New Directions in Mechanics and Cooling for Pixel Detectors

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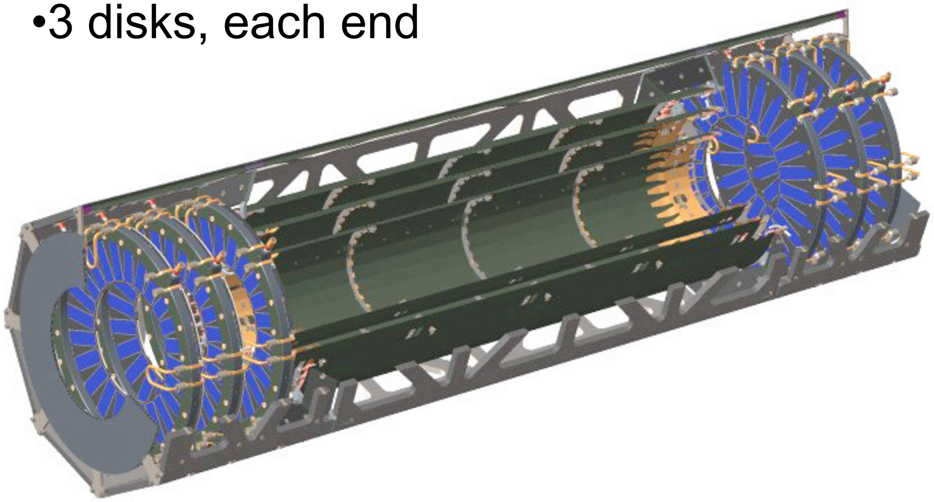
Objectives

- ATLAS is fielding a large Pixel Detector which represents a significant advancement over existing silicon-based detector systems
  - Achievements have been significant, the design is well established and supported with extensive testing-
- With some knowledge of the past, my objective was to step back and to look at the design, focusing on mechanical issues from a different perspective
- Hopefully, the outcome will influence future detectors
- To accomplish this objective, we first briefly review mechanical and cooling concepts embodied in the ATLAS Pixel Detector
    - Large in size, composed of both barrel and disk detector elements
    - Design was faced with major cooling issues; highly distributed heat loads, totaling over 15kWatts
    - Tight constraints on radiation length and stability
    - Some of the service issues are still emerging
- We conclude by summarizing an approach being studied that is a significant departure from the approach taken by ATLAS

ATLAS Pixel Detector

Pixel Detector
- 1744 modules
- 3 barrel layers
- 3 disks, each end



Heat loads
- ~7W/module
- 13kW in detector space
- 17.1kW in pixel volume
- 38.6kW total, balance from cables

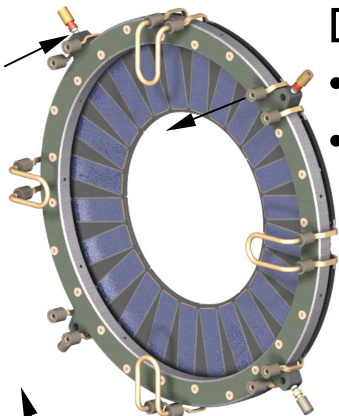
Cooling
- Evaporative (C_3F_8), two-phase flow
- -20°C inlet, providing -6 °C at detector
- For 17kW, mass flow rate of 185g/s

General Design Goals
- Stability, □ ~10 microns
- Radiation length-normal incidence
  - Local supports <0.7%
  - Frame <0.4%
- Low mass
- High Reliability
  - 10 year life cycle
  - Low maintenance

