Composites Manufacturing & Simulation Center

R&D considerations on lightweight mechanics

- The need
- Current activities & Future R&D
- Conclusions

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based on the Snowmass White paper on mechanics [arXiv:2203.14347]
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Snowmass Seattle workshop

PURDUE UNIVERSITY

July 19th, 2022

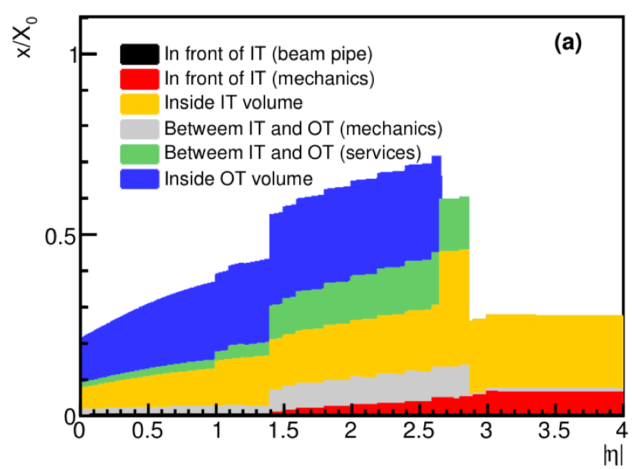
Future colliders (FCC-hh like)

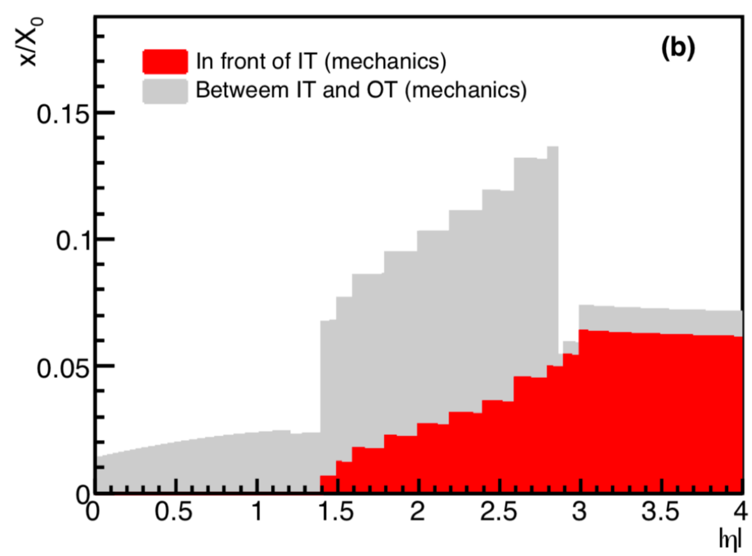
High-luminosity phase of the LHC as example in this talk, but future colliders
- Momenta and angular ranges up by 10x and 2x
- Challenging for forward tracking/detectors
- Pile-up of a thousand results in very harsh conditions

Pixel Layer dose (3.7cm)	HL-LHC $3ab^{-1}$	FCC $3ab^{-1}$	FCC $30ab^{-1}$	FCC (2.5cm) $30ab^{-1}$
$\times 10^{16}\, n_{eq}\, cm^{-2}$	1.5	3	30	70
Dose (MGy)	5	10	100	220

Example of the HL-LHC upgrades as example:

- Support structures need to be optimized, light-weight → minimal mass possible, highly thermally conductive
- CMS HL-LHC upgrades as example



