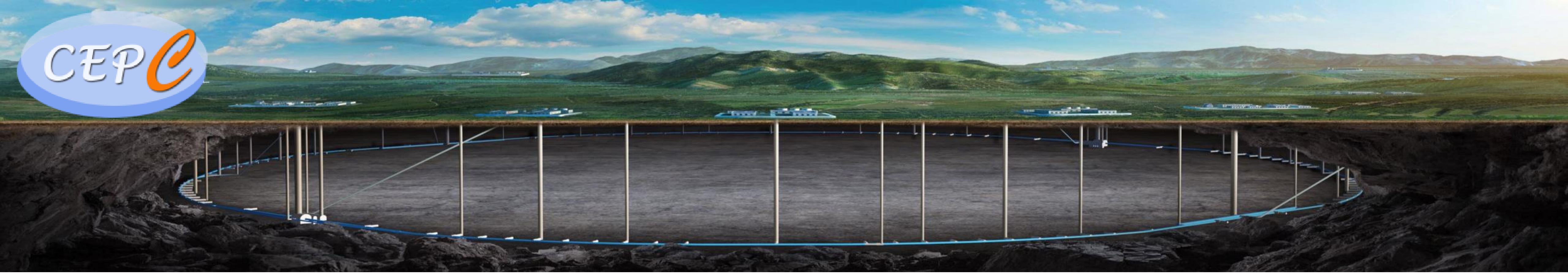

Mechanical Design and Future Prospects for the CEPC Silicon Tracker

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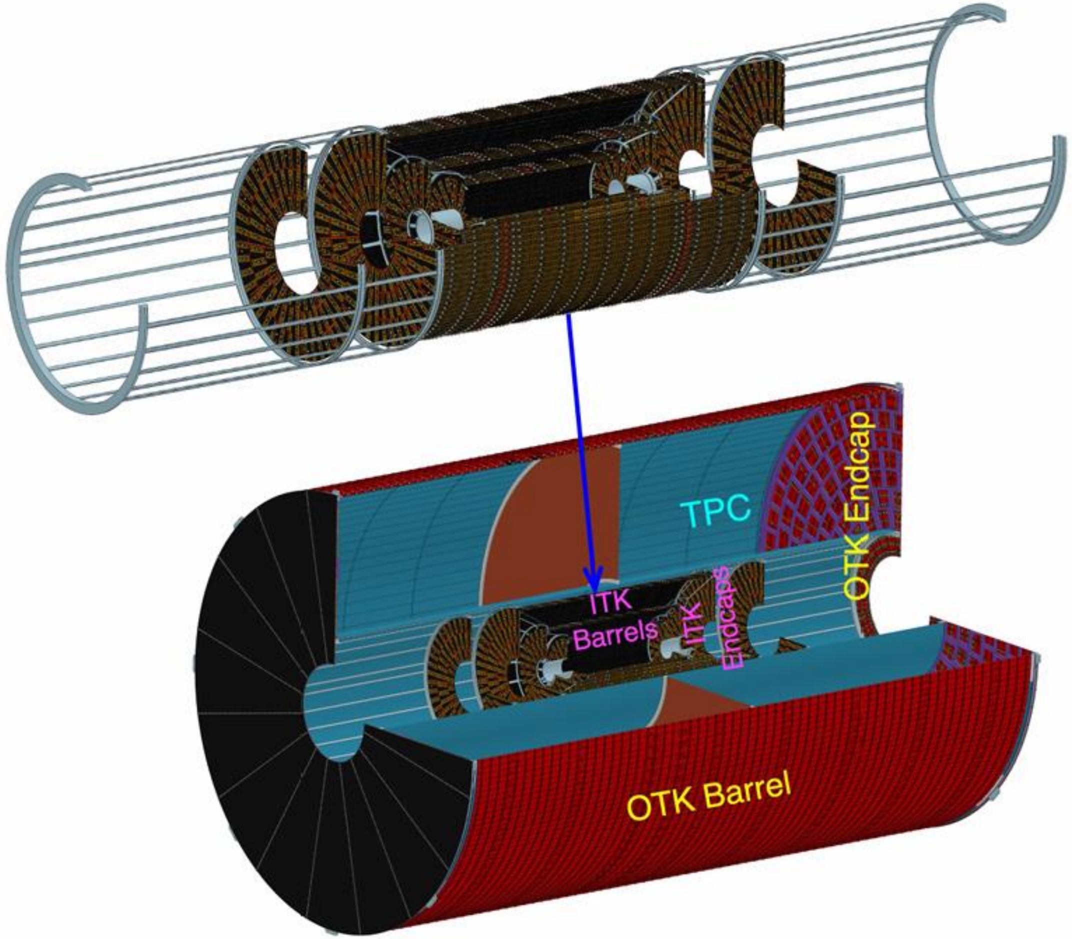
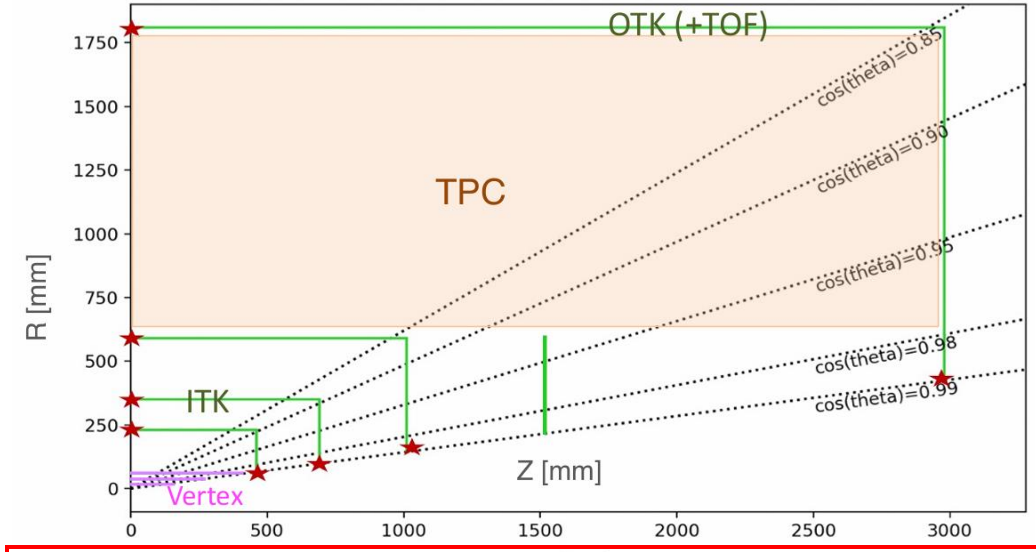
OUT LINE

- Overview of CEPC Silicon Tracker
- Design and Fabrication of Lightweight Carbon Fiber Support
    - Design and Simulation
    - Manufacturing Process
- Design and Simulation Analysis of Water Cooling
- CO_2 Cooling Analysis and Progress
- Summary

Overview of CEPC Silicon Tracker



Lay out of the Silicon Tracker (ITK and OTK)

