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Mechanical and Thermal Management for ATLAS Upgrade Silicon Tracking System

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Inner Detector Support and Cooling

- **Topics**
  - A continuation of Carl's talk:
    - Stave concept for the barrel region
      - Composite sandwich concept-embedded cooling tube
        - ❖ Focusing on 1m length
      - Stave FEA: static stiffness, gravity sag driven
      - Sub-cooled detector: based on ATLAS evaporative fluid
      - Solution for thermal strain and strain from pressurized tubing

ATLAS Silicon Tracker Upgrade

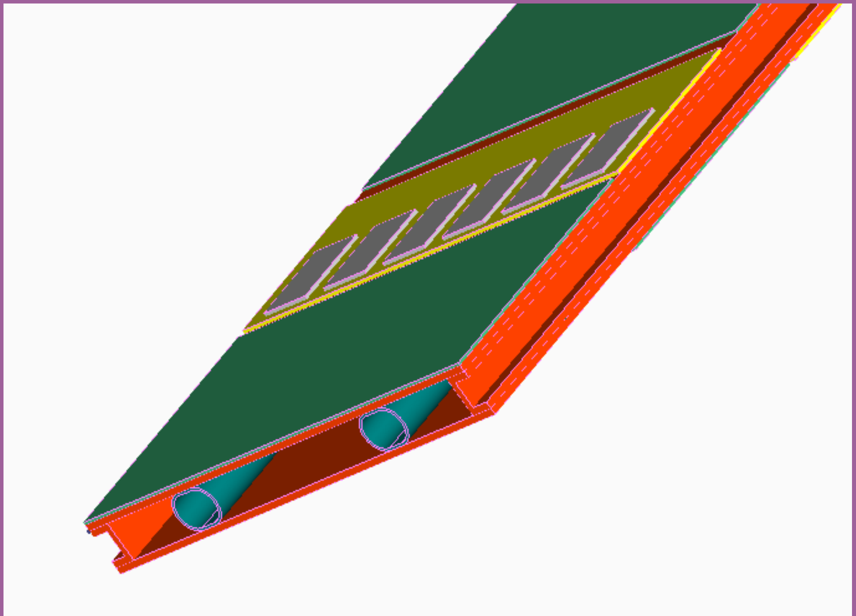
- **What are the goals from standpoint of mechanical?**
  - Dimensional (Static) stability
    - Out-of-plane distortion from gravity to be <50 to 60microns
    - Thermal distortions from sub-cooling detector to -25ºC to be <25microns
  - Cooling
    - Based on ATLAS evaporative (C_3F_8), with -20 to -25ºC at detector surface
    - An approach that assures that thermal runaway is not a problem
      - Places cooling directly beneath chip heat load
  - Radiation length-minimized, consistent with achieving mechanical objectives
  - Ease of Assembly and maintenance (when required)
    - Less time consuming
    - Precision module placement and bonding at earliest construction level
      - Facilitates testing and placement calibration
      - Added benefit in that provides potential for wider participation from institutions in building staves and detector assembly

ATLAS Tracker: Stave (Upgrade)

- **Analysis scope**
  - *Stave Stiffness*, evaluate ability to resist gravity sag, critical at upper and lower Φ
  - *Evaluate stave thermal/mechanical* aspects
    - Direct heat transfer to evaporative cooling tubes
    - Thermal strains from thermal gradient from chips to tubes
    - Thermal strains from cool-down, room temperature to initial state (minus 25°C)
  - *Coolant tube sizing* spaced the facing separation
- **Analysis guided by realistic constraints on radiation length**
- **Radiation length driven design as always, issues focus on:**
  - Composite material properties
    - High modulus, optimized fiber orientation for maximum axial stiffness
    - High conductivity fiber system for heat transport
    - Issue to be addressed is CTE mismatch in the assembly
  - Al cooling tube
- **Stave length, gravity sag, bounded between fixed end and simple supports**
    - ~60µm for fixed to ~320 µm for simple
    - Desire limit of <60microns

Stave Configuration

- **Composite Sandwich**
  - Facings high conductivity, high modulus K13D2U in 4:1 orientation (*modulus 1.77 times steel*)
  - Honeycomb core fills void not occupied by cooling tube
- **Cooling: Evaporative**
  - Cooling tube: U-shaped, allowing for entrance and exit at one end
  - Tube flatten slightly to improve thermal contact
- **Module Mounting on both composite facings: *balancing CTE mismatch to reasonable level***
  - Detector modules mounted on both sides, in alternating pattern
  - Hybrids mounted between detector modules



What key factors describe stiffness for this sandwich?

