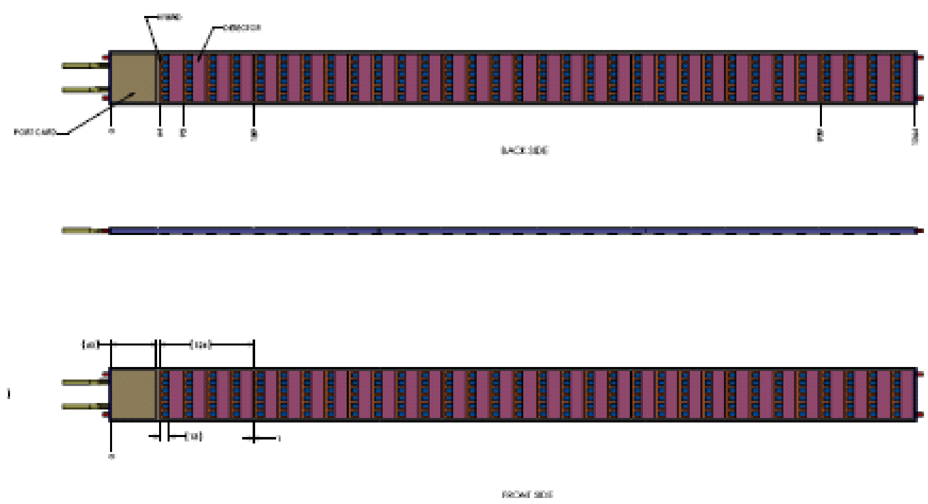
Upgrade Stave Study Topics

- Current Analysis Emphasis
  - *Thermal solution for stave with double-sided modules*
    - 192W per 1.064m stave length
  - *Coolant tube analysis*
    - Stress analysis for C_3F_8 and CO_2 working fluids
    - Pressure drop calculations
    - Convective/boiling film coefficients
- Design drawings
  - Doubled-sided module design, 4.6mm sandwich (core height)
  - Single-sided module *prototype* stave, 7.33mm sandwich
  - Assembly tooling for producing *prototype* composite sandwich structure---are complete

Double-sided module stave



Structural Considerations

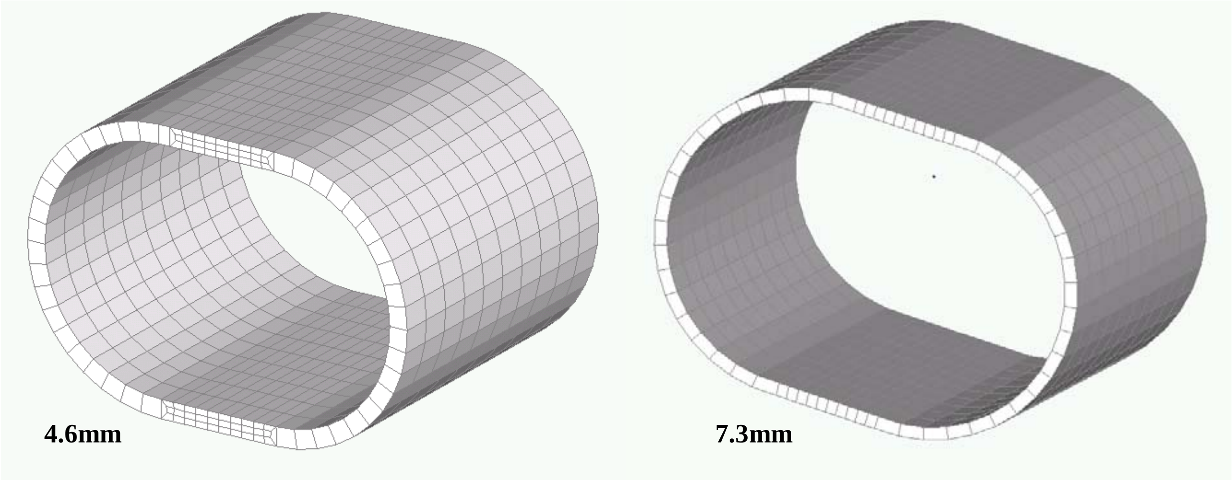
- Results of previous studies (108W stave)
  - Principal area of concern was gravity sag
    - Sandwich properties for stave chosen to hold sag to <60microns, horizontal orientation (thermal strain effects <10microns)
      - Quick summary:
        - » Resulted in core height of 4.6mm and K13D2U composite facings with 4 to 1 fiber orientation
        - » Slightly flat tube, with 2mm flat section for improved thermal contact
- Questions now address 192W stave-double-sided modules and hybrids
  - 1st Approach
    - Analyze thermal performance with same tube geometry (referred to as “semi-flattened tube”)
    - Add thermal solutions for round tube with two candidate coolants C_3F_8 and CO_2
- Eventually return to structural analysis