Local Supports

Coolant lines

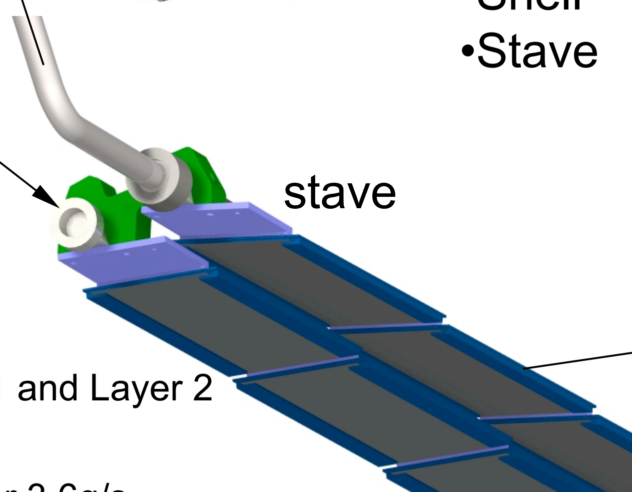
1.2g/s



Disk local support
- •Composite Ring
- •C-C sectors

Modularity of detector
- •Side A, 35 flow circuits
- •Side C, 45 flow circuits

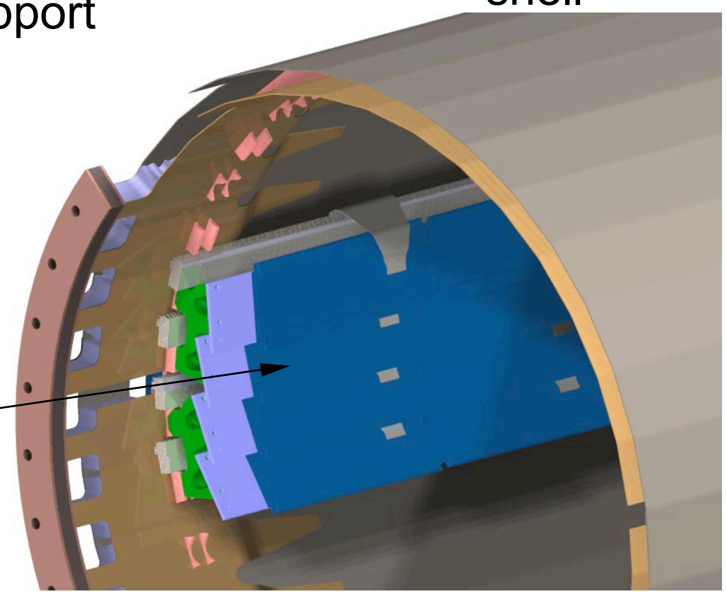
Coolant lines



stave

Barrel local support
- •Shell
- •Stave

shell



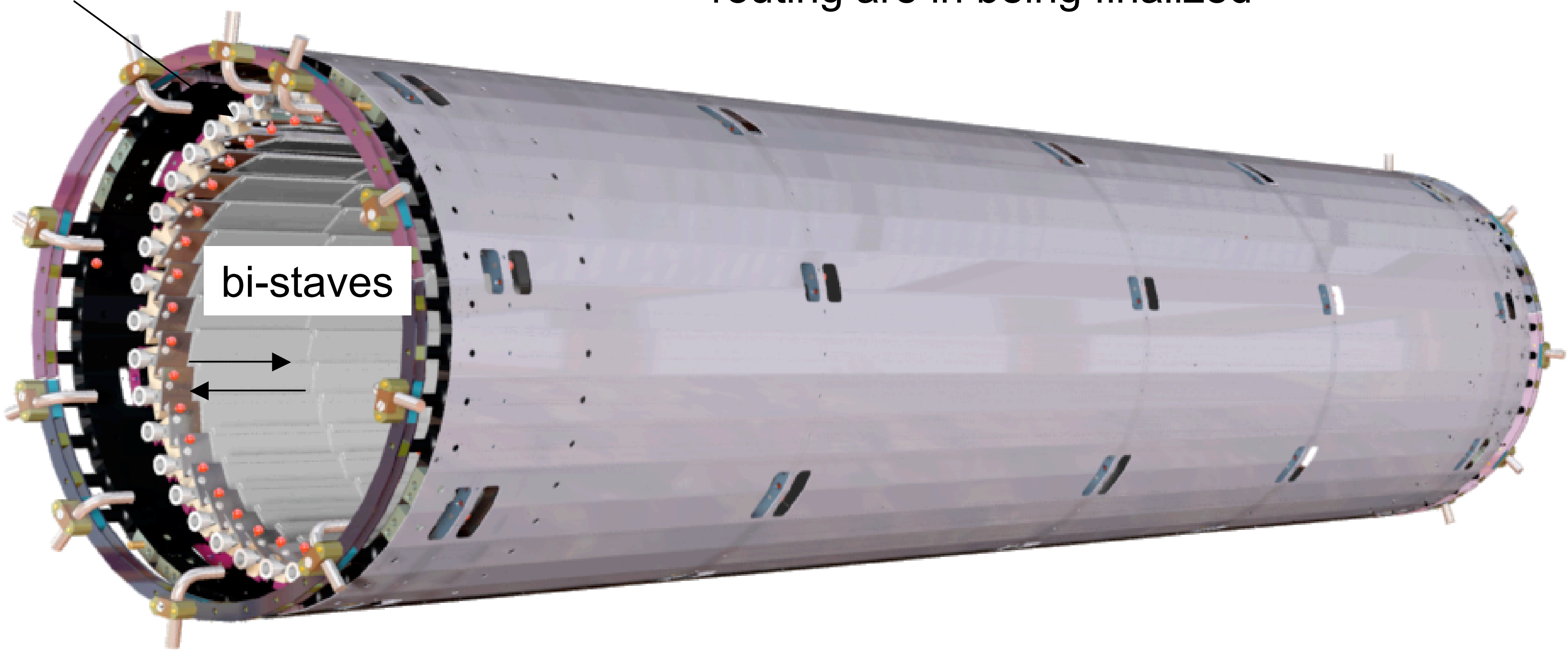
Layer 1 and Layer 2
2.6g/s

B-Layer 3.6g/s

Barrel Assembly

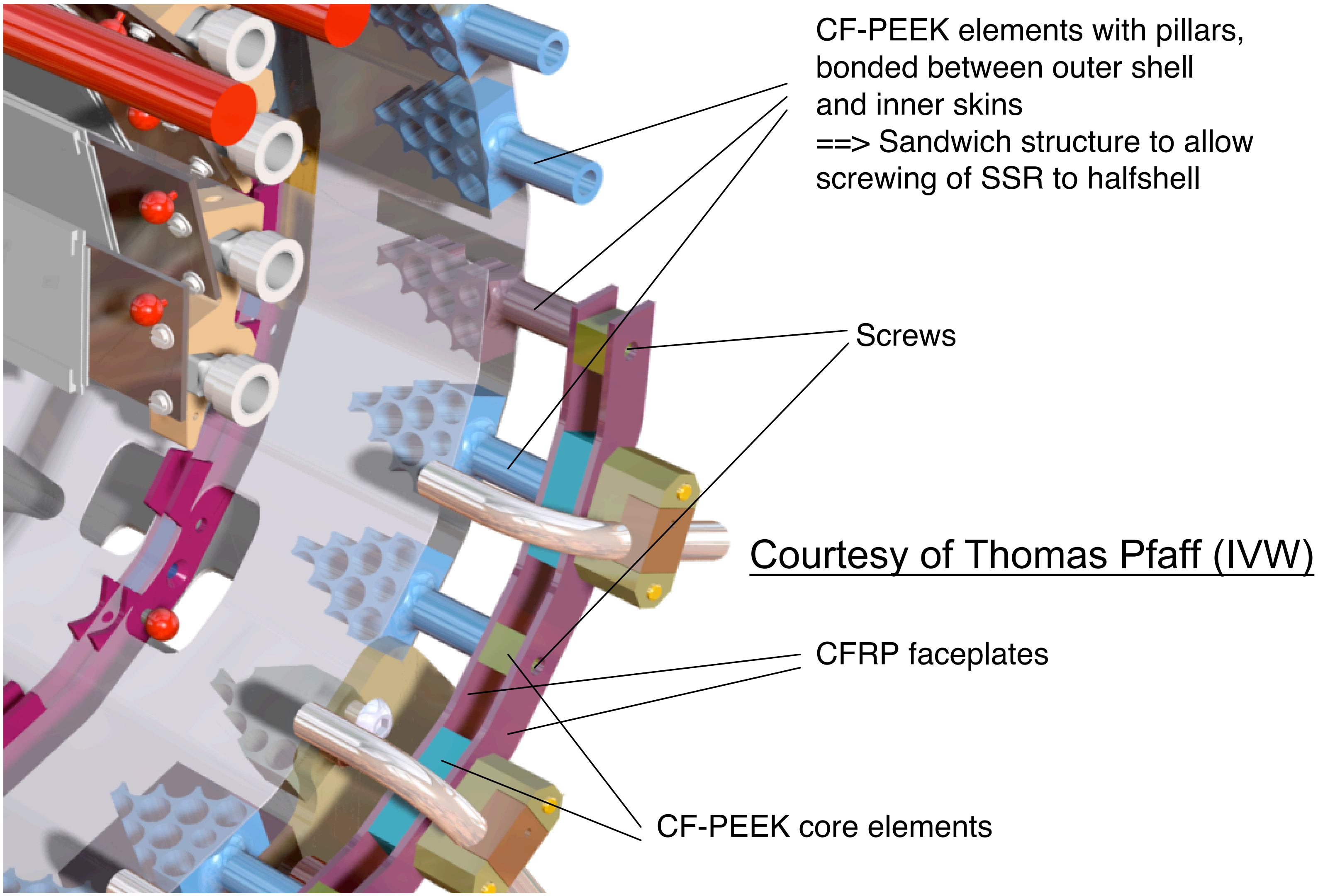
Mechanical design approach is mature, testing of key components complete