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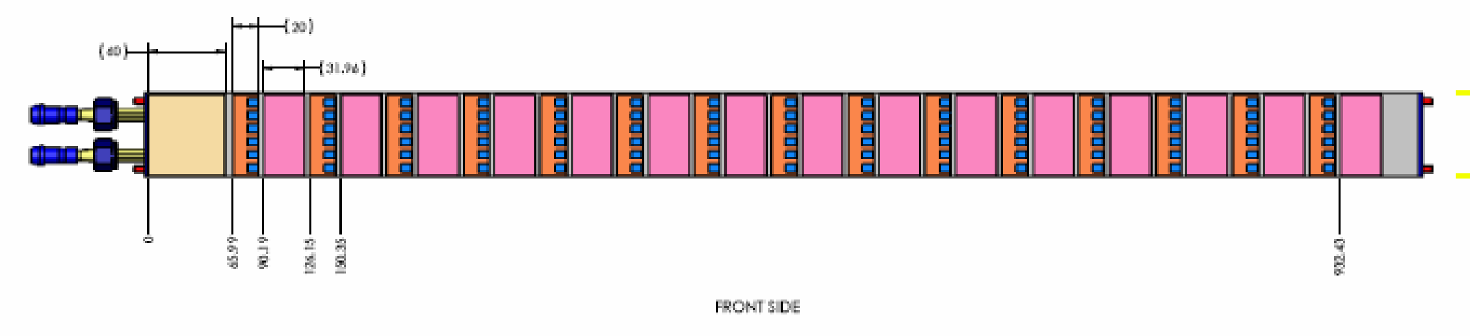
Stave Parameters Affecting Stiffness

- **Stave gravity sag (bending) results from uniform length-wise loading**
  - W=uniform loading, L=unsupported length, C varies from 1 to 5 based on end fixity, b=width of sandwich (w is generally a function of b so this essentially drops out)
  - D=flexural rigidity, E=facing Young's modulus, t=facing thickness, h=overall sandwich height, c=core height, v=facing Poisson's ratio

$$\delta(bending) = \frac{CwL^4}{384Db} \qquad D = \frac{Et(h+c)^2}{12(1-\nu^2)}$$

- **Where do we gain most?**
  - Minimizing unsupported stave length, *next*
  - Maximizing end support rigidity, next
  - Separation between facings, *finally*
  - Facing modulus and facing thickness
- **What difficulties do we encounter?**
  - Achieving stave lengths >1m by limiting $\delta < 60$microns
  - Cooling both composite faces with single cooling tube, limits c
  - Radiation length limits, t
  - Quasi-isotropic facings, places limit on E

