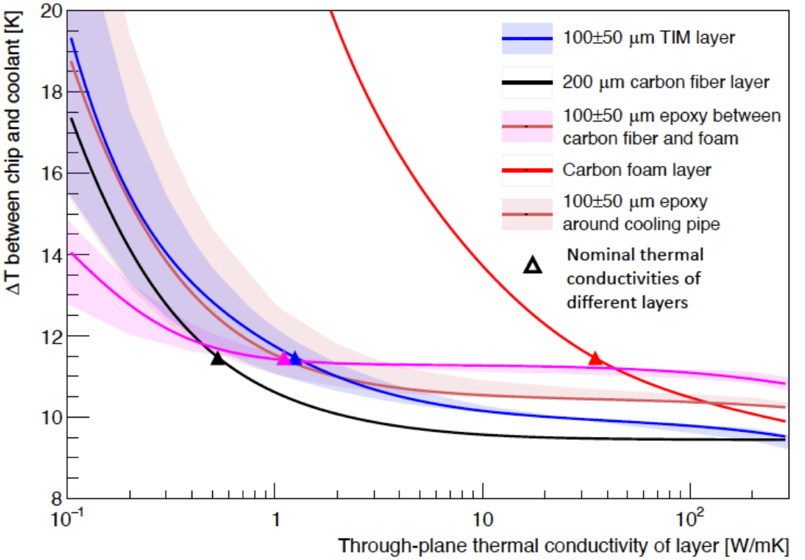
Advanced Mechanics & Composites

- The need
- Today's capabilities & Future R&D (biased view's)
- Remarks
- Summary



Andy Jung, B. Denos, E. B. Vaca, S. Karmarkar, A.M. Koshy

UG students: Pattiya Pibulchinda, Cameron J. Harstfield, Andrew S. Bruns, Pedro D. Soto.

1st Workshop for 2nd EIC detector, Temple University

Composites Manufacturing & Simulation Center

PURDUE UNIVERSITY

May 18th, 2023

Future colliders (FCC like)

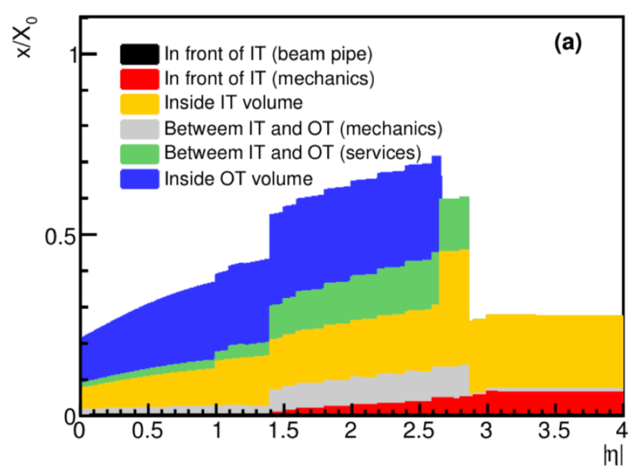
High-luminosity phase of the LHC as example in this talk, but future colliders

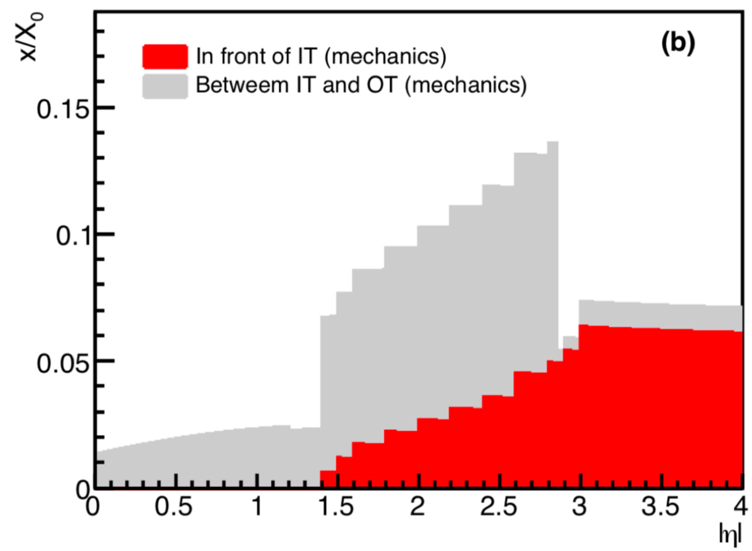
- Larger angular coverages extend into forward directions
- Challenging for forward tracking/detectors
- Pile-up of a thousand results in very harsh conditions (@FCC-hh)

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



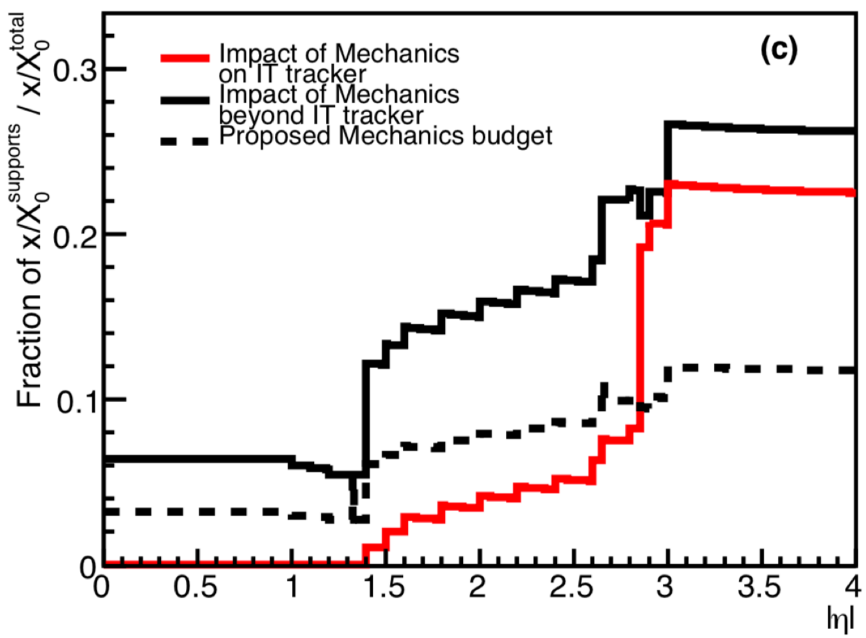


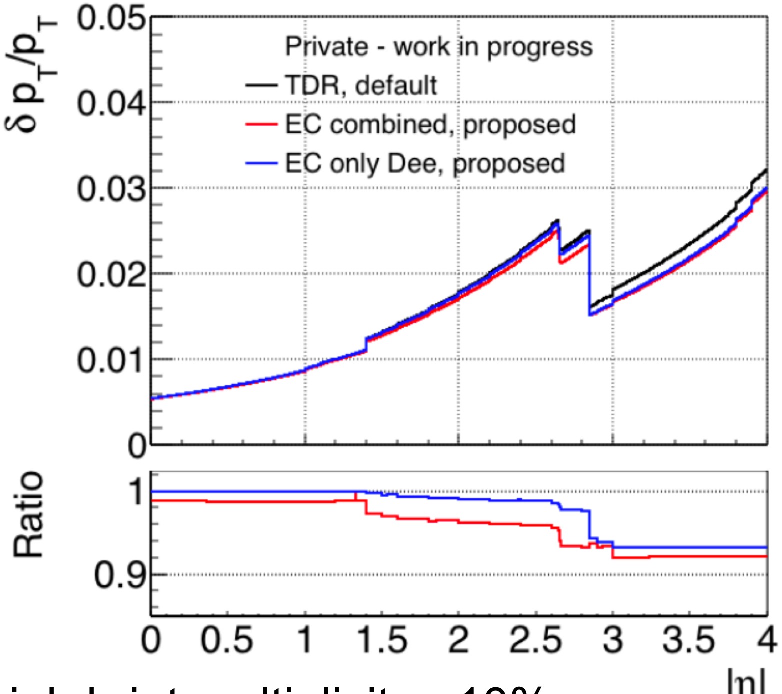
Material budgets & mechanics

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
- Integration & Services an integral part of ”detector mechanics”
- **Lowest mass possible requires new approaches to an old topic**

Fraction of mechanics vs entire Detector material



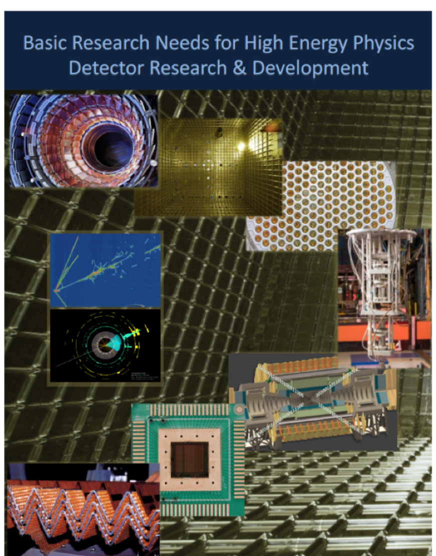


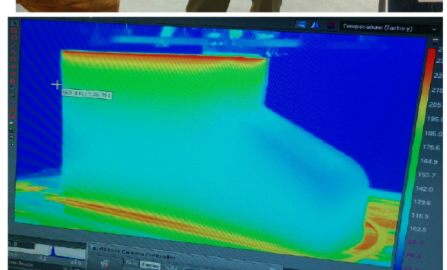
- Can improve b-ID efficiencies by ~2% per b-jet and high b-jet multiplicity ~10%
- Significant improvement by novel approach, b-ID relevant for top & Higgs physics