Details of services, connections and routing are in being finalized



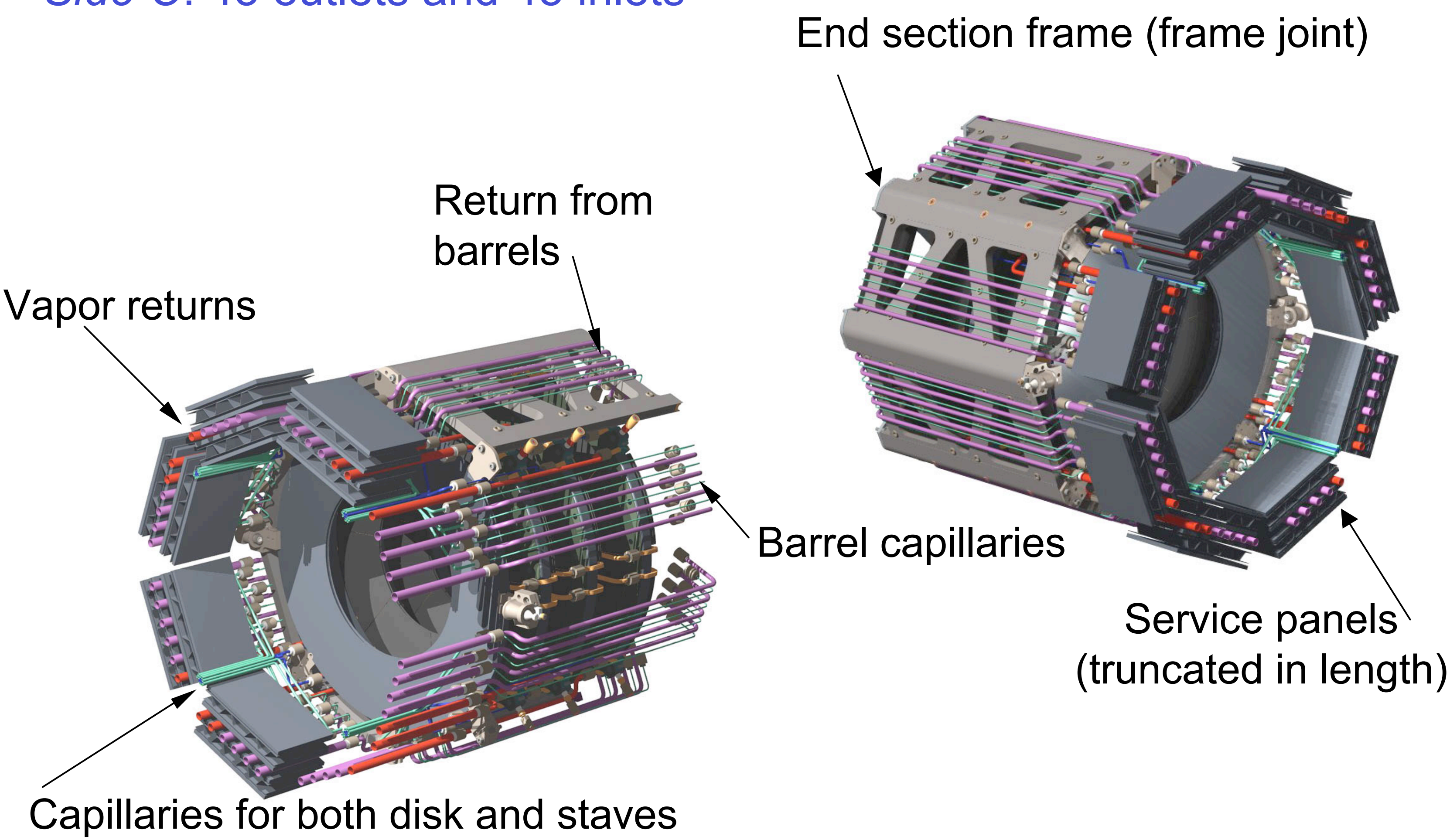
Courtesy of Thomas Pfaff (IVW)

Barrel Structure



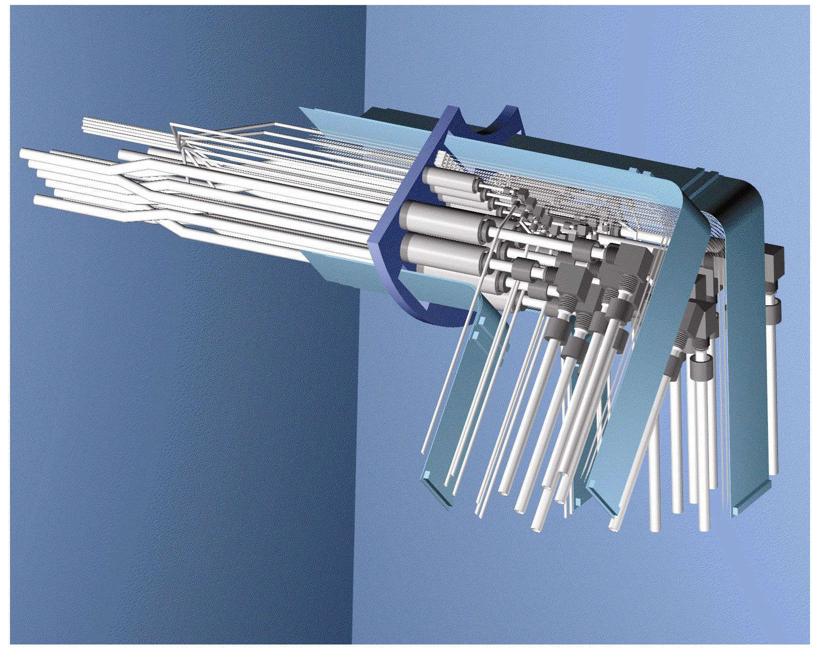
View of End Section (cooling)

