TRACKER MECHANICS R&D AT ANL

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Forum on Tracking Detector Mechanics

Tracking detectors – solid state

- High granularity is needed to achieve high spatial resolution & high radiation resistance. Lepton colliders require high granularity and small pixel size in the innermost region, and a broader area covered with pixel devices.
  - Pixel size ~10 μm
  - Large distributed system:
    - Low noise, low power electronics
    - Low mass integration (mechanics and cooling)
    - Large volume of data transmission (interconnection, data processing →intelligent tracker)
- Hadron colliders: all of the above + O(1ps timing) and radiation resistance up to fluences of the order of $10^{18} n_{eq}/cm^2$

Marina Artuso

Snowmass 2021 IF Report

Tracking detectors – solid state

- High granularity is needed to achieve high spatial resolution & high radiation resistance. Lepton colliders require high granularity and small pixel size in the innermost region, and a broader area

IF03-1 Develop high spatial resolution pixel detectors with precise per-pixel time resolution to resolve individual interactions in high-collision-density environments

IF03-2 Adapt new materials and fabrication/integration techniques for particle tracking in harsh environments, including sensors, support structures and cooling

IF03-3 Realize scalable, irreducible-mass trackers in extreme conditions

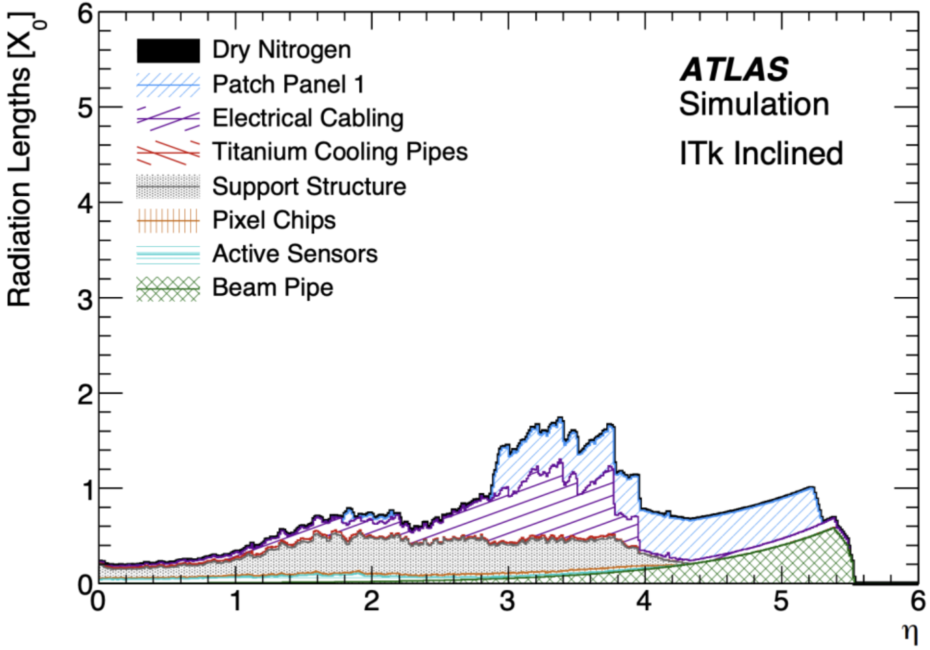
IF03-4 Push advanced modeling for simulation tools, developing required extensions for new devices, to drive device design.

- Hadron colliders: all of the above + O(1ps timing) and radiation resistance up to fluences of the order of $10^{18} n_{eq}/cm^2$

MATERIAL BUDGET

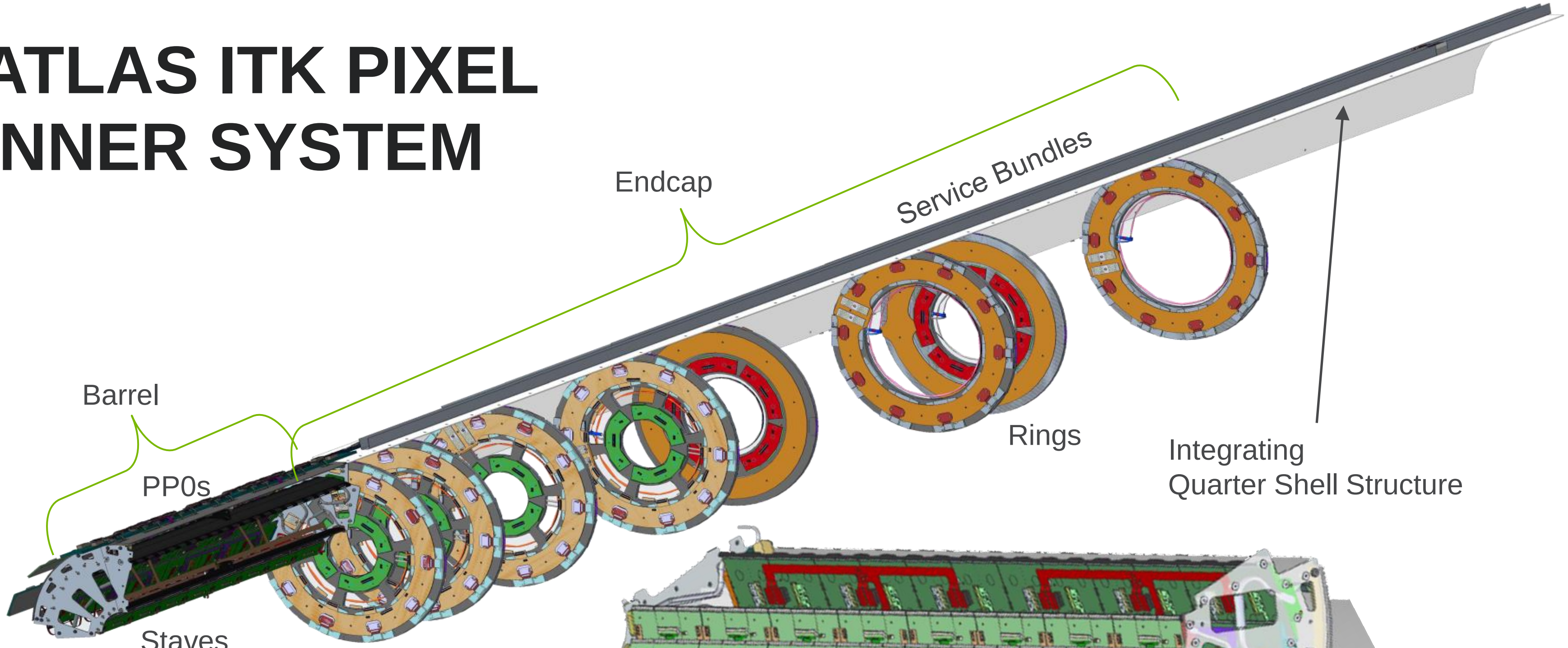
IF03-3 Realize scalable, irreducible-mass trackers in extreme conditions

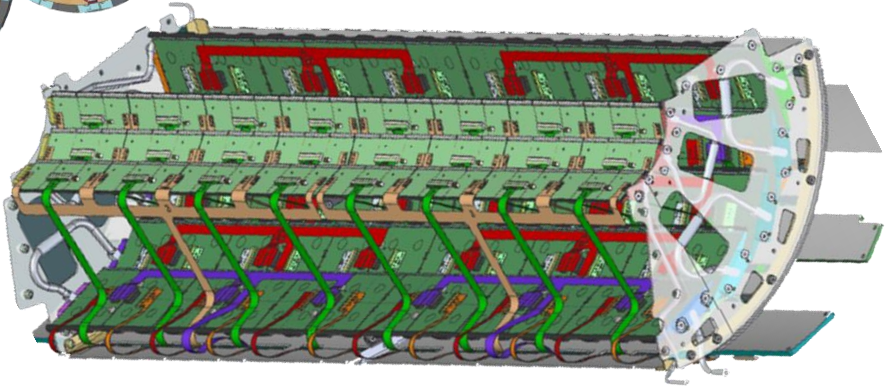
- Improving precision = reducing material budget, esp. inactive material
  - Non-negligible amount of this comes from support structures
    - Important to optimize the mechanics and cooling