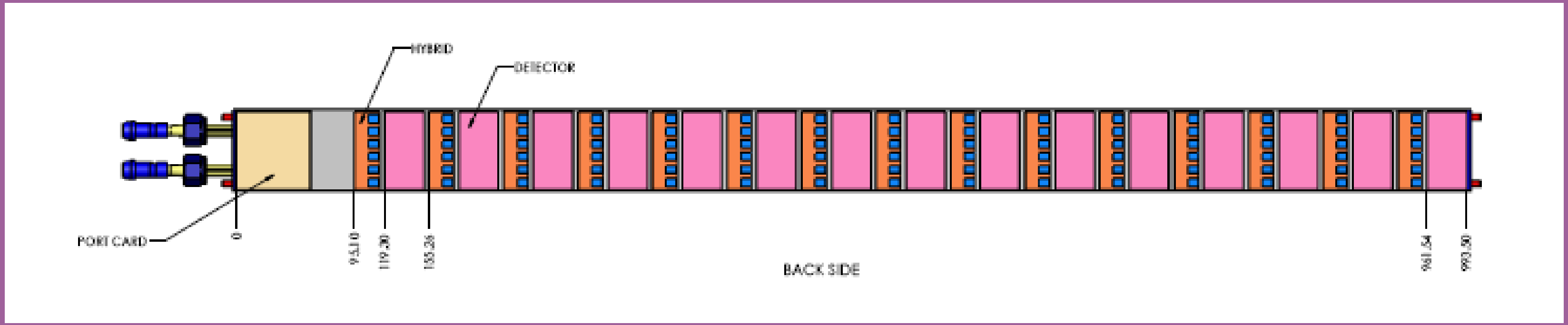
Stave Module Layout



width

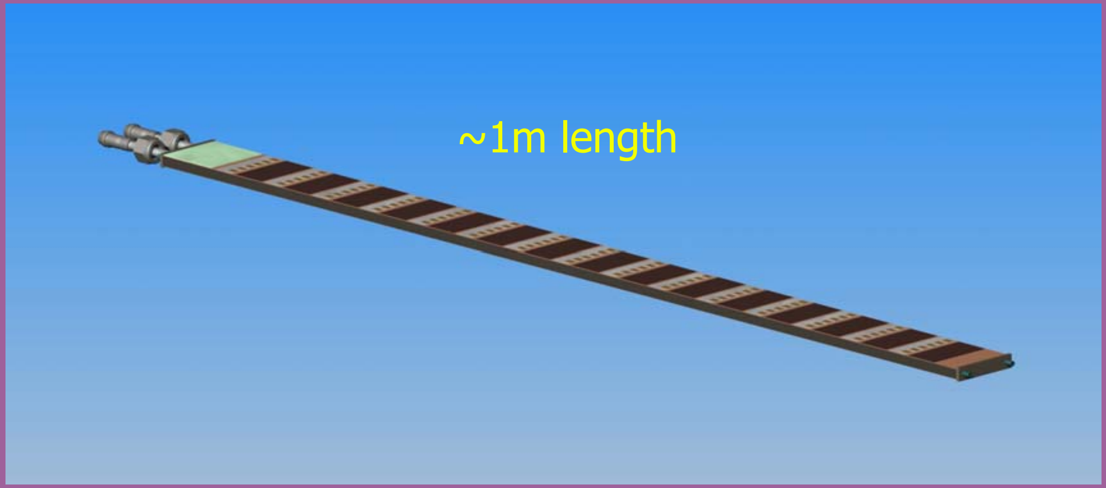
6.4cm

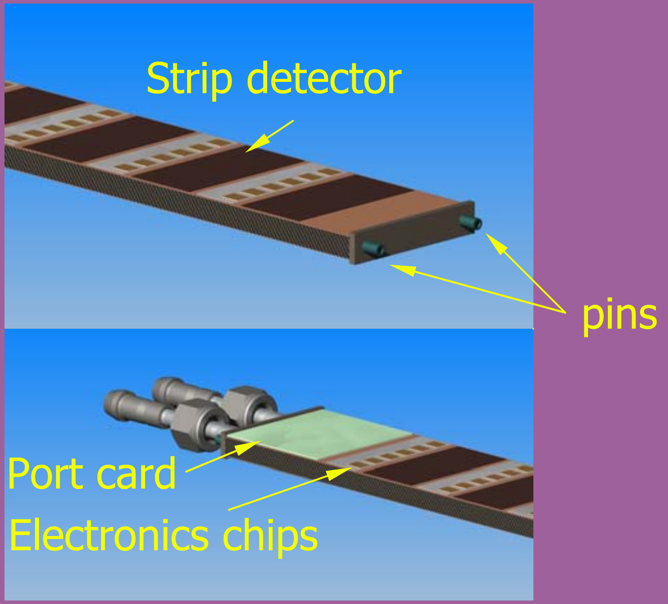
Physical length of stave ~99.4cm



Stave Support-via Alignment Pins

- **Stave End Cap**
  - Two pins at each end for stave support and alignment
  - Pin engagement in stave and end support disk are important to stave stiffness





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Stave Sag FEA Models (Three)

- **Full Length (96cm) model with wafers, hybrids and cable as dead weight**
  - 0.173in diameter support pins
  - Clamped support pins, vertical DOF only
  - Core thickness 4.6mm
- **Half length model with wafers, hybrids and cable as dead weight**
  - 0.173in support pins
  - ½ length model used to add structural coupling of wafers, and hybrids
  - Core thickness 5.88mm
- **Model of pins and end cap alone with stave weight imposed**
  - Two pin diameters (0.173in and 0.25in)
- **Coolant Mass**
  - Used density of two phase fluid. Mean density is 60kg/m^3, whereas liquid density is 1660kg/m^3
  - Round circular tube in half length model (5.88mm)
- **Sandwich Core (shear deflection)**
  - Varied core shear modulus, reflected in density change to material
    - 66 to 210kg/m^3, CVD carbon foam
    - 56 and 110kg/m^3, honeycomb
- **Sandwich core height**
  - FEA for 4.6mm and 5.88mm
  - Size for prototype stave driven by tube availability---8mm

