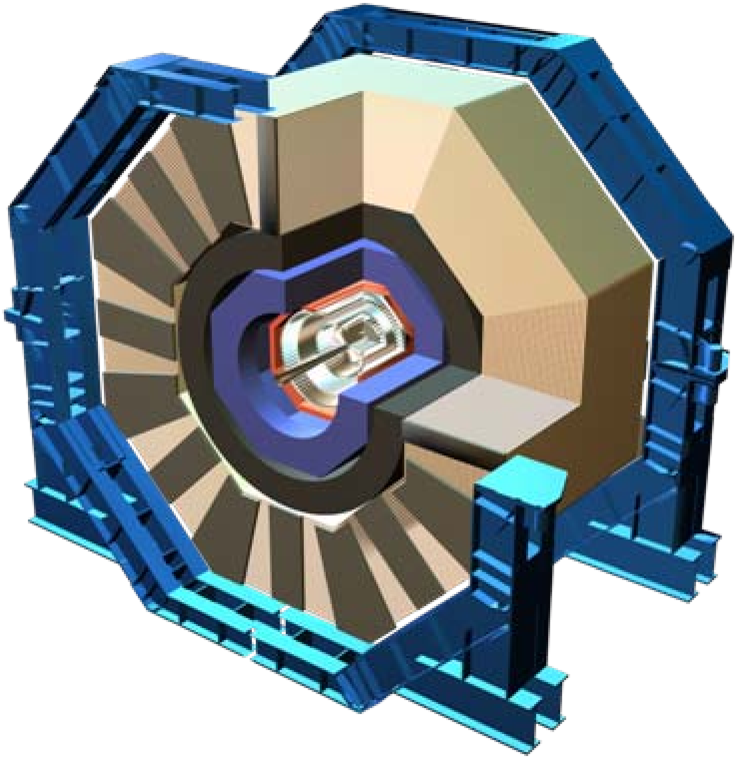
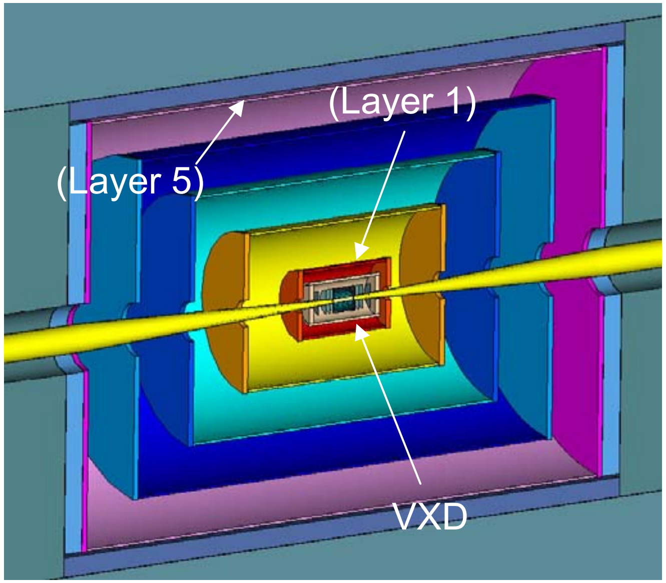
SiD Tracking:
Mechanical Design and R&D



Bill Cooper

Fermilab



R&D

- Mechanical R&D resources for the SiD silicon tracker include those necessary to develop designs, fabrication techniques, and procedures and to ensure they will work.
  - Prototyping of designs is included in the later years.
- Often, a portion of R&D has been included in project resources and has been concurrent with project fabrication.
  - That has not been done here.
  - Doing so may allow improvements in R&D cost and duration, but would need to be weighed against potential risks to project cost and schedule.

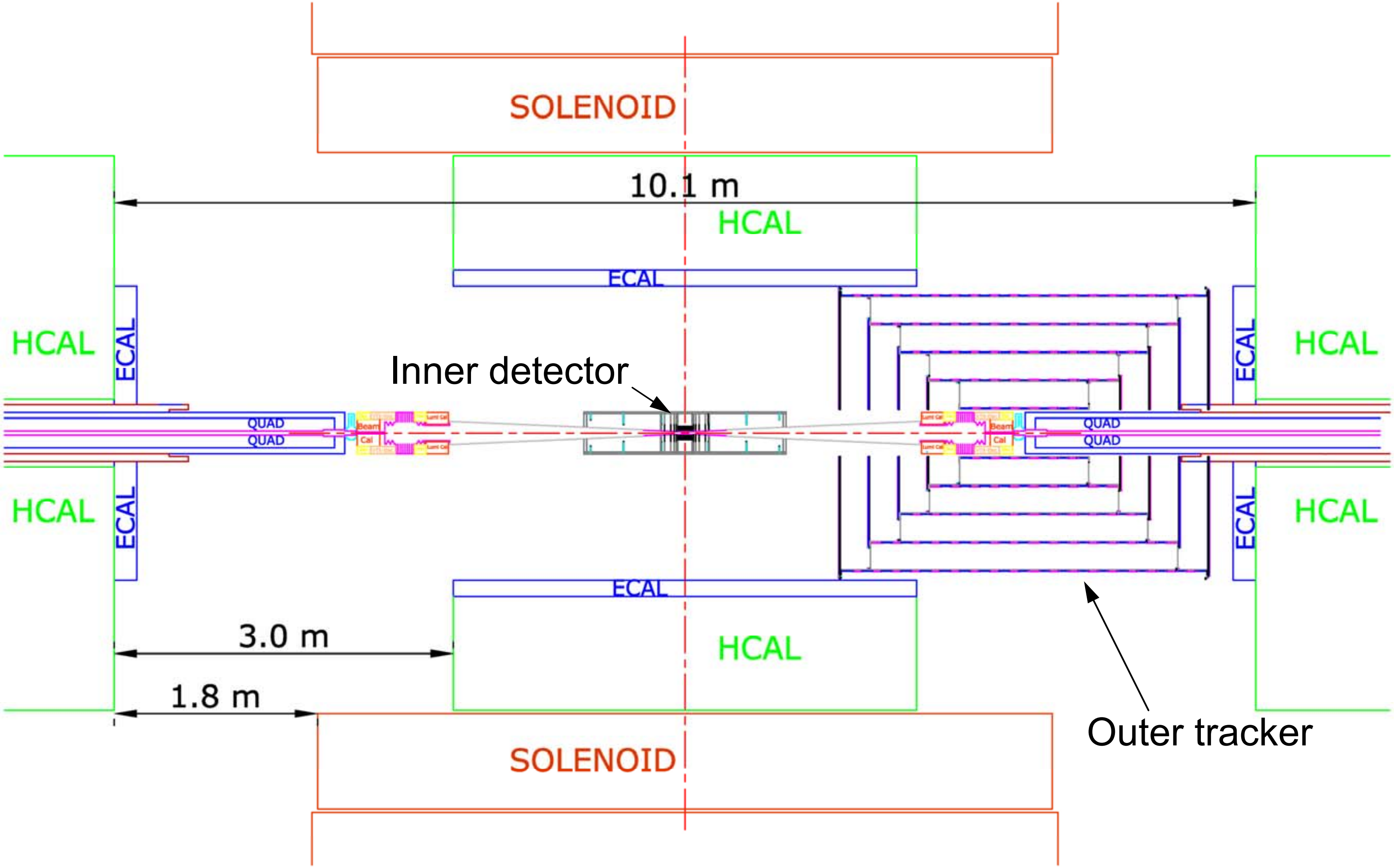
SiD Tracking Philosophy

- Vertex detector
  - Provides high precision measurements of tracks and vertices
  - ~3 μm vertex resolution
  - Provides an initial measurement of momentum
- Outer silicon tracker
  - Measures P_T
  - In combination with a track direction from the vertex detector, provides P
  - Connects tracks to calorimeters
- Calorimeters
  - Measure E, but rely upon tracking and a PFA to provide the planned resolution
  - Allow tracking backwards into the outer silicon tracker
- Expected P_T resolution in a 5 T field
  - $\sigma_{P_T}/P_T^2 < 2 \times 10^{-5}$ $(\mathrm{GeV}/c)^{-1}$ for 90°, high momentum tracks

Servicing

- A drawing with the detector open to allow servicing of the outer tracker and vertex detector follows.
- An inner stay-clear radius of 20 cm has been specified to allow the outer tracker to pass over beam delivery elements.
  - At present, tracker elements are > 0.5 cm from the 20 cm stay-clear boundary.
  - The vertex detector must also observe that boundary.
- Rails or equivalent to support the outermost tracker barrel from the inner surface of the electromagnetic calorimeter remain to be designed and tested.
- Additional temporary supports for the rails (or equivalent) will be needed to allow the tracker to be rolled.
  - Rails are expected to provide reproducibility of better than 0.25 mm after servicing has been completed.
  - Alignment requirements are modest provided alignment is measured after servicing and appropriate software corrections are made.
- Whenever the vertex detector is serviced, temporary supports for the beam pipe and vertex detector will be needed as well.

