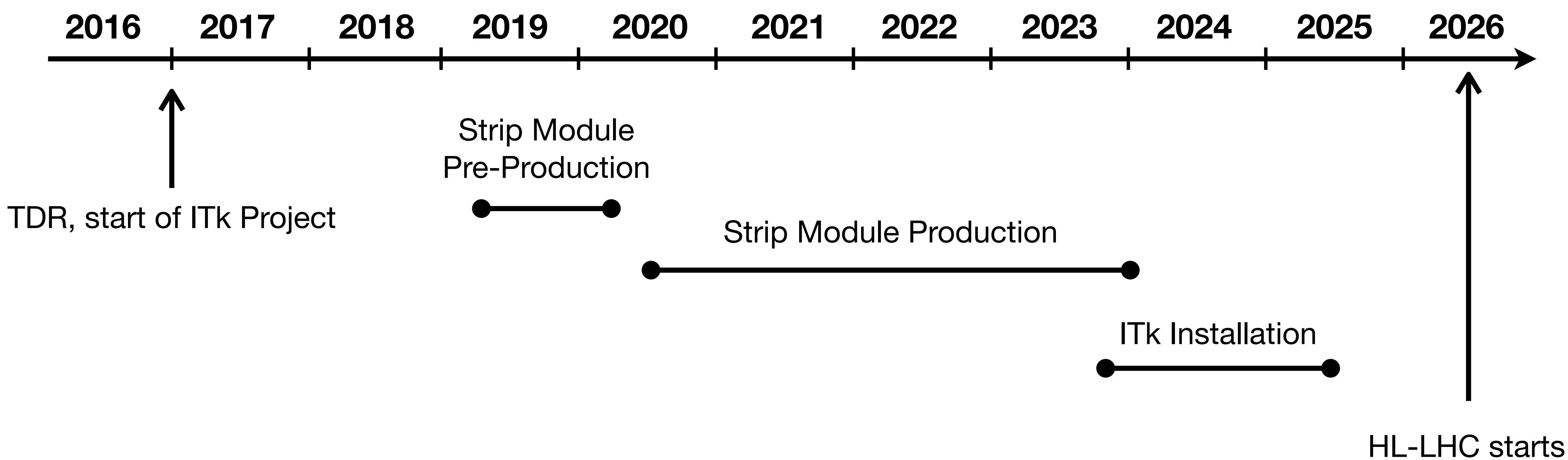
How I am personally destroying the future of collider physics

Anne Fortman
DICE, April 12, 2024

ITk Strip Schedule (TDR, 2017)



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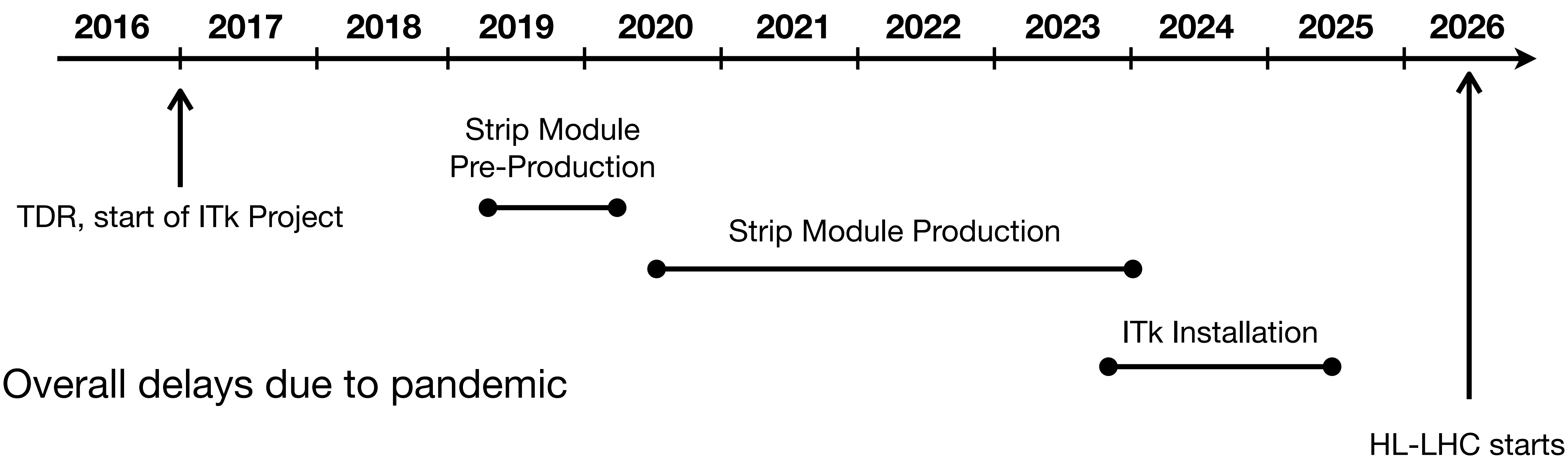
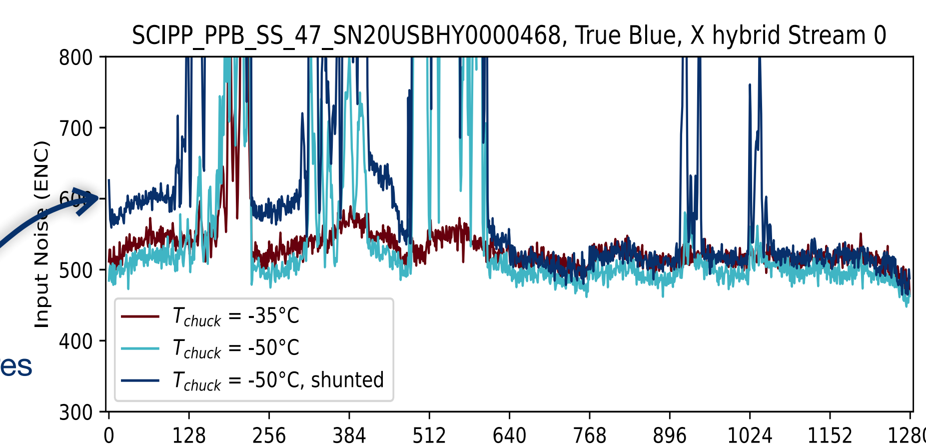


- Overall delays due to pandemic
  - Difficult to manufacture parts, supply workforce
  - HL-LHC start date moved back, now scheduled to start in 2029
- Cold noise problem observed in module pre-production delays the start of production by ~2 years



Noise appears on strips when testing at cold temperatures

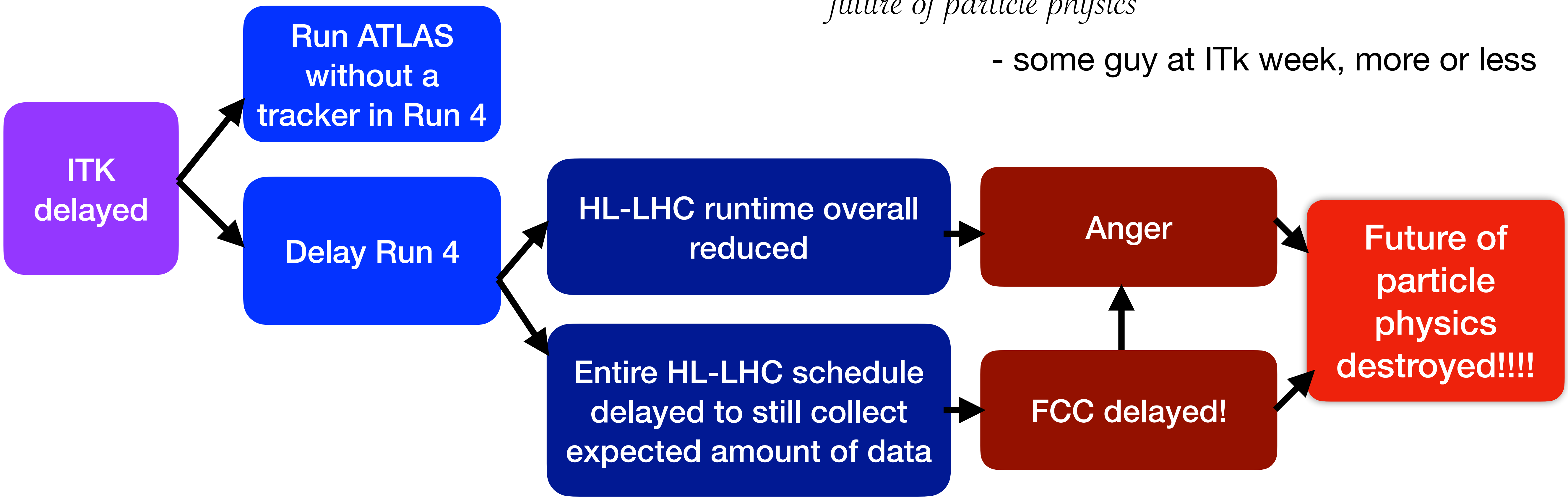
- Other problems I wasn't here for

From ITk to FCC

- Delays in ITk cause delays to FCC, which CERN cares about a lot

"Delaying the ITk strips project amounts to destroying the future of particle physics"

- some guy at ITk week, more or less



Reality: The Cracking Story

- Strip modules are cracking when loaded onto support structures and cycled to cold temperatures (-35C,-45C)

Barrel Modules on a Stave

Photo by Debra Dewhurst, RAL

Endcap Modules on a Petal

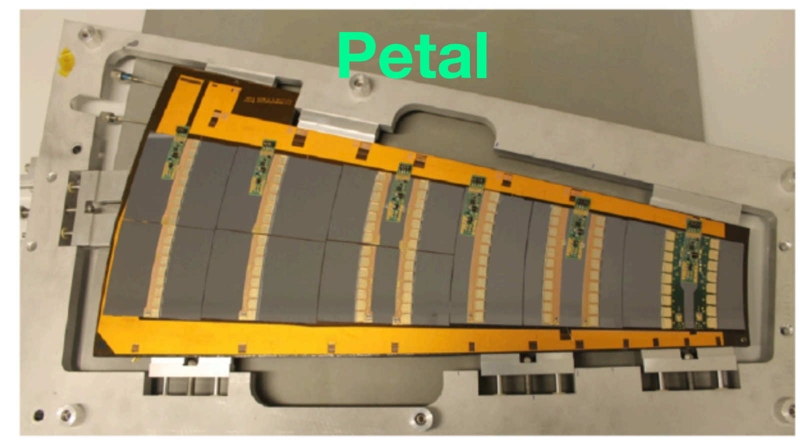
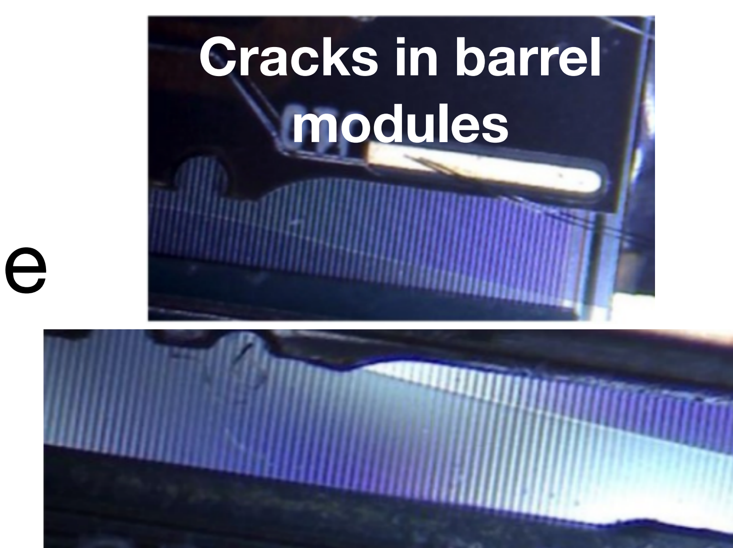


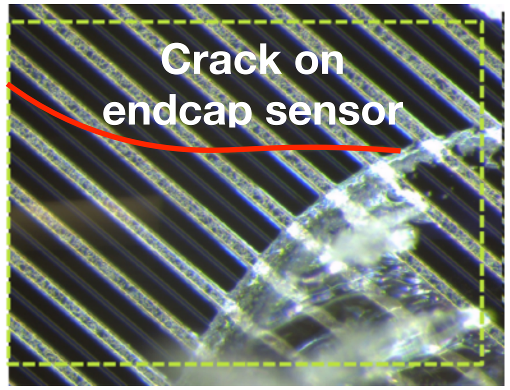
Figure 9.18: Photo of the thermo-mechanical petal prototype.

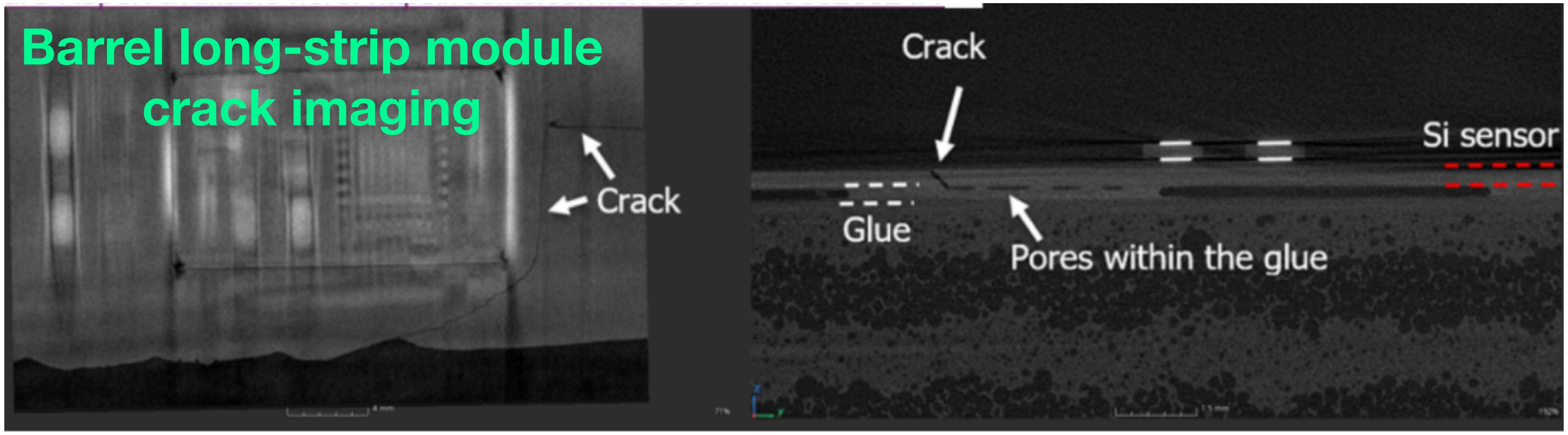
- Problem first observed spring of 2023
  - Special taskforce formed to address the issue
  - Still not solved as of April 12, 2024

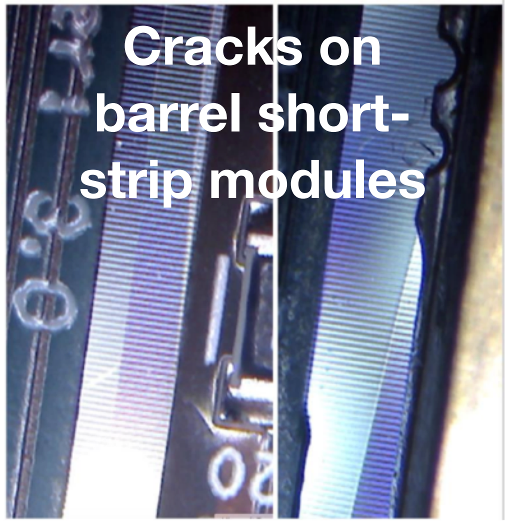


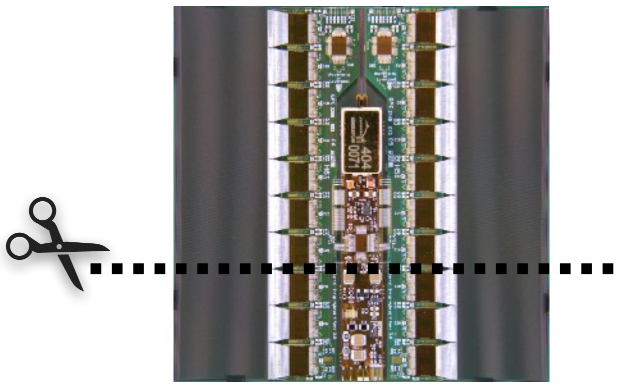
How big of a problem?

