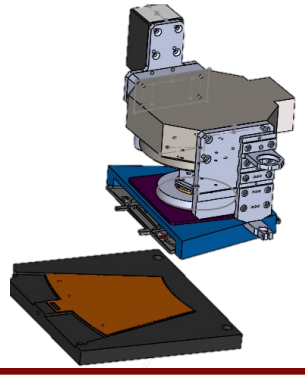
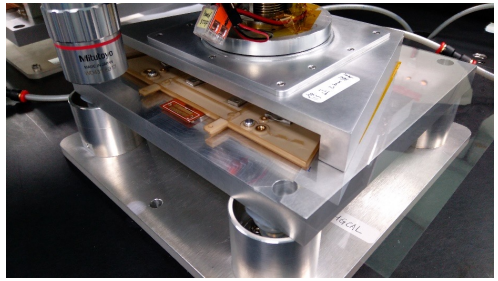


Outer MS + tray



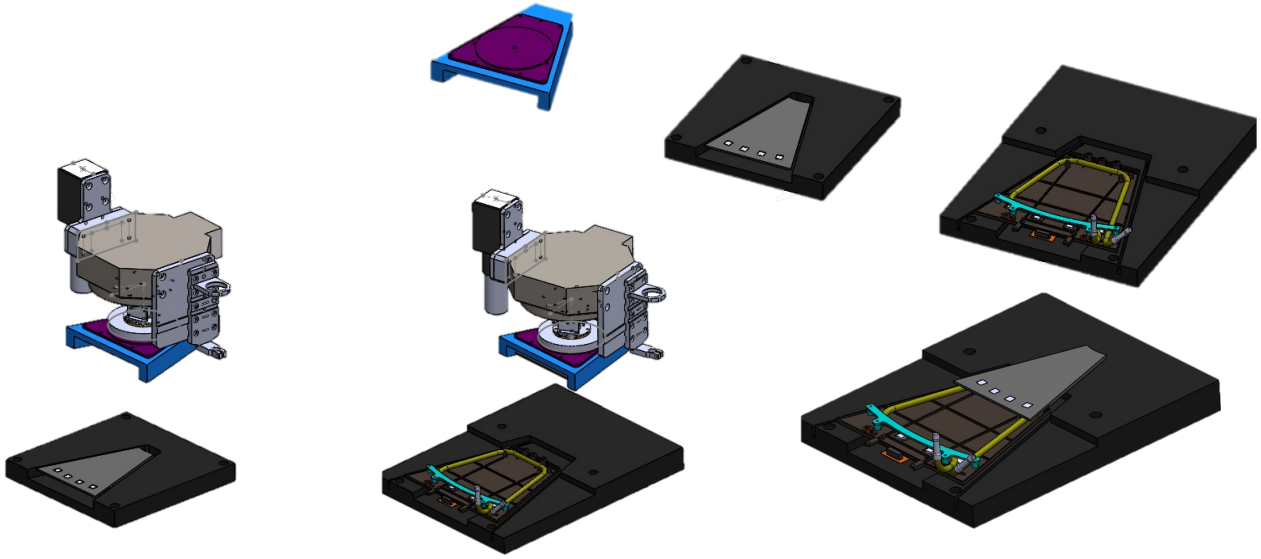
Outer Hybrid + tray



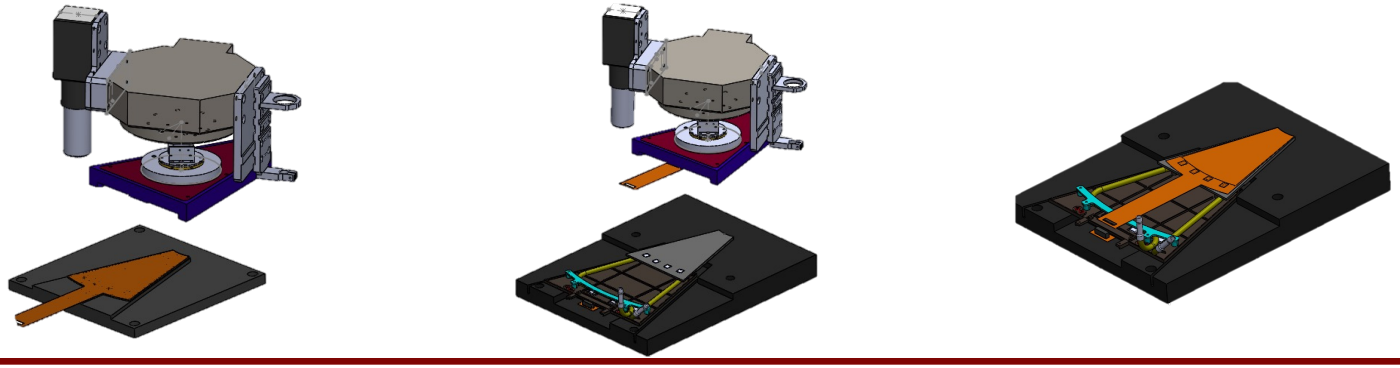




