CEPC Vertex Detector Mechanics and Cooling

Jinyu Fu on behalf of the CEPC VTXD group
Institute of High Energy Physics, CAS
The International Workshop on CEPC, Guangzhou
November 7, 2025

Feature and challenge

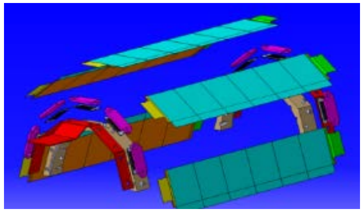
CEPC vertex detector (VTXD) features

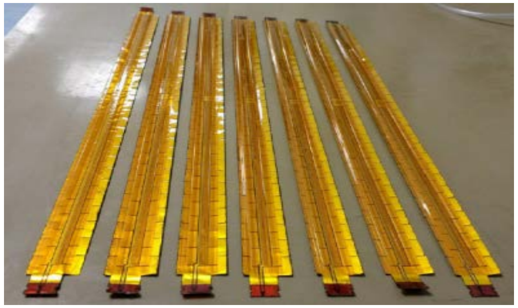
- ✓ Low material budget - 0.15% X/X_0 for a single layer
- ✓ High spatial resolution 5 μm
- ✓ Air cooling

Challenges to the mechanical design

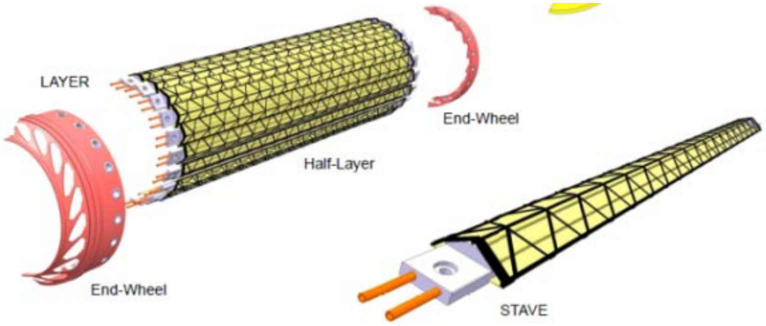
- Ultra-light support with robust mechanical performance

Mu3e (0.1% X/X_0)





Alice ITS Upgrade(0.3% X/X_0)

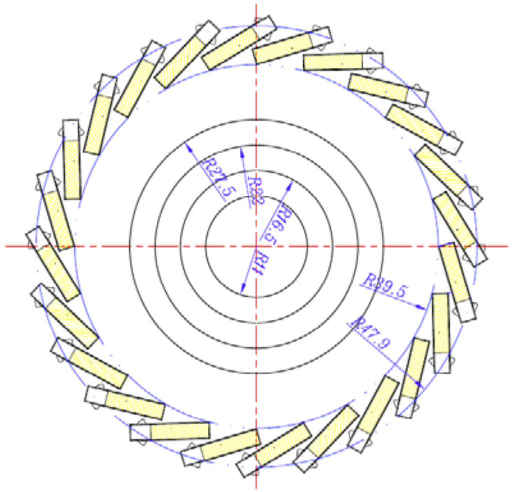


These two experiments both have silicon sensors on one side of the support.