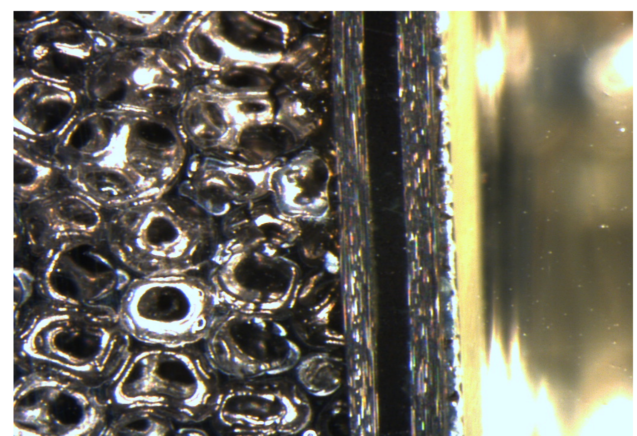
DOE Basic Research Needs

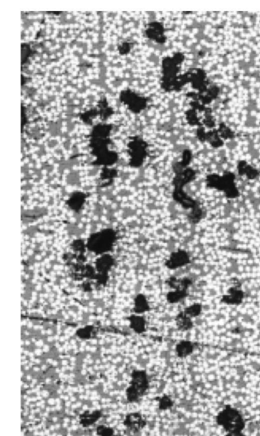
- R&D efforts on low-mass support structures with integrated services for silicon detector systems
- Targeting the Basic Research Needs for HEP by DOE topic of **“Realize scalable irreducible-mass trackers”**, thrust 2 on low mass detector system.
- Enhanced by current activities on high-TC, accurate 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**
- **Need to start early/ier with R&D…**





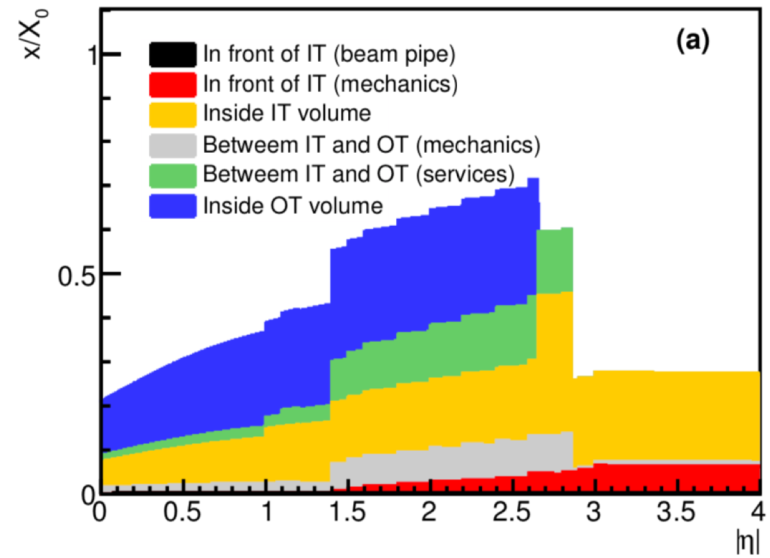


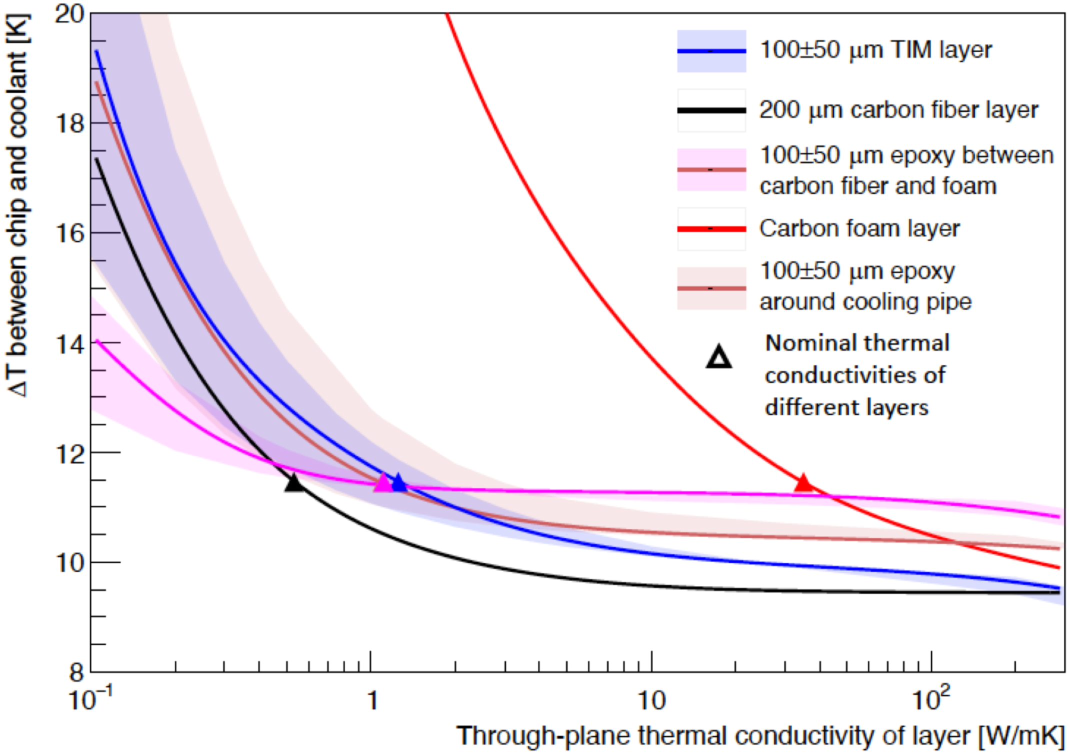


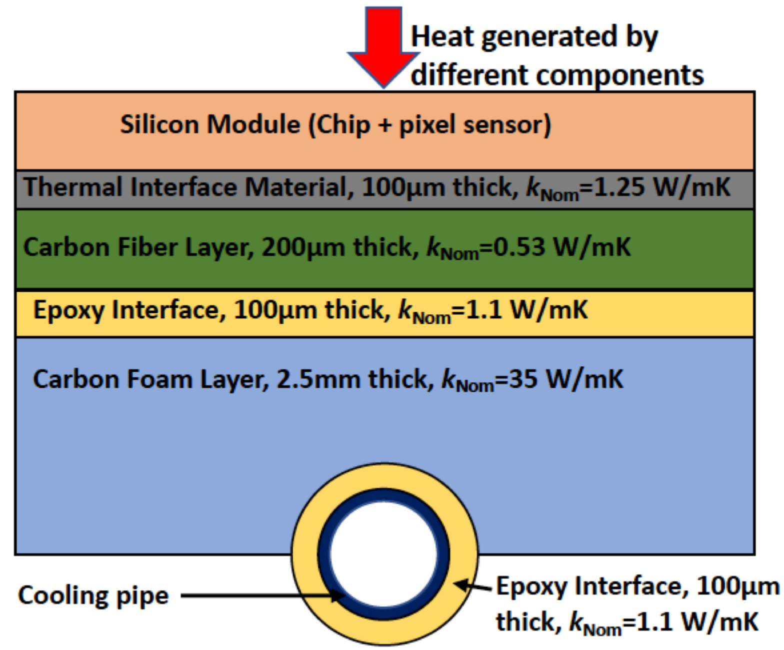
Impact of tracker mechanics…

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







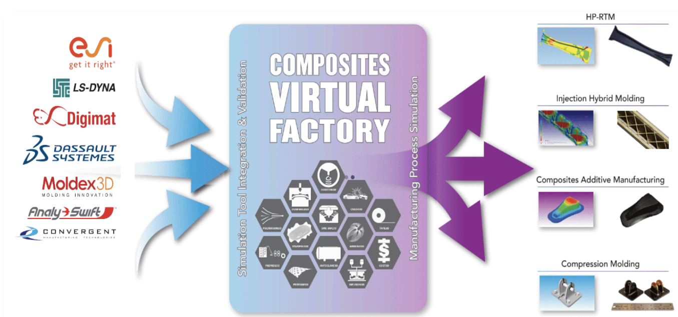
Advanced Mechanics: Facilities

Completed in summer 2016:

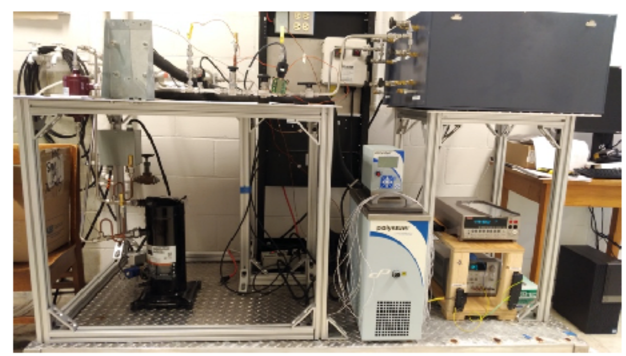
- Composite manufacturing & simulation center (CMSC)
- Multi-disciplinary center: Aeronautics, Chemical E, Materials E, Aviation Tech, Computer graphics

A Purdue Center of Excellence:

- Experts in simulation as a decision-making tool for composites
- Dassault Systems Simulation Center of Excellence
- Process-specific engineering workflows



