Preliminary cooling test of the CEPC VTX thermal mockup

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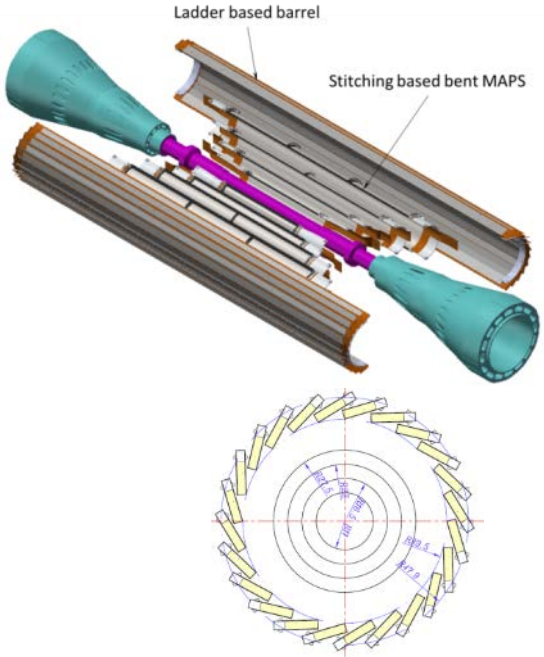
On behalf of the VTX group and the mechanical group

IHEP

VTX layout

Baseline design

- 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)
  - ✓ No dead area



VTX cooling test requirements

Scope: stitching layers



layer	Radius (mm)	Length (mm)
layer1	11	160
layer2	16.5	240
layer3	22	320
layer4	27.5	390

Heat generation of the stitching layers：

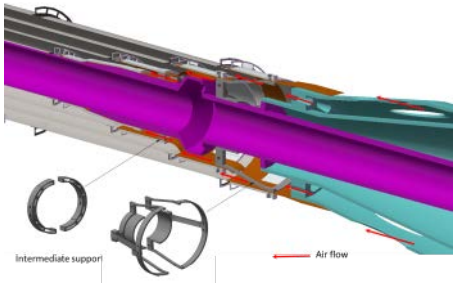
- 40 mW/cm^2 on sensor area
- high heat generation 485 mW/cm^2 on the ends (4.1mm wide，12× the average, drive the thermal design)
- ~ 80W in total

Cooling method: air cooling

Cooling targets: operating temperature of each layer within 30 ℃

Average dissipation on bent MAPS

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



Phased planning for the cooling test

Phase 1 Flat single-layer thermal mockup test (current phase, content of this report)

- Preliminary check: heating layer, thermal mockup integration, and test system
- Evaluate cooling performance under simple conditions
- Mockups: two lengths(Layer 1 & Layer 4) with the same width as Layer 1



Phase 2 Single-layer cylindrical thermal mockup test

- Assess cooling performance
- Optimize mockup or test procedure if needed, in preparation for the multi-layer campaign.



Phase 3 Multi-layer cylindrical mockup test

- Test overall VTX cooling performance
- Summarize issues, provide inputs for design optimization



Current-phase implementation

- Design and setup the air-cooling test environment
  - air supply and flow control;
  - test bench and cooling chamber
  - temperature and pressure monitoring and measurement
- Fabricate thermal mockups
  - heater + FPC + CFRP spt
- Perform testing and analyze results

Air-cooling test environment

Cooling air supply:

- Compressor (2 m³/min) /Tank (0.8 m³)/Refrigerated dryer and 3-stage filters (dew point: <10 ℃)
- Run in AC Lab, exhaust vented outside



