Mechanics and layout of the Silicon Vertex

Joao COSTA, Mingyi DONG, Jinyu FU, Quan Ji, Gang LI,

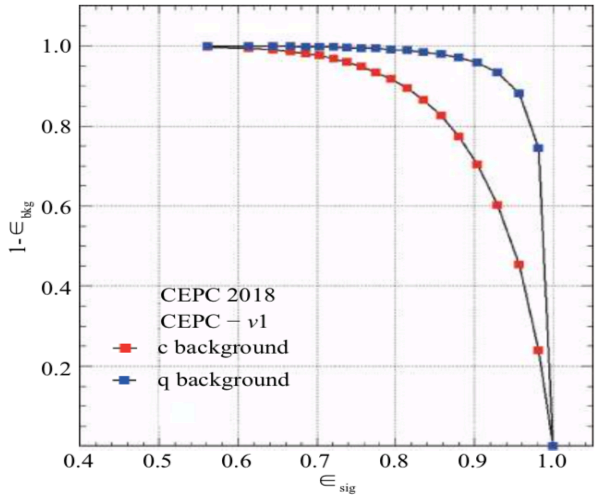
Zhijun LIANG, Kewei WU, Zhaoru ZHANG, Hao ZENG

IHEP, 2020-02-20

Outline

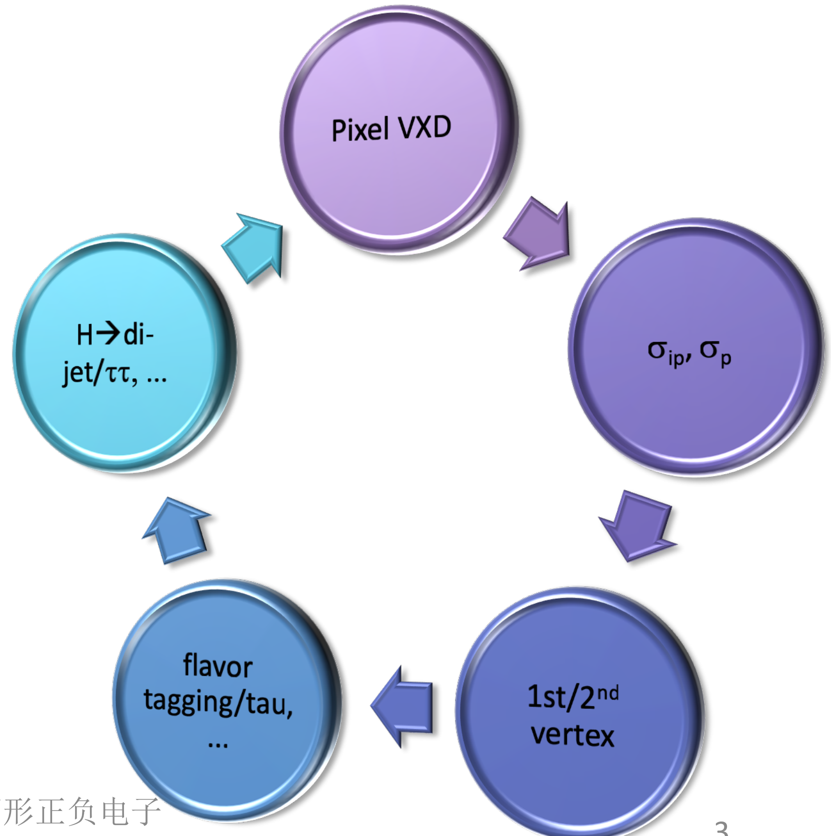
- Introduction
- Layout optimization
- Mechanical design
- Future plan

Motivation



- Detector design motivated by physics motivation
  - Jet identification strongly depends on impact parameter precision

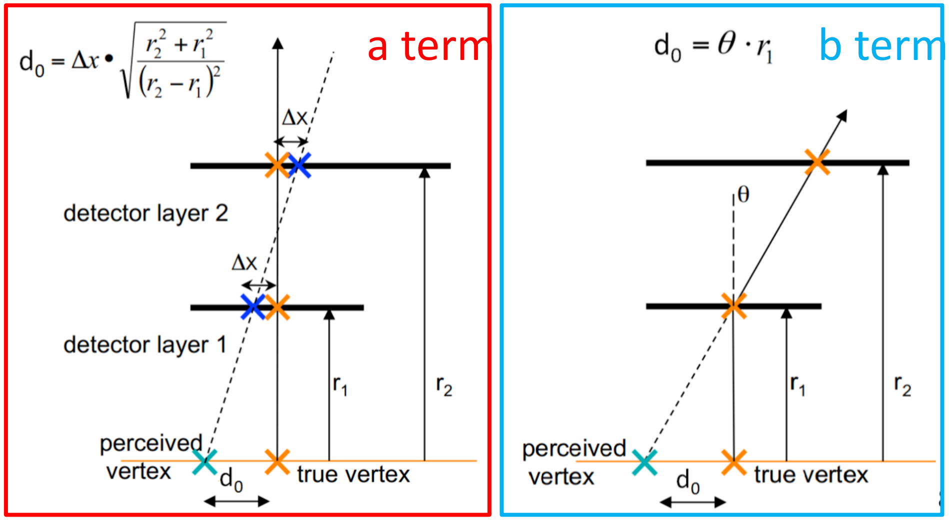
- CEPC dedicated to Higgs study, as well as SM and flavor physics
  - B, D, τ and other long-lived particles
- Physics always wants detector as good as possible
- Hardware gives the boundary
  - Resolution
  - Material budget
  - Power consumption
  - Layout
  - …
- Optimization …



Impact Parameter Resolution:

$$\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2} \theta}$$

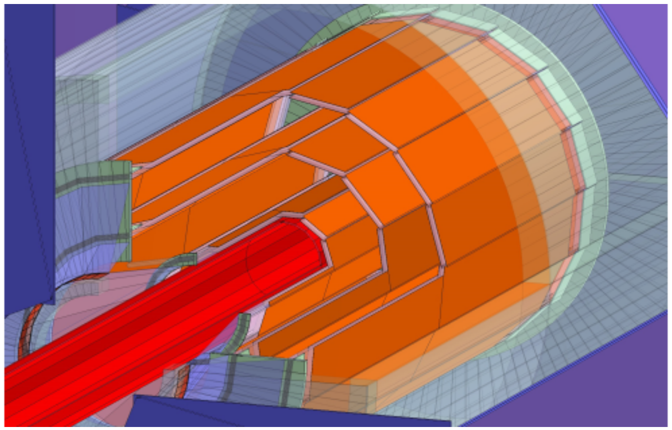
- p: the track momentum
- Θ: the polar track angle
- 'a' term: the intrinsic resolution of the vertex detector in the absence of multiple scattering, independent of the track parameters.
- 'b' term reflects the effects of multiple scattering.
- a = 5 μm and b = 10 μm · GeV from CDR.
- 3 double- layer pixelated vertex detector.



	R (mm)	$\|z\|$ (mm)	$\|\cos\theta\|$	σ (μm)
Layer 1	16	62.5	0.97	2.8
Layer 2	18	62.5	0.96	6
Layer 3	37	125.0	0.96	4
Layer 4	39	125.0	0.95	4
Layer 5	58	125.0	0.91	4
Layer 6	60	125.0	0.90	4

Design goal

CDR vertex detector concept



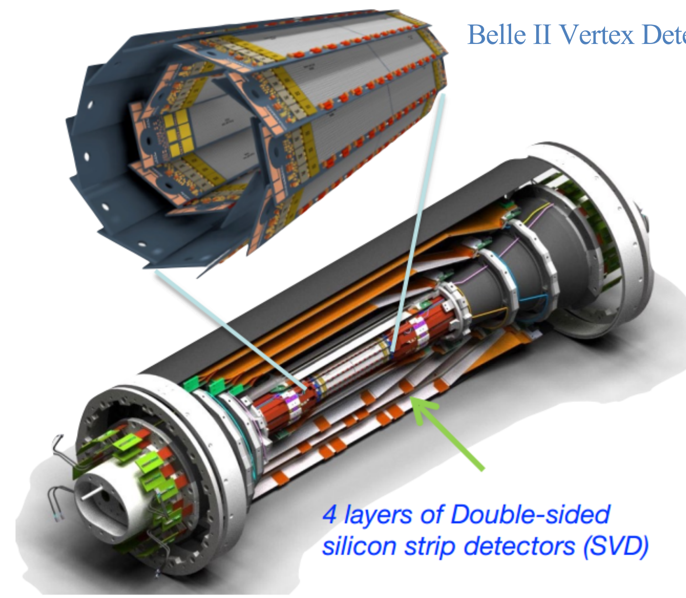
+ mechanics

+ electronics

+ cooling system

+ cable

Vertex detector prototype



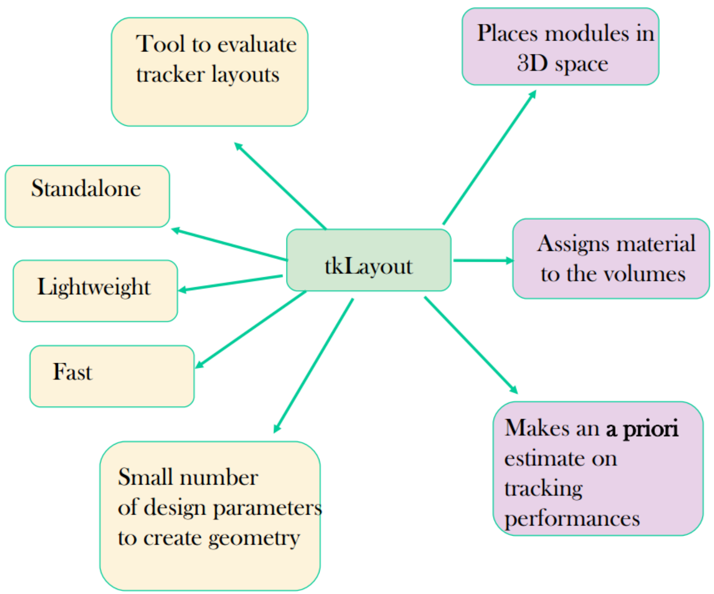
	R (mm)	$|z|$ (mm)	Current z in total
Layer 1	16	62.5	130.6 mm
Layer 2	18	62.5	
Layer 3	37	125.0	263.1 mm
Layer 4	39	125.0	
Layer 5	58	125.0	263.1 mm
Layer 6	60	125.0	

- Power dissipation: Final goal: ≤ 50 mW/cm2
- Current goal: ≤ 200 mW/cm2. (air cooling)
- Working temperature range: 20-50 °C
- Single point resolution better than 5 µm.

Layout optimization

Fast simulation tool - tkLayout

What is tkLayout?



- Compare different detector layouts
- Fair comparison of layouts with a priori estimate of performance(occupancy, tracking and trigger approximate efficiencies, approximate financial cost, power consumption)
- Narrow down the parameter space
- Pre-optimized designs
- Does not depend on optimised reco algorithms

- IS NOT a replacement for the MC simulation
  - estimate impact on trigger
  - physics channels
  - occupancy
  - efficiency
  - ……

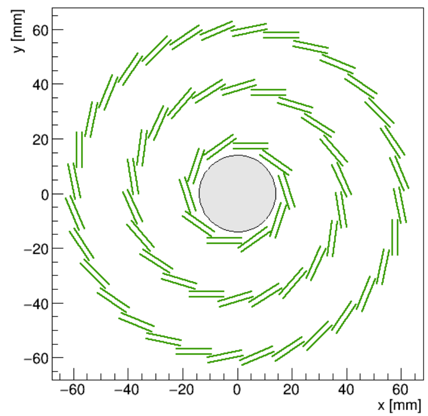
- From/validated by CMS
- Fast
- Flexibility to change detector design
- Automatic optimization
- Optimizing given layouts
- Realistic material description, power consumption, backgrounds, an so on

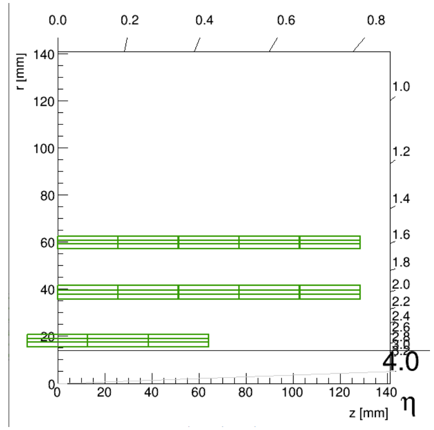
- Useful tool for CEPC vertex prototype layout optimization

Resolution, material, power, …

Fast tool LDT used as alternative, full GEANT4 simulation as validation

The impact of material on resolution



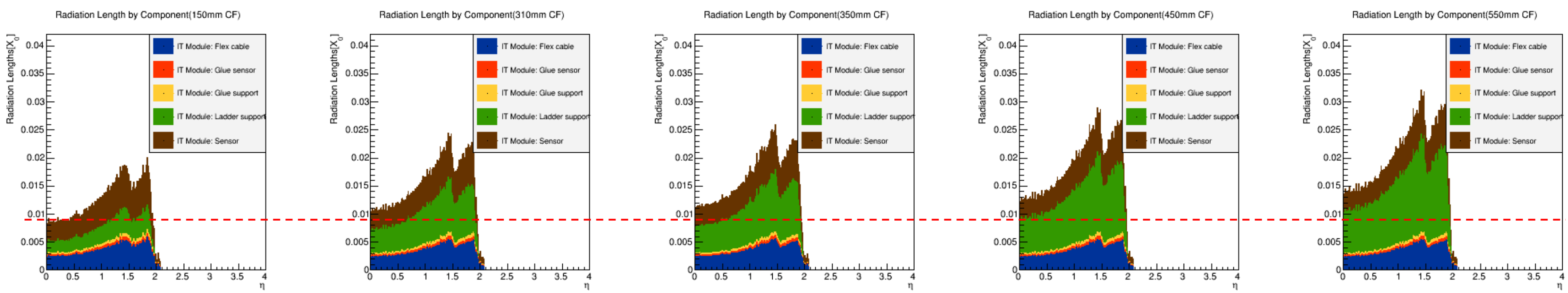


Only change the equivalent thickness of the support

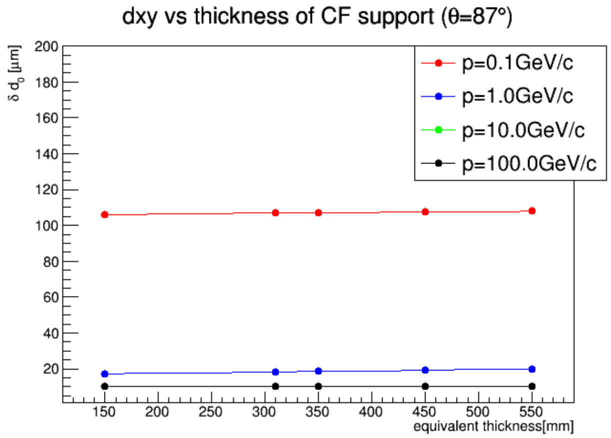
150um
310um
350um
450um
550um

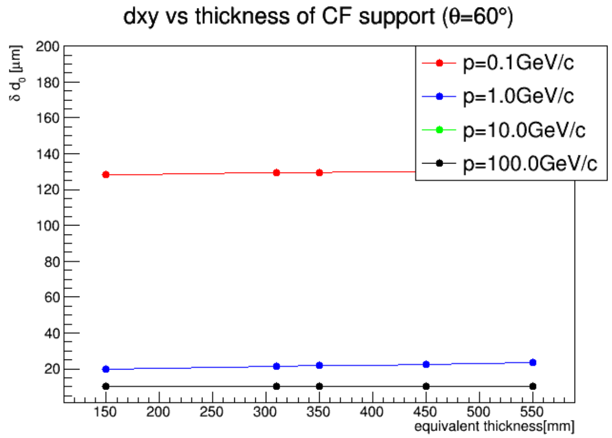
our design → 350um

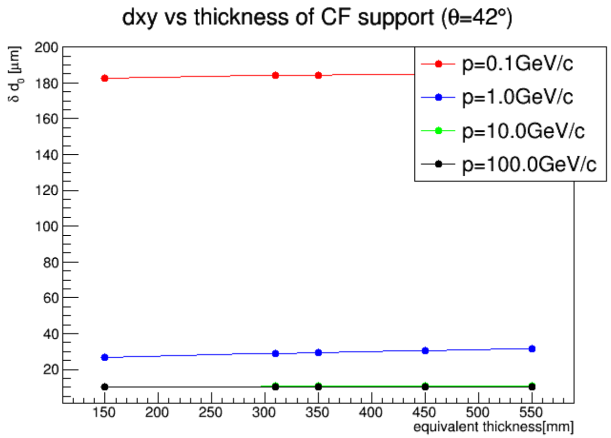
Sensor(Si, 50um)
glue(Epoxy, 15um)
Al(17.8um)
Kapton(50um)
Glue(Epoxy, 15um)
Ladder support(carbon fiber,100um)
PMI foam(1.5mm)
Ladder support(carbon fiber,100um)
Glue(Epoxy,15um)
Kapton(50um)
Al(17.8um)
Glue(Epoxy, 15um)
Sensor(Si, 50um)