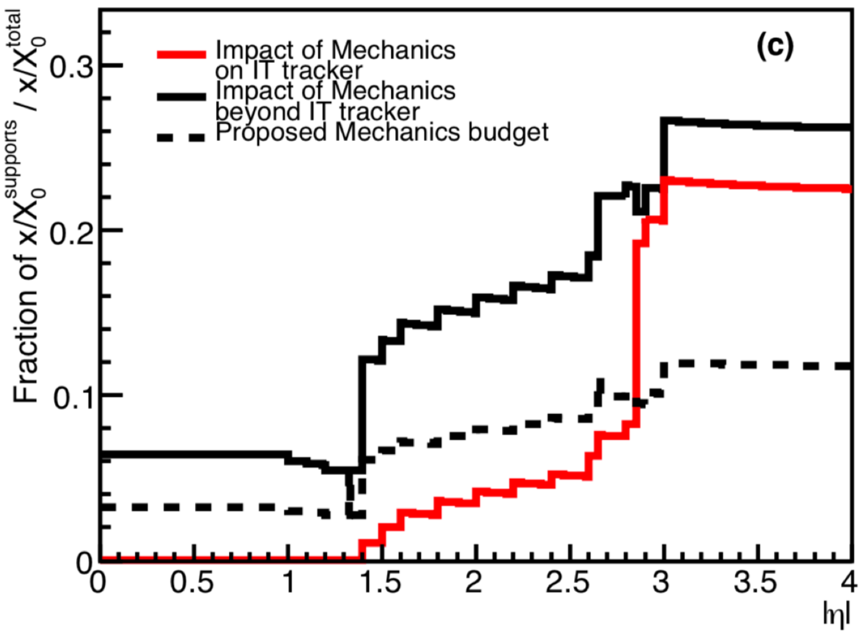


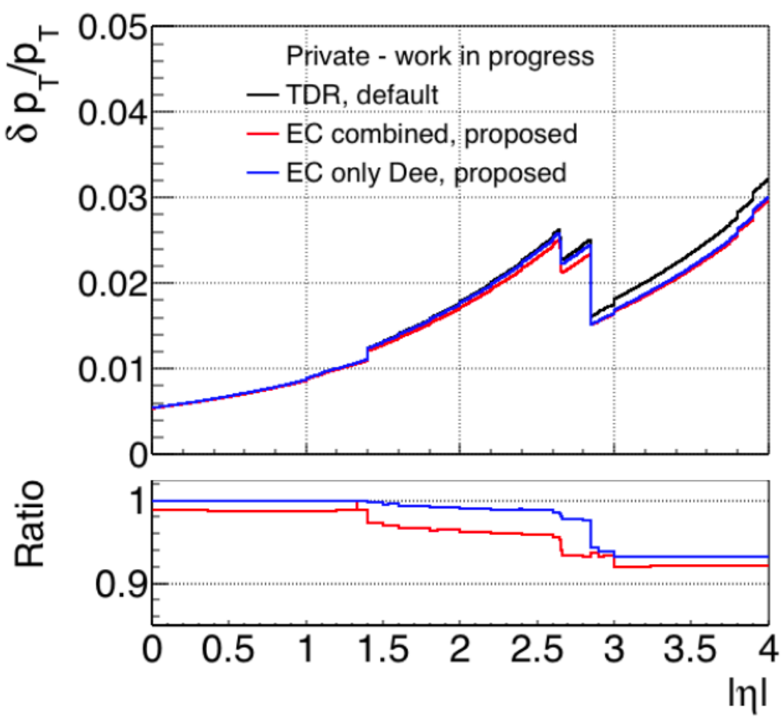
Material budgets & mechanics

Substantial R&D on all fronts to make a FCC-hh detector a reality

- Support & Cooling constrains Tracker performance, e.g. thermal runaway
- Mechanics is significant fraction of the material budget
- **Lowest mass possible requires new approaches to an old topic**

Fraction of mechanics vs entire Detector material



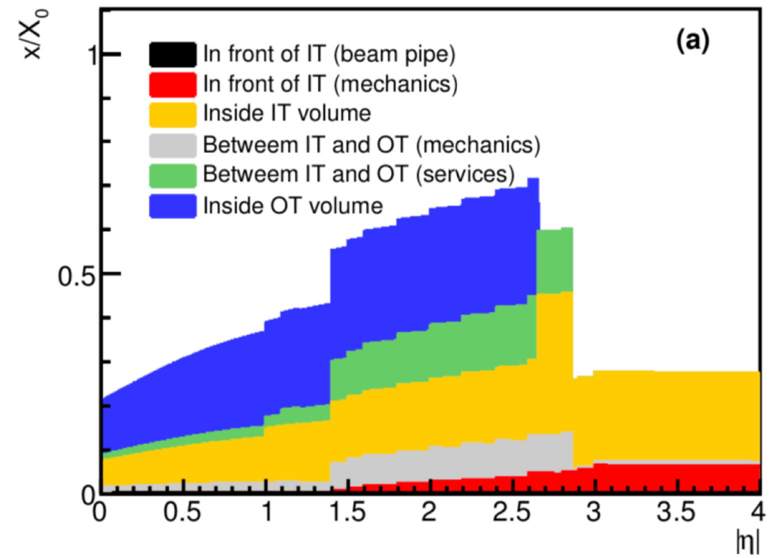


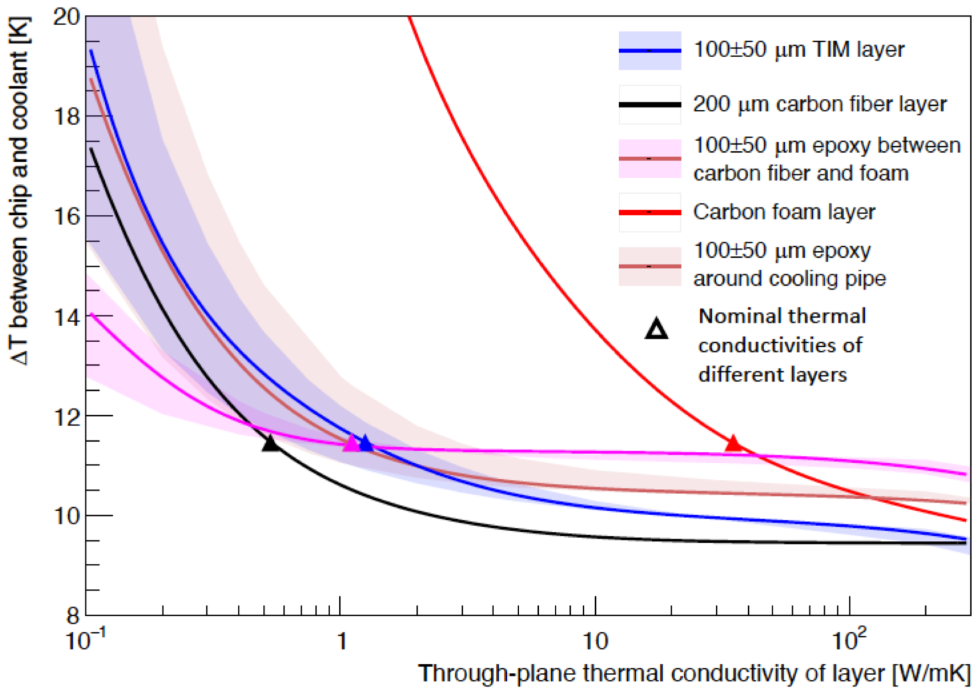
- Can improve b-ID efficiencies by 2-3% per b-jet and high b-jet multiplicity ~10-15%
- Significant improvement by novel approach, b-ID relevant for di-Higgs (priority @FCC-hh)

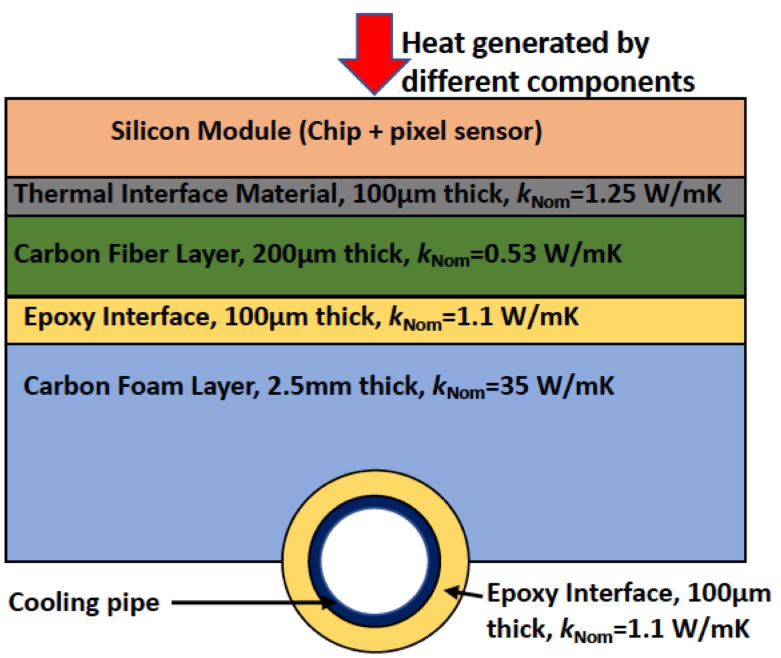
Impact of tracker mechanics…

Tracker of the HL-LHC is a very significant fraction of the total CMS upgrade budget