Experience from NCKU: STAR FST

3. Glue the inner MS using robotic gantry

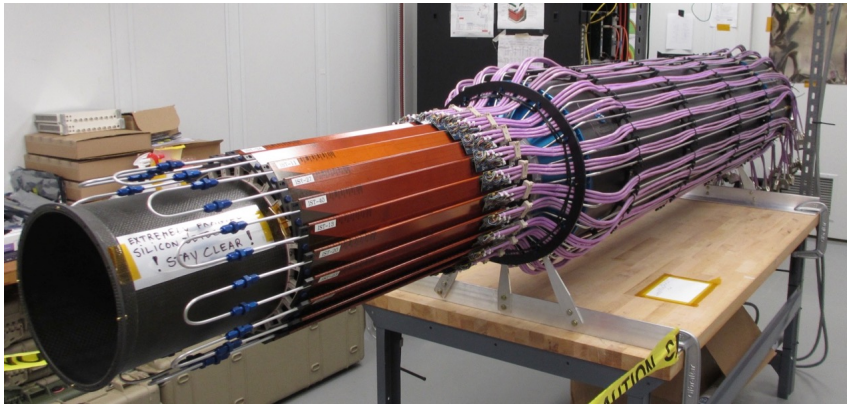


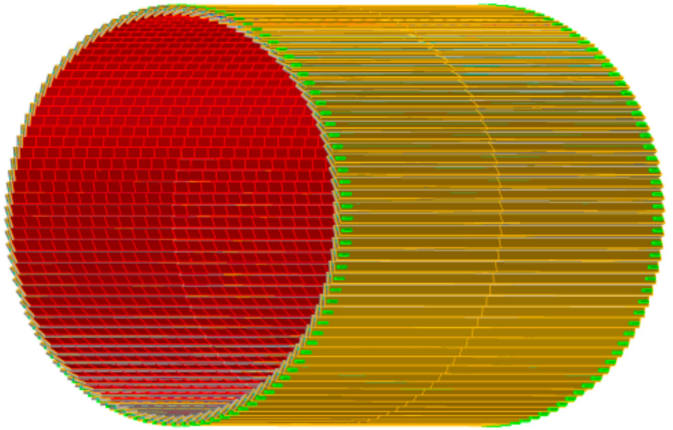
4. Glue the inner Hybrid PCB using robotic gantry