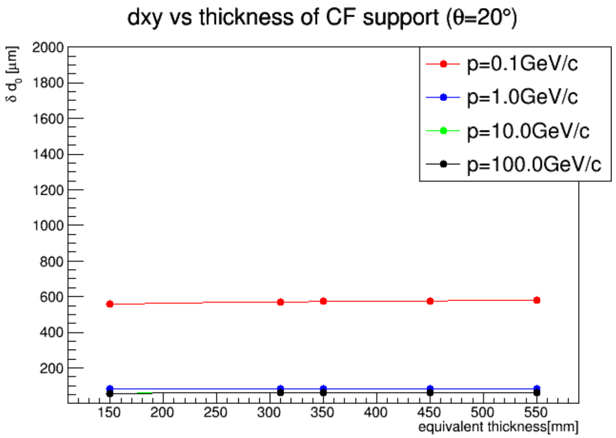


Material on σ_{xy}



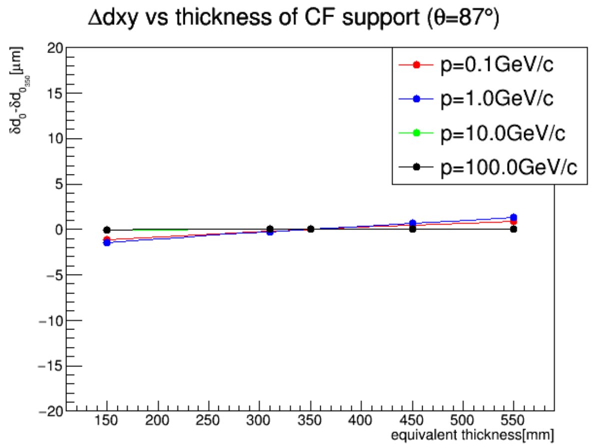


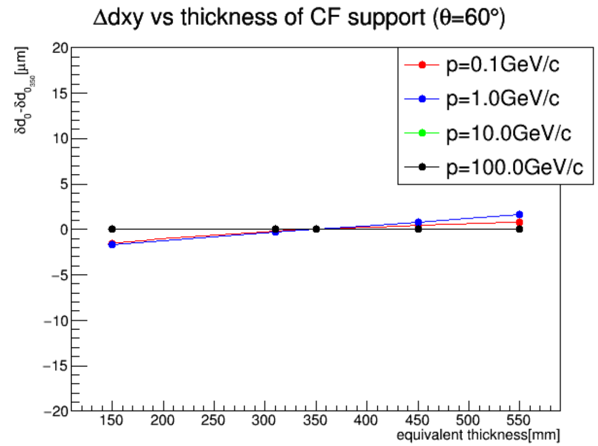


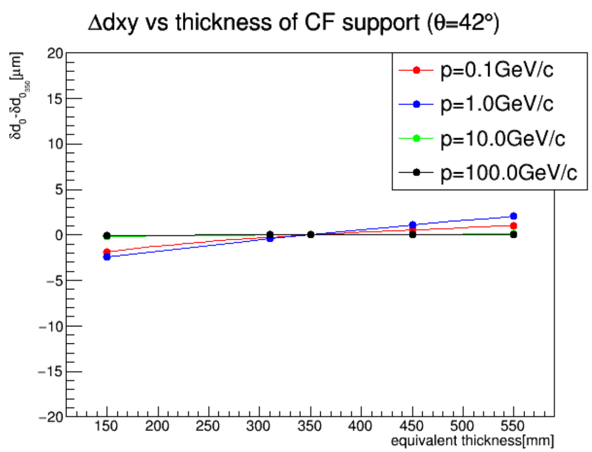


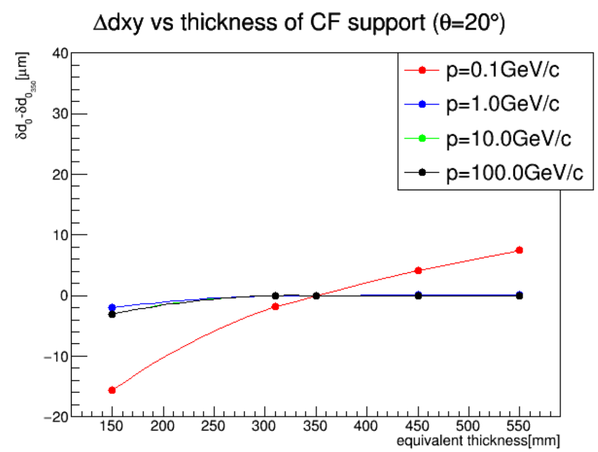
Resolutions almost the same

Material on σ_{xy}

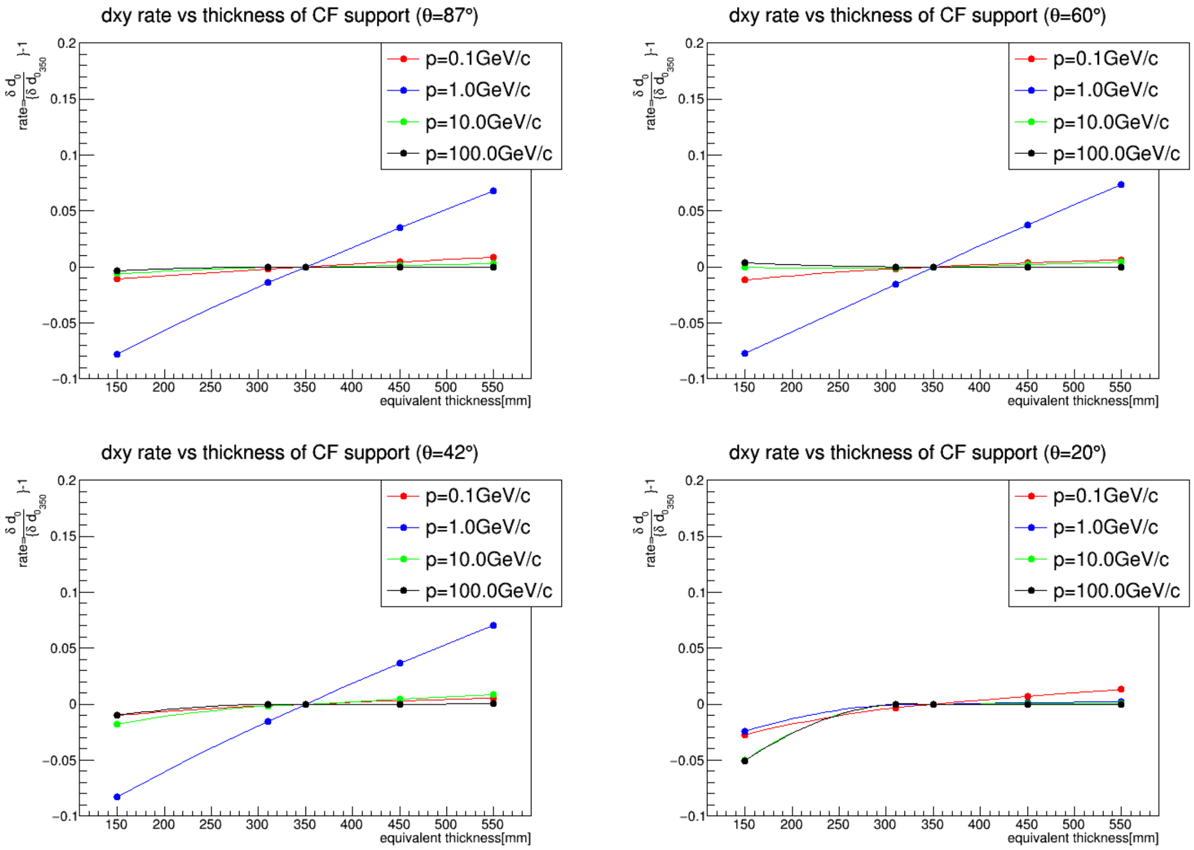








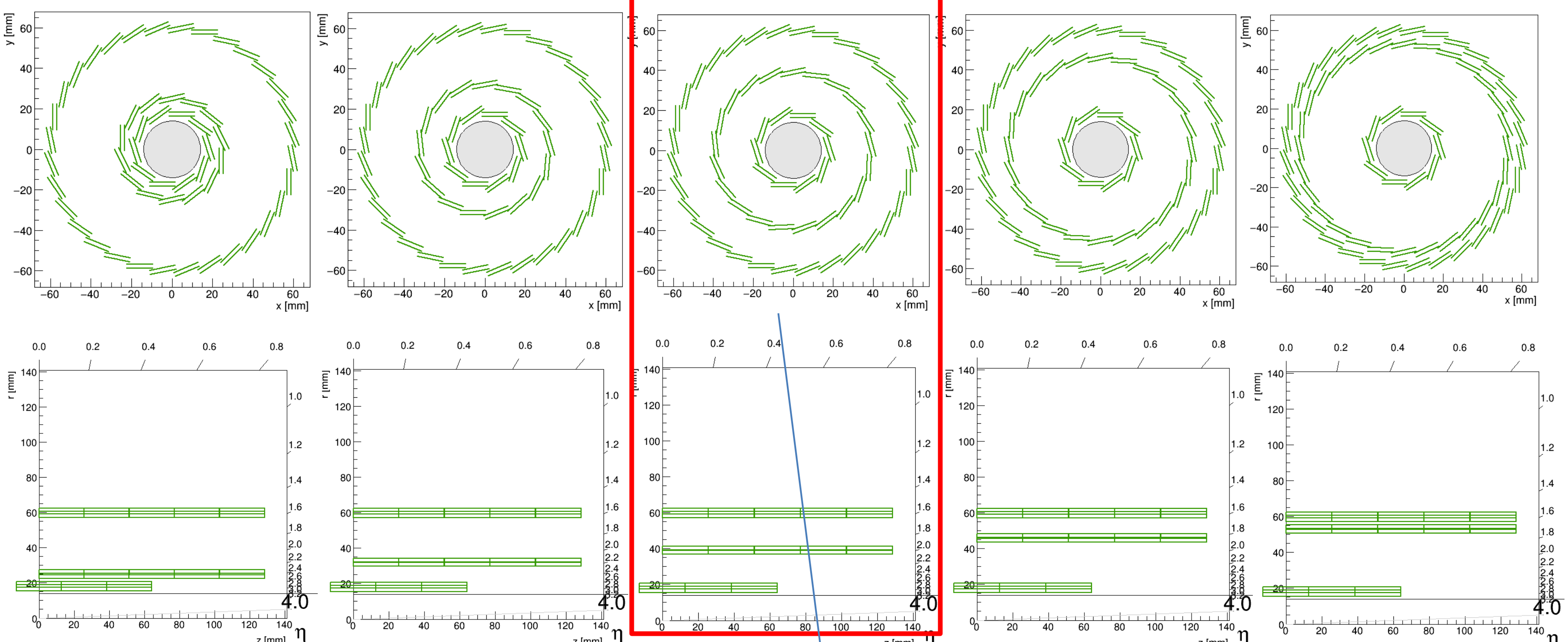
Material on σ_{xy}



1 GeV tracks seem more sensitive to material?

The impact of R_{2nd} on resolution

25mm	32mm	39mm	46mm	53mm

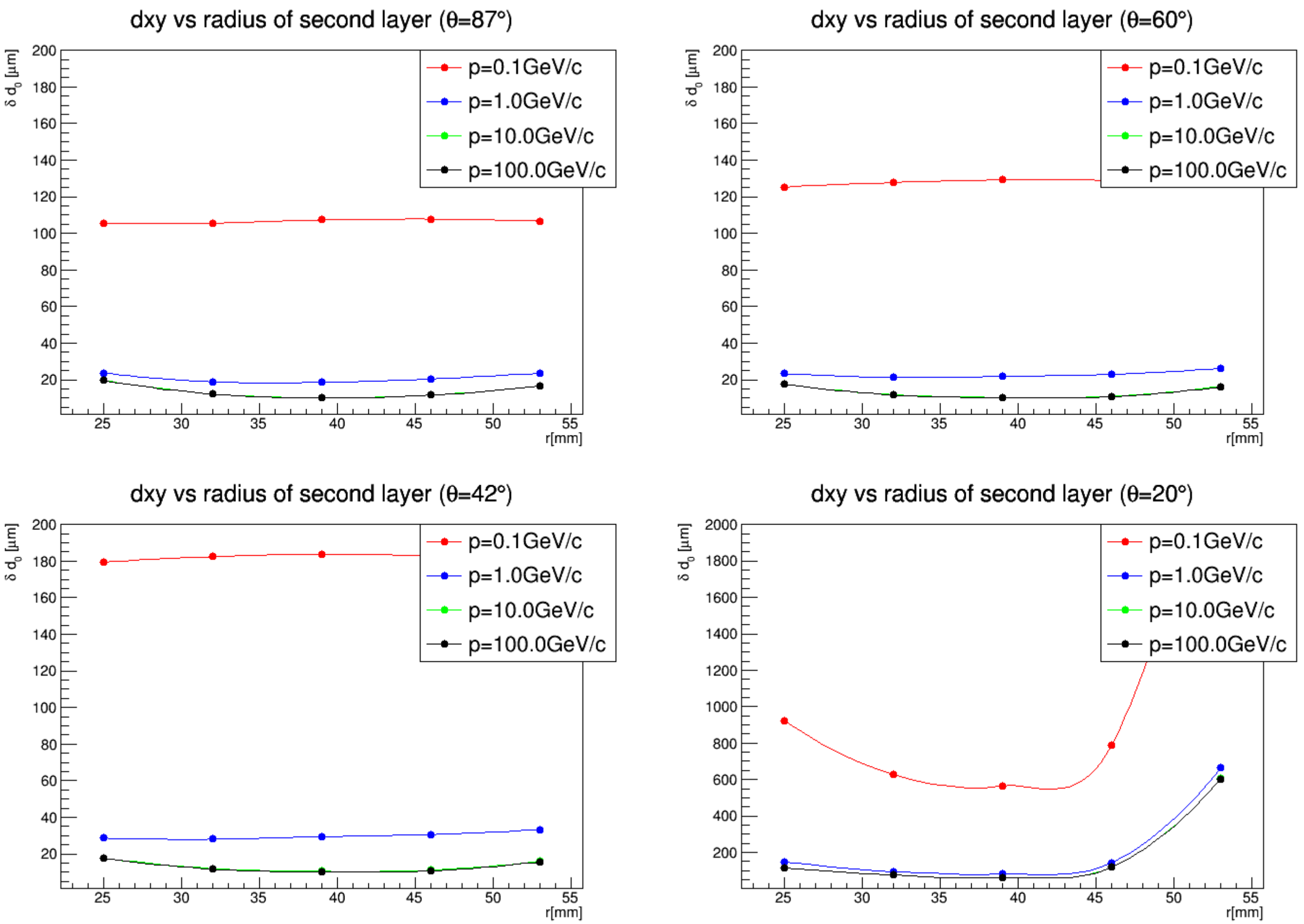


prototype V1:

Barrel : PXB1						
Layer	1	2	3	4	5	6
r	17.116	19.041	37.667	39.577	58.914	60.842
z_max	64.200	64.200	128.450	128.450	128.450	128.450

Barrel : PXB1						
Layer	1	2	3	4	5	6
r	17.116	19.041	38.019	39.982	58.914	60.842
z_max	64.200	64.200	128.450	128.450	128.450	128.450

The impact of R_{2nd} on resolution



The middle (~40 mm) gets the best resolution

Optimal layout based on a paper

The minimum r.m.s. curvature error occurs for clusters of points at the beginning, middle and end of the track with numbers of points in each cluster being in the ratio 1:2:1.

Uncertainties in track momentum and direction, due to multiple scattering and measurement errors https://doi.org/10.1016/0029-554X(63)90347-1

A very famous paper, many citations, the origin of Gluckstern formula

Generalization of the Gluckstern formulas I: Higher orders, alternatives and exact results

M. Regler, R. Frühwirth*

Generalization of the Gluckstern formulas II: Multiple scattering and non-zero dip angles

M. Valentan*, M. Regler, R. Frühwirth

An extension of the Gluckstern formulas for multiple scattering: analytic expressions for track parameter resolution using optimum weights

Z. Drasal[a,b], W. Riegler[b,*]

[a] Charles University, Prague, Czech Republic
[b] CERN EP, Geneva, Switzerland

Explicit Covariance Matrix for Particle Measurement Precision

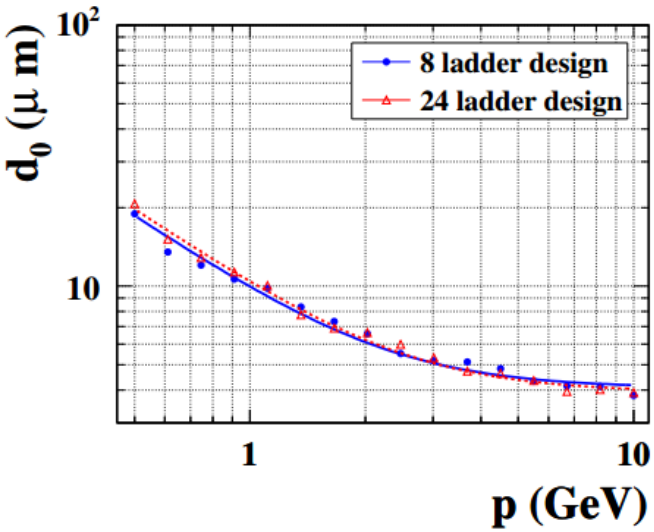
V. Karimäki

Helsinki Institute of Physics, Helsinki, Finland

The formulas tkLayout using, it concludes that: if the total number of points N is divisible by 4, the smallest possible curvature variance is obtained when N=2 measurements are at the center of track and N=4 at both ends

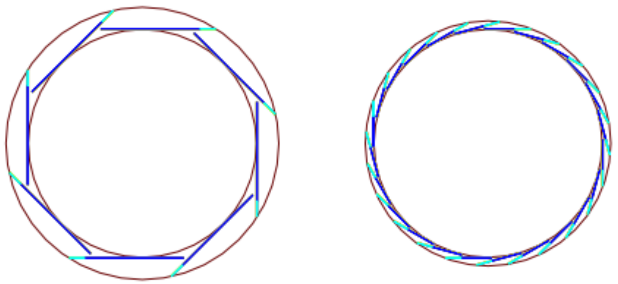
Different ladder size for the 1st layer?

Impact Parameter Resolution - Wide vs Narrow Ladders



First layer equipped with:

8 Ladders **24 Ladders**



Resolution function parameters:

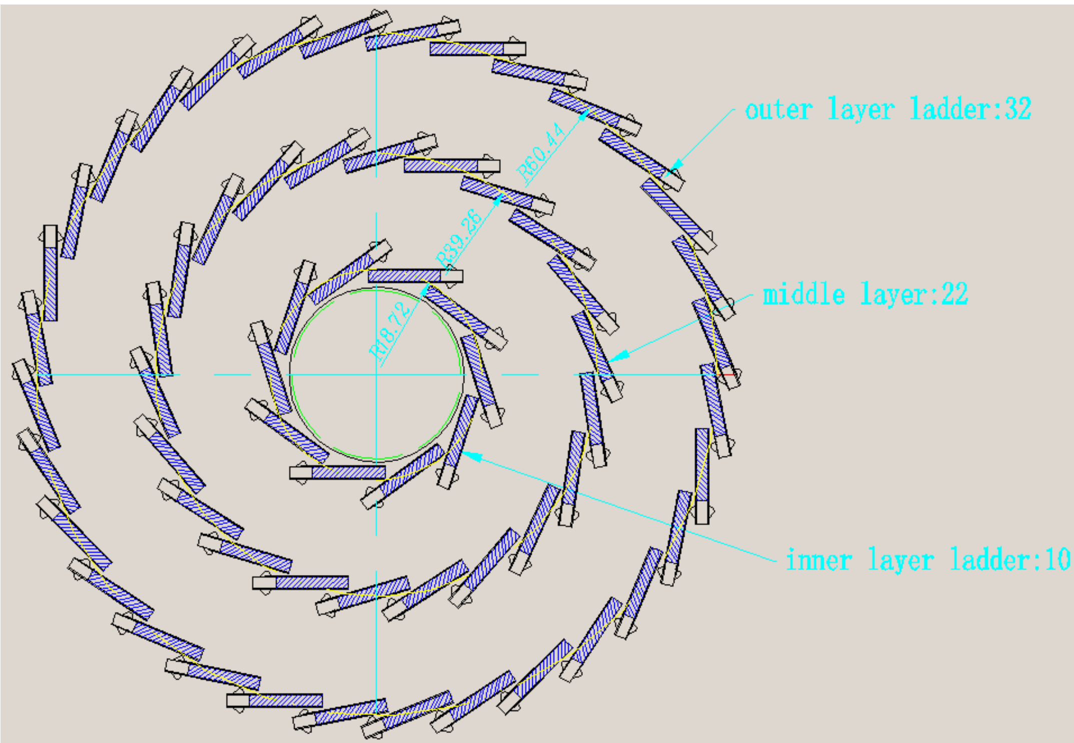
8 Ladders	24 Ladders	
4.1 ± 0.06	3.9 ± 0.06	$= a$
9.1 ± 0.1	9.7 ± 0.1	$= b$

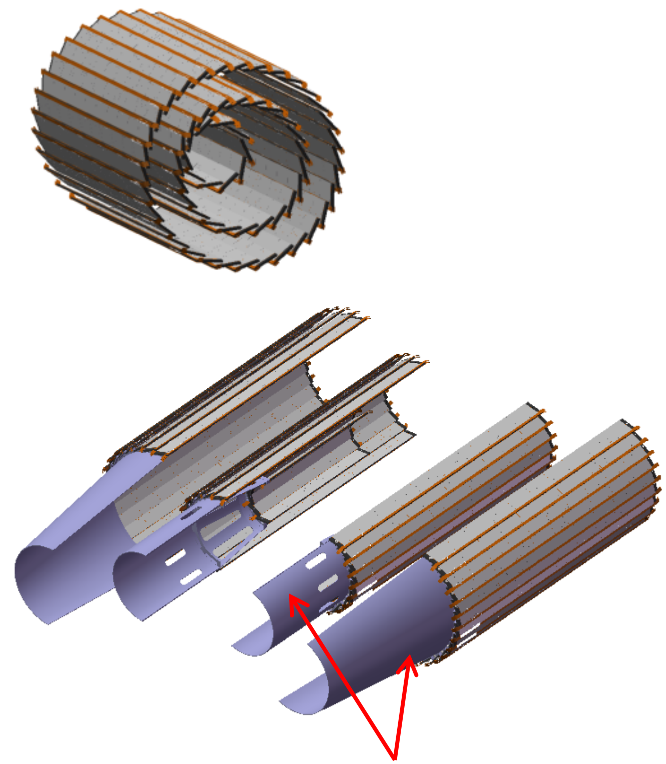
D.Grandjean, G.Gaycken Impact Parameter Resolution Studies ECFA Workshop Durham September 2004 12

Mechanical design

Prototype design of VXD

Ladder layout - optimized





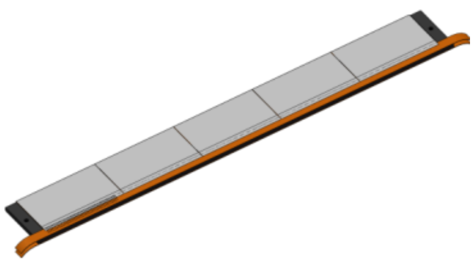
Half support barrel

Prototype design of VXD

Sensor chip : 14.8 x 25.6 x 0.05 mm (2 mm wide margin at one side for wire bonding)

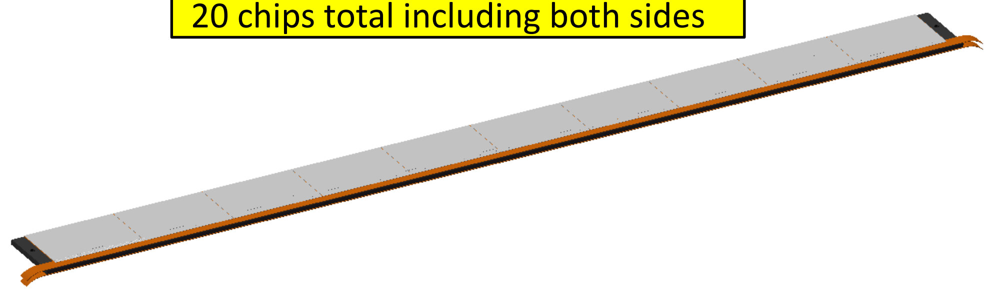
Ladder: support + chips + FPC

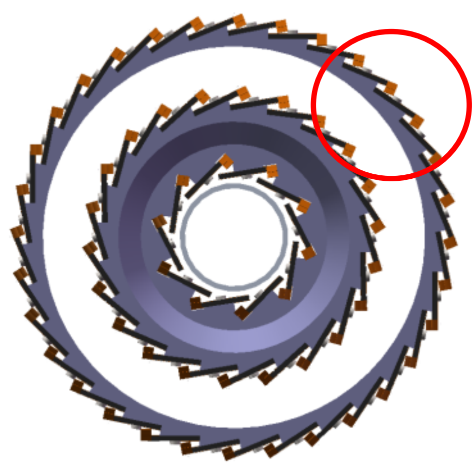
Ladder of inner layer:
10 chips total including both sides



0.1mm gap between chips

Ladder of outer two layers:
20 chips total including both sides





Ladder support

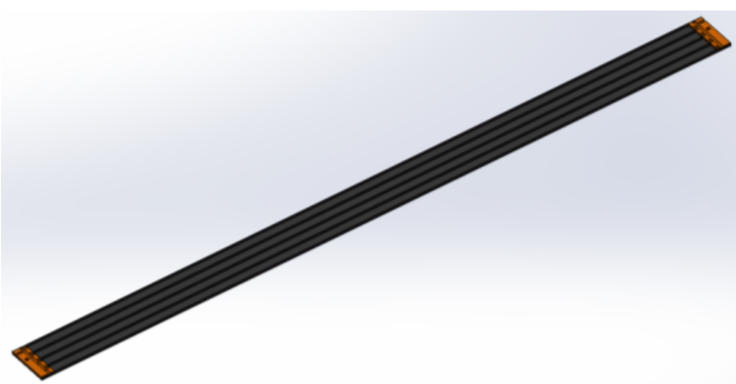
End Ring (CFRP): fix the end of ladder support.