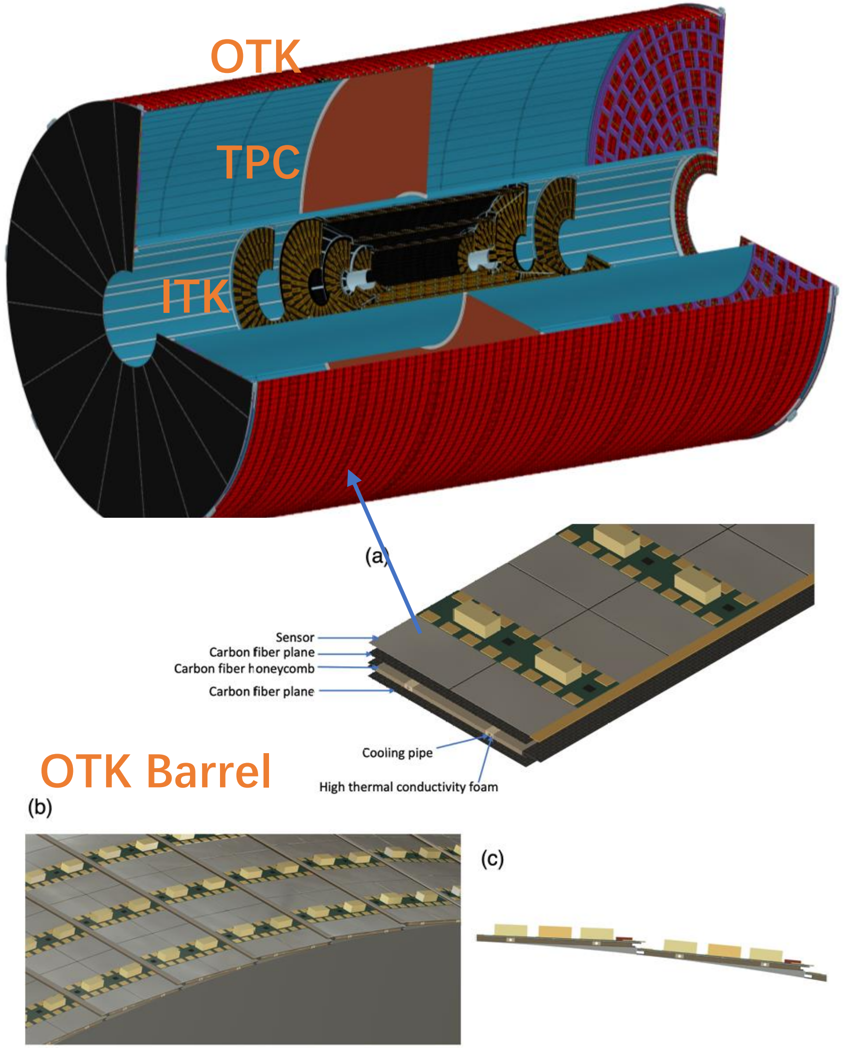


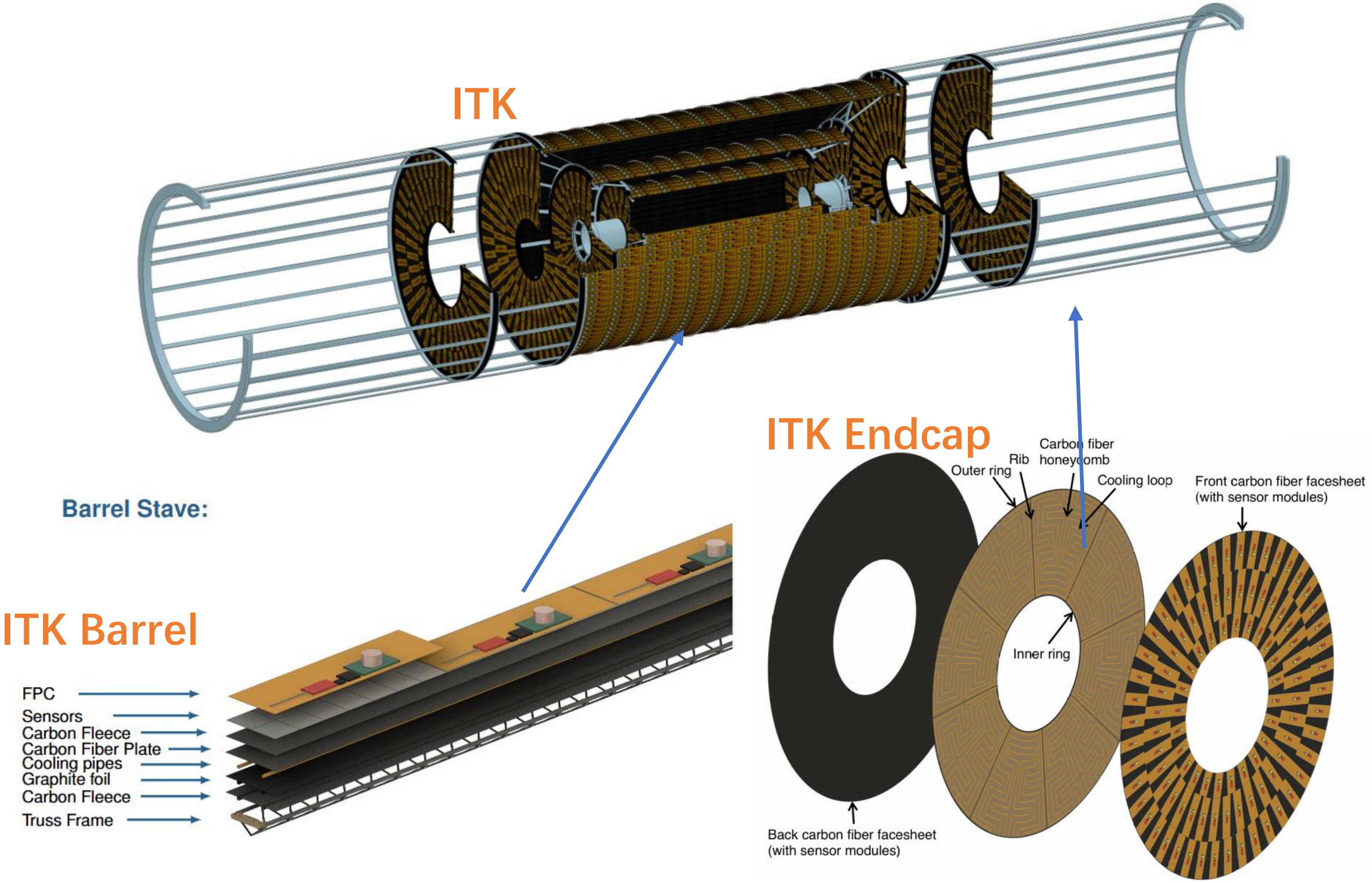
Heat Dissipation of the Silicon Tracker

Detector Component	Quantity	Surface Area (m^2)	Heat Dissipation (kW)
Inner Tracker Barrel	3	13.3	26.6
Inner Tracker End-cap	8	5.5	11.0
Outer Tracker Barrel	1	65.0	195.0
Outer Tracker End-cap	2	20.0	60.0
Total		104.0	293.0

- The ITK, positioned outside the beam pipe and vertex detector and inside the Time Projection Chamber (TPC), is composed of three barrel layers and four endcap disks.
- The OTK, located outside the TPC, consists of a single barrel layer and one endcap.
- A total of 293 kW is dissipated over a surface area of 104 m^2

