Low-Mass Tracker Mechanics

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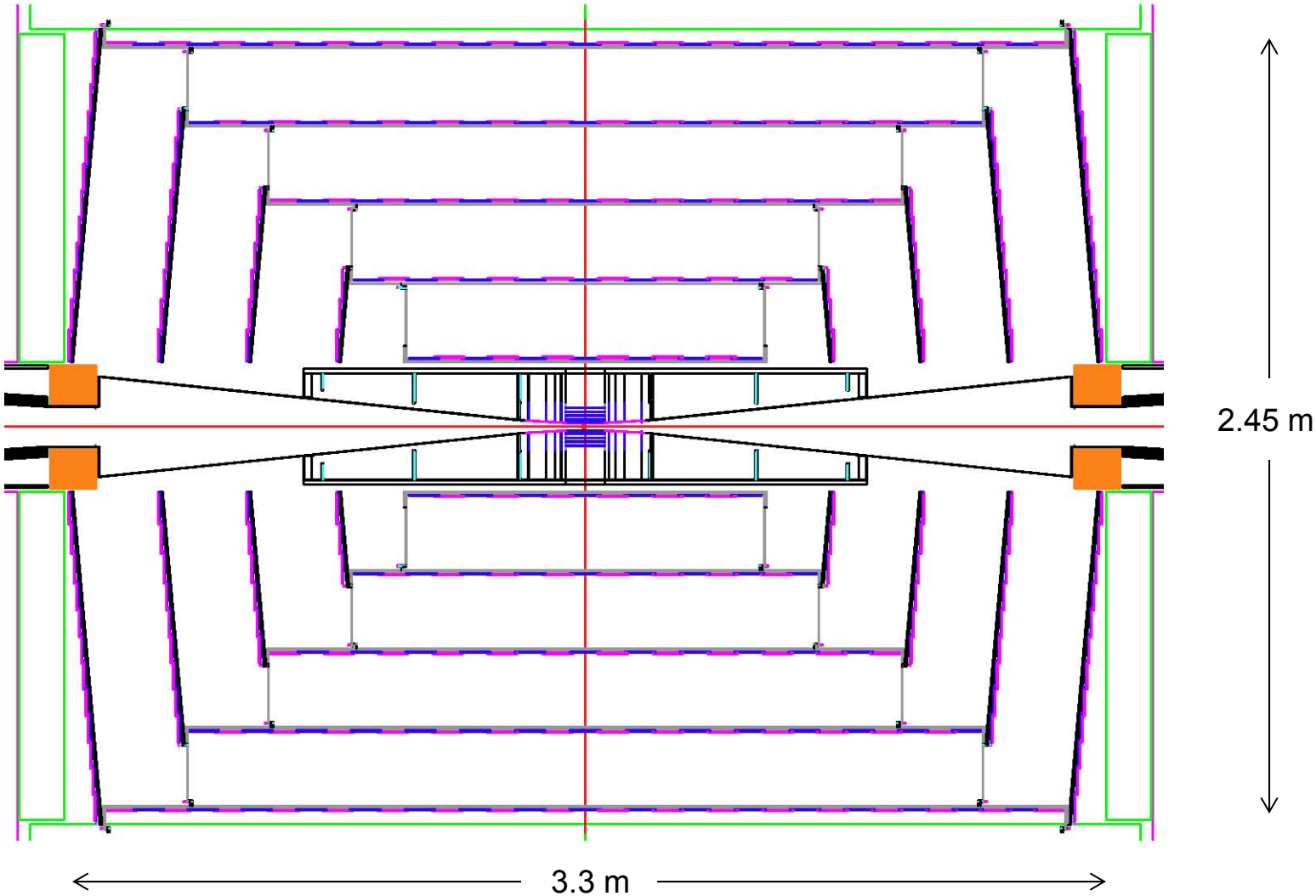
Introduction

- A few detector designs provide examples.
  - Some may be more relevant to Project X than others.
- SiD silicon tracker and vertex detector for the ILC
  - 5T solenoidal field
  - Relatively low occupancies at the ILC allow simplified tracking in which five barrel layers measure, to first order, only the r-ϕ coordinate.
    - Constraints in z are provided by noting in which sensor hits occurred (±50 mm).
    - A variant of this design would use charge division readout from each sensor to improve this constraint to ~ ±10 mm (but with more readout channels, power, and slightly more material).
  - Tracks found in the r-ϕ projection are joined with 3-D tracks from the vertex detector and matched with hits in calorimetry.
  - The barrels improve the P_T measurement of the vertex detector , and allow tracks to be extended outward to calorimetry and the muon system.
  - Four disks per end with small angle stereo provide true 3-D hits on each track.
- Beam structure and anticipated power dissipations allow forced air cooling of both the SiD tracker and vertex detector.

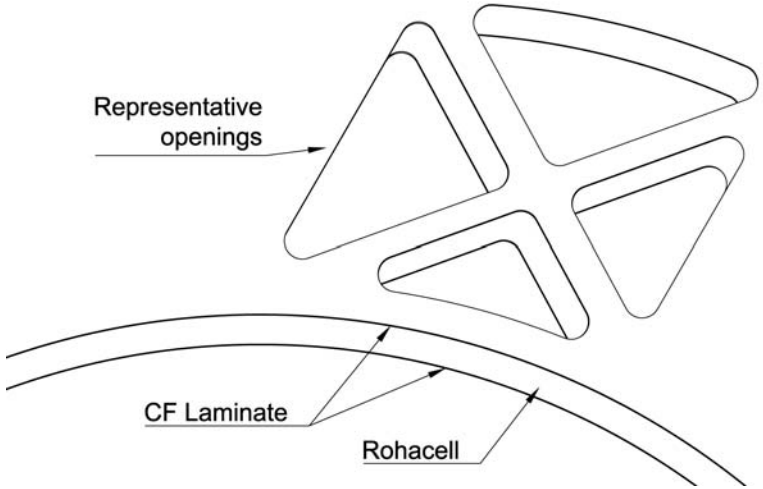
SiD Tracker / Vertex Detector Geometry

- Tracker modules are supported on carbon fiber barrels and shallow cones; vertex detector is supported independently (from beam pipe).

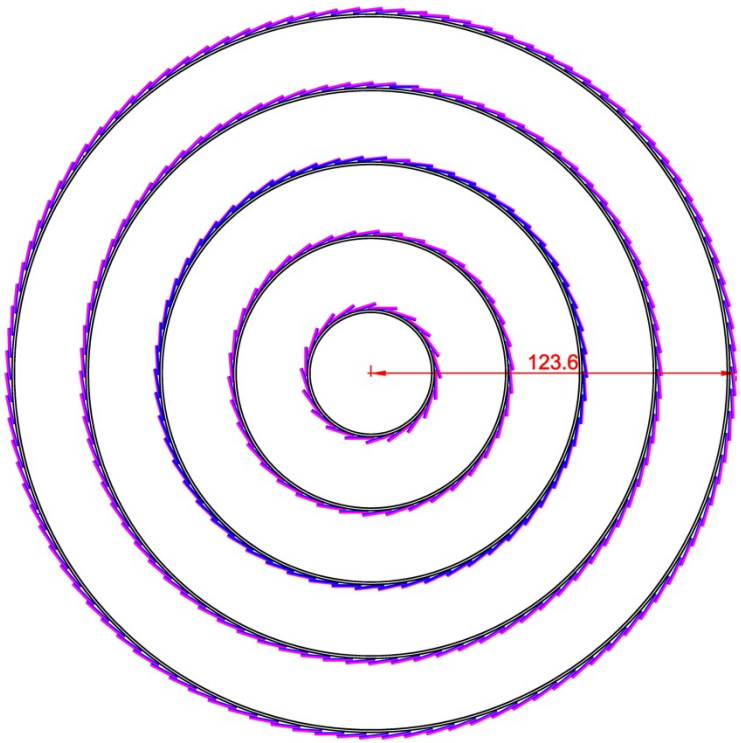


SiD Tracker Support Cylinders

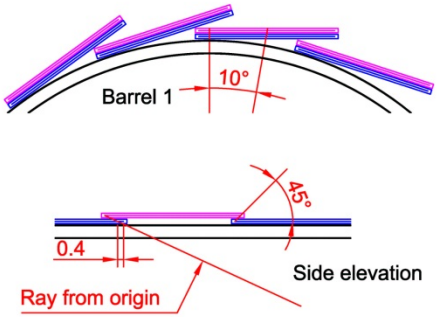
- Carbon fiber - Rohacell - carbon fiber support cylinders were developed for the D0 fiber tracker.
  - Similar cylinders were used by ATLAS for silicon support.
- The two carbon fiber (CF) laminate layers (3 plies of Mitsubishi K1392U fiber per layer), in conjunction with a 8.9 mm Rohacell spacer, provide out-of-round stiffness (0.23% X0 total per cylinder).
- Longitudinal stiffness is provided by the carbon fiber itself.
- Carbon fiber laminate end rings with ball and cone mounts tie barrels to one another, help with out-of-round stiffness, and provide a location and support for power conditioning and distribution.
- Finite element analysis (FEA) gave a maximum (local) deflection from gravity of ~ 13 μm.
- Openings can be cut to reduce average material but were not assumed in the FEA.



Tracker Endview Geometry



Sensors:
Cut dim's: 9.35 cm x 9.35 cm
Active dim's: 9.20 cm x 9.20 cm
Modules:
Outer dim's: 9.65 cm x 9.65 cm x 0.3 cm
Support cylinders:
OR: 21.5, 46.5, 71.5, 96.5, 121.5 cm
Number of phis: 20, 38, 58, 80, 102
Tilt angles: 6.6 to 10 degrees
Radii normal to silicon (mm):
Barrel 1: 2.175, 2.215 cm
Barrel 2: 4.675, 4.715 cm
Barrel 3: 7.175, 7.215 cm
Barrel 4: 9.675, 9.715 cm
Barrel 5: 12.175, 12.215 cm
Blue and magenta sensors are at different Z's to provide longitudinal overlap.
Within a given barrel, cyan sensors overlap in phi, as do magenta sensors.

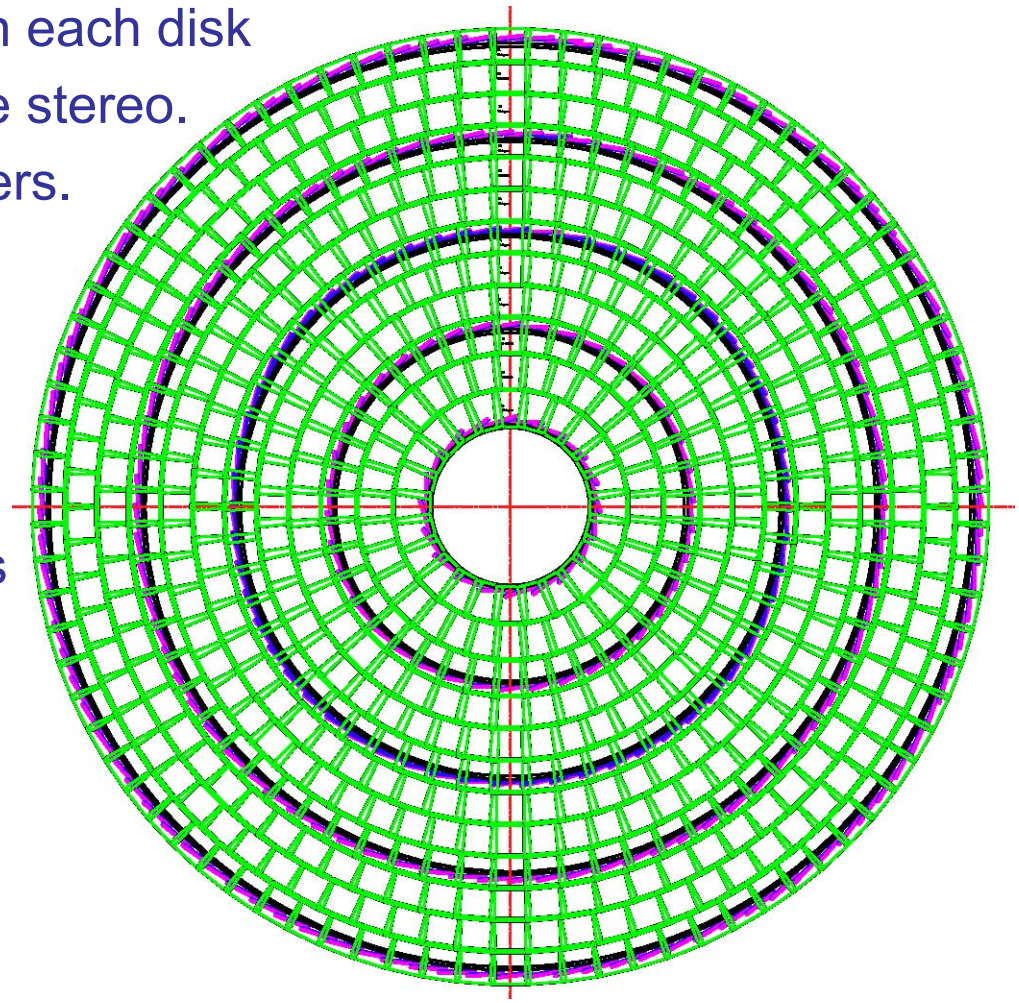


- Sensor modules will be described on a later slide.
- Single type of module for all barrel layers
- The drawings show sensors positioned mid-way through the thickness of a module.
- Closest separation between modules = 0.1 cm
- Modules are square
  - Outer dimensions = 0.3 cm x 9.65 cm x 9.65 cm
  - Sensor active dimensions assumed to be 9.2 cm x 9.2 cm

- SLAC has developed modules based on ~100 mm x 100 mm x 0.32 mm sensors and KPIX chips.
- Material budget ~ 1.1% X0 per layer at normal incidence including modules, support structures, and services.