Layout of the VTXD

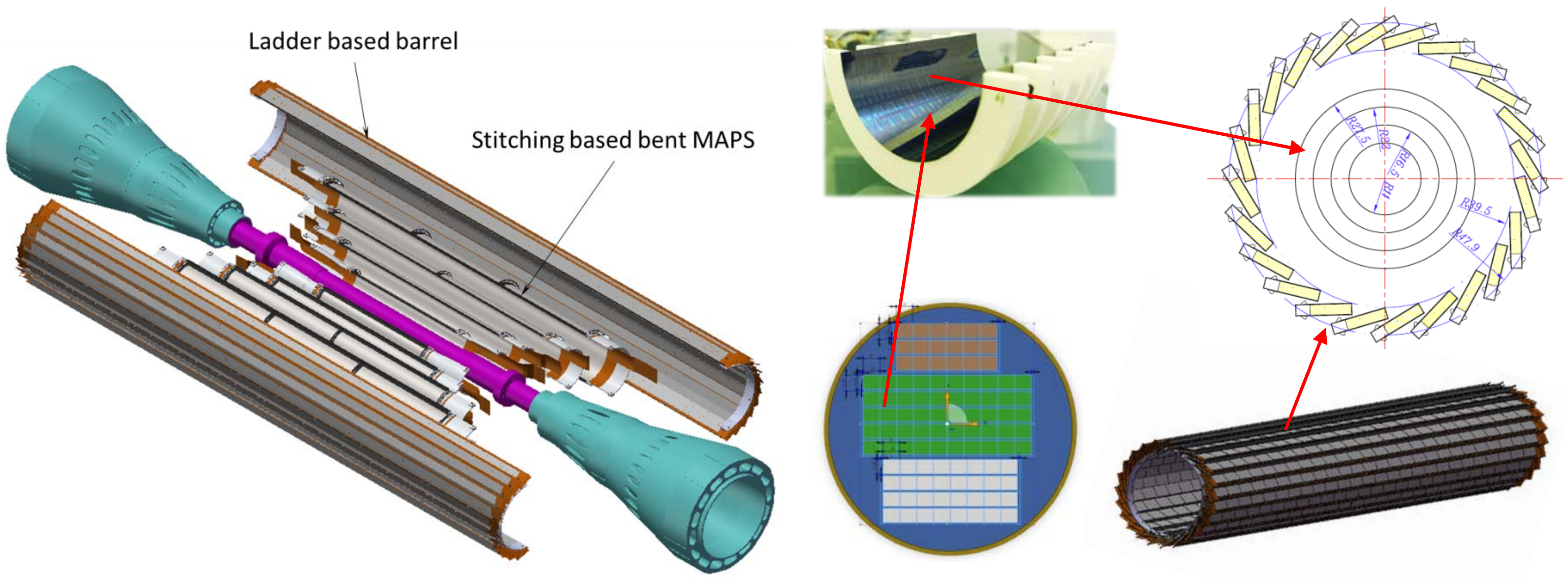
Baseline design

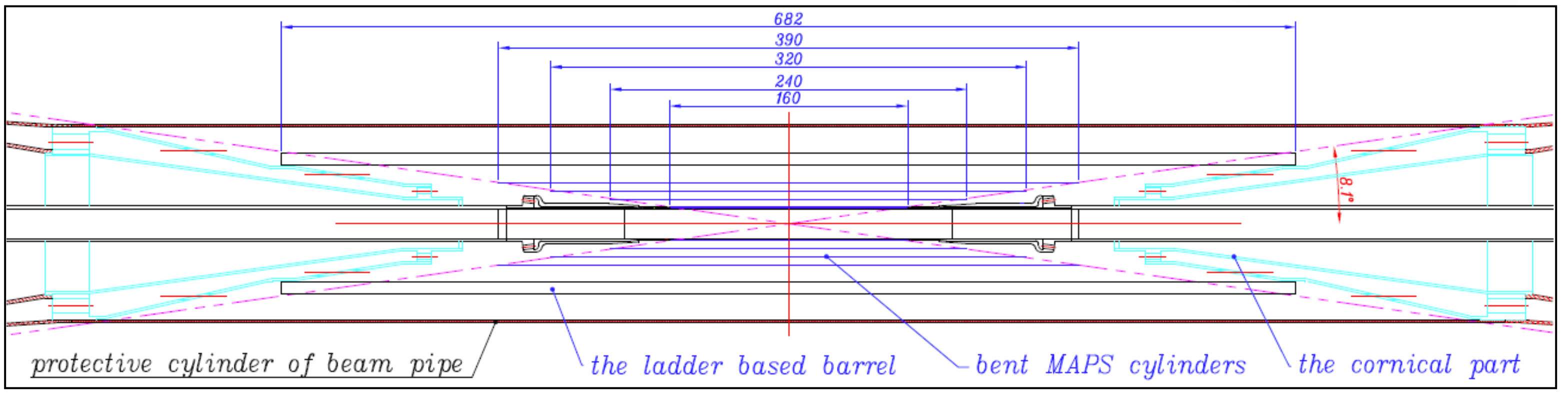
- 6 layers detector with acceptance coverage $\cos\theta=0.99$
- Inner four layers
  - ✓ Stitching tech based bent MAPS (*Monolithic Active Pixel Sensor*) cylinder
  - ✓ Low material budget per layer
- Outer two layers:
  - ✓ Flat MAPS based double-sided ladder (overlapped deployment)
  - ✓ No dead area



layer	Radius(mm)	Length(mm)
layer1	11	160
layer2	16.5	240
layer3	22	320
layer4	27.5	390
layer5/6	39.5-47.9	668

