Segmentation of Structures for Improved Thermal Stability and Mechanical Interchangeability

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Overview

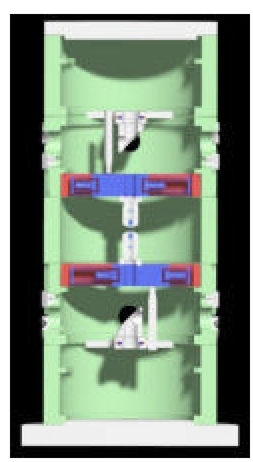
PROBLEM: Structural design and component packaging of conventional microscopes makes them inadequate for nanoscale observations.

Specifically, need improvements in:

1. Stability.
2. Flexibility.
3. Resolution.

SOLUTION: A symmetric, segmented structure:

- Tubular modules encourage uniform thermal expansion.
- Kinematic couplings between modules enable reassembly and reconfiguration with sub-micron repeatability.



HPM Project

The High Precision Microscope (HPM) Project seeks a new microscope for advanced biological experiments [1]:

- First use examining DNA strands during protein binding.
- Goal to improve:
  - Thermal stability.
  - Reconfigurability.
  - Design of optics, positioning actuators, and positioning stages.

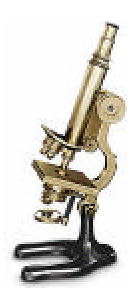
Work at MIT PERG during the past year to:

1. Design the HPM structure.
2. Test the structure's thermal stability and optimize through FEA.
3. Model kinematic coupling interchangeability.

Conventional Microscope Design

Designed for manual, one-sided clinical – not biological – examinations:

- Asymmetry of structures causes thermal tilt errors.
- Must be inverted and stacked for two-sided experiments.
- Difficult to switch optics, stages, etc.



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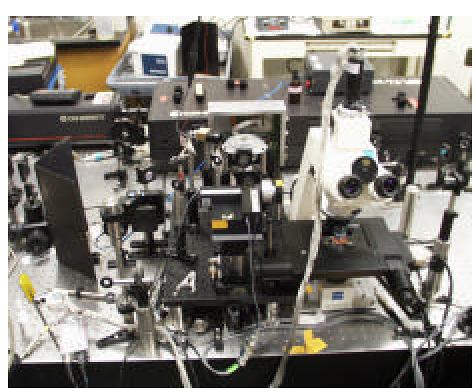
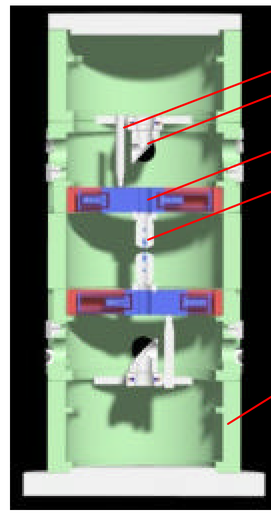
2000



Functional Requirements

1. Minimize structural sensitivity to thermal drift.
2. Support multiple optical paths.
3. Enable optics modules to be interchanged without recalibration.
4. Maintain stiffness close to that of a monolithic structure.

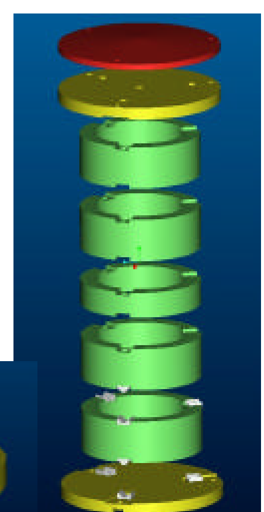
? In the future, accommodate:
  - Picomotor/flexure drives for the optics.
  - Multi-axis flexure stage for sample.

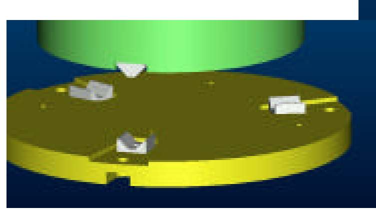


Segmented Structure Design

A modular tubular structure with kinematic couplings as interconnects*:

- Gaps constrain axial heat flow and relieve thermal stresses.
- Heat flows more circumferentially, making axial expansion of the stack more uniform.
- Canoe ball kinematic couplings give:
  - Little contact, high-stiffness.
  - Sliding freedom for uniform radial tube expansion.
  - Sub-micron repeatability for interchanging modules.



