

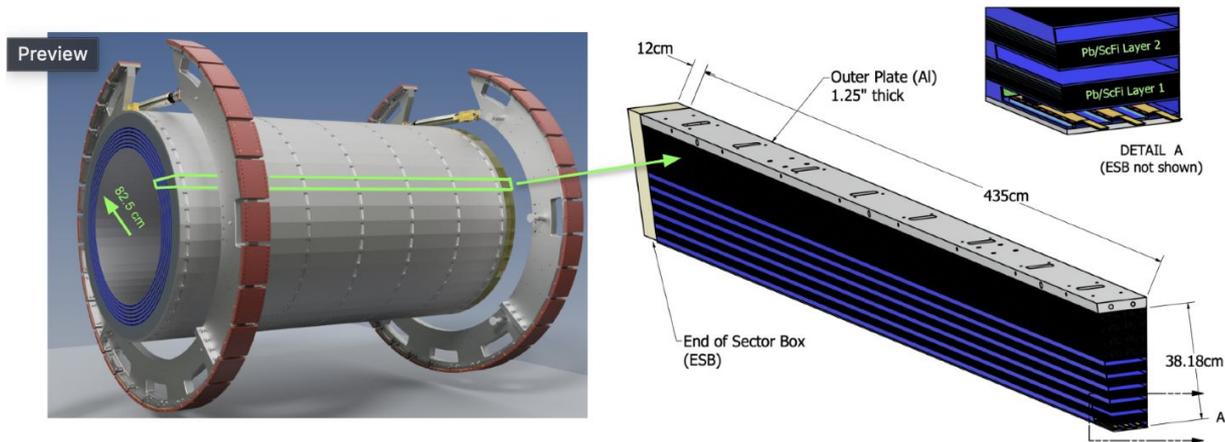
Thermal Simulations for Barrel Imaging Calorimeter for EIC

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Barrel Imaging Calorimeter

BIC uses two proven technologies: A Pb/ScFi calorimeter with SiPMs for precise energy measurement, and AstroPix silicon trackers interleaved with Pb/ScFi layers for excellent spatial resolution and position reconstruction.

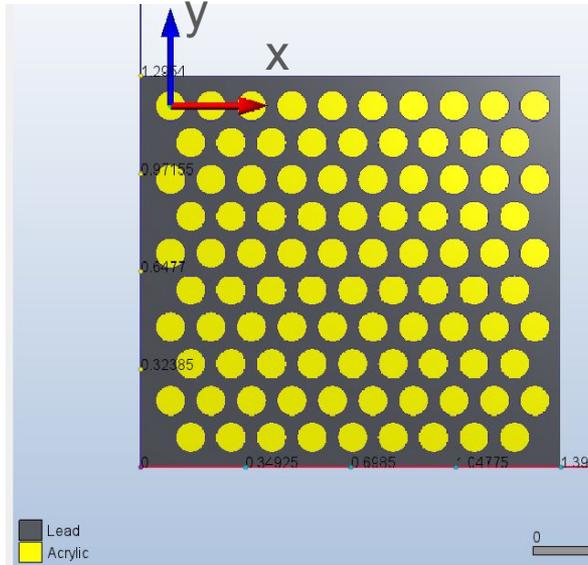


Barrel Imaging Calorimeter (BIC) with 48 sectors: each sector features interleaved Pb/ScFi layers and AstroPix trays for precision tracking and energy measurement. **PC: PreTDR.**

Pb/Scintillating Fibre's thermal conductivity in different directions:

The property that tells how well the heat is transferred through a material due to a temperature gradient is called the thermal conductivity. It can be described by Fourier's law in 1-D as: $\mathbf{q} = -\mathbf{k} (dT/dx)$.