Overview of CEPC Silicon Tracker

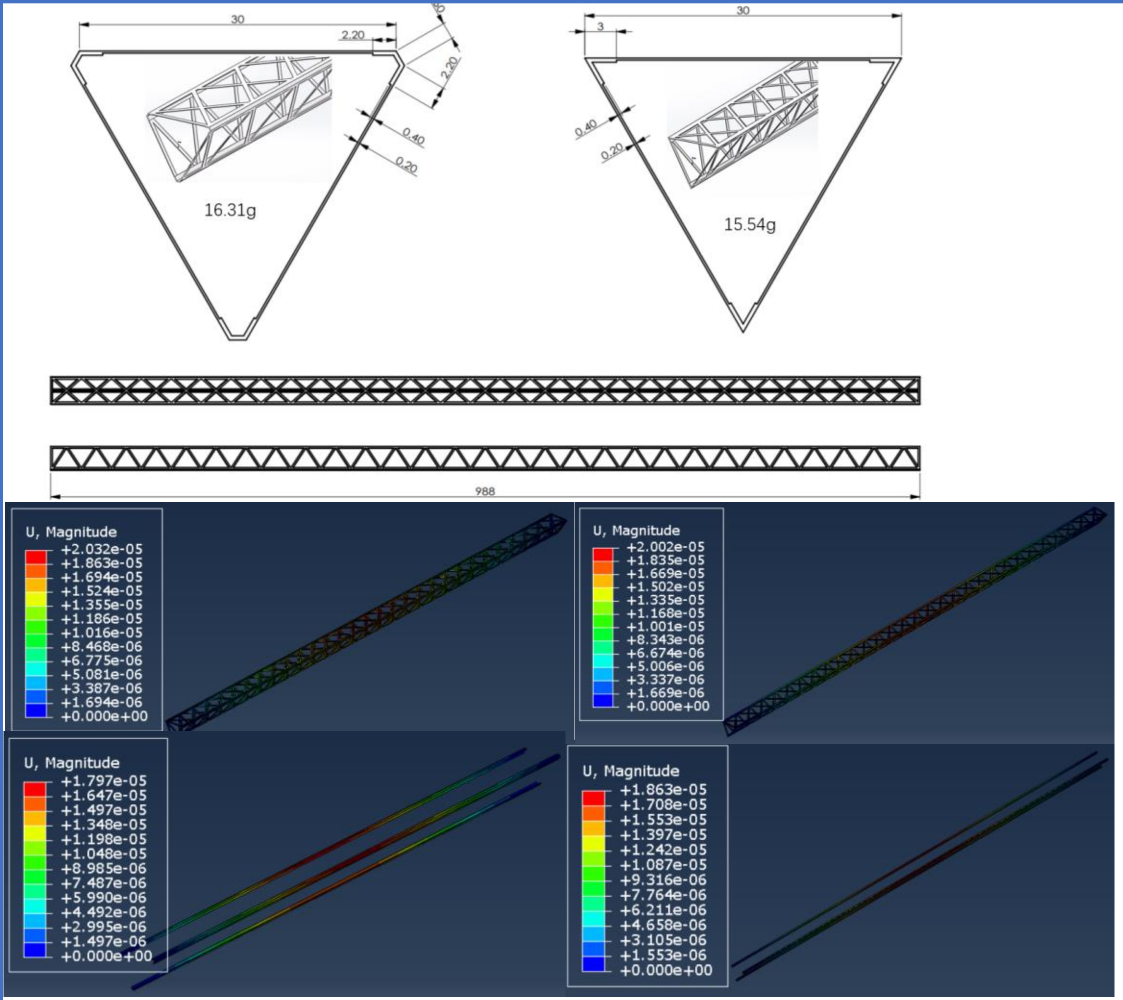




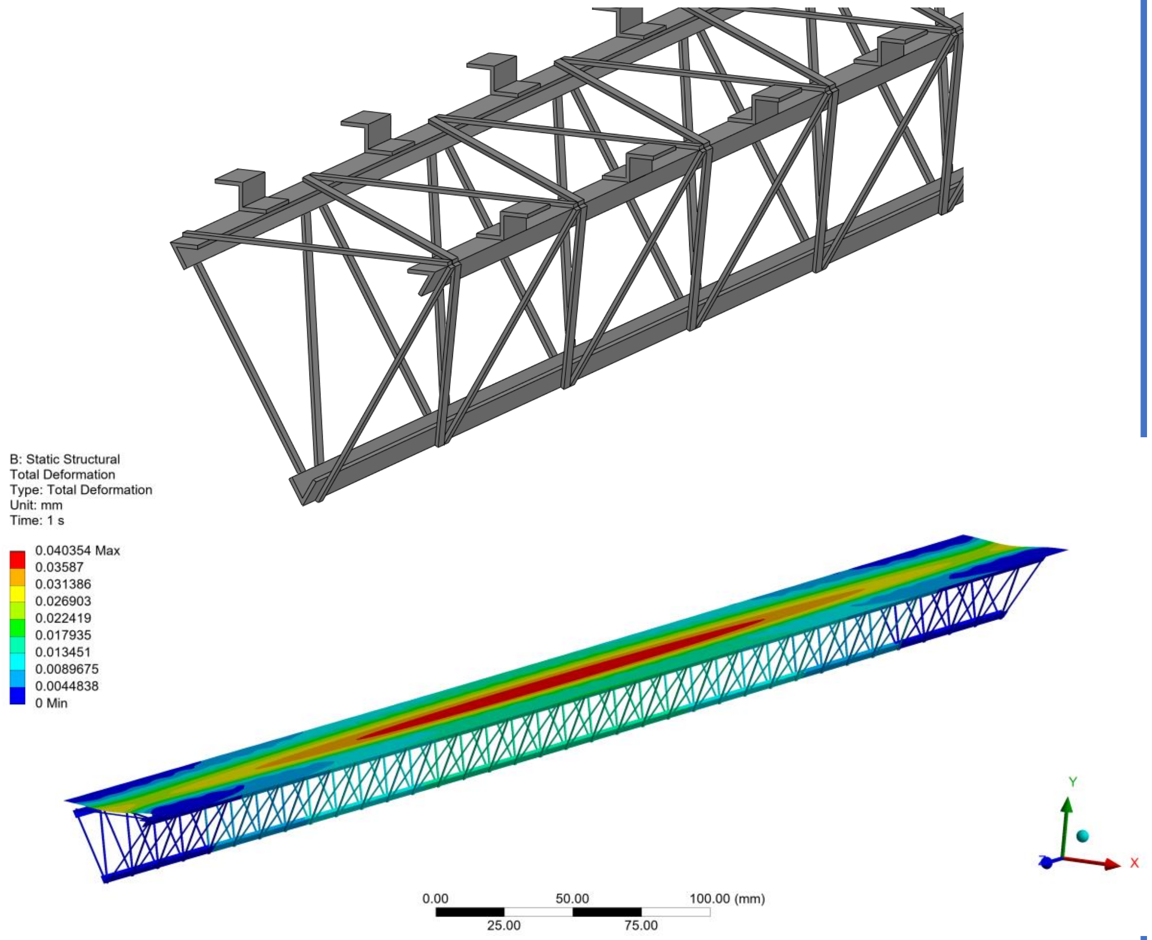
- The Inner Tracker (ITK) barrel incorporates a lightweight truss design, its endcaps and the entire Outer Tracker (OTK) utilize a honeycomb configuration.
- These structures are fabricated from high-strength, high-thermal-conductivity carbon fiber composites and thermally conductive graphite materials.

CEPC Silicon Tracker Structure Design and Simulation

- The preceding results all correspond to the structural analysis under self-weight and a uniformly distributed surface load of 20 Pa, with boundary conditions of fixed support at both ends.
- Multiple space truss were designed and analyzed through simulations, with all designs for the ITK inner barrel stave (986.6 mm) exhibiting a deformation of less than 50 micrometers.



