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Global Mechanics Challenges for Materials and Structures in Future Particle Detectors

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Coordinating Panel on Advanced Detectors 2025

Philadelphia, October 2025

Outline

01

Future Particle Detectors Mechanics

02

Emerging technologies for support structures

03

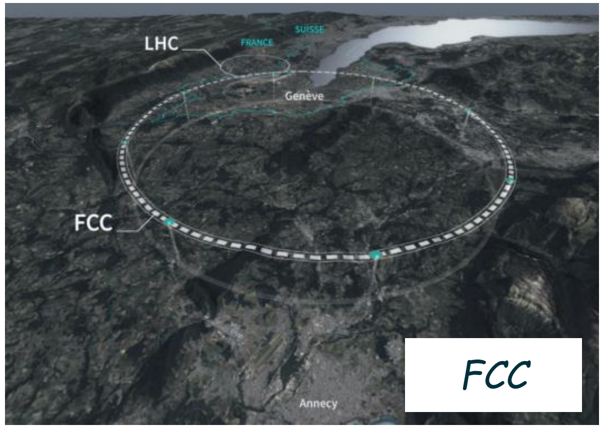
Emerging technologies for global mechanics materials

04

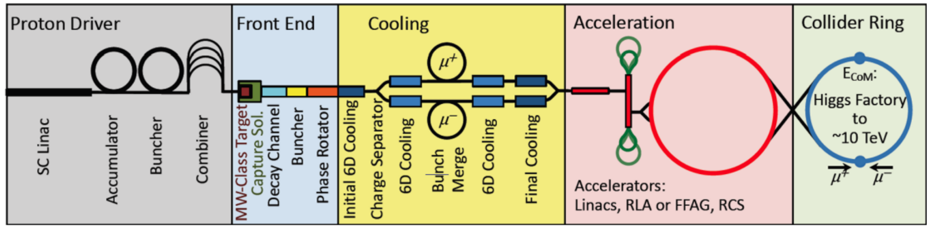
Conclusion

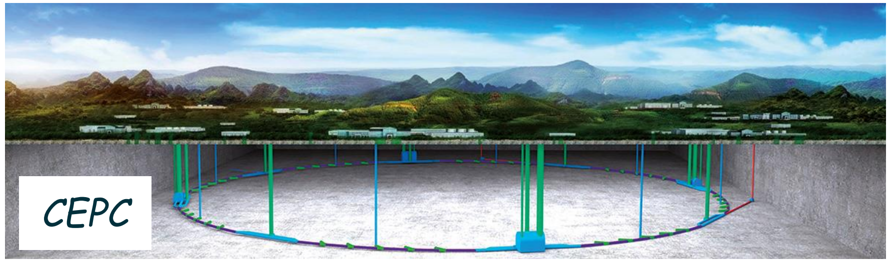
Future Particle Accelerators

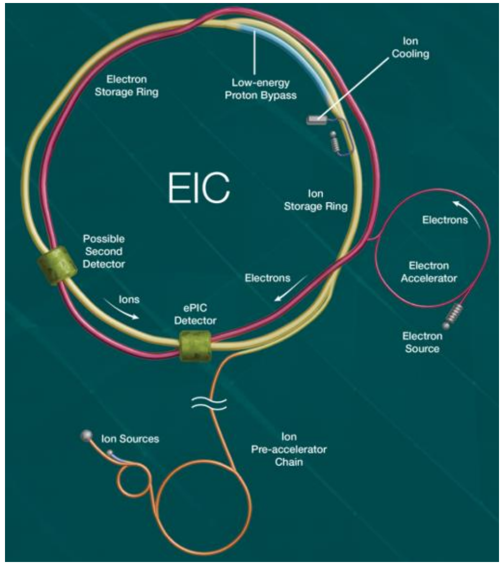
Planned or under development

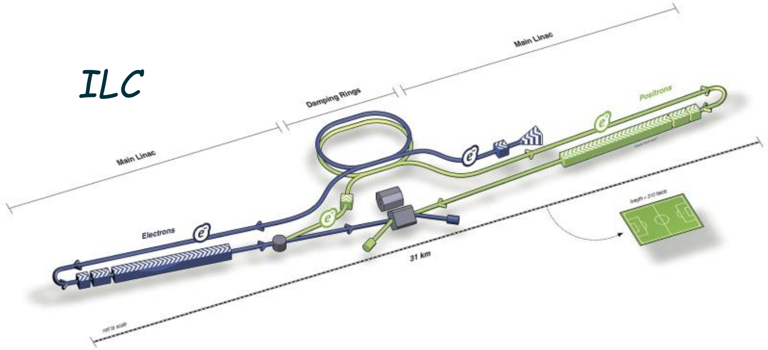


Muon



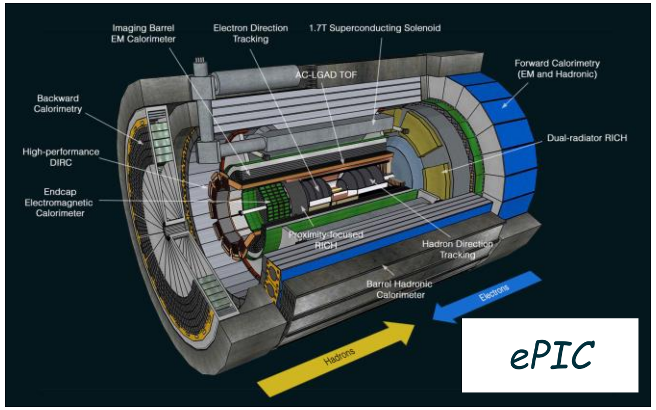


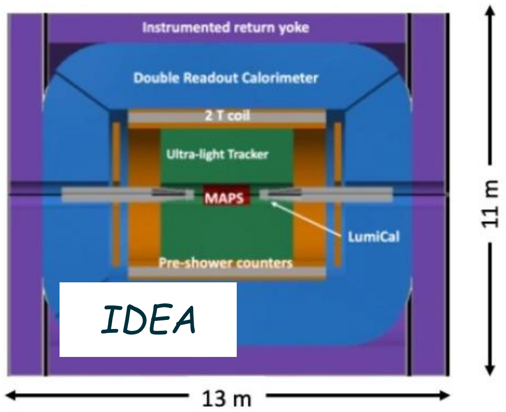


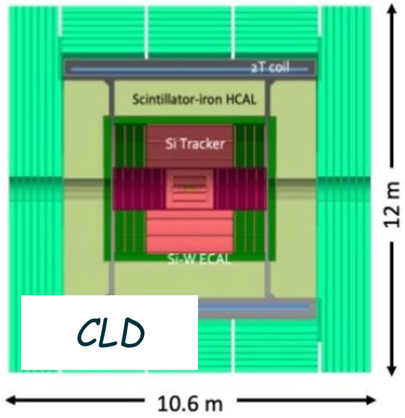


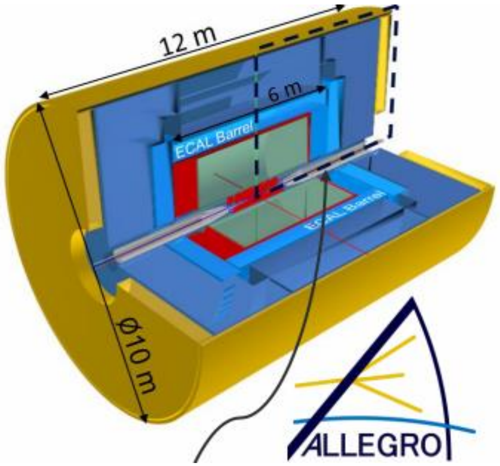
- Future **accelerators**
  - EIC, FCC-ee, FCC-hh, Muon collider, CEPC, ILC
- Different **collision rates** and **species**
  - Can lead to significantly different data rates, power requirements and radiation doses
- Different **location**: some underground, some not
  - Implications for detector integration, servicing and maintenance

Future Detectors





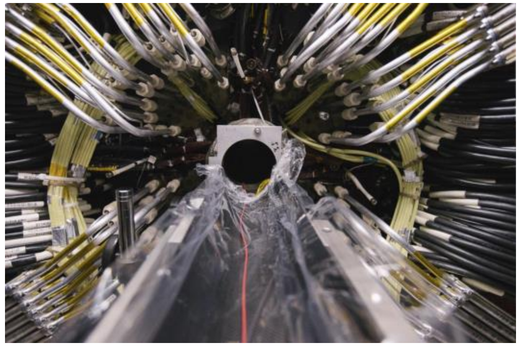


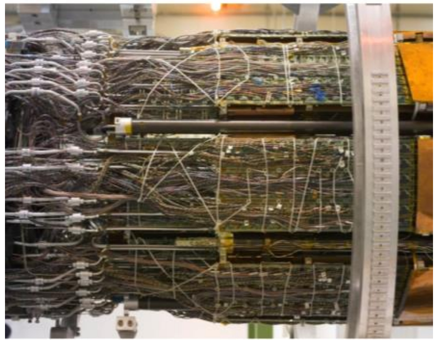


- Future silicon detectors will likely include **Strips**, **Hybrid Pixels** and **MAPS**
  - However, not all proposed trackers are **silicon** based
