
# Mechanics of CEPC Magnet and Calorimeter

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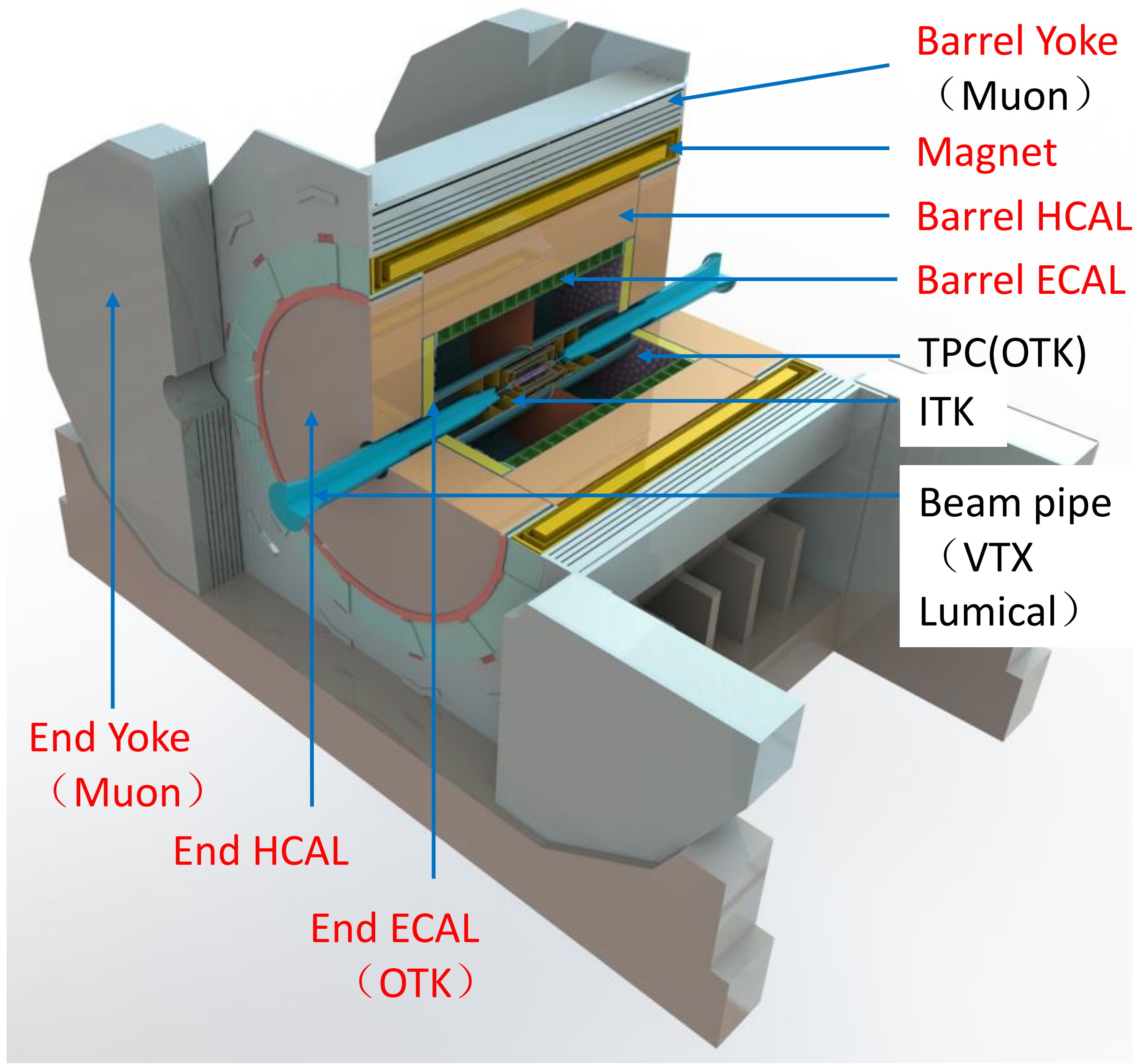
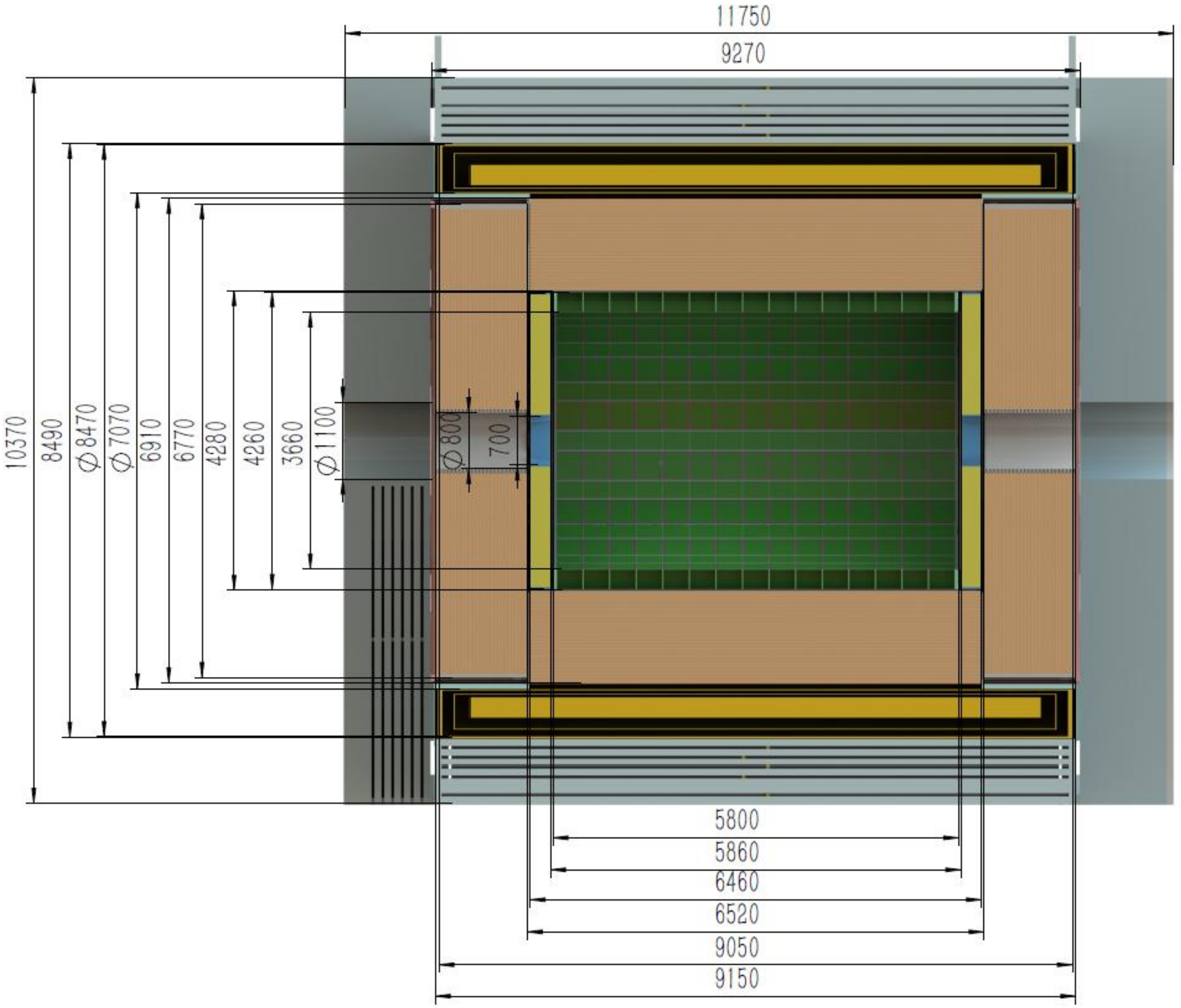
# Outline

- Overview of Magnet, HCAL and ECAL structure
- Technical design of Magnet
  - Detailed design of the detector magnet
  - Simulation of coil
  - Cryogenic system and cryostat
  - R&D and prototypes
- Mechanical design of HCAL
  - HCAL mechanics design
  - HCAL cooling system
- Mechanical design of ECAL
  - ECAL mechanics design
  - ECAL cooling system
- Next plan

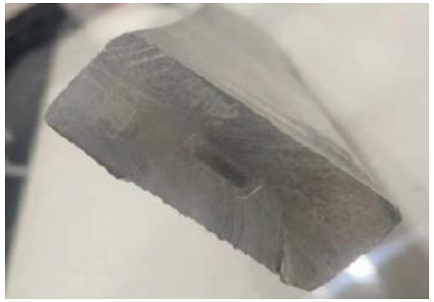
# Overview of Magnet, HCAL and ECAL structure

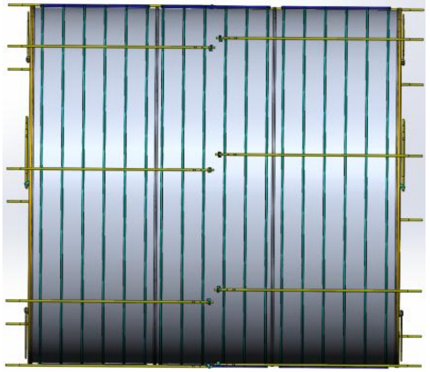


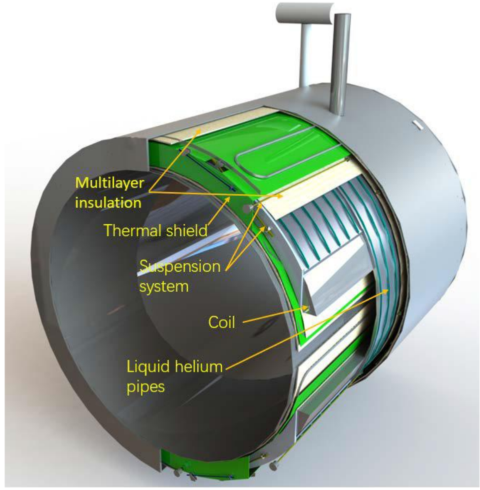



# Magnet

- Large-size and high-strength Aluminum stabilized superconducting cable;
- Suspension system of the huge coil (145 tons);
- High precision machining and assembly of large scale coil;
- There are lots of welds in low-temperature pipes, including pipes and coil supports, pipes and liquid/gas helium tanks.

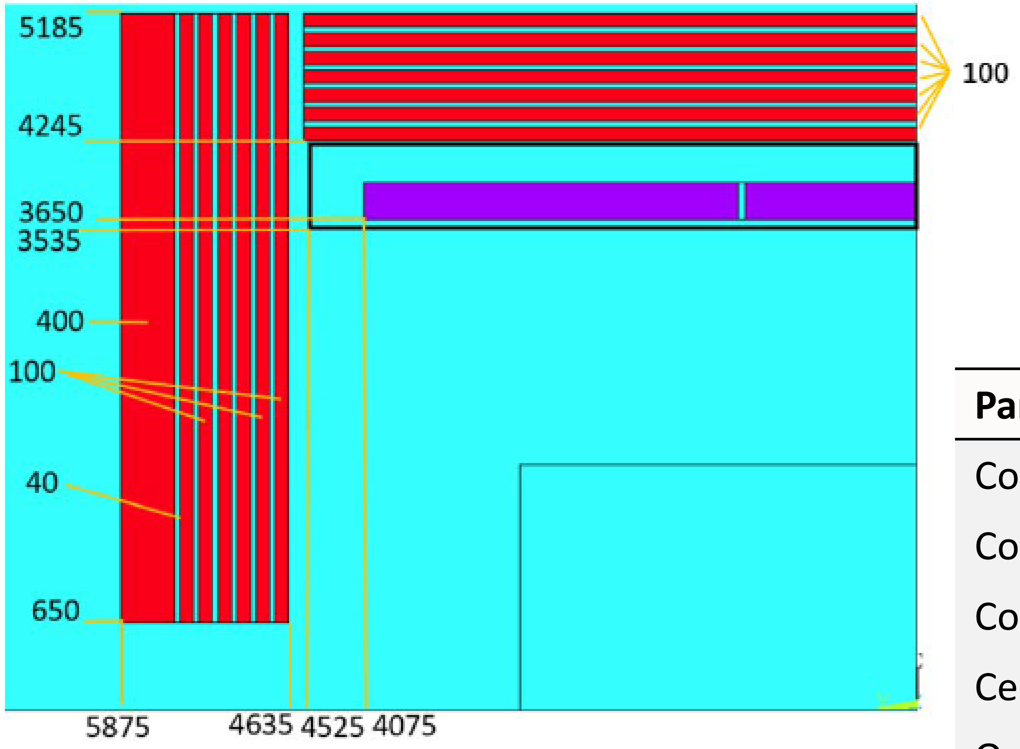






# Technical design of Magnet

## Detailed design of the detector magnet




- Red color is Yoke and its weight is 2960 tons
- Black border line is Magnet and its weight is 250 tons
- Purple color is coil and its weight is 145 tons

### Main parameters of Magnet

| Parameter | Value |
|---|---|
| Inner diameter | 7070 mm |
| Outer diameter | 8470 mm |
| Length | 9050 mm |

### Main parameters of coil

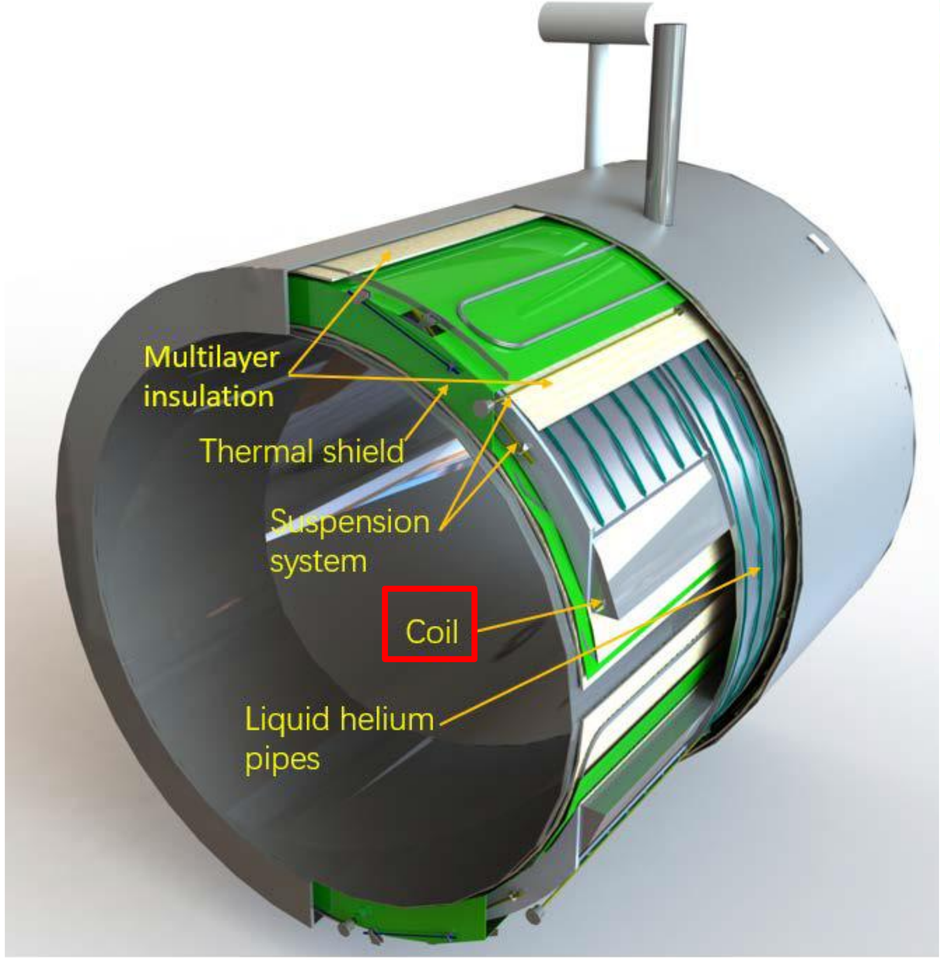
| Parameter | Value |
|---|---|
| Coil Inner diameter | 7300 mm |
| Coil Outer diameter | 7916 mm |
| Coil length | 8150 mm |
| Central magnetic field | 3 T |
| Operating current | 17 kA |
| Coil Module gap | 50 mm |
| Inductance | 11 H |
| Stored Energy | 1.54 GJ |

