Progress and planning of the Vertex detector

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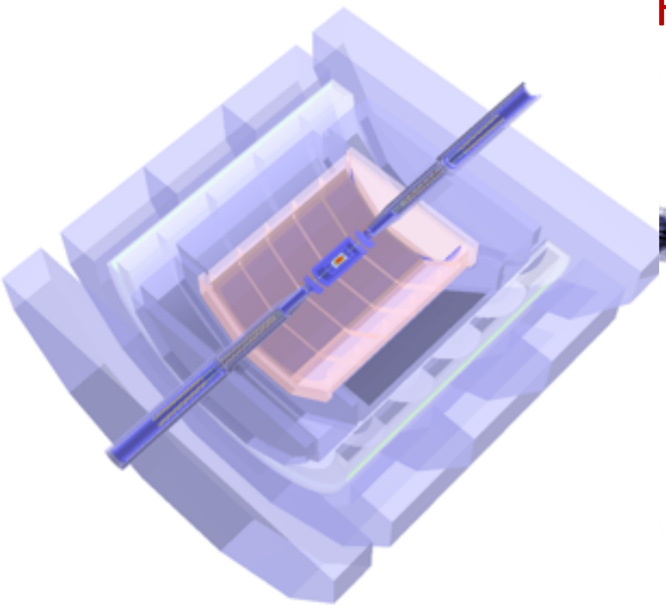
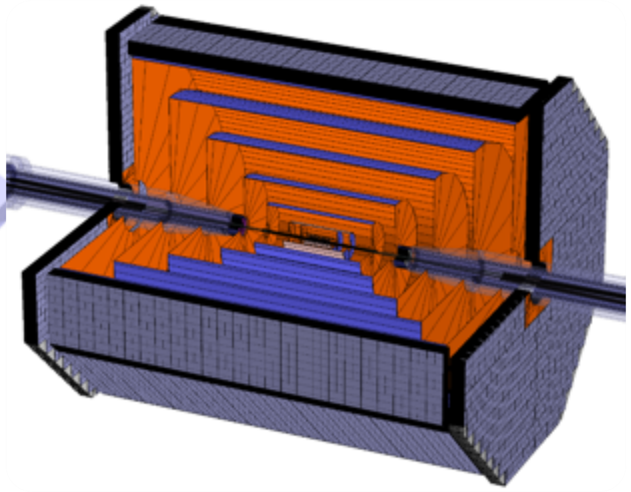
CEPC Detector Conceptual Designs

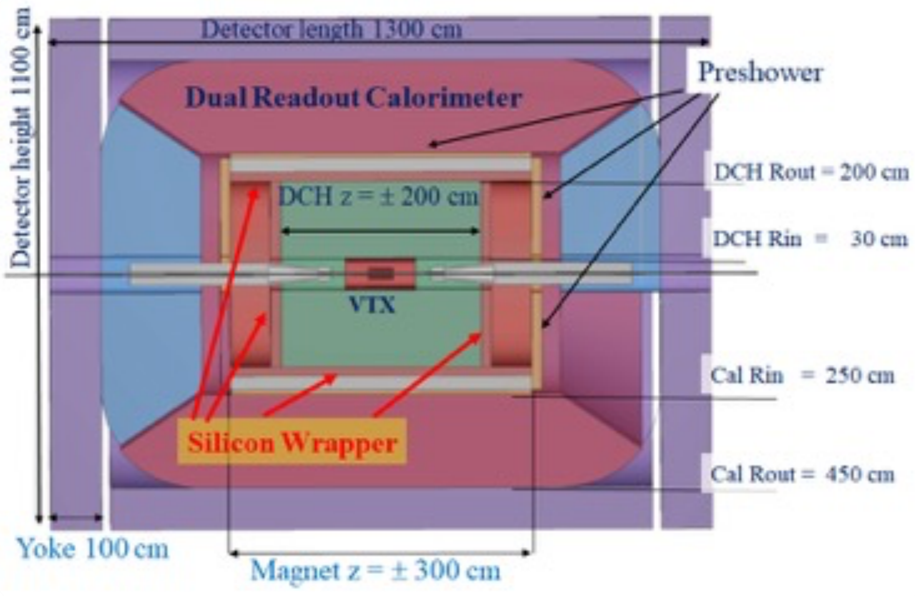
ILD-Like design



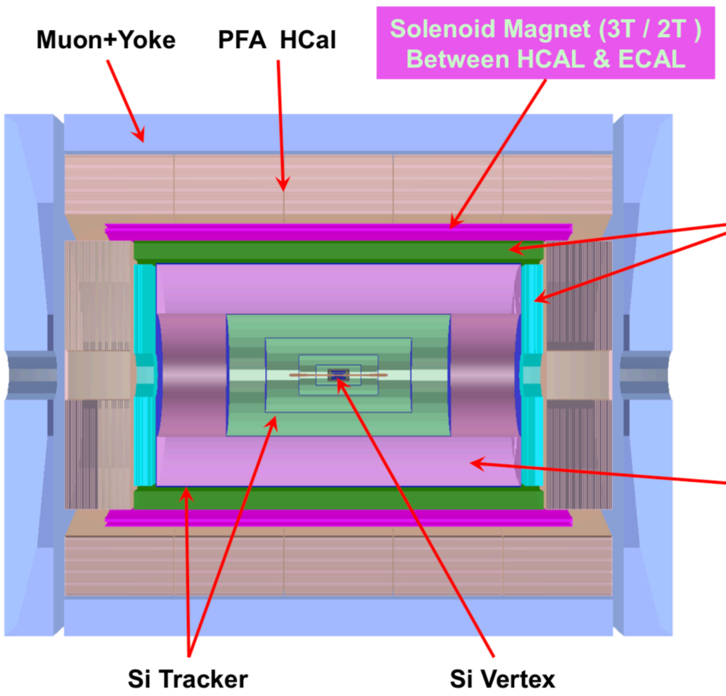
Full silicon



IDEA



The 4th Conceptual Detector Design



Advantage: the HCAL absorbers act as part of the magnet return yoke.

Challenges: thin enough not to affect the jet resolution (e.g. BMR); stability.

Transverse Crystal bar ECAL

Advantage: better π^0/γ reconstruction.

Challenges: minimum number of readout channels; compatible with PFA calorimeter; maintain good jet resolution.

Drift chamber
that is optimized for PID

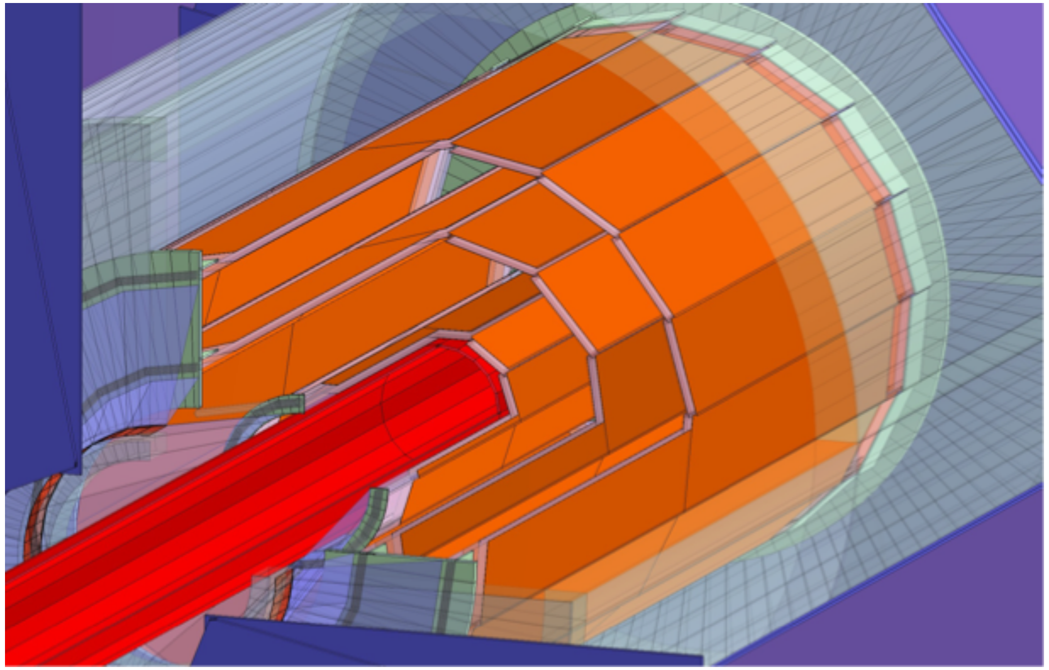
Advantage: Work at high luminosity Z runs

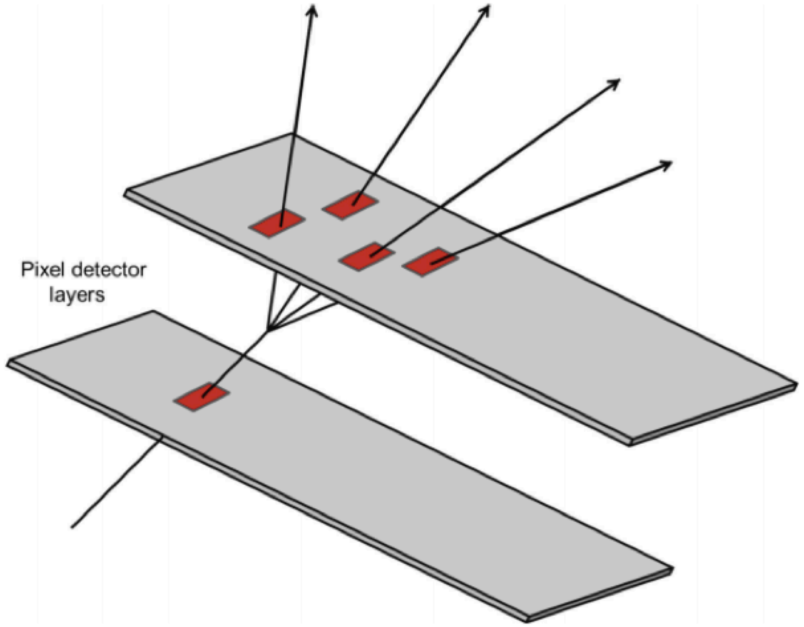
Challenges: sufficient PID power; thin enough not to affect the moment resolution.