Side C: 45 outlets and 45 inlets



Plumber's Nightmare

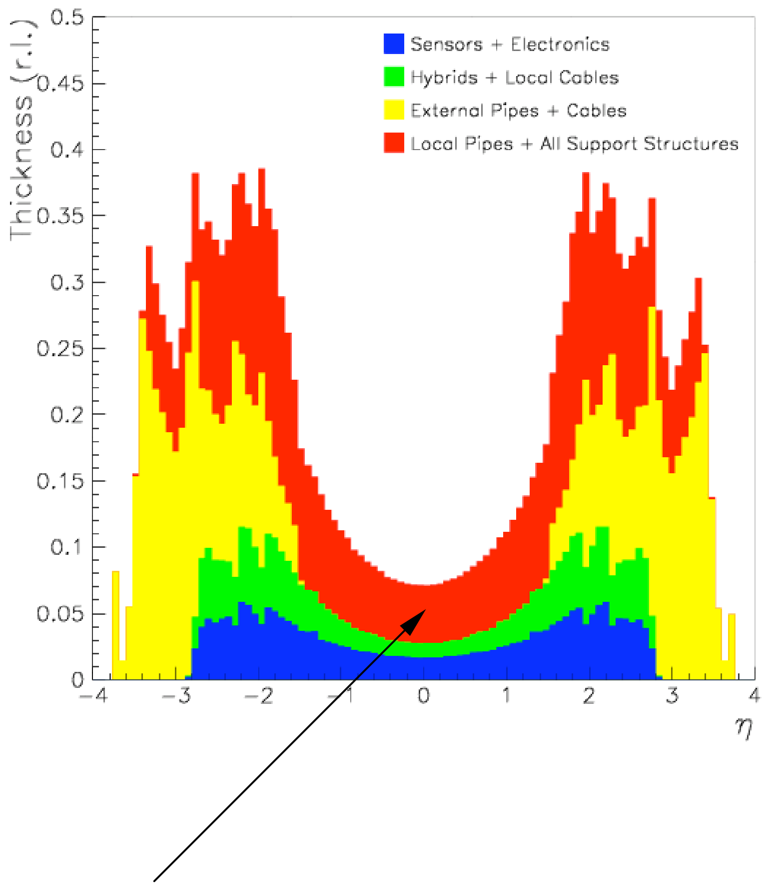
- Illustration represents the beginnings of the packaging required as the services pass out of the Pixel Detector Support tube
- 1/3rd of a quadrant bundled together



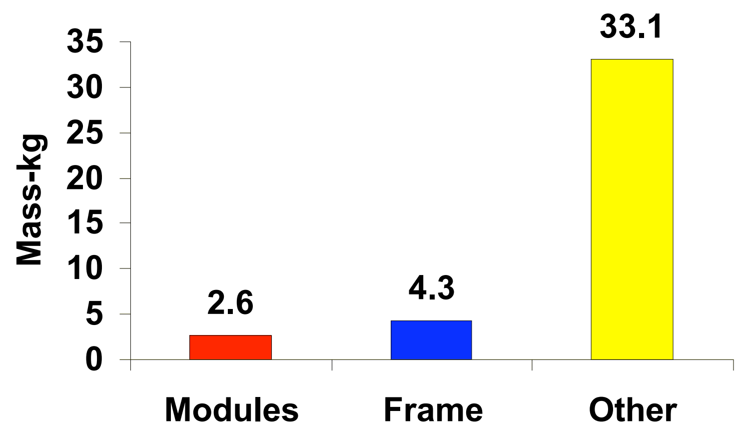
Courtesy Fred Goozen LBNL

Radiation Length Issue

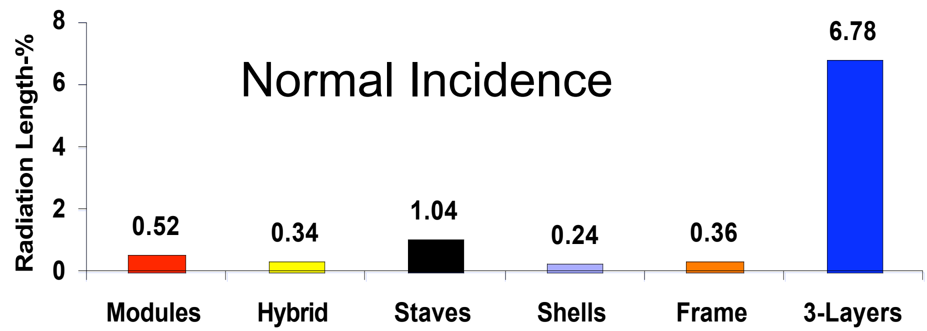
Courtesy of D. Costanzo-LBNL



Includes barrel pixel support tube



Total mass breakdown



Cooling System

- Concept based on controlled boiling in a stave or sector
- Saturation pressure in stave or sector nominally 1.7bar entrance, 1.3bar exit
- Capillary feed to stave or sector, with inlet to capillary of 9.3bar
- As tested, each flow circuit, i.e., bi-stave and adjacent sector pair, use upstream and down stream pressure regulator to control temperature
  - Extrapolation for 80 circuits: 160 pressure regulators (80 inlet and 80 outlet), and 80 outlet temperature regulators
- *Plumbing,* 3 connections in each barrel cooling line and 2 each for the disk from the local support to the end of the frame (PP0*)*-
  - Side C: 33*3*2+12*2*2=246 mechanical connections Side A: 23*3*2+12*2*2=186 additional mechanical connections
  - *Roughly, 432 mechanical fittings* to make and check at each assembly and disassembly
- The evaporative cooling system is quite sophisticated, but at what expense to earlier goals of low-mass, low radiation length, and possibly at some impact on reliability.