- Some **requirements** are **shared** for different detectors, even when different tracking technologies are used, e.g. **stability**, **resolution**
- Other requirements are **specific** to the application
  - **pp** and **hh** detectors often have higher **radiation** doses and **power** requirements with respect to **heavy ion** and **ee** ones
  - Lower **mass** (X_0) requirements for **heavy ion** and **ee**

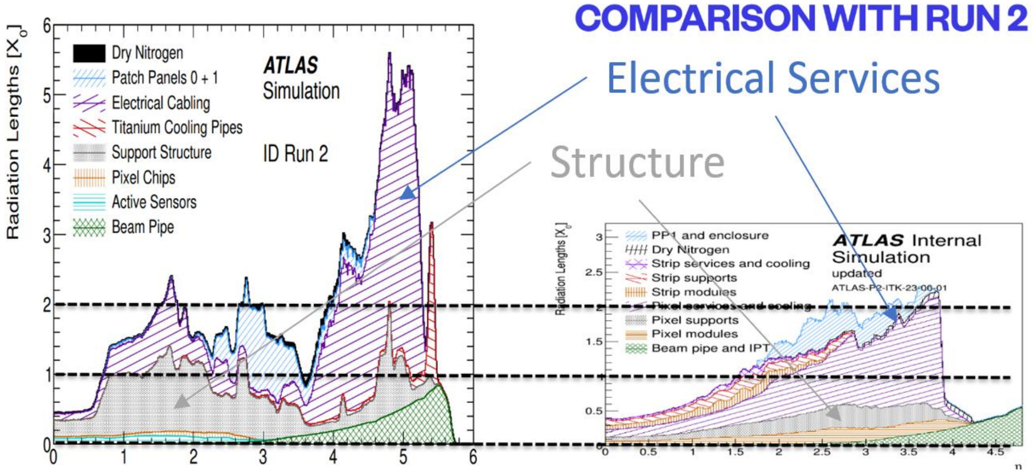
Future Detectors

Global Mechanics and Materials Challenges





Current ATLAS Pixel



- With respect to **current ATLAS/CMS**, foreseen **FCC** structures are **2X** diameter and **2-3X** active area (or more), while ePIC is similar in scale to current detectors
  - **Reduction** of 0.25-0.5%/layer to achieve **mass** goals
  - Larger detectors volumes will have longer inter-penetrating **services**
- **Electronics** and **detector technology** are not designed yet, but proposed to be '**lower power**' than current technologies
  - **Cooling** technology will be critical to achieving **mass** goals
  - **Services** at high η for high data rates will also be a challenge
  - **Radiation doses** will be 2-3X higher than current detectors, up to **10X** for FCC hh

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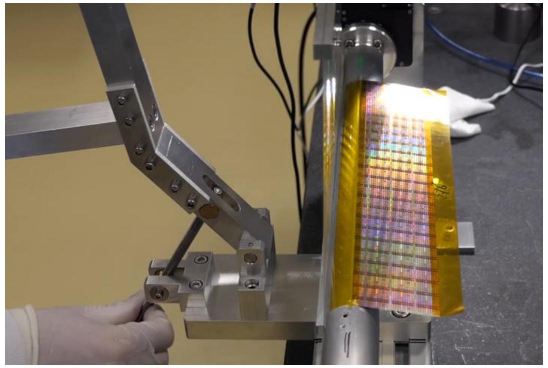
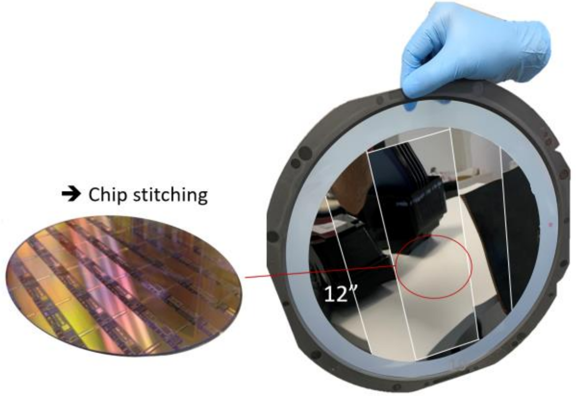
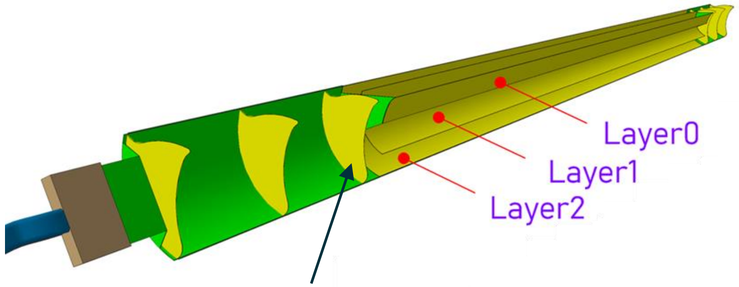
Monolithic Active Pixel Sensors (MAPS)