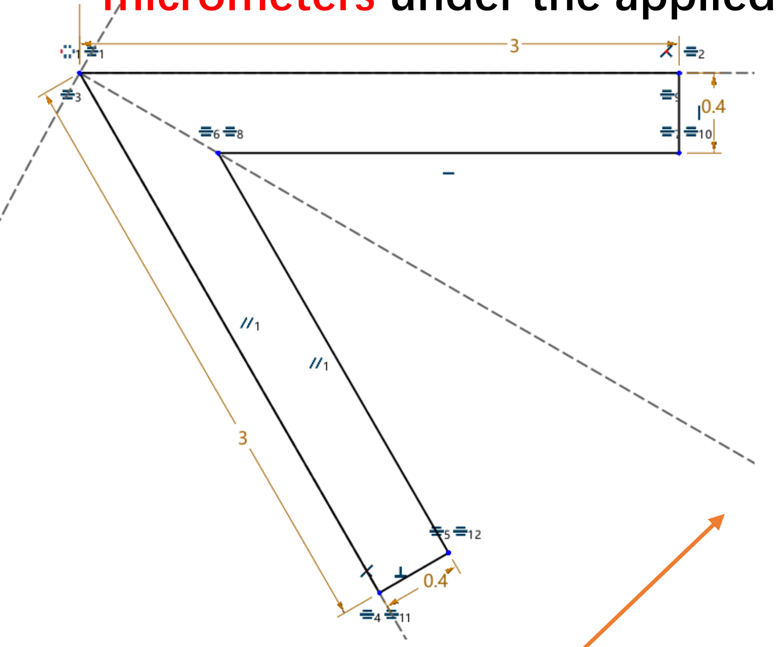
Truss Deformation≈20μm

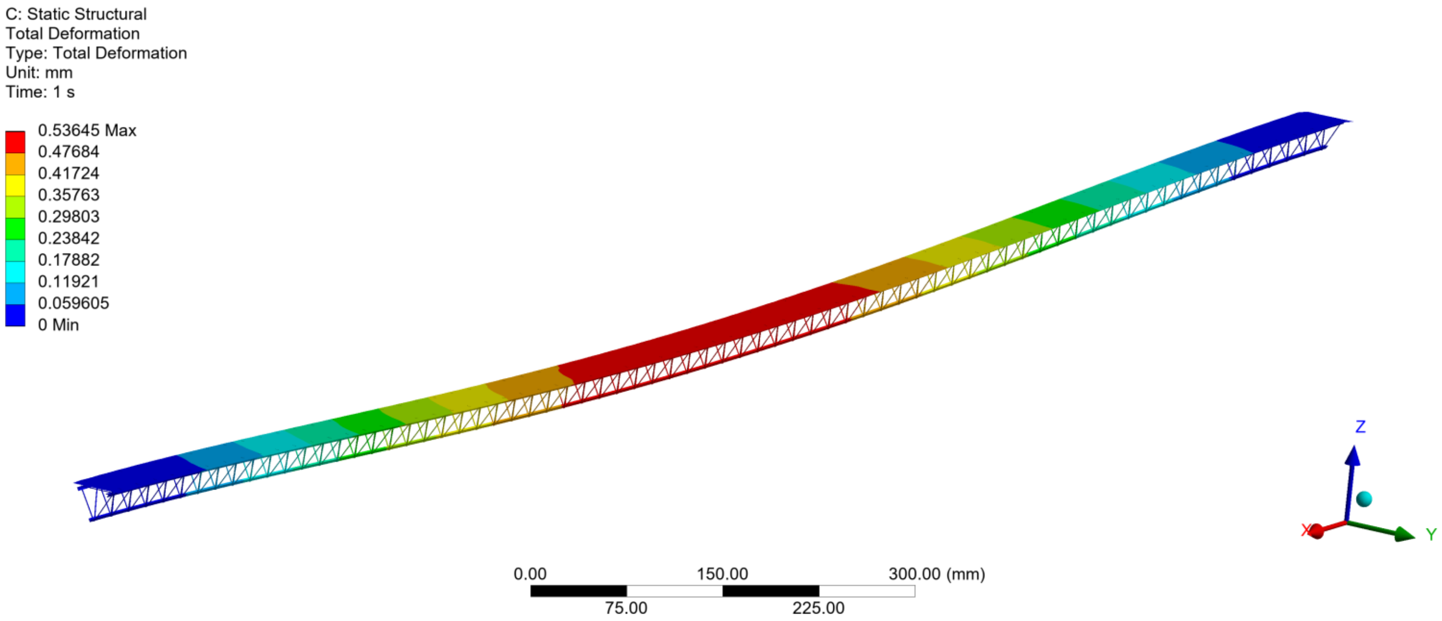


Global maximum deformation≈40μm

CEPC Silicon Tracker Structure Design and Simulation

- The ITK barrel layer3 stave (1973.2 mm), using the same specifications, exhibits a deformation of 536 micrometers under the applied load.





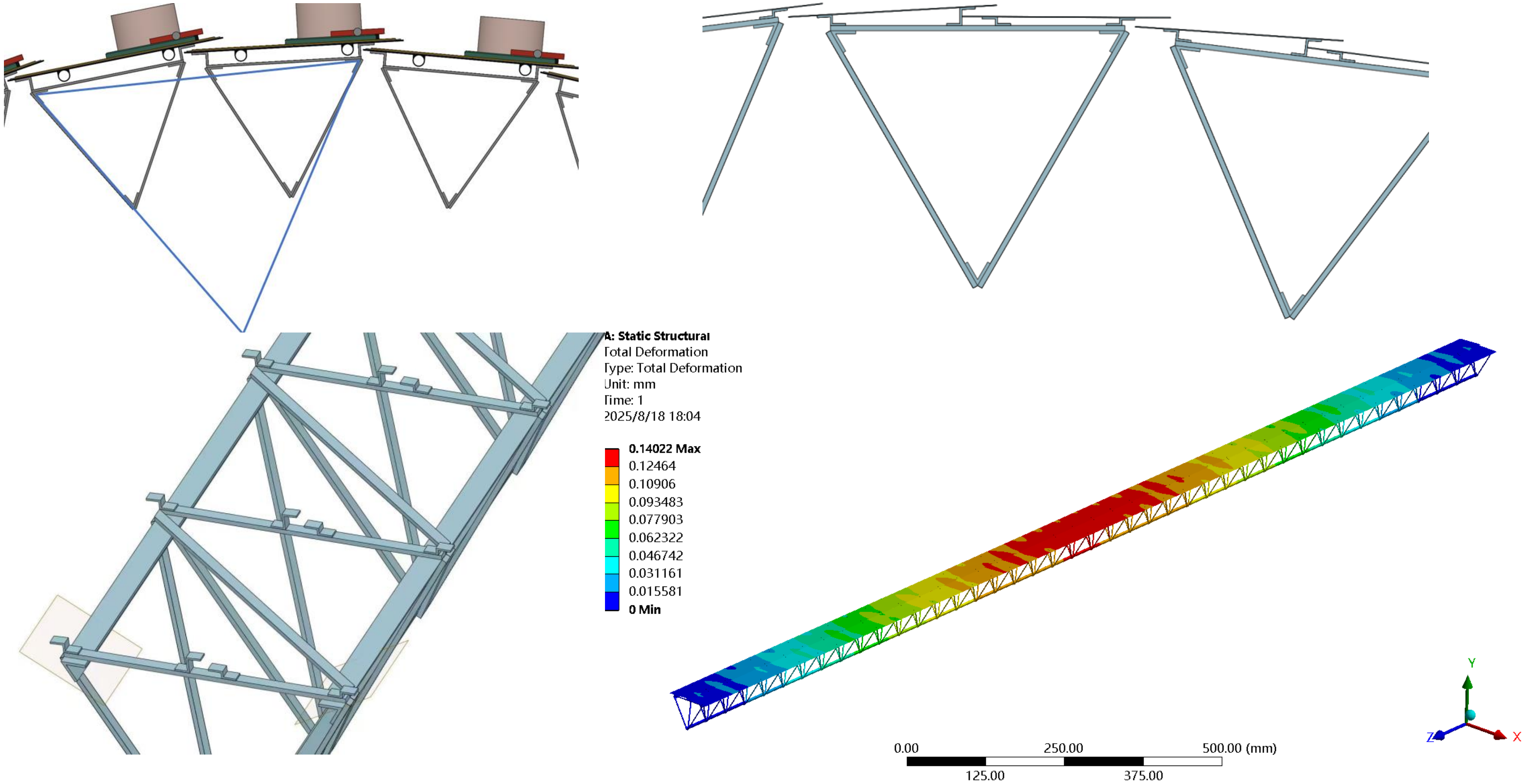
Results of Increasing strut dimensions

Size specification	Weight(g)	Maximum deformation(mm)
3mm；0.4mm	33.02	536
4mm；0.4mm	49.17	440
5mm；0.4mm	57.54	390
3mm；0.5mm	45.00	470
3mm；0.6mm	48.88	430
5mm；0.6mm	66.67	320

- Approach : Increased strut dimensions.
- Conclusion : Limited deformation reduction achieved at the cost of high mass penalty