- One crack in a module means entire module cannot be biased
  - ~10cm x 10cm area of useless detector per module
- Cracking observed in barrel AND endcap module types
- Recent stave at BNL: 5/28 modules cracked **(Sept 2023)**
- Recent petal in Vancouver: 2/12 modules cracked **(Nov 2023)**





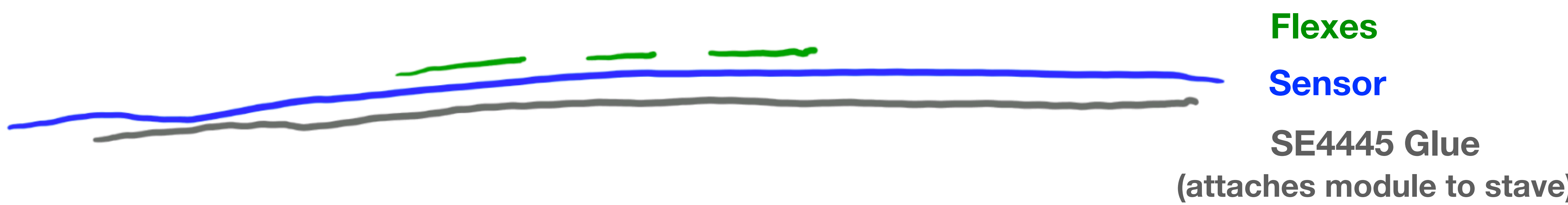




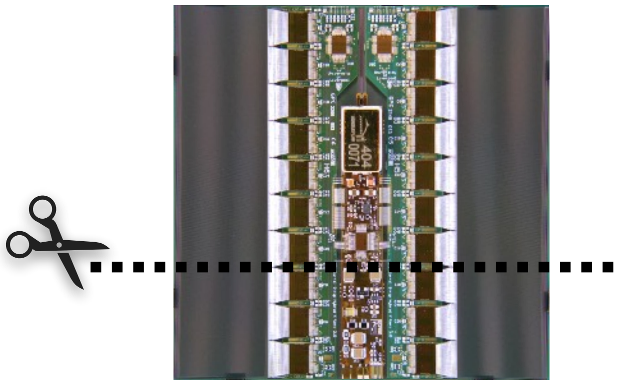
Why Cracking?

A drawing for intuition.

Room temperature (unstressed):



Intuitive scribble presented in ITk week talk by Sergio Diez



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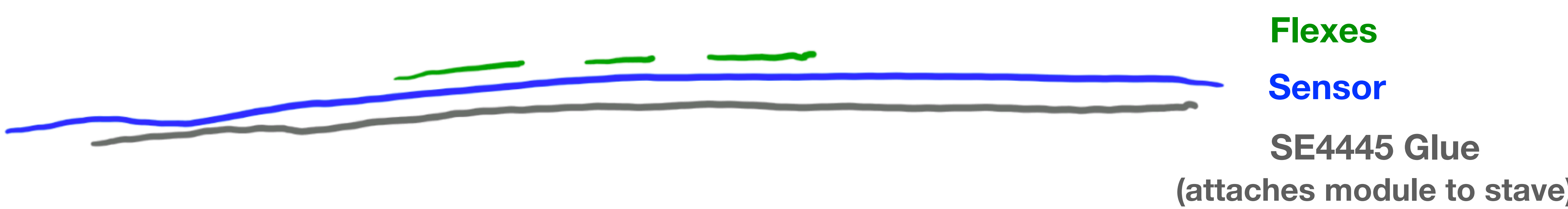
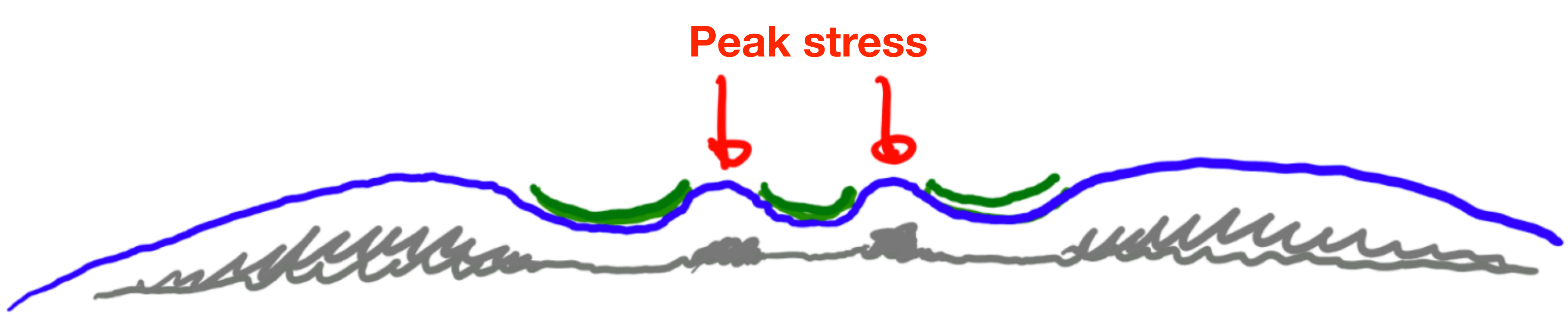


Cold operating temperature:

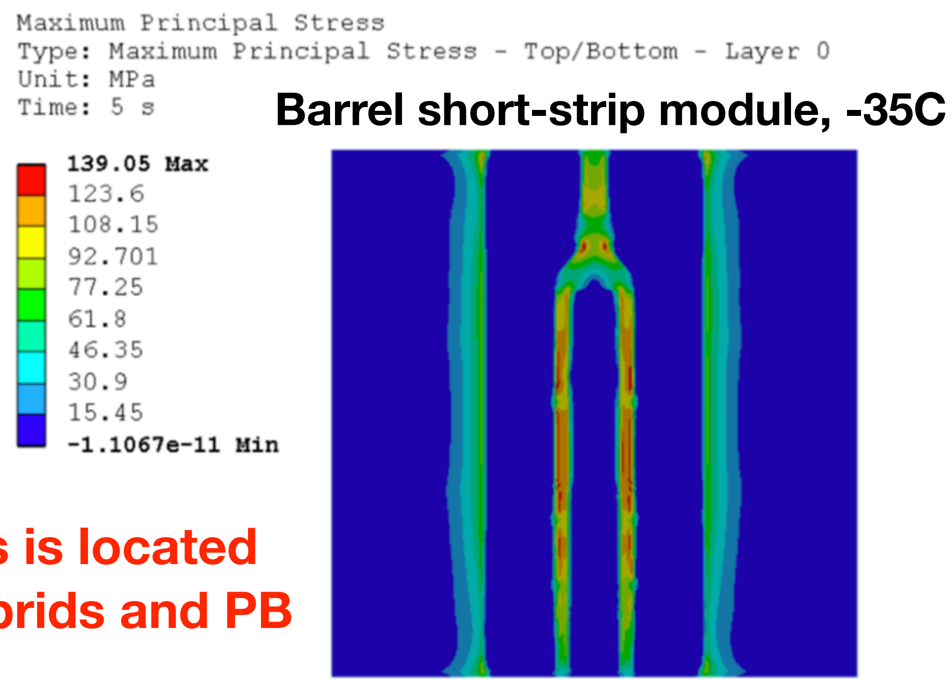
Differing coefficients of thermal expansion (CTEs) of flexes, sensor lead to stress with temperature change:



SE4445 glue too soft to provide support for sensor

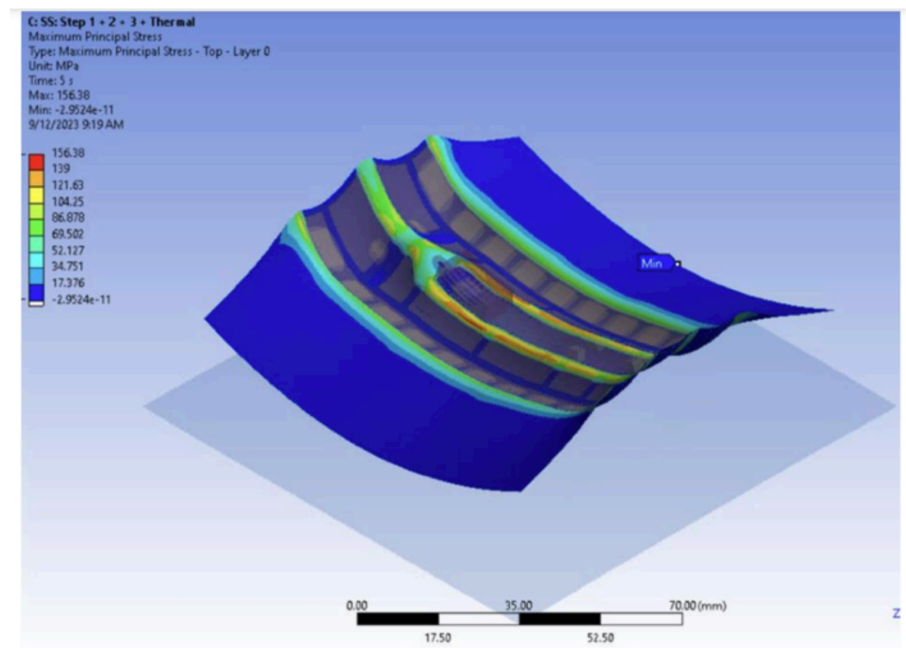
Actual Simulation

- Simulation confirms regions of high stress in narrow (1mm) gaps between hybrids and power boards



Peak stress is located between hybrids and PB

Simulation talk at ATLAS Upgrade Week, Nov 2023

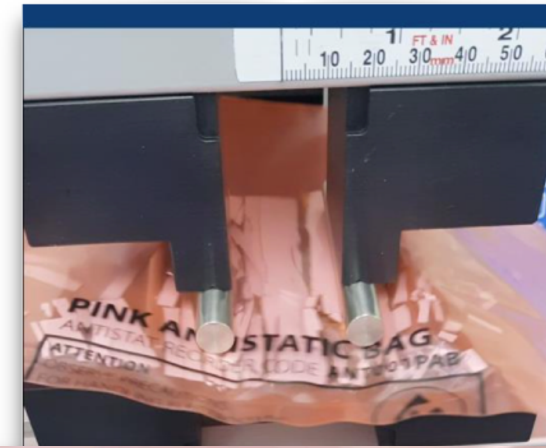


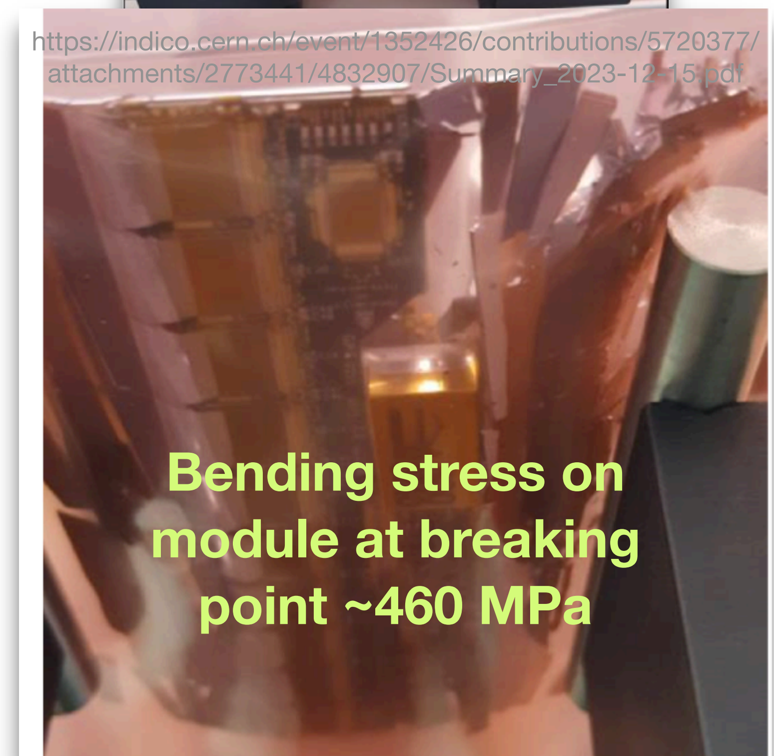
HV Breakdown talk at September 2023 ITk week

