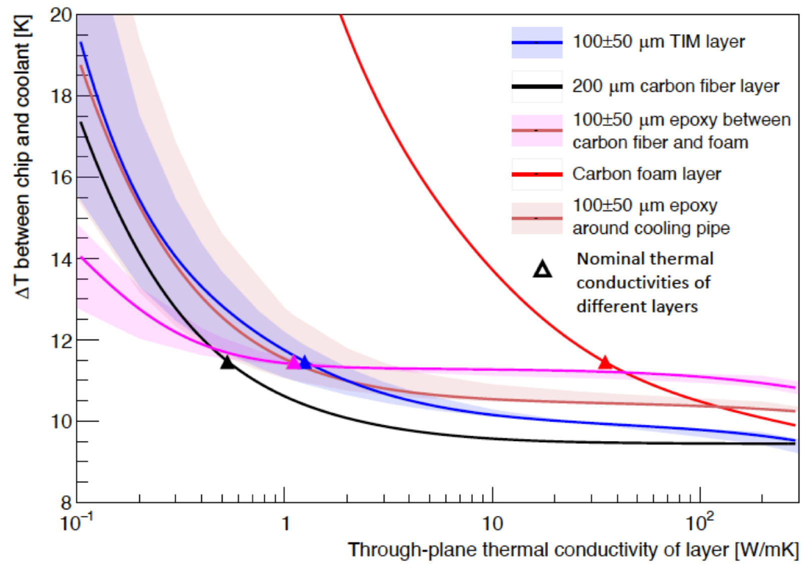
Light-weight minimal mass tracking detectors: active & passive

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



Andy Jung

Purdue team members: E. B. Vaca, S. Karmarkar and

UG students: Ben Pulver, Ian Holda, Morgan Shoop

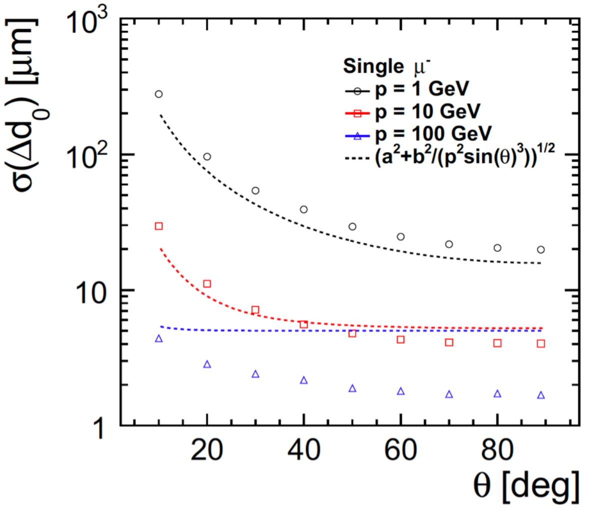
BNL Seminar

My own biased view

March 28th, 2024

The challenge…

- ee experiment target track p_T and impact parameter resolutions of ≃ 1/5 LHC
  - → $\sigma(p_T)/p_T^2 \simeq 3 \times 10^{-5}$ GeV^{-1} (p ≤ 100 GeV)
  - → $\sigma(d_0)/d_0 \simeq$ 2 / 3-5 / 10 - 20 μm (100/10/1 GeV at 90°)
- R&D challenge
  - → ≃ 3 μm hit resolution with ≃ 0.2 % X_0 per layer (low multiple scattering) in pixel vertex detector
  - → Low power (no power pulsing); readout electronics integrate over < O(1 μs)
  - → New paradigm for stability/alignment/calibration due to immense statistics
- Starting point concepts: CLD and IDEA
  - → Typical quoted performance numbers for impact parameter resolution:



Impact parameter resolution:

$$\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}\theta}$$

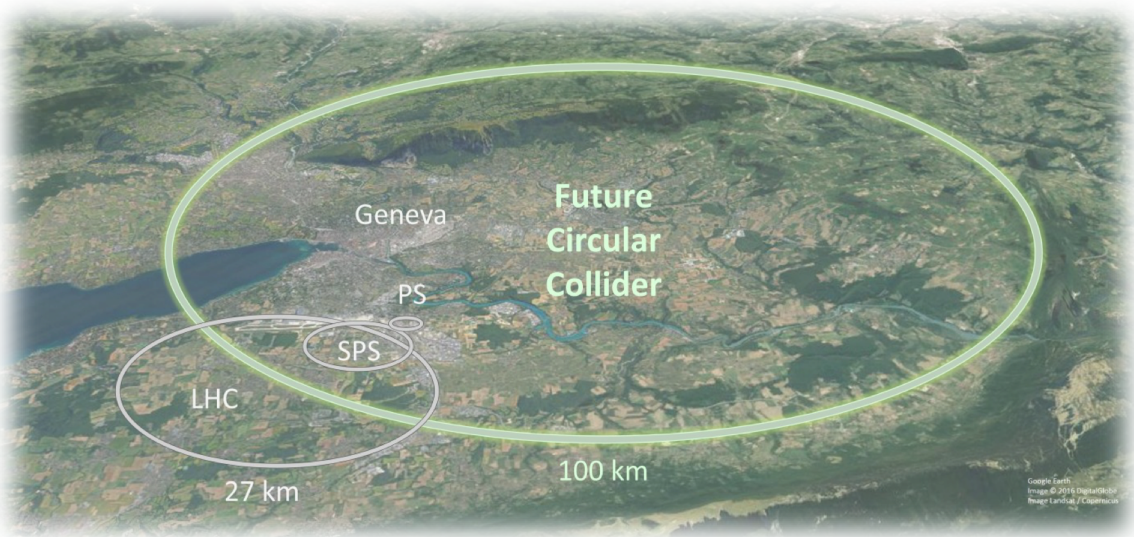
CLD: a ≃ 2 μm; b ≃ 20 μm

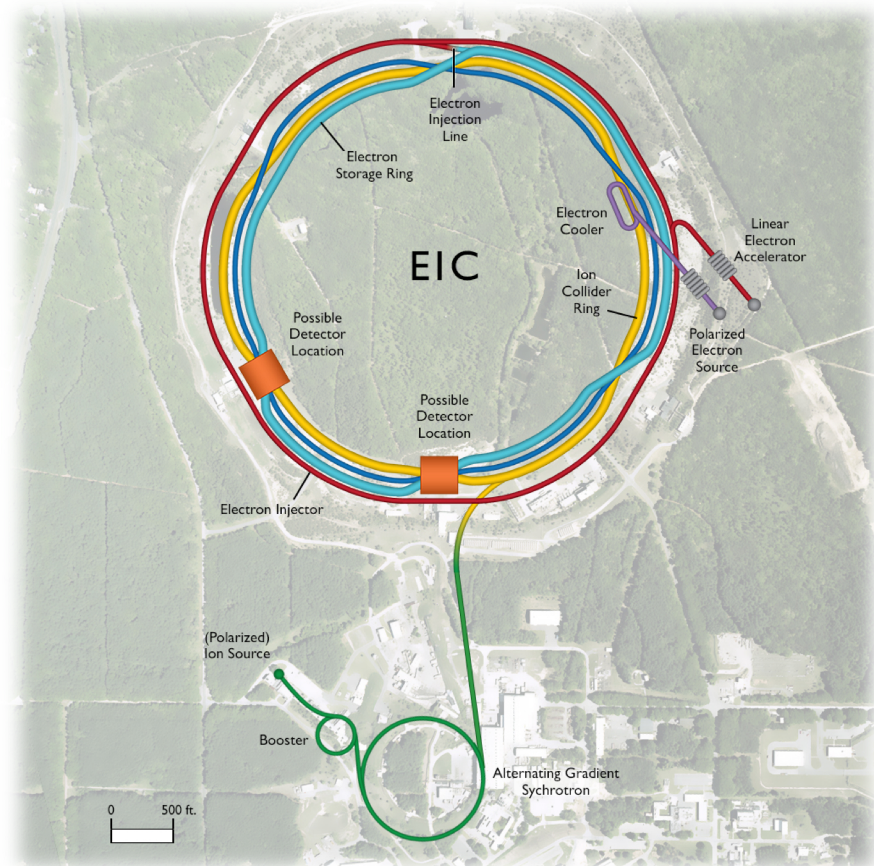
IDEA: a ≃ 2 μm; b ≃ 15 μm

ILD: a ≃ 5 μm; b ≃ 15 μm

Many avenues possible

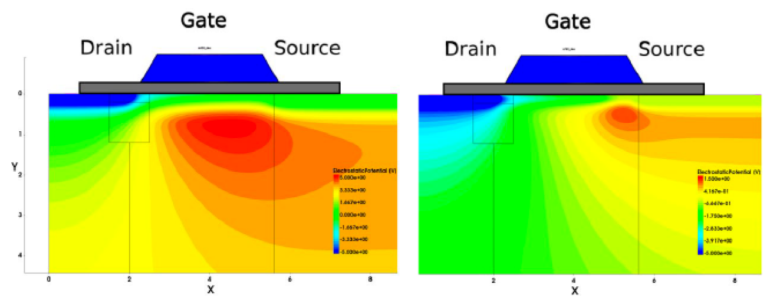
- Low mass detectors
- Low mass structures
- Dual use structures
- …

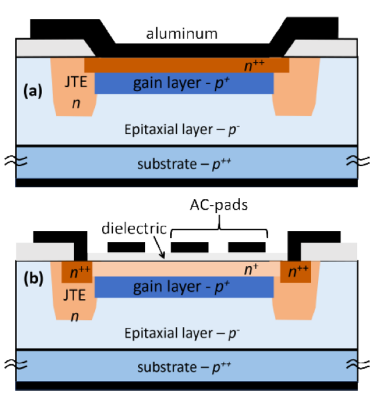




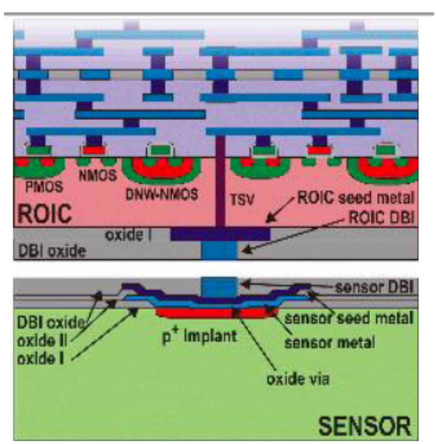
Strong ties to Foundries, allows…

- Manipulation of the CMOS process to boost technology
  - Uniform epitaxial layers → speed & radiation hardness
  - Usage of larger wafers & stitching
  - 65nm technology: charge collection properties uncertain with thinner epitaxial layers
- DEPFET improvements: Better drain implants
- 3d integration (not 3D technology)
- LGADs and inverted LGADs
  - Smaller pixel possible but lots of power for time resolution → cooling ? mass ?

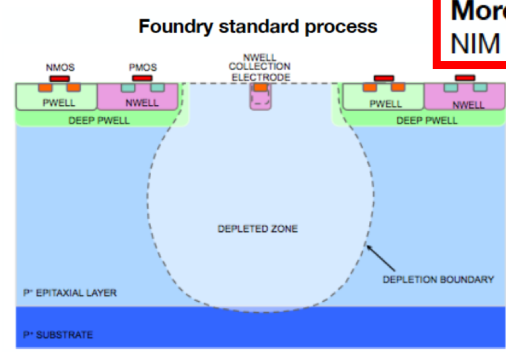




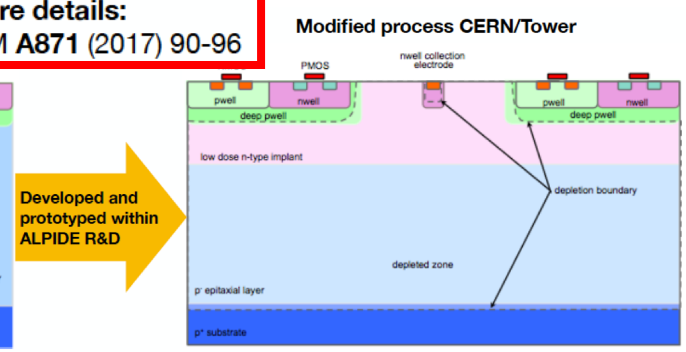
Gabriele Giacomini et al



More details:
NIM **A871** (2017) 90-96



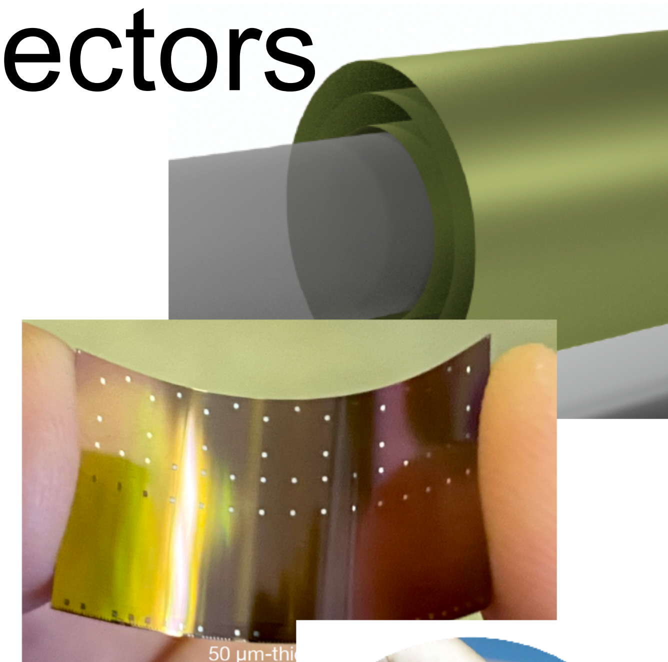
Partially depleted epitaxial layer
Charge collection time < 30 ns
Operational up to 10^{14} 1 MeV n_{eq}/cm^2



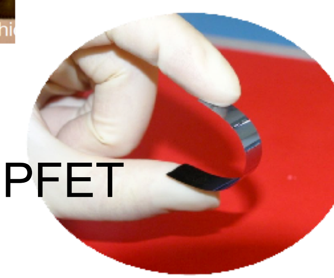
Fully depleted epitaxial layer
Charge collection time < 1 ns
Operational up to 10^{15} 1 MeV n_{eq}/cm^2