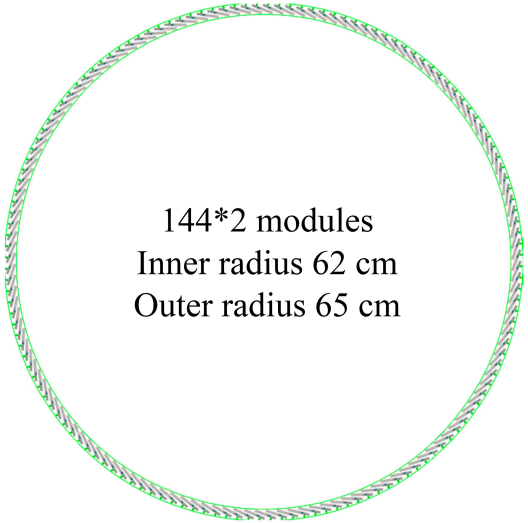


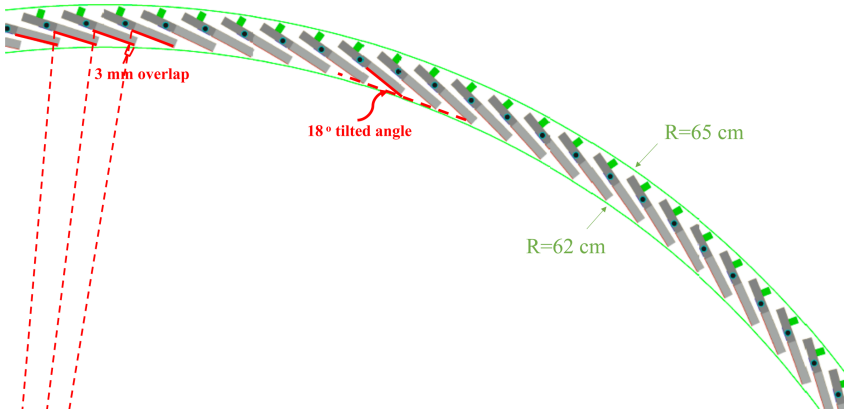
Barrel TOF

- Use the similar concept of STAR IST





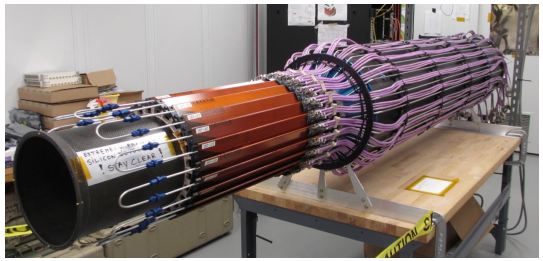


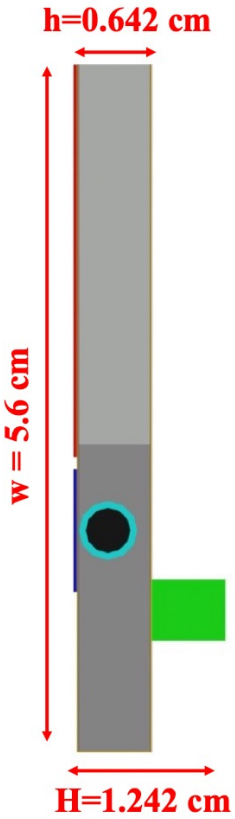


From Zhenyu's talk
https://indico.bnl.gov/event/16765/

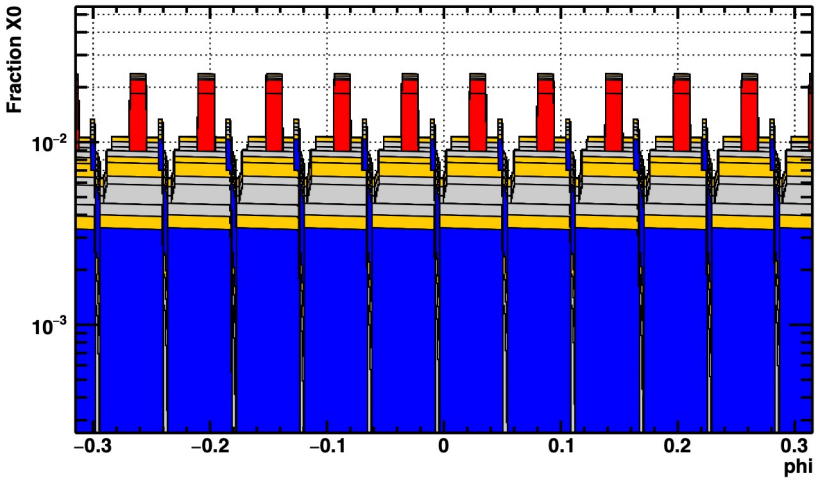
Barrel TOF

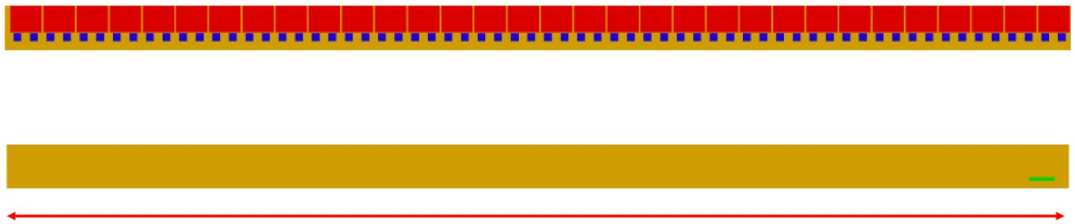
- In total 288 modules,
  - 9216 sensors, 18,432 ASICs, 2.4 M channels
  - ~70 kG, ~4 kW





- AC-LGAD sensor
- Frontend ASICs
- Carbon foam+
  Carbon honeycomb+
  CF skins
- Al cooling tube
- Liquid coolant
- Kapton PCB
- Connector