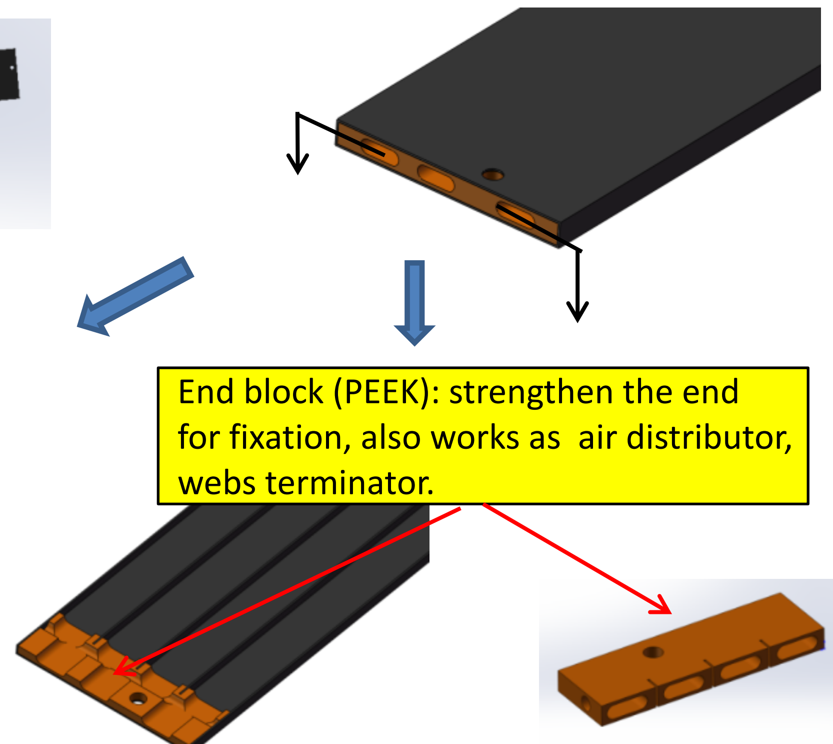
Ladder - support

Size: 264.1 x 16.8 x 2 mm (L x W x H), for outer and middle barrels.
131.6 x 16.8 x 2 mm for inner barrel. W is 2 mm wider than sensor.

Material: Carbon fiber in thickness of 0.15 mm (3 layers).

Channels inside the local support: to increase stiffness with less material, also work as a backup for air cooling from inside of the support.





Ladder - FPC & wire boding

FPC: shape and size of FPC of each ladder base on the current layout?

Can FPC be narrowed where it comes out of the ladder? The minimum width can be achieved?

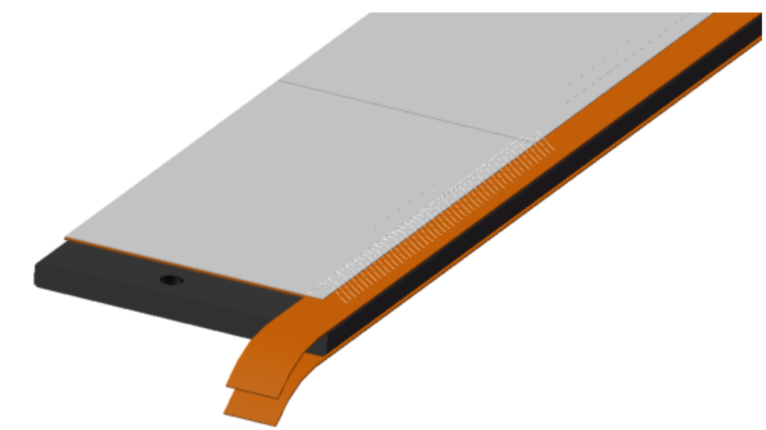
Will there be connectors of the FPC and where?

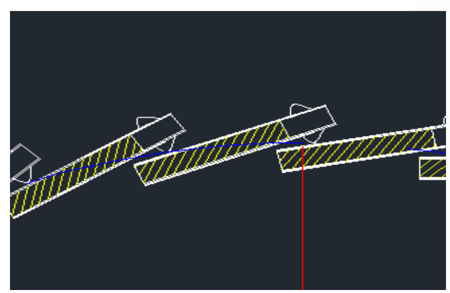
Wire bonding: Height?

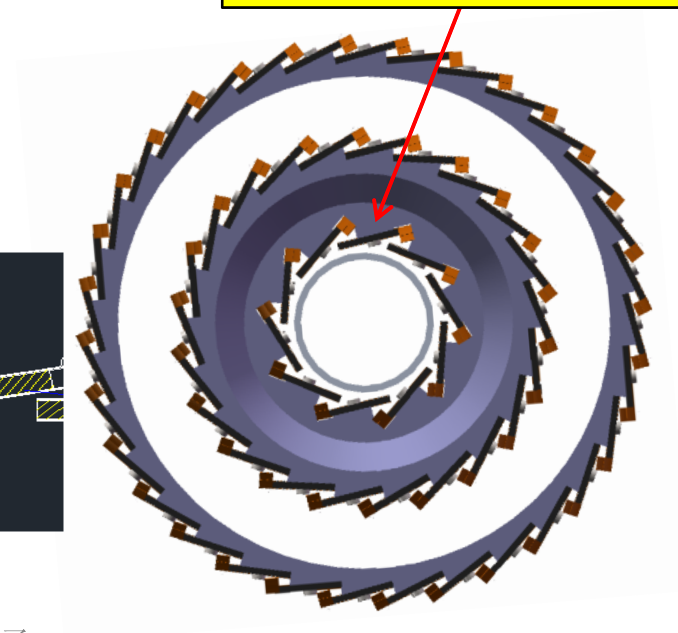
Materials of the ladder(?)- one side:

- FPC: kapton 50, Cu two layer 12x2=24, adhesive 15x2=30 um(Mingyi)
- the ladder: glue + flex+ sensor 15+105 +15+50= 185 um
- support : equivalent total thickness 0.15mmx3=0.45 mm
- Material budget need to be comfirmed.

Due to limited space and for easy installation, the ladders of inner layer are fixed onto the inner side of the neck flange, while those on middle and outer layers are fixed from outer side.



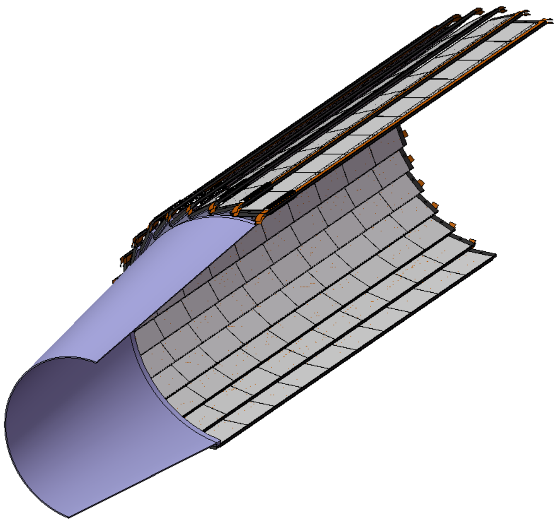


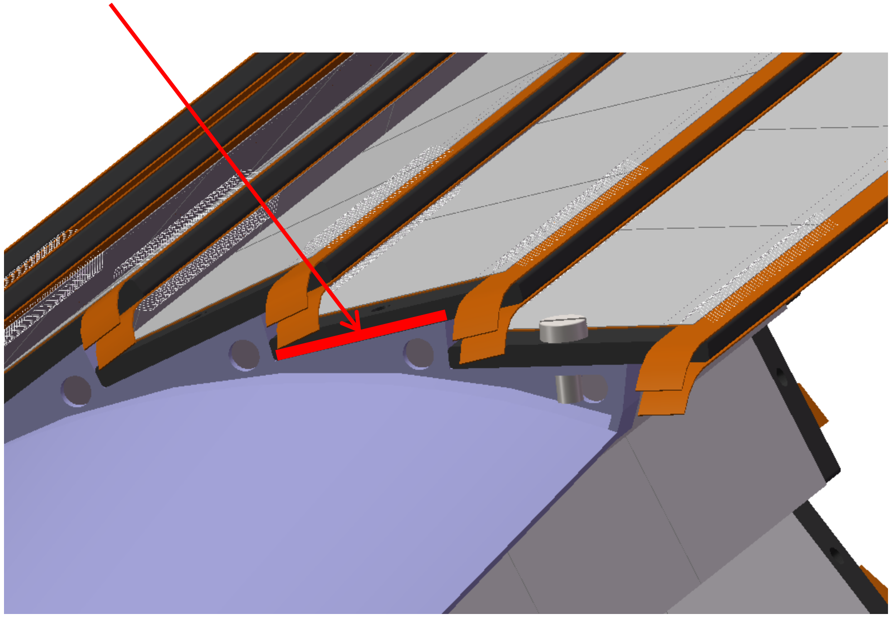


Ladder fixation

Option1: gluing.

Adhesive to be investigated, which has a good bonding strength at temperature lower than 80 ℃(?) but can be easily peeled off under certain temperature or by chemical method?





Option2: as a backup, using non-magnetic screw(e.g. copper) and nut (e.g. made of PEEK) glue on back side of the flange?

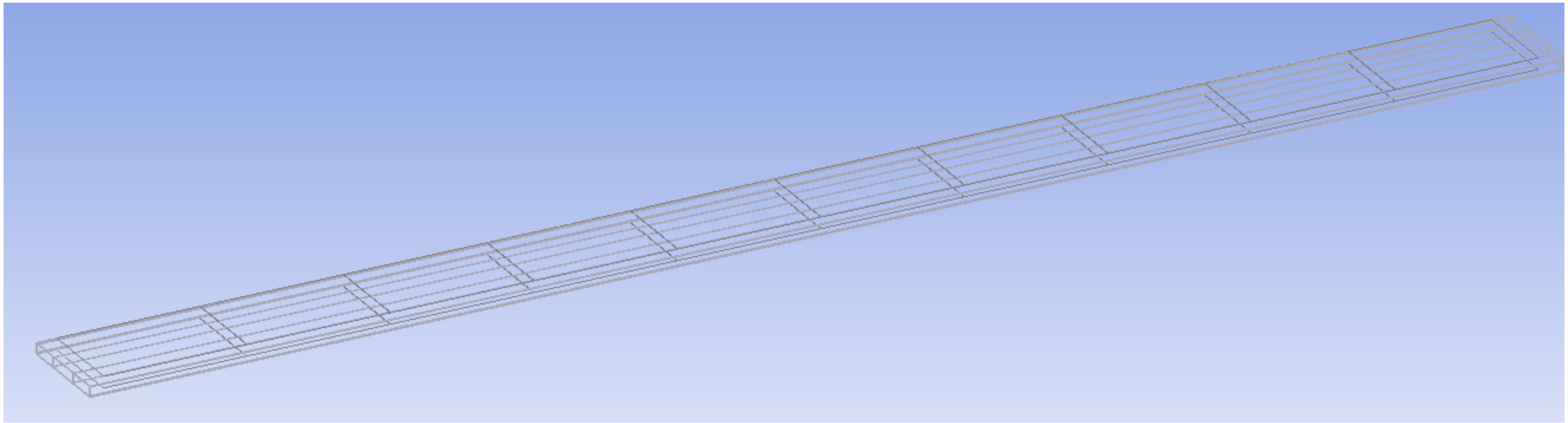
Cooling simulation-natural air convection

Single ladder (ladder-support + sensors on both sides)cooling simulation:

A outer layer ladder in horizontal direction independently suspended in the air.

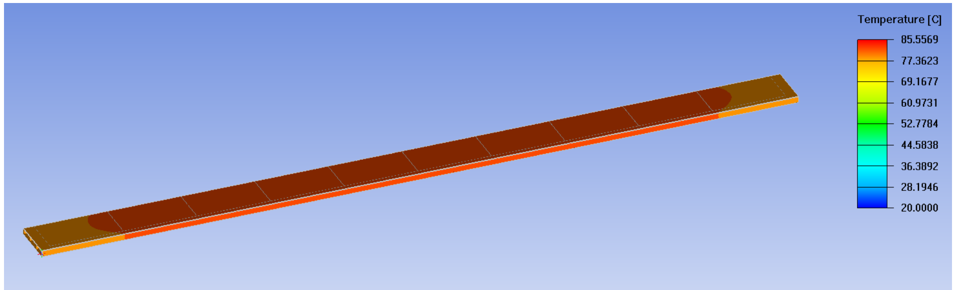
No glue and other material considered.

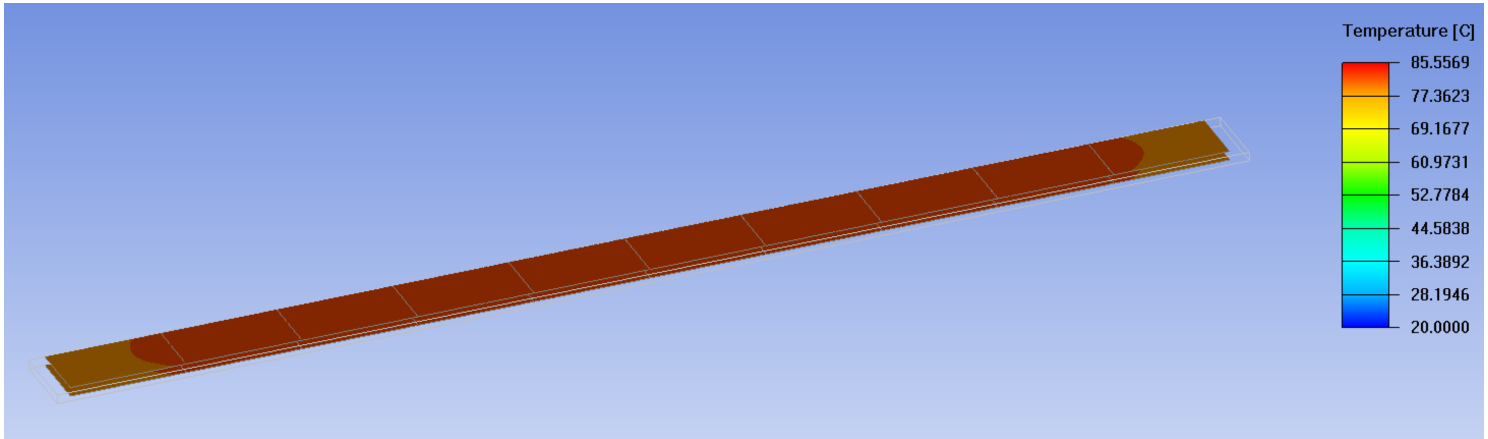
No radiation considered

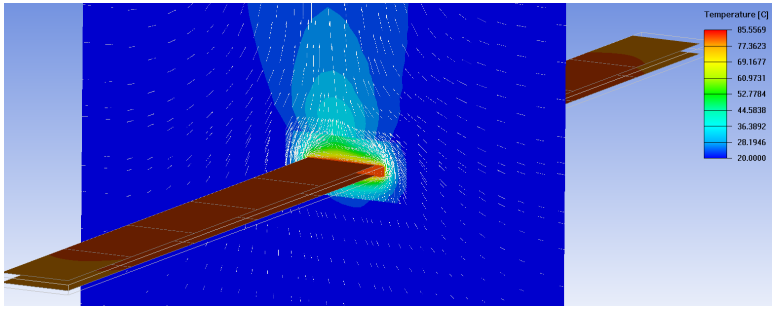


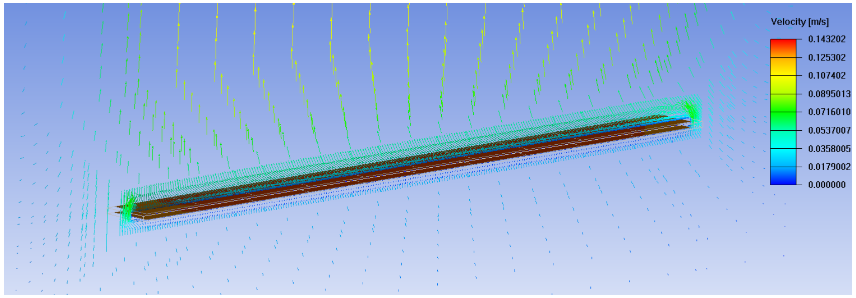
Result-1

Sensor power dissipation 100mW/cm^2
Ladder-spt material: Aluminum alloy.



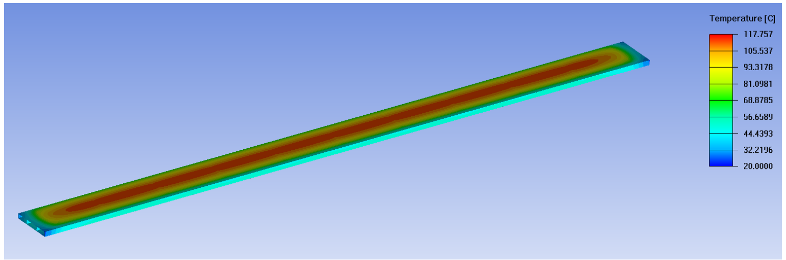


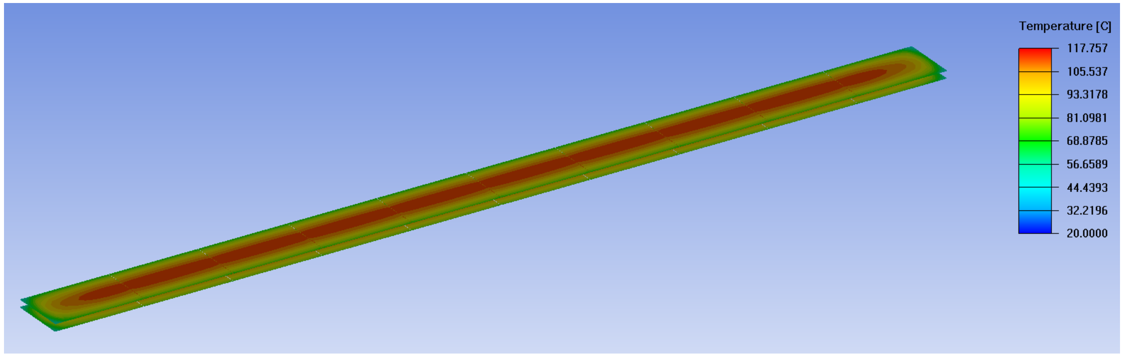


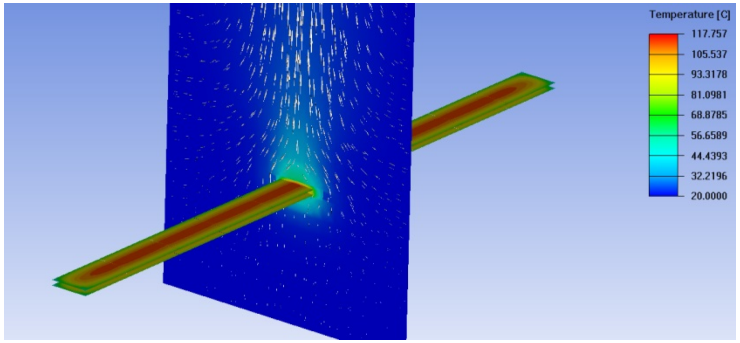


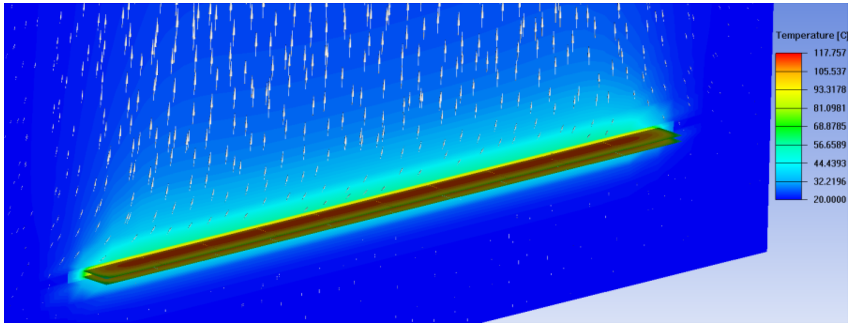
Result-2

Sensor power dissipation: 100mW/cm²
Ladder-support material: polyimide.









Natural air convection cooling results summary and comparison

Case number	Power dissipation （mW/cm² ）	Material of ladder-spt	max Temperature （℃）
1	200	Al-6061	136.1
2	200	polyimide	193.7
3	100	Al-6061	85.5
4	100	polyimide	117.8
5	50	Al-6061	56.8
6	50	polyimide	74.7

In these simulation, given the sensors directly contact with the ladder-spt. It is different as the real case, but simpler for estimation of the cooling effect. The real thermal conductivity of the ladder-support material is in between Al and polyimide.

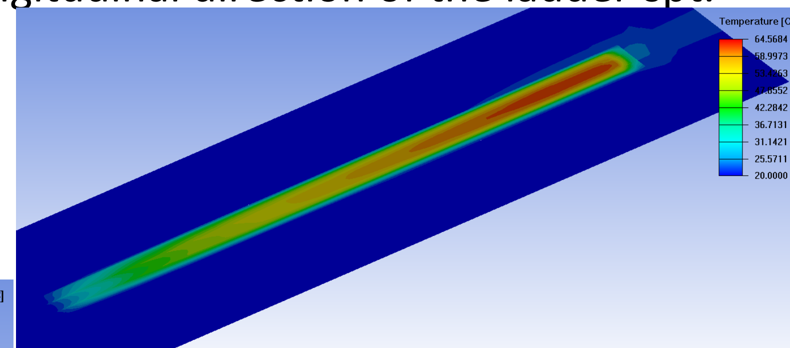
In current simulation, no radiation is considered. Next: will do the simulation with radiation contribution.

Cooling simulation - compressed air cooling

A single ladder (ladder-spt + sensors on both) in a cooling box:

A outer layer ladder in horizontal direction suspended in the air.

Air blows from one side to the other along the longitudinal direction of the ladder-spt.