### Main parameters of Yoke

| Barrel parameter | Value |
|---|---|
| Inner inradius diameter | 8490mm |
| Outer inradius diameter | 10370mm |
| Length of barrel | 9150 mm |
| Quantity of layer | 7 |
| Gap between two layers | 40mm |
| Weight | 1560tons |
| **End-cap parameter** | **Value** |
| Inner diameter | 1300mm |
| Outer inradius diameter | 10370mm |
| Thickness of one end | 1240mm |
| Quantity of layer | 7 |
| Gap between two layers | 40mm |
| Weight | 700*2tons |

# Technical design of Magnet

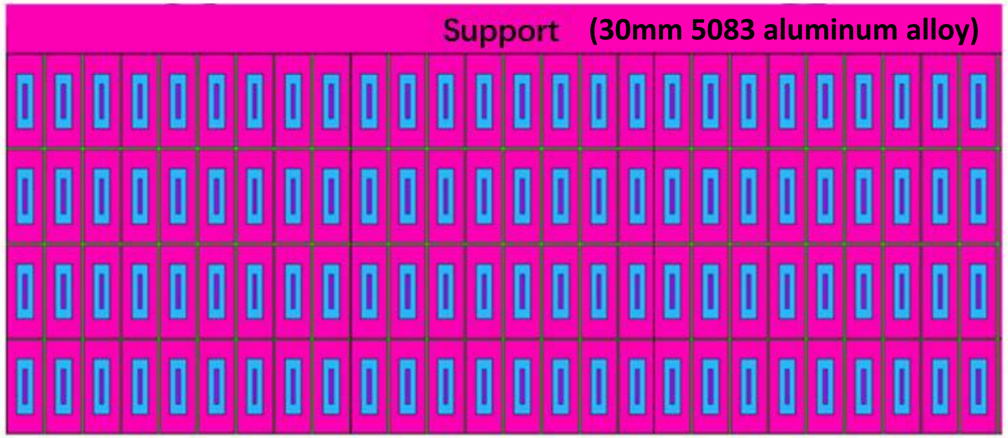
## Detailed design of the detector magnet




- Detailed structure of magnet

Coil

Internal winding technique



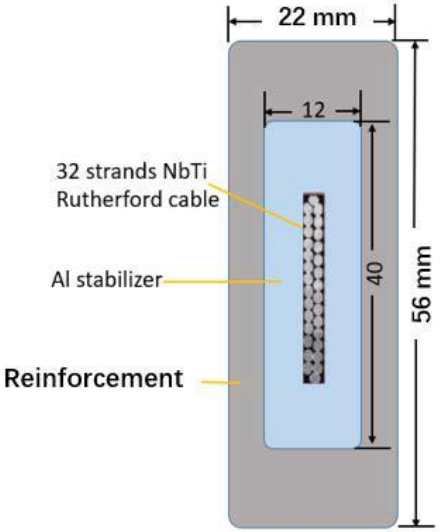



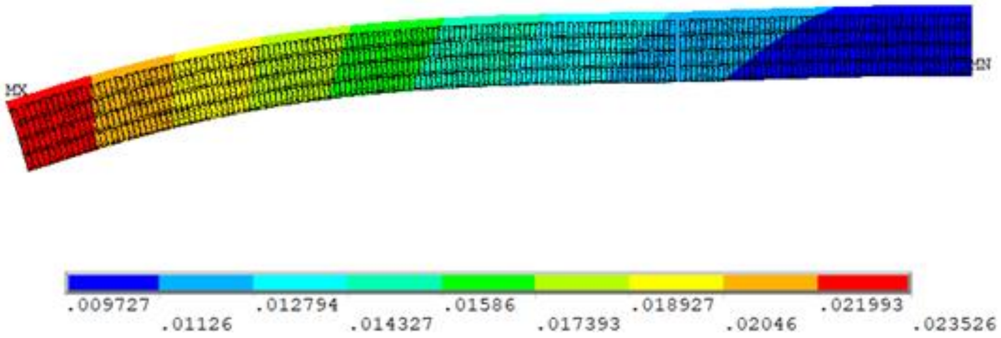

**Table 10.3:** Conductor overall characteristics

| Parameters | Value |
|---|---|
| Nominal design current | 17 kA |
| Critical current at 4.2 K and 5 Tesla | 51 kA |
| Total length of conductor | 33 km |
| Overall dimension (Without Insulation) | 56 mm × 22 mm |
| Superconducting cable cross section area | 2.2 mm × 20.5 mm |
| Al stabilizer cross section area | 12 mm × 40 mm |

# Technical design of Magnet

## Simulation of coil

The magnetic induction intensity at the point of interaction on the axis is 3 T, and the peak field on the coil is 3.8 T




Overall distortion of the coil

The coil mainly faces two working conditions: cooling to 4.2 K and excitation to 17 kA.

During the actual installation of the coil, deviations from the design position are inevitable due to processing and measurement errors

| Material | Von Mises stress(MPa) | Allowable stress(MPa) |
|---|---|---|
| | **Coil at 4.2K (After cooling)** | |
| Aluminum stabilizer | 7.7-20.0 | 34 |
| NbTi/Cu cable | 177-279 | ＞800 |
| Al alloy | 7.0-43.3 | ＞500 (160) |
| Al alloy support | 6.3-36.3 | ＞500 (160) |
| | **Coil at 4.2K (After exciting)** | |
| Aluminum stabilizer | 14.3-22.5 | 34 |
| NbTi/Cu cable | 28-246 | ＞800 |
| Al alloy | 60.8-137 | ＞500 (160) |
| Al alloy support | 62.2-127 | ＞500 (160) |

PASS

PASS

**Table 10.7:** Forces and torques of coil offset

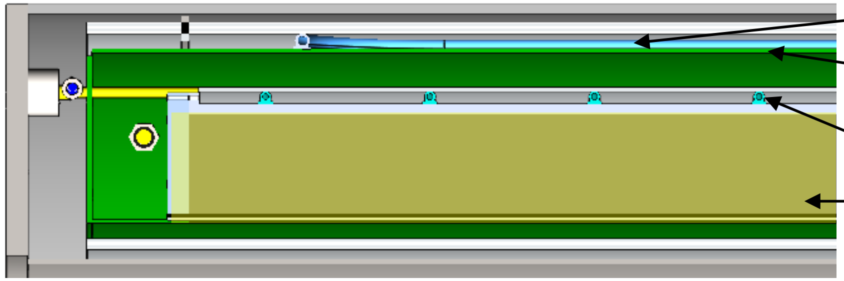
| **Axial displacement** $(cm)$ | **1** | **3** | **10** |
|---|---|---|---|
| **Axial force** $(kN)$ | 391 | 1247 | 5276 |
| **Radial displacement** $(cm)$ | 1 | 3 | 10 |
| **Radial force** $(kN)$ | 49.3 | 258 | 708 |
| **Angular tilt** $(degree)$ | $1/407.5 = 0.14°$ | $3/407.5 = 0.42°$ | $10/407.5 = 1.41°$ |
| **Torque** $(kN \cdot m)$ | 1678 | 7020 | 17647 |

# Technical design of Magnet

## Cryogenic system and cryostat

### Cooling methods: Thermal siphon

| | Thermal siphon | Forced flow |
|---|---|---|
| **Difference** | Need more space to install the phase separator | A liquid helium circulating pump is required |
| **Heat exchange capability** | 1200 W/(K·m$^2$) | 412.1 W/(K·m$^2$) |
| **Coil maximum temperature** | **4.982 K** | **5.383 K** |
| **Coil average temperature** | **4.591 K** | **4.972 K** |
| **Size of Liquid helium pipes** | Φ15 mm | Φ 20 mm |




### A 4 K liquid helium cryogenic system

① The coil cryogenic system within the coil vacuum vessel
② The compressor and refrigerator (including liquid helium Dewar)
③ The cryogenic transfer and distribution system (valve box and piping)
④ The recovery and purification system.

### Heat loads calculation

**Table 10.13:** The heat load of 4K

| Component | Heat Load (W) |
|---|---|
| Static heat loads | 157 |
| Peak value of dynamic heat load | 193 |
| **Total** | **350** |

**Table 10.14:** The heat load of 60 K thermal shield

| Component | Heat Load (W) |
|---|---|
| Radiation heat load | 373 |
| Support heat load | 54 |
| Phase separator / Pipes / Valves | 160 |
| Current leads | 2000 |
| Dynamic heat loads | 65 |
| **Total** | **2652** |

# Technical design of Magnet

## Cryogenic system and cryostat

**Temperature distribution result by FEA**

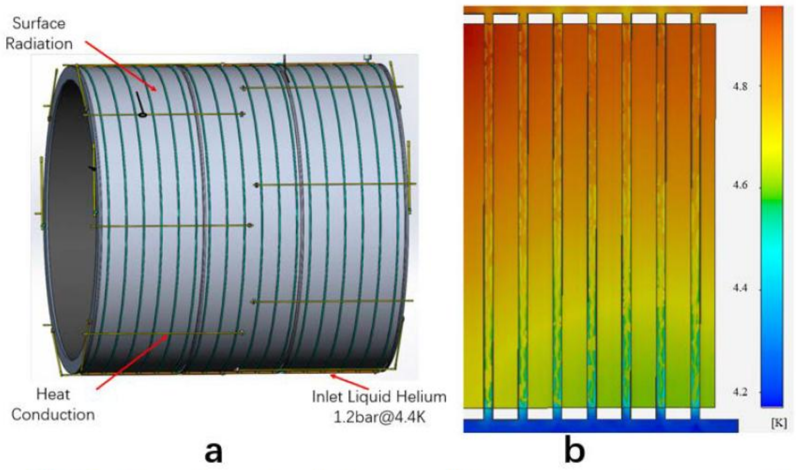



Figure 10.37: Boundary Conditions and Temperature Contour of the coil

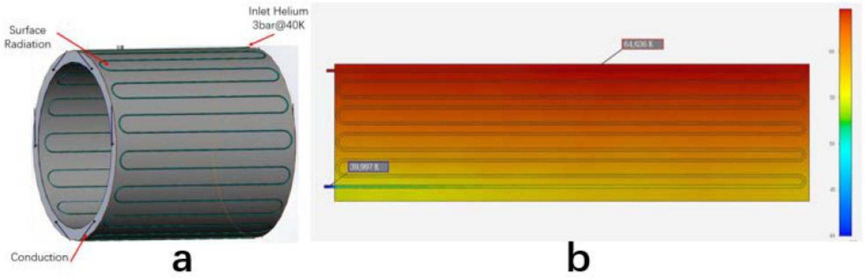
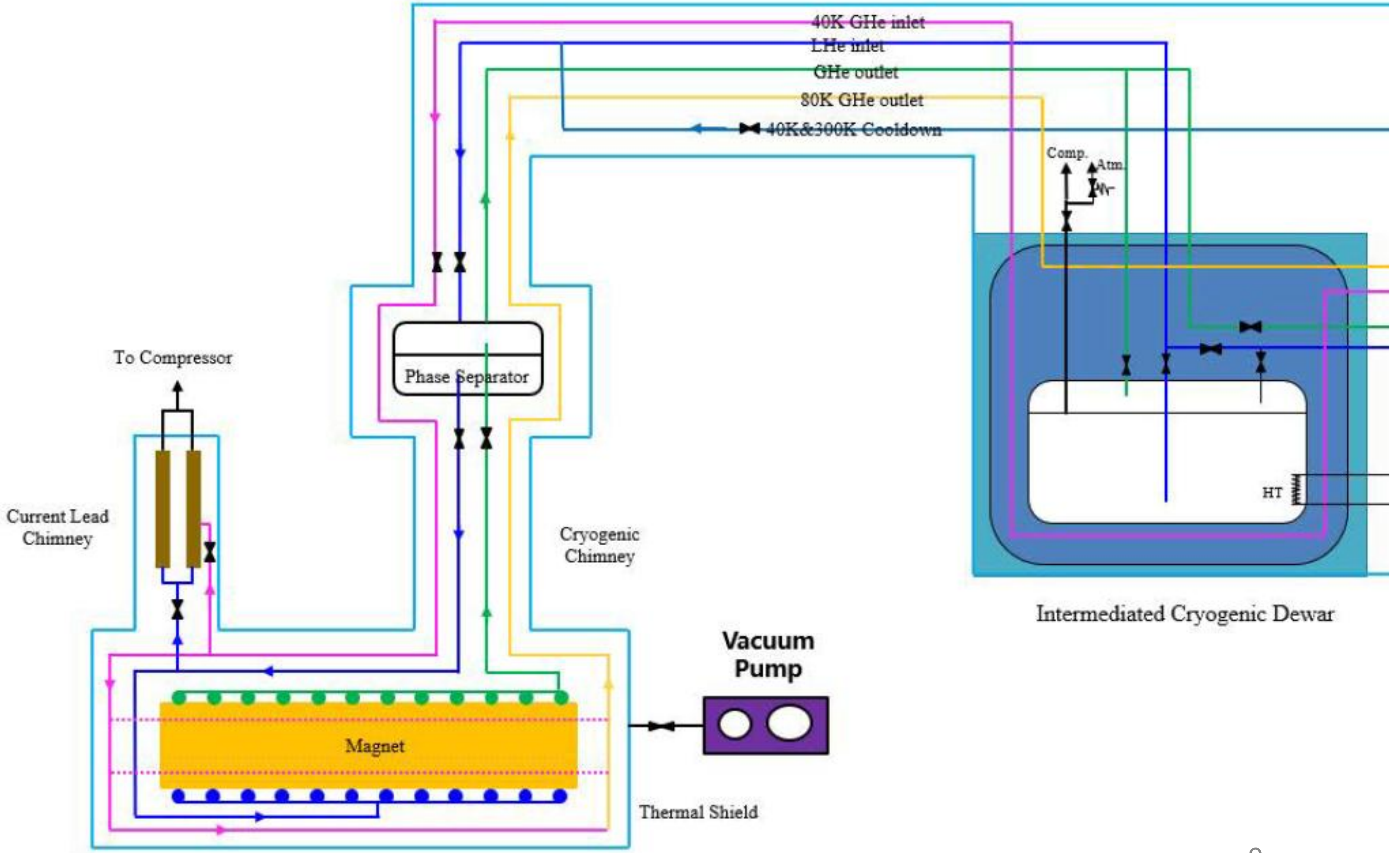