General structure of the VTXD





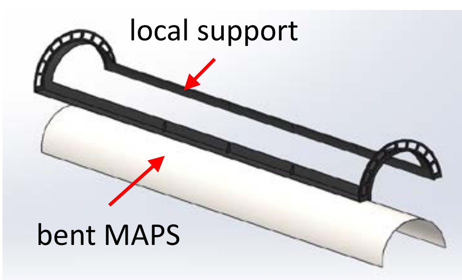
Stitching-based bent MAPS cylinders

The 4 layers of bent MAPS cylinders

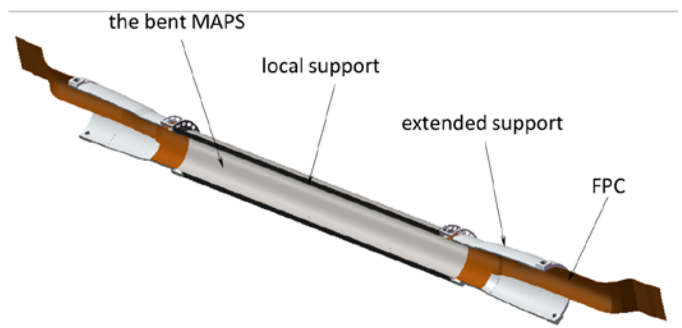
- Each formed by two half cylinders
- Half cylinder assembled by the MAPS and local support
- One bent MAPS for layer1, two pieces connected in Z direction for Layer2~layer4
- Wafer t= 40 µm, local CFRP support t=0.12~0.15 mm

layer	Radius (mm)	Length (mm)	CFRP Equivalent thickness (mm)
layer1	11	160	0.057
layer2	16.5	240	0.034
layer3	22	320	0.032
layer4	27.5	390	0.04

The inner cylinder



A half cylinder assembly (layer1)

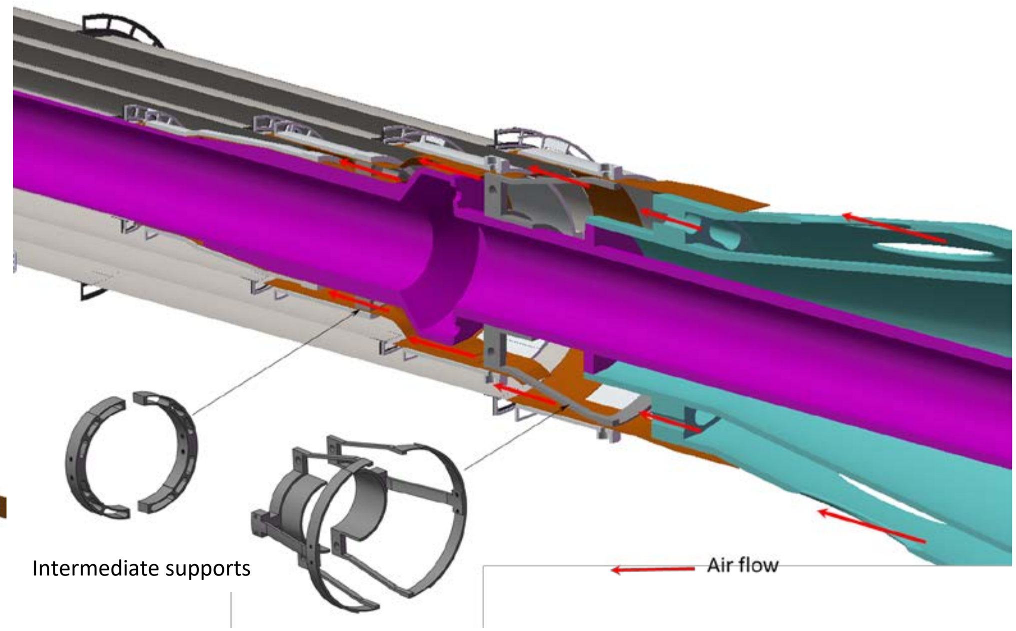


The half cylinder assembly (integration of the half cylinder, extended supports and FPCs)

- FPCs (flex printed circuit) connected to the ends of the bent MAPS by wire bonding
- The extended support assembled with the local support to constraint the FPC ends and protect the wire bonds

