US ATLAS Pixel Review

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LNBL

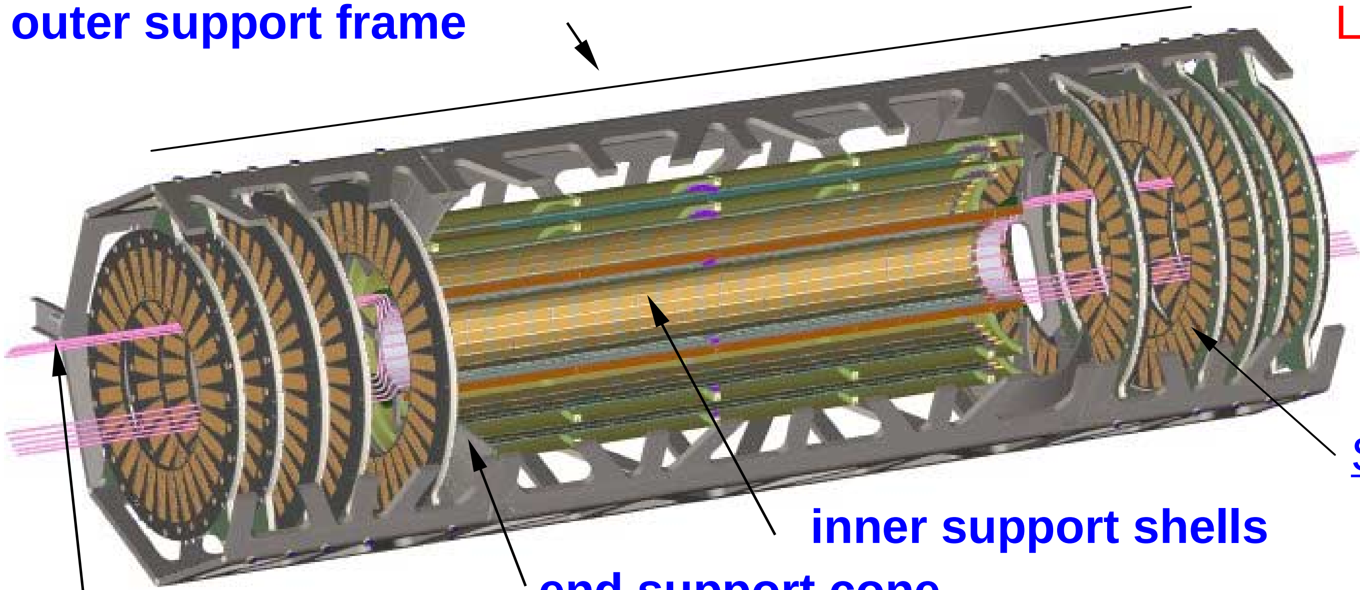
Definition of Terms

Support Structures-Definitions

Global-bold

Local supports

outer support frame



Sectors-local support

inner support shells

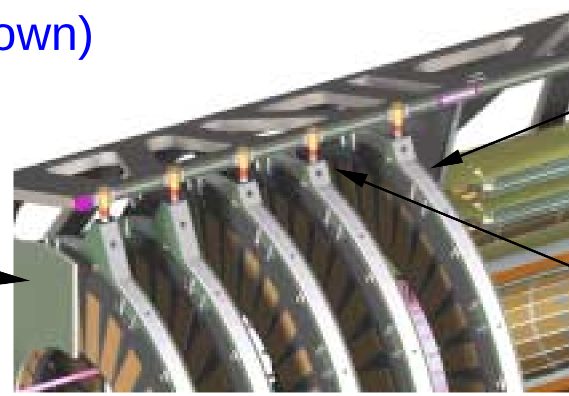
end support cone

external frame mounts

(insertion rail system not shown)

disk support rings

end support plate



support ring mounts (18)

(5 disk assembly-original)

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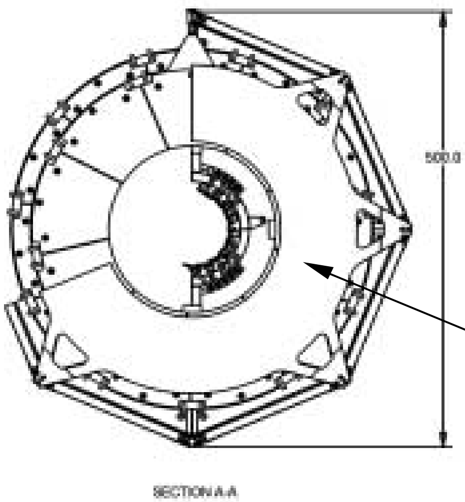
Detector Geometry

Geometry at time prototype effort commenced



Dimensions in mm

End plate structure

Technical Status Discussion

Design of:

- Outer Support Frame
- End Cone
- Disk Support Ring
- Disk Support Ring Mounts

Prototyping of:

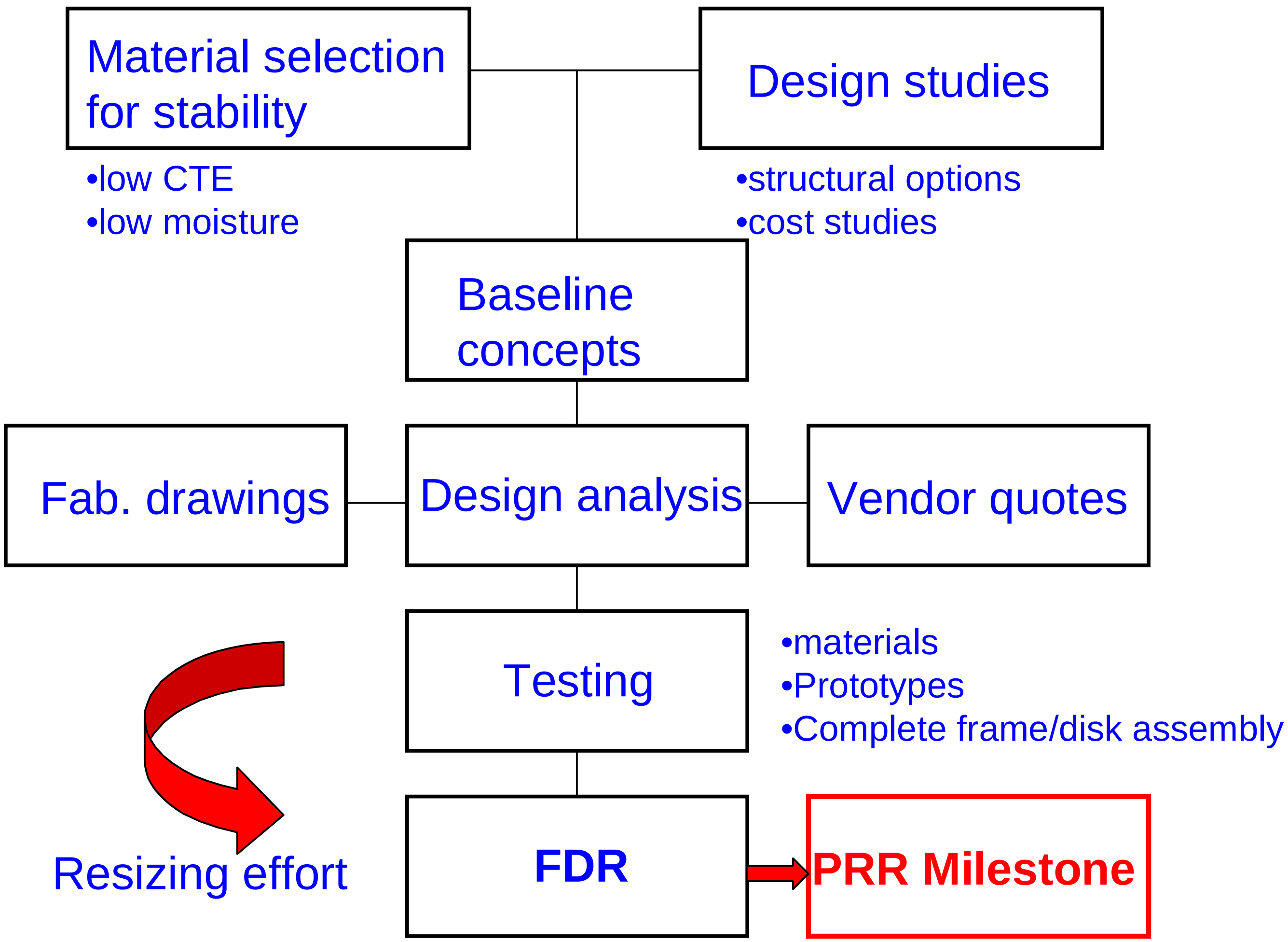
- Section of Outer Support Frame
- Disk Support ring
- End cone(in process)

Analysis of:

- Frame structures
- Disk
- Disk Support Ring and Ring Mounts

and comparison with prototype results

Technical Approach



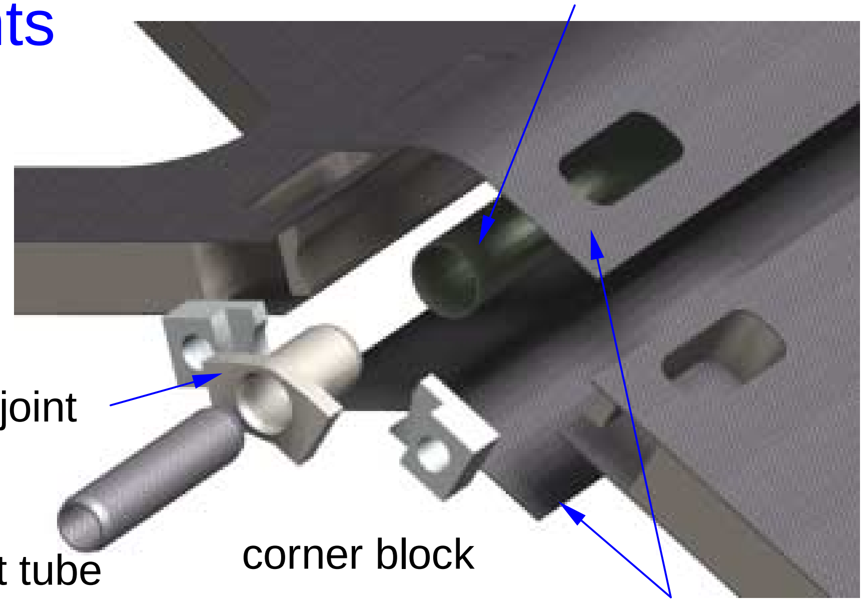
Outer Support Frame

Outer Frame Construction

Objective: Design ultra-stable lightweight precision frame

Frame Elements

flat panel sandwich with XN80 facings and YLA Cellular graphite fiber honeycomb



Corner design to transfer load between panels

Outer Frame Investigations

Overview

- Material testing
  - Complete: *laminate properties agree with predictions, E=158GPa (23Msi)*
- Single panel testing
  - Reduction in stiffness from light weighting: *follows predictions*
- Key frame construction details verified
  - Corner blocks constructed with M55J fiber with built-in alignment features: *completed*
  - Precision vertex corner joints with M55J and precision thin, small diameter corner reinforcement tubes with high modulus XN80 fiber: *completed*
  - Precision molded corner splices with XN80 fiber: *completed*
- Bi-panel assembly
  - Test results: *compared well with predictions*
- Disk frame section
  - Static and dynamic testing: *results agreed with predictions*

Composite Material Tests

Calculation for quasi-isotropic
Layup, 0/60/-60/s, 60% FV

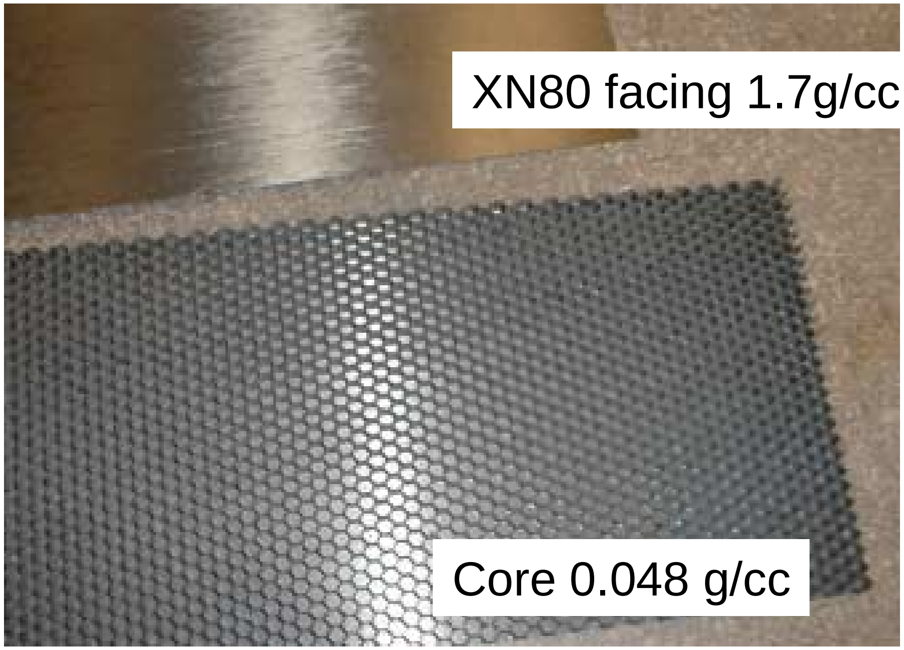
E	**23.58**	**Msi**
σ_u	**67.2**	**Ksi**
ε	**0.285**	**%**
ρ	**1.774**	**g/cc**
α	**-0.99**	**ppm/°K**

Tensile Modulus Msi	Tensile Strength Ksi	Strain to Failure %
0° Direction		
21.8	55.1	0.25
22.8	88.8	
23.3	71.6	0.31
23.9	72.8	0.31
23.4	79.8	0.33
Avg=23.5	***Avg=74.7***	***0.32***
90° direction		
21.0	61.3	
21.4	60.9	
20.7	60.3	
21.4	62.9	
21.6	61.1	
Avg=21.2	***Avg=61.4***	

Frame Sandwich Elements

Materials: low CTE and low CME

XN80 Graphite fibers/cyanate ester resin-8 layers quasi-isotropic~0.42 mm



XN50 graphite fiber/CE Core 10 mm thick

Item	**Wt.-g**	**%**
facings	93.9	61.8
core	30.1	19.8
Al blocks	14.4	9.5
total	151.9	

Adhesive average between two facings 106 g/m^2***—8.9%***
HYSOL- EA 9396, room temperature cure

Outer Frame Assembly Tooling

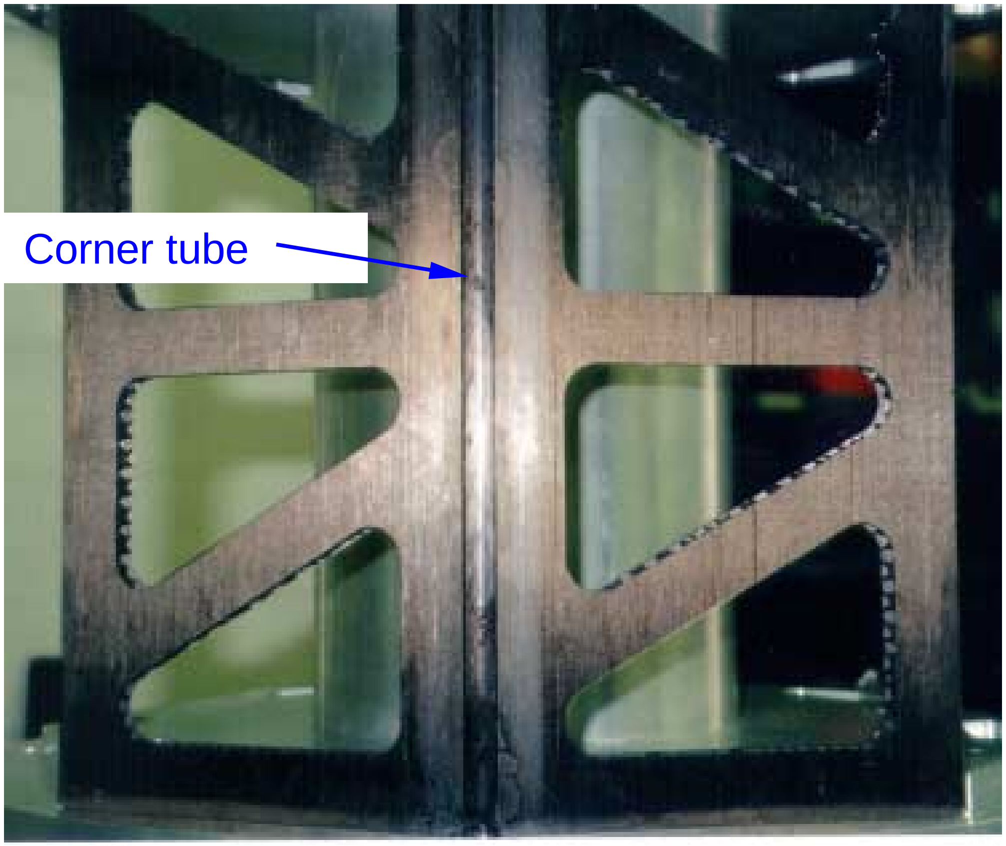
355 mm long Frame Section---*Disk Section*