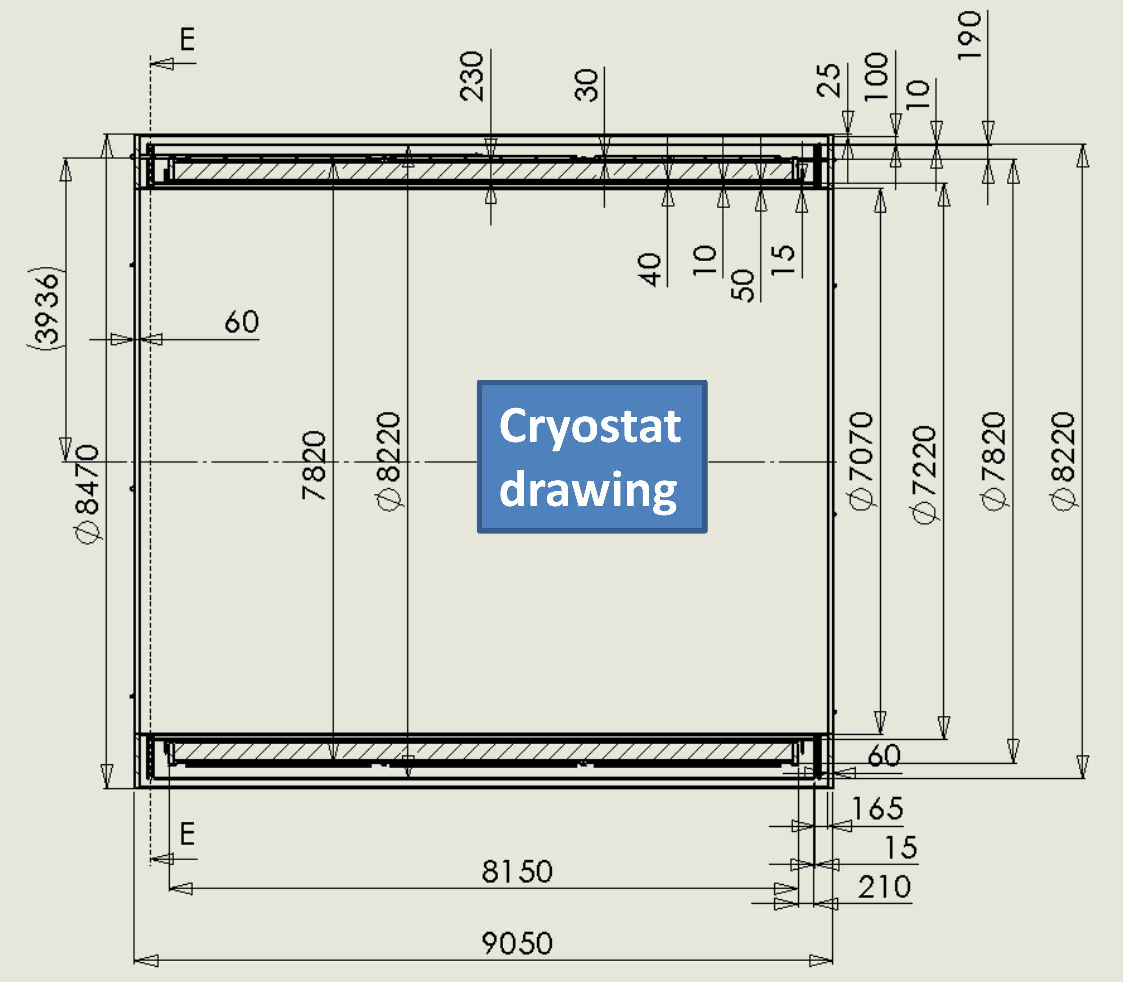

Figure 10.38: Boundary Conditions and Temperature Contour of the thermal shield

**Coil cryogenic circuits**



# Technical design of Magnet

## Cryogenic system and cryostat




**Suspension system**

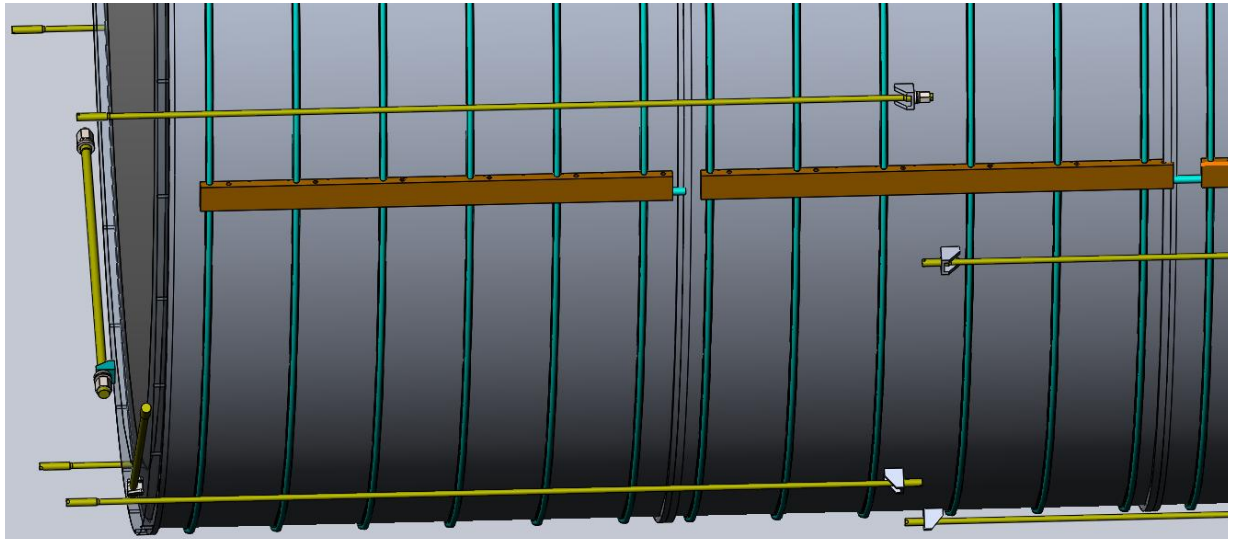


Table 10.18: Parameters of the titanium alloy rods. There are three types of rods used in the coil suspension system. Different rods have different functions.

| Rod Type | Diameter (mm) | Length (mm) | Screw |
|---|---|---|---|
| Axial rods | 30 | 3530 | M36×3 |
| Radial rods | 40 | 1700 | M48×4 |
| Main pull rods | 48 | 1650 | M56×4 |

# Technical design of Magnet

## Cryogenic system and cryostat

### Vacuum tank

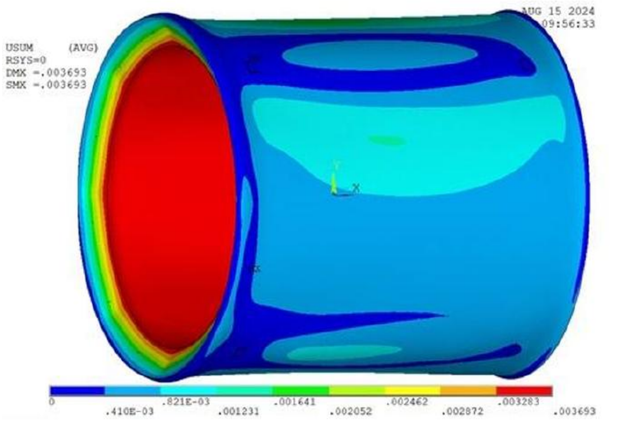


Figure 10.59: Deformation distribution of the vacuum tank

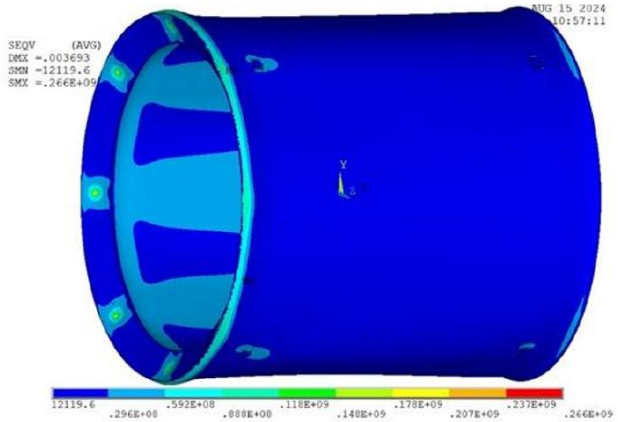


Figure 10.60: Stress distribution of the vacuum tank

### Magnet support system

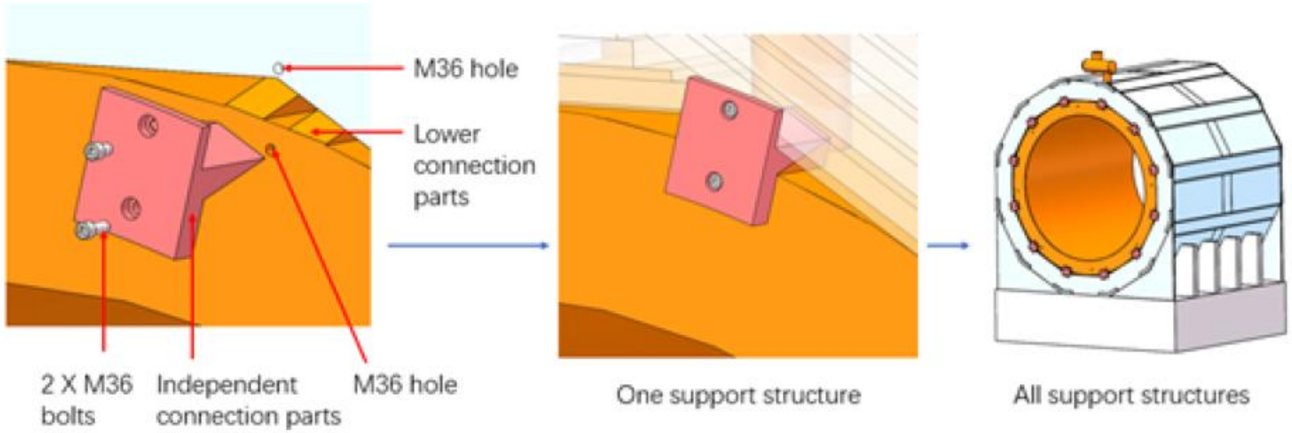



Figure 10.64: Final connection structure

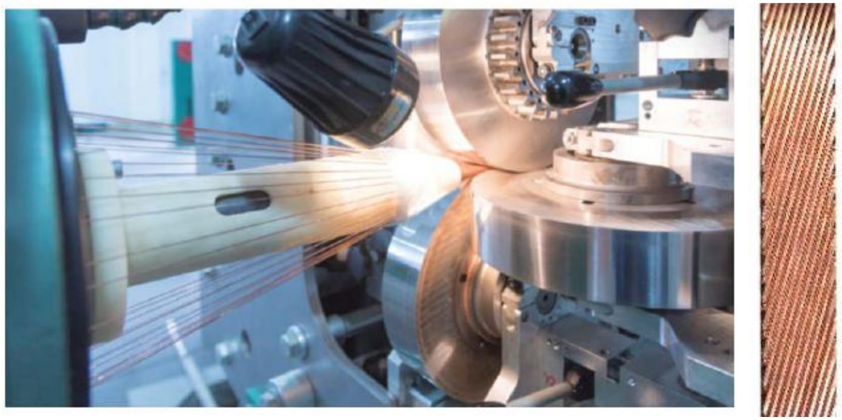
Table 10.21: Deformation and stress of support structure under different coil offset conditions

| Parameter | 1 cm | 3 cm | 10 cm |
|---|---|---|---|
| **Axial displacement** | | | |
| Deformation (mm) | 0.0556 | 0.0559 | 0.0568 |
| Stress (MPa) | 391 | 394 | 402 |
| **Radial displacement** | | | |
| Deformation (mm) | 0.056 | 0.057 | 0.059 |
| Stress (MPa) | 392 | 398 | 416 |
| **Angular tilt** | | | |
| Angular tilt (degrees) | 0.14 | 0.42 | 1.41 |
| Deformation (mm) | 0.064 | 0.025 | 0.062 |
| Stress (MPa) | 423 | 1308 | 3201 |

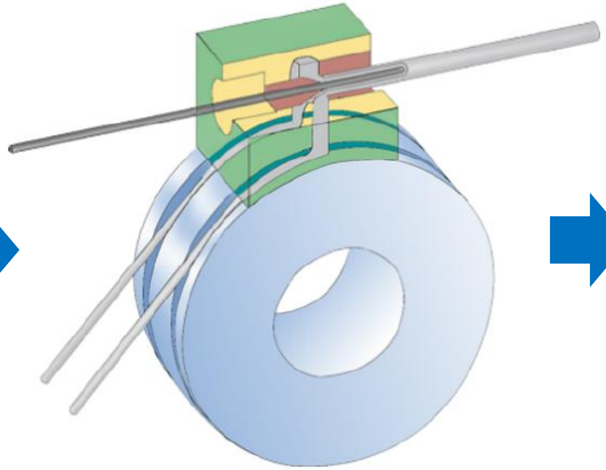
# Technical design of Magnet

## R&D and prototypes

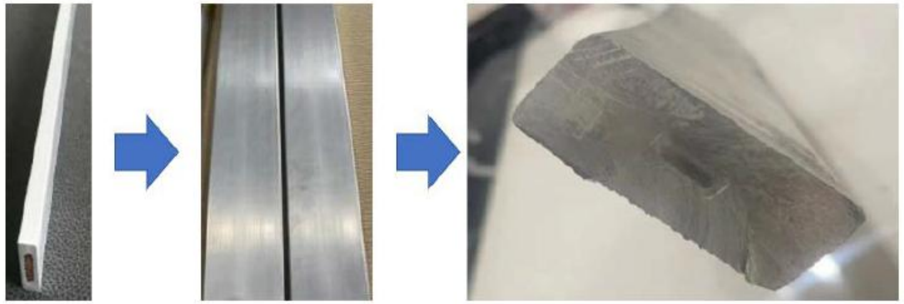
### Conductor R&D and prototypes



Stranding process



First and second co-extrusion forming



A 3m long sample conductor with box configuration superconductor

Table 10.8: SC strands parameters

| Parameters for wires | Value |
|---|---|
| Strand diameter | 1.30±0.01 mm |
| Cu/SC ratio | 1.07±10% |
| Ic @5 T,4.2 K | 1750 A |
| RRR of copper matrix | 100 |
| Filament diameter | About 34$\mu$m |
| Number of filaments | 708 |

- Before and after stranding, the NbTi wire's critical current decay is less than 5%, and the RRR value of copper declined by about 1/3 after the stranding process.
- After second co-extrusion process, the critical current decay is bout 10%
- A first 16 strands Aluminum stabilized superconductor was realized as the R&D （In the future it is 32 strands）.
- The shear strength between aluminum and Rutherford cable is 35 MPa

# Technical design of Magnet

## R&D and prototypes

### Dummy coil development

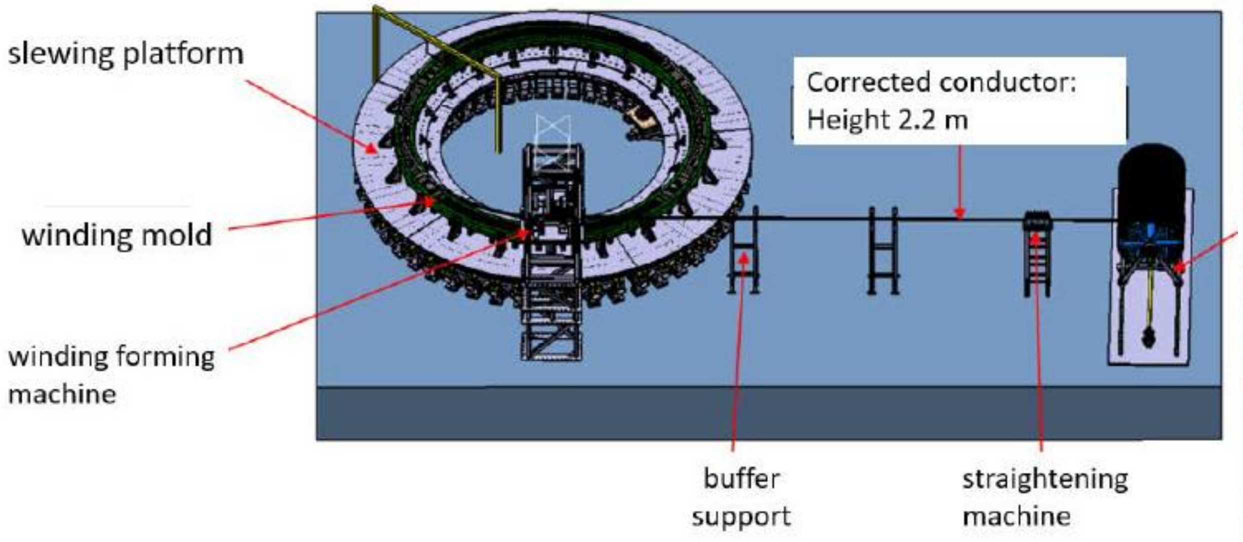
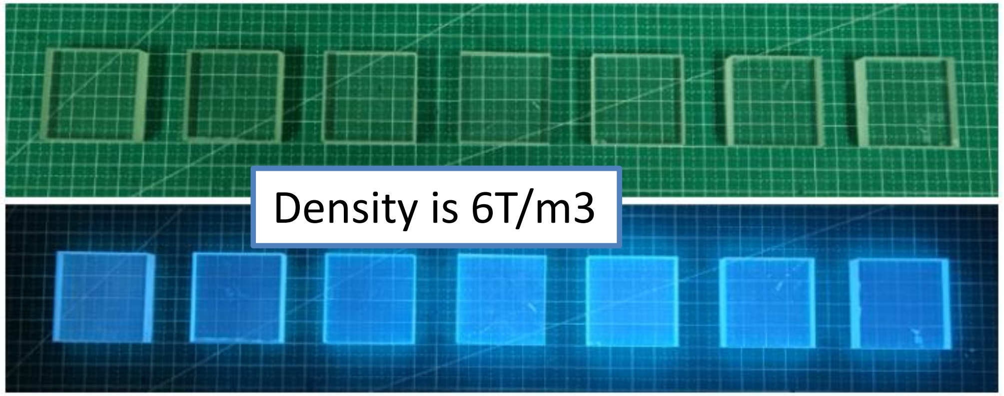