Very attractive for Low Mass

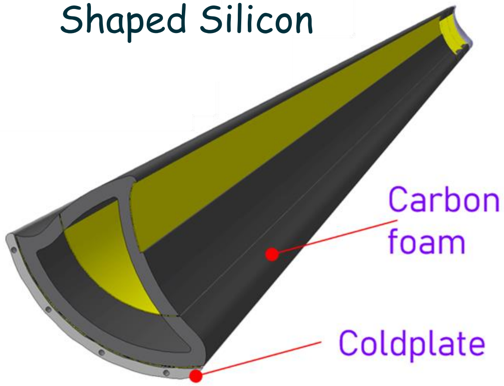


Bent Silicon





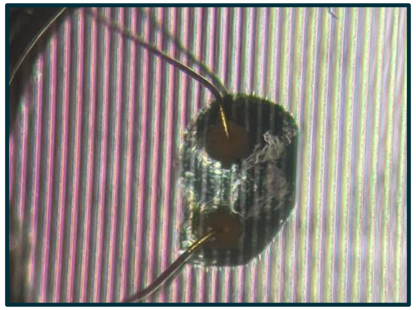
Shaped Silicon

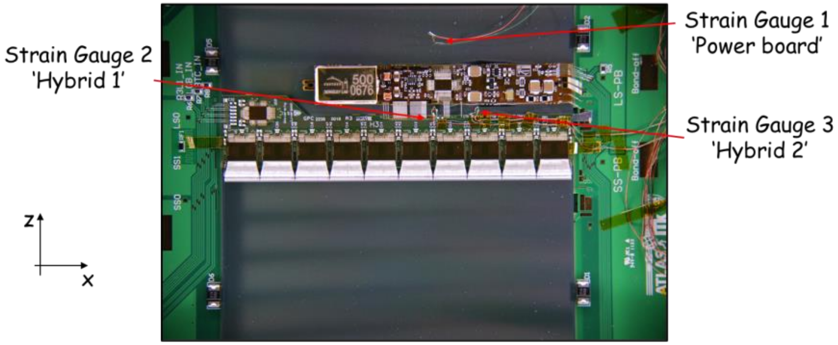


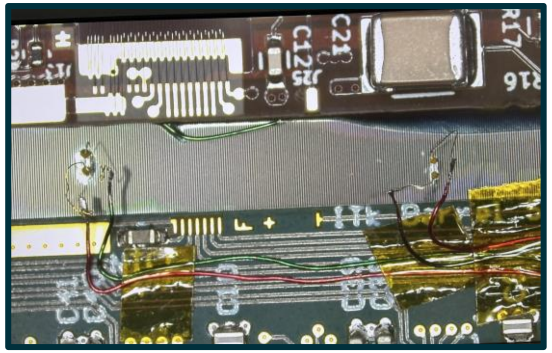
- Very **thin** silicon can be bent into **cylinders**, but also shaped to improve elastic stability (e.g. *venetian blind* like structures)
- **Chip stitching** can create **large** area **sensors** limited to wafer scale of up to 12” wafers (larger than ATLAS ITk Strip sensors)
- Column masking (in development) can allow for ‘**odd**’ **shaped sensor layout -** easier to tile for disk/endcap structures
- Air cooling may be a limit, other methods exist that may be useful

Silicon Strain Gauges

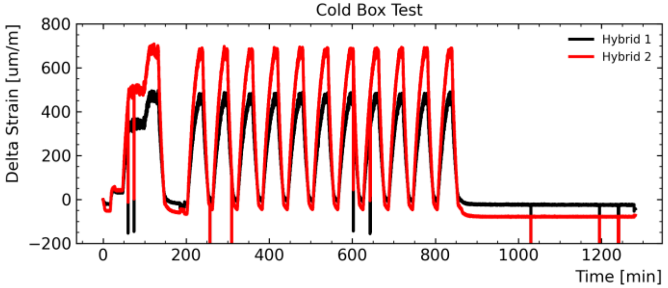
Silicon Structures with Structural Health Monitoring





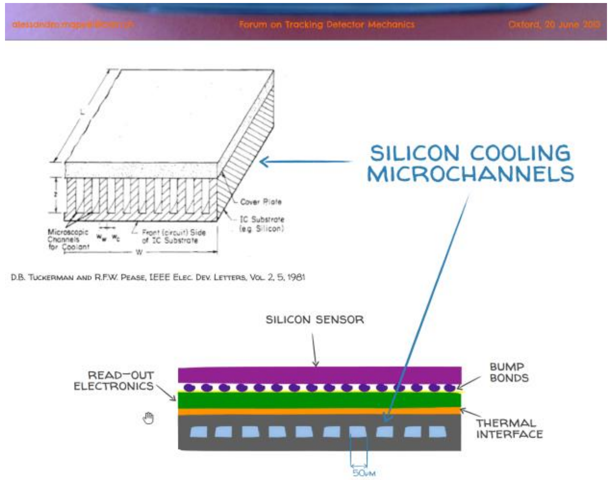


- If silicon is used to carry part of the '**load**', or if **bent** to shape (e.g. circular applications), measuring the **strain** might be crucial to **prevent failure**
  - Might also allow to measure sensor **position** (…control?)
- Silicon strain gauges might allow for a '**direct**', **low-impact** measurement
  - **Traditional** (constantan) strain gauges would introduce **thermal strain**
  - Might also be integrated within the wafer (?)
  - **Haptica** sensing gauges tested on ATLAS ITk strips with **good** success
- **Optical fibers** provide a potential alternative