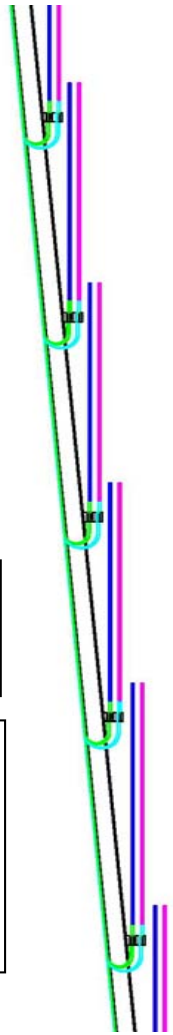
Tracker Endview Geometry

- R-ϕ projection of tracker barrels and disks:
- Only two types of modules are used in the disks.
- Two overlapping sensors in each disk module provide small angle stereo.
- Sensors come from 6” wafers.
- Except for outer radius, all four disks are identical.
- Precise ball and cone mounts support disks from barrels and connect barrels to one another.



Tracker Disk Geometry

- Modules are arrayed on conical surfaces, but are oriented perpendicular to the detector centerline.
- Each module carries back-to-back sensors to provide small angle stereo.
- Cones are double walled carbon fiber separated by Rohacell.
- Cables pass through the cone and are routed to the disk outer radius along its “inner” surface.

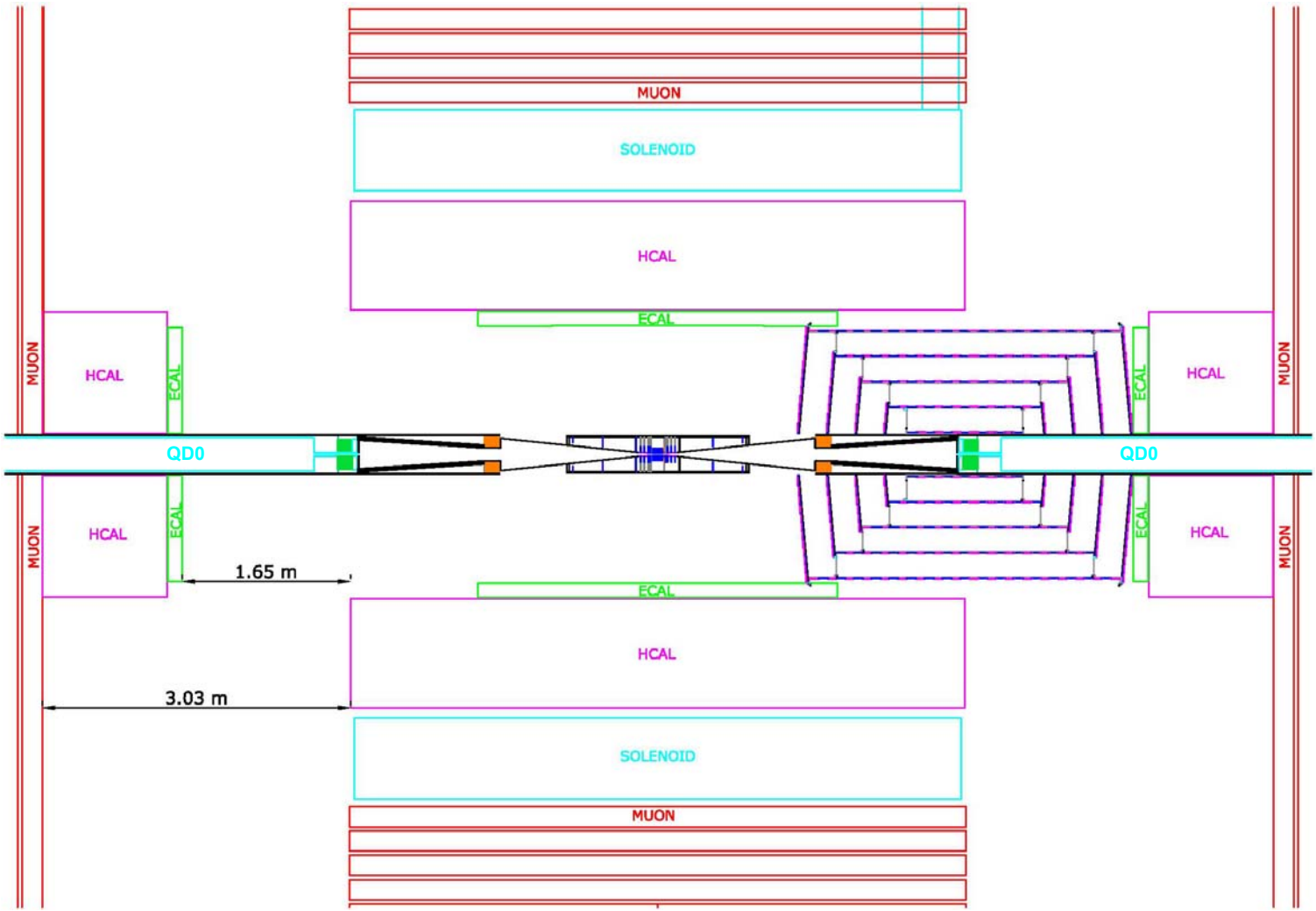


Side elevation of a portion of a disk

Blue and magenta modules are drawn at a common azimuth.
In practice, they would be at different azimuths to provide azimuthal overlap.

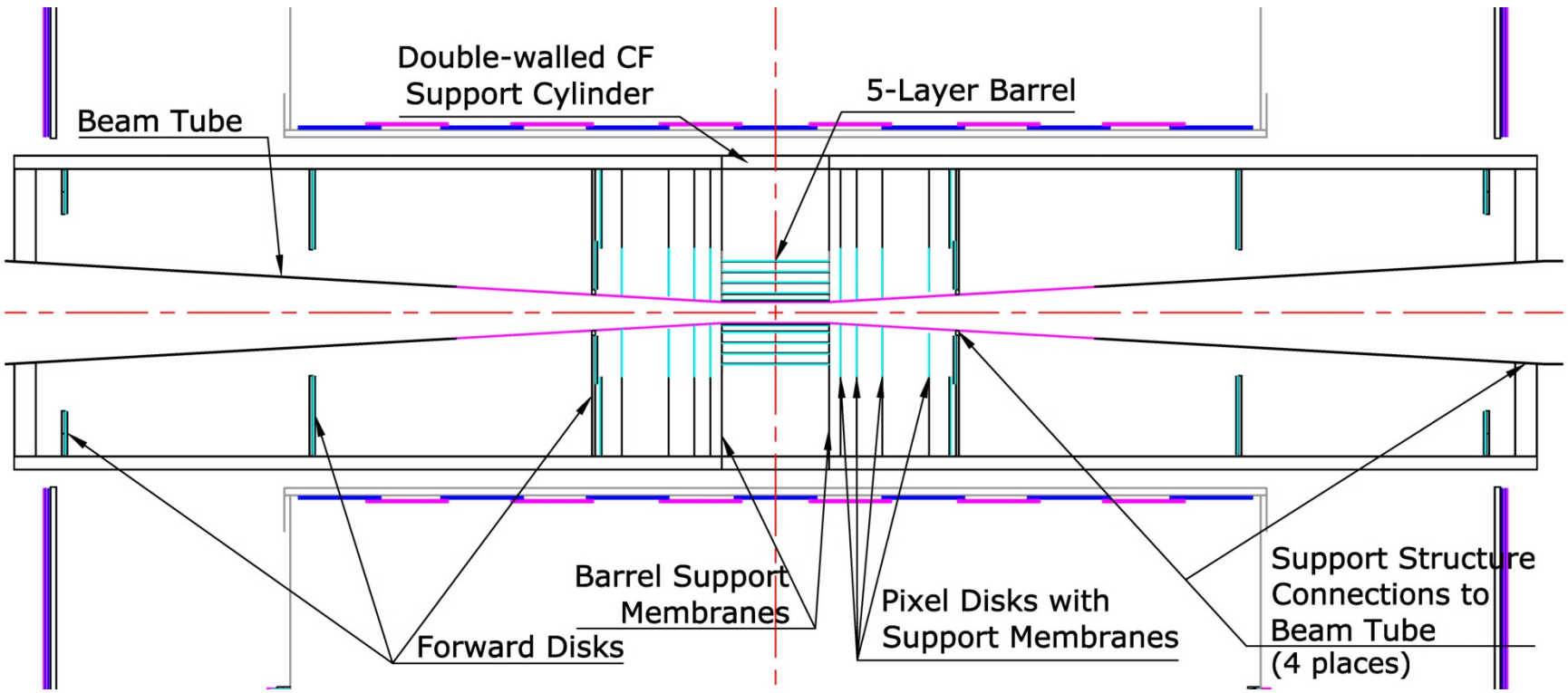
Servicing Vertex Detector & Tracker (SiD)

- The detector opens 3 m for servicing the vertex detector or tracker.
- Maintains beam pipe vacuum but constrains vertex detector support.



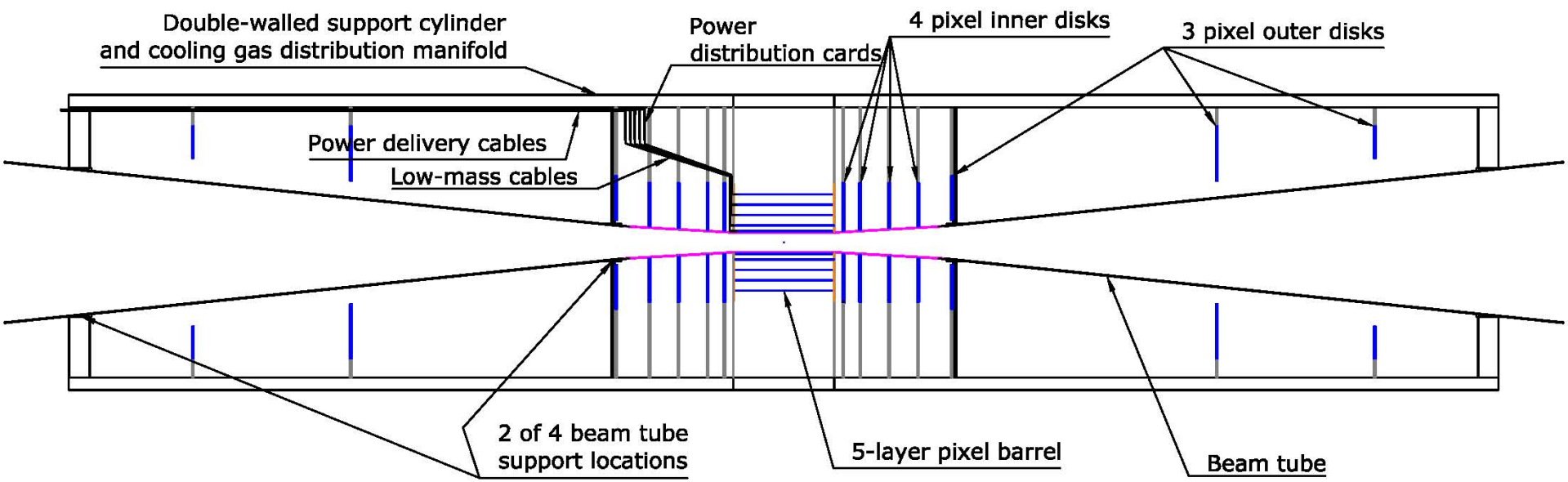
Vertex Detector Integration with the Beam Pipe

- The beam pipe inner diameter of 24 mm near Z = 0 presents a weak region in a fragile, beryllium structure.
- Bending and fracture are addressed by an exoskeleton of carbon fiber, which holds the beam pipe straight and supports the vertex detector.