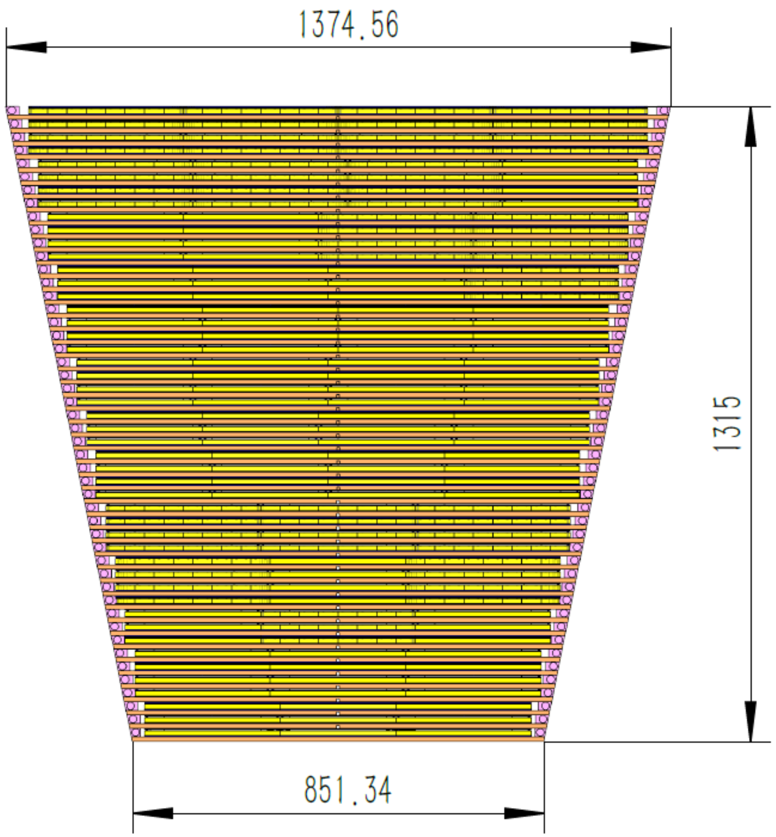

**Figure 10.12:** The diagram of the winding line

- Mainly includes cable drum, straightening machine, buffering support frame, winding forming machine, rotary platform, and winding mold
- Using the inner winding technique and vacuum impregnation of large-diameter coils
- The dummy coil consists of an aluminum alloy support cylinder and 4 layers of coils, with 10 turns per layer

# HCAL

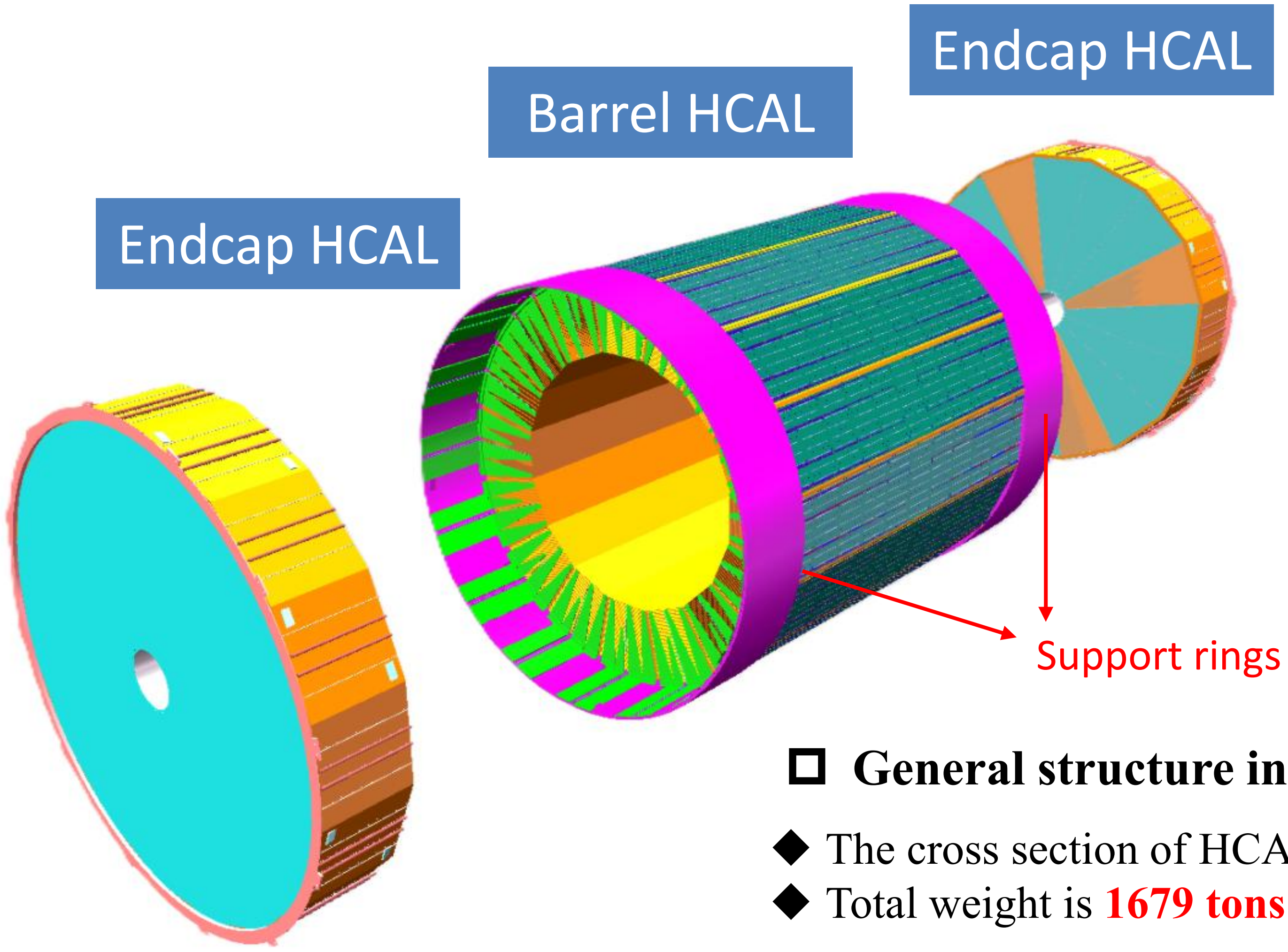
- The space for mechanics and services (e.g. cooling, cabling) integration is very narrow;
- Supporting structure need to ensure mechanical stability and alignment precision throughout the detector's lifetime. Which means how can we use 46% weight to support 54% weight.



# HCAL mechanics design

- **Layout for all the HCAL components**




**Requirements:**

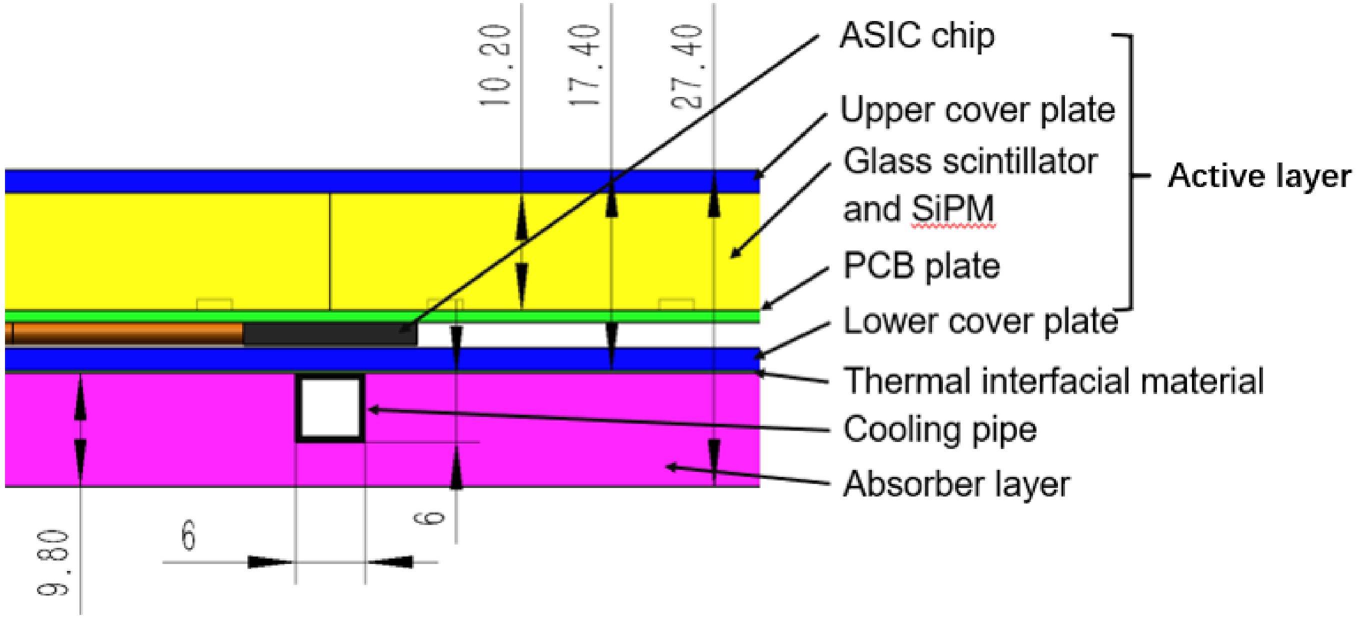
- The support structure zone is as lower as possible.
- The maximum stress of different materials need to be lower than their allowable stress level.
- The deformation of different materials need to be controlled so that there will be no broken parts under different conditions.
- Outer contour dimension tolerance need to be 0mm to -5mm and inner contour dimension tolerance need to be 0mm to +5mm.

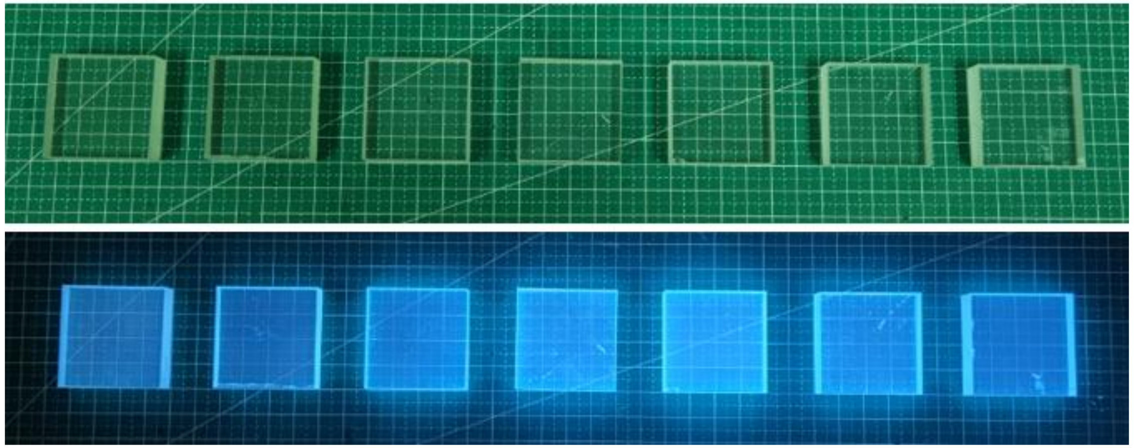
**General structure information:**

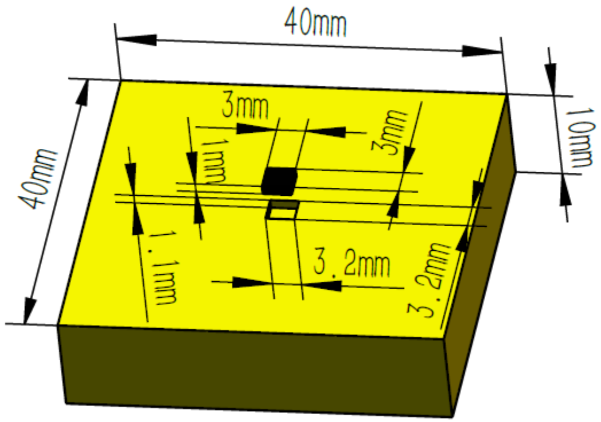
- The cross section of HCAL is a regular hexadecagon
- Total weight is **1679 tons** and there are totally **5224960 glass scintillator**