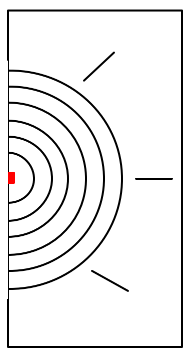


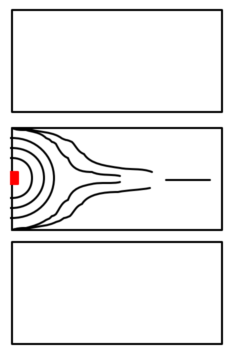
*Collaboration with Matt Sweetland

Heat Flow Theory

Locally apply heat to the midpoint of one side of a hollow tube:

- **Larger tube:**
  - Circular isotherms.
  - Uniform radial heat flow.
- **Shorter tube = axial constraint:**
  - Isotherms pushed circumferentially.
  - Gaps have negligible contact, high resistance.





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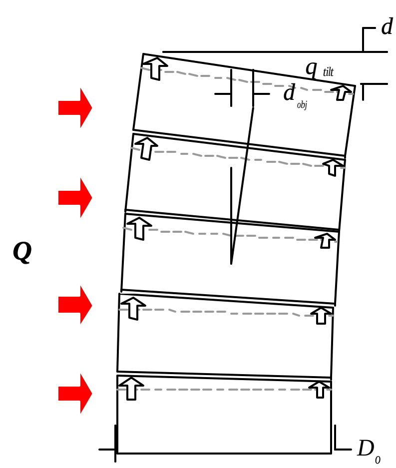
Thermal Expansion Theory

Circumferential temperature difference causes asymmetric axial growth [2]:

$$d = a_t L_o\left(\overline{T_h} - \overline{T_n}\right) = a_t \int_0^{L_o} \left(T_h(z) - T_n(z)\right) dz$$

$$q_{tilt} = \tan^{-1}\left(\frac{d}{D_0}\right)$$

$$? \quad d_{obj} = L_s \frac{a_t L_o\left(\overline{T_h} - \overline{T_n}\right)}{D_o}$$



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Steady State Expansion Model

- Assume axially uniform temperature on each segment:

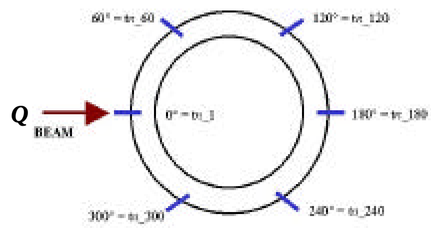
$$d_{obj} = a_t \left[\left(\sum_{i=1}^{5} L_i T_i \right)_{heated} - \left(\sum_{i=1}^{5} L_i T_i \right)_{nheated} \right]$$

- Material performance indices:

$$G_{ss} = \left(\frac{k}{a_t} \right) \qquad G_{tr} = \left(\frac{a}{a_t} \right)$$

k = Thermal conductivity
a = Thermal diffusivity
a_t = Coefficient of thermal expansion

Measurement Points:



Transient Expansion Model

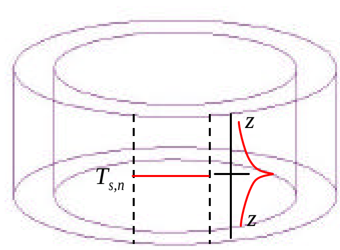
- Slice each segment into semi-infinite bodies [3], and project the axial heat flow:

$$T_{norm} = \frac{T(x,t) - T(t=0)}{\overline{T_{s,n}} - T(t=0)} = 1 - \text{erf}\left(\frac{z}{2\sqrt{a\,t}} \right)$$

- Moving average update of midpoint temperature of each slice [4]:

$$\overline{T_{s,n}} = \left(\frac{n-1}{n} \right) \overline{T_{s,n-1}} + \frac{T_{s,n}}{n}$$

? **Approaches a crude finite element method in 2D (*z*, q) + time.**



Finite Element Models

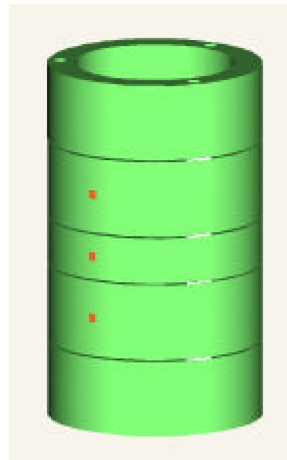
Sequential thermal and structural simulations (Pro/MECHANICA):

Thermal
- Couplings as 1” x 1” patches.
- Three 1W ½” x ½” heat sources.
- Uniform free convection loss on outside, *h* = 1.96.