M.Mager, L. Andricek

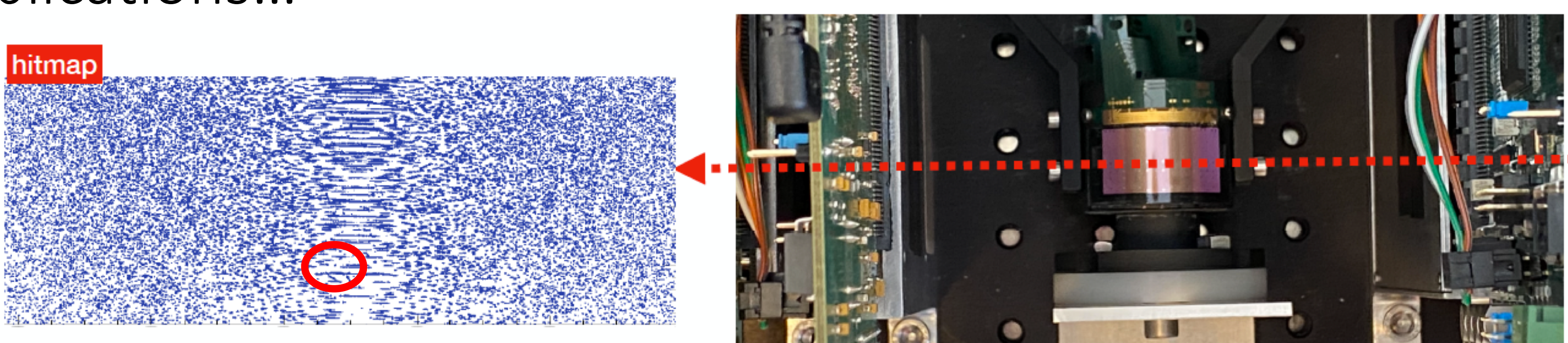
Very thin silicon detectors



- Bent ALPIDE (M. Mager) and the “golden detector” (ITS3)
- ALPIDE: amazing test beam results
  - Challenges remain, bending influences electric parameter
- DEPFETs are also bendable (L. Andricek)
- Allows very minimalistic support structures, i.e. almost “none”
- EPIC applications…

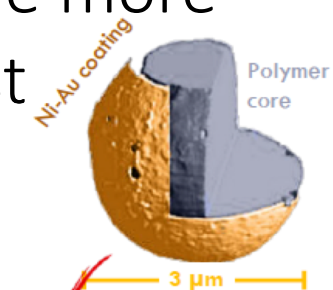


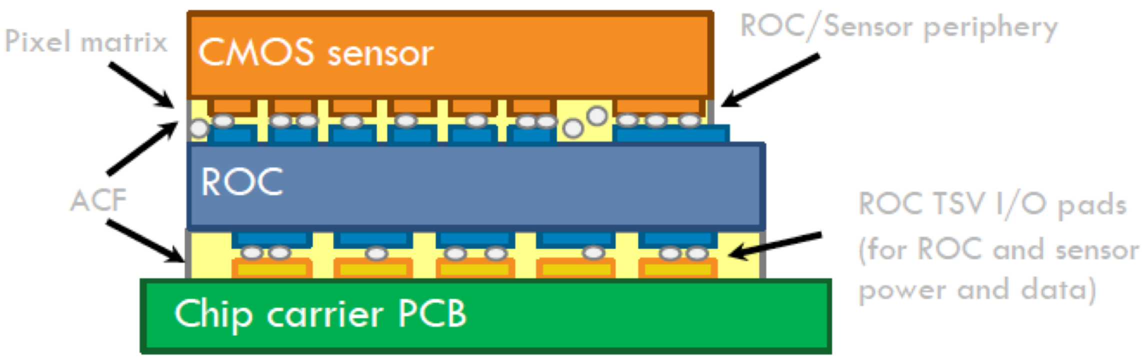
DEPFET

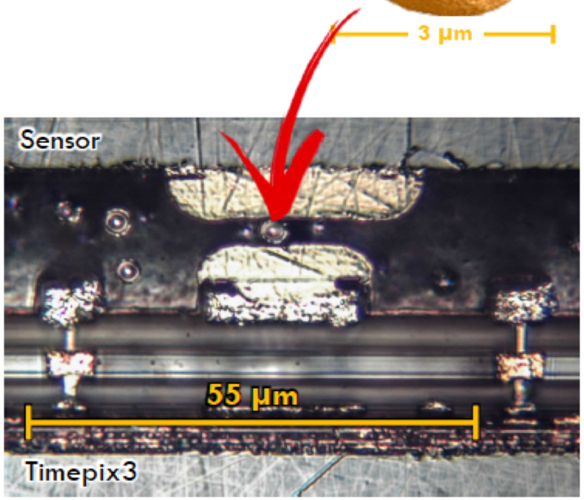


Hybridization

- While MAPS/CMOS is perfect for innermost layers, the more "classic" hybrid detectors still an option for outermost
  - Bonding forces doable, but yield remains low for now
  - Very small bond layers, almost like 3D integration…





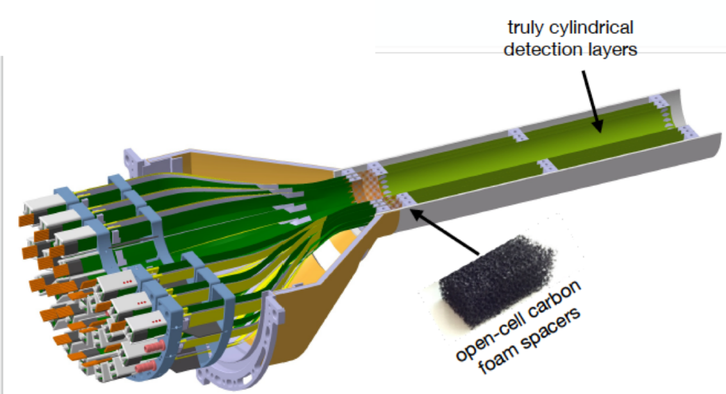


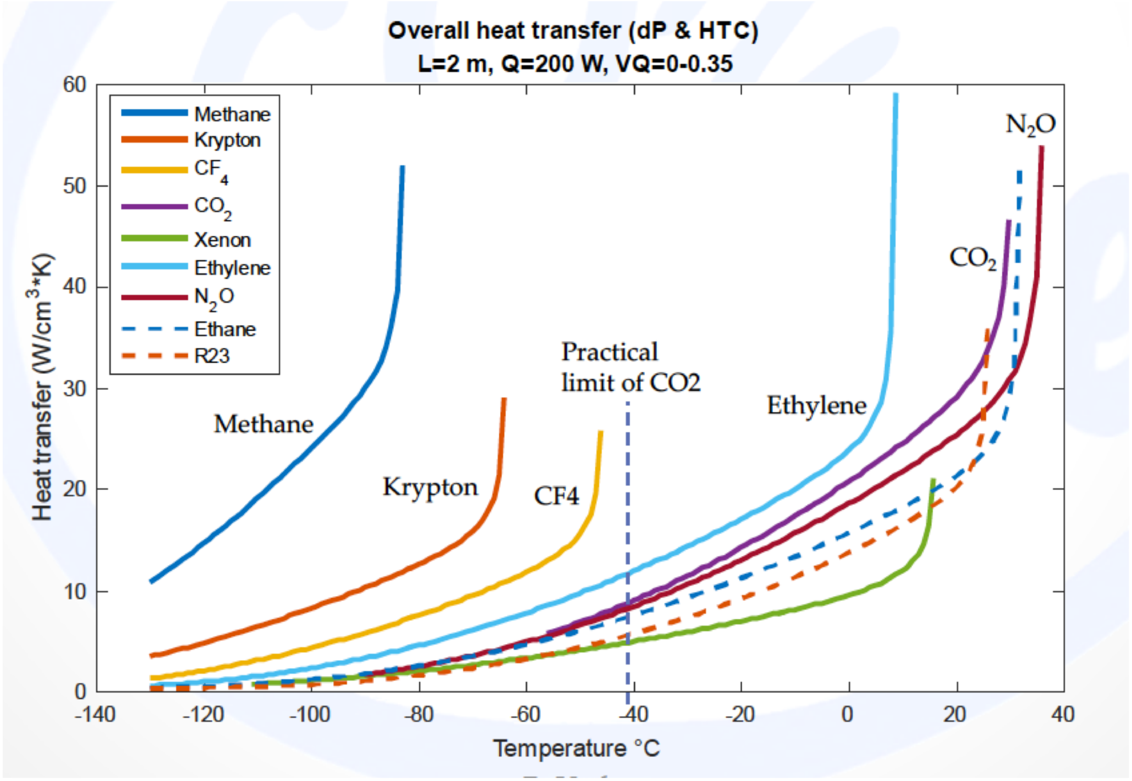
- Can this technology be a solution for interconnecting the ends of ALPIDE ladders?

Cooling & support structures

- Reached the limit for cold CO_2 technology
- Further improvement if power densities require it:
  - Super-critical krypton cooling (around -60C)

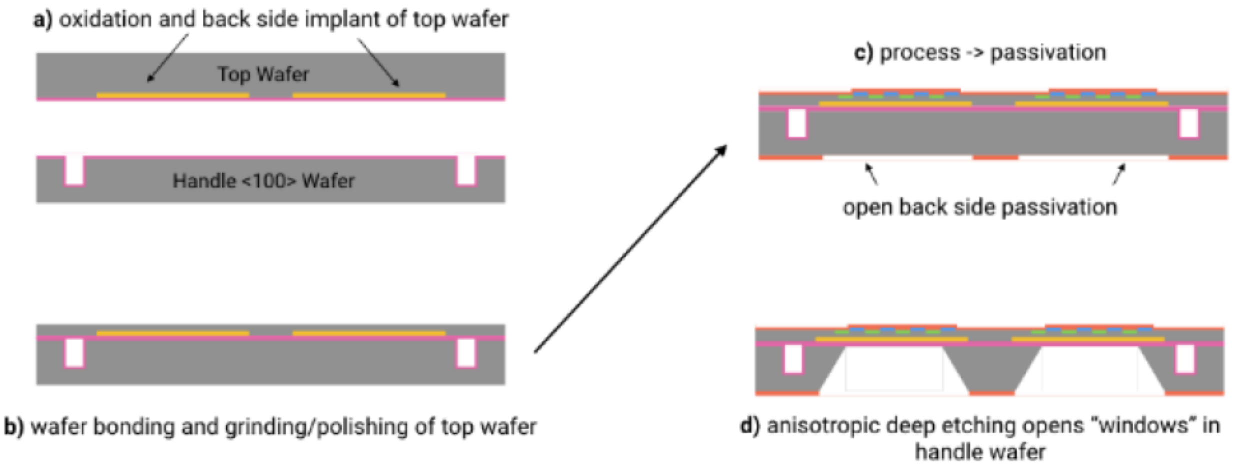
- …but air cooling the "weapon of choice" as long as power densities are low enough
- Little to no support mass needed, example ALICE ITS3
- Can we dream ? 1st layer of vertex detector into beam pipe
- Beam current shield vs. beam pipe mass

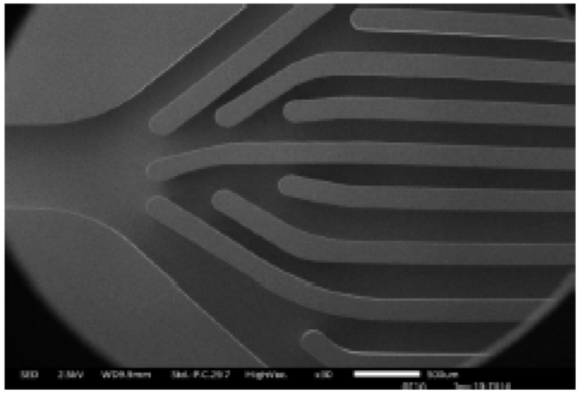


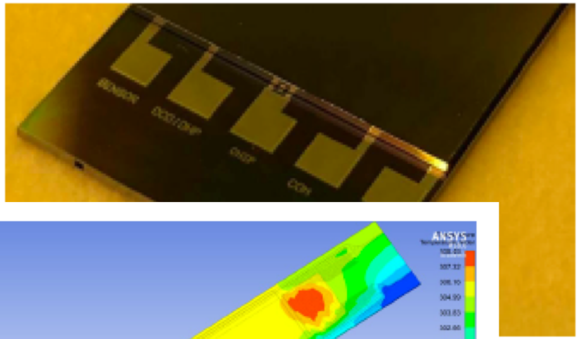


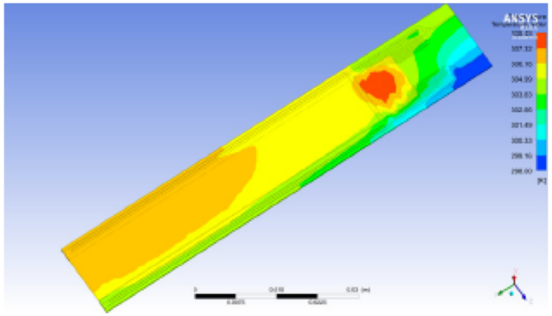
Micro-channel cooling

- Microchannel cooling is established to perform as expected by LHCb, now possible to consider for others







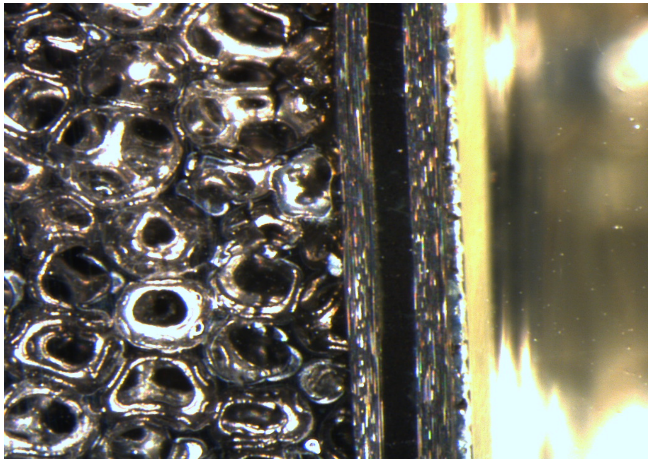


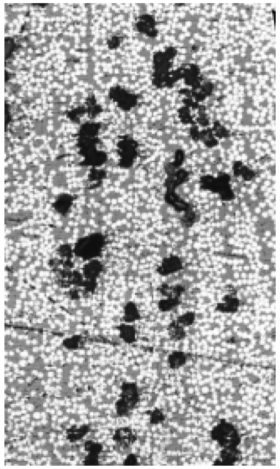
Cavity SOI process: can be adapted to any traditional silicon detector

Silicon on insulator (*SOI*) technology is fabrication of *silicon semiconductor* devices in a layered *silicon*–insulator–*silicon*

What about supports ?