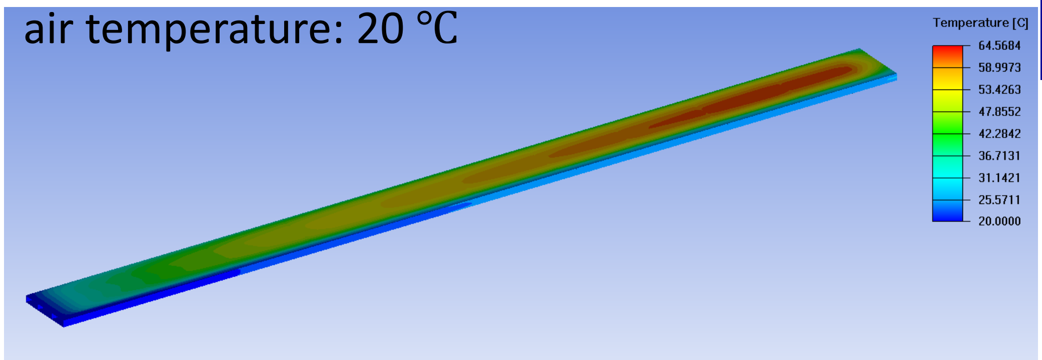
Result

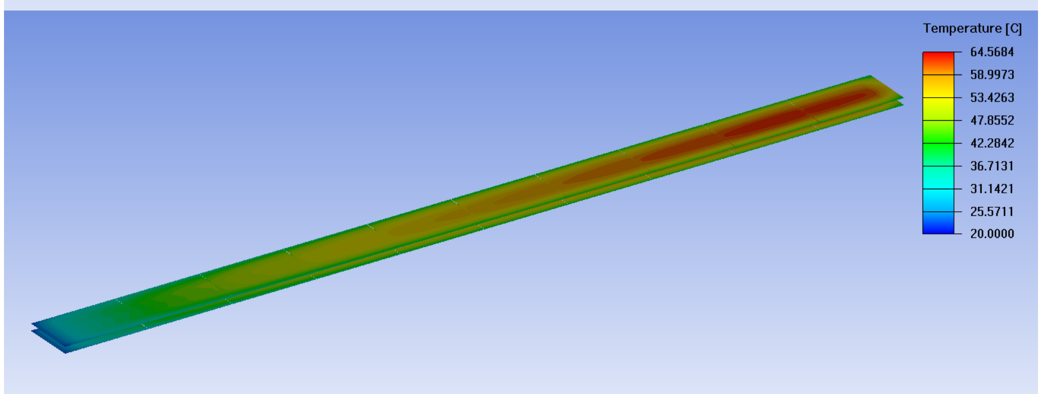
Sensor power dissipation 200mW/cm²

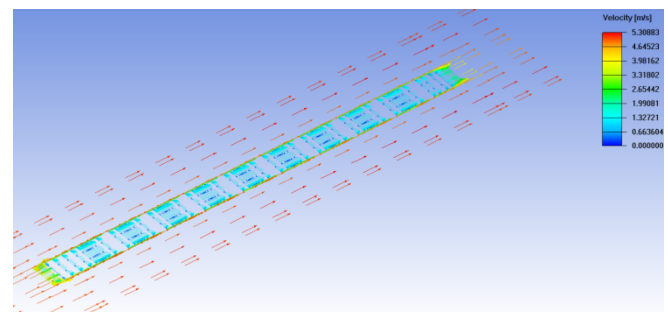
Ladder-support material: polyimide.

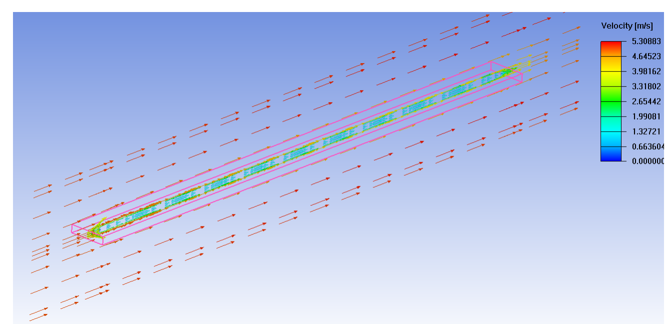
Air velocity: 5m/s

air temperature: 20 °C









Summary of the simulation results - polyimide ladder-support

Case number	Power dissipation (mW/cm^2)	Inlet air velocity (m/s)	Material of ladder-spt	max Temperature (℃)
1	200	5	Polyimide	64.6
2	200	4	Polyimide	71.6
3	200	3	Polyimide	82.1
4	100	3	Polyimide	51
5	100	2	Polyimide	59.8
6	50	3	Polyimide	35.6
7	50	2	Polyimide	39.8
8	50	1	Polyimide	49.5
9	50	0.8	Polyimide	53.2
10	50	0.5	Polyimide	62.2

Summary of the simulation results - Al ladder-support

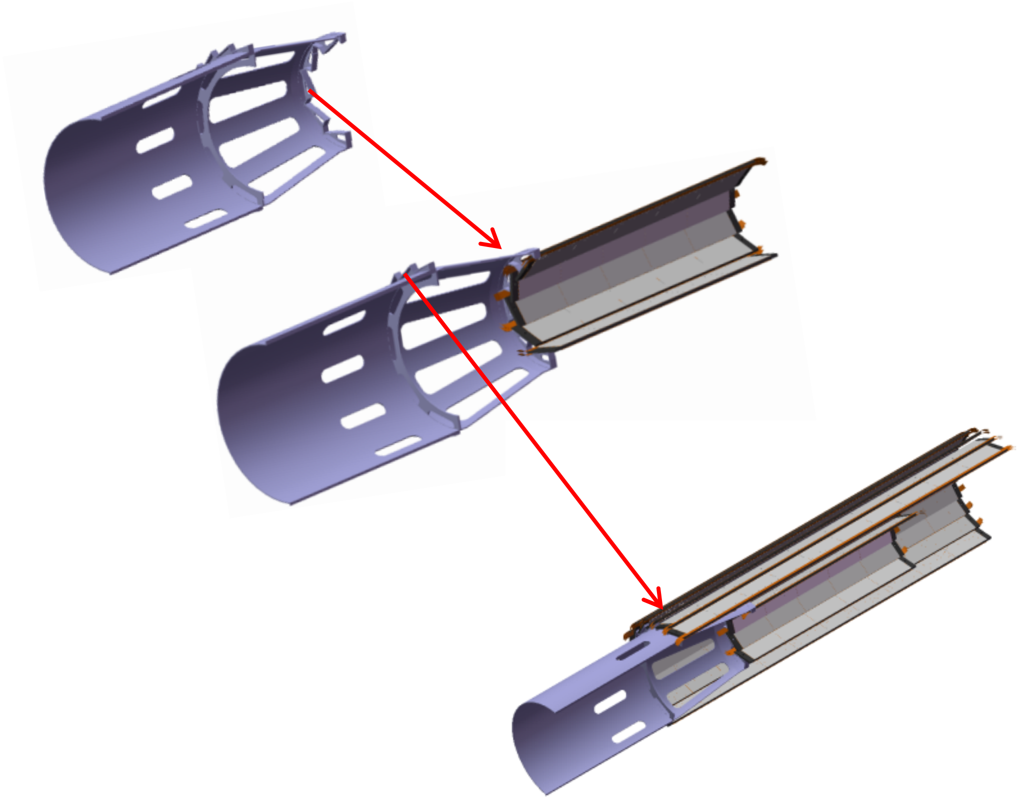
Case number	Power dissipation （mW/cm^2）	Inlet air velocity （m/s）	Material of ladder-spt	max Temperature （℃）
1	200	5	Al-6061	50.4
2	200	4	Al-6061	54.8
3	200	3	Al-6061	61.5
4	200	2	Al-6061	72.9
5	200	2	Al-6061	99.3

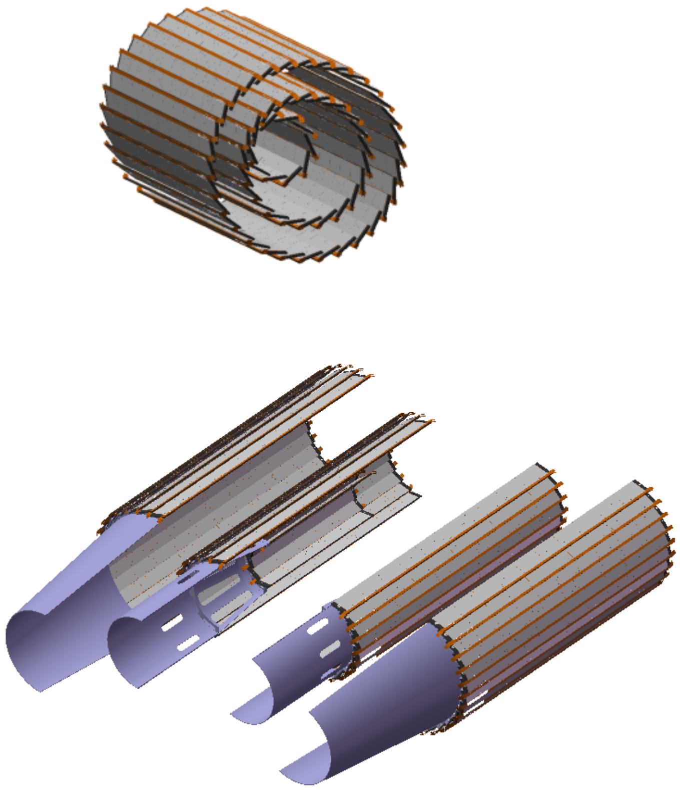
Note: the single ladder in all above related simulations has two open sides at it's two ends, which enable the air goes through the inside channel.

A simulation with the ladder sealed at two ends of the ladder-support is being conducted to evaluate the contribution of the channel to cooling effect. The very primary result shows not two much difference. More work needed to confirm this.

Vertex assembling and cable routing

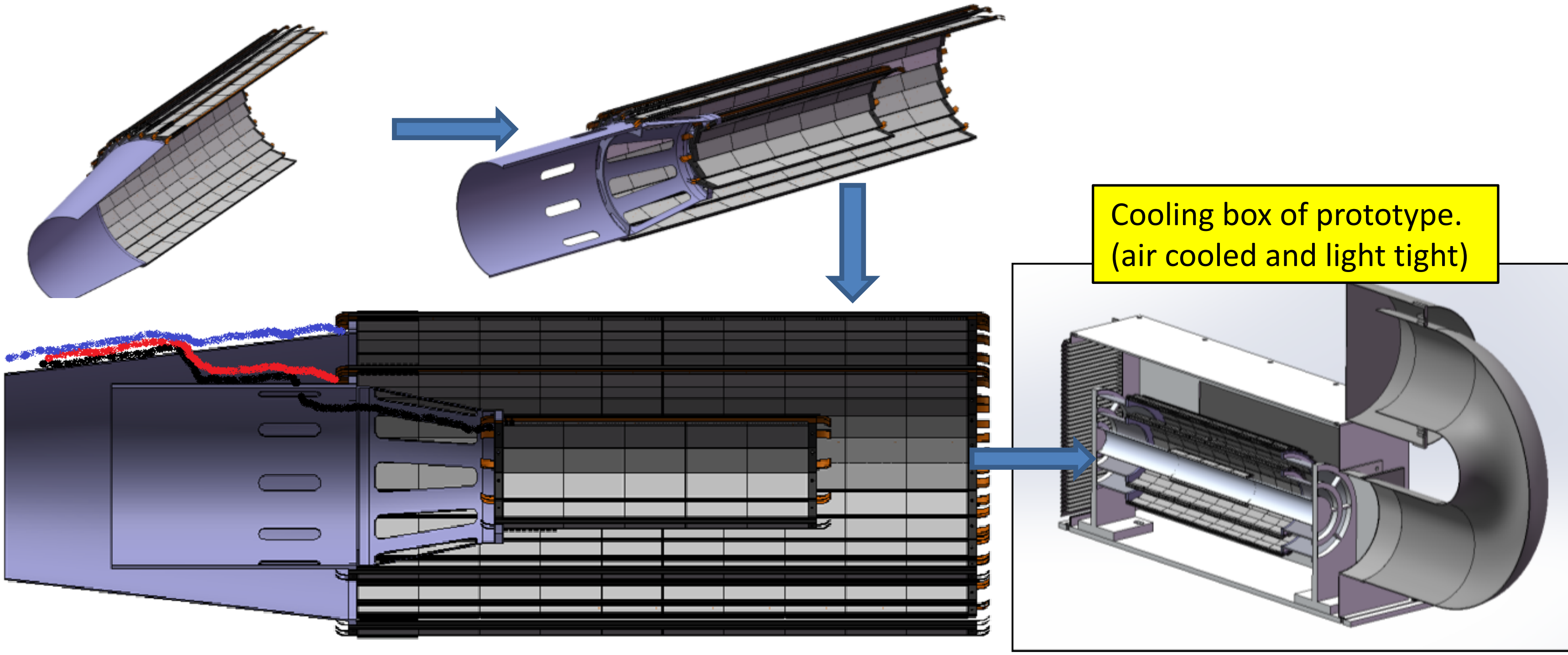
Ladders of inner and middle layers mounted to a half support barrel with double toothed rings.





Vertex assembling and cable routing

Ladders of outer layer mounted to a half support barrel which has one toothed ring.



Assuming FPCs or cables of several ladders can be put together to form a bundle, and then rout out from the slotted hole on the support neck to next layer. Finally, go out to the outer layer and lead out together 。

In CEPC, What else are outside the vertex can block the cable routing this way? e.g. End cap?

Works ongoing

- Layout optimization
  - Validate the resolution using alterative methods
  - Adding outer tracker
  - Optimizing material budget
  - More realistic detector in optimization
- Cooling simulation
- Cooling test system(structure and instruments) design for single ladder test and the VXD test.
- Contact with fabricators of the CFRP products.
- Design and accordingly necessary FEA update of the CFRP ladder-support

Future plan

Plan

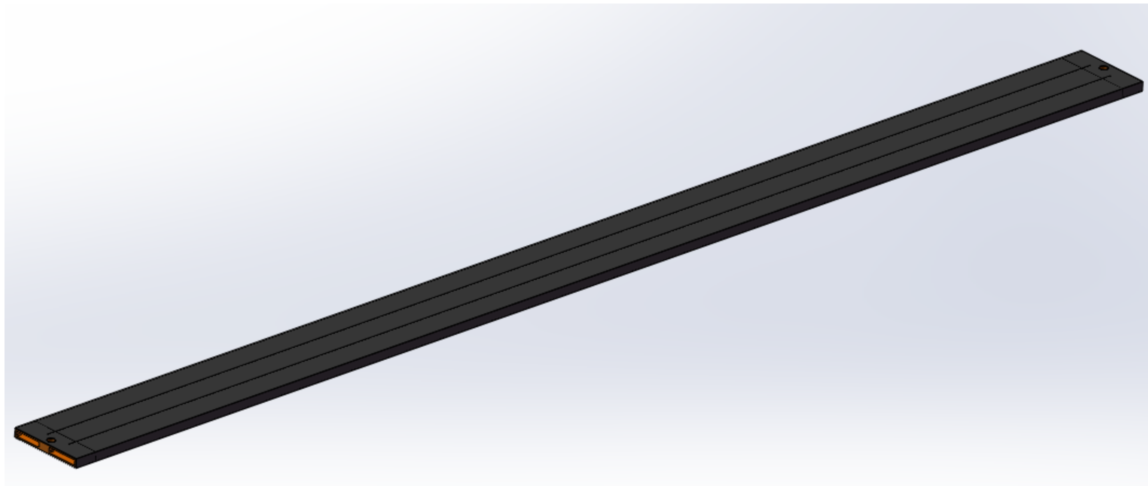
- Cooling simulation - by June.
- Material test (mechanical performance and radiation resistance) for the CFRP used for the ladder-support. - by August
- Ladder-support prototype (sample) fabricating? - by September.
- Cooling test
  - Colling box
  - Using a dummy ladder
  - Using a ladder-support prototype
- Ffabrication and assembly of prototype, need more discussion

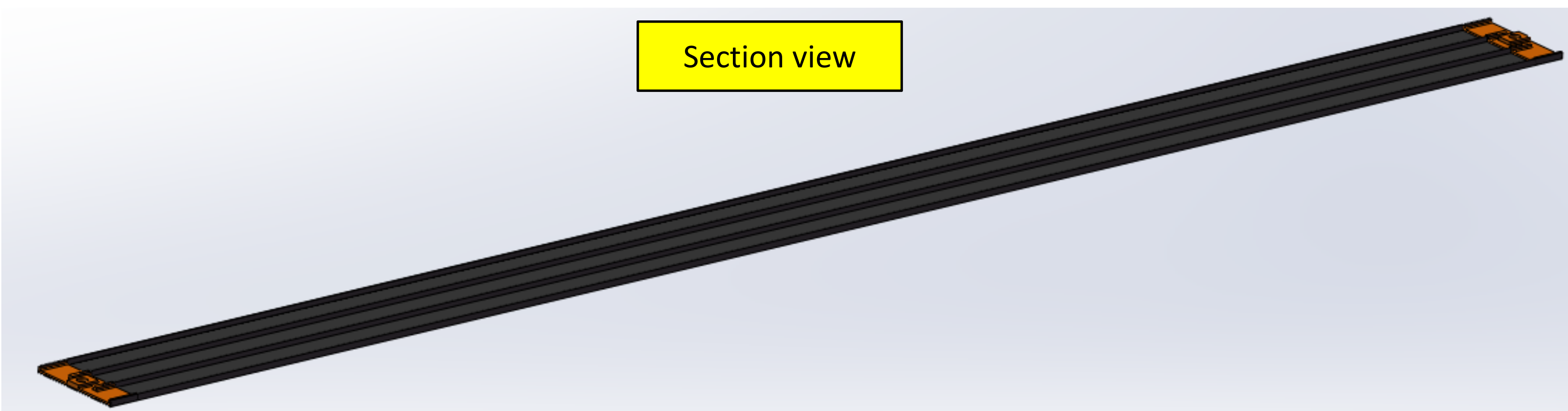
- Take the outer tracker into account, by June
  - TPC
  - Silicon tracker
- Consider more ladder and mechanics details, depends on mechanical design
- Validate the tkLayout using full simulation, by June

- **Converge to a preliminary layout design of prototype, by September**

Backup slides

1. The ladder-support





Work plan of mechanic design

1. Cooling simulation - *By end of May.*

More detailed simulation in structure, for both single ladder and the VXD system (i.e. the integrated cooling box), closer to real model and working condition, with fan, grillers, support and fixing structure integrated to system.

2. Material test (mechanical performance and radiation resistance) for the CFRP used for the ladder-support. - *By end of July.*

3. Ladder-spt prototype (sample) fabricating? - *By end of August.*

- first, just fabricate a few samples of the ladder-spt prototype.
- Static mechanical test to compare with FEA result. -*By end of August.*

Work plan of mechanic design

4. Cooling test.

this year just do cooling test for single ladder, requires a design of a simple cooling box, fan selection, temperature monitor instruments, high precision optical measuring instruments . etc. Two cases are considered:

A: a dummy ladder (not CFRP material, just simple material as current simulation used) loaded with heating sensors under natural air convection and forced air cooling conditions-to compare with the FEA resluts . - *by end of July?*

B: use a ladder-spt prototype instead of the dummy ladder to do cooling test, to know the cooling result and also measure the vibration magnitude. - *by end of October?*

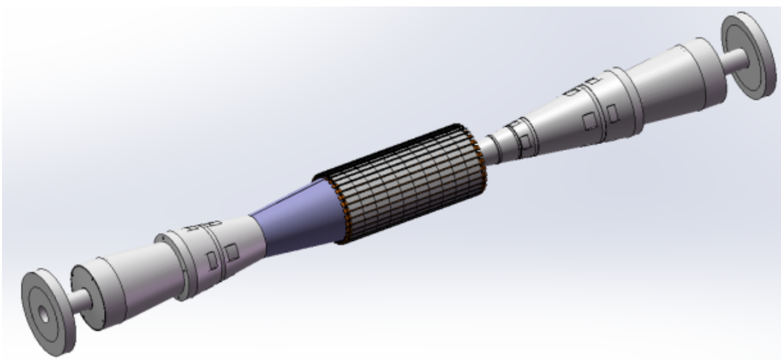
Note: in the above few plans, given that the ladder-support is just bare support structure without FPC. For Case B, during vibration magnitude test need at least effective FPC.

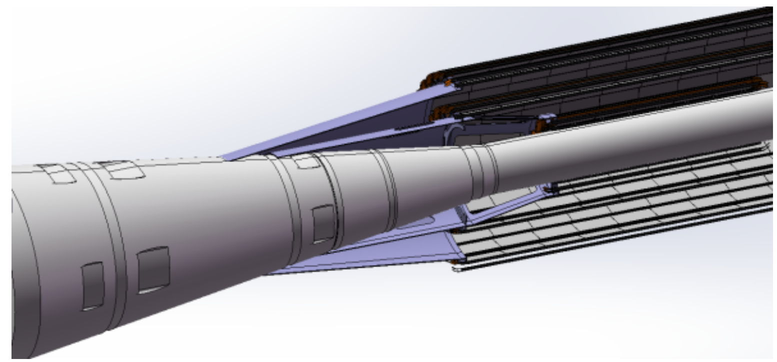
5. fabrication and assembly of the support structure (including ladder-spt and others) of VXD ? to be discussed.