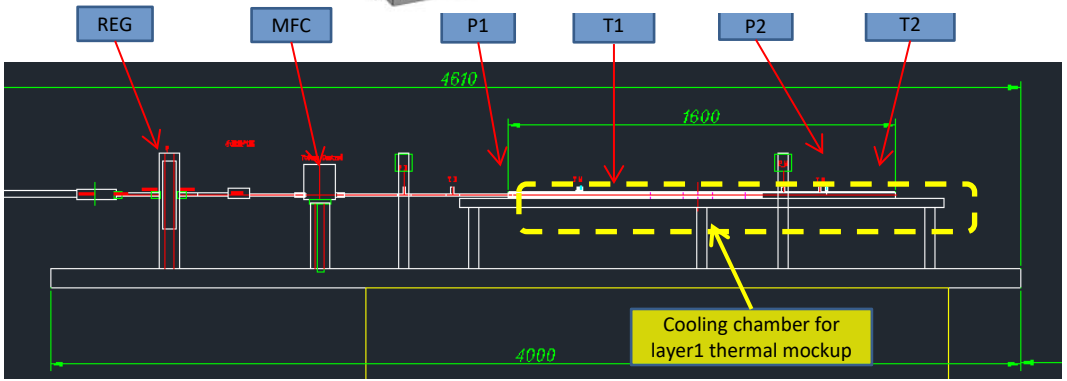


Test bench: Al alloy frame assembly for instrument support

Cooling chamber:

- Thermal mockup insulated fixed inside
- Cable routed from lateral side
- Auxiliary inlet/outlet adjustments





P & T Monitoring and Data acquisition:

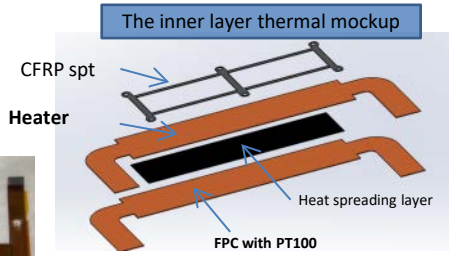
- Distributed modules acquire pressure and temperature(PT100) via RS-485 Modbus serial communication.
- A GUI-based data storage program

Thermal mockup (the composite heater)

Heater

- A serpentine heating film dissipates the chip-equivalent power, reproduce the 12× end heat flux.
- **Issues**: Serpentine → uneven temp; low conductivity (1.65-16 << 148 W/(m·K)) → hot spots, large gradient.





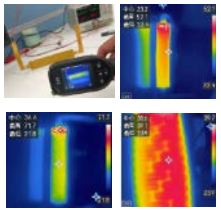
Heat spreading layer

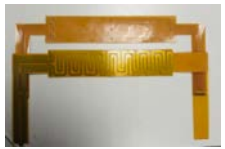
One AL layer added to make in-plane heat spreading equivalent to silicon

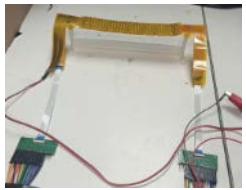
Temperature sensing and wires routing

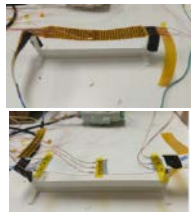
- specially designed FPC with PT100 probes soldered
- probe positions arranged according to CFD simulation
- Tested vs. direct-bonded PT100 probe:
  - ✓ Easier to route out of the chamber
  - ✓ No exposed wires & less airflow obstruction
  - ✓ Firmer resistor fixation & more stable signal











Thermal mockups development

Three optimized composite heater versions(layer 1), from "unknown parameters" to "designed values"

G1

Al tape + single layer thermal glue:

- The Al tape is backed with unknown adhesive with unknown thickness, the probes embedded inside.



G2

Al tape + single layer thermal optimization:

- Use the same Al, bonded through a single layer thermal glue: probes flipped to the outer surface.