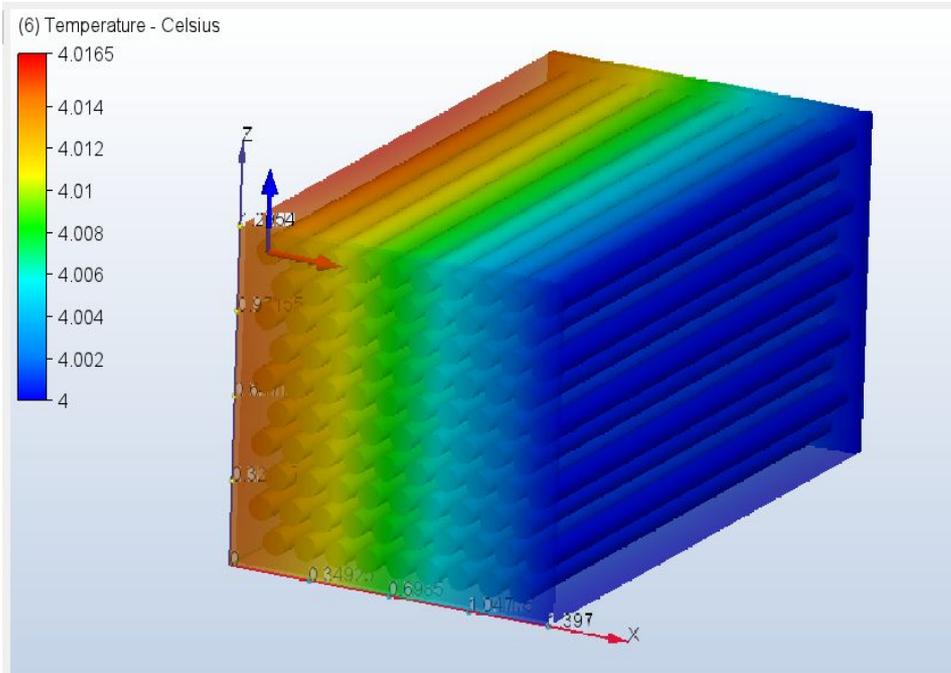
CAD model for the Pb scintillating fibres (glue layers ignored, probably similar k as acrylic):



ScFi Radial (y) separation: **1.22 mm**

ScFi Azimuthal (x) separation: **1.35 mm**

Pb/Scintillating Fibre's thermal conductivity in x-direction



Thermal conductivity (k) (x-axis): **15.7 W/(m-K)**.

Boundary conditions: Heat flux: **0.002 W/cm²**.
Temperature: **4°C**.

Length along x axis = 1.3 cm

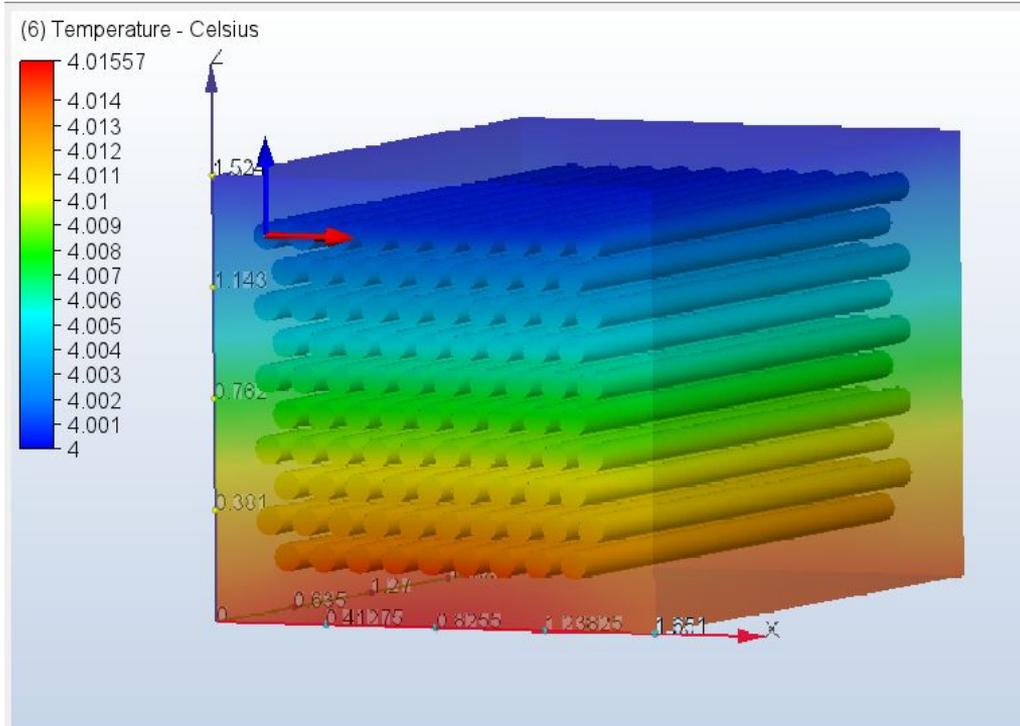
$$k_{Pb} = 35 \text{ W/(m-K)}$$

$$k_{Ac} = 0.19 \text{ W/(m-K)}$$

$$k_x = \mathbf{0.44} k_{Pb}$$

$$k_x = \mathbf{82.6} k_{Ac}$$

Pb/Scintillating Fibre's thermal conductivity in y-direction



Thermal conductivity (k) (y-axis): **18.4 W/(m-K)**.