Installation of the VXD on CEPC
-interface with beam pipe

VXD interface with beam pipe:

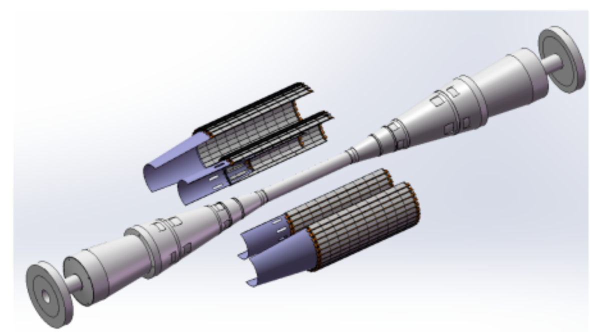
1-fixation of VXD support inside beam pipe
2-space for FPC or cable routing
3-inlets and outlets for cooling air, volume control



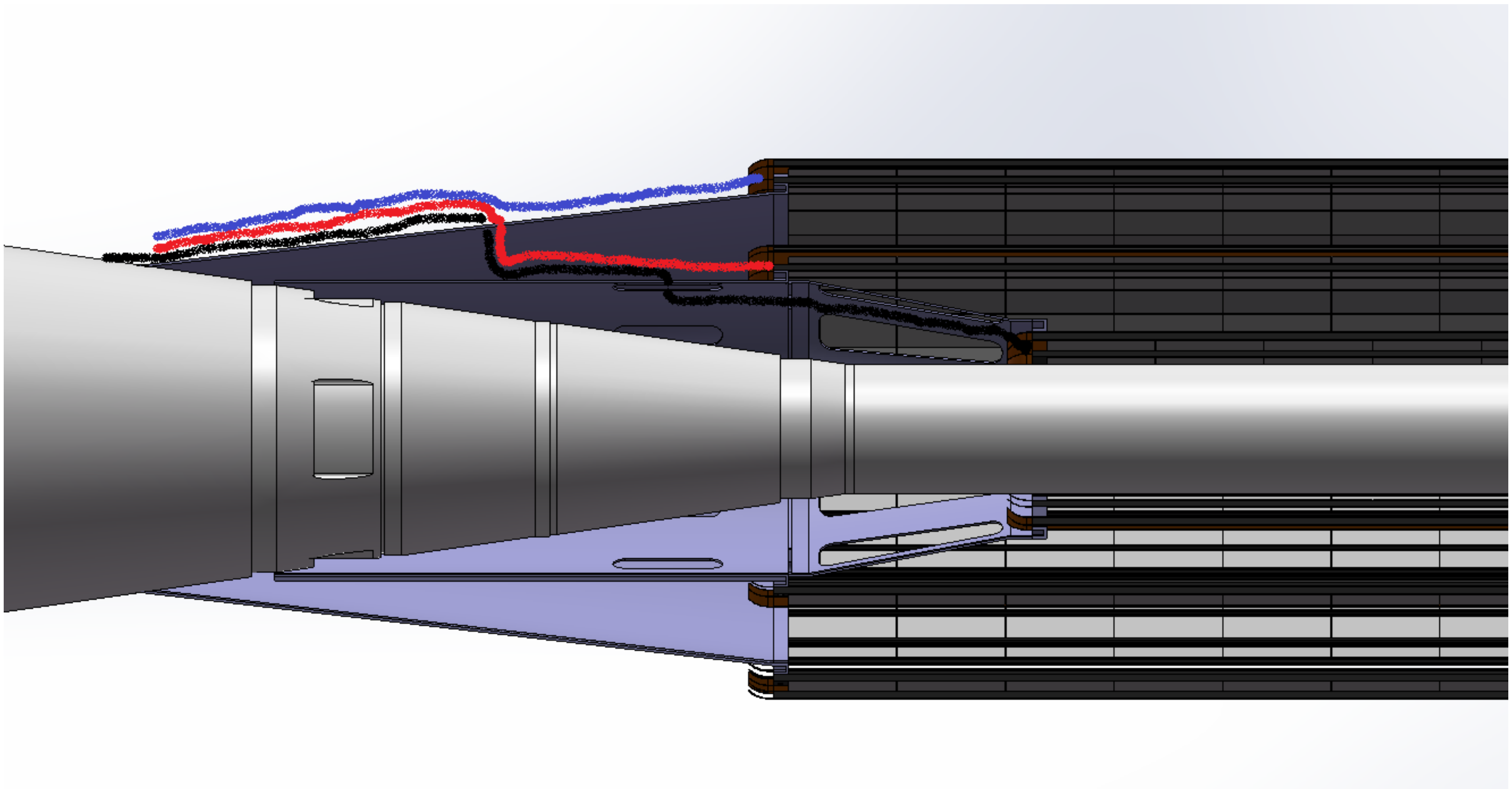


The latest ladder layout and preliminary estimation of air volume required by VXD has been provided to Quan.

More interactive work can be foreseen.



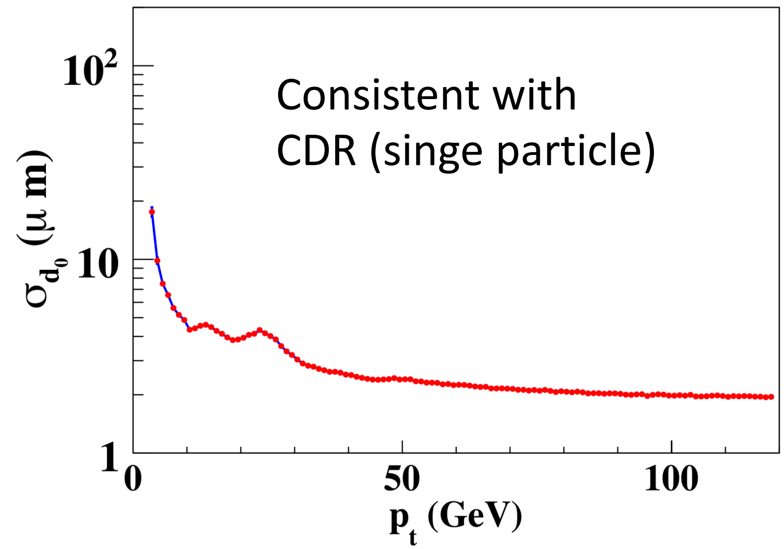
Cable routing at interaction area of CEPC

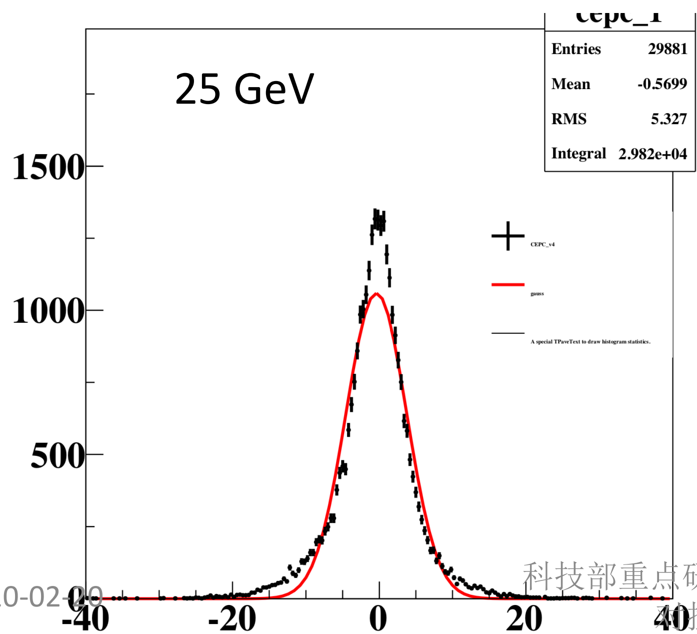


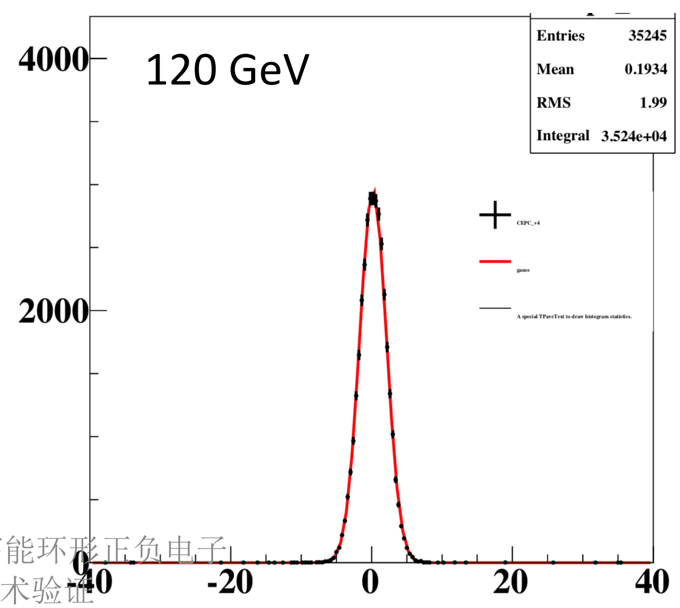
The same scheme as the cable routing inside the cooling box.

Full Simulation baseline design in CDR

- $e^+e^- \rightarrow \mu^+\mu^-$ @ 240GeV
- Full simulation : MokkaC & Marlin
- Point-like beam spot
- Energy = 3-120 GeV & full angle
- Best resolution ~ 2 μm

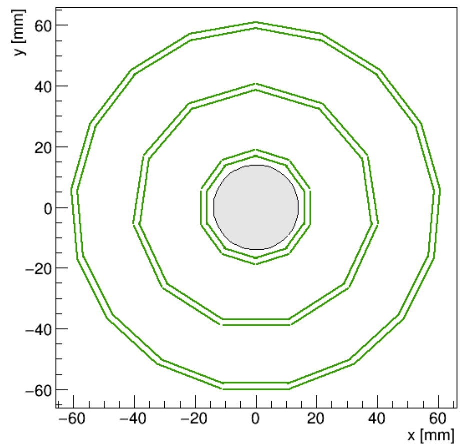




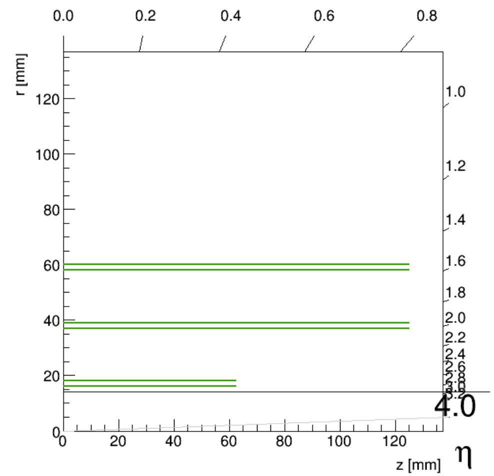


Vertex geometry simulation results

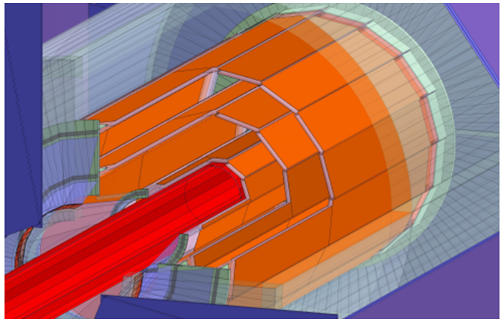
- CDR vertex detector geometry



XY Section of the tracker barrel. - (png) - (pdf) - (root)



RZ positions of the barrel modules. - (png) - (pdf) - (root)



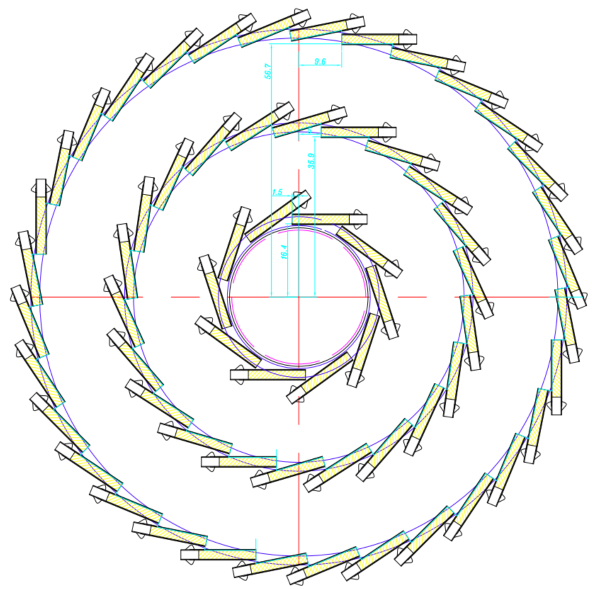
Barrel : PXB1							Total
Layer	1	2	3	4	5	6	
r	16.004	18.004	37.003	38.995	57.989	59.995	
z_max	62.500	62.500	125.000	125.000	125.000	125.000	
# rods	10	10	11	11	17	17	
# mods	40	40	88	88	136	136	528

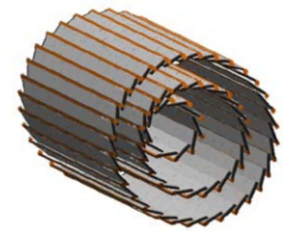
	R (mm)	$\|z\|$ (mm)	$\|\cos\theta\|$	$\sigma(\mu\text{m})$
Layer 1	16	62.5	0.97	2.8
Layer 2	18	62.5	0.96	6
Layer 3	37	125.0	0.96	4
Layer 4	39	125.0	0.95	4
Layer 5	58	125.0	0.91	4
Layer 6	60	125.0	0.90	4

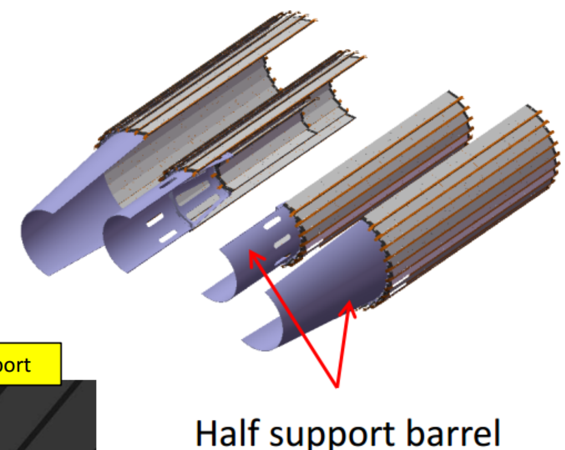
Prototype design by Jinyu

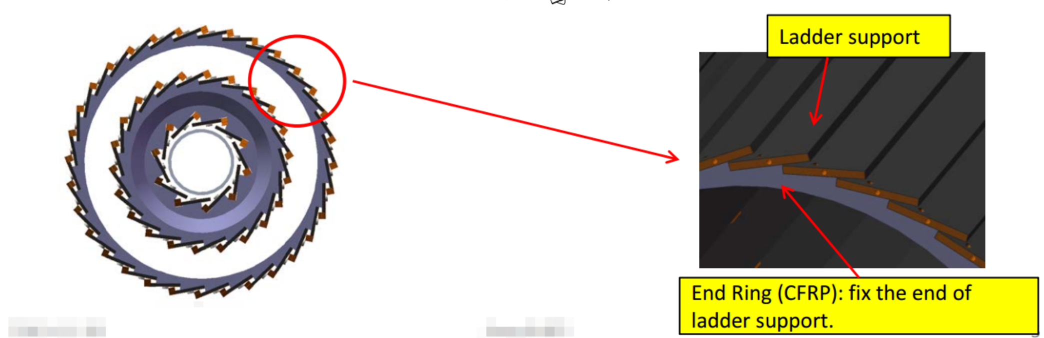
Prototype V1

- 3 layers of double-sided ladder
- Only need to rotate one ladder around Z axis with a fixed angle to cover the whole barrel
- Sensors are on both sides of the yellow slash region



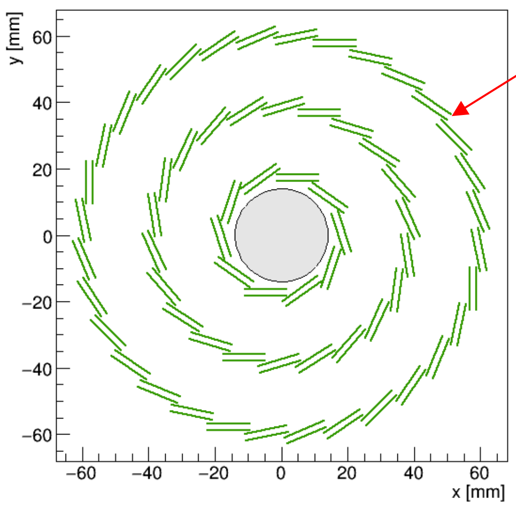






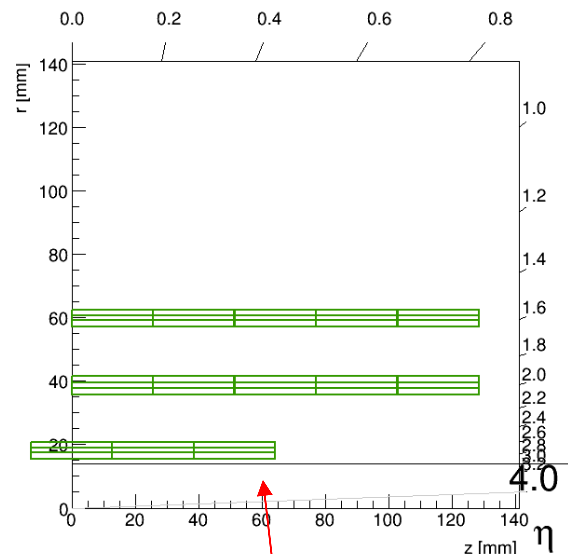
Vertex geometry simulation results

- Prototype V1



XY Section of the tracker barrel. - (png) - (pdf) - (root)

Contact the authors to change source code, Add skewed layer mode



RZ positions of the barrel modules. - (png) - (pdf) - (root)

	numRods	R(mm)	skewAngle(rad)	module width(mm)
Layer 1	10	17.11637	0.290338	12.8
Layer 2	10	19.04127	0.260264	12.8
Layer 3	22	37.66656	0.307478	12.8
Layer 4	22	39.57739	0.292183	12.8
Layer 5	32	58.91426	0.275036	12.8
Layer 6	32	60.84152	0.266108	12.8

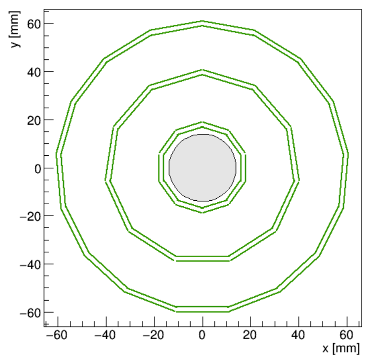
Calculated value

Barrel : PXB1							**Total**
Layer	1	2	3	4	5	6	
r	17.116	19.041	37.667	39.577	58.914	60.842	
z_max	64.200	64.200	128.450	128.450	128.450	128.450	
# rods	10	10	22	22	32	32	
# mods	50	50	220	220	320	320	1180

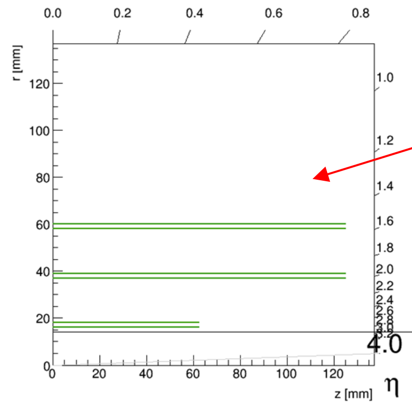
Output value of tkLayout

Comparing CDR baseline with Prototype V1

CDR



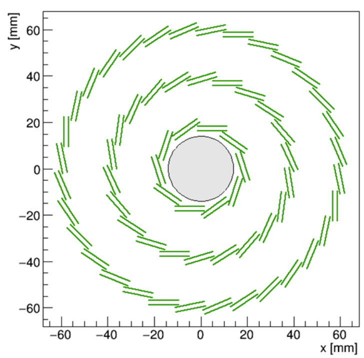
XY Section of the tracker barrel. - (png) - (pdf) - (root)



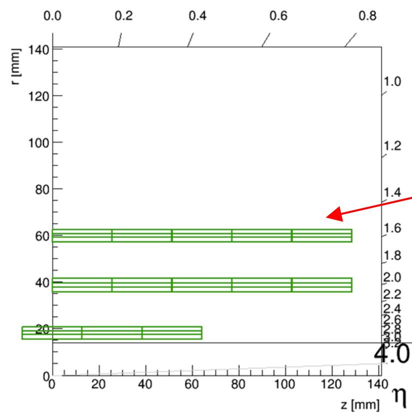
RZ positions of the barrel modules. - (png) - (pdf) - (root)

Barrel : PXB1							Total
Layer	1	2	3	4	5	6	
r	16.004	18.004	37.003	38.995	57.989	59.995	
z_max	62.500	62.500	125.000	125.000	125.000	125.000	
# rods	10	10	11	11	17	17	
# mods	40	40	88	88	136	136	528

Prototype V1



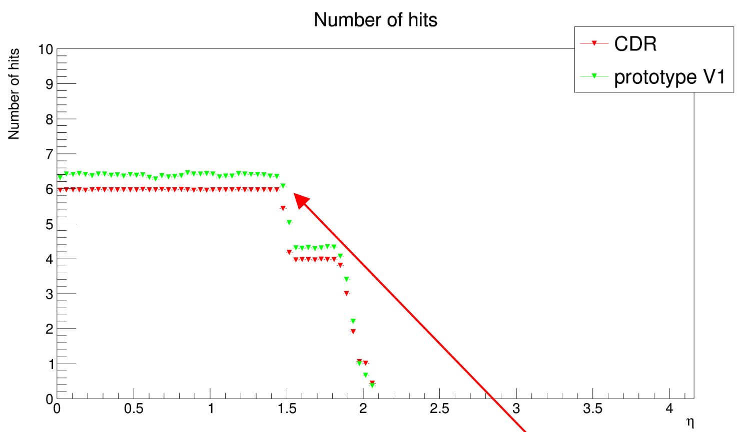
XY Section of the tracker barrel. - (png) - (pdf) - (root)