# HCAL mechanics design

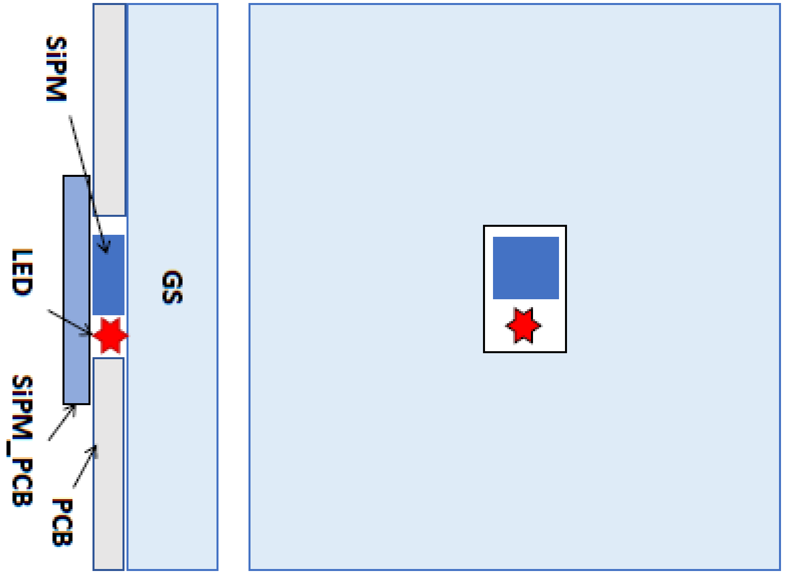
- Layout of one detect module





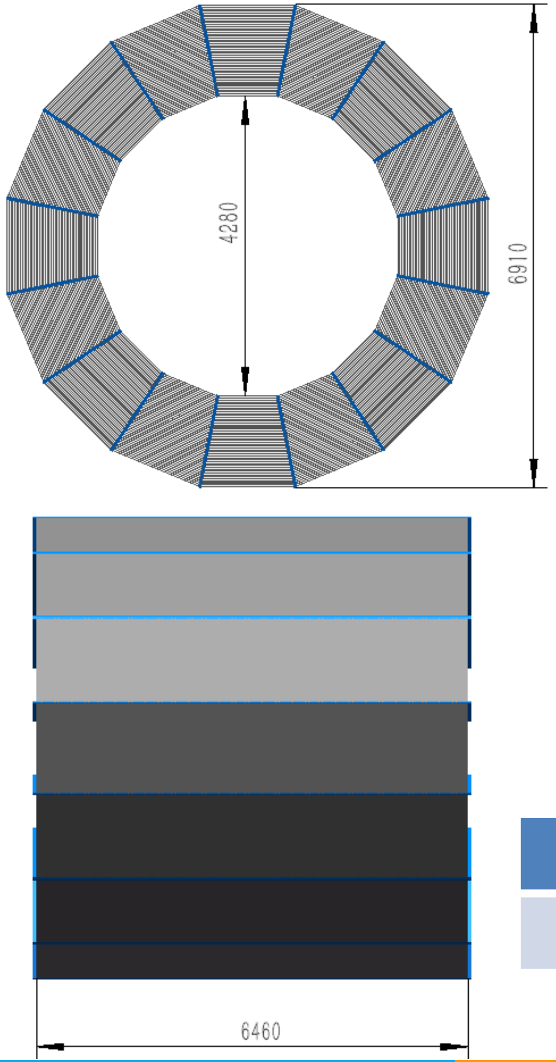

Basic plan for one cell



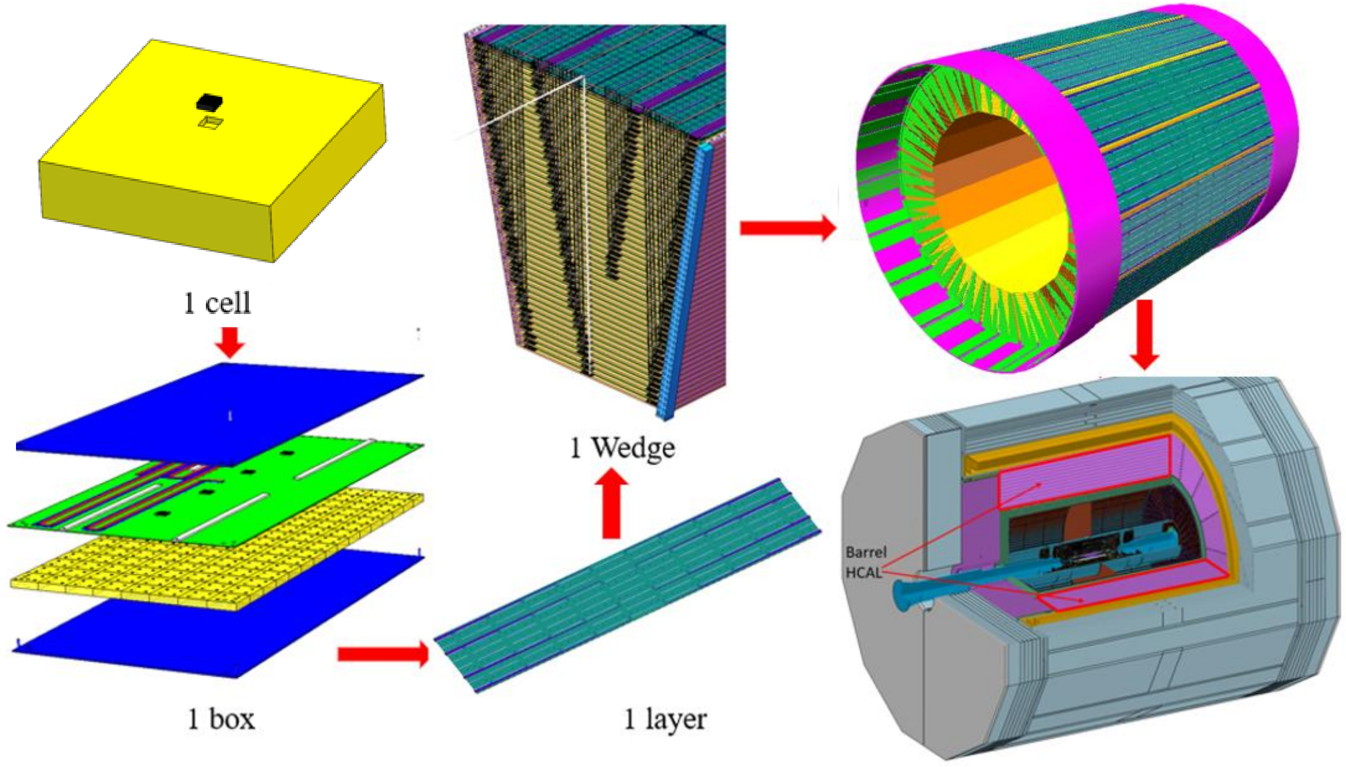

Updated plan for one cell

# HCAL mechanics design

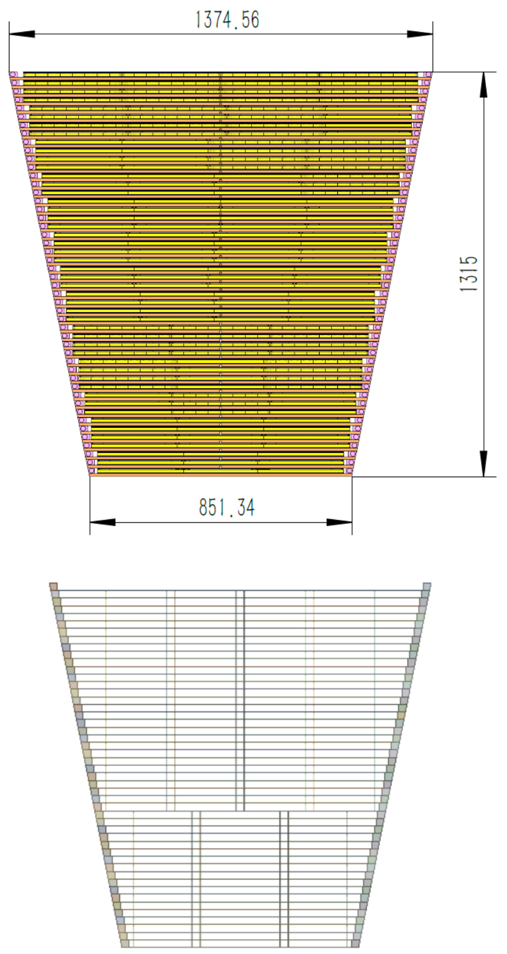
- **Barrel HCAL mechanics**




Integration of barrel HCAL structure




1 Wedge dimension



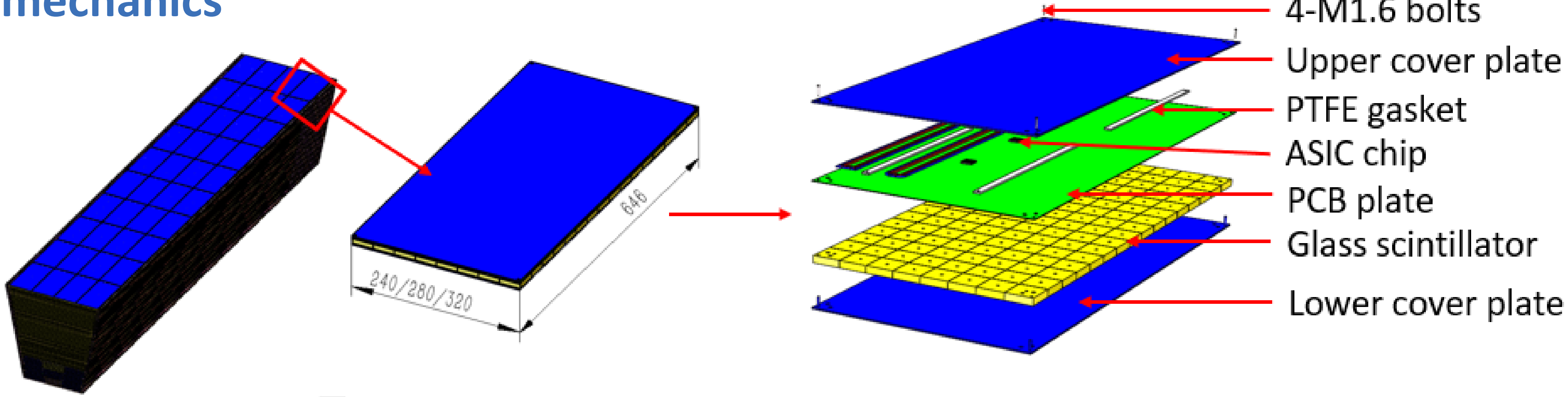

| | Cell | Box | Layer | Wedge |
|---|---|---|---|---|
| **Quantities** | 3212800 | 27840 | 48*16=768 | 16 |

**Total weight: 955 tons**

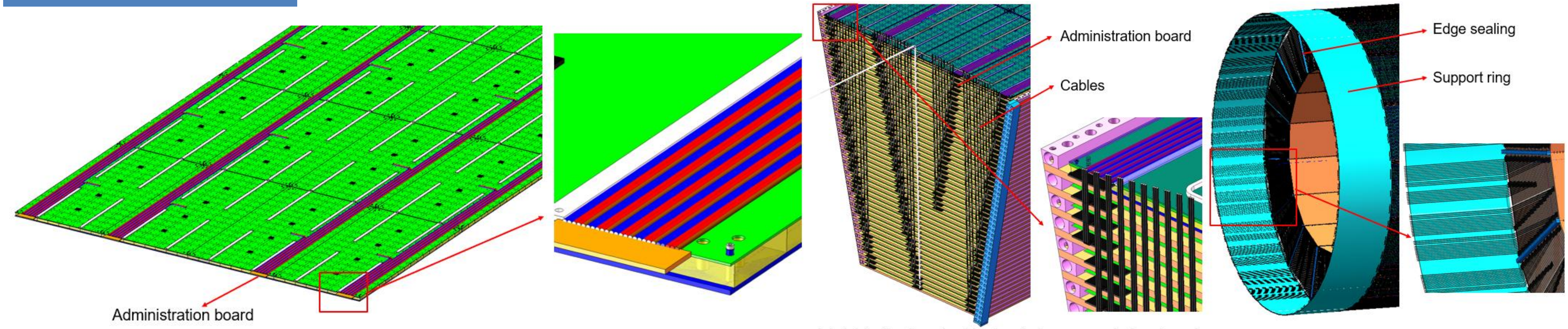
# HCAL mechanics design

## Barrel HCAL mechanics

One box structure



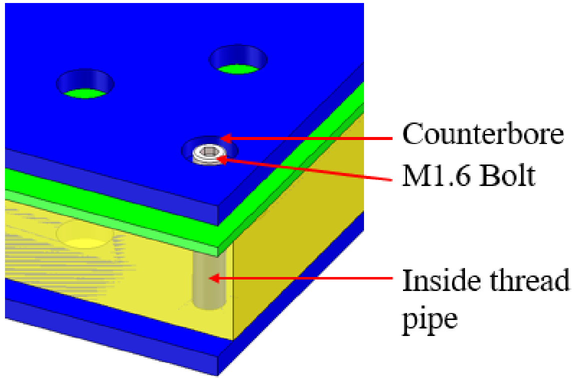

Cable routing scheme



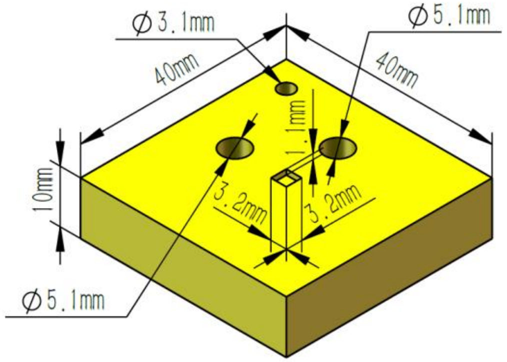
# HCAL mechanics design

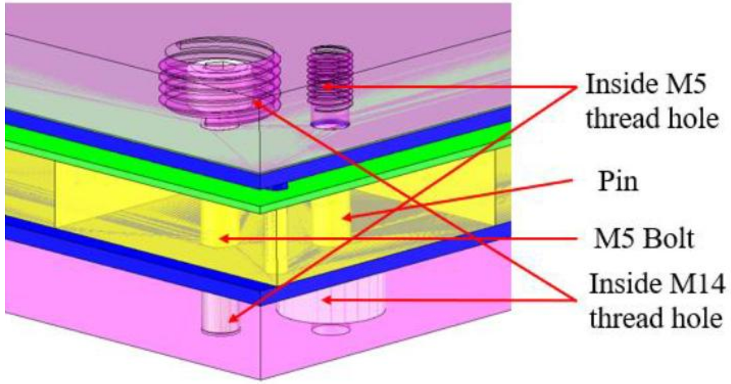
## Connection structure of barrel HCAL

Connection within one box

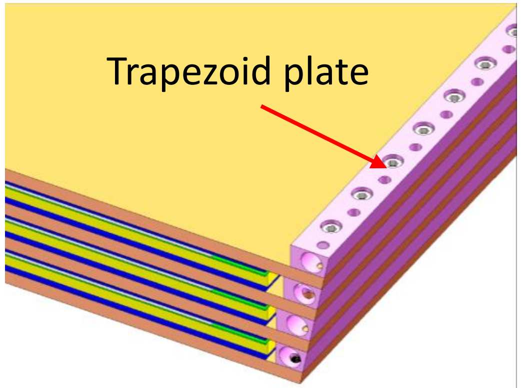



Connection between box and absorber layer

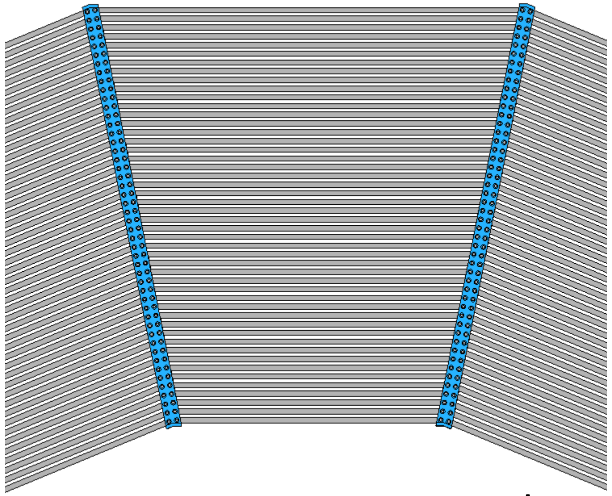


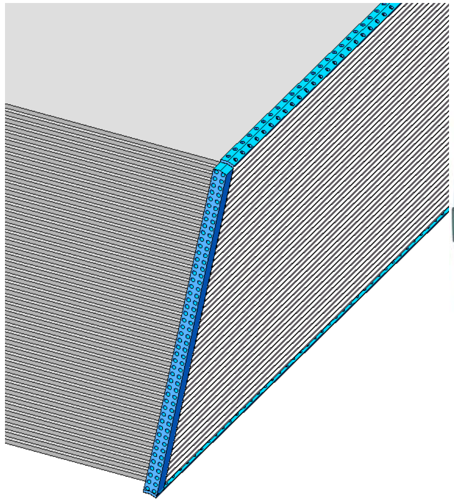




Connection between neighbor layers



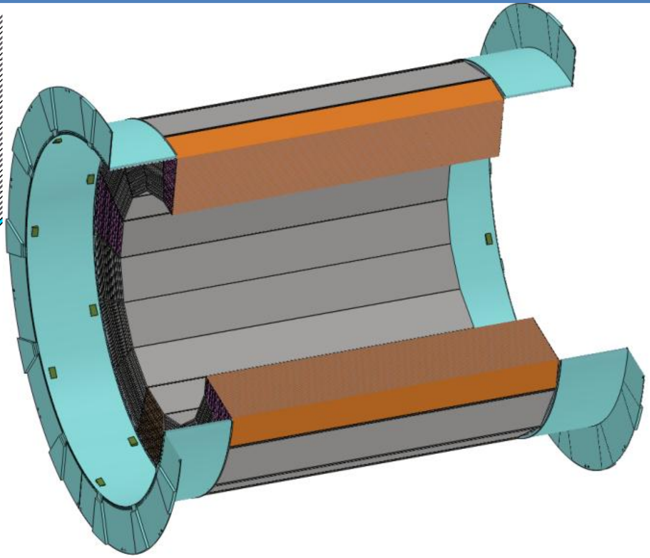

Connection between two wedges



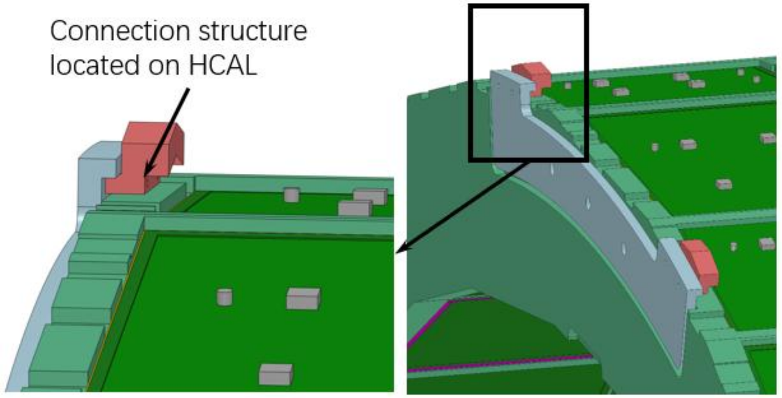


Edge sealings

Connection between Barrel HCAL and support rings



Connection between Barrel HCAL and Barrel ECAL



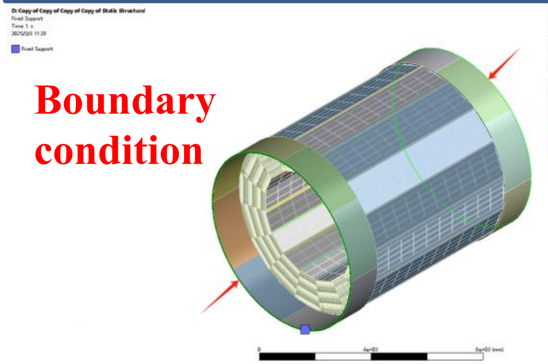
# HCAL mechanics design

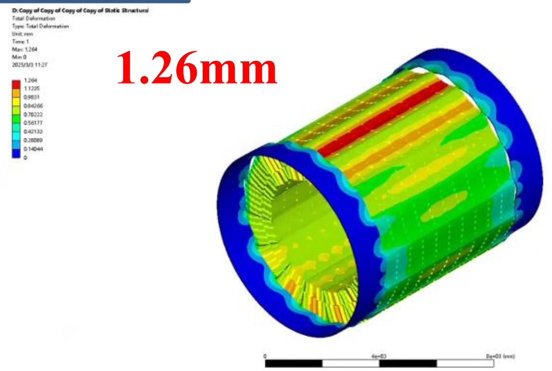
## FEA result

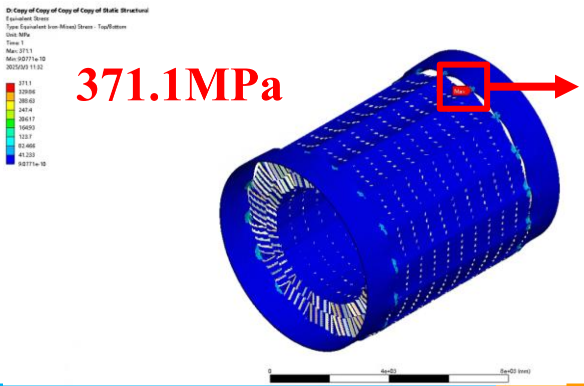
Stress and deformation of barrel HCAL under different conditions