Boundary conditions: Heat flux: **0.002 W/cm²**.
Temperature: **4°C**.

Length along y axis = 1.4 cm

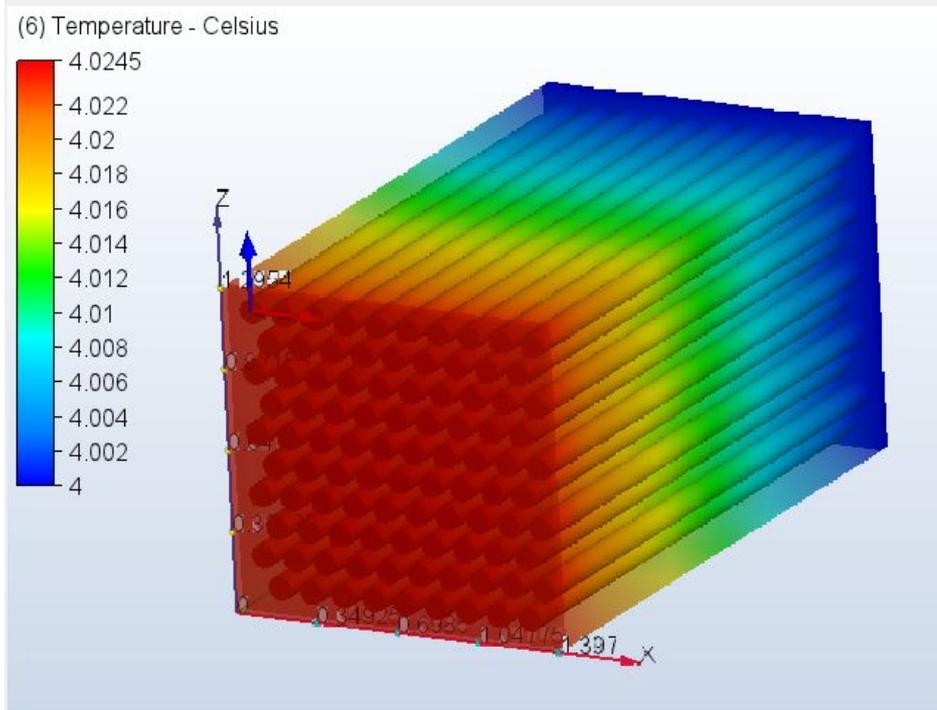
$$k_{Pb} = 35 \text{ W/(m-K)}$$

$$k_{Ac} = 0.19 \text{ W/(m-K)}$$

$$k_y = \mathbf{0.53} k_{Pb}$$

$$k_y = \mathbf{96.8} k_{Ac}$$

Pb/Scintillating Fibre's thermal conductivity in z-direction



Thermal conductivity (k) (z-axis): **21.55 W/(m-K)**.

Boundary conditions: Heat flux: **0.002 W/cm²**.
Temperature: **4°C**.