Detector Open / Full Access to Inner Detector



Inner detector

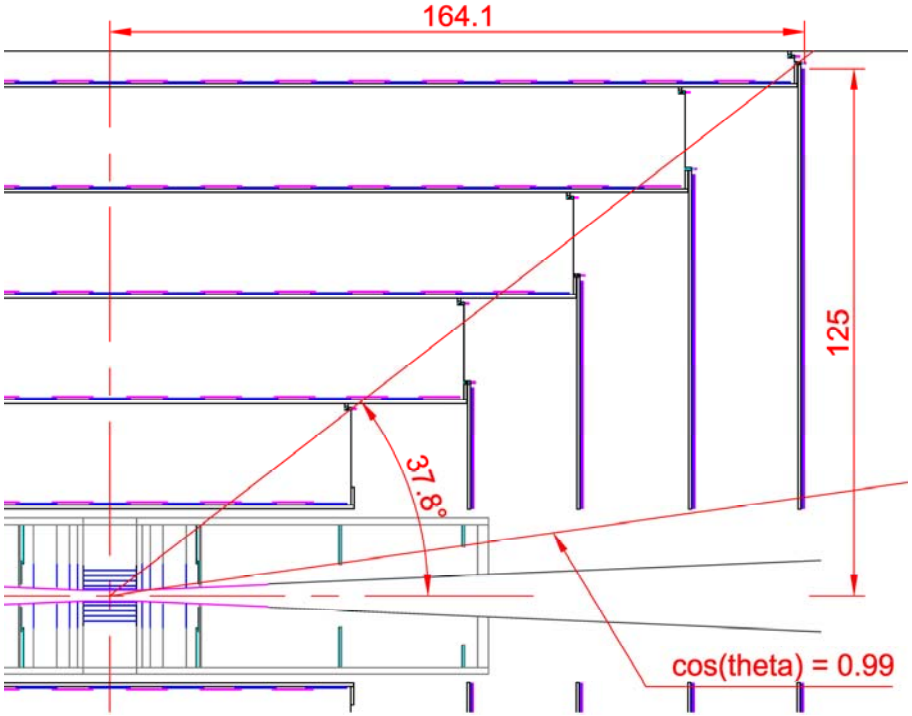
Outer tracker

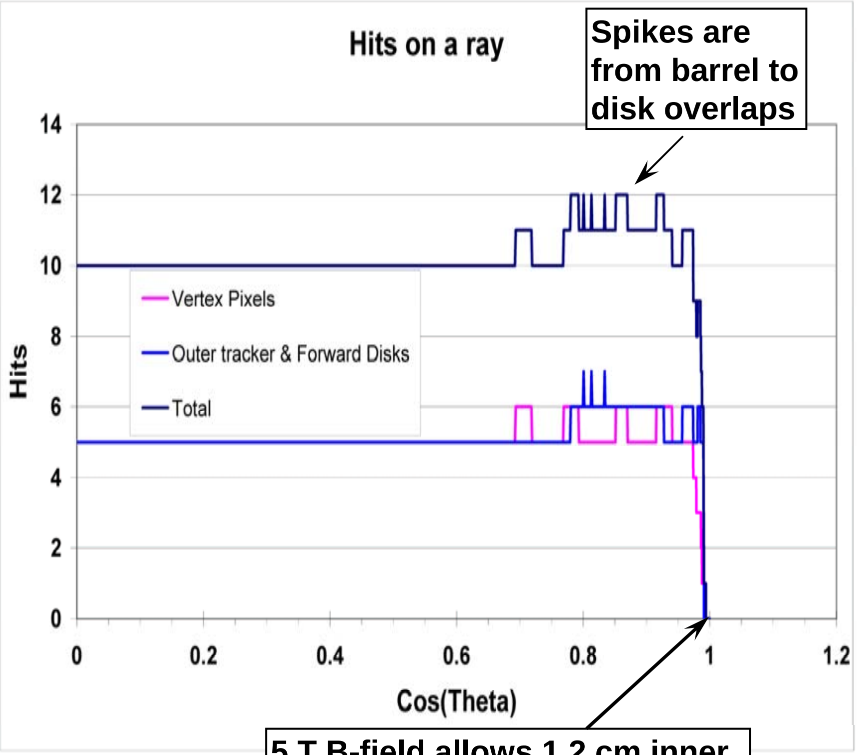
Silicon Considerations

- Silicon can provide excellent precision in measuring track hit positions.
- To optimize use of that precision, we have assumed a magnetic field of 5 T.
- Multiple scattering considerations have led to a baseline design with five outer tracker barrels, each of which measures r and phi.
  - Z-position is determined by extrapolating tracks forward from the vertex detector or backward from the electromagnetic calorimeter.
  - For stand-alone tracking, knowledge of Z comes from tracker readout segmentation ➔ short modules.
- The ends of each barrel are closed by disks to extend tracking and pattern recognition in forward/backward directions.
- Plan and end view drawings which follow show the overall outer tracker layout.
  - As can be seen in the plan view, barrel lengths have been adjusted to reduce the extent to which material in barrel – disk overlaps points to the origin.

R-Z View

- In the left figure, the 37.8° ray from the origin suggests the extent to which pointing material has been distributed.
- The right figure shows hits on a ray from the origin versus cos(θ).
- Vertex detector structures are shown in both plots for completeness.
  - Forward disks supported by vertex detector structures extend coverage of the outer tracker to cos(θ) = 0.99.

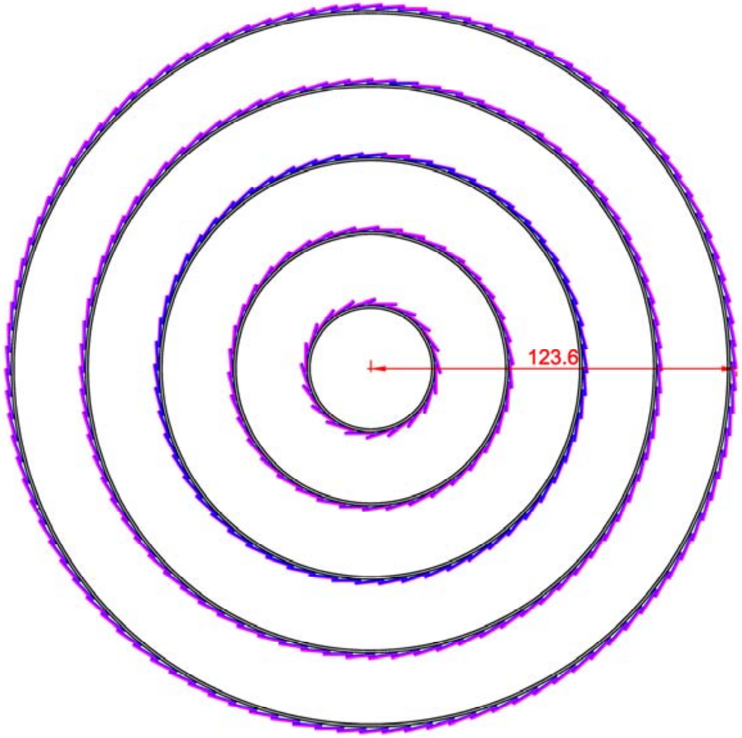




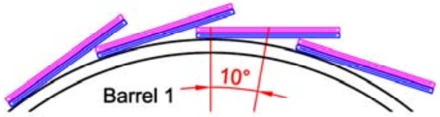
Spikes are from barrel to disk overlaps

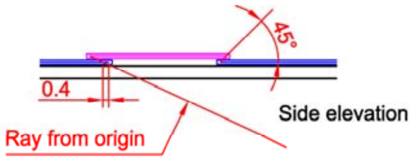
5 T B-field allows 1.2 cm inner radius beam pipe near Z = 0

Outer Tracker End View



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.

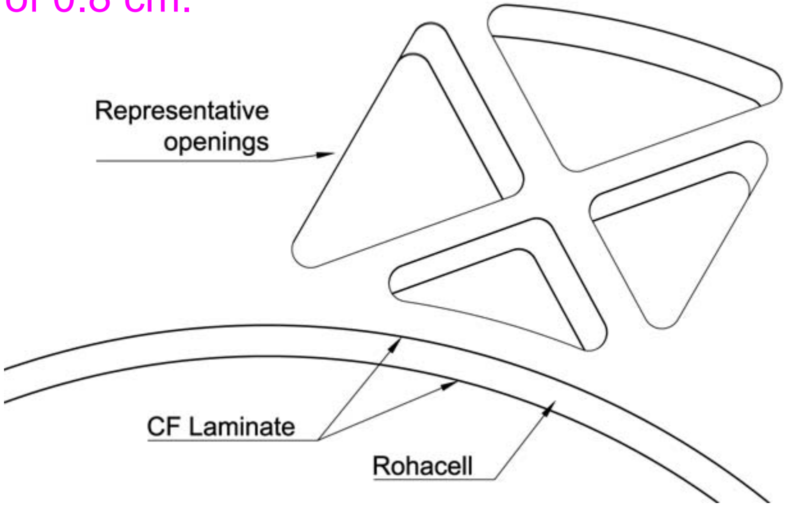




- Sensor modules will be described in a separate talk.
- Single type of module for all barrel layers
- The drawings show sensors positioned mid-way through the thickness of a module.
- Closest separation between modules = 0.1 cm
- Modules are square
  - Outer dimensions = 0.3 cm x 9.65 cm x 9.65 cm
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