Coolant Tube Stress Analysis

Compare Semi-Flatten Tube versus Round Tubes

FEA-Section of Tube

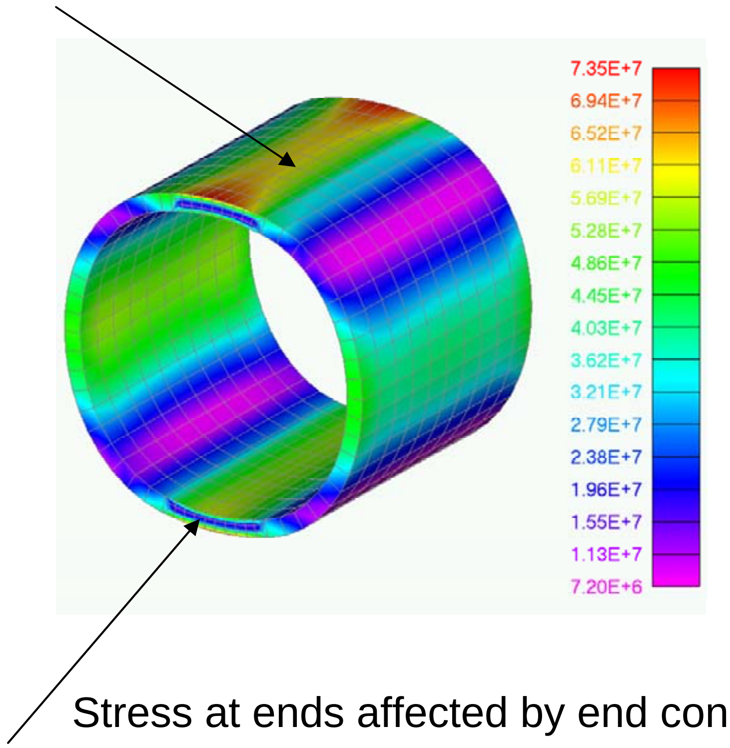
- Tube Shape
  - Both prototype stave tube and tube for the "*proposed stave*" geometry have a semi-flatten shape
  - Flat portion is ~2mm across, to enhance thermal contact.
  - Both tubes are Al tubes with 12mil wall
  - For simplicity the shape of the sides are assumed to be circular with radius defined by core height (distance between composite facings)



4.6mm Semi-Flattened Tube

- NASTRAN solution
  - Internal pressure of 100 psi
  - Stress bar is Pascal; average von Mises stress in middle between two truncated faces is 6062 psi.
  - Deflection of corresponding node in this region is 15.5 microns.
- 100 psi pressure is equivalent to 6.9bar
  - Pressure of C_3F_8 at -25ºC is 1.67 bar and at 25ºC the pressure is 8.7bar
  - Allowable yield stress for work-hardened 1100 Series Al is ~18,000 psi