CEPC Silicon Tracker Structure Design and Simulation

➢ A single space truss structure is designed to support two detector stave units

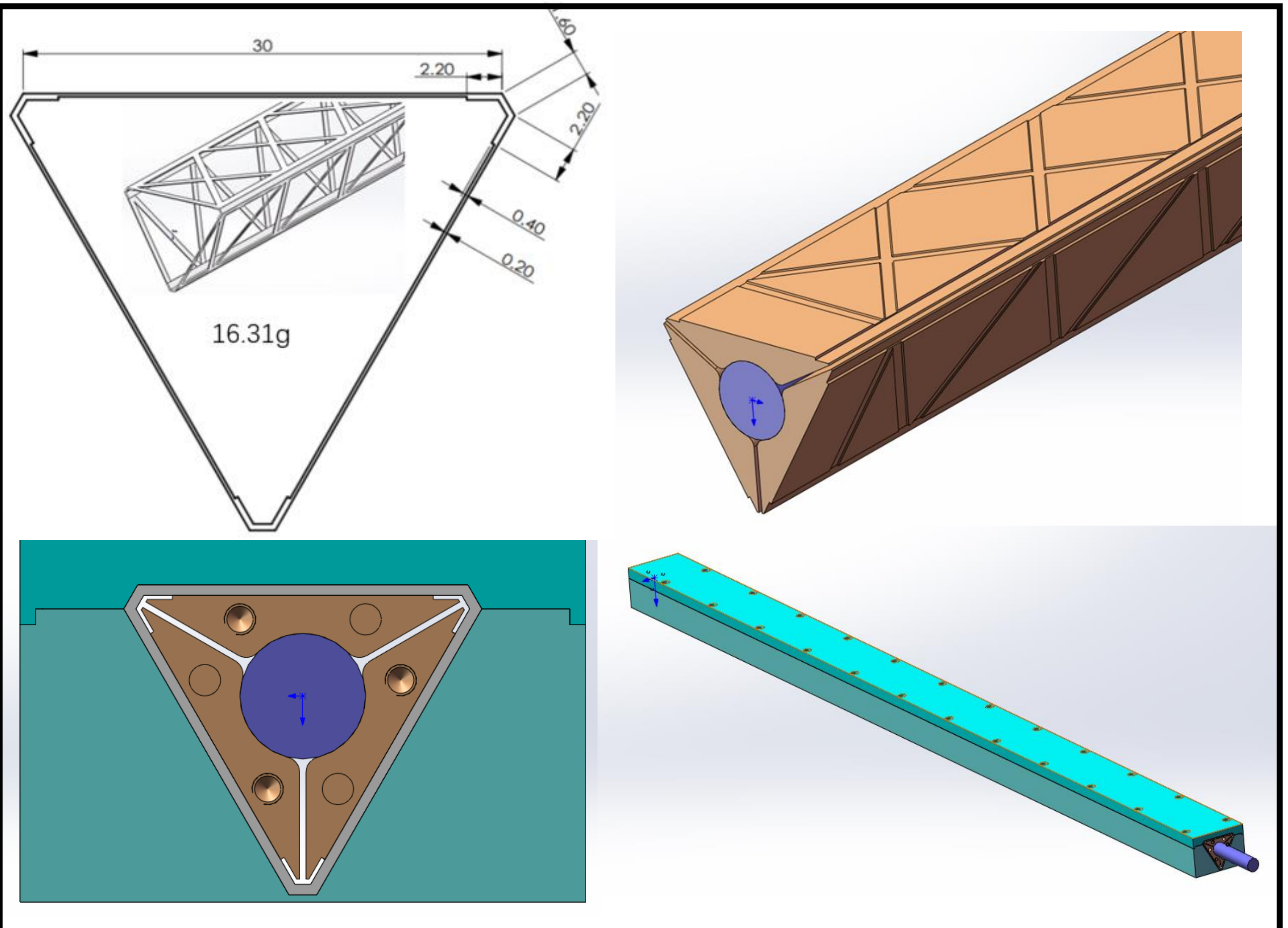


A truss frame with two detector stave

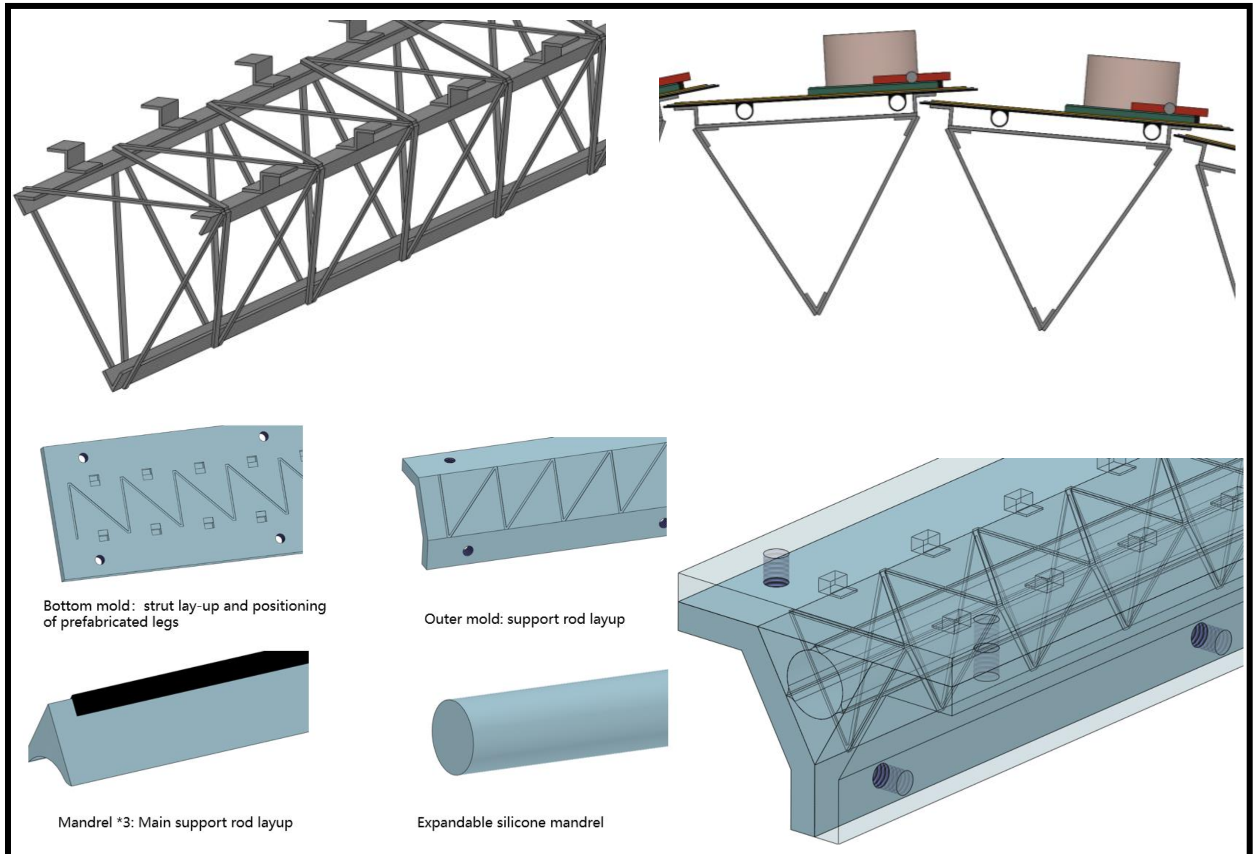
- Enhanced cross-section improves bending modulus
- Leading to 140 μm deformation and 21% mass reduction

CEPC Silicon Tracker Structure Manufacturing Process

- Corresponding forming processes have been developed for the respective design schemes, and an experimental investigation into their fabrication is now underway.