Length along z axis = 2.6 cm

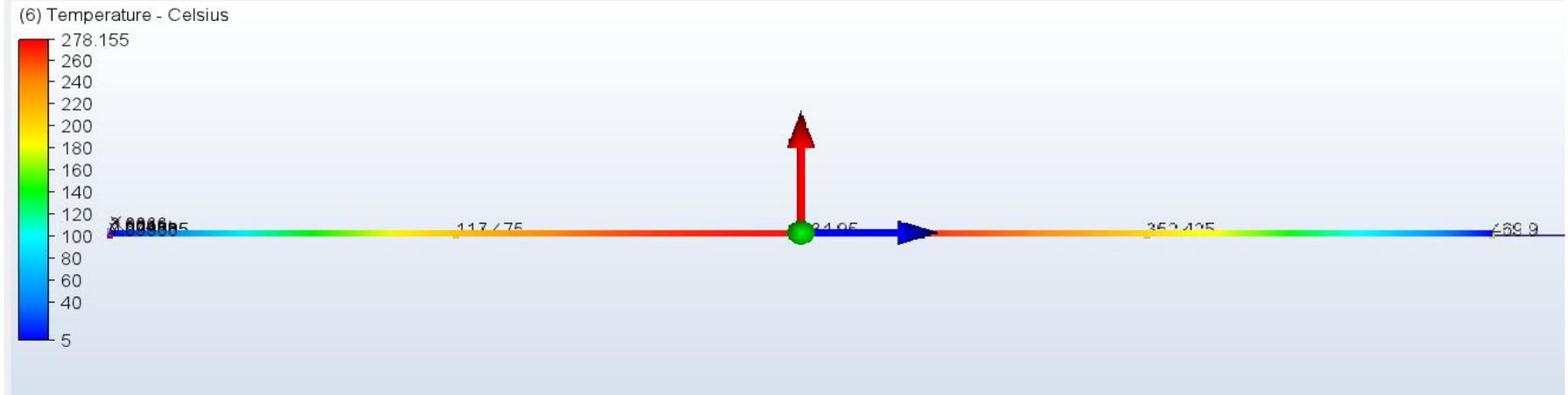
$$k_{Pb} = 35 \text{ W/(m-K)}$$

$$k_{Ac} = 0.19 \text{ W/(m-K)}$$

$$k_z = \mathbf{0.62} k_{Pb}$$

$$k_z = \mathbf{113.4} k_{Ac}$$

Simulation results for Aluminum stave with AstroPix sensors on it



Boundary Conditions: Temperature at both the ends of stave: **5°C**.
Heat Flux onto the stave : **0.002 W/cm²**.

Conductivity of Al: **2.04 W/(cm-K)**

Dimensions of Stave: Length: **4.7 m**, width: **2cm**, Thickness: **1mm**.

Maximum temperature at center of bar: 278°C

Analytical Calculation of Aluminum stave with AstroPix sensors

Heat flux $q(z) = -k (dT/dz)$, along stave perpendicular to cross sectional profile area (W/m^2)

$T(L/2)$



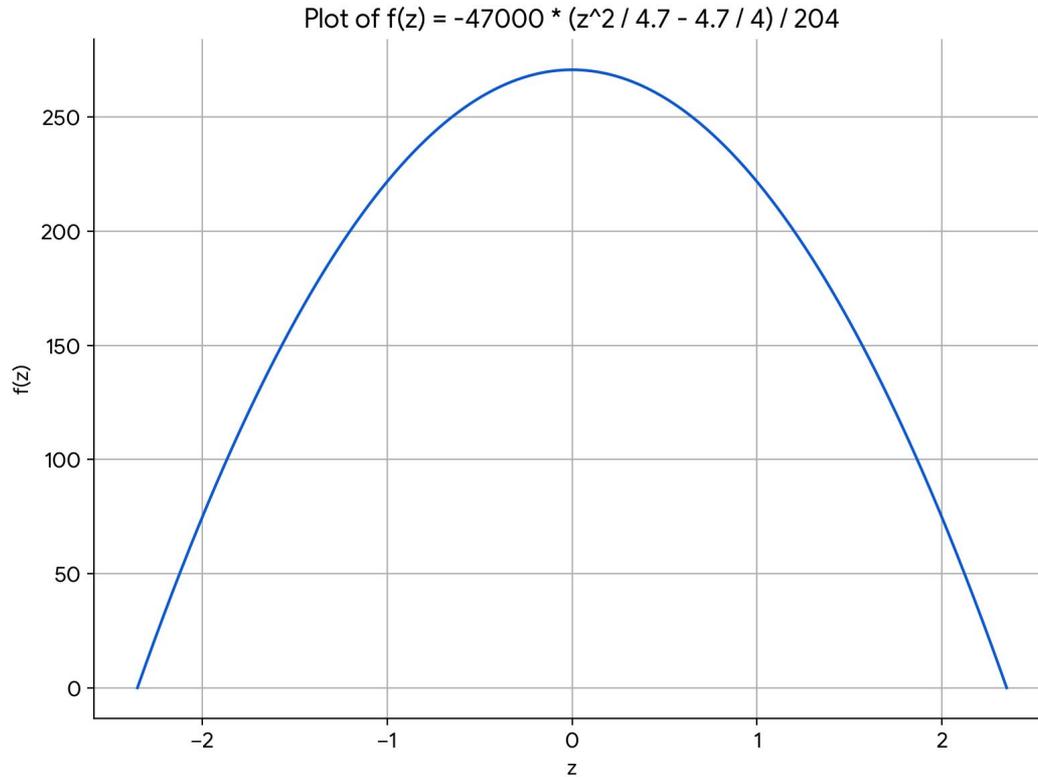
Assume all heat from AstroPix must be transported to end of sectors, i.e.

