Vertex Detector Mechanical R&D at Fermilab and the University of Washington

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Introduction

- Designs must:
  - Satisfy radiation length requirements
    - ~ 0.1% of a radiation length per layer
  - Ensure that sensor geometry is known and provides good stability of sensor positions
    - Goal is a vertex resolution < 5 μm in each coordinate
  - Allow reliable assembly
  - Ensure that connections for services and readout are made in such a way as to preserve sensor geometry
  - Take into account cooling requirements and sensor operating temperature.
- The Fermilab / University of Washington group has been most closely involved in designs for SiD and will show examples from that work.
- Ultimately, we want the best possible design for the vertex detector, so we have kept our minds open to all options.

Resources

- University of Washington (H. J. Lubatti, C. H. Daly, W. Kuykendall)
  - One physicist plus two engineers (all efforts part time)
  - Support from a precision machine shop for fabrication of tooling and parts
  - Support from the material properties and metrology group (M. E. Tuttle)
  - Expertise in finite element analysis, fabrication of thin support structures based upon unidirectional carbon fiber, and measurements of material properties
- Fermilab (W. Cooper, K. Krempetz)
  - One physicist plus one engineer (all efforts part time)
    - Prior contributions from an engineering associate (M. Hrycyk, now retired)
  - Technician, CMM, and facilities support from SiDet and Technical Centers
  - Expertise in analytic calculations, assembly of support structure components, handling and installation of silicon, and measurements of parts and assemblies
  - Participation in development of the design for the outer tracker and past experience in beryllium fabrication have been applied to integration of the vertex detector with other detector elements and the beam pipe.
- Interactions with and guidance from members of SiD and, more recently, LCFI and other international groups
- Good coordination with and support from beam delivery system and FCAL groups

Vertex Detector Mechanical R&D Meeting

- We participate in more global meetings approximately twice a month to discuss R&D and share results and resources.
  - Nine meetings since last May
  - Chaired by Joel Goldstein (University of Bristol, LCFI) and Bill Cooper (Fermilab)
  - Agendas: http://ilcagenda.linearcollider.org/categoryDisplay.py?categId=27
  - Mailing list: ILC-VXD-Mechanics@listserv.fnal.gov
  - Meetings are normally held on Tuesday at 11:00 AM Fermilab time
  - Approximately every third meeting is intended to be held at a time more convenient for the Asian community.
- Participation from each region
- The list of issues is certainly incomplete and needs to be tuned.
- People have been invited to suggest changes in the list and to sign up to investigate specific issues:
  - Sensor properties
  - Sensor handling
  - Power
  - Controls, I/O, and cabling
  - B-field
  - Noise, pick-up, shielding
  - Geometry, support, and cooling
  - Installation, servicing, and beam pipe
  - Technology dependencies

Mechanical R&D Categories

- Development of concepts (foundation for other R&D studies)
  - Geometries for sensor arrays
    - A short central barrel with disks at each end ← SiD baseline design
    - A longer central barrel with disks at each end
    - A longer central barrel with no disks
    - For each of these approaches, the number of barrel layers, layer radii, and the length of each barrel layer can be optimized.
    - For approaches with disks, the Z-position and radius of each disk can be optimized for hermeticity and to match the vertex detector to outer tracking and forward calorimetry.
    - Minimum radius is set by machine backgrounds and magnetic field strength.
  - Cooling
    - So far, satisfying the material budget appears to require dry gas cooling
  - Overall mechanical support
- Studies to understand the details for implementing particular concepts.
  - Properties of materials
  - Details of cabling and services
  - Implications of sensor options and requirements
- Fabrication, alignment, installation, and servicing
  - Beam pipe requirements
  - Integration with tracking, beam delivery, and forward calorimetry elements

Support Structures for Sensors

- We are investigating three approaches for barrels (should also be applicable to disks)
  - Direct mounting of sensors on a carbon fiber laminate support structure (SiD baseline)
    - Takes advantage of the greater beam-like stiffness of a curved structure
    - FEA and analytic calculations indicate that gravitational deflections are minimal.
    - Should provide reasonable stiffness against deformations from cabling
    - Thermal distortions are an issue unless ΔT is small.
      - That has led us to investigate material properties and CTE's.
    - With 50 μm silicon, the material budget should be satisfied on the average, but not locally, in a five-layer barrel.
    - In the cylindrical portion, foam could replace CF (single-sided LCFI ladders).
  - "All silicon" structure (sensors are the support structure of a barrel layer)
    - Takes advantage of the greater beam-like stiffness of a curved structure
    - FEA is in progress at the University of Washington and through LCFI institutions.
    - Deformations from cabling could be an issue.
    - Thermal distortions should be acceptable.
    - With 50 μm silicon, the material budget should be satisfied in a five-layer barrel.

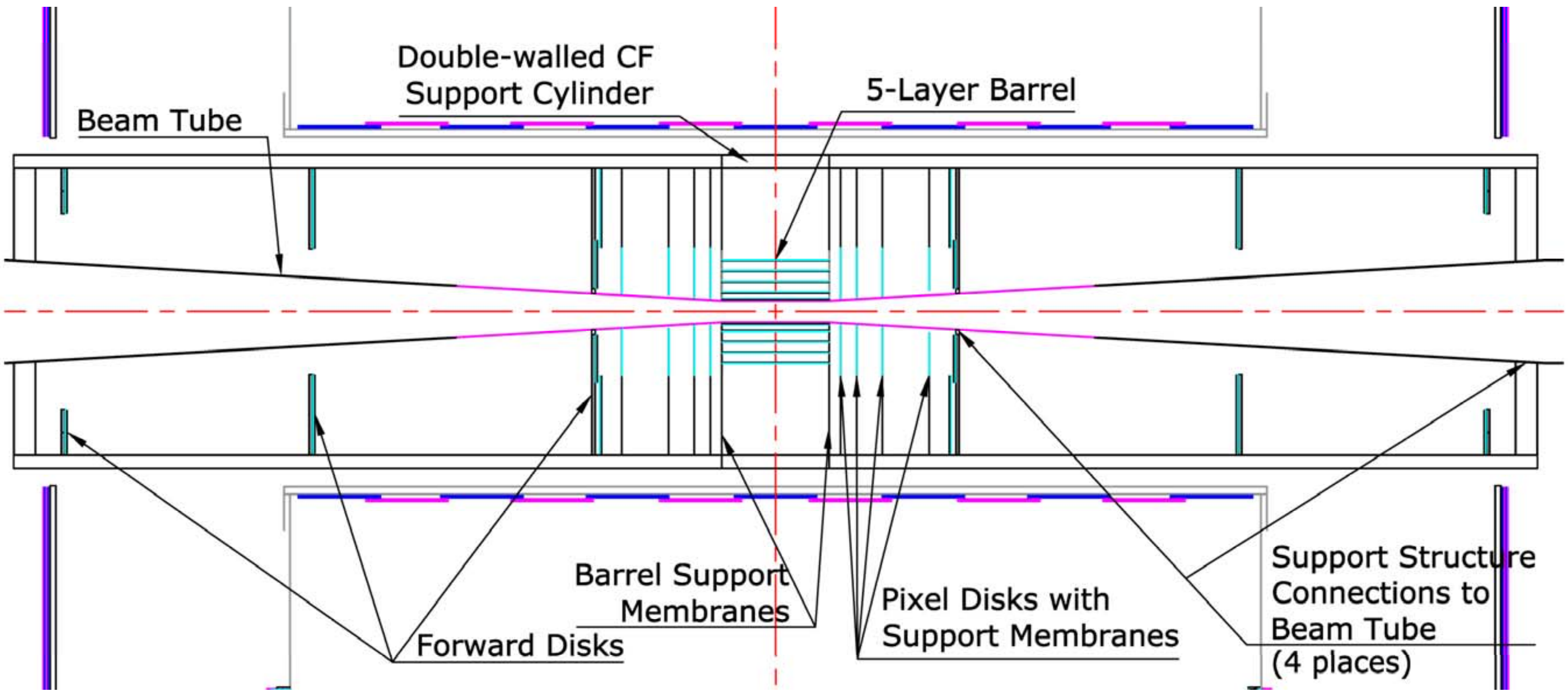
Support Structures for Sensors

- Silicon – foam – silicon "ladders"
  - Investigations were begun some time ago by LCFI, LBNL, and others.
  - Proposed for the GLD vertex detector
  - Our only contribution to this approach was a spreadsheet which suggested relationships between sensor thickness, foam thickness, gravitational deflections, and number of radiation lengths.
  - GLD FEA predicts minimal gravitational deflections for full-length sensors.
  - The material budget should be satisfied with 50 μm silicon provided both silicon layers are read out and the number of barrel layers is reduced accordingly.

- For each approach:
  - Fabrication techniques and tooling are likely to be key to success.
    - Flatness of sensors as received
    - Methods to control sensor flatness during assembly
    - Methods to apply adhesive in the desired pattern and with sufficient uniformity
  - Thermal distortions clearly depend on the required sensor operating temperature.
  - Structures for barrels should be applicable to disks.

SiD Vertex Detector Baseline Design

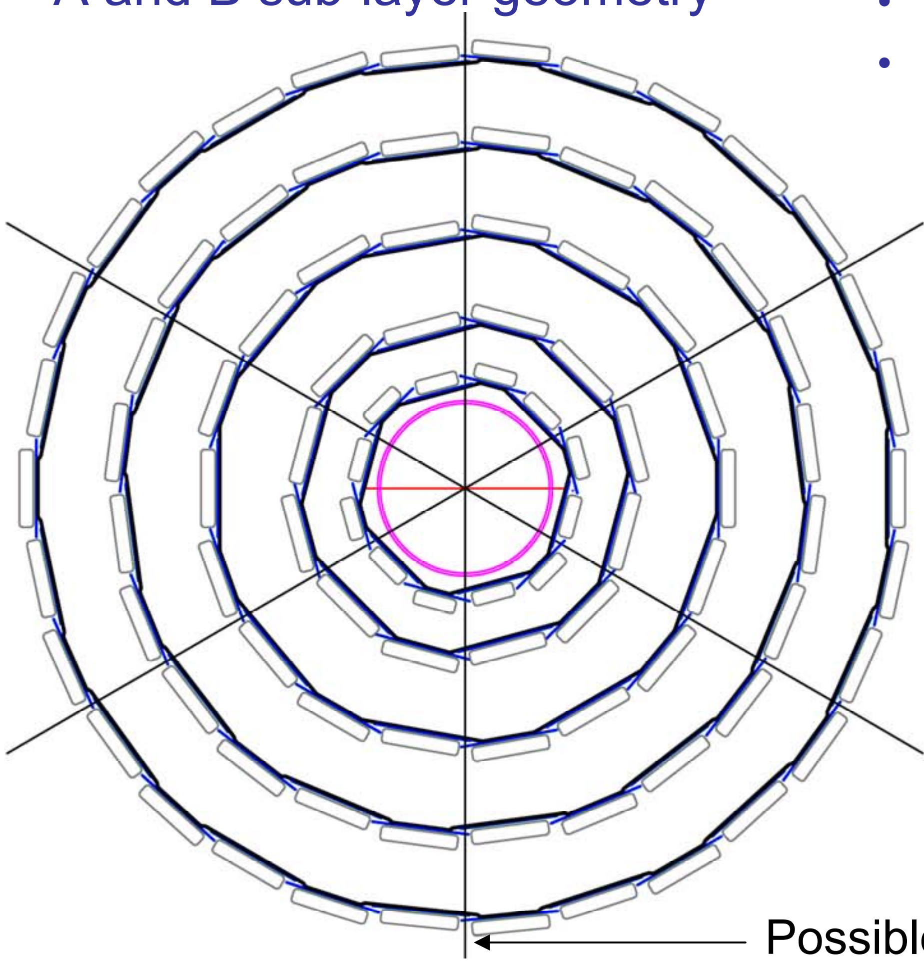
- The baseline design assumes a central, 5-layer barrel of length ~ 125 mm, four pixel disks at each end of the barrel, and three additional disks per end which extend coverage of the outer tracker.
- All elements are supported indirectly from the beam tube via double-walled, carbon fiber laminate half-cylinders with longitudinal ribs.



End View of SiD Baseline Design

- Basis for prototyping
- 2 types of sensors
- A and B sub-layer geometry

- 6-fold symmetry
- To reduce mass, barrel layers are glued to form a unit.
- Up to 15 sensors per unit
- Small variations in parameters with time



Sensors:
IR_A = 14, 22, 35, 47.6, 60 mm
IR_B = 15.15, 23.13, 35.89, 48.41, 60.77 mm
Active widths: 9.1, 13.3 mm
Cut widths: 9.6, 13.8 mm
Beam pipe IR: 12 mm
Beam pipe OR: 12.4 mm
March 3, 2006

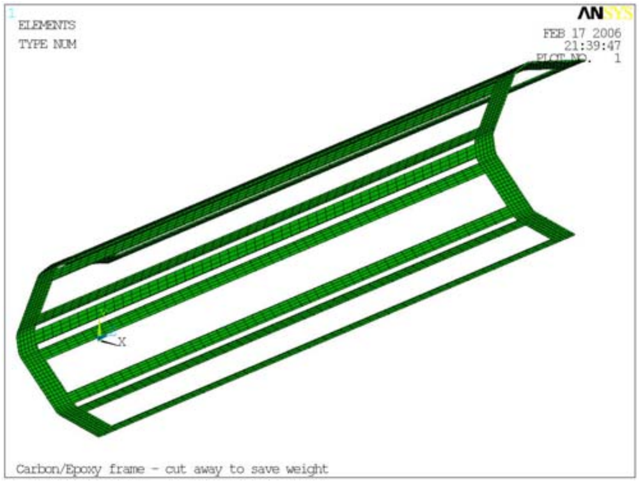
Oblong boxes are openings in end rings and end membranes for cables, optical fibers, and air flow.

Splitting into two halves allows assembly about the beam pipe.

Possible clam-shell split line

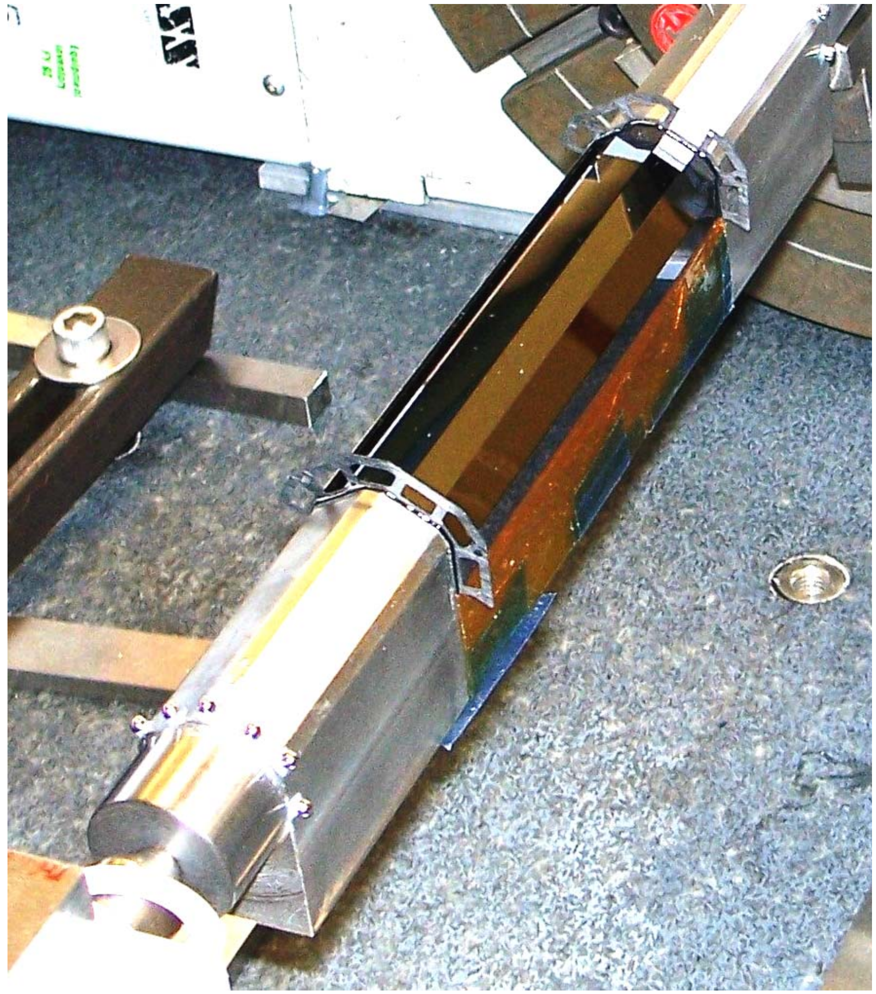
Layer 1 Prototypes

Mesh for Layer 1 finite element analysis (courtesy of the University of Washington)



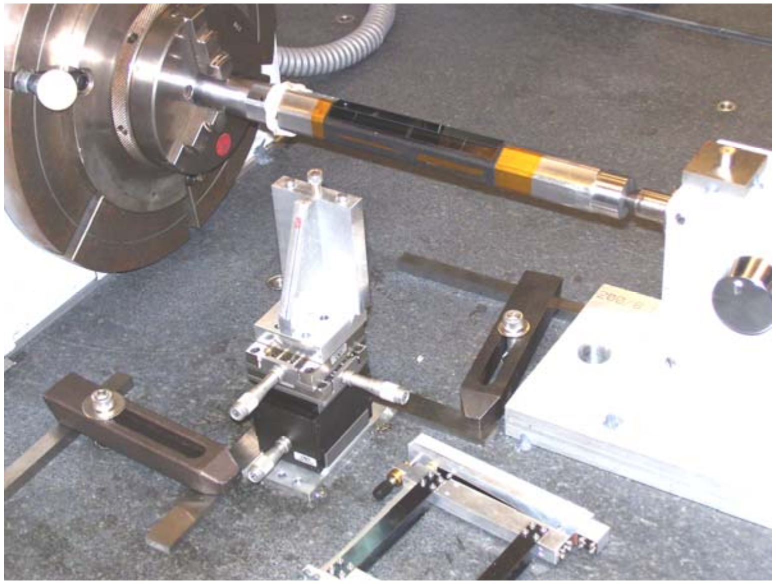
Layer 1 support structure with G-10, rather than carbon fiber, end rings

All CF structure populated with 75 μm thick silicon (CF cylinder and mandrel by UW, CF end rings and additional of silicon by Fermilab)



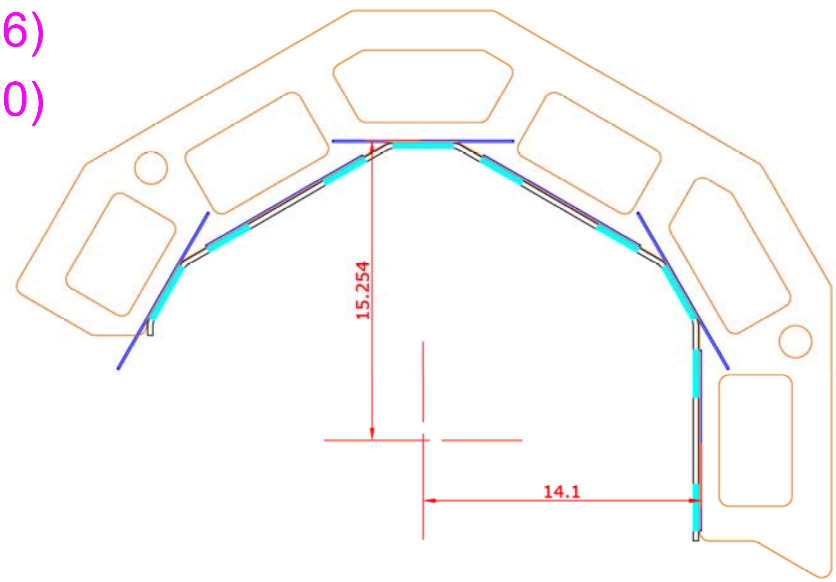
SiDet CMM Measurements of Layer 1 Structure

- 0.075 mm x 9.2 mm x 125 mm silicon
- Nominal epoxy thickness = 0.05 mm
- 4-ply CF laminate structure (0.26 mm)
- Vacuum puck held silicon flat during gluing.
- Sensors placed optically with structure orientation controlled by a Zeiss rotary table
- Measured at RT after completion with a “feather probe”
- On the exposed surface of each “sensor”, measurements were made at 3 transverse locations and 5 longitudinal locations (3 x 5 grid).
  - Total of 90 surface measurements per data set
  - Data analysis assumed:
    - All surfaces should have ideal spacings in azimuth and share a common centerline.
    - A single A-layer radius
    - A single B-layer radius



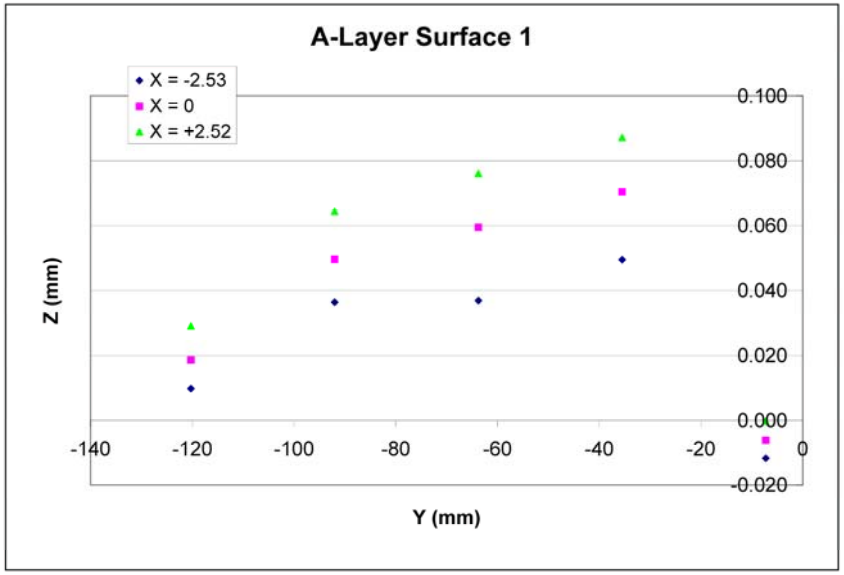
SiDet CMM Measurements of Layer 1 Structure