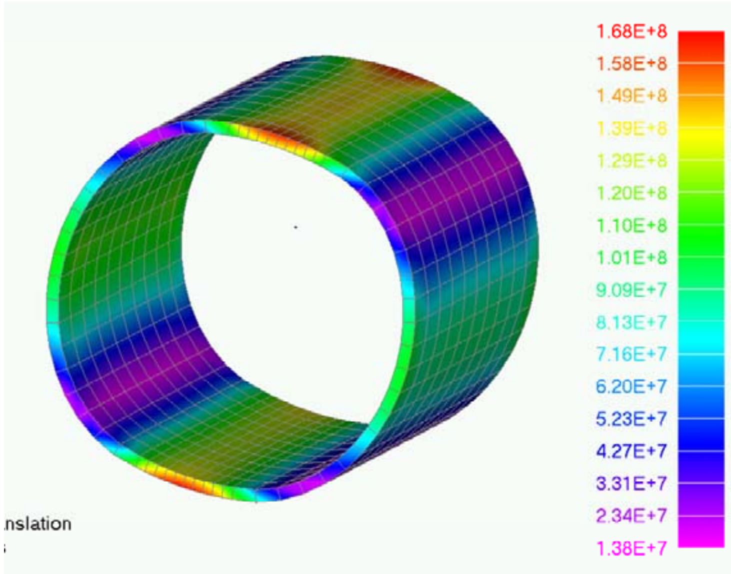
Middle is region of interest



Stress at ends affected by end conditions

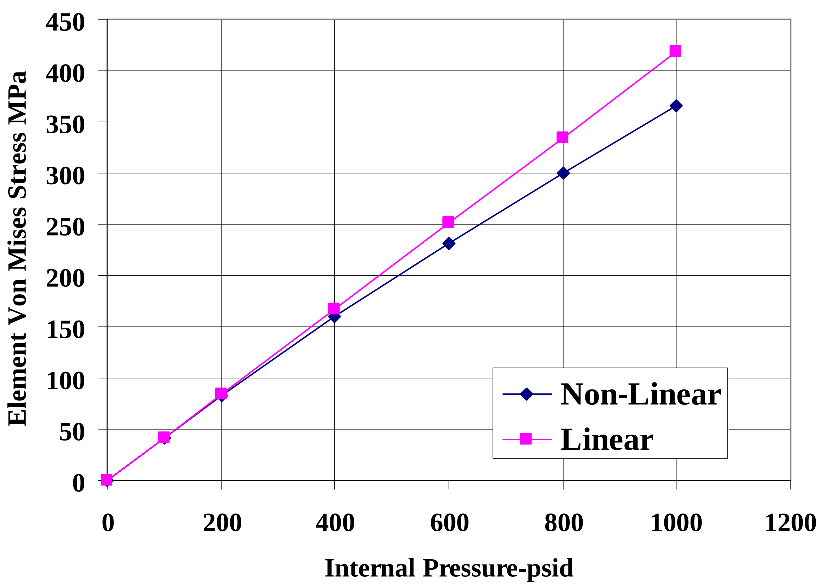
7.33mm Semi-Flattened Tube

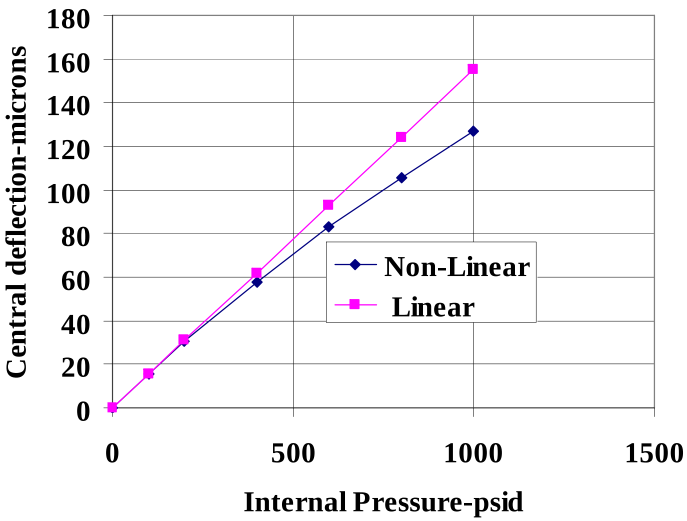
- FEA solution-Prototype stave
  - Average element Von Mises stress on the crown at 100 psi is 20308 psi. Stress bar legend is in Pascal.
  - Corresponding nodal deflection is 87.8microns
- Prototype test
  - Plan to use low pressure coolant, stress should not be a problem
  - *Not recommended to use C_3F_8 in this size of tube*