VERTEX DETECTOR FOR CEPC

- High precision vertex detector essential for H→bb/cc/gg and H→ττ
- Single point resolution < 3 μm → small pixel pitch, e.g. 16 μm
- Material budget 0.15%X_0 per layer
- Power consumption: < 50 mW/cm^2
- Fast readout time: <500ns @40MHz at Z pole
- Radiation tolerance **(per year):** 1 MRad & 2×10^{12} 1 MeV n_{eq}/cm^2

$$\sigma_{r\varphi} = 3\ \mu m \oplus \frac{10\ \mu m}{p(\mathrm{GeV}) \cdot \sin^{3/2}\theta}$$

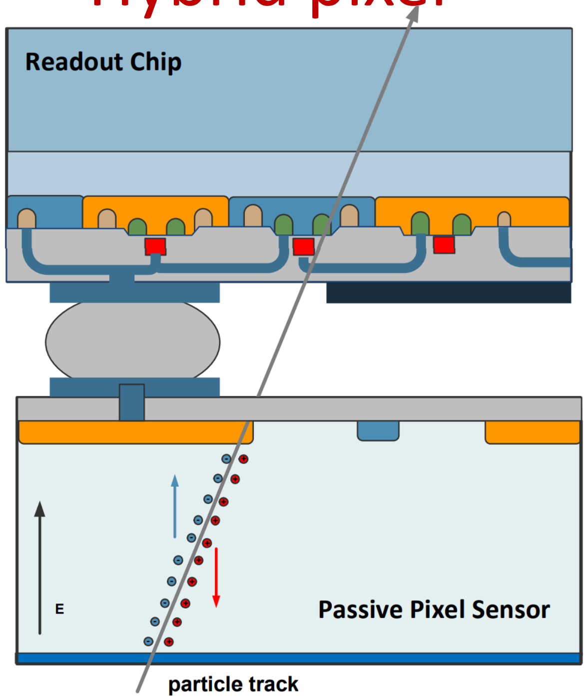




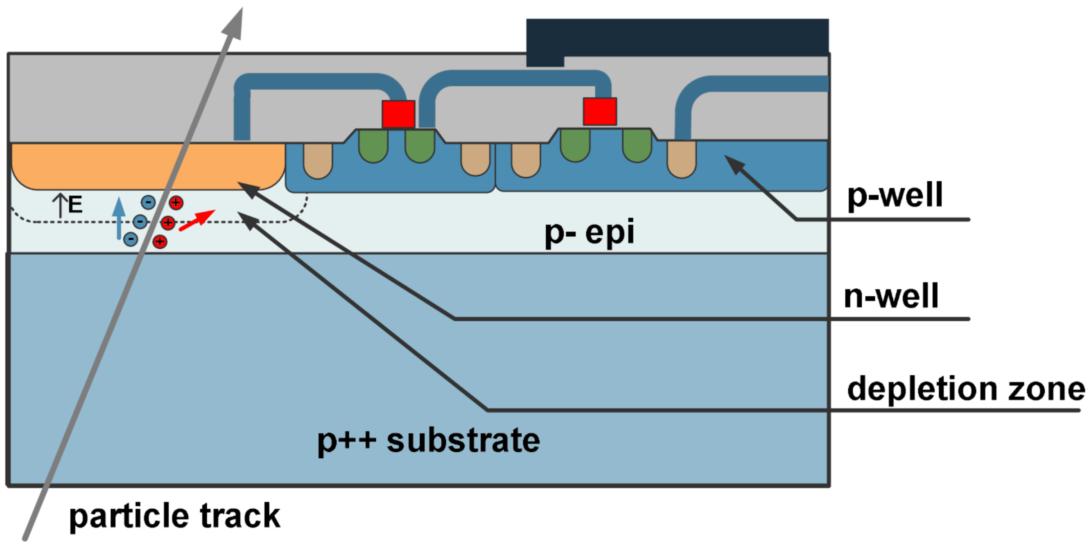
CMOS MONOLITHIC PIXEL SENSOR

- CMOS Monolithic pixel (CIS process or SOI process) is ideal for CEPC application
  - low material budget (can be thin down to 50μm)
- Hybrid pixel technology developed by ATLAS and CMS
  - Thickness of sensor is about 200~300 μm
  - Need to bump bonding with readout ASIC (ASIC thickness is about 300μm)
  - Material budget about silicon sensor is about 10 times larger than CIS process

Hybrid pixel



Monolithic Pixels



CMOS MONOLITHIC PIXEL SENSOR

- The existing CMOS monolithic pixel sensors can't fully satisfy the requirement
- Major constraints for the CMOS sensor
  - Pixel size: Single point resolution < 3 μm
  - <500ns deadtime @40MHz at Z pole
  - Radiation tolerance **(per year):** 1 MRad &2×10^{12} 1 MeV n_{eq}/cm^2

experiment	Chip	Resolution	Readout Speed	TID
ALICE	ALPIDE	✓	X	X (?)
ATLAS	Malta Monopix ATLASpix…	X	✓	✓
Star	MIMOSA	✓	X	X (?)

CEPC Pixel Sensor R&D

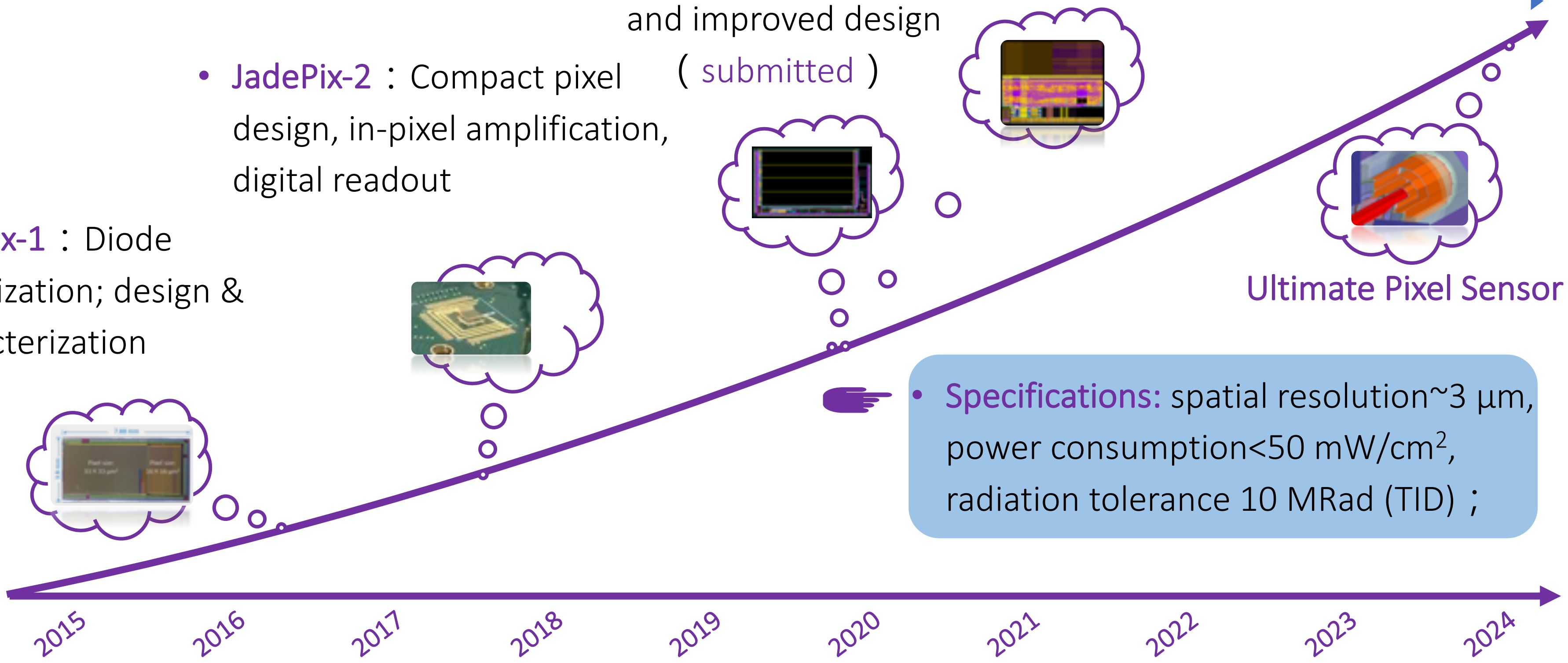
- JadePix-1：Diode optimization; design & characterization
- JadePix-2：Compact pixel design, in-pixel amplification, digital readout
- JadePix-3：bug-fix and improved design （submitted）

More details in Yunpeng's talk

- Taichu-1： Column Drained readout (FE-I3), two-stage FIFO （submitted）

More details in Wei Wei's talk

This Talk

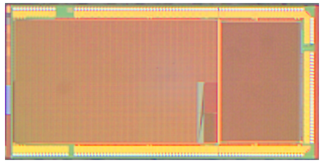


Ultimate Pixel Sensor

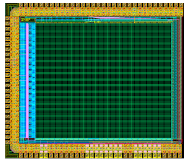
- Specifications: spatial resolution~3 μm, power consumption<50 mW/cm^2, radiation tolerance 10 MRad (TID)；

DEVELOPED CMOS PIXEL SENSOR PROTOTYPES FOR CEPC

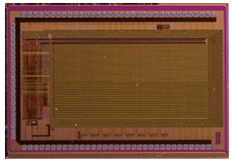
Prototype	Pixel size (μm^2)	Readout time	Pwer Consumption (mW/cm^2)	In-piel circuit	R/O architecture	Main goals	Status
JadePix1	33×33 16×16	~100 μs	~ 100	SF/amplifer, analog output	Rolling shutter	Sensor optimization	Lab. and beam test finished
JadePix2	22×22	~100 μs	< 100	amp., discriminator, binary output	Rolling shutter	Small pixel, Power < 100 mW/cm^2	functionality verified
MIC4	25×25	~10 μs	<26	Low power front-end, address encoder	Data-driven, Asynchronous	Small pixel, fast readout for ZH run	functionality verified
JadePix3	16×26 16×23	~10 μs	<26	Low power front-end, binary output	Rolling shutter with end of col. priority encoder	Small pixel, low power	Fabricated, Testing
Taichu-1	25×25	~50ns	50~100	binary output	Data-driven, Priority encoder	Full Functionalities Fast readout for Z pole	Fabricated, Testing



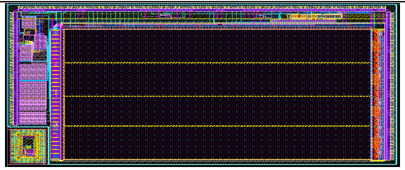
JadePix1 (IHEP)
3.9×7.9 mm^2



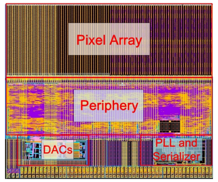
JadePix2 (IHEP)
3×3.3 mm^2



MIC4 (CCNU & IHEP)
3.2×3.7 mm^2



JadePix3
IHEP, CCNU, Dalian Minzu Unv., SDU
6.1×10.4 mm^2



Taichu-1
IHEP, SDU, NWPU, IFAE & CCNU
5×5 mm^2

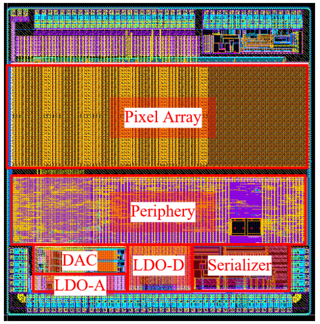
All prototypes in TowerJazz 180 nm CIS process

FUNDED BY MOST AND IHEP

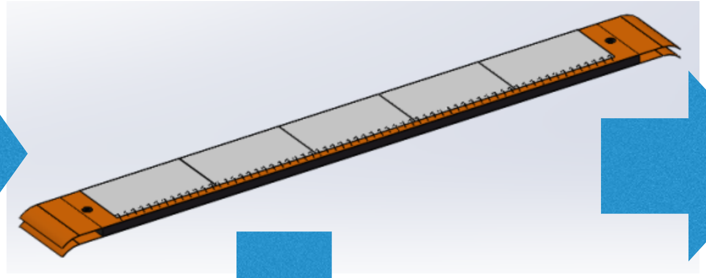
FROM SENSOR TO VERTEX DETECTOR

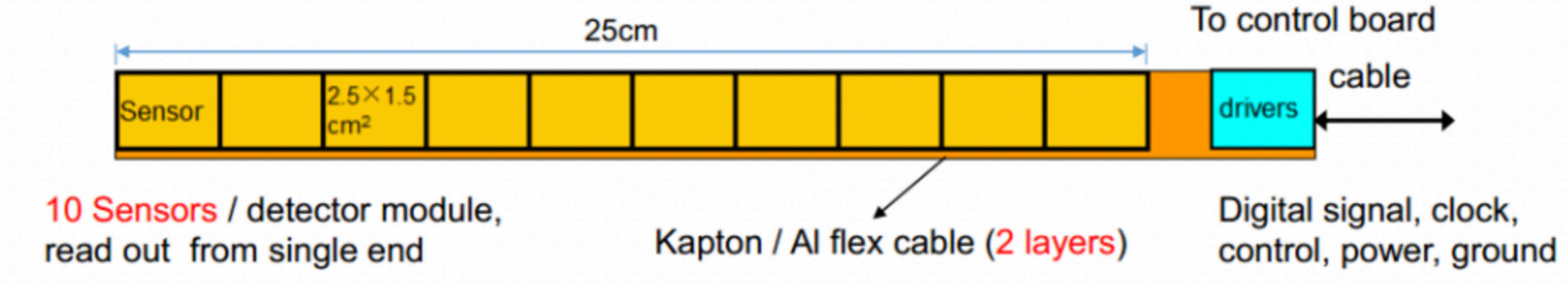
- CMOS sensor R & D is the first step
- Detector layout optimization
- Ladder and vertex detector support structure R & D
- Detector assembly and Data acquisition system R & D