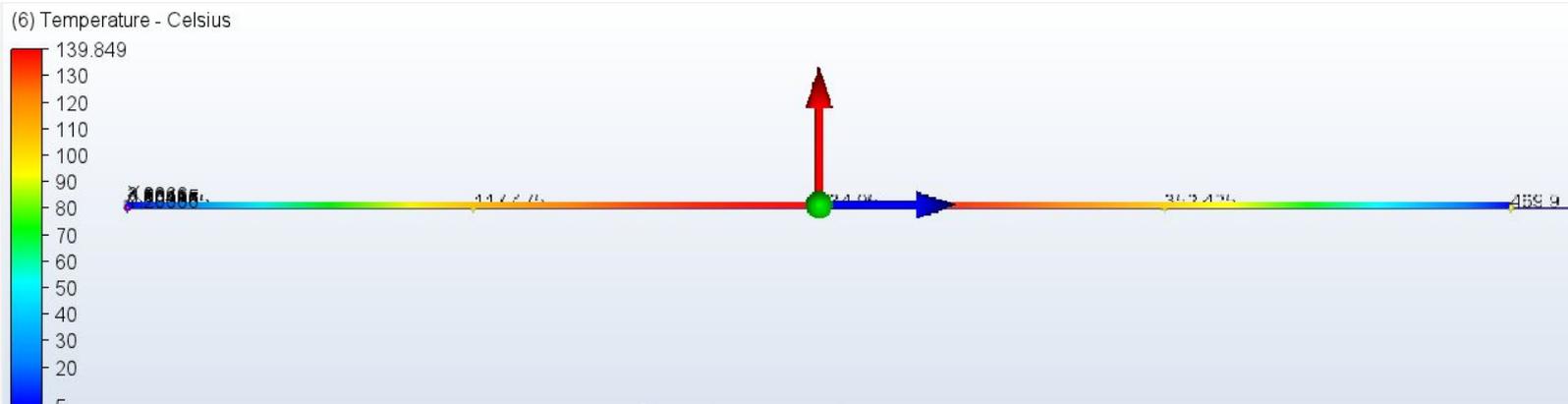
- $q(z = 0) = 0$, i.e. no heat moving longitudinally through center of stave (symmetry)
- $q(z = L/2) = (0.002 \text{ W/cm}^2 \cdot 2 \text{ cm} \cdot L/2) / (2 \text{ cm} \cdot 1 \text{ mm}) = 0.94 \text{ W} / 20 \text{ mm}^2 = 47,000 \text{ W} / \text{m}^2$, i.e. each ESB needs to remove “only” 1 W per stave, but has to do so through a small surface area
- $q(z) \propto z$, i.e. linear dependency on z under uniform heat load for full strip population
- $q(z) = q(L/2) \cdot 2z / L$

Temperature $T(z) = - \int q(z) / k dz = T(0) - q(L/2) \cdot z^2 / kL = T(L/2) - q(L/2) \cdot (z^2 / L - L / 4) / k$