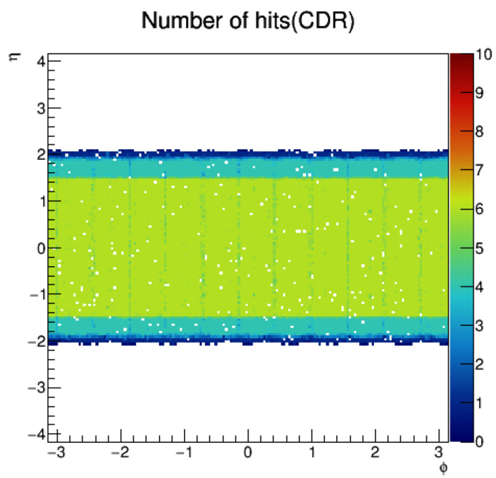


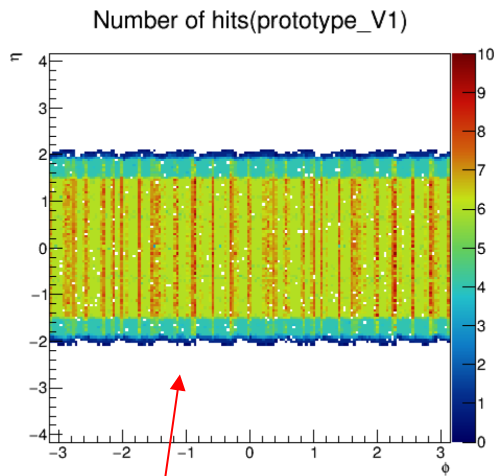
RZ positions of the barrel modules. - (png) - (pdf) - (root)

Barrel : PXB1							Total
Layer	1	2	3	4	5	6	
r	17.116	19.041	37.667	39.577	58.914	60.842	
z_max	64.200	64.200	128.450	128.450	128.450	128.450	
# rods	10	10	22	22	32	32	
# mods	50	50	220	220	320	320	1180

Hit map and statistics of baseline design and prototype V1





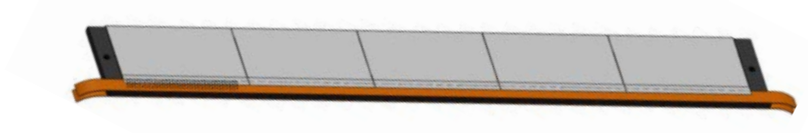


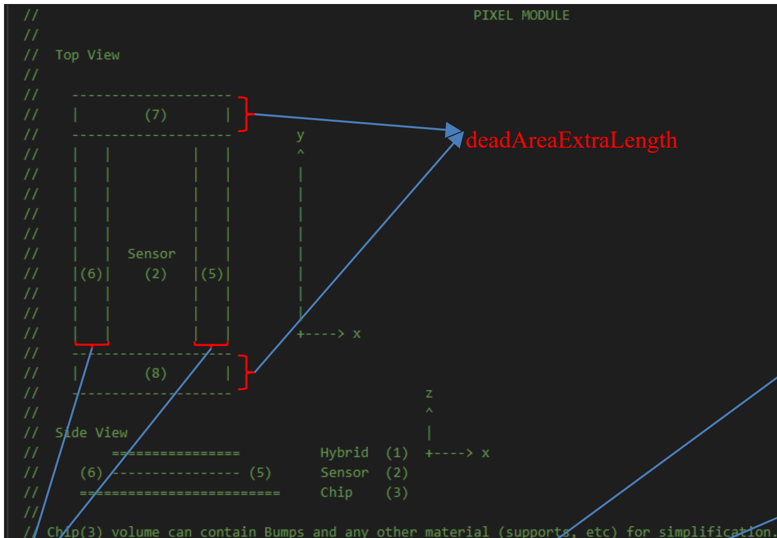
	R (mm)	$\lvert z \rvert$ (mm)	$\lvert \cos\theta \rvert$	σ(μm)	η
Layer 1	16	62.5	0.97	2.8	2.09
Layer 2	18	62.5	0.96	6	1.95
Layer 3	37	125.0	0.96	4	1.95
Layer 4	39	125.0	0.95	4	1.83
Layer 5	58	125.0	0.91	4	1.53
Layer 6	60	125.0	0.90	4	1.47

On average, more hits for prototype V1, because of more overlaps.

Vertical bands in 2D hits distribution. At Φ , our prototype V1 is not very uniform due to overlaps.

PrototypeV1 module



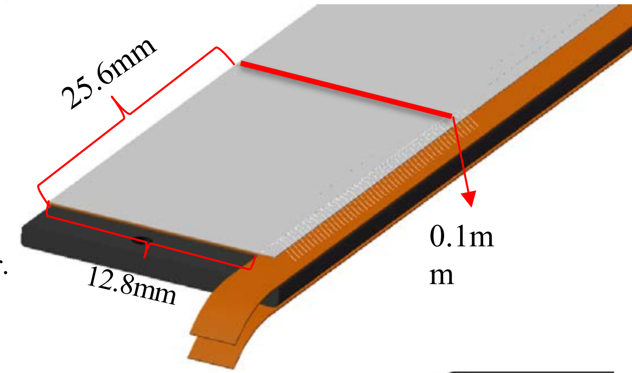


```
//                                  PIXEL MODULE
//
//  Top View
//
//    -------------------
//    |      (7)        |
//    -------------------          y
//    |  |          |  |           ^
//    |  |          |  |           |
//    |  |          |  |           |
//    |  |          |  |           |
//    |  |          |  |           |
//    |  |  Sensor  |  |           |
//    |(6)|  (2)    |(5)|          |
//    |  |          |  |           |
//    |  |          |  |           |
//    |  |          |  |           +----> x
//
//    -------------------
//    |      (8)        |
//    -------------------                    z
//                                           ^
//  Side View                                |
//         ===============        Hybrid  (1) +----> x
//     (6) --------------- (5)    Sensor  (2)
//     =======================    Chip    (3)
//
// Chip(3) volume can contain Bumps and any other material (supports, etc) for simplification.
```

deadAreaExtraLength

Dead Area Extra Width

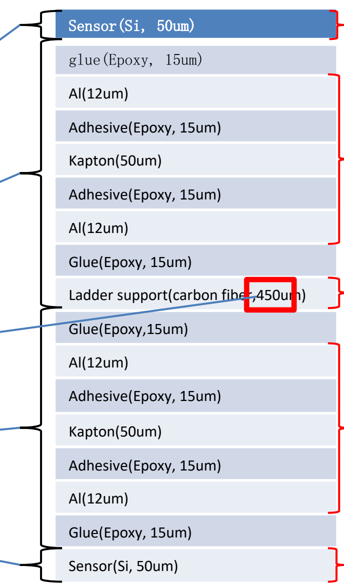
Top view:
Only consider the sensor area:
12.8mm × 25.6mm
Not consider the sensor dead area and electronics
Side view:
5 symmetric layer, gluing together.
From Jinyu(replace copper with aluminum)



Outer pixel module:
Sensor (2)
Chip (3)

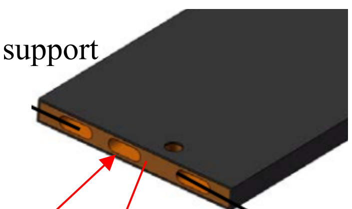
Carbon fiber with an equivalent thickness of 450 microns

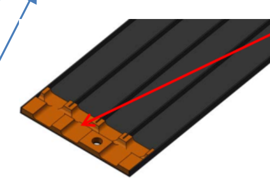
inner pixel module:
Hybrid (1)
Sensor (2)

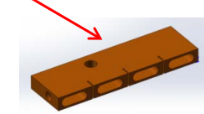


(1) Sensor
(2) FPC
(3) Ladder support
(4) FPC
(5) sensor

hollow support



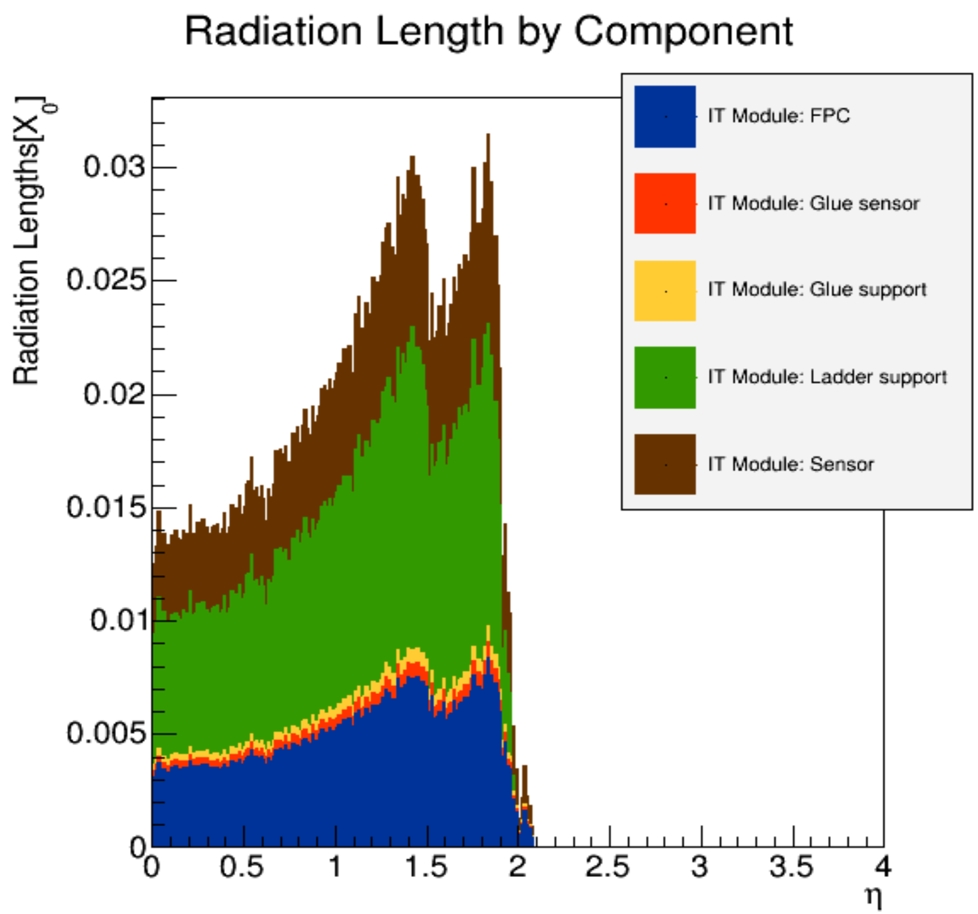




PrototypeV1 material budget

Components details:

Average (eta = [0, 4.0])	Radiation length	Interaction length
IT Module: FPC	0.00256	0.00092
IT Module: Glue sensor	0.00021	0.00010
IT Module: Glue support	0.00021	0.00010
IT Module: Ladder support	0.00444	0.00221
IT Module: Sensor	0.00256	0.00052
Services	0.00000	0.00000
Supports	0.00000	0.00000



Material budget in CDR: $0.15\%X_0$ per layer

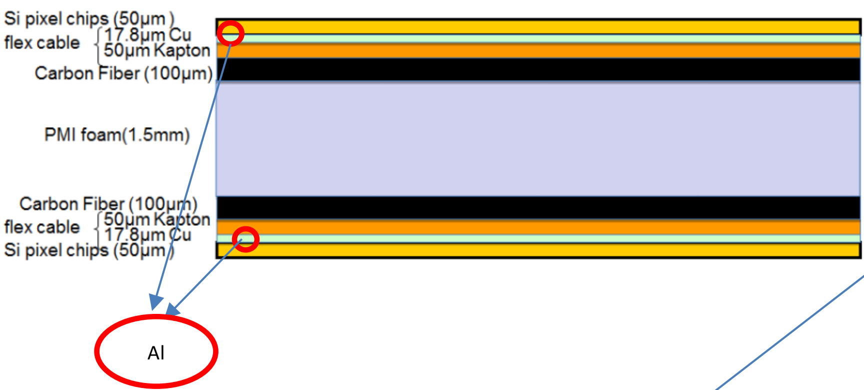
$0.15\% \times 6 = 0.9\% < 0.01$

Bear in mind: 0.9% is on average

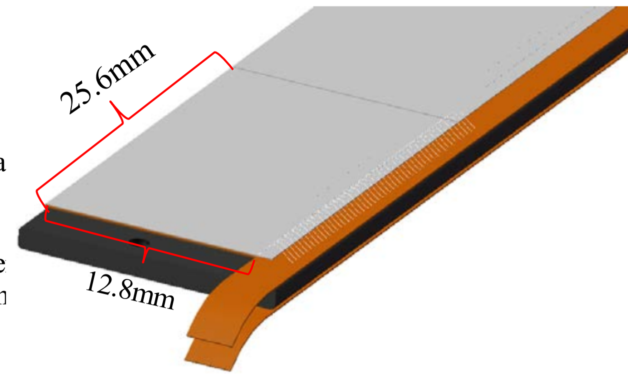
Too much material!

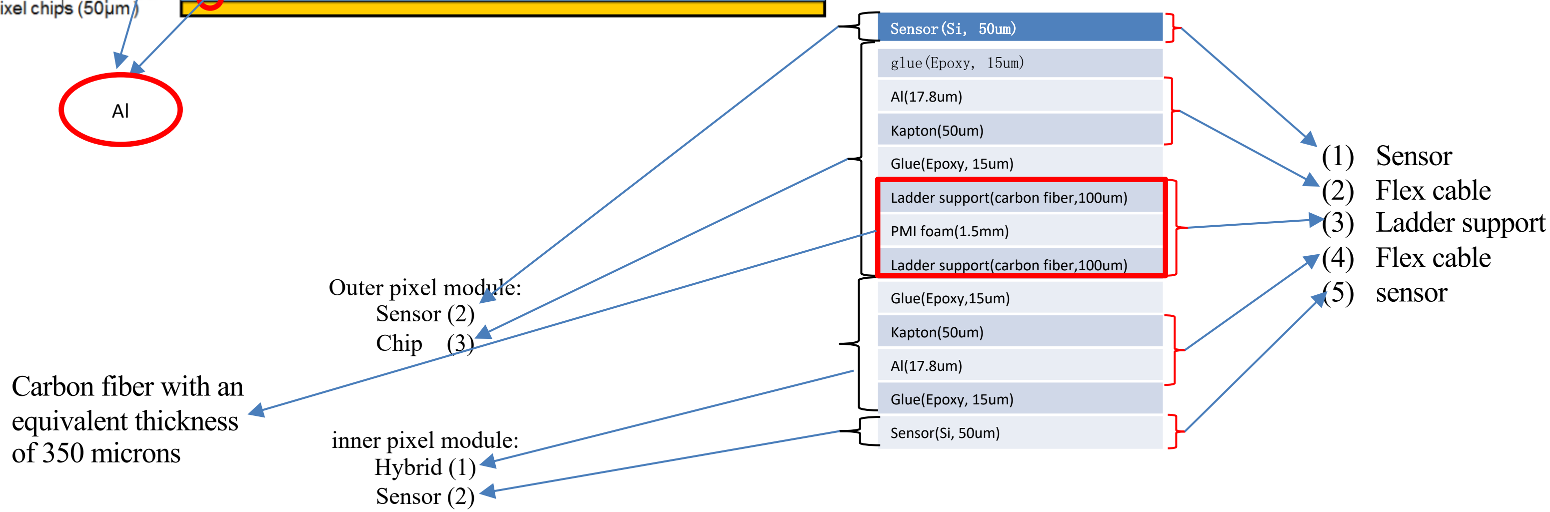
Material budget: alternative design

From Mingyi DONG

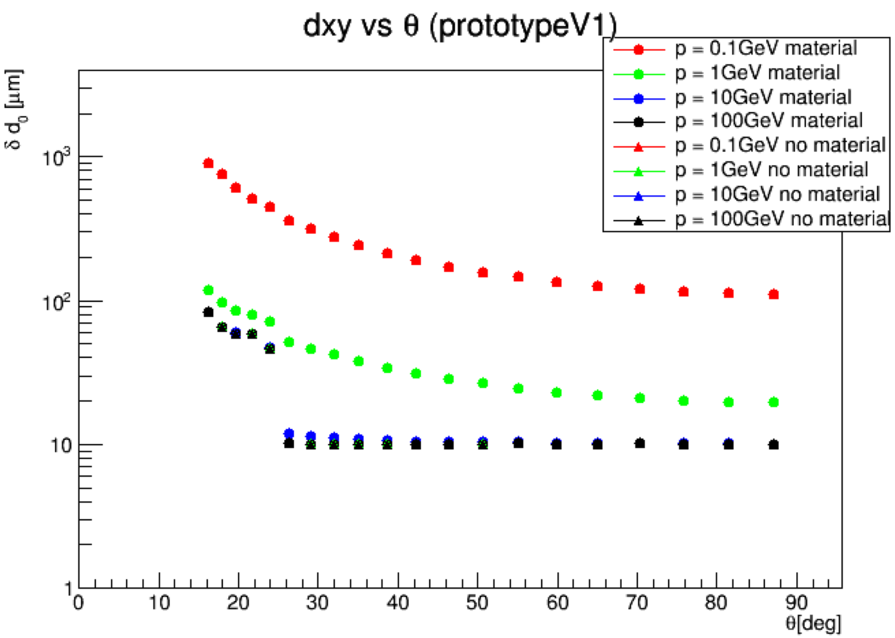


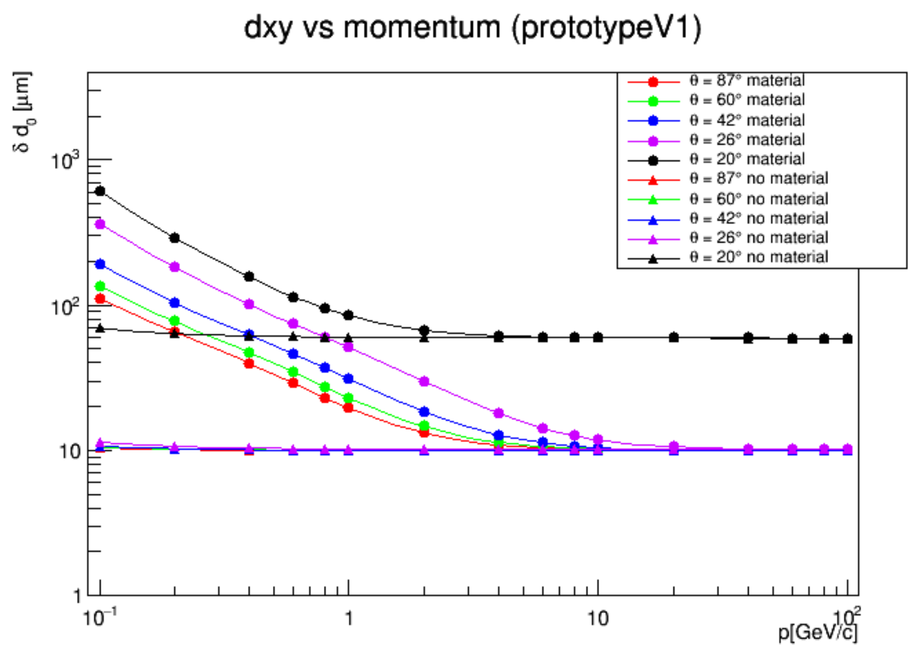
Top view:
Only consider the sensor area:
12.8mm × 25.6mm
Not consider the sensor dead area and electronics
Side view:
5 symmetric layer, gluing togethe
From Mingyi(replace copper with aluminum)