CMOS imaging sensor prototyping

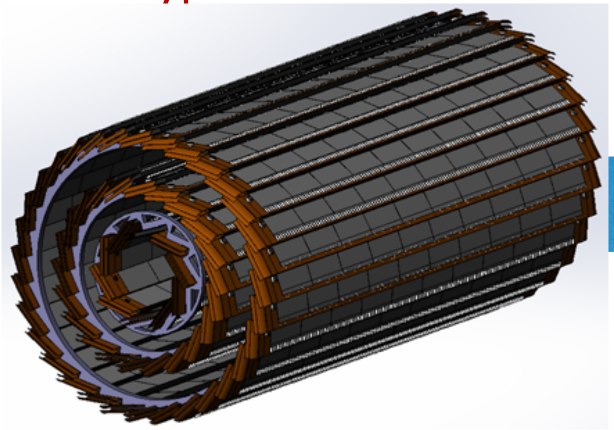


Detector module (ladder) Prototyping

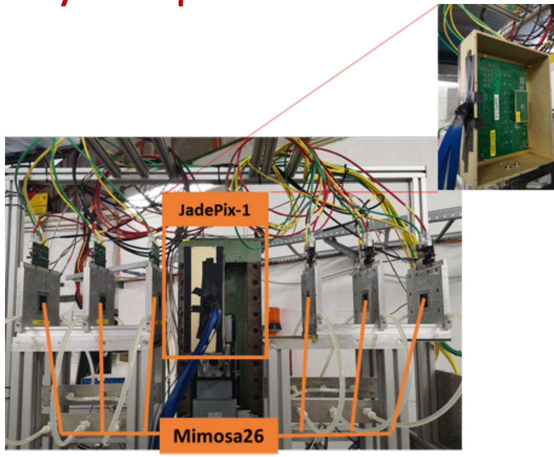




Full size vertex detector Prototype



Beam test to verify its spatial resolution



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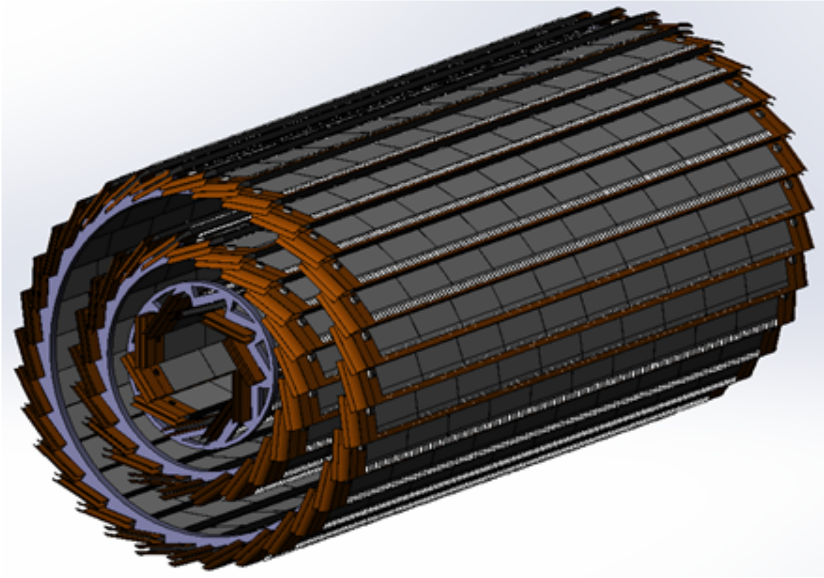
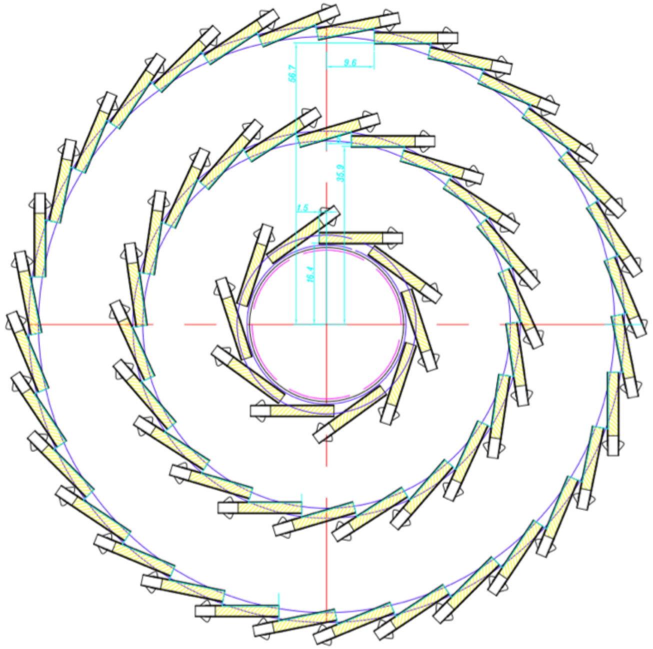
VERTEX DETECTOR PROTOTYPE

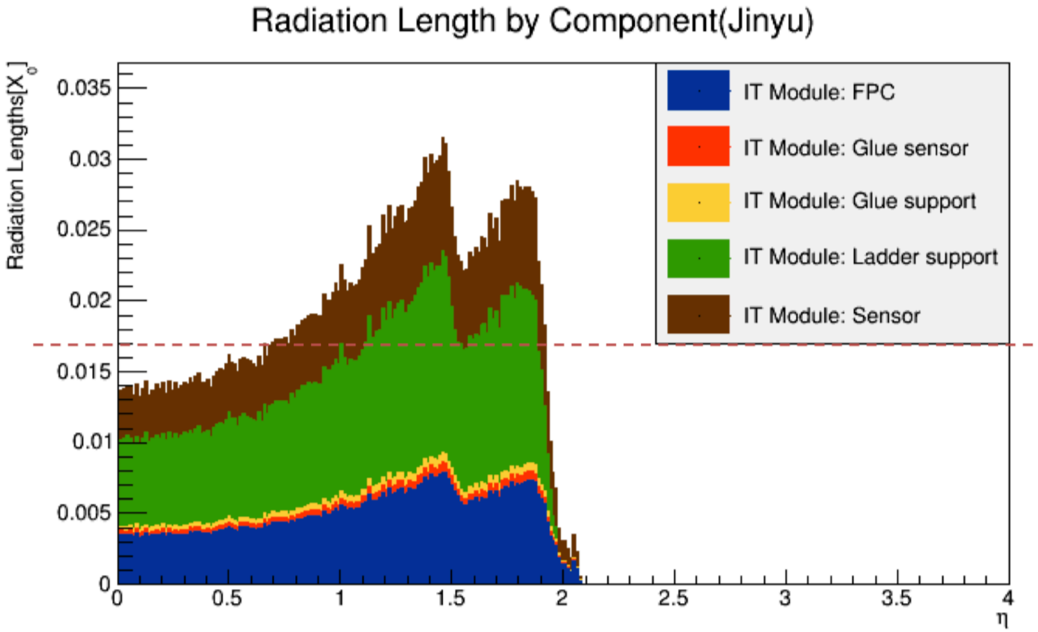
Funded by MOST

- Plan to build full size vertex detector prototype
  - Three double layer vertex detector
  - With Fractions of the modules will be installed
  - Supported by MOST , 12M RMB



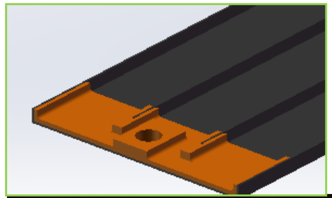
	R (mm)	$\|z\|$ (mm)	$\|\cos\theta\|$
Layer 1	16	62.5	0.97
Layer 2	18	62.5	0.96
Layer 3	37	125.0	0.96
Layer 4	39	125.0	0.95
Layer 5	58	125.0	0.91
Layer 6	60	125.0	0.90

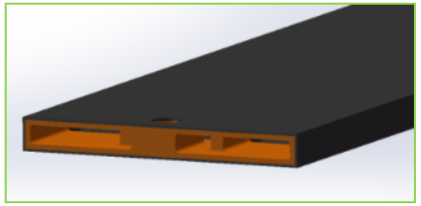


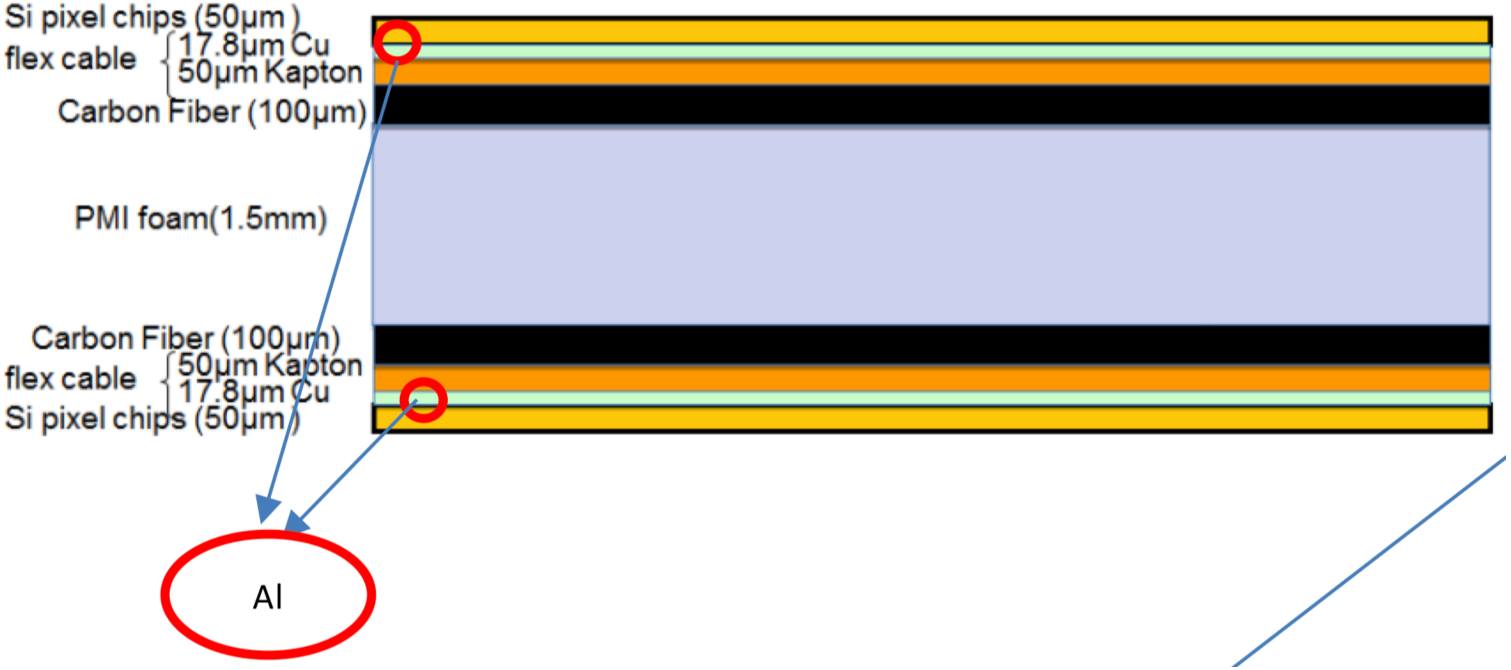


VERTEX DETECTOR PROTOTYPE: LADDER DESIGN

- First draft of CEPC module design:
  - Material budget can barely $0.15\ \%X_0$ per layer
  - Need to be rigid in air cooling, Difficult to reduce material budget
  - First prototype of ladder support
    - 3 layer of carbon fiber, 0.15mm thick
    - 3 time thinner than conventional carbon fiber