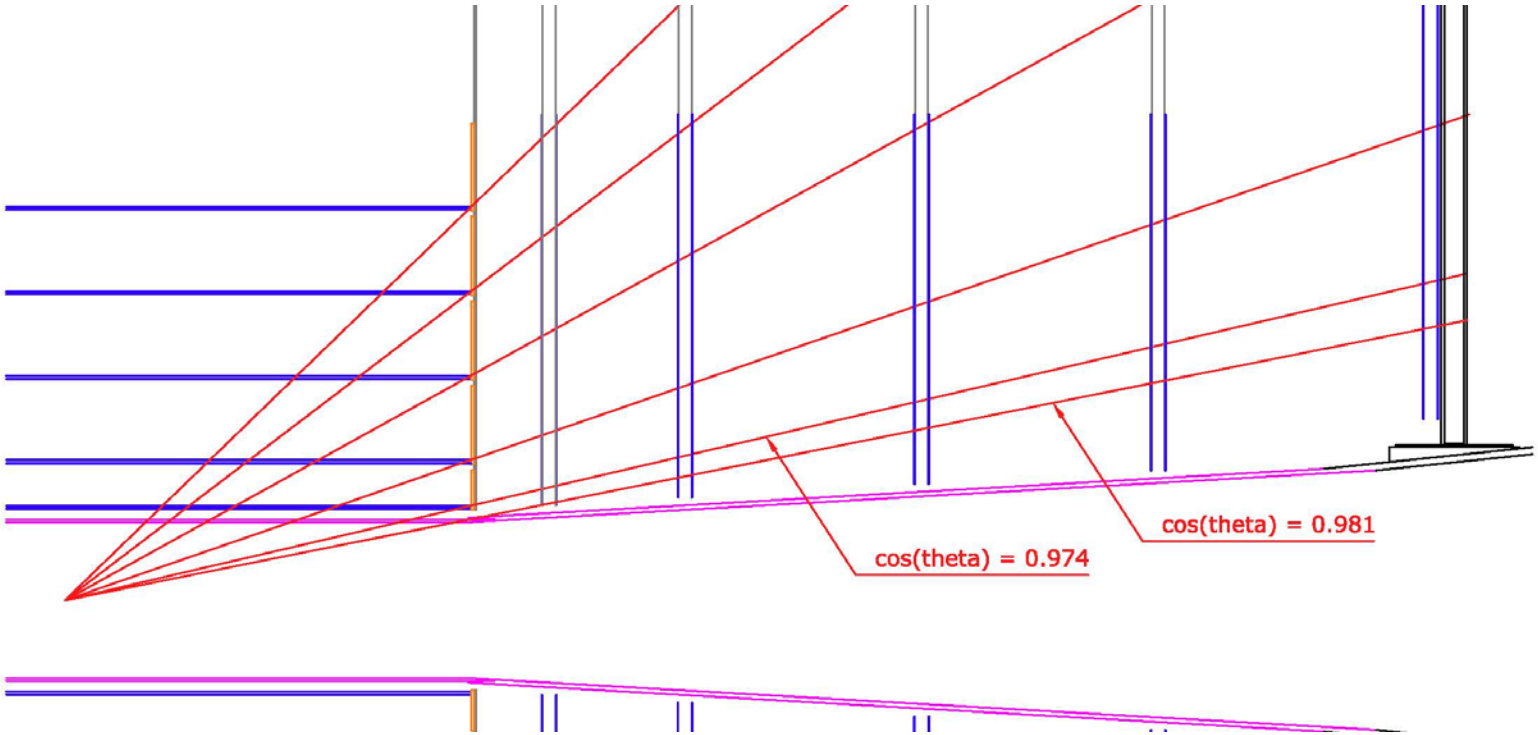
SiD Vertex Detector

- Central 5-layer barrel (~20 μm x 20 μm pixels)
- 4 pixel disks beyond each barrel end (probably the same pixel size as the barrel)
- 3 additional pixel disks per end, possibly with larger pixels, augment coverage of the Si tracker.
- Power delivery presents a challenge to the material budget.
  - DC-DC converters help with cabling from the outside world.
  - A proposed location with 30 cm cables after the converters is shown.



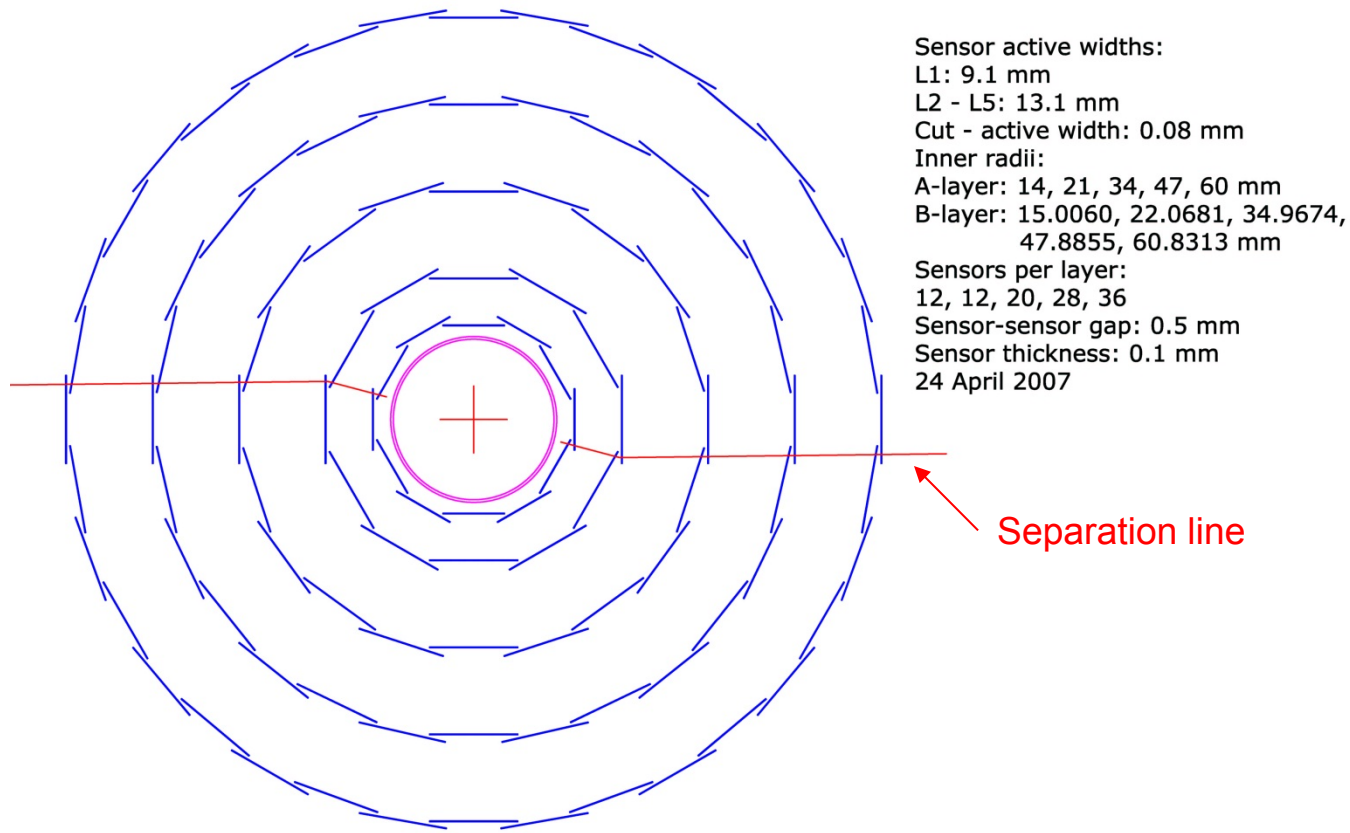
SiD Vertex Detector

- Pixel disks pick up coverage as coverage from barrel layers is lost.
- Originally, wedge-like disk sensors were imagined to alternate between support structure surfaces to provide azimuthal overlap.
- So-called “edgeless” sensors (under development) may reduce inactive distance between sensor reticules to a few microns, allowing all sensors of a disk to lie in a common plane.



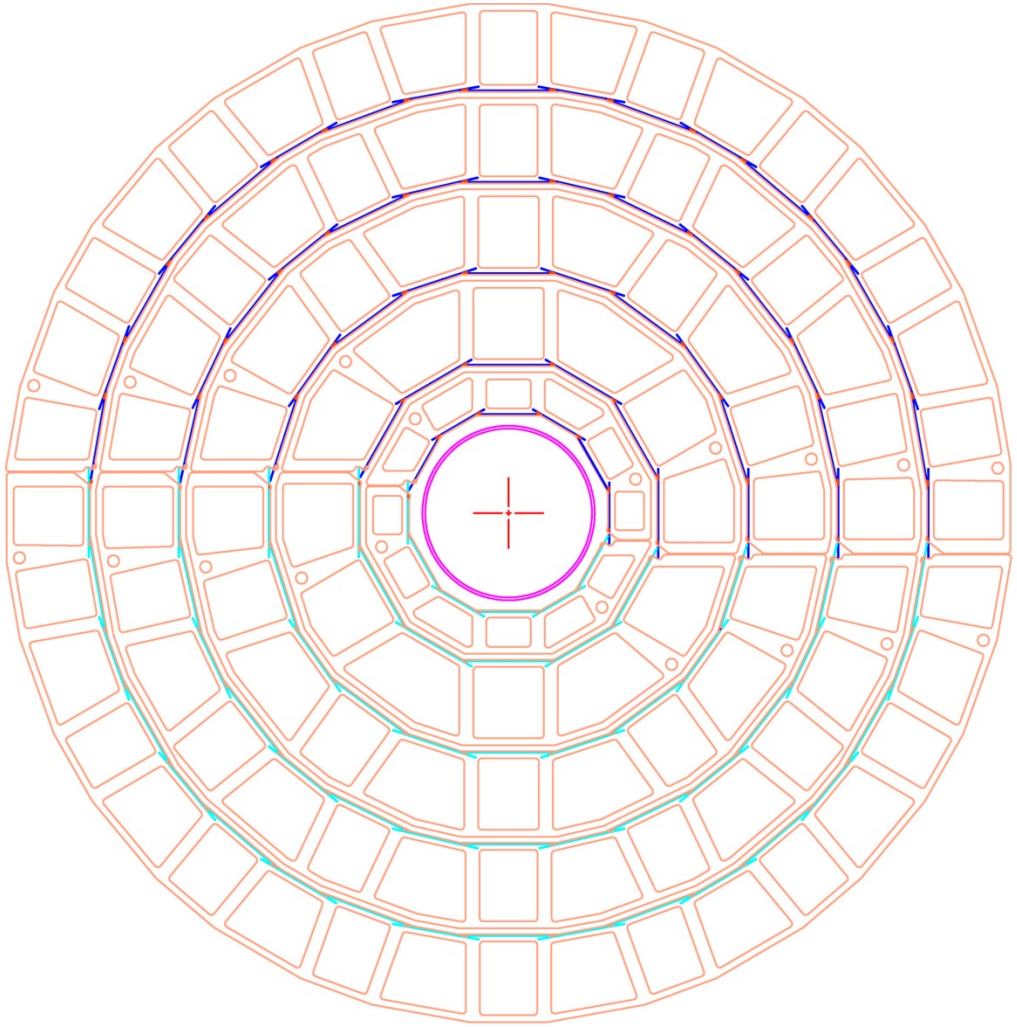
SiD Design Studies and Issues

- Separating into top and bottom halves presents a few issues.
  - Separating into left and right halves gives a little more deflection.
- Sensor counts per layer must be a multiple of 4 to allow separation while maintaining identical halves.



“All-Silicon” Layout

- **Goal = 0.1% X0 per layer (+ cables)**
- **Sensors glued to one another along edges and supported from ends**



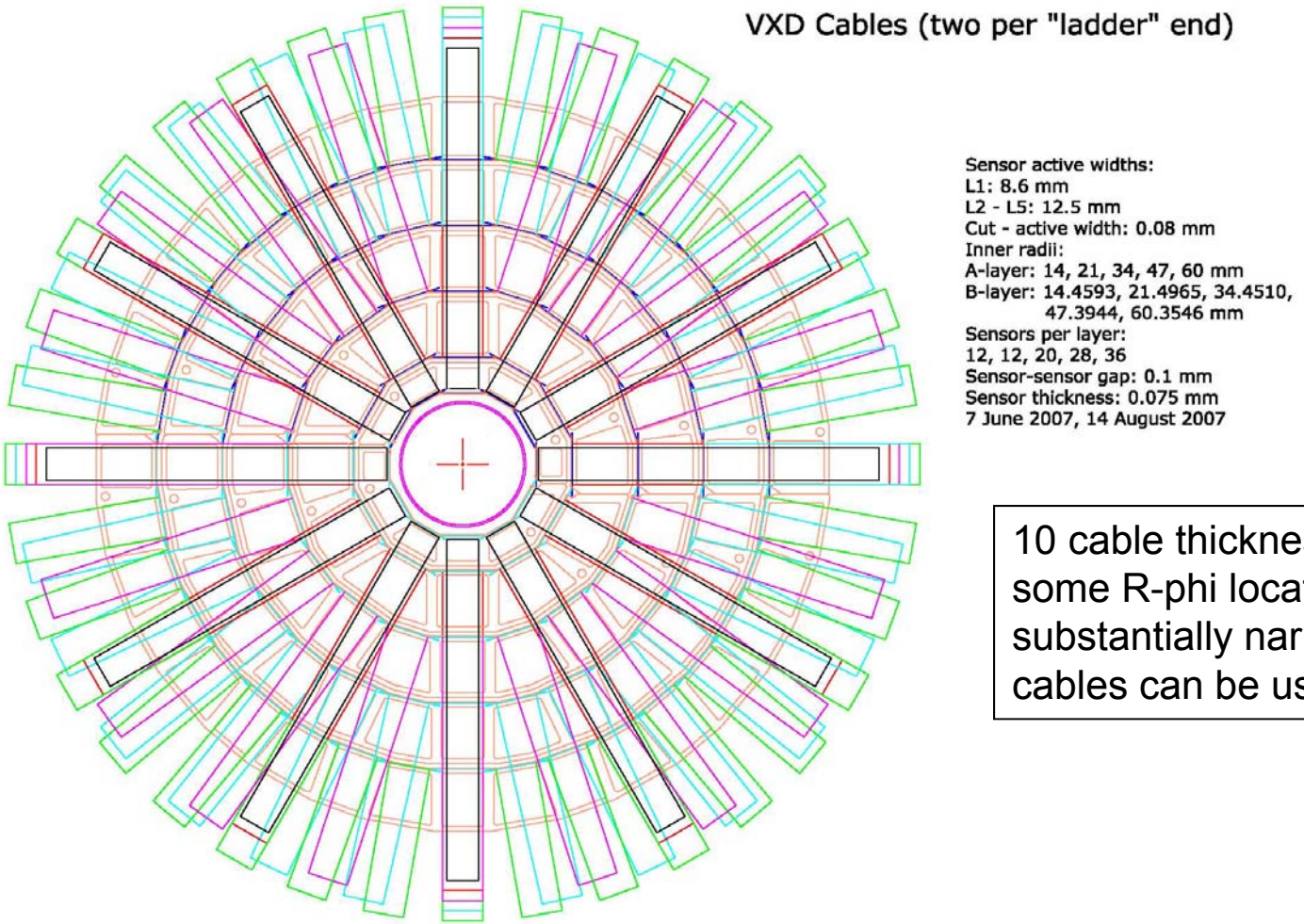
- **75 µm silicon thickness assumed (3D sensors)**
- **Could be modified for thicker or thinner sensors**