- Support & Cooling is the constrain in which Tracker is operated, e.g. thermal runaway
- Mechanics is sizeable fraction of the material budget
- Requires detailed FEA & mock-up's to understand and verify experimental measurements





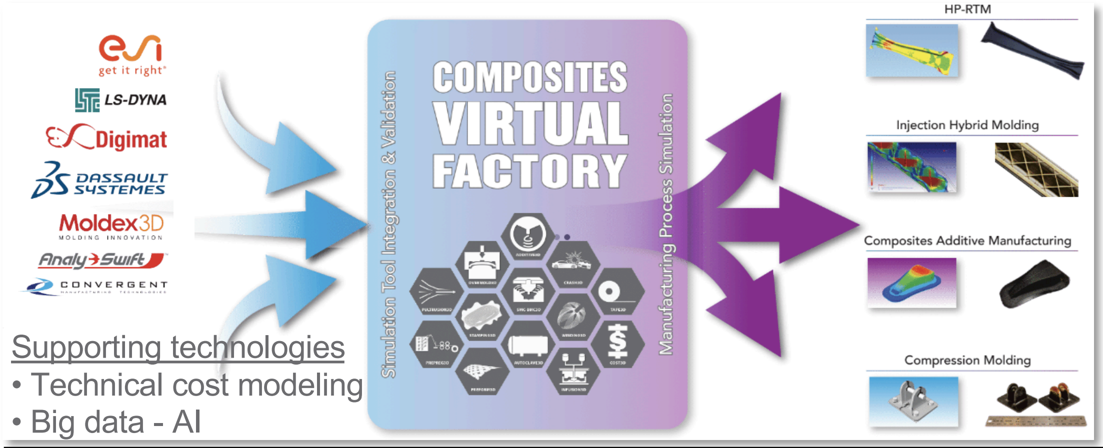


The facilities at Purdue: CMSC

Composites Manufacturing & Simulation Center

<u>Completed in summer 2016:</u>
- Composite manufacturing & simulation center (CMSC)
- Multi-disciplinary center: Aeronautics, Chemical E, Materials E, Aviation Tech, Computer graphics

<u>A Purdue Center of Excellence:</u>
- Experts in simulation as a decision-making tool for composites
- Dassault Systemes Simulation Center of Excellence
- Process-specific engineering workflows



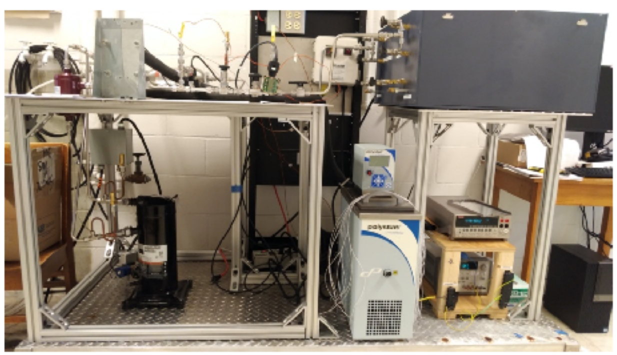
Facilities at Purdue: CTRC & PSDL

Cooling Technologies Research Center:

- Multi-disciplinary center to study micro-channels, fluid dynamics, cooling (air & fluid), thermal interface materials, etc.

Purdue Silicon Detector Laboratory:

- Large clean rooms for automated pixel module assembly & electronic tests
- Thermal conductivity setups, etc.



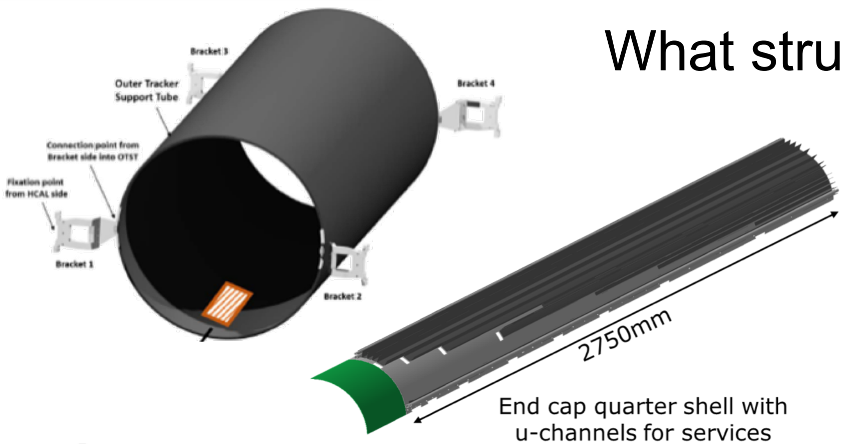

CTRC center:

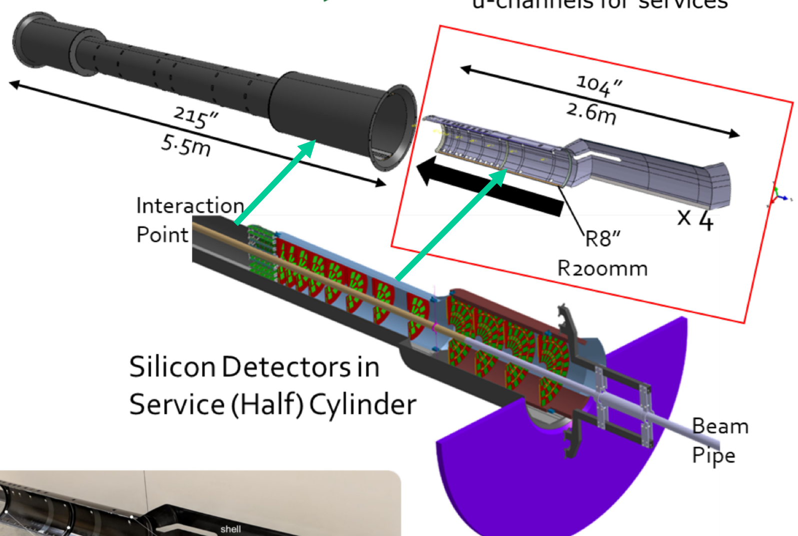
https://engineering.purdue.edu/CTRC/research/index.php