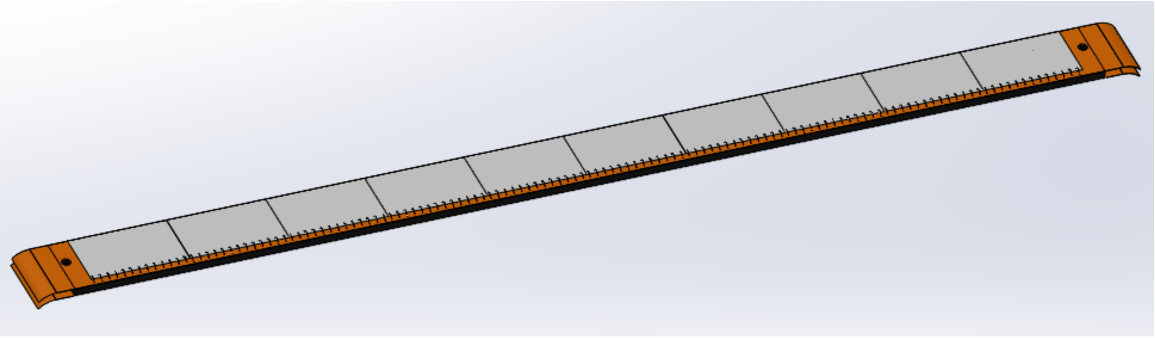




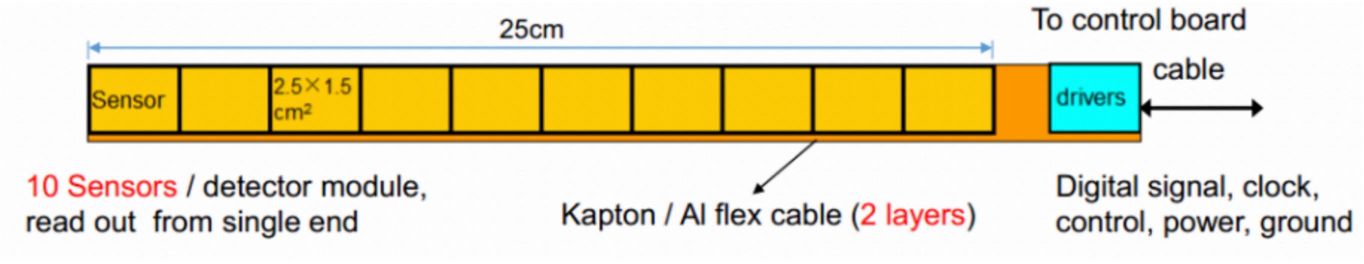


VERTEX DETECTOR PROTOTYPE: LADDER DESIGN (2)

- Completed preliminary version of detector module (ladder) design
  - Detector module (ladder)= 10 sensors + support structure+ flexible PCB+ control board
  - Sensors will be glued and wire bonded to the flexible PCB
  - Flexible PCB will be supported by carbon fiber support structure
  - Signal, clock, control , power, ground will be handled by control board through flexible PCB



Gantry automatic module assembly



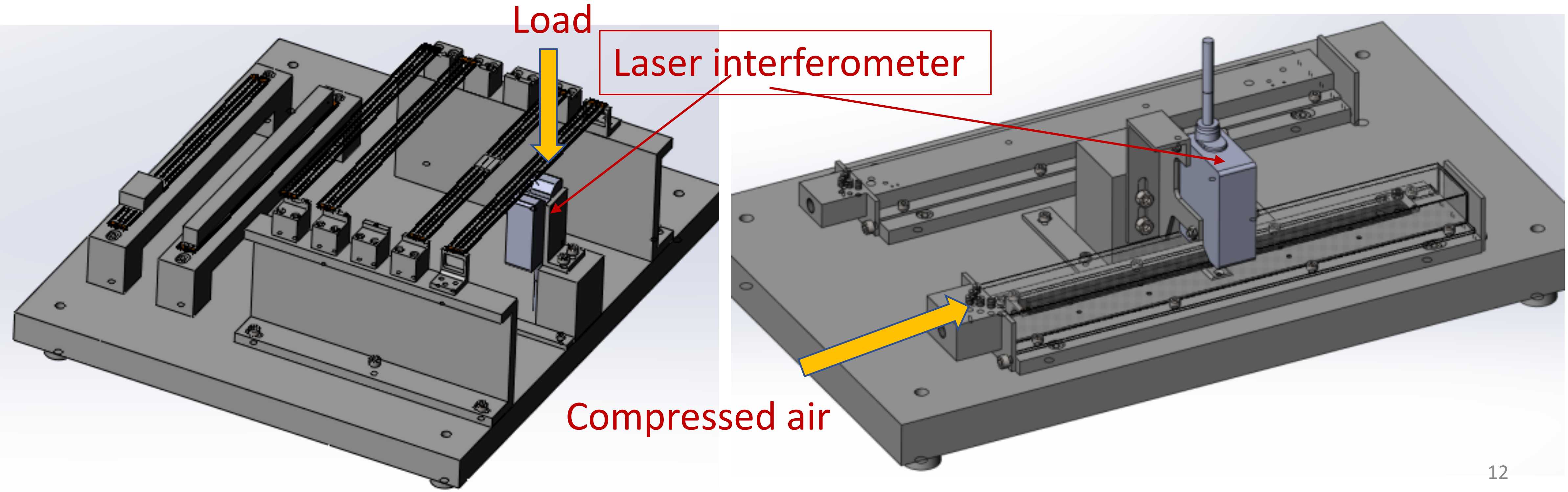
	Achieved Thickness (μm)	Optimization goals (μm)
Polyimide	25	12
Adhesive	28	15
Plating Cu	17.8	17.8
kapton	50	50
Plating Cu	17.8	17.8
Adhesive	28	15
Polyimide	25	12

LADDER MECHANICAL TESTING

- Detailed designs of platform and tooling for different test.
  - ➢ Static (different support and load cases)
  - ➢ Vibration and cooling + pressed air (different cases):
    - ➢ Measure Deformation, temperature, air speed, flow rate, etc.
  - ➢ Goal: Measure vibration to 1µm level with air cooling with laser interferometer

Static mechanical test

Vibration and cooling test

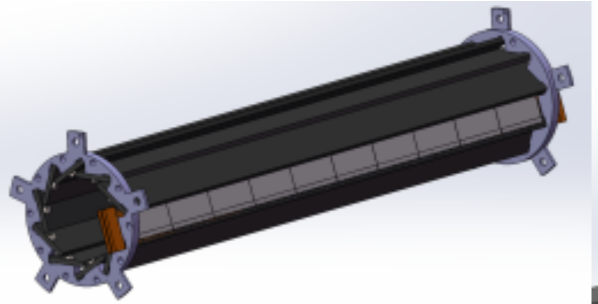


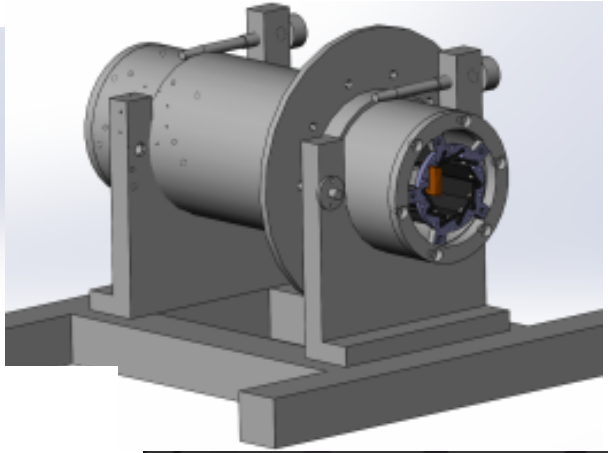
Design of vertex detector prototype installation

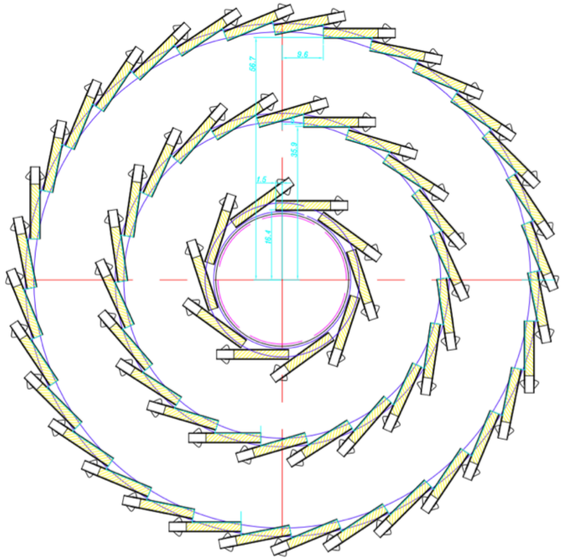
- 64 ladders will be installed in vertex detector prototype
- Dedicated global detector support for whole vertex detector has been designed
- Installation tool and procedure has been designed