CURRENT WORK: ITK PIXEL MECHANICS

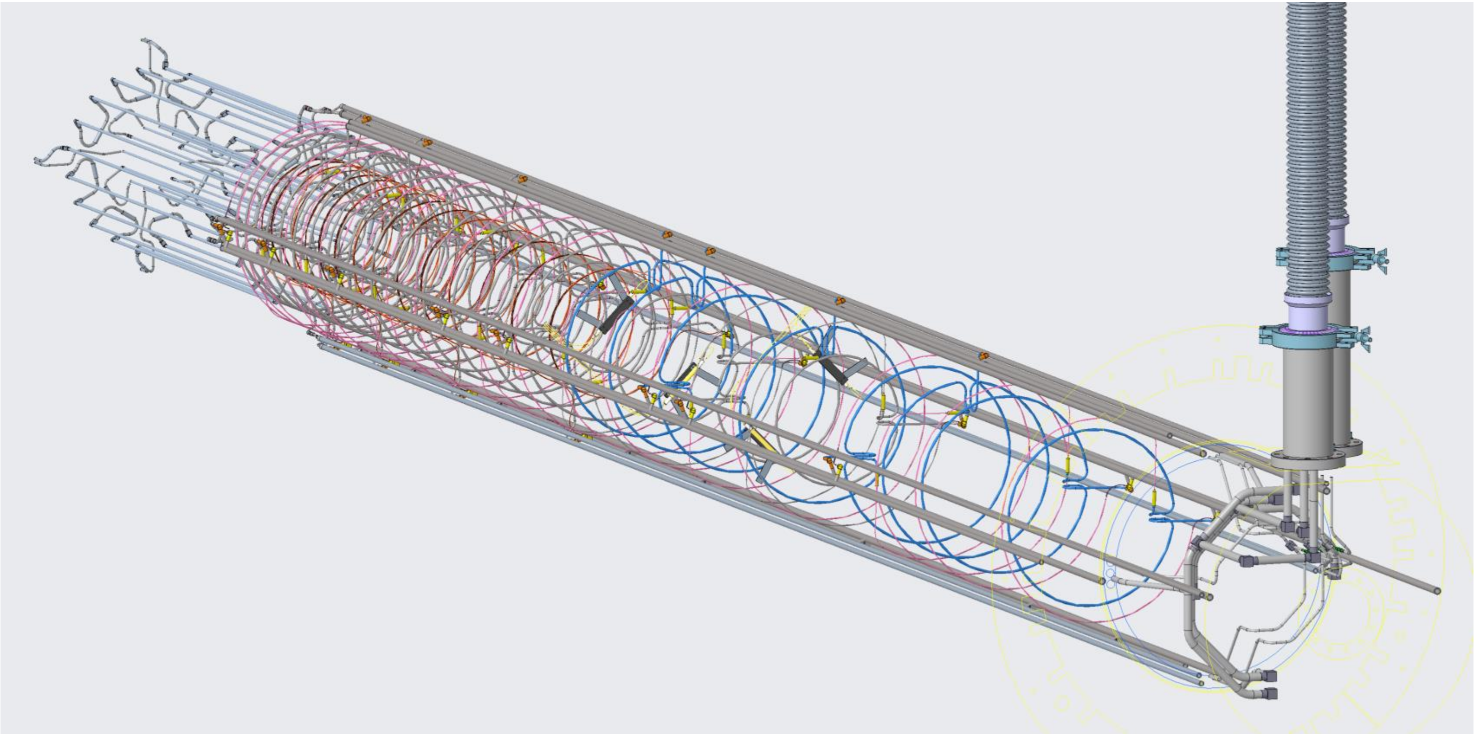
ATLAS ITK PIXEL INNER SYSTEM





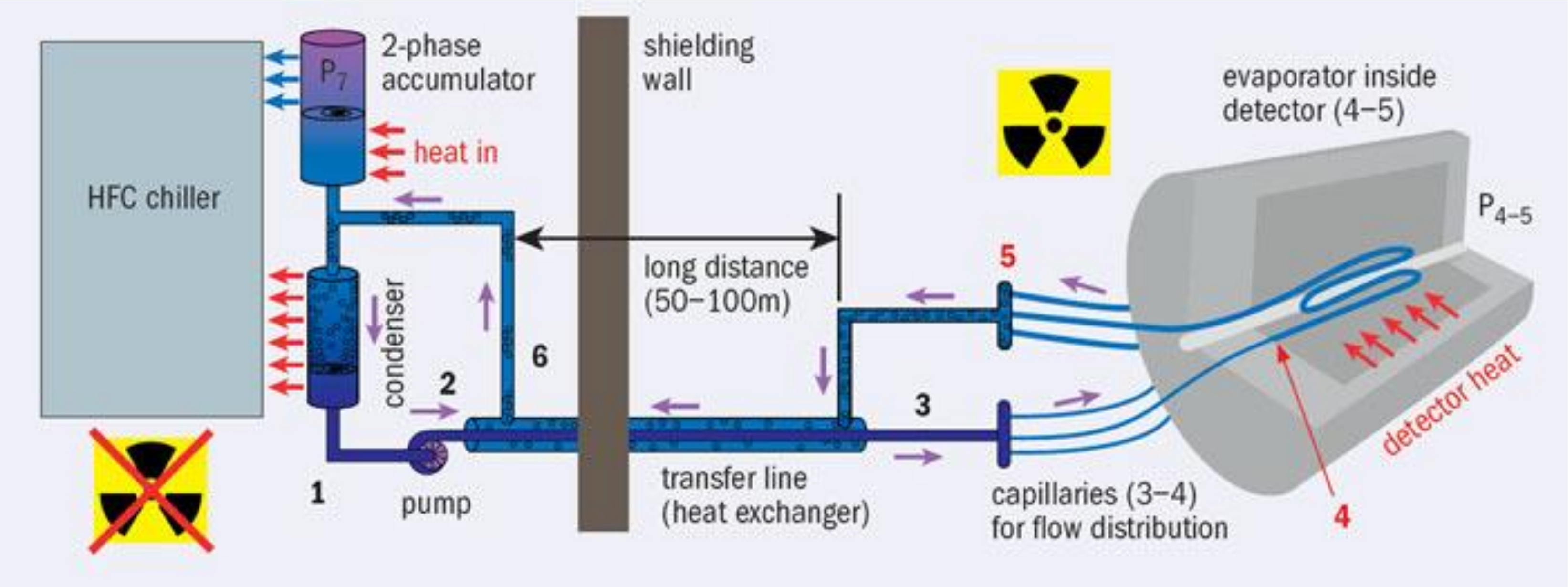
ATLAS ITK PIXEL INNER SYSTEM (IS) COOLING

200+ meters of titanium cooling tubes – built at ANL



CERN Courier

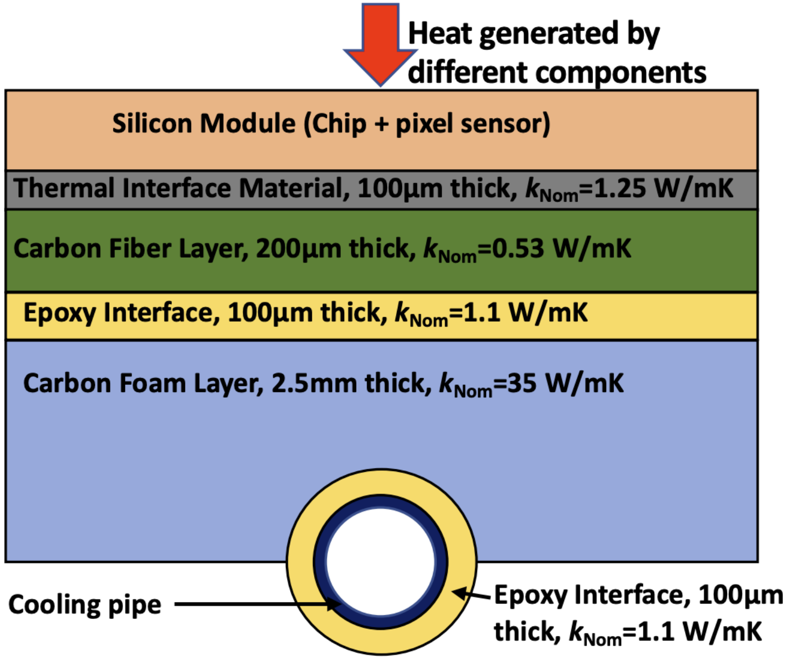
TWO-PHASE CO_2 COOLING

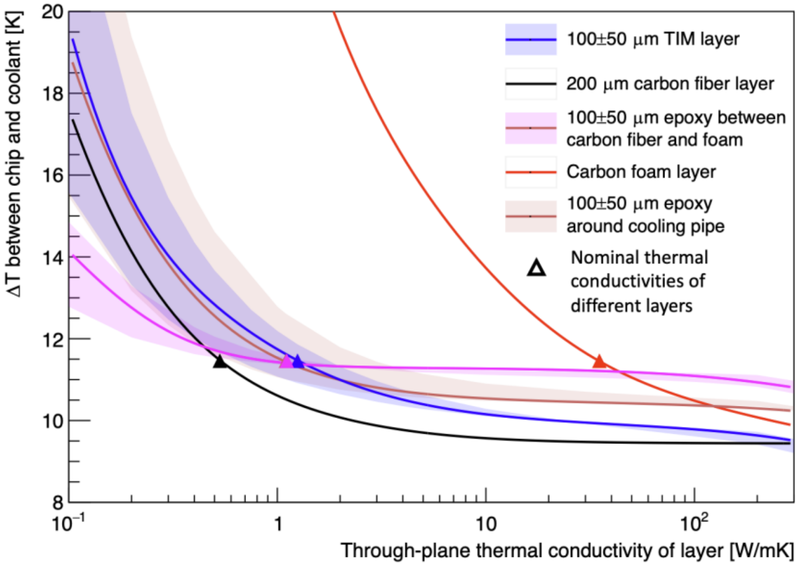


arXiv:2203.14347v1

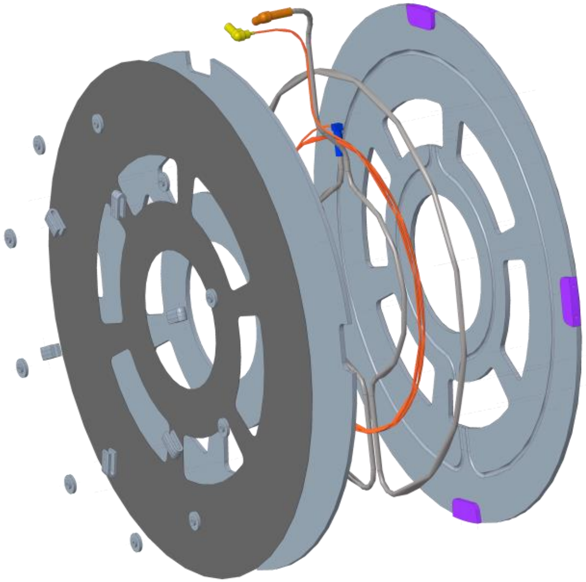
DETECTOR COOLING

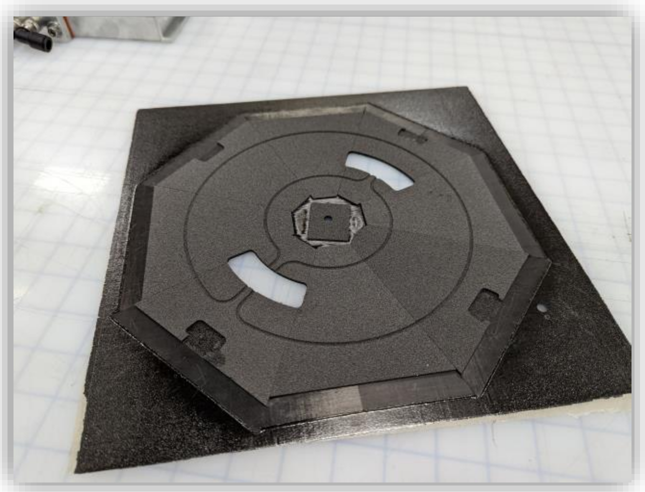
Thermal conductivity of support structures important

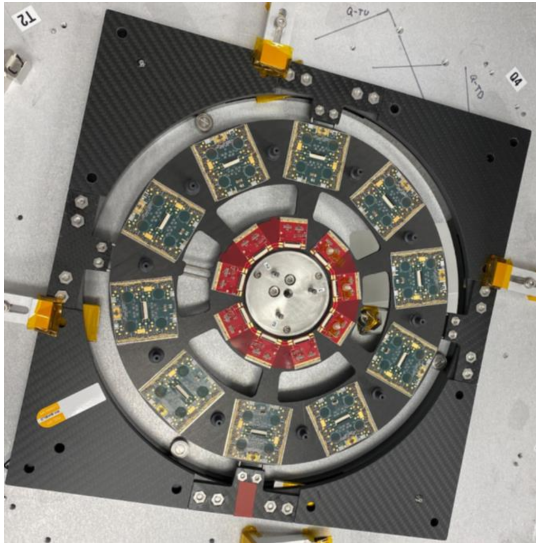




ATLAS ITK PIXEL IS COOLING & LOCAL SUPPORTS



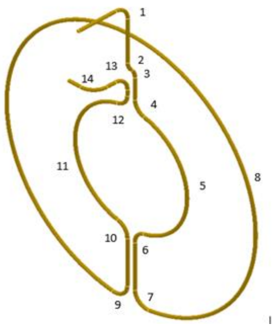




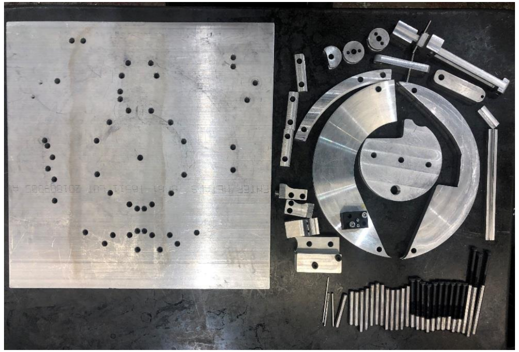
LIMITATIONS
Due to small spaces

- Complex geometries
- Time consuming bending, weld qualification, welding, annealing, etc
- Long lead times: custom tubes, carbon foam from defense contractors, laser welding vendors

- How do we make this more scalable, more granular, and even smaller?