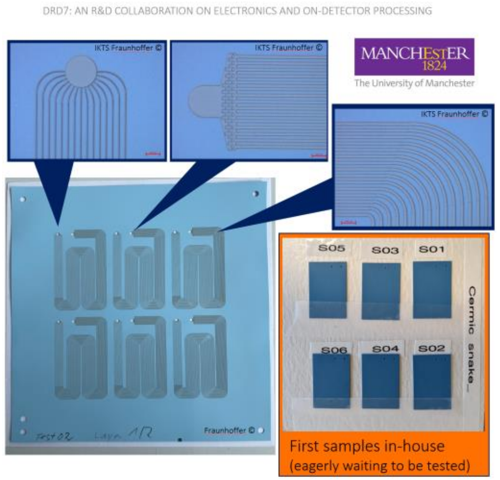


Cooling for Low Mass

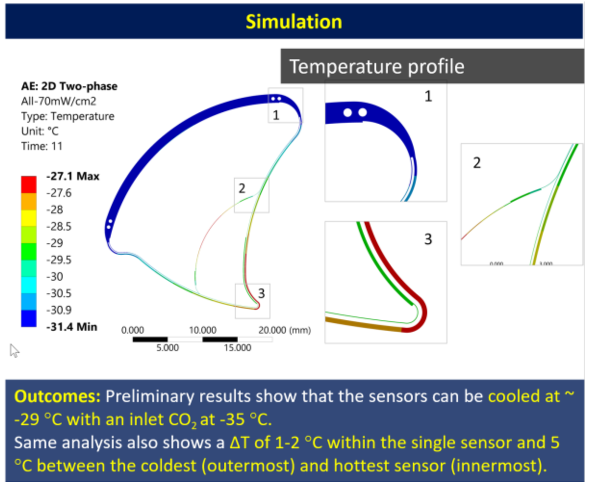
New solutions for Silicon Trackers



A. Mapelli, FTDM13



O. Augusto, FTDM24

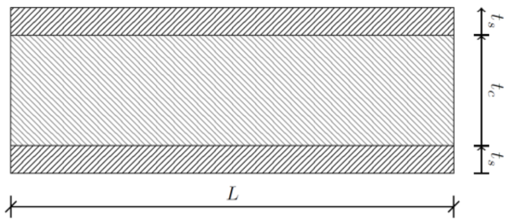


C. Gargiulo, FTDM24

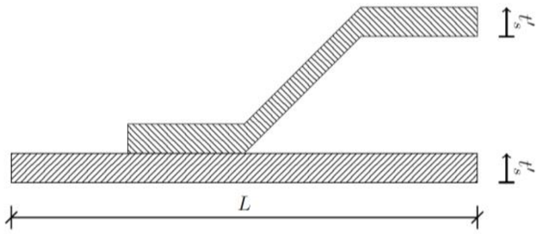
- **Air cooling** may be **insufficient** for detectors approaching or exceeding 100 kW
- R&D in mechanics have been looking a **distributed micro-channel cooling** and **conductive cooling** with different working fluids for well over a decade
- Can be **integrated** with most **silicon** technologies, may consider how to integrate with ‘**bent**’ **MAPS** (very **challenging**).
- Service **connections** to wafers remain a **challenge**, but is being actively addressed

3D Woven Composites

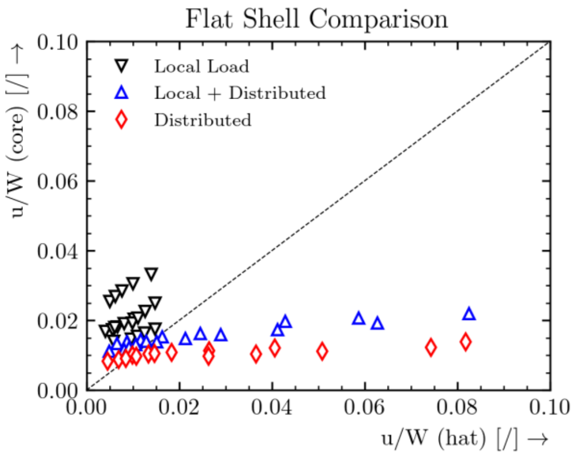
Towards Higher Stiffness and Lower Mass



Sandwich

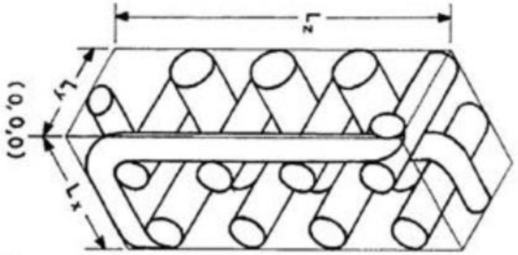


Hat-stiffener

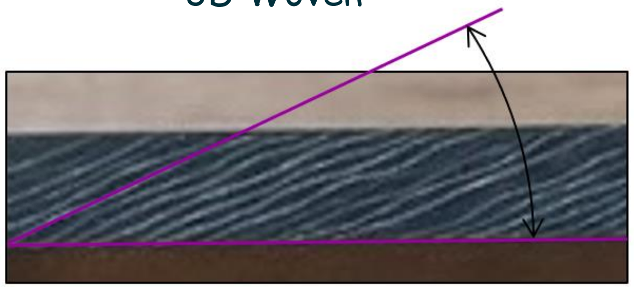


Traditional Laminate

- Traditionally, **support** structures built with two main **strategies**: **sandwich** and **eccentrically stiffened**
  - Best solution depends on the **load nature** (distributed, local), **repairability**
- **3D woven fibers** provide a potential alternative for **local reinforcement** at the **load introduction points**
  - Developed for rocket engines in 1960...
  - Might **further improve** mass/stiffness
  - Simpler (cheaper?) LBNL 'inclined' laminate (~rotated 2D) solution