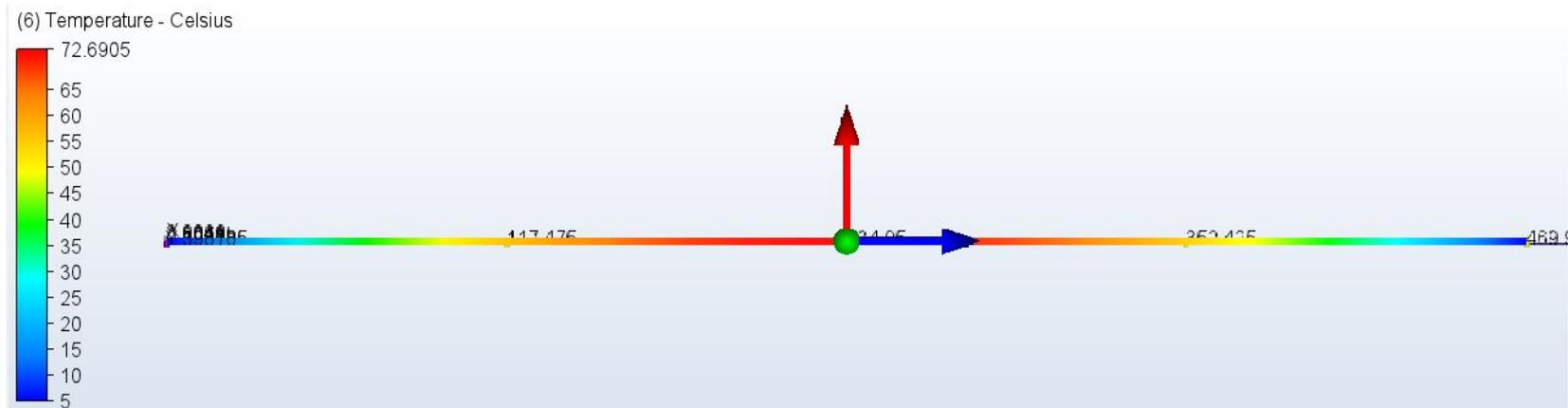
- $T(z = L/2) = T(L/2)$, i.e. boundary condition
- $T(z = 0) = T(L/2) + q(L/2) L / 4k$, i.e. temperature higher in center by $q(L/2) \cdot L / 4k = 47 \text{ kW/m}^2 \cdot 4.7 \text{ m} / (4 \cdot 204 \text{ W/m}\cdot\text{K}) = 270 \text{ K}$, i.e. center of bar is 270 K higher than ESB

Analytical Calculation of Aluminum stave with AstroPix sensors





Stave thickness: 2mm



Stave thickness: 4mm

Pb/Scintillating Fibre's thermal conductivity in x,y,z directions

Summary: k is dominated by Pb,

- $k_x = 15.7 \text{ W/(m-K)}$
- $k_y = 18.4 \text{ W/(m-K)}$
- $k_z = 21.6 \text{ W/(m-K)}$

Ref:

- $k_{\text{Pb}} = 35 \text{ W/(m-K)}$
- $k_{\text{Ac}} = 0.19 \text{ W/(m-K)}$

In the y direction (radially outwards), a uniform heat flux of $q = 2 \text{ mW/cm}^2$ results in a temperature gradient:

$$dT/dy = q/k = 1.1 \text{ K/m} = 0.01 \text{ K/cm}$$

This results in a reasonable gradient outwards, resulting in only few degrees increase of stave temperature.

Challenge: how to get heat across the trays?

$$k_{\text{N}_2} = 0.024 \text{ W/(m-K)}$$

$$dT/dy = 830 \text{ K/m} = 8.3 \text{ K/cm}$$

Analytical Calculation of Pb/Scintillating Fibre with AstroPix sensors

Heat flux $q(z) = -k (dT/dz)$, along stave perpendicular to cross sectional profile area (W/m^2)

$T(L/2)$



Assume all heat from AstroPix must be transported to end of sectors, i.e.

- $q(z = 0) = 0$, i.e. no heat moving longitudinally through center of stave (symmetry)
- $q(z = L/2) = 6 \cdot (0.002 \text{ W/cm}^2 \cdot 2 \text{ cm} \cdot L/2) / (15 \text{ cm} \cdot 3 \text{ cm}) = 5.64 \text{ W} / 45 \text{ cm}^2 = 1,250 \text{ W} / \text{m}^2$, i.e. each ESB needs to remove “only” 6 W per layer, but has to do so through a small surface area
- $q(z) \propto z$, i.e. linear dependency on z under uniform heat load for full strip population
- $q(z) = q(L/2) \cdot 2z / L$