FEA Sandwich Core Summary

Carbon Foam Core Shear Modulus (MPa)	Foam Density (kg/m^3)	Stave Central Deflection (1G loading)	Foam Radiation Length (%)	Equivalent Foam Radiation Length (mm)
Half Length Model				
Separation between facings -5.88mm (equivalent t=4.48mm)				
26.9	66	62.1	.069	6470
34.4	110	63.9	.115	3882
229.7	210	65.1	.221	2033
Full Length Model (96cm)				
Separation between facings -4.61mm (equivalent t=3.15mm)				
26.9	66	53.7	.049	6470
34.4	110	54.7	.081	3882
229.7	210	54.8	.155	2033
Honeycomb Core Shear Modulus (MPa)	**HC Density (kg/m^3)**	**Stave Central Deflection (1G loading)**	**Foam Radiation Length (%)**	**Equivalent HC Radiation Length (mm)**
Half Length Model				
Separation between facings -5.88mm (equivalent t=4.48mm)				
626/337 (resin)	56	58.7	0.059	7611
1551/710 (CC)	160	61.6	0.168	2669
Full Length Model (96cm)				
Separation between facings -4.61mm (equivalent t=3.15mm)				
626/337 (Resin)	56	50.1	0.046	7611
1551/710 (CC)	160	51.7	0.168	2669

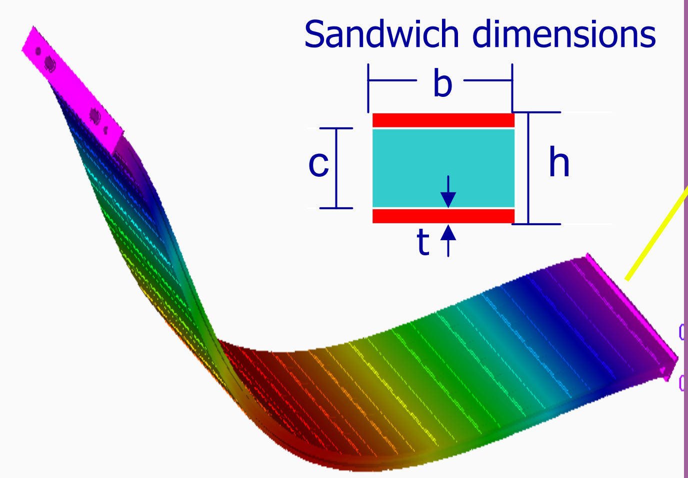
Stave FEA Results-Core Shear

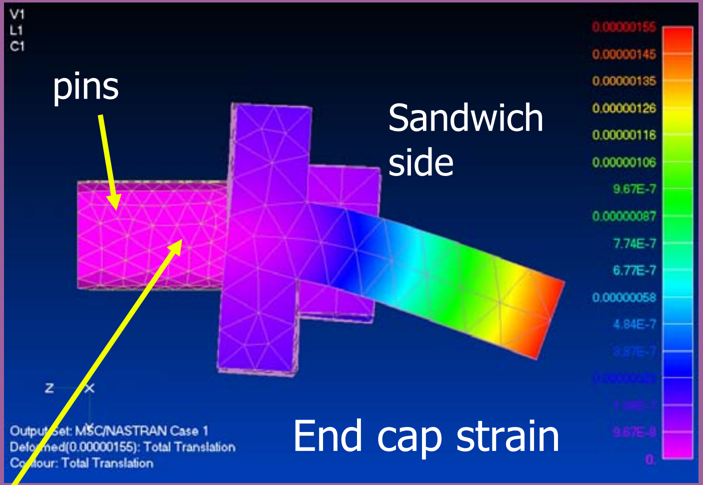
- **Varied core shear modulus**
  - Looked at carbon foam versus honeycomb
  - Results did not come out entirely as expected
  - Example:
    - Increased shear modulus led to increased sag
    - Increased shear modulus with carbon foam comes at expense of increased core density, this seemed to be over-riding factor
- **Suspicion: coolant tube with direct coupling to facing was a major contributor to shear load transfer**
- **Approach**
  - Estimate degree of sag from core shear
  - Uncouple tube by reducing the modulus

Idealized Sandwich Stiffness

- **Deflection from Uniform Loading**
  - Bending Deflection
  - Core Shear Deflection
  - End Cap Strain (mounting pins): somewhere between simple and fixed

L-unsupported length
w-load per unit length





G-core shear modulus

$$\delta(shear) = \frac{wL^2}{8bB} \qquad B = G\left[\frac{h(h+c)}{2c}\right]$$

E-facing modulus

$$\delta(bending) = \frac{CwL^4}{384Db} \qquad D = \frac{Et(h+c)^2}{12(1-\nu^2)}$$