Bending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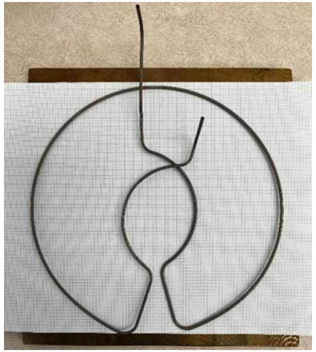
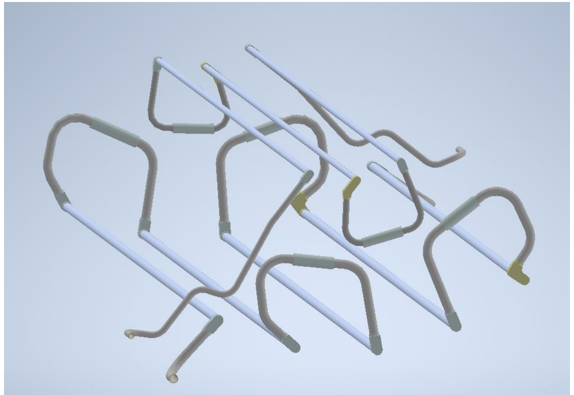
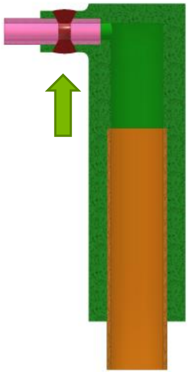

Annealing


Many flavors of cooling tubes

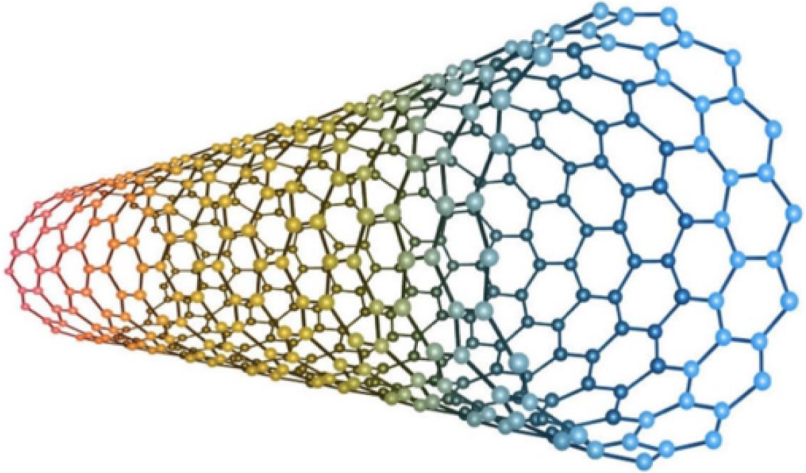

Laser welding ~1 mm welds

DETECTOR R&D AT ANL: EARLY IDEAS

NANOMATERIAL RESEARCH AT ANL

Zach Hood

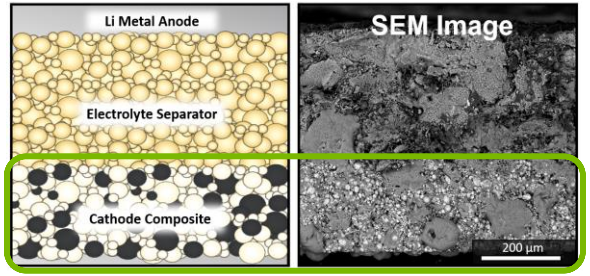
Carbon Nanotubes (CNTs) for solid state devices



CNTs: rolled-up graphene sheets

- Single layer of carbon atoms
- Diameter ~nm, length ~µm

Engineering Cathode Composites for Solid-state Li Metal Secondary Batteries



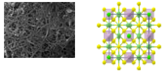
Desirable cathode composites must have:

- ➢ High electronic and ionic conductivity
- ➢ High capacity (e.g. >160 mAh/g)

Multi-walled carbon nanotubes have desirable properties to increase the electrical conductivity of solid-state cathode composites

Synthesis:

Mix Precursors



Carbon nanotubes | Solid-state electrolyte

→ Mill

→ "Dry" Cast → Press Cathode

NANOMATERIAL RESEARCH AT ANL

Zach Hood

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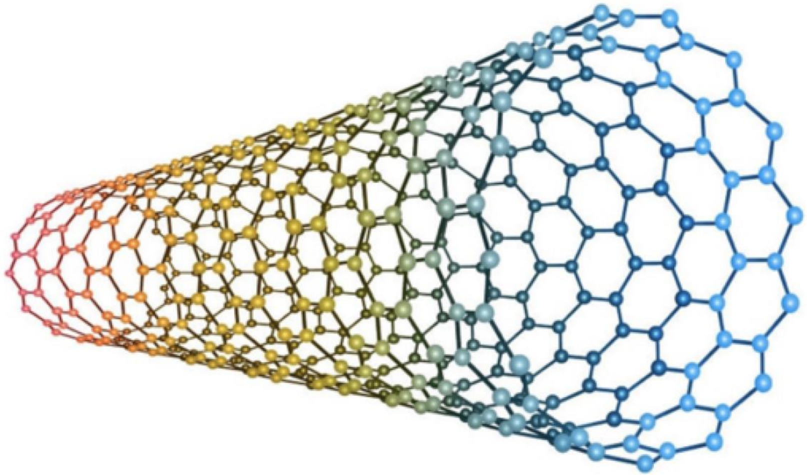

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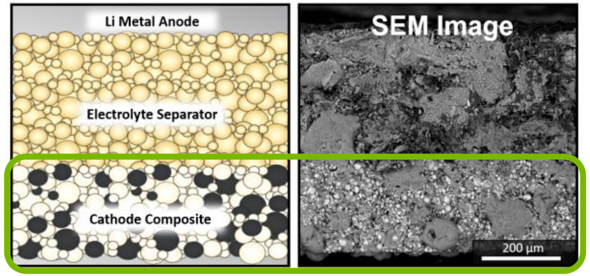

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High conductivity

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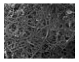
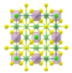


Carbon nanotubes



Solid-state electrolyte

Mill

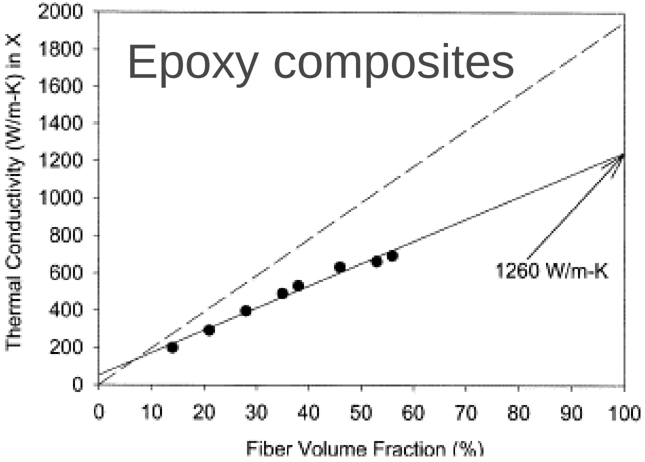
"Dry" Cast

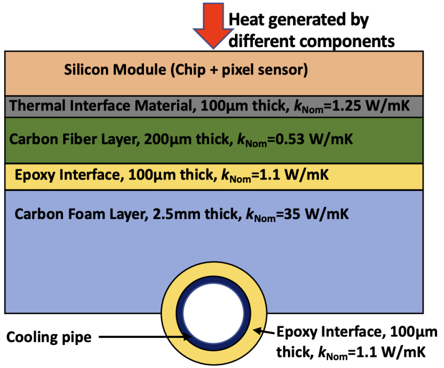
Press Cathode

doi:0.1016/S0008-6223(01)00112-9
doi:10.1016/j.progpolymsci.2010.11.004
doi: 10.1039/D2EE00279E
LBNL CNT Cooling

APPLICATIONS TO HEP DETECTORS

- Synthesis of new composites
- Epoxy matrix composites - high thermal conductivity
- Carbon nanotubes, etc
  - High thermal conductivity
  - Non-absorbent
  - Film can be sprayed onto composites
  - Possible use for embedded cooling channels
  - Bond directly to active detector material for cooling?
- To investigate: radiation hardness, strength, material budget, scaleability, chip and services integration





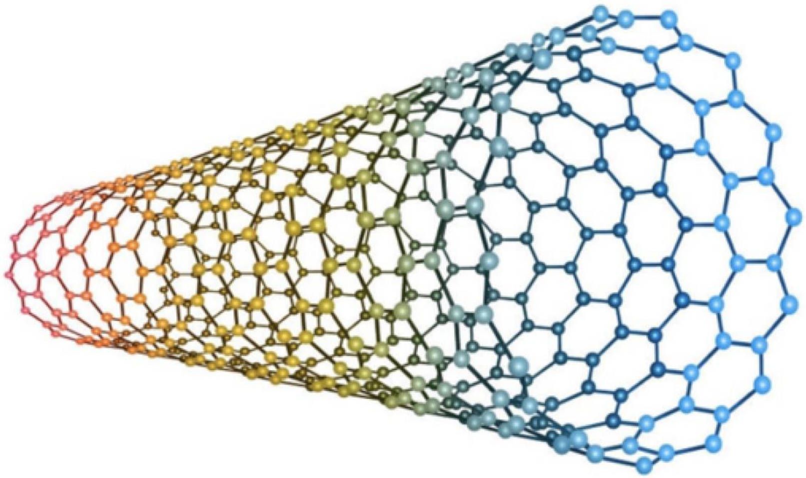
ATLAS-TDR-030

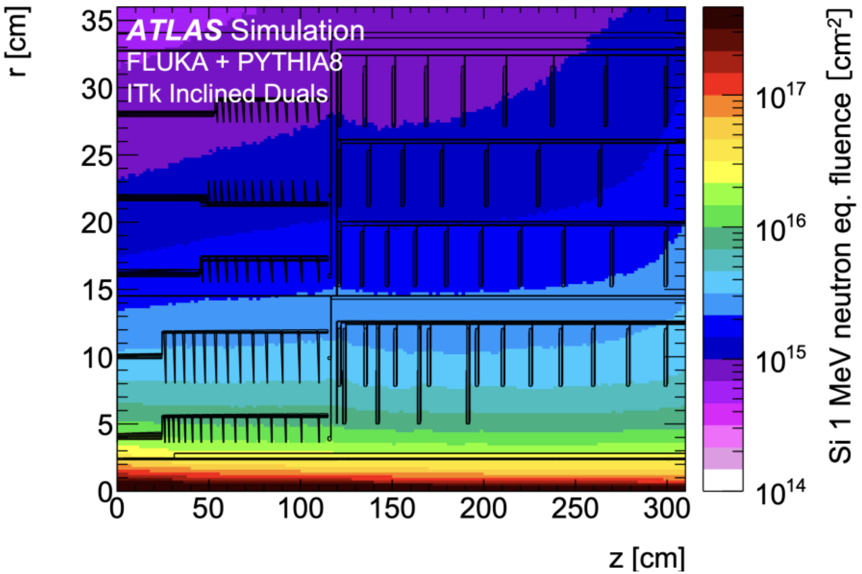
Embedded Computing

MaxRAD CERN Database

RADIATION HARDNESS

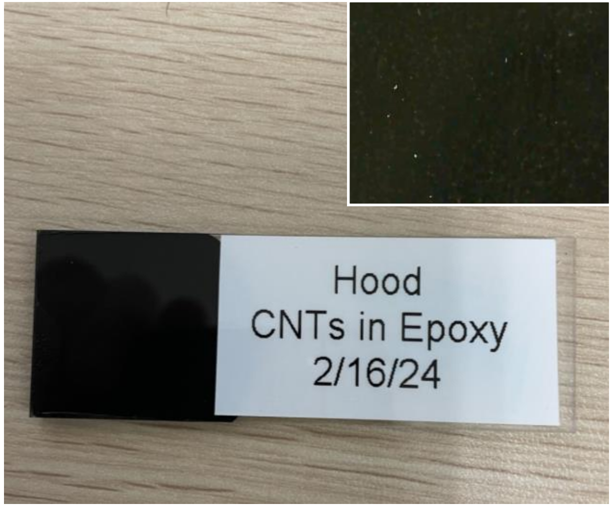
- Carbon nanomaterials ☑
- Epoxies ☑
- Composites to be checked