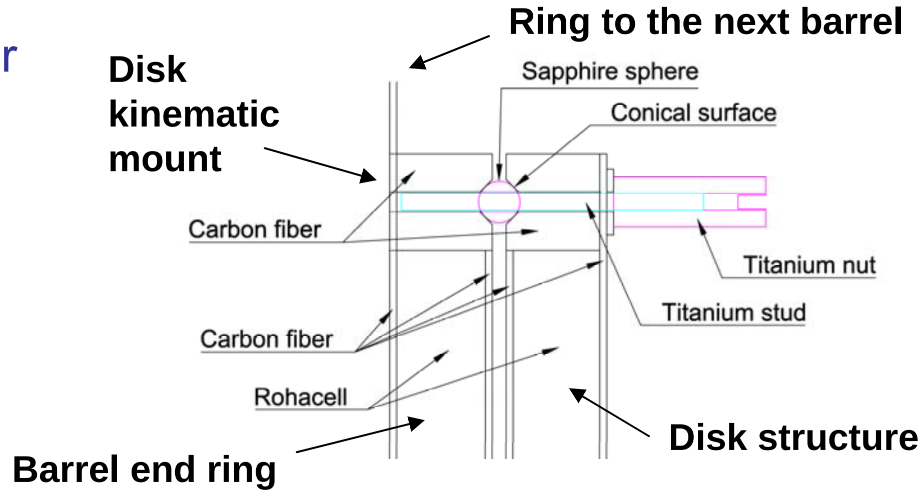
Major Support Structures

- In the barrels, silicon sensor modules will be supported by double-walled cylinders to provide good stability in sensor positions while limiting multiple scattering.
- Structural analyses have assumed that each cylinder shell is a 3-ply, quasi-isotropic, carbon fiber – resin laminate (~0.11% of a radiation length).
- The carbon fiber amount, its modulus, the ply orientations, and cylinder length and radius determine stiffness against longitudinal deflections.
  - Mitsubishi K1392U carbon fiber was assumed.
  - To reduce material, we may elect to use Mitsubishi K13C2U carbon fiber, which has a slightly higher elastic modulus (900 GPa versus 760 GPa).
- The two shells of a cylinder are separated by a layer of Rohacell.
  - The thickness of the Rohacell can be adjusted to control out-of-round distortions.
  - The present design assumes a thickness of 0.8 cm.
- Openings will be cut in the Rohacell, and probably also in the carbon fiber laminates, to reduce the average amount of material seen by tracks.
  - Opening configurations remain to be determined
  - They must take into account module mount locations.



Major Support Structures

- Each barrel is connected to the inner surface of the next barrel outboard via a carbon fiber laminate ring.
  - Ball and cone kinematic mounts allow reproducible connections.
  - Openings in the connecting rings reduce material.
  - End rings, the barrel to barrel connecting rings, and the disks stiffen each barrel against out-of-round distortion.



- Disk support structures are expected to be similar in construction to those of the barrels: a carbon fiber laminate – Rohacell – carbon fiber laminate sandwich, but with a flat geometry.
  - Present drawings show a Rohacell thickness of 0.8 cm.
    - It may be possible to reduce that to 0.3 cm.
  - The required Rohacell thickness will depend upon regions which are available to attach a disk structure to tooling for handling.
    - Disk out-of-plane distortions are expected to be greatest when a disk is rotated from a horizontal orientation to a vertical orientation for installation on the end of a barrel.
  - Openings will be cut in the Rohacell, and probably in the carbon fiber laminates, to reduce material.
  - Once mated, barrels aid in holding disks flat.

Outer Tracker Barrel Sensor Arrangement

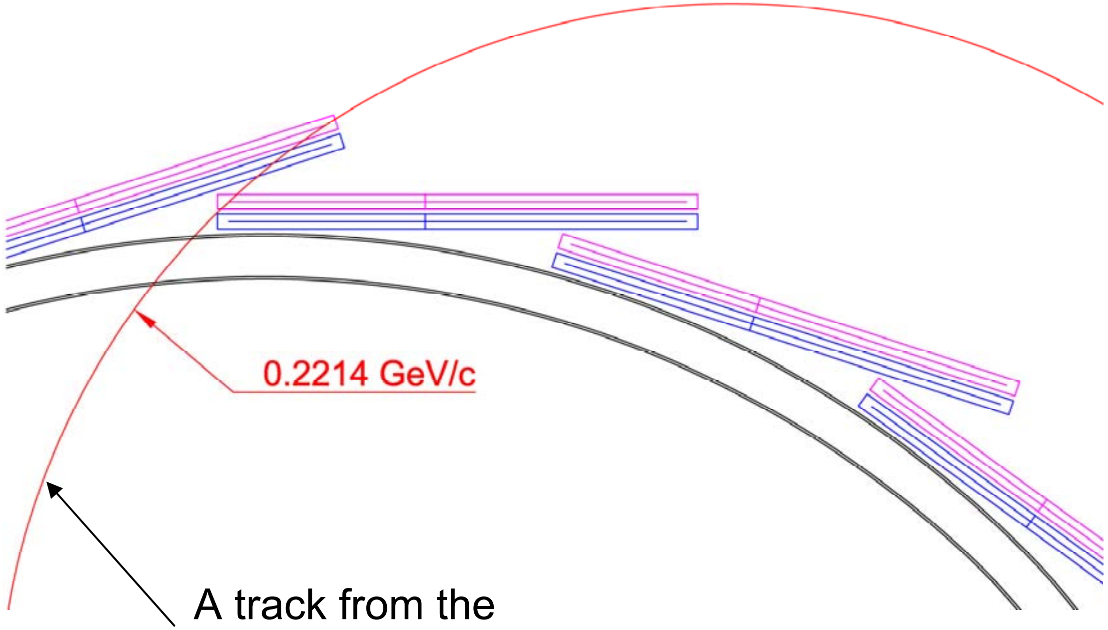
Layer	# Phi	# Z	Rot. Angle	R (cm)
1A	20	7	10.12°	21.75
1B	20	6	9.94°	22.15
2A	38	9	7.03°	46.75
2B	38	10	6.97°	47.15
3A	58	13	6.60°	71.75
3B	58	12	6.57°	72.15
4A	80	15	6.60°	96.75
4B	80	16	6.58°	97.15
5A	102	19	6.58°	121.75
5B	102	18	6.56°	122.15

This layout corresponds to 8686 barrel sensors, each with 1840 readout channels

Strip pitch = 25 μm. Readout pitch = 50 μm.

R-Phi Overlap

Barrel 1 is shown.

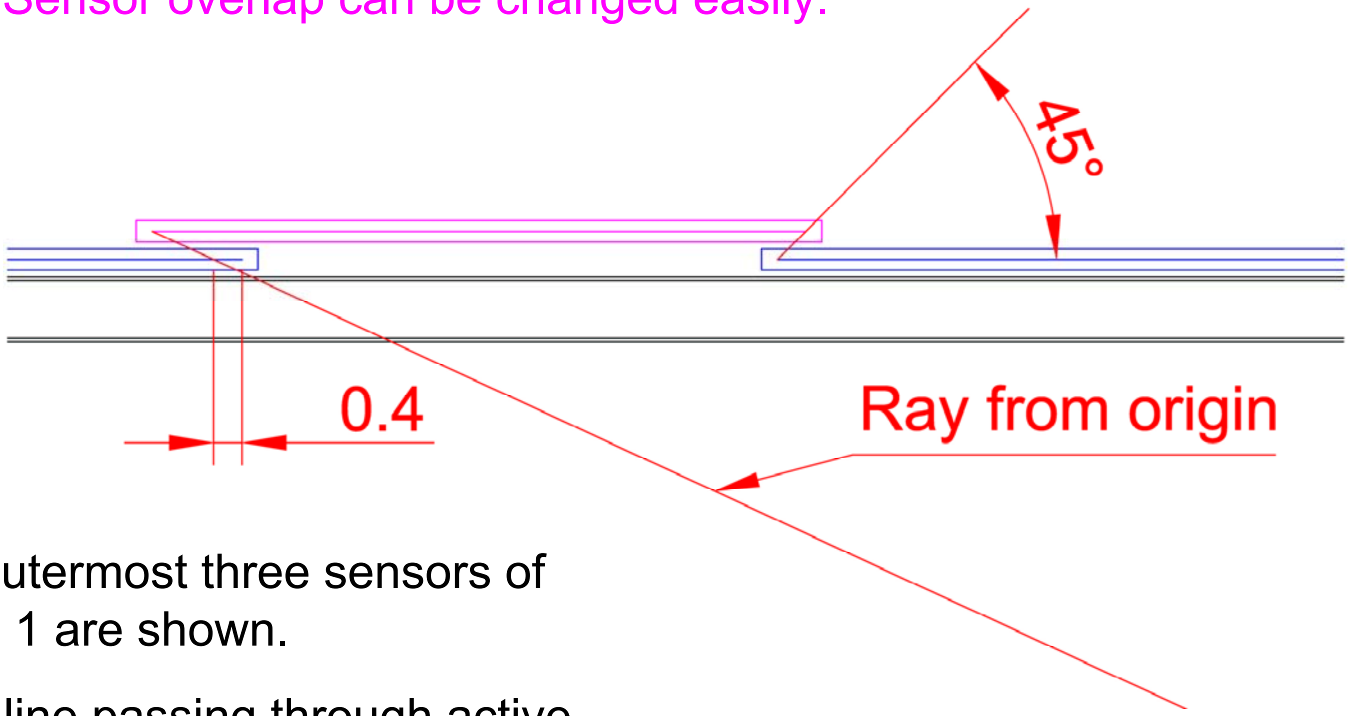


A track from the origin is shown (unit charge, 5 T field).

- With a pinwheel geometry, R-Phi coverage for one charge polarity is essentially hermetic.
- For the other polarity, a small fraction of low P_T tracks can pass between sensors.
- Studies will be needed to understand these small effects and the trade-offs between hermeticity and added material.

Outer Tracker R-Z View

- Typical A-layer to B-layer overlaps (all layers)
- Hermeticity for separated vertices versus material remains to be studied:
  - Sensor overlap can be changed easily.