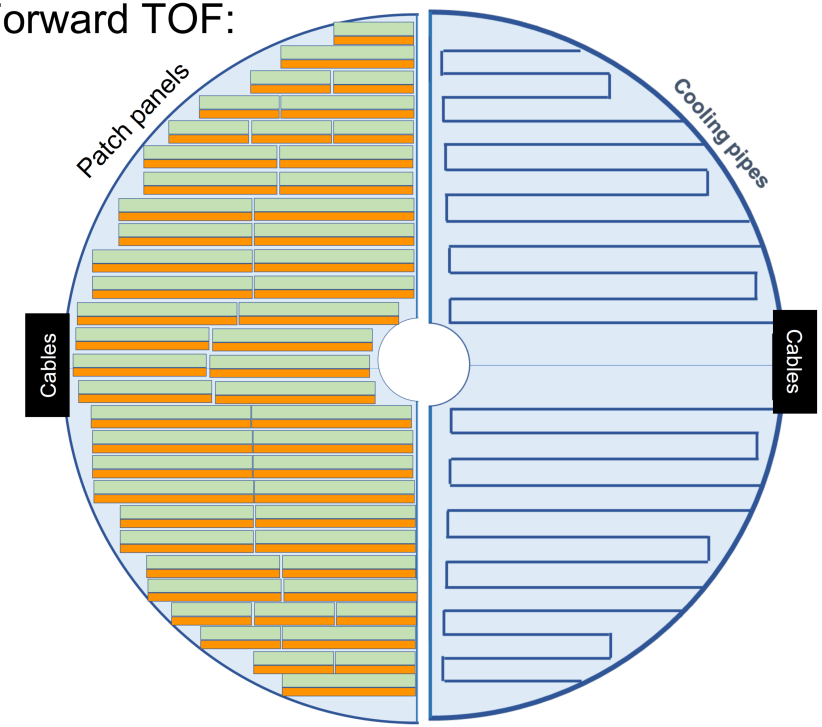


From Zhenyu's talk
https://indico.bnl.gov/event/16765/

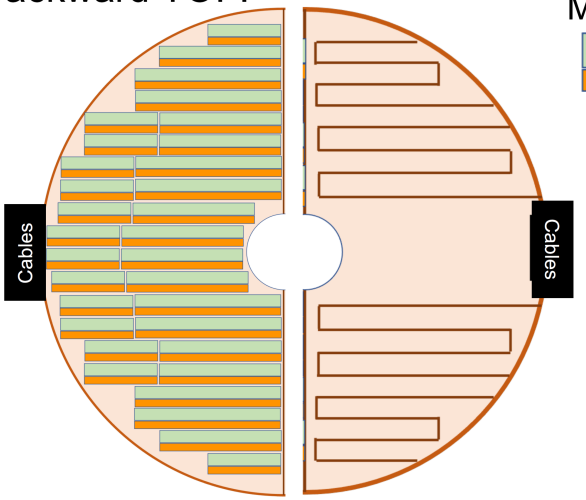
Endcap TOF

From the talk of Wei Li
https://indico.bnl.gov/event/16742/

Forward TOF:



Backward TOF:



- "Clam shells" or DEEs
  - Convenient for installation/maintaenance
  - Each is patched by TOF modules (one or more types) on both faces

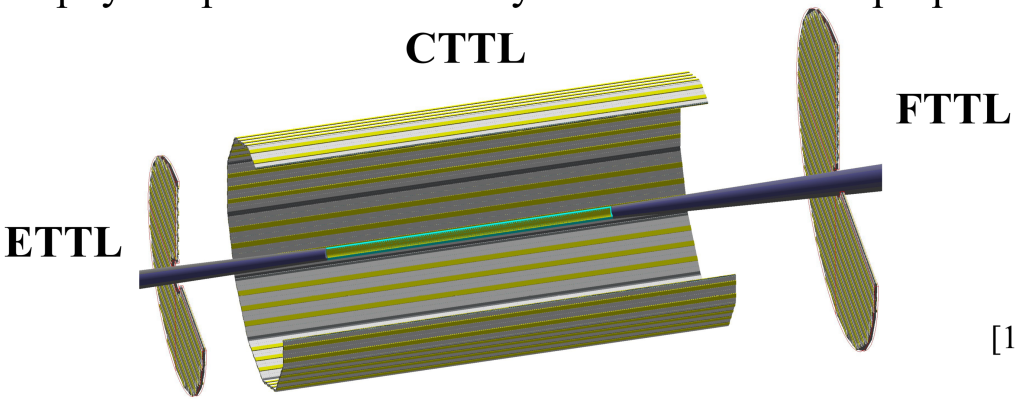
Power Budget

	Forward	Backward
Sensors	0.6kW	0.35kW
EPTROC	8.5kW (17kW)	4.8kW (9.6kW)
DC-DC	3.5kW	2kW
lpGBT, VTRx+, SCA	0.5kW	0.3kW
Power cables	0.5kW	0.3kW
Total	13.6kW (22.1kW)	7.75 (12.55kW)

From Zhenyu's talk
https://indico.bnl.gov/event/16765/

AC-LGAD Layer for TOF PID + Tracking

- The goal is to conceive a reference layout and technical design (v0) as inputs to GD/I group to advance the detector integration (service routing etc.)
- However, there are still on-going studies to investigate the optimal channel granularity based on physics performance so by no means this is a proposal for final design.