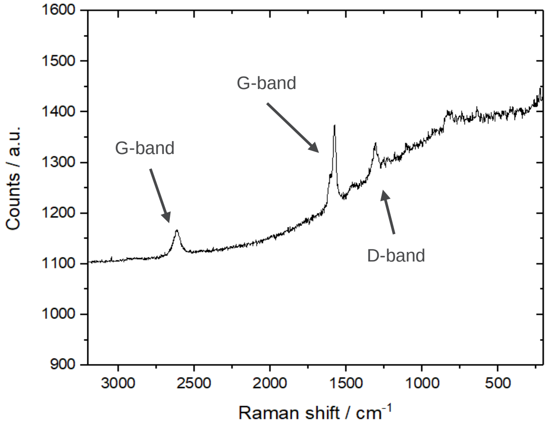


EPOXY-CARBON NANOTUBES COMPOSITE FILMS

Epoxy Composites Fabrication



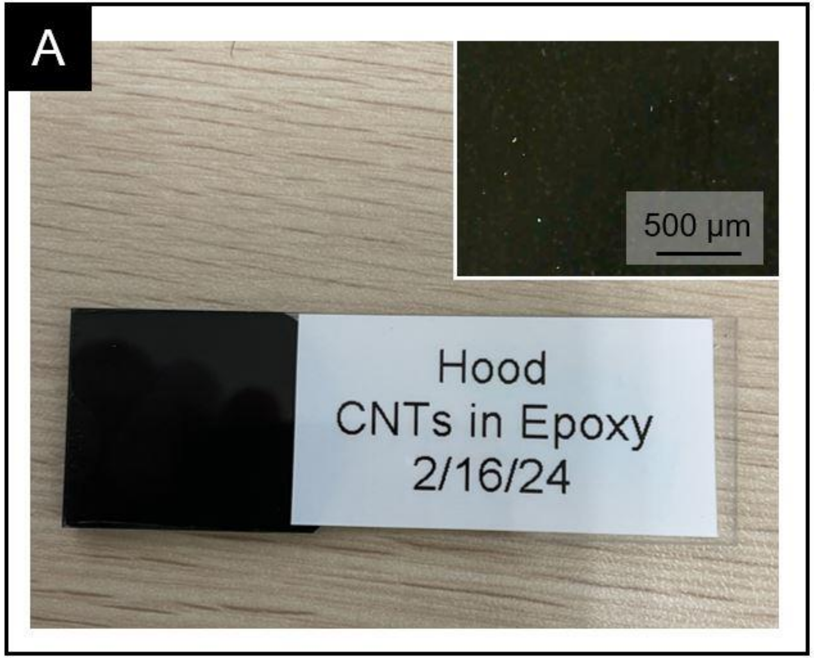
Raman Analysis

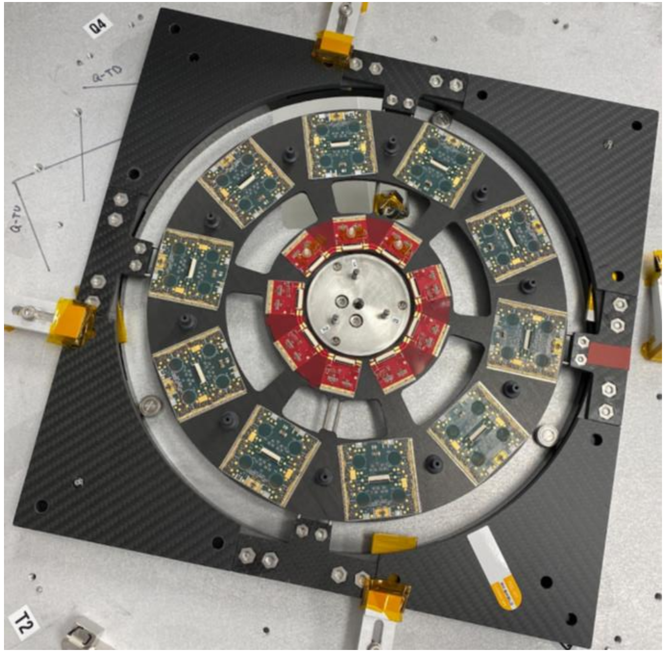


- **Epoxy-carbon nanotube composites can be formed with high throughput without degradation of the carbon structure; future studies will evaluate the thermal properties of these composites**

NEXT STEPS: MECHANICAL STRENGTH

Can we support the active detector material and maintain stability?





NEXT STEPS: SCALEABILITY

Scale up for a full detector using ANL’s MERF

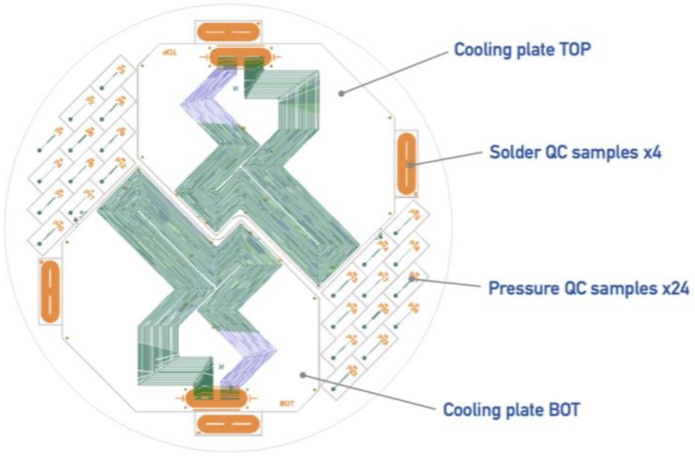
- Slot die coating
  - Equipment with variations < 5% across many meters, and < 50 µm over 100 mm (0.05%)
  - Can be used for roll-to-roll scale-up
  - Deposit epoxy composite onto non-adhering substrate

Roll-to-roll thin film detector: Kim CPAD

COOLING CHANNELS

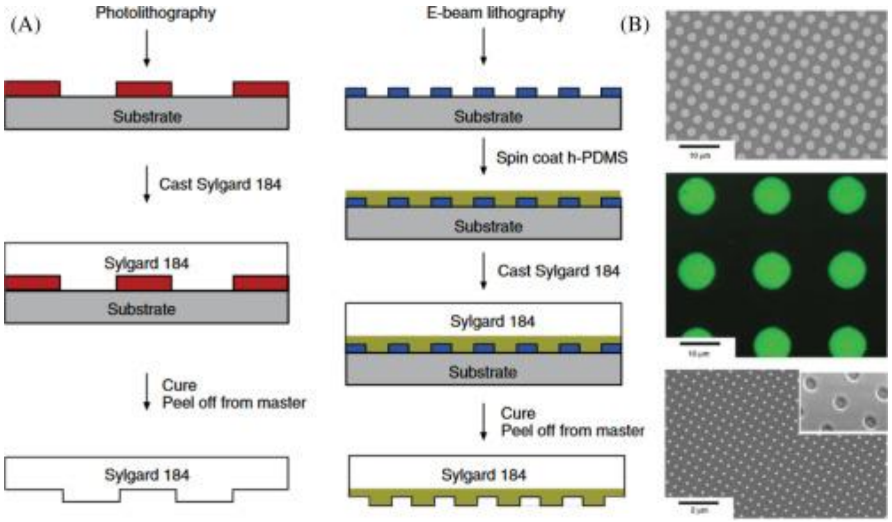
How do we add in cooling?

- [Micro]fluidic channels
- Use well-established soft lithography



LHCb Velo microfluidic channels

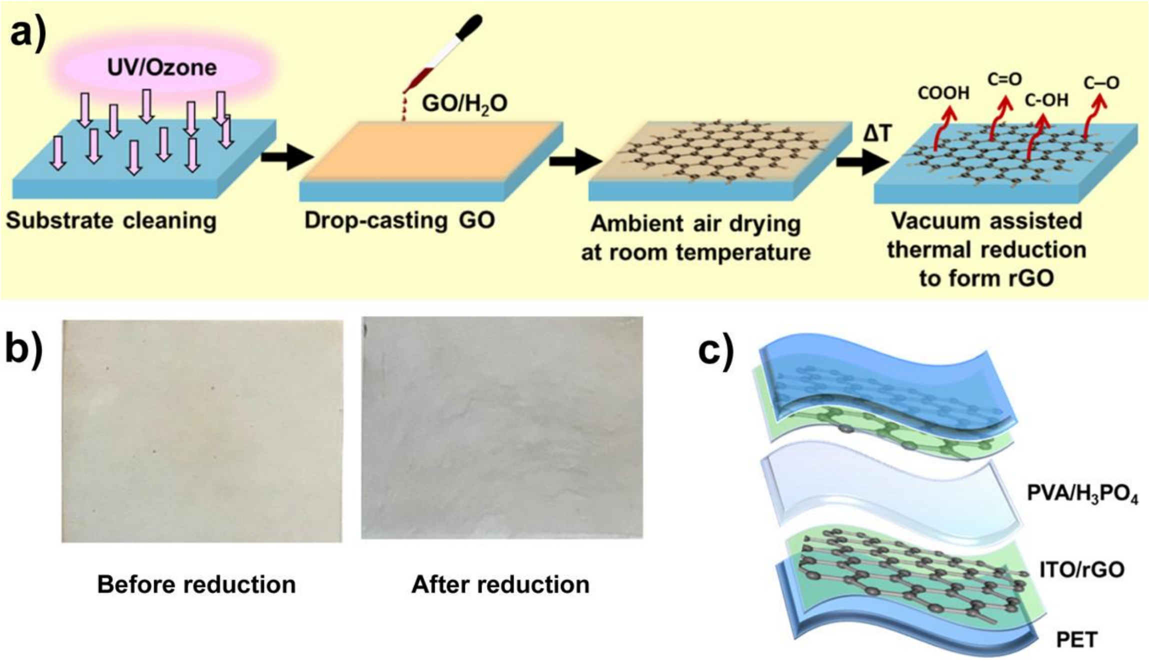
Soft lithography



arxiv:2112.12763

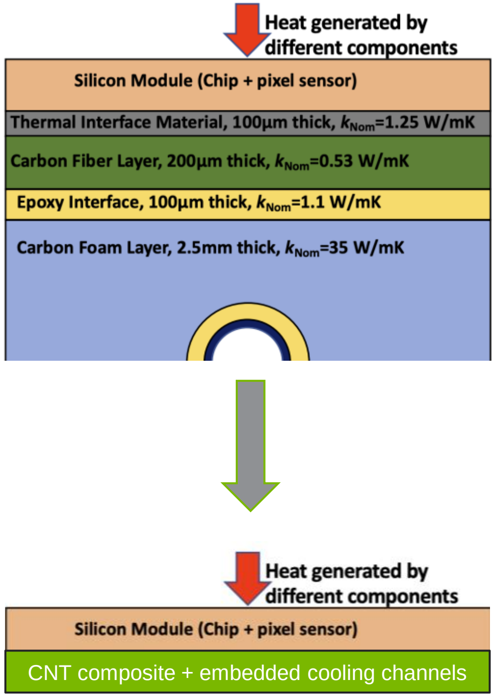
LONGER TERM: INTEGRATE READOUT

Example option: graphene oxide thin-film electrodes for high-performance transparent and flexible all-solid-state supercapacitors



OUTLOOK

How can we leverage materials science research to make **scalable**, multifunctional support structures?