- Fixture function
  - Holds panel parts in place during bonding, utilizing self-jigging features of the corner parts
  - Index pins machined into top and bottom fixture plates hold circumferential alignment
- Assembly steps
  - Assemble sandwich panels with corner blocks
  - Place inner corner splice in fixture recess
  - Place two adjacent panels onto inner corner splice
  - Insert corner tube and vertex alignment joint
  - Install outer splice
  - Repeat process 4 times

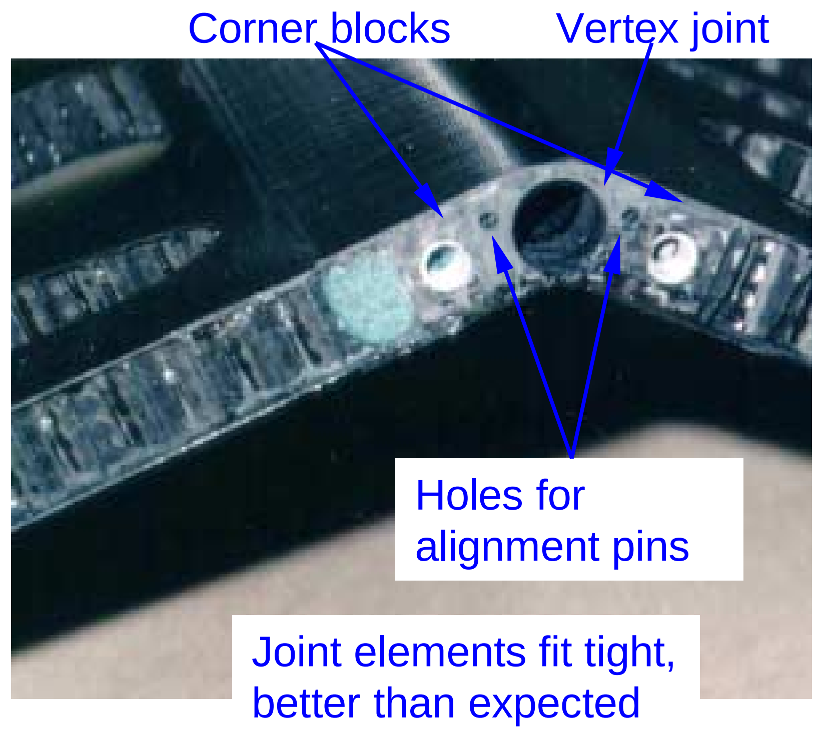
Panel weight 84.3 g after removal of material (39.7% reduction)

Outer Frame Assembly

Verification of Bonding/Assembly Methods



Tube fit-up in recessed cavity



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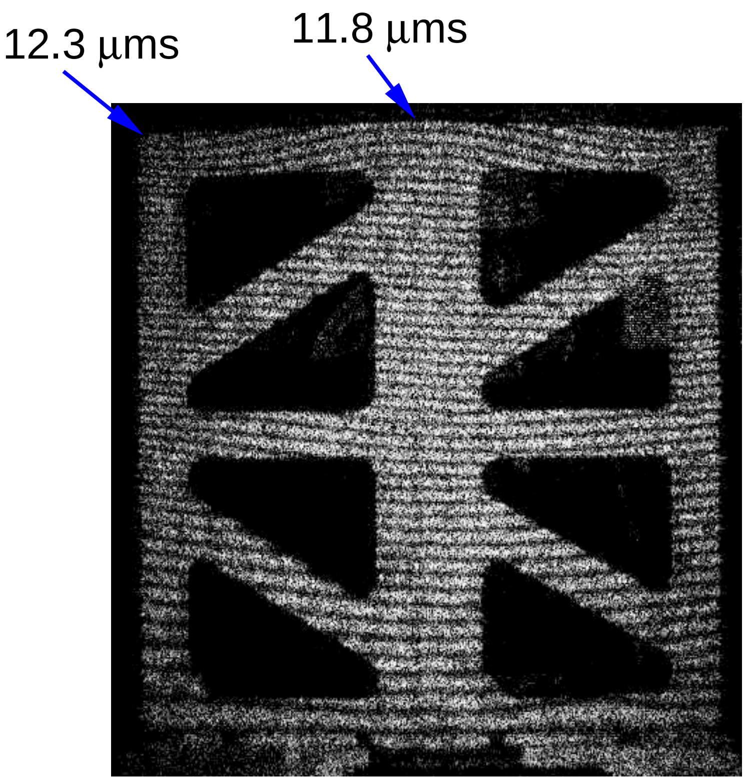
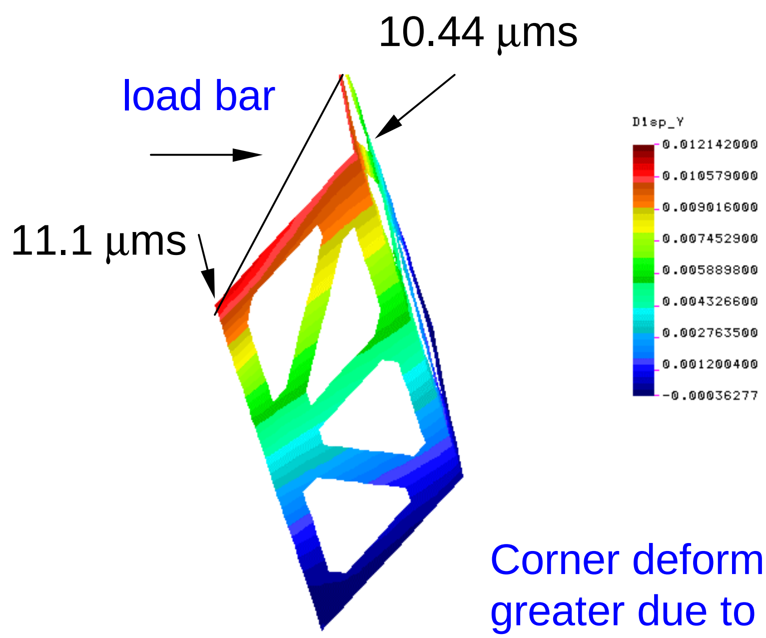
Bi-Panel Testing



TVH fringe pattern

Displacements normal to corner



Corner deformation greater due to panel bending at point of load application

FEA using properties of prototype panel dimensions

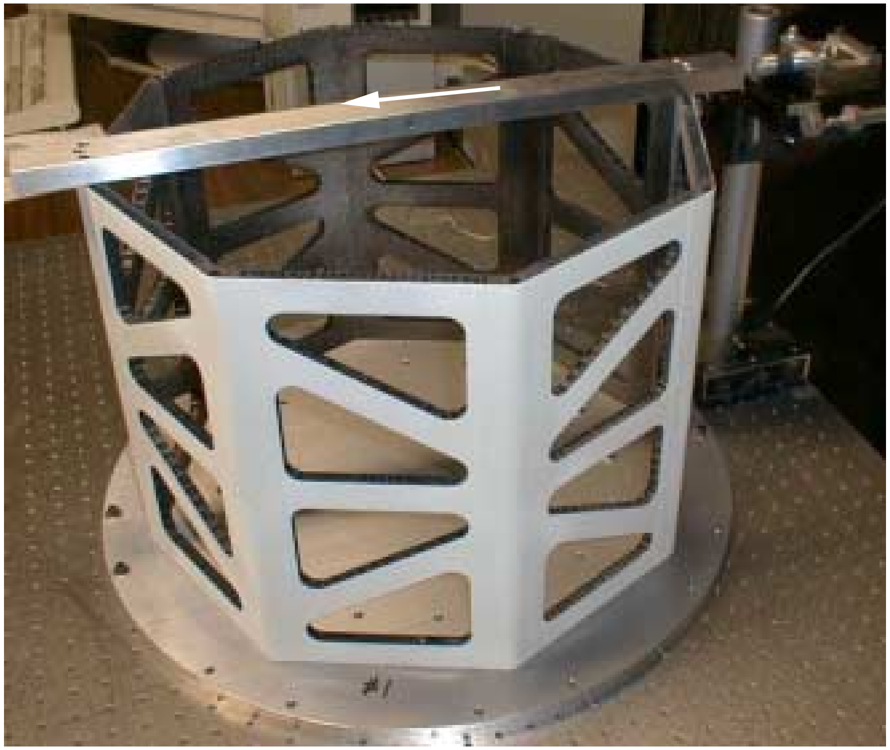
Disk Frame Prototype

- Testing evaluated:
  - Stiffness at low strain levels, at level simulating the application
    - Composite properties measured at higher strains, yet properties were used to design at low strains
  - Effect of bonded joints
  - FEA modeling approach for Global Supports
- Testing issues
  - Load Application
    - Difficult to apply load without influencing measurement
  - Boundary conditions
    - To test, frame is mounted to a base support structure
      - Objective is to limit compliance at base

Transverse Loading-*In Line With Corners*

- Frame test-setup
  - Octagonal frame is attached by #8-32 screws to 1.9cm (0.75in.) Al plate
  - Attachment plate is mounted to optics table
  - Cross bar attached to top of frame using #8-32 screws, at the corner joint
- TV holographic imaging of distortion
  - Load applied at center of bar axis
    - Axis alignment is achieved by adjustment of line of action
  - Symmetry noted in fringe pattern, suggesting good alignment