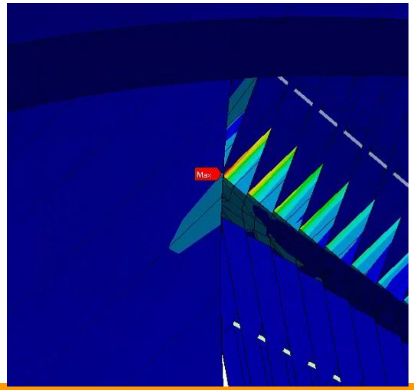
| Parameter | Stress | Deformation |
|---|---|---|
| One wedge assembling condition | 24.7MPa | 0.33mm |
| 16 wedges assembling condition | 190MPa | 0.66mm |

### Barrel ECAL connection condition



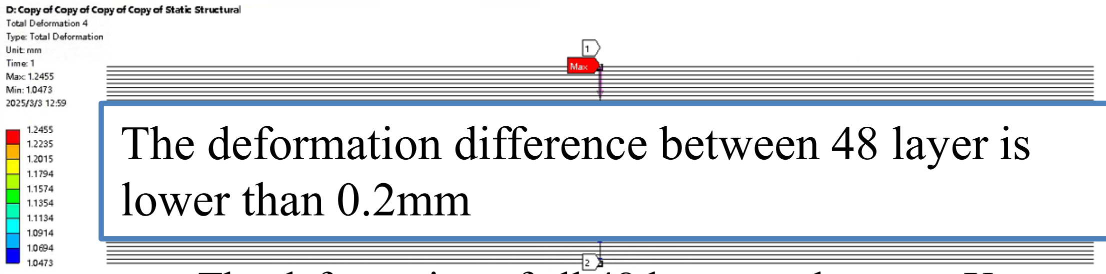



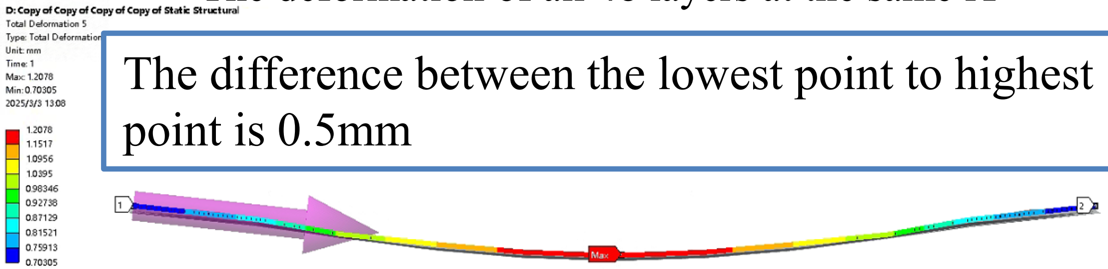
Changing the trapezoid beam from stainless steel to titanium alloy

### Active layer space analysis




The deformation difference between 48 layer is lower than 0.2mm

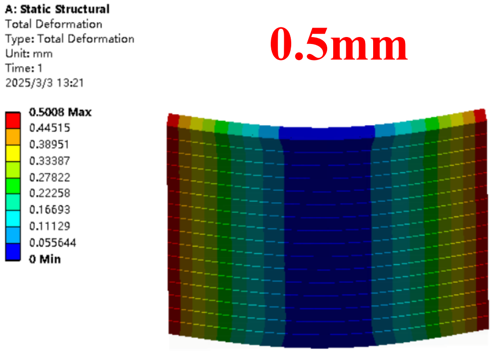
The deformation of all 48 layers at the same X

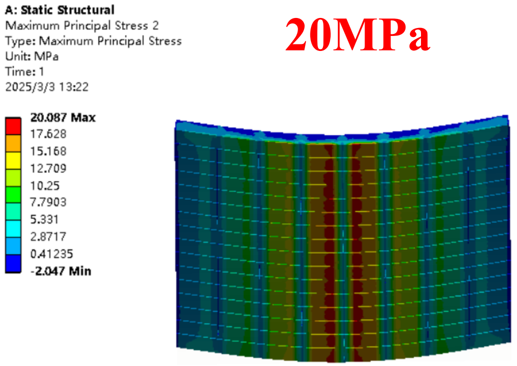



The difference between the lowest point to highest point is 0.5mm

Deformation within one layer

### GS analysis



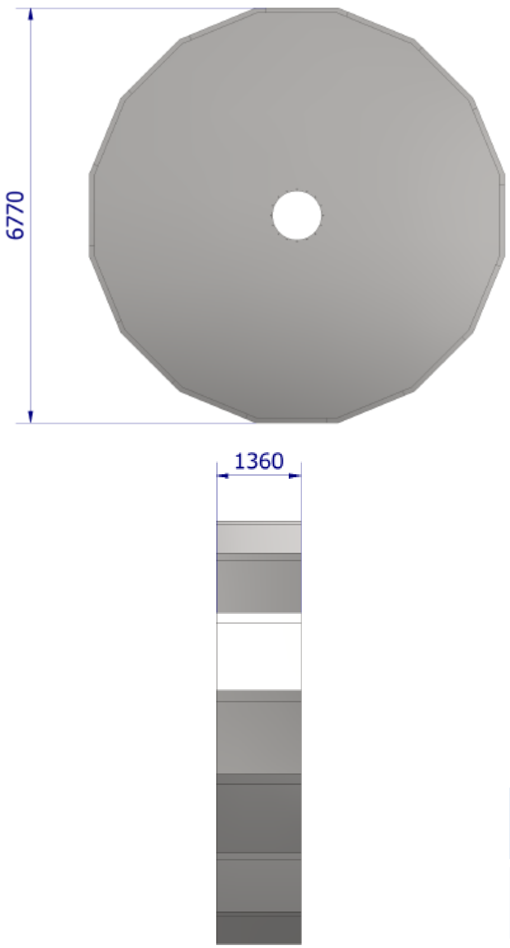



# HCAL mechanics design

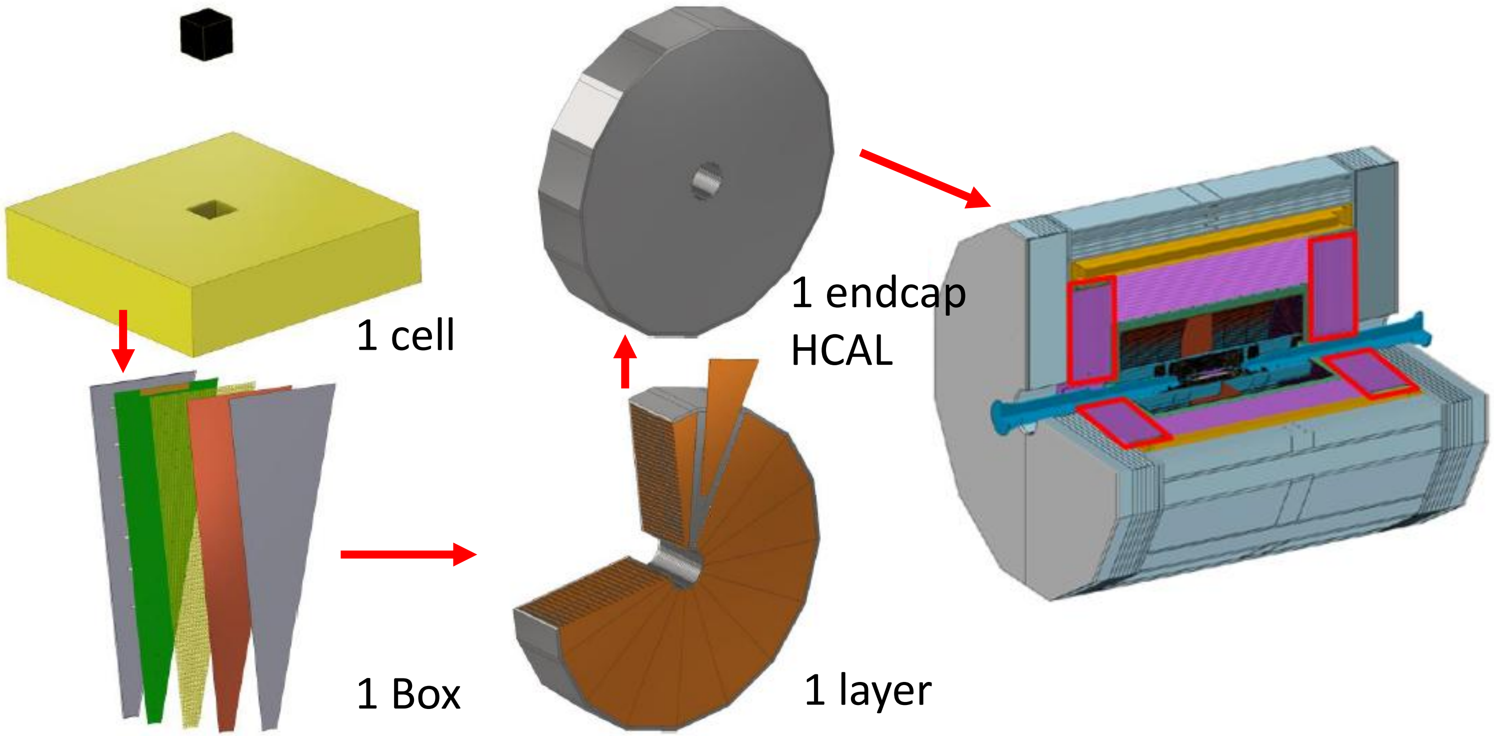
## Endcap HCAL mechanics

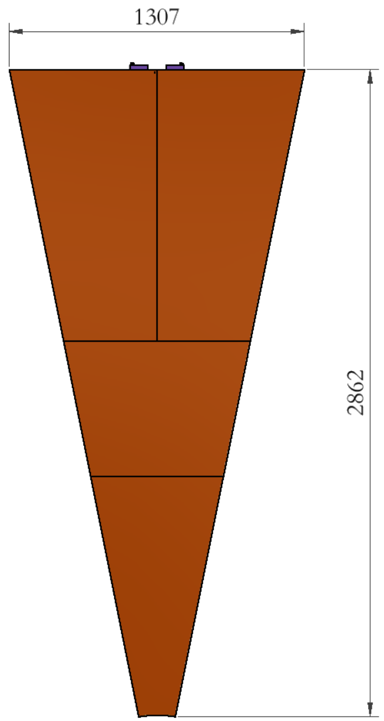
Integration of barrel HCAL structure

Boxes in one layer




Two endcap HCAL




| | Cell | Box | Layer | Wedge |
|---|---|---|---|---|
| **Quantities** | 1006080*2 | 3072*2 | 48*16*2 | 16*2 |