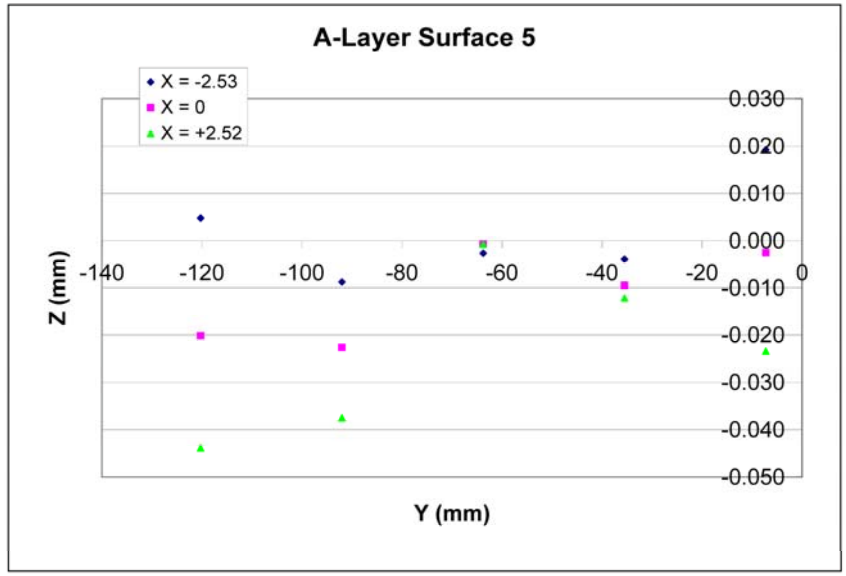
- Preliminary results based upon partial analysis of 4 sets of data
- Radii were expected to be slightly larger than nominal, since an 0.002” thick layer of kapton was used to prevent the CF from being glued to the mandrel.
- Fit radii:
  - R_A = 14.148 mm (expect 14.126)
  - R_B = 15.283 mm (expect 15.280)
- Standard deviations:
  - A-layer = 35 μm
  - B-layer = 16 μm
- Worst deviations:
  - A-layer = +87 / -54 μm
  - B-layer = +38 / -34 μm
- Some indications of twist in the A-layer
- Overhangs look OK in B-layer

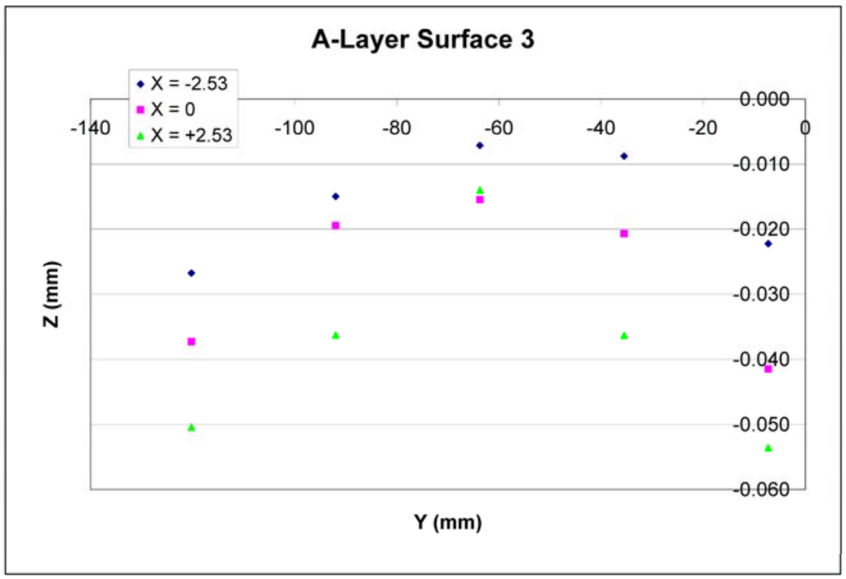


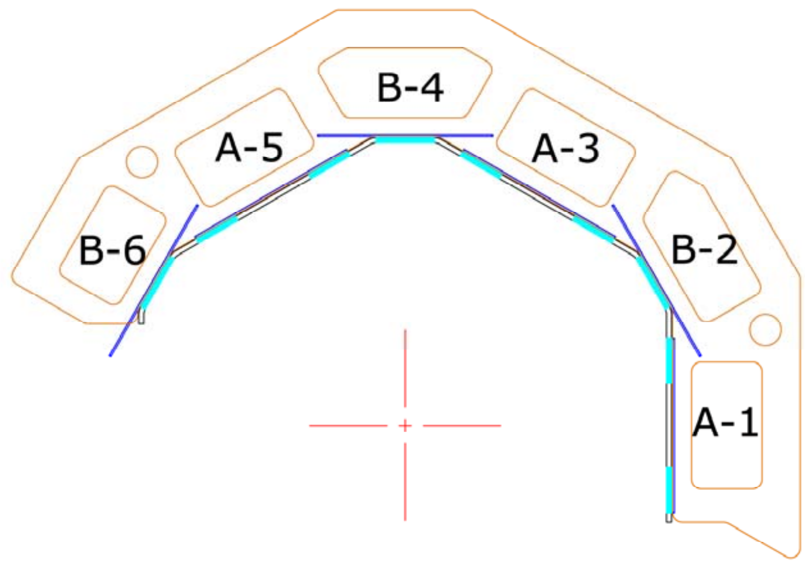
Radii above correspond to 100 μm silicon. Actual silicon thickness = 75 μm.

A-Layer Results

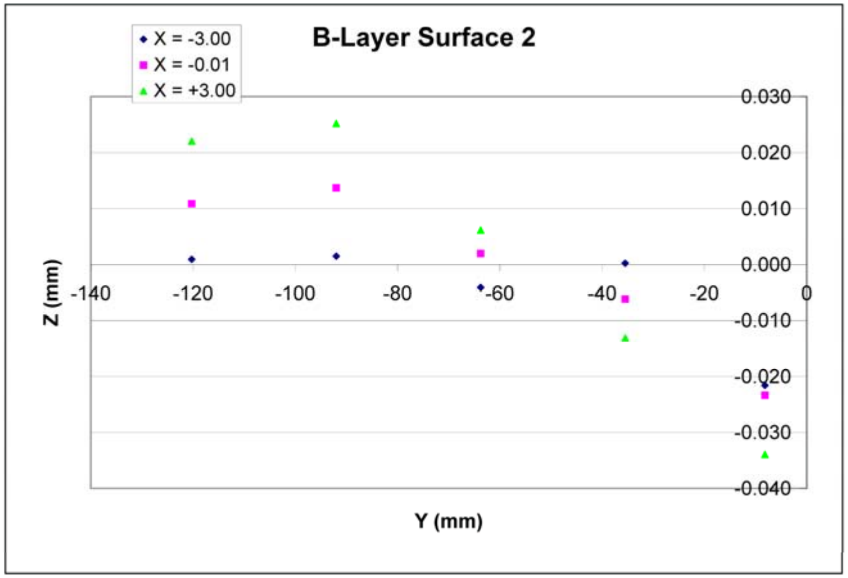


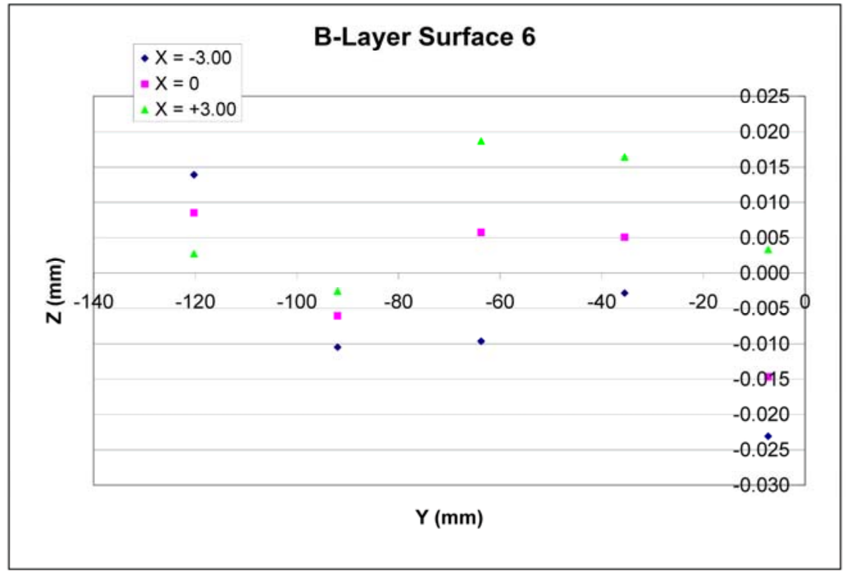


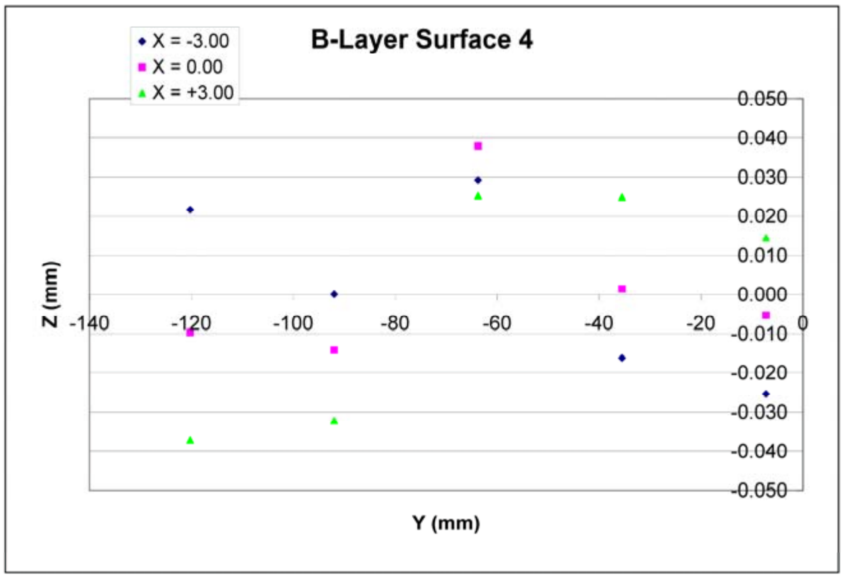


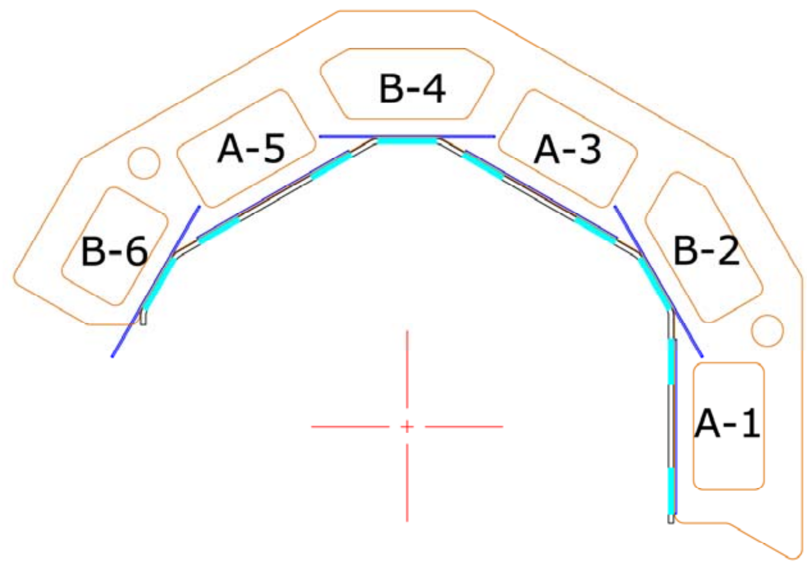


B-Layer Results



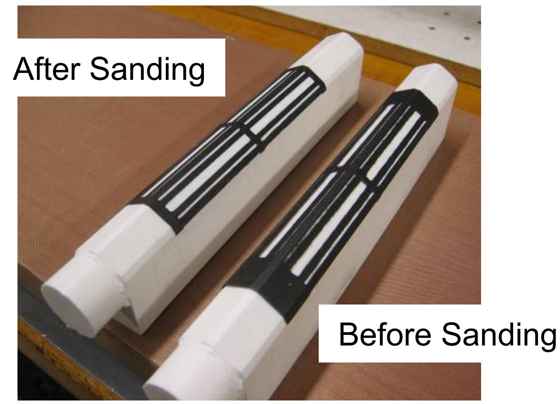






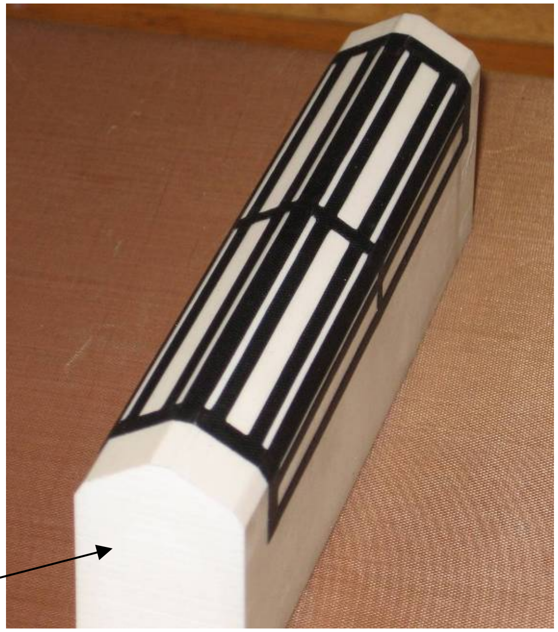
Layer 1 Prototype Support Structures (UW)

- Structures are made from carbon-fiber/epoxy composite.
- Fabrication techniques and mandrel design were developed for production of the prototypes.
  - Windows are hand cut from the flat, uncured material using an aluminum template.
  - After curing, the window edges are cleaned up with fine sandpaper.
  - The ends are left long to maintain structural integrity during removal from the mandrel and while sanding the window edges.
  - A belt sander is used for the final operation of cutting the ends to length.



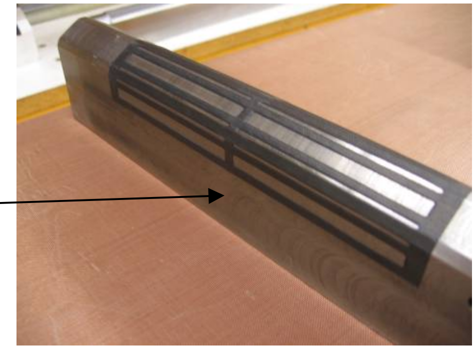
Layer 1 Prototype Support Structures

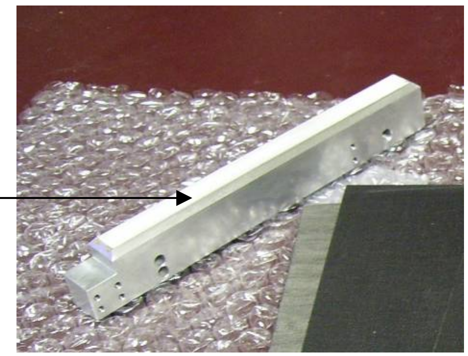
- Three structures made by UW from K13C2U material.
  - Fiber orientation is [0,90,90,0]. Thickness is 0.26mm
  - 3-ply, [0,90,0] parts will be made using new material. Thickness will be 0.16mm
- Parts are delicate but reasonably robust if handled properly.
- Each structure is shipped with a handling mandrel (polyurethane castings of the lay-up mandrel).

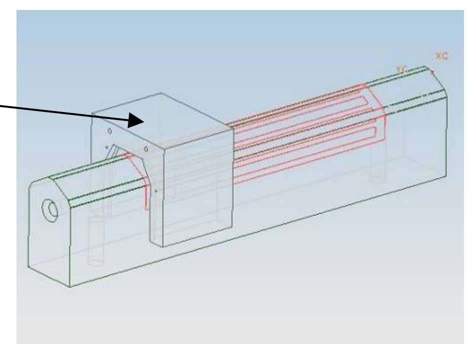


Tooling

- Two identical steel mandrels were CNC machined.
  - One mandrel is used in Seattle for carbon fiber lay-up.
  - The second mandrel is used at Fermilab as an assembly fixture, and for mounting silicon.
- A vacuum chuck with a porous ceramic surface was fabricated. The chuck will was used to install silicon on the Layer 1 prototype.
- Fixtures (2) for positioning of the end-rings during glue-up to support structure were machined. Fixtures are also used as support structure thickness gauges.

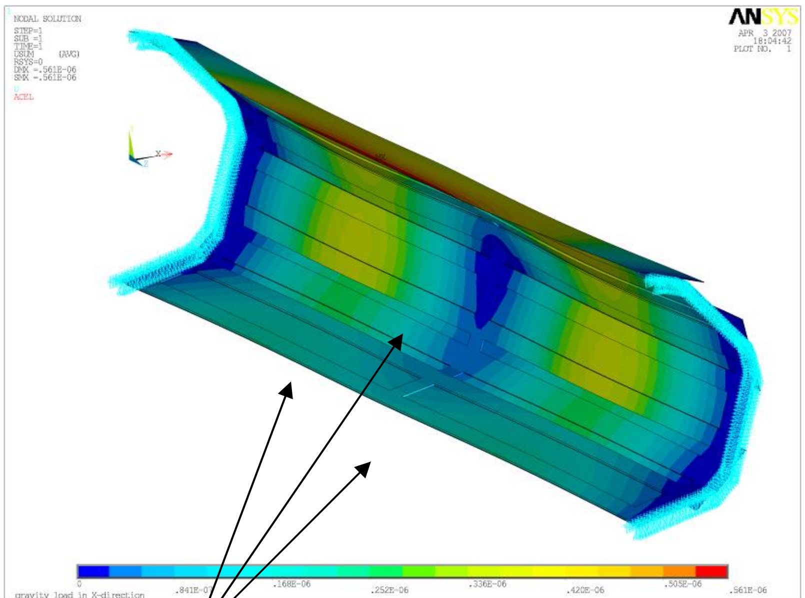




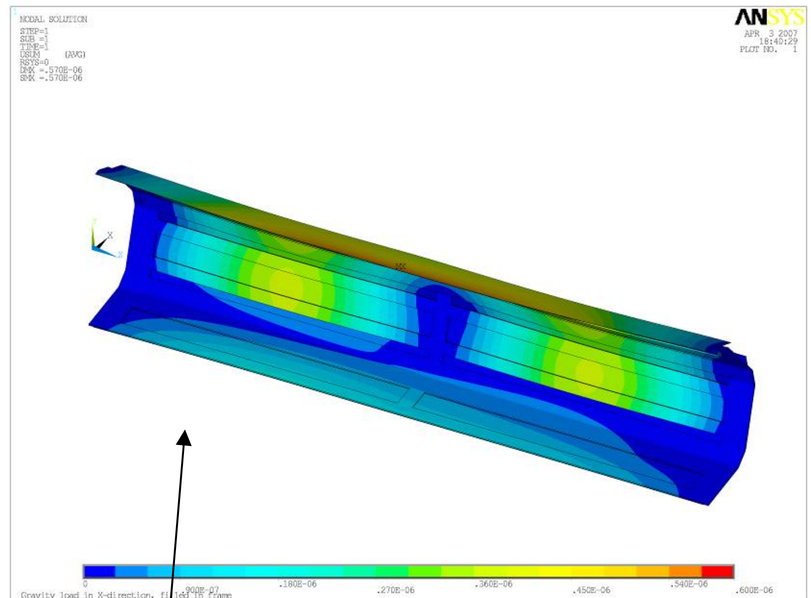


UW FEA Studies, Silicon on CF Structure

- This work has the aim of understanding how to optimize the geometry of the carbon fiber/epoxy composite frame to minimize deflection due to gravity and temperature changes.
- This model uses a 4-layer (0,90,90,0 degree) lay-up. The gravitational deflections of two slightly different structures are:



Open slots to reduce material



One slot closed to reduce thermal deflection

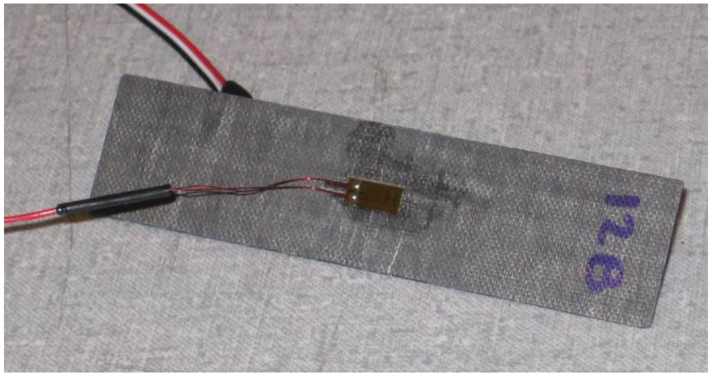
- The maximum deflection vector is about 0.6 mm in each case.
- Work continues of models with 3-layer CF structures and different CF geometry with the aim of optimizing the mass of the CF and the thermal deflections.

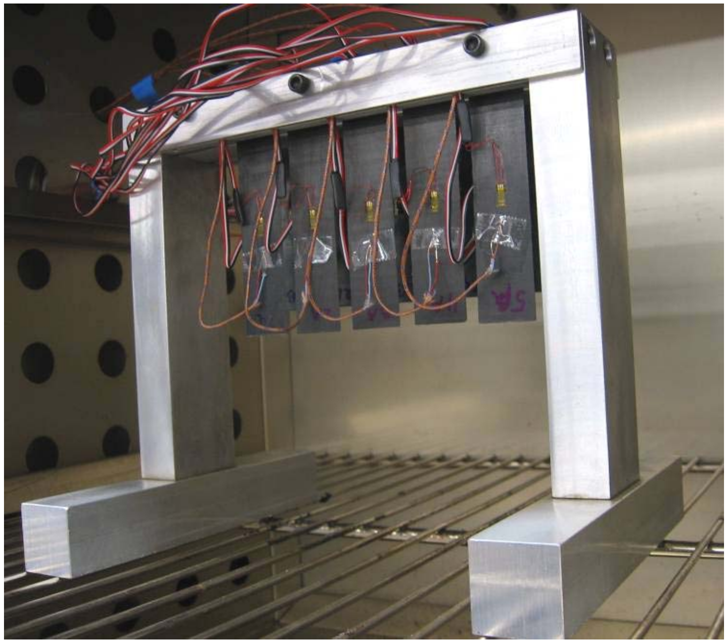
UW Measurements of Carbon Fiber Thermal Expansion

- Initial FEA suggests that thermal distortions are likely to dominate gravitational deflections for temperature changes > 10^{o}C.
- Published values of the CTE of carbon fiber laminate range from roughly -5 ppm/^{o}C to +1 ppm/^{o}C for ply orientations under consideration.
- To ensure that input for modeling is sensible, efforts are underway to measure the Coefficient of Thermal Expansion of the cured carbon fiber used in the support structure. This information is needed to better understand the stresses and deflections that the silicon will experience when cooled from ambient to the -15°C operating temperature. The very thin carbon fiber has presented difficulties in making an otherwise straight-forward measurement.
  - Use environmental chamber to reach -20C
  - Thermal response measured using strain gages bonded to the CF specimen.