Load Case A

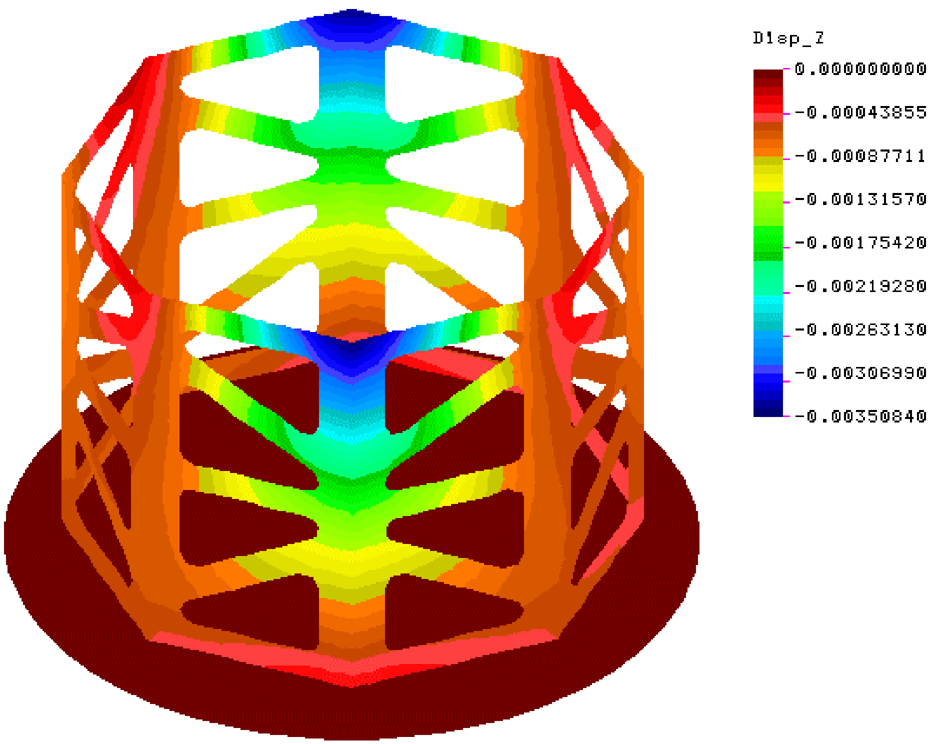


Disk Frame Prototype

Transverse Loading-*Load Case A*

0.53 μm/N

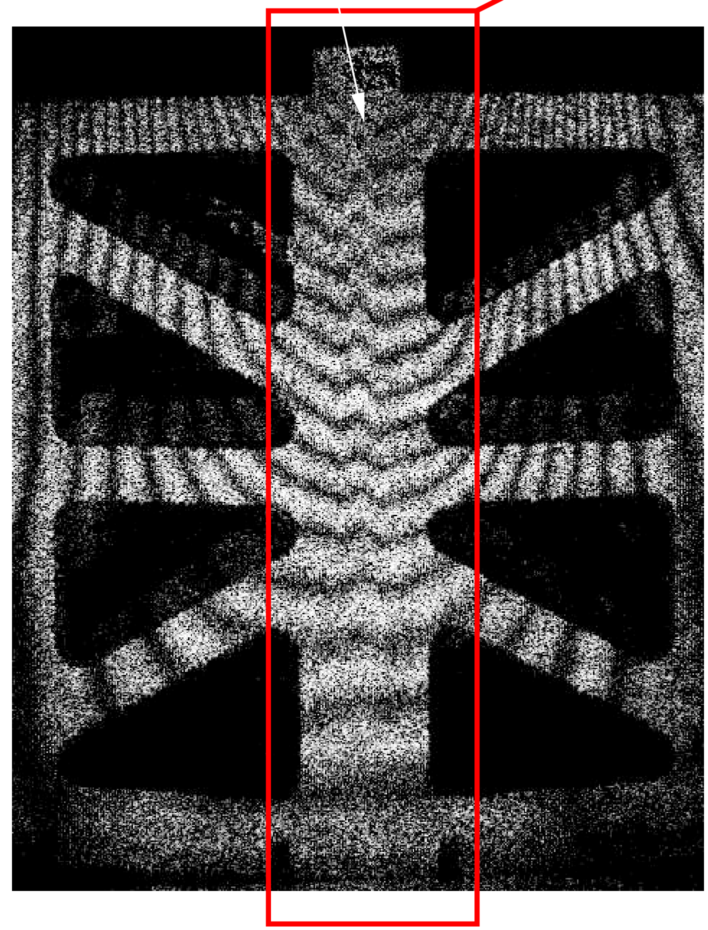
Peak distortion in corner



Finite element model result

0.69 μm/N

Corner region

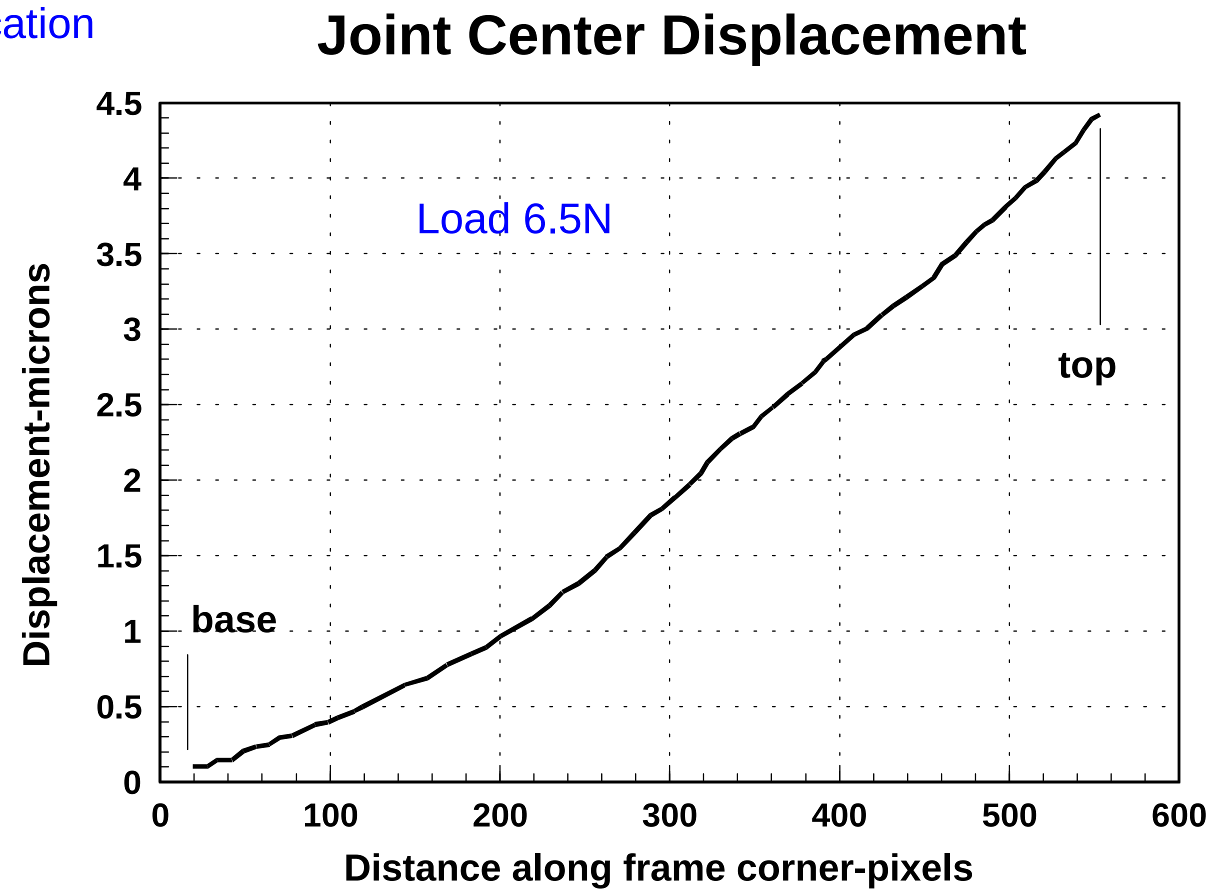


Disk Frame Prototype

TVH Measurement of Corner/Joint Behavior

Top

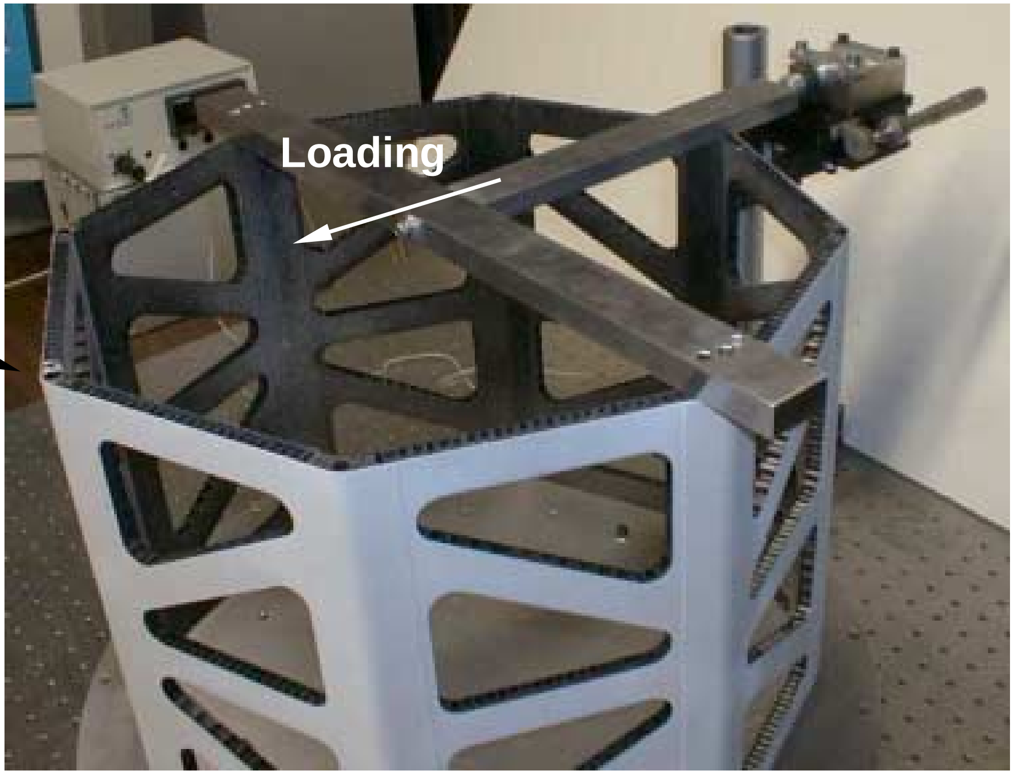
Base



Disk Frame Prototype

Transverse Loading-*Load Case B*

TVH Phase Plot



Disk Frame Prototype

Frame Prototype Vibration Testing

- Test setup
  - Frame section for disk region
    - Mounted to an aluminum plate in cantilever setup, same as for static tests
  - Used small PZT crystal to excite the frame
    - Frequency generator swept frequency range, 30 to 730 Hz, at constant displacement amplitude, not constant force (makes interpretation a little more difficult)
    - Test procedure amounted to watching for occurrence of fringes, indicating response in the structure
- Evidence of response tied to number of fringes produced, a large number of fringes corresponding to a resonance peak
    - Response to excitation in the vicinity of actual mode is characterized by fewer fringes on either side of peak response
      - Lightly damped structure number of fringes increases quite rapidly as the mode is approached and conversely falls off quite rapidly as the modal frequency is passed
      - Structure with higher damping, the response is broader and fringes (fewer) are observed on either side of the peak response, over a significant frequency range

Disk Frame Prototype

Comparison between predicted and measured frequencies

FEA Prediction- mode number/Hz		TVH results-Hz	Comments
1st	515.6	546	Fringe pattern agrees with FEA
2nd	520.8		No corresponding fringe pattern
3rd	705.8	721	Fringe pattern agrees with FEA
4th	705.8		*Duplicate predicted mode*
5th	748.8		Appears to be nearly pure cantilever motion
6th	748.8		*Duplicate predicted mode*
7th	986.3		TVH test did not span this point

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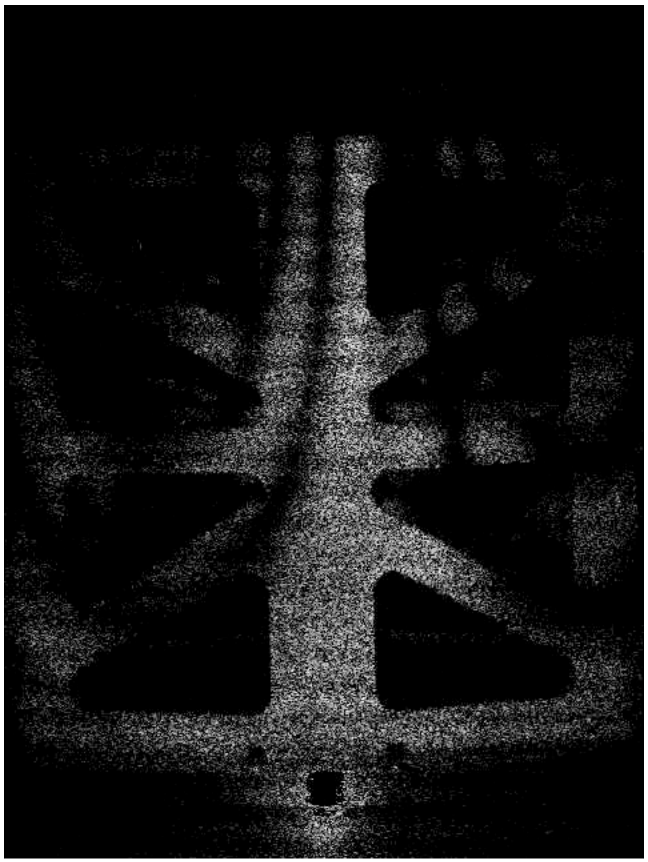
Disk Frame Prototype

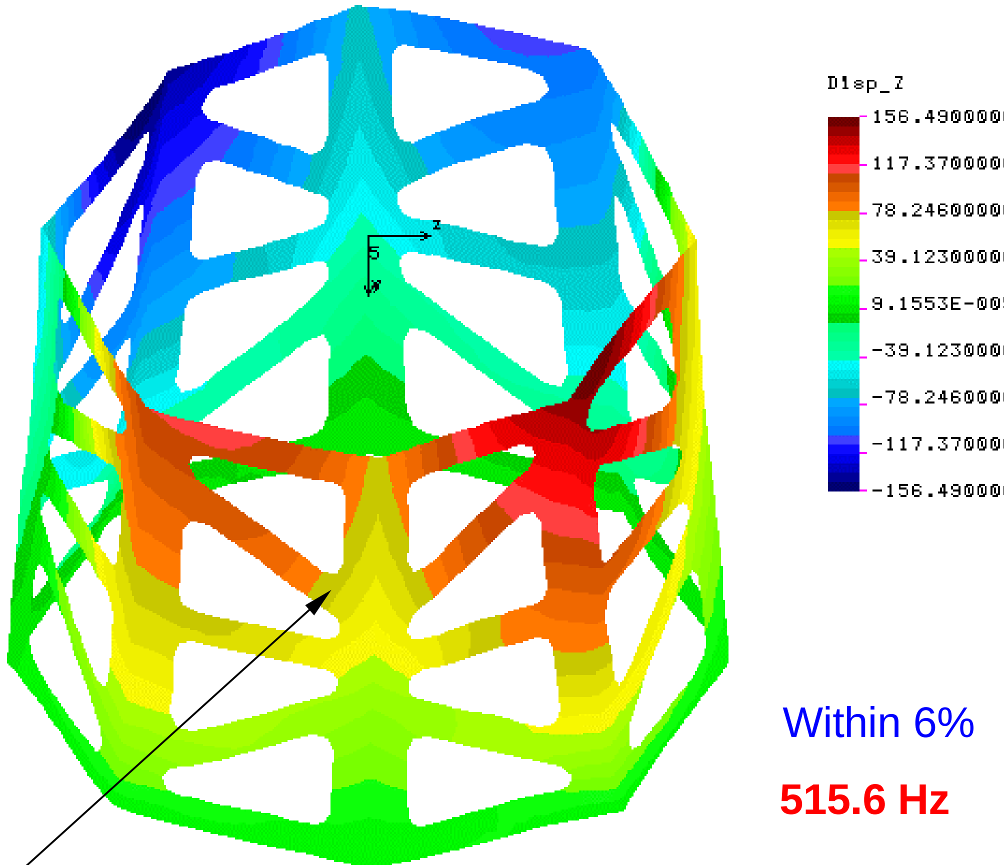
1st significant mode for the Frame Prototype

TV holography result



546 Hz

FEA prediction



Within 6%

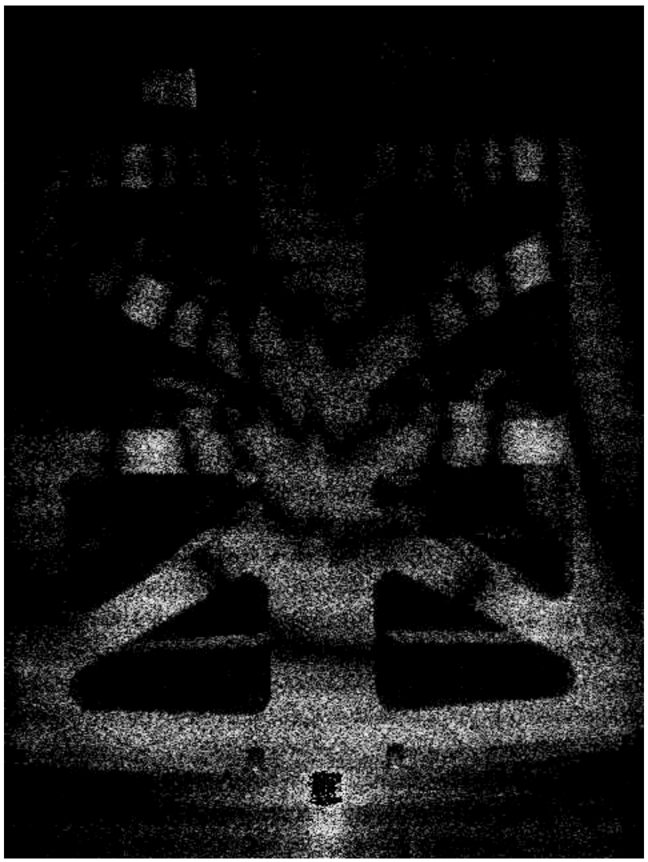
515.6 Hz

Shape of contours quite similar to fringe pattern

Disk Frame Prototype

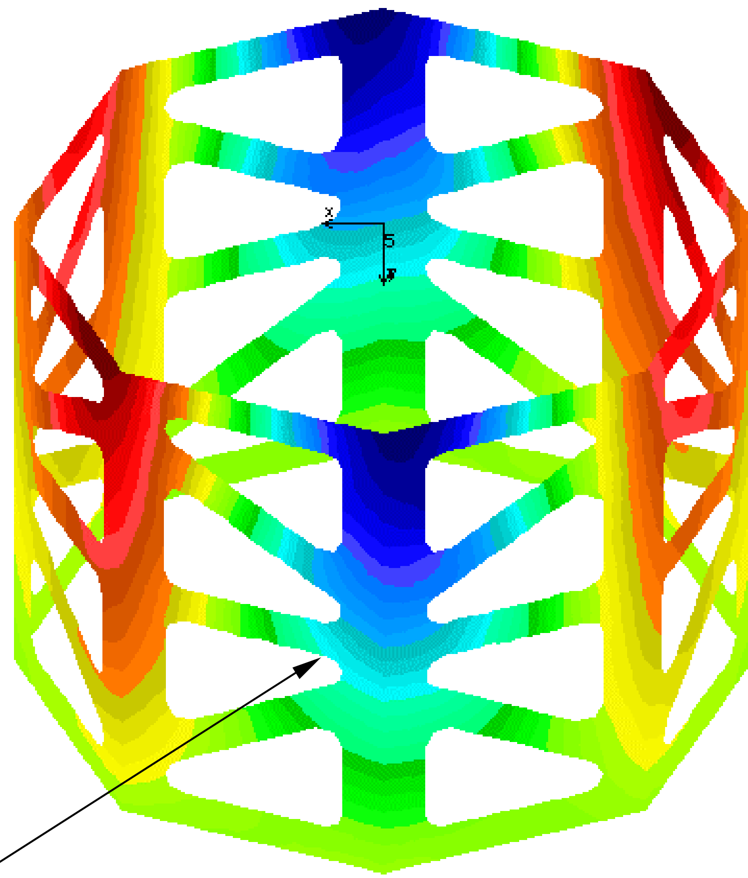
2nd Significant Mode of Prototype Frame Vibration

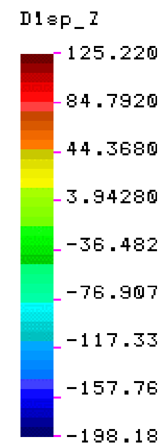
TV holography result



721 Hz

FEA Prediction





Within 2%

705.7 Hz

Again similarity with fringe pattern

Global Supports FEA

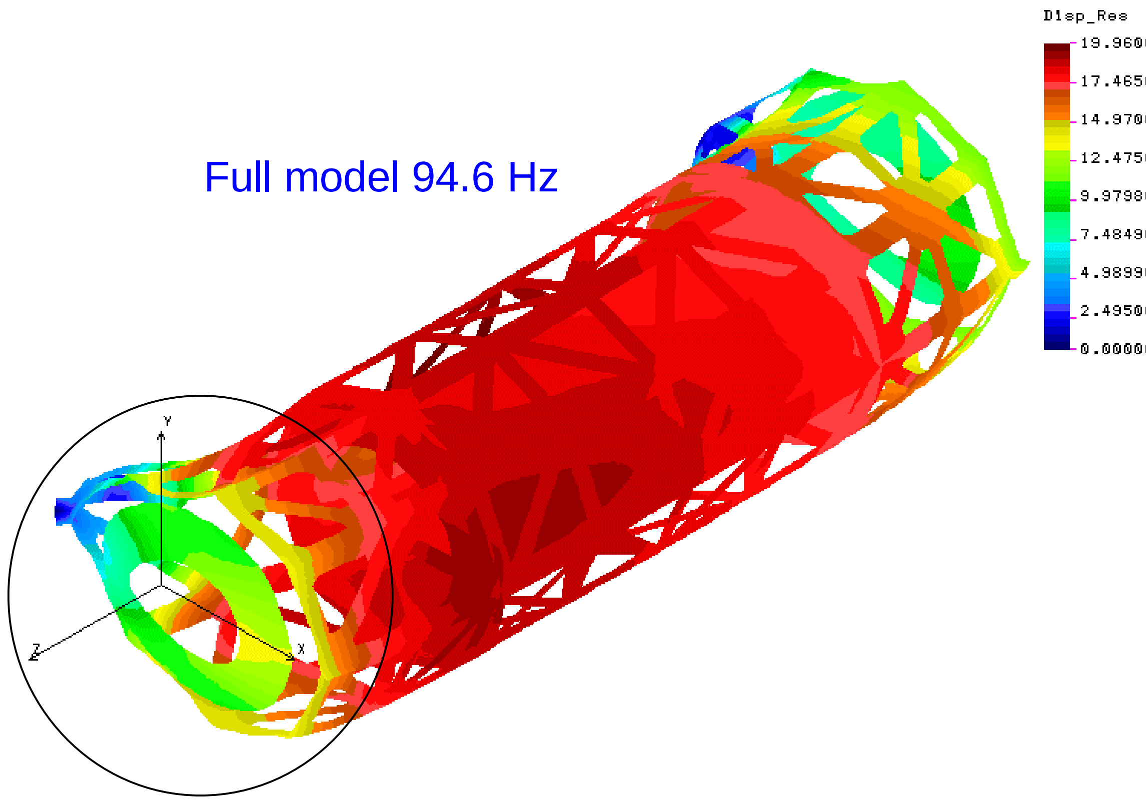
Dynamic Stiffness Considerations

- Study of overall Global Supports using FEA has been made
  - Model had a complete representation of the inner barrels, radial supports interconnecting two layers and B-layer, and all the staves. Derived structure with:
    - Global support structural mass of 4.4kg and total mass of 37.5kg,
      - Structure ~13% of mass supported (33.1kg)
  - Middle layer and B-layer axial natural frequency of slightly greater than 100 Hz was attained by fixing the number and size of radial interconnections
  - Entire structure dynamic stiffness design goal was achieved:
    - > 70Hz goal, achieved above 90Hz by providing end plate on outer frame and four mount points to SCT
- Global support FEA models must be re-done to account for changes to supports
  - Insertion, mounting, and service connections for entire pixel detector
    - Rail concept, extraneous loading of frame
  - B-layer insertion, mounting, and service loads
    - Thermal barrier loads