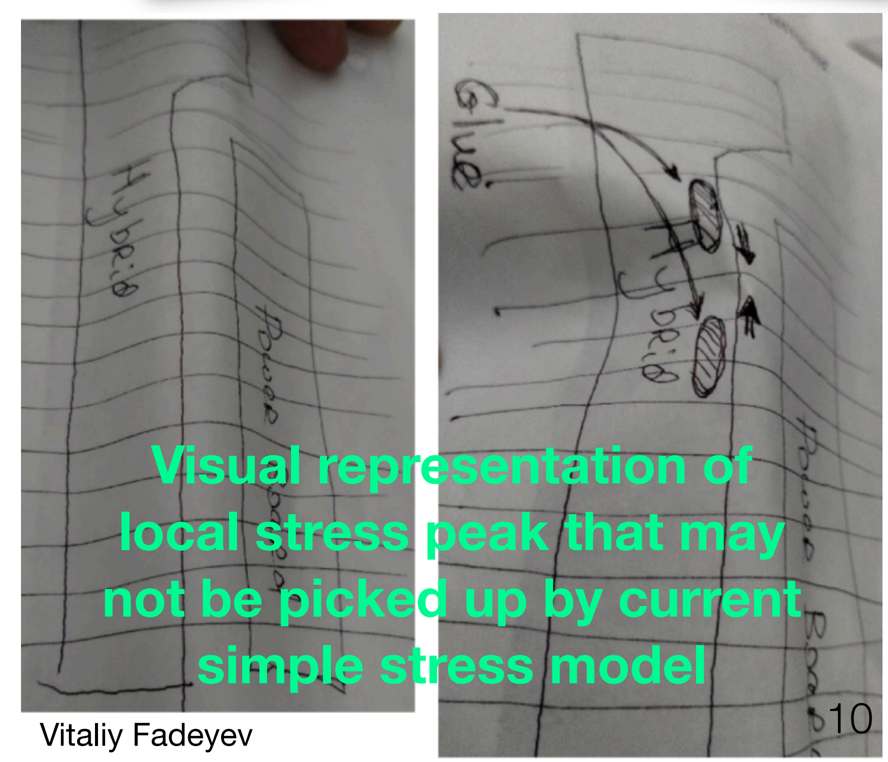
- Recommended mitigations:
  - Use stiffer glue between module and stave (20-30% reduction in stress) **Maybe up to 50% depending on glue pattern**
  - Widen gaps between hybrids, powerboard (+1mm lessens stress by ~O(10%))
  - Reduce hybrid thickness (~5% less stress), limit thermal cycling during QC to +20C rather than +40C to reduce module deformation (~5% less stress)

Nuance

- Stress simulation does not predict stresses commensurate with cracking
    - Max stress in simulation ~140 MPa, but takes ~460 MPa to mechanically shatter a module
- Simulation must not capture all effects
    - Unable to pick up very local peaks in stress (perhaps from random defects)?
    - Is there another mechanism we are missing?
- Saying “X mitigation leads to 50% stress reduction” is not complete
    - “X mitigation leads to 50% reduction *of the stresses we understand/are able to reliably simulate*”







Let’s Talk Solutions

- Recommended mitigations abound. Which should be implemented?
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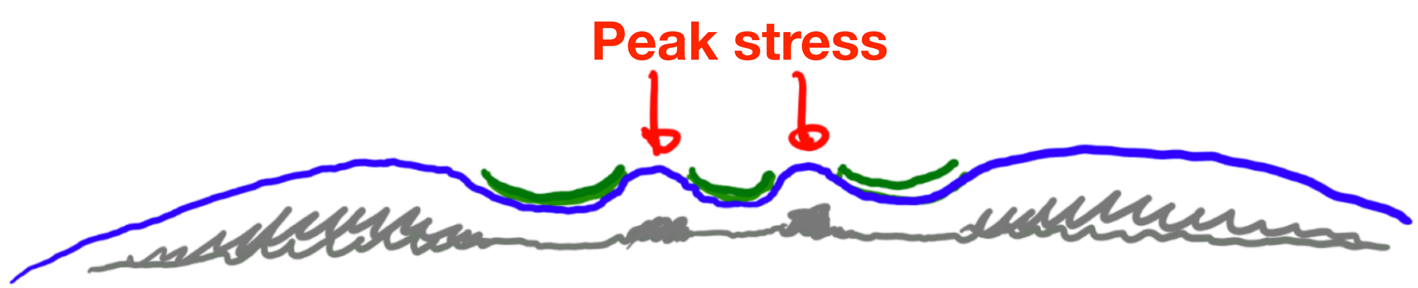
- An acceptable solution must be:
    - Cost-efficient: negligible in extra cost
    - Time-efficient: can cause no extra delay, in fact should reduce the existing delay
    - Extremely convenient and cause little to no extra work for anyone

The Hysol Solution

- Swap out soft SE4445 glue under module for stiffer glue (hysol)



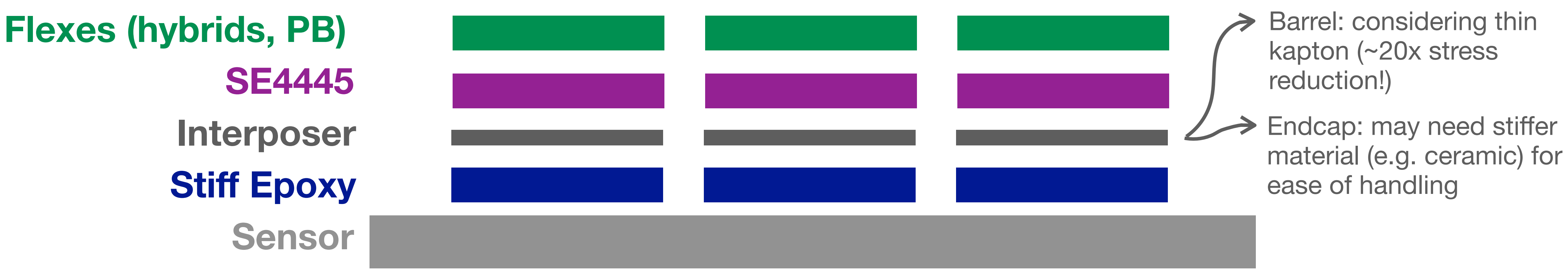
SE4445 glue too soft to provide support for sensor -> switch to stiffer glue: hysol

- Intuition: more rigid glue might help support the module, prevent it from bending

- Up to 50% stress reduction depending on glue pattern

The Interposer Solution

- Add a layer of soft glue (SE4445) underneath flexes, separate from nominal layer of epoxy by thin layer of material ("interposer")



- Intuition: softer glue underneath flexes decouples stress between flexes and sensor
  - Also may eliminate cold noise!
  - If stiff interposer needed, could be CTE-matched to silicon to redistribute stress
- Above configuration (kapton, SE4445 glue) eliminates thermal stress issue altogether in simulation- 20x stress reduction

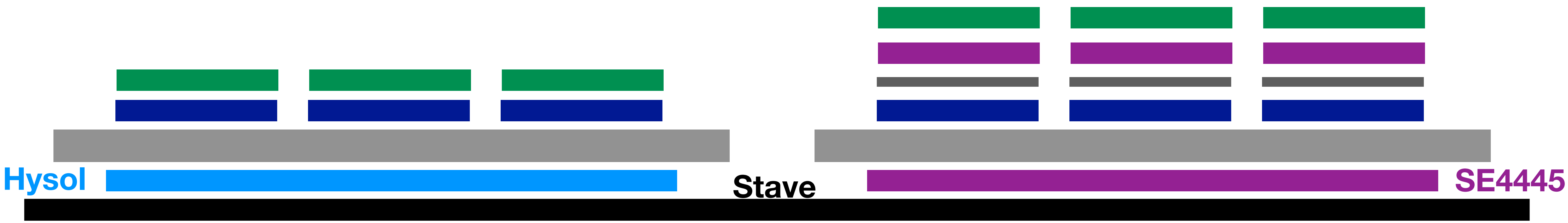
Hysol vs Interposers

Hysol Solution

Use stiffer glue between sensor and stave

Interposer Solution

Add soft glue + material between sensor and flexes



- Up to 50% stress reduction
- Change loading process- no change to modules, inconveniences loading sites
- Time loss of several months- need to cycle staves (how many?) without cracks
- Accept as “baseline” solution
  - i.e. really really hope this works or we need to turn to the “radical” interposer solution

- Eliminates stress from this mechanism (20x reduction)
- Change flex manufacturing- add interposers to flexes during manufacturing or at flex sites. Inconveniences flex assembly sites
- Time loss undetermined- may need to do preproduction again? Repeat irradiation tests?
- Considered “radical” backup solution
  - Develop in parallel to hysol investigations in case needed

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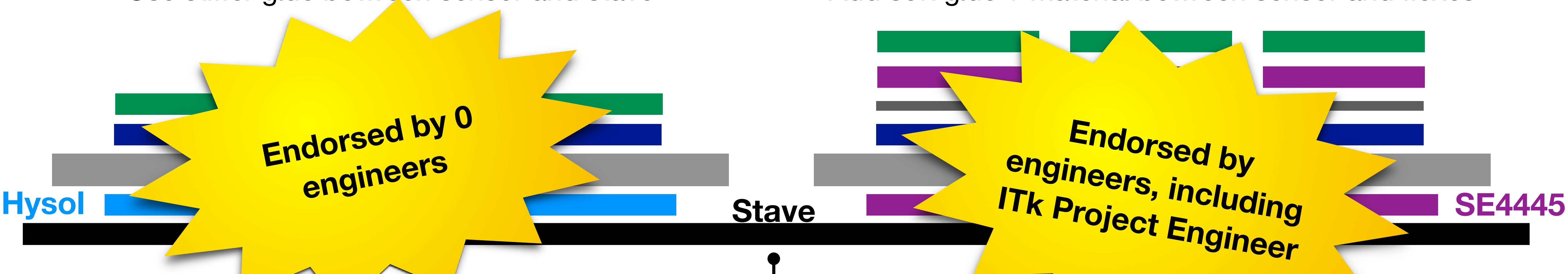

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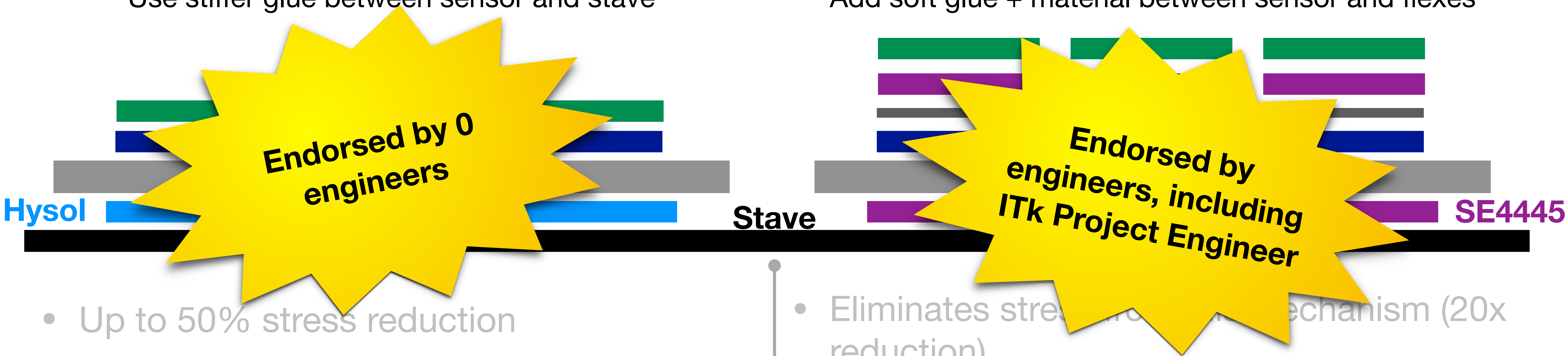

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Objection to changing to a more rigid glue underneath module

Simulation clearly does not account for all effects.
Could worsen these by changing to a more rigid glue.
Safer to keep soft glue that absorbs more stresses.

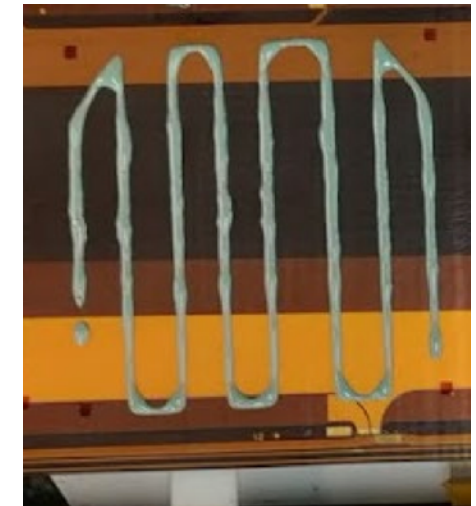
The Strategy (start of 2024)

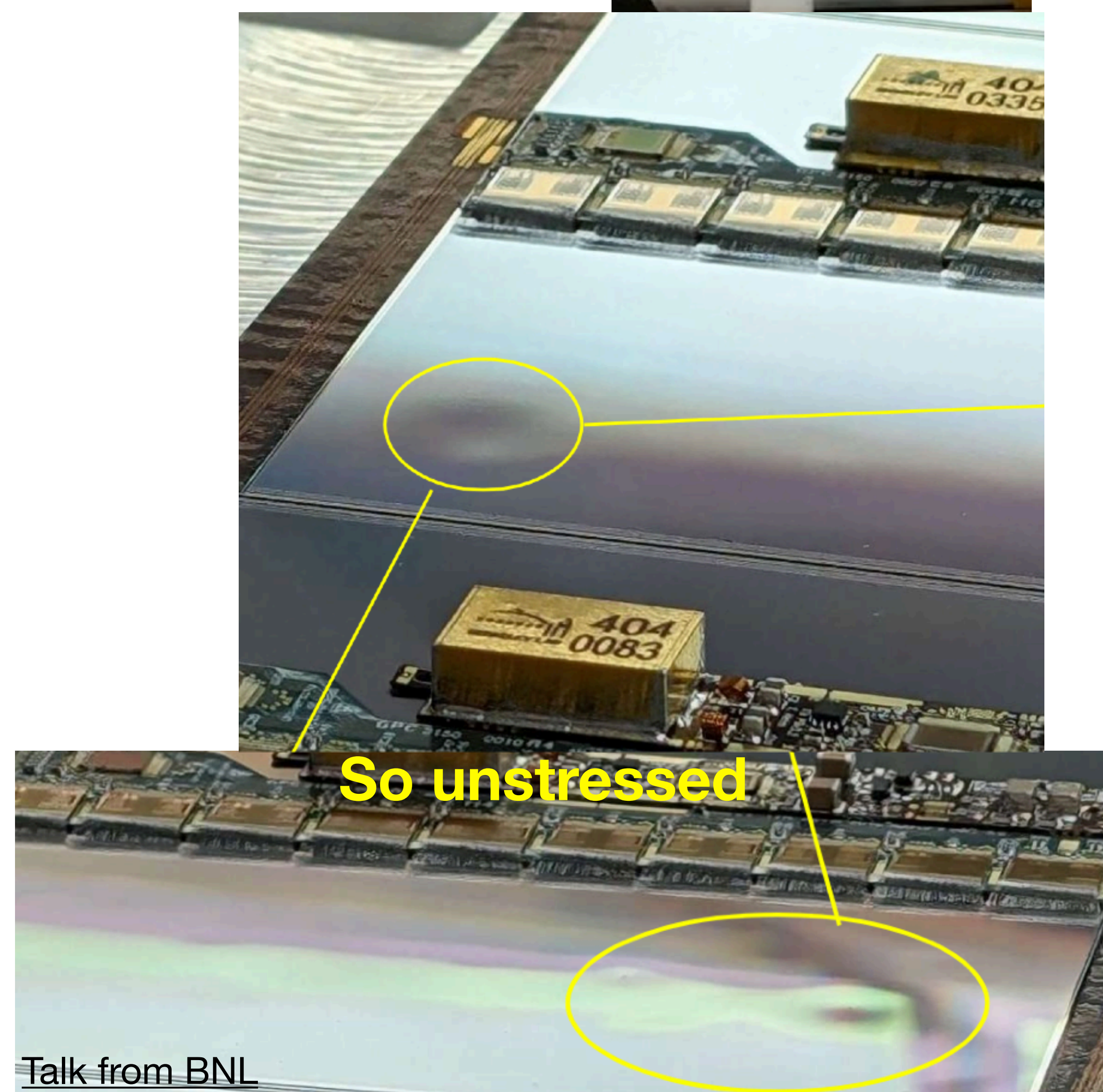
- Decide to continue development of hysol solution as the "baseline" most likely solution to adopt
  - Investigate new loading pattern, new glue at loading sites
  - Build staves with hysol glue at BNL and RAL, petal with hysol at Vancouver
- Also develop interposer solution at module/flex sites in case we need it
  - Principally LBNL, also SCIPP and Cambridge recently interested in barrel investigations, Freiburg investigating interposers for endcap modules