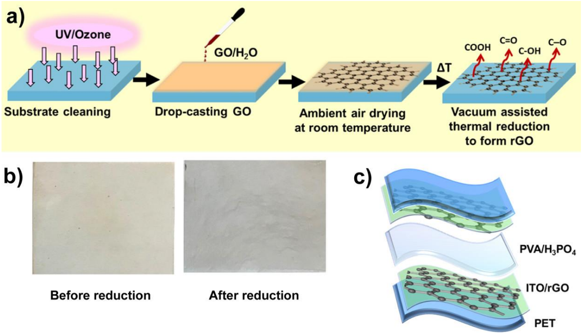
Supports + cooling

Short term goal: reduce material budget of supports

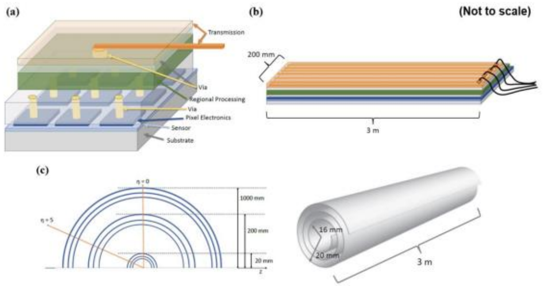
- CNT/epoxy composites with embedded cooling
- Determine properties and applications

Long term goal:

- Incorporate readout electronics (carbon-based?)
- **Fully printable, in-house scalable roll-to-roll detectors**



Thin-film electrodes



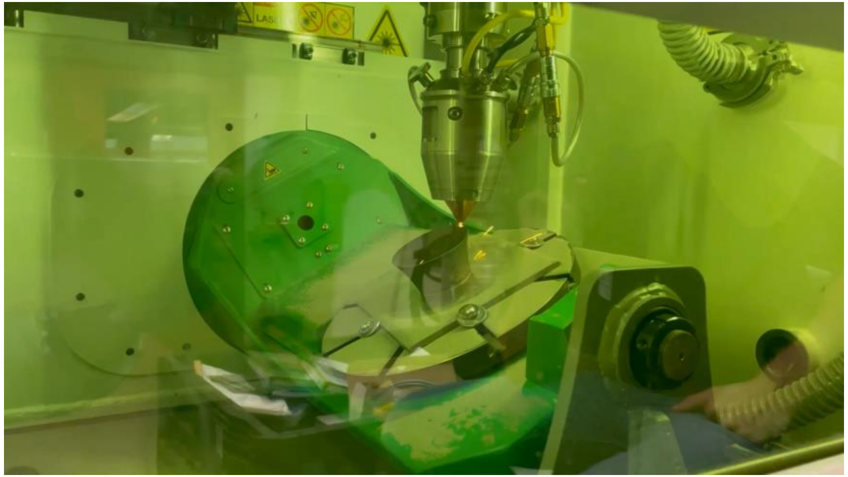
Thin-film roll-to-roll detectors

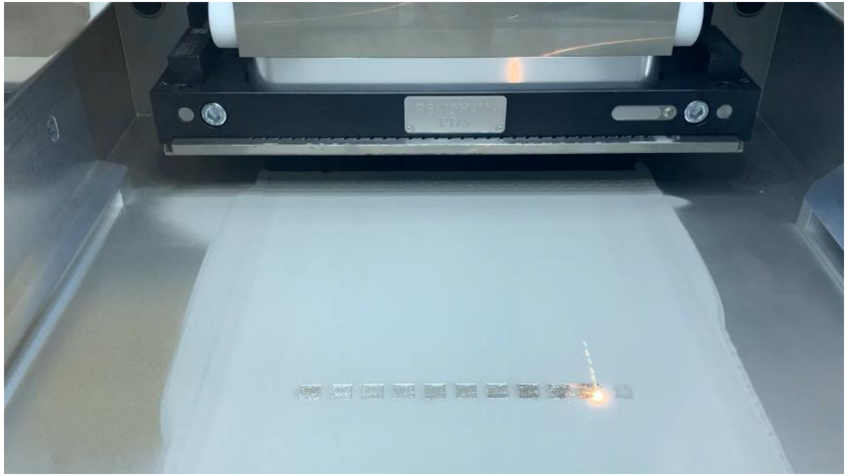
ADDITIONAL MATERIAL

AT ARGONNE: 3D METAL PRINTING

3D PRINTING

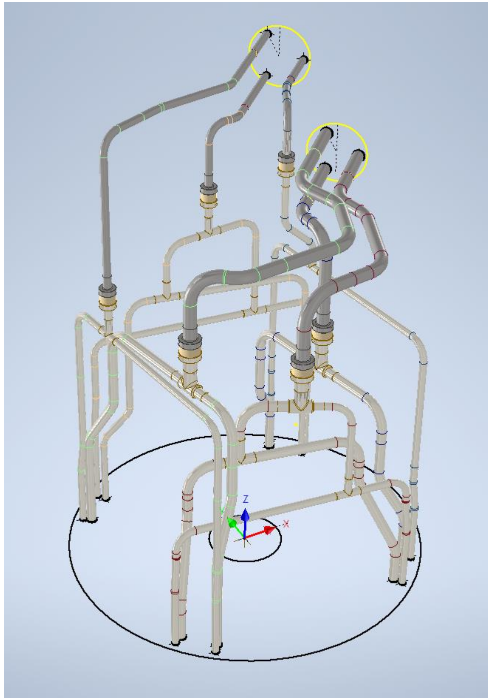
- Advantages:
  - Eliminate welding and machining
  - Enables more complex geometries – needed for tighter spaces
- Considerations: cost, microstructure changes
- At Argonne:
  - 70-micron resolution
  - For microreactors – two different materials on each side
  - Print steels and some nickels; looking into titanium
- More information: ANL Metal Additive Manufacturing

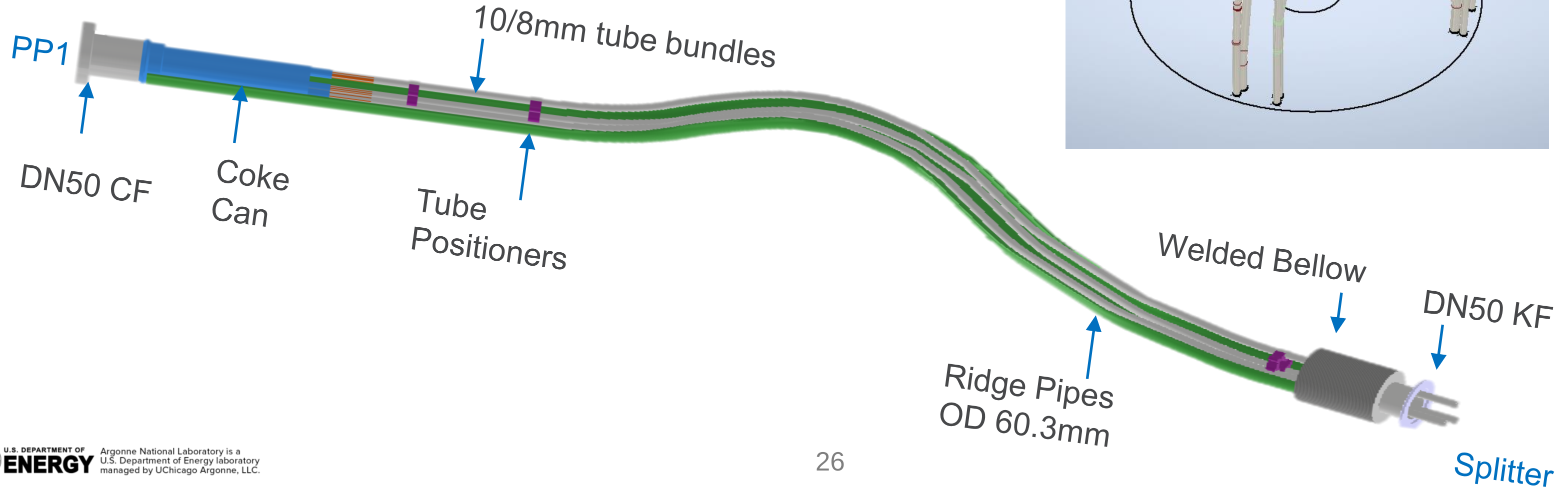




3D PRINTING APPLICATION TO ITK

- Decrease difficulty of distribution piping – can print internal structure

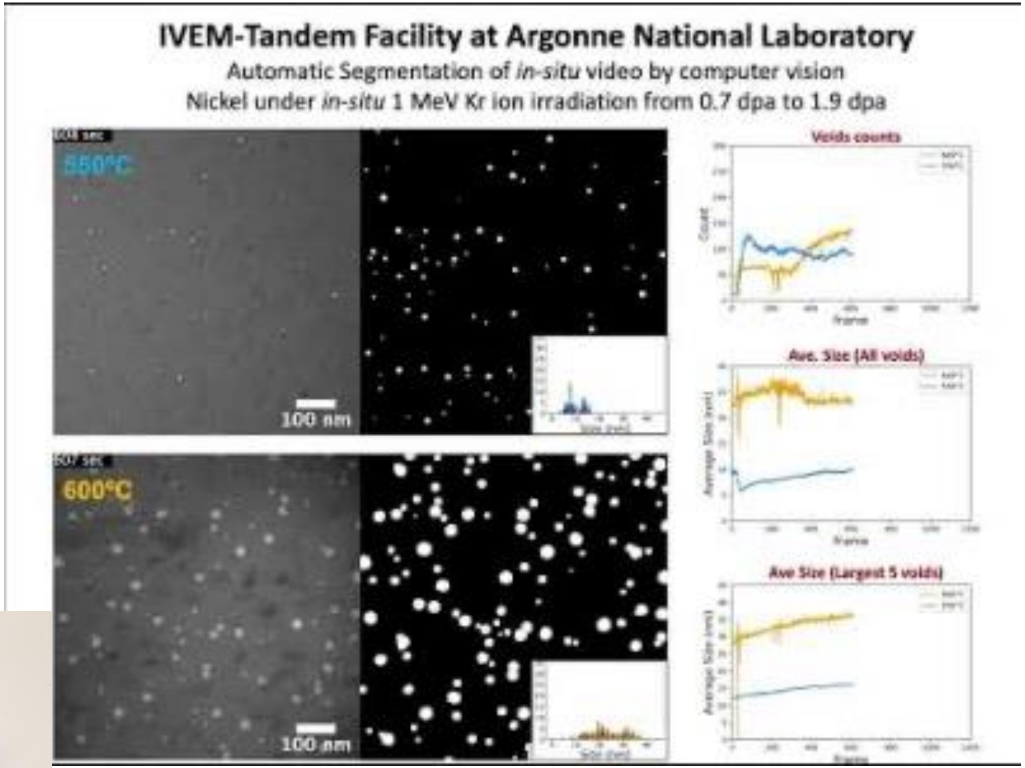


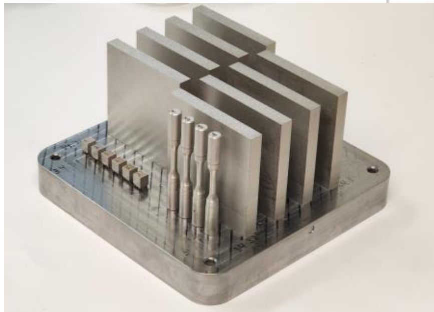


doi:10.1016/j.jnucmat.2021.153469

STRUCTURAL ANALYSIS

- IVEM – Intermediate Voltage Electron Microscope
  - Automated analysis of irradiation-induced voids
  - Individual voids measured frame-by-frame to understand microstructural evolution during irradiation
- Example: comparing printed vs machined “dog bones” after heat treatment and creep tests





AT ARGONNE: STRUCTURE OPTIMIZATION

Gary Hu

TOPOLOGY OPTIMIZATION

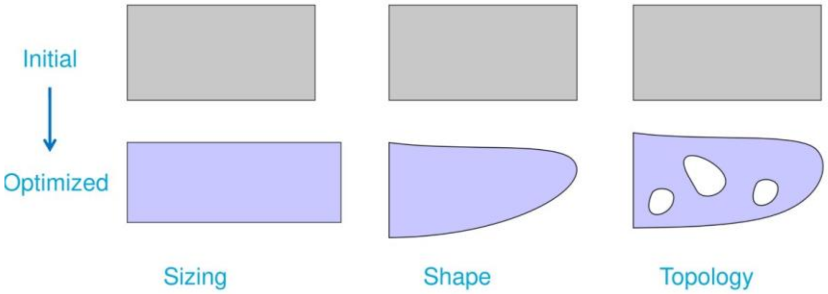
...in one slide

$$s^* = \arg\min_{s \in \mathcal{S}} f\left(\mathcal{M}(x; s)\right)$$

Material model

Objective function

Optimal topology



Typical application

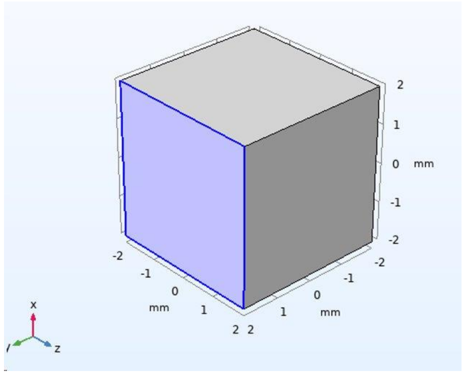
Find the optimal topology of the material to maximize property X subject to constraint Y.