CTE Measurements using Strain Gages

- Coefficient of Thermal Expansion measurements were first made on 4-ply [0,90,90,0] specimens. This is the same layup as the prototype structures delivered to Fermilab.
  - Test method: Measurement Group Tech Note TN-513-1.
  - Strain gages mounted front and back on flat coupons; Steel coupons used as reference material. CTE of strain gage (STC#) ~matched to steel coupon. .
  - Samples mounted in rack and placed in lab oven with thermocouples taped to each CF sample .
  - Strain and temperature are monitored and dwell time at each temperature is 30 minutes.





CTE Measurements using Strain Gages

- **Data Reduction**
  - **Equation 6 from Vishay Tech Note TN-513-1**

$$\alpha_S - \alpha_R = \frac{\left(\varepsilon_{(G/S)} - \varepsilon_{(G/R)}\right)}{\Delta T}$$

Where:

α_S = CTE of specimen coupon

α_R = CTE of reference coupon

$\varepsilon_{G/S}$ = Measured thermal strain of specimen coupon

$\varepsilon_{G/R}$ = Measured thermal strain of reference coupon

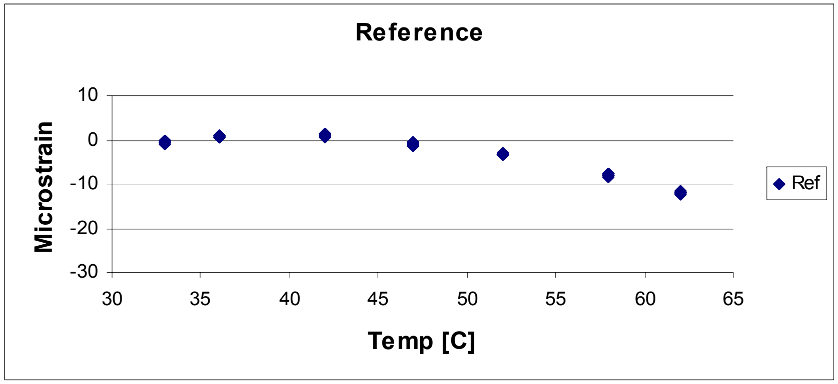
ΔT = Temperature change

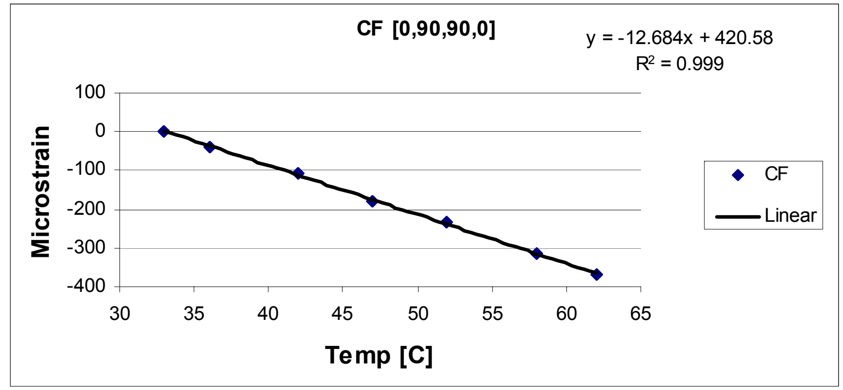
CTE Measurements using Strain Gages

- **The thin coupons required that gages be mounted on both sides to provide cancellation of strains due to bending. Therefore, four gages are needed to measure each specimen (compared to two gages as described in the Vishay Tech Note).**

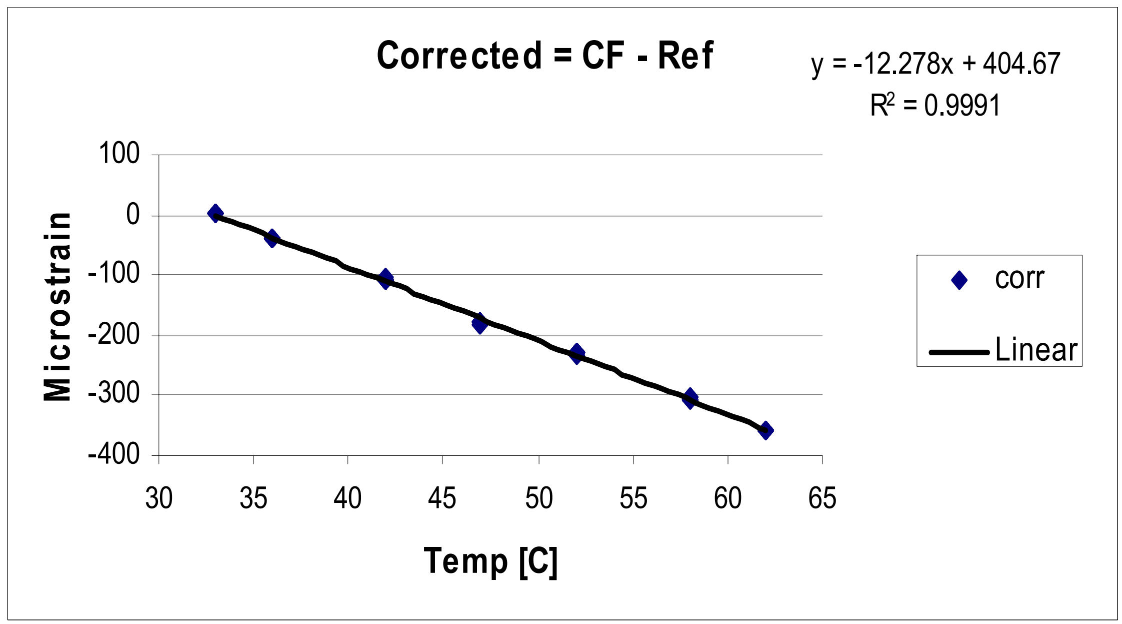
- **Quarter bridge measurements were used to resolve the CF strain and the steel strain separately. Each gage is wired to its own channel and the differential strain correction is done offline.**

CTE Measurements using Strain Gages





- Average CTE of 5 coupons = -1.5E-6/°C
- Steel CTE used = 10.8E-6/°C
- Standard Deviation = 0.1E-6/°C

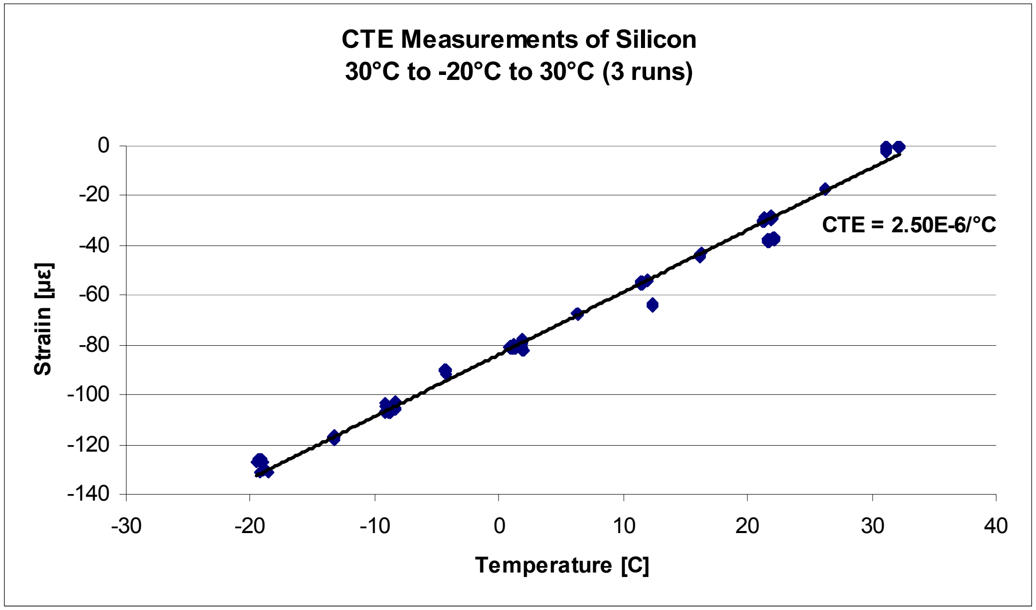


CTE Measurements using Strain Gages

- Sources of uncertainty
  - Actual CTE of steel specimen not well known. Any error is added directly to the calculated specimen CTE.
  - Possible reinforcement of thin specimens by strain gages.
  - Lab oven does not allow the sub-ambient temperature excursions expected in practice.
  - Moisture content of CF may affect CTE measurements.
- Adjustments made
  - Titanium Silicate reference specimen purchased with CTE certification. CTE is effectively zero.
  - Environmental chamber acquired allows sub-ambient temperature excursions matching the expected operating conditions.
  - 3-ply [0,90,0] CF and Silicon specimens now being tested. Biaxial gages used to measure both axial and transverse strain.

CTE Measurements using Strain Gages

- First results using the environmental chamber
- Silicon used as a control sample.
- Silicon specimen thickness = 0.66mm
- **Measured CTE after 3 runs = 2.50E-6/°C.** This agrees with CTE value listed on Matweb (2.49E-6/°C @20°C).
- Results are promising, but more data needed before verifying this method. Thin CF may not behave so well.

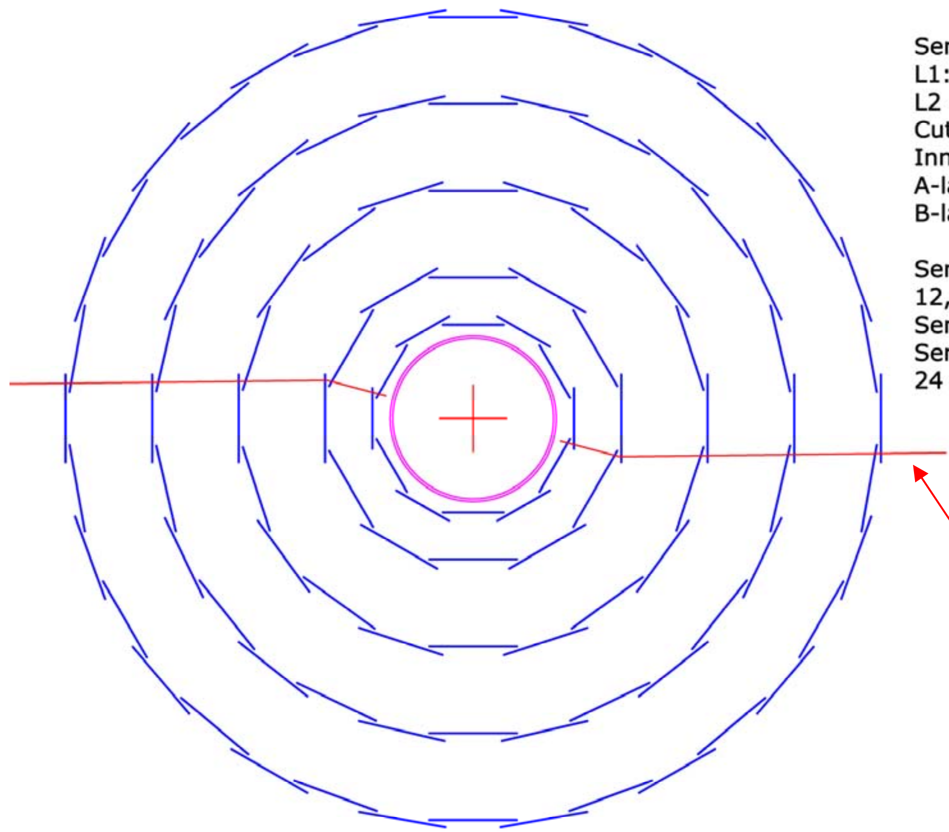


Future CTE Measurements

- The silicon results look promising, but more data must be taken before the method can be declared reliable.
- The next step will be to begin measurements of 3-ply [0,90,0] and 4-ply [0,90,90,0] CF specimens.
- Also to be measured:
  - [0,0,0] specimens
  - [90,0,90] specimens
  - Thinner silicon.
  - Silicon in the transverse orientation.

SiD Design Studies and Issues

- New barrel end-view geometry developed last spring
- Sensor counts were increased in L3, L4, L5 to obtain multiples of 4 and fully identical barrel halves.

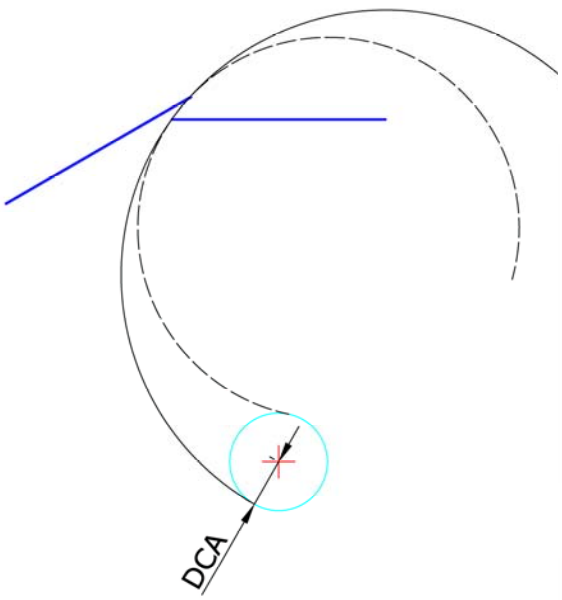


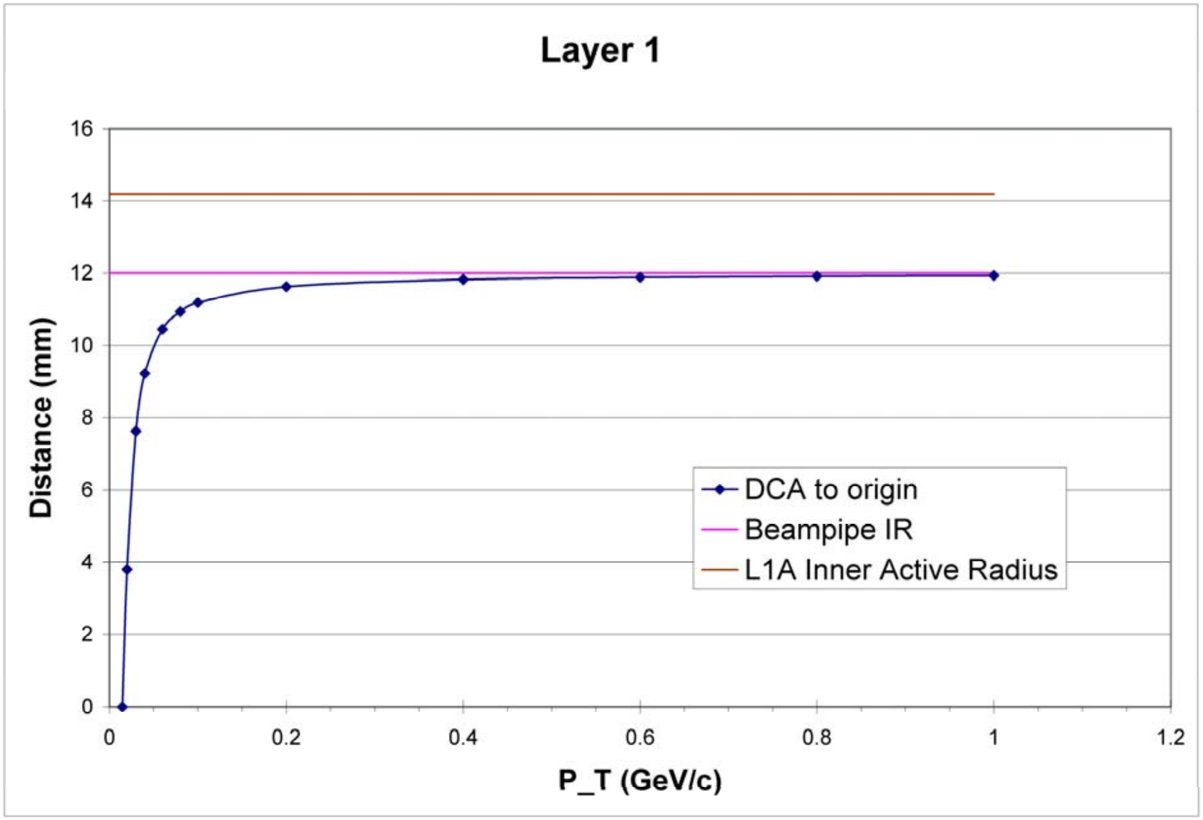
Sensor active widths:
L1: 9.1 mm
L2 - L5: 13.1 mm
Cut - active width: 0.08 mm
Inner radii:
A-layer: 14, 21, 34, 47, 60 mm
B-layer: 15.0060, 22.0681, 34.9674, 47.8855, 60.8313 mm
Sensors per layer:
12, 12, 20, 28, 36
Sensor-sensor gap: 0.5 mm
Sensor thickness: 0.1 mm
24 April 2007

Possible separation line (under study)

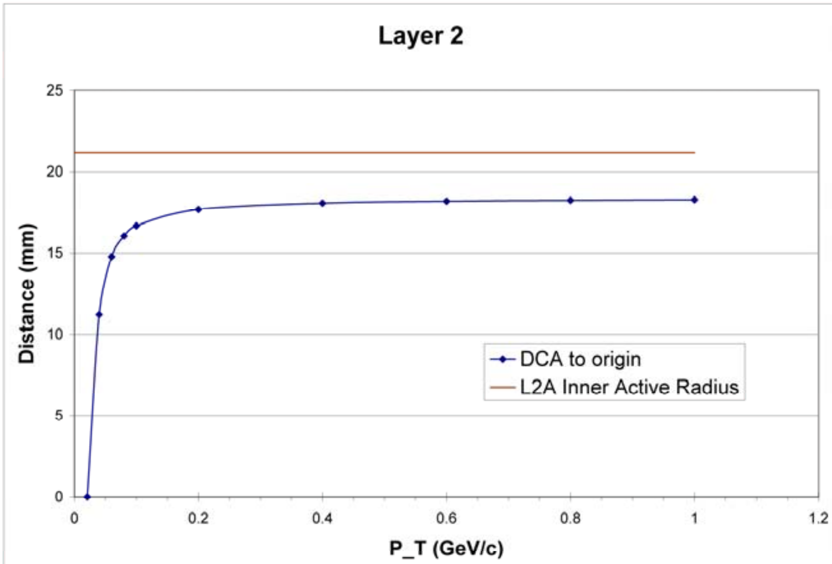
Geometric Efficiency in the Transverse Plane

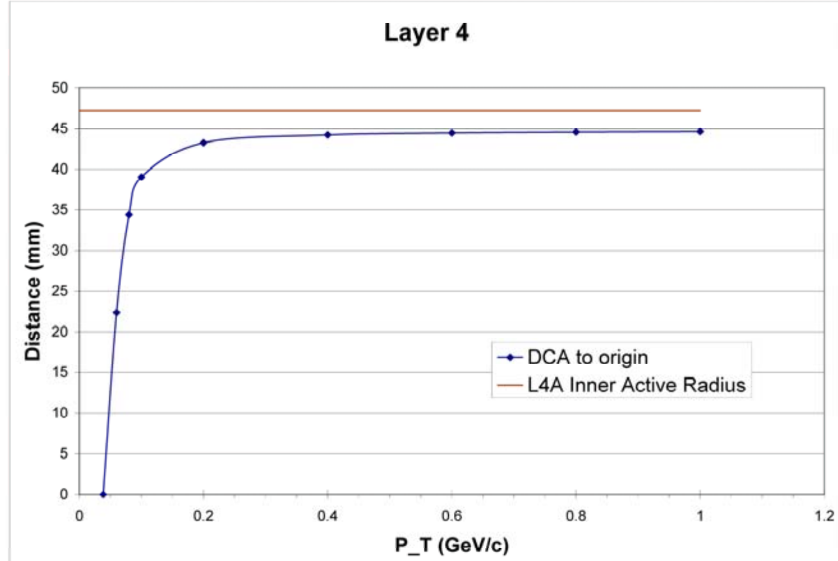
- A- to B-layer gaps to accommodate “ladder thickness” determine geometric efficiency.
- Full geometric efficiency is obtained for tracks below and to the right of the curve in the right plot (spreadsheet calculation).
- Tangency to the beam pipe surface is accidental.