Hysol at BNL

- Started building half a stave (14 modules) with hysol in February 2024
- Reportedly hysol is a difficult glue to work with
    - Trouble evenly dispensing patterns
- Modules do not lie flat- some raise up at corners
- Can visually observe dimples in the silicon sensors across the entire stave

Clumpy glue pattern

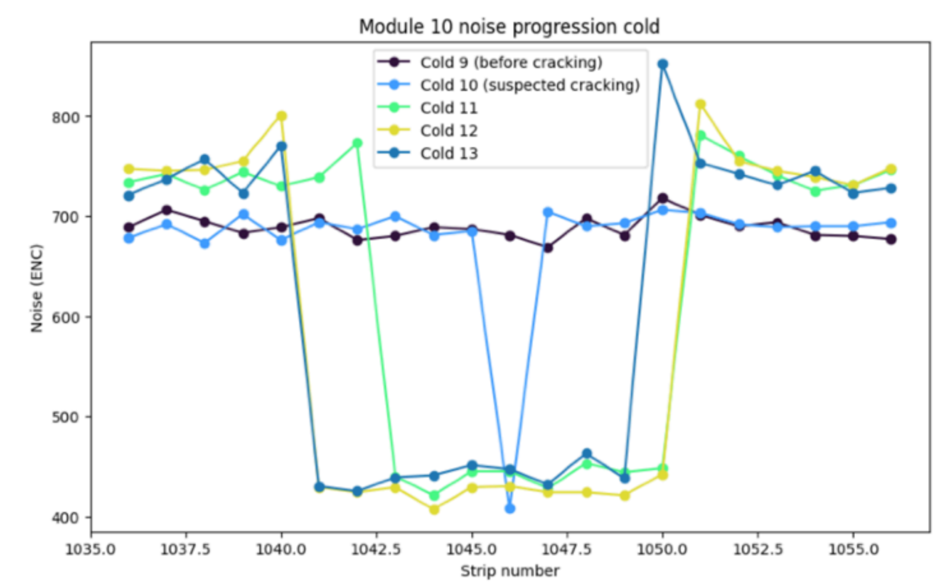


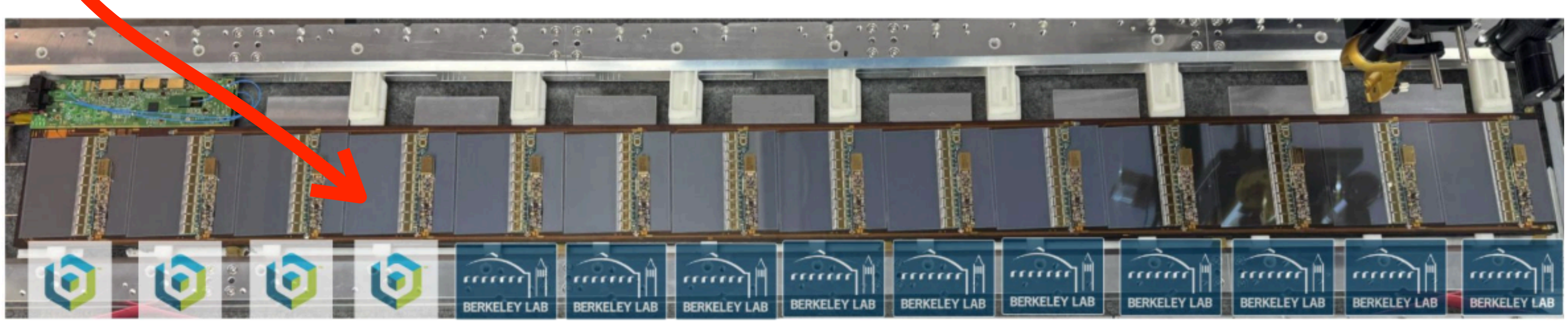


Hysol at BNL

- Thermal cycled the stave from +20C to -35C 5 times, no cracks appeared
- Then thermal cycled 5 times from +20C to -45C
  - On the fourth cycle, 1/14 modules **cracked**

Crack appears in noise plot as low (unconnected) channels.
<u>Area widens after more cycles</u>





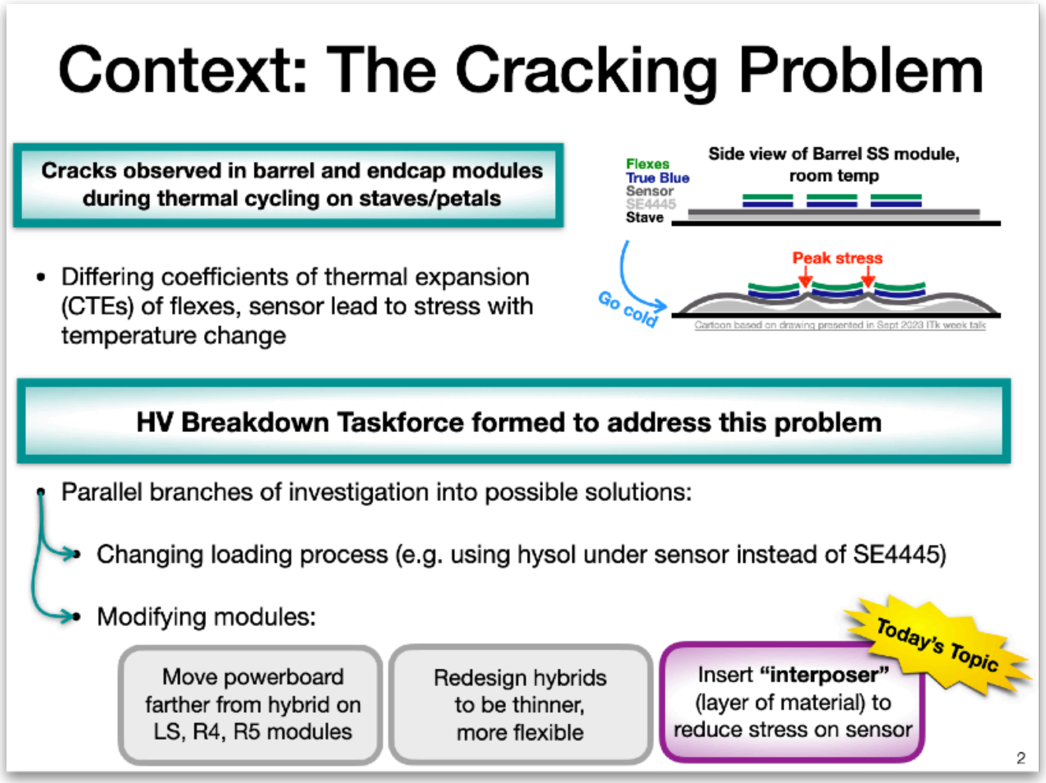
A Word on Temperatures

- How to interpret cracking temperatures?
- -35C is lowest nominal operating temperature for ITk strips
  - Very bad to crack at this temperature
- -45C is the temperature ITk strip detector reaches when turned off
  - Also very bad to crack at this temperature
- -55C is catastrophic failure, lowest temperature the CO2 cooling can reach
  - Still very bad, but will likely have other problems to worry about as well in this scenario

Intermission: ITk Week

- March 18-22: many ITk strip folk gather at CERN to discuss issues and push narratives
- Confidence in hysol solution shaken by crack at BNL
- Overarching narrative spin:
    - BNL just messed up the hysol, hysol is actually fine, let's not overreact to one single crack at -45C :)
- Bury interposer discussions in sessions unrelated to cracking taskforce
    - Causes confusion to people who stumble upon such talks without context…

My talk on interposers was very controversial



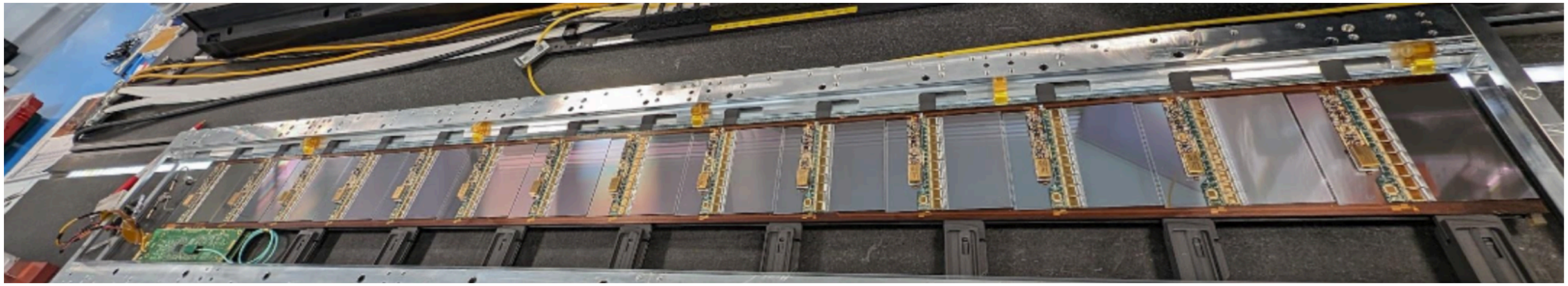
…like this guy, who accused me/interposer plans of forcing ATLAS to run without a tracker in Run 4 and delaying FCC

Back to Business.

Hysol at RAL

- Built half-stave (14 modules) with hysol in March
- No problems whatsoever mixing or dispensing hysol glue
- Suspected crack in module 5
  - Unable to bias module past 120V (need 350V) on second cycle to -42C
  - Visual inspection did not reveal crack, accident with gantry while taking photos has laid this module to rest

Thermal cycle number	Temperature (°C)	Status
1	-42	
2	-42	Suspected crack module 5 (Hysol side)
3	-42	
4	-42	
5	-42	



Hysol in Vancouver

- Made one petal (double-sided, 12 modules total) of endcap modules loaded with hysol in March

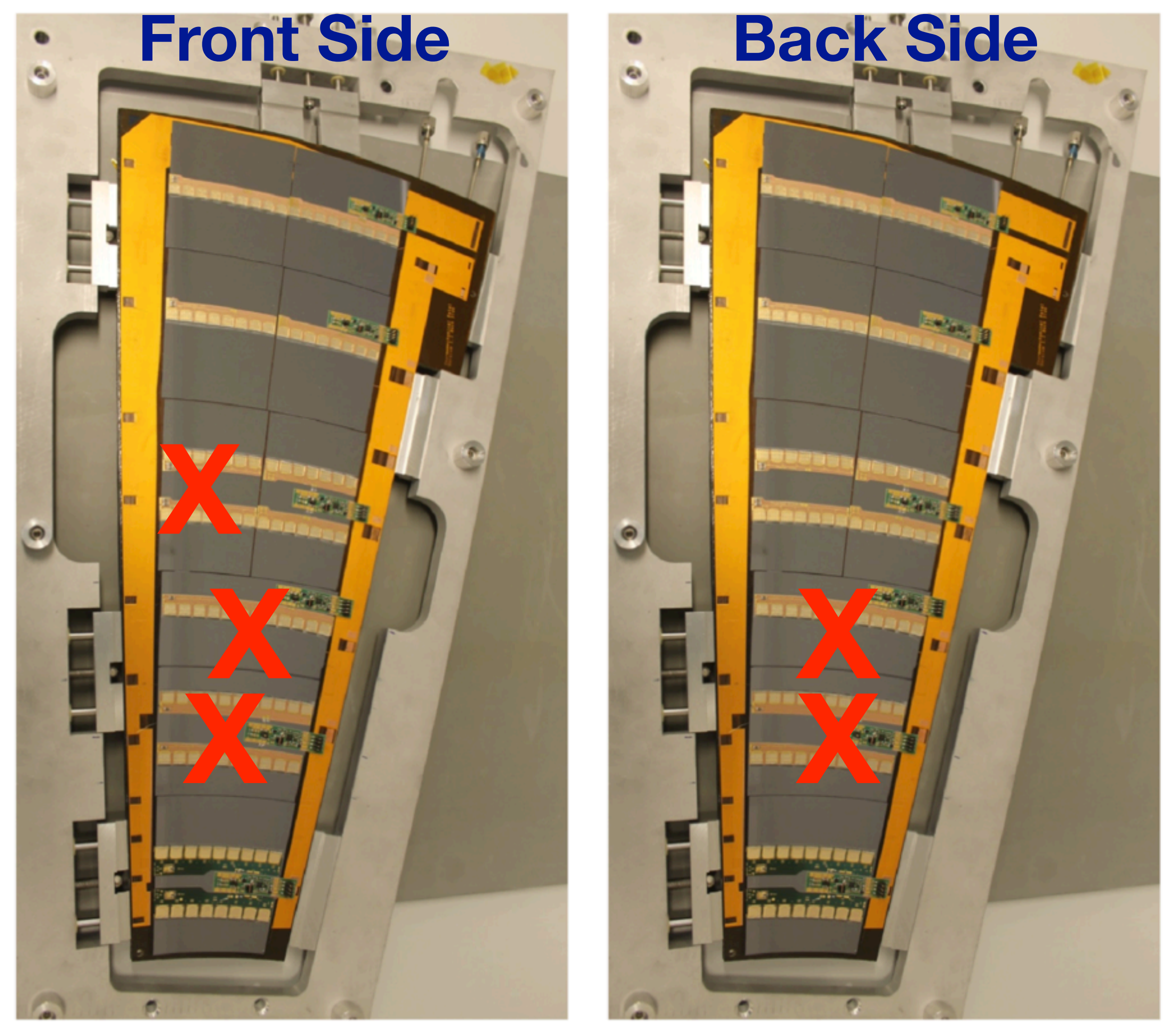
- 4 modules experiencing high voltage breakdown at -40C