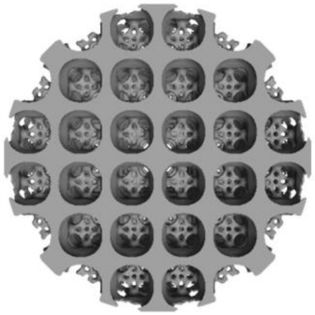
APPLICATION 1

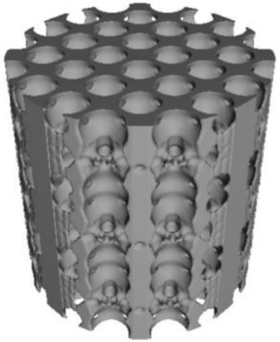
Solar receiver

Objective

Find the optimal topology of the material to maximize the outlet temperature subject to appropriate pressure drop constraints.







APPLICATION 2

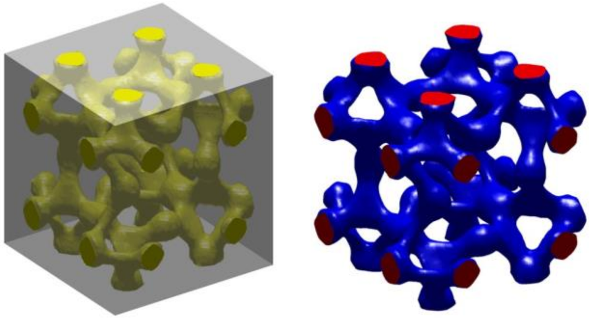
Lattice material

Objective

Find the optimal lattice structure to minimize the coefficient of thermal expansion subject to appropriate stress constraints.

Idea

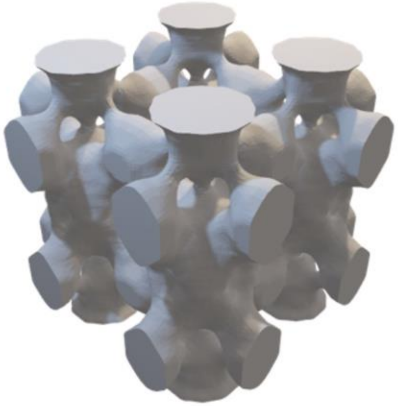
Material A has good thermal stability, while material B has high mechanical strength.
So why don't we mix A with B?



OTHER CONSIDERATIONS

Challenge

Traditional manufacturing techniques have trouble with most of the optimal topologies.



Our solution

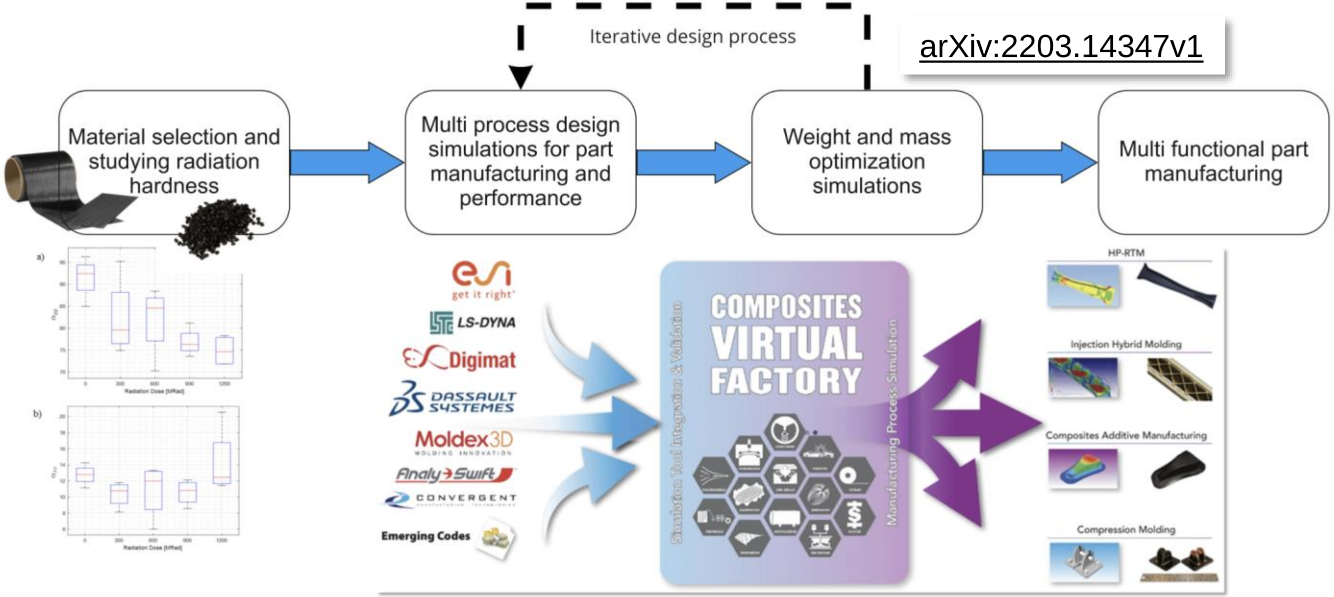
1. Additionally impose printability constraint.
2. Use additive manufacturing.

Other applications

Find the optimal topology/shape of the material to maximize electrical/thermal conductivity subject to stress constraints.

R&D + DESIGN

arXiv:2203.14347v1

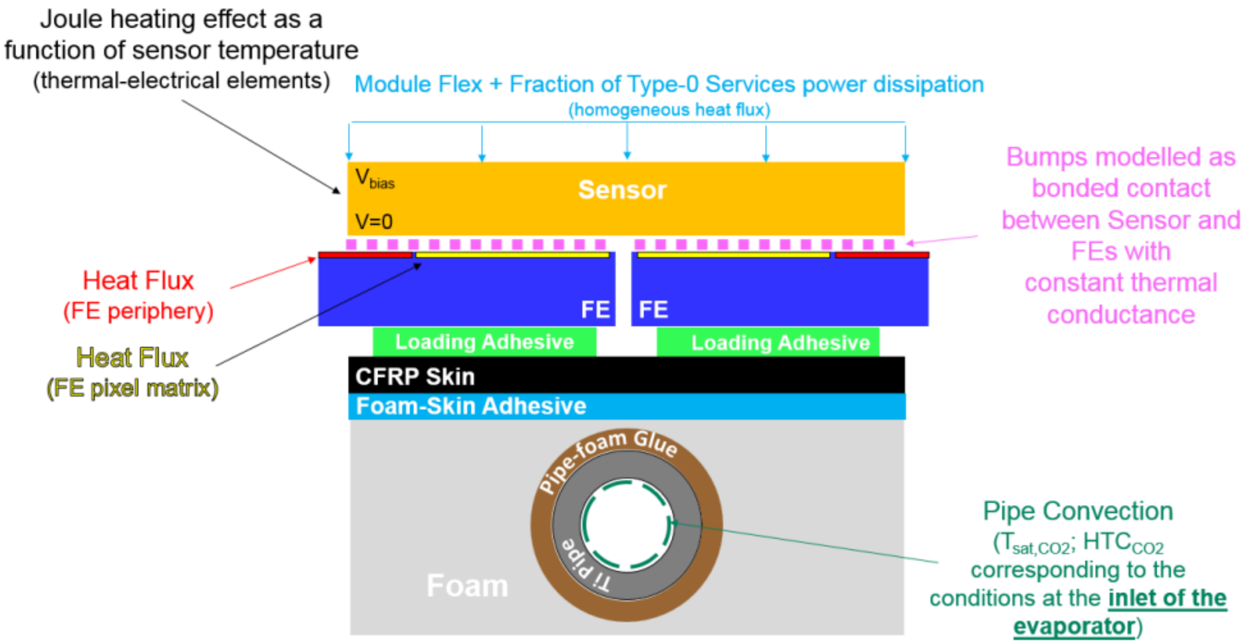


- Add on:
  - Composites R&D
  - Other ANL additive manufacturing and materials science
  - Interfaces between mechanics/cooling + sensors and electronics