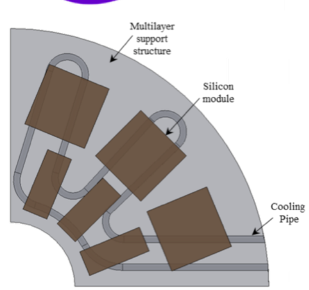
PSDL-CTRC Collaboration on:

- Various aspects of thermal management relevant for the applications at LHC
- Common 2-phase CO_2 cooling box setup

Current activities







What structures are we involved with? (HL-LHC Upgrade)

Large Support Structures – light-weight but rigid

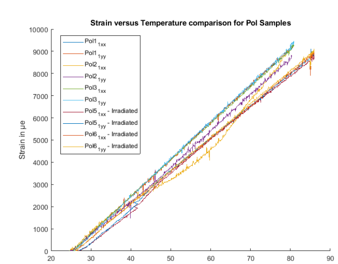
1. Boundary Tracker Support Tube (CMS)
2. Inner Tracker Support Tube (CMS)
3. Inner Tracker Service Cylinder (CMS)
4. End Cap Quarter-Shells (ATLAS)

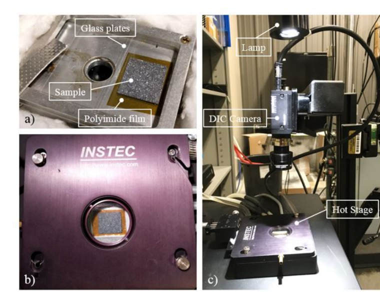
Small Structures – extremely flat and thin

1. Pixel Dees Support Structure (CMS)
2. High-TC flat sheets for modules (CMS)

Irradiation campaigns:

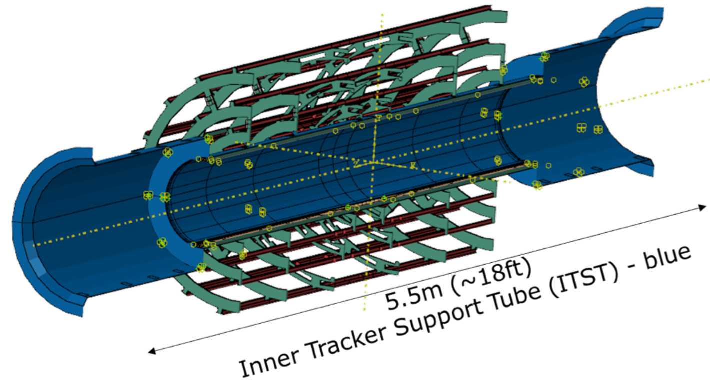
- In collaboration with US TFPX institutes (Cornell, Rice, others)
- Open to European institutes, e.g. Zuerich has sent samples in the past

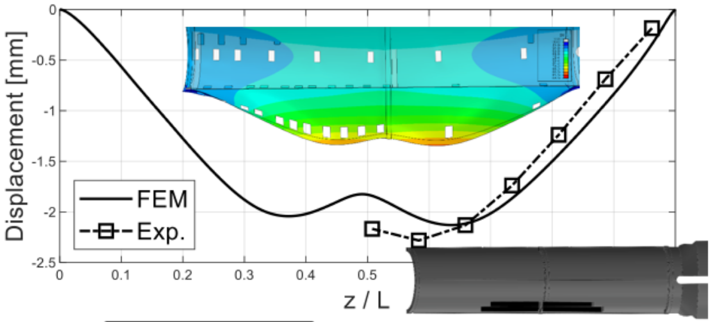


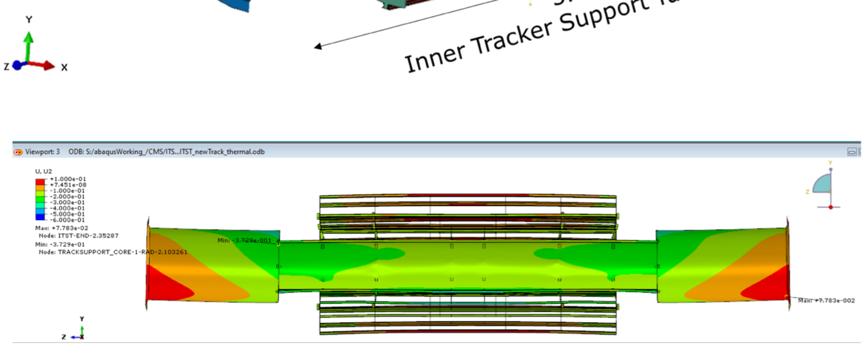


Process & Performance Simulation

- Use simulation and prediction based on material characterization to ensure accurate prediction of final part performance
- Applied to CMS structures already with full chain of tool compensation, machining, cure and load test