    - 3 of them likely cracked, one is being pitched as a glue issue

- R2 on main side: **expected crack** seen at −40
  → expected (Hysol pattern), unexpected crack location
- R2 on secondary side: suspect crack at −40
  → **expected** (Hysol pattern), no crack observed
- R1 on both sides: breakdown at about 400 V
  → do not think there are cracks; strange glue feature
- R3 on main side: very early breakdown
  → suspect there may be a crack, not observed
  → if there is a crack, location does not make sense

- Continuing thermal cycling (−45 over weekend; −50 next week) to see evolution of features, verify cracks
- If the R3M1 cracked before R3M0, that's a big worry; the simulation says this gap should be safe

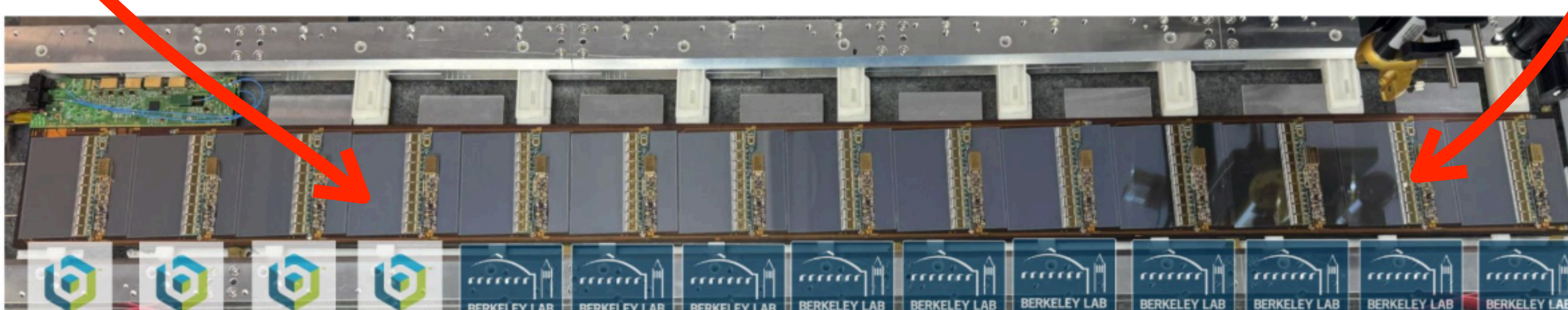
Slides from this morning's cracking taskforce meeting



Just a representation- not a photo of the actual petal

Hysol at BNL Again

- From before ITk week, one module cracked on the fourth cycle from +20 to -45C (9th cycle total)
- A second module cracked at a temperature between +20 and -38.5C
  - Survived 5 cycles to -35C, 11 cycles to -45C, then cracked during one cycle to -35C
  - On the 17th overall cycle! Complicates issue- cracks can show up much later than previously thought

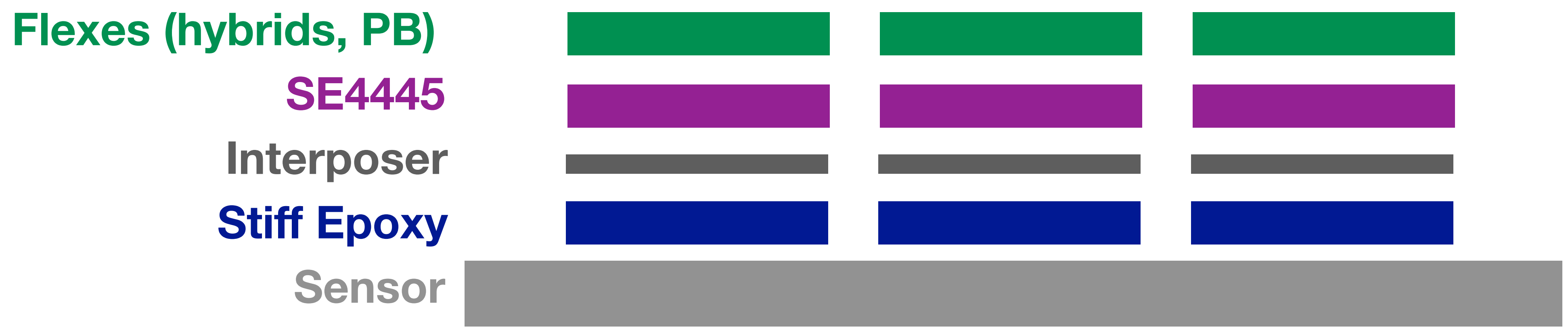


What next?

- One competing view: don't overreact too much to only a few cracks that happened at temperatures < -35C!
  - Still have other mitigations to try in conjunction with hysol before throwing out the hysol solution altogether
  - Can use thinner hybrids! (~5% reduction in stress)
  - Can widen gaps between flexes (~20% improvement expected)
    - Only feasible for some types of modules, impossible for many others

- Other competing view: Even if we don't see cracking with the above mitigations, we know cracking is not far away. Would we trust this result enough to build a whole detector?

Can Interposers Save Us?



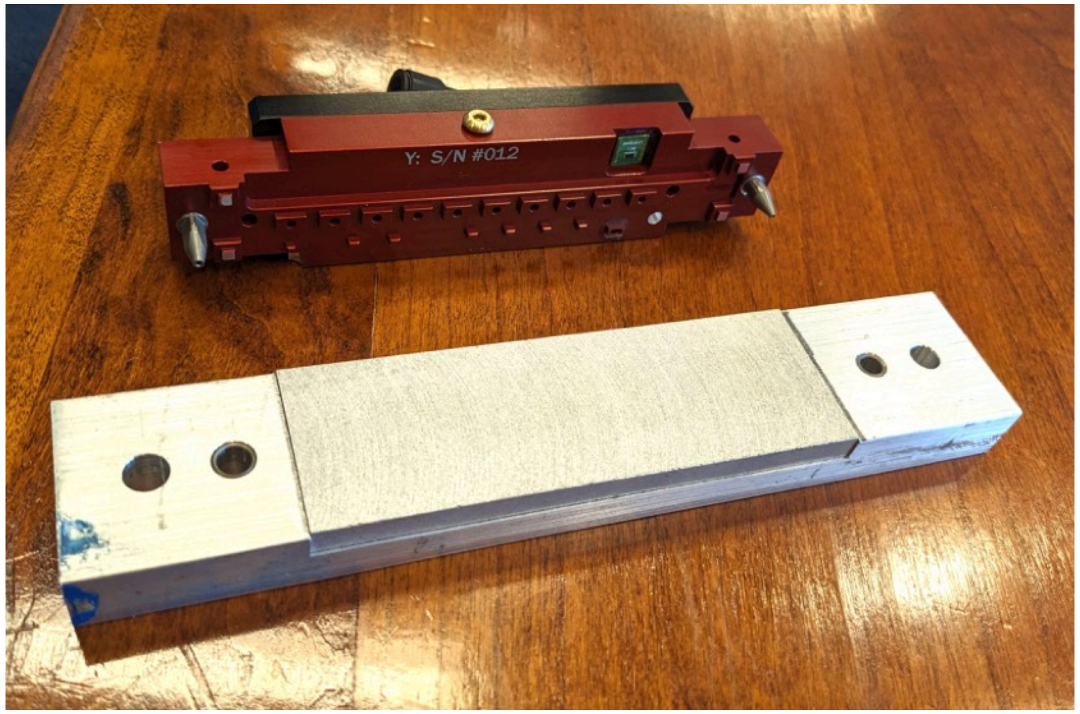
- Interposer solution promises much more stress reduction than hysol (for the stresses we were able to simulate)
- Would take effort to develop, both technically and logistically
- Then need to define plan for pre-production, reviews, site qualifications etc.

Logistical Concerns

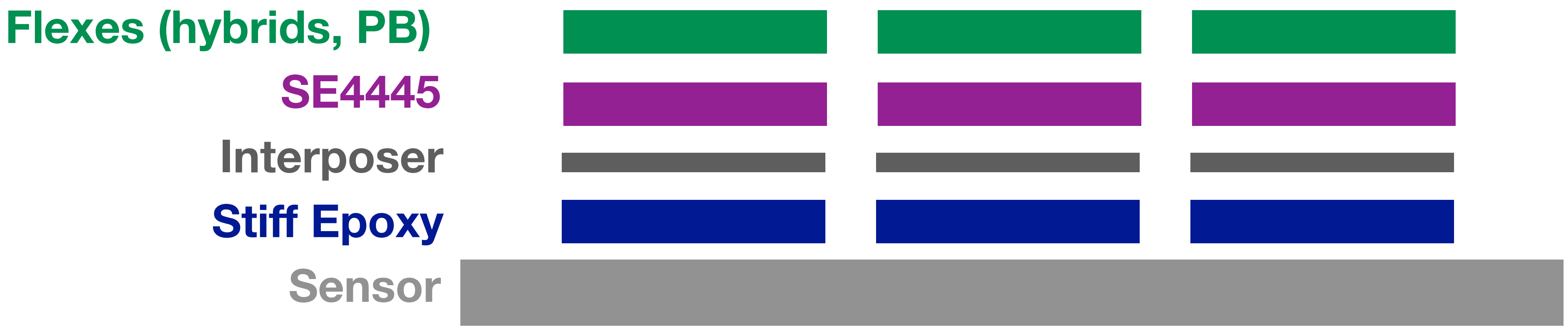
- How to interpose many flexes at once? Can we convince a manufacturer to do it?
    - Different processes need to be worked out to interpose many powerboards and hybrids at once
- Fresh SE4445 glue can be hard to get- how to distribute to interposing sites? Distribute instructions for mixing?
- Any adjustments to usual module-building procedure that need to be sent to all module-assembly sites? E.g. need to use shims while building to account for increased height

Have tooling for single-flex interposing- how to scale up to production?

Porous aluminum vacuum fixture. Holds kapton flat while assembling to flexes for test modules



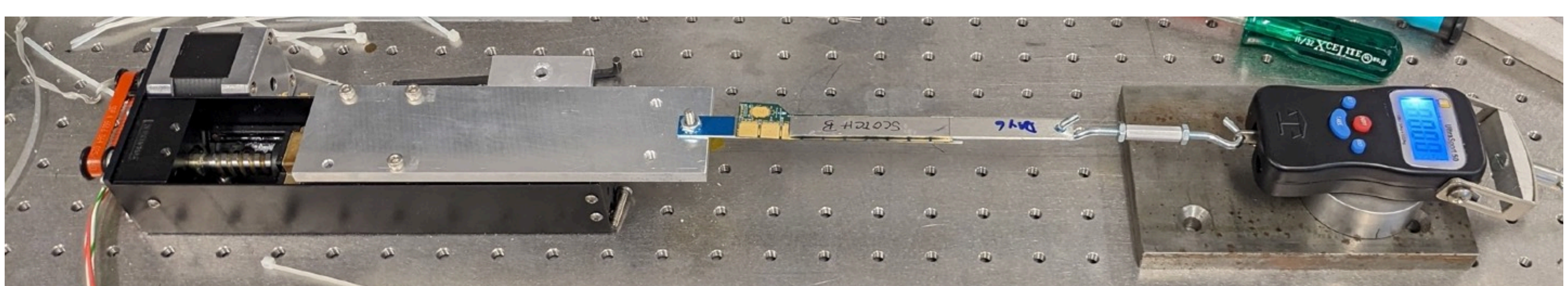
Technical Concerns



- Glue adhesion- do any of these materials even stick to each other?
  - What about after thermal cycling? After irradiation?
- Noise performance- is there cold noise? Is there unexpected noise from any other source?
- Thermal performance- how much do the kapton+SE4445 layers impact the cooling of the powerboard and hybrids?
- What other issues come up while building test modules, doing module QC, and testing them on staves?

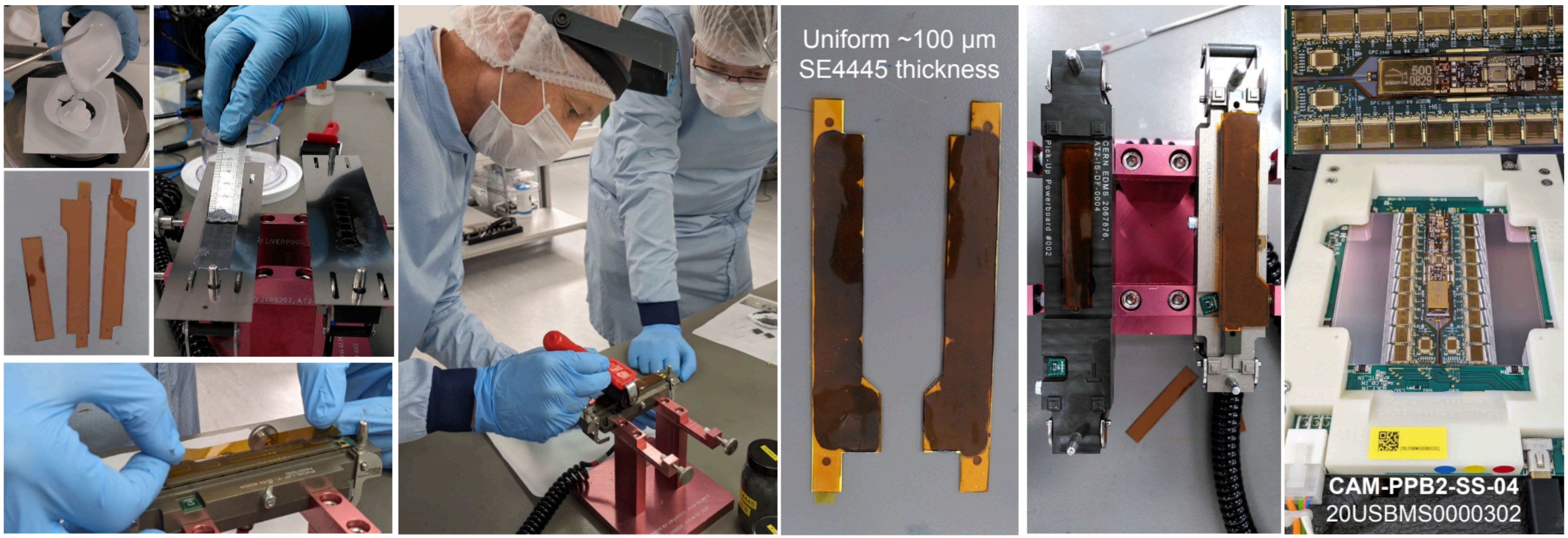
Glue Tests at LBL

- Testing adhesion to surfaces via shear, pull tests
- No matter what surface preparation used (isopropyl alcohol, abrasion with scotch-brite, plasma etching) on any material, shear forces were comparable
  - Defined new standard procedure for building interposer modules: clean all surfaces with isopropyl alcohol