C=1 for fixed and C=5 for simple

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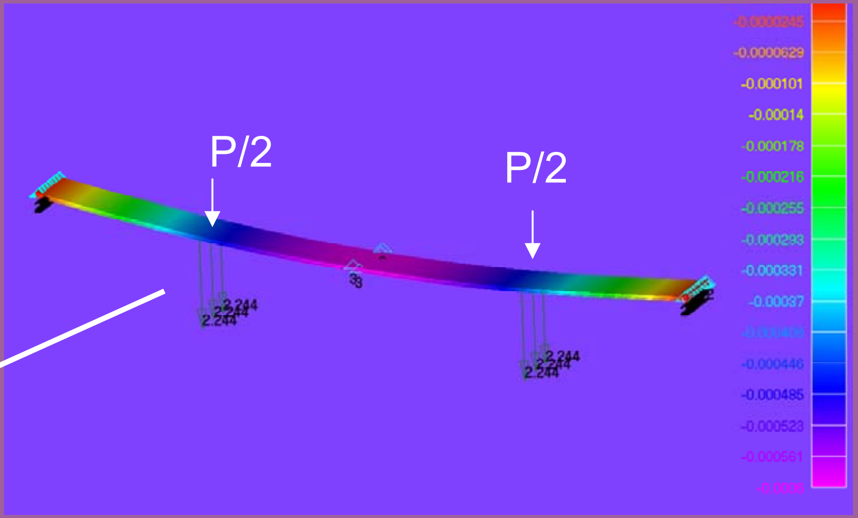
Establish Cooling Tube Interaction

- **96cm Model of Stave**
  - Use simple edge supports, K13D2U 4/1
  - Apply force at quarter points,
  - Extract deflection at Δ_4 and Δ_2, quarter point and mid-span
- **Use relationship to solve for core shear modulus**

$$G_{.c1} := \frac{1.5 \cdot P \cdot L1 \cdot c1}{(h1 + c1)^2 \cdot b \cdot \left(11 \cdot \delta_{.4} - 8 \cdot \delta_{.2}\right)}$$

- **Result for 4.6mm core with Al tubes**
  - ~128 MPa calculated versus 26.9 MPa input for virgin foam
  - Tubes contribute most of the shear stiffness, except at very high foam densities



Division between bending and shear, based on estimate of core shear of 128MPa

Using sandwich relationships for fixed ends

$\Delta_{bending}$ est=35μm
$\Delta_{core\ shear}$ est=8.3 μm

Combined Δ=43.3microns (FEA 53.7 μm)

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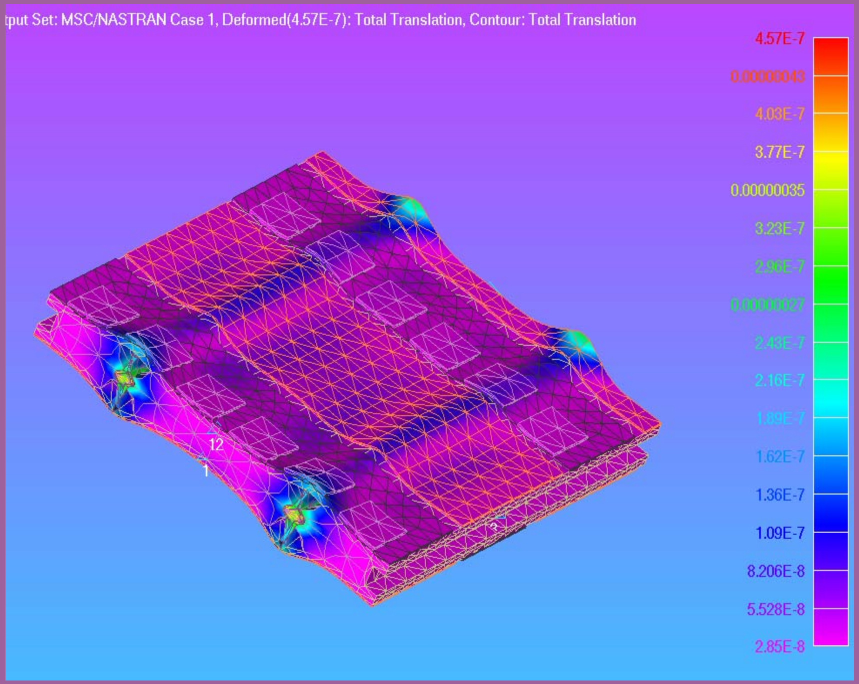
Removed Cooling Tube Interaction