Effects of Higher Coolant Pressure

- 4.6mm Semi-Flattened tube for stave cooling
  - In spite of work-hardened tube structure:
    - Suspect pressure above 500psi (34bar) becomes a significant issue in terms of stress (29,000psi) and deflection (70microns)
    - *Would not be recommended for CO_2 coolant*





C_3F_8 saturation pressure at room temp is 8 bar (116psi)

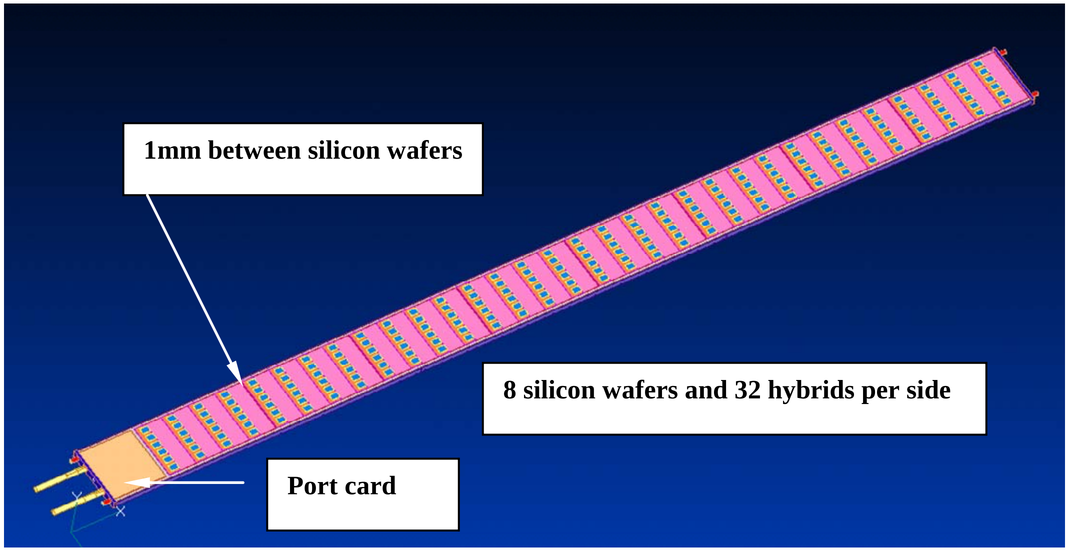
Thermal Solutions

- Objective: Evaluate Effect of Increased Heat Load for Stave with Double-Sided Modules (192W)

- Establish 1st order result of thermal gradient for two tube geometries, semi-flattened and circular