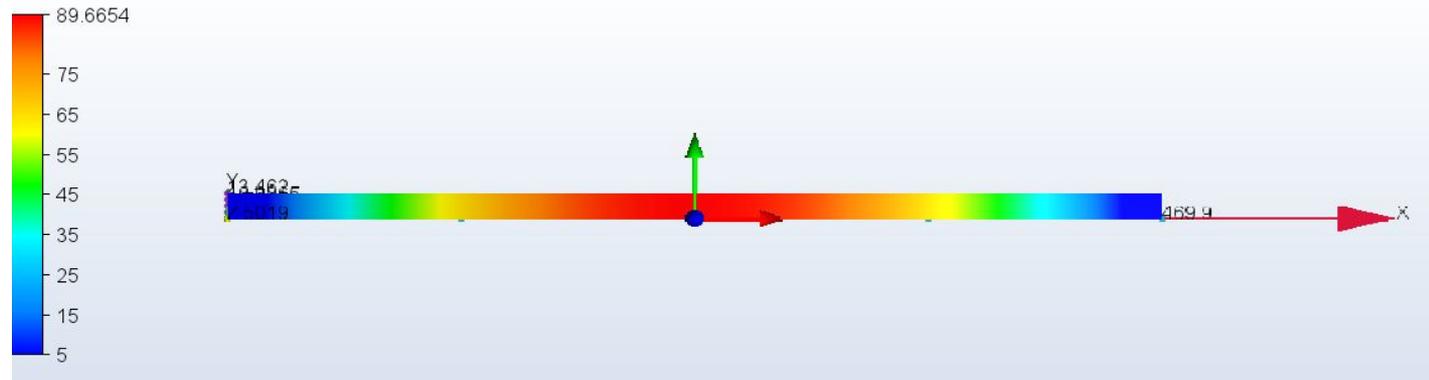
Temperature $T(z) = - \int q(z) / k dz = T(0) - q(L/2) \cdot z^2 / kL = T(L/2) - q(L/2) \cdot (z^2 / L - L / 4) / k$

- $T(z = L/2) = T(L/2)$, i.e. boundary condition
- $T(z = 0) = T(L/2) + q(L/2) L / 4k$, i.e. temperature higher in center by $q(L/2) \cdot L / 4k = 1.25 \text{ kW/m}^2 \cdot 4.7 \text{ m} / (4 \cdot 21.5 \text{ W/m} \cdot \text{K}) = 68 \text{ K}$, i.e. **center of layer is 68 K higher than ESB**

Thermal simulation for Pb/Scintillating Fibre with AstroPix sensors



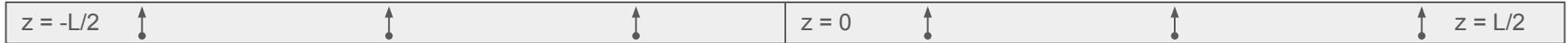
(6) Temperature - Celsius



Analytical Calculation of Carbon Fibre Trays with AstroPix sensors

Heat flux $q(z) = -k (dT/dz)$, along stave perpendicular to cross sectional profile area (W/m^2)

$T(L/2)$



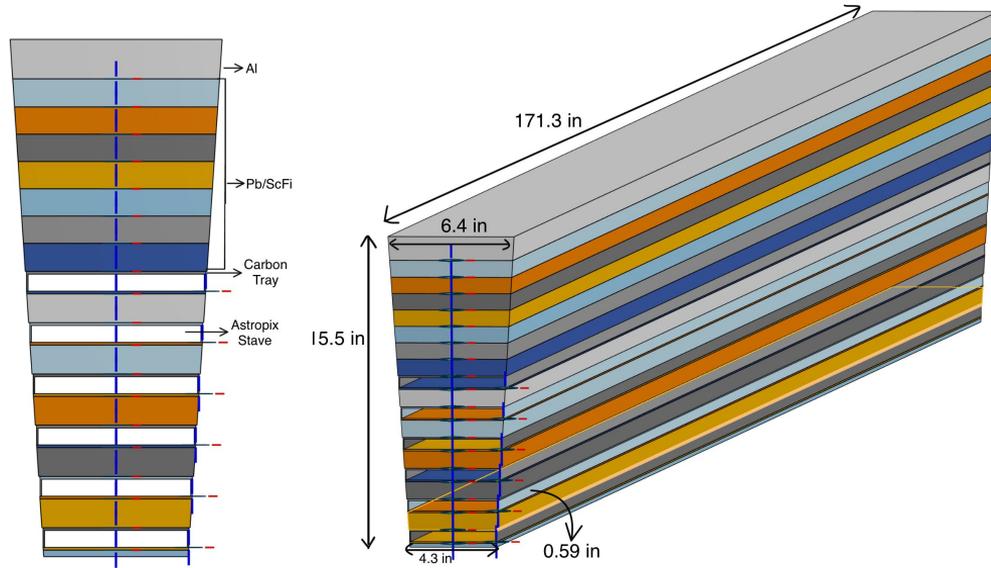
Assume all heat from AstroPix must be transported radially outwards through two 1mm CF trays, i.e.