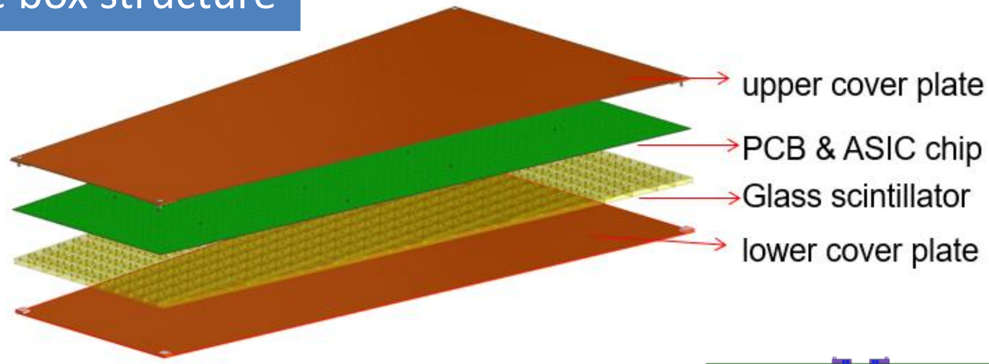
4 types Box

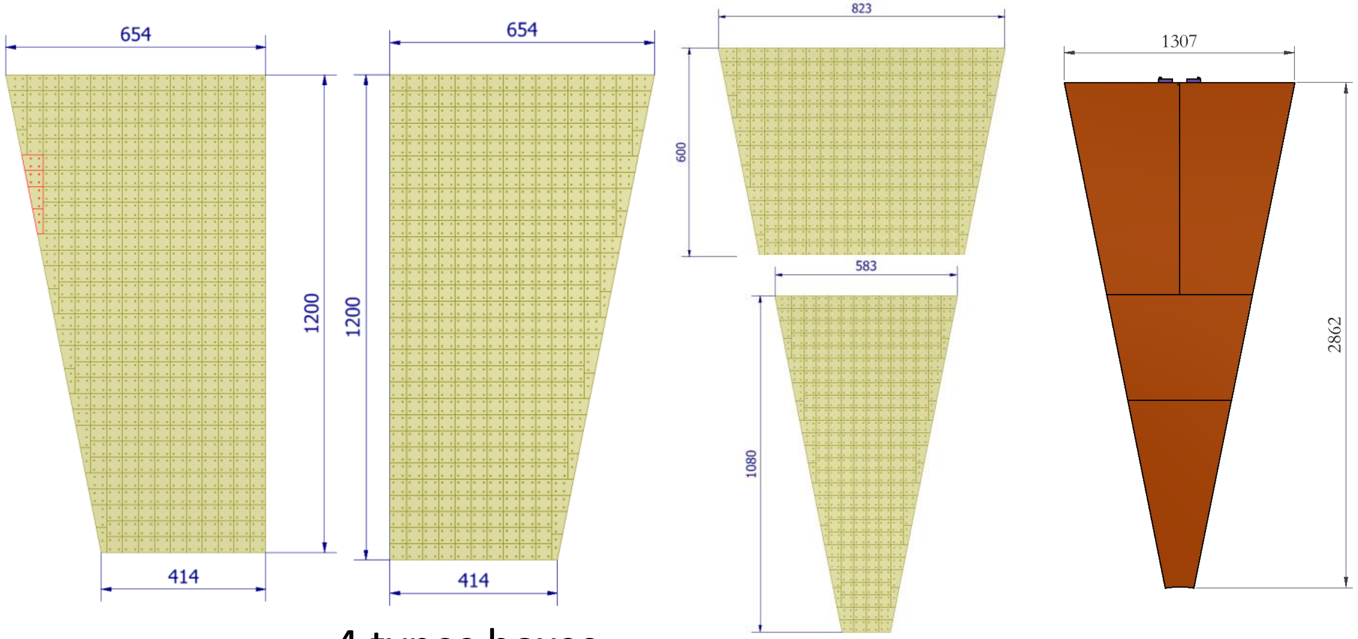
**Total weight: 362*2=724 tons**

# HCAL mechanics design

## Endcap HCAL mechanics

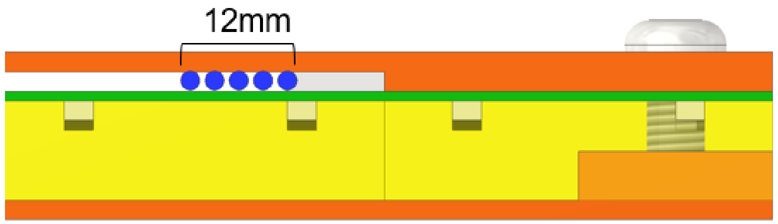
One box structure

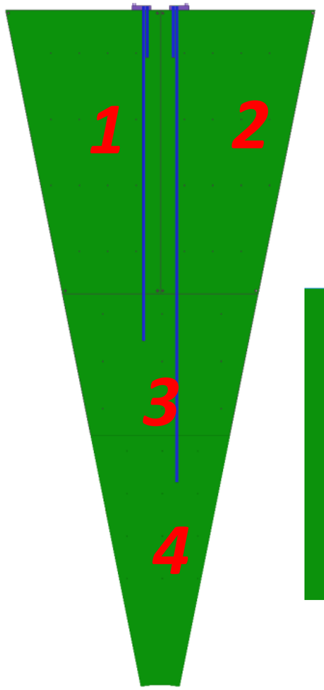


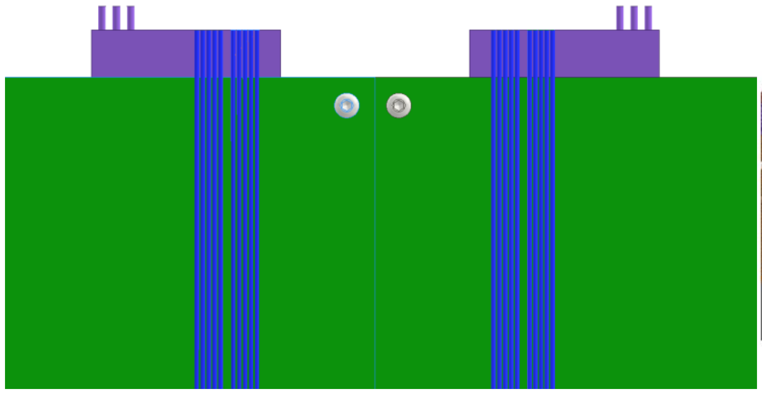



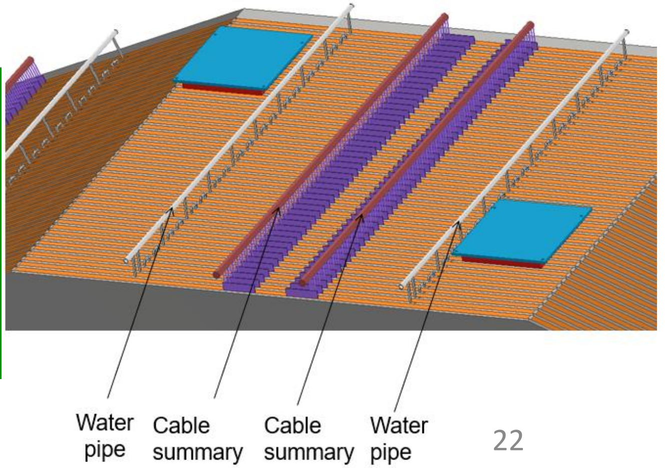

4 types boxes

Cable routing scheme



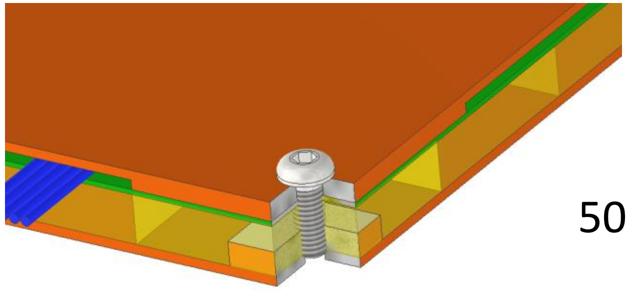



1 box have 5 cables
Cable diameter is 2mm

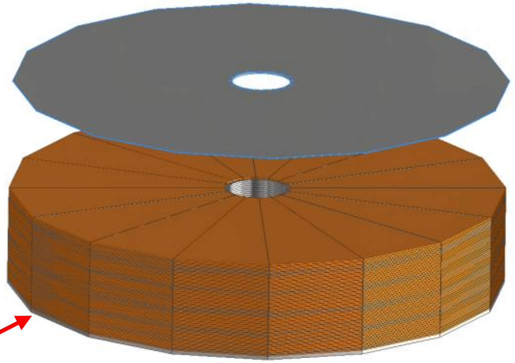
# HCAL mechanics design

- **Connection structure of endcap HCAL**

Connection within one box

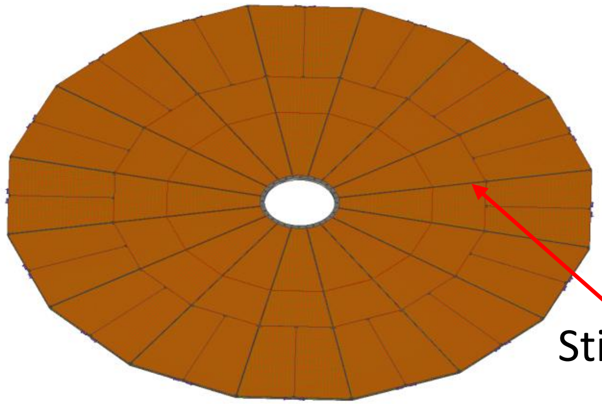


Connection between layers



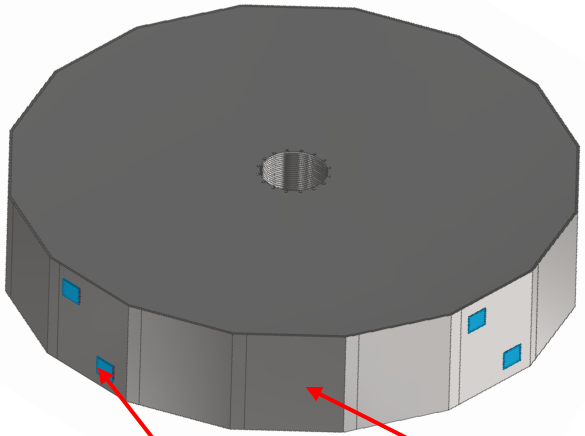
50mm

Structure between neighbor wedges



Stiffeners

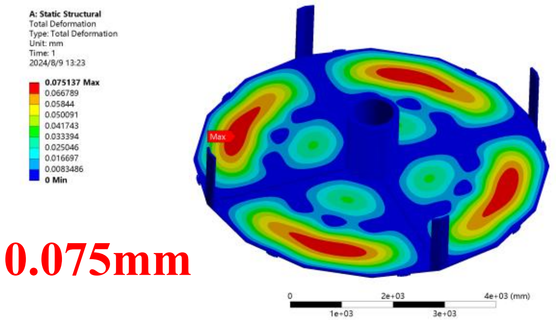
Connection between end HCAL and support rings



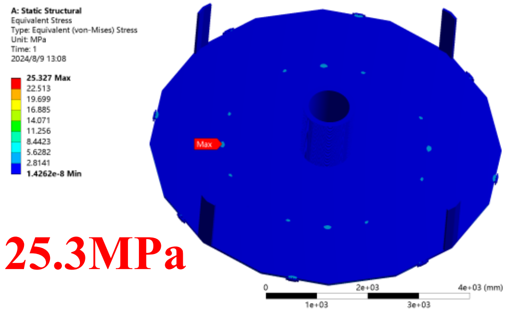
Wedge connector

Side cover plate

- **FEA result**

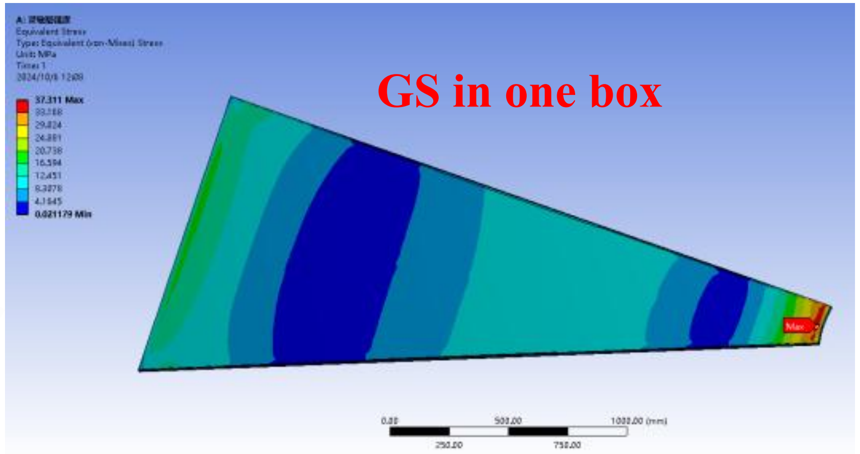



0.075mm




25.3MPa

Absorber structure during self-gravity condition

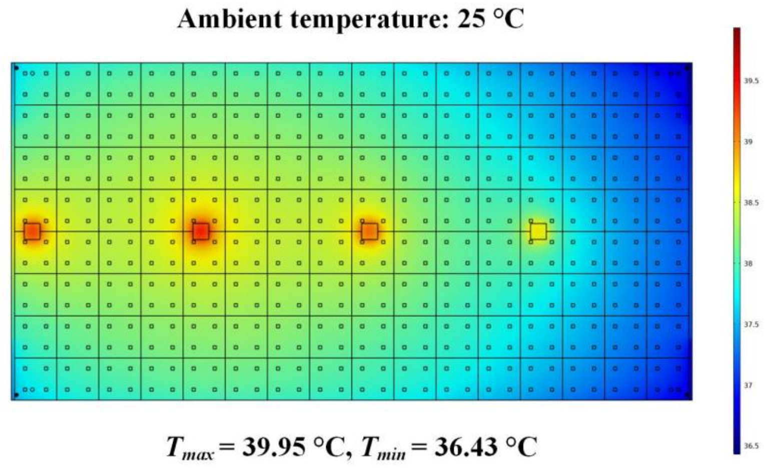



- The max principal stress of GS is 37MPa which is lower than its allowable stress 60MPa

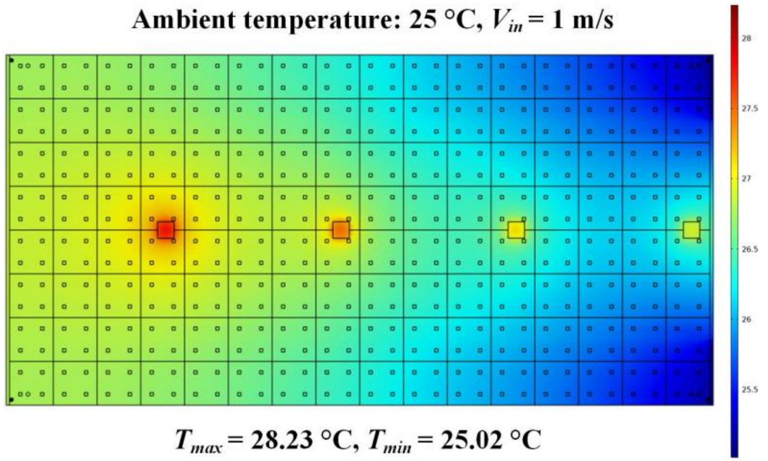
# HCAL cooling system

## Cooling scheme definition

The temperature error of different SiPM need to be controlled less than ±1.5℃



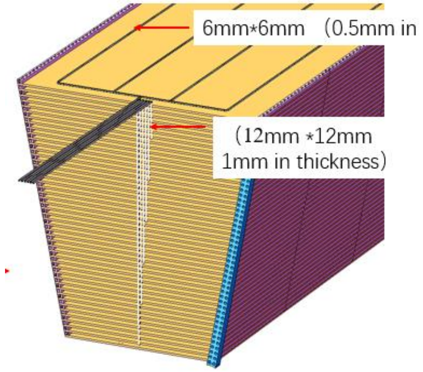

FEA result of thermal performance of natural convection

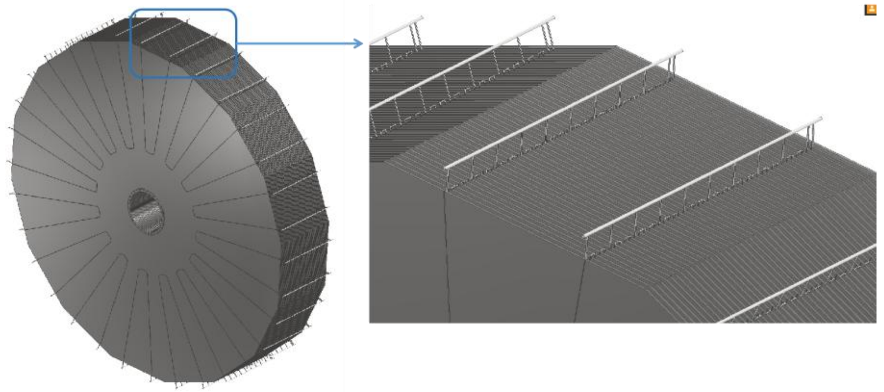



FEA result of thermal performance of air-cooling

- The excessively narrow interlayer gaps significantly reduce the efficiency of natural convection and air cooling, thereby failing to address the thermal management demands.
- **It is imperative to adopt liquid cooling technology to ensure efficient heat dissipation and temperature uniformity.**

## Cooling structure of barrel and end cap HCAL



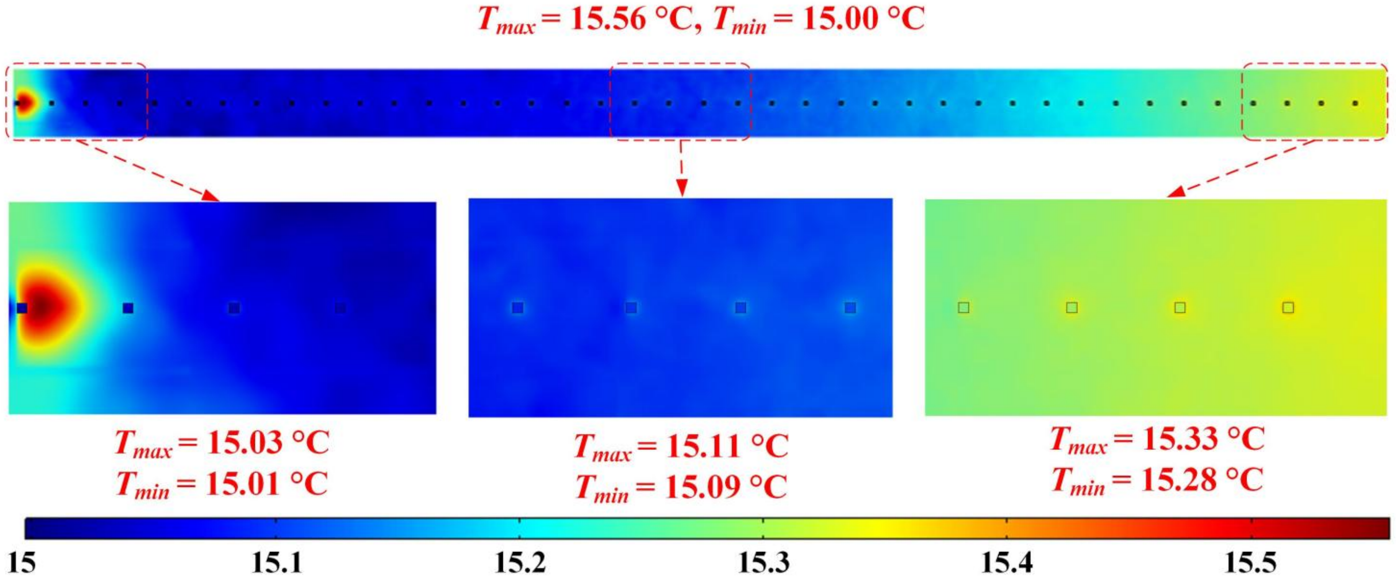



- 4/3 pipes in each layer in parallel
- 8 layers gather in one pipe in parallel
- One end is inlet and another end is outlet

- 1 pipe in each layer
- 5 layers gather in one pipe in parallel
- 16 wedges, with each region having one inlet and outlet.