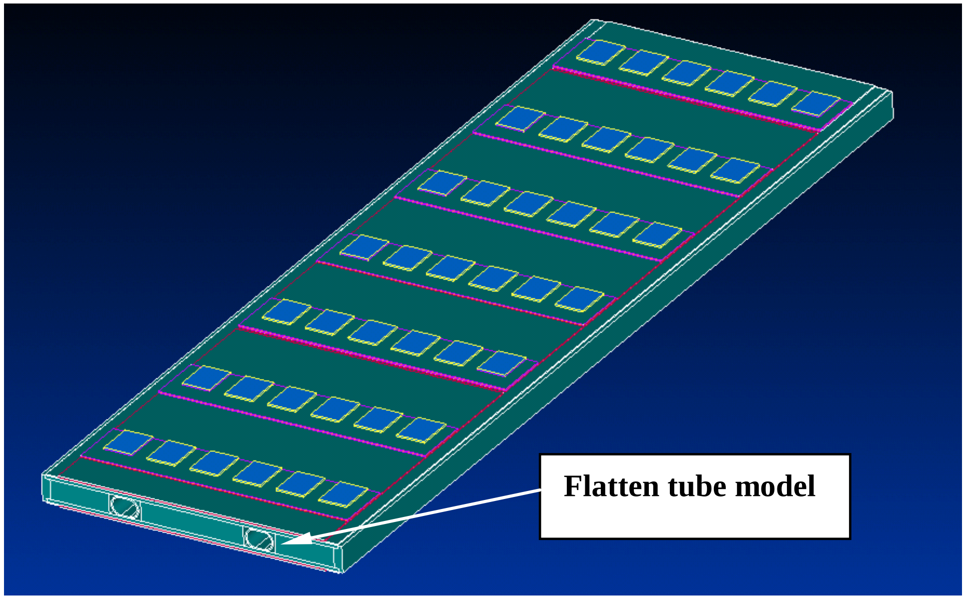
Thermal Analysis

- Parasolids model of stave
- Double-sided silicon wafers, 12.4cm long
- 4 hybrids per wafer
- 6 chips per hybrid
- Dissipated power to the coolant U-Tube is 192W.
- The stave length (exclusive of end caps) is 1064mm long. The width is 71.5mm (including the side strips)



Stave Thermal Model

- Computational Economy
  - Sliced the stave into short section providing full length module with partial modules at each end
  - Thermal result has a slight periodicity from 1mm separation between 12.4cm modules—creates break in heat spreading by silicon module



Thermal Property Parameters

FEA Model Properties

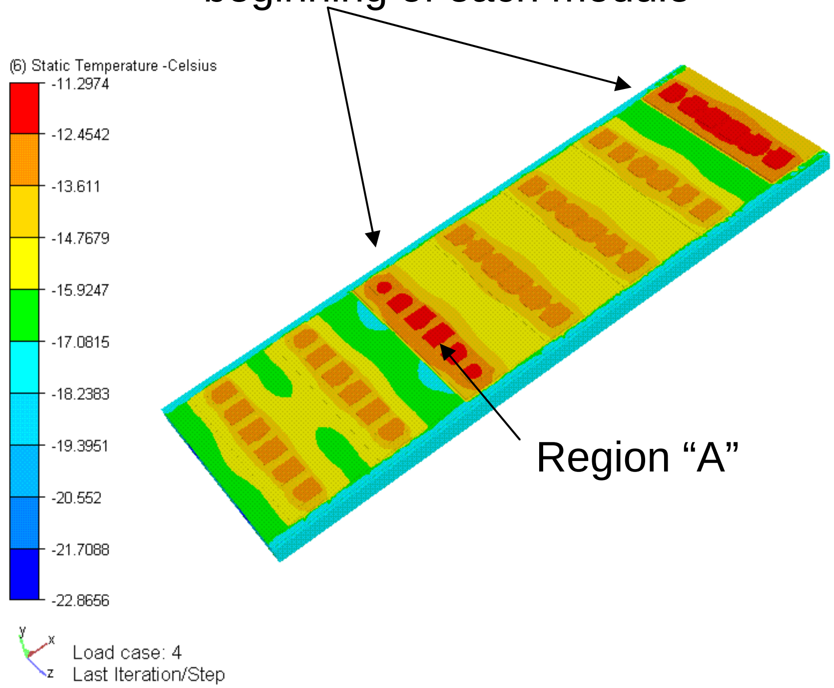
Material	K- (W/mK)	Thickness (mm)
Silicon Wafer	148	0.28
Silver-Adhesive	1.55	0.0508
Dielectric/BeO Hybrid	8	0.38
Cable Bus	0.12	0.125
Composite Facing		0.75
Stave axis	384	
Transverse	97	
Through thickness	1.44	
Coolant tube (Al)	204	0.3048
CGL Adhesive	1	0.0762

Suspect the cable bus thermal conductivity is somewhat low; thermal property will be determined in order to improve thermal quality of results