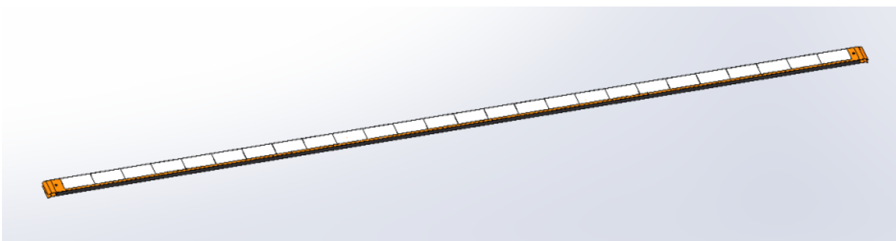
The bent MAPS cylinders installation

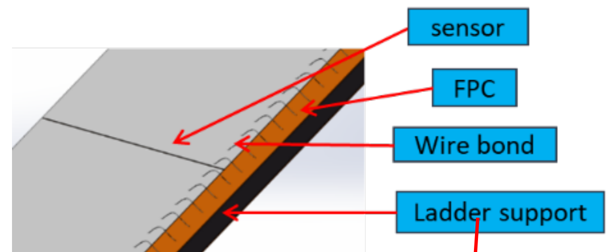
- Each cylinder assembly is independent and separately mounted
- The innermost layer mounted to the BP via its extended supports
- Layers 2-4 employ intermediate supports, layer3 and layer4 share one.
- All intermediate supports are assembled by two parts to facilitate installation.



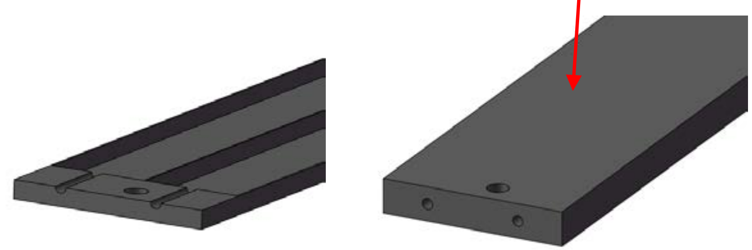
Ladder and support

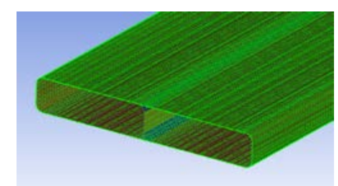
- Ladder components (similar to previous VTXD prototype)





- The ultra-light ladder support
  - Size: 3.2 mm × 17.3 mm × 682mm
  - Material - high modulus CFRP
  - Feasible section design
  - Layup design of laminate
  - Laminate thickness of the shell is 0.15 mm (equal to 0.05 % X/X_0) and *can be further reduced to 0.14 mm.*

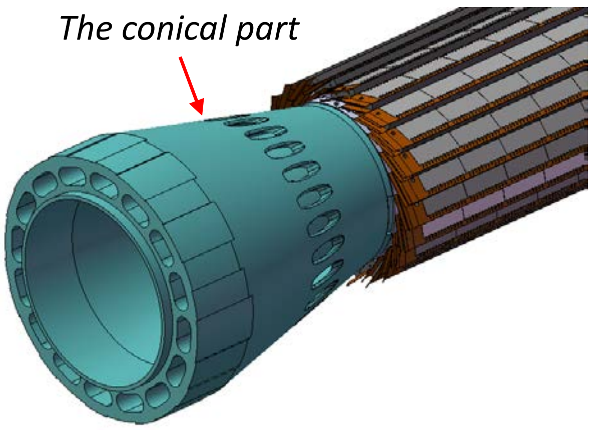


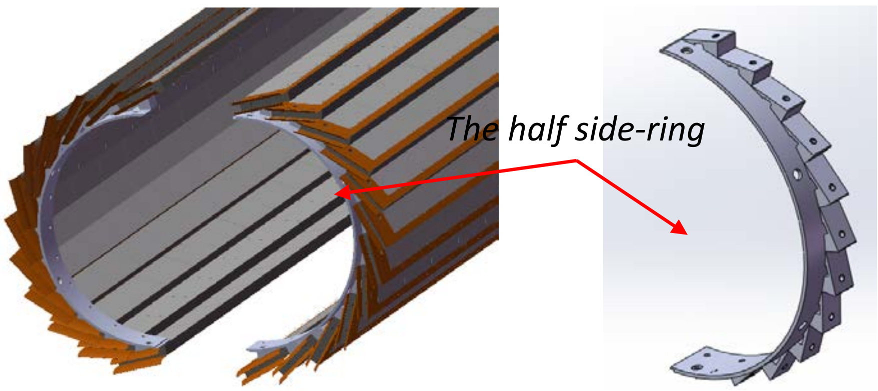


Ladder-based barrel

- **The barrel**: provides hermetic sensitive layers with minimal ladders
  - Consists of two half-barrels
  - Each half barrel assembled by two half side-rings at ends, with ladders connected between them.
  - Ladders are aligned with the serrated faces of the side- ring and secured with screws.