G3

Al + double layer thermal optimization:

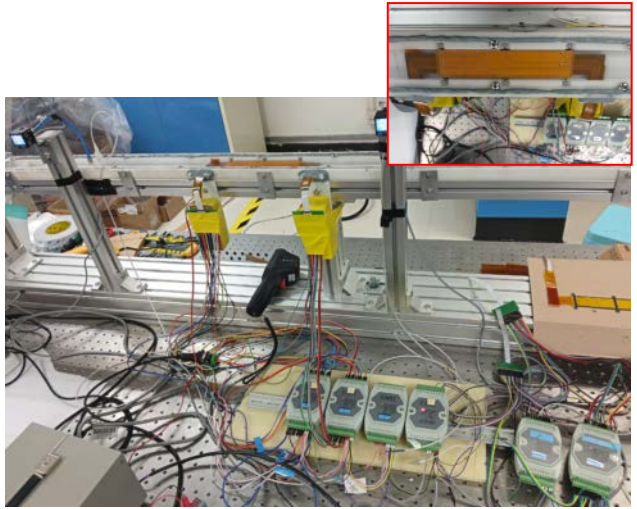
- The Al spreading layer is bonded on both sides thermal glue; every interface has known parameters; two layers in series, low-k interlayers are gone.

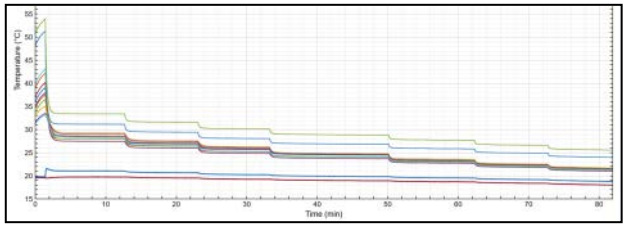


The heaters and FPCs of layer 4 have been fabricated and are ready for integration.

Forced air cooling test

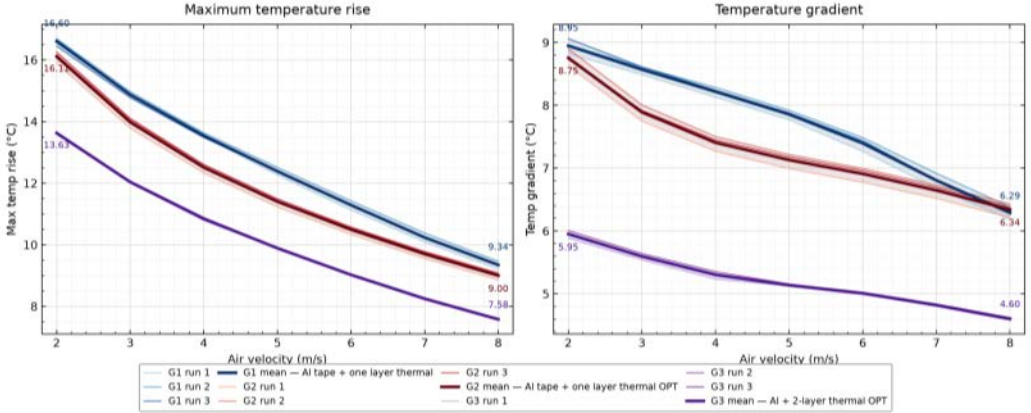
- Room temperature 19-21 ℃
- Air velocity： 2~8 m/s, in seven steps
- MFC mass-flow control converted per step to volume flow at the actual inlet temperature
- Each thermal mockup was tested for at least 3 runs
- One test bench, same chamber, same instrumentation, every dataset is directly comparable