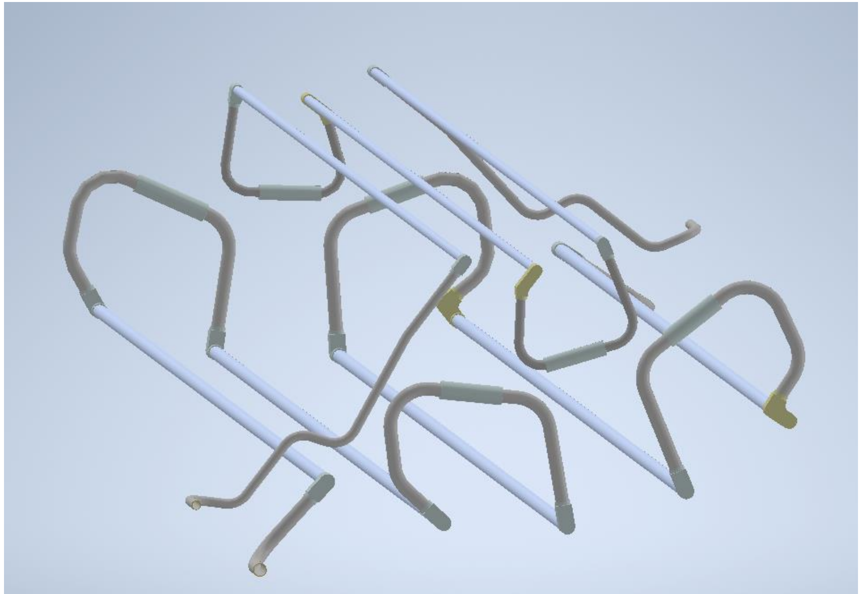
OTHER BACKUP

TWO-PHASE CO_2 COOLING

Low-mass evaporative cooling option

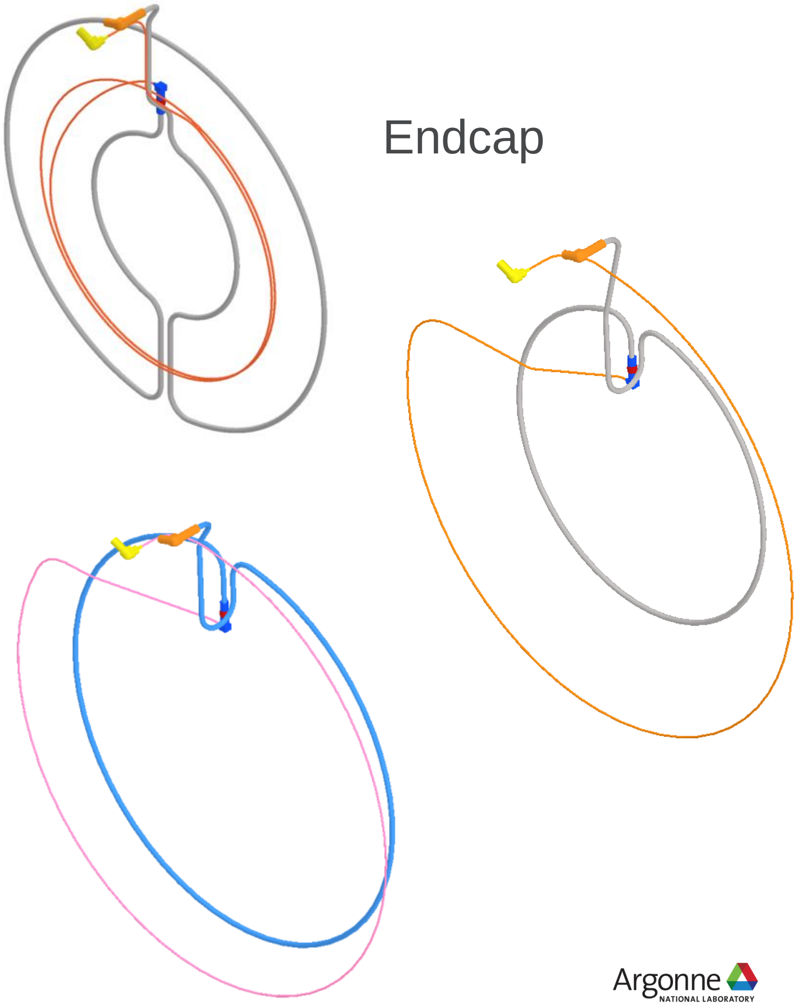


31 FLAVORS OR SO



Barrel quarter – 8 unique flavors

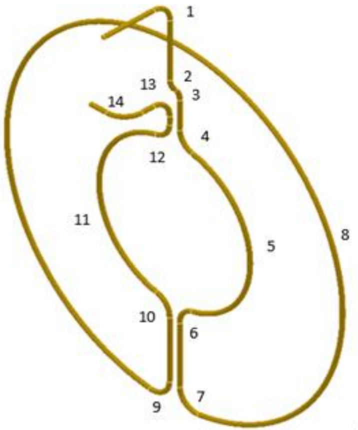
Endcap

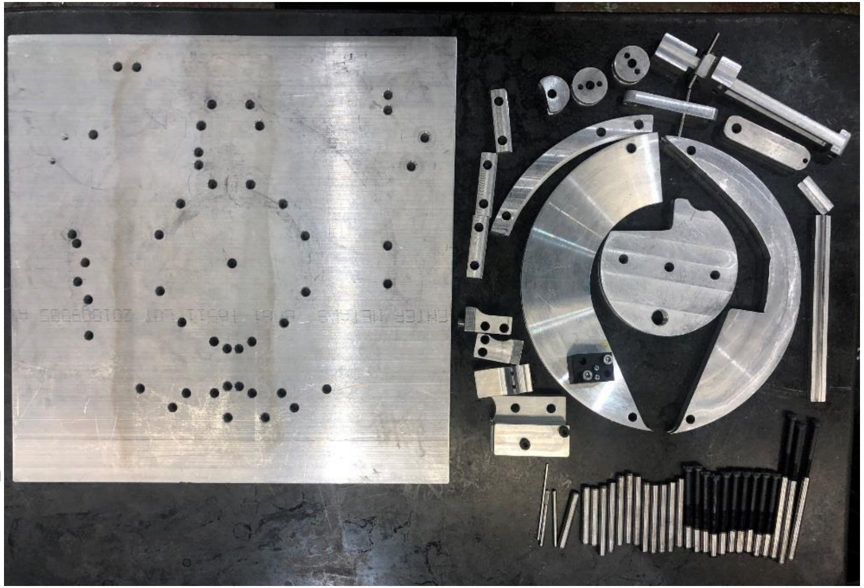


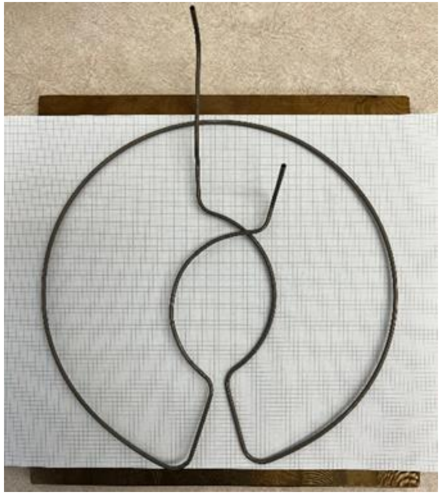
HOW IT'S BUILT

Barrel

- 14 bends, then annealing to hold shape





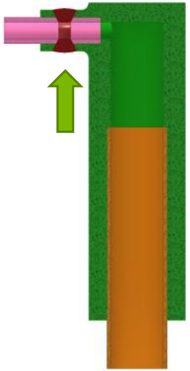


HOW ITS BUILT

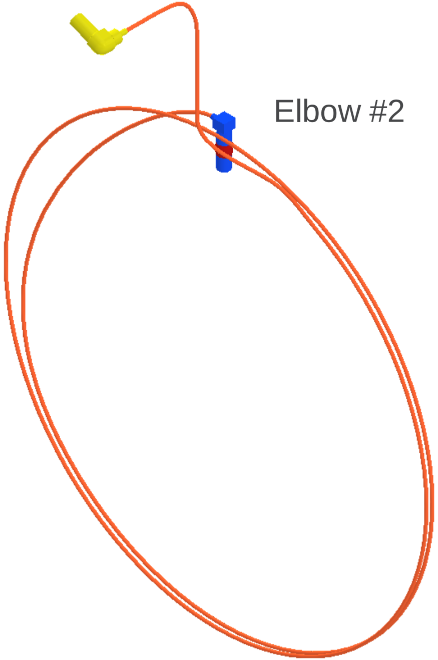
Barrel

- Constrained spaces require laser welding

Vendor laser welds elbows to capillary

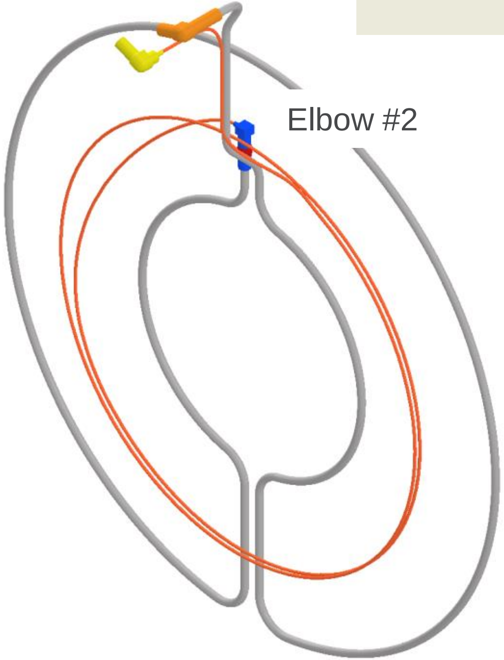


Elbow #1

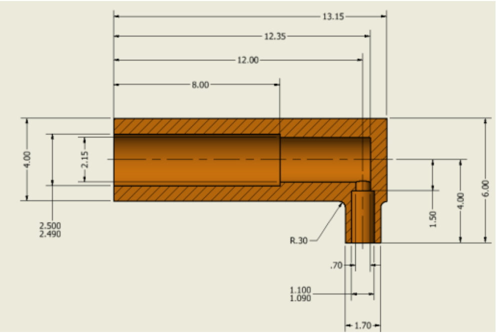


Elbow #2

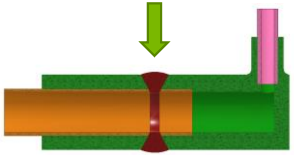
Elbow #3



Elbow #2

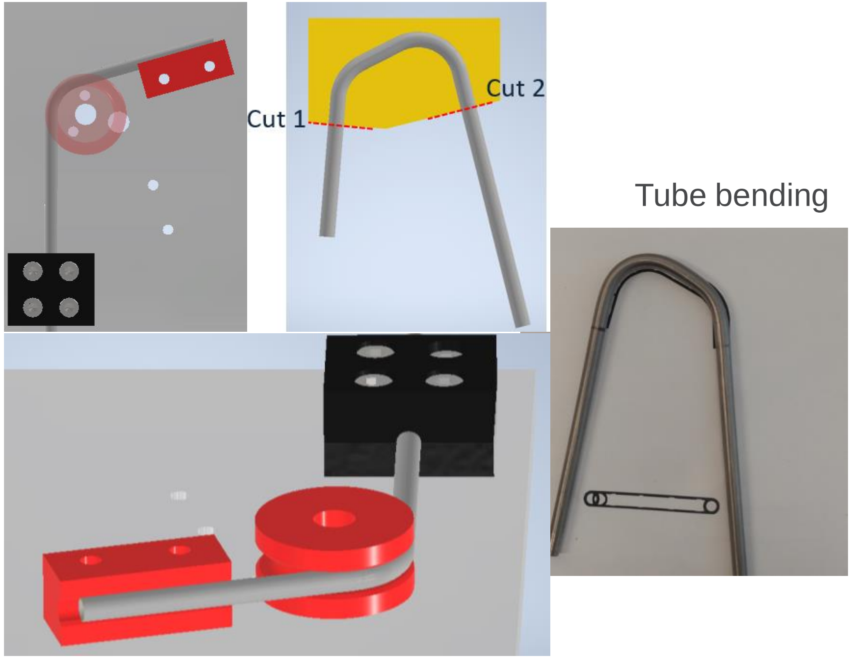


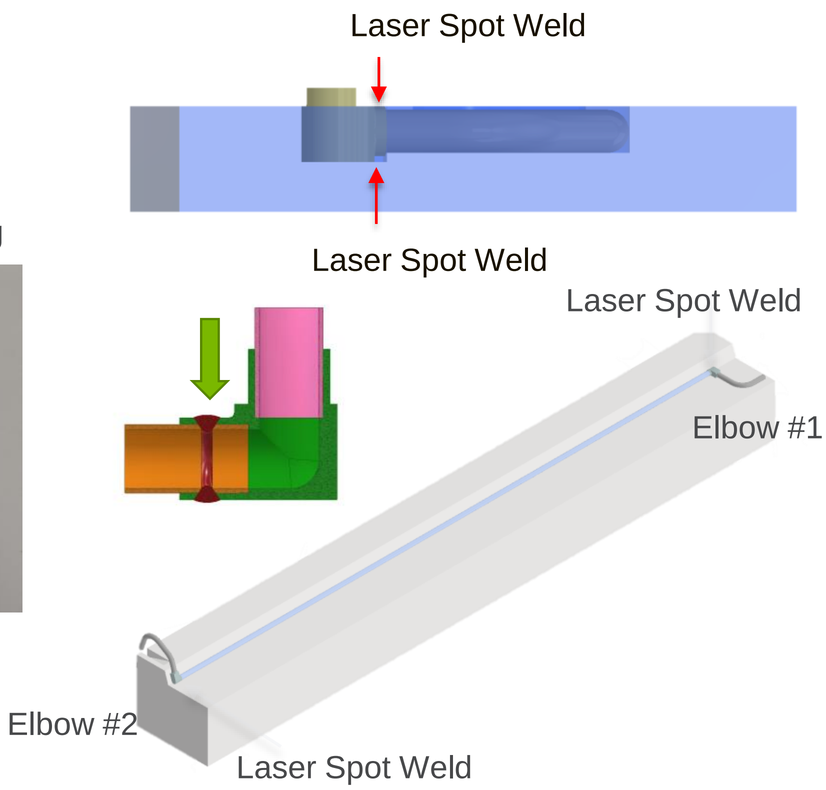
In-house orbital welding of elbows to evaporator