- Carbon Fiber is THE material of choice for structures
- Highly thermally conductive
- Extremely strong, e.g. support 10x self-weight
    - 500kg structure for 5 tons (CMS BTST)
    - 3 kg structure for 30 kg pixel detector
    - Minimal mass





Future colliders (FCC like)

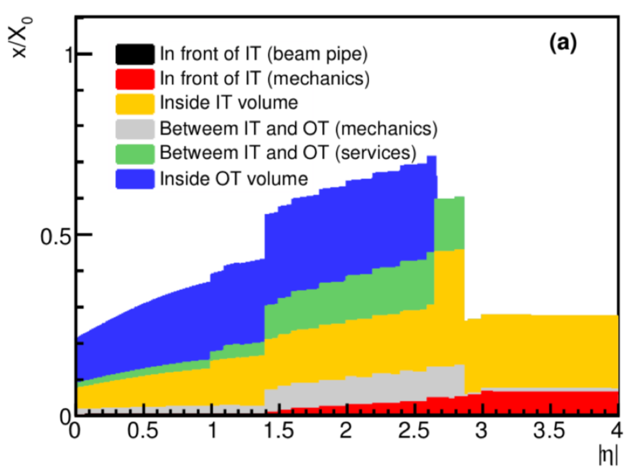
High-luminosity phase of the LHC as example in this talk, but future colliders

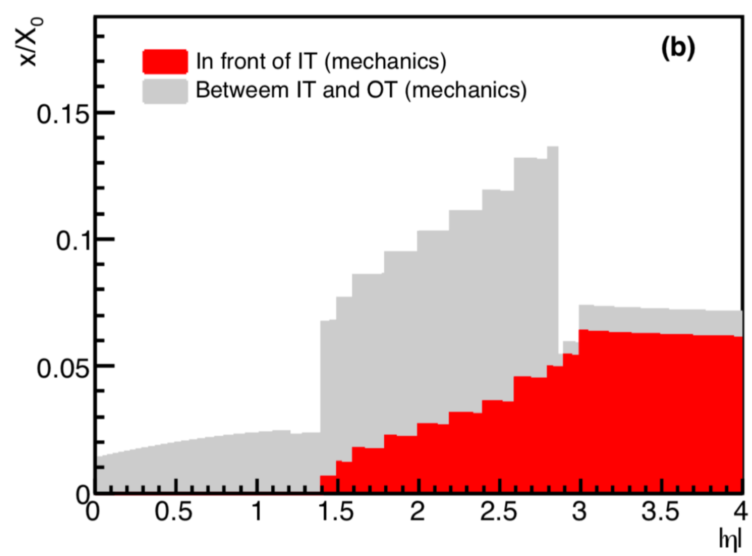
- Larger angular coverages extend into forward directions
- Challenging for forward tracking/detectors
- Pile-up of a thousand results in very harsh conditions (@FCC-hh)

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



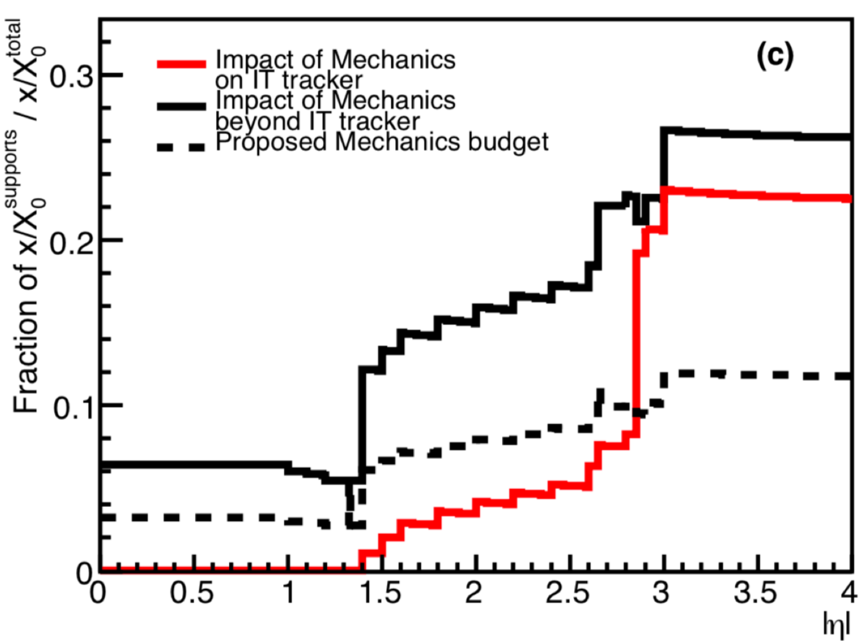


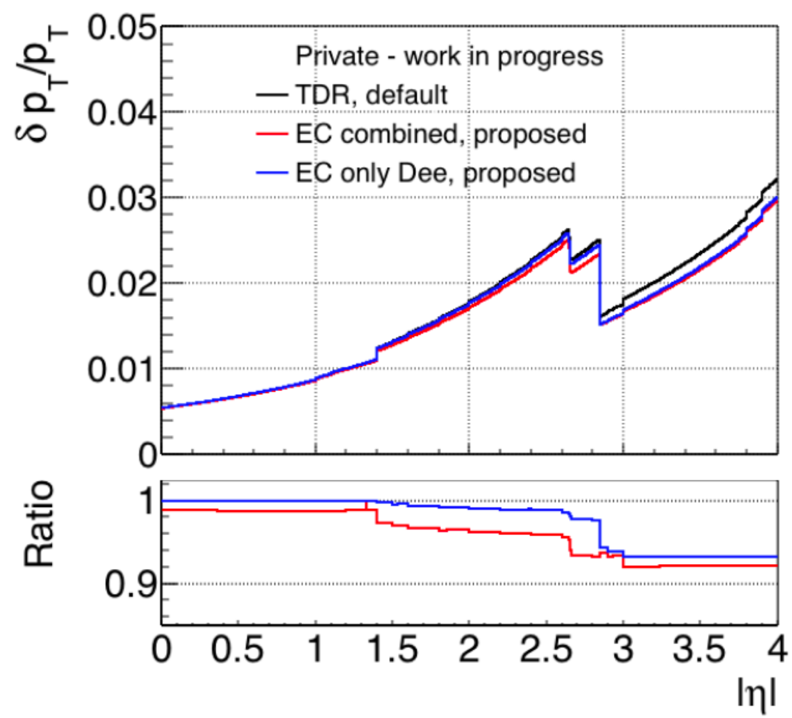
Material budgets & mechanics

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
- **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

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Are we harvesting all physics and performance out of great instruments to unravel mysteries of nature ?

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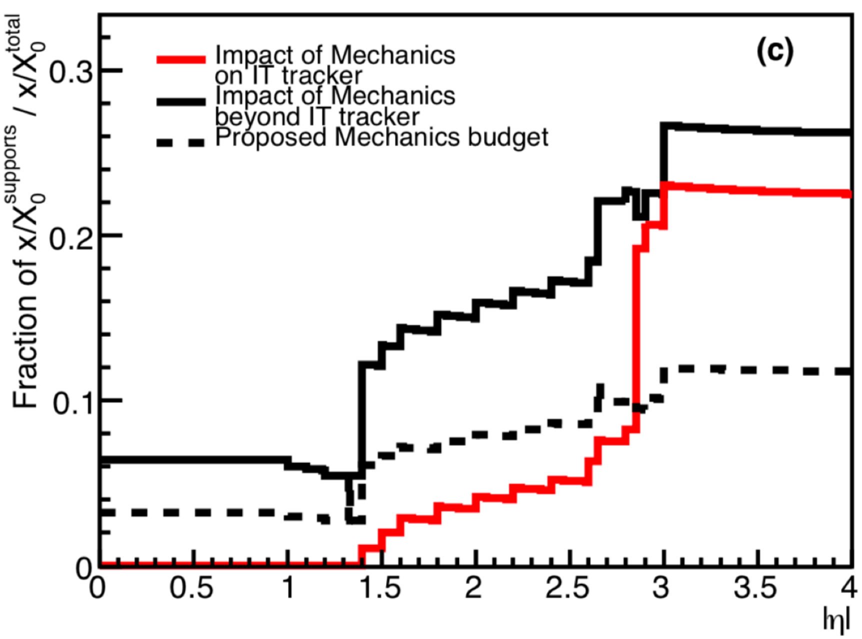

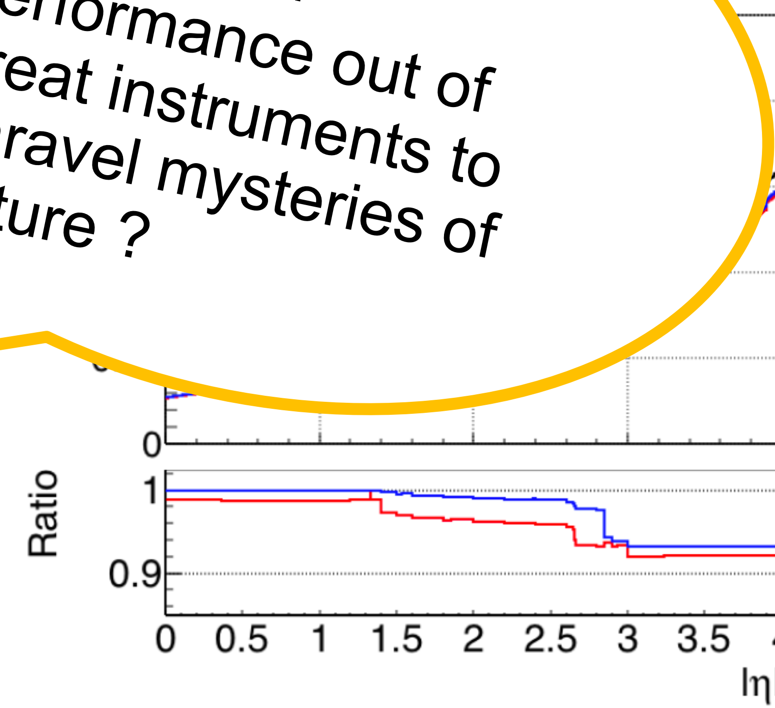

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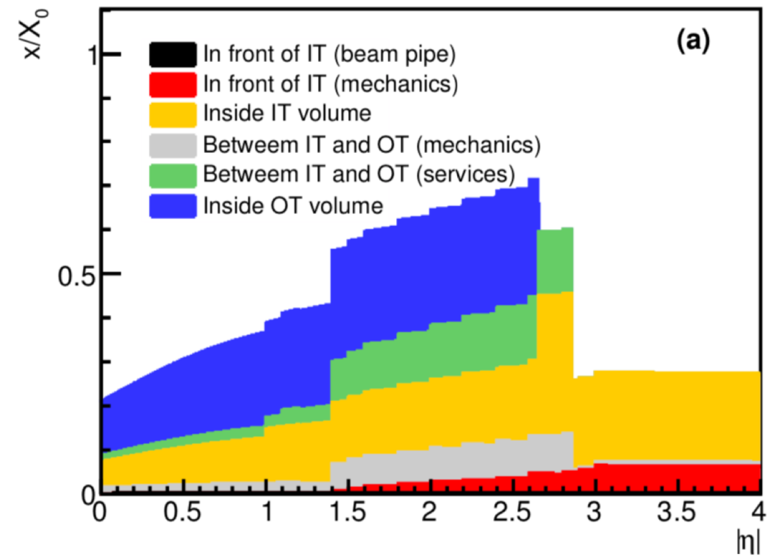
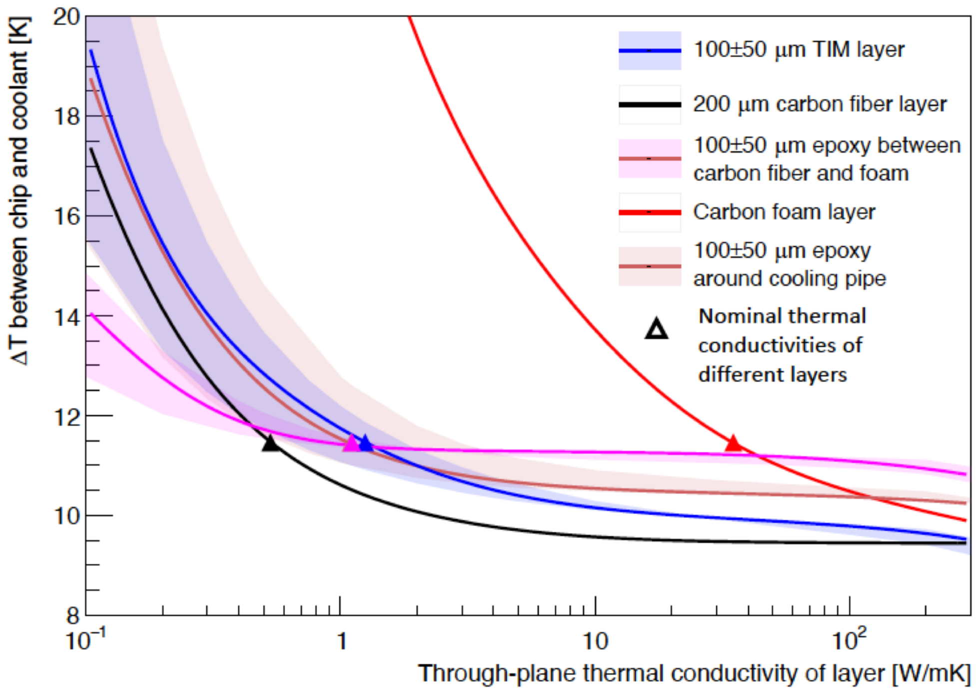
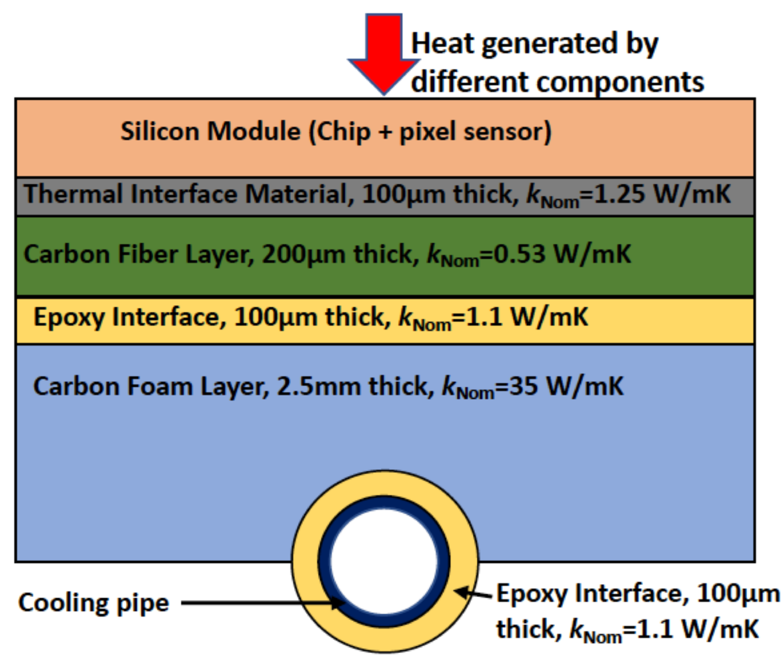
Impact of tracker mechanics…