Dynamic Stiffness

Global Support Frame FEA

Full model 94.6 Hz



Support concept design focused on suppressing sway frequency

End mounting region where most of the distortion occurs

Disk Support Ring Status

Support Concept for Disks

Disk and Sector Support Considerations

- Technical Approach
  - Low profile, thin composite ring structure to minimize material in tracking volume
  - Three point support of sectors
  - Rigid attachment of sectors to the support ring to enhance local stability
  - Three point support of ring (may be revised to 4)
    - Requires demonstration that thermal strains in support ring are held within acceptable bounds

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Composite Ring Construction

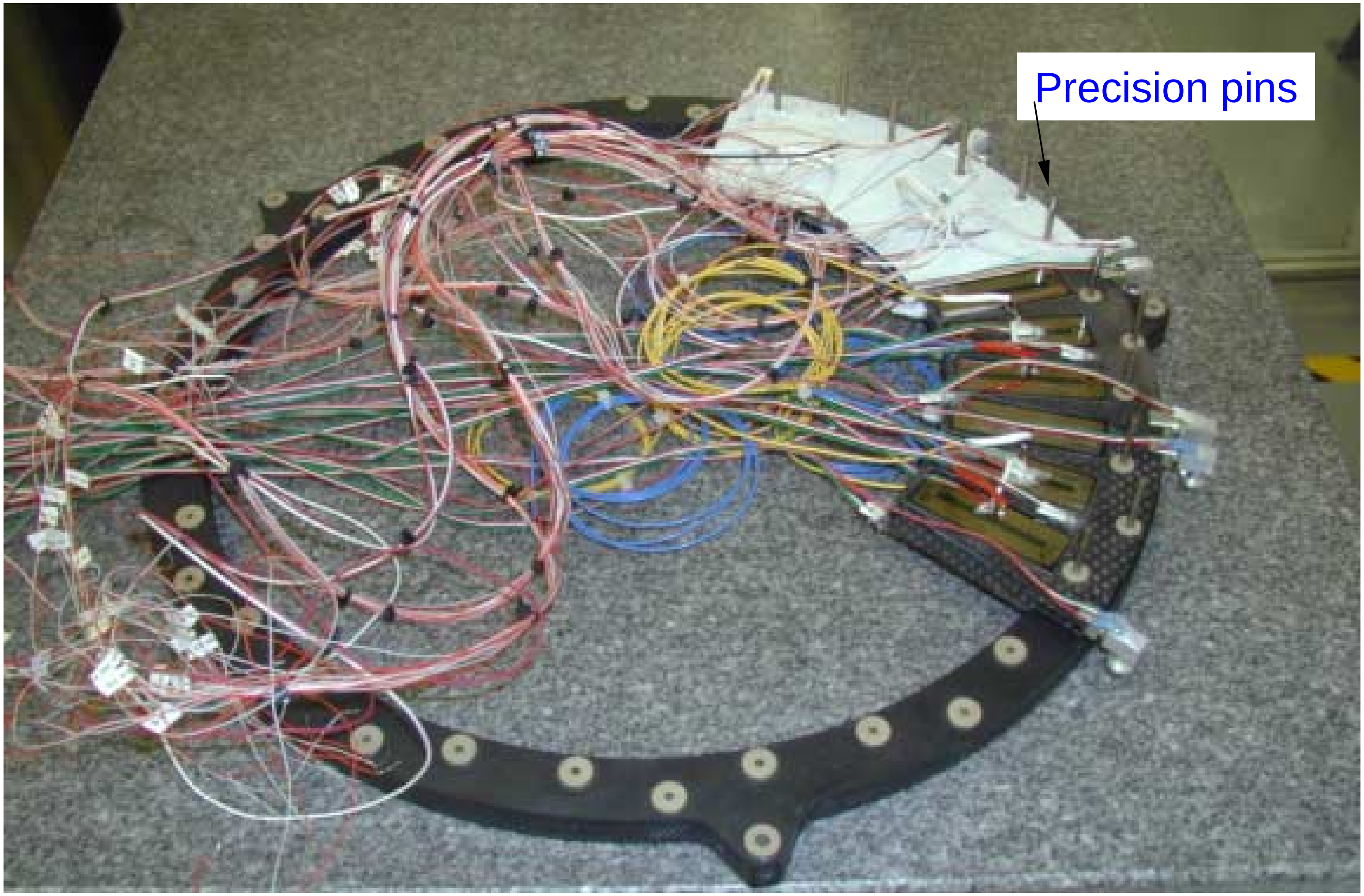
Precision machined PEEK bushings for sector attachment

P30 Unitape C-C facings

C-Channels
YSH50 GF/CE resin
4 layers woven cloth

Three point support with suspension point behind the ring

Trial Setup with Sectors



Able to install the 3-precision mounting pins (light press fit) for sectors, in all twelve mounting positions

Ring Fabrication Comments

- Quality of ring fabrication
  - Bond fixture used in assembling ring was machined from graphite plate
    - HYTEC inspection indicated ring precision hole pattern was achieved, but flatness was not
      - Major improvement in dimensional quality, but ring flatness that will require further work—possibly solved by using Invar tooling
    - LBNL inspected tooling plate, results of inspection are under evaluation
    - Preliminary observations from LBNL data:
      - 39 precision hole pattern, location tolerance of 12.5µm was achieved
      - Several (~20%) counter-bores to allow space for *head* of PEEK inserts were out of planarity by 50µm, whereas drawing specified 25µm
        - » Explains only a small part of the ring flatness problem
- C-Channel dimensional quality improved significantly, but slight out of flatness was evident before bonding ring
  - C-Channel may be causing the ring to cup. We will re-evaluate the consolidation process used in constructing the C-Channel.
    - Autoclave and post-machining are additional process steps which will be considered

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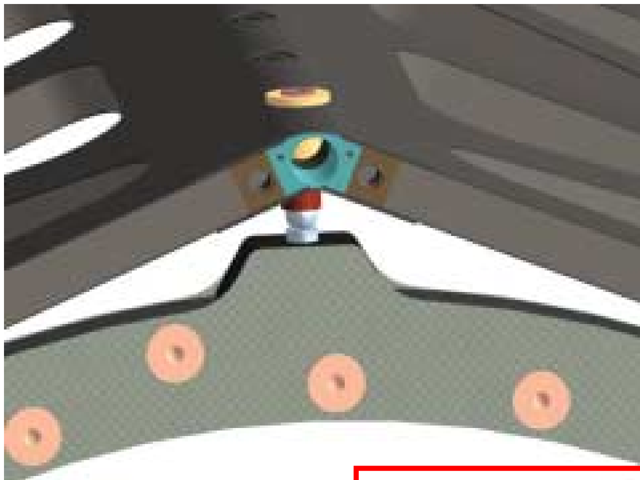
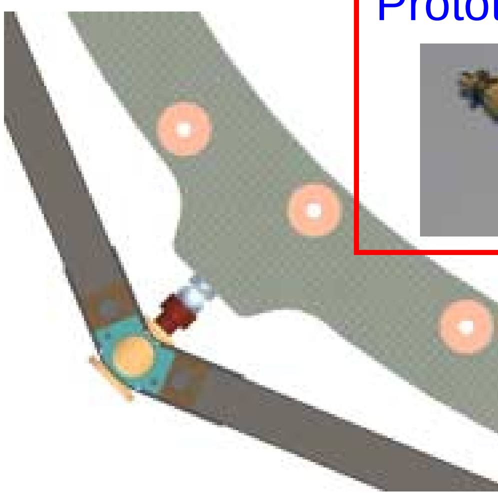
Composite Ring Mounting

Support Ring Radial Mount-*new*

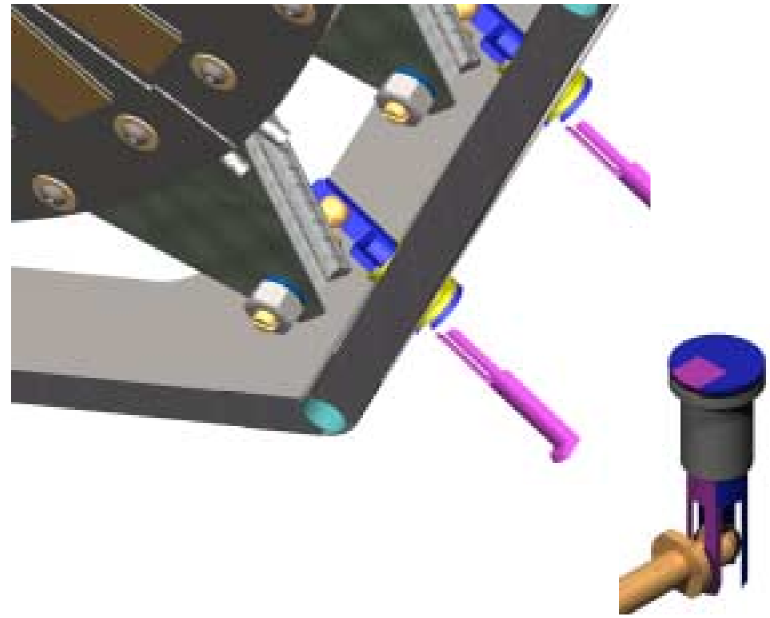




Prototype to be tested

Alignment pin

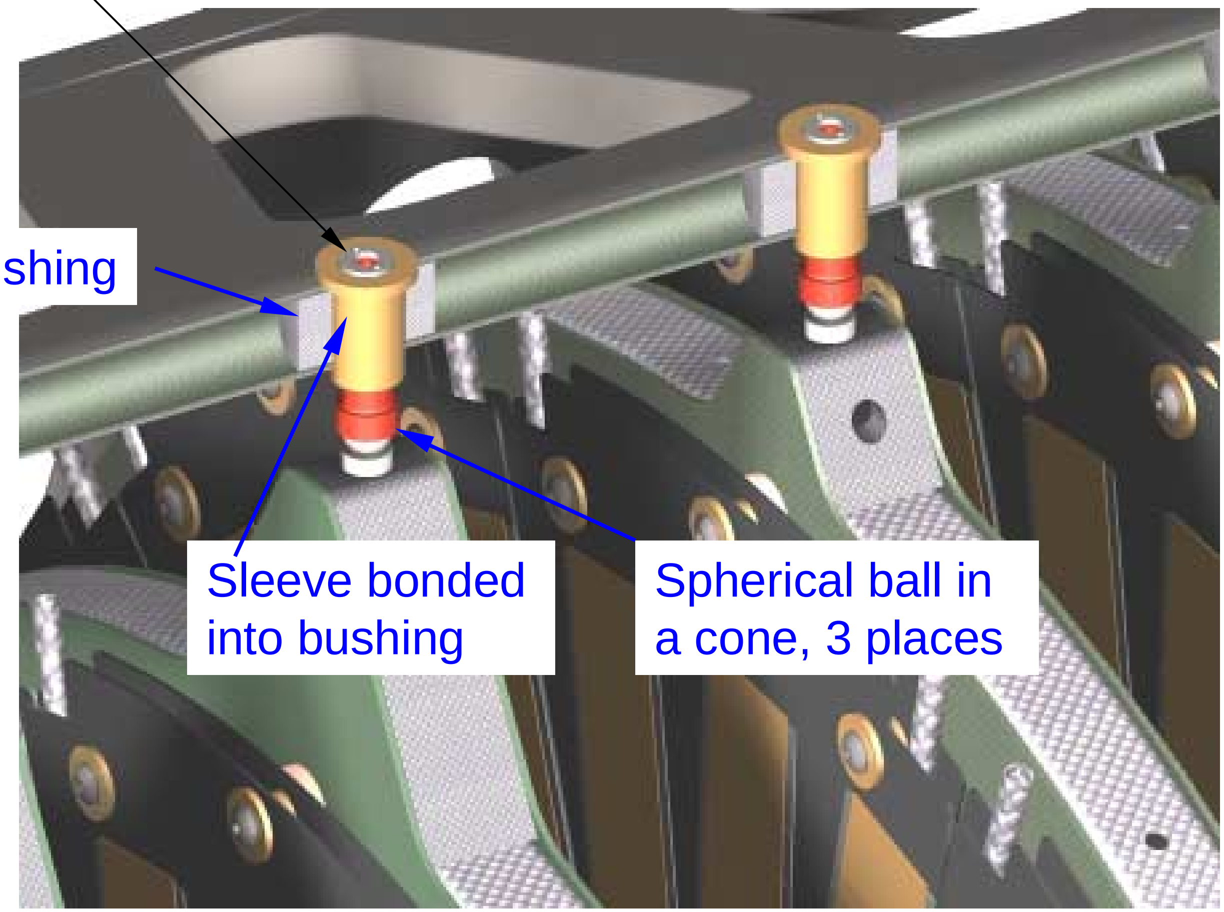
Radial Groove Support Ring Concept



Prototype-tested

Composite Ring Mounting

Top mount uses a spring to load-up the two lower mounts—backing out the spring retention screw releases the restraint allowing disk to be removed

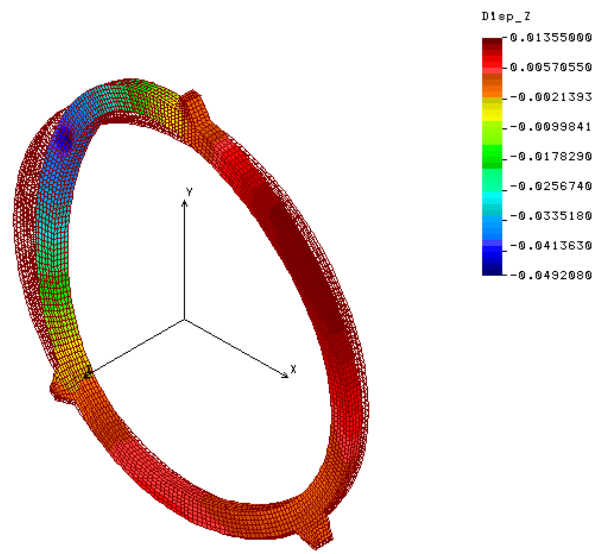


Composite Ring

Preliminary Ring Static Tests

- Static tests *with spherical ball in radial V-grooves (suspension behind ring)*
  - Applied static load normal to the ring midway between the upper and lower support points on one side
  - Load also applied midway between the inner and outer edges of the ring
  - Load is applied over a 2.29 mm diameter contact point
  - Three spherical balls are drawn into V-grooves and mechanically restrained, it is anticipated that rotation of spherical contact is fixed by friction
- FEA model
  - Load concentrated at one node
  - Support boundary conditions for the spherical ball are fixed in three degrees of translation at the ball joint. Two solutions were performed, one with rotation fixed another with rotation free, no significant change in stiffness