Double-Sided Stave Geometry

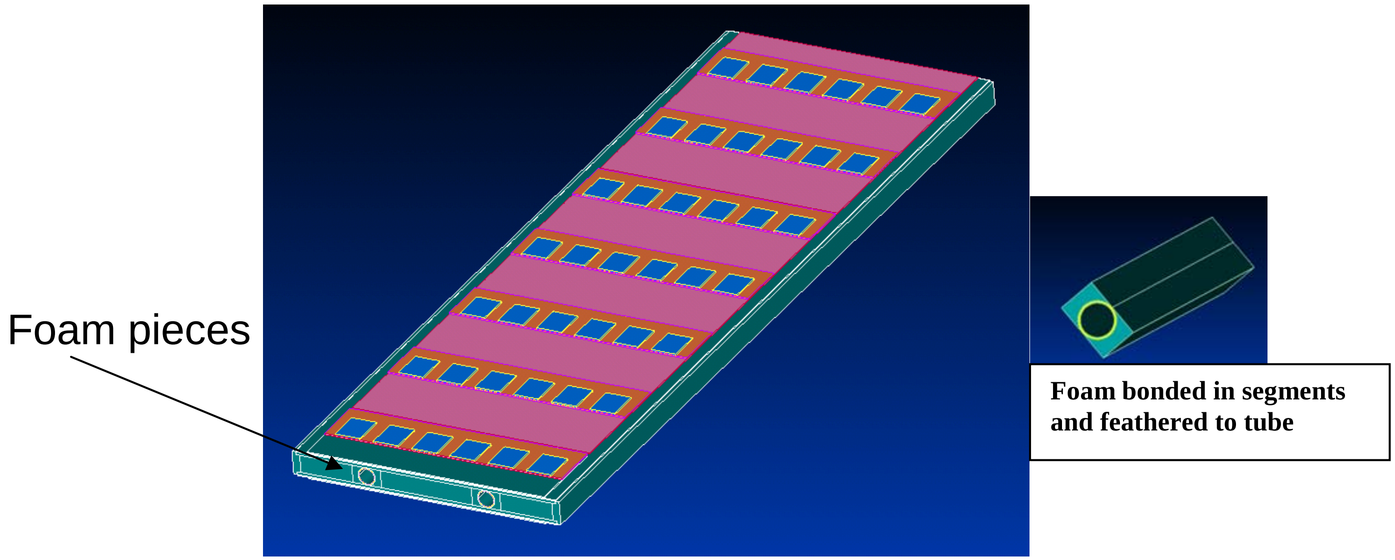
- Stave parameters
  - 4.6mm semi-flattened Al tube, 12mil wall.
  - 192W for double sided module, 0.5W per chip, 12chips per module
  - Module length is 12.4cm, with row of chips nominally every 3cm
- Coolant
  - C_3F_8, entering at -25ºC, assumed film coefficient of 2342W/m^{2}K
- Results
  - Peak chip temperature approximately -12ºC at region "A"
  - Module temperature nominally minus 15ºC

Slight periodicity due to 1mm separation at beginning of each module



High Pressure Coolant Tube

- Geometry of coolant circuit modified to accommodate a round tube
- Aluminum tube: 4.6mm OD (4mm ID), hoop stress for 60bar (1000psi) would be 6546psi
- Saturation of CO_2 at 25ºC is 933psi.

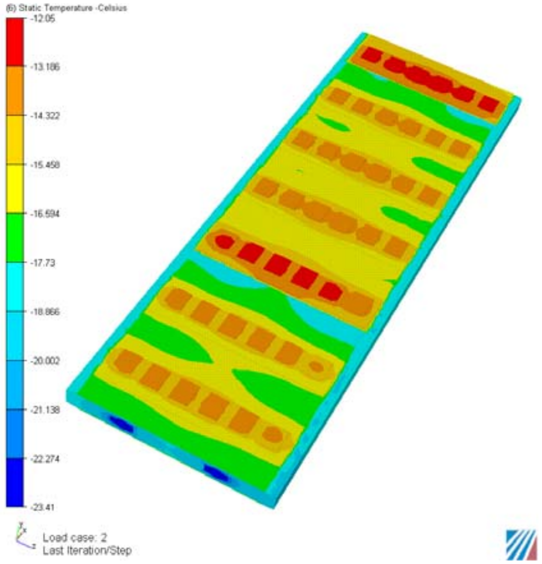


Round tube is supplemented with graphite foam transition to enhance thermal contact