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

- **End rings dominate what you see.**
- **It should be straight-forward to ensure end ring out-of-round stiffness is large compared to that of sensors.**
- **End ring material has been assumed to be CF in initial modeling.**

Cables

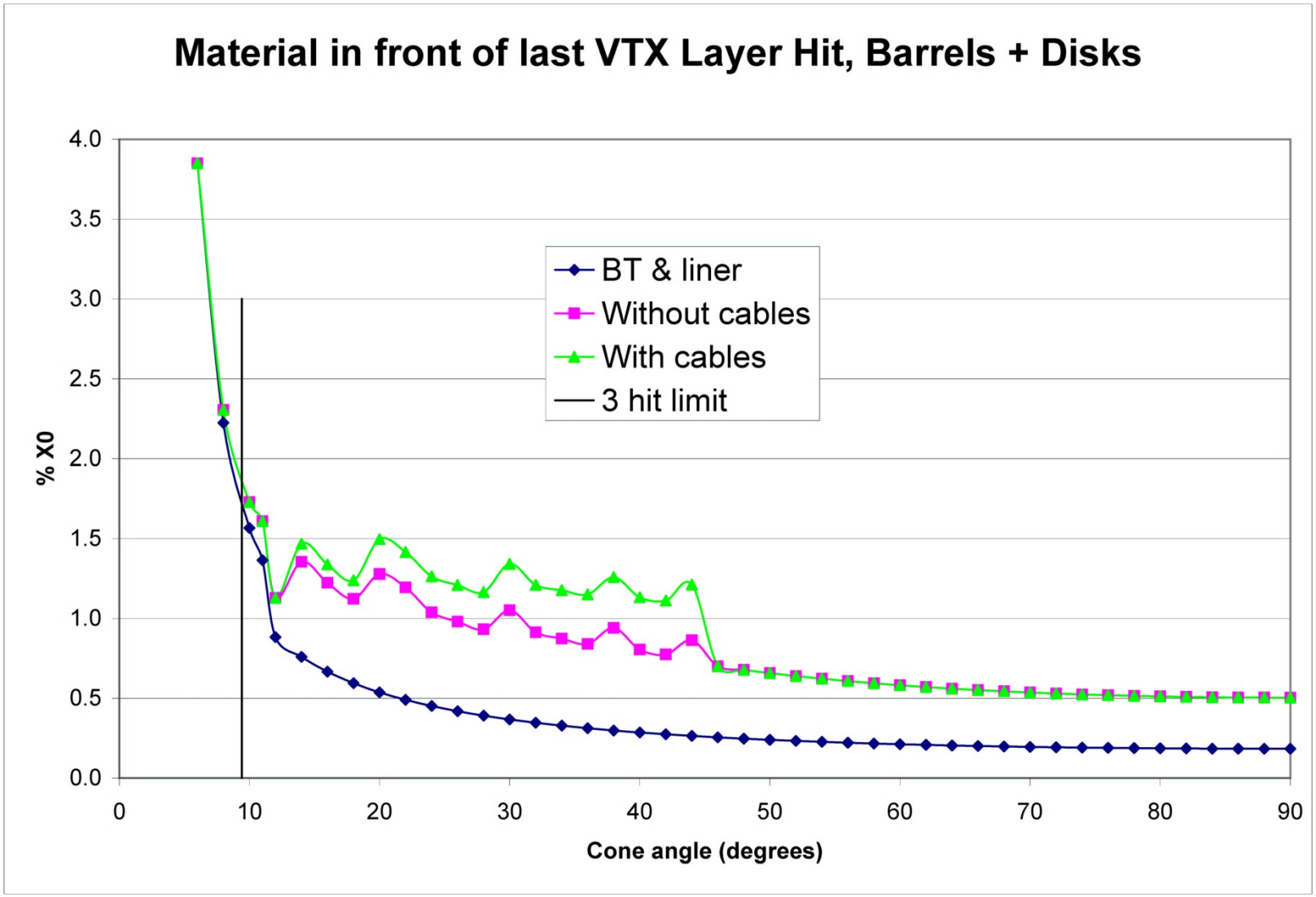
- **An “all silicon” layout with two cables per “ladder” end (only one of the two is shown)**
- All cables run radially outward to the periphery of the first disk.



10 cable thicknesses at some R-phi locations unless substantially narrower cables can be used

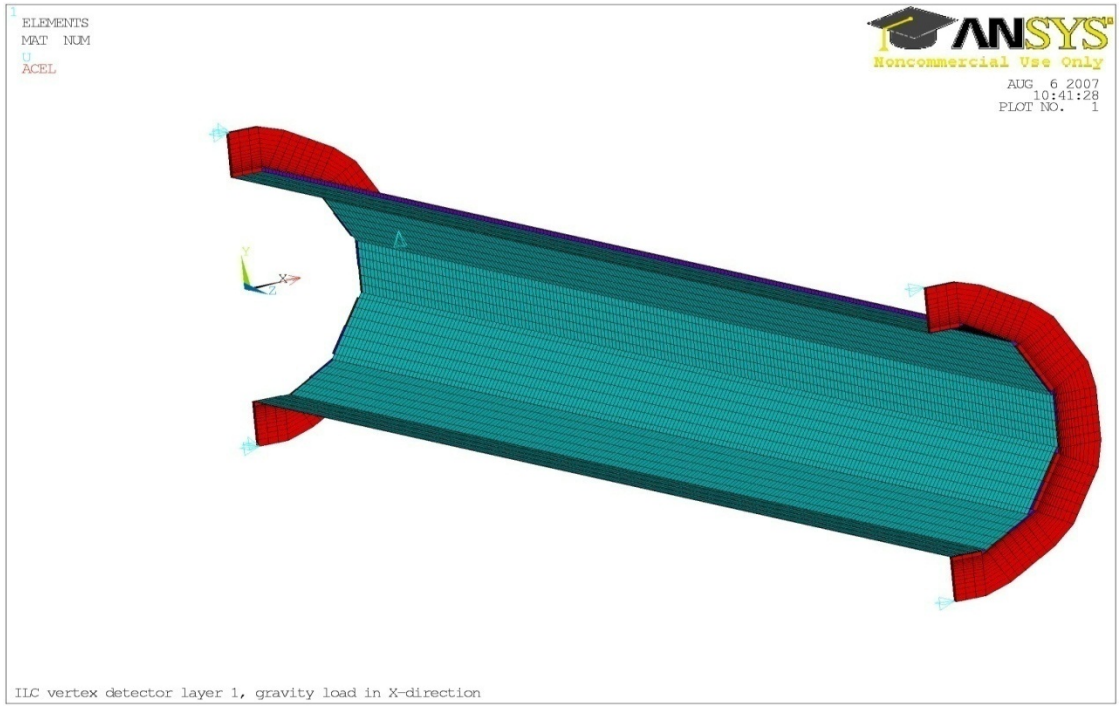
Cables

- SiD all-silicon layout with disks

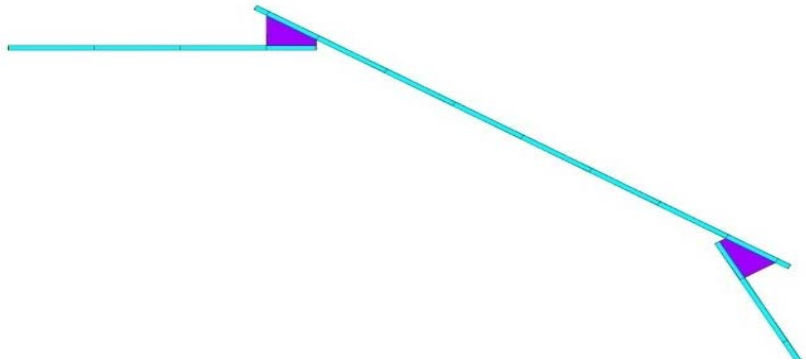


UW All-silicon FEA

Model of layer 1

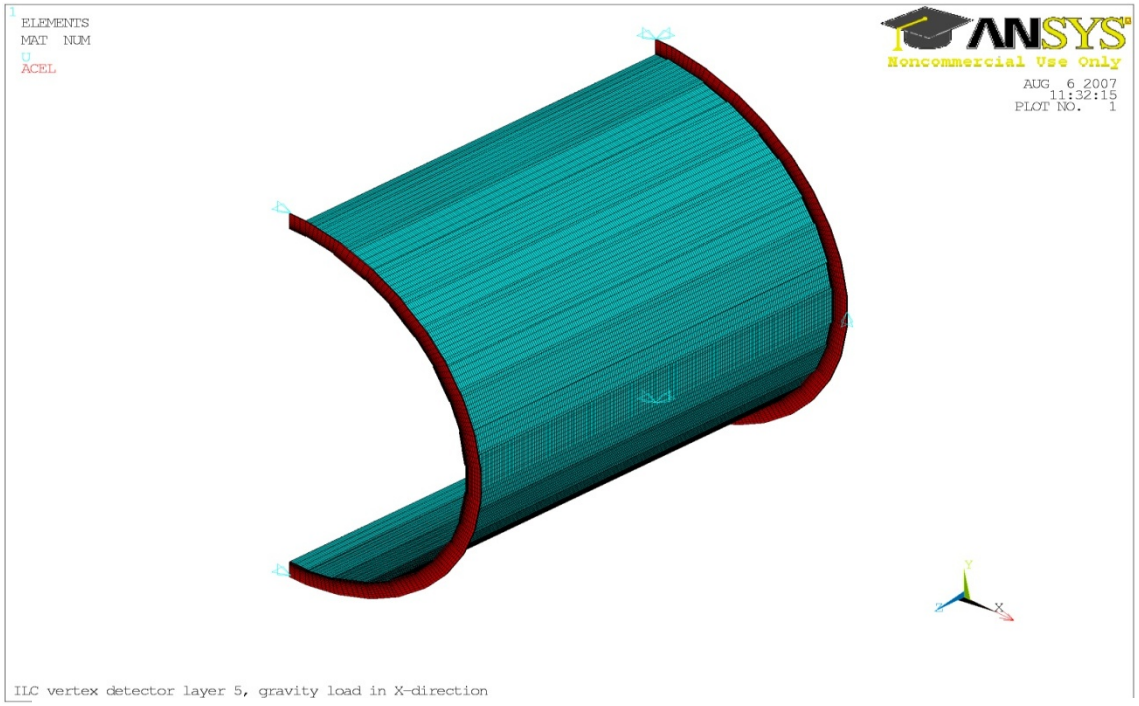


Detail of model of layer 1 showing the 0.7 mm wide epoxy joints.

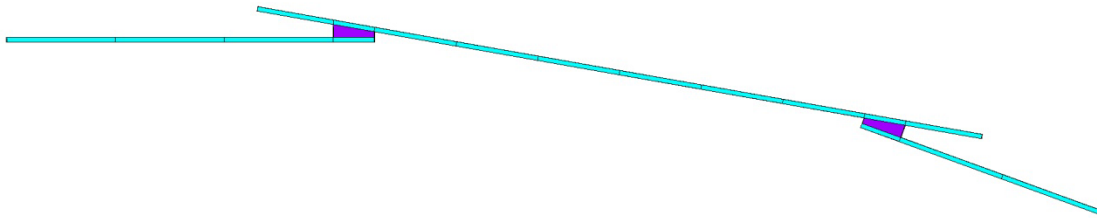


UW All-silicon FEA

Model of layer 5.