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







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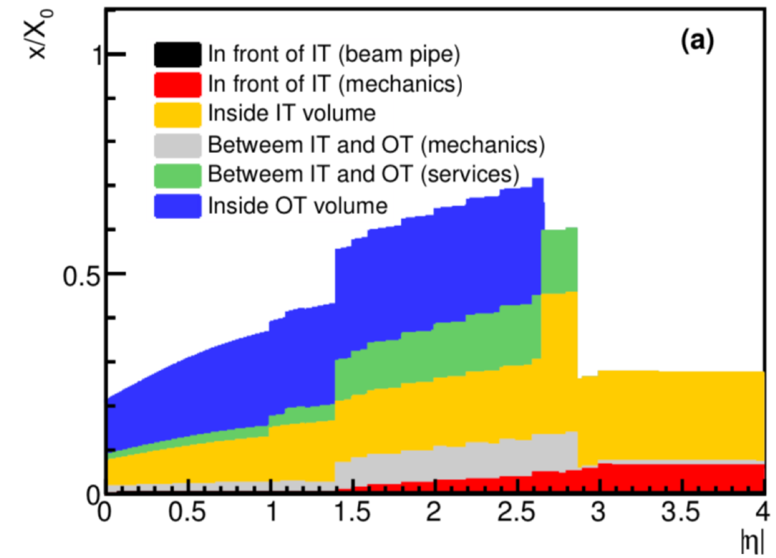
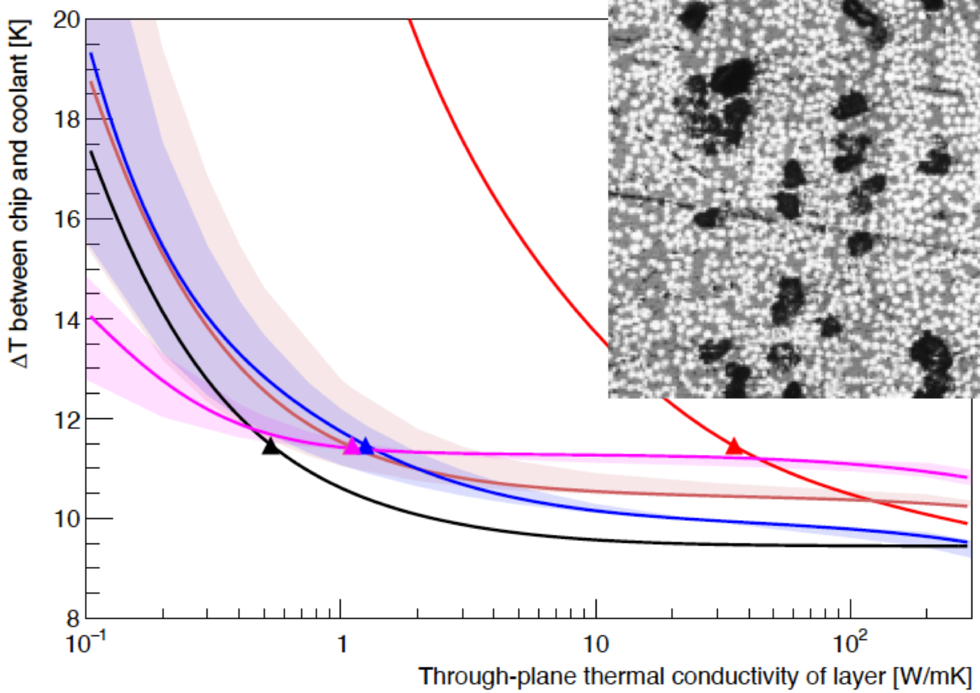
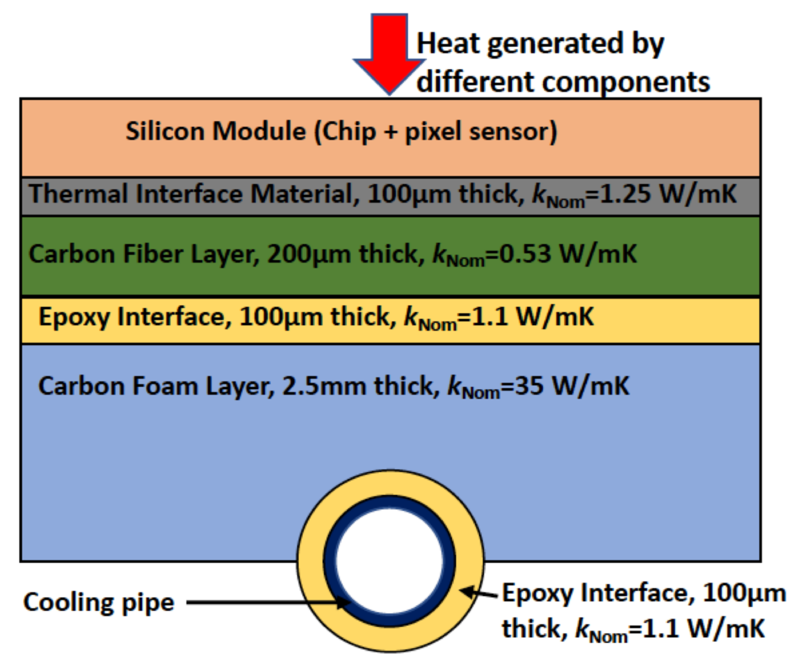






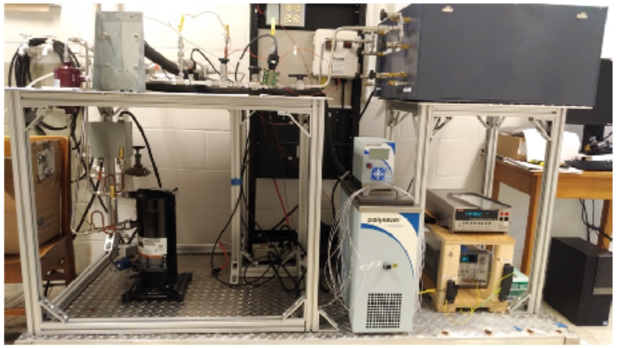
The facilities at Purdue: CMSC

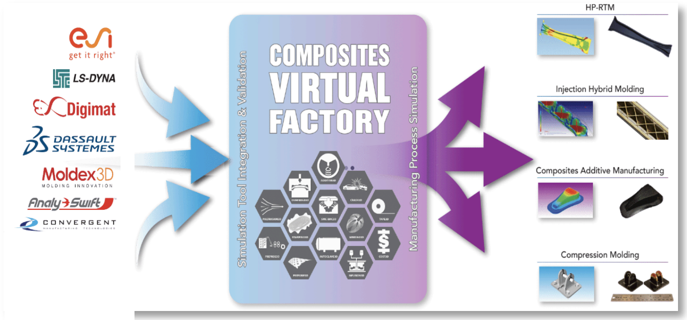
Completed in summer 2016:

- 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

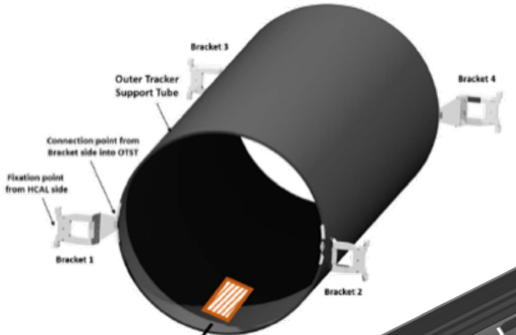


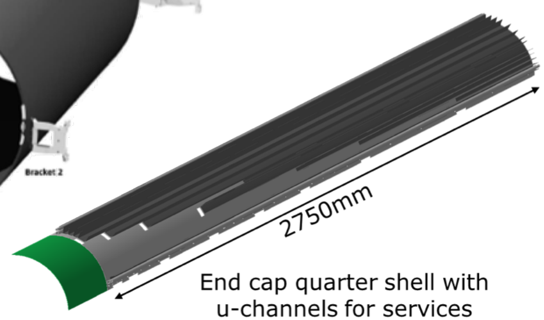


Supporting technologies

- Technical cost modeling
- Big data - AI

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

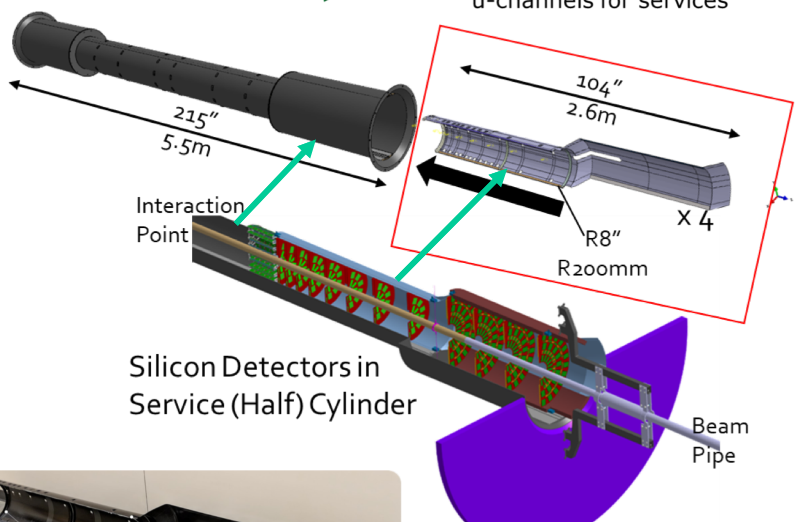




Advanced Mechanics & Composites activities at Purdue

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)

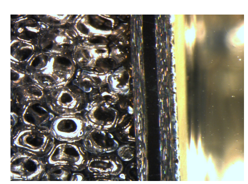


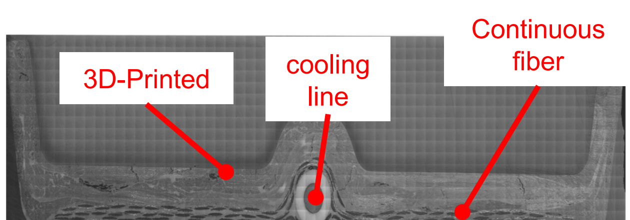
Small Structures – extremely flat and thin

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)





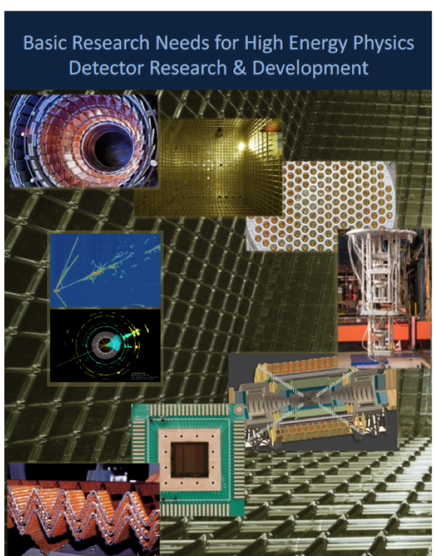
Future Mechanics and R&D:

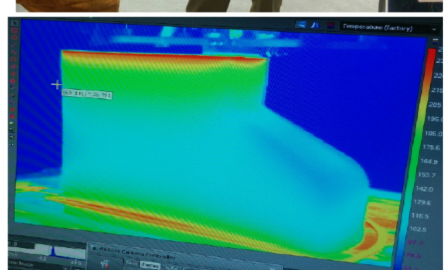
1. "BlueSky Mechanics" for detectors at future Colliders (FCC, muon, LC, etc.) https://arxiv.org/abs/2203.14347
2. "CalVision" project for mechanics of dual readout calorimetry https://arxiv.org/abs/2203.04312