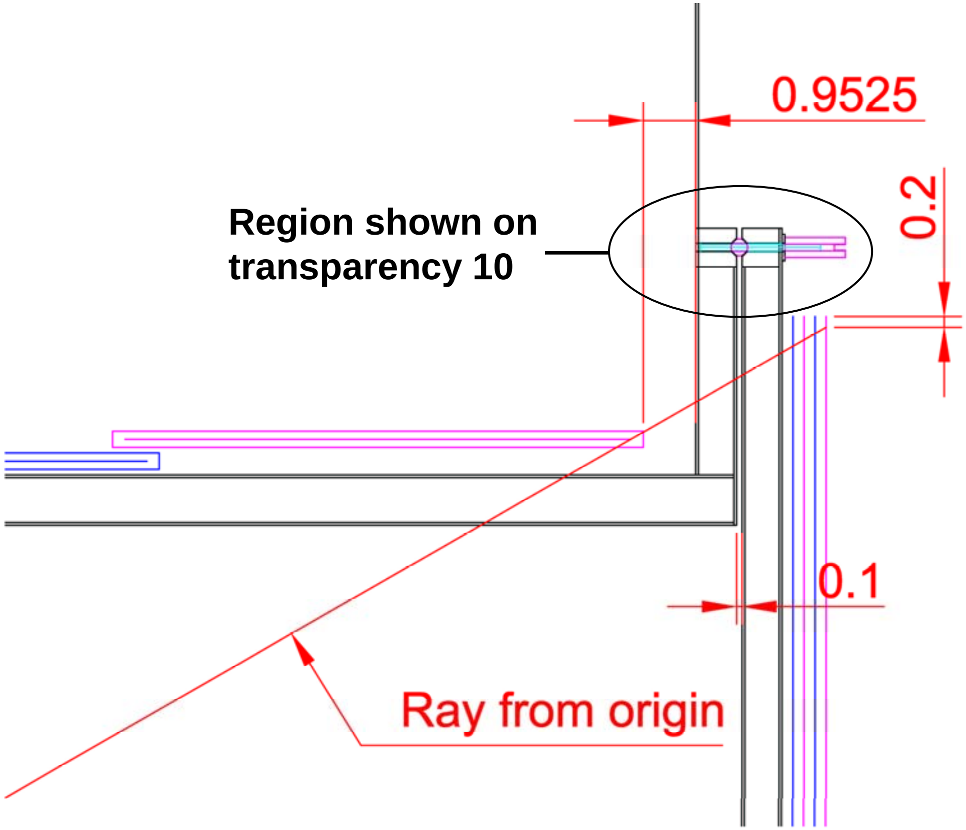


The outermost three sensors of barrel 1 are shown.

For a line passing through active edges of the left two sensors, DCA to origin = 6.7 cm (worst case).

Outer Tracker Disk-Barrel Interface

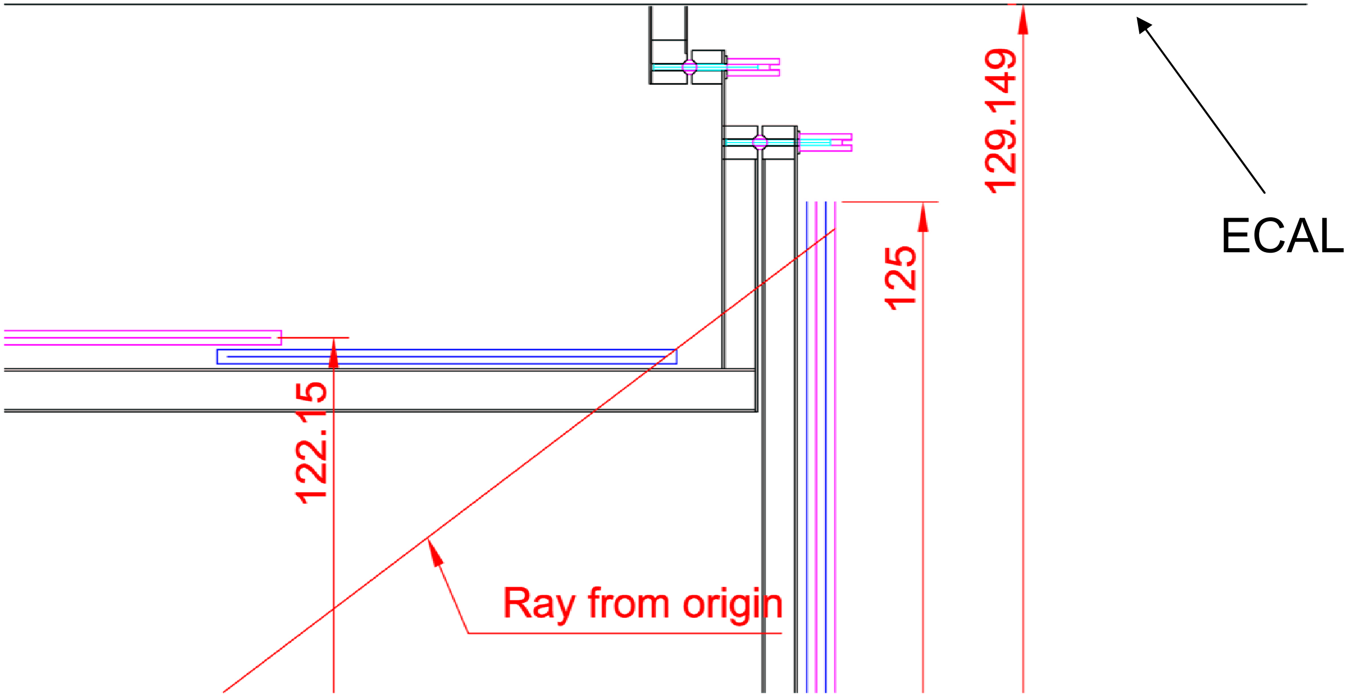
- Disks have been represented in drawings by four planes with a plane-to-plane separation of 0.2 cm.
  - That will need to change once we have developed a tiling concept.
  - Gaps for cabling also need to be understood.



Region shown on transparency 10

Mounts from ECAL

- A difficulty arises at barrel 5 mounts, where the present radius exceeds the nominal 125 cm.
  - It will be addressed when rails are designed to mount the tracker from the electromagnetic calorimeter.
  - A combination of adjusting barrel radii and matching the outer tracker geometry to the expected polygonal geometry of the inner surface of the electromagnetic calorimeter should work.

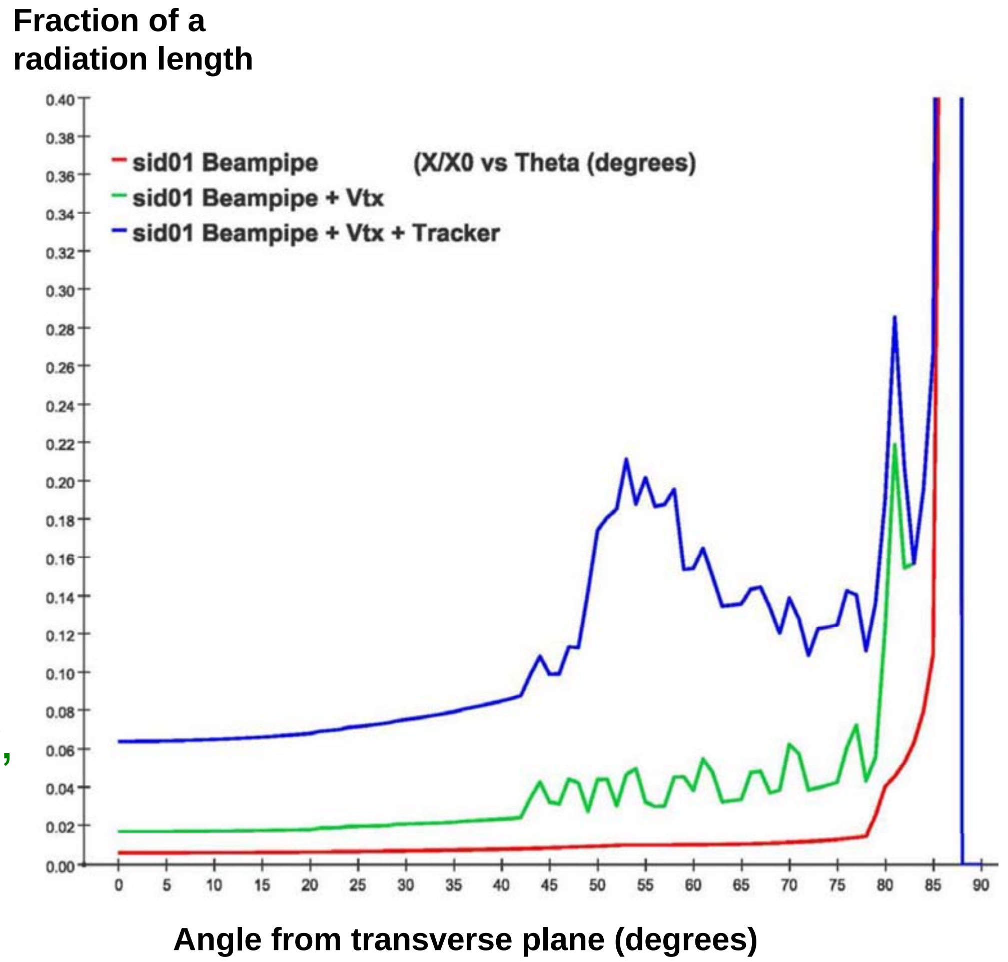


Disk Sensor Arrangement

- R&D includes the development of a disk tiling arrangement, as well as optimization of barrel tiling.
- A number of disk tiling arrangements with sensor modules similar to those of the barrels are under consideration.
- To limit the number of radiation lengths, double-sided sensors and pairs of sensors within a module have been suggested.
- The choice of disk tiling should take into account pattern recognition capabilities, balance track finding efficiency with minimization of fakes, and allow a natural extension of tracking algorithms from the barrel region to the disk region.
- It should also take into account ease and precision of fabrication and assembly.
- Paths for cables and services will need to be preserved.