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



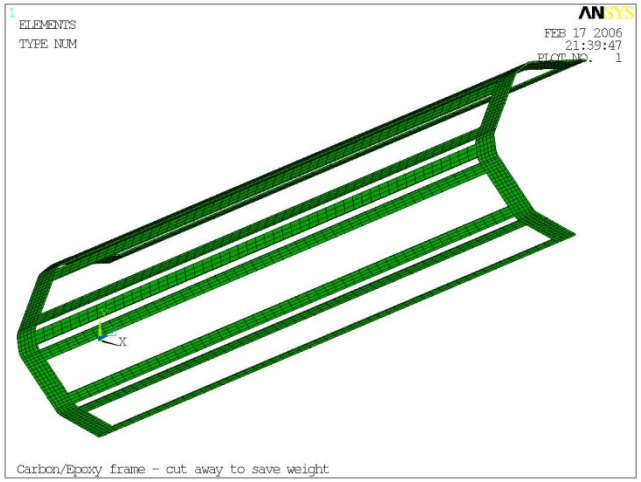
Initial FEA results for ILC vertex detector - all silicon structure
(8/6/2007 C H Daly)

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 carried out similar FEA.

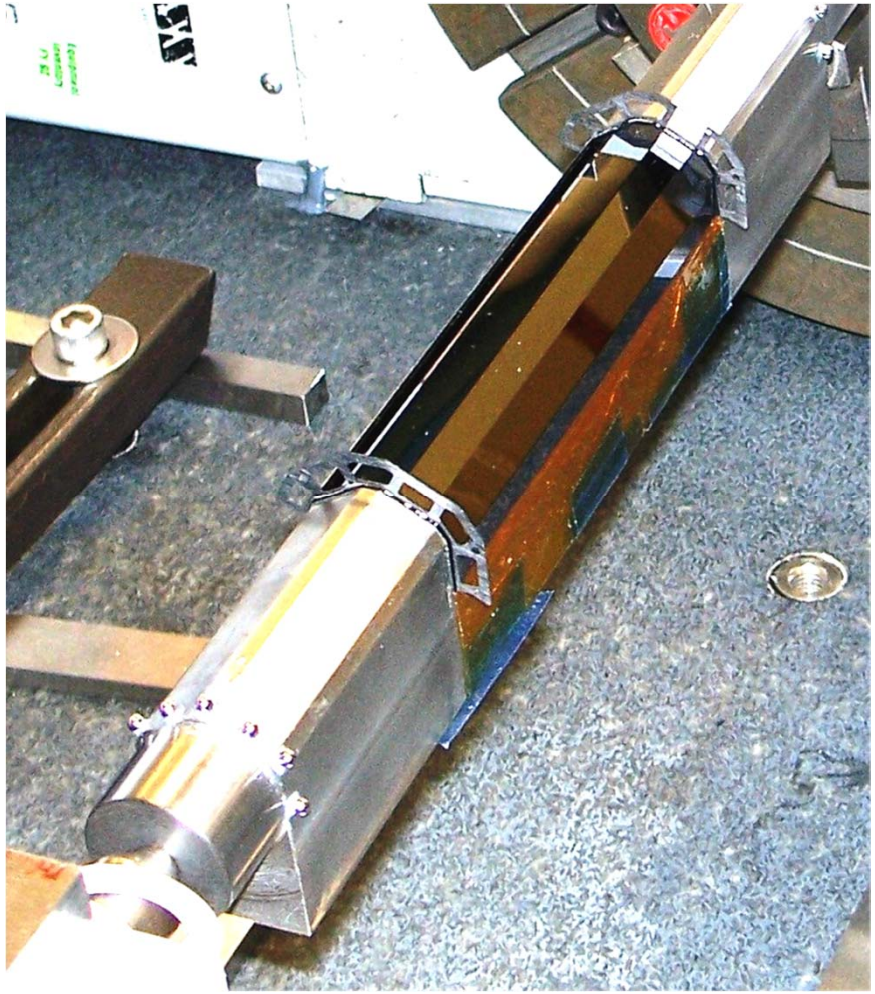
Back-up Solution

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



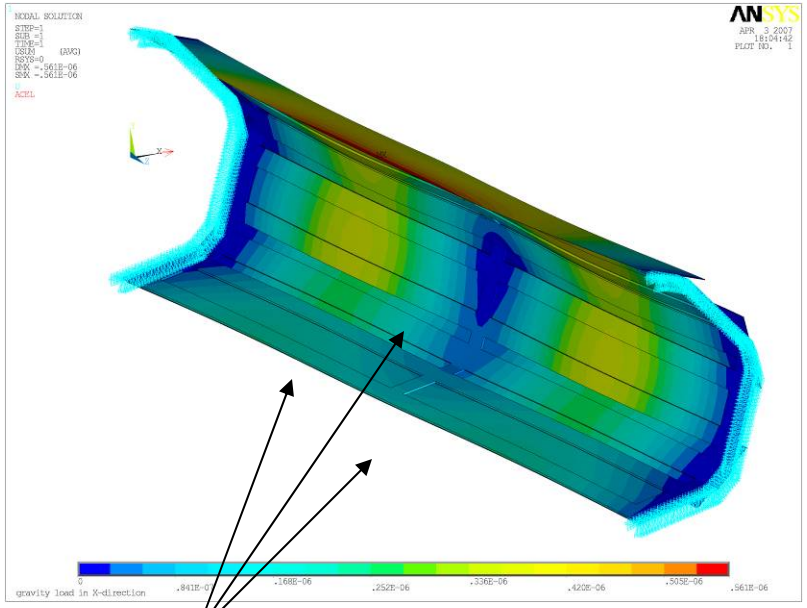
Layer 1 support structure with G-10, rather than carbon fiber, end rings

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

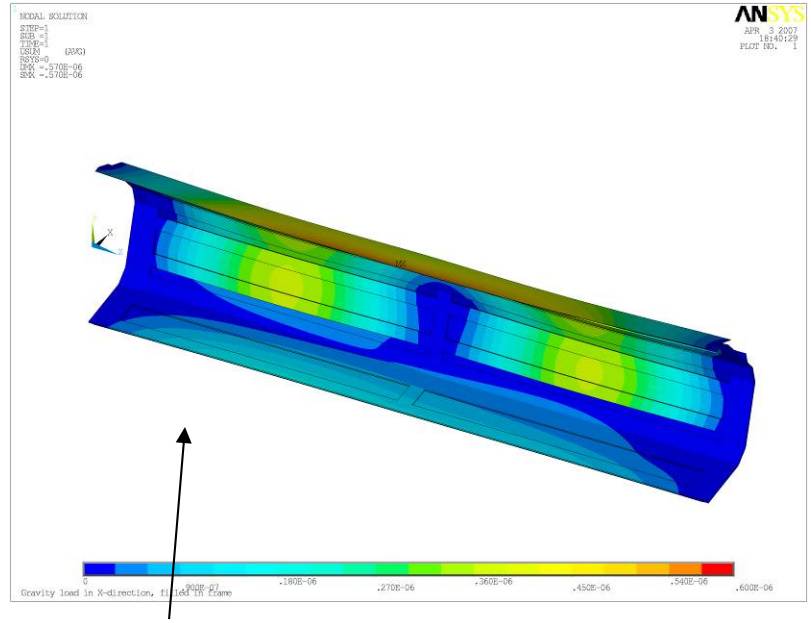


UW FEA Studies, Silicon on CF Structure

- 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

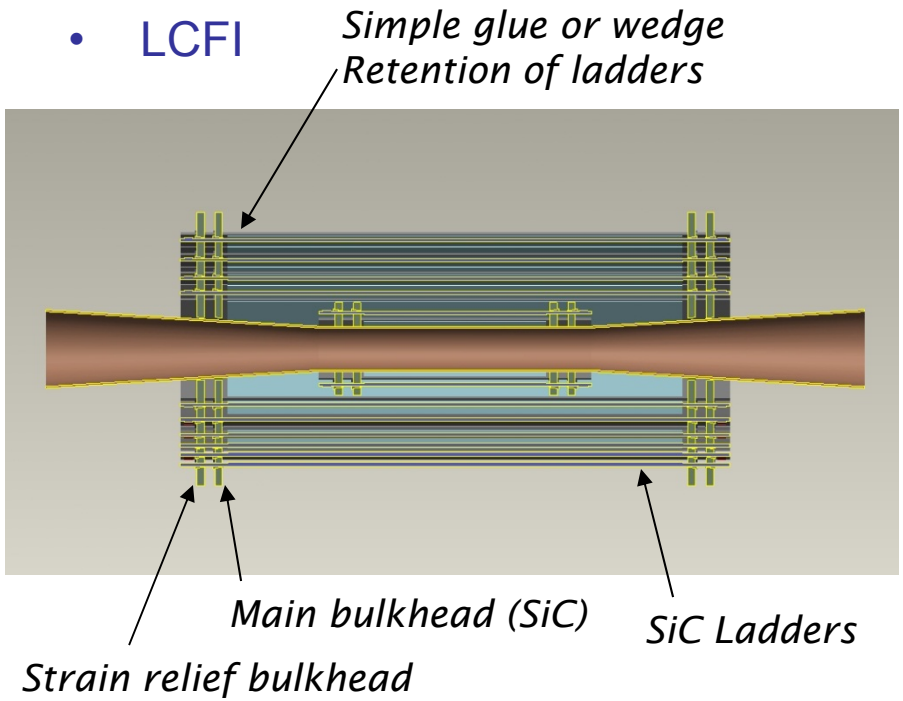


One slot closed to reduce thermal deflection

- The maximum deflection vector is about 0.6 μm 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.
- **Thermal distortions are a serious issue for sensors below ~ 10°C.**

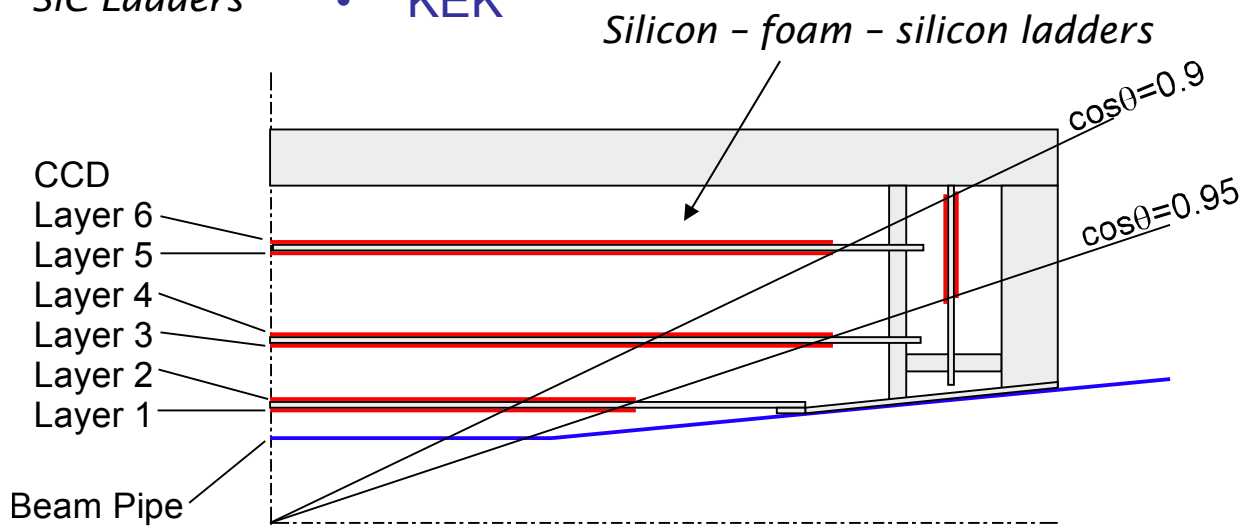
Designs with Longer Ladders

- LCFI



- Both approaches include interesting ladder features and assume foam is used as a structural element.

- KEK

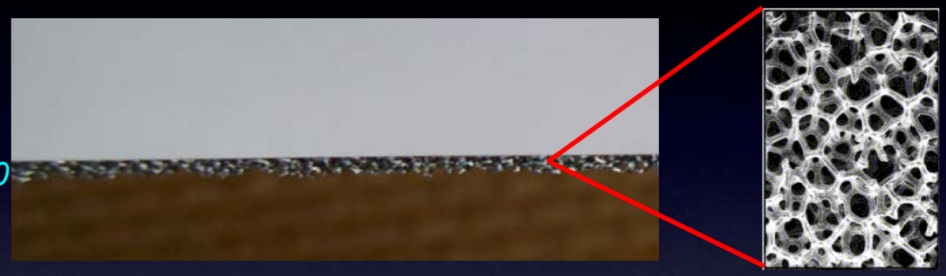


KEK design meets the radiation length budget.