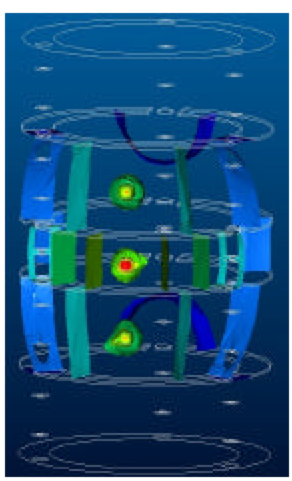
? Solved for steady-state temperature distribution.

Structural
- Specify steady-state temperatures as boundary condition.
- Constrain non-sliding DOF at bottom couplings.

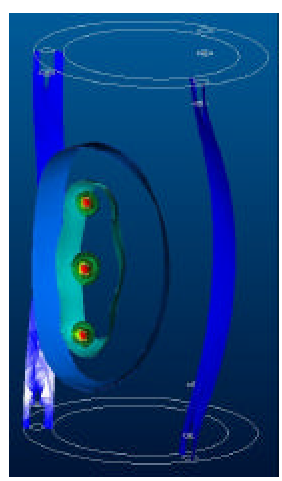
? Solved for steady-state deflections.



Simulated Isotherms

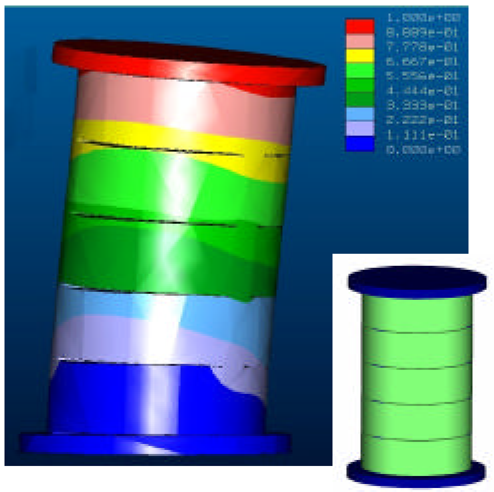


Segmented



One-Piece

Resonant Behavior



Segmented: $w_{n,1}$ = 356 Hz

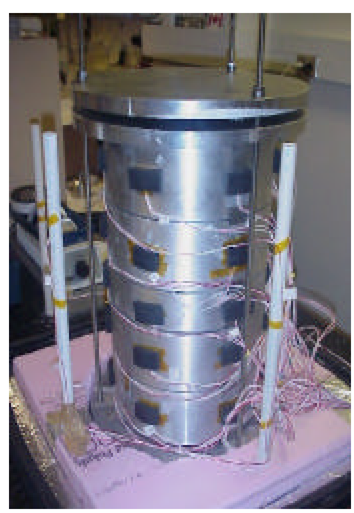
One-Piece: $w_{n,1}$ = 253 Hz

29% Reduction

Experiments

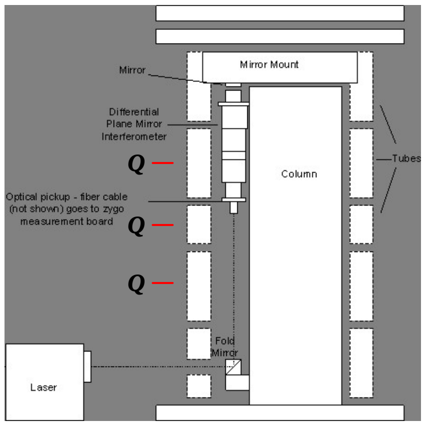
Measured tilt under controlled boundary conditions for 8-hour durations*:

- Tube structure mounted between two plates and preloaded with threaded rods.
- Isolated from vibration on optics table.
- Isolated from thermal air currents using 4”-wall thickness foam chamber.
- 54 3-wire platinum RTD’s; 0.008^o C (16-bit) resolution; +/- 1.5^o C relative accuracy.
- Tilt measured using Zygo differential plane mirror interferometer (DPMI); 0.06 arcsec resolution = 72 nm drift of the objective.
- Three 1W disturbances to stack side by direct contact of copper thin-film sources.