Static Results

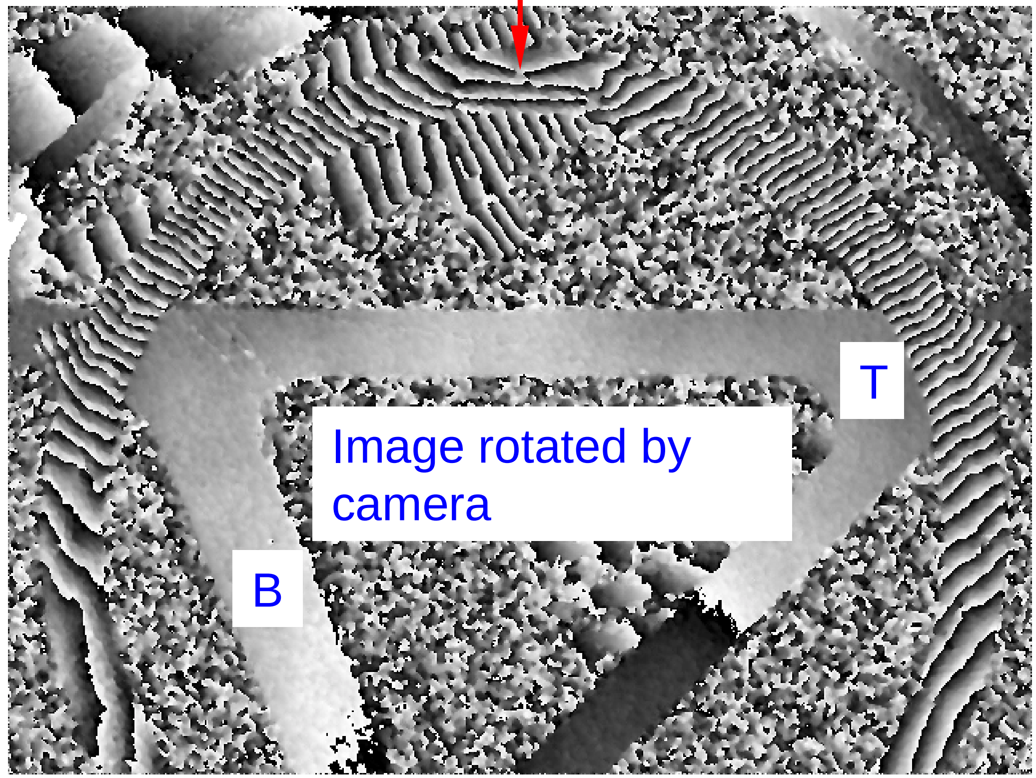


Load 2N from front
46.9μm=23.45 μm/N

Ring appears to deflect 70.7% of that predicted by FEA

(2N= 204g=0.45lbf)

Load application from back in ring center



Experimental TVH result average of three tests: 163μm/kg=16.6 μm/N

Test load nominally 56g

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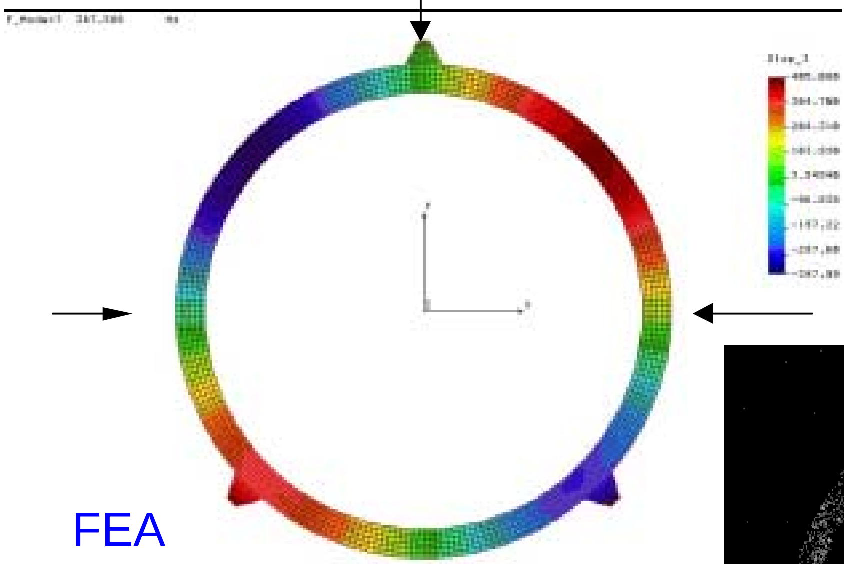
Vibration Results

Ring Modal Tests

- Dynamic test with “free-free” support conditions
  - Reason for “free-free” boundary conditions
    - Too many modes in the Invar support plate and associated support structure that are close to ring natural frequencies precluding mode identification
  - Ring supported on foam at three support points to effect “free-free” condition
    - Foam placement resulted in the ring being slightly off vertical relative to the support frame---disregard this appearance
- FEA
  - Mass of model was adjusted for the weight increase due to adhesives
    - Results in prediction being slightly lower than experimental result
  - Comparison is quite good all things considered

Ring Free-Free Vibration Tests

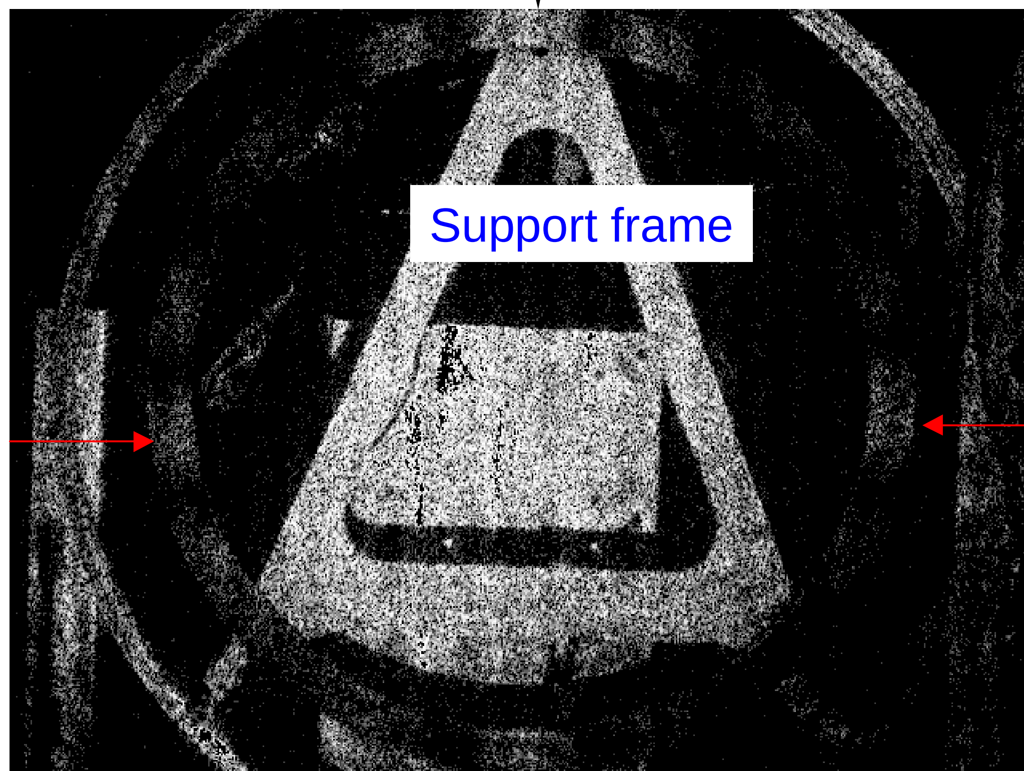


FEA

317.02 Hz

Four vibration nodes
(zero motion)

Experimental TVH
results-330 Hz



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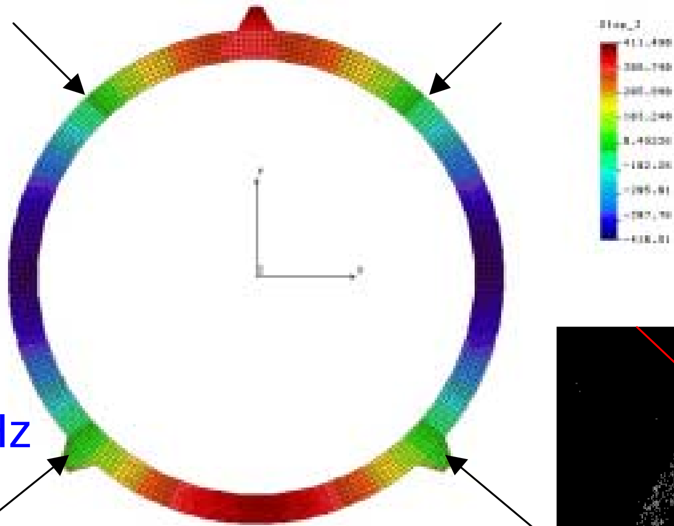
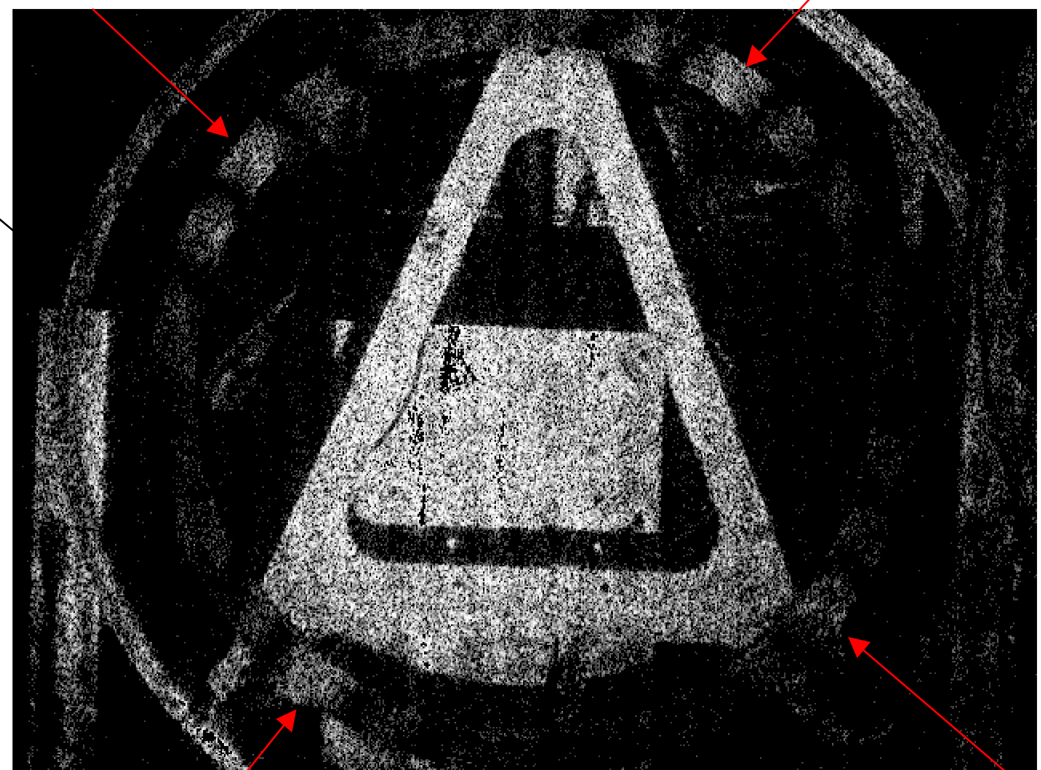
Ring Free-Free Vibration Tests



FEA
335.9 Hz

Four vibration nodes
(zero motion)

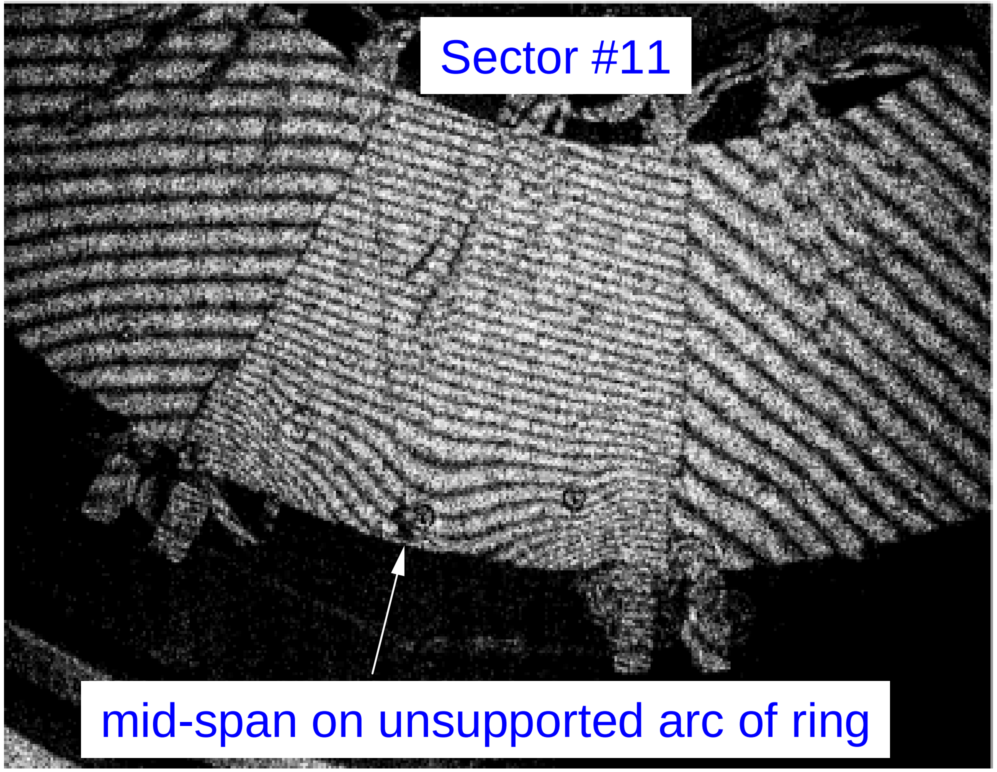
Experimental TVH results –352 Hz



nodes

Ability of Ring To Resist Loads

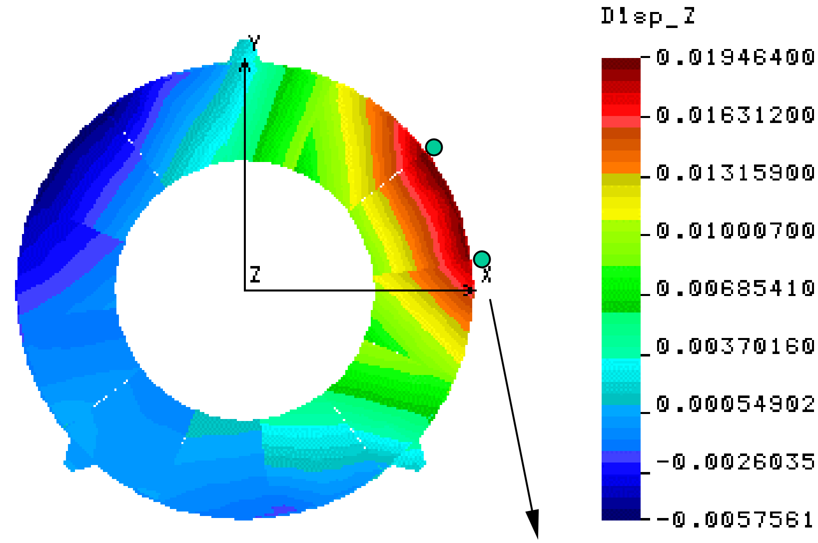
This image shows the deflection fringes for a 0.089 lb force applied to the sector with the manifold connections removed. The deflection measured from the center support out to the left tip is -6.52 microns. The deflection from the center support out to the right tip is -6.78 microns



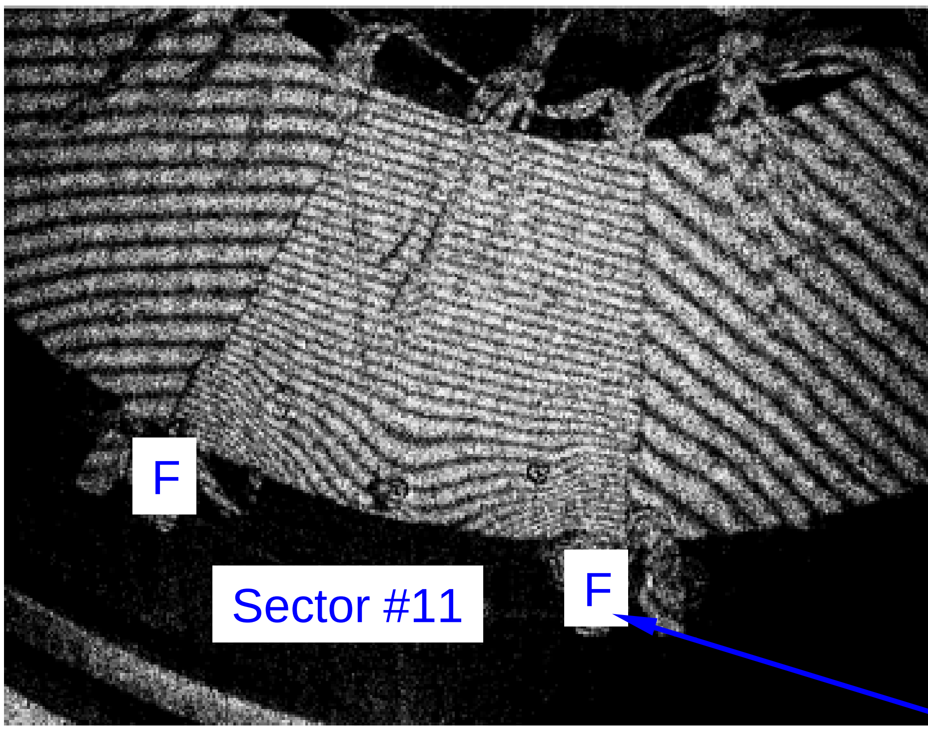
Sensitivity of sector tip motion is roughly 74.7μm/lbf (16.8 μm/N)