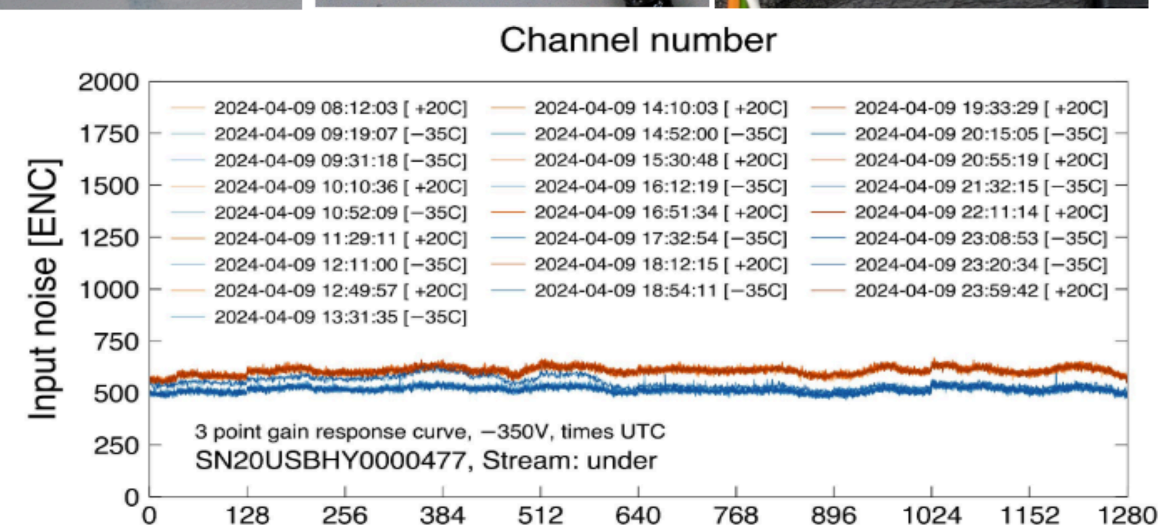
First Modules

- Excited community building interposer modules any way they can
  - Cambridge: built toy interposer module, used paint roller to spread SE4445 glue to uniform thickness on kapton



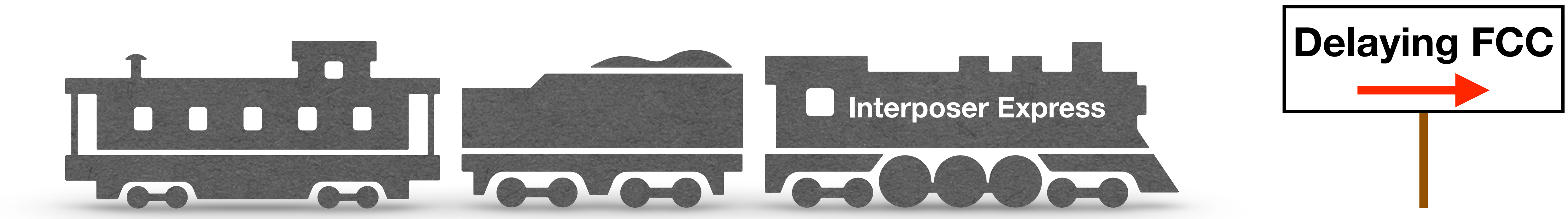
- First module temperatures look reasonable (match thermal simulation within a few degrees)

- No cold noise at -35C!



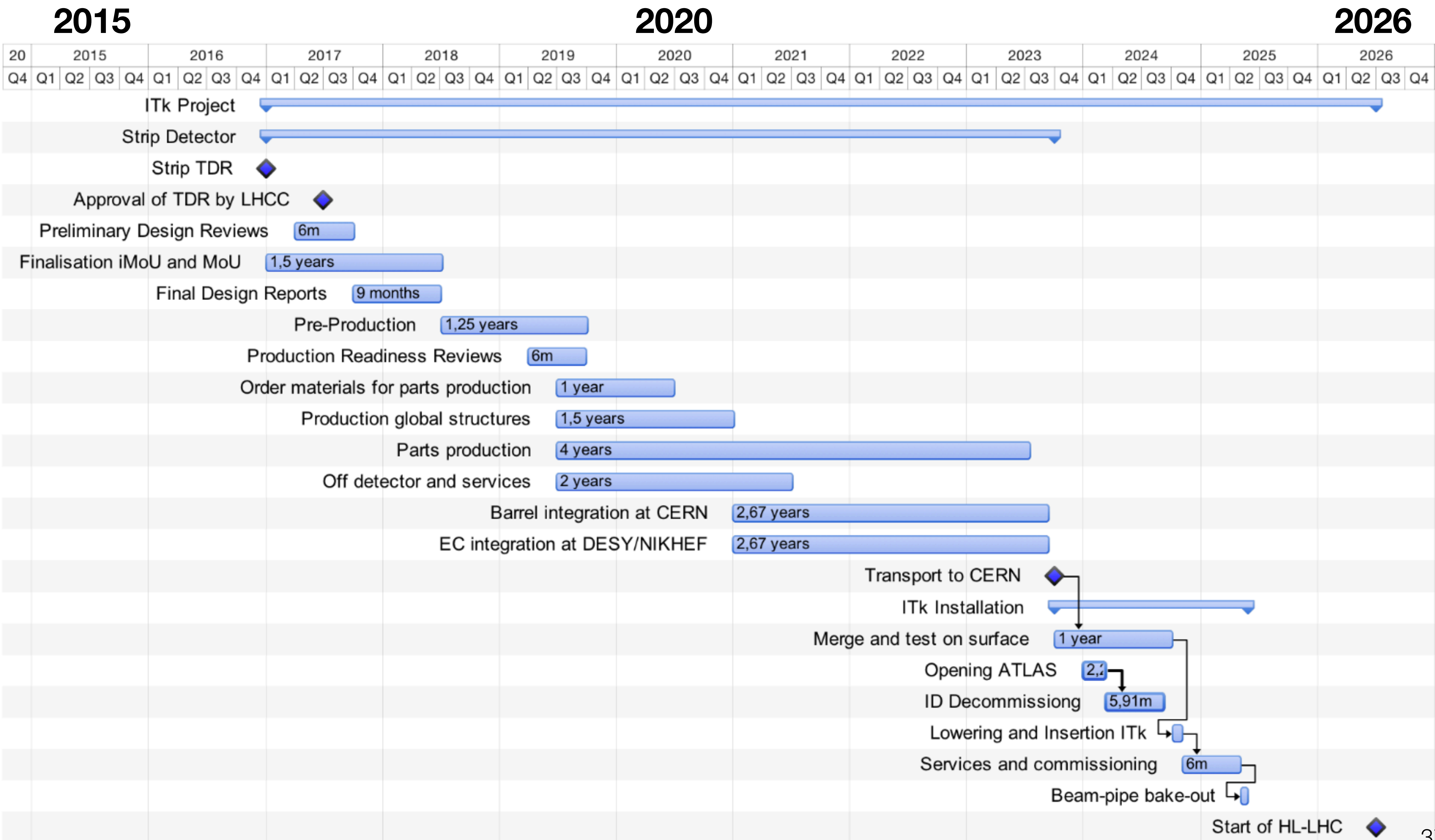
Next Steps

- Build test modules! One already built at LBL, two more planned next week. Others being built in the UK
- Continue to test for cold noise, check thermal performance, vigilant for other issues cropping up
- Tests at LBL planned to check for glue delamination with thermal cycling, irradiation
- Discussions in the community ramping up toward large-scale production of interposed flexes
- All aboard the Interposer Express, on the fast track to destroying the entire future of collider physics



Backup

ITk Schedule (TDR, 2017)



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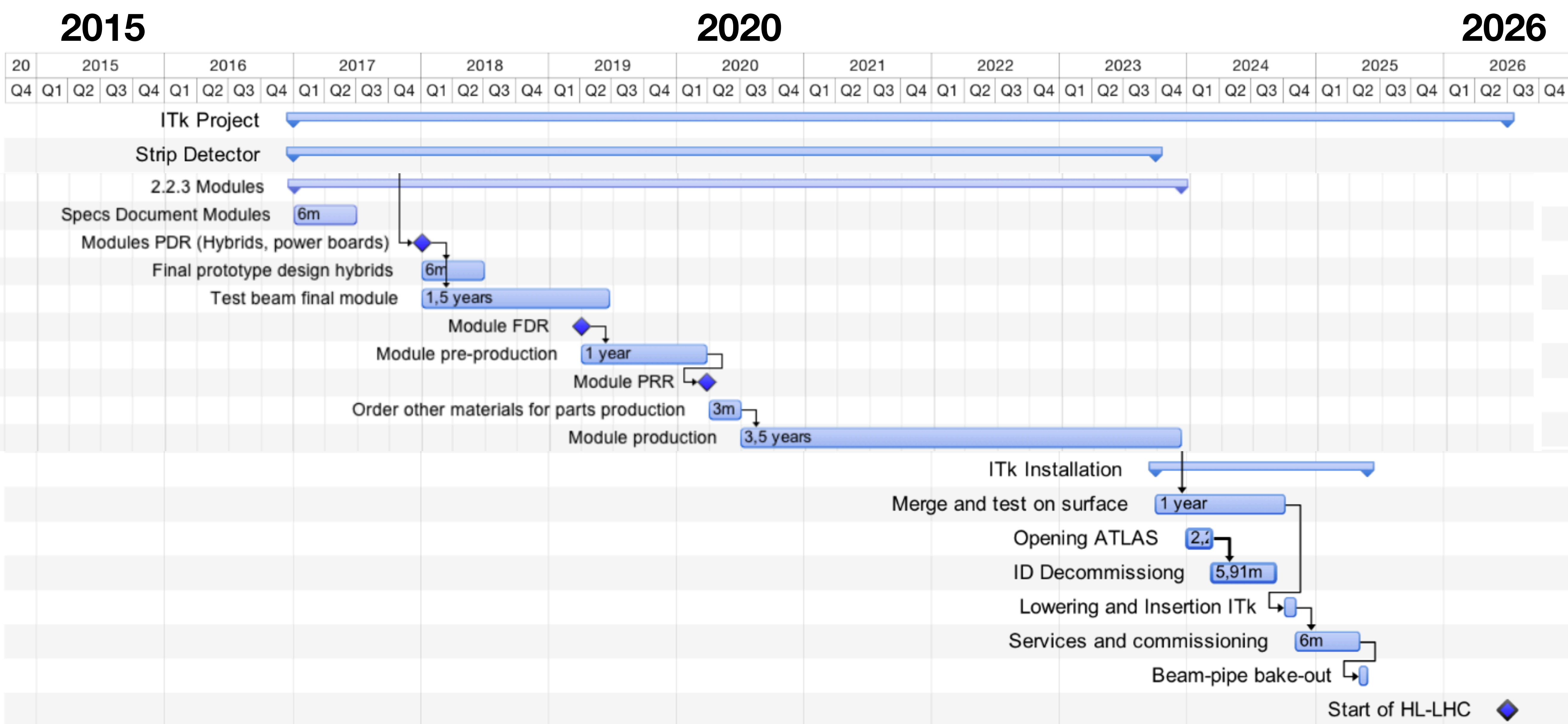
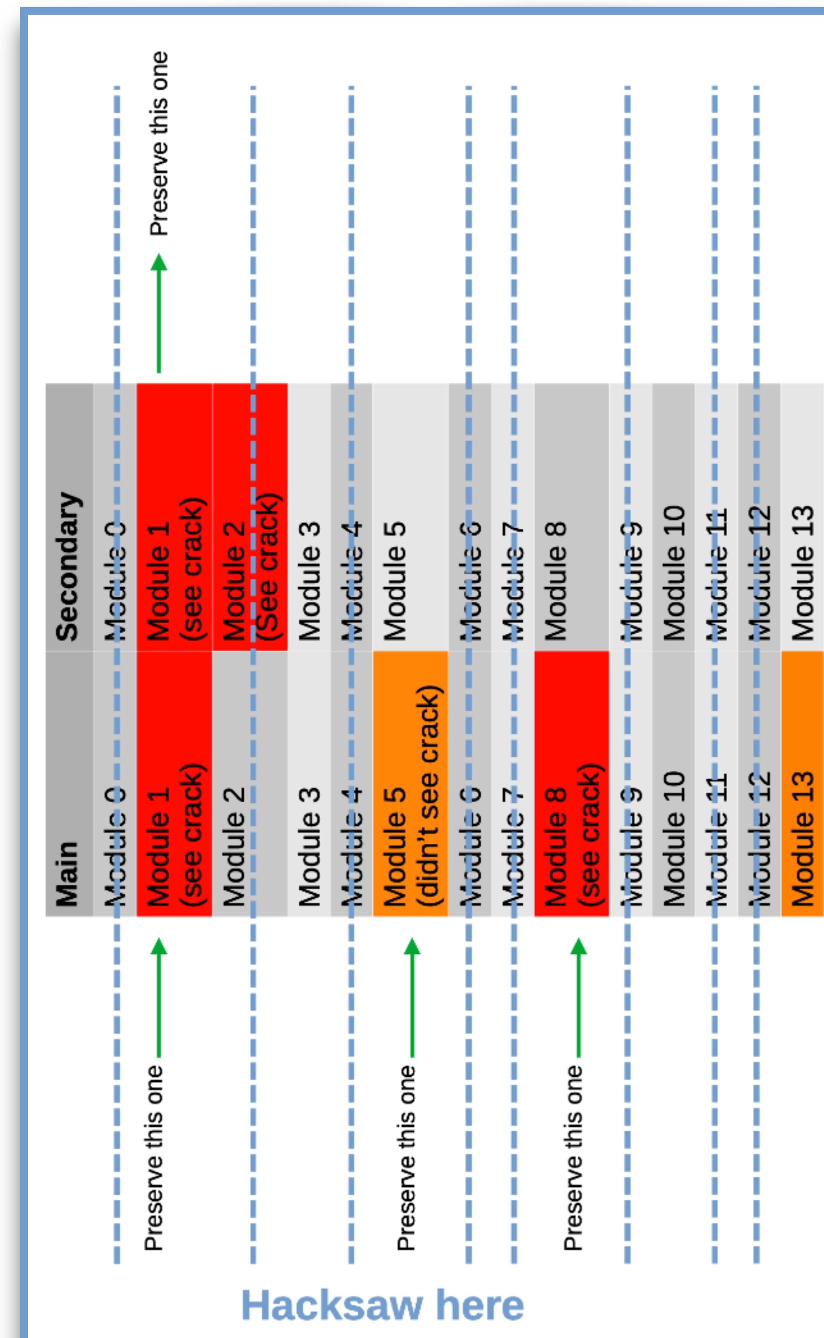