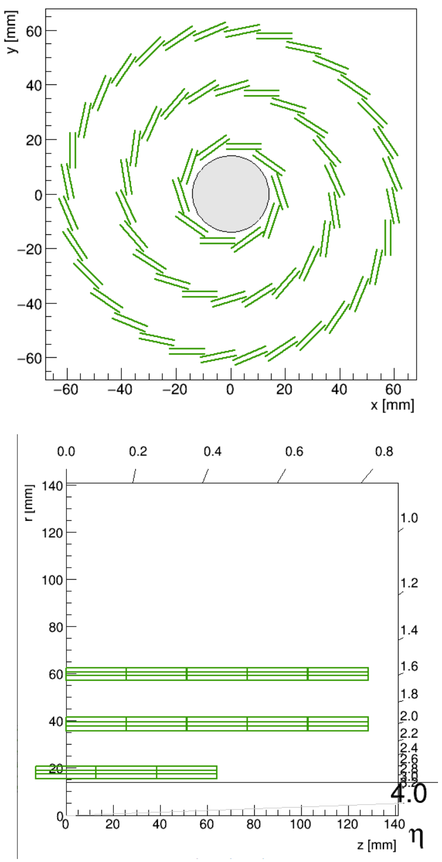


Impact parameter resolution of Prototype V1

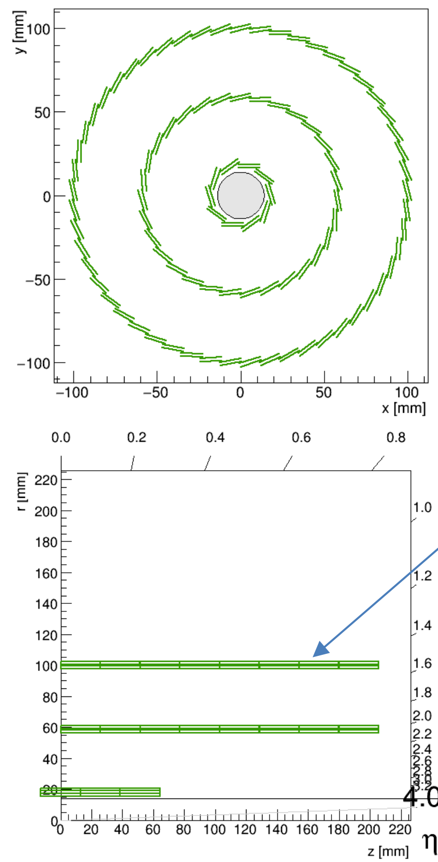




Changing radius

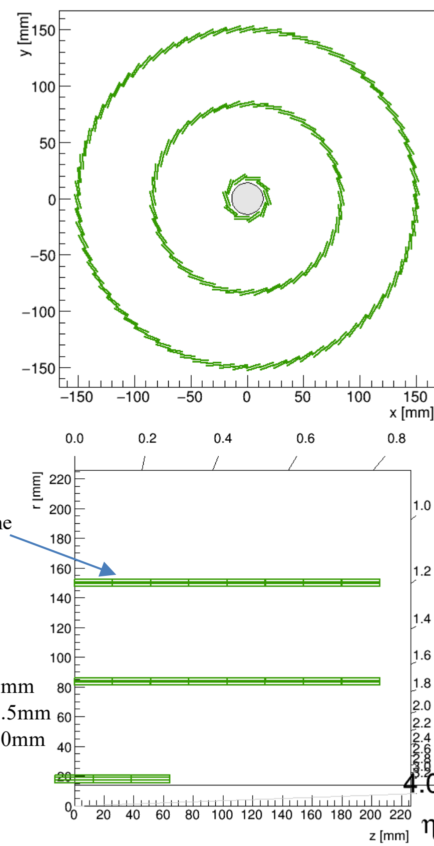


Layer 1: 18mm
Layer 2: 38mm
Layer 3: 60mm



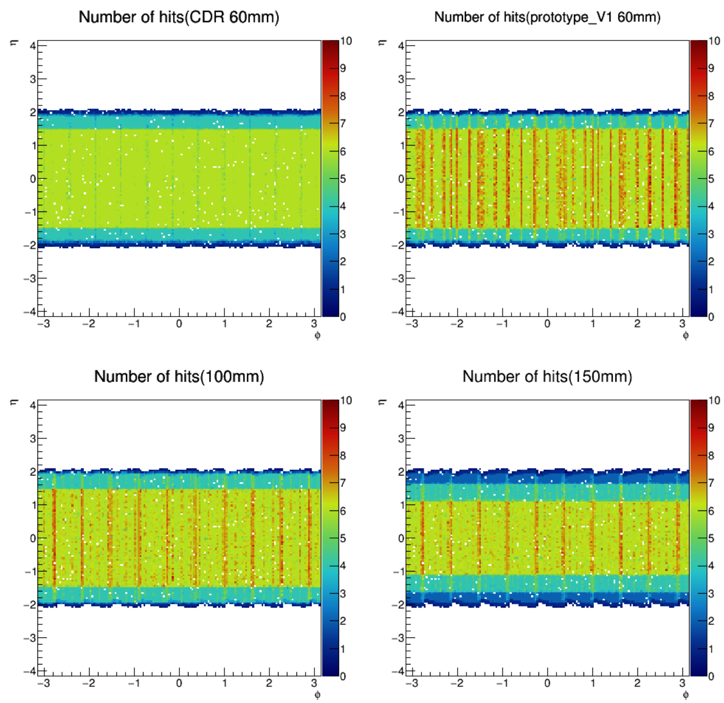
Z lengths are the same

Layer 1: 18mm
Layer 2: 58.5mm
Layer 3: 100mm

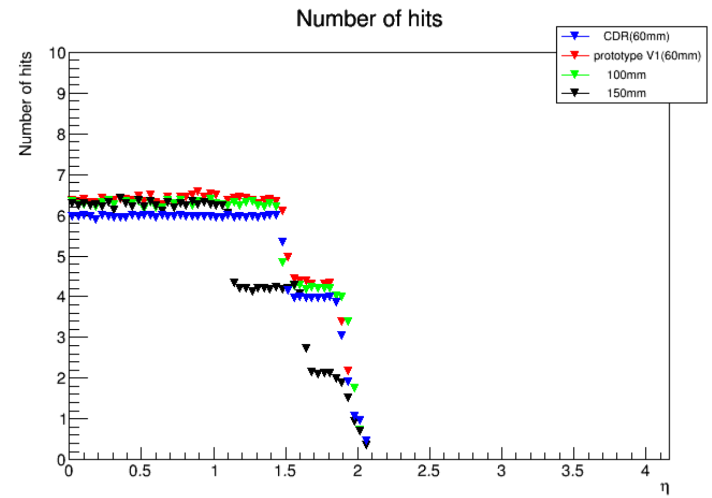


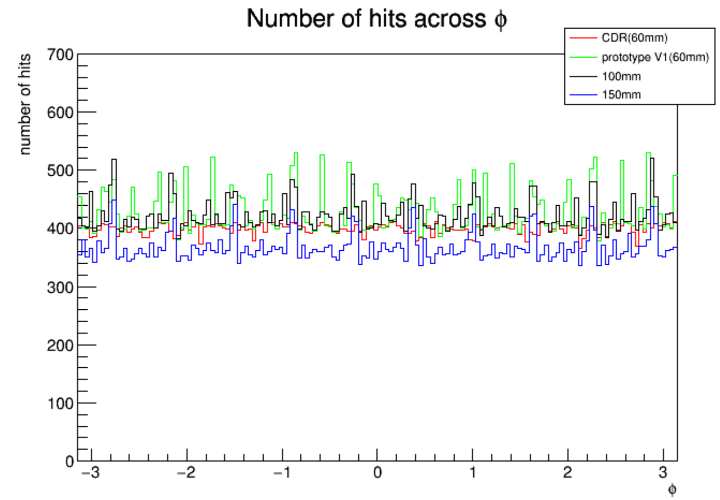
Layer 1: 18mm
Layer 2: 83.5mm
Layer 3: 150mm

Hit map and statistics of different radius

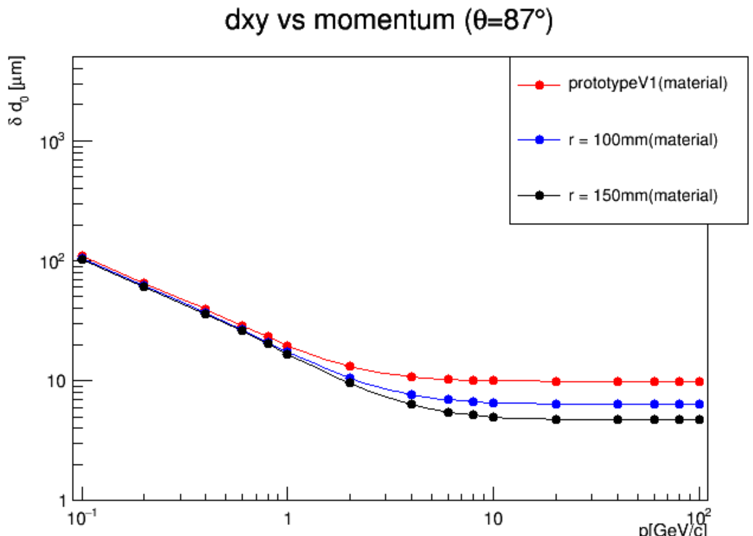


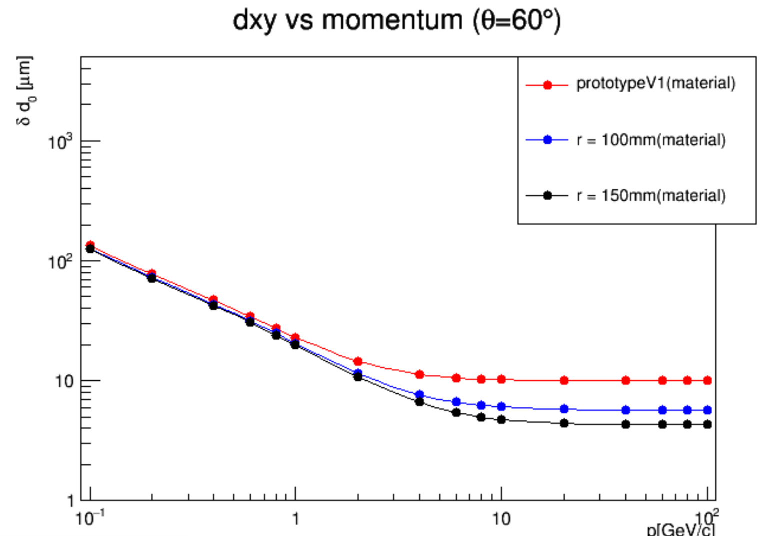
increase radius, number of stripes approaches 10.
Equal to the number of ladders of the first layer.



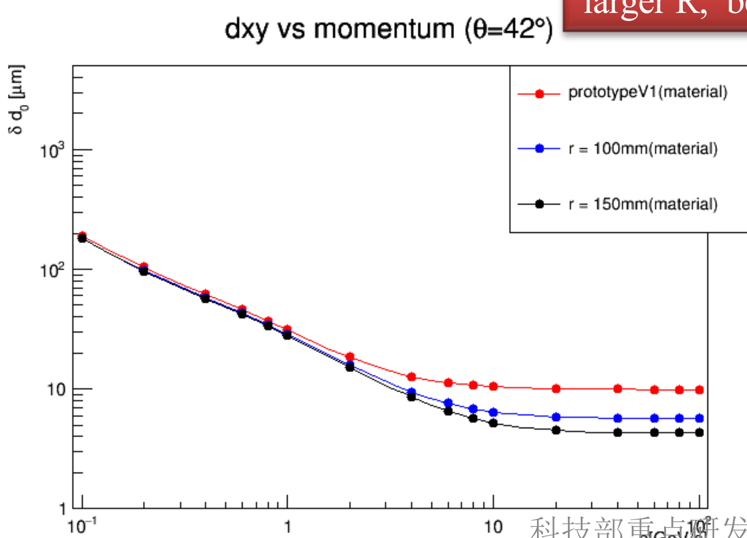


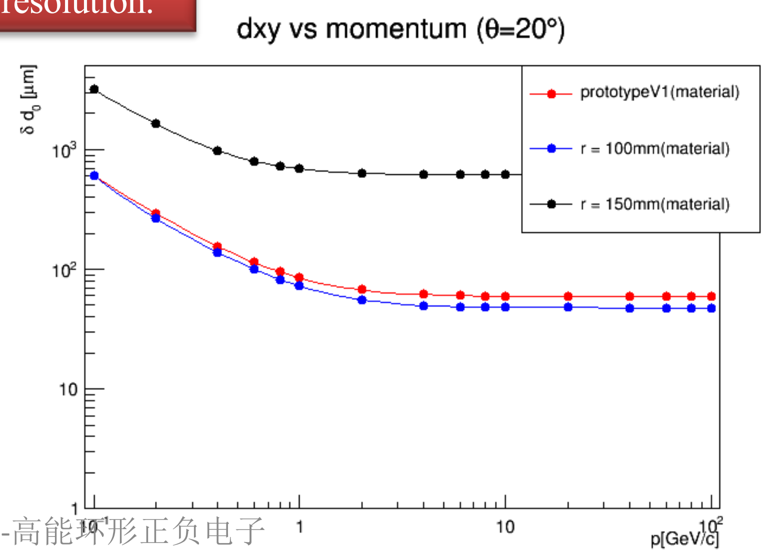
Impact parameter resolutions of different radius



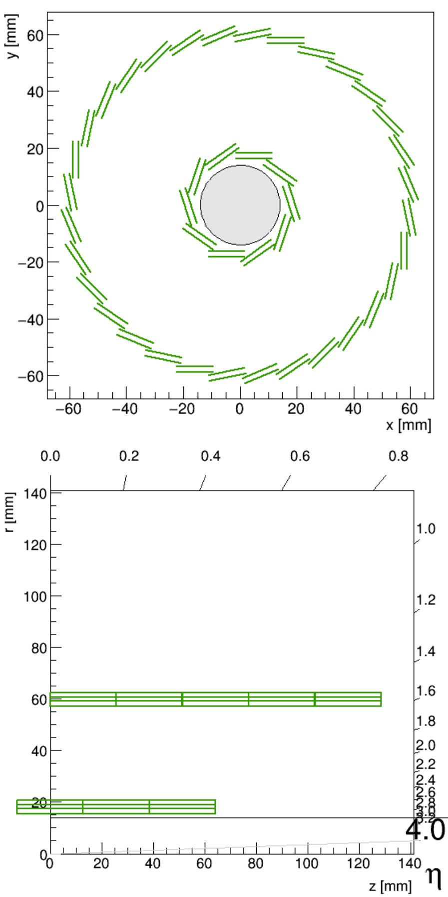


larger R, better resolution.

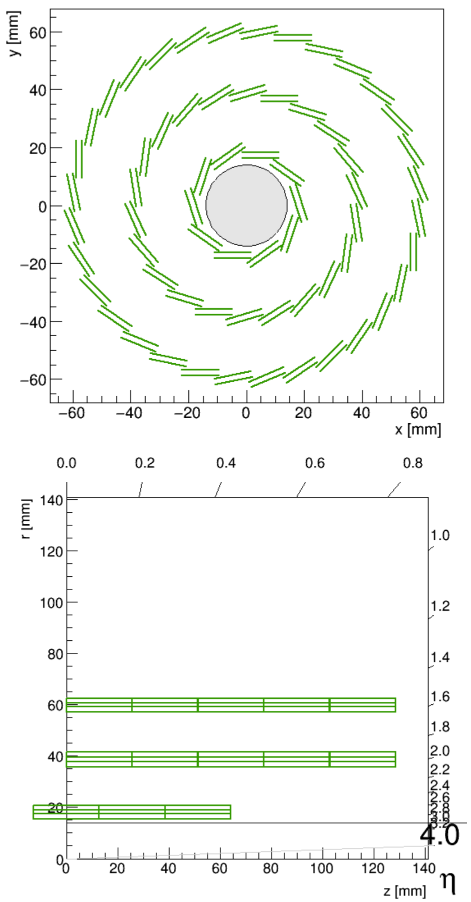




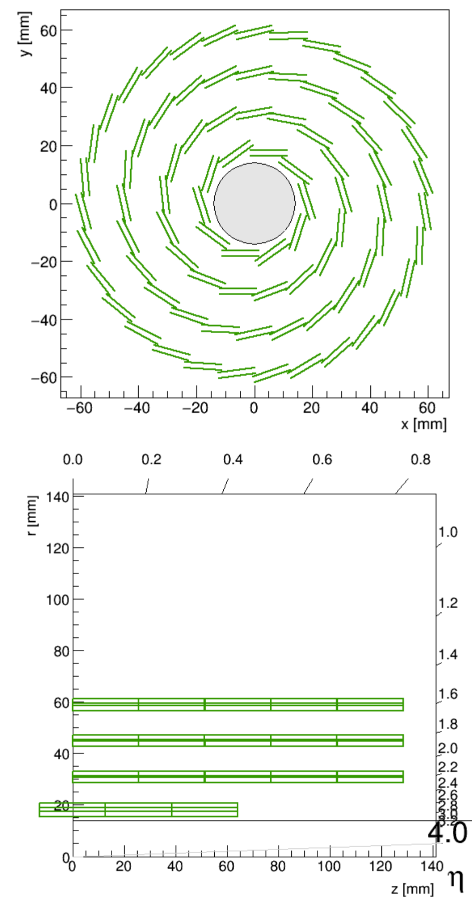
Changing the number of layers



Layer 1: 18mm
Layer 3: 59mm

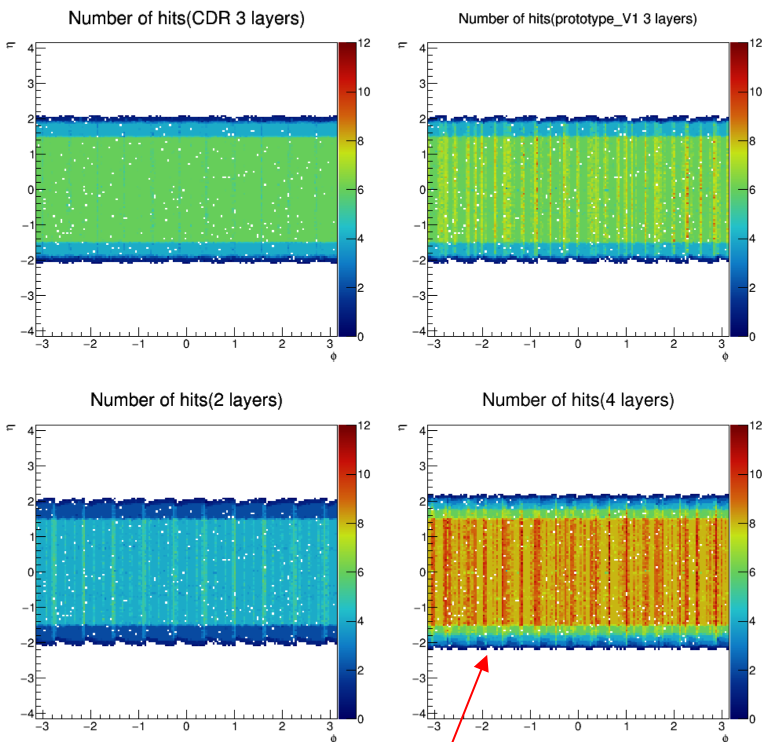


Layer 1: 18mm
Layer 2: 38mm
Layer 3: 60mm

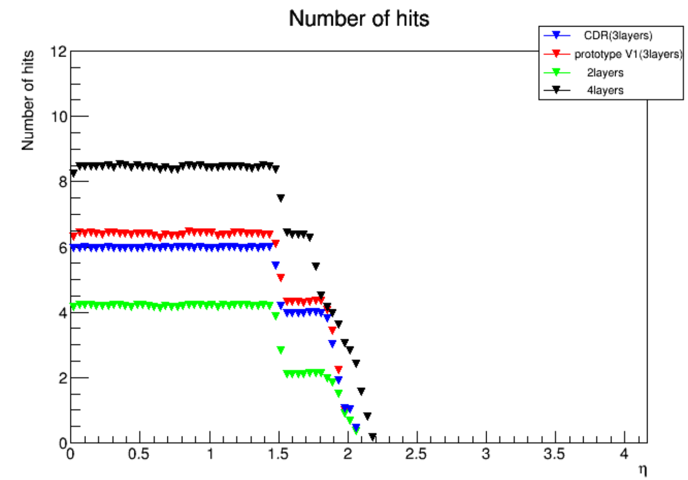


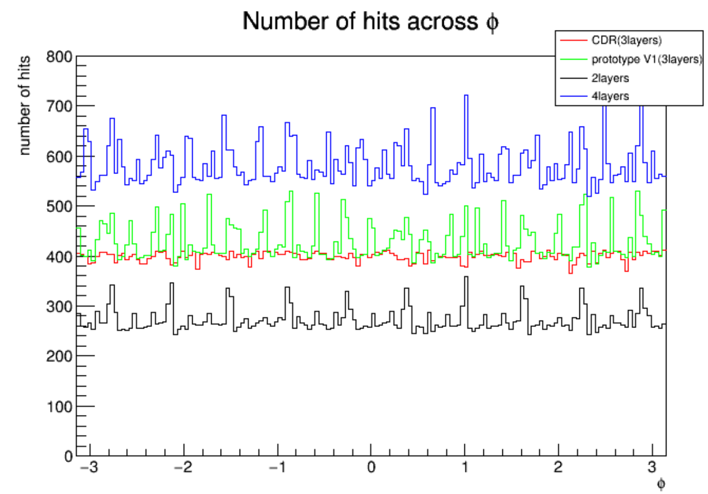
Layer 1: 18mm
Layer 2: 31mm
Layer 3: 45mm
Layer 4: 59mm

Hit coverage comparison

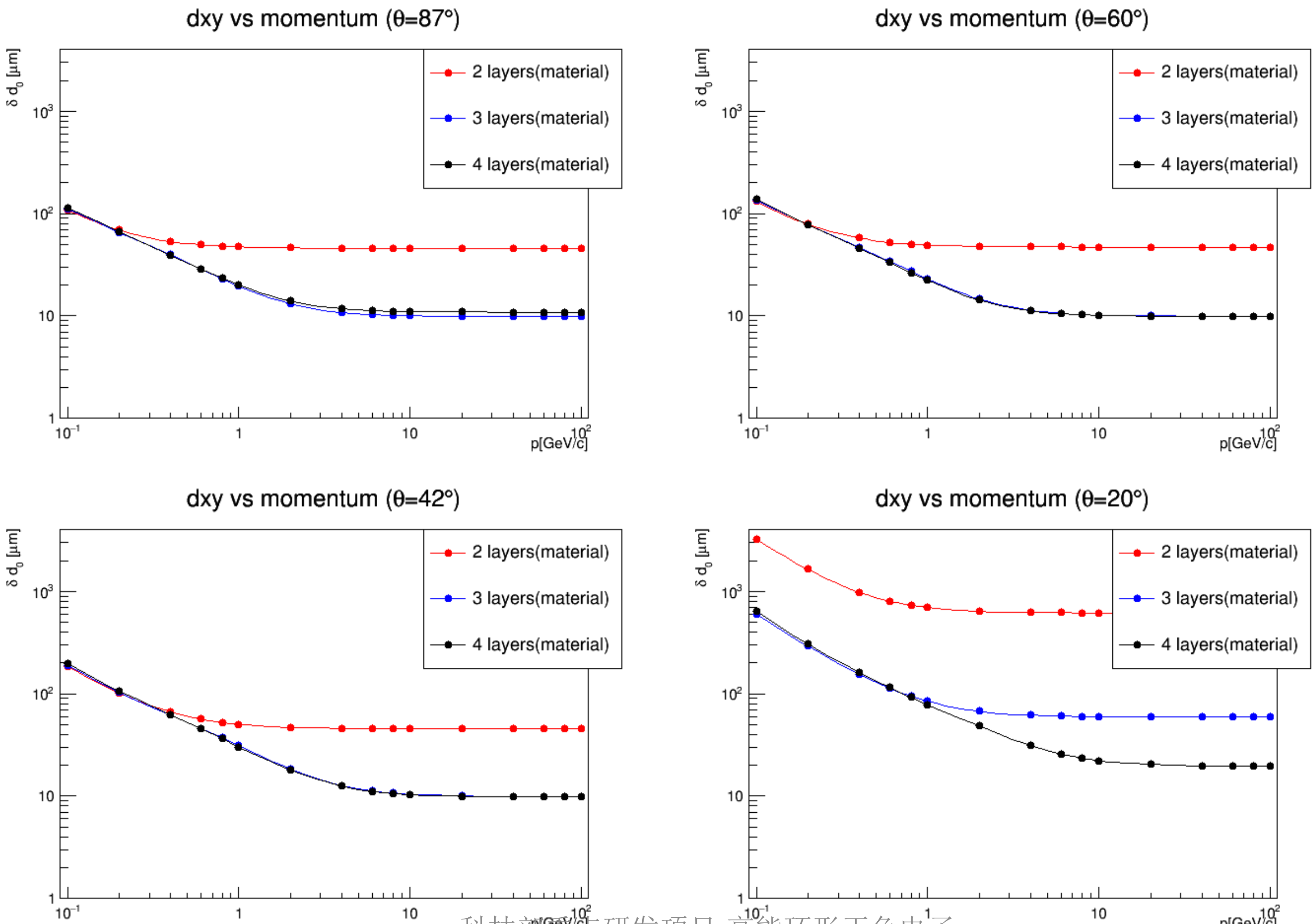


More layers, more stripes.