Comparison With Ring FEA

23.8µm/N tilt extracted from ring FEA. Note load was applied at mid-span on outer edge of ring, does not include the entire offset like in test (*<u>sector tilt is about 77.3% of that predicted by FEA</u>*)



Load points at edge of ring, 0.396N total



18.4µm/N tilt across the sector, <u>outside</u> edge to *inner* edge obtained by TVH

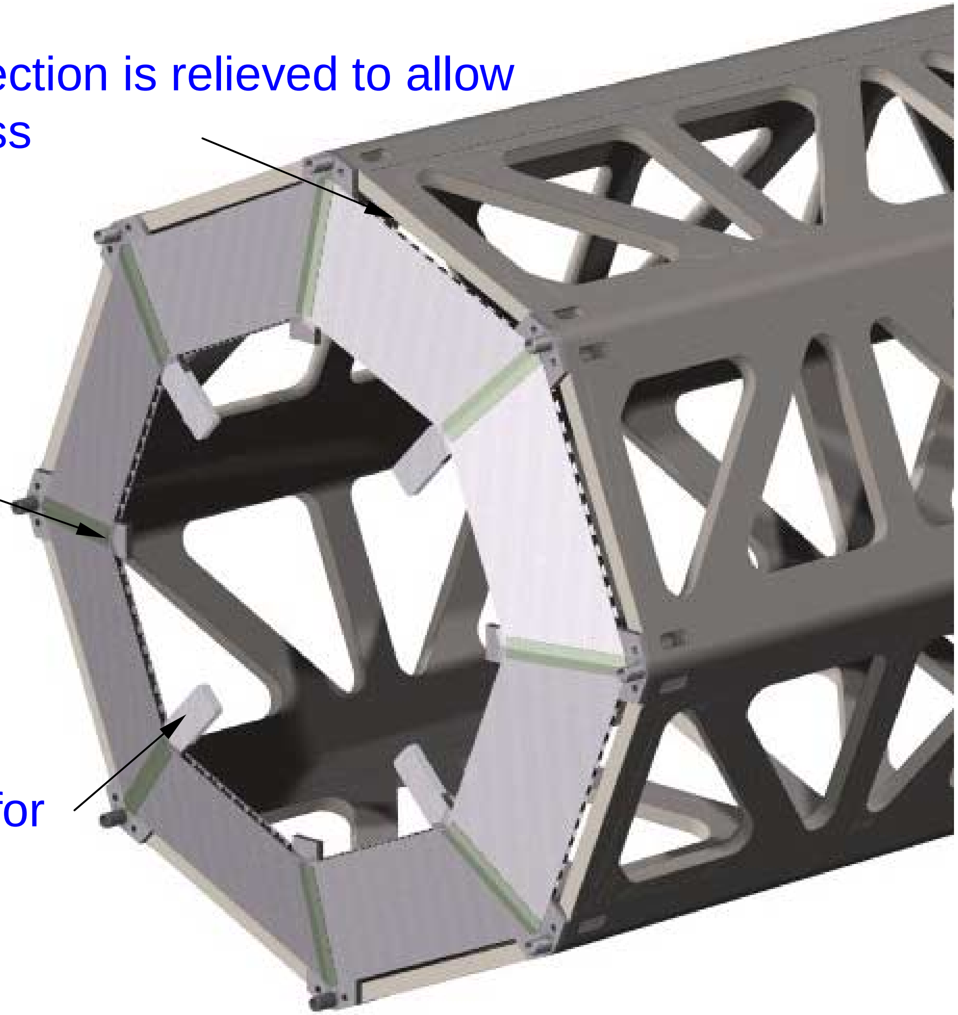
F-denotes area of load application in test

End Cone

End Cone Concept

End cone mounted on Outer Frame

Uses Flat Panel Geometry



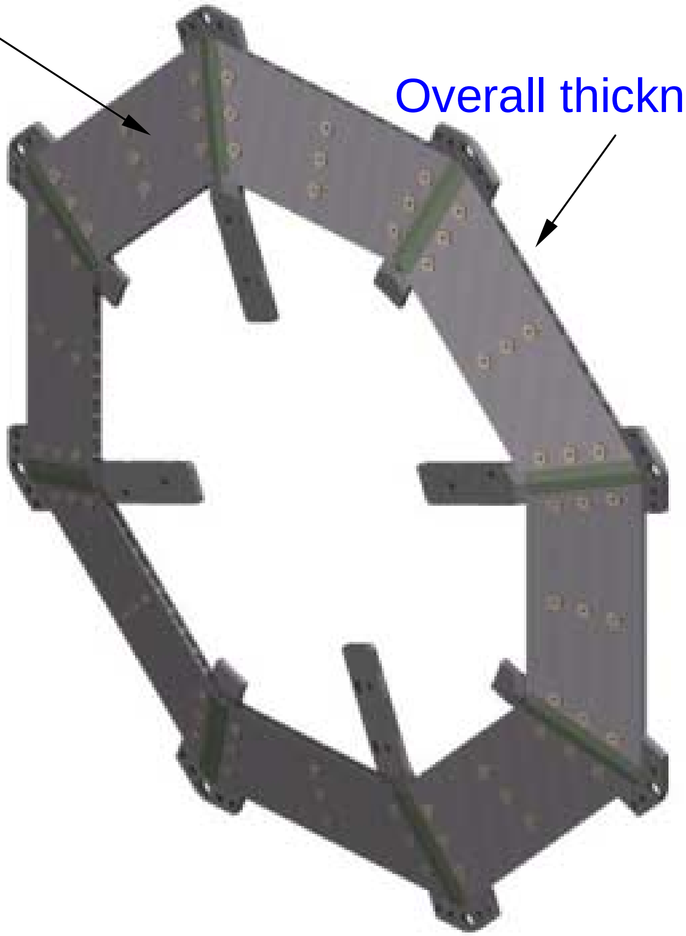
End Cone Prototype

Plans for End Cone Prototype

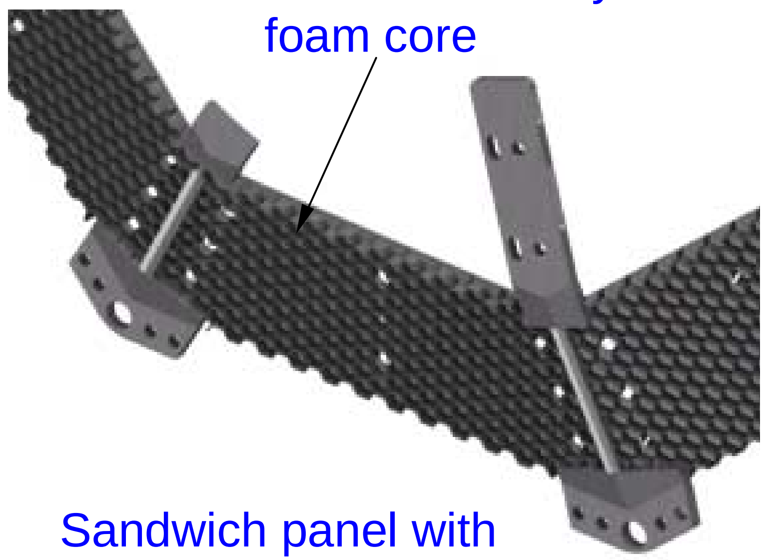
- Use original frame size
- Validate construction techniques