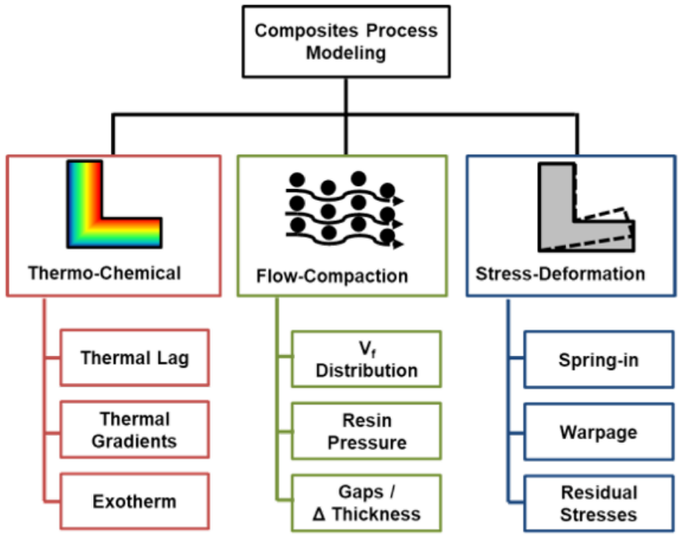
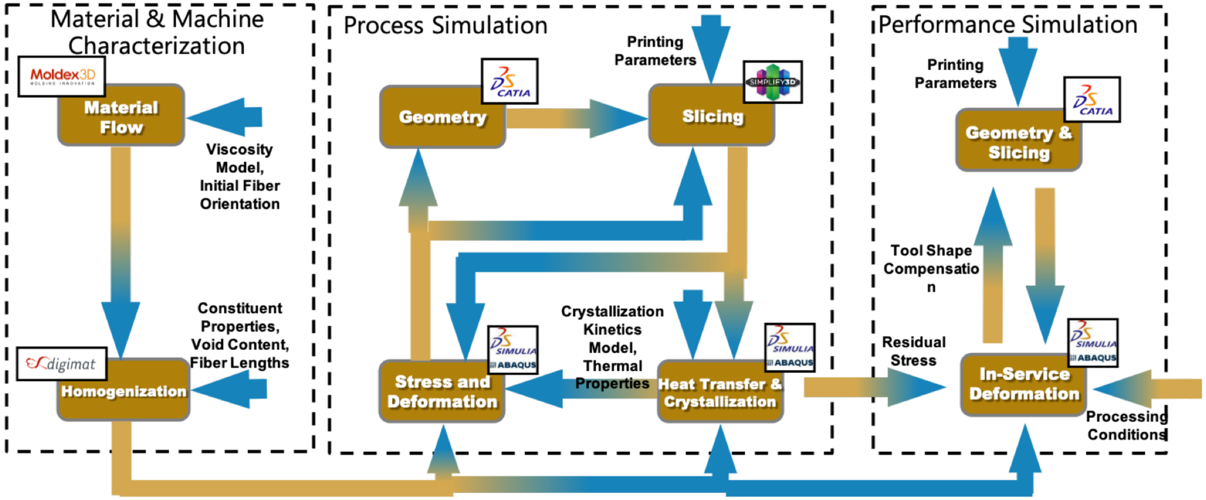
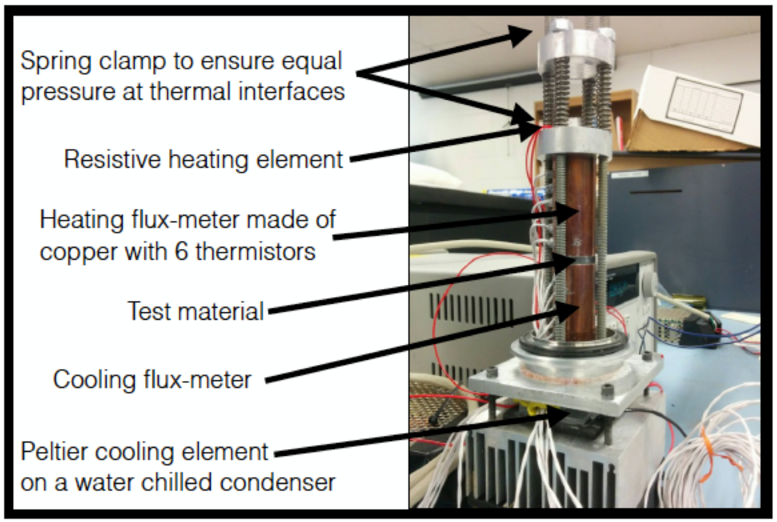


Figure 1-1 Composites process modeling problem types

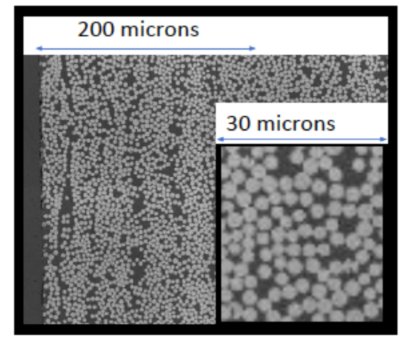


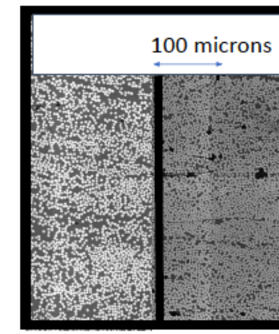
Thermal conductivities

→ UG student driven activities, low-cost but precise
→ High pressure curing to boost TC, factor 2 improvement
→ Additional fillers to boost TC while maintaining mechanical strength
→ Method & Results to be submitted to JINST soon…

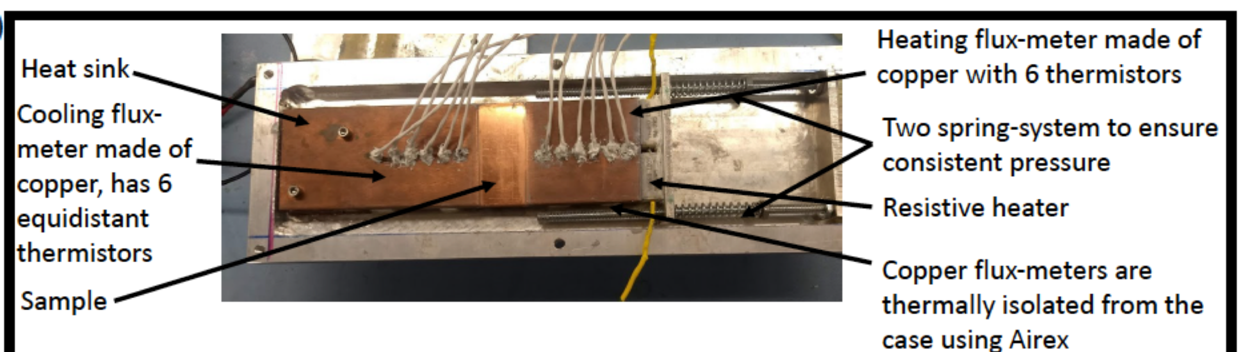


→ High pressure samples increase volume fraction to 72%
→ Microscopies to measure volume fractions