- **Cooling tube as a shear component is affected by compliance of thermally enhanced adhesive bond (CGL7018)**
  - FEA model modification placed reliance for shear transfer on the composite fiber honeycomb, 626MPa
  - Increase in sag by small amount (~4microns for HC only)
- **Experimental tests with stave prototype hopefully will reveal extent of contribution from coolant tube on shear**
  - If tube contributes significantly to shear load transfer, what will be the benefit?
    - Slight increase in stiffness predicted, but if higher than expected, may be possible to reduce the number of uni-tape layers in the composite facing
    - Slight benefit in radiation length in using different core material

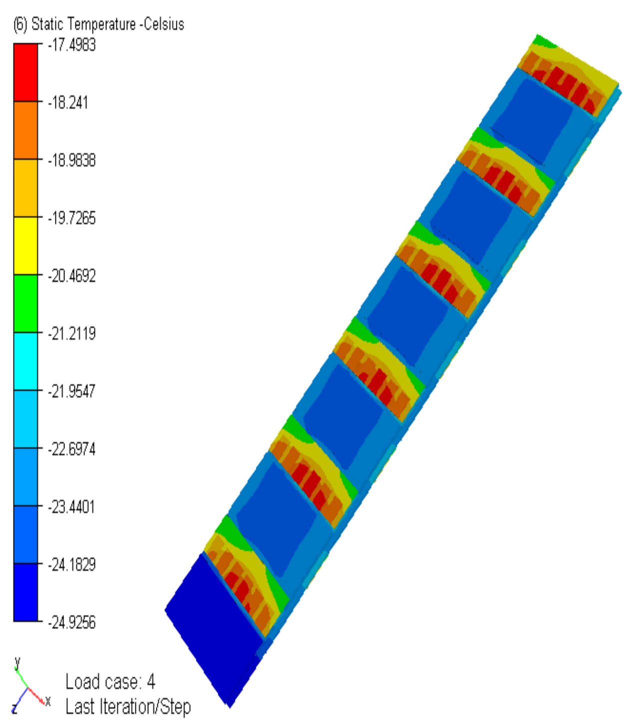
Stave Distortion From Cooling Tube Internal Pressure

- **Stave Model (Very early model)**
  - 4.6mm diameter cooling tube
  - Material: Aluminum
  - Pressure: 8bar absolute (101psia)
  - Distortion: small fraction of micron
  - Resulting silicon detector stress: 0.69MPa (100psi)
- **Open Issue**
  - Assess distortion for larger diameter tube (8mm)

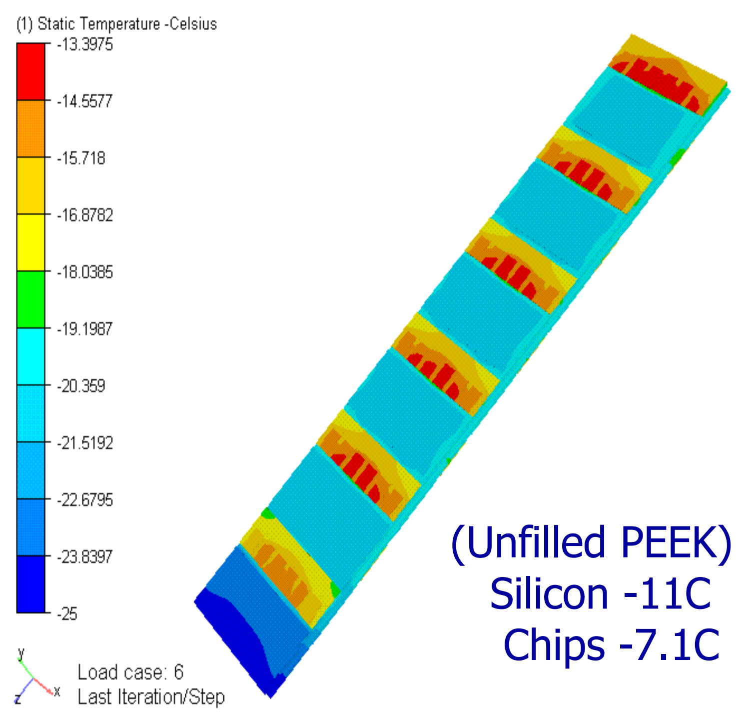


Stave Thermal Solution

- **FEA solution for both Al and Carbon-Fiber Filled PEEK tubes**
  - 6 chips for each hybrid, 0.5W each: heat zone shifts top to bottom
  - Film coefficient 3000W/m^{2}K, typical of Pixel stave for C_3F_8, two parallel tubes
  - Lower peak wafer temperature favors Al cooling tube