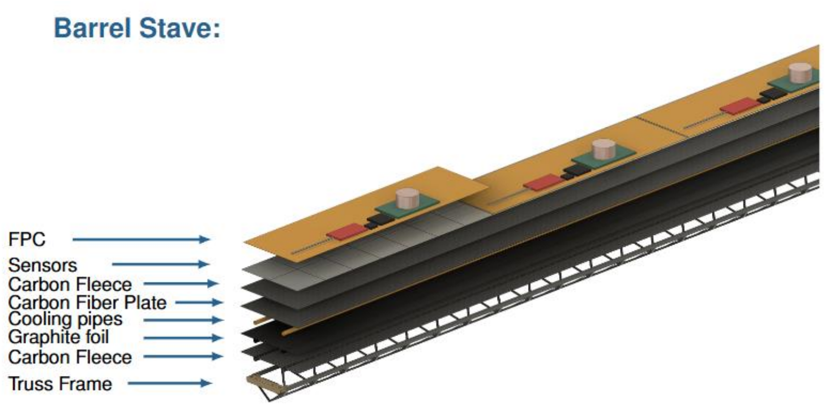
Scheme 1



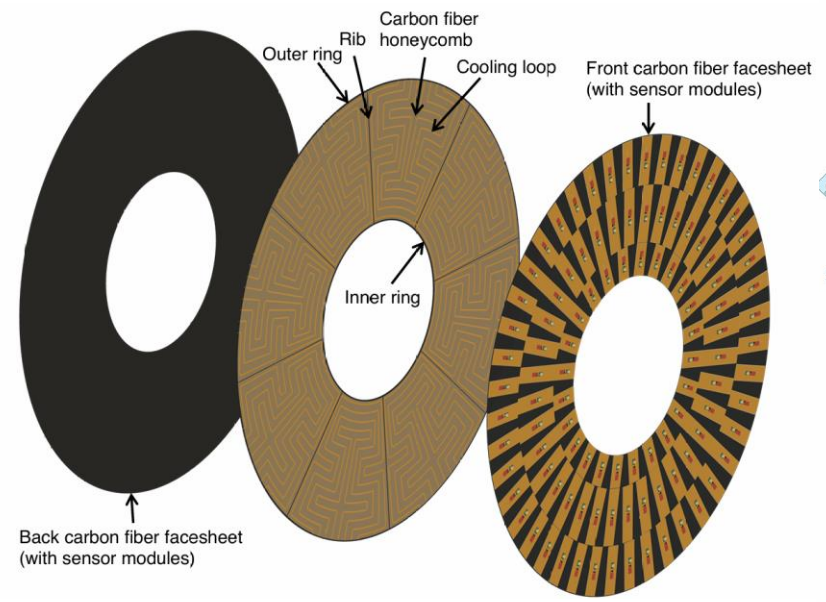
Scheme 2

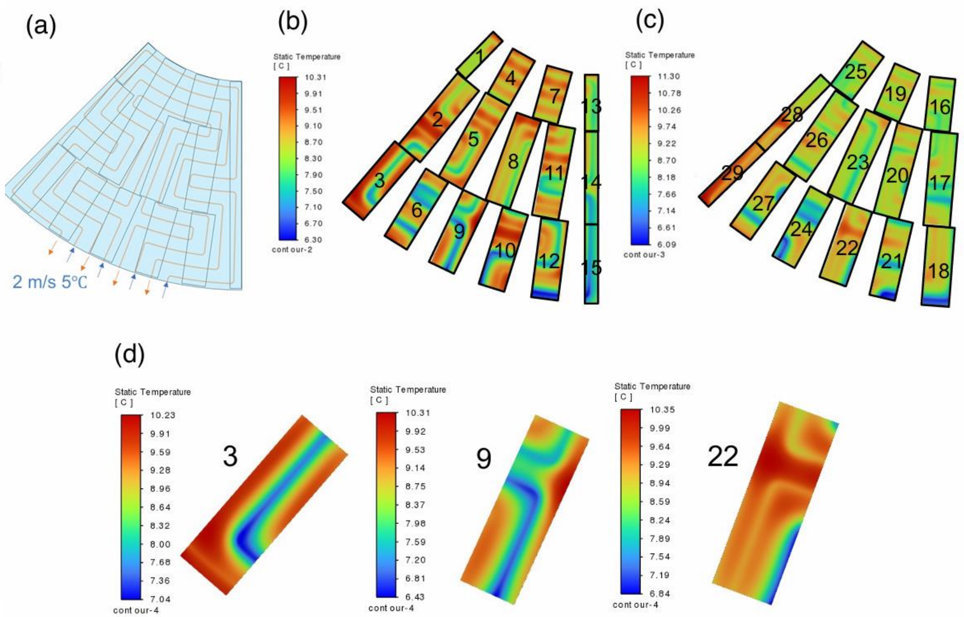
Two kinds of space truss forming craft

Design and Simulation Analysis of Water Cooling



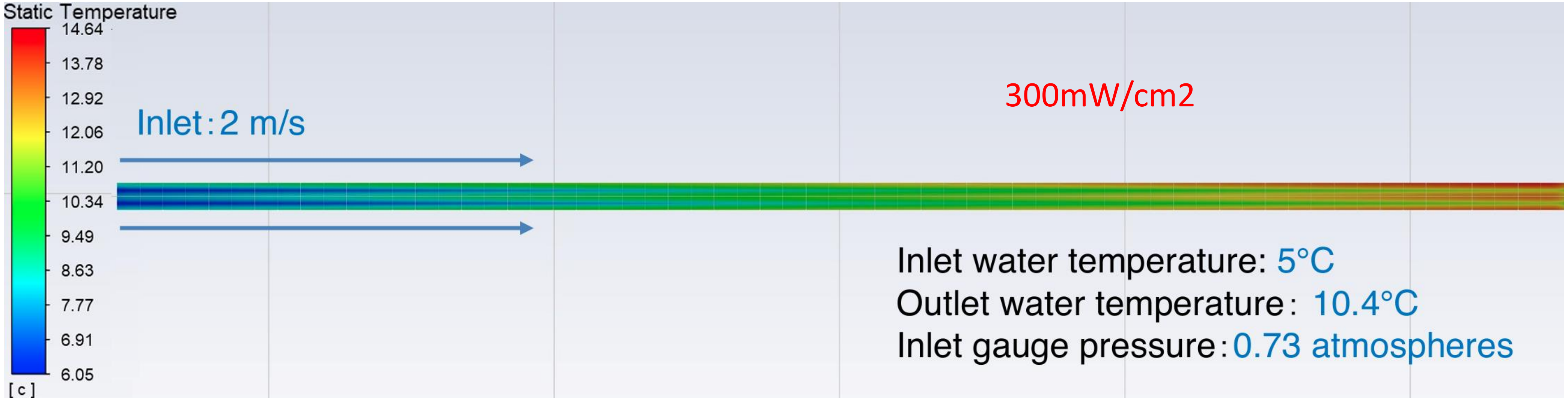
- With a coolant flow velocity of 2 m/s in 1.6 mm inner diameter tubes, The maximum chip temperature remains below 15.6°C, with a global temperature gradient ＜ 5°C.





- Figures (b) and (c) show the maximum temperature within a 1/8 sector is below 12°C, while Figure (d) confirms local gradients are controlled within 4°C per module and 2.5°C per individual chip.

Design and Simulation Analysis of Water Cooling



Simulation result of water cooling for the OTK stave（5680mm×110mm)

Assumptions：

- ➢ The detector dissipates heat at a flux of 300mW/cm2.
- ➢ Cooling water enters the stave with a flow velocity of 2m/s and a temperature of 5°C.
- ➢ Natural convection and radiative heat transfer were not considered.

Result:

- The temperature across the stave remains below 14.6 °C, and the temperature gradient along the stave is within 8.6°C.
- The temperature variation across a single sensor is found to be below 3 °C， satisfying the preliminary requirement.

CO_2 Cooling Analysis and Progress

➢ Building on our baseline water cooling system, we are exploring a two-phase CO_2 cooling alternative to pursue enhanced thermal uniformity, which is critical for the detector's ultimate performance.

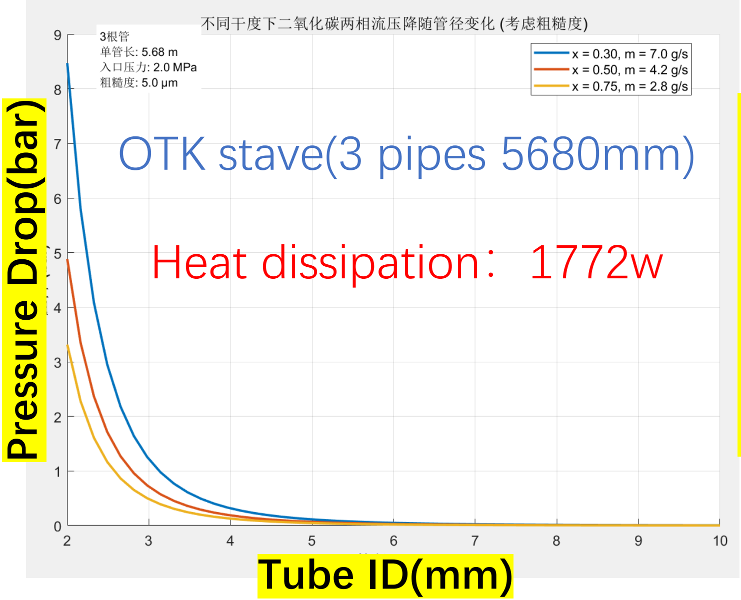
Two-Phase CO_2 Cooling

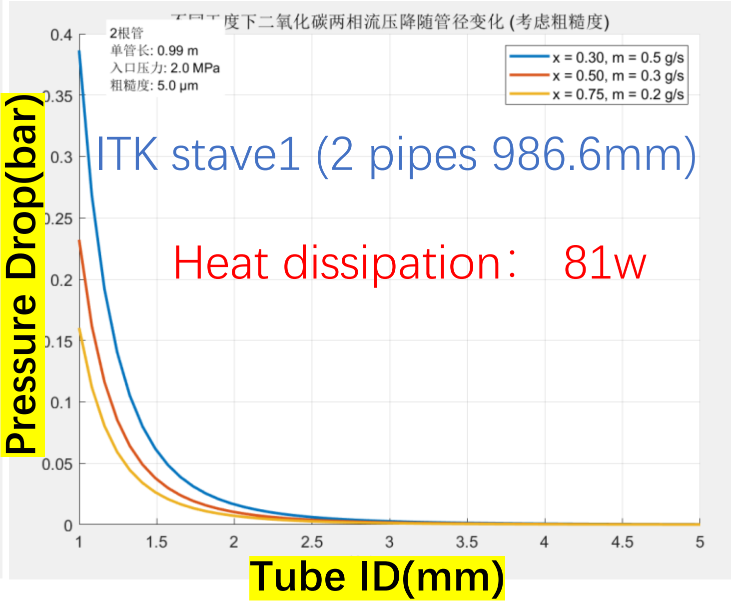
- Lower Operating Temperature Reduces Radiation Damage
- Exceptionally High Heat Transfer Coefficient
- Low Mass Flow & Compact System Design
- Exceptional Temperature Uniformity

The Strategic Advantages of CO_2 as a Refrigerant

- Excellent Radiation Resistance
- High-Pressure Operation for Miniaturization
- Environmental Sustainability & Safety