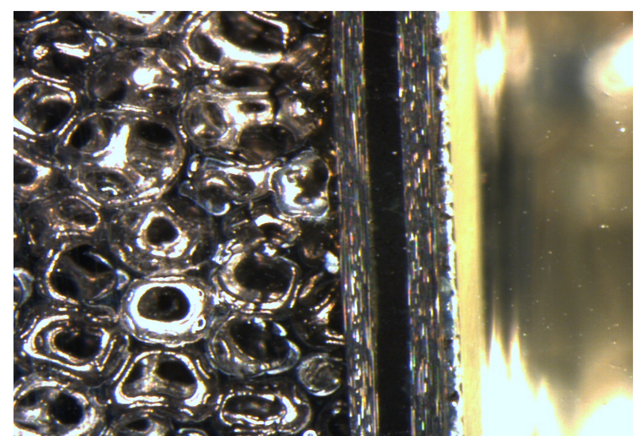
Future R&D work

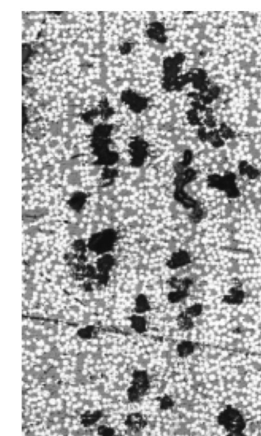
- R&D efforts on low-mass support structures with integrated services for silicon detector systems
- Targeting the Basic Research Needs for HEP by DOE topic of “Realize scalable irreducible-mass trackers”, thrust 2 on low mass detector system.
- Leverage current activities on high-TC, accurate predictive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





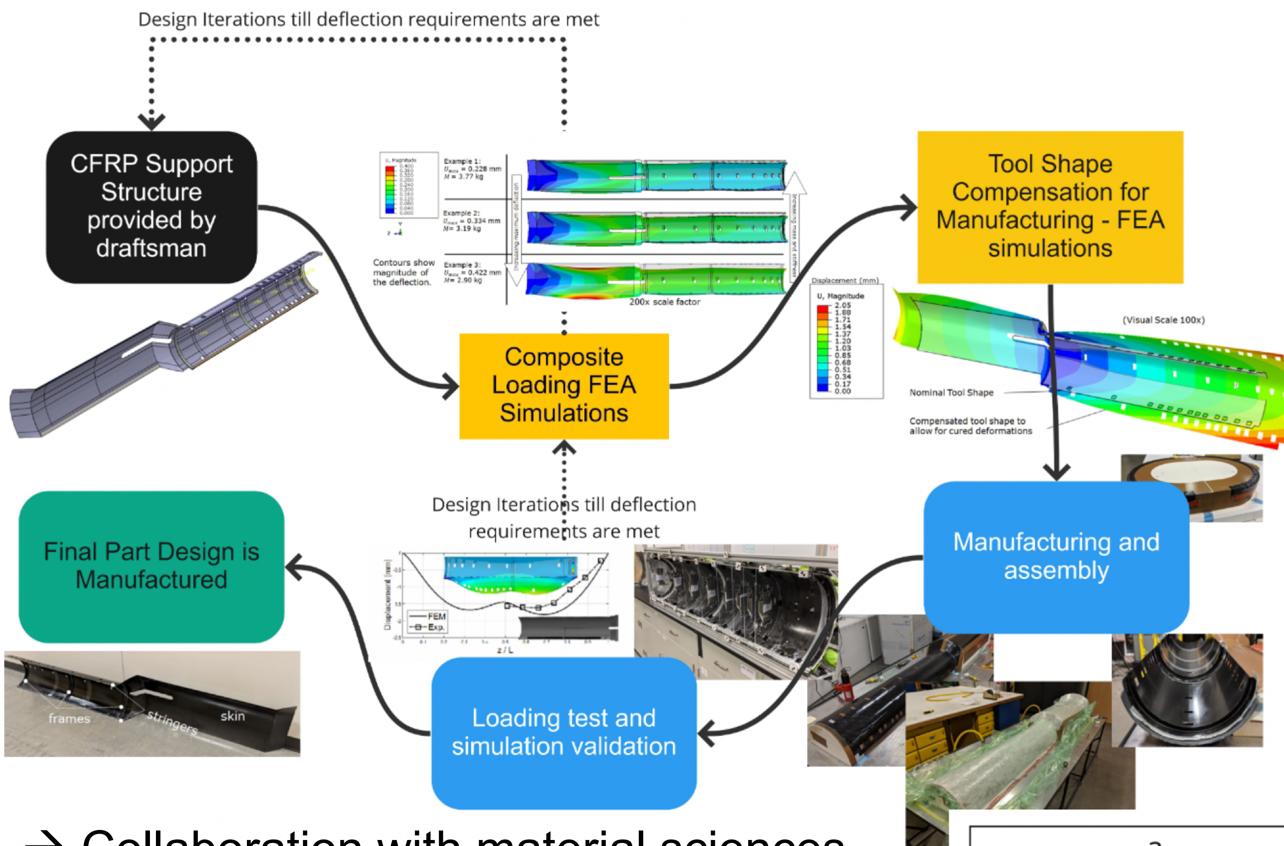




Going into the future of mechanics

Composites Manufacturing & Simulation Center

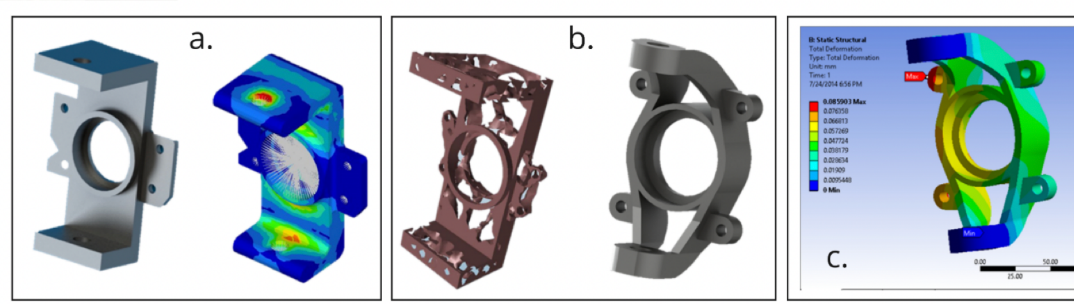
→ Scalable mechanics structures: multi-functional & mass optimized
→ Ease integration, applies also to calorimetry, TOF, etc.



Full cycle of Process & Performance simulation:

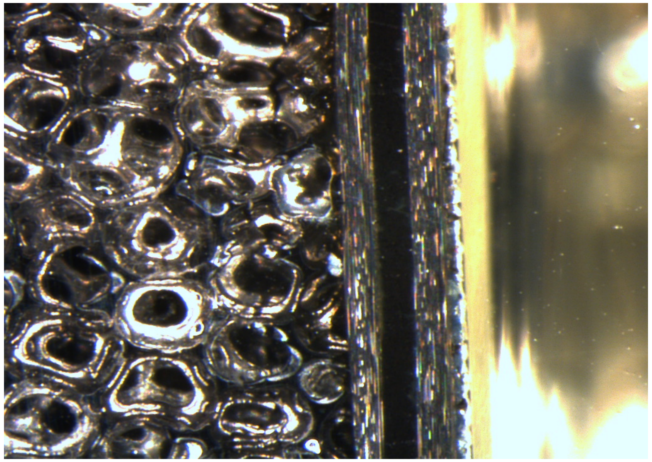
→ FEA, prototypes, iterative process.
→ Consistent approach to better controlled manufacturing process, eases assembly.
→ Especially true the larger the structures become, integration is a "challenge"

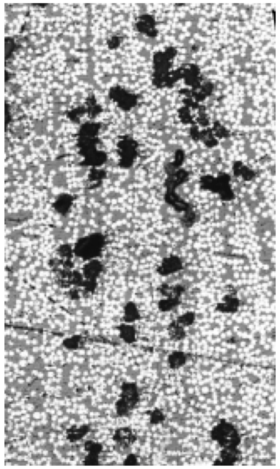
→ Collaboration with material sciences, companies for novel materials, and latest techniques.
→ Example: ML for optimization with HEP inputs, **excites future generation**



What about supports ?

- Carbon Fiber is THE material of choice for structures
- Highly thermally conductive
- Extremely strong, e.g. support 10x self-weight
    - 500kg structure for 5 tons (CMS BTST)
    - 3 kg structure for 30 kg pixel detector
    - Minimal mass by dual-use

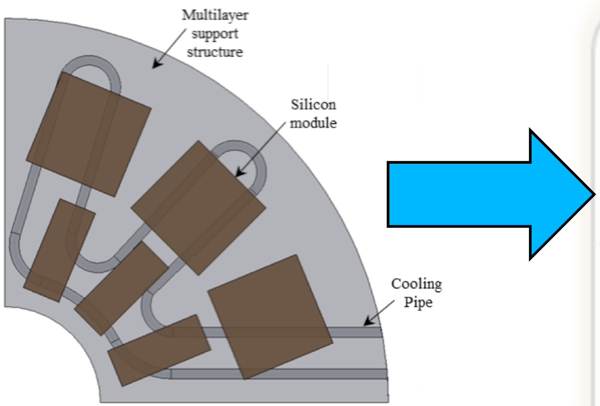


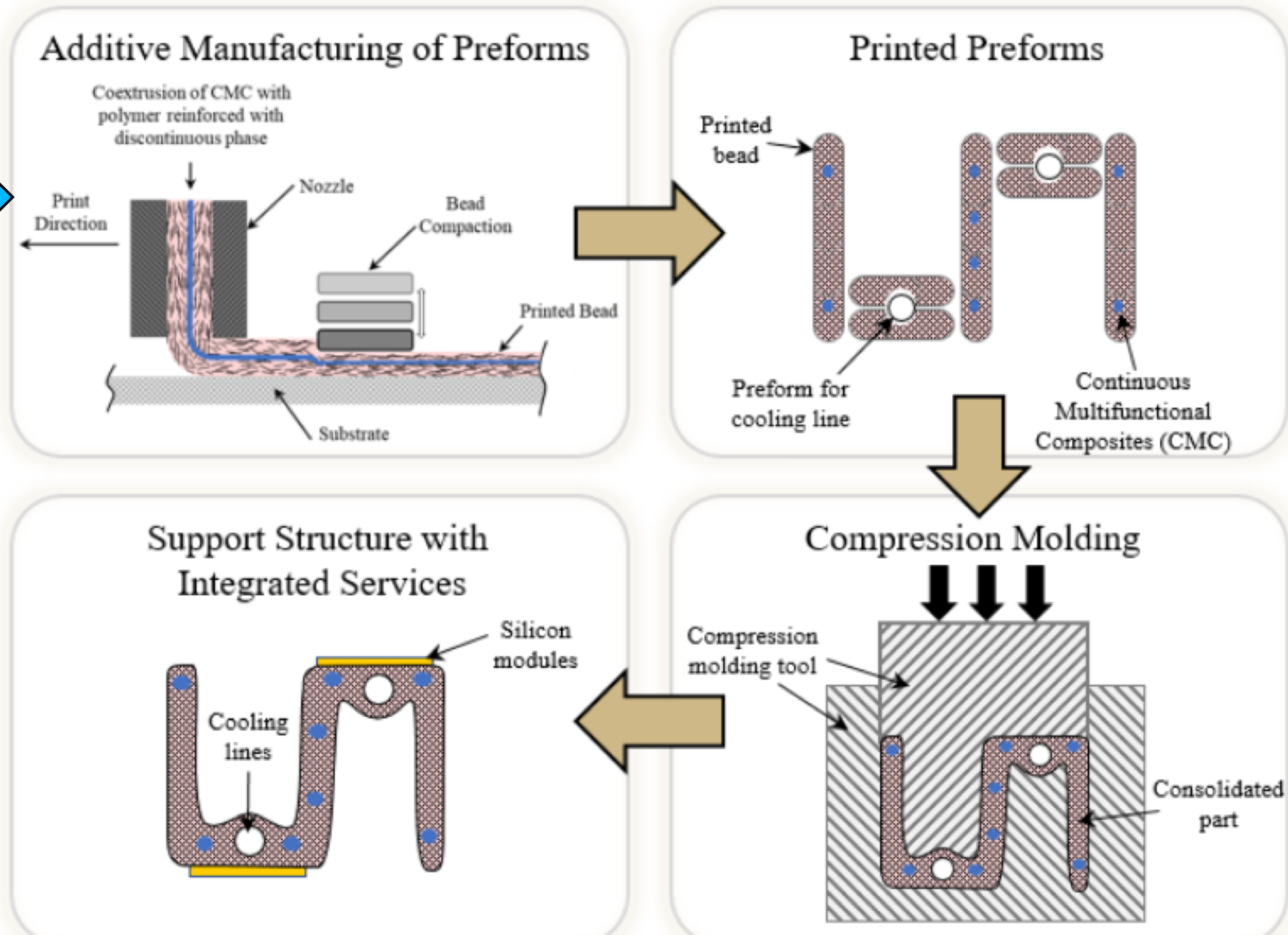


Going into the future of mechanics

Identified by DOE BRN effort & CPAD

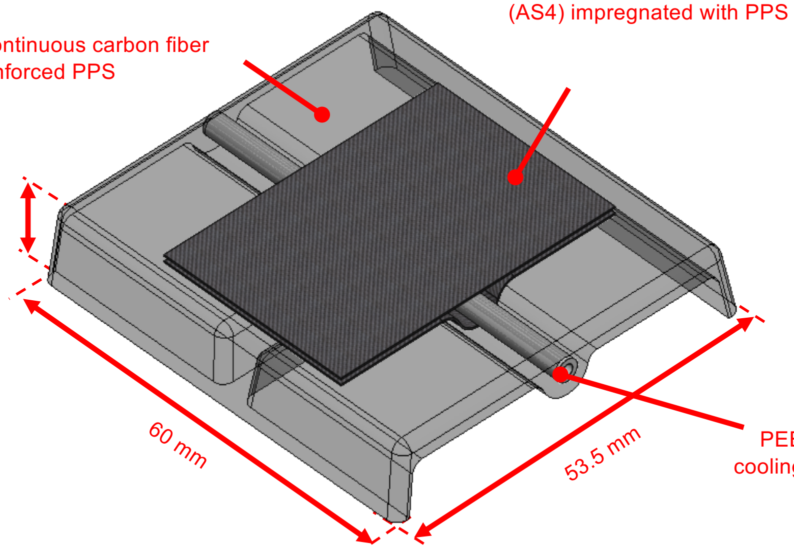
- Scaling of low-mass detector system towards irreducible support structures with integrated services. Includes: integrated services, power management, cooling, data flow, and multiplexing.