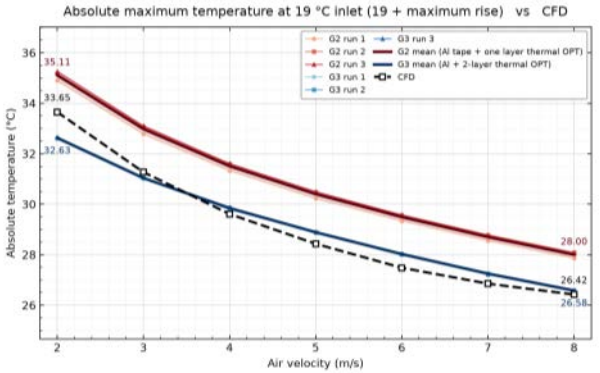


Test results

Latest three thermal mockups tests: maximum temp rise and gradient



G2 vs G3 vs CFD(baseline): absolute temp at 19 ℃ inlet



Repeatability proves the platform

Within-group max–min spread: G1 ≤ 0.29 / 0.24 ℃, G2 ≤ 0.36 / 0.27 ℃, G3 ≤ 0.10 / 0.12 ℃ (rise / gradient) — an order of magnitude below the between-group gaps. Flow control, heater power and the data chain are reliable.

Interface improvement clearly works

Ordering G1 > G2 > G3 at every speed, in both metrics: G2 mean sits 3–8% below G1; G3 mean sits 18–37% (rise) and 28–36% (gradient) below G1. Each interface upgrade lowers both indicators — the trend is monotonic and improving.

G2 runs above CFD at every speed

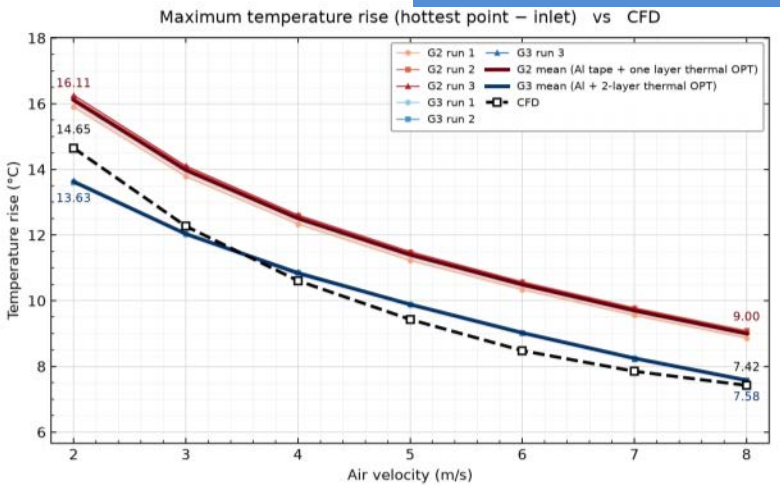
Absolute deviation +4.3% ~ +7.3% — the un-modelled contact resistance of the Al-tape stack keeps the whole plate hotter than the ideal simulation.

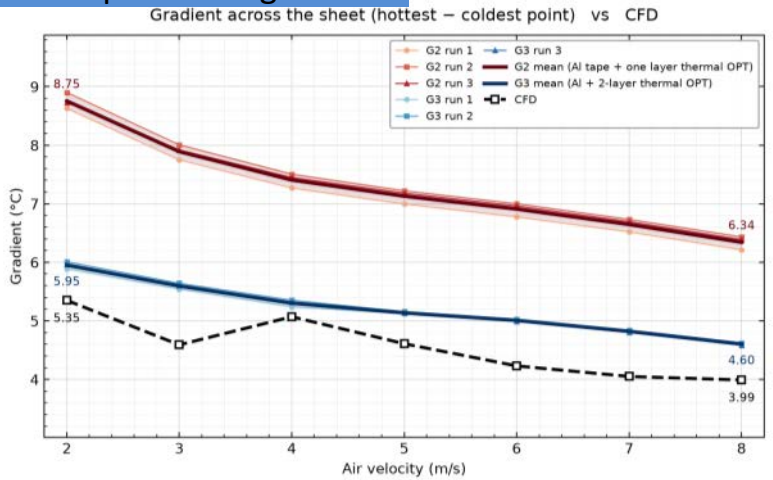
G3 sits essentially on the CFD level

with the Al + 2-layer thermal OPT stack the absolute cooling temperature matches the silicon-equivalent CFD target — the optimization is effective.