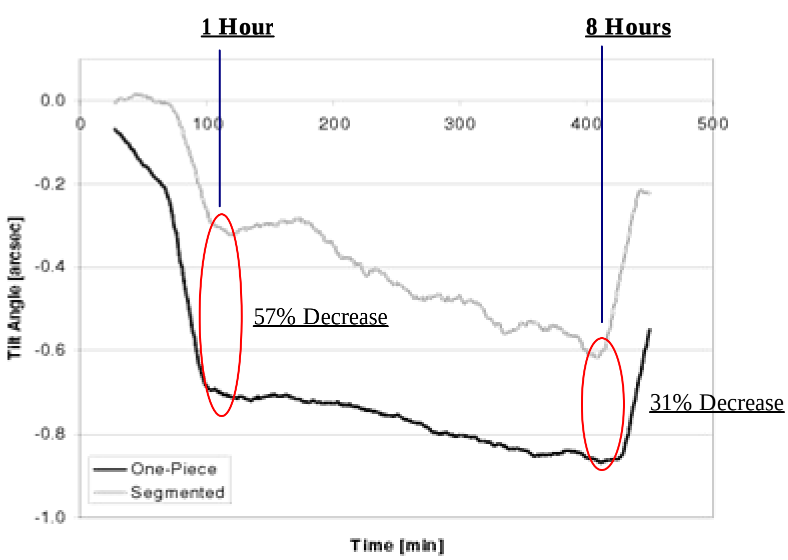


*Fabrication and measurement help from Philip Loiselle.

Experiments

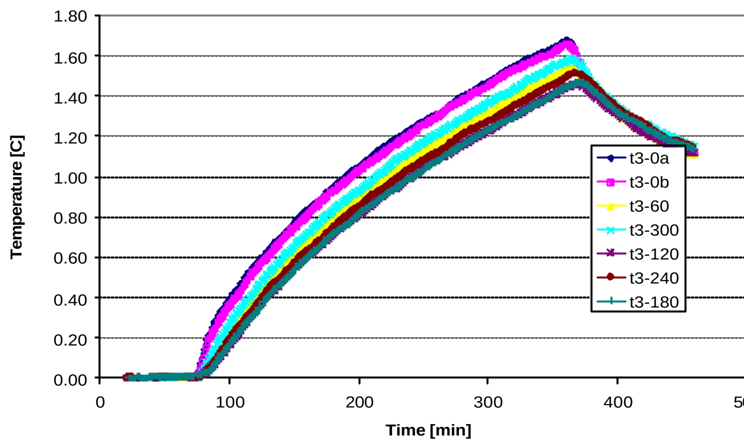


Tilt Error - Experimental



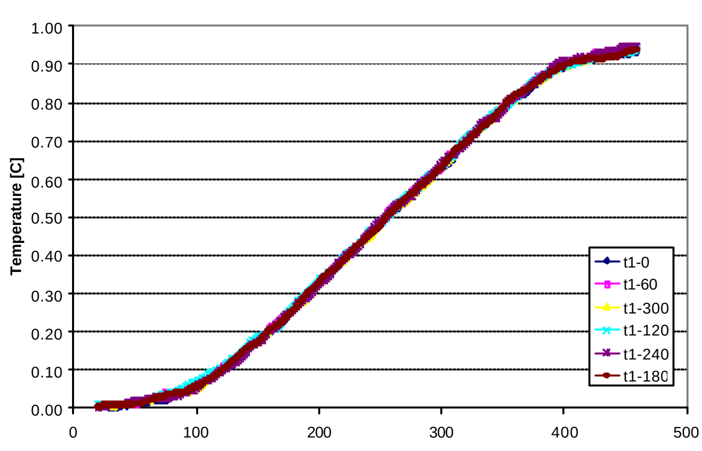
Circumferential Heat Flow

Heated segment:
- Near-perfect bulk heating after decay of ~20 minute transient
- ~1.60º C total increase.