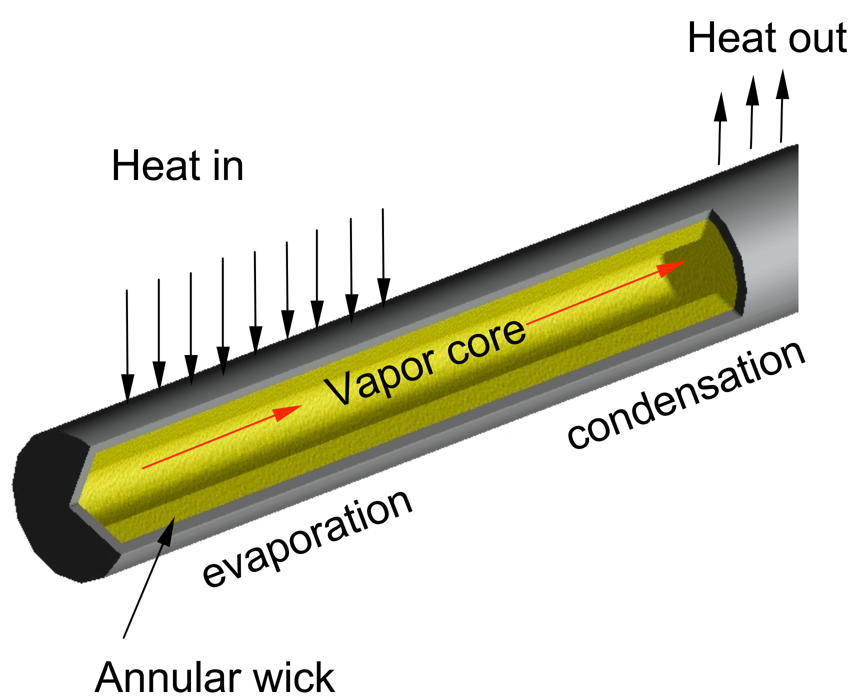
New Design Option

- Passively remove heat from modules, without using forced convection
- Transfer the heat from the modules to collection points, where the energy is removed by convection
  - Circulated fluid could be either single or two phase, but presently assumed to be two phase
- Use passive heat removal system to extract heat from cables as well
- Reduce fluid connections, potentially by a factor of 10, or so
  - Reduction constrained only by desire for redundant flow circuits
- Efficient passive heat removal can not be provided solely by highly conductive composite
  - *Proposal uses evaporative fluids*

Heat Pipes (HP)

- We propose that detectors involving hundreds of cooling lines can be simplified using heat pipes
  - Propose to explore this option using the ATLAS barrel system as an example
- Heat pipes transport heat efficiently from the evaporator to the condenser
  - Here, the two sections are close coupled
- Design options
  - 1st, HP that replaces stave, eliminating OMEGA piece, Al tube, and grease film.
  - 2nd, HP becomes part of the structure, eliminating the outer shell
- Options are introduced to lower radiation length

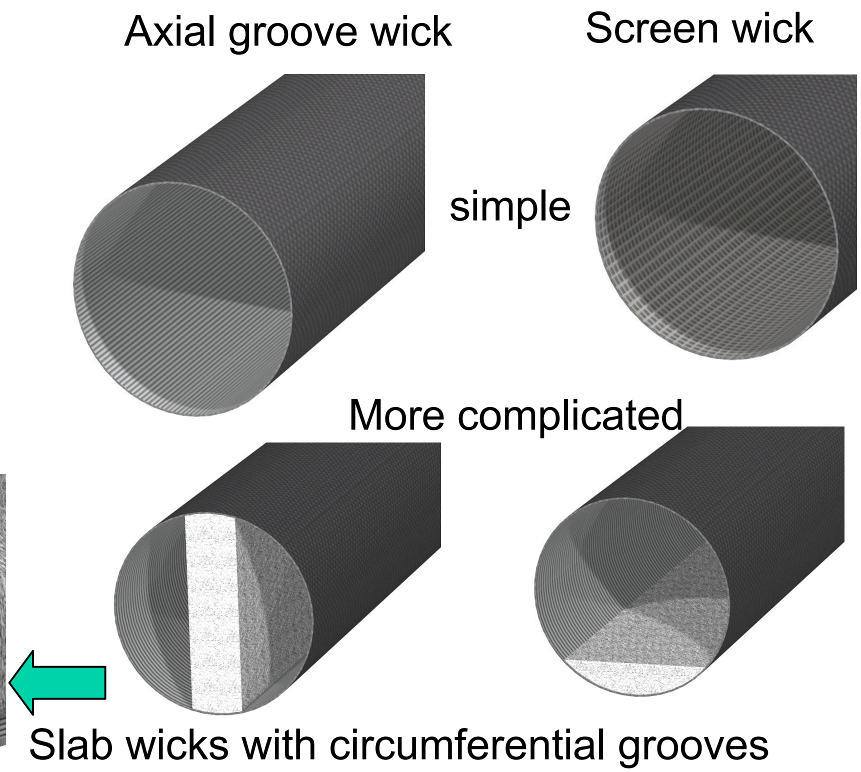
Very efficient, effective thermal conductivity about 1000x of Cu



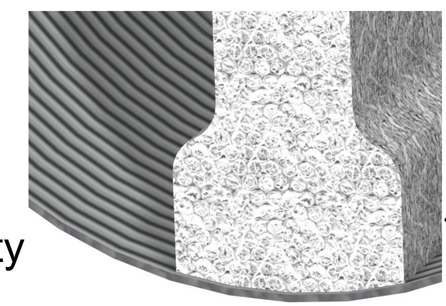
Typical Wick Geometries

- Heat Pipes for HEP Application
  - Must achieve low radiation length
  - Must be lightweight
  - Conceivably can be used as part of the structure, with modules mounted directly
- Proposal
  - Thin Carbon-Carbon (C-C) shell with integrated wick
  - C-C wall porosity sealed by the wick material

Process is to find the best tube size and wick configuration that minimizes mass and thickness, as a function of candidate fluids