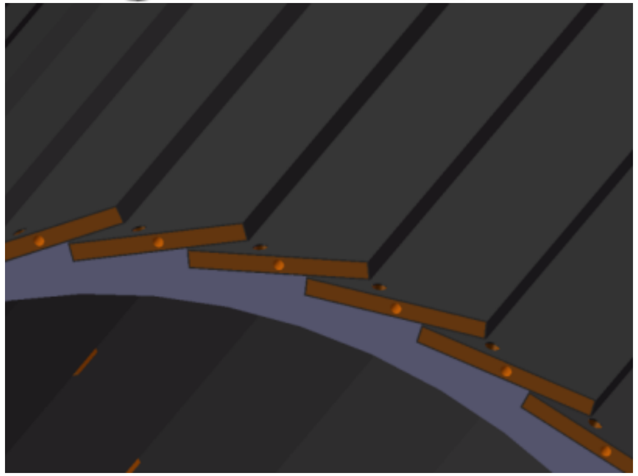
Middle barrel and tooling

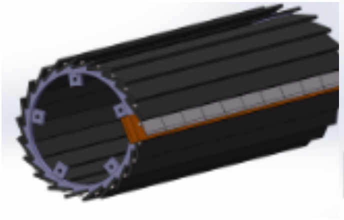
Inner barrel and tooling

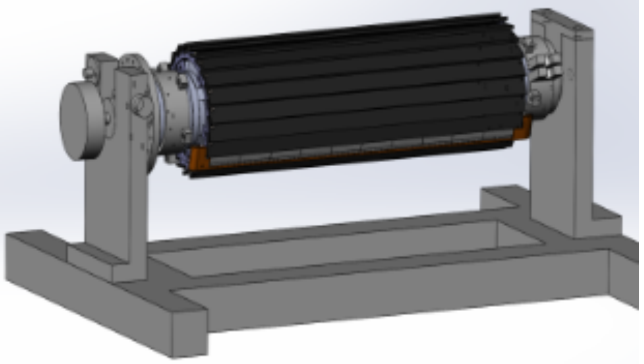




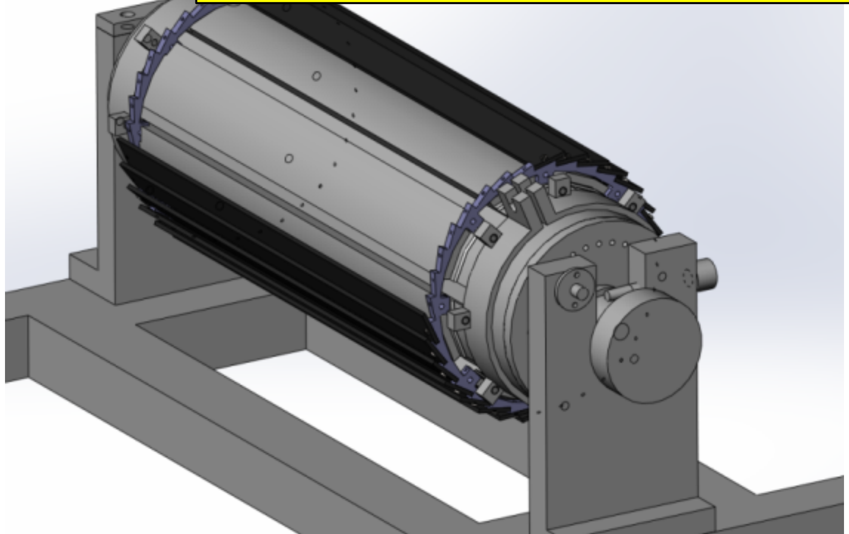






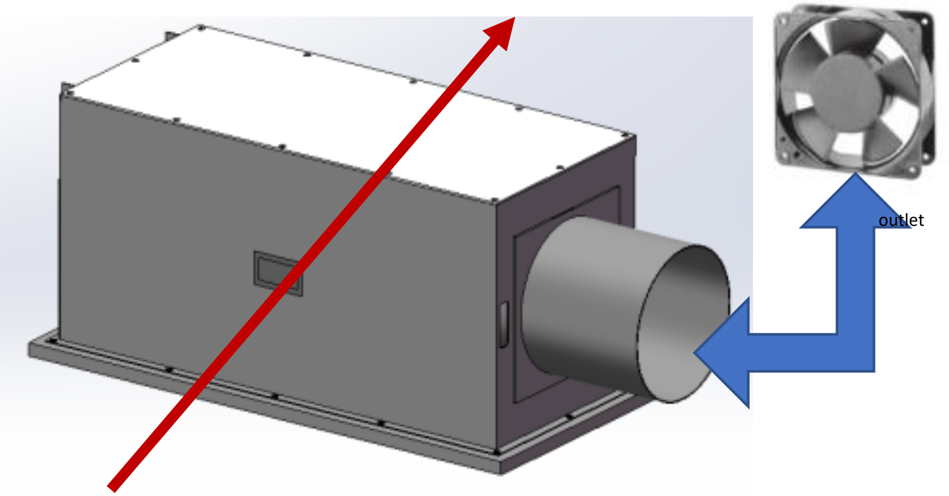


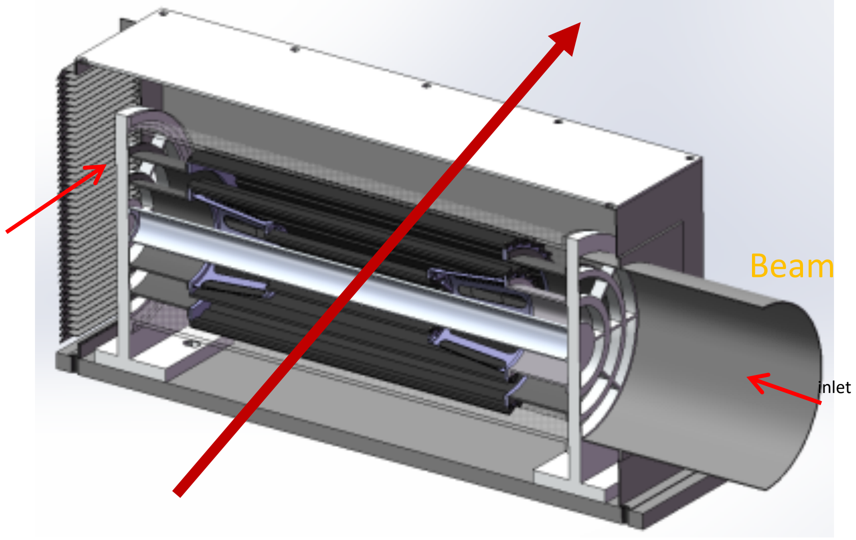
Outer barrel tooling

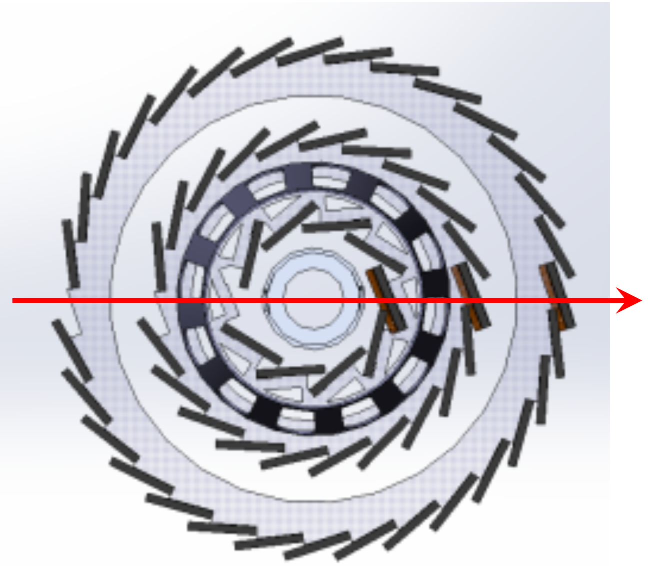


PLAN FOR TESTBEAM

- Expect to perform beam test in DESY(3 - 7GeV electron beams)
  - IHEP test beam facility as backup plan (a few hundreds MeV electrons)
- Enclosure for detector with air cooling is developed for beam test
  - Beam is shooting at one sectors of vertex detectors



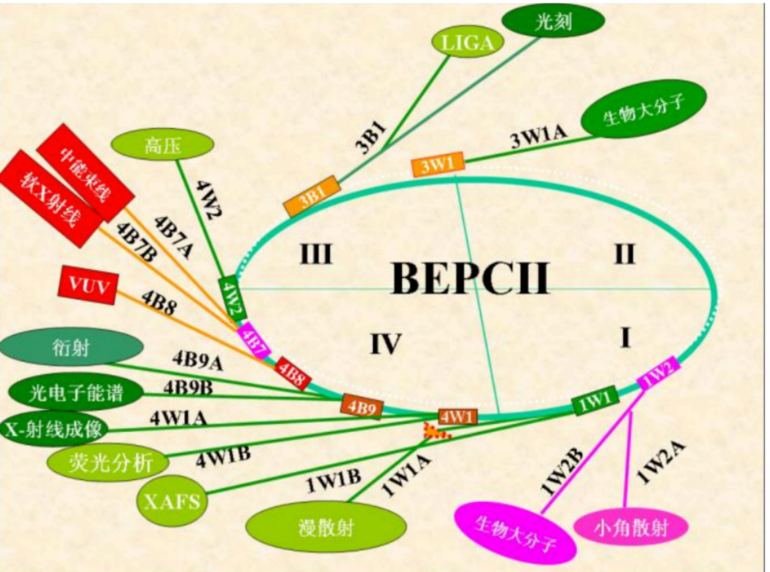


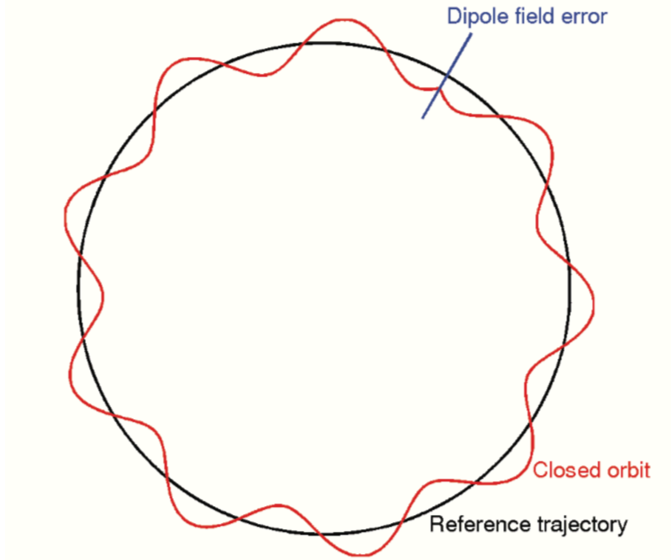


Plan for Testbeam (2): new opportunity at BSRF

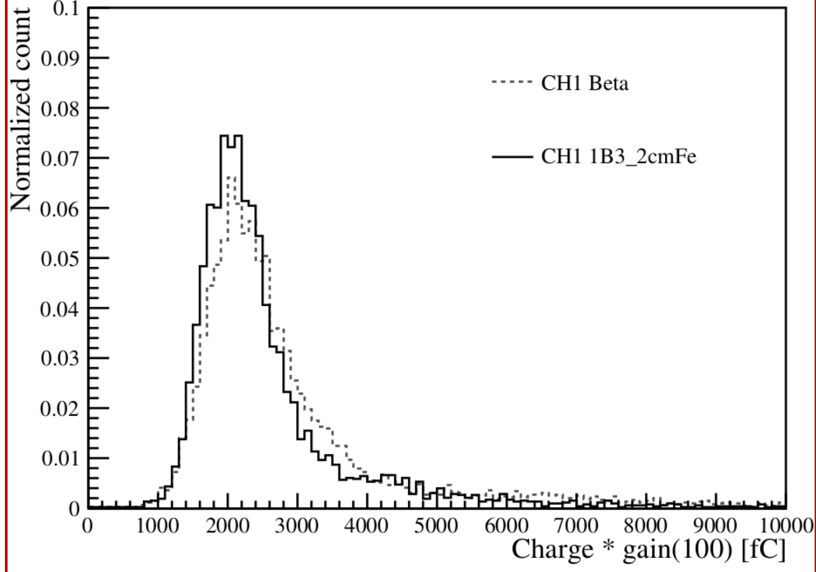
- New opportunity in Beijing Synchrotron Radiation Facility (BSRF)
  - High energy electron (1~2.5 GeV) leakage from BEPC
  - High trigger rate (up to 50Hz/cm^2)
  - Can be used to vertex detector position resolution

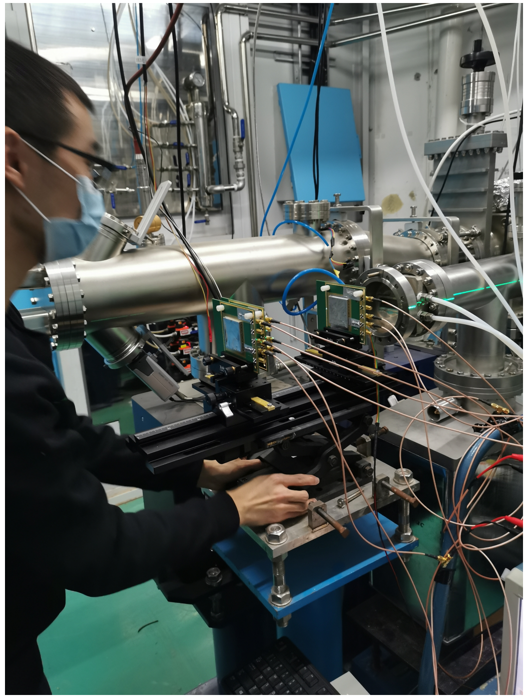
	DESY	IHEP E3 beam	BSRF
Momentum	1-6 GeV	<1 GeV secondary beam	1~2.5 GeV
Particles	electrons	Protons/ Pions/ /Electrons	electrons
Trigger rate	4000 Hz/cm^2	0.6 Hz/cm^2	~50 Hz/cm^2





Charge deposition in Beta tests
And Beam tests in BSRF





SUMMARY

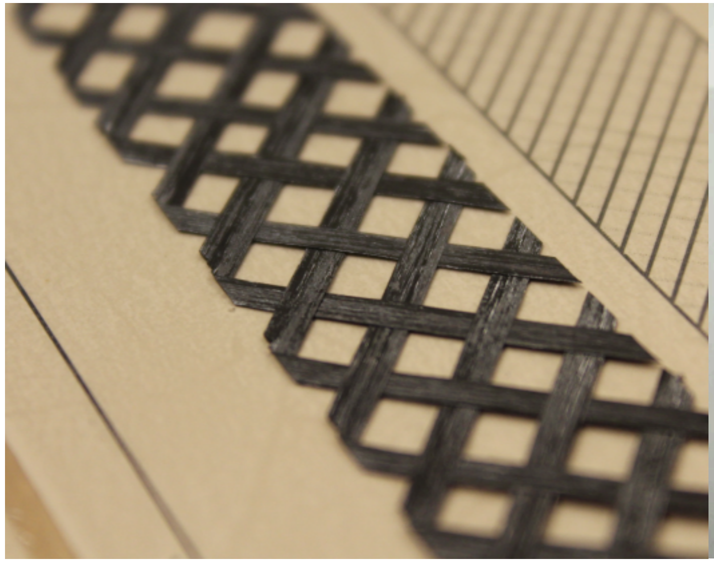
- Lots of R & D activities for CEPC vertex detector
- Sensor prototype has been fabricated and tested
  - More details in Wei and Yupeng's talks.
- Full-size three double layer vertex design prototype is under development
  - Ladder support has been designed and fabricated.
  - Global detector support for whole vertex detector has been designed
  - Plan for test beam has been presented