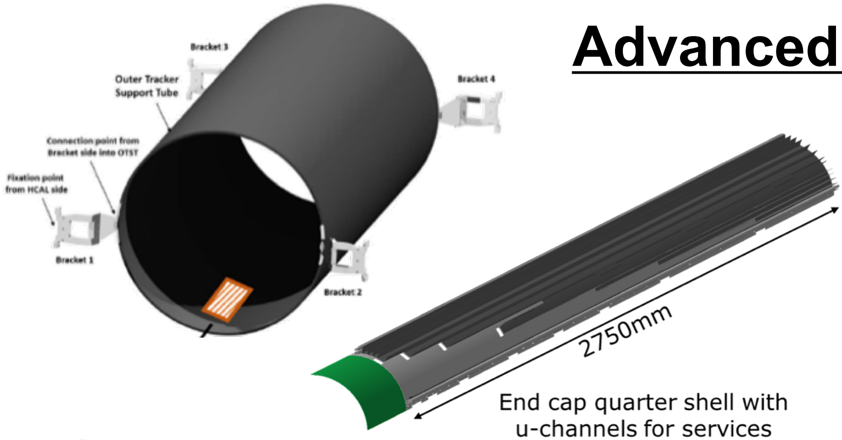
Supporting technologies
- Technical cost modeling
- Big data - AI



What's possible today... *(biased view/selection)*

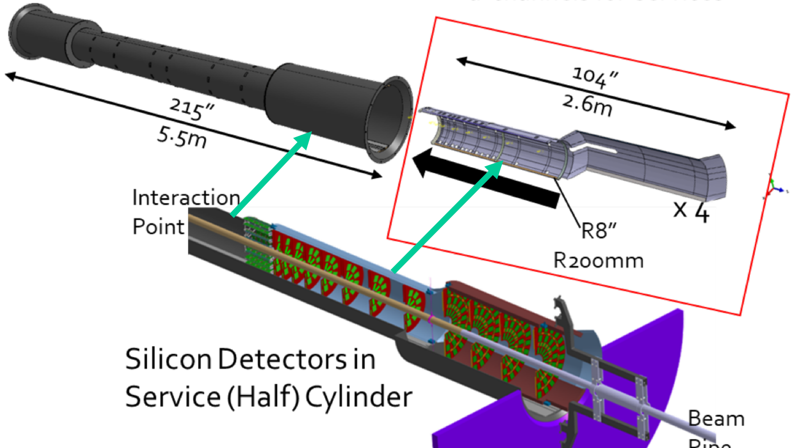
Composites Manufacturing & Simulation Center

Advanced Mechanics & Composites activities at Purdue



Large Support Structures – light-weight but rigid

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

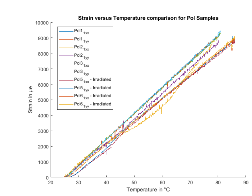


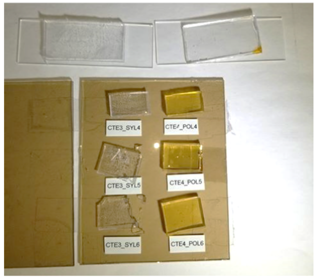
Small Structures – extremely flat and thin

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

Irradiation campaigns:

- In collaboration with US TFPX institutes (Cornell, Rice, others)



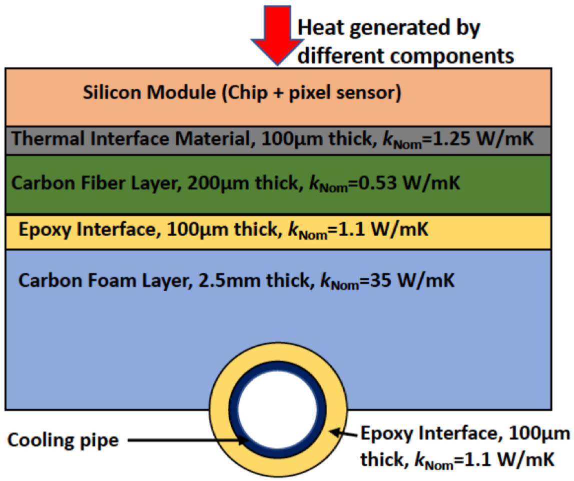


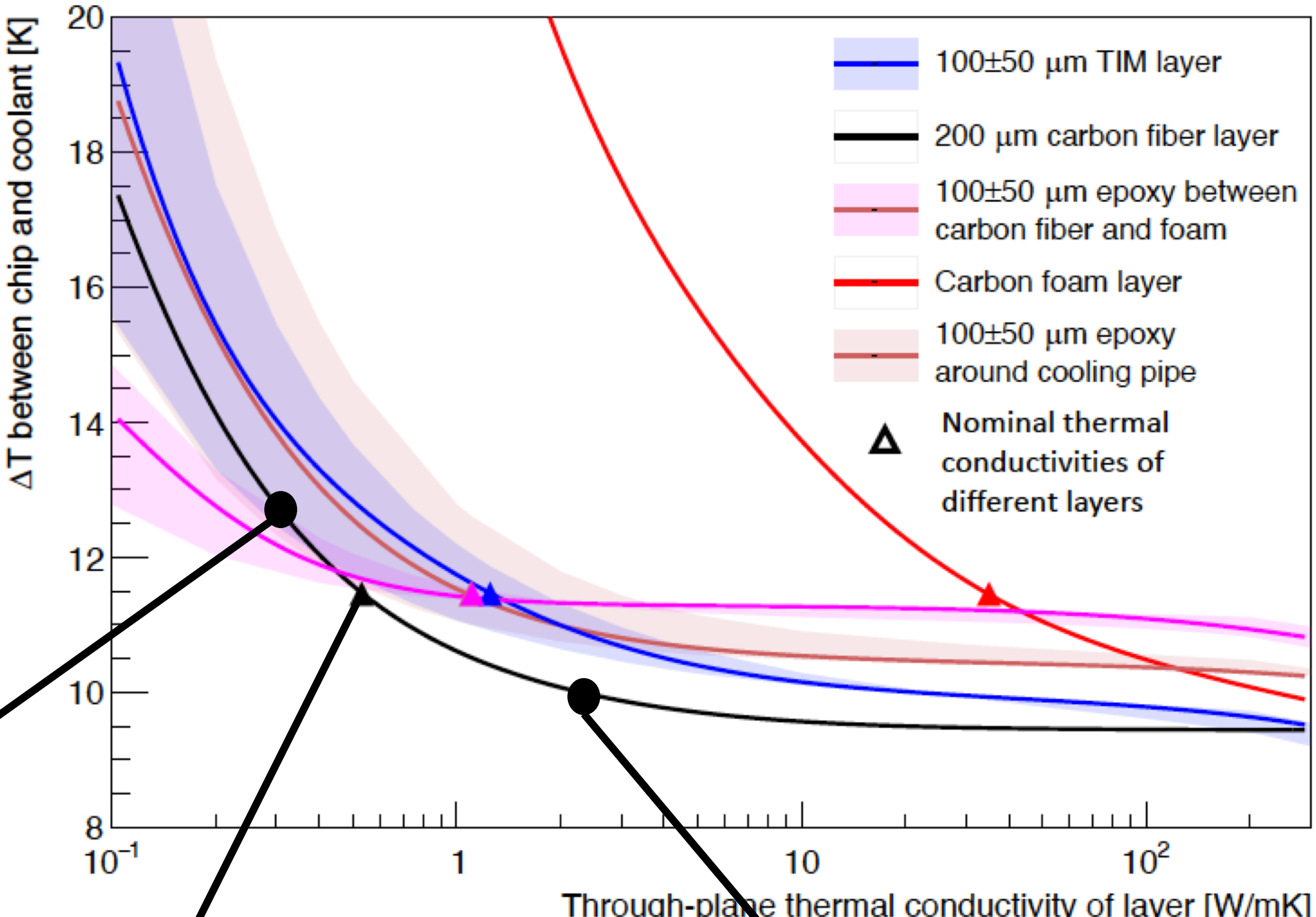
Future Mechanics and R&D:

1. "BlueSky Mechanics" for detectors at future Colliders (FCC, muon, LC, etc.) https://arxiv.org/abs/2203.14347
2. "CalVision" project for mechanics of dual readout calorimetry https://arxiv.org/abs/2203.04312