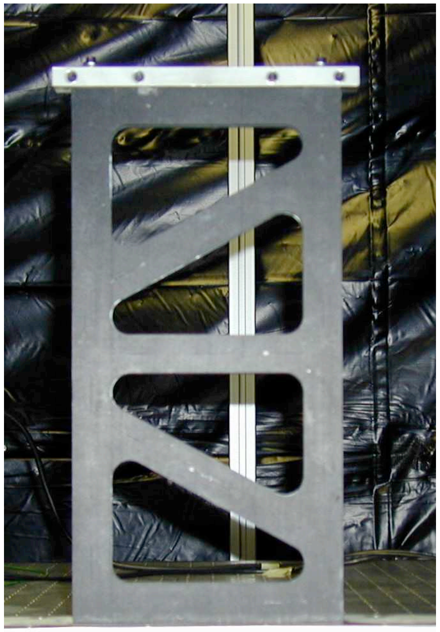


Arteries can be added, but another degree of complexity



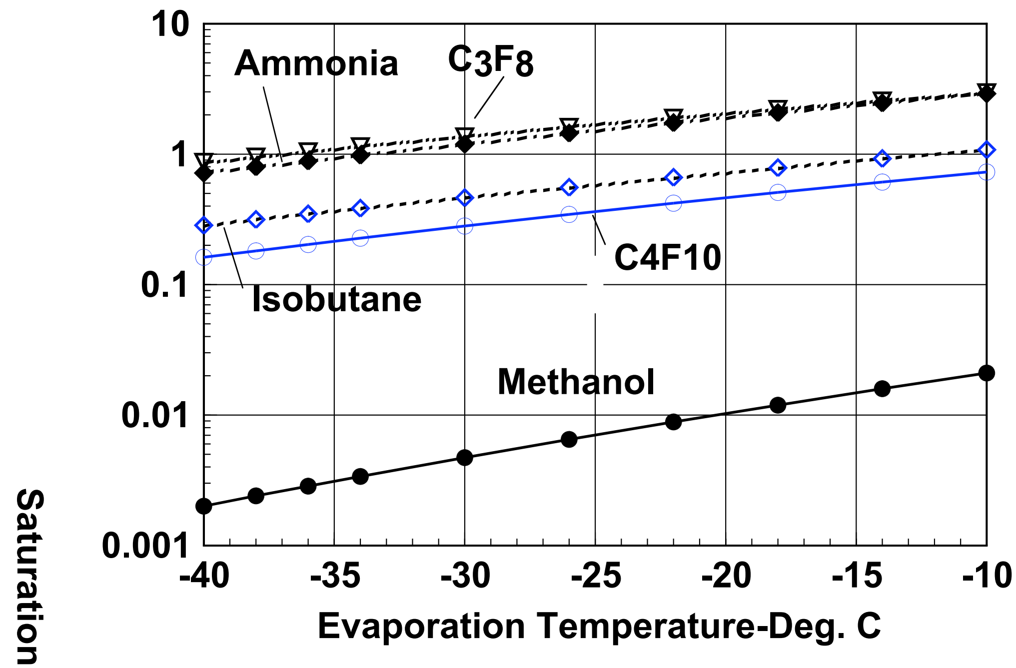
"C-C" What is it?

- *Carbon-Carbon*
  - Denotes composite composed of carbon (or graphite) fibers in a carbon matrix
  - C-C may be formed as flat laminates or into structural shapes
  - Material properties can be enhanced by densification of the carbonized material, followed by heat treatment to obtain high modulus, high strength and high thermal conductivity
    - Carbon infiltration by CVD , and or pitch
- C-C Material: properties are tailorable
  - 2D K1100 Laminate, E~3X AL, K~2X AL, CTE ~-0.75ppm/K
  - K_z= 45 W/mK, ~50-60X resin based laminate
- C-C characteristics
  - Typical radiation length of 23cm
  - Hydrophobic, insensitive to moisture
  - Negative CTE, ranging from –0.5 to –1.5 ppm/K depending upon laminate layup, expands when cooled
  - Strength rivals steel, but strain to failure is lower


C-C sandwich panel

HP Fluid Options

- Basis for selection
  - Low temperature two-phase fluids
  - Preferably low saturation pressure in temperature range of interest, -20 to –10°C
- Fluid surface tension and heat of vaporization criteria
  - Very important as we will see next
- Process has just started
  - Selection of fluid
  - Design of HP
  - Integration with structure



Candidate Fluids-Groove Wick

Description	NH_3	CH_3OH	C_4H_{10}	R12	C_3F_8	C_4F_{10}
Fluid Conditions						
Saturation Pressure-bar	2.9	0.021	1.08	2.2	2.9	0.73
Temperature-°C	-10	-10	-10	-10	-10	-10
Groove Wick Dimensions						
Number of grooves	24	32	31	25	47	63
Vapor core diameter-mm	6	7	6	4	6	6
Width-mm	0.4	0.33	0.3	0.25	0.2	0.15
Depth-mm	1.0	1.65	1.2	2.5	4.0	3.0
Wick Performance		***For half stave length, 55W***				
Capillary limit-Watts	123	32	19	13	9	5
Sonic limit-Watts	14490	180	2782	1578	3704	1036
Boiling limit-Watts	478	4603	192	14	20	80
Entrainment limit-Watts	452	56	97	38	78	50
FOM-kW/cm^2	16140	1735	1375	1079	745	510

Ammonia: NH_3 Methanol: CH_3OH Isobutane: C_4H_{10} R12: CCL_2F_2

Perfluoropropane: C_3F_8 Perfluorobutane: C_4F_{10}

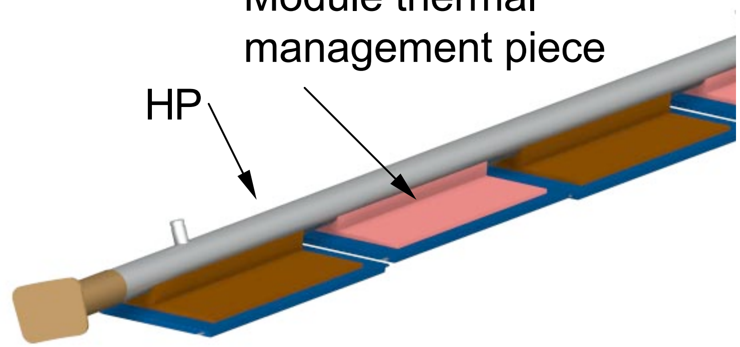
$$FOM = \frac{\square_l \square\square}{\square_l}$$