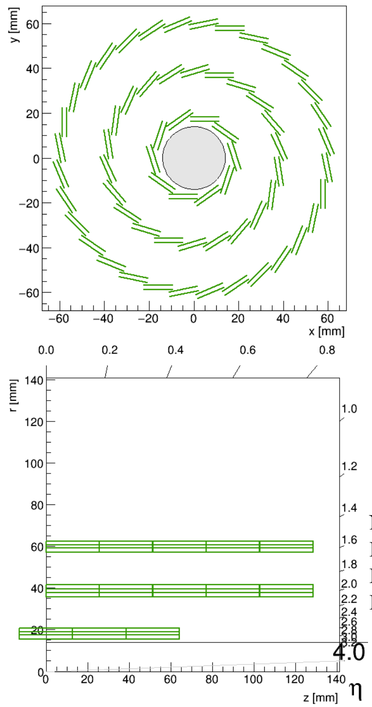


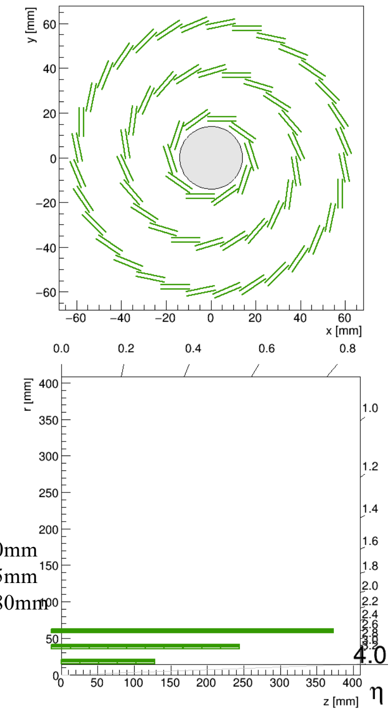


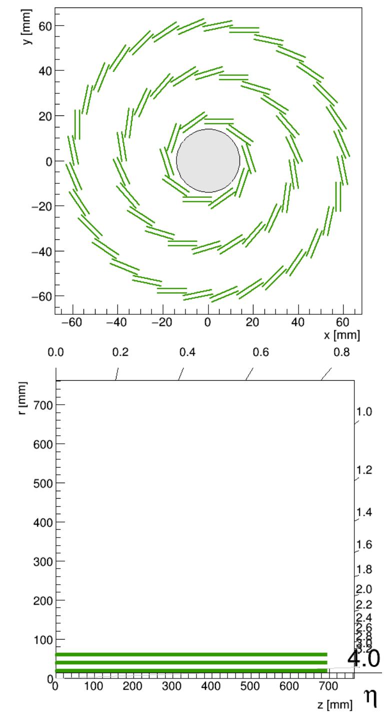
Impact parameter resolutions of different number of layers



Layouts comparison







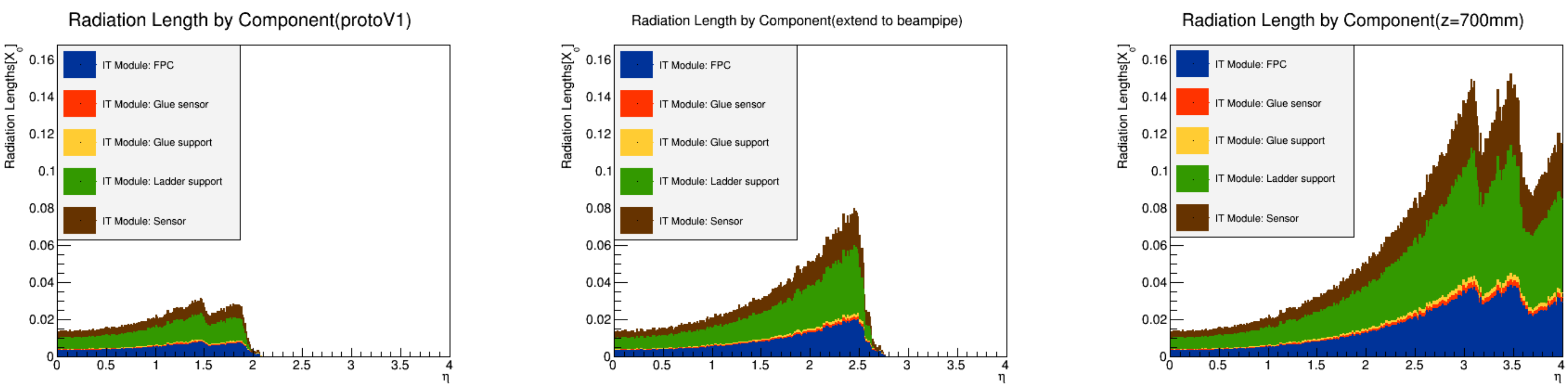
New beam pipe:
Layer 1: Ø33mm, +z=130mm
Layer 2: Ø68mm, +z=255mm
Layer 3: Ø103mm, +z=380mm

Barrel : PXB1							Total
Layer	1	2	3	4	5	6	
r	17.116	19.041	37.667	39.577	58.914	60.842	
z_max	64.200	64.200	128.450	128.450	128.450	128.450	
# rods	10	10	22	22	32	32	
# mods	50	50	220	220	320	320	1180

Barrel : PXB1							Total
Layer	1	2	3	4	5	6	
r	17.116	19.041	37.667	39.577	58.914	60.842	
z_max	128.450	128.450	244.100	244.100	372.600	372.600	
# rods	10	10	22	22	32	32	
# mods	100	100	418	418	928	928	2892

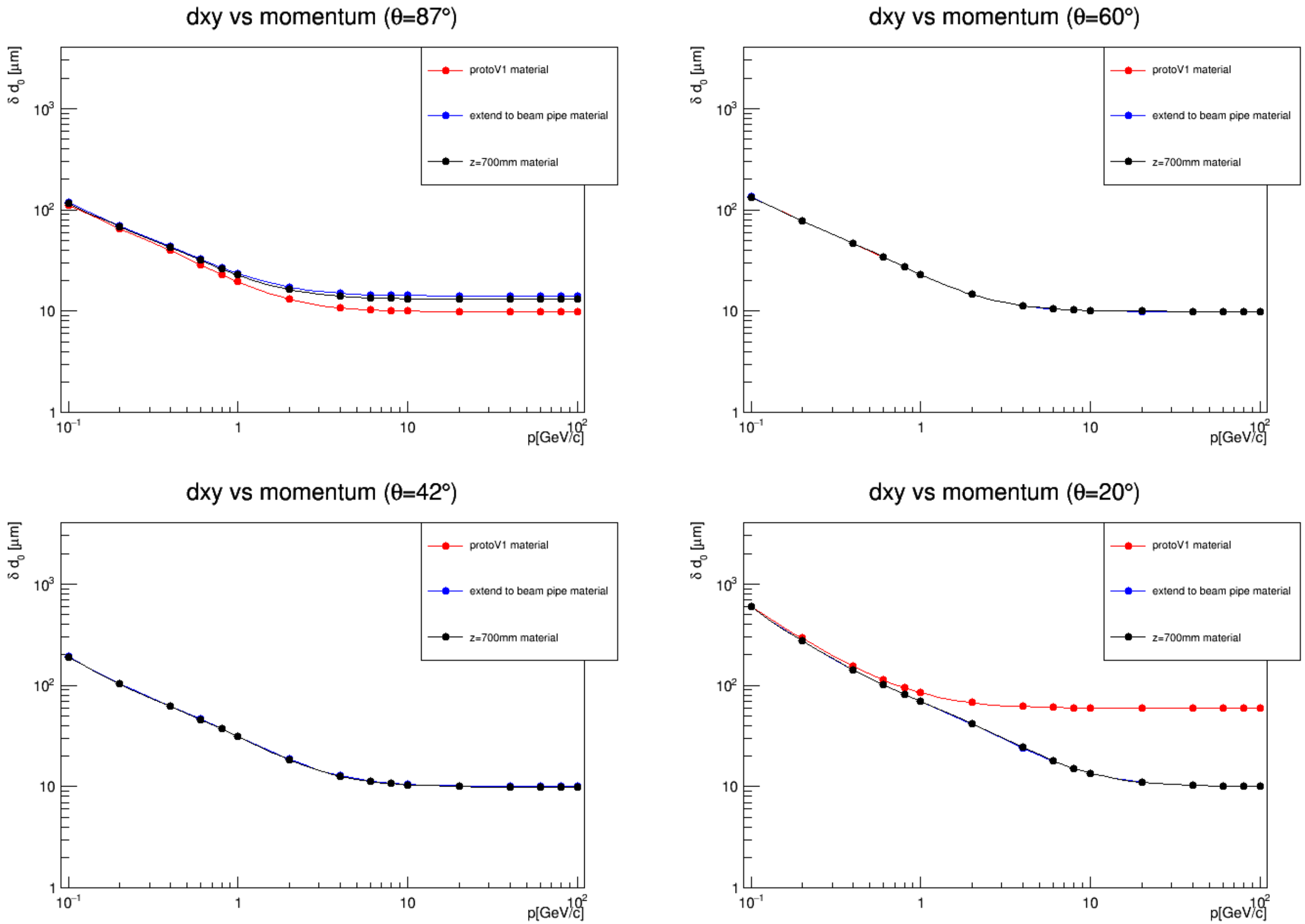
Barrel : PXB1							Total
Layer	1	2	3	4	5	6	
r	17.116	19.041	37.667	39.577	58.914	60.842	
z_max	693.850	693.850	693.850	693.850	693.850	693.850	
# rods	10	10	22	22	32	32	
# mods	540	540	1188	1188	1728	1728	6912

Material budget comparison

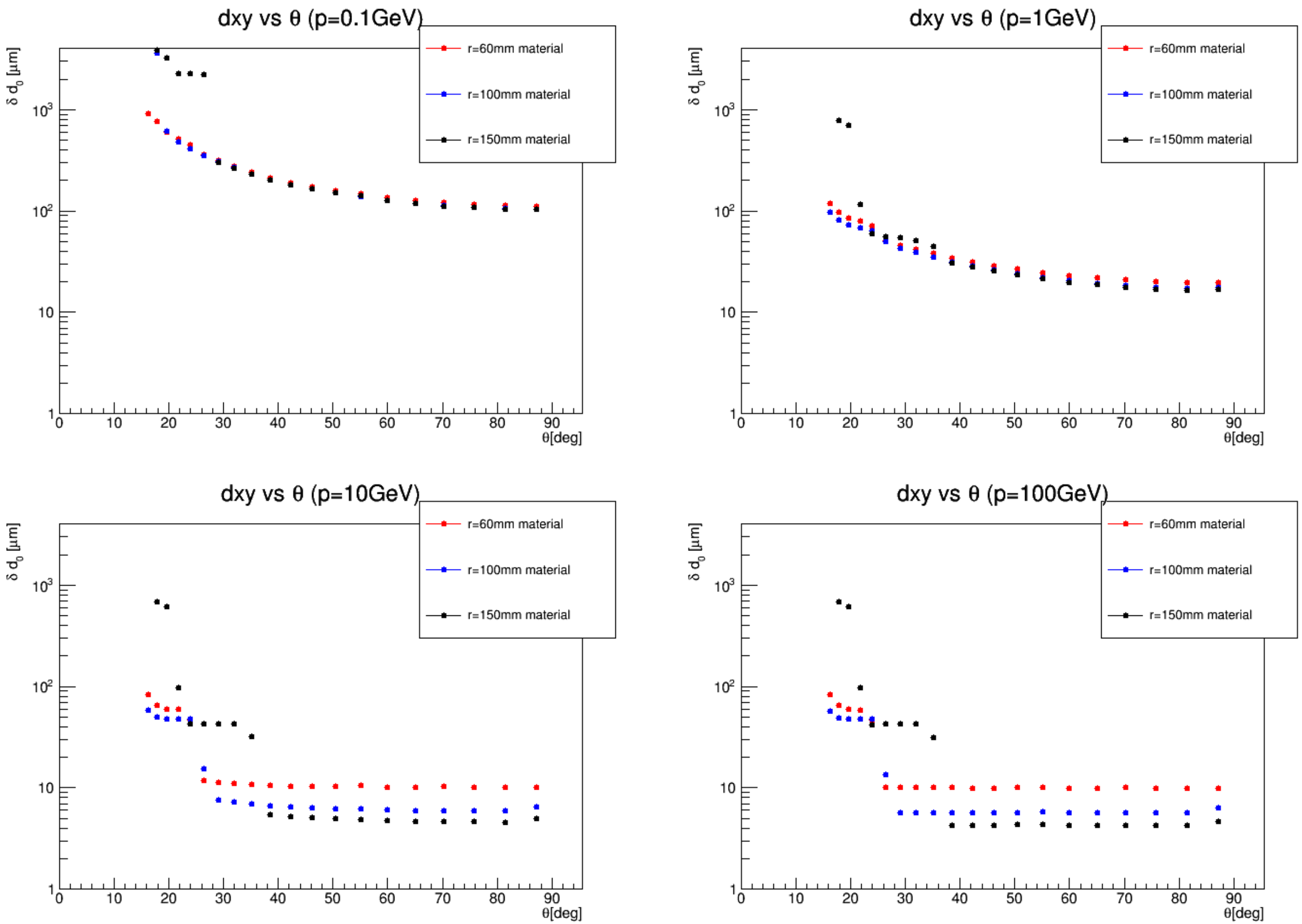


All > 0.9% X_0 !

Impact parameter resolutions of different number of layers

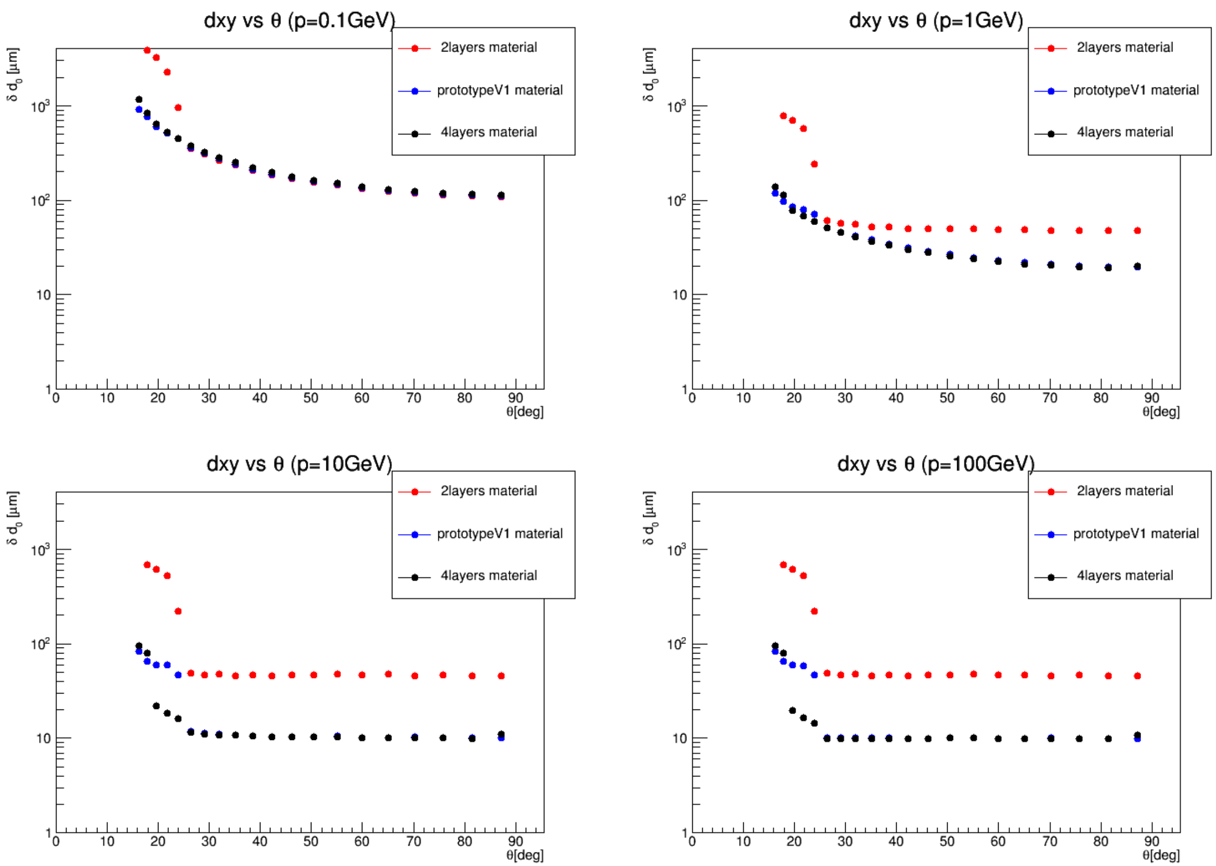


Impact parameter resolutions of different radius



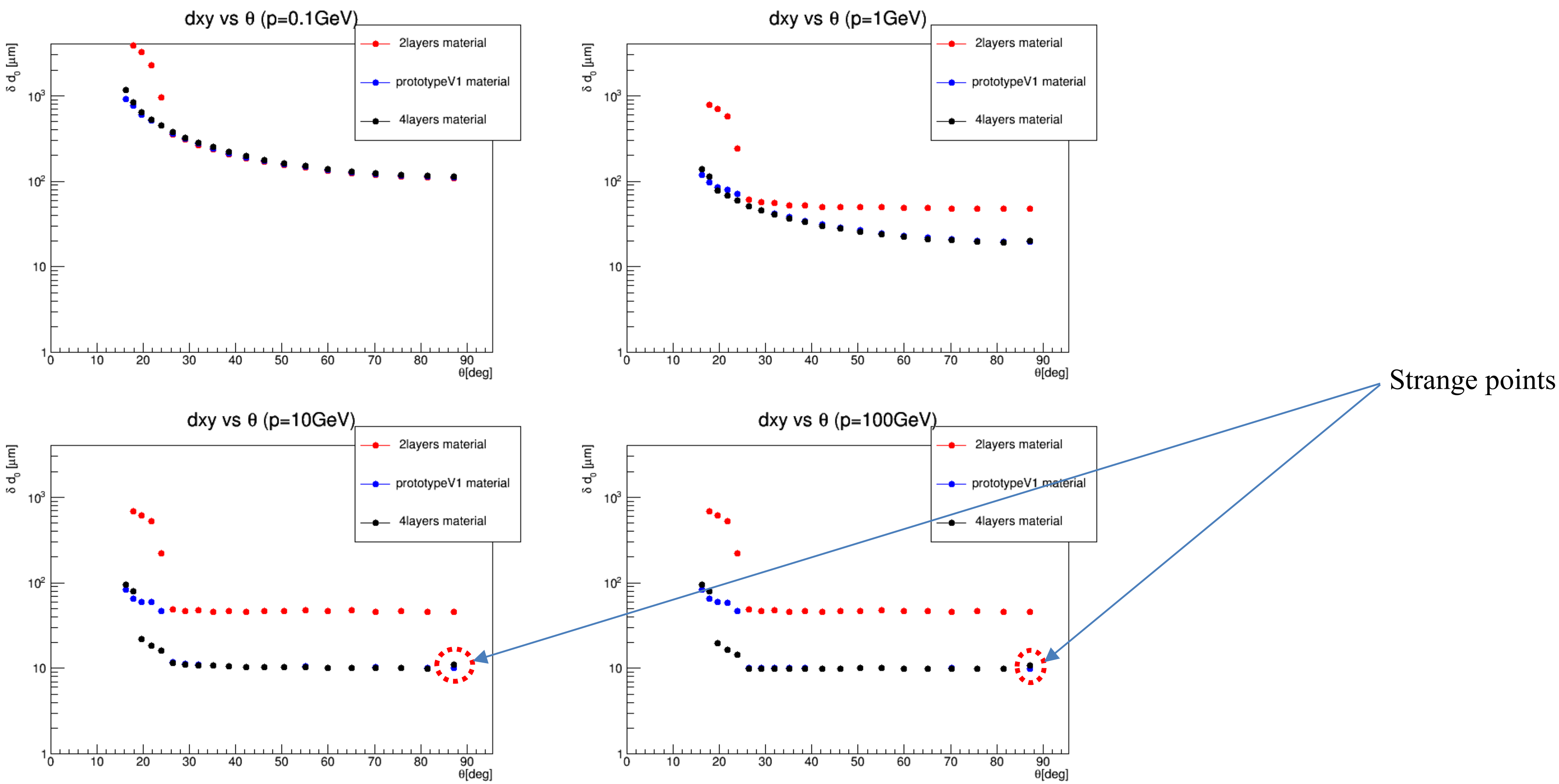
Layouts comparison

- Different number of layers(resolution vs θ)



Layouts comparison

- Different number of layers(resolution vs θ)



Layouts comparison

- Different number of layers(resolution vs p)