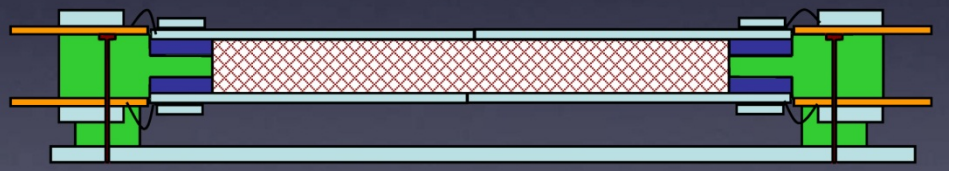
Other Vertex Detector Options - LCFI

Foam Ladders

- 25 micron silicon on 1.5mm 8% SiC
  - Very rigid
  - Achieved 0.14% X_0



- 20 micron silicon sandwiching 1.5mm 2% carbon
  - Could be double-sided
  - Achieved 0.07% X_0



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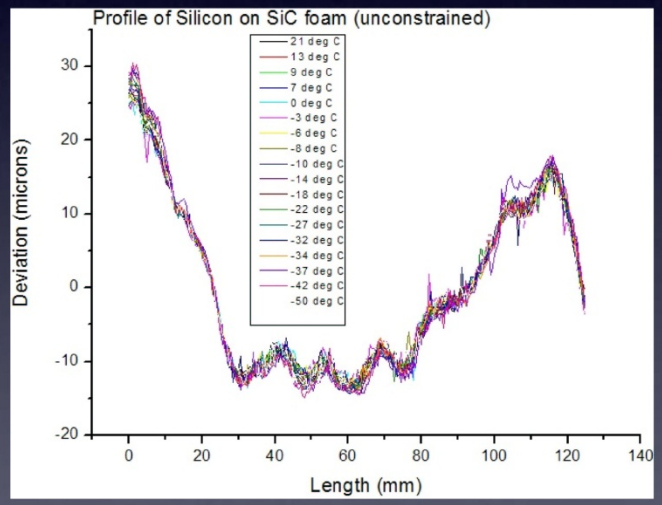
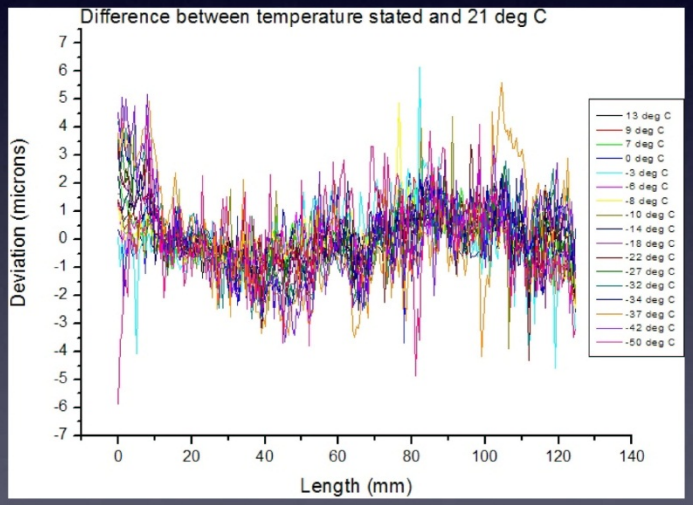
LCFI Studies

SiC Foam Results

- SiC Foam substrate ladder cooled
- Negligible thermal distortion over 70°C





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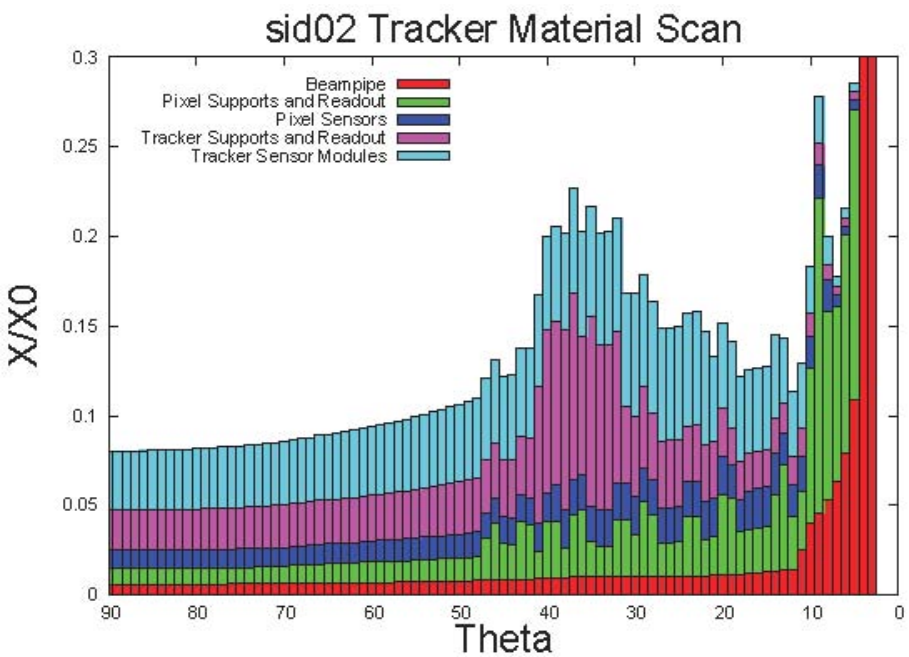
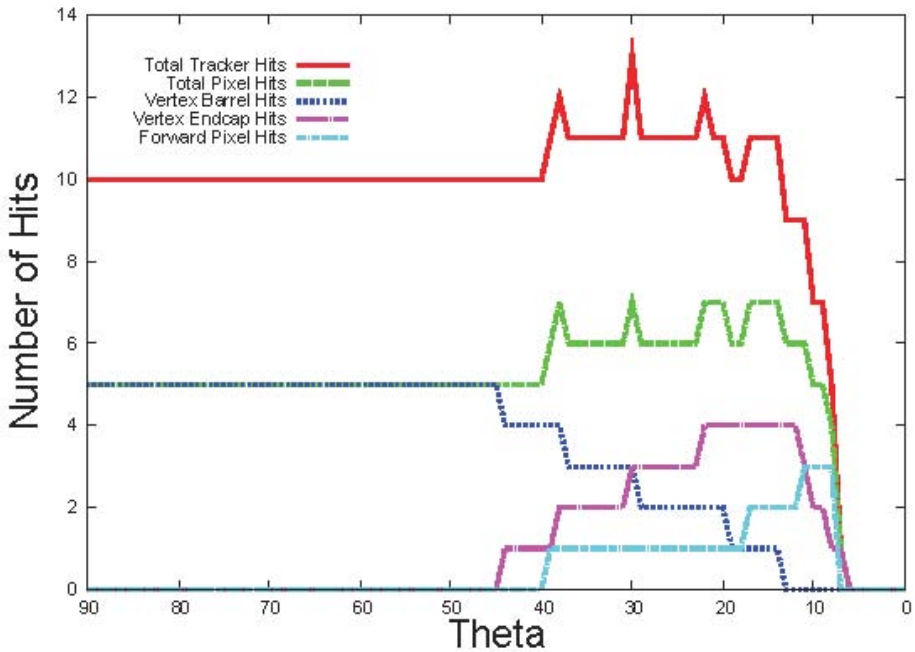
SiD Material and Number of Hits

- Material contributions are shown in the left plot.
  - The bump above = 40° is a consequence of barrel / disk overlaps and services (power conditioners and cables) in that region.
  - Longer barrels suffer from shallow incidence angles of tracks, so it's a matter of choosing between penalties.
- The number of hits on a track, shown in the right plot, suggests that track reconstruction efficiency should be reasonable.





SiD Track Finding Efficiency

- Track finding efficiency is close to 100% over most of the acceptance.
- Dips in the left plot correspond to low momentum tracks (P_T < 500 MeV/c) in the barrel-disk transition region and may be an artifact of the tracking algorithms.

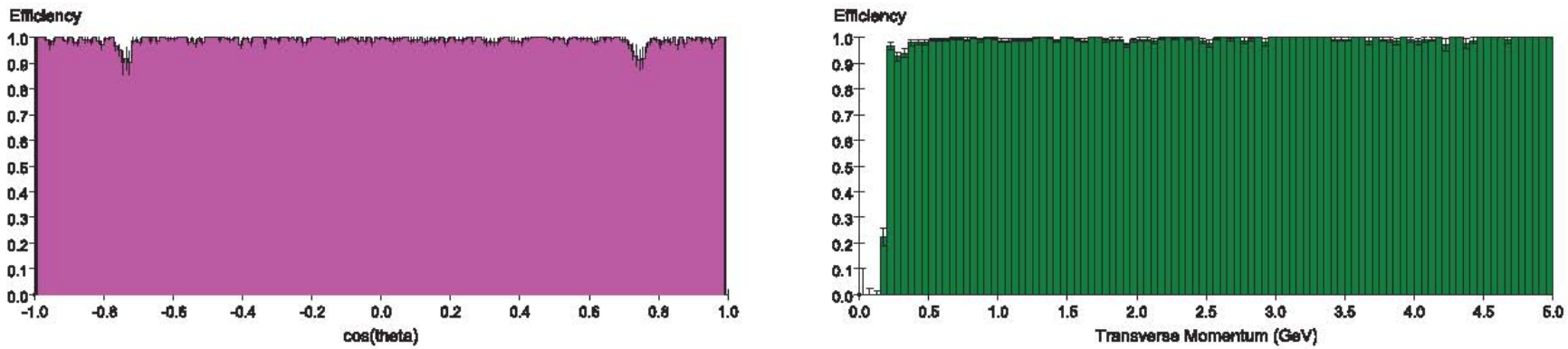
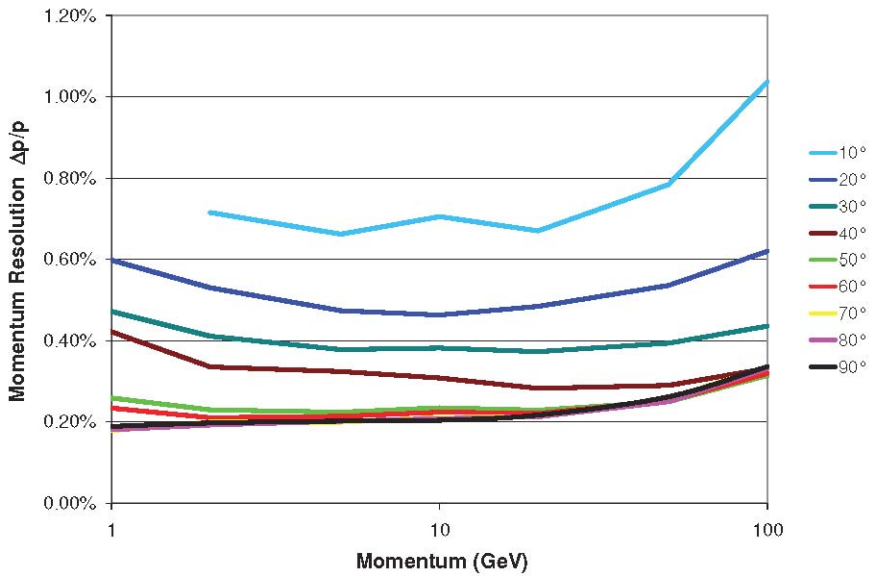
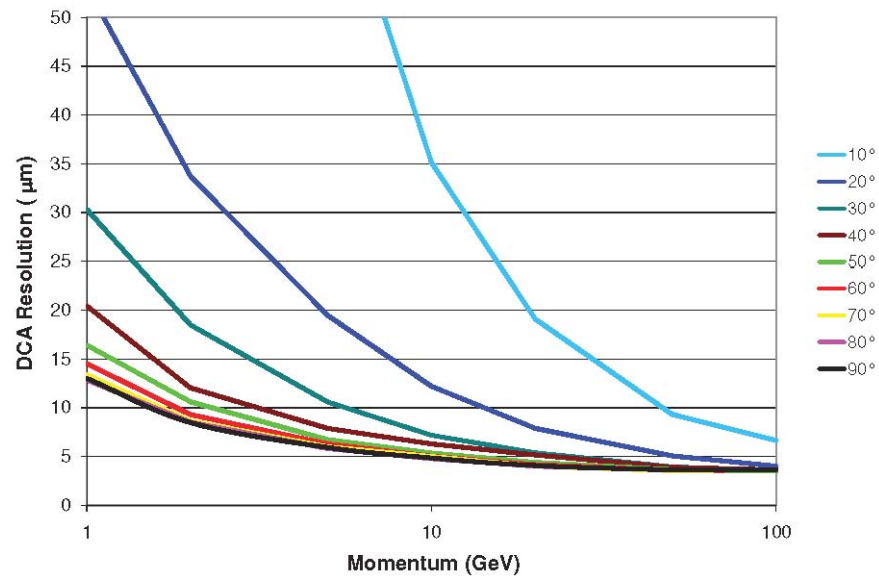


Figure 2.8: Track finding efficiency as a function of track $\cos\vartheta$ (left) and p_T (right).

SiD Tracker Resolution

- Momentum resolution and DCA resolution are shown in the left and right plots, respectively.
- Both are quite respectable.