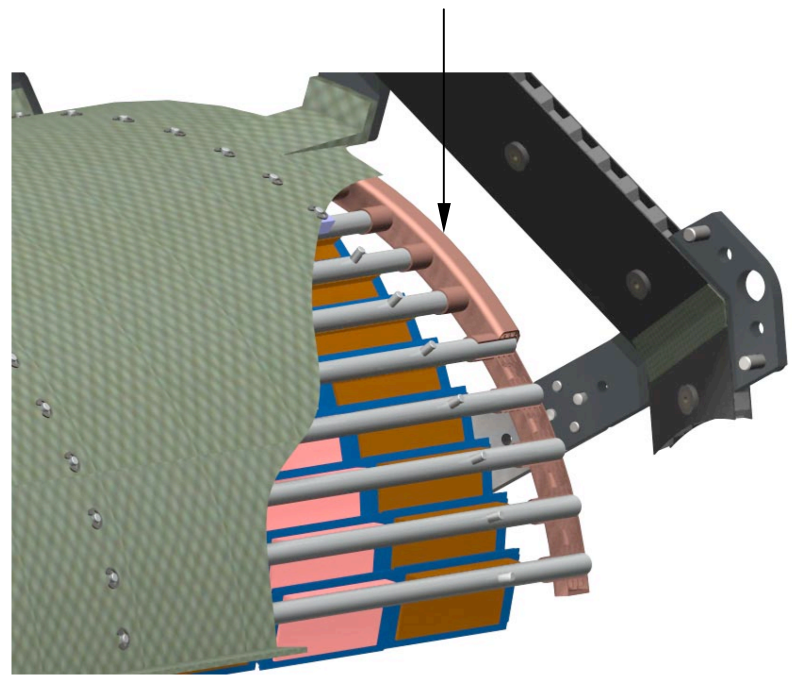
1st Order Groove Wick

- Ammonia fluid satisfies the goal of a small diameter HP rather easily
  - Advance notice of this comes from the fluid Figure of Merit (FOM) calculation
  - FOM brings together key fluid parameters that are important to HP applications.
- Methanol does not attain the goal of 55W with a simple wick geometry as hoped
  - Option to a groove wick with constant dimensions is to change shape with axial dimension, improving the wick permeability
  - Changes to groove geometry are being investigated
- Other candidate fluids show major short comings with the simple groove wick
  - Possible one of these fluids will work with another wick geometry, e.g., screen wicks
- Work will continue to select a fluid and wick geometry to minimize the HP profile dimensions

1st Structural Option

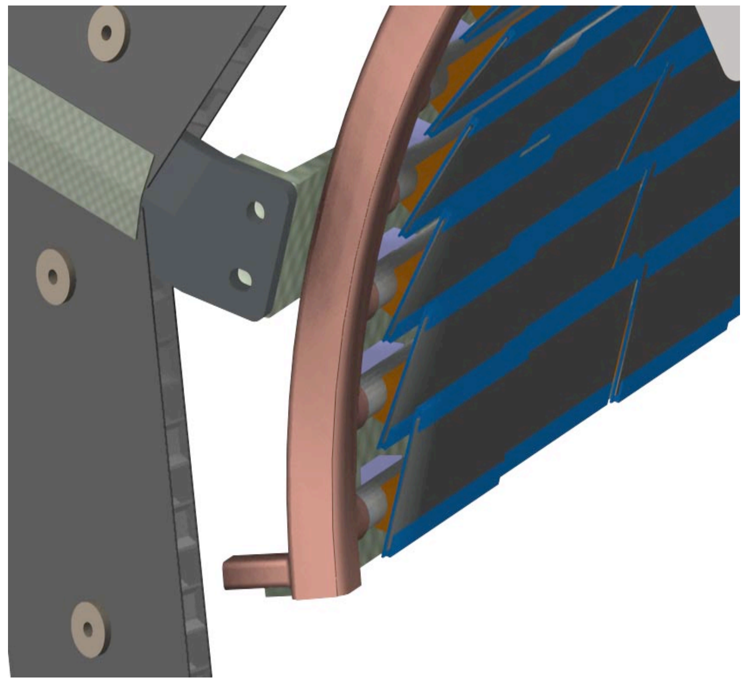
- Description
  - HP stave with “step-up/step-down” geometry for axial overlap
  - HP is a stiff tube, overcoming gravity sag between supports
  - Modules are mounted on flat machined C-C plates
  - Introduce condenser manifold
- Improvements
  - Eliminates several ATLAS stave components
  - Condenser manifold eliminates the 432 tube connections in the tracking volume
  - Condenser manifold can be built with multiple coolant passes to add redundancy





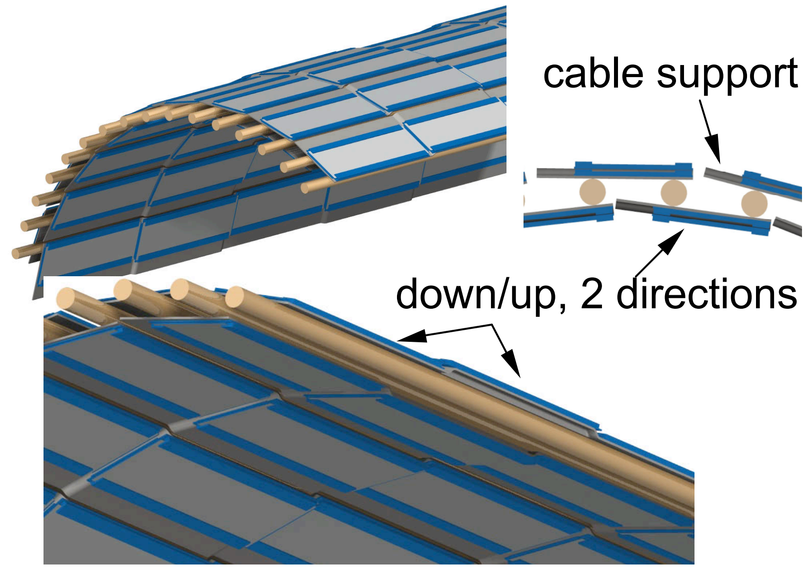
Condenser Manifold

- Condenser manifold objectives
  - Condenser manifold is an external flow circuit, replacing the 80 or so flow circuits
  - Condenser is supplied with multiple flow circuits, say 3 for system redundancy
  - Manifold accepts heat from ends of the heat pipes
  - We choose to confine the heat transfer to nominally 40mm axial distance at end of HP
  - If necessary, we will use surface area enhancements, like foam to reduce temperature drop in the manifold
  - Fluid in manifold could be C_3F_8, using the system as developed by ATLAS