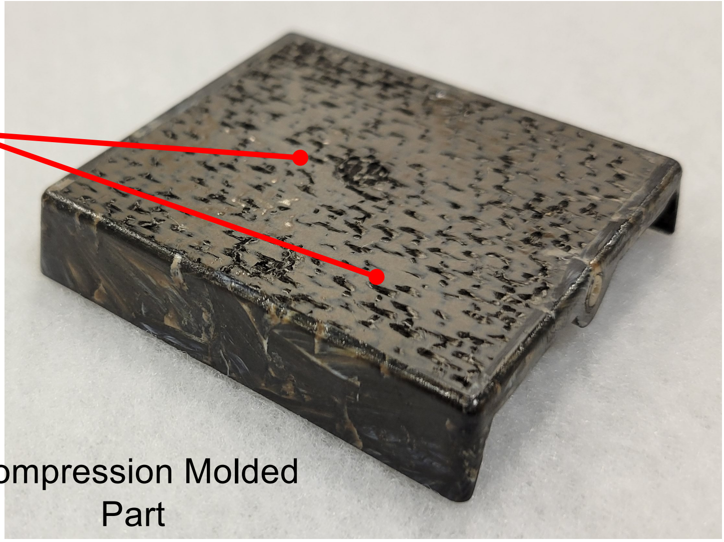




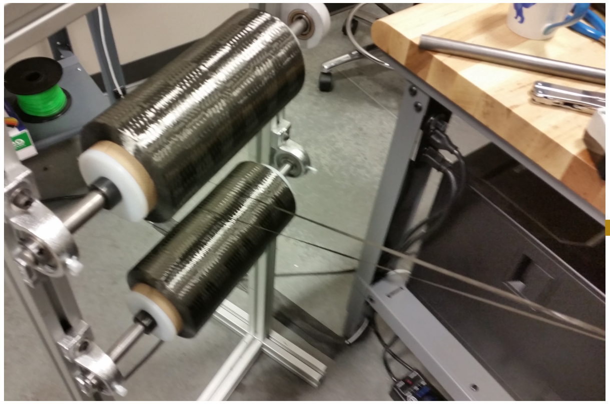
→ Collaboration with material sciences, companies for novel materials, and latest techniques.
→ Example: Cutting-edge composite manufacturing techniques, in-house
→ **Reduce mass & boost thermal performance**

First prototypes look promising…

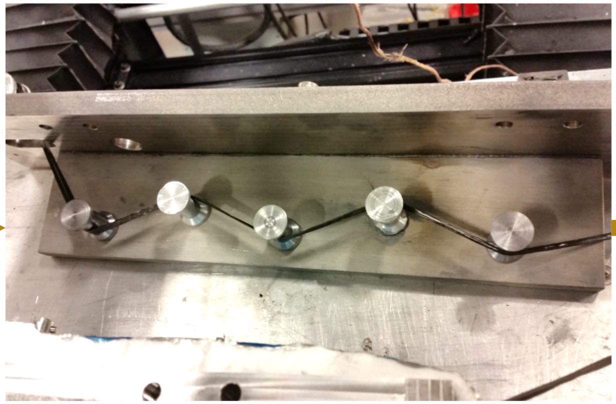




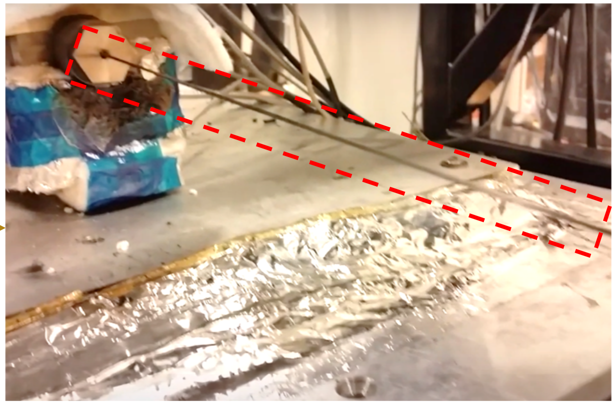
Compression Molded Part



Spools of Carbon Fiber

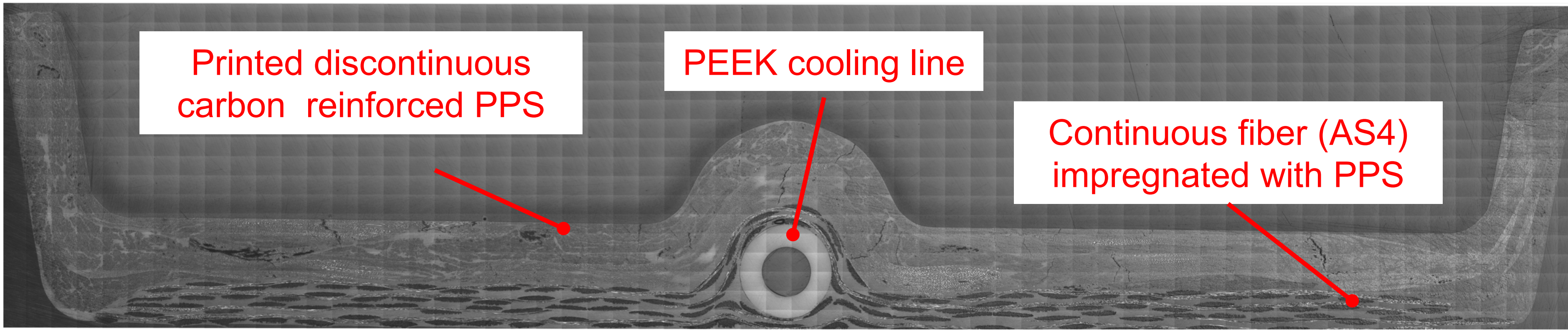


Interior of Impregnation Chamber



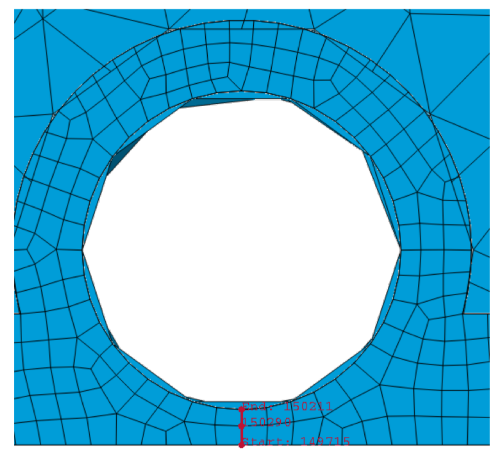
Carbon Fiber Impregnated with PPS

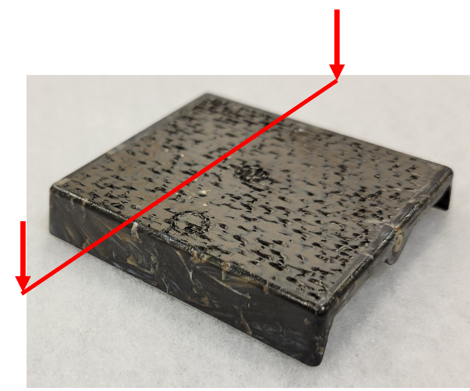
Cross-sectional micrograph of first prototypes

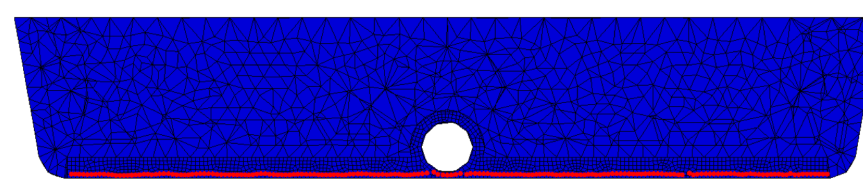


Detailed FEA studies:

- 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

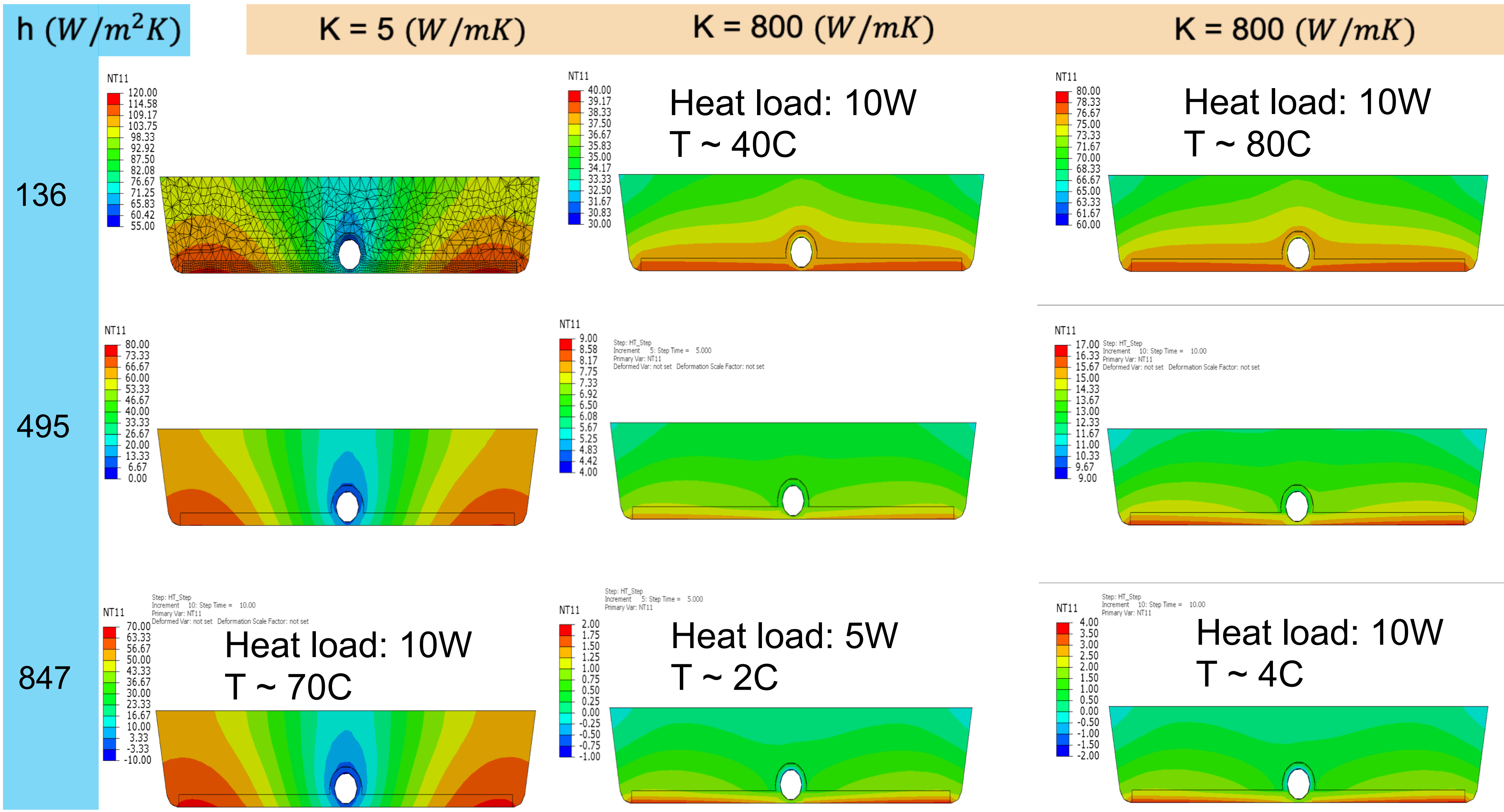






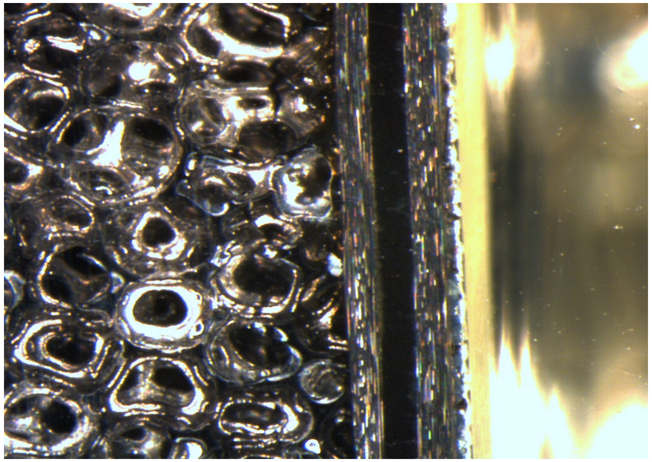
Thermal performance improved compared to state-of-the-art

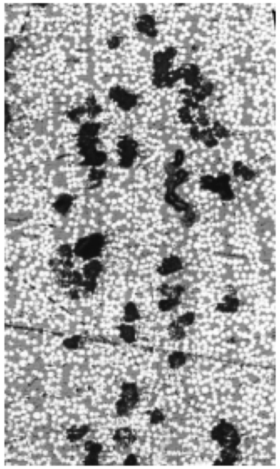
- Already at a lower mass and can be further reduced…



Carbon Fiber is great material

- Can it be active…
- A Carbon Fiber wire chamber offers great prospects to save material





Applications & Community

Dual readout calorimetry w carbon fiber supports…

Drift chamber, e.g. using “CF” wire chambers…

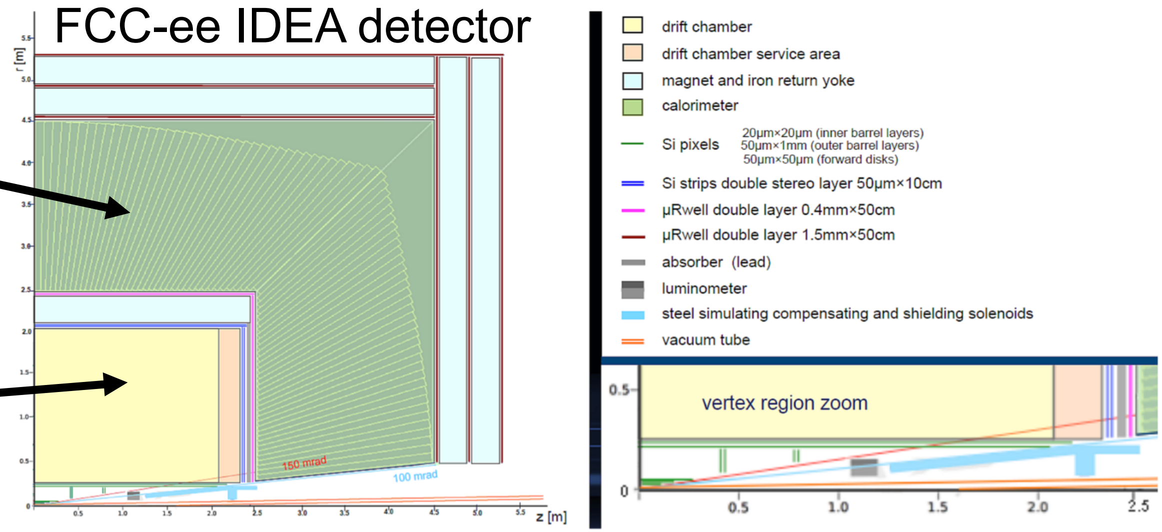


Figure 6: Cross section of the proposed layout for the IDEA detector concept.