Radiation Lengths

- Our goal has been to limit the tracker to 0.8% of a radiation length per layer at normal incidence.
  - We are at ~ 0.92% in the barrels.
  - R&D will show whether improvement can be made, or whether material has been overlooked.
- Upper, middle, and lower curves show fraction of a radiation length within an envelope containing the outer tracker, an envelope containing the vertex detector, and the beam pipe, respectively.



Outer Tracker Power Dissipation

- Barrel power has been estimated assuming 8686 sensors, each with1840 readout channels (from transparency 11), and an average power dissipation of 20 µwatts per channel.
  - Power dissipation per channel is consistent with design assumptions for KPIX readout chips.
  - Power cycling has been assumed to reduce peak power by a factor of approximately 80.
  - Barrel average power = 319.6 watts.
- Disk power has been estimated assuming that, on the average, each sensor has the same area and number of readout channels as do barrel sensors.
  - Phi overlap was assumed to be provided by a pinwheel geometry.
  - Each disk was assumed to measure two coordinates.
  - That leads to 4738 disk sensors (sum of two ends).
  - Disk average power = 174.4 watts.
- Power dissipated in cabling within the sensor region is expected to add at least 4% to the heat to be removed.
- Other heat sources include power conversion, conditioning, and transceivers. Controlling those will require careful attention.

Outer Tracker Power Dissipation

- Assumes 20 μwatt per sensor readout channel.
- Assumes that barrel modules are arrayed as described earlier.
- Assumes that disk power dissipation per unit area is the same as the barrel average.
- Assumes each disk measures two coordinates.

Total = 494.2 watts

Barrels	P (watts)	Disks	P (watts) 2 ends
Barrel 1	9.6	Disk 1	10.9
Barrel 2	26.6	Disk 2	28.2
Barrel 3	53.4	Disk 3	52.2
Barrel 4	91.3	Disk 4	83.1
Barrel 5	138.9		
Sub-total	319.8	Sub-total	174.4

- Note that, with power ramped up, expected dissipation would be 80(494.2 watts) = 39.5 kilowatts.

Lorentz Forces

- Lorentz forces on cables and structures need to be studied and are likely to impact designs.
- At 2.5 volts, 39.5 kilowatts corresponds to 15.8 kilo-amps.
- Hence the interest in Lorentz forces due to the 5 T field.
  - Granted, the current would be distributed over many conductors.

Air Flow

- Assume air enters the tracker region at +15^o C and that heat removal increases its temperature by ΔT = 10^o C.
  - The required flow rate depends primarily on ΔT and weakly on the assumed entry temperature.
    - 10% decrease in volumetric flow rate with a delivery temperature of -10^o C.
  - Density of dry air at 20^o C = 1.206 kg/m3
  - Specific heat = 1.0056 kJ/kg-K
- Then the required flow rate to remove 494.2 watts is 0.0408 m^3/s = 86.3 cfm.
  - To take into account other known and not-so-well known sources of power dissipation, we will plan for a flow rate of 100 cfm.
- Efficiency of heat transfer and paths for air distribution will be studied.
- A reliable air cooling system and extremely reliable cooling monitoring and interlocks will be essential.
  - Back-up tube trailers could address cooling system glitches and allow time for the interlocks to act.

Support Cylinder Fabrication

- We have previous experience in building a carbon fiber cylinder of 2/3 the length and 0.4 the diameter of the outermost barrel.
  - That cylinder was built on a mandrel.
  - All carbon fiber of the inner shell was placed on the mandrel, vacuum-bagged, and cured.
  - A Rohacell layer was placed on the carbon fiber, vacuum-bagged, and glue was cured.
  - All carbon fiber of the outer shell was placed on the Rohacell, vacuum-bagged, and cured.
- Precision of the outer surface was approximately ±150 μm.
  - We will seek to improve that precision by a factor of 4.
    - Surface irregularities and lack of cylindricity contribute to the thickness of glue that will be needed to attach module mounts.
    - Our goal is to limit the required glue thickness to 75 μm.
- We will investigate how to make openings in Rohacell and whether openings can be extended through the carbon fiber shells.
  - Assuming fabrication on an inner mandrel, we are likely to need to water-jet cut openings after a cylinder has been otherwise completed.
  - Stability of the cylinder under that operation will need to be checked.

Reality Check: DZero CFT

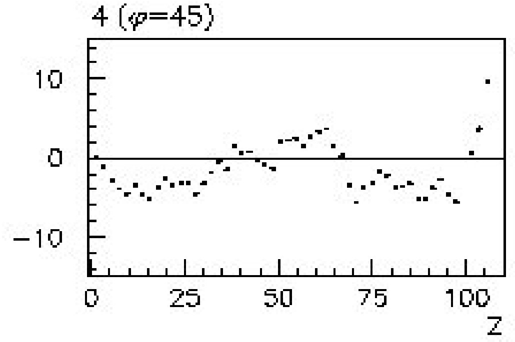
- ANSYS calculation of CFT deflections
  - 0.25” Rohacell thickness
  - Higher scintillating fiber weight
  - Lower modulus carbon fiber (factor of slightly more than 2)
  - Except for cylinder 3, loads from other cylinders transmitted only at ends
- Results agree reasonably with predictions for the SiD outermost tracker barrel (13 μm local deflection, 7 μm deflection with local stiffening).
  - Please note that fabrication tolerances are likely be more important than deflections.

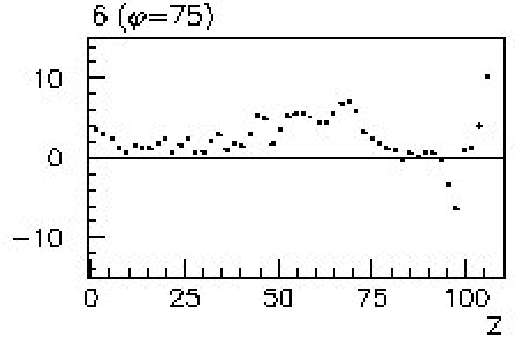
Cylinder Layer	*Maximum Deflection (mils)*
1	1.48
2	1.50
3	1.51
4	1.37
5	1.18
6	1.07
7	0.98
8	1.02

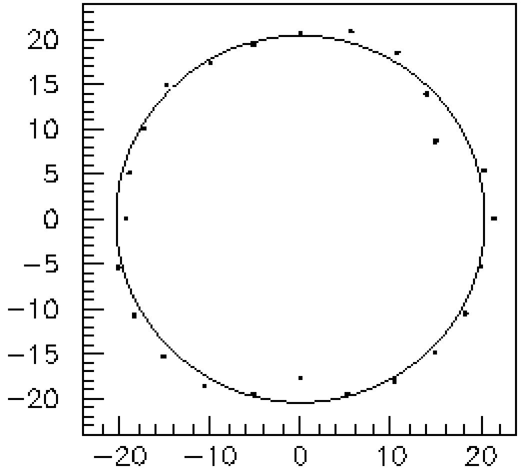
CFT cylinder outer radii range from 20 cm to 52 cm.

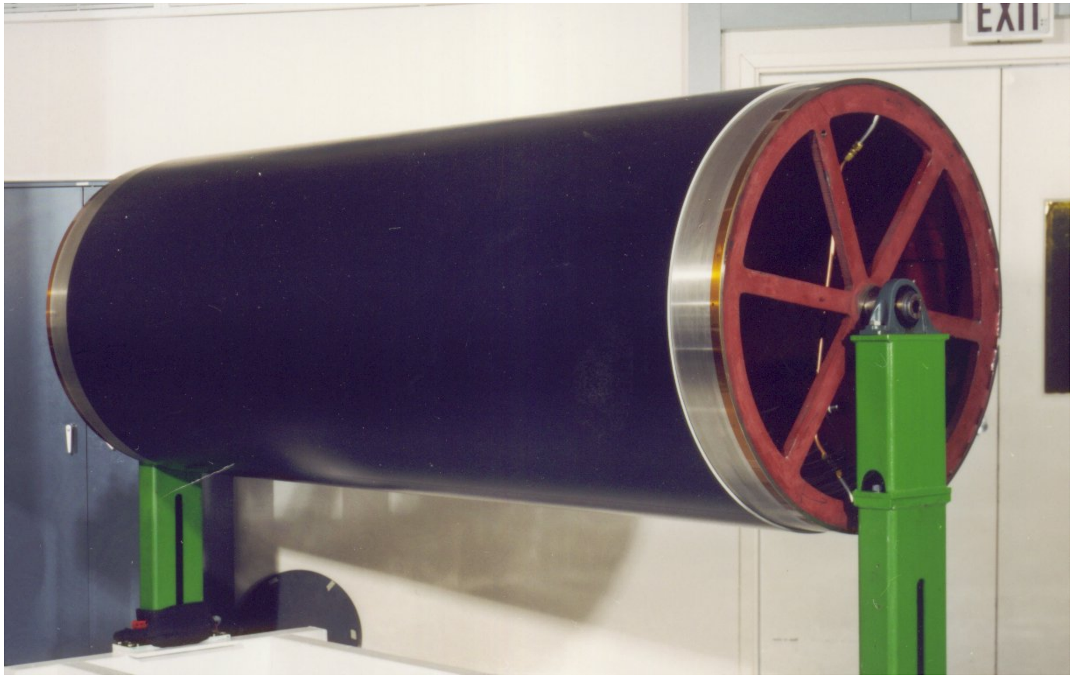
Data from Lehman Review,
June 1999

DZero CFT Cylinder 8









Cylinder 8
50 meas. Along L
3.5 mil RMS

CFT cylinder 8:

L = 2.50 m, R = 0.52 m

SiD cylinder 3:

L = 2.20 m, R = 0.72 m

Data from Lehman Review,
June 1999

Assembly of Outer Tracker Barrels / Disks

- Assembly assumes modules which reproducibly engage mounts.
- Tooling would be provided to hold a barrel support cylinder from its end rings or inner surface.
  - The tooling could consist of the cylinder fabrication mandrel.
  - Precise control of the cylinder orientation and position is not required provided the cylinder carries reference features which allow a cylinder-based coordinate system to be established.
  - We assume that changes to cylinder shape are negligible when the cylinder is rotated to a different azimuth.
    - The reference features allow that to be checked.
- Precision bars would carry mounts and position them on the cylinder outer surface, where they would be glued or otherwise attached.
  - A bar need not extend the full length of the barrel.
  - For design purposes, we have assumed that a bar would carry eight modules.
    - The intent is to limit the self-deflection and cost of a precision bar.
    - For the outermost barrel, that implies roughly five placements per azimuth.
    - We will study the trade-off between tooling cost and the cost and duration of module installation.

Assembly of Outer Tracker Barrels / Disks

  - Reference features on each bar would guide placement of the bar on the support cylinder..
  - The bar must be stiff enough to ensure that module mounts are adequately known with respect to the bar reference features.
  - Bar alignment requires a CMM, laser alignment system, or equivalent.
  - A CMM may allow more extensive and automated characterization of barrels or disks.
  - Mounts of at least the first barrel will be measured and characterized.
- Once mounts have been attached to the cylinder surface, modules can be installed by hand.
  - Locations of a subset of modules of each barrel will be measured.
- Cabling can be added in stages, allowing periodic checks that modules read out.
- Disk assembly would be similar to that of barrels, except that a disk would most likely be oriented horizontally and plates would be used to place module mounts.

Mating of Barrels / Disks

- Barrels and disks would remain on their fabrication tooling until we are ready to mate them.
- We propose mating from the outer barrel inward, so that support of mated assemblies can always be from the outer barrel.
- Two approaches seem reasonable depending on height clearance.
  - If height is sufficient, a C-frame lifting fixture can be used in conjunction with a crane or equivalent.
    - Overall inner length needs to be at least as great as the sum of the lengths of the outer two barrels plus longitudinal clearance.
    - Tooling must allow transverse and rotational adjustments.
  - If height is limited, a carriage system could provide support from below.
    - That was done in mating the DZero fiber tracker barrels.
- Once all barrels have been mated, their cabling should be dressed before disks are added.
- Disks would be added either one at a time or in end-to-end pairs.
  - Cabling needs to be dressed after each disk is installed.

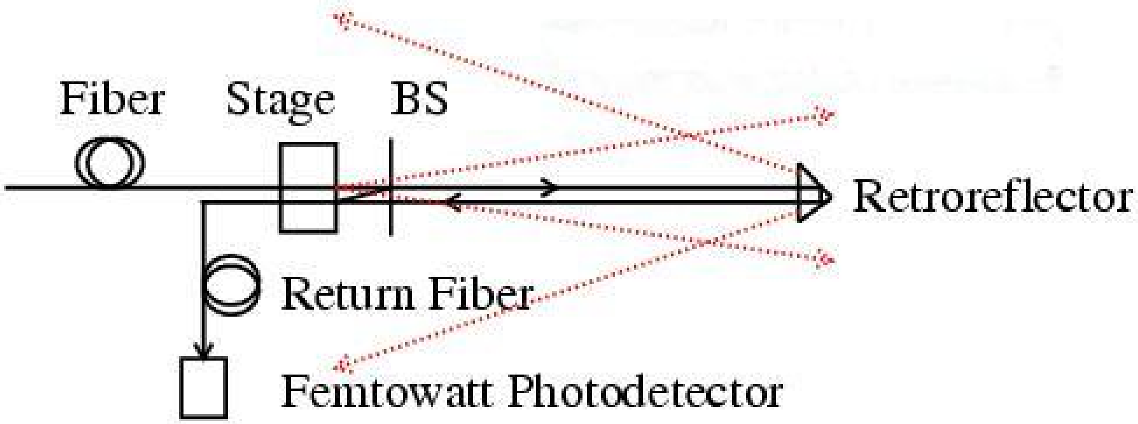
Frequency Scanned Interferometry for ILC Tracker Alignment

University of Michigan ILC Group

Hai-Jun Yang, Eui Min Jung, Alex Nitz, Sven Nyberg, Keith Riles (PI)

- Measure hundreds of absolute point-to-point distances of tracker elements in 3 dimensions by using an array of optical beams split from a central laser.
- Absolute distances are determined by scanning the laser frequency and counting interference fringes.
- Grid of reference points overdetermined → Infer tracker distortions

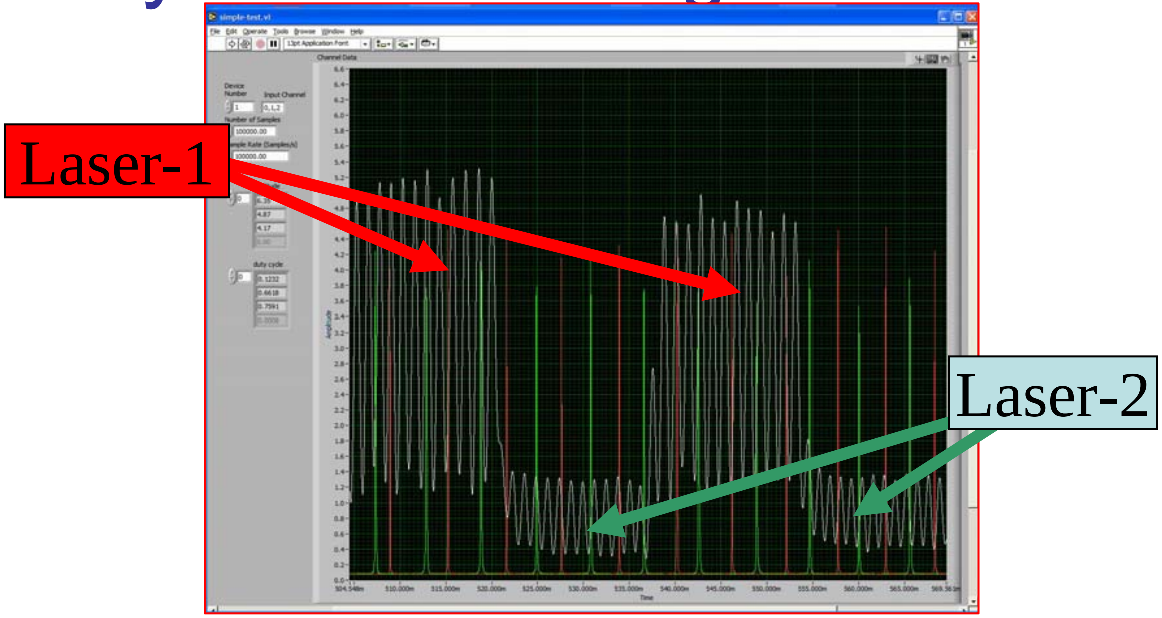
Technique pioneered by Oxford ATLAS group