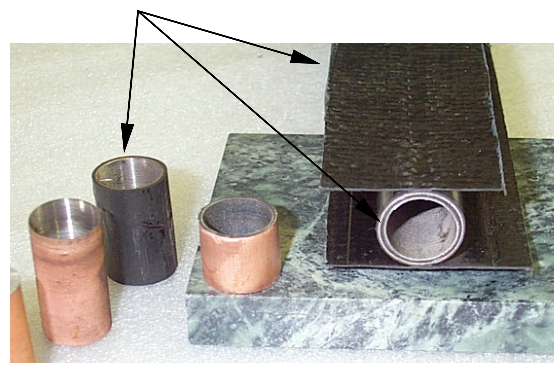


2nd Structural Option

- HP-Structure Integration
  - Adjacent HP tubes are joined with thin composite strips, *upper and lower strips*
  - The strips form a circumferential “step-up/step-down” pattern, providing a continuous shell like structure
  - Structural concept is similar to the CMS barrel concept
- Module Overlapping
  - Provided circumferentially by step pattern
  - Step-up/step-down pattern is molded in the axial strip to permit overlapping in the axial direction

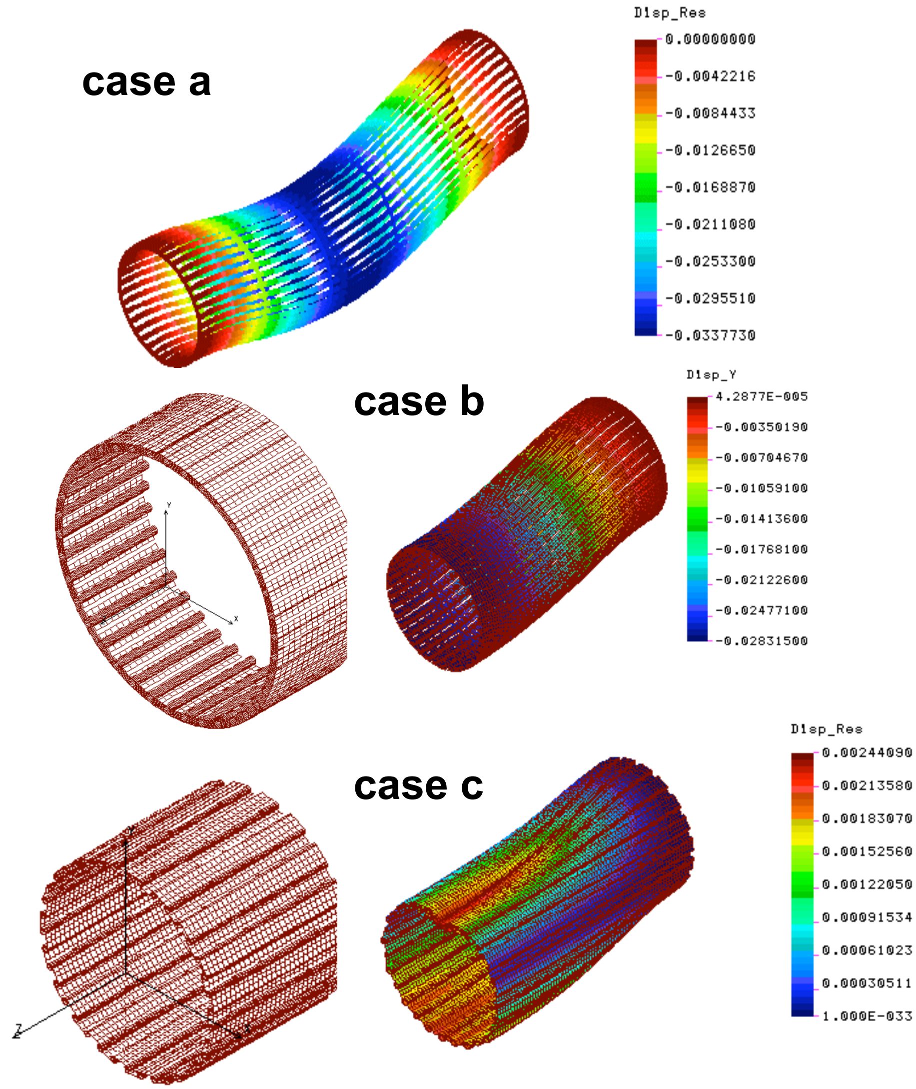


C-C tube structure with C-C facings



Stave Support Options

- Gravity sag solutions
  - Case (a)- HP tubes tied together with rings
  - Case (b)-HP tubes stave only
  - Case (c)- HP tubes integral with shell
- Results
  - Case (a) sags excessively
  - Case (b), stave with 6 supports will sag 28μm, a supporting shell <3 μm
  - Case (c), composite strips between HP tubes sag <8μm with module and cable weights added
- Radiation length
  - Preliminary results for lowest mass and radiation length favor case (c)



Benefits/Risks

- Potential Benefits of Passive Heat Extraction with Heat Pipes in the ATLAS Pixel System
  - Improved local thermal stability-passive, not subject to change by individual performance of regulators
  - Major reduction in number of tube connections, and associated mass
  - Elimination of 160 pressure regulators
  - Improved structural thermal stability, eliminate adjacent coupling of Al tubing
  - Less mass, lower radiation length at □>1
  - Potential for modularity of 1 versus present modularity of 2
  - Improved system reliability and functionality
- Risks
  - Demonstrate C-C heat pipe technology with 10 year life
    - Address low mass and sealability
    - Address thermal design, leading to pipes of the order of 6mm diameter
  - Demonstrate stability of HP fluid in radiation environment

Conclusion

- HP Design
  - Construction concepts for achieving sealed C-C are being formulated
  - 1st order specimens of wall structure have been constructed
  - Performance studies for wick geometries are underway
- HP Testing
  - Expect to test a1/2 length 55W HP composed of carbon-carbon elements by end of CY2002
- Financial support
  - Provided by DOE Phase I SBIR
- Related application
  - NASA Nuclear Electric Propulsion initiative in sore need of carbon-carbon HP radiator, using C-C sandwich facings