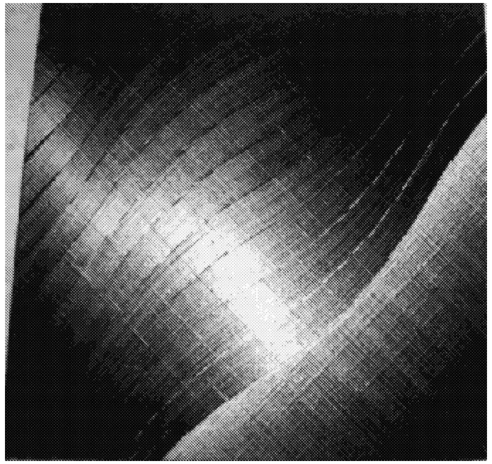
3D Woven



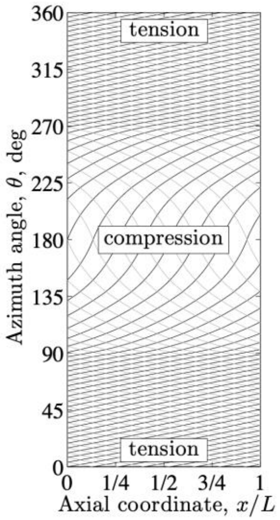
Inclined Laminate

Curved Plies

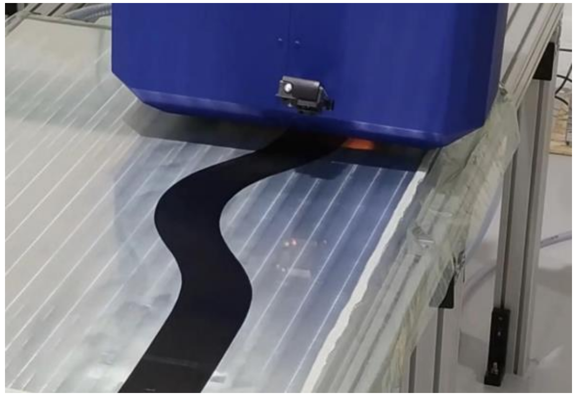
Fiber/load alignment in 2D



B. F. Tatting, NASA CR, 2002



A. W. Blom, Ph.D. Thesis, 2010

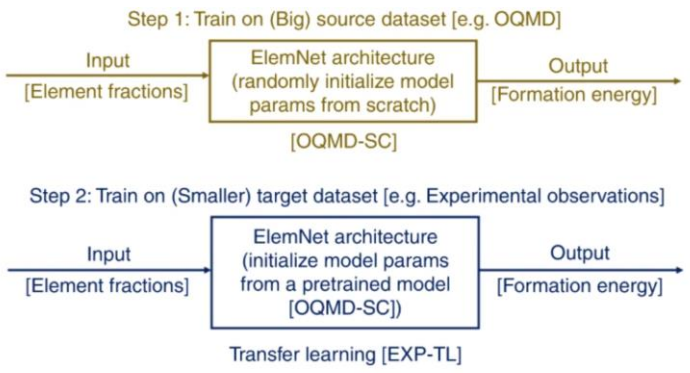


ICOMAT, FTDM 2025

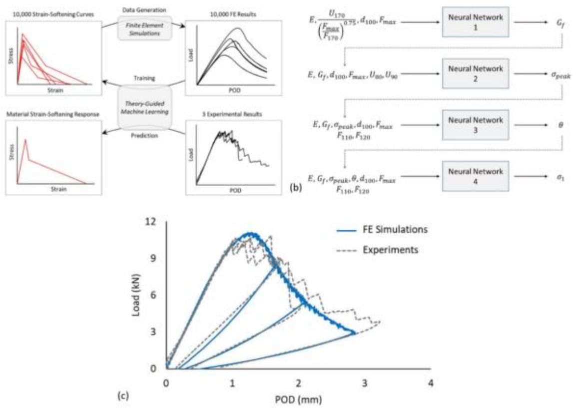
- **Traditional** composite layups use straight fibers, stacked at fixed angles
  - Recent **advances** in **automated fiber placement** might allow for 'local' fiber orientation, resulting in a more **efficient** material distribution (lower **mass**, higher **stiffness**)
- Interesting **optimization** problem, especially with the complex detector boundary conditions
  - Might need dedicated **analysis** tools

A Word on AI/ML

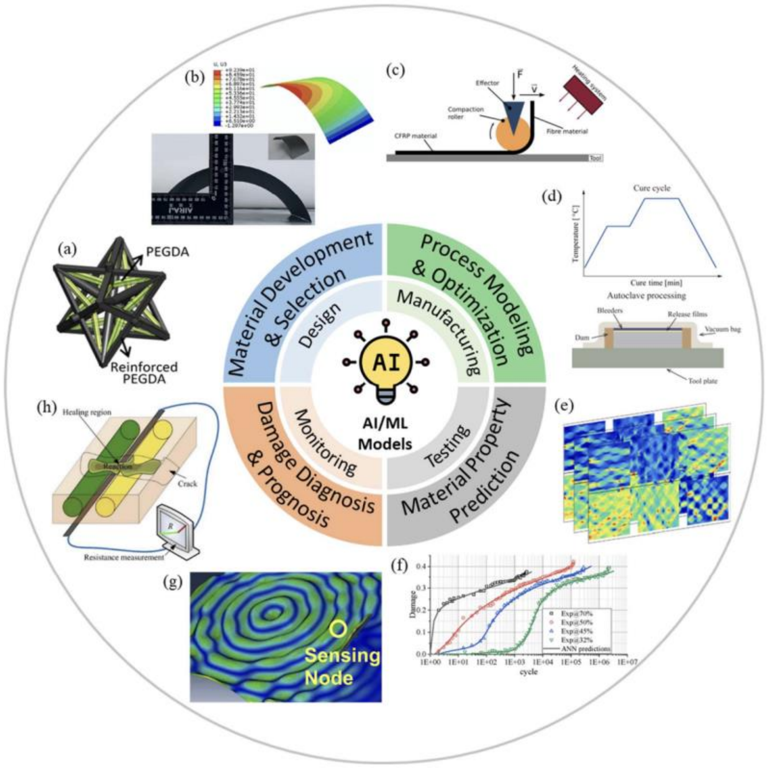
Transfer Learning and Opportunities



B. Jha et. al, 2019



J. Y. Y. Loh et al., 2024



Y. Wang et. al, 2024

- Detector mechanics: **complex & multi-physical**
  - Difficult to **optimize** considering all aspects at once (and even more difficult to define desired performance…)
  - Actual performance will depend on **manufacturing** process, making it difficult to predict numerically
- **ML surrogates** & physics-informed models can speed up simulation, design, and optimization
  - E.g. **Predict outcomes:** Link process parameters → dimensional accuracy, defects, mechanical properties.
  - Requires experimental data – need can be reduced integrating model data (**transfer learning**)
    - Few parts produced — **collaboration** is key to build shared datasets for next-gen tools