For v0 design, we propose:

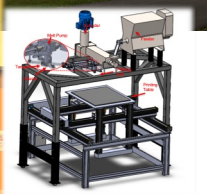
- **Barrel: 0.5x10 mm² strips**
- **Endcap: 0.5x0.5 mm² pixels (same as RPs) [1]**

[1] Wei Li, TOF-PID WG Meeting Aug 29, 2022

	acceptance	Z (m)	Radius (m)	Area (m²)	Channel size (mm²)	# of Channels
ETTL	$-3.7<\eta<-1.74$	-1.61 to -1.71	0.12 to 0.63	1.20	0.5*0.5	4.8M
CTTL	$\|\eta\|<1.4$	-1.2 to 1.5	0.625 to 0.655	10.9	0.5*10	2.4M
FTTL	$1.5<\eta<3.5$	1.555 to 1.705	0.12 to 0.85	2.22	0.5*0.5	8.8M

Resources from Purdue

- Composite Manufacturing & Simulation Center (CMSC) at Purdue, completed in summer 2016
  - Purdue Center of Excellence across disciplines: Aeronautics, Chemical Eng, Materials Eng, Aviation Tech, Computer graphics, **and Physics**
  - A. Jung – Associated member of CMSC
- Professional composite experience:
  - Seven full-time technical staff, five post-doctoral researchers, twenty grad's
  - 35,000 sq. ft. of office and laboratory space
    - 2 large pressurized ovens, 1 larger oven with vacuum hook-ups
    - Larger ovens accessible with industry partners



About TIDC

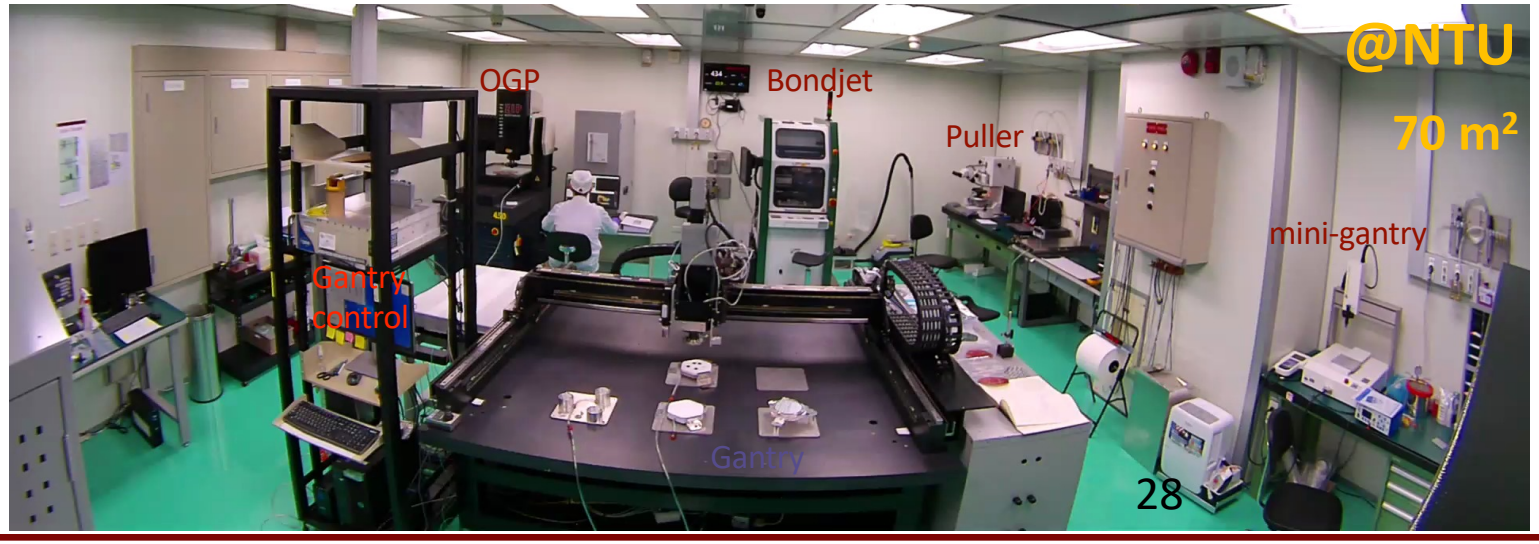
- **Taiwan Instrumentation and Detector Consortium (TIDC)** was established in 2019 by 5 institutes (AS, NCU, NTHU, NCKU, and NTU) in Taiwan (supported by National Science and Technology Council in Taiwan)