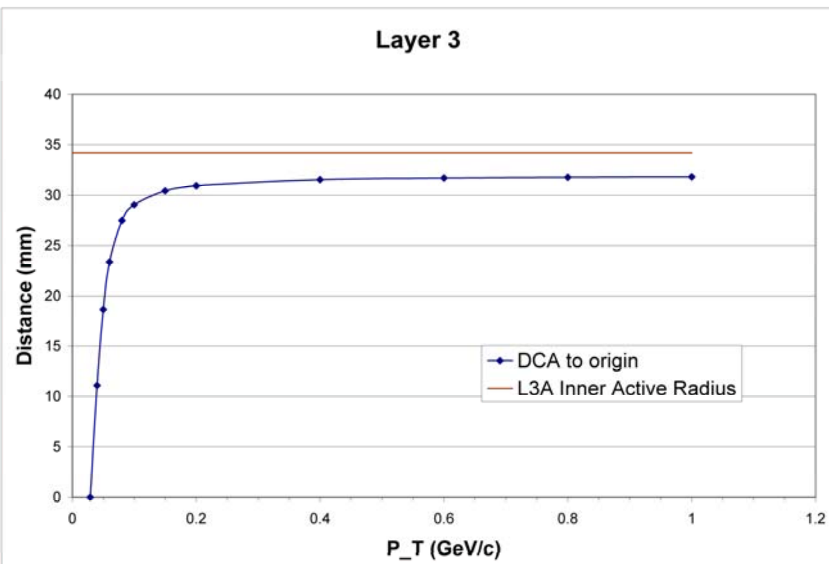


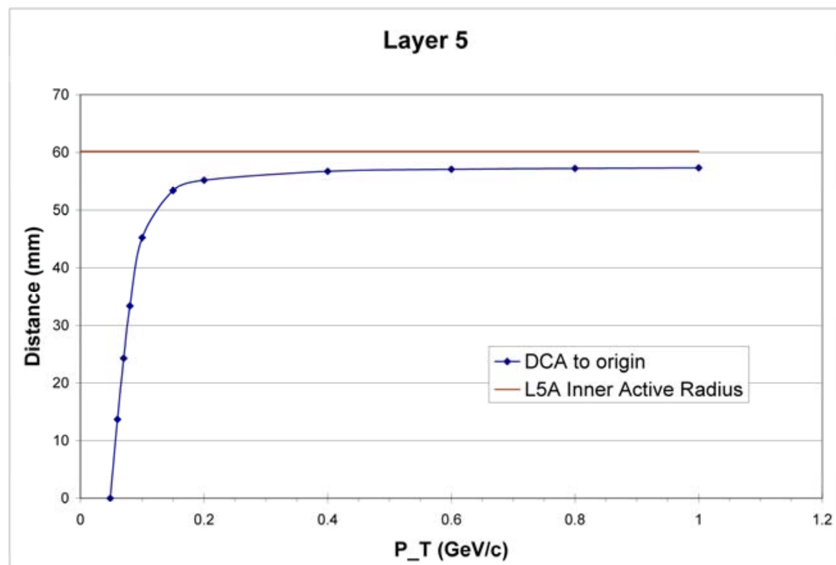


Geometric Efficiency in the Transverse Plane

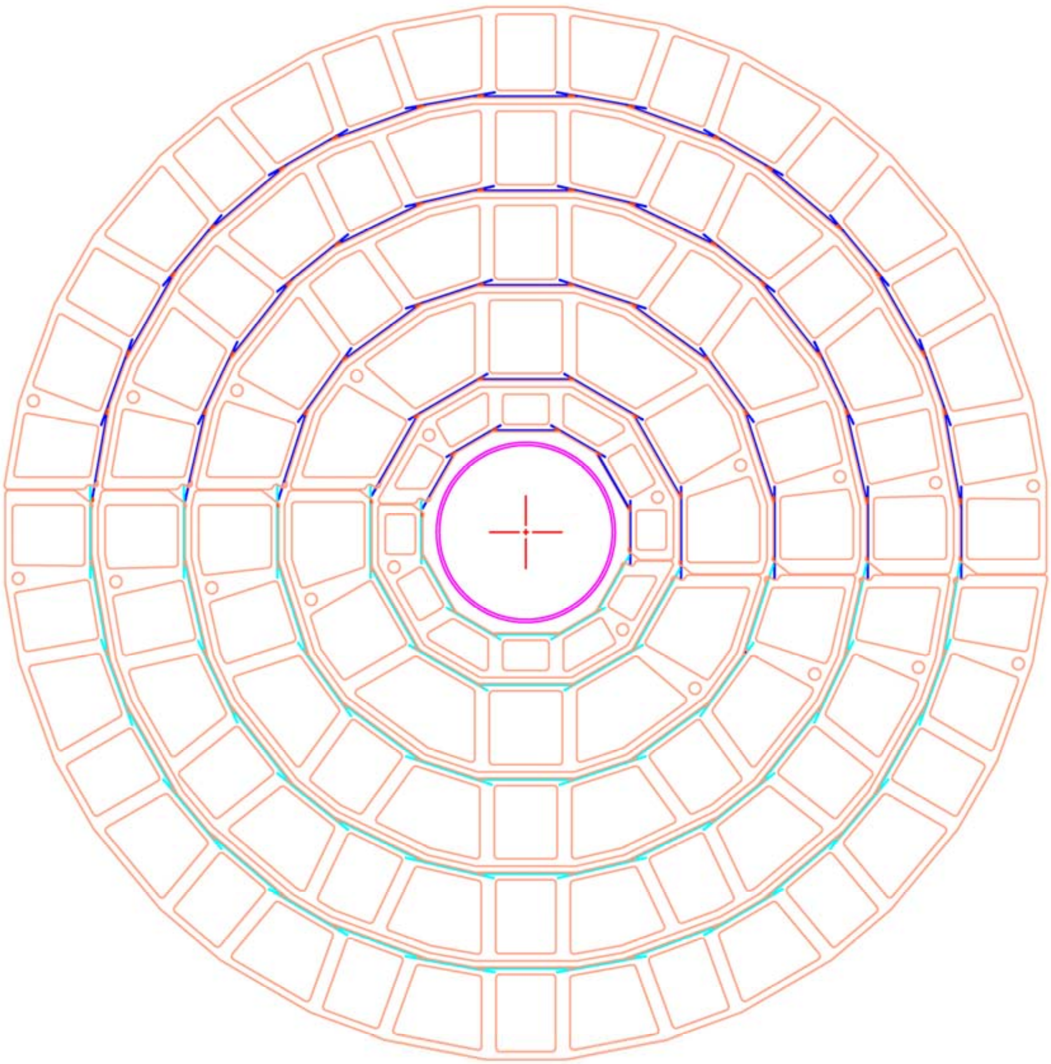








"All-Silicon" Layout



- Proposed to mitigate CTE issues

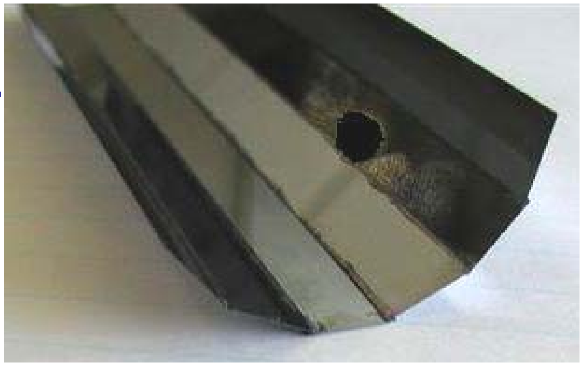
Sensor active widths:
L1: 8.6 mm
L2 - L5: 12.5 mm
Cut - active width: 0.08 mm
Inner radii:
A-layer: 14, 21, 34, 47, 60 mm
B-layer: 14.4593, 21.4965, 34.4510,
47.3944, 60.3546 mm
Sensors per layer:
12, 12, 20, 28, 36
Sensor-sensor gap: 0.1 mm
Sensor thickness: 0.075 mm
7 June 2007, 14 August 2007

- 75 µm silicon thickness assumed
- Could be modified for thicker or thinner sensors
- End rings dominate what you see.
- It should be straight-forward to ensure their out-of-round stiffness is large compared to that of sensors.
- End ring material has been assumed to be CF in initial modeling.

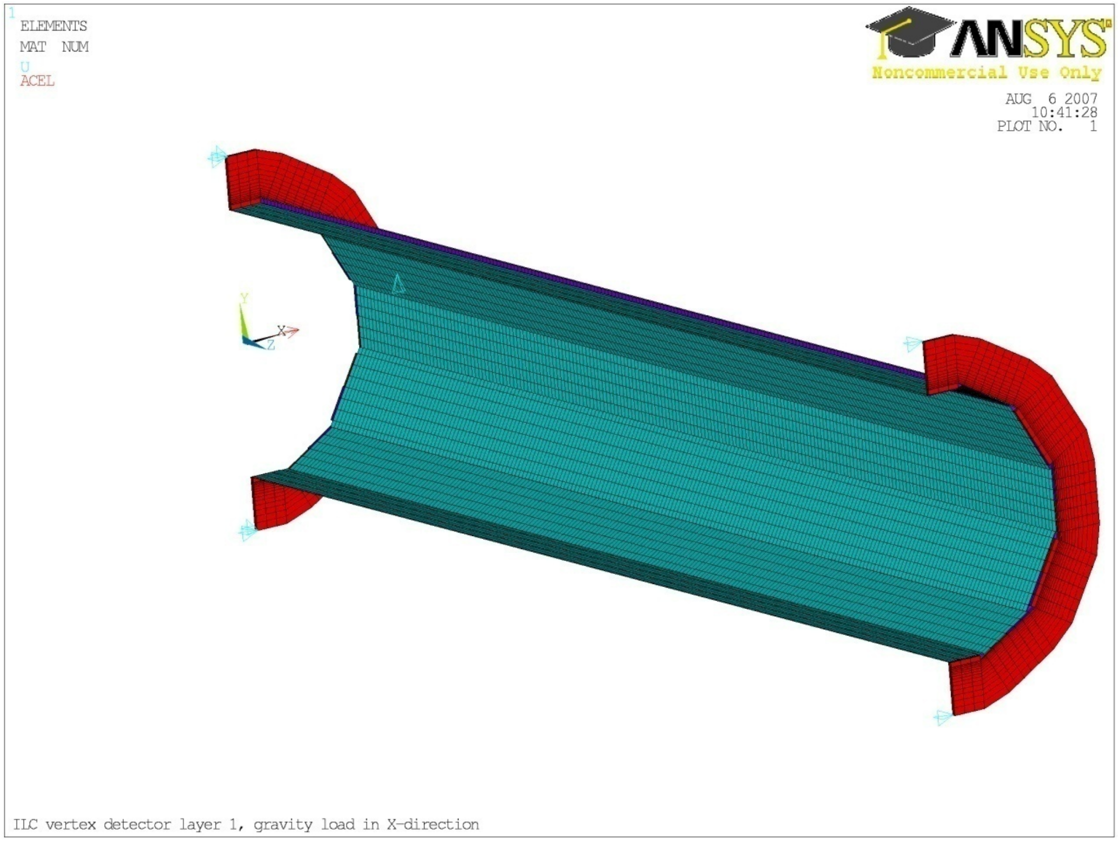
UW FEA of an All Silicon Structure

- This version of the vertex detector uses only the silicon sensors in "cylindrical" portions of the structure.
  - They are connected along their long edges by thin beads of epoxy.
  - Thin, flat carbon fiber/epoxy end membranes included in the model.
  - These membranes will be refined as a more detailed design is developed.
- Model is parametric and can generate models for all 5 layers of this detector.
  - Only a 180 degree segment is modeled. It is assumed here that the detector will be built as two such segments to permit assembly onto the beam pipe and that these will not be connected.
- The gravity sag is calculated and displayed as deflection in the gravity (X) direction.
- Maximum displacements in the X, Y and Z directions are calculated for a 10 C delta T.
  - Note that the Z deflection is composed mainly of the simple change in length of the detector.

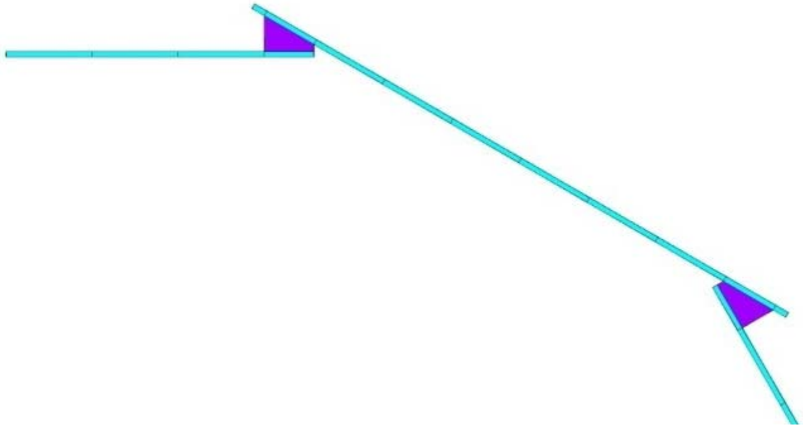
Layer 1 mechanical prototype (Kurt Krempetz)

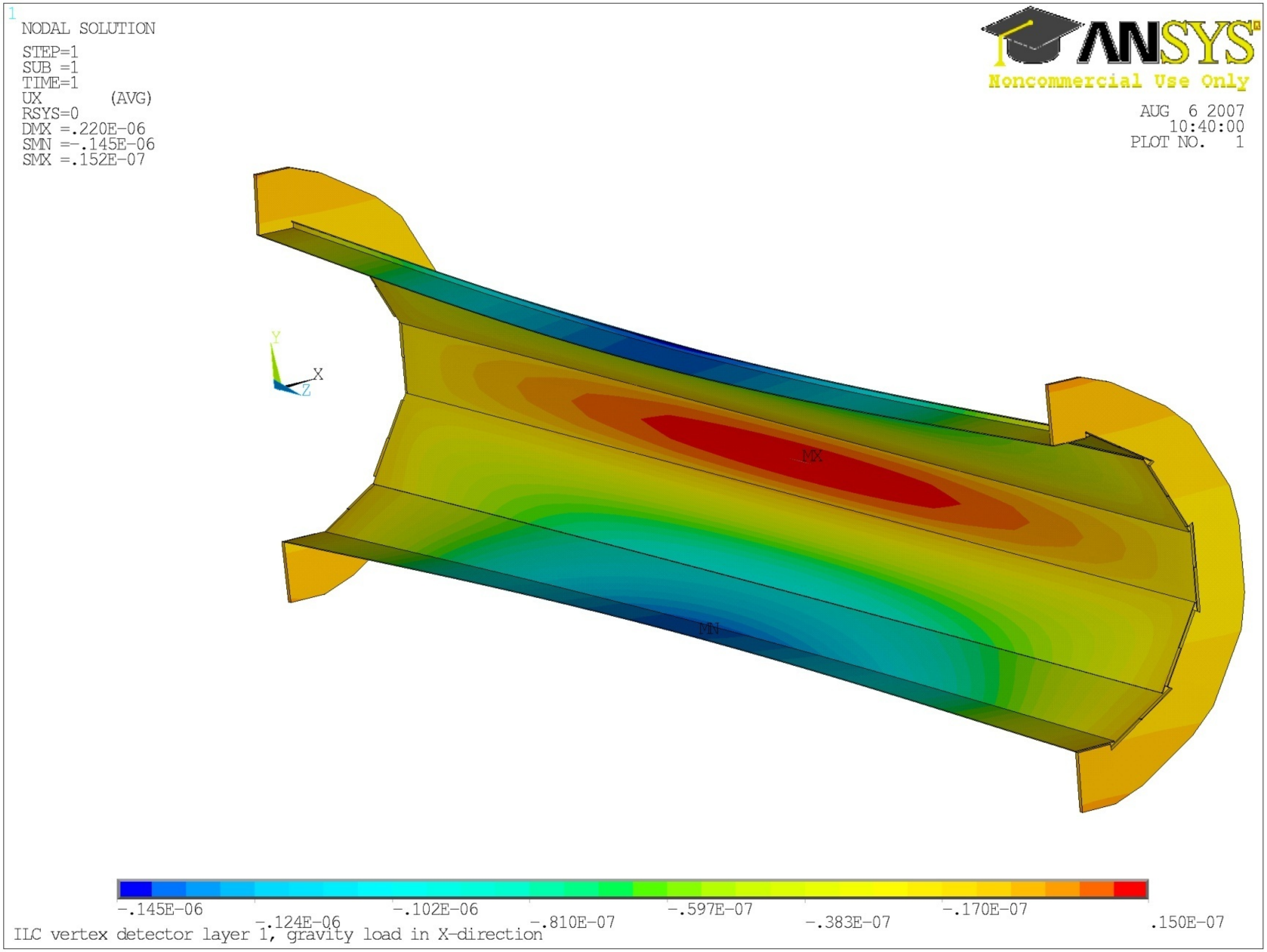


Model of layer 1

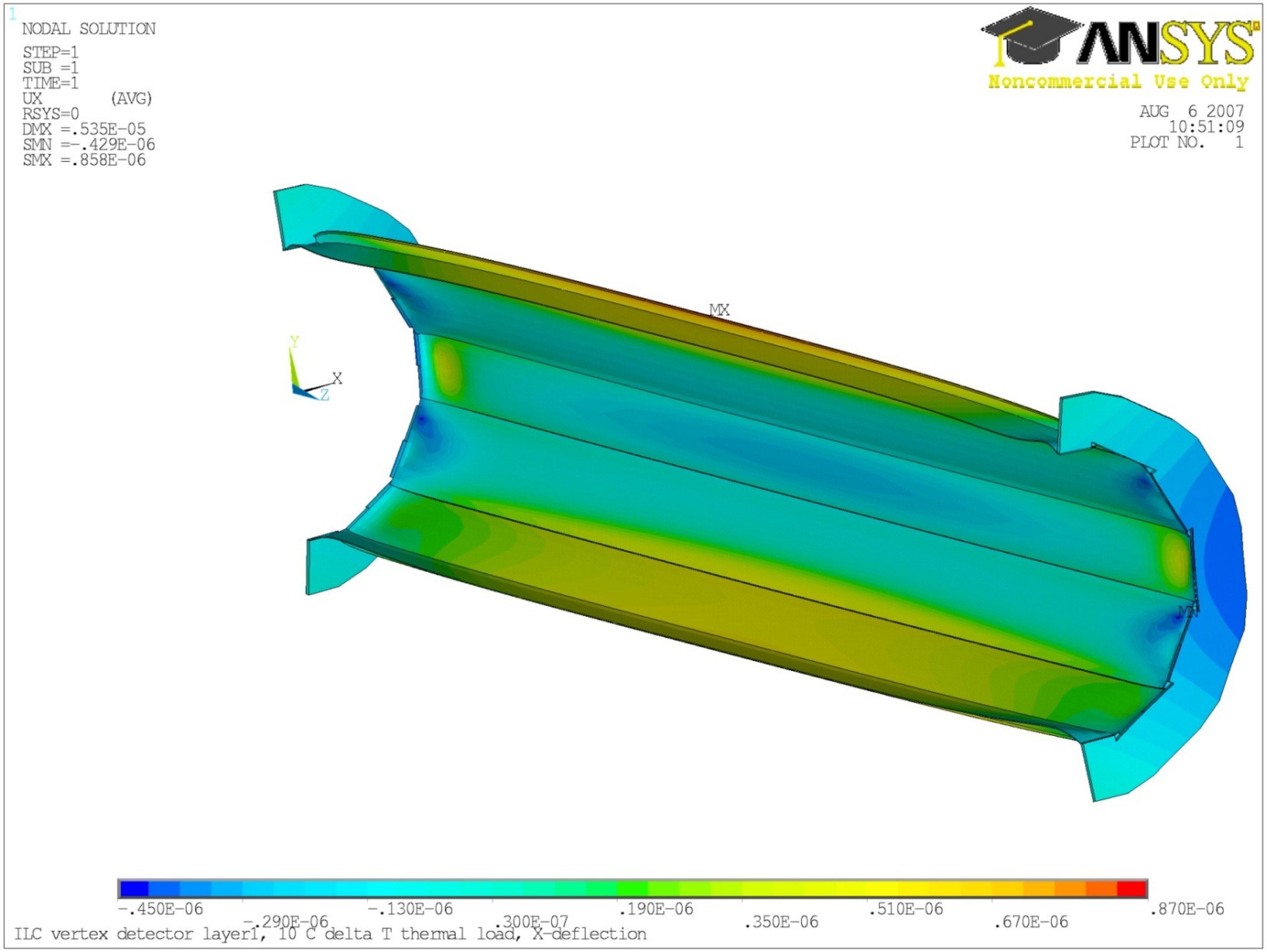


Detail of model of layer 1 showing the 0.7 mm wide epoxy joints.