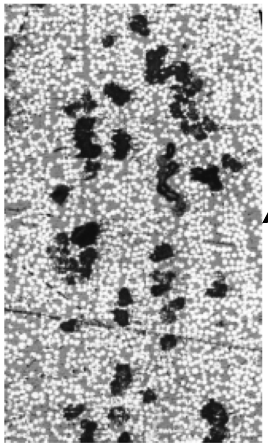
Advanced mechanics I

"Critical interface" scan via detailed FEA

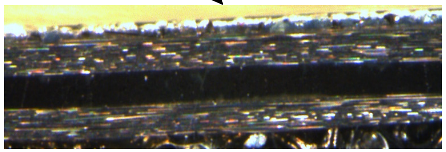




What can go wrong…



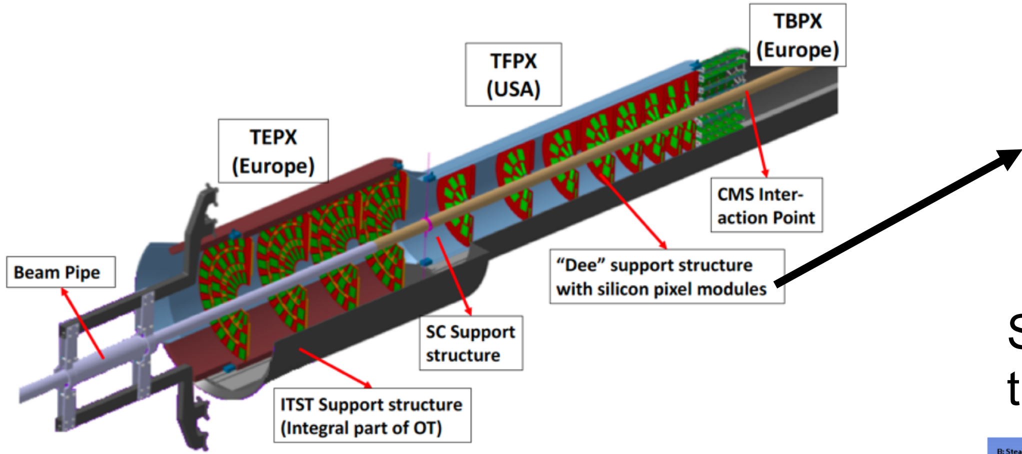
"State-of-the-art" values

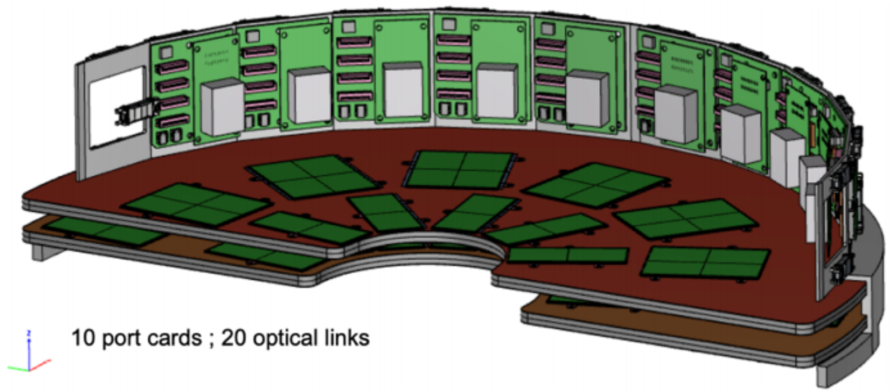


Boosted TC Structure used in barrel Pixel

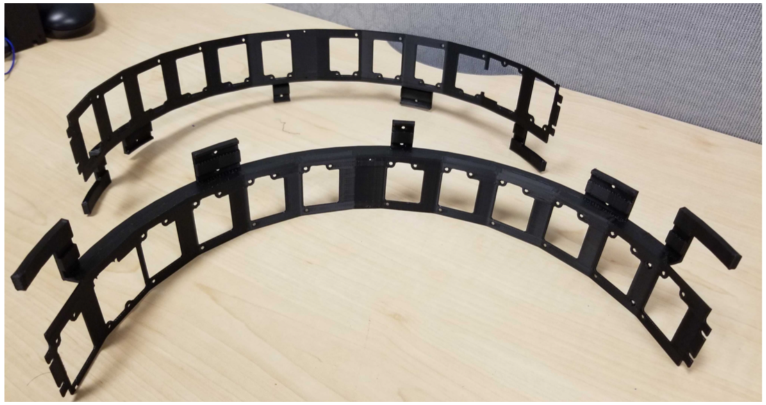
Advanced mechanics II

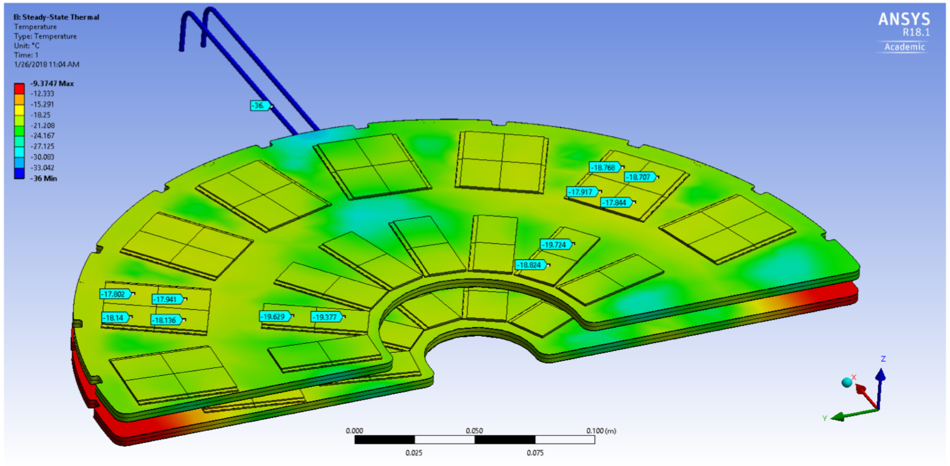
- Challenge: Remove 35 kW of heat…
- Join Carbon Fiber laminates w 3D printed material
  - Manufacturing scales & is better controlled than one-off's
  - Optimized thermal path ways & heat sinks





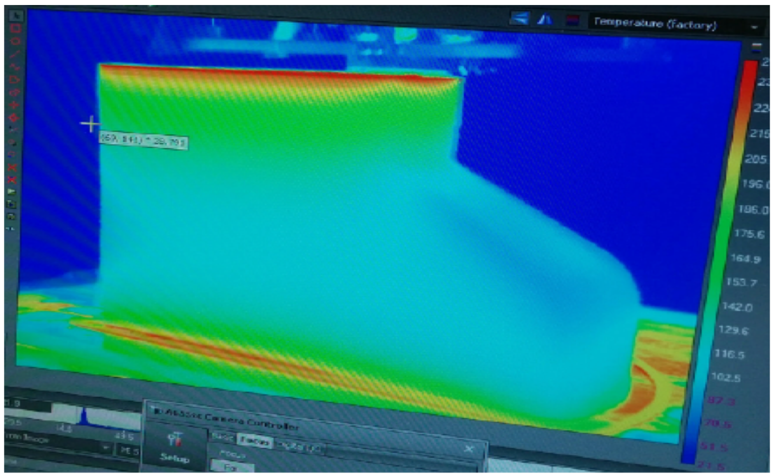
Service cards "heat" structure – provide a thermal path way…

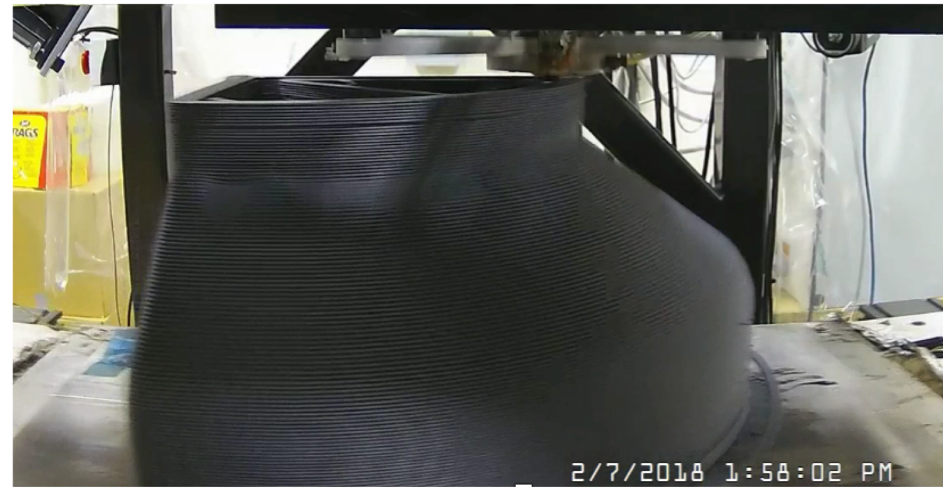




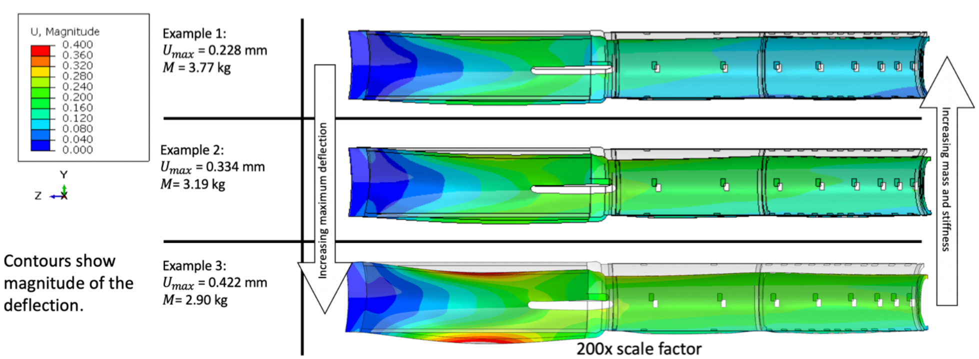
Advanced mechanics III

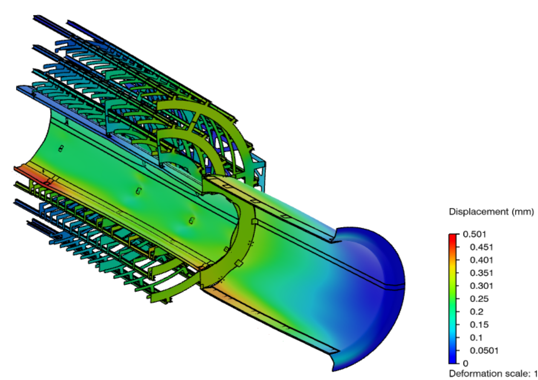
- Tight tolerances…dual-use structures
  - Examples: Minimize CTE mismatch during manufacturing…improves precision!