XN80GF/CE resin or C-C panels

Overall thickness 4mm



XN50 GF Honeycomb or carbon foam core



Sandwich panel with
low cost C-C facings
As replacement to
XN80 GF/CE

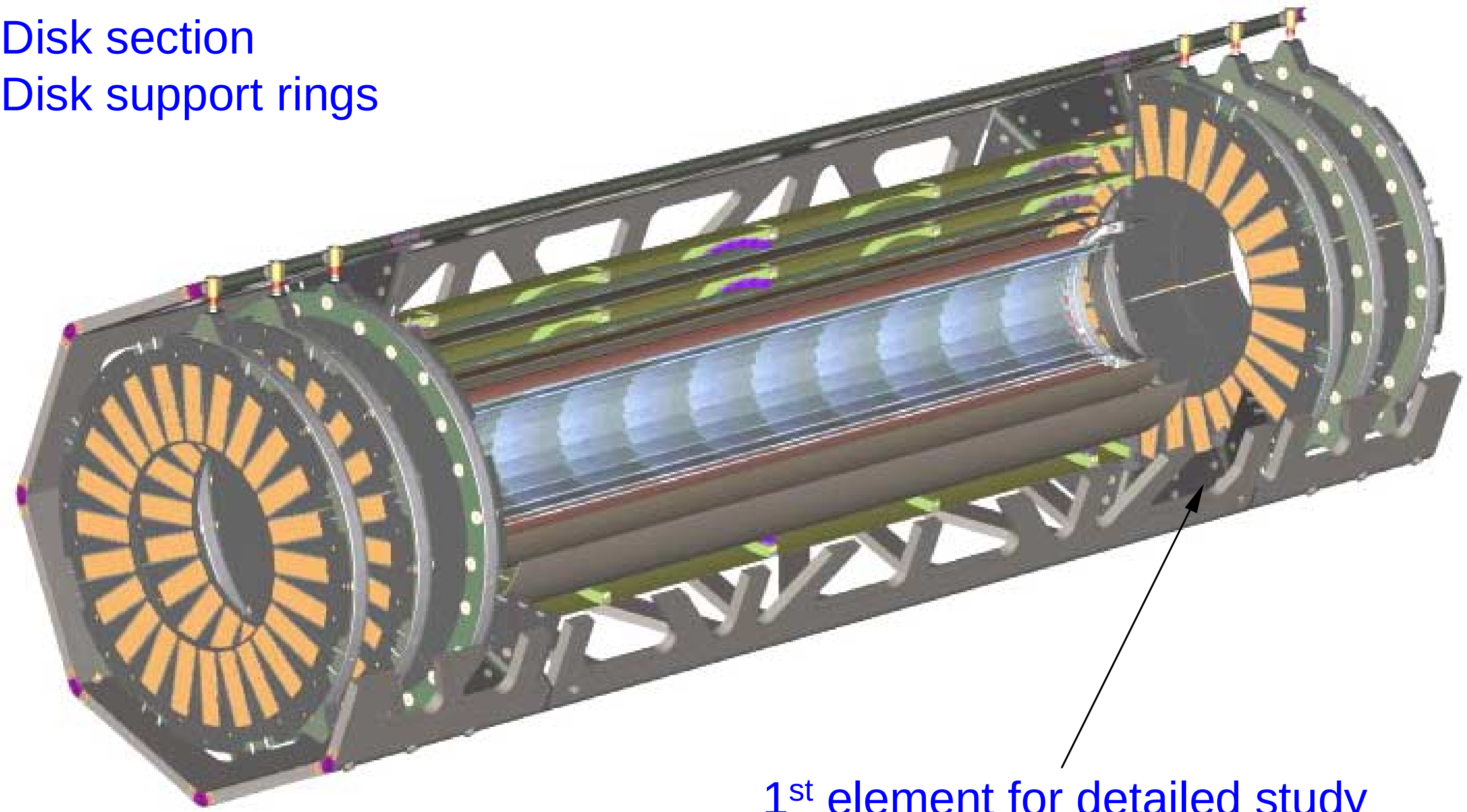
Global Supports Restructuring

Commencing with resizing of structural elements

End cone

Disk section

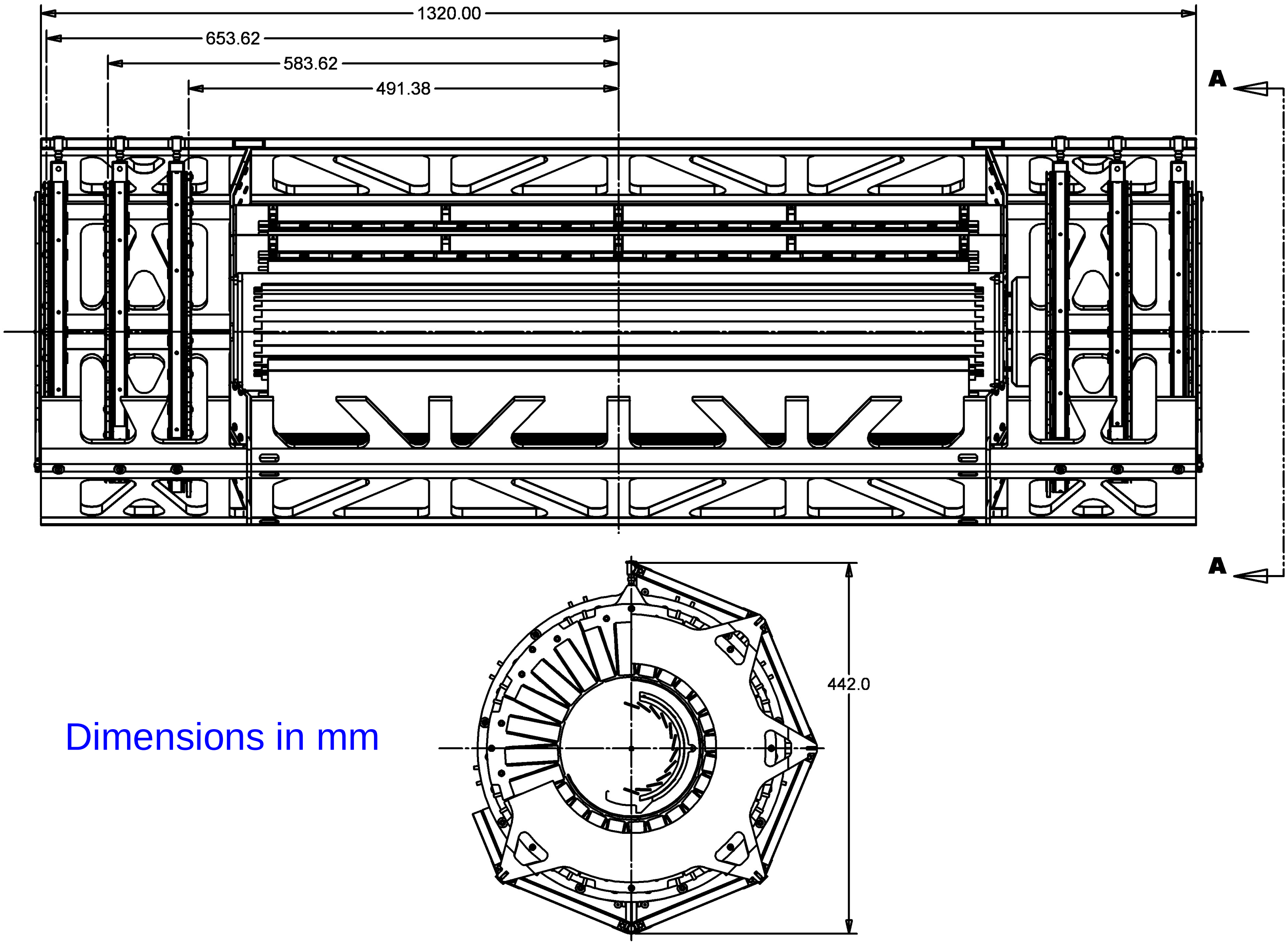
Disk support rings



1st element for detailed study

End Cone

Resized Structure



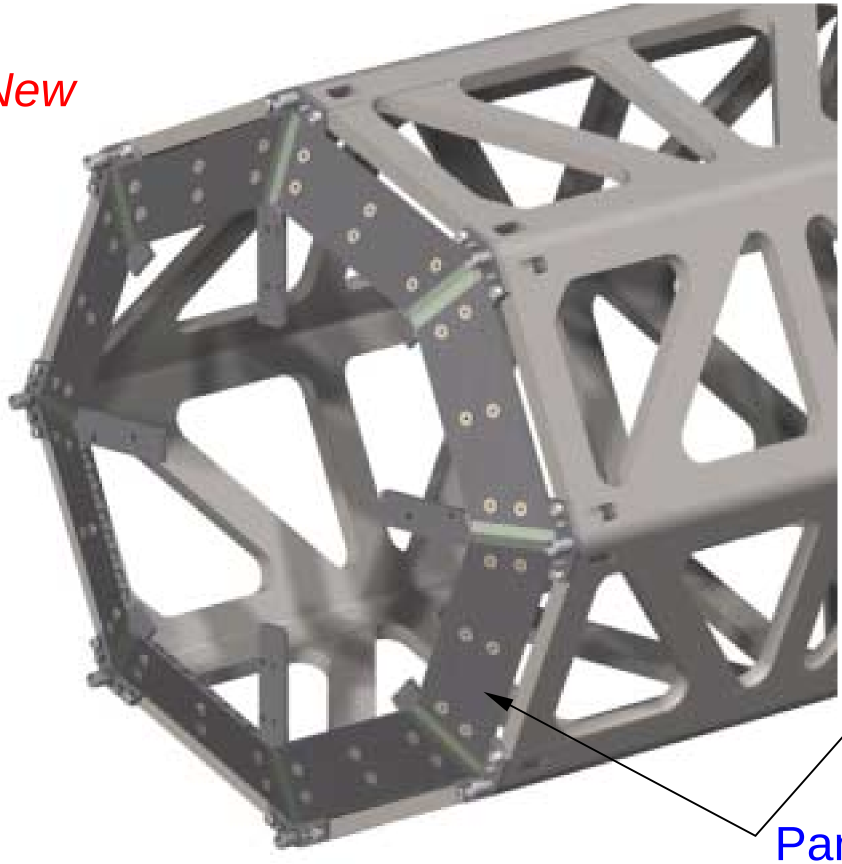
Dimensions in mm

Cone Size Restructured

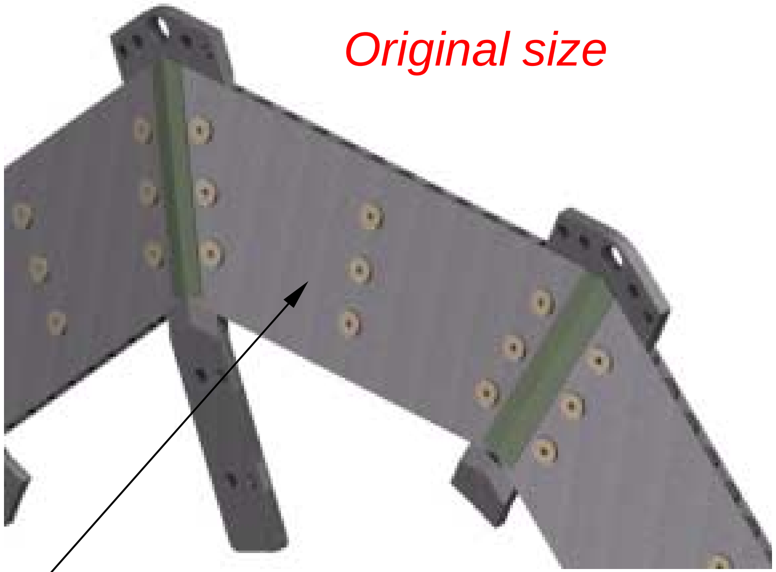
Next step FEA studies

Geometry to fit scaled down frame

New

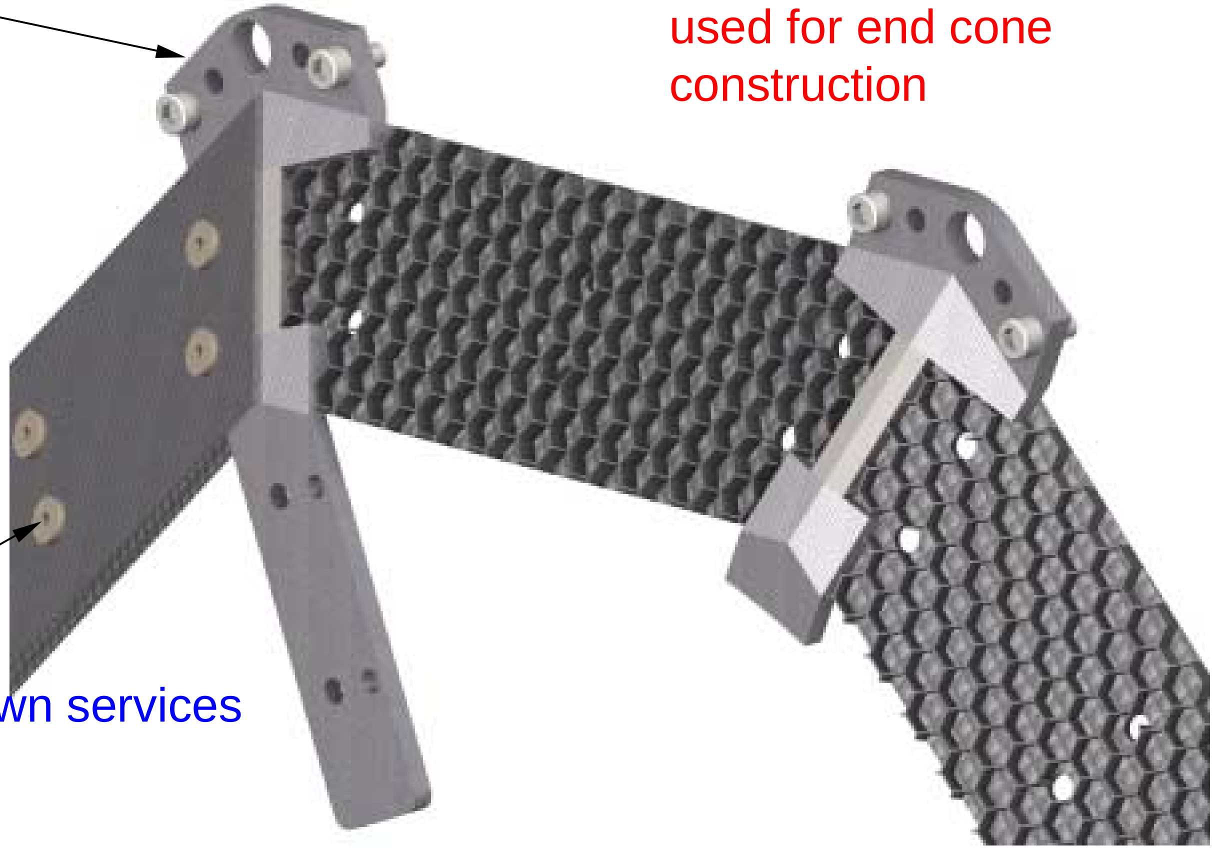


Original size



Panels are narrower and shorter

Cone Uses Honeycomb Core

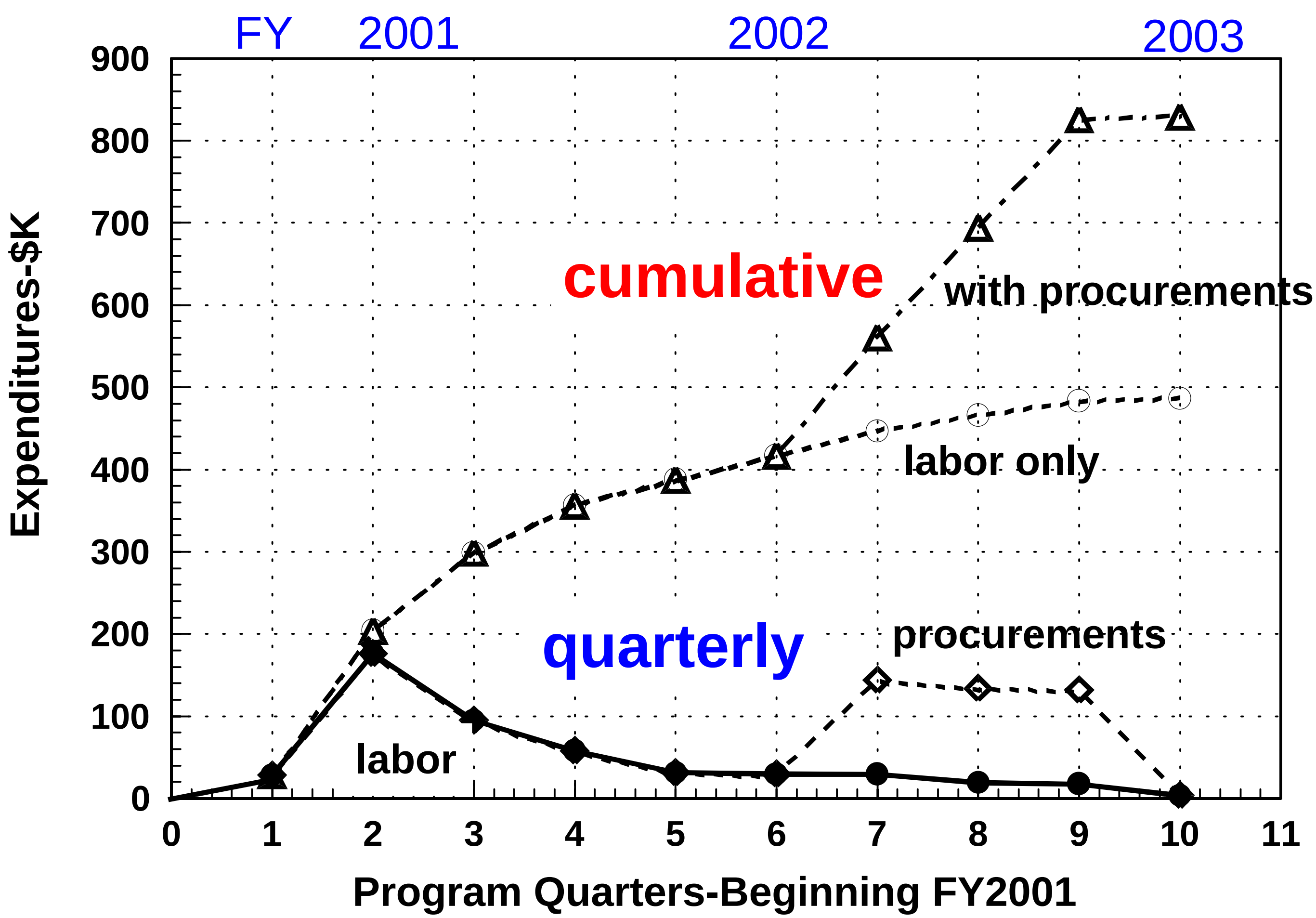


Summary Costs

Cost Summary

Item	Labor hours	Labor Cost $K	Fixed Cost $K	Total Cost $K
Support Frame and External Mounts				
Design Engineering	2818	$243.6	$7.5	$251.1
Production engineering	1346	$113.1	$5.0	$118.1
Global Support System Fab.	1202	$112.3	$117.7	$230.0
Total	**5366**	**$469.0**	**$130.2**	**$599.2**
Disk Support Ring and Mounts				
Design Engineering	460	$39.2	$0	$39.2
Production engineering	900	$73.4	$4.5	$77.9
Disk Support Rings and Mounts Fab.	947	$80.0	$33.3	$113.3
Total	**2307**	**$192.6**	**$37.8**	**$230.4**
Grand total	**7786**	**$661.6**	**$168**	**$829.6**

Engineering Expenditures



Plans

Approach to Mitigate Remaining Technical and Cost Issues

- Technical
  - Complete construction of prototypes and validate remaining design concepts in areas of:
    - End cone-*static stiffness*, using TVH methods
    - Disk/Frame assembly, composed of end cone, outer frame, disk and disk mounts, and end plate assembly
      - *Static and dynamic stiffness,* measurements using TVH
- Cost
  - Complete construction drawings and solicit final bid information
    - If necessary adopt refinements to construction details to stay within fabrication cost projections

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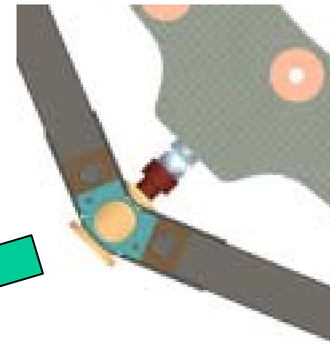
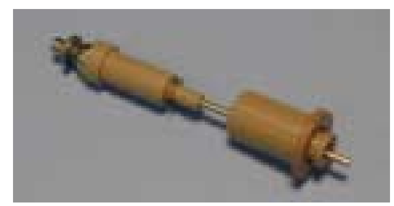
Approach To Design Confirmation

Objective is to test all design aspects together



Add fully assembled
disk with mounts



Add end plate

Add end cone

Risk Mitigation

Wiggle Room Within Present Design Approach

- Options Designed to Minimize Design Impacts—primarily due to reduction in radial dimension and length
  - Increase Disk Support Ring Stiffness
    - 4 radial supports in place of 3, stiffness increases inversely proportional to unsupported length cubed, $1/L^3$
    - It is important that we provide maximum radial depth in ring cross section
  - End Cone
    - Axial stiffness of a simple cone will increase with a reduction in r, inversely by r^2
    - However, stiffness of plate sandwich elements may decrease by a change in proportions necessitated by geometry changes
      - Thus, offsetting influence would be to increase core thickness, e.g., from 4mm to 6mm, with virtually no impact on material, with plate stiffness increasing as t^2, a 2.25 increase
  - Outer frame-bending stiffness decreases by r^3 (0.69), but stiffness increases inversely by reduction in L, by L^3 (1.65)
    - Optimistic that a small loss in frame stiffness can be regained decreasing the frame lightweighting , I.e., frame cut-outs
    - New FEA model to be generated and new proportions determined
    - *However, the method of inserting into and mounting to SCT is the big question mark*

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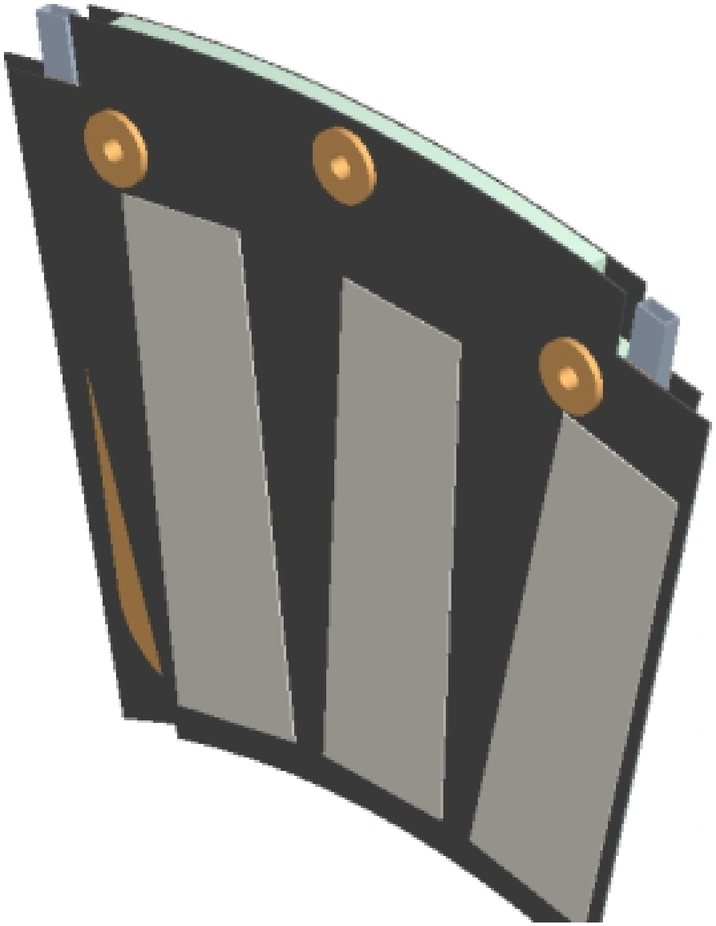
3D Model of LBNL Sector