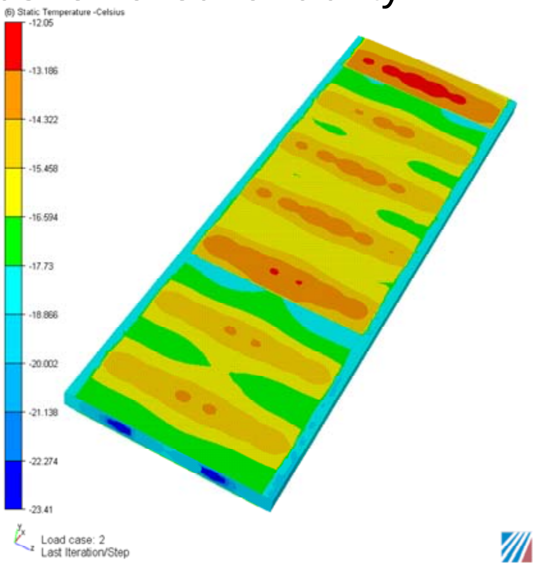
Stave with Round Cooling Tube

- Thermal Solution-effective 192W per stave, 4.6mm round tube Cable K=0.12W/mK
  - High conductivity graphitic foam bonded to tube to enhance thermal contact coefficient
  - Foam material has thermal conductivity of 125W/mK normal to tube axis and 50W/mK along tube axis
  - Average convective film coefficient of 3000W/m²K used in model
- Results
  - Peak chip temperature -12.6ºC, with module peak surface temperature nominally -13ºC

Display of Chips

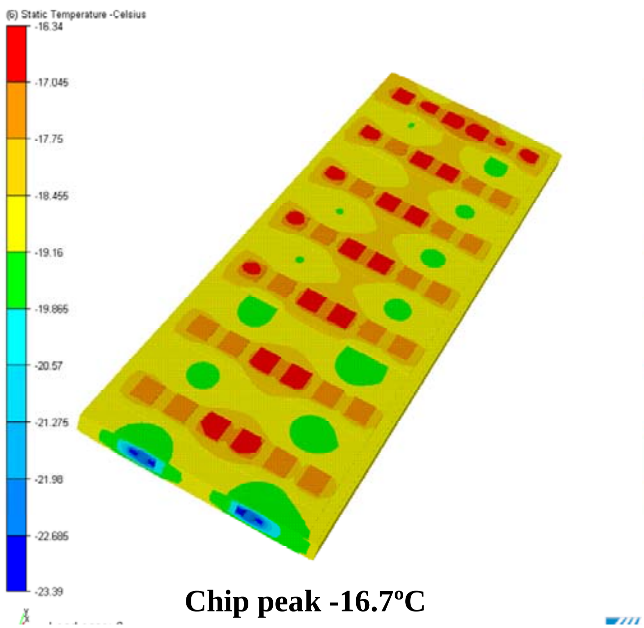


View of module surface temperature with hybrids removed for clarity



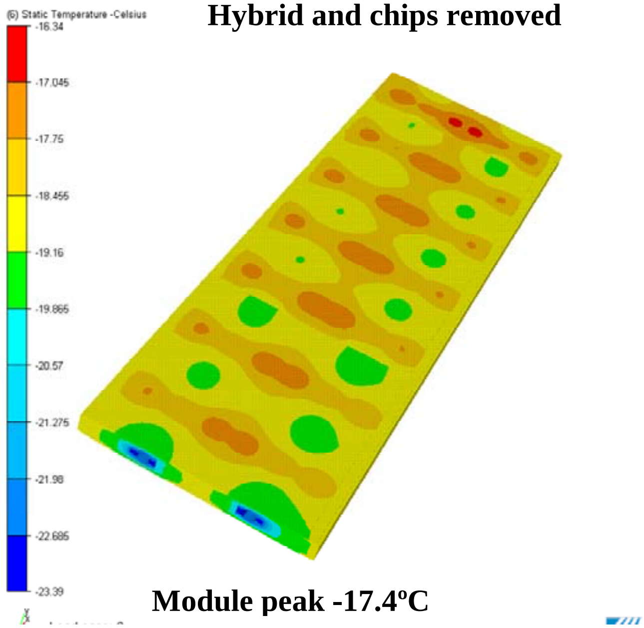
Uncertainty in Cable K

- Thermal Solution-repeated with higher K, *increased to 1W/mK*
  - High conductivity graphitic foam bonded to tube to enhance thermal contact coefficient
  - Foam material has thermal conductivity of 125W/mK normal to tube axis and 50W/mK along tube axis
  - Average convective film coefficient of 3000W/m²K used in model
- Results---improves chip temperature by ~4ºC and silicon by ~2ºC
  - Peak chip temperature -16ºC, with module surface temperature nominally -17ºC