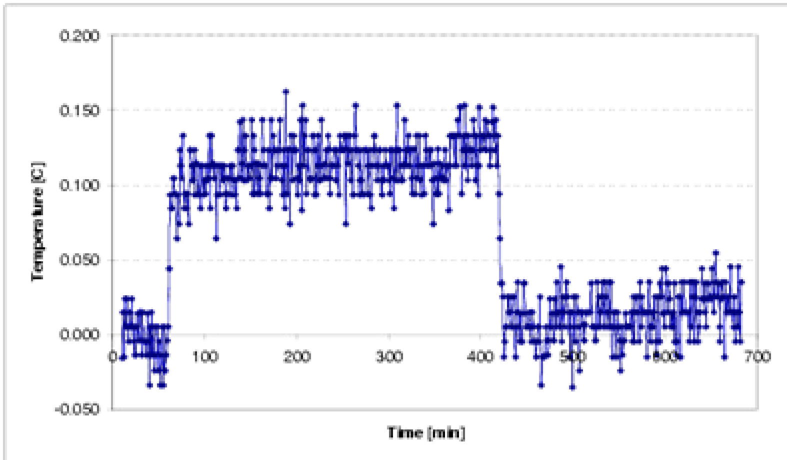
Circumferential Heat Flow

Non-heated segment:
- Near-perfect bulk heating.
- ~1.0º C total increase.



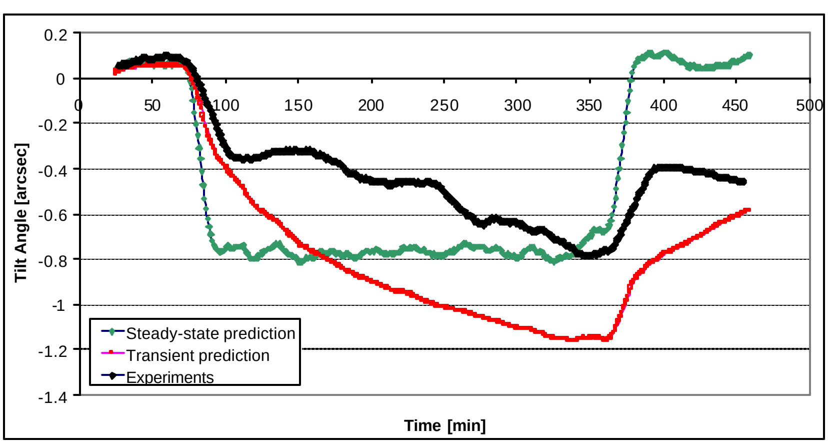
Circumferential Heat Flow

Center segment: difference between heated and opposite (180^{o}) points:



Analytical Model vs. Experiments

- Steady-state prediction is correct for final value.
- Transient prediction fits for first hour; diverges afterward.



FEA vs. Experiments

- = 0.03° C discrepancies.
- FEA tilt ~15% less than from experiments.

? **Ordinally sufficient for design iteration; discrepancies from:**
  - Uniform *h* loss.
  - Square contact modeling of couplings.
  - FEA is steady-state only.

Level (1 = bottom)	*DT* Segmented – Simulated	*DT* Segmented – Measured	*DT* One-Piece – Simulated	*DT* One-Piece – Measured
1	0.01	0.00 ± 0.01	0.07	0.06 ± 0.01
2	0.12	0.13 ± 0.02	0.12	0.09 ± 0.02
3	0.18	0.21 ± 0.03	0.12	0.12 ± 0.01
4	0.12	0.12 ± 0.02	0.12	0.09 ± 0.02
5	0.01	0.00 ± 0.01	0.07	0.06 ± 0.01

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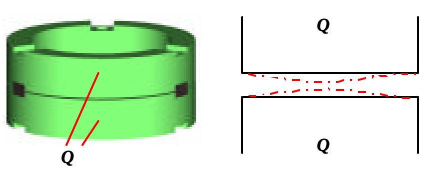
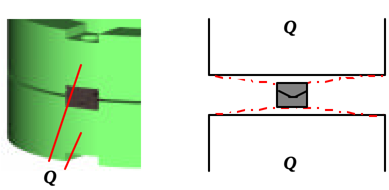
Source Placement

Sources aligned between couplings:
Thermal strain relief in the gaps.