→ Example of ”large detector” but detector mechanics / services / cooling play a significant role in a detector's performance

→ **Highly relevant also to small experiments & EIC ?!**

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 https://cpad-dpf.org
- Bridges nuclear, high energy physics but space applications / satellites too – broad field!
- Forum on tracking detector mechanics @Purdue: https://indico.cern.ch/e/ftdm24

Carbon Fiber wires

- G. Charles et al. compared gold-plated tungsten wires to carbon wires for applications in multi-wire chambers
- This example: **factor 5 reduction** in material when moving from W+Al to C+Ag/Cu
- Supports also a topic
- Volume separation

NIM A Vol 855, 2017

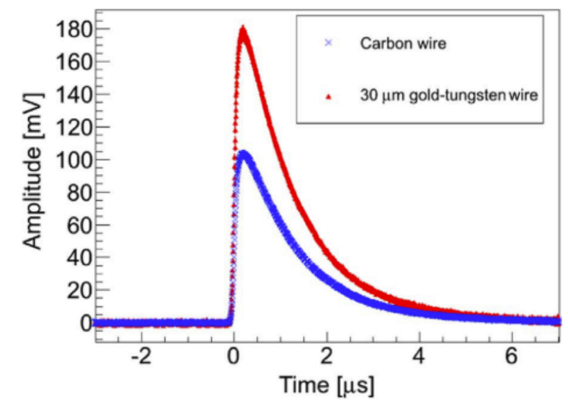
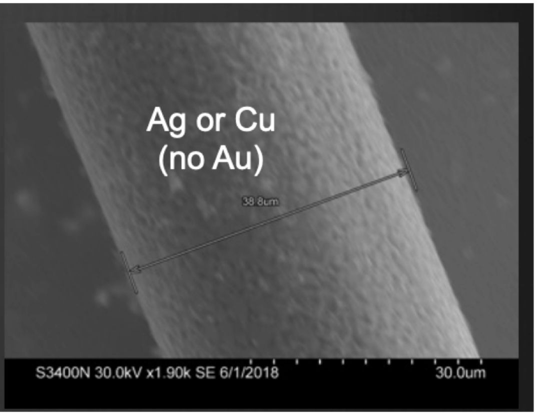


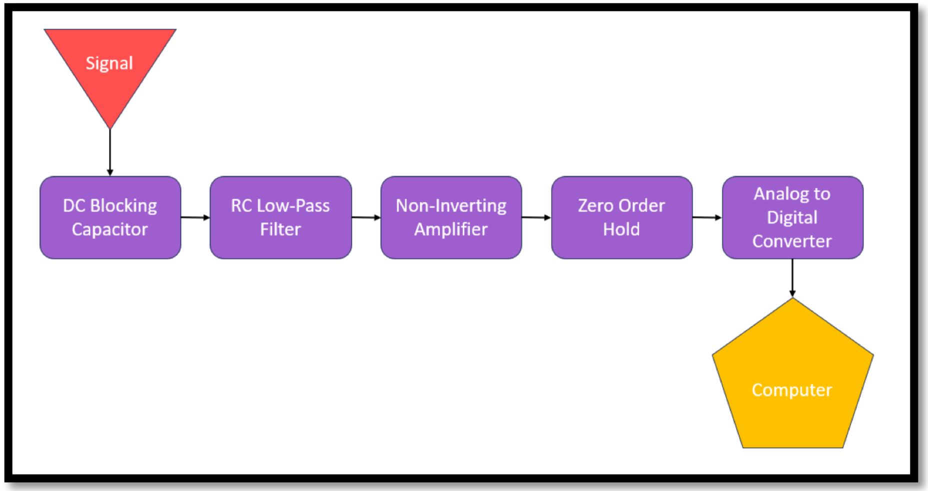
Fig. 5. Comparison between the signals from a carbon and a tungsten wire. The signals have been shifted by their respective T_{event} so that they appear at the same time reference for easier comparison.

G. Charles et al.

Grancagnolo et al. (INFN)

High-power impulse magnetron sputtering (HiPIMS)
physical vapor deposition of thin films based on magnetron sputter deposition (extremely high power densities of the order of kW/cm² in short pulses of tens of μs at low duty cycle <10%)



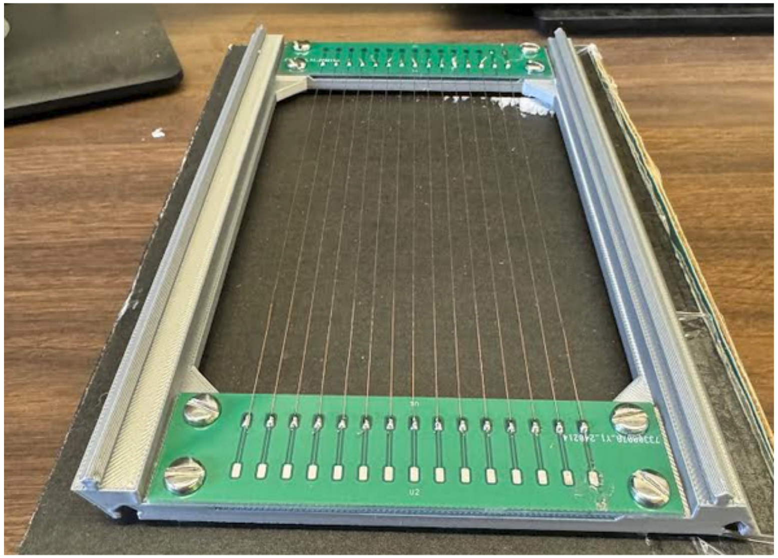


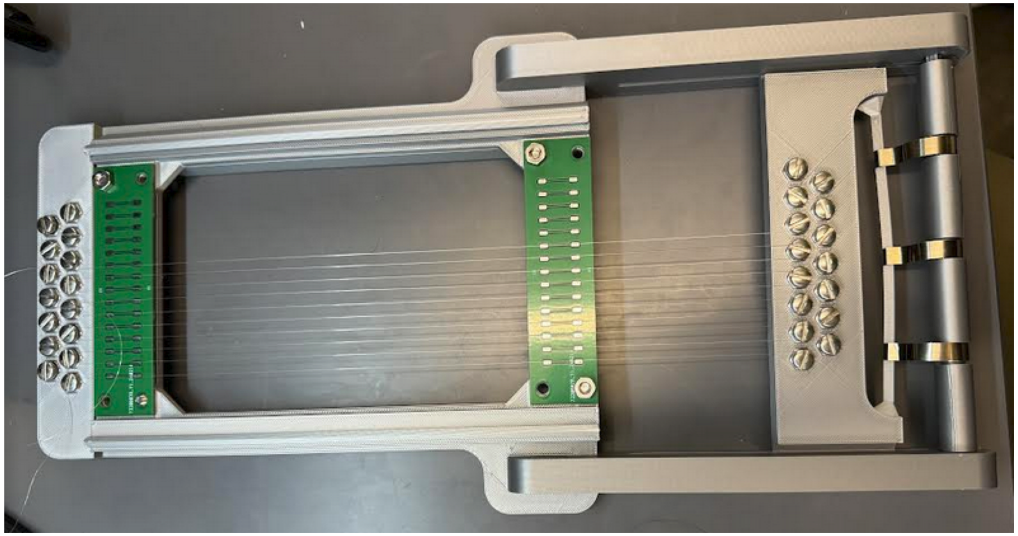
Small R&D activities @Purdue

- Purdue is using 30 um diameter Dexmat carbon sense wires
- Purdue benchmark is 25 um diameter tungsten wire from Midwest Tungsten
- Metal coating is a future project
  - Purdue has infrastructure
    - Atomic Layer Deposition (ALD)
    - Chemical Vapor Deposition (CVD)
    - Plasma Enhanced Chemical Vapor Deposition (PECVD)
    - High Density Plasma CVD (HDPCVD)
    - E-beam Evaporation DC/RF Sputtering multi-deposition (E-Beam Evaporation + Sputtering)
    - GaN Molecular Beam Epitaxy (MBE)
    - PVD Pulsed Laser Deposition (PLD)
    - Electrodeposition

Bench-test setup @Purdue

- Printed Circuit boards control the location of each wire
- Chamber is built in layers that can be stacked and offset for alternating sense and cathode wires
- Tension is applied using constant force springs and screws on a carriage
- Next steps: Sealed source & record data & spectra
- Stay tuned…



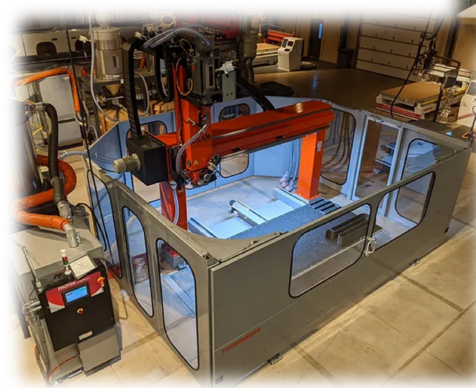


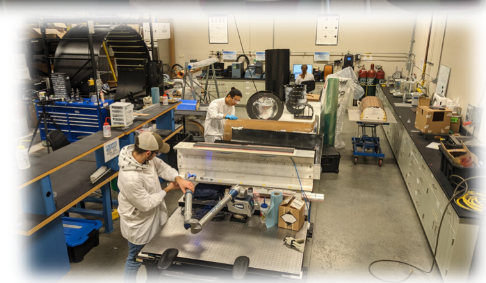
Advertisement

EPIC specific Mechanics workshop at Purdue

- Aimed specifically at Mechanics
- https://indico.cern.ch/event/1336746/page/32301-satellite-events
- Potential topics
  - Subdetector mechanics
  - Global mechanics
  - Integration & Assembly
  - Service & Mass optimization

- Ahead of the forum for tracking detectors, Tuesday 28th May: https://indico.cern.ch/e/ftdm24
- 2nd Bulletin to come today





Mechanics community

Exchange of ideas & progress across existing collaborations:

- Snowmass process, ~~but no dedicated forum in the US to exchange on this~~
    - **CPAD RDC 10 “Detector Mechanics R&D”** https://cpad-dpf.org

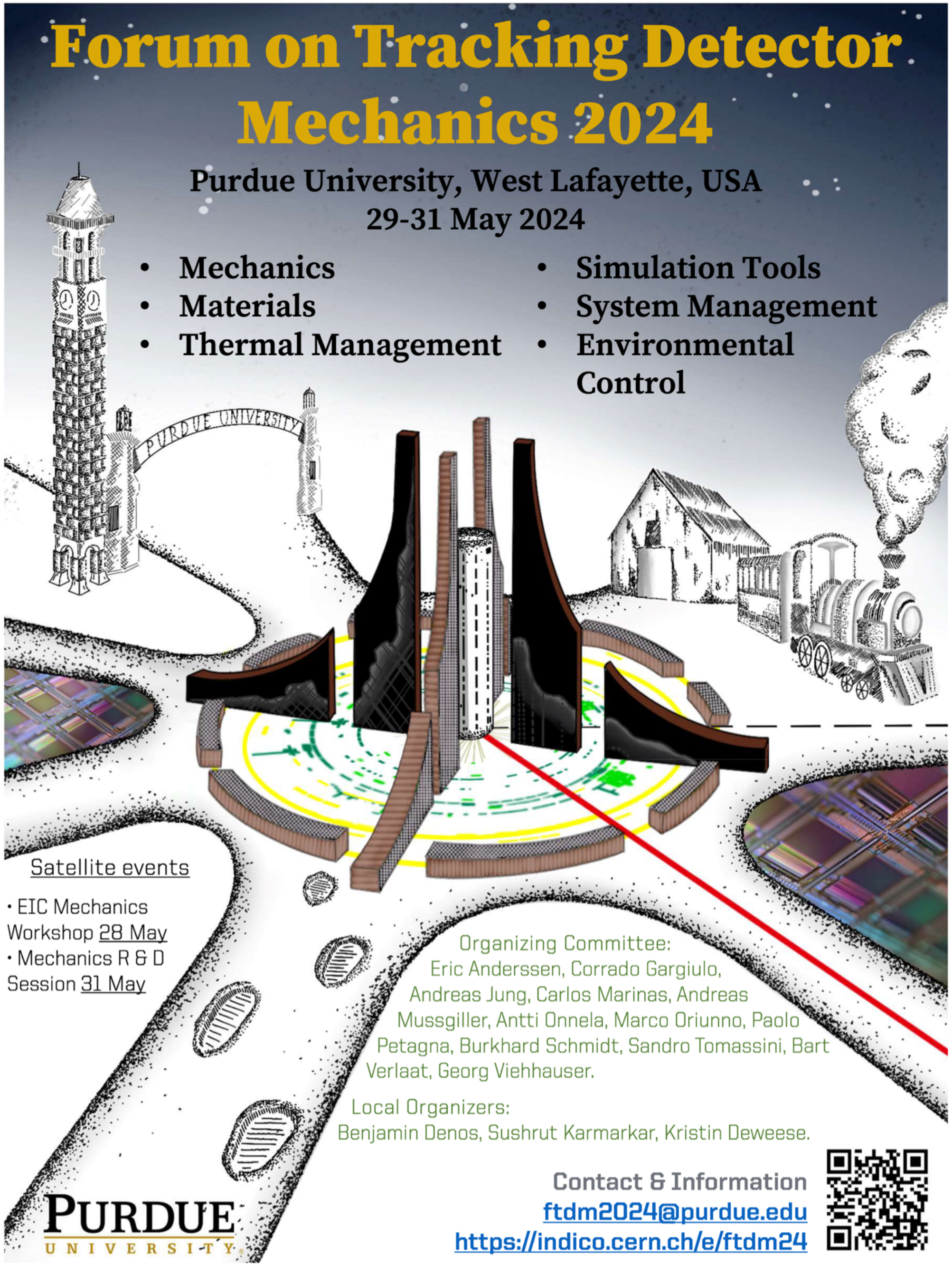
FTDM workshop

- Forum on Tracking Detector Mechanics @Purdue
  - Registration Fee's likely around ~250$ / person
  - FTDM 2024, May 29th – 31st
  - 3 days at Purdue
  - Tours of Silicon & Composite labs @Purdue
  - Poster Session & Industry sponsors