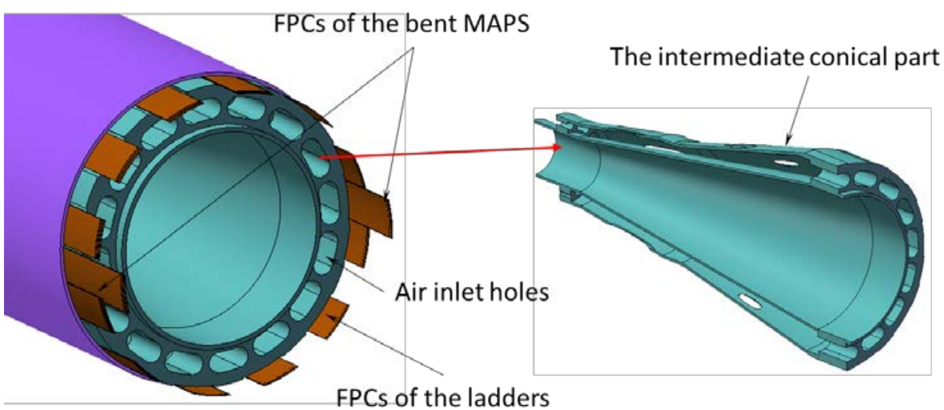
- **Barrel installation on the beam pipe (BP)**
  - Pre-assemble the half barrels
  - Install the half barrels onto the intermediate conical parts, secure them with screws.

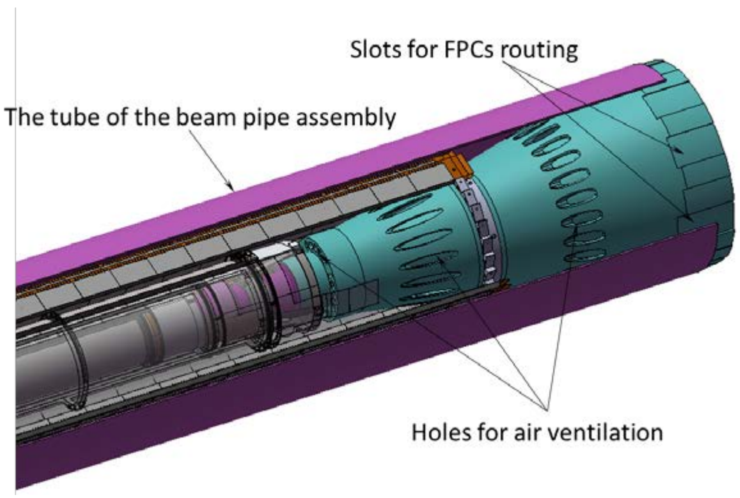




Cable routing and air ventilation

- **All FPCs of the VTXD need to be routed out of the BP assembly**
  (outside the BP assembly the FPCs will be transferred to optical fibers)
  - ✓ **For the stitching layers**: FPCs routed along their extended supports, converged at ends of the outermost layer, then go through the conical part via slots.
  - ✓ **For the ladders/barrel**: converge FPCs of two adjacent ladders into one conduit guided by a frame, then go through the conical part via specified slots.