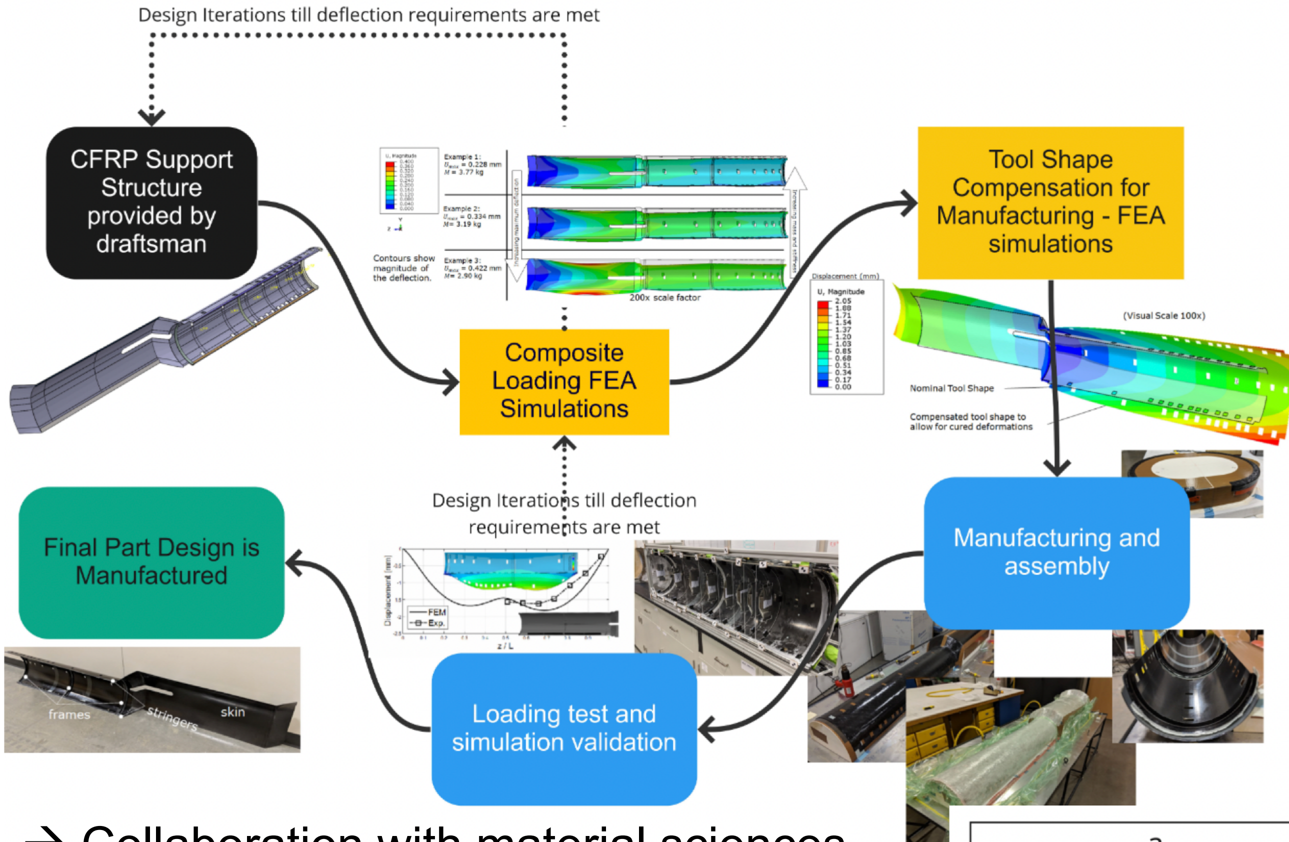
- Tradeoff between mass and stiffness
  - Examples: 1 kg of "support mass" yields about 200





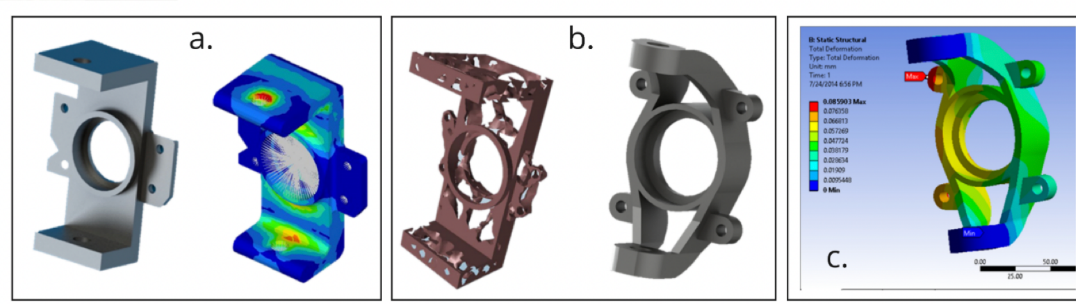
Going into the future of mechanics

→ Scalable mechanics structures: multi-functional & mass optimized
→ Ease integration, applies also to calorimetry, TOF, etc.



Full cycle of Process & Performance simulation:
→ FEA, prototypes, iterative process.
→ Consistent approach to better controlled manufacturing process, eases assembly.
→ Especially true the larger the structures become, integration is a "challenge"

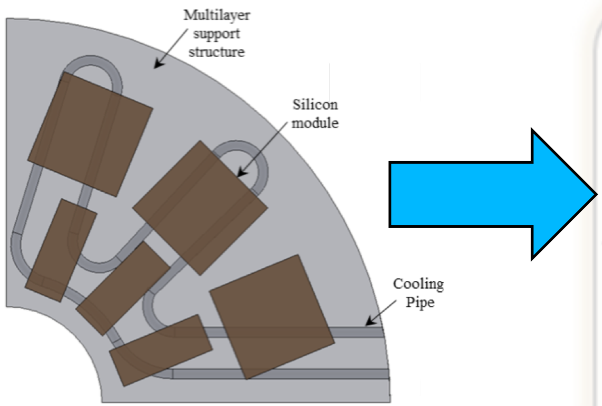
→ Collaboration with material sciences, companies for novel materials, and latest techniques.
→ Example: ML for optimization with HEP inputs, **excites future generation**

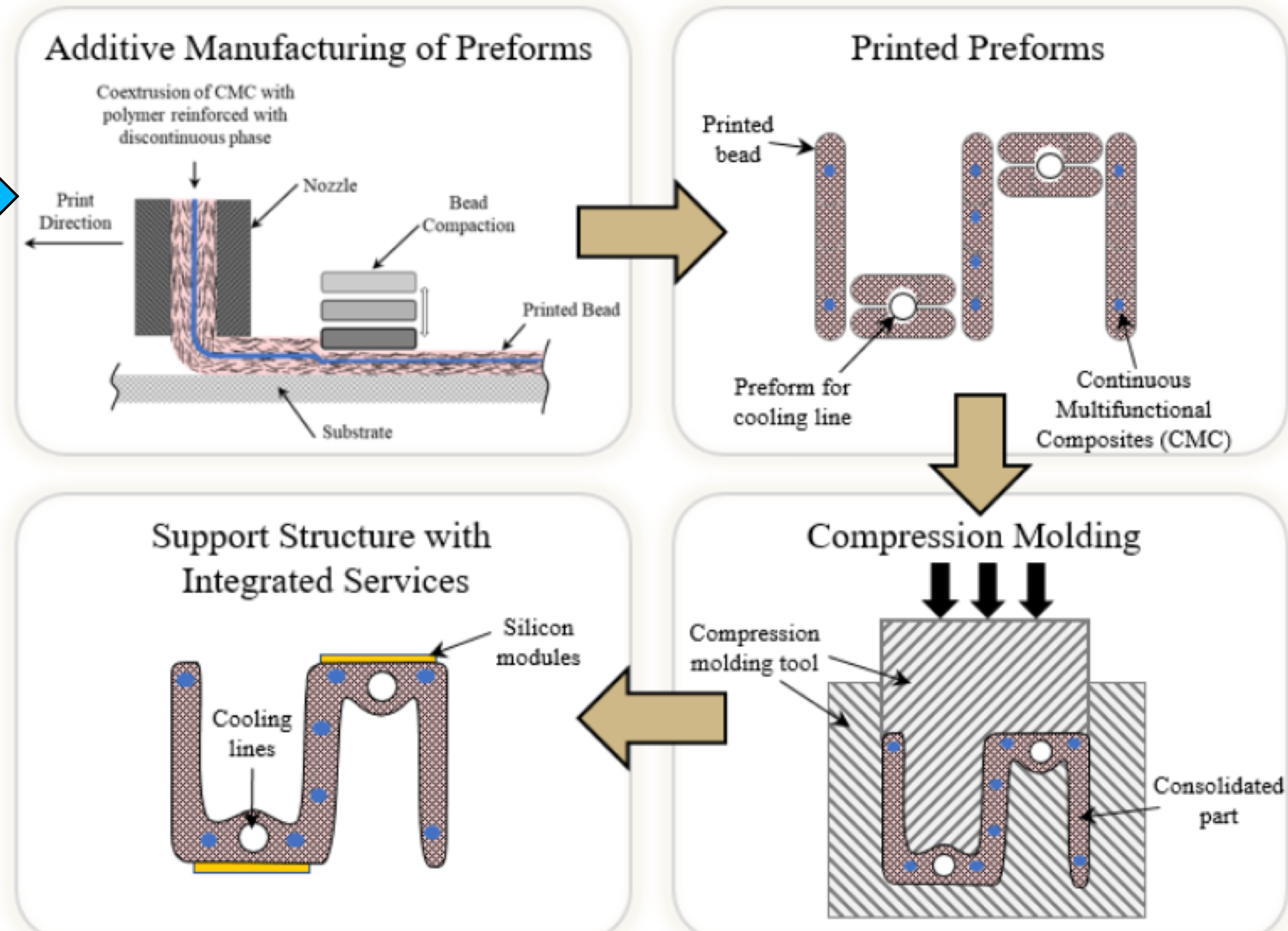


Going into the future of mechanics

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.