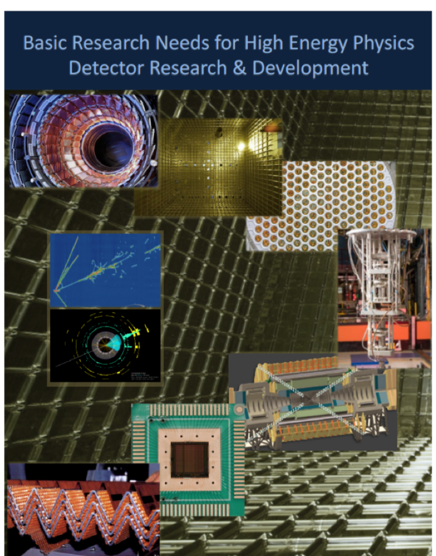
Sample/ Direction of measurement	Thermal conductivity (k) [W/mK]	Interface thermal resistance of Flux-meter-TIM-Sample (R_{int}) [Km^2/W]	Reduced χ^2 of the linear fit	Expected value of k [W/mK]
K13C2U+EX1515 carbon fiber composite (Unidirectional)				
x-axis	(320 ± 28)	$(1.8 \pm 0.4) \cdot 10^{-5}$	0.83	318 [3]
y-axis	(6.0 ± 2.6)	$(3.8 \pm 2.8) \cdot 10^{-4}$	0.17	0.53 [3]
z-axis	(1.09 ± 0.15)	$(-6.0 \pm 17.0) \cdot 10^{-5}$	0.05	0.53 [3]
z-axis (20 bar)	(2.21 ± 0.31)	$(3.0 \pm 7.0) \cdot 10^{-5}$	0.09	1.2 [3]
K13D2U+EX1515 carbon fiber composite (Unidirectional)				
x-axis	(376 ± 31)	$(1.7 \pm 0.3) \cdot 10^{-5}$	0.65	410 [3]
y-axis	(7.5 ± 4.4)	$(3.9 \pm 3.5) \cdot 10^{-4}$	0.01	0.53 [3]
z-axis	(1.44 ± 0.24)	$(1.4 \pm 1.4) \cdot 10^{-4}$	0.44	0.53 [3]
z-axis (20 bar)	(2.79 ± 0.46)	$(2.0 \pm 9.0) \cdot 10^{-5}$	0.43	1.2 [3]
Other materials				
IM7 8552 (x-axis)	(8.0 ± 2.3)	$(1.2 \pm 0.8) \cdot 10^{-4}$	0.85	5.50 [20]
Celstran© PPS-CF50-01 (z-axis)	(0.34 ± 0.08)	$(-2.2 \pm 4.6) \cdot 10^{-4}$	1.09	0.39 [21]

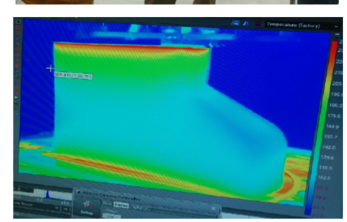


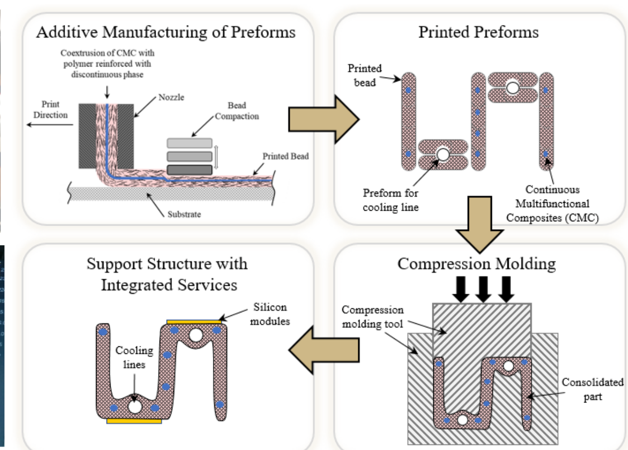
Future R&D work

- R&D efforts on low-mass support structures with integrated services for silicon detector systems
- Targeting the Basic Research Needs for HEP by DOE topic of “Realize scalable irreducible-mass trackers”, thrust 2 on low mass detector system.
- Leverage current activities on high-TC, accurate predictive manufacturing of large composite structures, etc.
- Connections with companies engaged in high-TC carbon foam development

- Multi-functional composite structure research
- Integration of cooling and other services into the support structures to reduce mass further
- Novel approach to mechanics design from inception phase of the detector