W.O. Miller, R. Smith
HYTEC

Baseline Sector Model

Sector #8-Constructed 3D FE Model

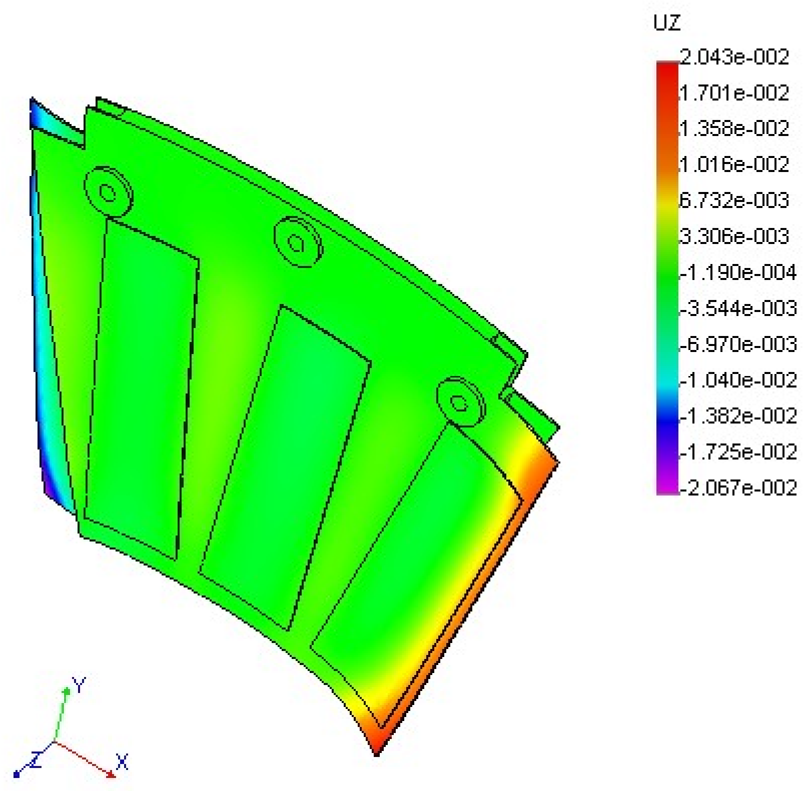
- Parameters
  - Al tube 2.31 by 4.64 mm by 0.29mm wall
  - P30 C-C facings, 0.4mm thick
  - 3D C-C brake material for sector bushings
  - 6 silicon strips 0.3mm thick
  - Carbon foam core, 2X normal density, achieved through CVD carbon process



Baseline Sector Model

First model without Aluminum cooling tube—*uniform temperature change*

- Provides measure of the effect of the tube
- ΔT=15.95°C, for a total edge distortion of 20.5µm
- Sensitivity of 1.28µm/ °C



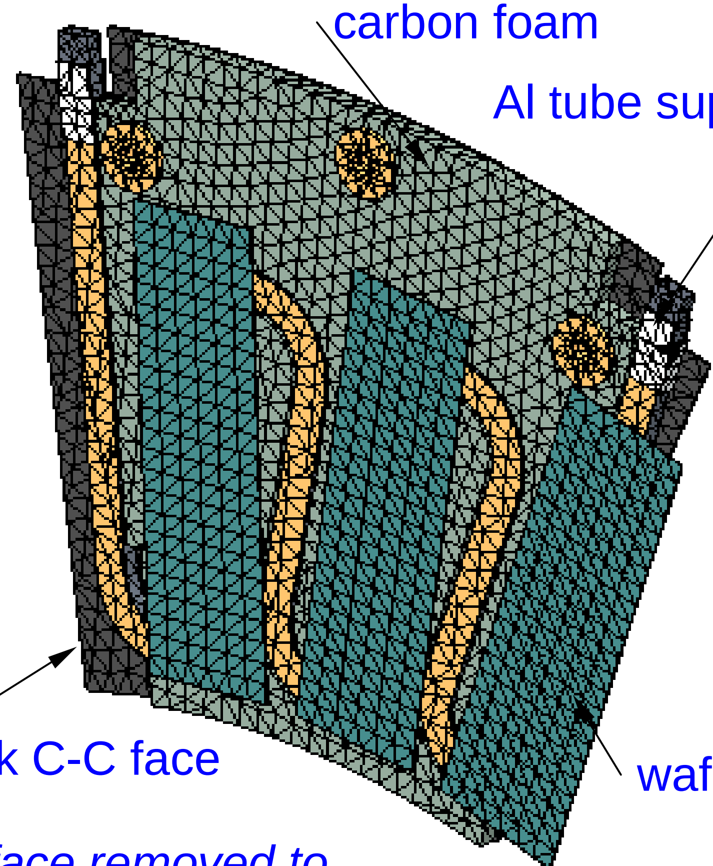
LBNL test with Smartscope provided 0.94µm/ °C

Units of displacement in mm

Baseline Sector Model

- Sector (*view-one face removed*)
  - Model simulates the outer and inner foam cores
  - Coupling of foam core is rigid to facings-presumption is rigid adhesive
  - Coupling of coolant tube to facing is via CGL7018, compliant adhesive
    - To achieve mesh the layer was increased from .075mm to 0.150mm
- Model consists of:
  - 36,559 parabolic tetrahedral elements and 59,676 nodes

With Al cooling tube and Al support connections



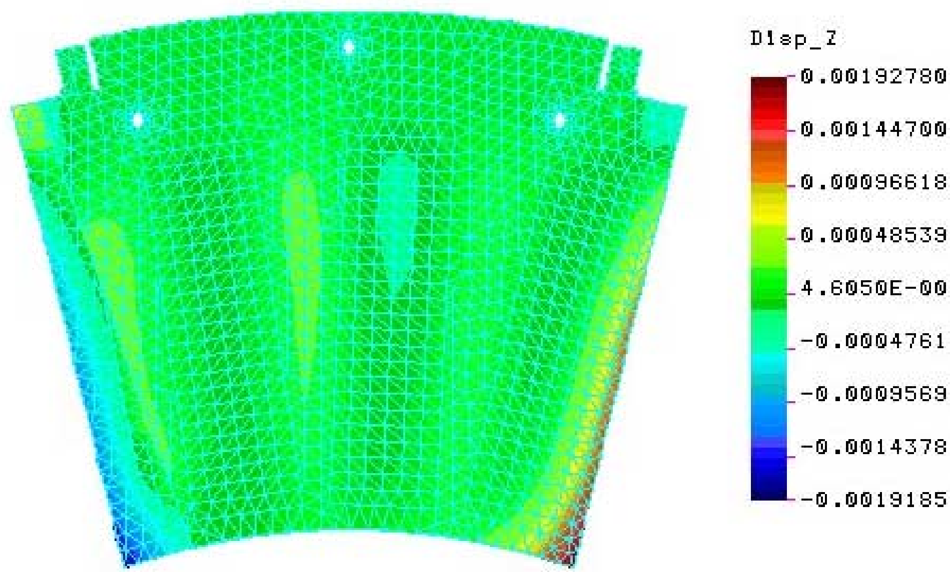
Front C-C face removed to show tube and tube supports

Sector Thermal Strains

Results for 15.95°C Delta T

- Boundary conditions-*fixed rigid at 3-support points*
    - LBNL sector mounted to rigid graphite fiber composite plate
- Peak deflections in the two extreme lower corners are nominally 19.1µm (1.2µm/ °C)
    - Corners curl in opposite directions
    - CGL7018 shear modulus used in FEA was .021N/mm^2 (3psi)
- CGL7018 shear modulus increased to 0.21N/mm^2, decreased the distortion to 16.3µm or 1.02µm/ °C
    - Comparative data from LBNL is 0.94µm/ °C

Units=mm

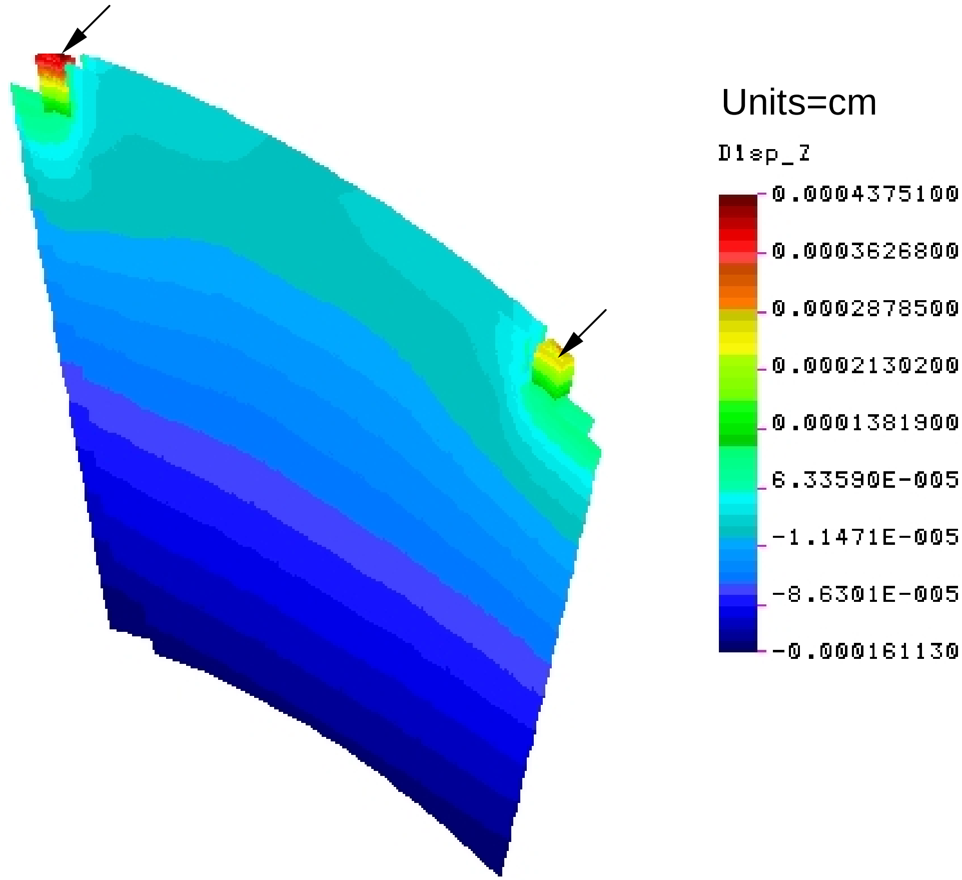


Z-normal to sector surface, positive direction toward observer

Sector Mechanical Strains

Reaction to Concentrated Forces at Coolant Tube

- Loading Condition
  - 1.113N(=113.4g=0.25 lbf) applied at each cooling tube
- Boundary condition
  - *3-support points held rigid*
- Result
  - Sector tips 1.6μm at tip (extreme corners)
- *Rigid boundary conditions at three support points believed to largely prevent tilt motion*
  - Further studies are planned



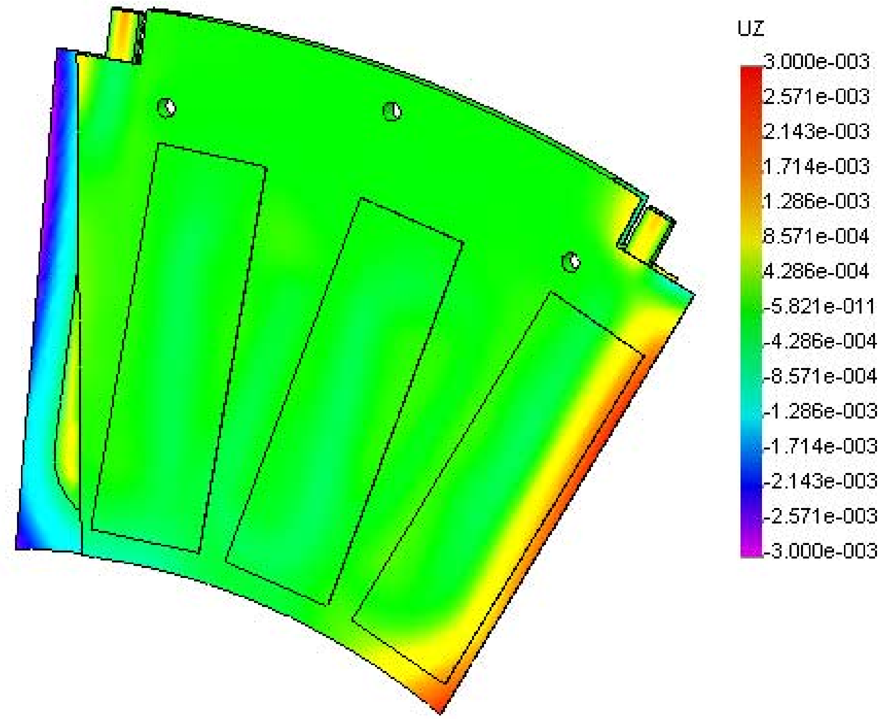
Z-normal to sector surface, positive direction toward observer

Sector Mechanical Strains

Response to 4 bar Coolant Pressure

- Loading condition
  - Internal tube pressure of 4 bar (~=60psi)
- Boundary condition
  - *3-support points held rigid*
- Results
  - Very little distortion throughout sector face
- Rigid boundary conditions probably have little effect in this solution

Units=mm



Z-normal to sector surface, positive direction toward observer

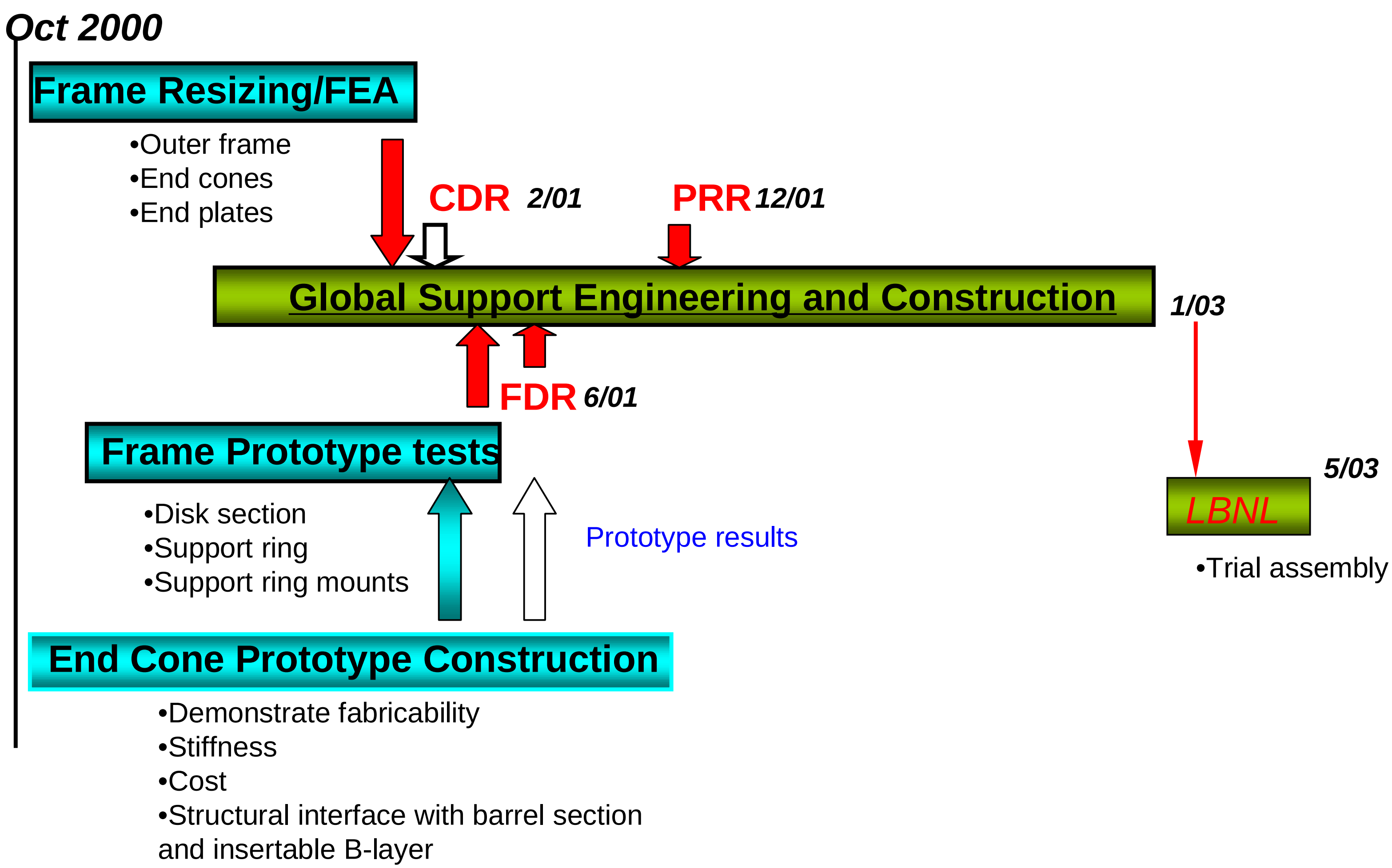
LBNL Sector FEA Studies

Investigate Stability Under Non-rigid Support

- Benefit of further FEA analysis
  - Modified model of sector and ring would evaluate static and dynamic stiffness of system
    - Thermal/mechanical---*preliminary model completed*
    - Pressure---*preliminary model completed*
    - Modal studies
  - Explore more detail the effect of varying CGL7018 shear properties on thermal distortion
    - Assess coupling of Al tube with sector facings---*preliminary model completed*
  - Heat transfer model
    - By demonstrating agreement with test data the result will add credence to the basic model---*preliminary model completed*
- *New studies to explore effect of changing boundary conditions-relaxing the 3-point rigid support*

Summary Schedule

Schedule Overview



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