Chip peak -16.7ºC

Hybrid and chips removed



Module peak -17.4ºC

Coolant Pressure Drop and Convective Heat Transport

•Objective: 1st order calculations for the semi-flatten tube and circular tube for both C_3F_8 and CO_2

Tube Hydraulic and Thermal Evaluation

- Stave with C_3F_8 Coolant: *Semi-Flattened tube*
  - Assumptions: entering quality 5%, exiting 75%
  - Resulting mass flow for 192W, 2.7g/s
  - 4.6mm semi-flattened tube, D_h=5.0mm
  - Entering Fluid -25ºC and 1.67bar
  - Average frictional pressure drop 0.137bar, resulting saturation exiting fluid temperature becomes -27ºC
  - Average film coefficient is 1800W/m^2K
- Conclusion
  - From hydraulic and heat transport standpoint the tube is *slightly too large*
  - *Need to update the thermal solution for lower than estimated film coefficient*
    - Original estimate based on higher coolant inlet quality and higher mass flow rate

Tube Hydraulic and Thermal Evaluation

- Stave with C_3F_8 Coolant: *Round tube*
  - Assumptions: entering quality 5%, exiting 75%
  - Resulting mass flow for 192W, 2.7g/s
  - 4.6mm round tube, D_h=4mm
  - Entering Fluid -25ºC and 1.67bar
  - Average frictional pressure drop 0.41bar, resulting saturation exiting fluid temperature becomes -32ºC
  - Average film coefficient is 2500W/m^2K
- Conclusion
  - Coolant temperature varying between -25ºC and -32ºC helps to hold silicon temperature
    - Similar to having average coolant temperature of approximately -28.5ºC
  - From hydraulic standpoint the tube is *slightly small*
    - *Average predicted frictional pressure drop encroaches on requisite vapor return pressure*

Tube Hydraulic and Thermal Evaluation

- Stave with CO_2 Coolant: *Round tube*
  - Assumptions: entering quality 5%, exiting 75%
  - Resulting mass flow for 192W, 0.82g/s
  - 4.6mm round tube, D_h=4mm (satisfies our core height issue in a sandwich to minimize gravity sag)
  - Entering Fluid -35ºC and 12bar
  - Average frictional pressure drop is negligible, 0.034bar, essentially no change in saturation temperature over the 2m tube length
  - Average film coefficient is 4650W/m^2K
- Conclusion
  - From hydraulic and heat transport standpoint the tube is *more than adequate*
  - *Stress, for a 1000 psi max pressure is 6545 psi, which would be considered allowable for Aluminum tubing*

Hydraulic and Thermal Summary

- Silicon Module Temperature for 2m stave with 192W heat load
  - If requirement is -25ºC, the coolant most likely must enter at -35ºC or at least minus 30ºC.
  - C_3F_8 saturation pressure at -35ºC is 1.04bar, which means a 0.67bar reduction in available return pressure to the compressor from ATLAS conditions, may be a system problem
    - Is -30ºC acceptable from system standpoint?
  - Frictional pressure loss in a 4.6mm semi-flatten tube with a hydraulic diameter of 5mm at -35ºC coolant inlet is estimated to be 0.18bar, further contributing to return pressure problem
  - For a “hard” silicon temperature of -25ºC, CO_2 entering at -35ºC is preferable
- Prospects for C_3F_8 at -25ºC---most of problem comes from the 192W heat load
  - Need to improve thermal modeling by quantifying the thermal conductivity of the components
  - Consider strategy of augmenting heat spreading beneath the chips