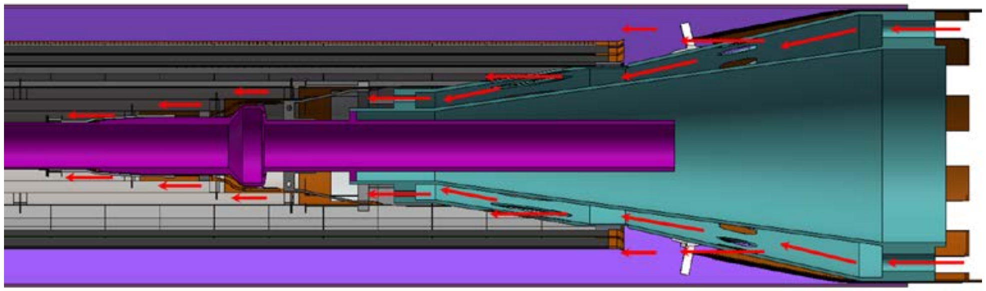




Cable routing and air ventilation

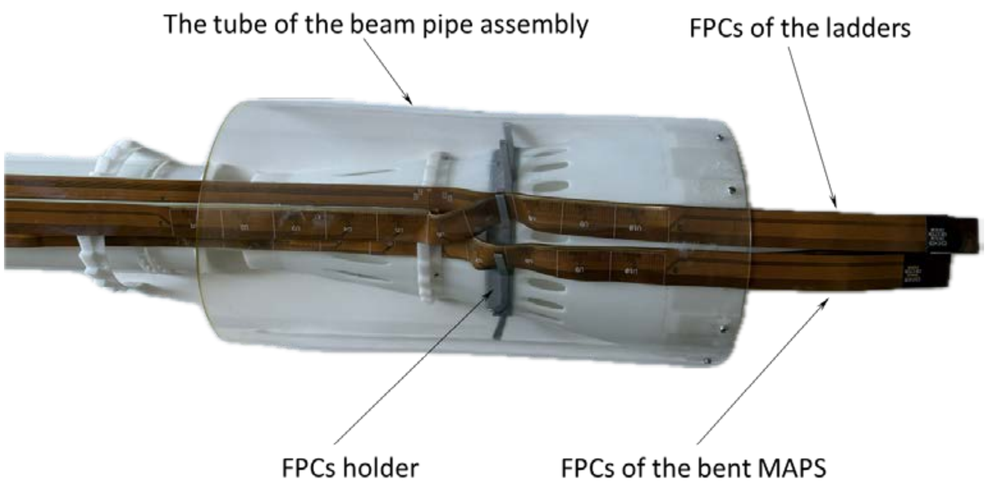
■ **Structural features for enhanced air ventilation**

- ✓ The conical air distributor
- ✓ Slotted holes on the local and extended supports of bent MAPS
- ✓ Slotted and space-frame intermediate supports



□ **FPCs routing test on a half dummy VTXD model**

- ✓ A half-dummy mechanical mockup was constructed.
- ✓ The test demonstrated the feasibility of the proposed service integration approach under realistic spatial constraints.

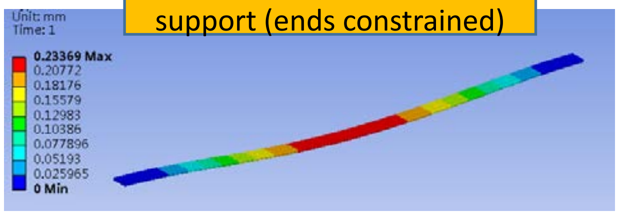


FEA of the ladder and bent MAPS

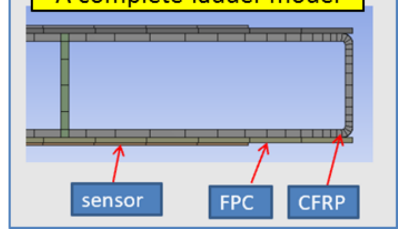
■ The ladder support

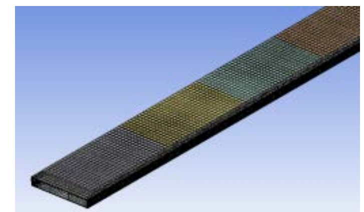
The simulation of the thin-walled structure with a detailed CFRP layup design **resulted in acceptable deformation and very low IRF** (<0.02) under full load including the weight of sensors, FPCs and glue.

Deformation of the ladder support (ends constrained)



A complete ladder model





Previous FEA of the shorter-ladder VTXD prototype showed that a complete ladder deforms 20% lower than the bare ladder support under full load.

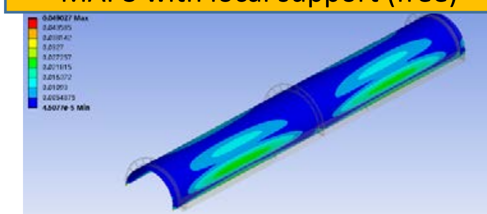
■ The bent MAPS cylinder assemblies.