CO_2 Cooling Analysis and Progress

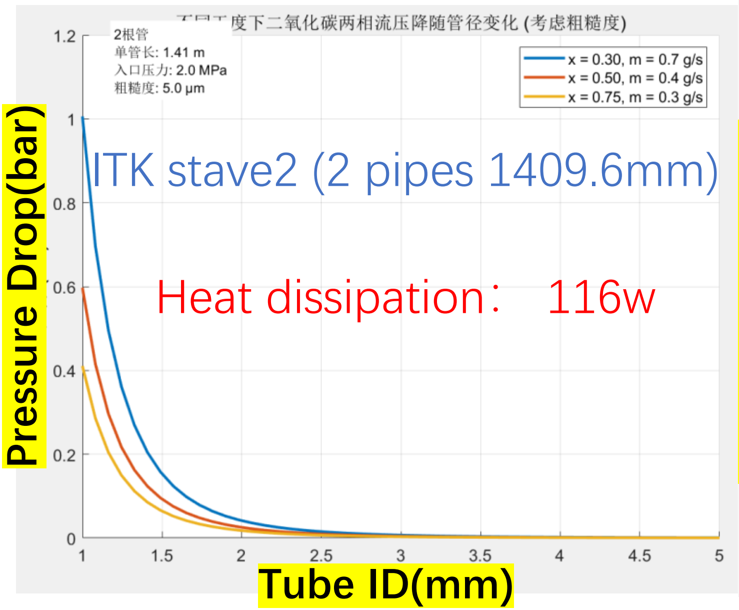


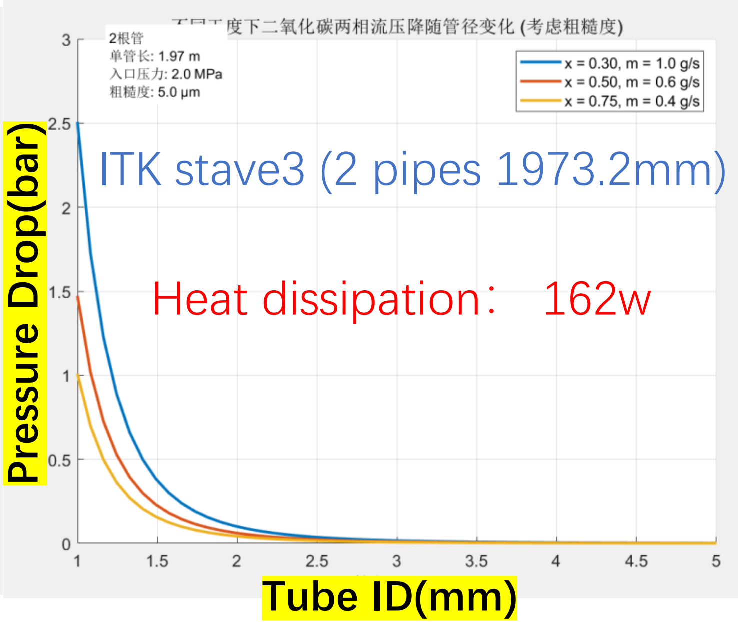


The tube diameter was determined by calculating the two-phase flow pressure drop in a horizontal circular tube using the Friedel correlation.

$$\Delta P_{TP} = \phi_{LO}^{2} \cdot \Delta P_{LO}$$

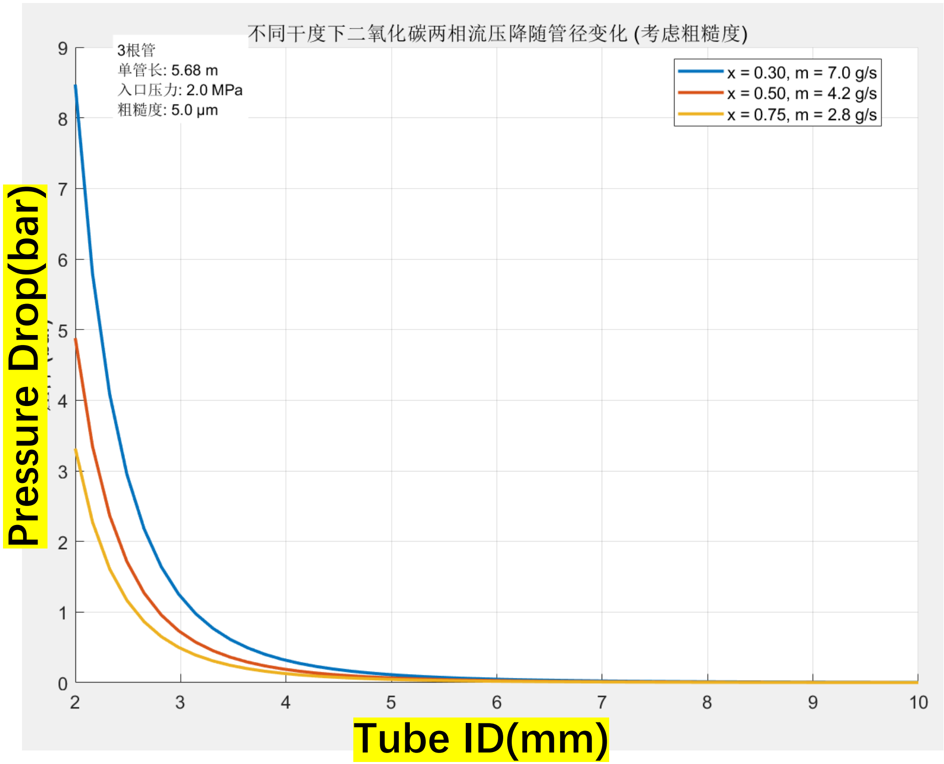
$$\phi_{LO}^{2} = \frac{E + 3.24 \cdot F \cdot H}{Fr_{TP}^{0.045} \cdot We_{TP}^{0.035}}$$



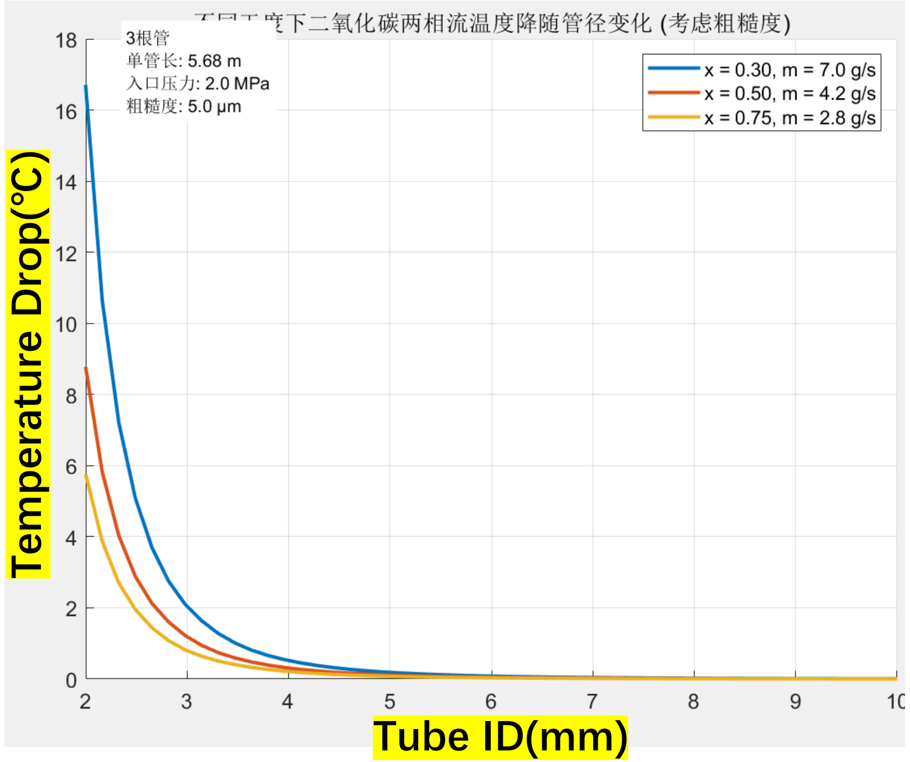


These curves illustrate the pressure drop as a function of tube diameter at varying vapor qualities for the two-phase CO_2 cooling system in the ITK and OTK staves, operating at 2 MPa and approximately -20°C.