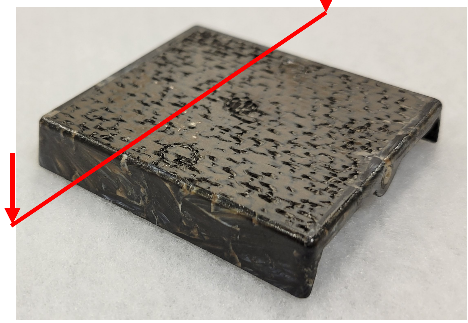


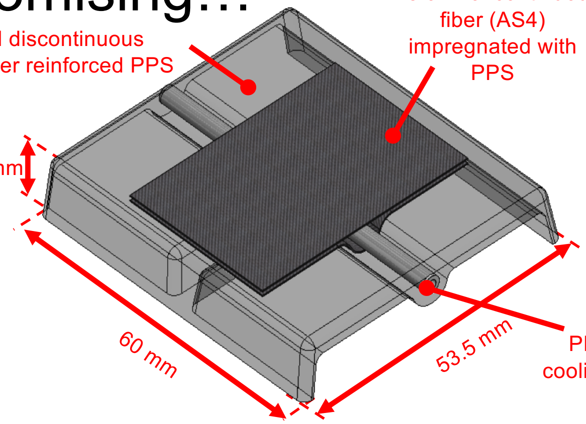
→ Collaboration with material sciences, companies for novel materials, and latest techniques.

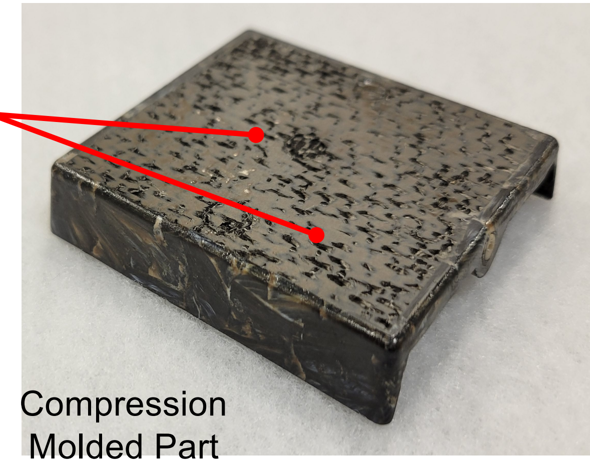
→ Example: Cutting-edge composite manufacturing techniques, in-house

→ **Reduce mass & boost thermal performance**

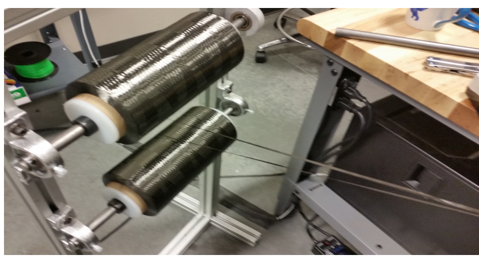
First prototypes look promising…



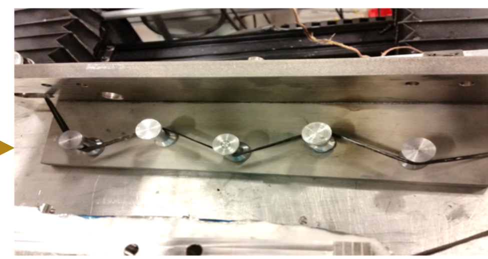




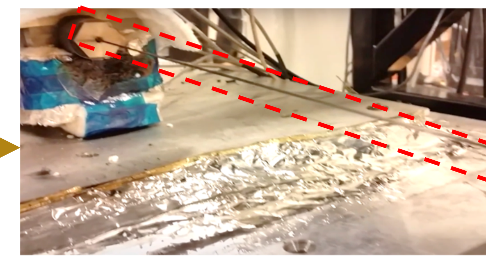
Compression
Molded Part



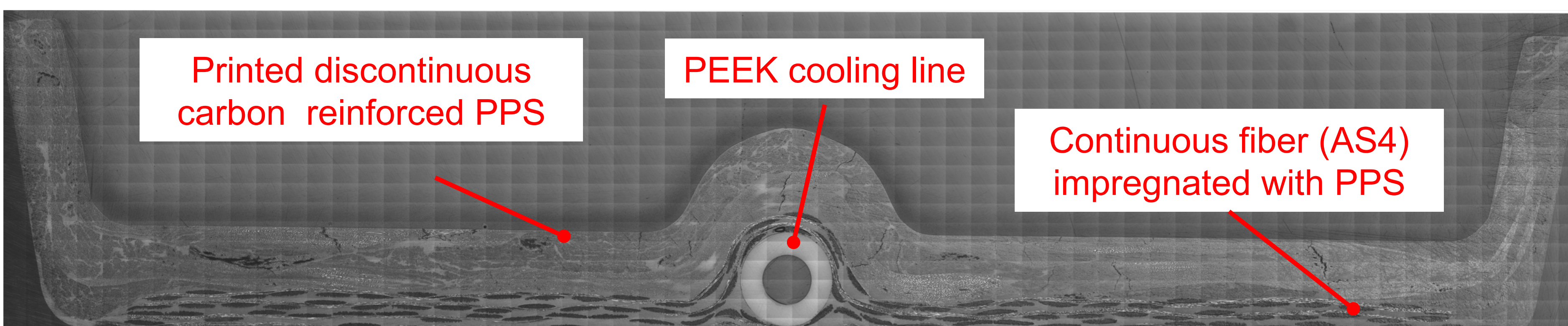
Spools of Carbon Fiber



Interior of Impregnation Chamber

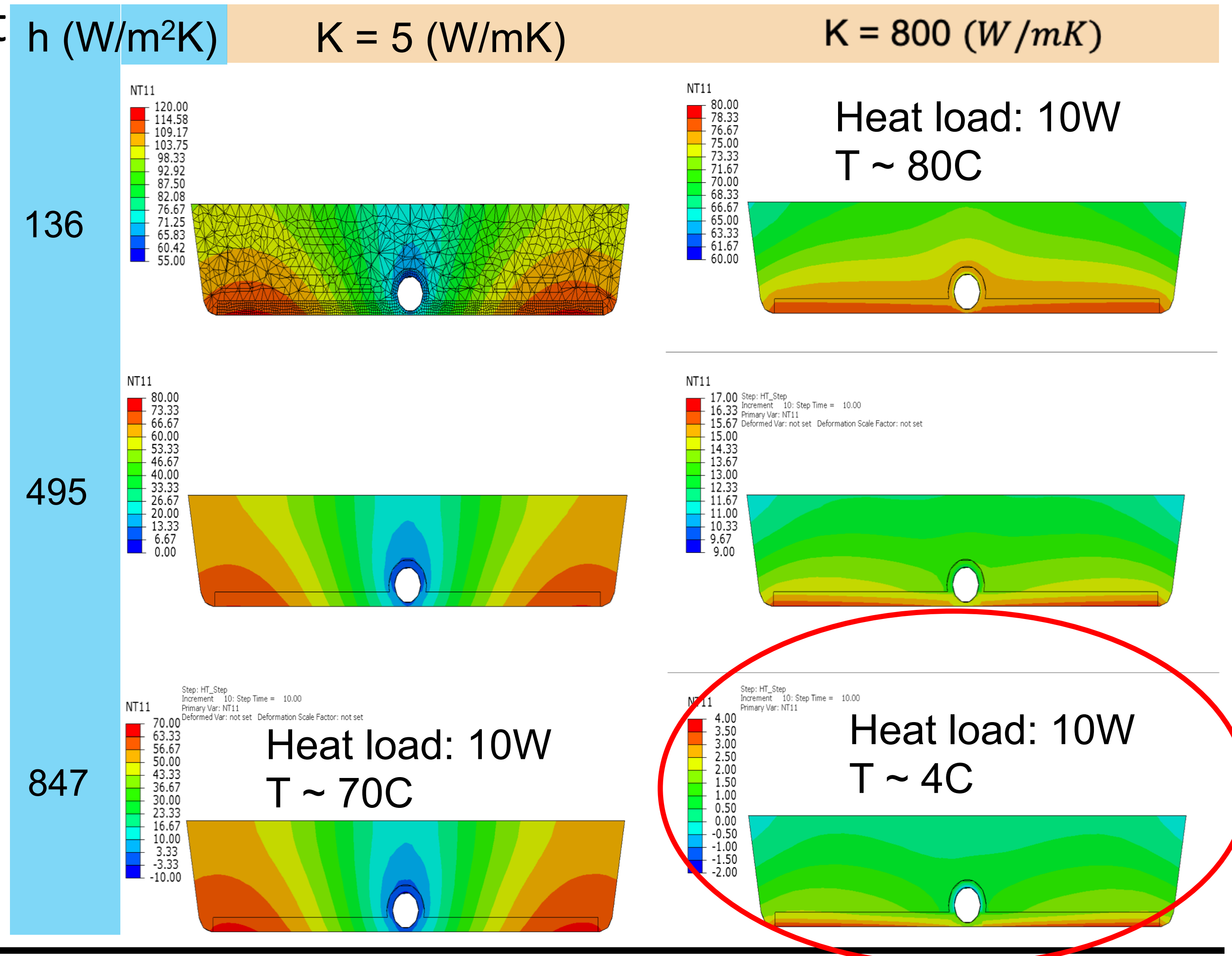


Carbon Fiber
Impregnated with PPS



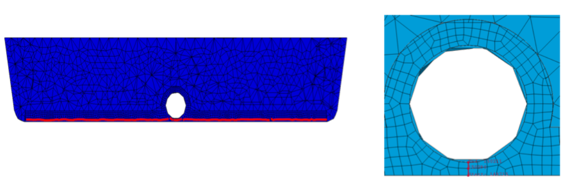
Thermal performance improved compared to state-of-the-art

- Already at a lower mass and can be further reduced…
- Aiming for CO_2 coolant



<u>Detailed FEA studies:</u>

- Similar conditions as for CMS HL-HLC FEAs
- For now: Modeled as an N2 turbulent flow at –20 Celsius with a constant volumetric flow
- Different scenarios for thermal transfer coefficient
- Compare results along continuous fibers and between "pipe" and surface



Mechanics community

Bridge HEP and NP Mechanics ?!