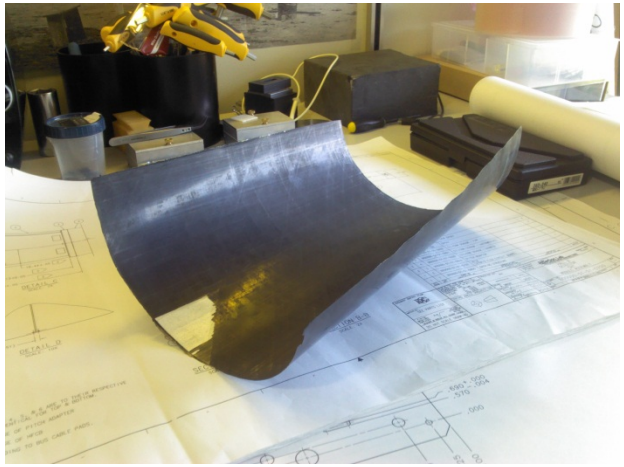


A Few Comments on Carbon Fiber

- Support structures normally rely upon unidirectional carbon fiber because of its favorable elastic modulus to mass and radiation length ratios.
- A common fiber for low-mass structures is Mitsubishi K13C2U.
  - Fiber elastic modulus = 130 MSI (4.45 that of stainless steel).
  - Normally obtained as “prepreg” with either epoxy or cyanate ester resin.
  - K13D2U has a slightly higher modulus, but is more difficult to handle.
- Unidirectional prepreg is normally “layed up” in several layers (6-8) to form laminate.
  - The angle of each layer is chosen to control laminate properties.
  - Cure at 250 - 275 ^{o}F and 1 - 5 atmospheres pressure.
  - Cured laminate is roughly 50% fiber and 50% resin by volume.
  - Laminate elastic modulus $\approx$ 24 MSI for a quasi-isotropic lay-up (~80% that of stainless steel).
- Typically, cured fiber ply thickness is 57-63 μm.
  - Depends on the amount of resin removed during cure.
- X/X0 per ply $\approx$ 0.025%.

Carbon Fiber Laminate

- A quasi-isotropic laminate provides in-plane properties which are independent of angle.
- Typical angles are $0^o/60^o/-60^o$ (3 plies) or $0^o/45^o/-45^o/90^o$ (4 plies).
- To avoid bowing and "potato chipping", lay-ups are usually symmetric.
  - $0^o/60^o/-60^o/-60^o/60^o/0^o$ (6 plies) or $0^o/45^o/-45^o/90^o/90^o/-45^o/45^o/0^o$ (8 plies)
  - Not necessary for cylindrical structures



Bowing of a 3-ply (asymmetric) lay-up

Carbon Fiber Laminate

- Lay-ups which are not quasi-isotropic are often chosen to enhance properties in a particular direction or to avoid fiber bending radii which are too small.
  - $0^o/\phi^o/-\phi^o/-\phi^o/\phi^o/0^o$
  - Minimum bending radius to avoid fiber fracture ~8 mm for K13C2U.

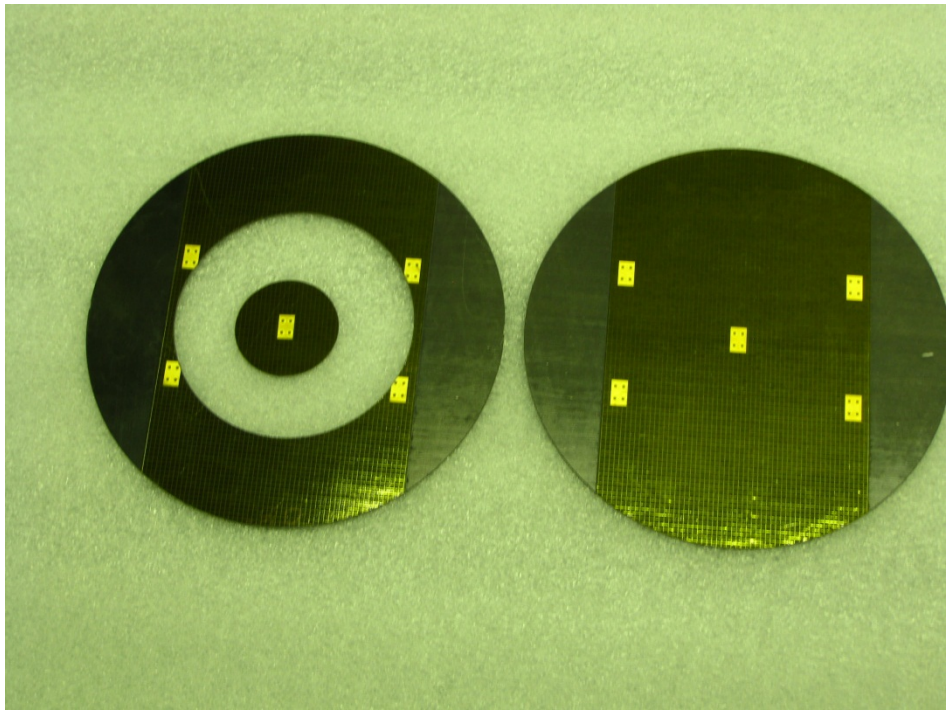
Prototype box structure for CMS Track-Trigger module support

- Lay-up = $90^o/-15^o/+15^o/+15/^o-15^o/90^o$
- 90° plies are truncated at corners to avoid fracture
- $+/-15^o$ plies wrap around corners

- Surface flatness ~220 μm (±110 μm)

Grounding

- Carbon fiber has a DC conductivity roughly 1/300 that of copper.
- Almost identical to copper above 1 MHz.
- We need to be careful that conductors which sandwich sensors are at a common potential, preferably sensor ground.
- Reliable ground connections to carbon fiber can be obtained with copper or copper mesh circuits which are “co-cured” with the fiber.



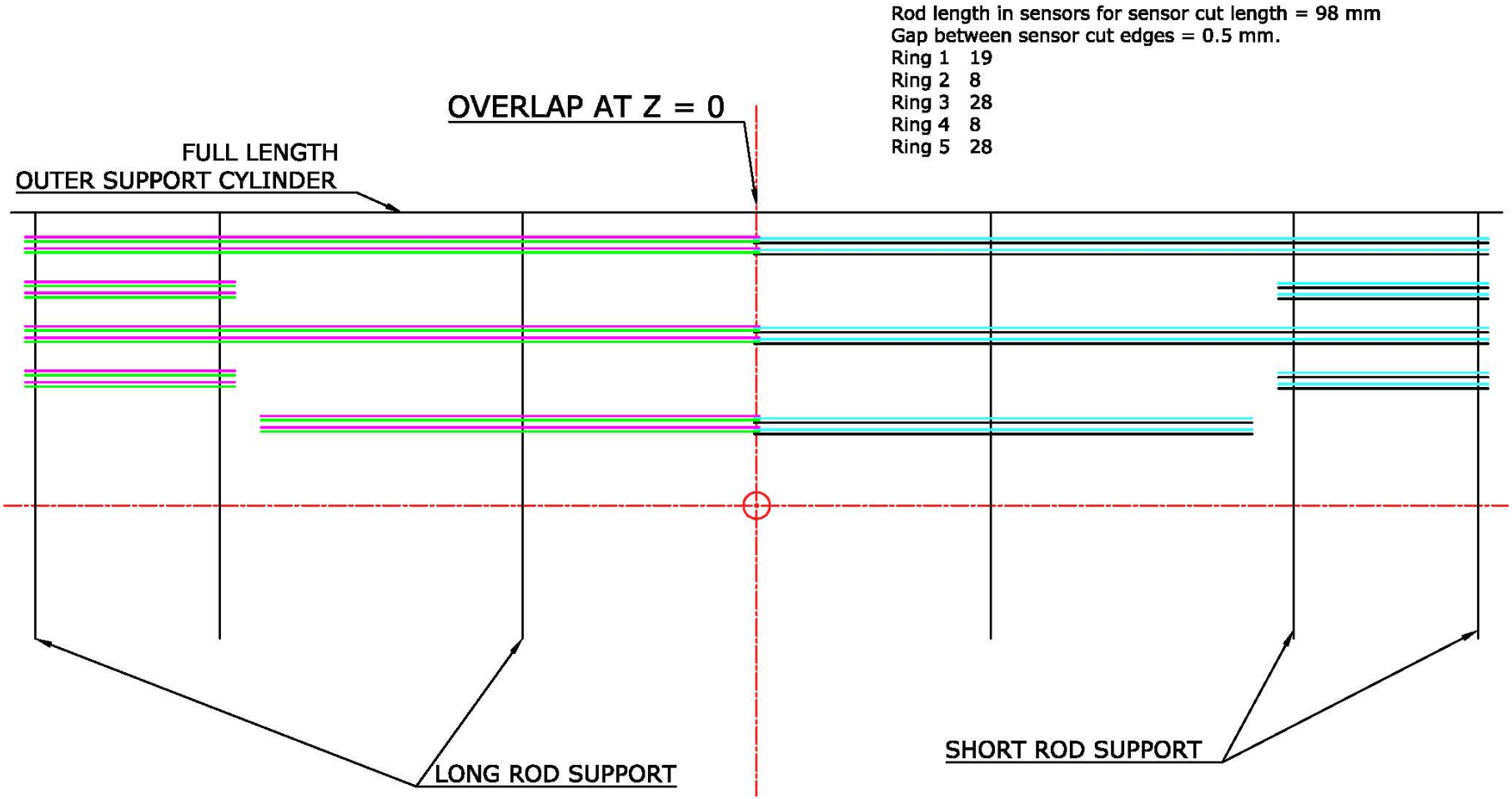
- Examples of copper on kapton mesh circuits
- Mesh is in contact with the carbon fiber.
- Vias through the kapton connect 5 mm x 8 mm pads to the mesh.
- 5 μm copper with ~30% mesh coverage, 25.4 μm kapton → $X/X0 \approx 0.044\%$ except at pads, where it roughly doubles.

CMS Track Trigger

- The LHC represents the opposite end of the spectrum from the ILC.
- Rates are high and getting data to a location where triggers can be formed is a major issue.
- To reduce the data that needs to be transmitted to a convenient location, Marcello Mannelli (CERN), Ron Lipton (FNAL), Marvin Johnson, and others have been developing a track trigger for the CMS phase 2 upgrade.
- Hits from radially separated silicon layers would be combined locally (at the sensors) to form trigger stubs within a “stack”.
  - A stack module consists of a sensor (with integrated electronics), an “interposer” which separate sensors radially and transmits sensor signals, and a second sensor.
  - Radial separation of sensors in a stack module ~1-2 mm.
- “Rods” would support modules in longitudinal arrays.
- In turn, rods would be supported by thin disks to form barrels with azimuthally overlapping double-stacks.
- Evaporative CO2 cooling is assumed with the capability of maintaining sensors at -20° C.
  - Baseline assumes SS cooling tubes (Al, Ti, and PEEK are options).

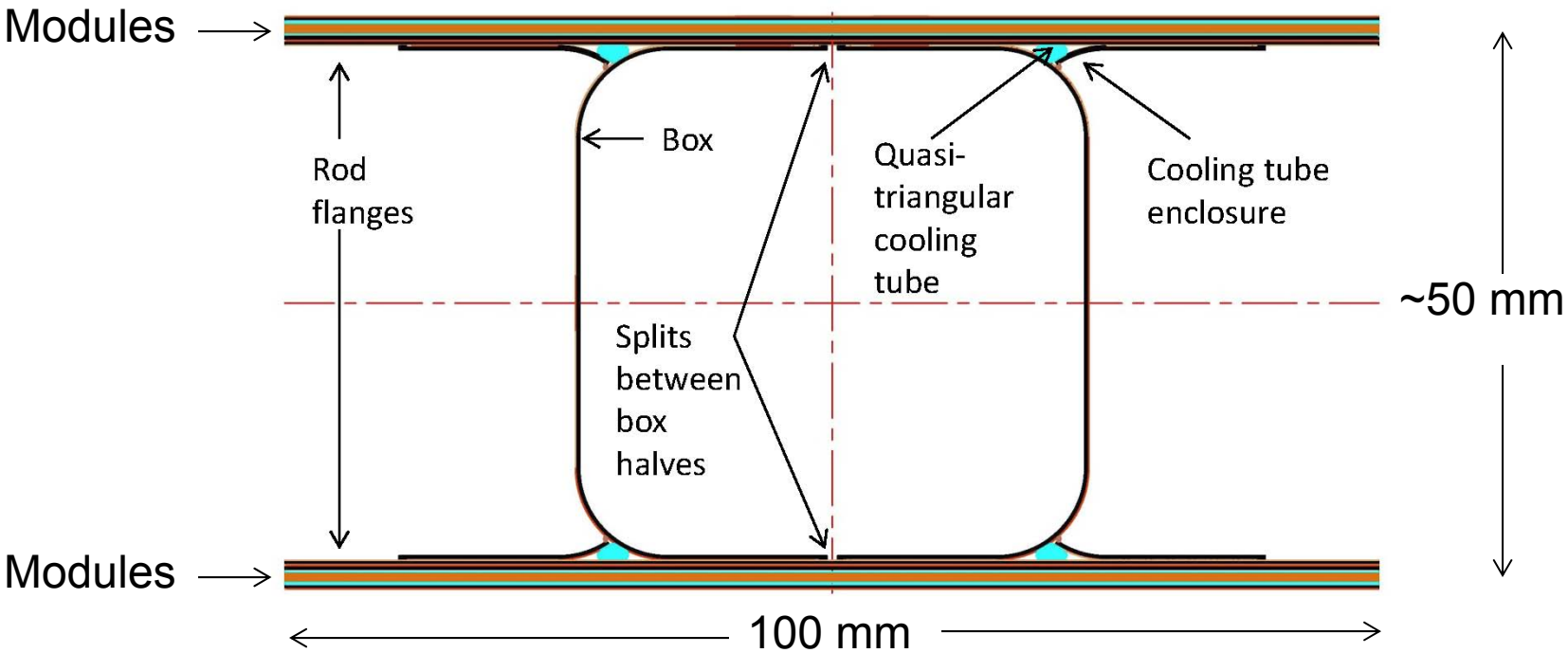
Updated Track-Trigger Design

- Side elevation (half tracker) in this concept:
- Only portions of rods populated with modules are shown.