  ➔ Form a strong team to participate the EIC

  https://tidc.phys.ntu.edu.tw/WordPress/

TIDC: Silicon Detector Facility

- Class 10,000, with temperature and humidity controlled at 23 ^{o}C and RH 50% all year round
- Fully operation with Pressured dry-air supply and vacuum services
- Aerotech 1.25x1.25 m^2 robotic gantry with Labview control
- OGP optical 3D measurement
- Hesse BJ820 automatic Bondjet and DAGE 4000 Bondtester (puller)
- Manual probe station and picoprobes
- Glue dispensers, mini-gantry, microscope, degassing chamber, Keithley 2410 and tools …

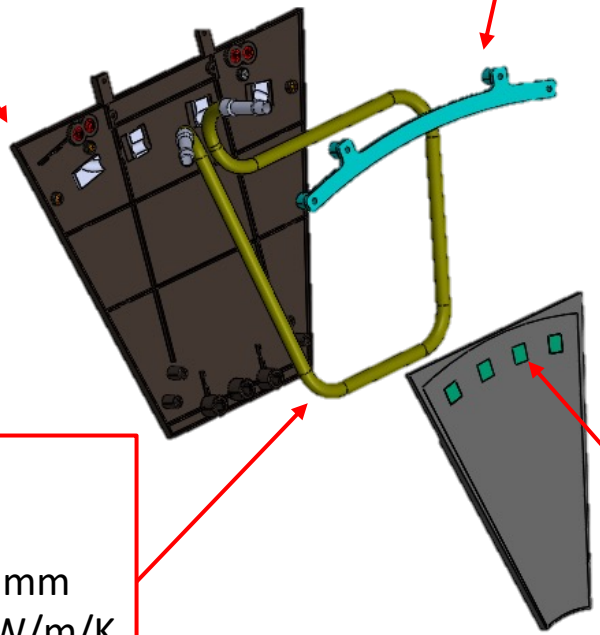


STAR Forward Silicon Tracker

Main structure:
- ❑ Material: PEEK
- ❑ Thermal Conductivity: 0.24 W/m/K
- ❑ ES&H: **Good**
- ❑ Rad.: **Good**

Tube fixture:
- ❑ Material: PEEK
- ❑ ES&H: **Good**
- ❑ Rad.: **Good**

Thermal grease:
- ❑ Material: Thermalrigh TF8 2G
- ❑ ES&H: **Good**
- ❑ Rad.: **Good**



Glue (inner MS+outer MS):
- ❑ Material: Loctite EA 9359.3 AERO
- ❑ ES&H: **Good**
- ❑ Rad.: **Good**

Glue (hybrid+MS):
- ❑ Material: Araldite 2011
- ❑ ES&H: **Good**
- ❑ Rad.: **Good**

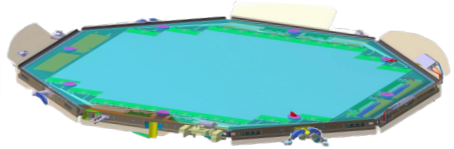
Tube:
- ❑ Material: Stainless 316
- ❑ Size: OD 6.35 mm, ID 5.54 mm
- ❑ Thermal Conductivity: 14 W/m/K
- ❑ ES&H: **Good**
- ❑ Rad.: **Good**

Heat sink:
- ❑ Material: Al 6061
- ❑ Size: ~8.2 x 8.0 x 3 mm^2
- ❑ ES&H: **Good**
- ❑ Rad.: **Good**

*PEEK has been used in collider experiments: e.g. STAR HFT

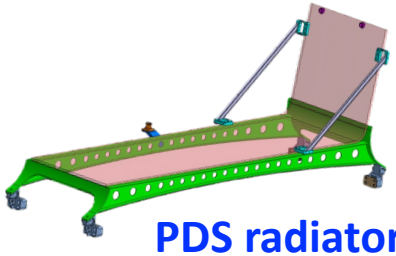
AMS-02 Upgrade Project

- Two main new upgrades on AMS-02:
  1. **PDS radiator**: extend the lifetime of AMS-02
  2. **Layer-0 tracker**: expand our physics understanding