Exchange of ideas & progress across existing collaborations:

- **"CPAD RDC 10": R&D Collaboration for "Detector Mechanics R&D"**
- 9 others, so covers also your favorite topic's
- Signup for emails lists via fnal

https://cpad-dpf.org

Internationally: Forum on Tracking Detector Mechanics

- 11th iteration in 2023: Tuebingen, Germany
- Typically ~80 participants

https://indico.cern.ch/event/1228295/

My own opinions & HEP-biased

- 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.
    - 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

Concluding Remarks…

Carbon Fiber: Gold-standard and versatile material

- Laminates, Compression, join with 3D printing
- Not just structural aspects, continuous carbon fibers mono-filaments can also be used for “drift chamber” wires and reduce mass
- Holistic approach for services, structures and cooling choices

Detector Mechanics R&D

- Improved performance compared to current state-of-the-art solutions
- Applicable also to calorimetry, TOF, other systems
- Snowmass white paper: https://arxiv.org/abs/2203.14347

Concluding Remarks…

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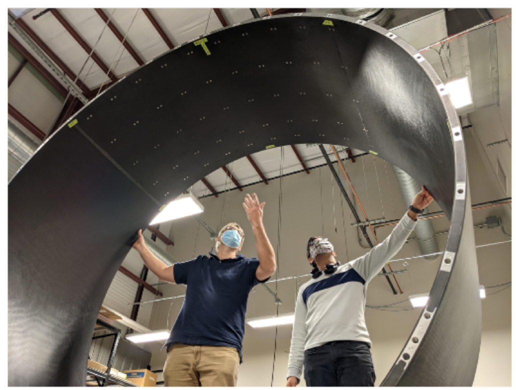
Personal Remarks

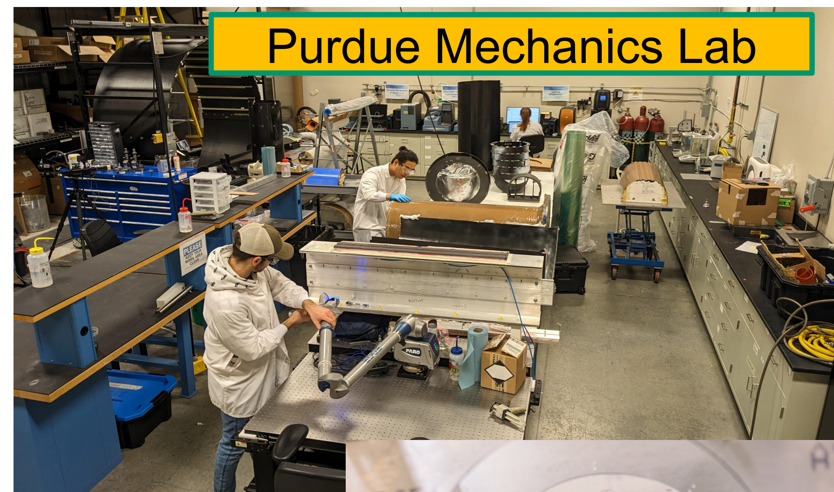
- Design of tracker mechanics has to **start early**
- Any design starts with **defining envelopes**, dictates space constraints and tolerances of structures
- Can significantly **improve detector performance**
- Can "optimize" for future special runs, i.e. shifted vertex

Summary

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

- In-depth study of total mass folded w thermal performance
- Novel ways to reduce the total mass
- Ever near Purdue: Pass by & you'll get a lab tour…





Backup

This research is supported by:

U.S. DEPARTMENT OF ENERGY
Office of Science

PURDUE RESEARCH FOUNDATION

Pixel support structures

Composites Manufacturing & Simulation Center

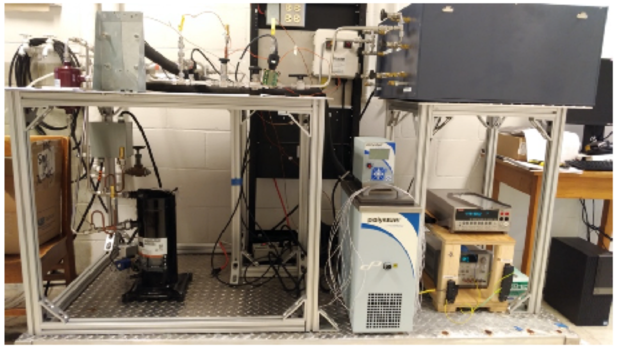
- Composite Manufacturing & Simulation Center (CMSC) at Purdue, completed in summer 2016
  - Purdue Center of Excellence across disciplines: Aeronautics, Chemical Eng, Materials Eng, Aviation Tech, Computer graphics, **and Physics**
  - A. Jung – Associated member of CMSC
- Professional composite experience:
  - 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

Facilities at Purdue: CTRC & PSDL

Composites Manufacturing & Simulation Center

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:

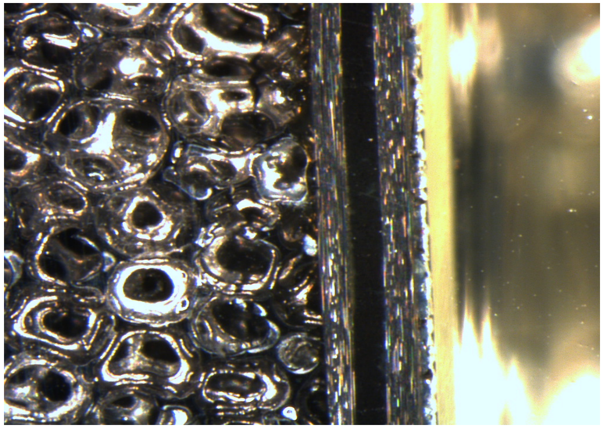
https://engineering.purdue.edu/CTRC/research/index.php

PSDL-CTRC Collaboration on:
- Various aspects of thermal management relevant for the applications at future collider
- Cooling box setup for thermal tests

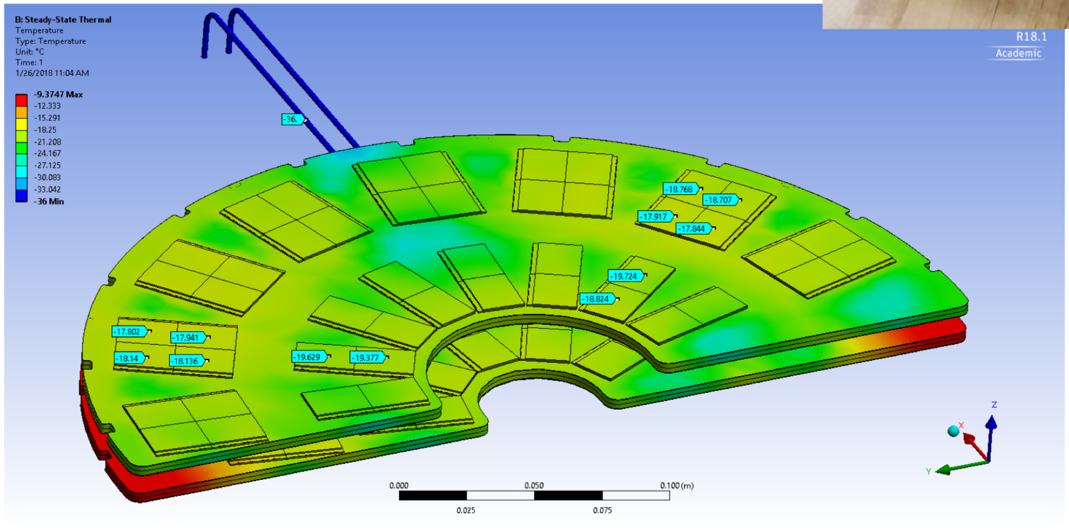
Pixel support structures

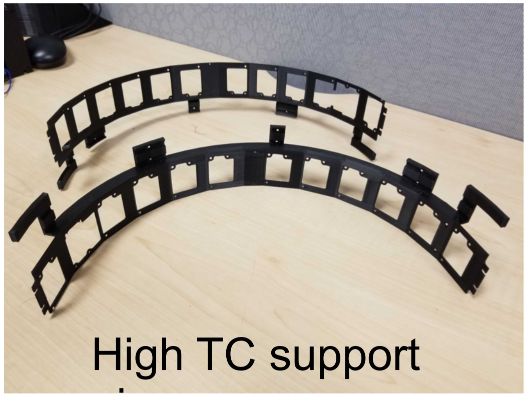
→ Disc-like support structures made from Carbon Foam & Fiber
→ FEAs use TC measurements as inputs
→ Capable of cooling all ~1800 pixel modules
→ Carbon is light-weight, and strong