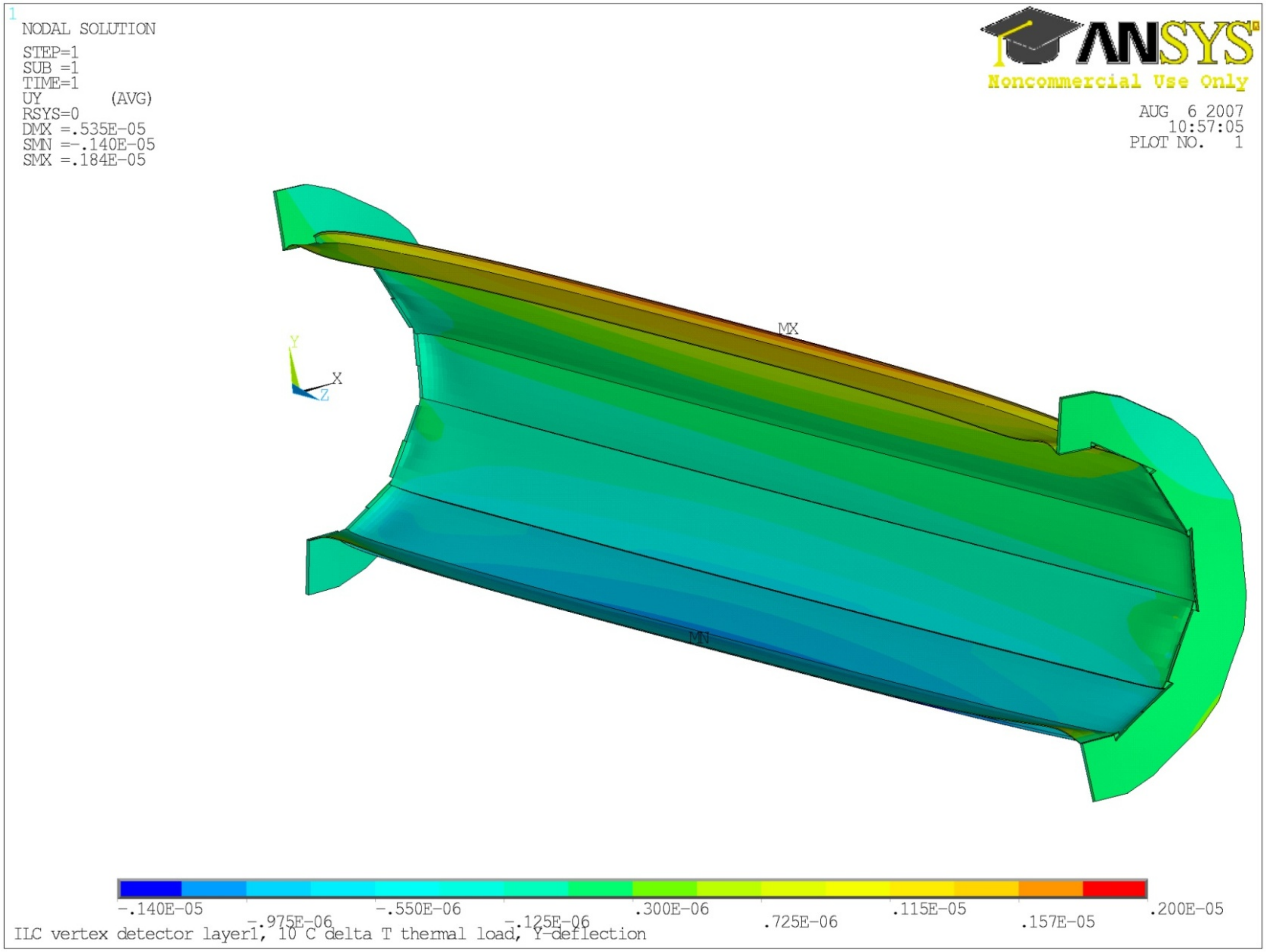




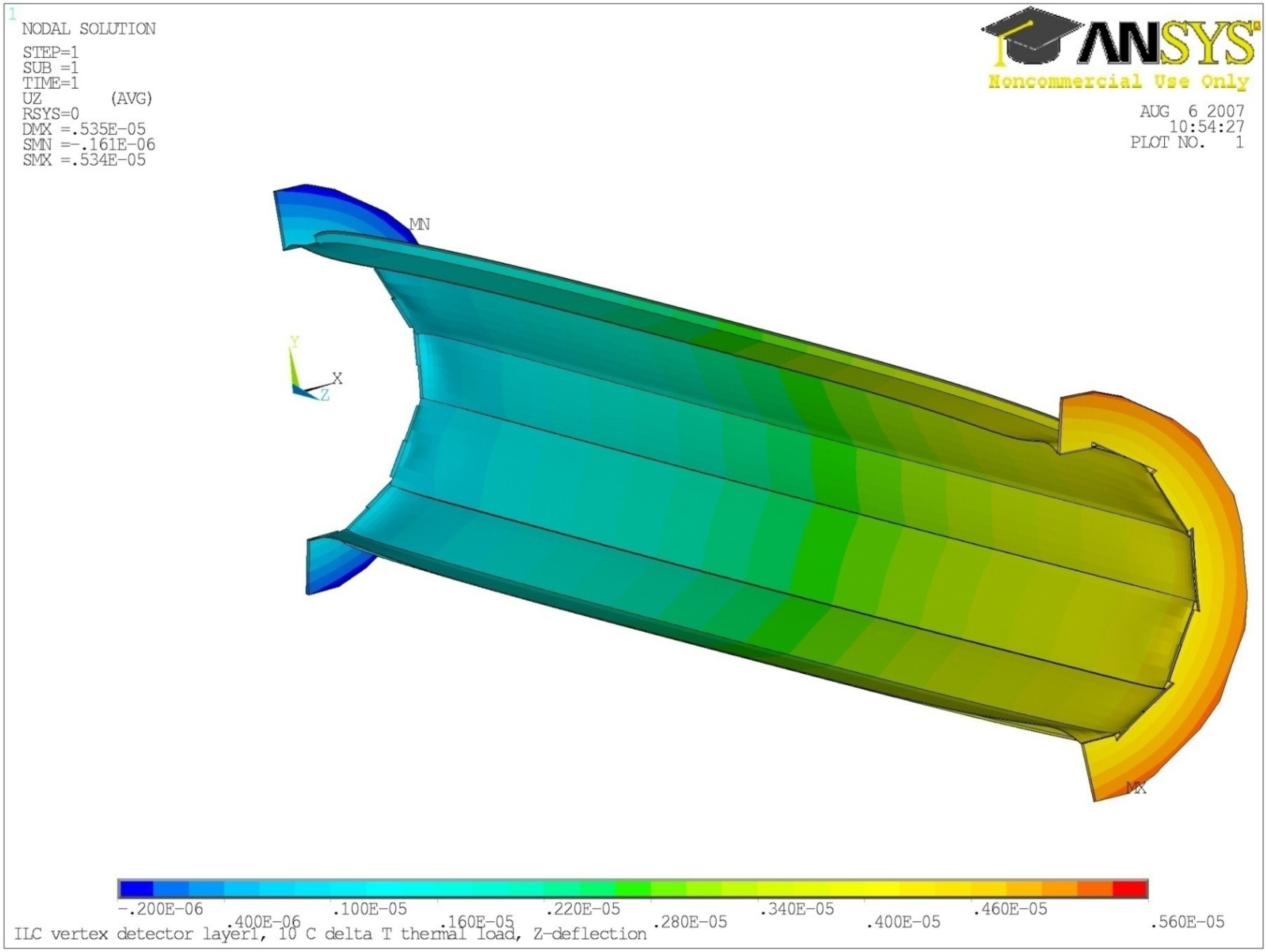
Gravitational deflection of layer 1 (1.5 μm max) .



Thermal displacement in X-direction of layer 1 for $\Delta T = 10$ C (0.9 μm max)

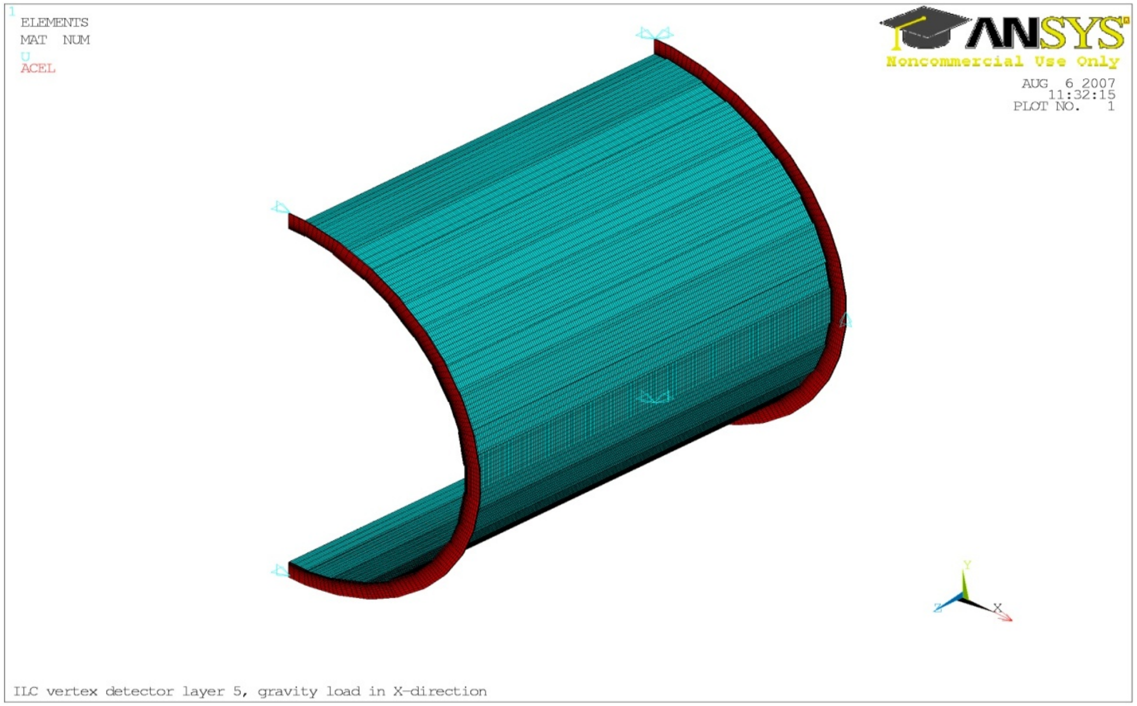


Thermal displacement in Y-direction of layer 1 for $\Delta T = 10$ C (1.8 μm max)

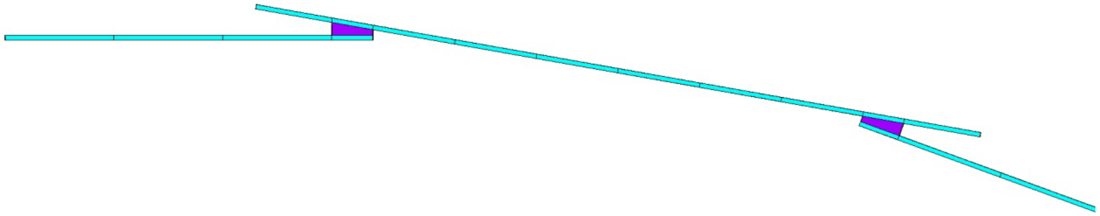


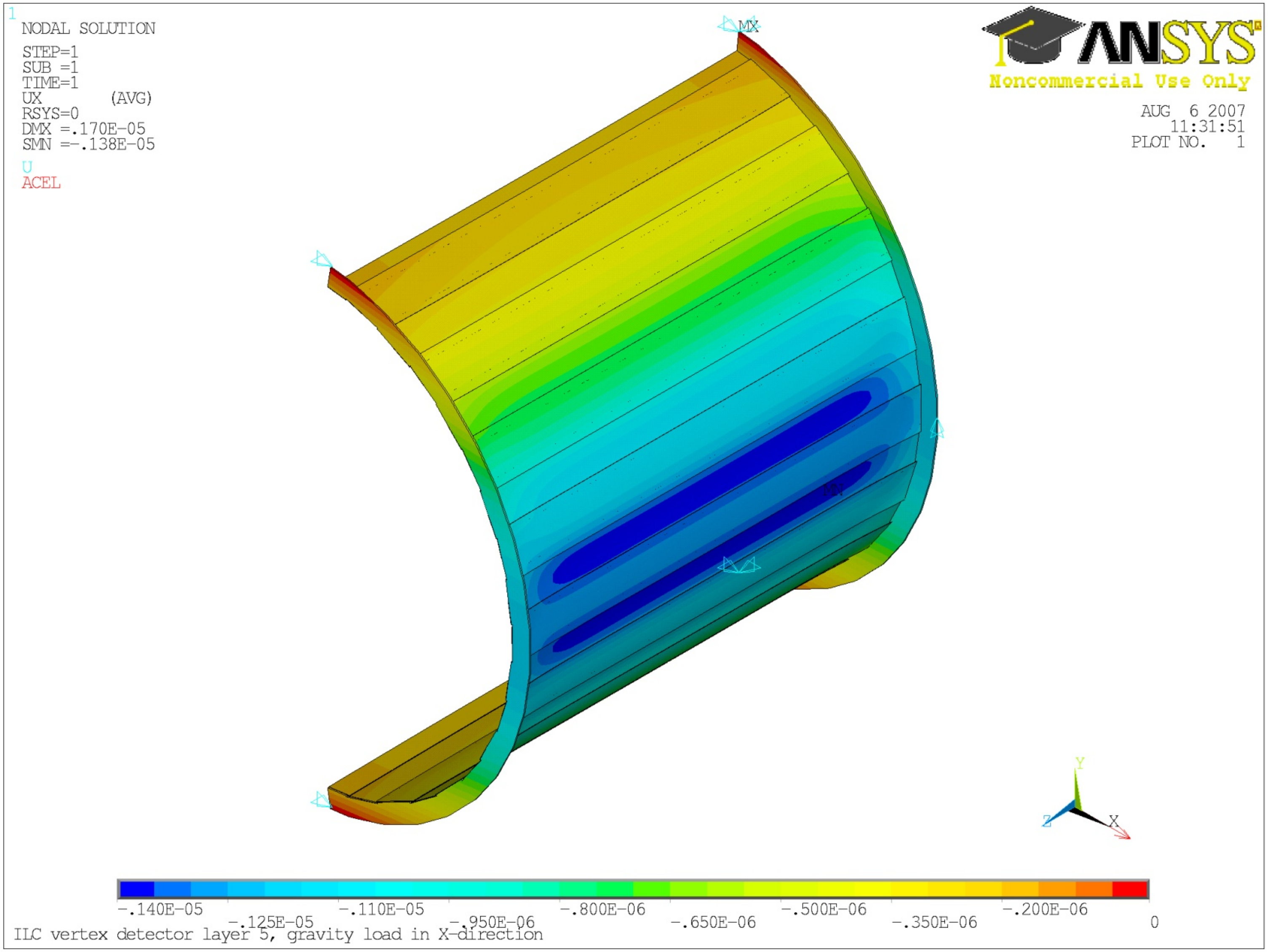
Thermal displacement in Z-direction of layer 1 for a $\Delta T=10$ C
(5.3 μm max)

Model of layer 5.

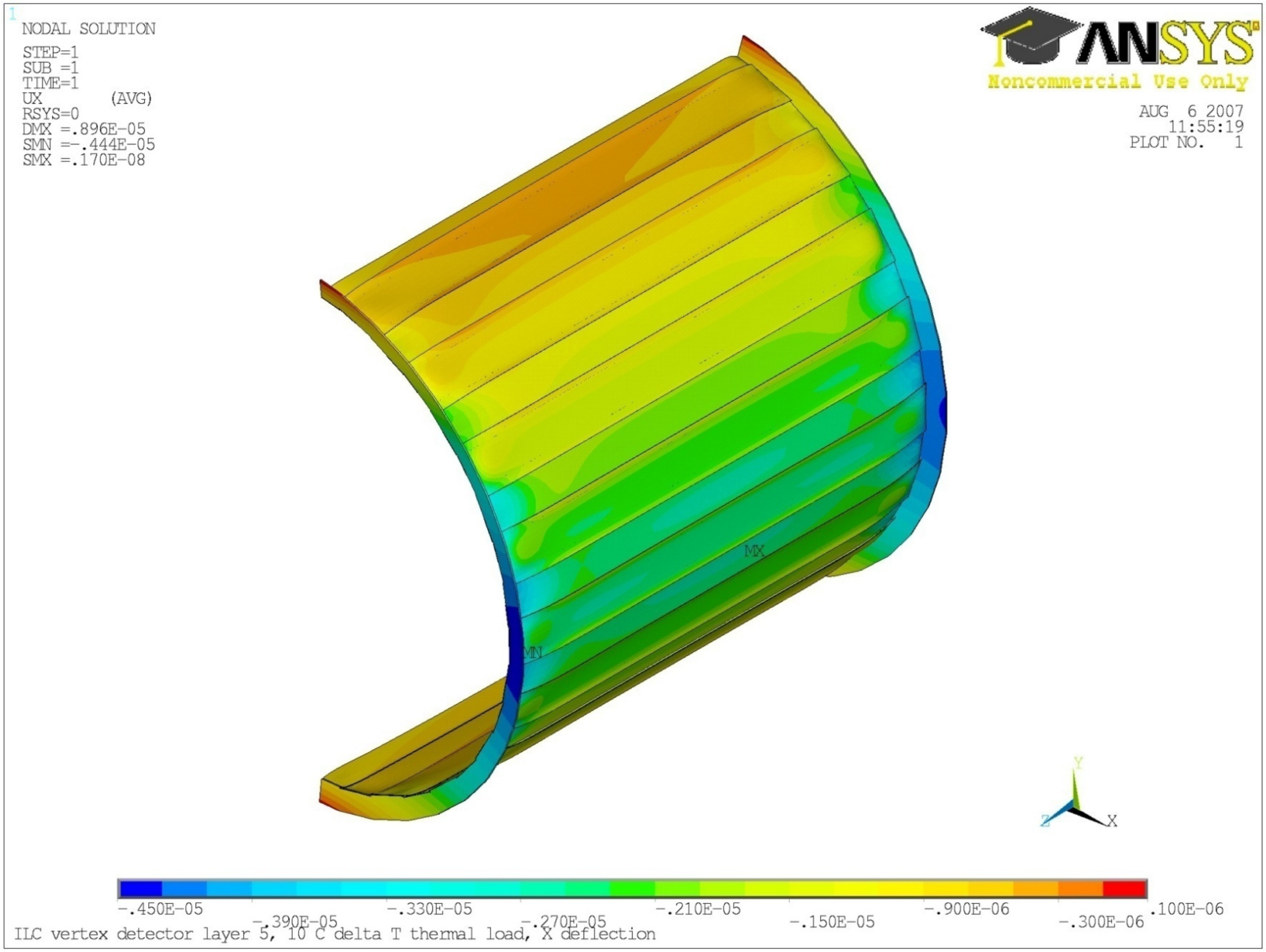


Detail of model of layer 5 showing the 1.0 mm wide epoxy joints.

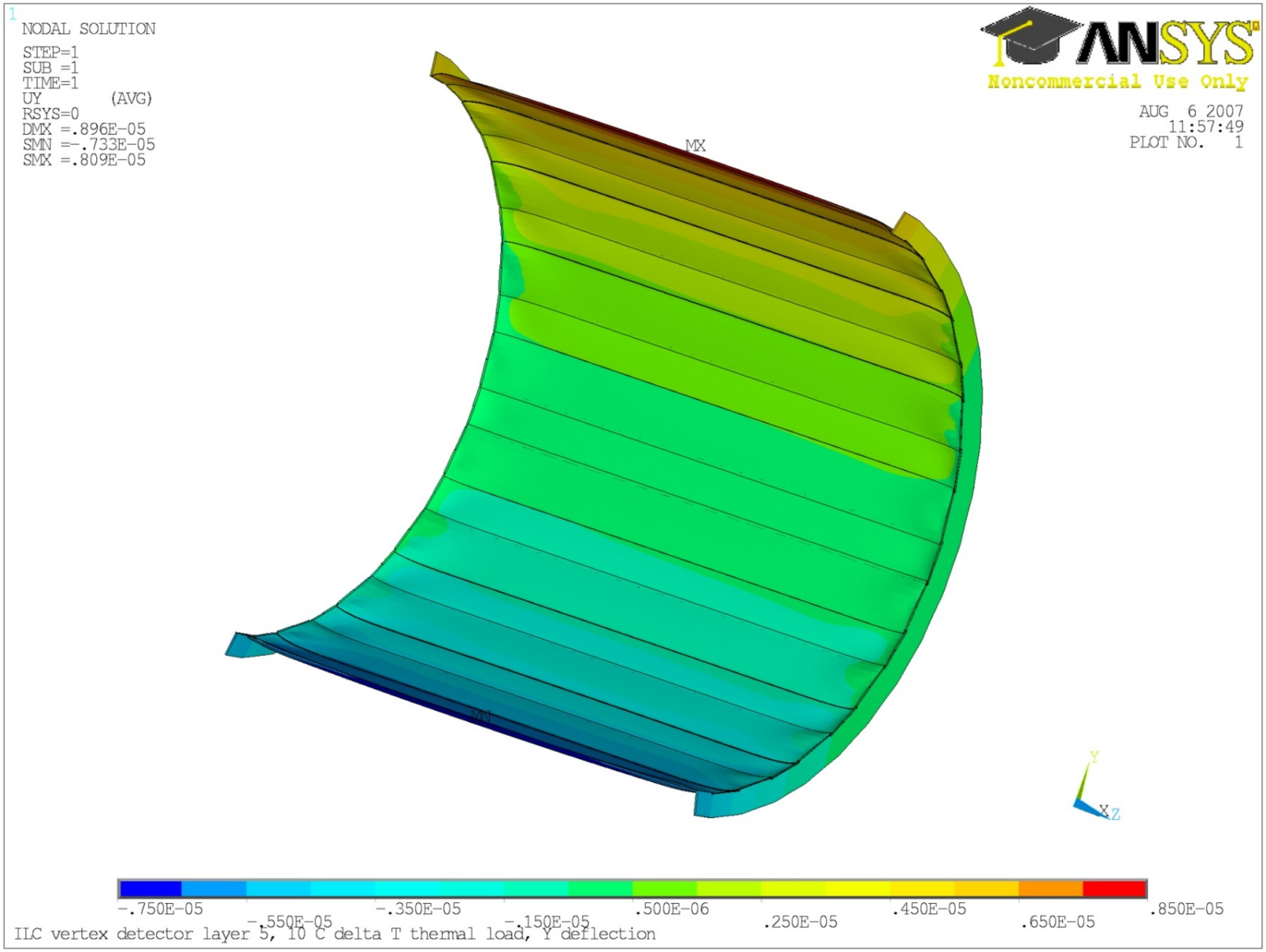




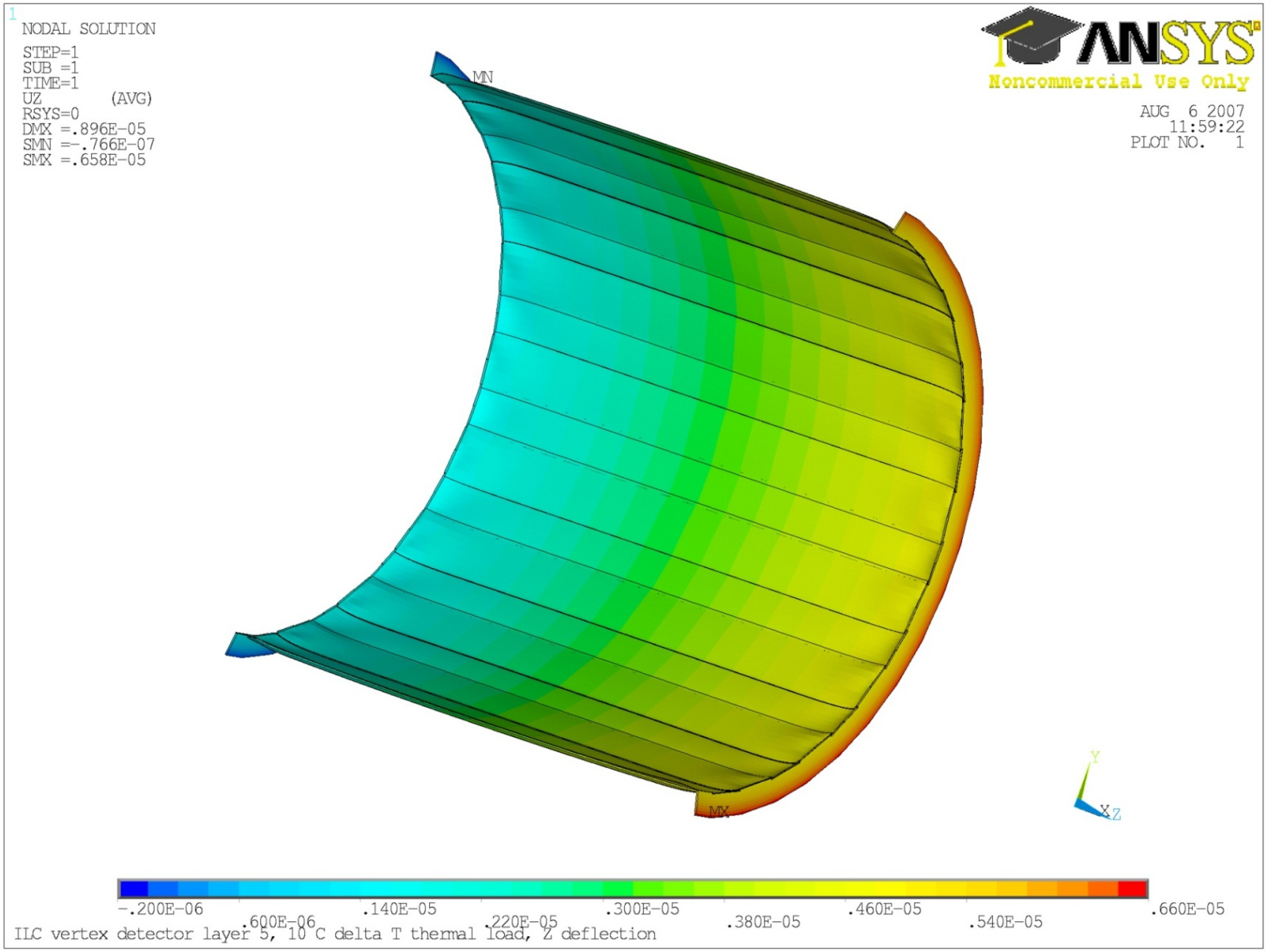
Gravitational deflection of layer 5 (1.7 μm max).