Layer-0 tracker

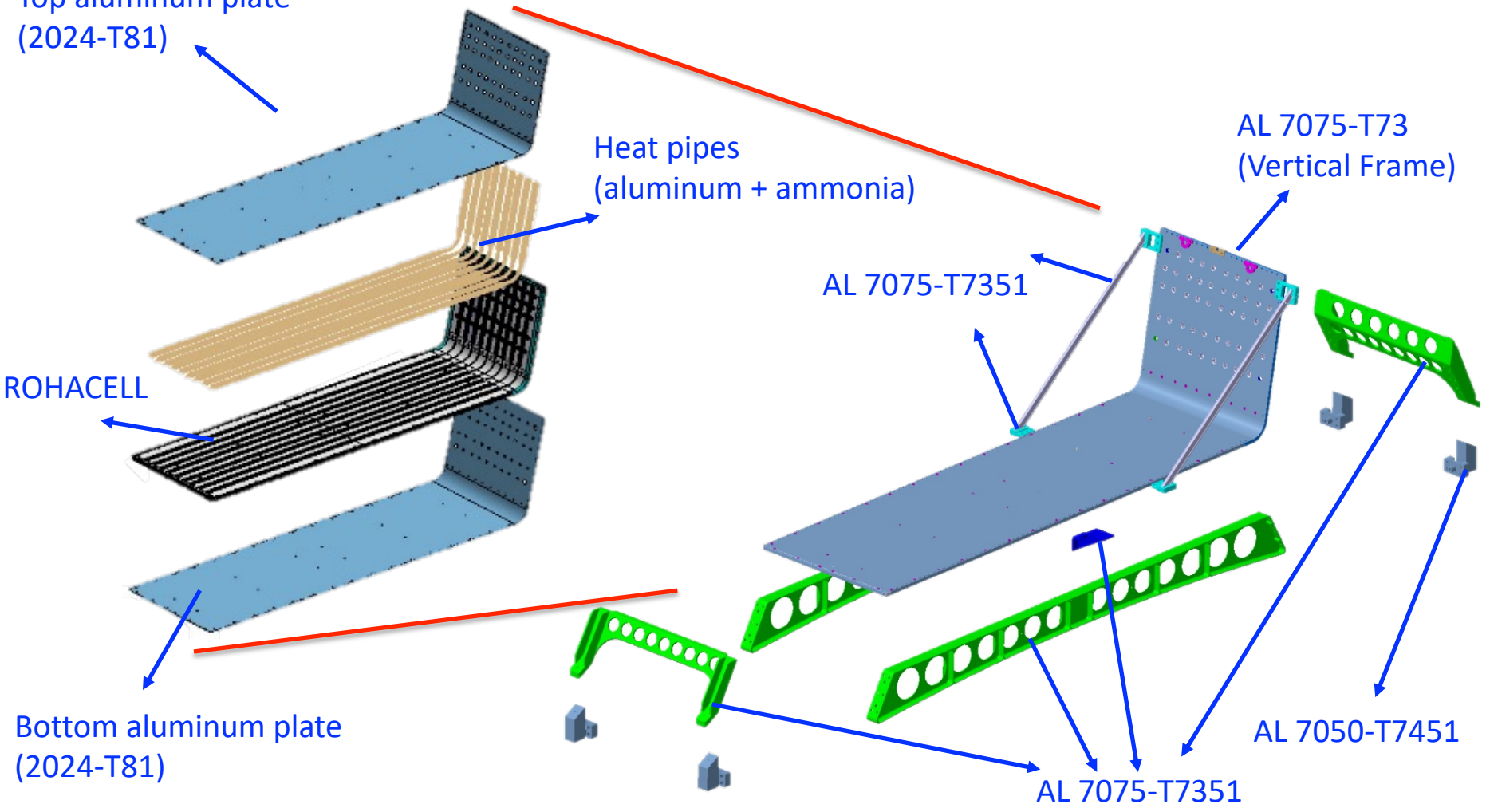
AIDC



PDS radiator

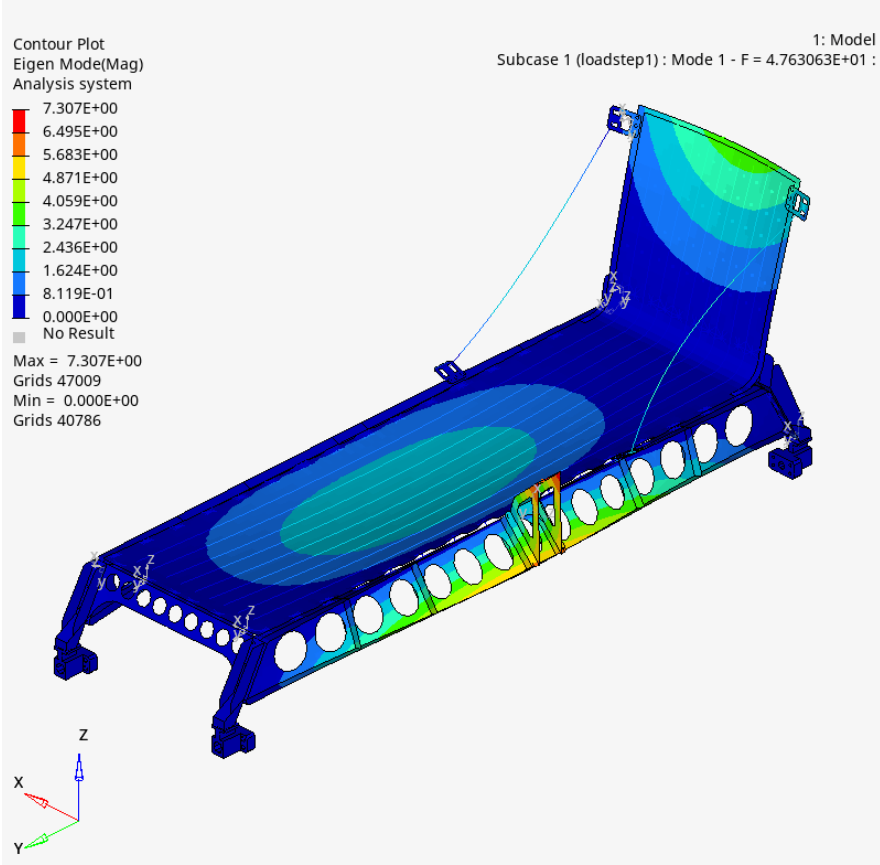
Main Material

Glue: EC-2216