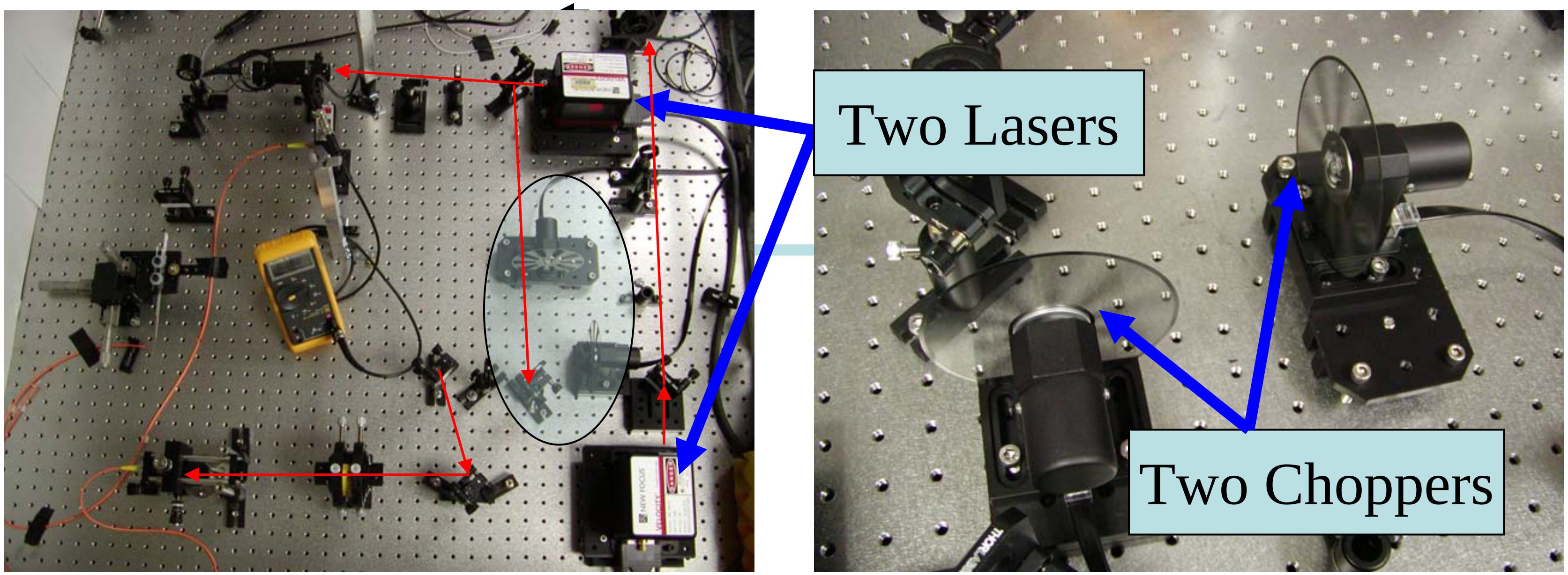


Dual-laser R&D System in Michigan Lab

Dual-laser scanning suppresses systematic errors

Allows precise measurement under poor conditions



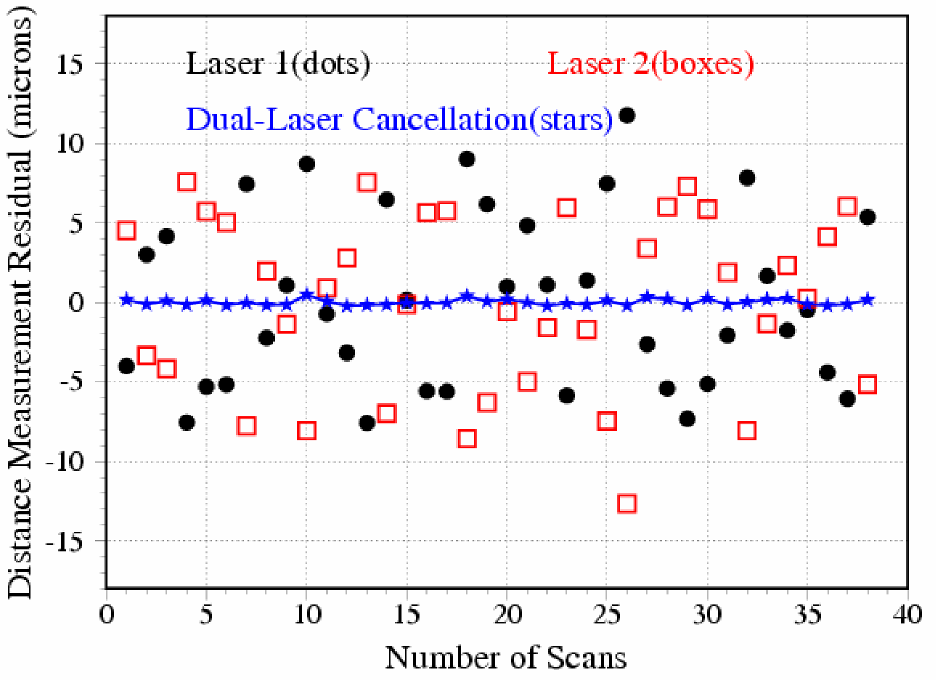


Distance Measurement Precision to Date

➔ Combining multi-distance-measurement and dual-laser scanning techniques to reduce and cancel interference fringe uncertainties, vibration and drift errors
Dual-laser precision (RMS) ~ 0.20 microns under realistic conditions

High-precision absolute distance and vibration measurement with frequency scanned interferometry,
H.J. Yang, J. Deibel, S. Nyberg, K. Riles,
Applied Optics, 44, 3937-44, (2005)

High-precision absolute distance measurement using dual-laser frequency scanned interferometry under realistic conditions,
H.J. Yang, K. Riles
[Physics/0609187]
Submitted to Applied Optics



FSI R&D Needs

- Need to miniaturize optical components using low-X_o materials
- Need to ensure robustness of beam alignment
- Need to ensure robustness and efficiency of beam delivery and return network, including photodiode readouts
- Need to carry out integration tests with small FSI grid under controlled motion
- Need to build a prototype system compatible with prototype tracker elements and use in a test beam
- Need to develop simulation software to optimize the layout of the FSI grid for a full tracker

Tentative Alignment Goals and Plans

- In the barrels, goals are based upon the assumption that we identify the sensor in which a hit occurred but do not have addition information on longitudinal position (first pass pattern recognition).
- Minimal degradation of sensor transverse position resolution:
  - Sensor strip pitch = 0.025 mm
  - 17% degradation → 0.015 mm misalignment
- Accordingly, we propose to align strips with respect to the detector axis to ±0.015 mm over a sensor readout length.
  - ±0.0105 mm from module fabrication accuracy
    - Requires either a CMM or equivalent, or
    - Certified tooling and at least one precisely cut sensor edge
  - ±0.0105 mm from module placement accuracy
    - Implies that module mounts have good reproducibility
    - Implies that a coordinate system has been established based upon cylinder reference features and that mounts have been accurately placed
  - With considerable effort, these goals have been achieved before.
- Overall alignment of barrels
  - To ensure that sensor positions within a barrel are well known, reference features on the ends of each barrel and on barrel connecting rings will be measured once barrels have been mated to one another.
    - Our tentative goal is a measurement precision of ±0.010 mm in each coordinate.
  - That task can be done more completely if barrels are mated, and then disks are added.

Tentative Alignment Goals and Plans

- In the disks, requirements are different since these devices provide the equivalent of 3-D hits.
  - Except for overlap considerations, sensors need not be precisely placed.
  - We do need to know where they are.
  - If separate sensor planes are used for 3-D information, relative locations and orientations of sensors within pairs of planes must be known.
- Good reproducibility of sensor mounts and disk mounts is necessary.
- After disks have been added to the ends of a barrel, reference features on the disk will be measured relative to the set of reference features visible on barrels.
  - Our tentative goal is a precision of ±0.010 mm in each coordinate.
  - Please note that larger radius disks cover the reference features of smaller radius barrels and disks.
    - That places a premium on the stability of barrel and disk structures as disks are added.
- Reconstruction of tracks seen in both the barrels and the disks should aid in verifying as-installed tracker internal alignment.
- Frequency scanned interferometry can provide monitoring essential to understanding short-term and long-term stability of alignment.
  - In principle, it can be used to measure changes in tracker alignment with respect to other detector elements.
  - It can also provide a starting point for re-alignment with tracks and guide the frequency with which re-alignment needs to be done.

Summary of R&D

- Design studies of barrel and disk support structures
  - Measurements of carbon fiber properties, particularly CTE
  - Optimization of Rohacell thickness
  - Optimization of openings to reduce material
  - Verification by both spreadsheet calculations and FEA
  - Documentation via notes and drawings
- CMM procurement, commissioning, and installation
  - Procurement will require a clear set of specifications, which means we will need to understand the planned use and required precision in detail.
  - A proper foundation will need to be designed.
    - Sometimes CMM vendors will engineer the foundation, but at a cost and at the expense of a more complicated bidding procedure.
  - CMM services will need to be provided.
  - Once installed, the CMM will need to be “certified” to the satisfaction of both the vendor and the purchaser.
  - We could defer CMM purchase to the project phase and concentrate R&D on cylinders 1 and 2.
    - Substantial savings in R&D costs
    - Higher risk to the project

Summary of R&D

- Carbon fiber purchase and tests
  - The cost of carbon fiber has increased due to demand and our requirements are unusual.
    - The present cost of K13C2U prepreg is approximately $1500 per pound.
    - We need a resin which is free of high-Z components (to control radiation length) and compatible with silicon.
    - Both are an issue with standard resins, which contain flame retardants.
  - Price depends upon the quantity purchased.
  - We should test each batch we receive.
    - Chemical and spectrographic tests
    - Possibly beam tests to directly determine the radiation length
  - The carbon fiber purchase is shown relatively late. We would expect to obtain carbon fiber for the vertex detector earlier.
- Design and fabrication of tooling
  - Requires proposed procedures
  - Required precision must be known
- Fabrication and testing of structural support prototypes
  - Deflection can be predicted, but not precision of fabrication.
  - Precision will depend on skill, techniques, and resources, particularly if it is to be improved by a factor of 4.
  - The outer barrel is larger than past structures we have built.

Summary of R&D

- Interferometer system tests
  - Interferometry can link fabrication geometry to installed geometry.
  - It may be extremely valuable to monitor distortions as the detector is opened and closed and distortions associated with push-pull operation.
    - For normal opening and closing, the primary issue is knowledge of geometry after closing.
    - For push-pull operation, we have the added possibility that distortions could lead to breakage. Real time feedback could provide an essential warning.
  - Lines of sight must be preserved.
- Design and testing of support rails
  - We want to be able to open the detector for servicing, close it , and have negligible change to position and geometry.
  - Suitable rails need to be designed and the design needs to be confirmed by testing.
- Design of modules and module arrays
  - This needs to occur early, since many of the other tasks depend upon it.
  - Barrel arrays have received more attention so far than disks.