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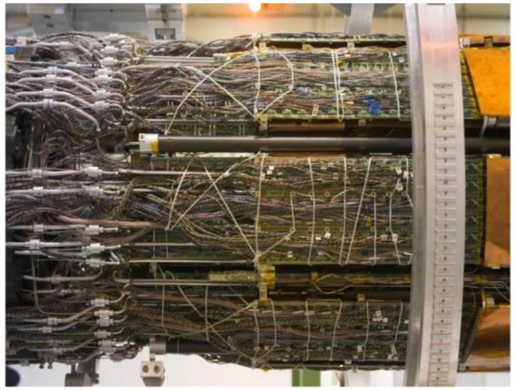
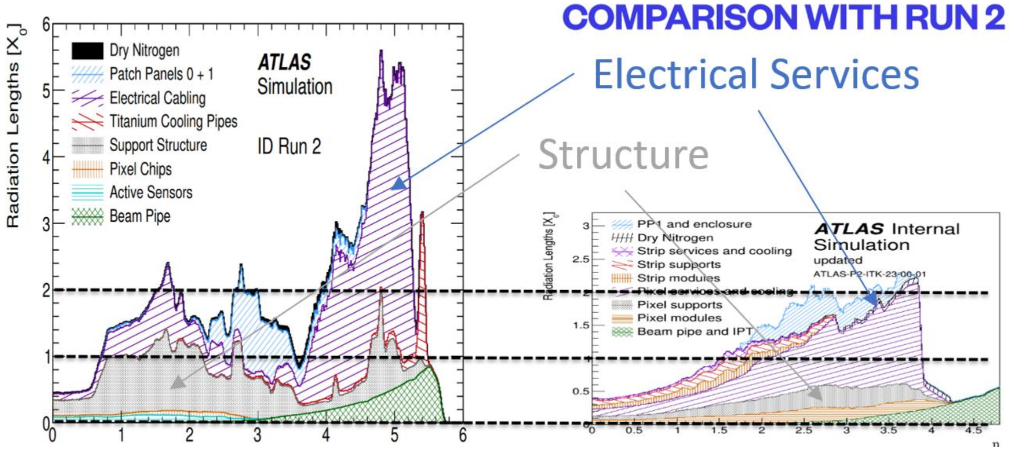
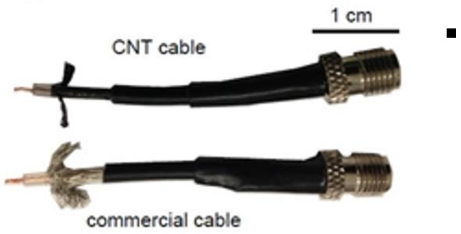
Service Mass Reduction

Carbon Fiber Lines



Current ATLAS Pixel





carbon-nanotube cables. *Common **coaxial cables** could be made 50 percent lighter with a new nanotube-based outer conductor.*

Twisted conductive yarn

- **Structural mass** already optimized (~factor of 2 reduction). Another factor 2 (maybe) possible, but not as impactful
- **Services** run along the length of detectors and increase in cross-section along length as more of the detector is 'serviced'
  - With HiLumi, services mass 'share' went from **power** to **data**
- Development of **Carbon conductors** for **data transmission** could be a key enabling technology
  - Copper has an X0 of 1.7 cm, Carbon is 22 cm (more than 10X better) – might allow for **5-10X less mass** to meet performance requirements

e.m. shielding

Multi-Functional Materials and Components

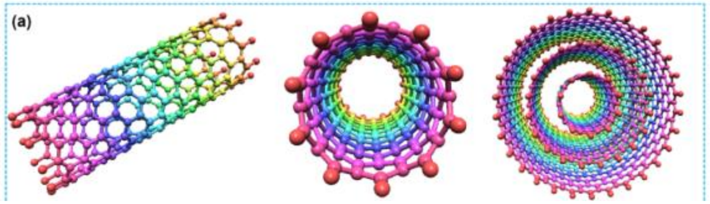
Merging the material budget

C. Luan et al., Funct. Compos. Struct. 2019

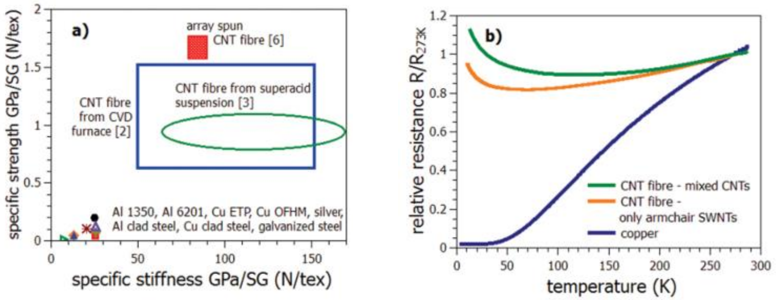
Table 5. Different additives in the multifunctional application.

Additives	Reinforcement	Sensing	Actuation	Self-healing	Thermal	Electrical
Carbon fibers	++	++	+	+	—	+
Carbon nanotube	++	++	++	—	++	++
Graphene, GO	++	++	++	+	+++	+++
Glass fibers	++	—	—	—	—	—
Hollow fibers	++	—	—	++	—	—
Cellulose nanofibers/ nanocrystals	++	—	—	+	+	+
Quaternized tunicate cellulose nanocrystals	++	—	—	+	—	—

Notes: The symbol '+' represents the quality of the function the additive imparts to the composite; '—' means no literature related to this functional application of the additive has been reviewed in this study.

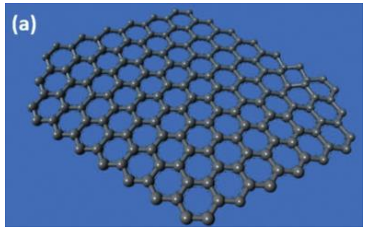


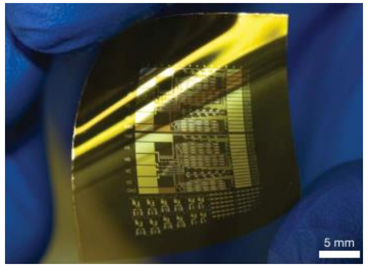
M. Syduzzaman, Results in Materials, 2025



A. Lekawa-Raus, Advanced Functional Materials, 2014

- **Stiffer**, **lower-mass** detectors enabled by increasing **integration** with **multi-functional components** made with new material technologies
  - **Nanotubes**, **Carbon** (CNT) or Boron-Nitride (BNNT)
    - High **strength/stiffness-to-weight** ratio, good **thermal, electrical** conductivity
  - **Graphene:** e.g. for lightweight, robust PCB substrates
  - **Hybrid textile** composites (different fibers woven together to provide distinct capabilities)