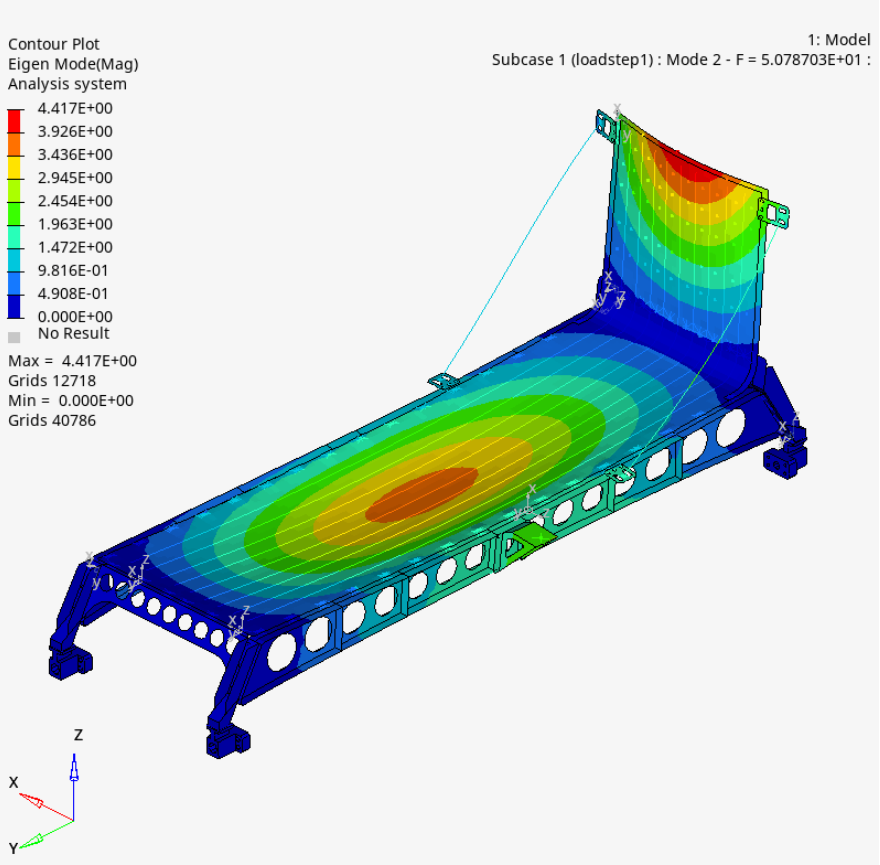


Modal Analysis: Results

First mode: 47.63 Hz



Second mode: 50.79 Hz



Temperature/Heat Flux Profile: Example