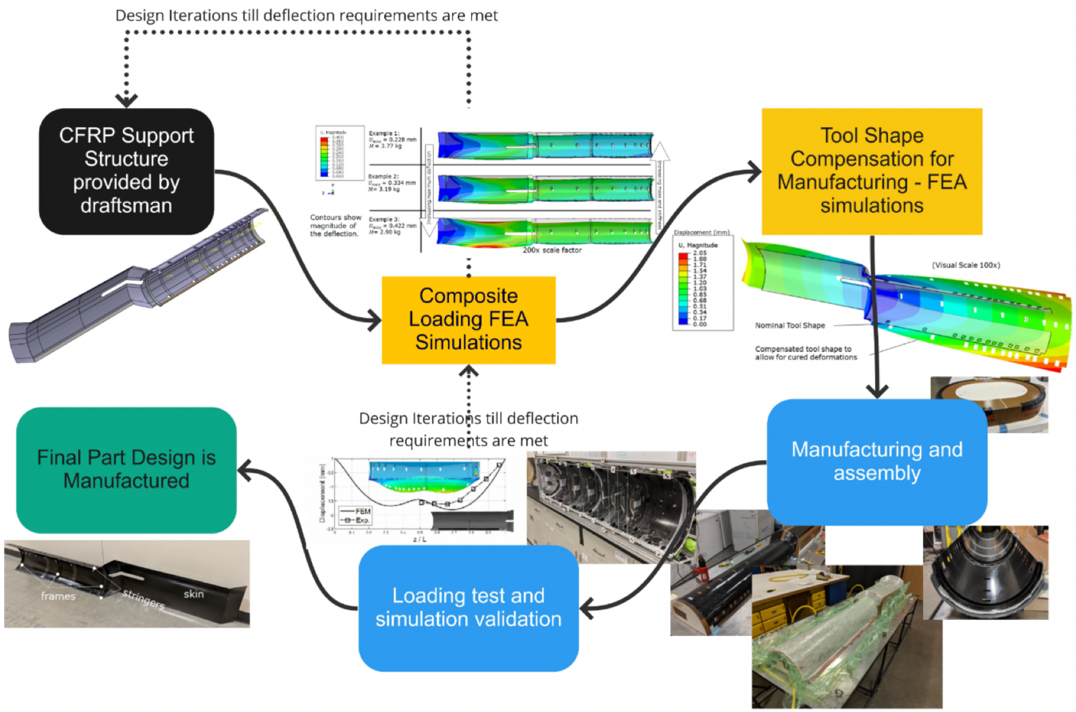






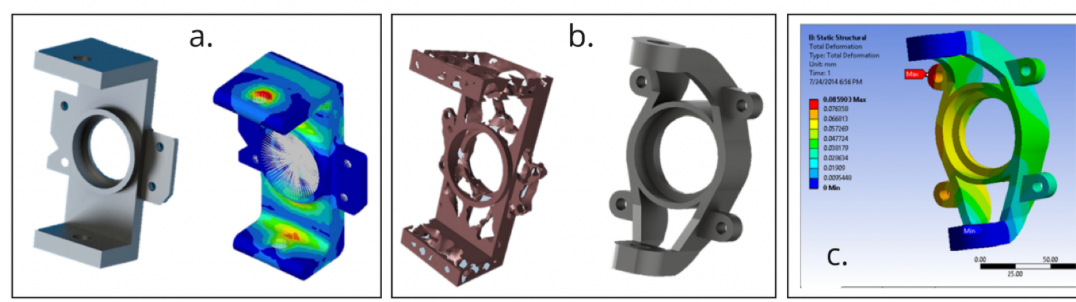
Going into the future of mechanics

→ Scalable large mechanics structures
→ Multi-functional support structures
→ Ease integration, applies also to calorimetry [arXiv:2203.04312]



→ FEA, prototypes, iterative process.
→ Consistent approach to better controlled manufacturing process, eases assembly.
→ Especially true the larger the structures become, integration is a "hassle"

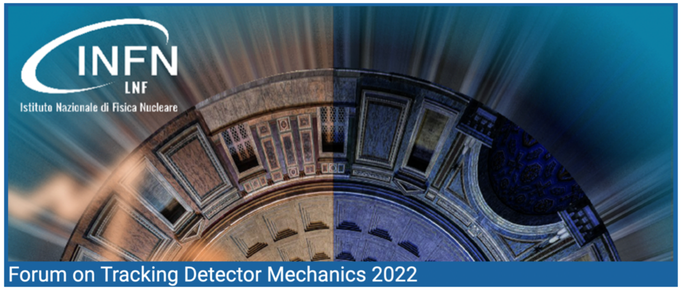
→ Collaboration with material sciences, companies for novel materials, and latest techniques.
→ Example: ML for optimization with HEP inputs, excites future generation



Mechanics community

Exchange of ideas & progress across existing collaborations:

- Snowmass process, but no dedicated forum in the US to exchange on this
- Internationally we have the Forum on Tracking Detector Mechanics
    - 10th iteration in 2022: https://indico.cern.ch/event/853861/
    - ~70 participants
    - Form a "CERN RD Mechanics" …



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<u>My own opinions</u>

- In the past largely focused at national labs, single Universities.
  - Community building in the US around the US participants of the Forum and Snowmass, consistent funding is a problem.
  - Establish more long term funding as a future around existing "seeds" ?
  - Interdisciplinary R&D can realize additional synergistic activities
- Future detectors are huge, mechanics is a significant fraction of material and also of the cost – serious / critical risks related to material availability
  - Ample evidence in the past years, not going away

Summary

Detector mechanics can play a significant role in a detector's performance, improvements require:

- In-depth study of total mass
- Novel ways to reduce the total mass

Over the past years established Purdue collaborations to benefit HEP tracker mechanics activities and R&D efforts

→ For now: the "Forum on tracker mechanics" is the ideal place to exchange progress on detector mechanics at boundary of material science, engineering and physics.