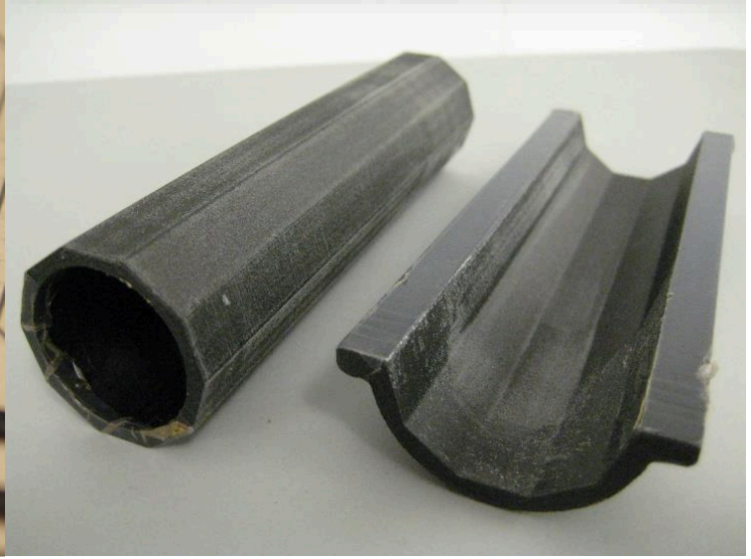
VERTEX DETECTOR PROTOTYPE

- IHEP has experience on building single-side modules
  - R & D module assembly scheme for double-side modules
- Collaboration with Livepool on detector support structure
  - New idea from Livepool of the ladder structure reinforcement.
  - Produce sample and test them in next step

Single-side HRCMOS pixel module for BESIII

Idea about the detector support structure





DETECTOR REQUIREMENT

- Requirements:
  - Constraints from physics (similar to LC …. more or less)

From F. Bedeschi's talk in Last CEPC workshop

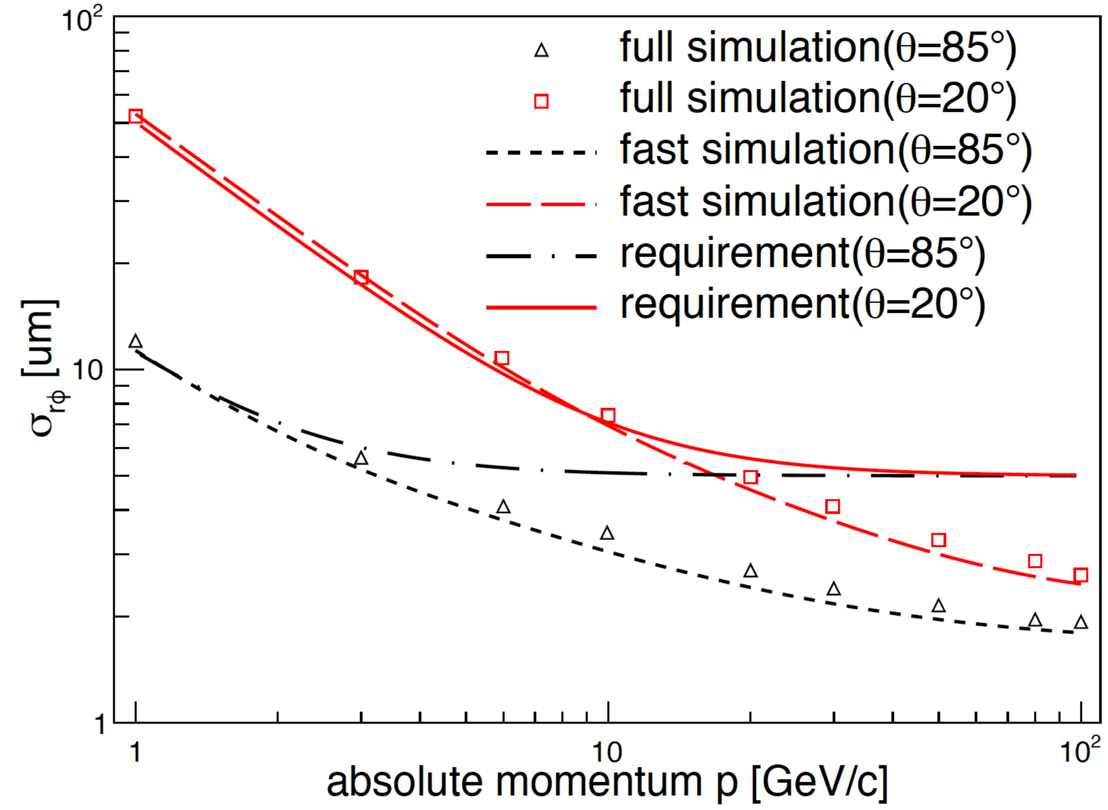
Physics process	Measurands	Detector subsystem	Performance requirement	From CDR
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$	Too tight?
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$	Not enough?
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E = 3 \sim 4\%$ at 100 GeV	Too tight?
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$	Not enough?

- Additional constraints
  - Excellent acceptance and luminosity control
  - PID & π^0 ID for HF/τ physics
  - Low B field to avoid emittance blow up
  - Power pulsing not allowed

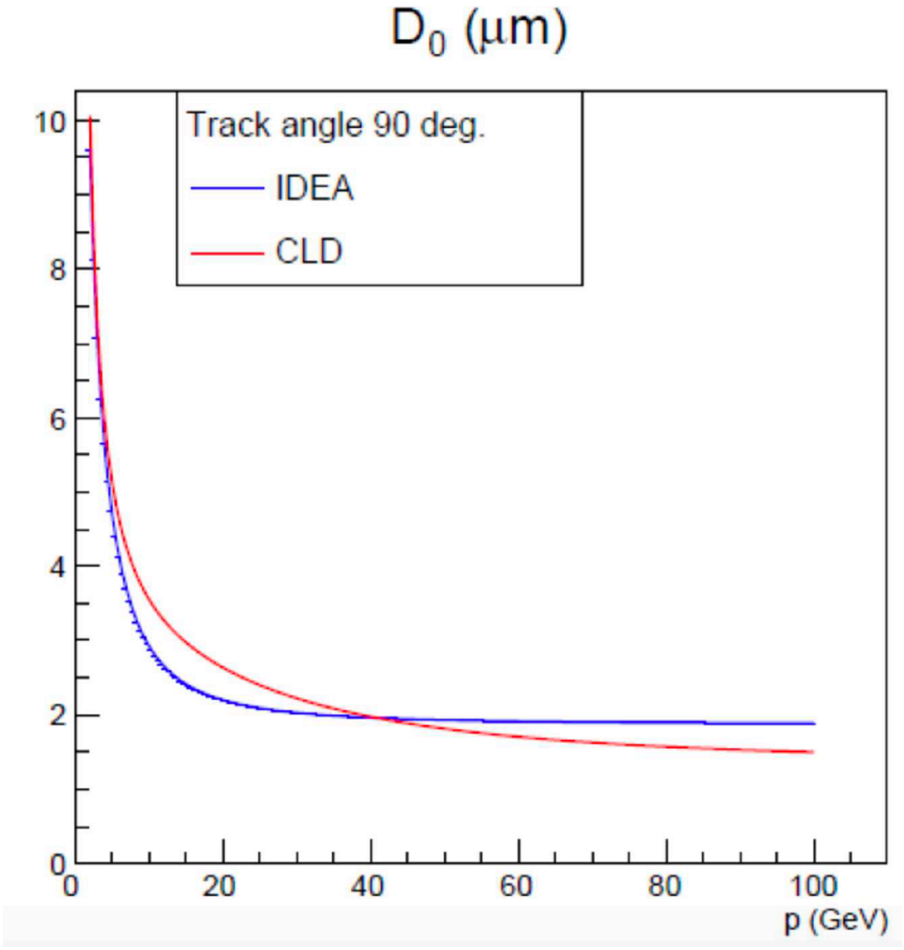
Not present at LC

CEPC Detector Conceptual Designs

CEPC baseline detector
(Inspired by ILD detector design)



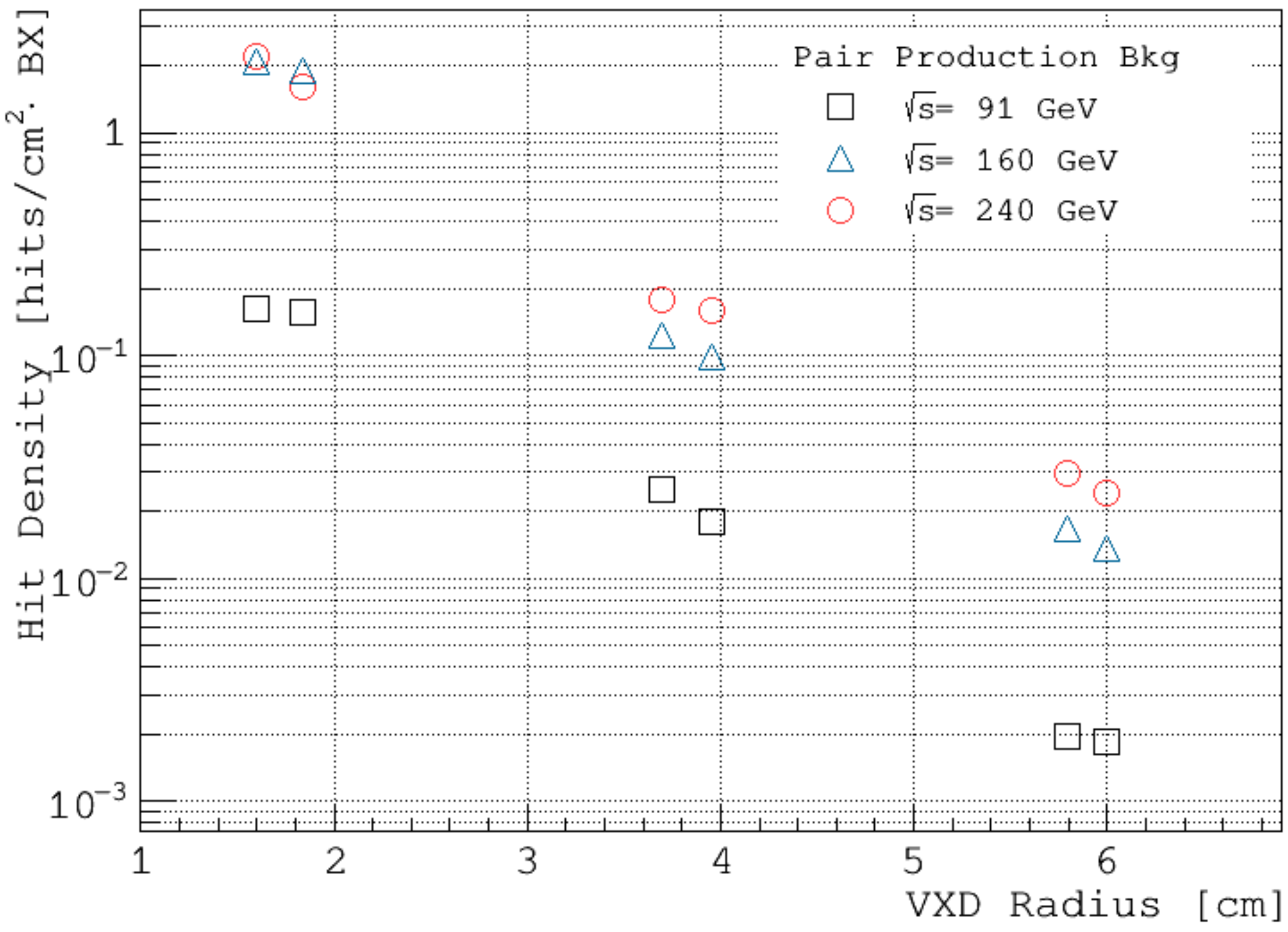
Fcc-ee detector
(Franco Bedeschi 's talk in Fcc workshop)