HOW ITS BUILT

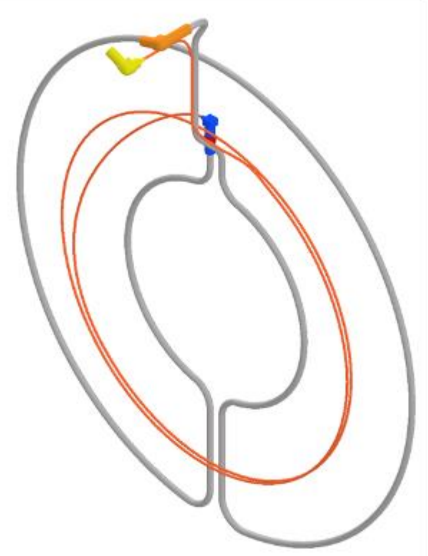
Endcap

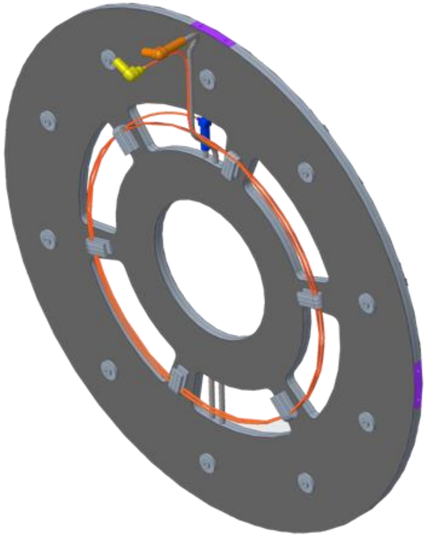


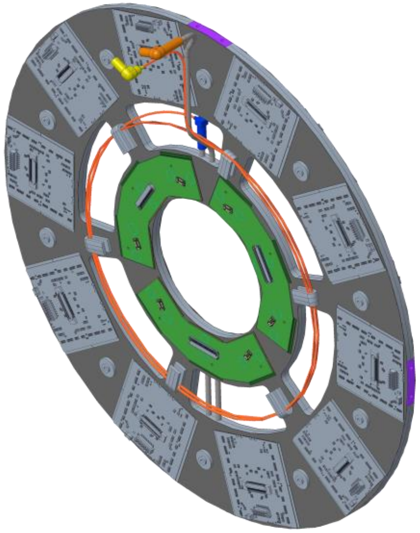


LOCAL SUPPORTS PRODUCTION MODEL

Cooling Tube Assemblies	Bare Local Supports		Loaded local Supports
Fabrication ANL →	Fabrication LBNL →	Testing UMass →	Loading SLAC

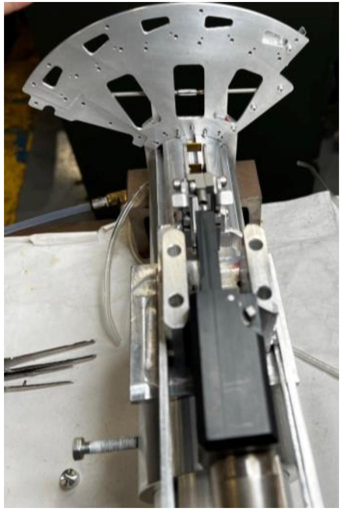


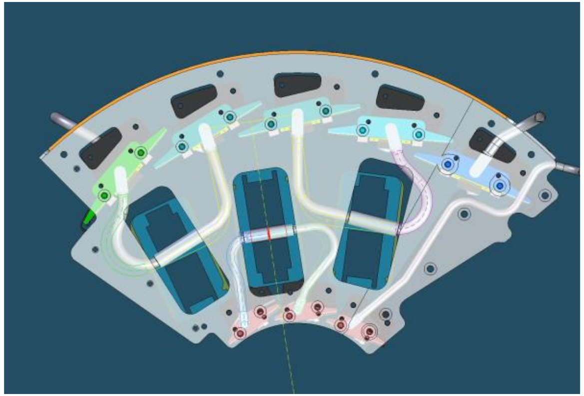


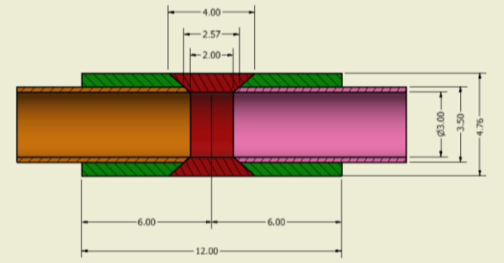


INTEGRATION AT SLAC

- Barrel staves orbital welded at SLAC
- Developed custom welding fixture

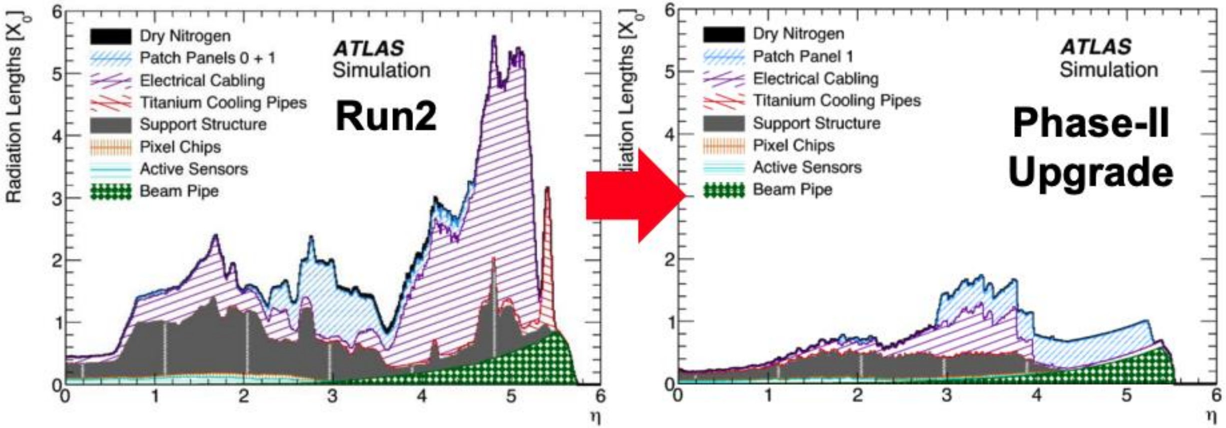






TRACKING DETECTOR R&D

"Invisible" detectors for Higgs



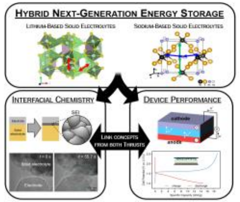
- Community goal: < 0.1% X0 per detector layer
  - Large portion of community focused on the active sensors
  - **My focus – cooling pipes and support structures**

RESEARCH OVERVIEW

Zach Hood

Advanced Electrochemical Materials (AEM)

Advanced Solid-State Electrolytes and Membranes for Next-Generation Batteries

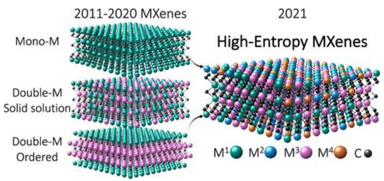


- Synthesis and processing of sulfide-, oxide-, and polymer-based solid-state electrolytes and their composites
- This thrust is expected to enable future solid-state battery architectures with more room for cathode volumes and reduce processing temperatures and costs

References:

1. Z.D. Hood, H. Wang, A. Samuthira Pandian, J.K. Keum, and C. Liang. *Journal of the American Chemical Society*, 138(6), 1768-1771.
2. M. Balaish, J.C. Gonzalez-Rosillo, K.J. Kim, Y. Zhu, Z.D. Hood, J.L.M. Rupp. *Nature Energy*, 6(3), 227-239.
3. Z.D. Hood, X. Chen, R. Sacci, G. Veith, X. Liu, Y. Mo, J. Niu, N.J. Dudney, M. Chi. *Nano Letters*, 21, 151-157.
4. E.C. Self, Z.D. Hood, T. Brahmbhatt, F.M. Delnick, H.M. Meyer, G. Yang, J.L.M. Rupp, J. Nanda. *Chem. Mat.*, 32, 8789-8797.

New Two-Dimensional Materials and Heterostructures for Electrocatalysis

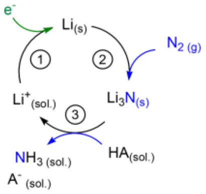


- Synthesis and processing of two-dimensional transition metal carbides and nitrides (known as MXenes)
- This thrust is expected to enable more efficient electrocatalysts that have higher faradaic efficiency and selectivity towards specific reactions

References:

1. S.K. Nemani, B. Zhang, B.C. Wyatt, Z.D. Hood, S. Manna, R. Khaledialidusti, S.K. Sankaranarayanan, and B. Anasori. ACS Nano, 15(8), 12815-12825.
2. S.P. Adhikari, Z.D. Hood, K.L. More, V.W. Chen, and A. Lachgar. ChemSusChem, 14, 1869-1879.
3. T. Su, Z.D. Hood, M. Naguib, L. Bai, S. Luo, C.M. Rouleau, I.N. Ivanov, H. Ji, Z. Qin, Z. Wu. ACS Applied Energy Materials, 2, 4640-4651.

Decarbonized Electrochemical Processes for Industrial Manufacturing

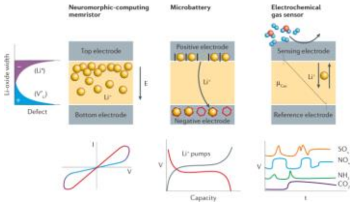


- Decarbonized ammonia production by electrochemically converting N_2 and protons to NH_3 via Lithium metal at room temperature and under ambient pressures
- This thrust is expected to enable low-cost and environmentally-friendly methods to replace state-of-the-art industrial processes

References:

1. Z.D. Hood, S.P. Adhikari, J. Hryn. 2022 Invention Disclosure (ANL).
2. M. Zhao, Z.D. Hood, M. Vara, K.D. Gilroy, M. Chi, and Y. Xia. *ACS Nano, 13*, 7241-7251.

Emergent Electrochemical Materials, Processes, and Devices



- Fabrication of next-generation electrochemical devices (e.g., memristors, thin film batteries, sensors, etc.) and tailored heterostructures at the nanoscale
- This thrust is expected to enable architectures with energy storage, sensing, and memory on the same chip

References:

1. Y. Zhu, J.C. Gonzalez-Rosillo, M. Balaish, Z.D. Hood, K.J. Kim, J.L.M. Rupp. Nat. Rev. Mat., 6(4), 313-331.
2. W. Gao, Z.D. Hood, and M. Chi. Accounts of Chemical Research 50(4), 787-795.

CAPABILITIES: MANUFACTURING AND TESTING

Zach Hood

362 C288: Sulfides, oxides, polymers, and composite synthesis

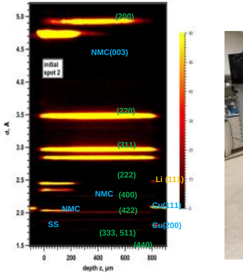
- Dry processing of sulfides, oxides, polymers, and composites in an Ar-filled glovebox
- Membrane prototyping (1 – 4 cm^2)
- Custom solid-state cells for testing materials under pressure

362 B200: Solution-based processing of composites

- Solution phase processing and scale up
- In-line TCD + GC/MS for the identification of off-gas products
- Integrated electrochemical capabilities inside an Ar-filled glovebox

241 A229: Dry/wet processing and analysis of composite materials

Example X-ray diffraction data set:



- **Composite fabrication**
- Solution-based casting of solid-state materials
- Solid-state battery prototyping and testing

362 B324: Materials testing

- Potentiostat/galvanostat for testing material properties from -60 °C - 190 °C
- **Mechanical testing of composite and polymer materials (Instron)**
- Glovebox for prototyping solid-state batteries