Thermal displacement in X-direction of layer 5 for a $\Delta T=10$ C (4.4 μm max)



Thermal displacement in Y-direction of layer 5 for $\Delta T = 10$ C
(8.1 μm max)



Thermal displacement in Z-direction of layer 5 for $\Delta T = 10$ C
(6.6 μm max)

Initial FEA results for ILC vertex detector - all silicon structure
(8/6/2007 C H Daly)

Layer no.	Gravity sag µm	Thermal displacement X-direction µm (10 C delta T)	Thermal displacement Y-direction µm (10 C delta T)	Thermal displacement Z-direction µm (10 C delta T)
1	0.145	0.86	1.84	5.34
2	0.1	1.01	2.97	5.61
3	0.266	1.62	3.99	5.82
4	0.642	2.64	5.67	6.22
5	1.4	4.4	8.1	6.6

In a collaborative effort to develop an all-silicon design, LCFI institutions are carrying out similar FEA.

Disk Concepts and Miscellaneous R&D

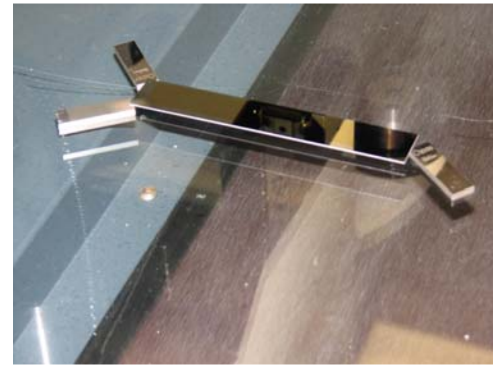
One idea for support of forward / backward disk sensors

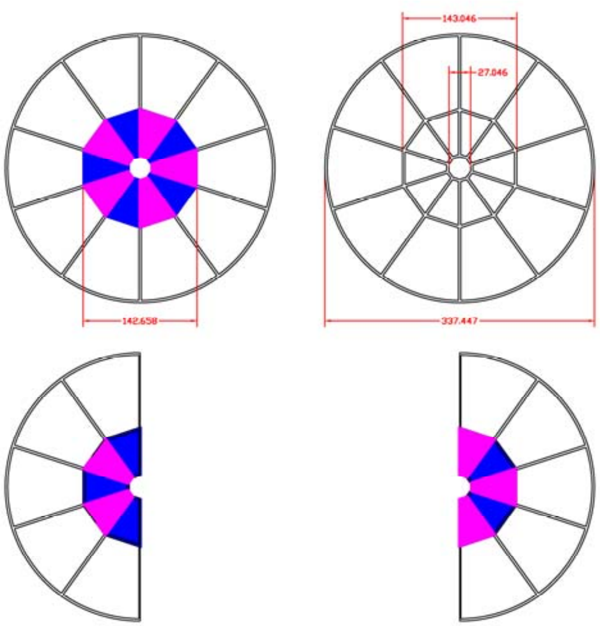
- Provide a CF-foam-CF frame on which sensors would be mounted.
- Alternate wedges between the two frame surfaces to provide overlap and stability against thermal distortions.

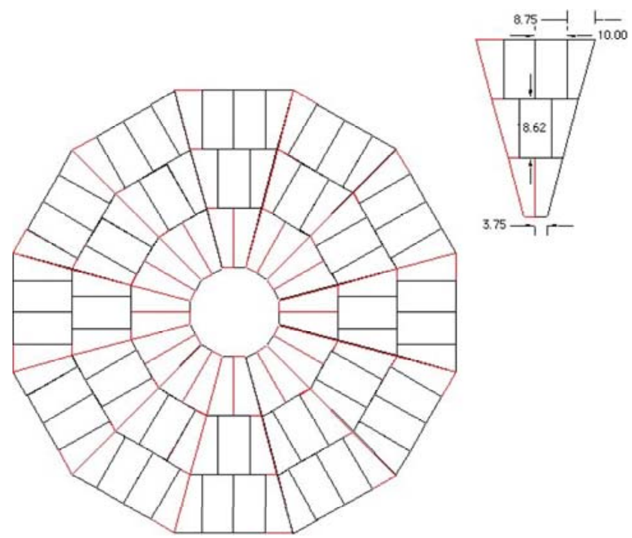
An alternative approach

- Mount sensors directly to a continuous membrane.
- Build up a wedge from pieces which would fit within a ½ reticle, butting them edge to edge.

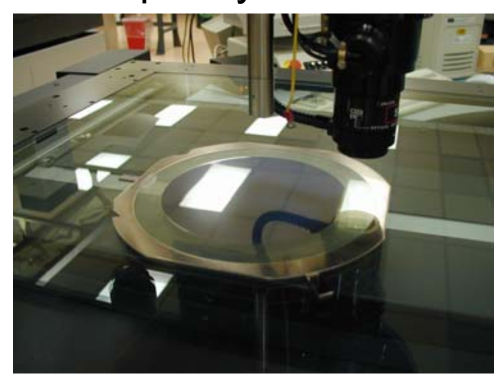
Set-up at SiDet for OGP measurements of an MPI DEPFET







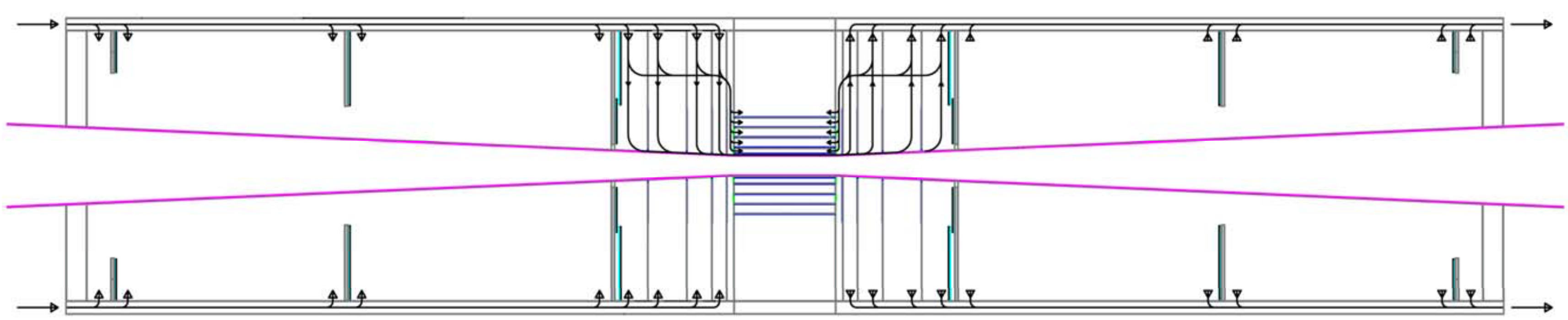
Set-up at SiDet for OGP measurements of a silicon wafer thinned to 20 μm by DISCO



Power Delivery

- Power cycling and series power affect designs in different ways.
- Power cycling will be crucial to allow dry gas cooling with most present sensor and readout technologies.
  - A factor ~80 reduction of average power with respect to peak power has been assumed.
- Connecting sensors so that they are powered in series:
  - Limits power dissipated by cables and / or reduces material represented by cables.
  - We have just begun investigating the benefits of series power in reducing moments imposed on sensors by cabling.
    - Trade-off between power dissipated by cable and cable stiffness
- Initial estimates of heat removal capability apply to the sum of power dissipated by sensors, cables, and readout within the volume of interest.

VXD Barrel Cooling

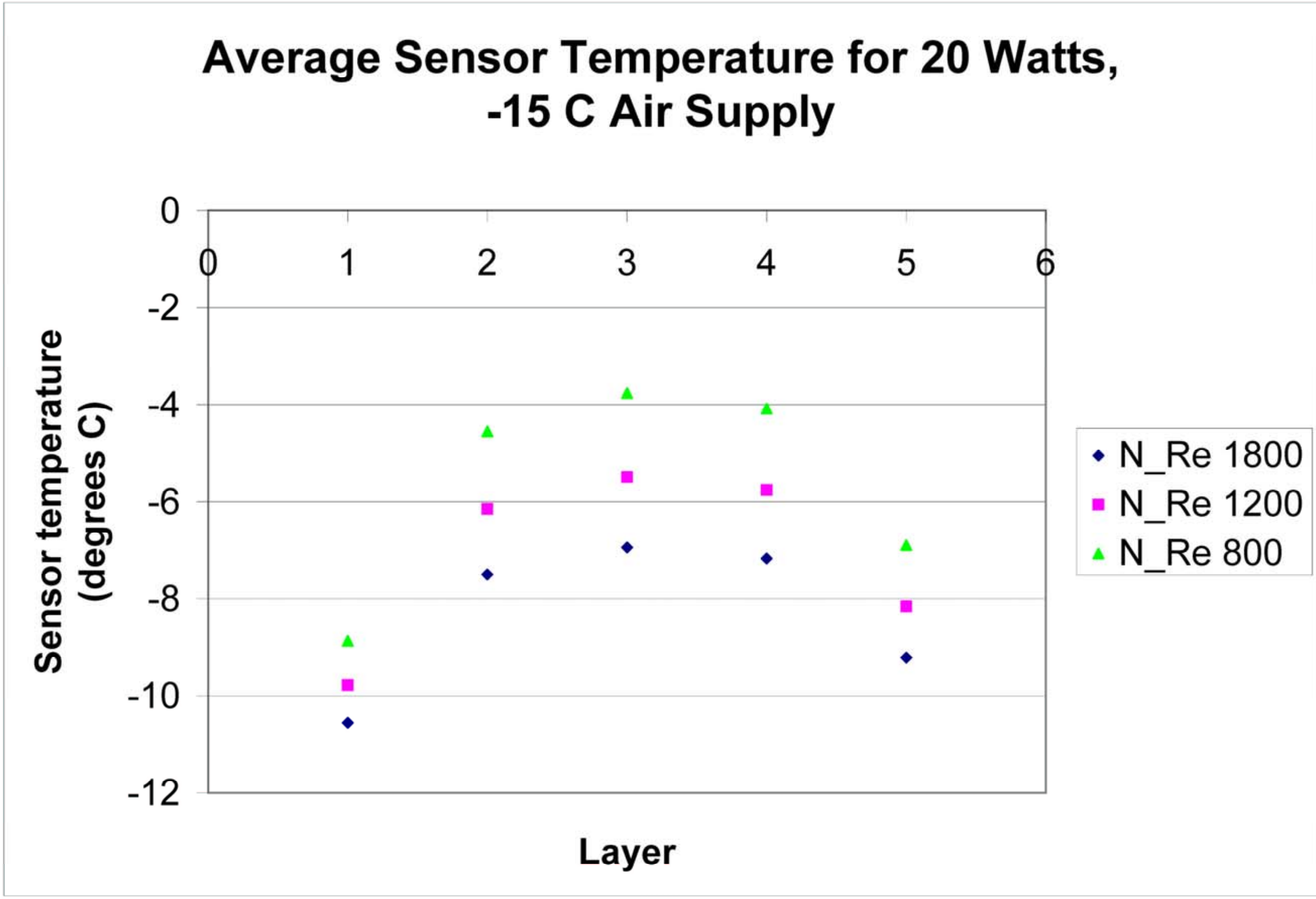


- Dry air was assumed to enter the barrel at a temperature of -15^{o} C. (Results with dry nitrogen would be nearly identical)
- We assumed no heat transfer from the beam pipe to the innermost layer, that is, the beam pipe would have thermal intercepts.
- A total power dissipation of 20 watts was assumed for the barrel.
  - Based upon the results, that seems reasonable.

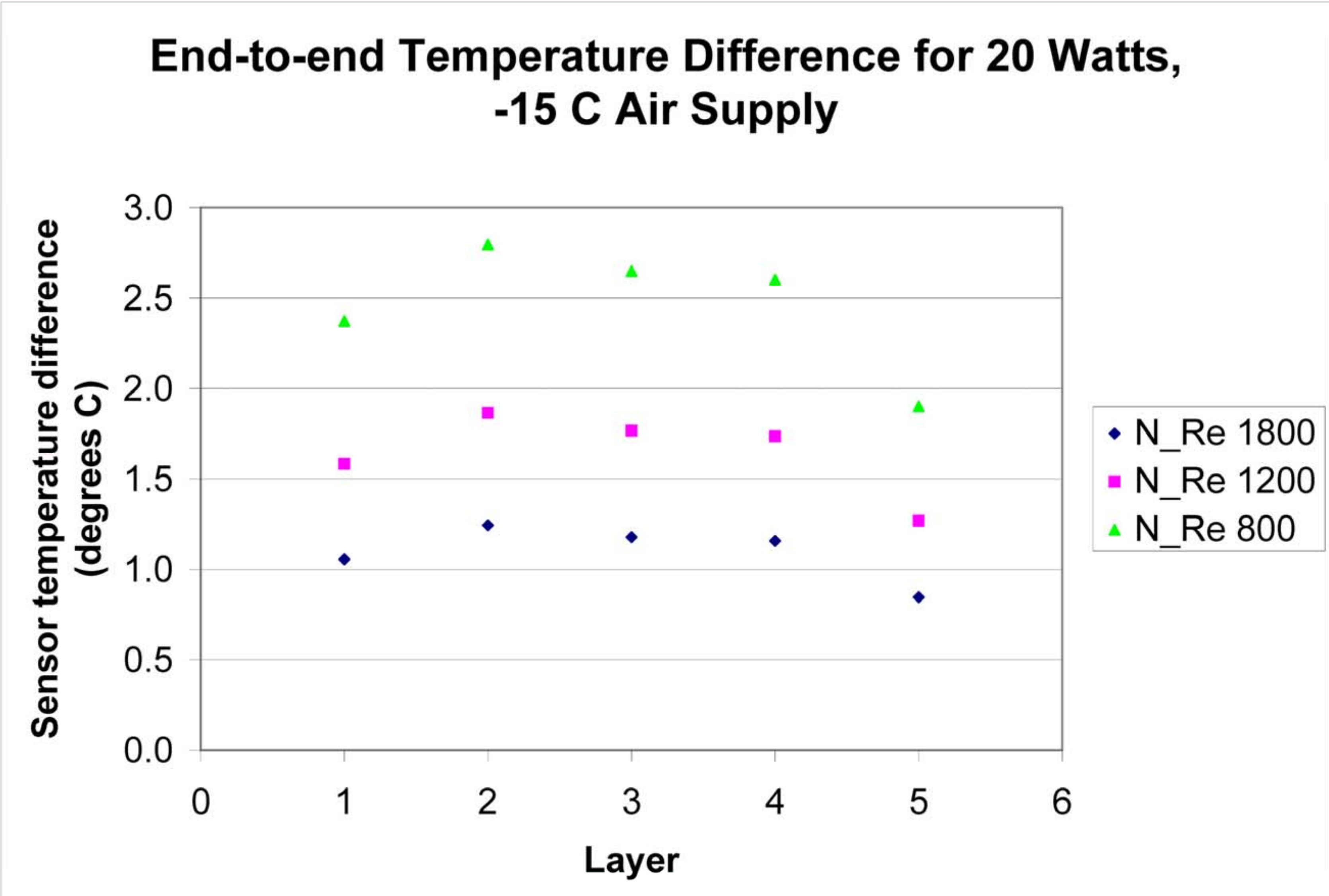
Reynold's number	Total barrel flow (g/s)	Ave. ΔT air (°C)	Max sensor T (°C)
800	9.0	2.21	-2.44
1200	13.5	1.47	-4.61
1800	20.2	0.98	-6.36

- For N_{Re} = 1800 and maximal openings in end membranes, average velocity = 1.7 m/s; maximum velocity (between L1 and the beam tube) = 4.6 m/s.
- Results as a function of layer are shown on the transparencies which follow.

VXD Barrel Cooling

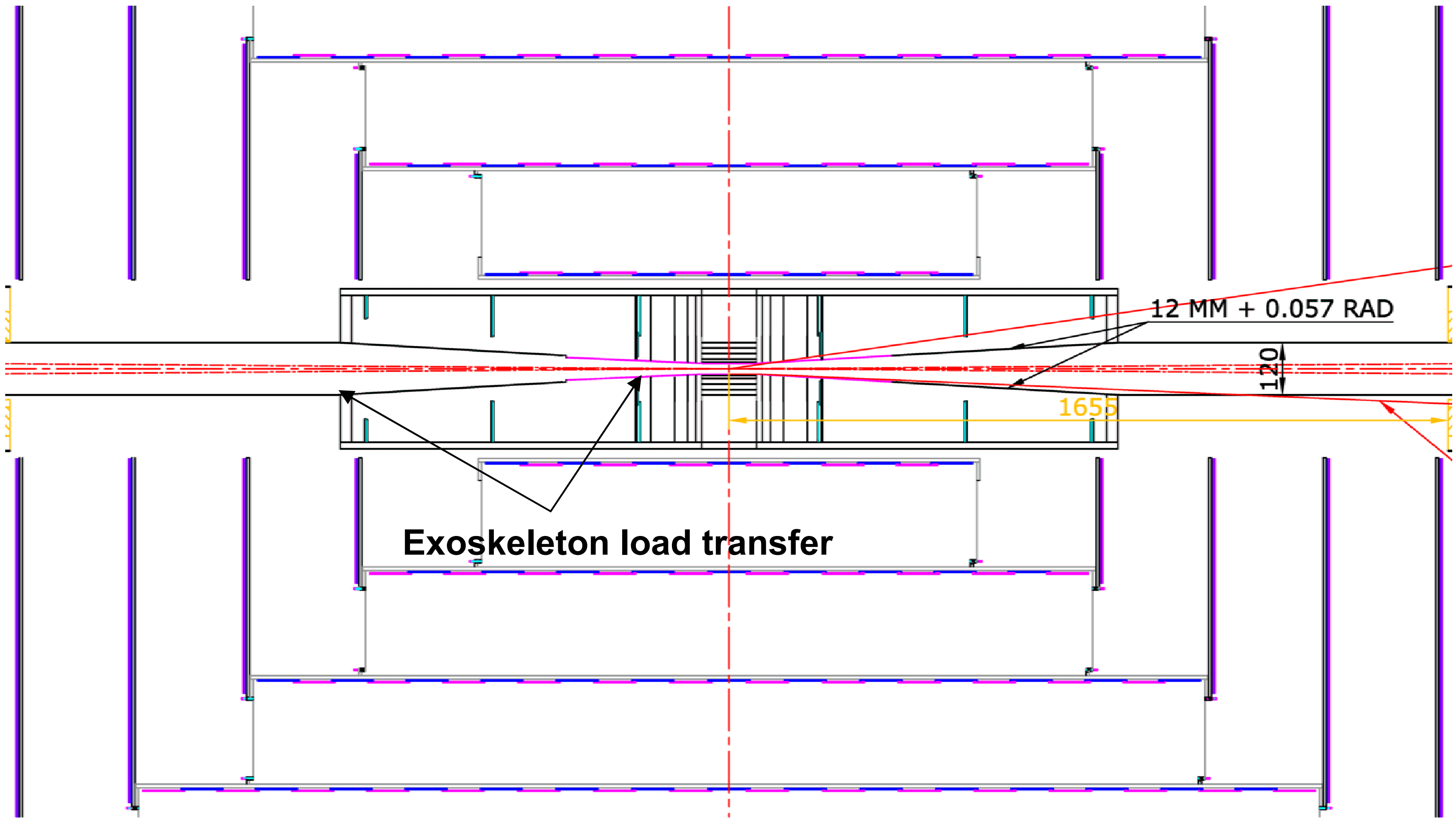


VXD Barrel Cooling



SiD Vertex Detector & Beam Pipe Support

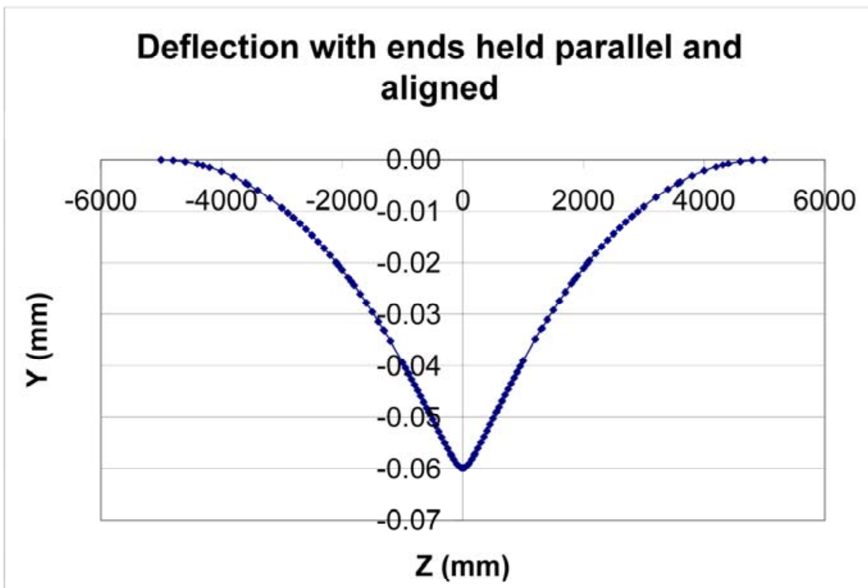
- The CF laminate exoskeleton not only supports the vertex detector from the beam pipe, it also holds the small radius, beryllium portion of the beam pipe straight.
- Both the beam pipe and the exoskeleton bend in the process.