1st half dee prototype, Cornell University



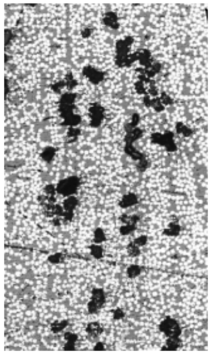
Carbon foam
3-ply skin





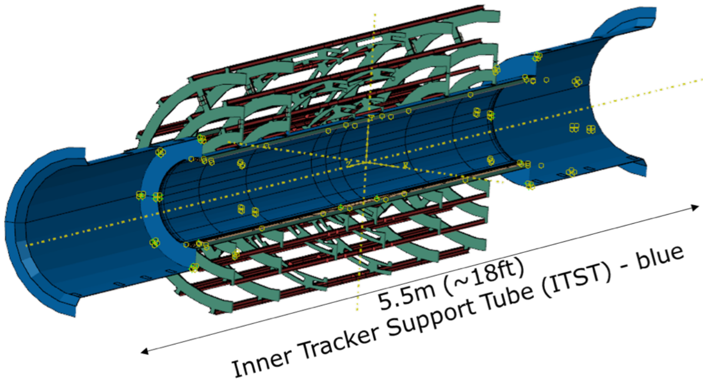
High TC support pieces

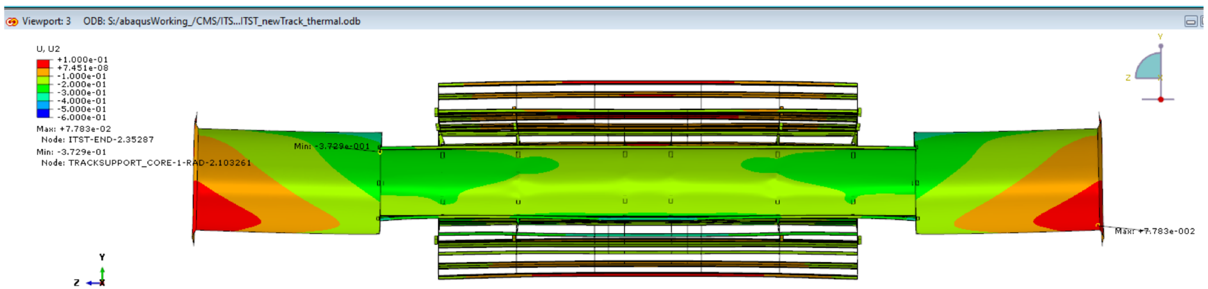
Bad laminate



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
- Minimize material budgets and optimize thermal performance





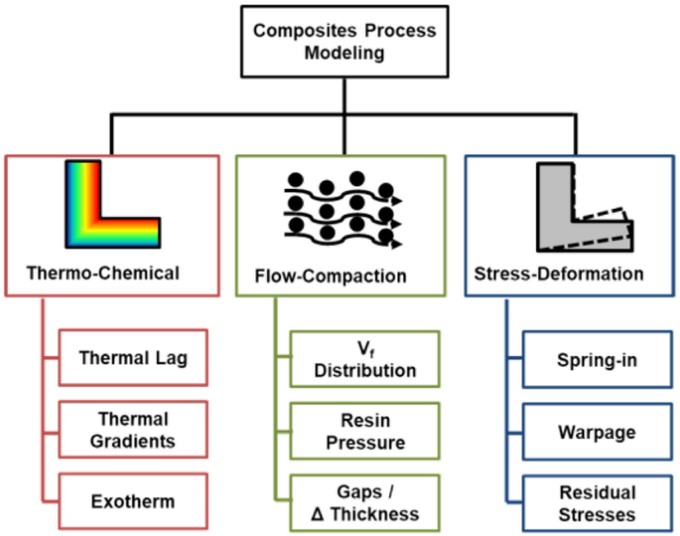
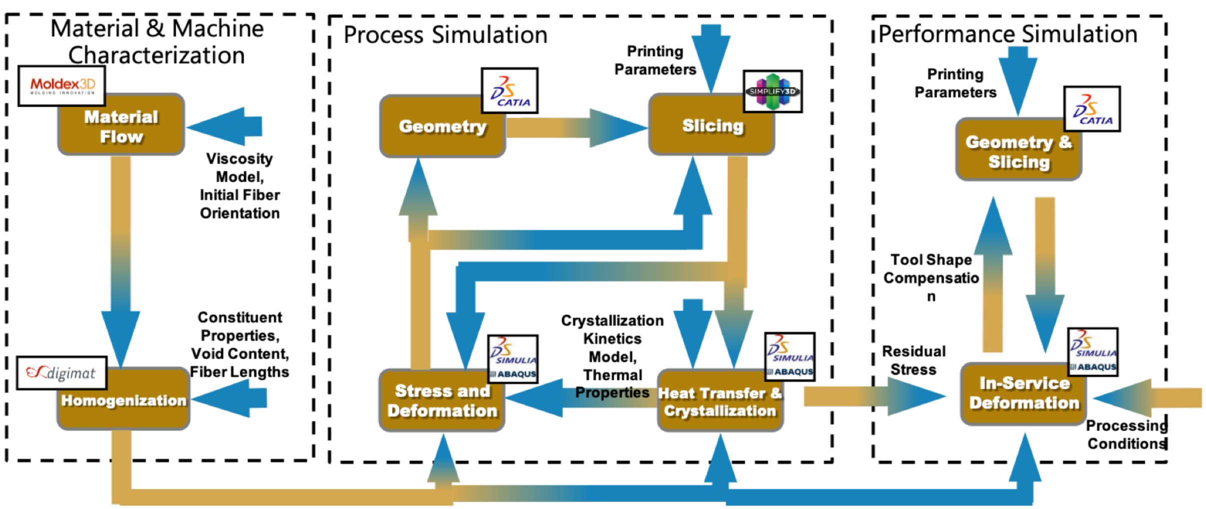
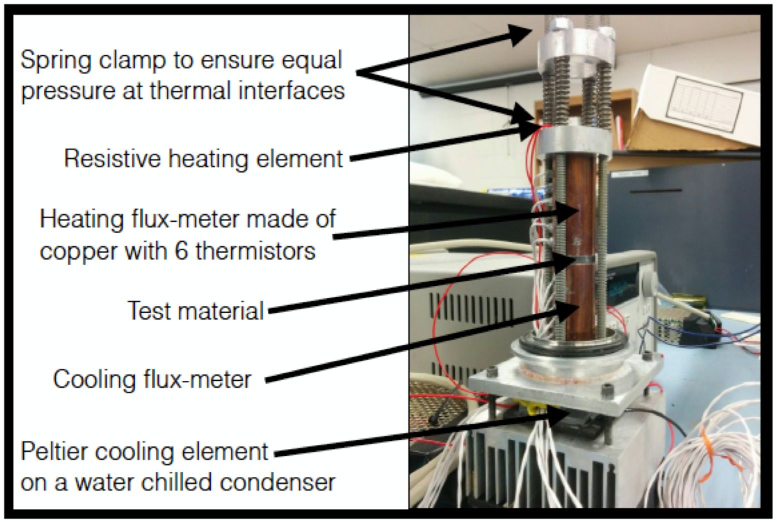


Figure 1-1 Composites process modeling problem types

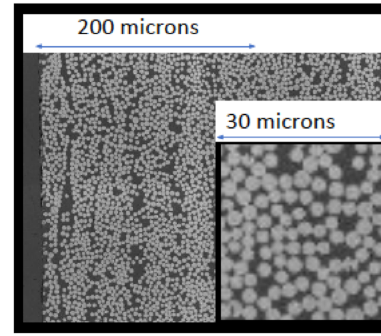


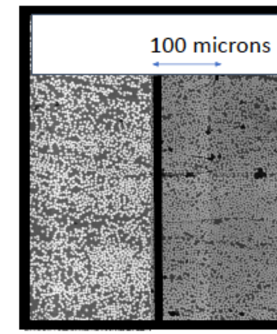
Thermal conductivities

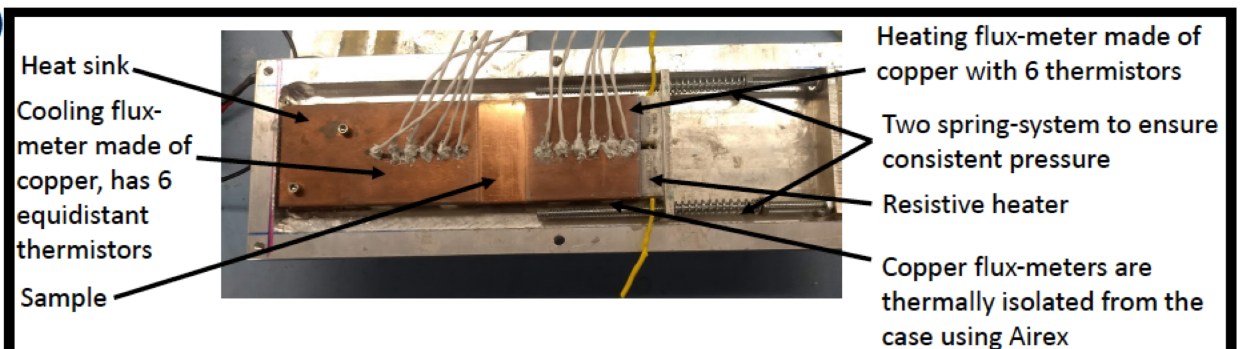
→ UG student driven activities, low-cost but precise
→ High pressure curing to boost TC, factor 2 improvement
→ Additional fillers to boost TC while maintaining mechanical strength
→ Method & Results to be submitted to JINST soon…



→ 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]