CO_2 Cooling Analysis and Progress



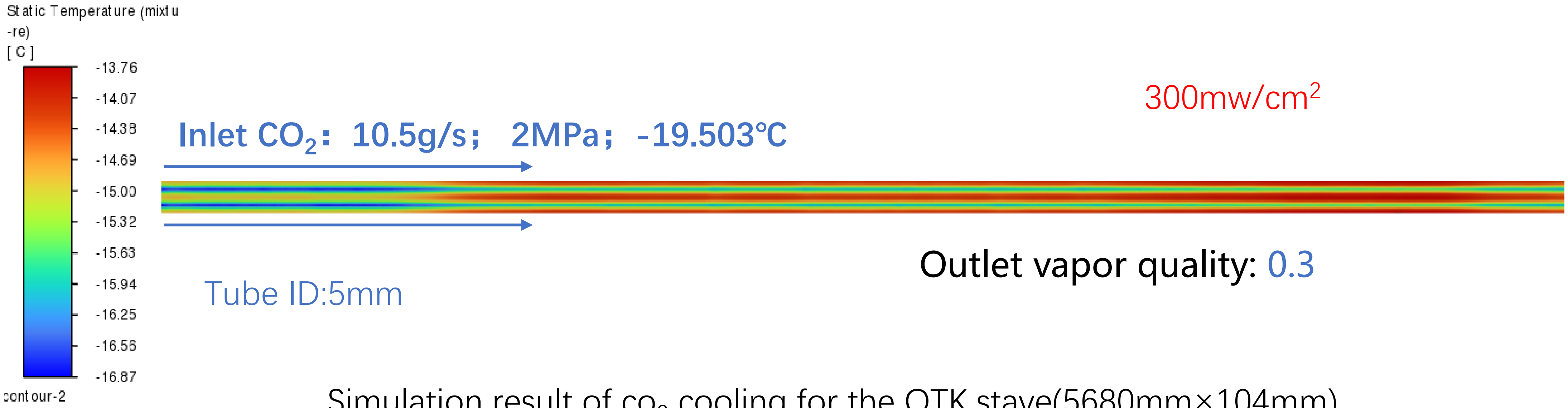
Pressure Drop in the OTK as a Function of Tube Diameter



Temperature Drop in the OTK as a Function of Tube Diameter

- The temperature drop of the refrigerant can be directly correlated with the pressure drop as a function of tube diameter, allowing for its derivation from the plotted data.
- Based on the correlation between the refrigerant temperature drop and the pressure drop as functions of tube diameter, a design basis is established for the selection of CO_2 cooling tube diameters.
- For a target outlet quality of 0.3 (see Curve blue), the 3 mm tube diameter is optimal, providing a favorable balance :
  - Mass Flow Rate: 7 g/s
  - Pressure Drop: ~1.2 bar
  - Temperature Drop: ~2 °C

CO_2 Cooling Analysis and Progress



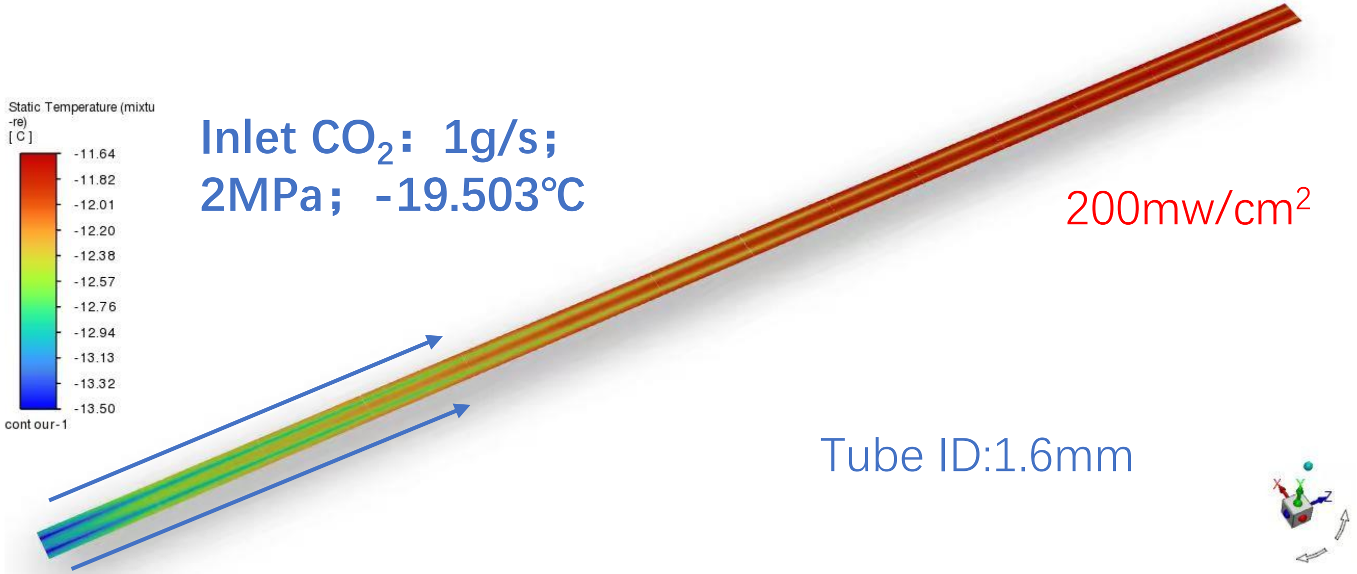
300mw/cm^2

Inlet CO_2： 10.5g/s； 2MPa； -19.503℃

Outlet vapor quality: 0.3

Tube ID:5mm

Simulation result of co_2 cooling for the OTK stave(5680mm×104mm)



Inlet CO_2： 1g/s；
2MPa； -19.503℃

200mw/cm^2

Tube ID:1.6mm

- Excellent temperature uniformity is achieved, with variations below 3°C across the entire stave chips of both the ITK and OTK.
- Compared to water cooling, the two-phase CO_2 system provides superior temperature uniformity and requires a lower flow rate. This performance advantage subsequently allows for a reduction in the required tube diameter.

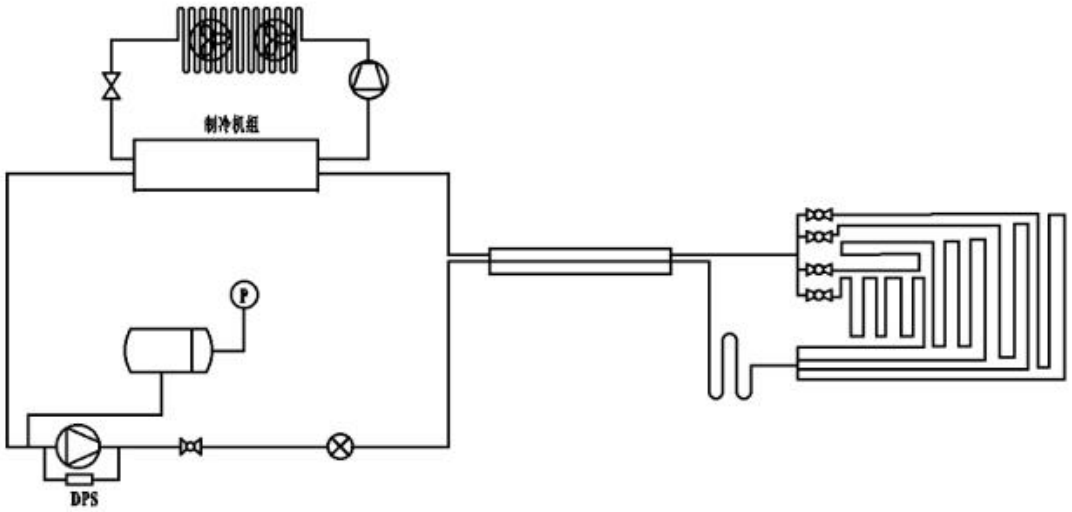
Simulation result of co_2 cooling for the ITK stave(1973.2mm×41mm)

CO_2 Cooling Analysis and Progress

We have collaborated with the Technical Institute of Physics and Chemistry (TIPC), CAS, on the development of the CO_2 cooling system. Several rounds of detailed discussions have been conducted on key aspects,

- accumulator (hydraulic type selected),
- pump (gear pump selected),
- two-stage cascaded cooling (Freon–CO_2 or Methanol–CO_2),
- the pressure regulating valve,
- overall cooling system dimensions,etc.

The first CO_2 cooling system prototype is designed to be compact and portable, handle a nominal heat dissipation power of 2kW (up to 4kW),with a CO_2 inlet temperature adjustable between–40°C and 20°C, and maintain a temperature control accuracy of <0.5°C.We aim to complete the first CO_2 cooling system prototype in 2026.



CO2 laboratory of the TIPC in Lang fang

Summary

1. Validated Design: Mechanical & Water-Cooling performance va by simulation.

2. Structures in Production: Lightweight, high-conductivity carbon fiber parts now in manufacturing; optimization via testing to follow.

3. Future Cooling in Development: CO_2 cooling prototype underway for next-phase thermal management iteration.