Test results continued

G2 vs G3 vs CFD: maximum temp rise and gradient

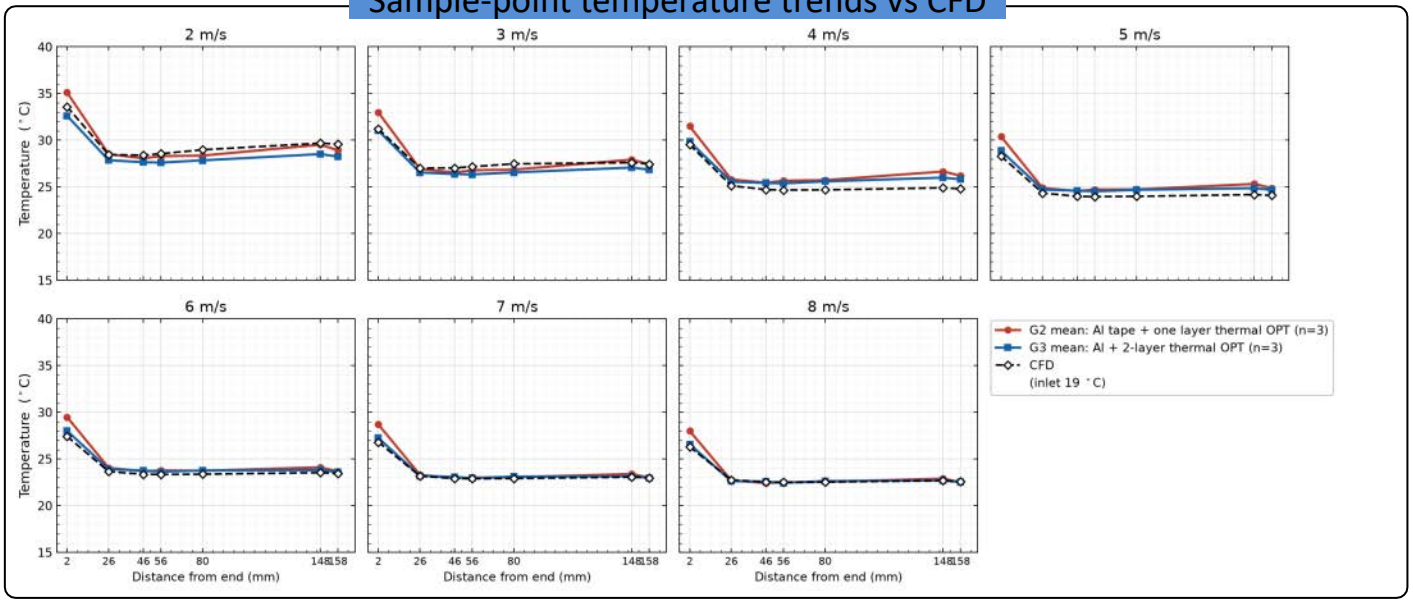




- G3 is clearly the closest to CFD in both metrics
- The interface optimization is effective and the composite heater design is reasonable.

Test results continued

Sample-point temperature trends vs CFD



The comparison on a common19 ℃ inlet basis shows :

- the G2/G3 means and the CFD curve agree in shape and trend, sample points effectively captured heat distribution.
- Within ±1 ℃ for ≥ 4 m/s; the final design (G3) is the most reasonable — the basis for subsequent tests.

Conclusion and outlook

- Phase 1 cooling test environment and overall system preliminarily verified and reliable.
- The latest composite heater design is reasonable: in-plane spreading close to silicon; measured vs CFD within ±1 ℃ for ≥ 4 m/s; end region slightly hot, giving a conservative assessment.
- CFD supports engineering design: the measured profile shape agrees with simulation, with care at low speeds.
- Layer-4 (390 mm) mockup: heater and FPCs fabricated, pending integration; testing starts soon.
- Ongoing: silicon dummy chips containing only heating circuits as substitutes for real chips.

Thanks