→ Many opportunities for external collaborations

  → Low mass detectors

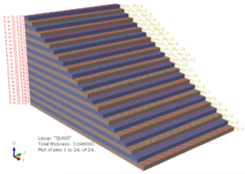
  → High-performance cooling

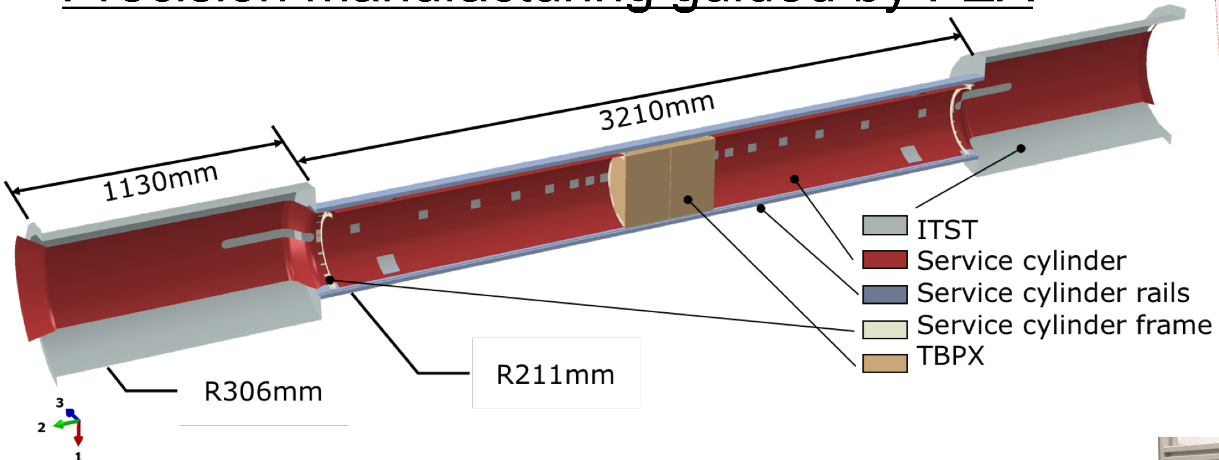
Backup

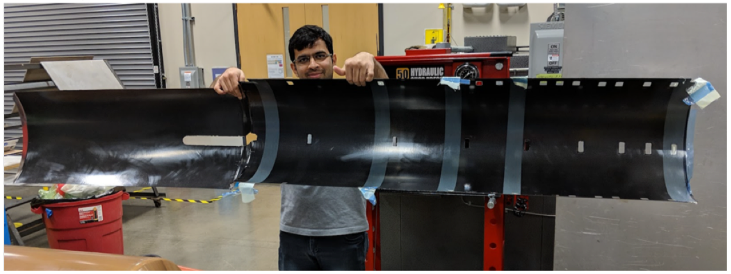
Early results on structures

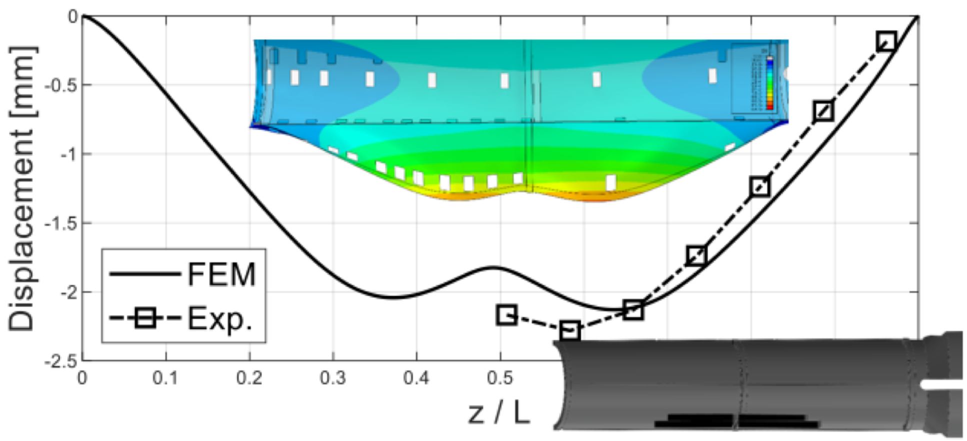
First prototype of the Service Cylinder, **sub-mm tolerances**
- Structure mass is 2.77kg
- Loaded mass is large, shows deflection more easily
- Very good agreement with the FEA

→ <u>Precision manufacturing guided by FEA</u>





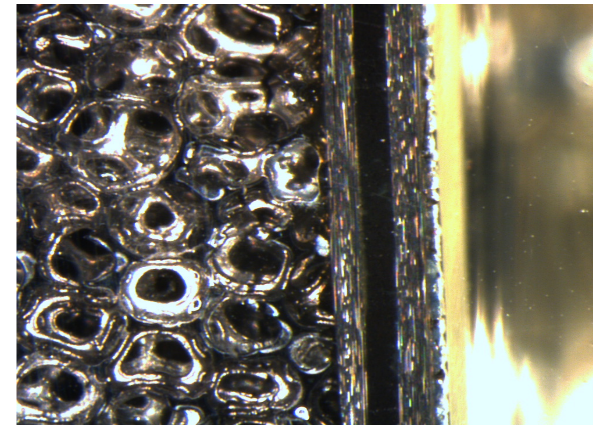




Pixel support structures

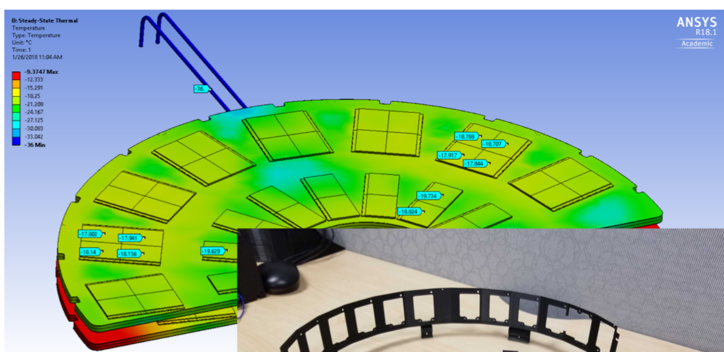
- → Disc-like support structures made from Carbon Foam & Fiber
- → FEAs use TC measurements as inputs
- → Capable of cooling all ~1800 pixel modules
- → Carbon is light-weight, and strong

1st half dee prototype, in collaboration with Cornell University

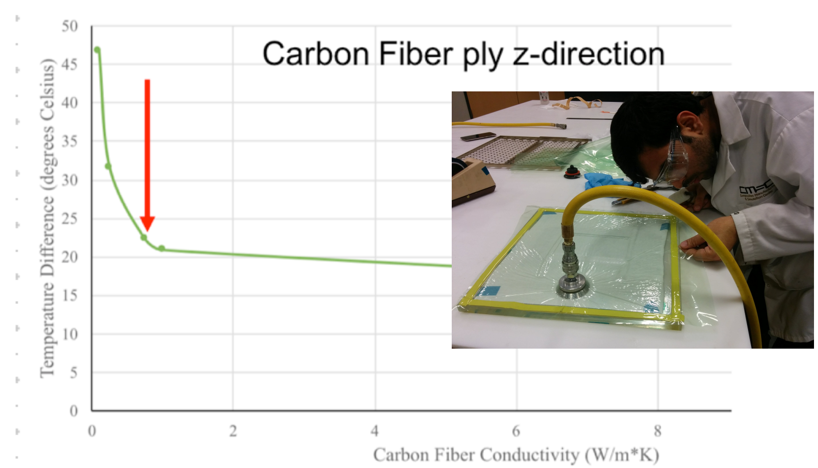


Carbon foam

3-ply skin



High TC support pieces



Bad laminate