REQUIREMENT ON RADIATION HARDNESS

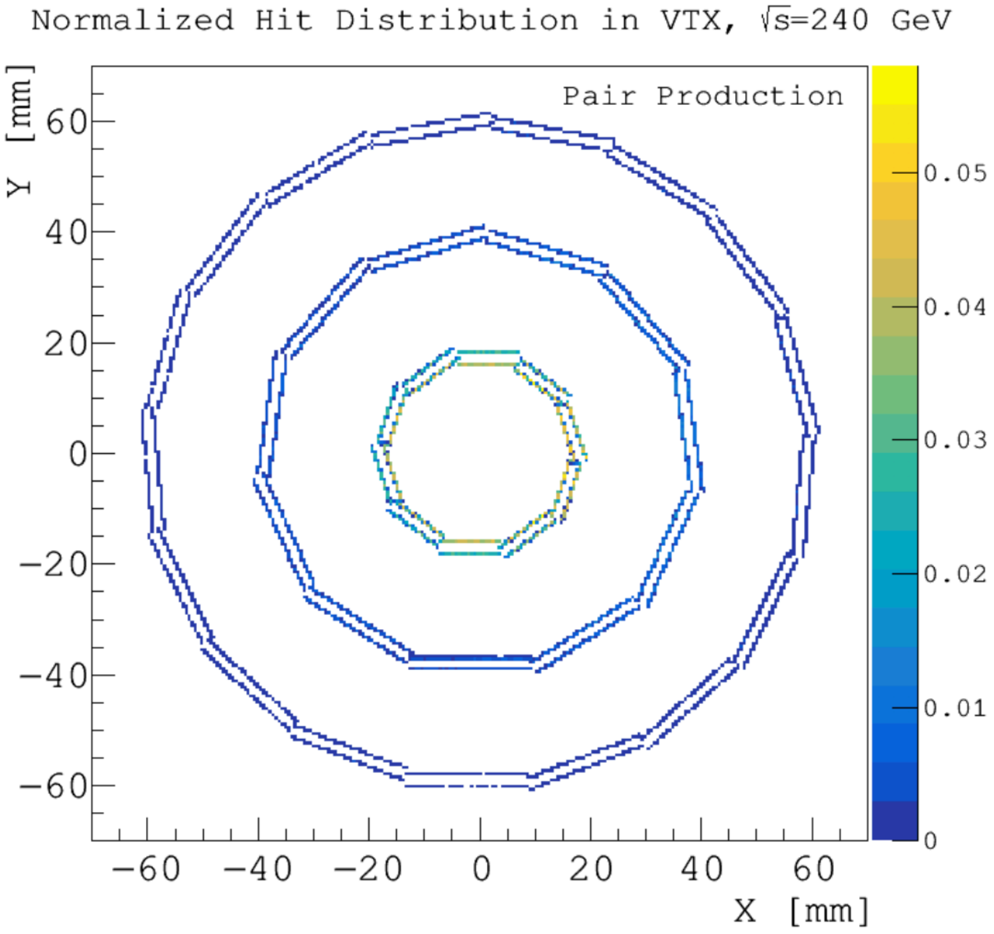
- Bunch spacing
  - Higgs: 680ns; W: 210ns; Z: 25ns
  - Meaning 40M/s bunches (same as the ATLAS Vertex)
- Hit density
  - 2.5hits/bunch/cm^2 for Higgs/W; 0.2hits/bunch/cm^2 for Z
- Cluster size: 3pixels/hit
  - Epi- layer thickness：~18μm
  - Pixel size：25μm×25μm

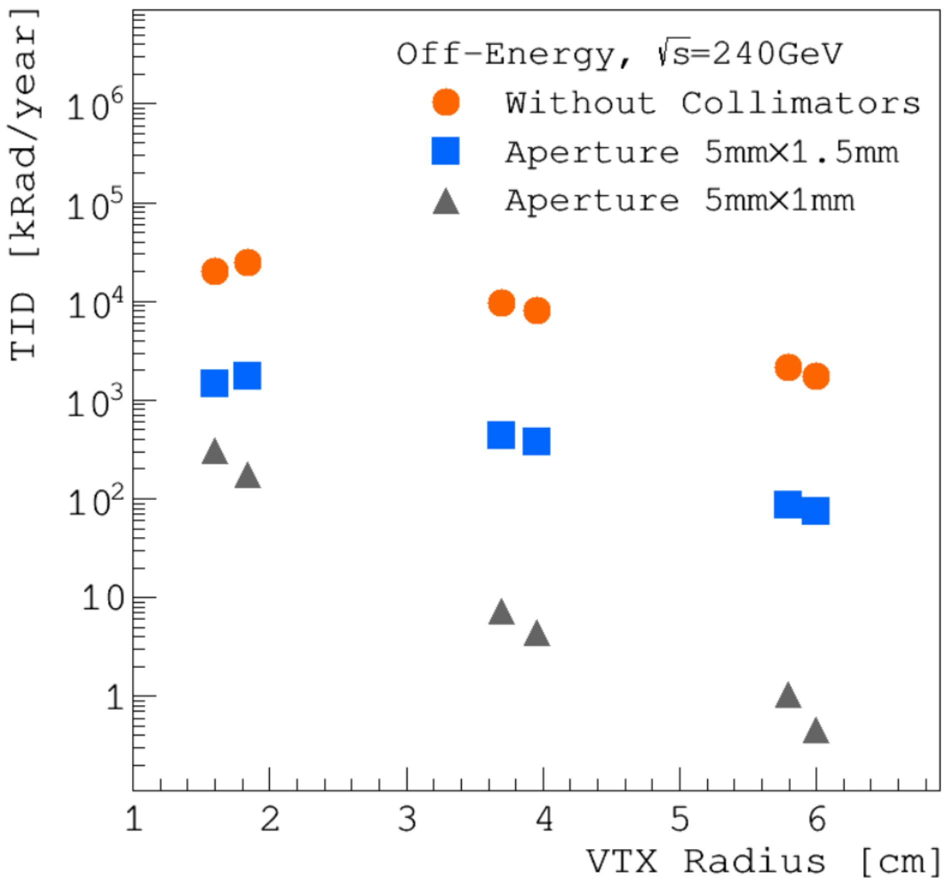
From the CDR of CEPC



Requirement on radiation hardness

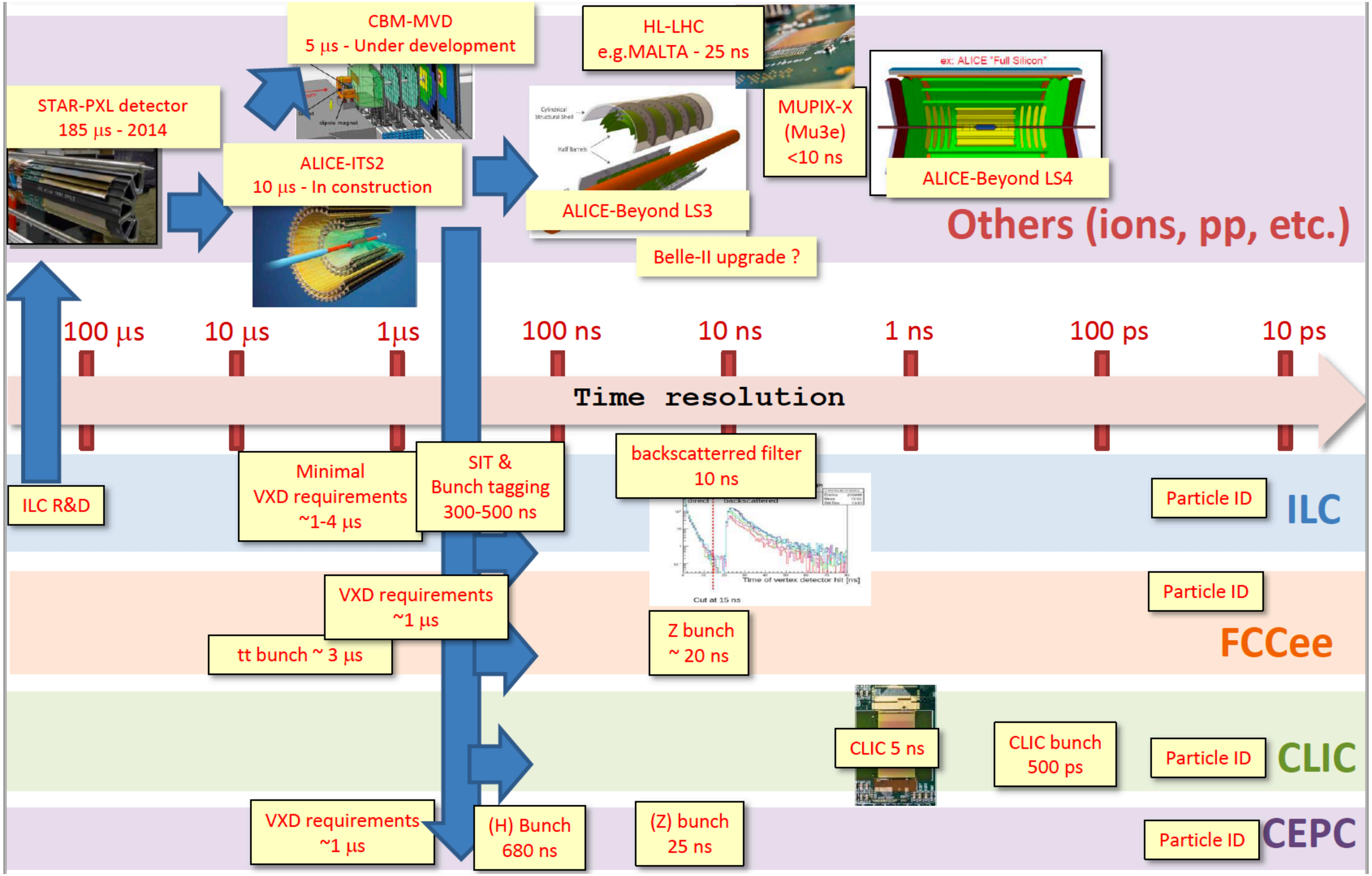
- Radiation tolerance **(per year):** 1 MRad &2×10^{12} 1 MeV n_{eq}/cm^2