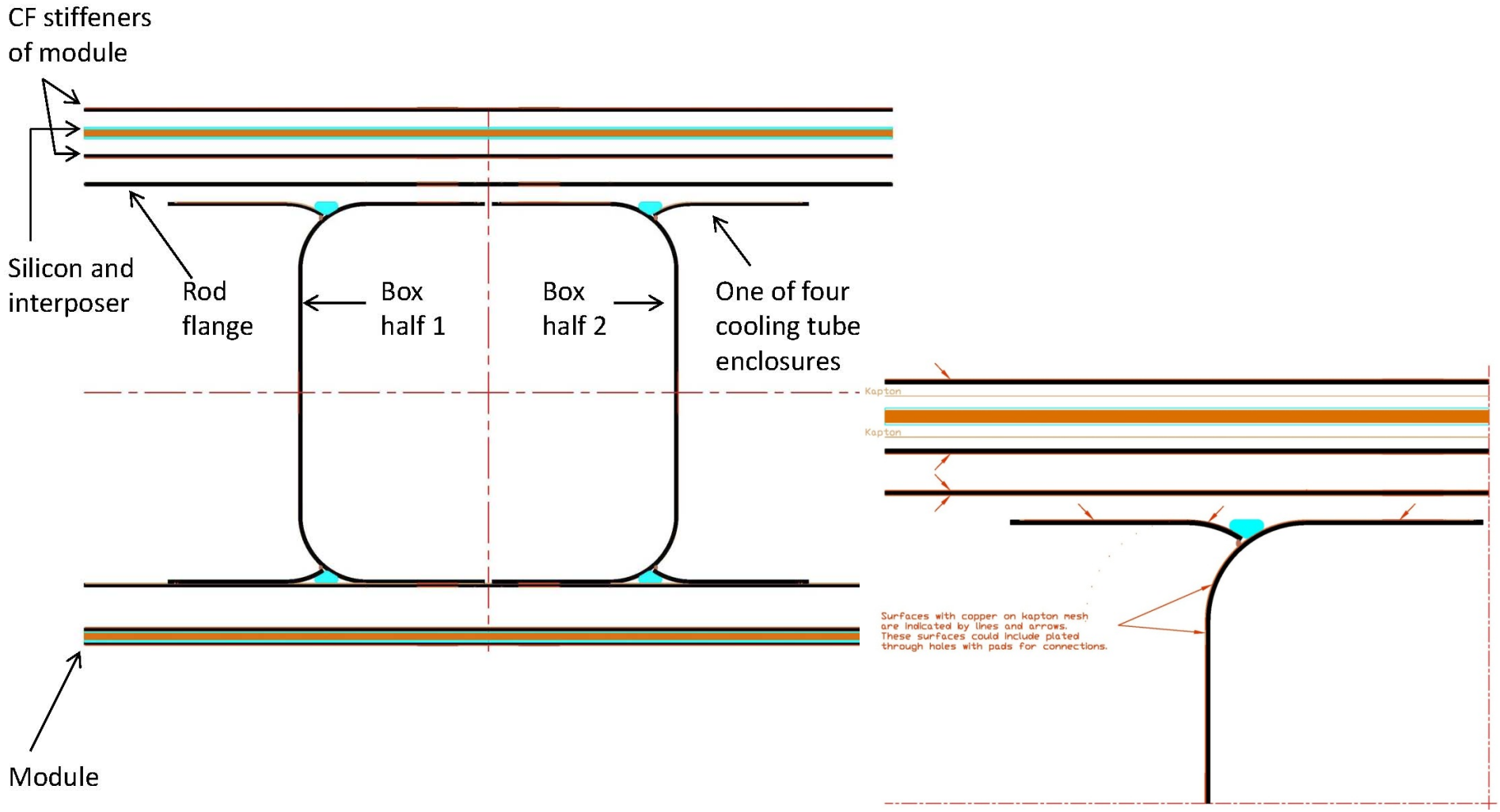
Updated Track-Trigger Design

- Endview of a rod:
- Sensor-interposer modules mount on top and bottom flanges attached to the rod box.
- Corner radii of box have been increased to allow 90° CF plies.
- DC-DC converters and fiber optics would be located within the box.
- Optics drivers, etc. can be mounted on the outer box surface.



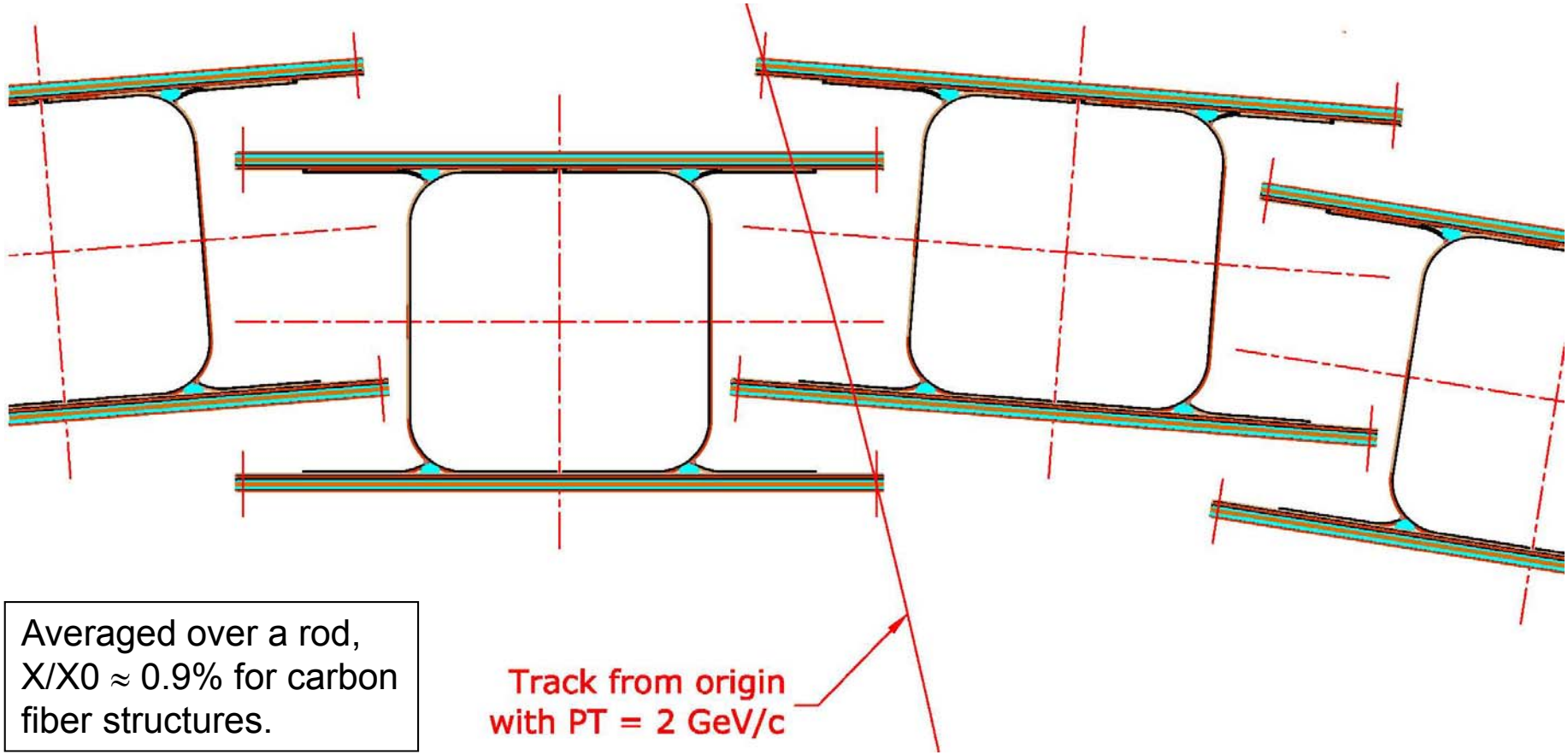
Updated Track-Trigger Design

- Exploded view:
- We are working to understand grounding and cabling arrangements.



Updated Track-Trigger Design

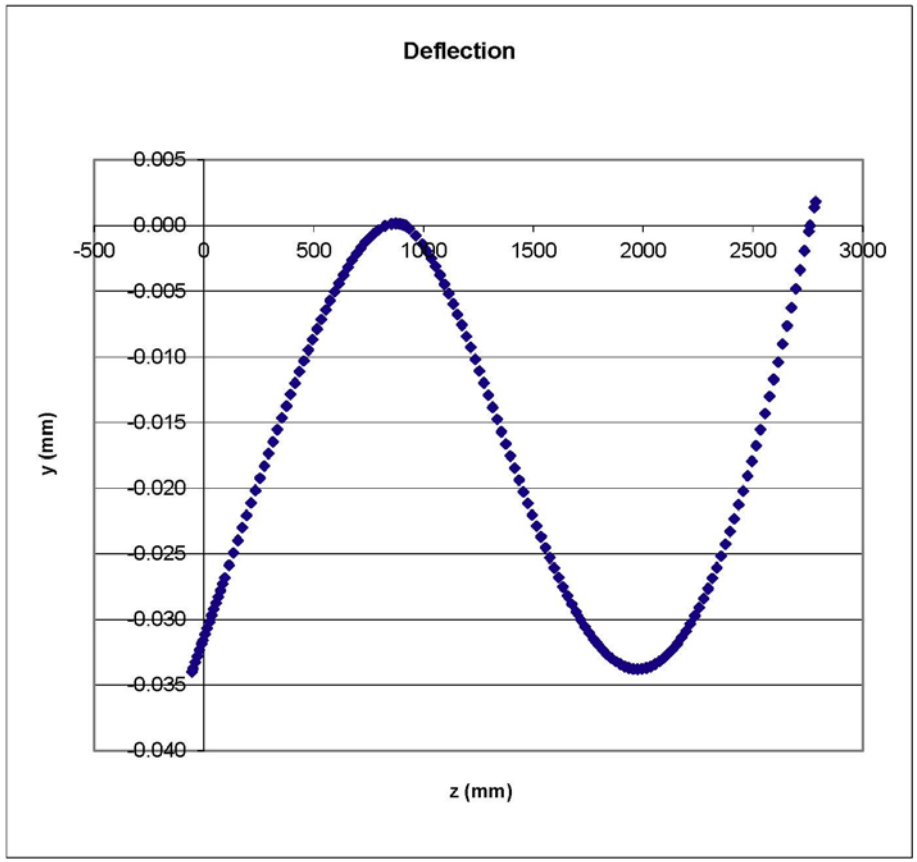
- Example showing rod overlap in the outer barrel with 80 rods.
- Sensor active area is assumed to start 5 mm from each module edge to leave space for connections, capacitors, etc.



Averaged over a rod, X/X0 ≈ 0.9% for carbon fiber structures.

Updated Track-Trigger Design

- Calculated deflection of a 2.8 m long rod with this geometry and orientation
  - Assumes modules contribute to rod stiffness.
  - Rod geometry can be adjusted to obtain the same stiffness for all orientations.
  - The small deflection suggests that support structure material can be reduced.
  - Rod is simply supported at z = 0.918 m and 2.761 m.
  - If modules don't contribute to stiffness (not a particularly realistic assumption), then deflection would be greater by a factor of 2.9 (still OK).



Final Comments

- Carbon fiber can be effective in supporting sensors with a stability compatible with their intrinsic resolution.
- Silicon carbide and other foam materials provide an alternative.
- For small structures, such as in the vertex detector, $X/X0 \approx 0.1\%$ per layer at normal incidence is a reasonable goal, with 0.2% a more realistic estimate.
- For larger structures, such as a silicon tracker, $X/X0 \approx 1\%$ per layer at normal incidence is more realistic.
- Though not discussed, air cooling works reliably at a heat flux of 0.013 W/cm^2 and becomes a greater challenge as the heat flux approaches 0.05 W/cm^2.
- Liquid or evaporative cooling for higher heat fluxes typically adds 0.1% to 0.3% X0 per sensor layer.

- Thank you!