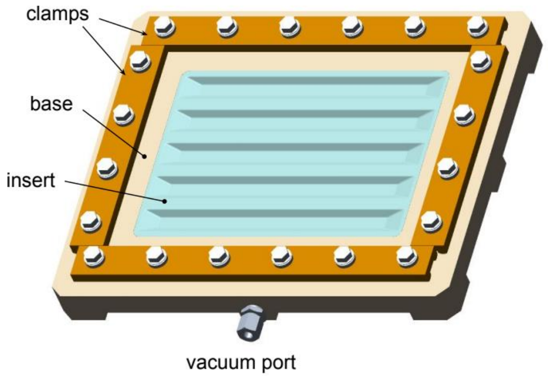


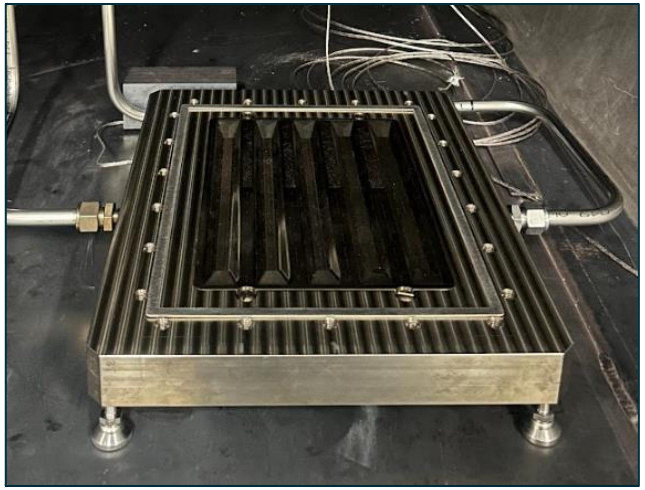


Q. Cao, Nature, 2008

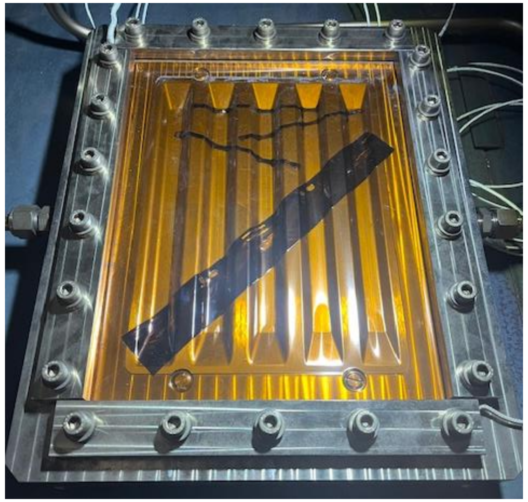
Thermoforming

Towards Ultra-Low Mass



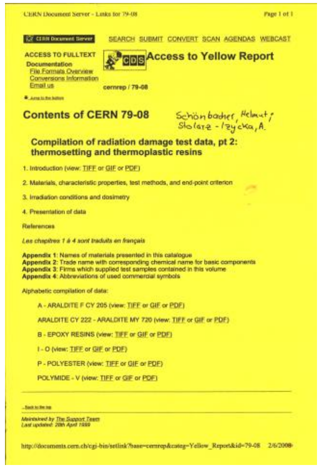


- Formed **polyimide** (a.k.a. "**Kapton**") films can produce **stable**, **high-performance complex** polymer **shapes** with precise control of **mass**
- Not as stiff as CFRP, but promising in ultra-low mass detector applications:
  - Easily-formed **shapes** for detector structures with two directions of **curvature**
  - Formed shapes for Cu/Kapton or Al/Kapton **cables** (traces)
    - Multifunctional: incorporates services in the structure
    - Material development needed for flexes to withstand forming temperatures
  - **Corrugated cores** for use in ePIC detector support panels
- Work in progress at **LBNL** to assess/develop **capabilities**



Material Characterization

Radiation effects



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Contents of CERN 79-08

Schönbacher, Helmut; Stolarz - Izycka, A.

Compilation of radiation damage test data, pt 2: thermosetting and thermoplastic resins

1. Introduction (view: TIFF or GIF or PDF)
2. Materials, characteristic properties, test methods, and end-point criterion
3. Irradiation conditions and dosimetry
4. Presentation of data

References

Les chapitres 1 à 4 sont traduits en français

Appendix 1: Names of materials presented in this catalogue
Appendix 2: Trade name with corresponding chemical name for basic components
Appendix 3: Firms which supplied test samples contained in this volume
Appendix 4: Abbreviations of used commercial symbols

Alphabetic compilation of data:

A - ARALDITE F CY 205 (view: TIFF or GIF or PDF)
ARALDITE CY 222 - ARALDITE MY 720 (view: TIFF or GIF or PDF)
B - EPOXY RESINS (view: TIFF or GIF or PDF)
I - O (view: TIFF or GIF or PDF)
P - POLYESTER (view: TIFF or GIF or PDF)
POLYMIDE - V (view: TIFF or GIF or PDF)

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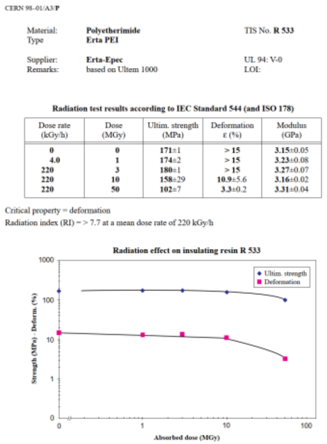


CERN 98–01/A3/**P**

Material: **Polyetherimide** TIS No. **R 533**
Type **Erta PEI**

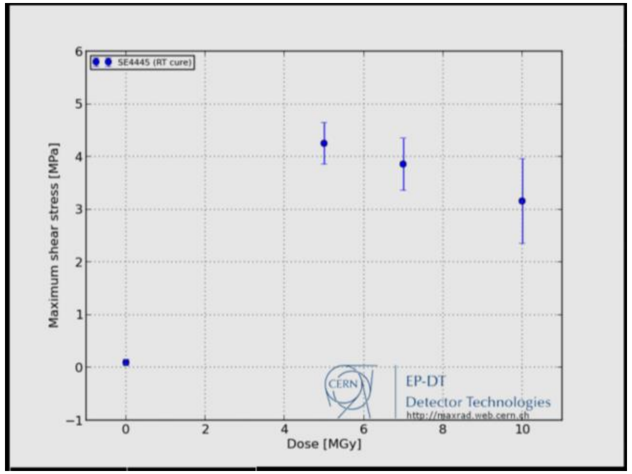
Supplier: **Erta-Epec** UL 94: V-0
Remarks: based on Ultem 1000 LOI:

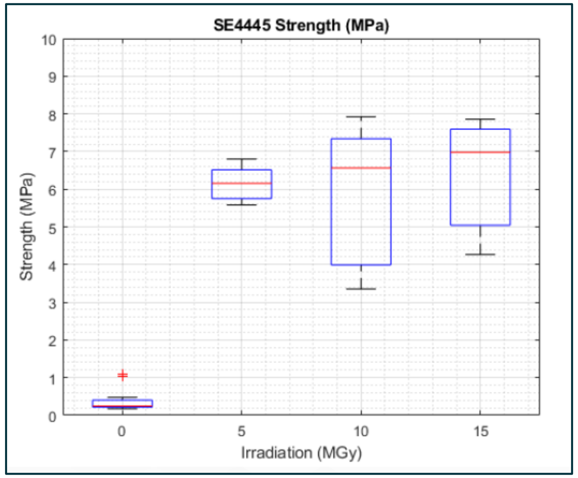
Radiation test results according to IEC Standard 544 (and ISO 178)