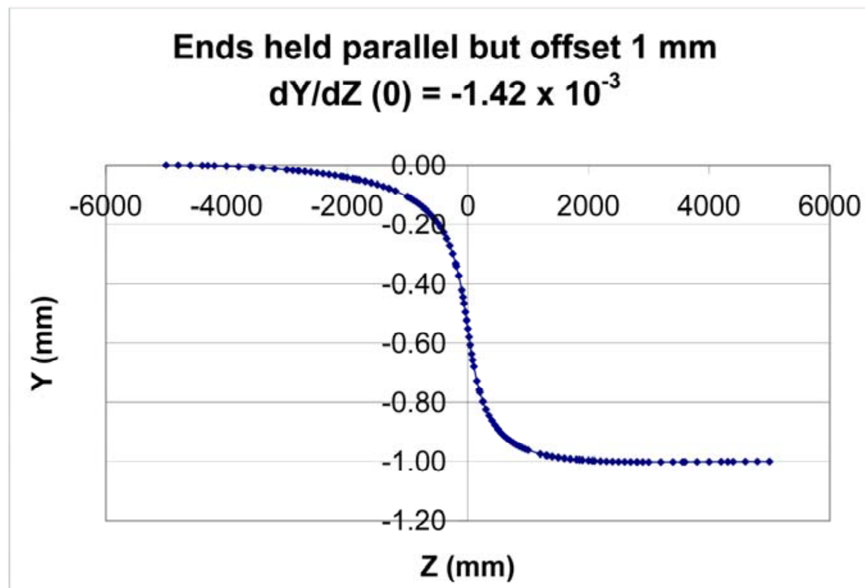
Beam Pipe Deflections

- For these calculations, an all-beryllium beam pipe was assumed.
  - Wall thickness of 0.25 mm was assumed in the central, straight portion.
- The radius of conical portions was assumed to increase with dR/dZ = 17/351.
  - Wall thickness in the conical portions was chosen to correspond to collapse at slightly over 2 Bar external pressure.
- An inner detector mass of 500 g was assumed to be simply supported from the beam pipe at Z = ± 900 mm.

Inner detector weight contributes ~ 0.008 mm.

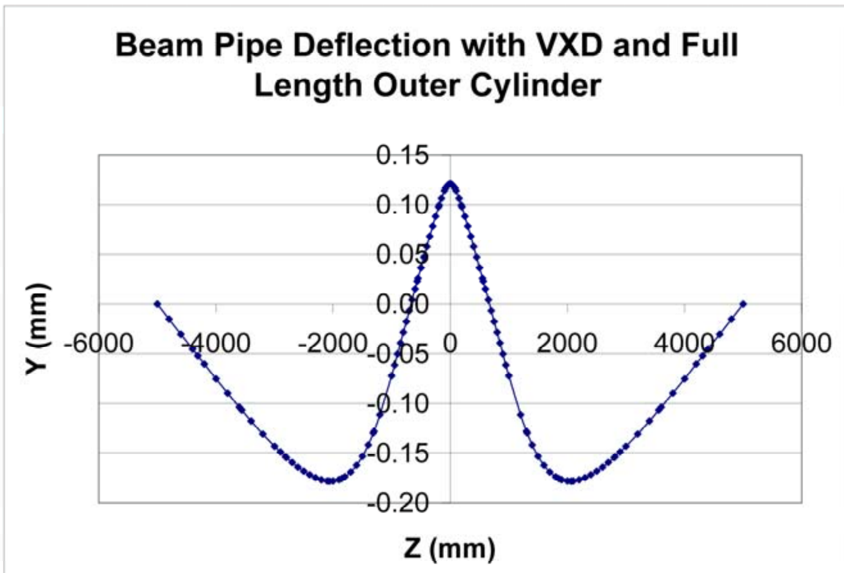


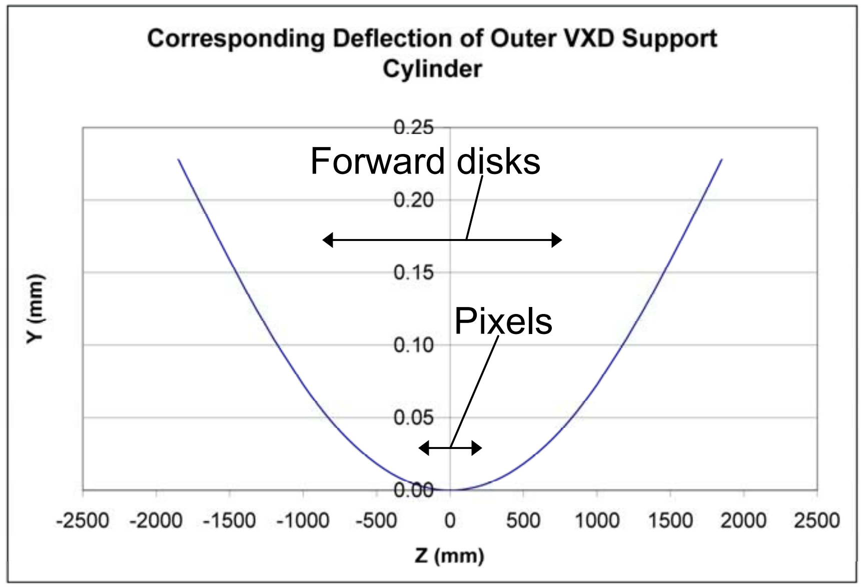
Maximum stress ~ 20 MPa



Beam Pipe Deflections

- A basic assumption has been that the beam pipe would be guided, not just simply supported, at its ends.
- If one assumes that the beam pipe would be simply supported (more realistic), then the outer support cylinder for the vertex detector could be extended to ±1.85 m.
- Connect to beam pipe at ±1.85 m and ±0.90 m (not optimized).





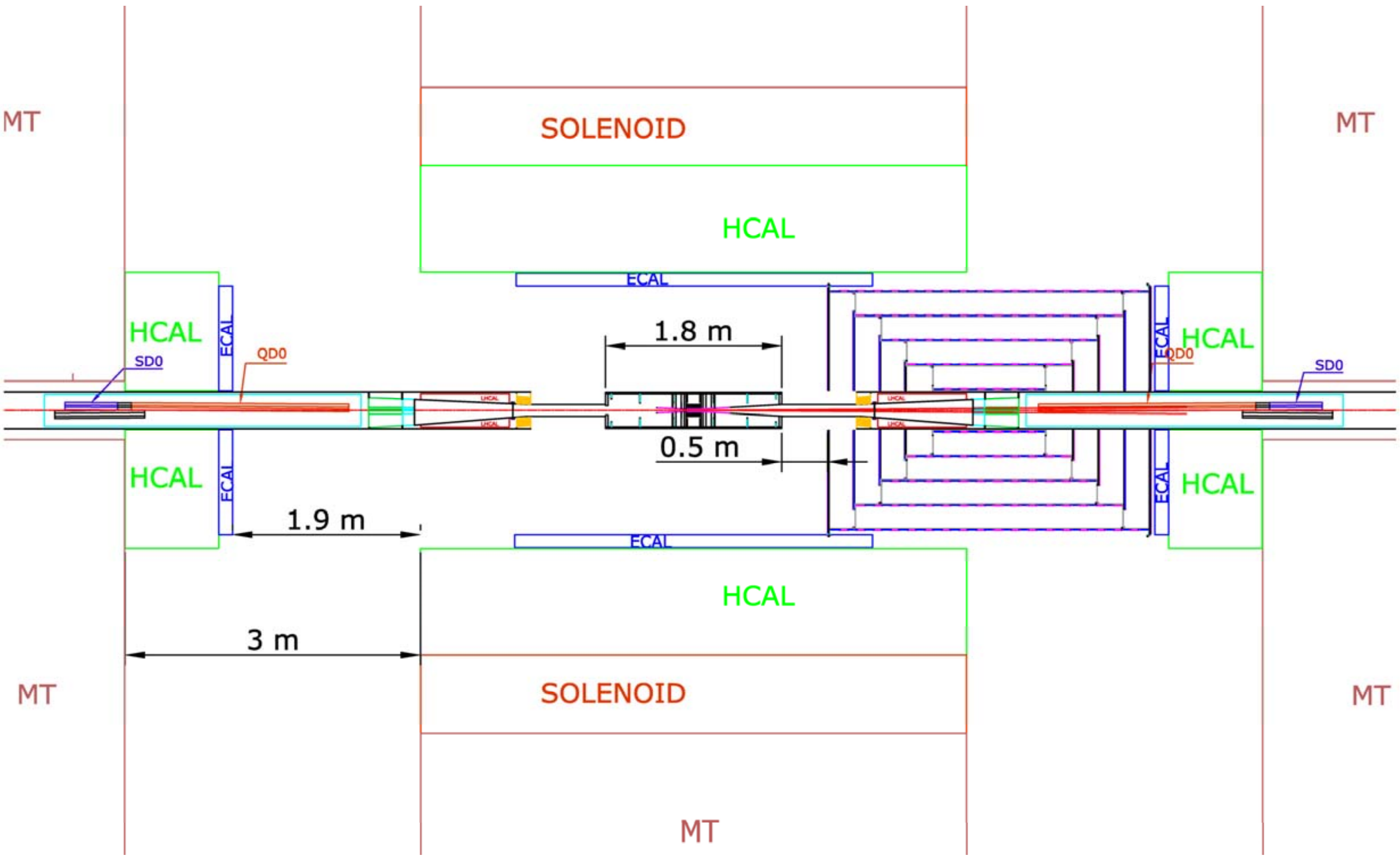
- Calculations remain to be made with a beam pipe which is partially of denser material, such as stainless steel.

SiD Geometry of Beam Pipe Region

- Beam pipe geometry for SiD is driven by vertex detector, outer tracker, forward calorimeter, and servicing considerations.
  - The vertex detector is assumed to be supported from the beam pipe.
    - To allow a beam pipe inner radius of 12 mm in the central region, bending of the beam pipe is controlled via an exoskeleton.
    - The exoskeleton, based upon carbon fiber laminate, also supports and positions vertex detector sub-assemblies.
  - The boundary between the outer tracker and vertex detector ($R \approx 200$ mm) allows the outer tracker to be moved longitudinally for vertex detector removal or servicing.
  - In the forward direction, the shape of the beam pipe must accommodate forward calorimetry requirements.

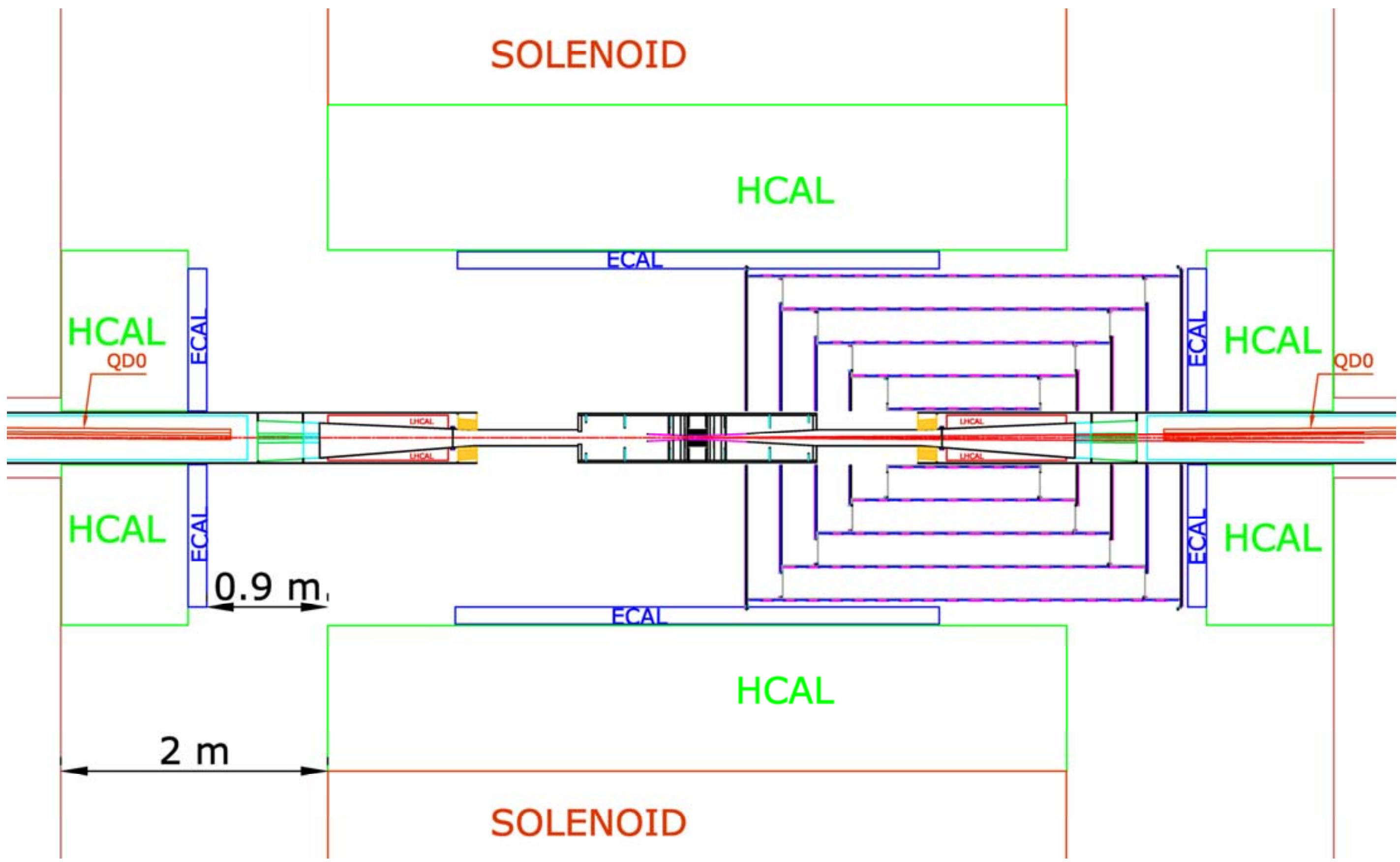
Servicing Vertex Detector & Tracker (SiD)

- Detector open 3 m for off-beamline servicing
- Vertex detector can be removed / replaced.



Servicing Vertex Detector & Tracker (SiD)

- Detector open 2 m for on-beamline servicing
- Access is limited to the ends of the outer tracker and outer surfaces of vertex detector support structures.



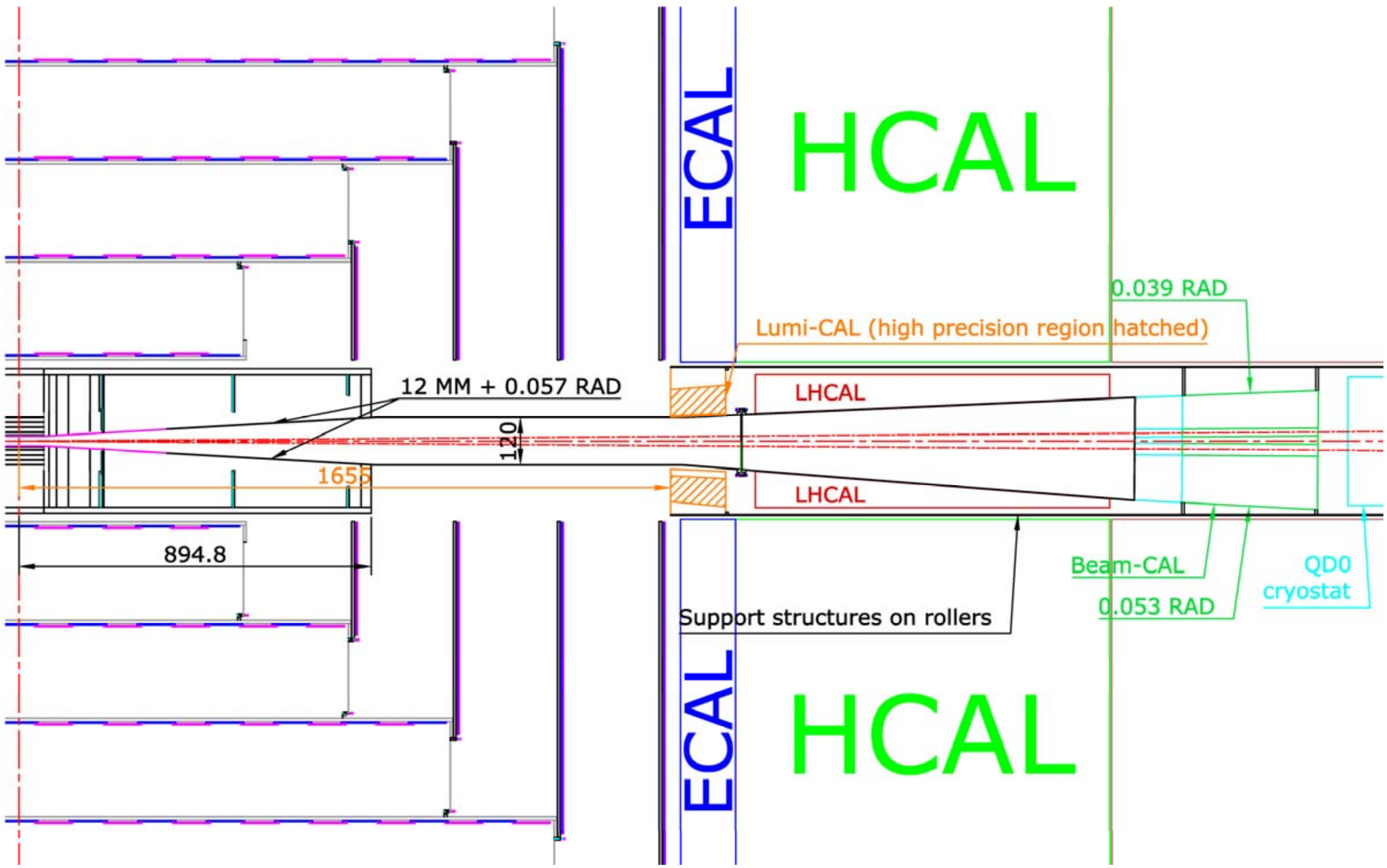
SiD Forward Region

- Very useful discussions at SLAC during IRENG07
- The general layout of forward calorimetry follows parameters provided by Bill Morse and concepts suggested by Tom Markiewicz.

LumiCal inner edge	≈36mrad about outgoing
LumiCal outer edge	≈113mrad about 0mrad
LumiCal fiducial	≈46-86mrad about outgoing
BeamCal outer edge	≈46mrad about outgoing
LumiCal	$30X_0$ Si-W
BeamCal	$30X_0$ rad-hard Si,diamond....

SiD Beam Pipe

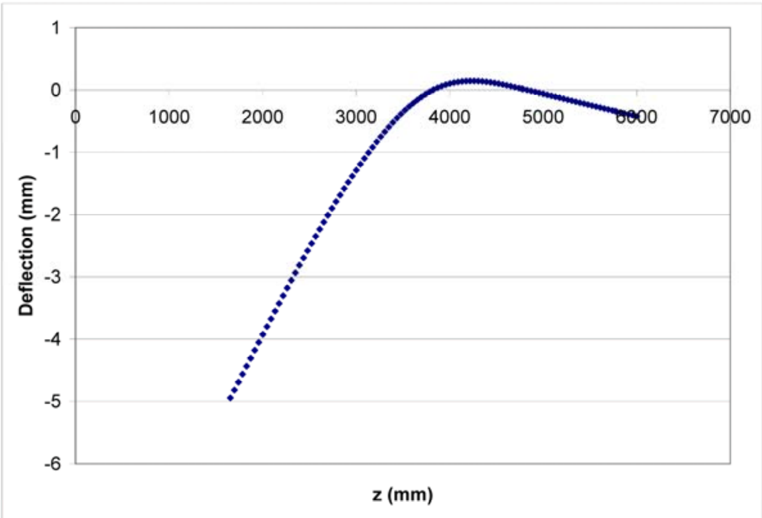
- The beam pipe shape in the forward region is shown below.