Summary of R&D

- The design of power conditioning mounts and the specification of paths for cables and services.
  - This should be straight-forward, but should not be forgotten.
  - Paths for cables and services should be integrated with the remainder of SiD, that is, should continue to the outside world.
- Cooling studies
  - These have been pushed early, since their intellectual portion can be done without much M&S.
  - Predictions will need to be confirmed.
  - A second round of studies has not been listed, but may be appropriate once partially populated support structures are available.

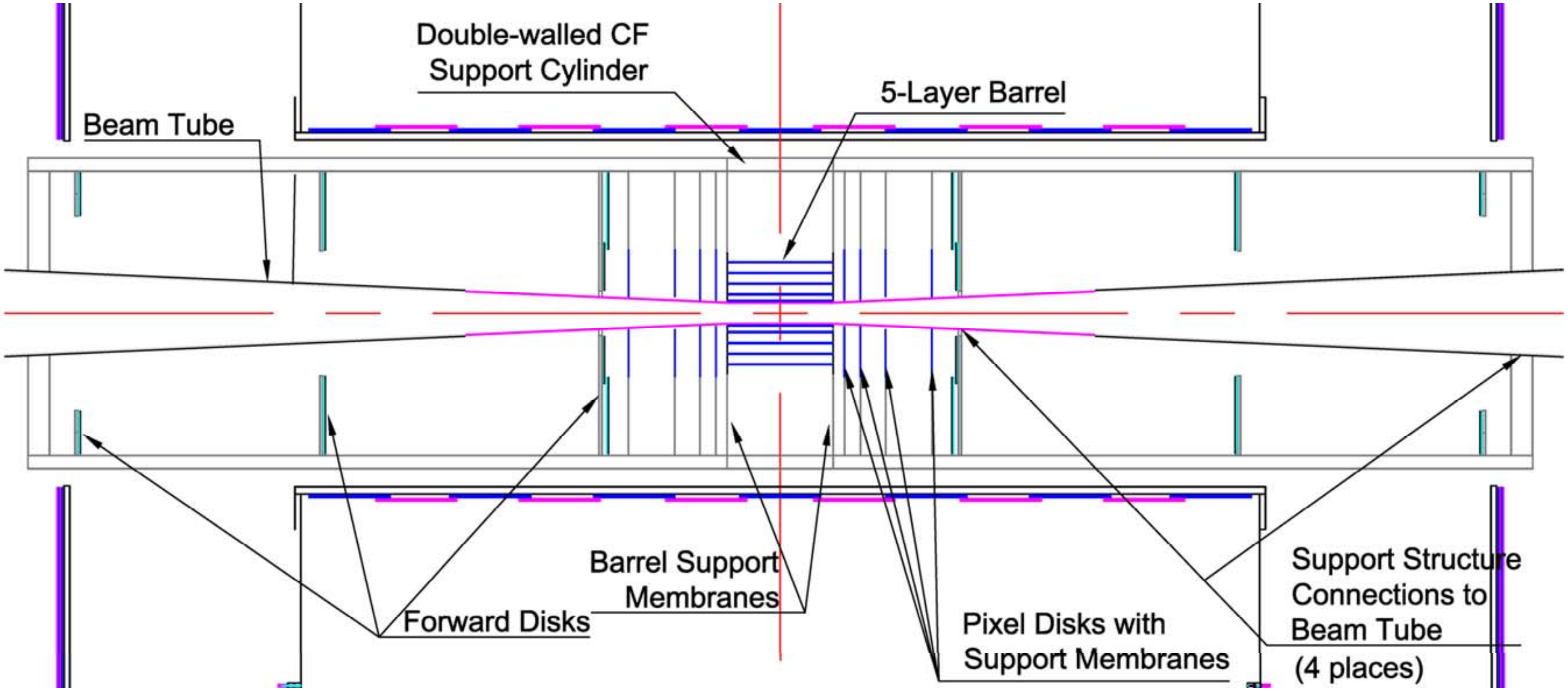
Tentative R&D Time Lines

	2007	2008	2009	2010	2011
Design of barrel and disk structural supports	—	—	→		
CMM procurement, installation, and commissioning			→		
Carbon fiber purchase and pre-preg tests			→		
Tooling design and fabrication			—	→	
Fabrication and testing of structural support prototypes, a barrel, and a disk				—	→
Interferometer system tests				—	→
Design and testing of support rails		—	→		
Design and tests of support structure kinematic connections	—	→			
Module array and design	—	—	→		
Design of power conditioning mounts and the specification of paths for cables and services		—	→		
Cooling studies		→			

- Back-up slides follow.

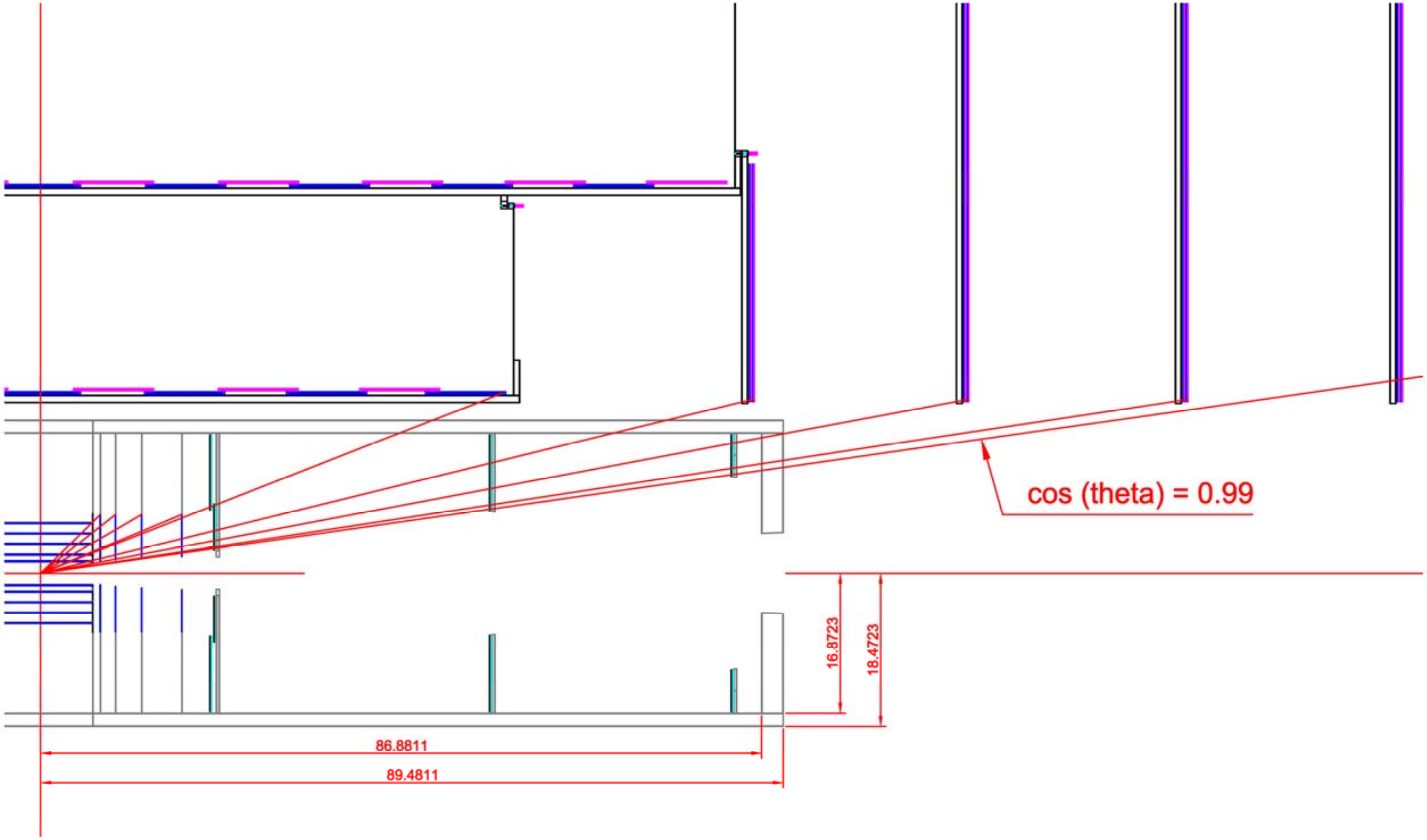
Vertex Detector

- The arrangement of sensors has been updated, but changes were minor.
- Carbon fiber half cylinders are supported from the beam pipe and stiffen the beam pipe.
- Sensor support structures tie to the half-cylinders.
  - Support structures utilize carbon fiber – resin laminate.
  - No foam, except possibly in the disk supports



VXD / Outer Tracker Overlaps

- Minimum material radius of the outer tracker is 20.5 cm.
- The first three outer tracker disks do not reach cos (theta) = 0.99, but forward disks in the VXD region do.



Simplified Mechanical Labor Comparison

SiD R&D proposal

- Physicists: 1 FTE
- Mech. Engineers: 1 FTE
- Designers/drafters: 1 FTE
- Technicians / CMM operators: 1 FTE
- 5 year period → 20 FTE-years

DZero Run IIa silicon (1993)

- Physicists: 4 → 2 FTE
- Mech. Engineers: 3 → 2 FTE
- Designers/drafters: 2 → 1 FTE
- Technicians / CMM operators: 6 → 2 FTE
- 8 years to complete project, >3 years R&D → >21 FTE-years R&D
- CDF labor was comparable

Run IIa silicon benefited from past silicon experience, as will SiD silicon.

The SiD proposal was developed independently.

The labor it proposes is consistent with past experience.

This level of R&D effort is necessary to design and to be prepared to build a state-of-the-art tracker.