-17.5C Chip/Silicon -23.5C

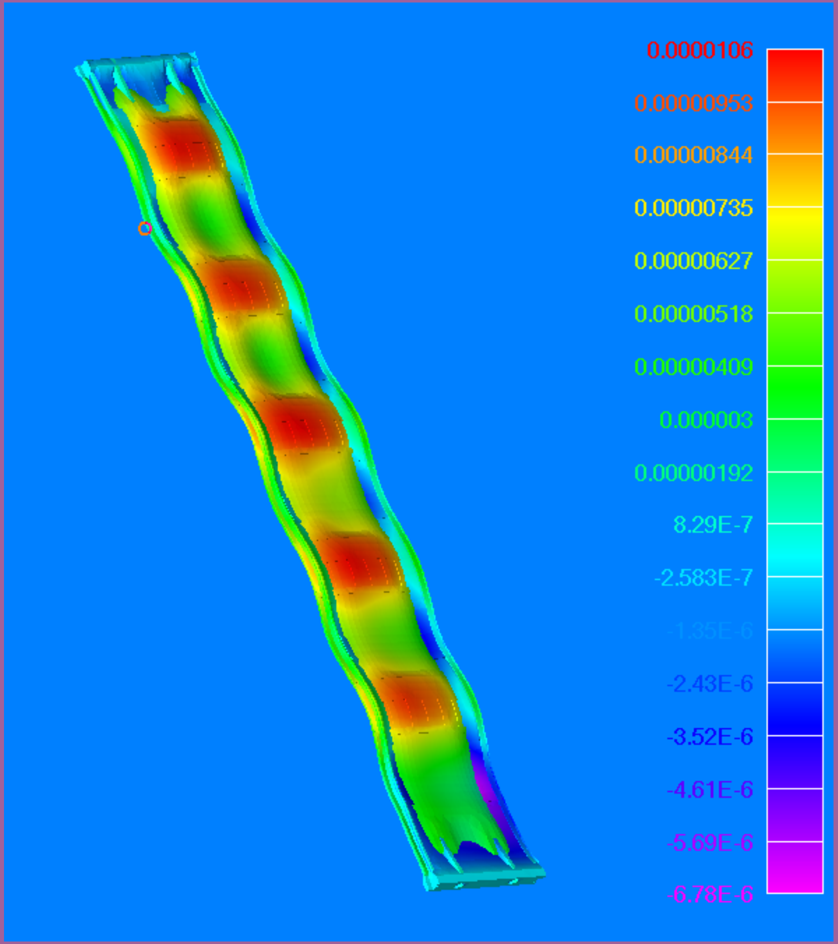


(Unfilled PEEK)
Silicon -11C
Chips -7.1C

-13.4C Chip/Silicon -20.2C

Stave Thermal Strains

- **FEA solution**
  - Used 48cm long stave, symmetry BC at mid-length
  - Limit to stave length permitted addition of wafers and hybrids, still model required large number of elements
- **Thermal strain for change 50°C in temperature (RT to -25°C**
  - Results for stave with 5.88mm core height, round tube
  - K13D2U 4:1 fiber orientation
  - 0.75mm thick facings
  - Detector modules and hybrids coupled to facing without interface compliance
- **Distortion pattern**
  - ~11micron peak to peak, alternating in z-direction



Evaporative Film Coefficient

- **Thermal FEA based on film coefficient from ATLAS (3000W/m^{2}K)**
  - 3000W/m^{2}K chosen to expedite thermal solutions
  - *Question: what might the film coefficient be for larger diameter tubes?*
- **Using Kreith-Bohn**
  - As a check, calculated for 3mm (8mil wall) round tube (ATLAS) Dh=2.59mm
    - 3040W/m^{2}K at entrance (x=0.3 after throttling)
    - 4451W/m^{2}K at exit (x=0.8, mostly vapor)
  - Based on 4.6mm flatten tube (FEA thermal solution) Dh=4.956mm
    - 1228W/m^{2}K at entrance and 1645W/m^{2}K at exit, *noticeably lower*
  - Now for the 7.33mm flatten tube (planned for prototype stave) Dh=7.791mm
    - 811W/m^{2}K entrance and 1000W/m^{2}K at exit
  - Important to note that since ΔT_{film} is proportional to inner wall surface area, the lower heat transfer film coefficients have no real impact for same heat load
    - 2.42°C (3mm), 2.96°C (4.6mm), and 2.94°C (7.33mm)
  - The pressure drop is different, lower for the bigger tubes, since the mass flow rate is the same for each case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Stave Radiation Length Estimate