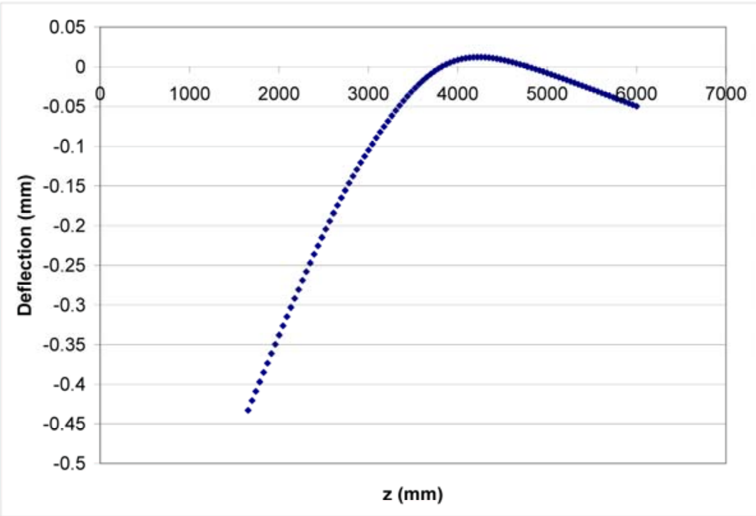


Deflections of Forward Elements when Open 2m

- Support points with rollers were assumed at front and rear of HCAL (Z = 3820, 4770 mm).
- Forward calorimeters supported at their ends as dead weights
- QD0 weight ignored

4 - 20 mm x 20 mm bars	Stepped cylinders (3, 10, 20 mm walls)
Deflection at front of Lumi-CAL = 4.9 mm	Deflection at front of Lumi-CAL = 0.43 mm
Stress in bars = 12.7 ksi	Stress in cylinders = 1.0 ksi

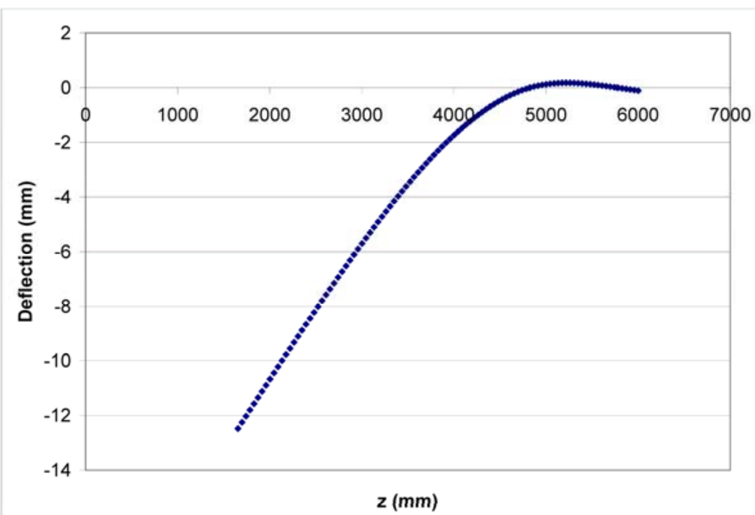


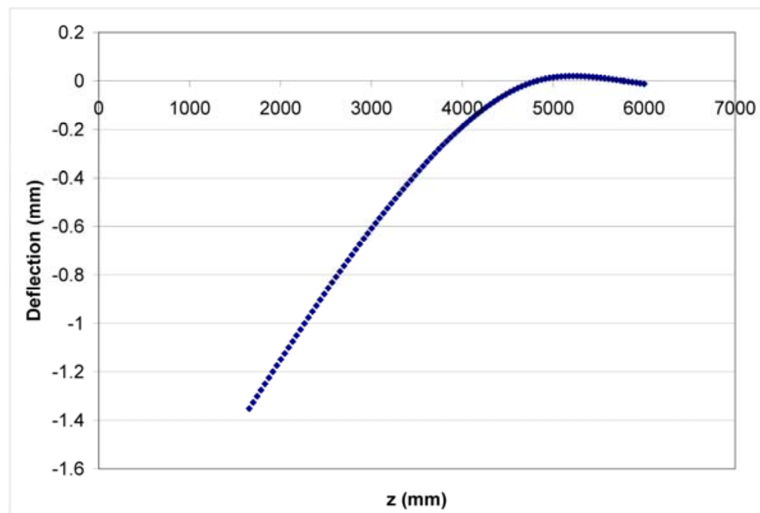


Deflections of Forward Elements when Open 3m

- Support points with rollers were assumed at front and rear of HCAL (Z = 4820, 5770 mm).
- Forward calorimeters supported at their ends as dead weights
- QD0 weight ignored

4 - 20 mm x 20 mm bars	Stepped cylinders (3, 10, 20 mm walls)
Deflection at front of Lumi-CAL = 12.5 mm	Deflection at front of Lumi-CAL = 1.4 mm
Stress in bars = 16.6 ksi	Stress in cylinders = 1.8 ksi



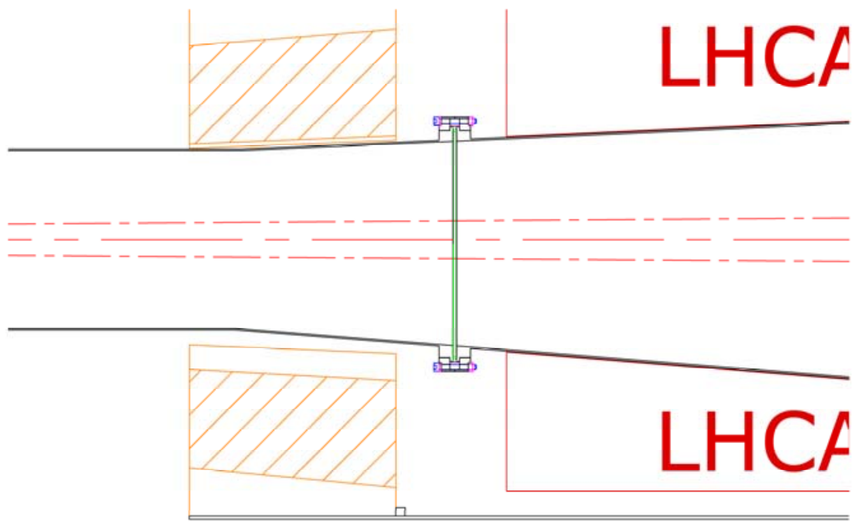


Comments on Supports

- Based on these initial calculations, cylinders, rather than bars, are likely to be needed.
  - Multiple beam pipe bellows may be necessary with support via bars.
  - Running tie rods from the front of Lumi-CAL to the central HCAL would help.
    - Dealing with them during servicing would present issues.
    - They probably would not be needed with support via cylinders
- Bellows to address alignment and thermal contractions of the beam pipe are likely to be needed in any case.
- Laser interferometry between the central ECAL and the beam pipe could be used to monitor alignment in the closed position and as the detector is opened.

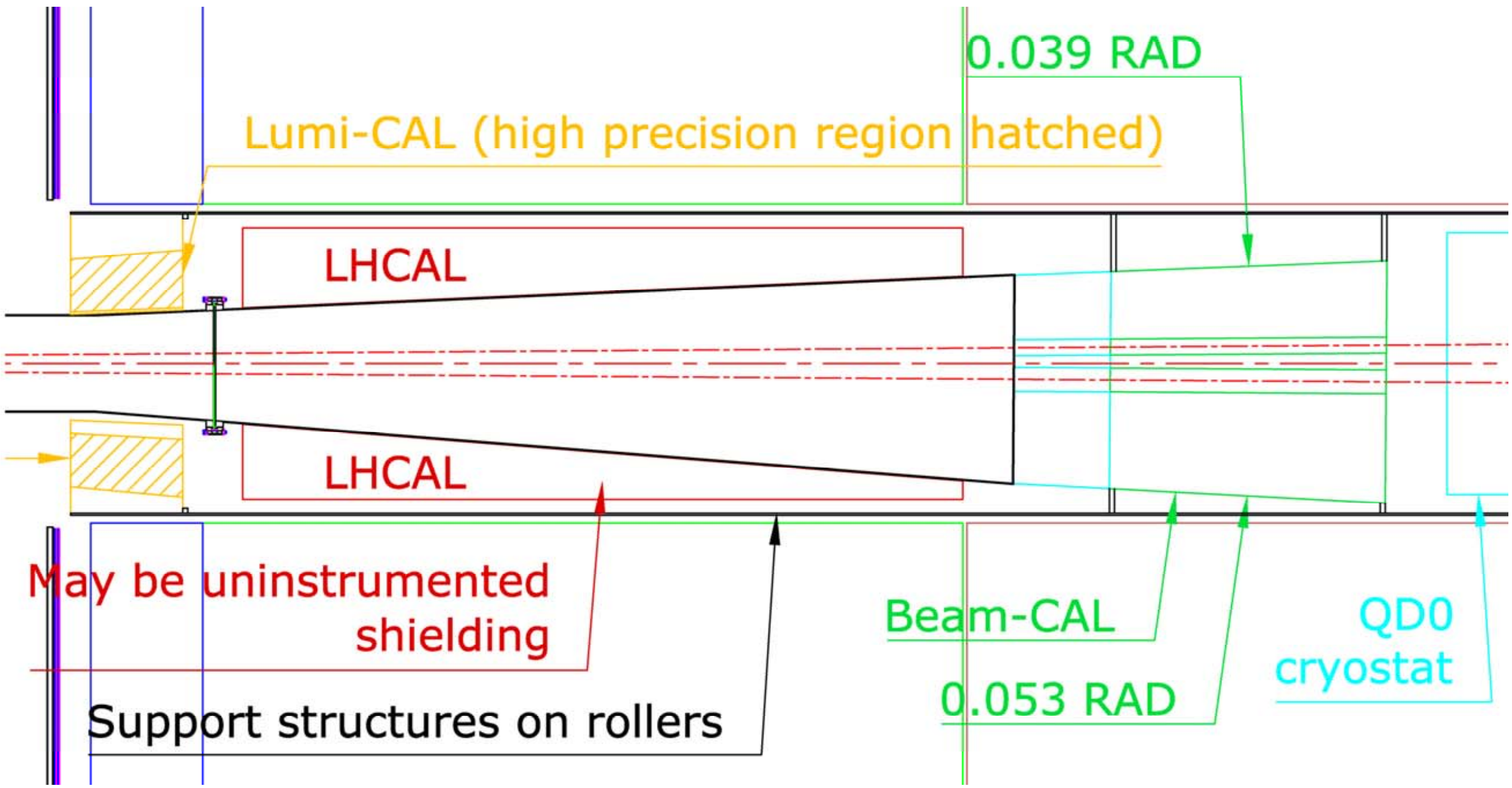
Beam Pipe Flanges

- Flanges and bellows assemblies will be needed.
- A low profile split flange is shown after Lumi-CAL.
- The flange design was scaled from one in use at DZero.
- The flange material is in the Lumi-CAL shadow, but that location presents other issues.
  - Disconnecting the flange would require Lumi-CAL removal.
  - Lumi-CAL support bars or cylinders probably need to end at the back face of Lumi-CAL to allow the beam pipe to be removed.



Support of Forward Calorimeters

- Deflection calculations have been made for two types of support:
  - Bars at 3, 6, 9, and 12 o’clock
  - Cylinders of stepped wall thickness



Questions to Be Investigated

- Are there special beam-related requirements for bellows assemblies?
- What are cable paths for the vertex detector and forward calorimetry?
- Where should bellows and flanges be located?
- What are the advantages and disadvantages of the straight sections of beam pipe upstream of Lumi-CAL?

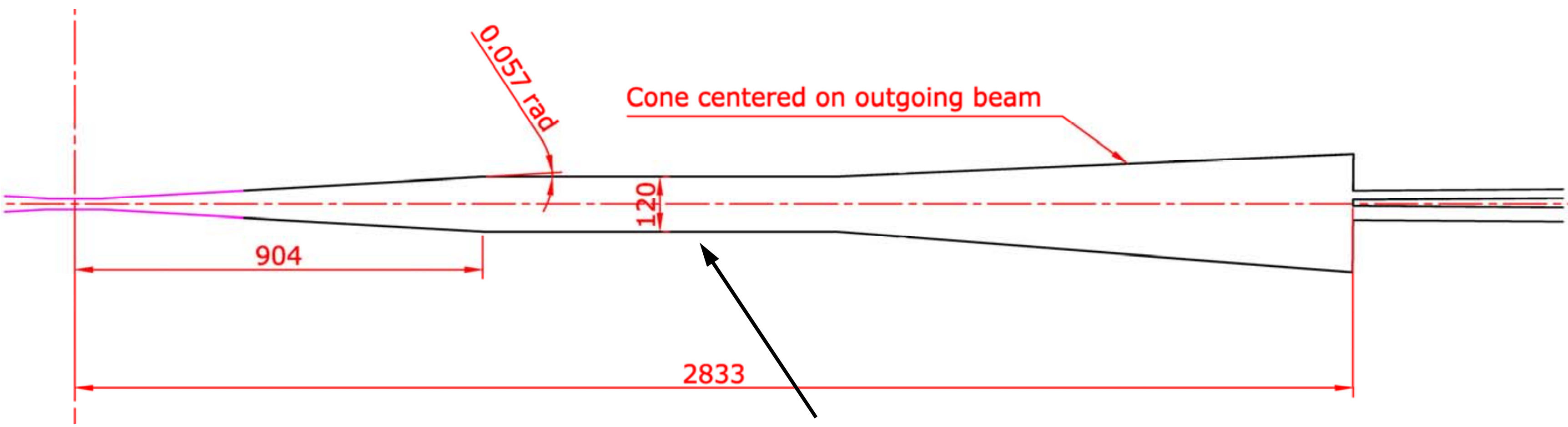
Tentative Beam Pipe Materials for SiD

Z (mm)	Material	IR (mm)	Wall (mm)
<62.5	Be	12	0.4
62.5 to 379	Be	12+0.0571*(Z-62.5)	0.7
379 to 904	SS	12+0.0571*(Z-62.5)	1.07
904 to 1688	SS	60	1.07
1688 to 2833	SS	60.04+0.0614*(Z-1688), centered on outgoing beam	2.23 (to be confirmed)

- Support connections to exoskeleton at Z = ± 214, ± 882 mm
- A titanium liner of thickness ≈ 0.025 mm is assumed in the central region. Extent in Z remains to be determined.

Beam Pipe Fabrication

- The present SiD design assumes stainless steel beyond Z = 759 mm.
  - That allows more standard welding and fabrication techniques.
  - Requirements are not so different from those of other detector concepts.
  - Beryllium to stainless transitions should be done by the fabricator of beryllium portions, but the stainless steel portions could be made by a different vendor.
  - The feasibility of using other materials (beryllium, aluminum) in the BeamCAL region is under discussion.



This portion may need to be modified so that it either is centered on the outgoing beam or is conical.

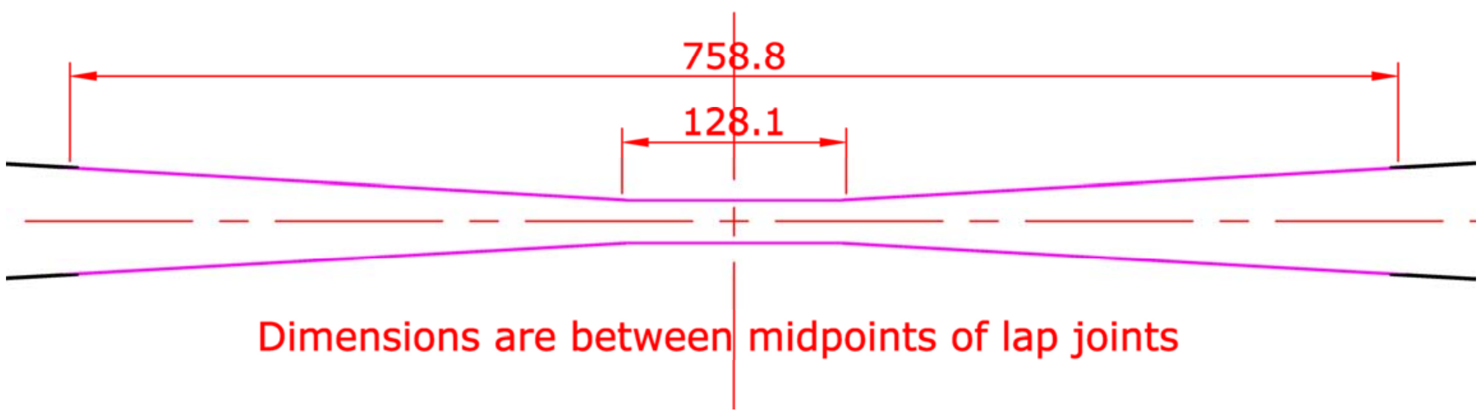
Beam Pipe Fabrication

- The main US fabricator of beryllium beam pipes is Brush-Wellman Electrofusion.
- Historically, their beam pipes have been made of rolled material with a brazed longitudinal joint the full length of the pipe (splitter joint with aluminum braze and an additional beryllium strip).
- Recent beam pipes have been made from billet and have no longitudinal joint.
  - Length of a segment of beam pipe has generally been limited to 0.75 m.
  - Segments of a longer pipe are connected via circumferential electron-beam-brazed half-lap joints.
  - Requirements for the SiD central straight pipe are comparable to those for the existing D0 straight pipe (CDF pipe is similar, but longer).
- Z-extent, fabrication, and addition of the titanium liner need to be understood.

	IR (mm)	Wall (mm)	Beryllium length (mm)
D0 (3 segments)	14.22	0.51	1750 = 750 + 500 + 500
SiD central	12.00	0.40	128

Beam Pipe Fabrication

- We think that SiD conical beryllium portions could also be made from billet, but that machining the cones and developing fixturing to align and connect them to the central straight portion will require R&D.
  - Present length of each of two conical portions = 315 mm
  - Estimated wall thickness = 0.7 mm
  - Overall beryllium length = 759 mm
  - Maximum cone radius = 30.5 mm
  - Note that the area of a cylindrical billet is a factor of ~ 4.5 larger than for D0 ➔ higher cost per unit length.
- Fabricating the entire beryllium portion from a single billet may also be possible, but would be more of a challenge and require a greater R&D effort.



Near-term Design Studies

- Carbon fiber laminate CTE relative to silicon & CME
  - Thermal distortions between assembly temperature and operating temperature
  - Measurements of CTE via strain gage techniques (University of Washington) and via thermal bowing of “bi-metallic” carbon fiber laminate – silicon strips (Fermilab)
  - Control of moisture in assembly and operating environments
- Assembly of models at SiDet
  - Continue modeling barrel layers with silicon supported from CF
  - Develop and test fixturing for “all-silicon” layers
  - Modify fixturing to accommodate cables and investigate cable stiffness and connections
- Detailed beam pipe support, shape, and fabrication methods
  - Integration with the geometry of forward calorimeters
  - Integration with supports for forward calorimeters and beam line elements
  - We propose contacting Brush-Wellman Electrofusion to check feasibility & cost of beam pipe fabrication.

Plans / Costs

- Kurt Krempetz will describe future plans and costs.

Back-up Slides Follow

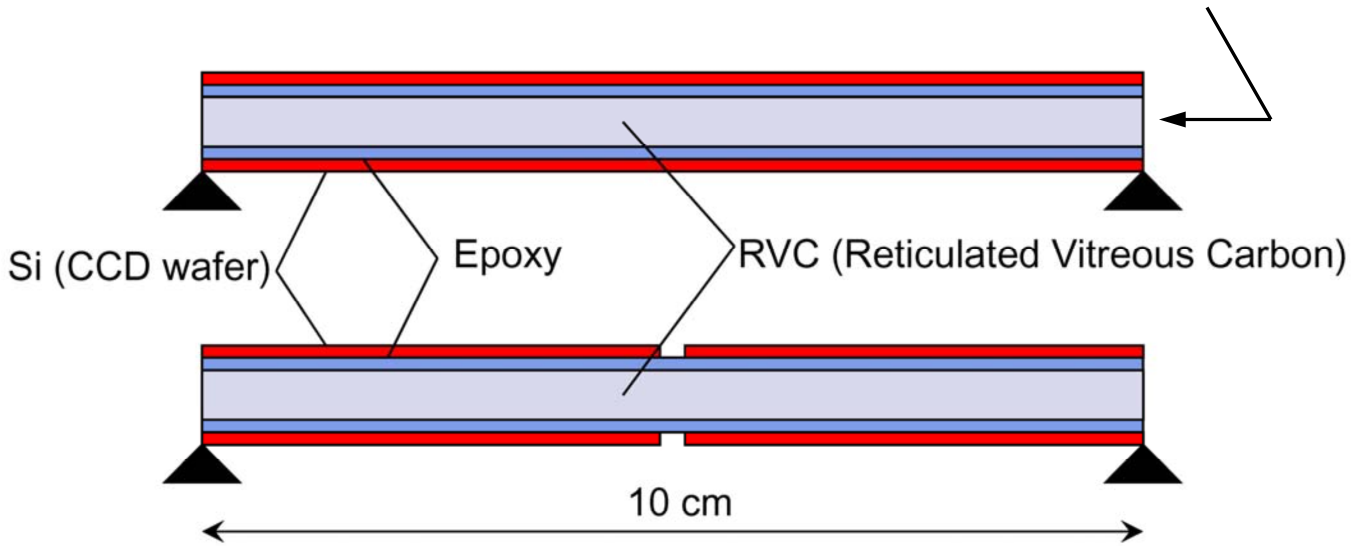
Yasuhiro Sugimoto, 7/24/07

FEA of Ladders

Deflection:

0.54 μm for 100 mm length

~8.6 μm for 200 mm length



Deformation by self-weight is calculated by FEA program COMSOL

9

Yasuhiro Sugimoto, 7/24/07

Material budget allows 50 µm silicon, which may simplify handling during fabrication.

FEA of Ladders

- Parameters (assumption)

	Density (g/cm^3)	X0 (g/cm^2)	E (GPa)
Si	2.33	21.8	110
Epoxy	1.15	40.9	3
RVC	0.05	42.7	0.031

- Geometry

	Thickness	Weight	Radiation length
Si	50 µm	0.01165 g/cm^2	0.0534%X_0
Epoxy	50 µm	0.00573 g/cm^2	0.014%X_0
RVC	2 mm	0.0084 g/cm^2	0.0234%X_0
Epoxy	50 µm	0.00573 g/cm^2	0.014%X_0
Si	50 µm	0.01165 g/cm^2	0.0534%X_0
Sum		**0.04316 g/cm^2**	**0.1582%X_0**

0.08%X_0/layer

10

Thickness allows initial determination of track vector

Vertex Detector Design Concepts

- A significant portion of our efforts have gone towards vertex detector geometry and integration of the vertex detector with surrounding detectors.
  – The overall vertex detector concept forms the foundation for more detailed R&D investigations.
- We note that most baseline designs have assumed the vertex detector and associated support structures would be split at the equator and clamshell around the beam pipe.
  – That allows them to be installed or removed without disconnecting the beam pipe.
- An alternative would be to assemble the vertex detector around the beam pipe in a clean room, then install the completed (and tested) vertex detector / beam pipe assembly.
  – Work on a spare assembly could begin immediately after completion of the first.
  – A spare beam pipe is implied, but having one on hand may be wise in any case.
  – Flanges outboard of the vertex detector support structure and inboard of Lumi-CAL appear to be necessary in this option.
- Given push-pull detectors in which beam pipes are regularly disconnected, reconsideration of baseline choices may be warranted.

Beam Tube Heating

- Heat is assumed to be intercepted at locations yet to be determined, but outside the vertex detector support structure in Z.
- From the talk of H. Yamamoto at IRENG07:
  - Image current heating is estimated to be 0.075 watt/m assuming a skin depth corresponding to that of copper.
  - HOM loss by an iris of a=1cm to b=10cm is estimated to be 5.6 watts.
  - Losses associated with H-Cal and Beam-Cal apertures are estimated to be 22.4 watts.
- This will need to be watched and checked once a more detailed beam pipe geometry has been determined.