Satellite events

- Satellite event on May 28th focus on EPIC:
- Half-day on Friday devoted 1st RDC10 collaboration meeting, 31st May

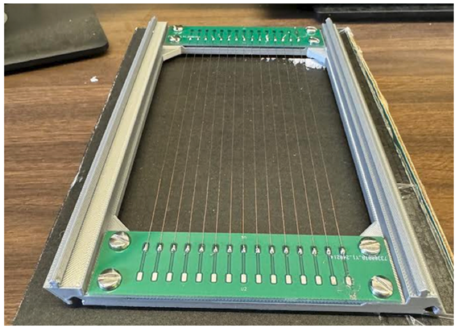
https://indico.cern.ch/event/1336746/

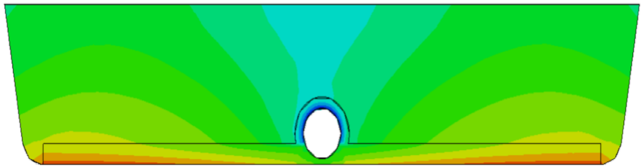


Summary

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





Detector Mechanics R&D

- First prototypes w improved performance compared to current state-of-the-art tracker mechanics
- Applicable also to calorimetry, TOF, other systems
- Next steps: Pressure test and connections to form a larger structure
- Snowmass white paper: https://arxiv.org/abs/2203.14347

Backup

This research is supported by:

U.S. DEPARTMENT OF ENERGY
Office of Science

PURDUE
RESEARCH FOUNDATION

Pixel support structures

- 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

Composites Manufacturing & Simulation Center

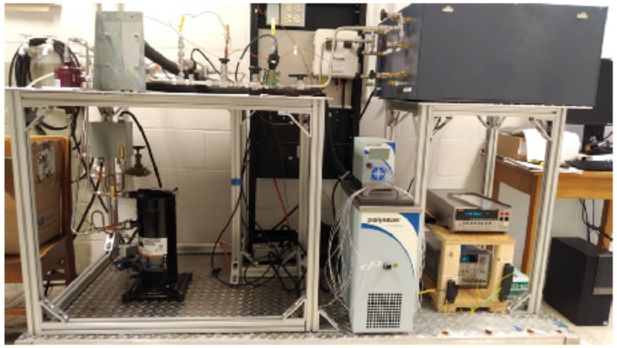
Facilities at Purdue: CTRC & PSDL

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

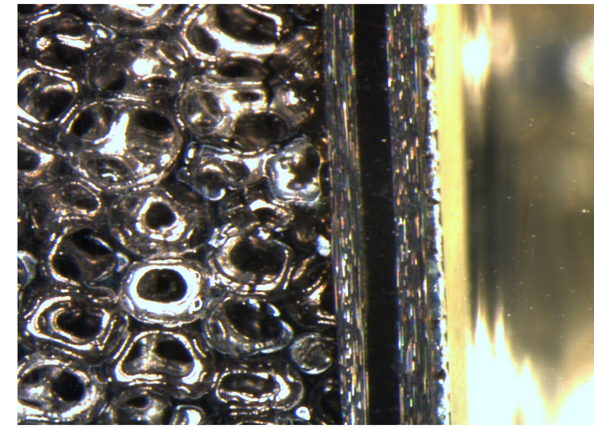
PSDL-CTRC Collaboration on:

- Various aspects of thermal management relevant for the applications at future collider
- Cooling box setup for thermal tests

Pixel support structures

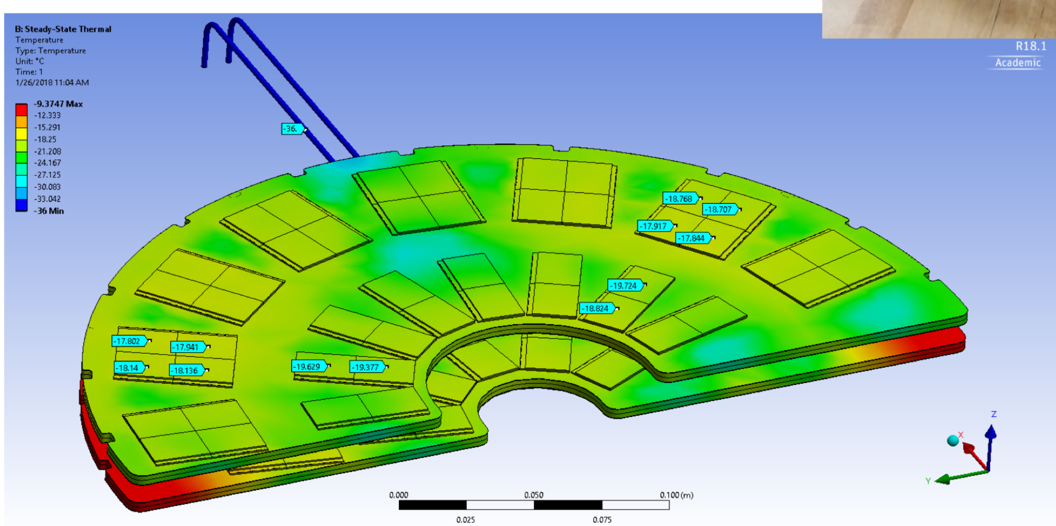
→ Disc-like support structures made from Carbon Foam & Fiber
→ FEAs use TC measurements as inputs
→ Capable of cooling all ~1800 pixel modules
→ Carbon is light-weight, and strong

1st half dee prototype, Cornell University



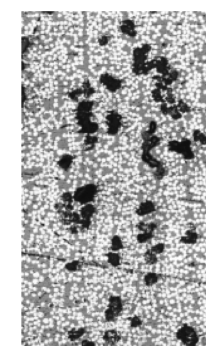
Carbon foam

3-ply skin



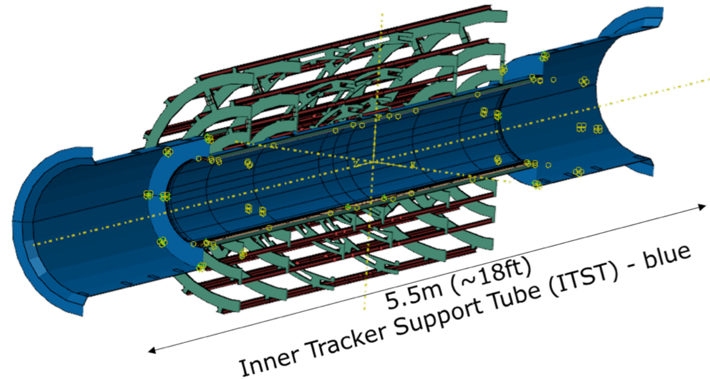
High TC support pieces

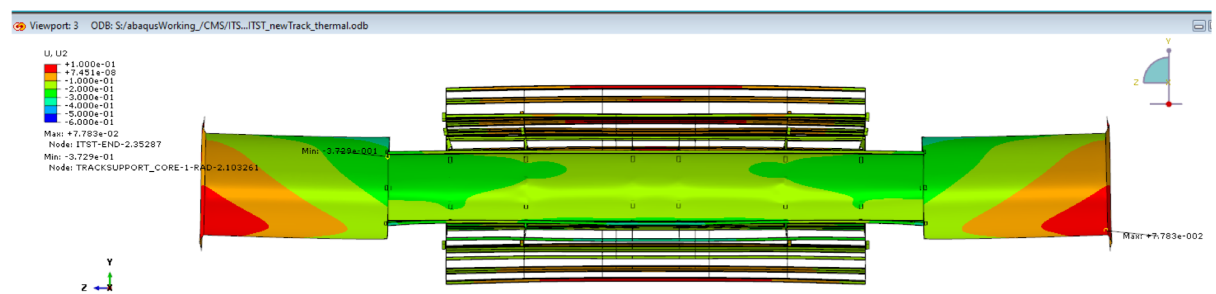
Bad laminate



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





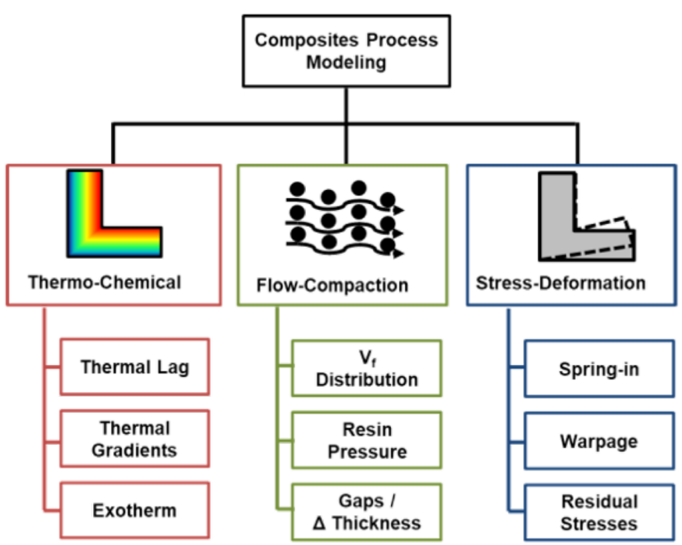
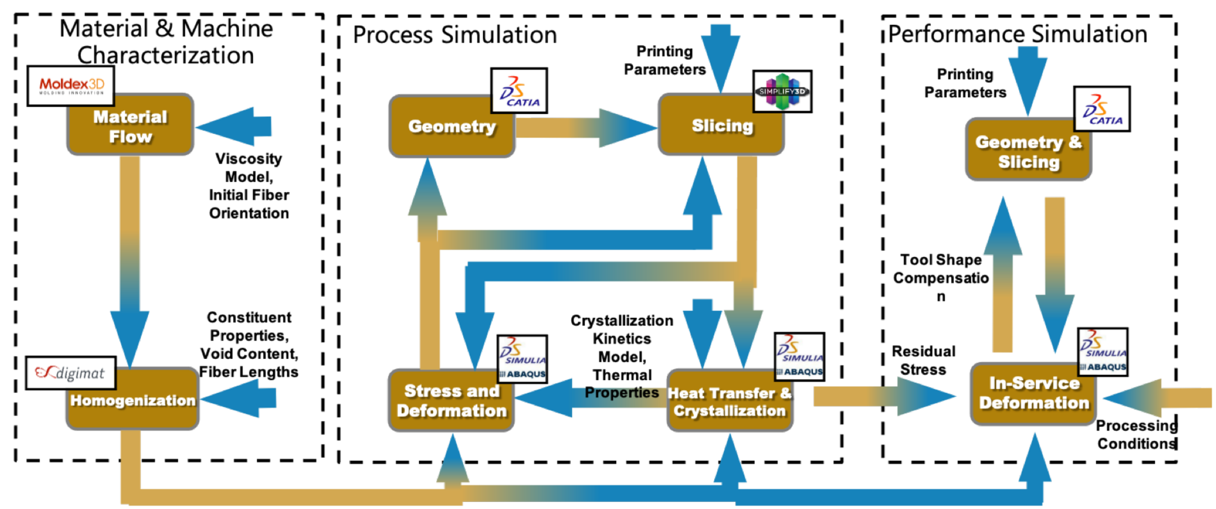
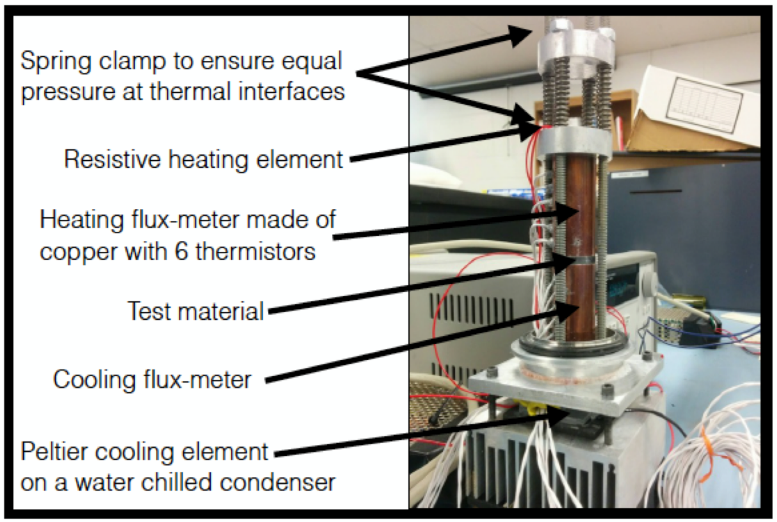


Figure 1-1 Composites process modeling problem types

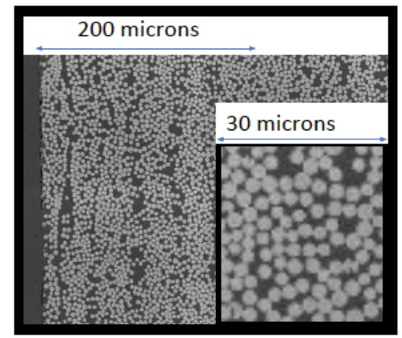


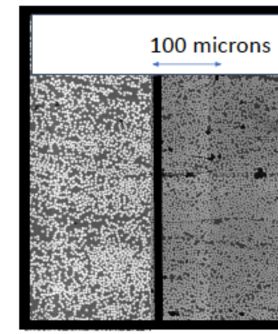
Thermal conductivities

- → 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]