R&D considerations on lightweight mechanics

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

Andreas Jung

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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

### Future colliders (FCC-hh like)

<table>
<thead>
<tr>
<th>Pixel Layer dose (3.7cm)</th>
<th>HL-LHC 3ab⁻¹</th>
<th>FCC 3ab⁻¹</th>
<th>FCC 30ab⁻¹</th>
<th>FCC (2.5cm) 30ab⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \times 10^{16} n_{eq} \text{ cm}^{-2} )</td>
<td>1.5</td>
<td>3</td>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>Dose (MGy)</td>
<td>5</td>
<td>10</td>
<td>100</td>
<td>220</td>
</tr>
</tbody>
</table>

Example of the HL-LHC upgrades as example:

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

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R&D considerations on lightweight mechanics
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)

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R&D considerations on lightweight 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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R&D considerations on lightweight mechanics

Impact of tracker mechanics...

- Heat generated by different components
  - Silicon Module (Chip + pixel sensor)
  - Thermal Interface Material, 100μm thick, $k_{\text{Nom}}=1.25 \text{ W/mK}$
  - Carbon Fiber Layer, 200μm thick, $k_{\text{Nom}}=0.53 \text{ W/mK}$
  - Epoxy Interface, 100μm thick, $k_{\text{Nom}}=1.1 \text{ W/mK}$
  - Carbon Foam Layer, 2.5mm thick, $k_{\text{Nom}}=35 \text{ W/mK}$

- Nominal thermal conductivities of different layers
- Through-plane thermal conductivity of layer [W/mK]
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 Systemes Simulation Center of Excellence
• Process-specific engineering workflows

Supporting technologies
• Technical cost modeling
• Big data - AI
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.

PSDL-CTRC Collaboration on:
• Various aspects of thermal management relevant for the applications at LHC
• Common 2-phase CO$_2$ cooling box setup

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

<table>
<thead>
<tr>
<th>Sample/D</th>
<th>Thermal conductivity (k) [W/mK]</th>
<th>Interface thermal resistance of Flux-meter-TJM-Sample (R_{in}) [Km²/W]</th>
<th>Reduced r^2 of the linear fit</th>
<th>Expected value of k [W/mK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>K13C2U+EX1515 carbon fiber composite (Unidirectional)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>x-axis</td>
<td>320 ± 28</td>
<td>1.8 ± 0.4 · 10^{-5}</td>
<td>0.83</td>
<td>318 [3]</td>
</tr>
<tr>
<td>y-axis</td>
<td>6.0 ± 2.6</td>
<td>3.8 ± 2.8 · 10^{-4}</td>
<td>0.17</td>
<td>0.53 [3]</td>
</tr>
<tr>
<td>z-axis</td>
<td>1.09 ± 0.15</td>
<td>(−6.0 ± 17.0) · 10^{-5}</td>
<td>0.05</td>
<td>0.53 [3]</td>
</tr>
<tr>
<td>z-axis</td>
<td>2.21 ± 0.31</td>
<td>(3.0 ± 7.0) · 10^{-5}</td>
<td>0.09</td>
<td>1.2 [3]</td>
</tr>
<tr>
<td>K13D2U+EX1515 carbon fiber composite (Unidirectional)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>x-axis</td>
<td>376 ± 31</td>
<td>3.8 ± 0.3 · 10^{-5}</td>
<td>0.65</td>
<td>410 [3]</td>
</tr>
<tr>
<td>y-axis</td>
<td>7.5 ± 4.4</td>
<td>3.9 ± 3.5 · 10^{-4}</td>
<td>0.01</td>
<td>0.53 [3]</td>
</tr>
<tr>
<td>z-axis</td>
<td>1.44 ± 0.24</td>
<td>1.4 ± 1.4 · 10^{-4}</td>
<td>0.44</td>
<td>0.53 [3]</td>
</tr>
<tr>
<td>z-axis</td>
<td>2.79 ± 0.46</td>
<td>2.0 ± 9.0 · 10^{-5}</td>
<td>0.43</td>
<td>1.2 [3]</td>
</tr>
<tr>
<td>Other materials</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IM7 8552 (x-axis)</td>
<td>8.0 ± 2.3</td>
<td>1.2 ± 0.8 · 10^{-4}</td>
<td>0.85</td>
<td>5.50 [20]</td>
</tr>
<tr>
<td>Celstran® PPS-CT50-01 (z-axis)</td>
<td>0.34 ± 0.08</td>
<td>(−2.2 ± 4.6) · 10^{-4}</td>
<td>1.09</td>
<td>0.39 [21]</td>
</tr>
</tbody>
</table>
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

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Going into the future of mechanics

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

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

*Example: ML for optimization with HEP inputs, excites future generation.*
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/](https://indico.cern.ch/event/853861/)
  - ~70 participants
  - Form a “CERN RD Mechanics” ...
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My own opinions
- 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
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
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
→ Precision manufacturing guided by FEA
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

High TC support pieces

Carbon foam
3-ply skin
Bad laminate

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