- $q = 3 \cdot (0.002 \text{ W/cm}^2 \cdot 2 \text{ cm} \cdot L/2) / (1 \text{ mm} \cdot L/2) = 2.82 \text{ W} / 23.5 \text{ cm}^2 = 1,200 \text{ W} / \text{m}^2$, i.e. each tray wall needs to remove “only” 3 W per layer, but has to do so through its surface area

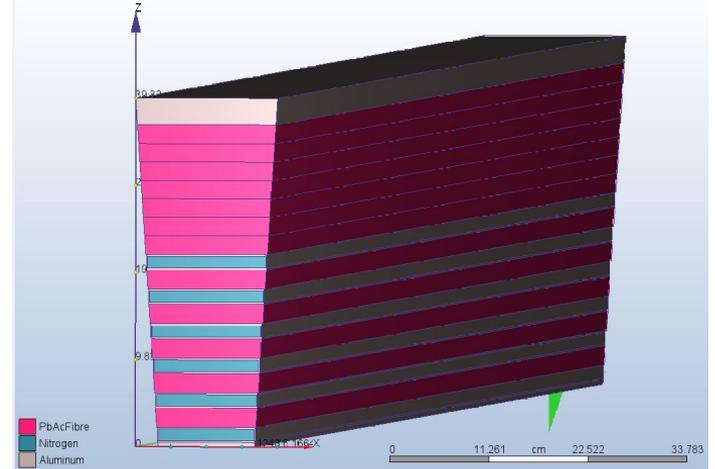
Temperature step $\Delta T/\Delta y = -q / k = 6 \text{ K/m}$, or 0.1 K over a 1.5 cm tray thickness

Needs to be confirmed with CFD simulations for full system!

CAD model of the complete sector

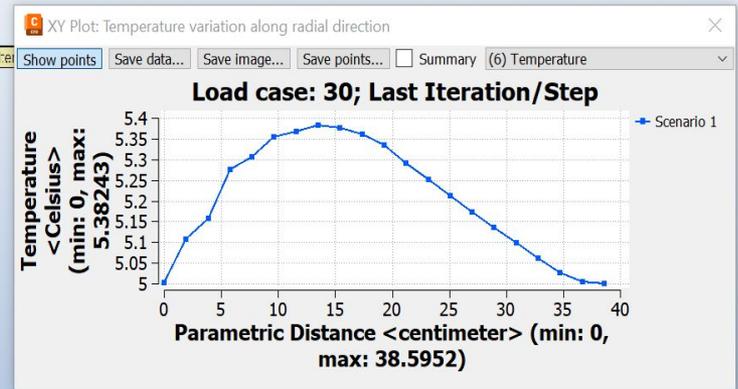
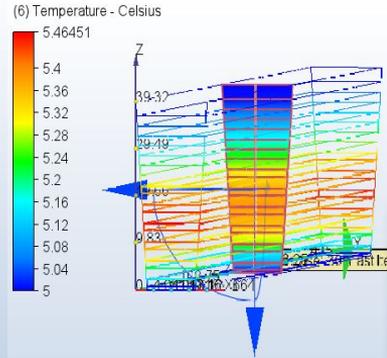
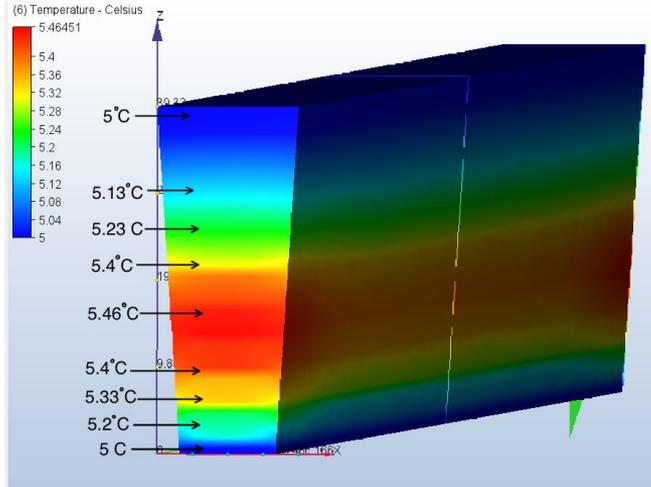


CAD Render of the sector



Material distribution

Thermal simulations for the complete sector



Next Steps

Performing simulations for the sector involving the correct alignment of the astropix sensors, and subsequently running simulation for the complete BIC involving 48 sectors.