Multiple configurations to assess structural deformation and chip stress:

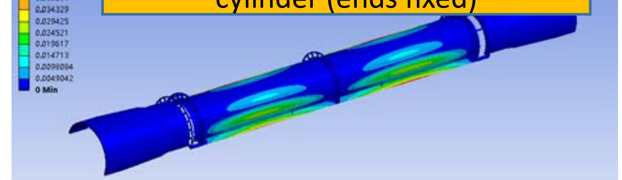
- Top-bottom assembly vs. left-right assembly
- Ends support vs. cantilever support

The results indicate minimal deformation and safe chip stress levels in all cases.

Deformation. of the innermost bent MAPS with local support (free)



Deformation of The innermost cylinder (ends fixed)



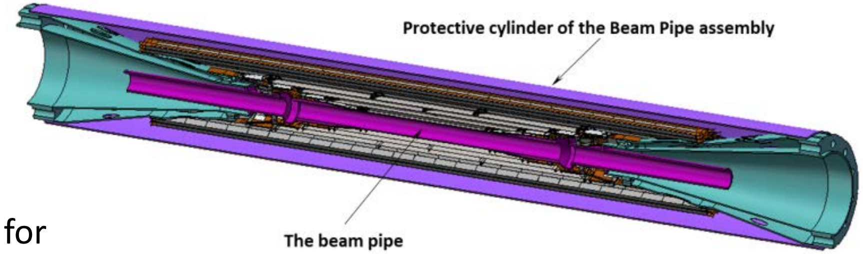
VTXD Cooling

- **Cooling requirement**: detector operating temperature within 30 ◦C
- **Detector power dissipation**
  - ladders: 40 mW/cm^2
  - Bent MAPS: high heat generation on ends
  - Total heat generation: 270 W (barrel~190 W, stitching layers~80 W)

Average dissipation on bent MAPS

Components	Power density [mW/cm^2]
Repeated Sensor Unit	38
Left-end Readout Block	485

- **Cooling method: Forced air cooling**
  - driven by the very stringent low material requirement



- **Cooling simulation conducted** (separately for barrel and cylinders)
  - Inlet air temperature 5 ◦C
  - Beam pipe temperature considered

Simulation results of the ladder/barrel

Air flow(m/s)	Total heat generation of the barrel (W)	Max/min temperature on ladder (Celsius)
3.5	190	29.4/7.5

- **For the ladder/barrel, the simulation results indicates**:

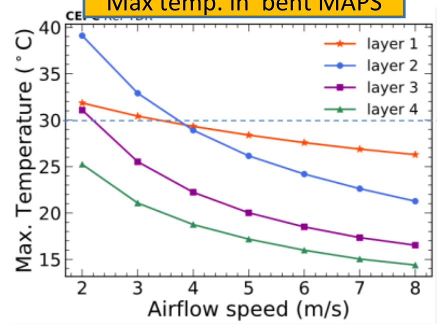
At airflow speed above 3.5 m/s, the sensors can be cool down to < 30 ◦C.

VTXD Cooling

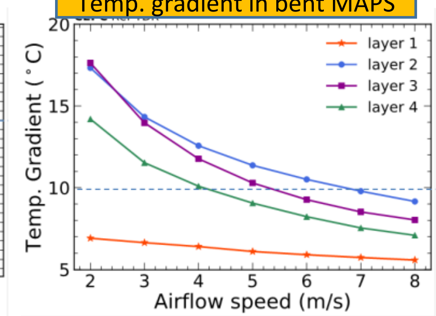
- **For the stitching layers**:
  At airflow speed >= 7 m/s, all four bent MAPS maintain temperatures < 30 ◦C with temperature gradients reduced to less than 10 ◦C .

Results in Ref-TDR

Max temp. in bent MAPS



Temp. gradient in bent MAPS

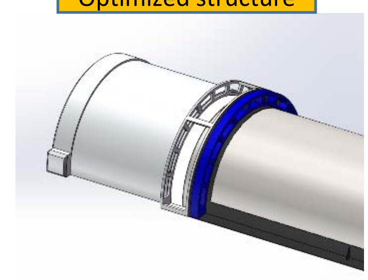


✓ **Air flow speed of 7 m/s, equivalent to a total flow rate of 3500L/min is selected as the baseline for the VTXD cooling design.**

- In addition, an optimized structural design aimed at improving cooling in the outermost high-heat regions has been proposed to further reduce the temperature gradients of the stitching layers.