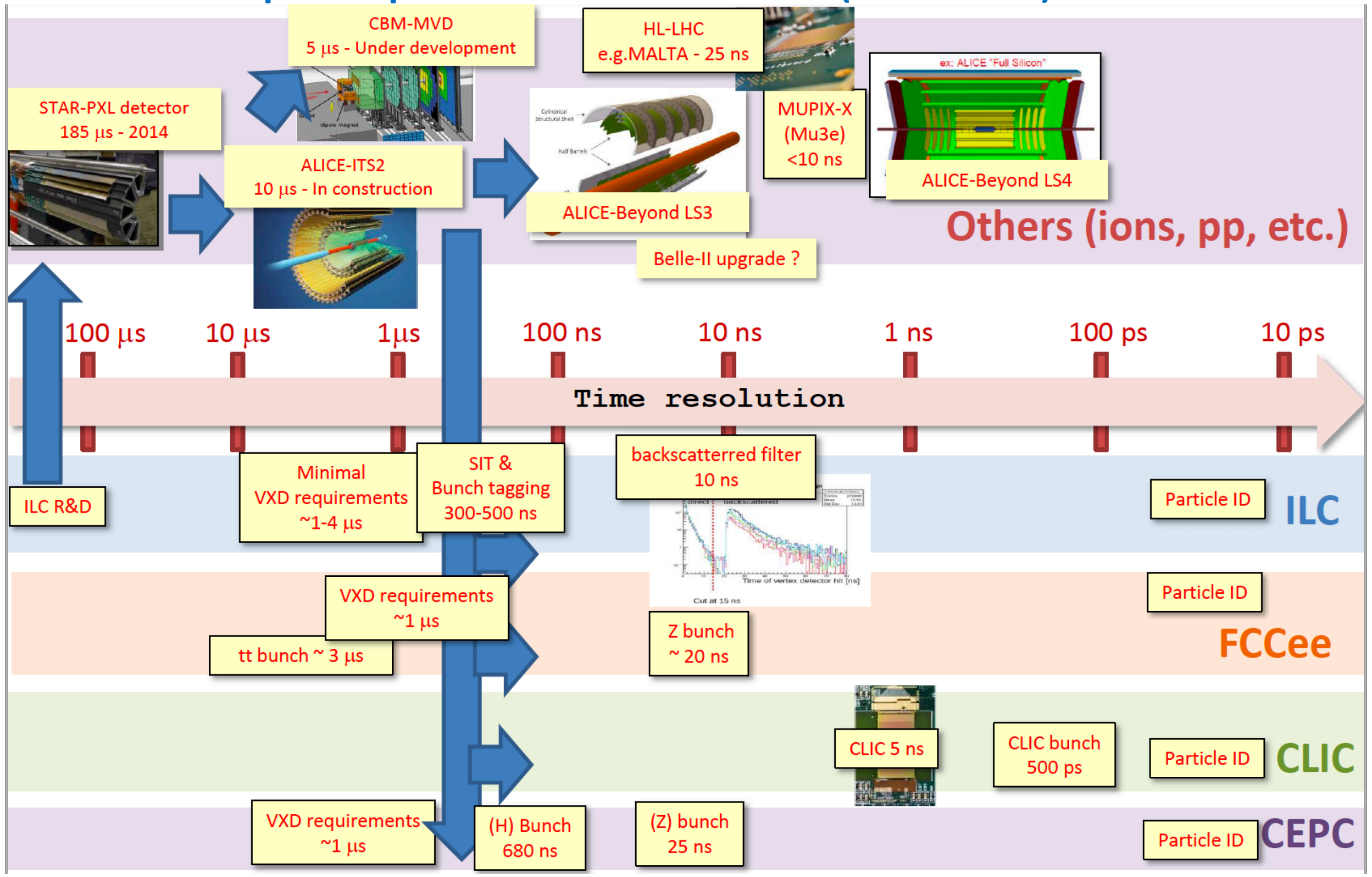
Requirement on timing

From Auguste Besson's talk in Fcc workshop



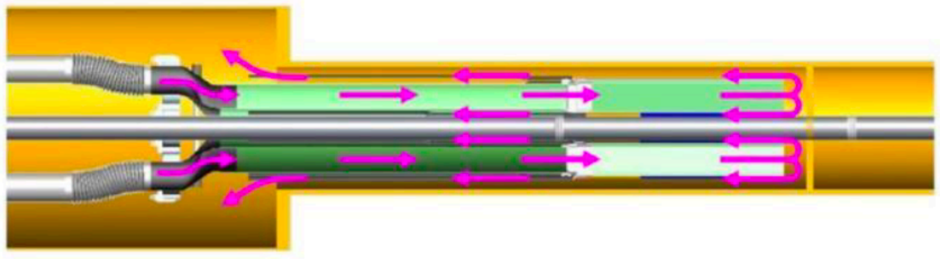
REQUIREMENT ON TIMING

- Bunch crossing rate at Z pole: ~40MHz (every 25ns)
- Signal rate at Z pole is about 20kHz (about one event every 50μs)
- Time stamp resolution goal : 25ns (identify bunch in Z pole runs)
- Readout time target: 10μs (CEPC pre-CDR) → 100~500 ns (new goal for CEPC and Fcc-ee)
- To avoid pileup of two Z events (<0.01%) and for Z event shape study



Requirement on power consumption and cooling

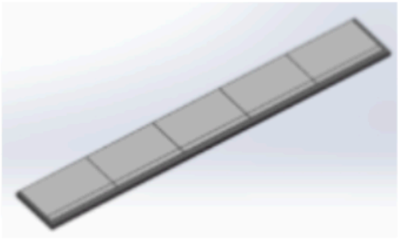
- To reduce material budget, air cooling is prefer in lepton collider
- How much power consumption can air cooling handle ?
  - Most of us consider the upper limit is about $25mW/cm^2$
  - Star HFT detector managed to cool $150mW/cm^2$
    - One of the key is without endcap disk in Star detector
    - Air flow can be much larger (10m/s) without endcap



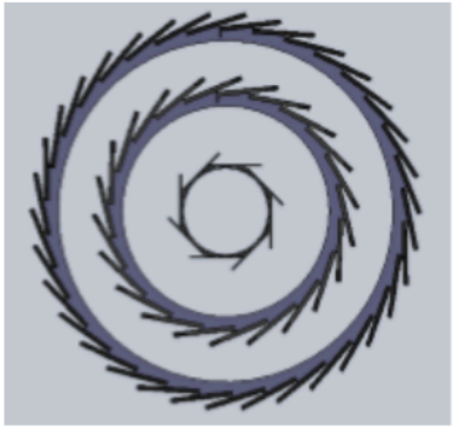
The STAR MAPS-based PiXeL Detector NIM, A 907 (2018) 60-80

VERTEX DETECTOR WITHOUT ENDCAP ?

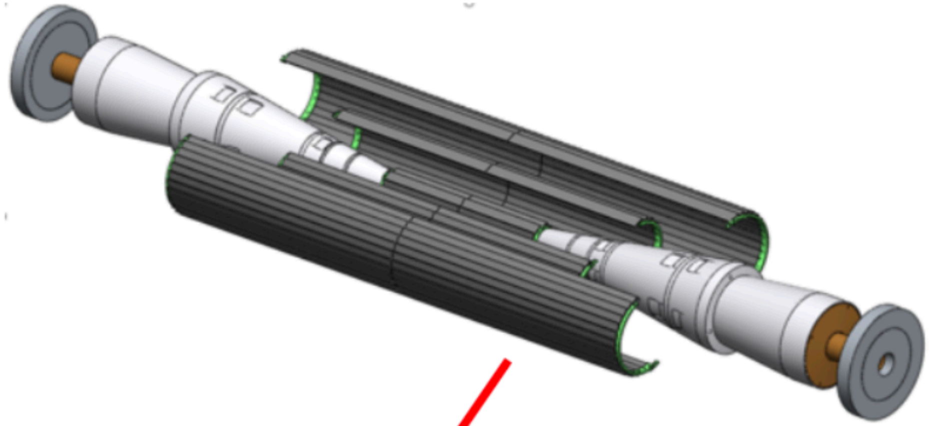
- Long barrel without endcap design can have good air cooling performance
- First design draft from Quan Ji



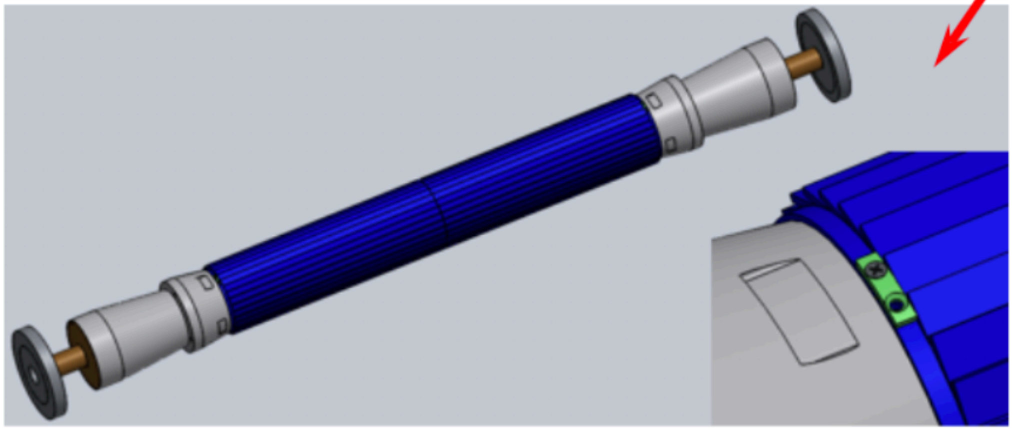
Detection unit



Ring arrangement



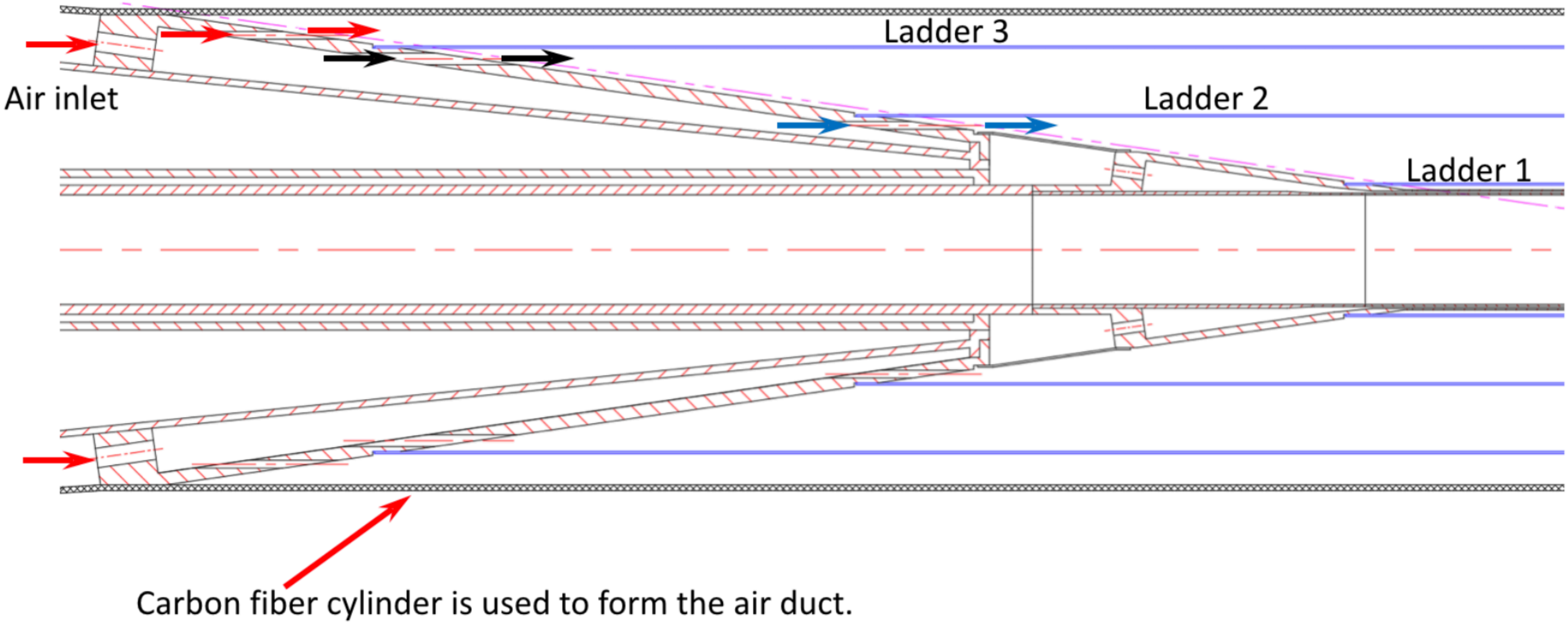
Half ring structure



Vertex detector without endcap ?

- Long barrel without endcap design can have good air cooling performance

1) Silicon Vertex Detector --- air cooling design



SUMMARY

- Requirement on vertex detector
  - Single point resolution < 3 μm → small pixel pitch, e.g. 16 μm
  - Material budget 0.15%X_0 per layer→ thin & low power 50 mW/cm^2
  - Detector occupancy below 0.5% @40MHz at Z pole → <500ns deadtime
  - Radiation tolerance **(per year):** 1 MRad &2×10^{12} 1 MeV n_{eq}/cm^2