The Sacrificial Stave

- Hacksawed up a stave to get it CT-scanned

- Imaging while thermal cycling the stave pieces resulted in an additional crack

https://indico.cern.ch/event/1352425/contributions/5694765/attachments/2763971/4814071/Proposal%20for%20stave%207.pdf

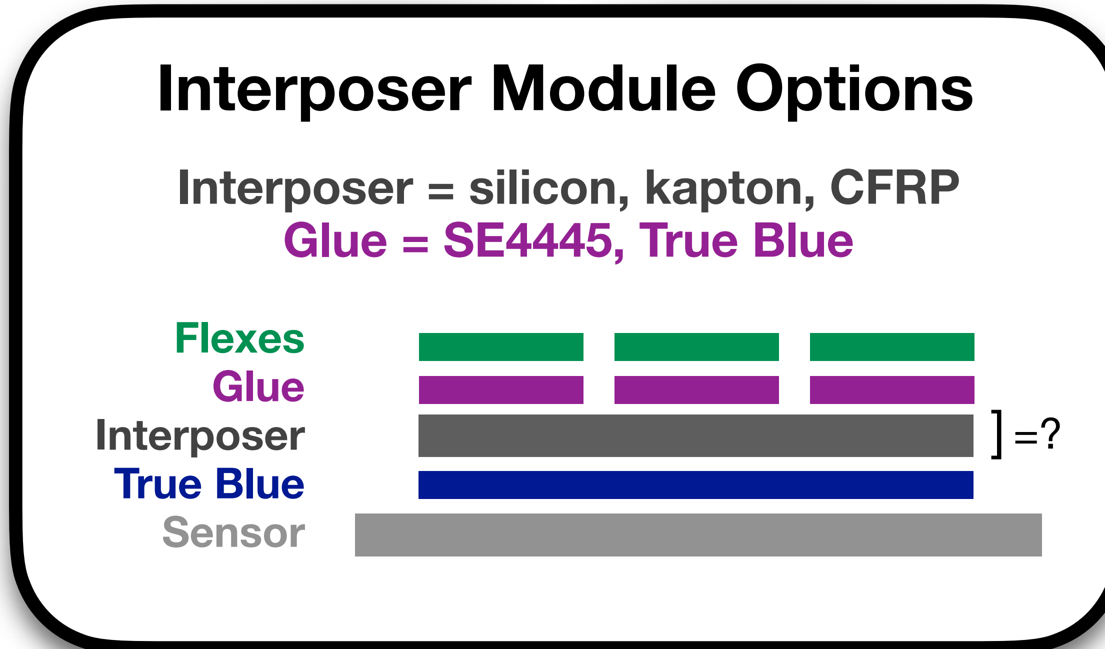


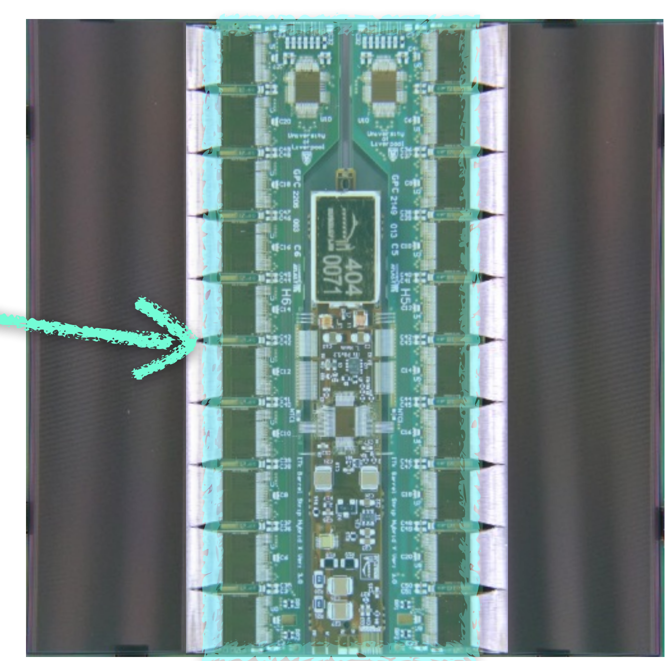
"This is not a bad price to CT scan 6 modules"

Sample #1	CT on (on 6 modules) for glue pattern	22-30 Jan. 24	72/R-009	3 to 5	600 CHF
Sample #2	CT on (on 6 modules) for glue pattern	22-30 Jan. 24	72/R-009	3 to 5	600 CHF
Sample #1	High resolution CT on (on 3 modules) for crack detail	22-30 Jan. 24	72/R-009	3 to 5	550 CHF
Sample #2	Digital Image Correlation strain observations during thermal cycling	22-30 Jan. 24	376/R-003	4 to 5	2500 CHF

Interposer Modules vs Material Budget

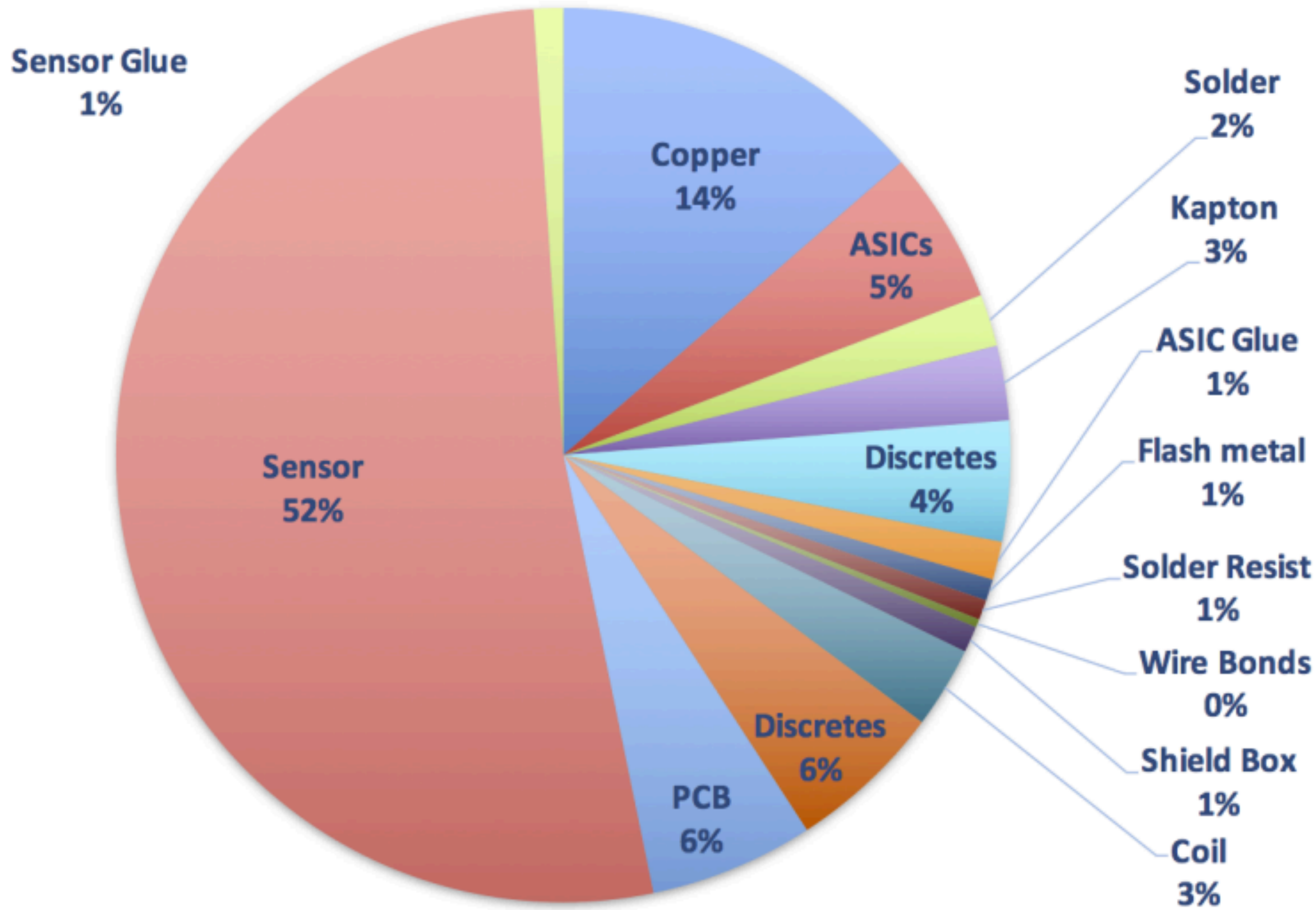
- Considering many variations with different interposer materials of varying thicknesses, different glues above interposer
  - Today: assume interposer covers area underneath all flexes, edges flush with hybrids
- Concern: addition of material to module increases radiation length X_0 of strip tracker





Strip Module Material Budget

- TDR claims total radiation length of one SS module = **0.65% X_0**
  - Also provides breakdown of component contributions:

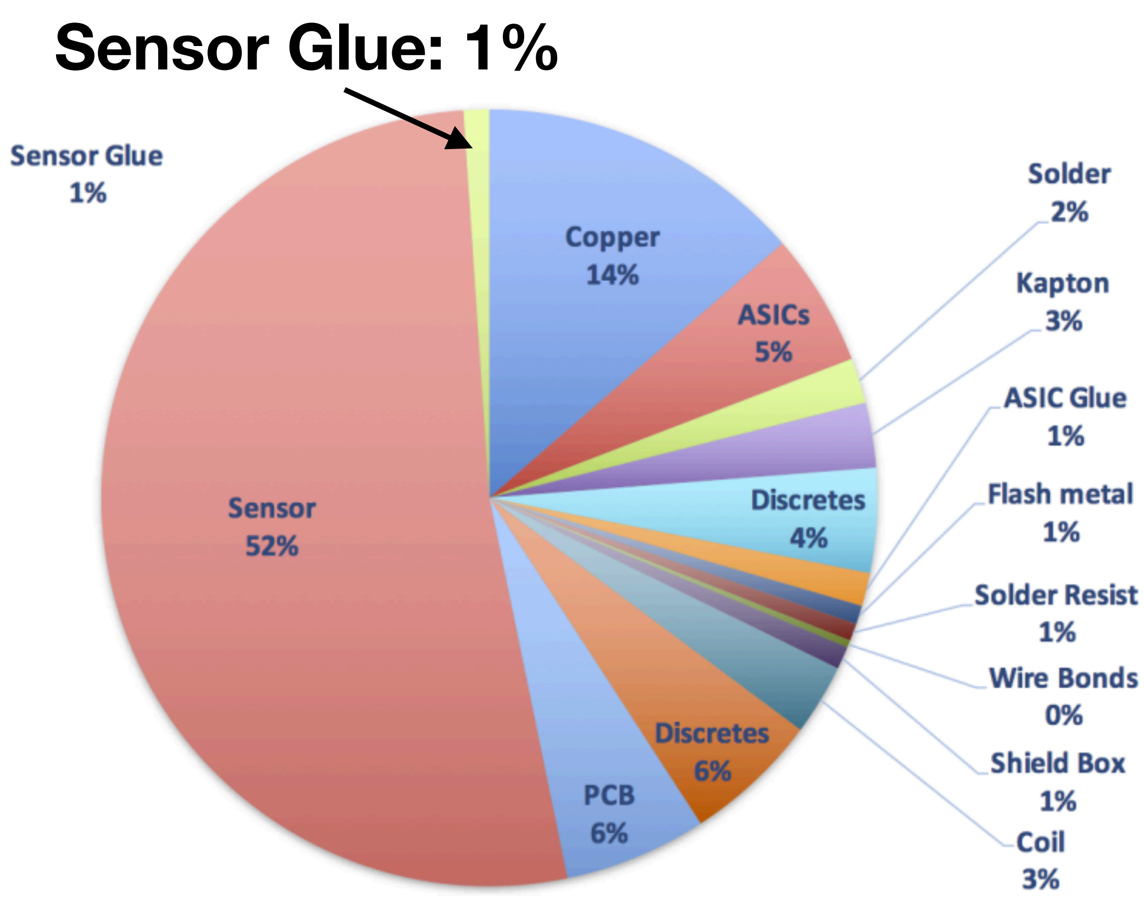


Note: proportions and amount of copper, kapton etc. have likely changed since the TDR. Could use a recalculation…

ITk Strip TDR

Concern #1: Additional Glue

- All interposer module versions have second glue layer above interposer
- Will this appreciably affect the module material budget?

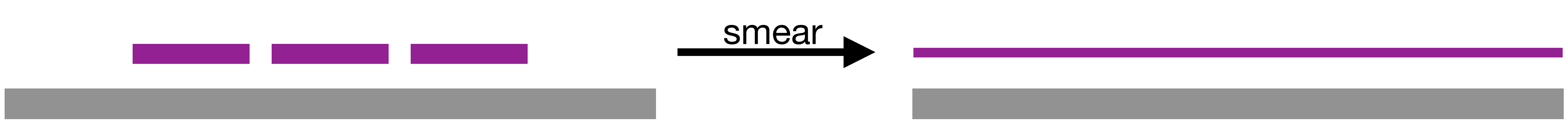


- TDR claims nominal glue layer (120 μm of Epolite) contributes only 1% of total module X_0, or 0.0065% X_0
- Assuming a second glue layer of the same thickness, and that SE4445/True Blue have similar X_0 to Epolite:
  - X_0 of entire module increases to 0.66%, negligible contribution from extra glue
- However, 1% contribution (0.0065% X_0) from glue layer seems optimistic- estimate appears to have been inherited from SCT, could use a recalculation

Glue Contributions

- Estimation procedure: use nominal glue weight spreadsheet to find density, glue weight of True Blue, SE4445, calculate volume (~346 mm^3)

- Smear glue volume over entire module area to mimic average particle experience passing through the module:



- Use smeared glue thickness to find X_0 contribution for each glue
  - X_0 of SE4445 = 12 cm
  - X_0 = 35 cm for an epoxy (Araldite 420 A/B), use as stand-in for True Blue

Glue Contribution to Module

- Comparing with **nominal SS module X_0 = 0.65%**
  - X_0 of SE4445 ~3x less than X_0 of True Blue, so SE4445 has ~triple the impact on total module X_0, but still <5% relative increase
- Easy to expand this study as a function of glue layer thickness if desired

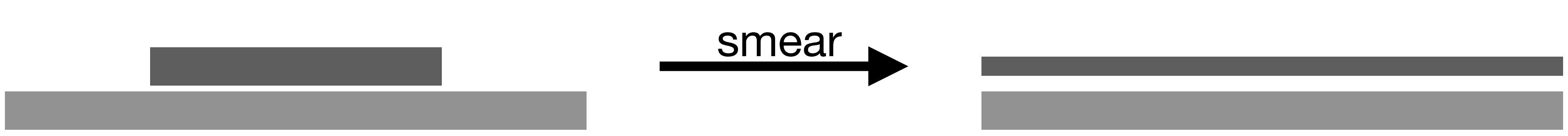
Material	Radiation Length (cm)	Smeared Thickness (μm)	Adds X_0 [% X_0]	New Module Total X_0 [% X_0]
SE4445	12	36	0.03	0.68 (+4.7%)
True Blue	35	36	0.01	0.66 (+1.6%)

Concern #2: Interposer

- We are considering various interposer thicknesses and materials. How will they affect the module material budget?