Original structure

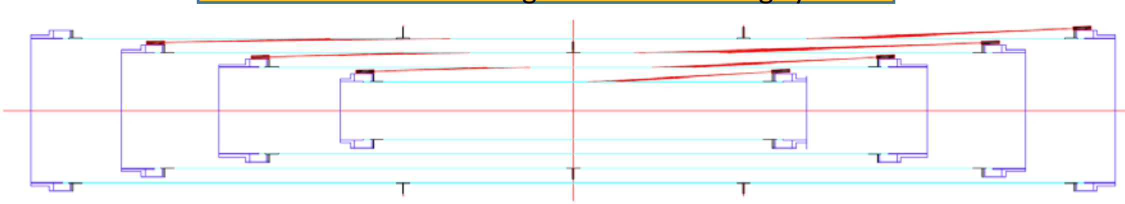
Optimized structure



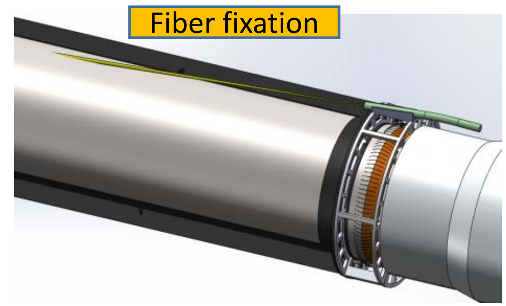
VTXD Cooling

- **Vibration caused by air cooling**
  - The vibration of the baseline design will be evaluated by prototyping and testing the ladders and the bent MAPS cylinders with air cooling
  - Optical displacement probes (non-contact measurement) will be employed
- **Real-time monitoring** (beyond the vibration case)
  - A laser-based alignment system is proposed
    - ✓ to track bent MAPS' movements from environmental factors
    - ✓ to verify alignment accuracy
  - Laser delivery to each layer via optical fibers fixed on the support and aimed at specified locations.
  - Physical simulations and tests with tilted incident lasers demonstrate that the system determines positional shifts from the pixel ID distribution, achieving micrometer-level precision.

A laser-based online alignment monitoring system



Fiber fixation

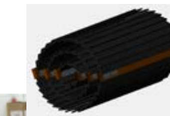


Previous mechanics related R&D

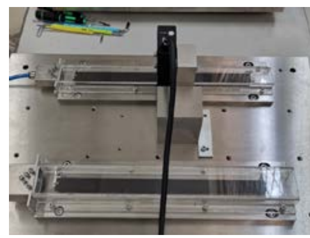
- **A flat MAPS based VTXD prototype** has been developed and evaluated (backup now)
  - Ladder(length=273 mm) with CFRP support
  - 3 layers of ladder-based barrels
  - Air cooled by fan
  - Ladder support tested under static and dynamic loads (forced air flow) on dedicated platforms

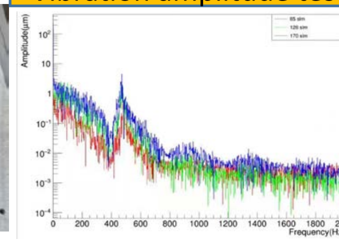
- **The overall structural performance verified by the prototype beam test** (vibration and isolation, temperature etc. all meet requirements)

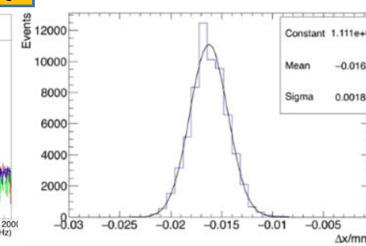
Prototype of the ladder and barrels

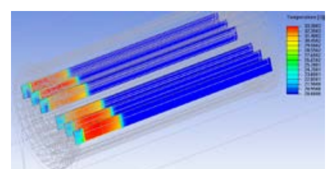


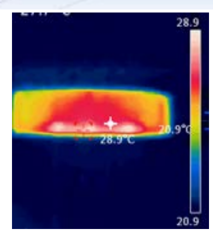
Vibration amplitude test











VTXD prototype beam test in DESY

Summary

- The support structure of the VTXD and its integration with the Beam Pipe assembly have been designed.
- FEA has been performed for the VTXD structure and cooling and the results indicate that structural designs and cooling scheme can meet the physical requirements.
- Further R&D studies will be conducted

  - optimization and simulations

  - prototyping of the stitching layers (using dummy wafers) for structural and cooling validation