Dose rate (kGy/h)	Dose (MGy)	Ultim. strength (MPa)	Deformation ε (%)	Modulus (GPa)
0	**0**	**171**±1	**> 15**	**3.15**±0.05
4.0	**1**	**174**±2	**> 15**	**3.23**±0.08
220	**3**	**180**±1	**> 15**	**3.27**±0.07
220	**10**	**158**±29	**10.9**±5.6	**3.16**±0.02
220	**50**	**102**±7	**3.3**±0.2	**3.31**±0.04

Critical property = deformation
Radiation index (RI) = > 7.7 at a mean dose rate of 220 kGy/h

Radiation effect on insulating resin R 533

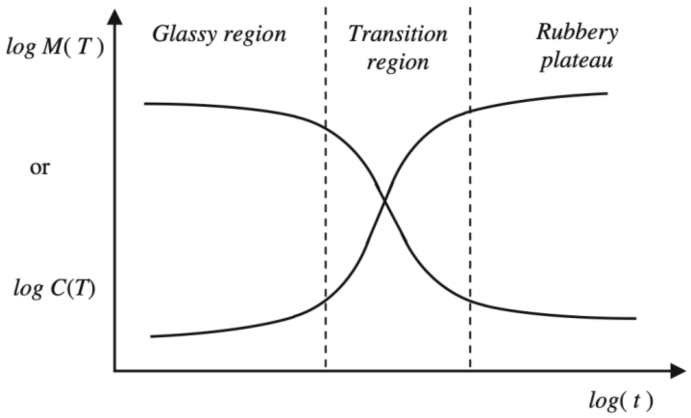




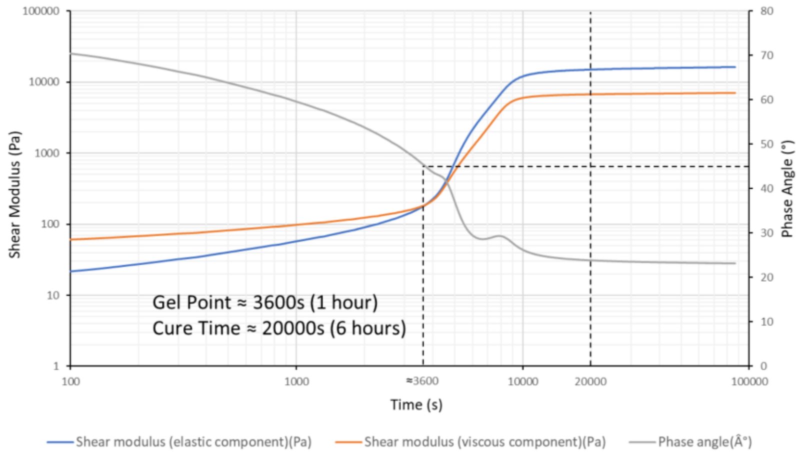
- CERN **Yellow Reports** dating from 1979 thru 2001—some results up to 50 MGy, many only to 7 MGy and typically only report **strength**
  - May need **modulus** or other properties (multi-directional?), and data at **lower radiation** doses
  - Nobody else will measure this for us – these radiation doses do not apply to other fields…
- Data for **Gamma** Ionizing radiation most **relevant** for **Plastics** and Composites, **neutron** data relevant when approaching fractional **DpA**
- MaxRAD *https://maxrad.web.cern.ch/maxrad/index.php*, is a recent **DB** at CERN intended to collect new **radiation** data for **materials**

Elastomers

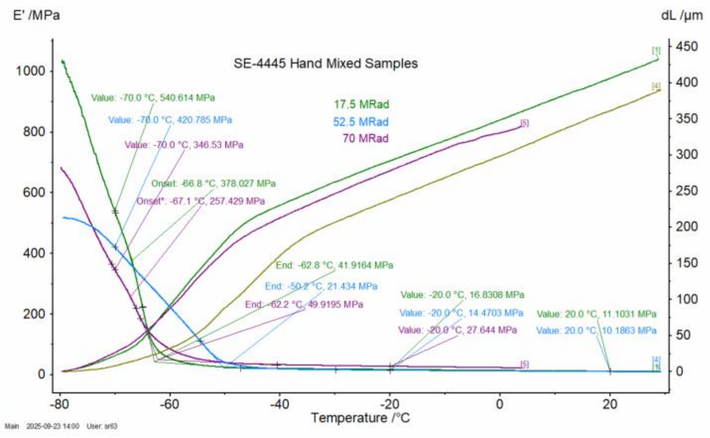
New material properties needed



D. Gutierres-Lemini, Springer, 2014



B. Corbett, Internal Report, 2023



S. Robertson, Internal Report, 2025

- Some of the materials used in detectors **cannot** be completely **described** by the usual mechanical **models**
  - We might need **more** material **properties**: e.g. **frequency**/time **dependent** response in elastomers, also strongly dependent on applied **radiation, temperature…**
- This might be especially relevant for some of the glues we are using
  - See for example ITk **strips 'interposer'** solution **(see A. Fortman talk):** strongly dependent on glue **properties**
- It might be important to have a larger **'portfolio**' of **glues**, we might need them in the future…
- Effort **coordination** strongly required, both here and for **global mechanic materials** to avoid duplicated efforts

Outline

01

Future Particle Detectors Mechanics

02

Emerging technologies for support structures

03

Emerging technologies for global mechanics materials

04

Conclusion

Summary

Multiple **accelerators** are being **considered** for future construction

- They involve different **collision rates** and **species**, potentially leading to very different **requirements**
- A major **goal** will be **mass** reduction, with very challenging **cooling**, **servicing** and **radiation hardness requirements**

We have highlighted some **technologies** that could help facing these challenges:

- **MAPS** for low mass, **silicon** strain **gauges** for SHM, distributed/conductive **cooling**, **carbon conductors** for lighter services, **thermoformed polyimide** for very low mass structures, **advanced CFRP** solutions for mass/stability, **multi-functional** components merging portions of the material budget

Collaboration now could enable better designs in the future:

- E.g. Transfer learning **ML**, **material** characterization (and in particular **radiation** effects) will require coordinated efforts to address limited resources