- Estimation procedure: smear interposer over entire module area to mimic average particle experience passing through the module

    - Preserve interposer volume as the material is averaged over the sensor, use smeared thickness to find X_0 contribution



Interposer Contributions

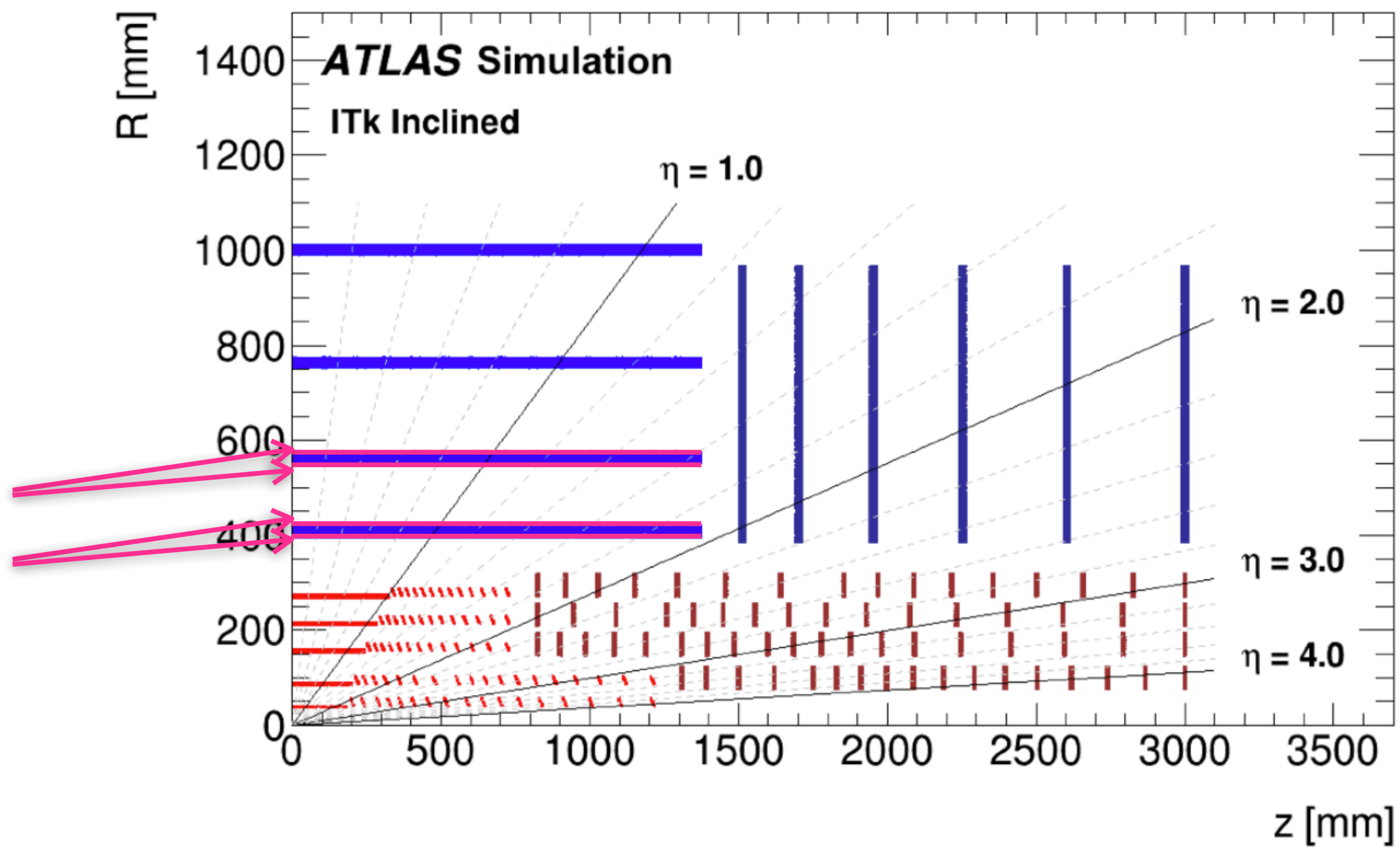
- Comparing with **nominal SS module X_0 = 0.65%**
  - Silicon interposers add 10-20% due to low X_0 and higher thicknesses considered, Kapton and CFRP interposers add 1-4% depending on thickness

Material	Interposer Thickness (µm)	Smeared Thickness (µm)	Adds X_0 [% X_0]	New Module Total X_0 [% X_0]
Silicon X_0 = 93.70 mm	150	64	0.069	0.719 (+11%)
	250	107	0.114	0.764 (+18%)
Kapton X_0 = 285.70 mm	25	11	0.004	0.654 (+0.6%)
	100	43	0.015	0.665 (+2.3%)
	150	64	0.022	0.672 (+3.5%)
CFRP X_0 = 240.0 mm	45	19	0.008	0.658 (+1.2%)
	90	39	0.016	0.666 (+2.5%)
	135	58	0.024	0.674 (+3.7%)

Compare to Whole ITk

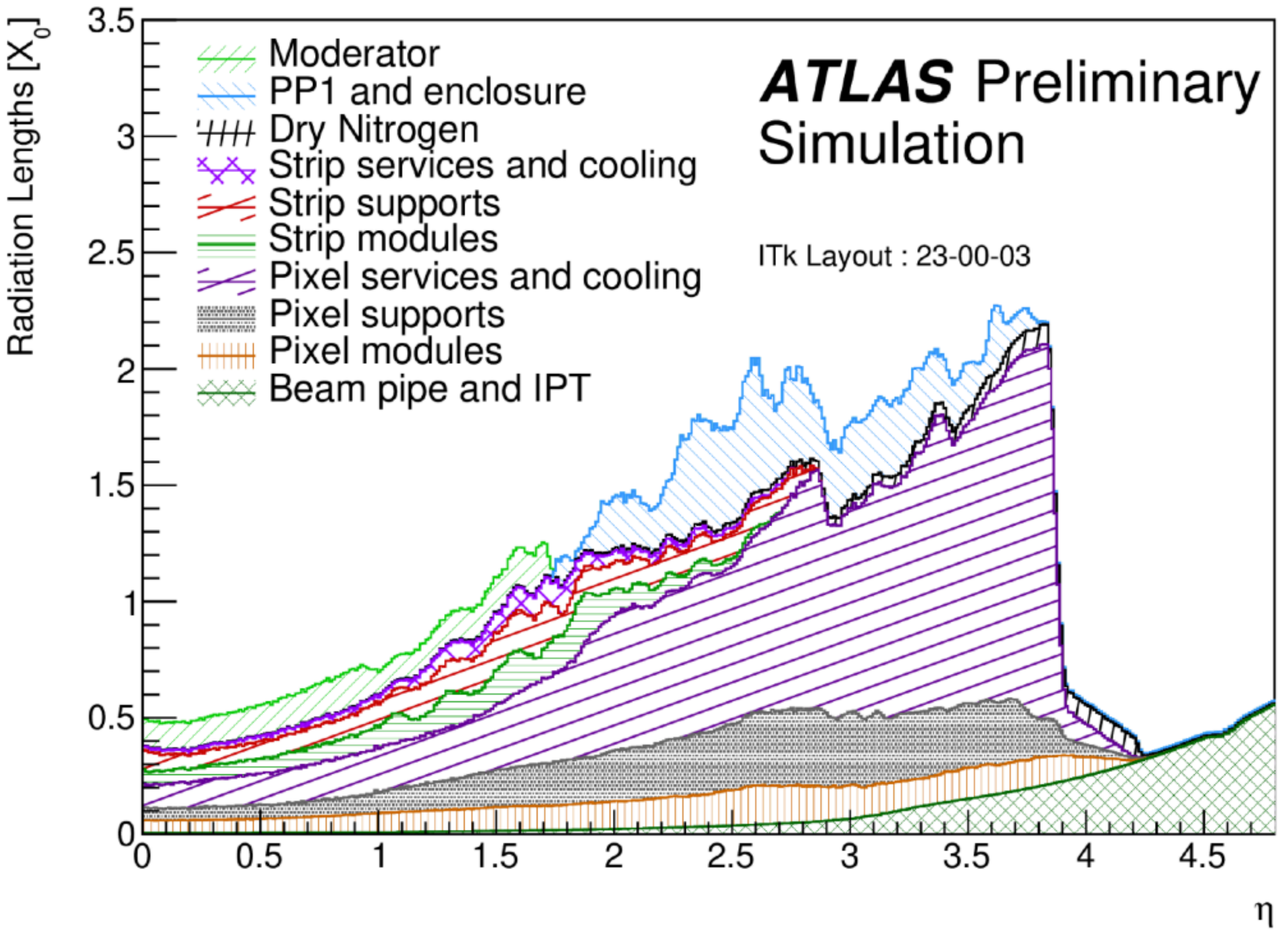
- Also calculated contribution of interposers to ITk material budget
  - Assume two double-sided layers of SS modules at r = 405, 562 mm extending to $|z|$ = 1400 mm, assuming negligible width in r
  - Assume module-averaged interposer thickness is uniform over entire layer

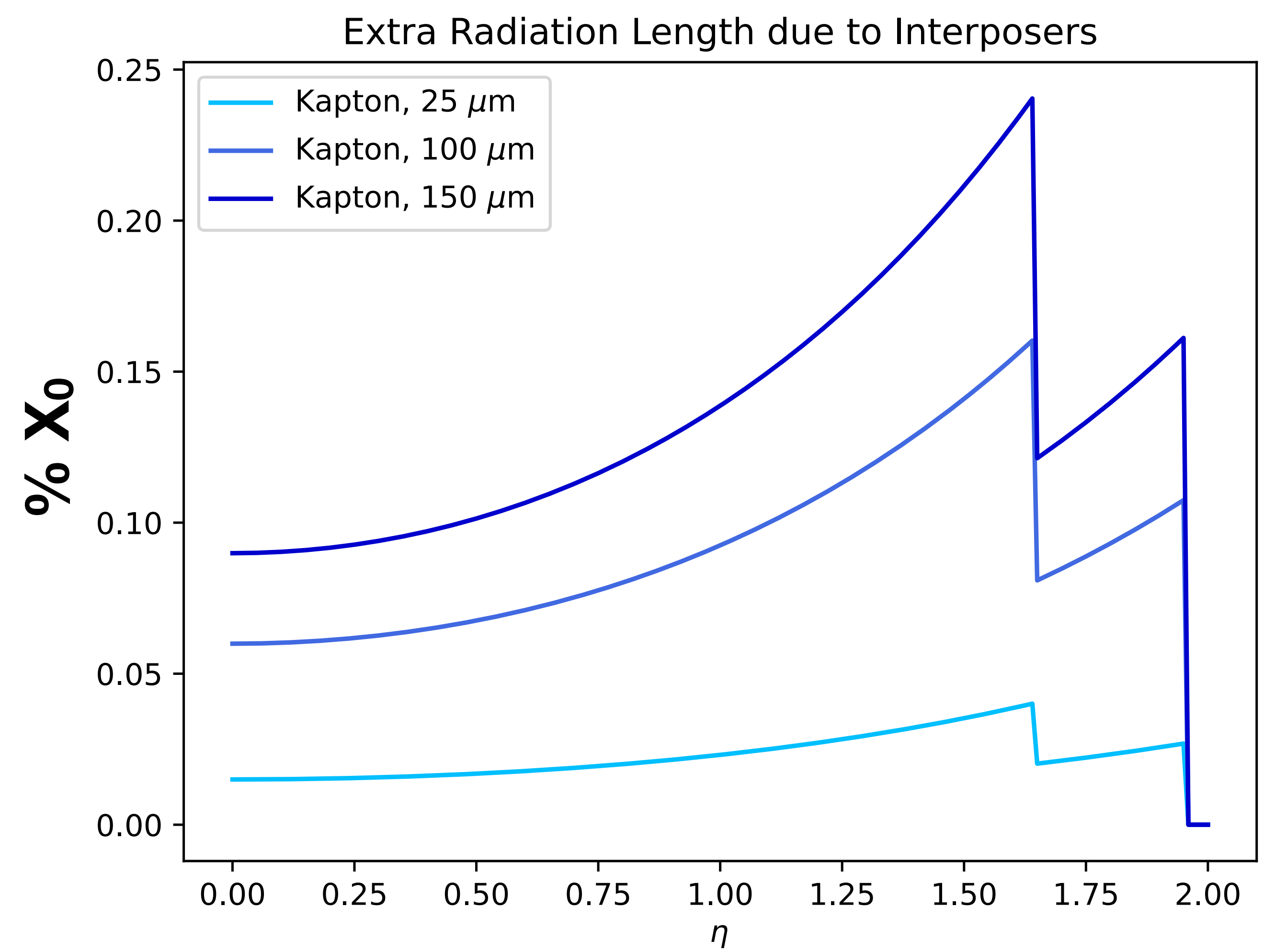
Essentially adding smeared interposer layer on either side of both innermost strip layers



Kapton Interposers

- At $\eta = 0$, **100 μm kapton** interposer adds 0.06% X_0 to the ITk material budget of 50% X_0, relative increase of 0.1%
- At $\eta = 1.5$, 100 μm kapton adds 0.16% X_0 to ITk material budget of ~1 X_0, relative increase of 0.16%





Glue Layers

- **SE4445 layer** comparable in impact to thickest kapton, CFRP layers considered
  - 0.2% increase at η = 0, ~0.3% increase at η = 1.5
- **True Blue layer** comparable in impact to thinnest kapton, CFRP layers considered
  - 0.08% increase at η = 0, ~0.1% increase at η = 1.5