Sources aligned along couplings:
Thermal strain transmission across the gaps.



<u>**Comparison (FEA):**</u>

	Tilt – point-to-point	Tilt – variance
Segmented – *Q* between couplings	0.46	0.026
Segmented – *Q* along couplings	0.58	0.026
One-piece	0.70	0.034

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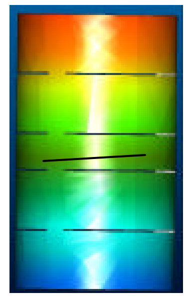
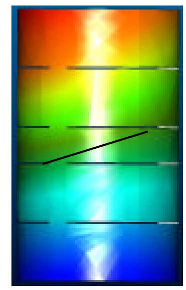
Material Optimization

Material	Tilt – (Normalized)
Aluminum (6061-T651)	1.00
Copper	**0.35**
Brass	1.40
Stainless (AISI 1040)	4.20



Copper
0.16 arcsec



Stainless
1.93 arcsec

Copper vs. Stainless = 92% improvement

Copper vs. Aluminum = 72% improvement

Dimensional Analysis

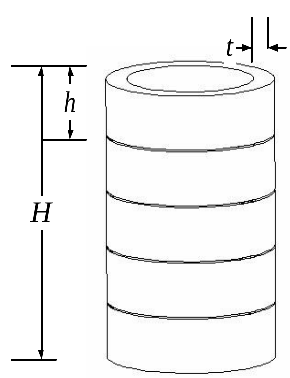
Geometry of segmented structure – material properties fixed:

1. Dimensionless temperature difference across single segment:

$$\frac{(\Delta T)kD}{Q} = f\left(\frac{h}{t}\right)$$

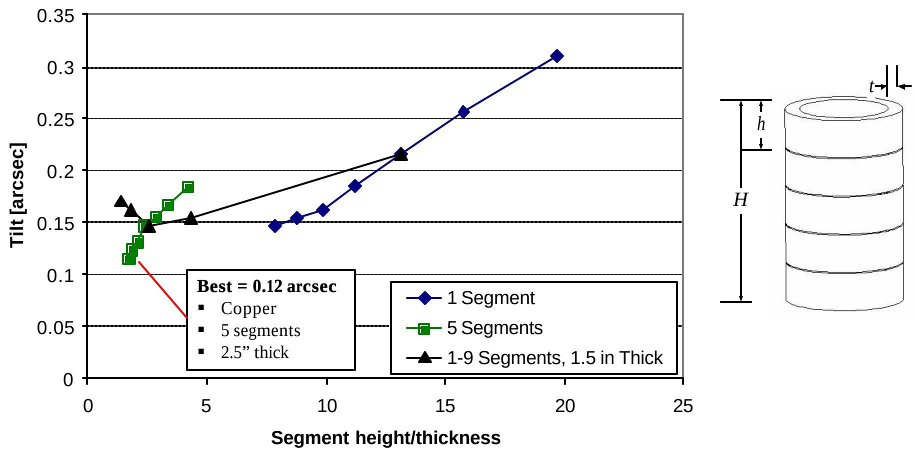
2. Error motion of the stack:

$$q_{tilt} = f\left(\frac{h}{t},\frac{h}{H}\right)$$



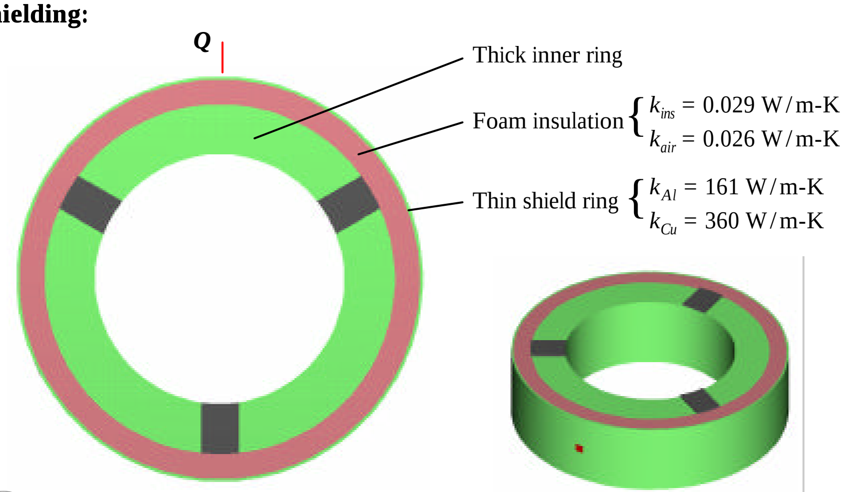
Geometry Optimization

Vary segment height (*h*) **and segment thickness** (*t*)**:**



Thermal Shielding

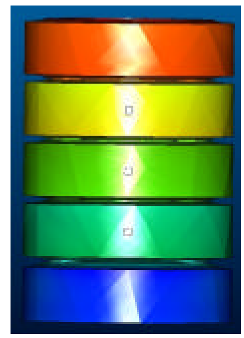
Isolate tubes using concentric outer rings of insulation and high conductivity shielding:



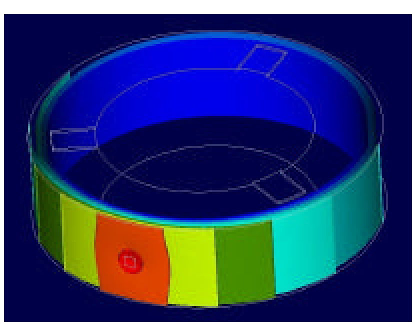
Shielding – FEA Results

Effect of shielding on tilt of a single segment: (Al inner only normalized to 1.00)

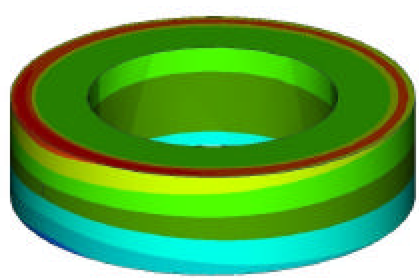
Design	**Tilt** [arcsec]: **No Insulation**	**Tilt** [arcsec]: **½” Insulation**	**Tilt** [arcsec]: **1” Insulation**
2” Al inner only	1.00	-	-
2” Cu inner only	**0.49**	-	-
2” Cu inner w/ no shield	-	0.36	0.27
2” Al inner w/ ? ” Al shield	-	0.38	0.33
2” Al inner w/ ? ” Cu shield	-	0.35	0.27
2” Cu inner w/ ? ” Cu shield	-	0.22	0.16
2” Cu inner w/ 1/16” Cu shield	-	0.19	**0.13**



Shielding – FEA Results



Temperature



Displacement

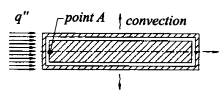
Cost vs. Performance

Must consider cost of segmentation + shielding, versus:

- Solid, shielded Al or Cu structure?
- Solid Invar structure (rolled plate)?
- Segmented Invar structure?

Tradeoffs:

- Functionality of segmentation – cost of couplings.
- Secondary machining costs – mounts for optics and stages.



Configuration	*Frame deformation due to temperature gradients [nm]*		
	x-axis	*y-axis*	*z-axis*
Aluminium frame with shielding	*5*	*5*	*15*
Aluminium frame without shielding	*100*	*100*	*300*
Invar frame with shielding	*2*	*2*	*7*
Invar frame without shielding	*45*	*45*	*135*

*Ruiji, Theo. Ultra Precision Coordinate Measuring Machine, Ph.D. Thesis, Eindhoven, The Netherlands, 2001, p.66.

Implications

Segmenting improves dynamic thermal accuracy and interchangeability:

- Best case drift = 144 nm at objective under 3x1W localized sources.
- Segmentation reduces tilt error:
  - 57% transient
  - 31% steady-state.
- Thin sheet shielding and/or insulation reduces tilt 3x-6x.
- Kinematic couplings give high gap resistance and enable precision modularity.

Next Steps:

- Improve transient analytical model.
- Transient design study and comparison to steady-state results.
- Study sensitivity to magnitude, intensity, and location of sources.
- Design, packaging and testing of flexure mounts.

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