prototype

Item	X_o (g/cm^2)	ρ (g/cm^3)	t_{eff} (mm)	R_L (mm)	Stave %R_L
Stave Sandwich Height-7.33 mm					
Coolant-C_3F_8	33.2	.060	1.529	5530	0.028
Coolant tube-Al	24.01	2.7	0.124	89	0.14
Facings	42	1.7	1.27	247	0.514
Sandwich close-out	42	1.7	0.172	247	0.07
Honeycomb	42	0.056	1.595	7500	0.021
					0.772

Sag Est.

30 µms
(extrapolated)

Item	X_o (g/cm^2)	ρ (g/cm^3)	t_{eff} (mm)	R_L (mm)	Stave %R_L
Stave Sandwich Height-4.6 mm					
Coolant-C_3F_8	33.2	.0660	0.406	5530	0.0073
Coolant tube-Al	24.01	2.7	0.064	89	0.094
Facings	42	1.7	1.27	247	0.514
Sandwich close-out	42	1.7	0.108	247	0.044
Honeycomb	42	0.056	1.0	7500	0.013
					0.672

54 µms
(FEA)

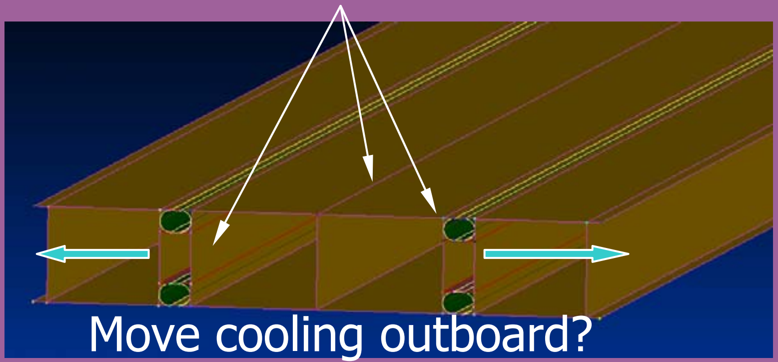
2m Long Stave

- **Sag**
  - For fixed geometry previously discussed, sag from bending alone would increase by L to the 4th
  - 50microns would increase to 800microns, without factoring in potential increase in core shear
- **Increased Sag can be mitigated by increasing structure moment of inertia**
  - Larger separation between facings for sandwich structure
    - From 7.3mm to 20mm
    - This complicates cooling and requires internal structure to provide high core shear modulus
  - Entirely different structural approach?
    - Any approach where support is provided at two opposing ends becomes a beam problem
- **Preferred solution is to provide a mid-span support at 1m**
  - Allows retention of basic construction concept

2m Unsupported Stave Length

- **Structural and Cooling Issue**
  - Question will become how best to minimize temperature spread between coolant inlet temperature and strip detector, and chips
  - We have chosen an embedded cooling tube versus outboard circuits for these reasons
    - Decision become less attractive for 2m length because of larger facing separation
    - Second disadvantage is increased material mass and radiation length

Internal ribs for shear stiffness



Move cooling outboard?

Arrangement is possible, but rather extreme solution, making 1m and 2m staves entirely different problems

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Summary

- **Prototype Stave Construction.- for thermal and mechanical tests**
  - Basic stave arrangement as outlined earlier
    - Flattened a 8mm tube; size based on available extrusion
  - Separation between facings increases to 7.33mm because of larger tube
    - Anticipate increased out-plane stiffness
      - Gravity sag reduced to range of ~30microns for 1m length, if pin end support is as predicted
- **Current tasks**
  - Working on design of assembly tooling
  - Will re-visit effect of internal tube pressure on stave distortion
    - Prototype with larger tube diameter, same wall thickness
    - FEA of distortion at module
  - Cooling
    - Update cooling FEA for larger tube (4.6mm versus 8mm)
    - Cooling for 12cm wide detector, tube spacing, thermal runaway potential
  - Tube bend tests needed to confirm ability to bend tube through 180º within 6.4cm stave width