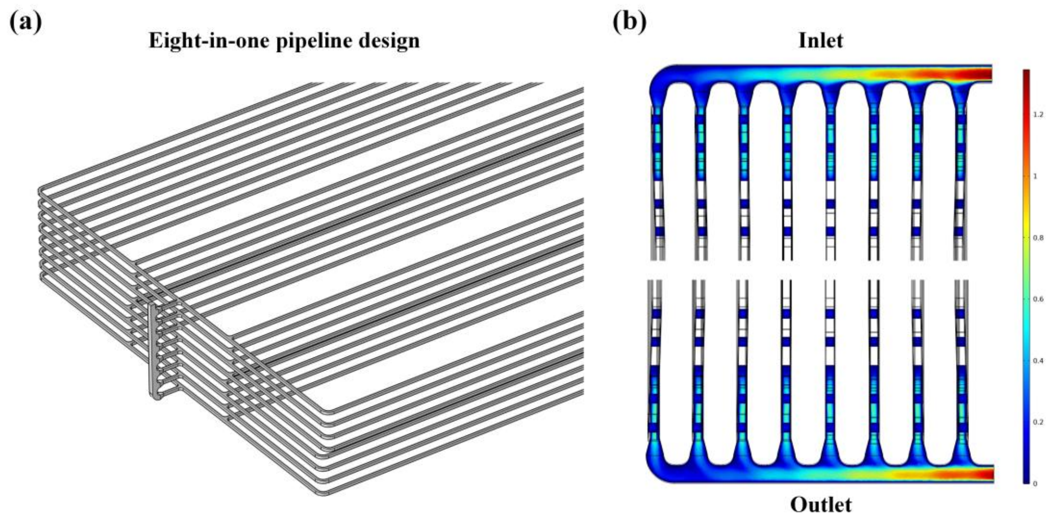
# HCAL cooling system

## FEA simulation of cooling system




Temperature distribution of the HCAL through liquid cooling

- Inlet temperature is 15 °C with a flow rate of 0.005 kg/s (corresponding to an inlet velocity of 0.1 m/s).
- **Effectively maintaining the temperature rise below 0.6 ° C.**
- **The maximum temperature variations of chips under the same box were under 0.1 ° C**

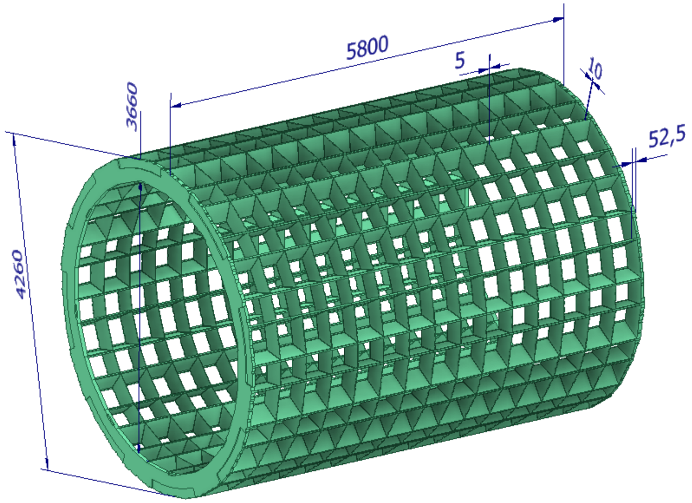


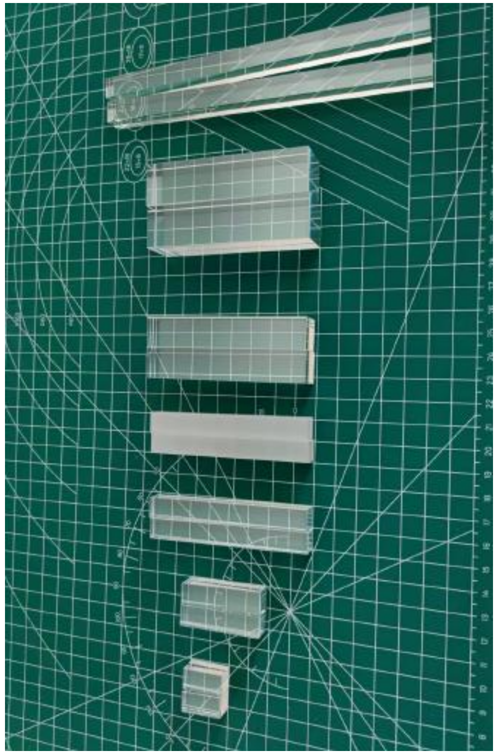

(a) Eight-in-one design of flow pipe
(b) Flow velocity distribution across different layers

- **Achieving a uniform flow velocity distribution across different layers**
- **The pipe resistance and length of endcap HCAL is smaller than barrel HCAL, so the same scheme can also meet our requirement**


# ECAL

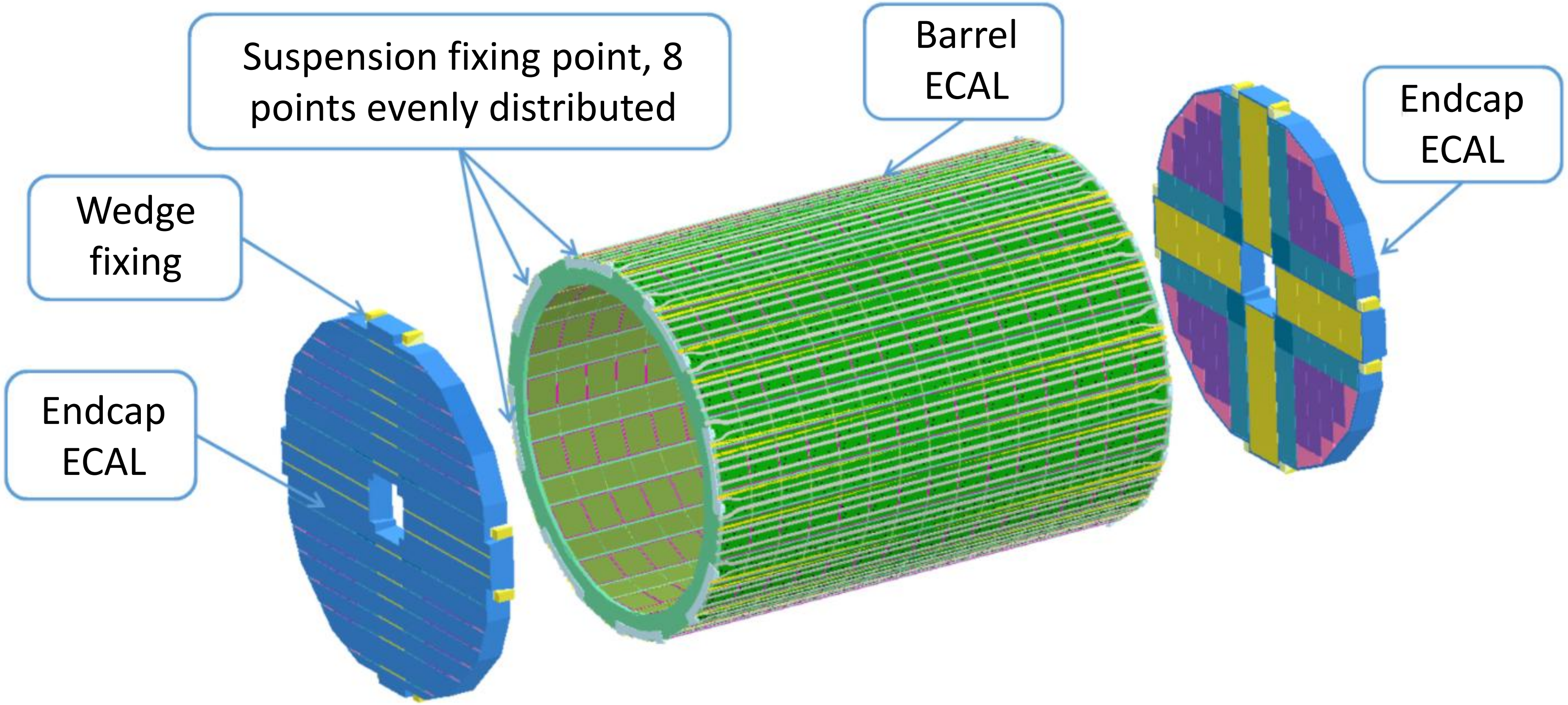
- The calorimeter design must be hermetic, meaning minimum space for mechanics and services (e.g. cooling, cabling) integration;
- Large-size carbon fiber structure processing
- High precision manufacturing and assembling;



# ECAL mechanics design

## Layout for all the ECAL components




### General structure information:

- The transverse cross-section of the barrel ECAL is defined as a 32-sided polygon
- Total weight is **180 tons** and there are totally **about 210000 BGO**

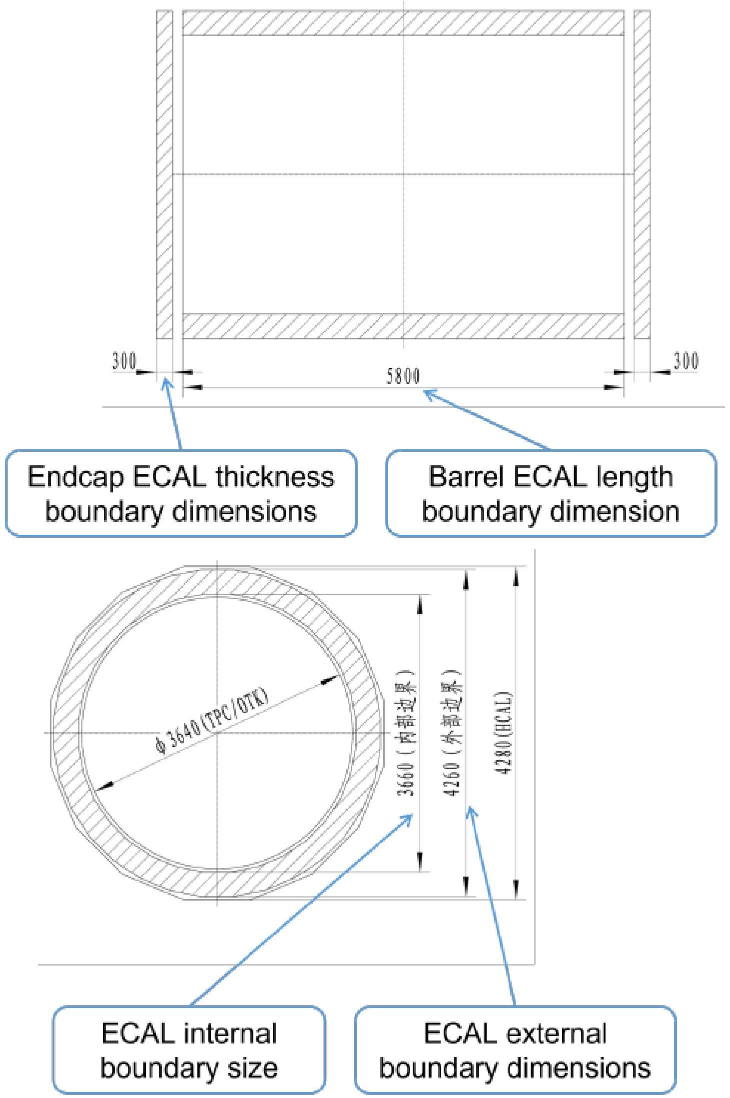
### Requirements:

- Minimize the material volume of the support structure to reduce passive material within the sensitive volume.
- Ensure that maximum stress in each component remains below the respective material's yield strength.
- Deformations of different materials must be controlled to prevent structural failure under varying operating conditions.
- Maintain outer contour dimension tolerances within [0, −5] mm and inner contour tolerances within [0, +5] mm.

# ECAL mechanics design

## ECAL dimensions and layout of one detect module

- Typical crystal Length:400mm
- Crystal granularity:$15 \times 15\ \mathrm{mm}^2$



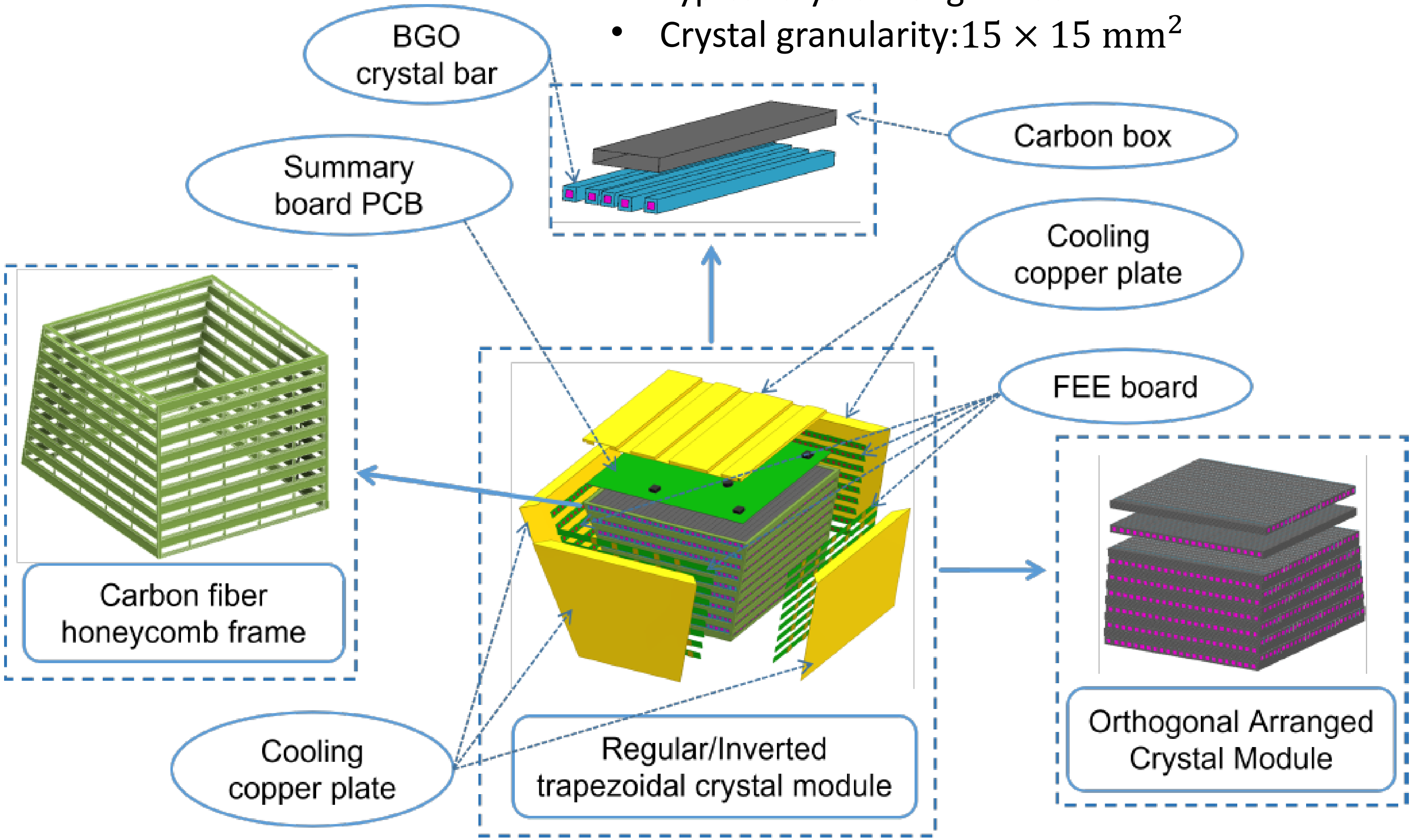



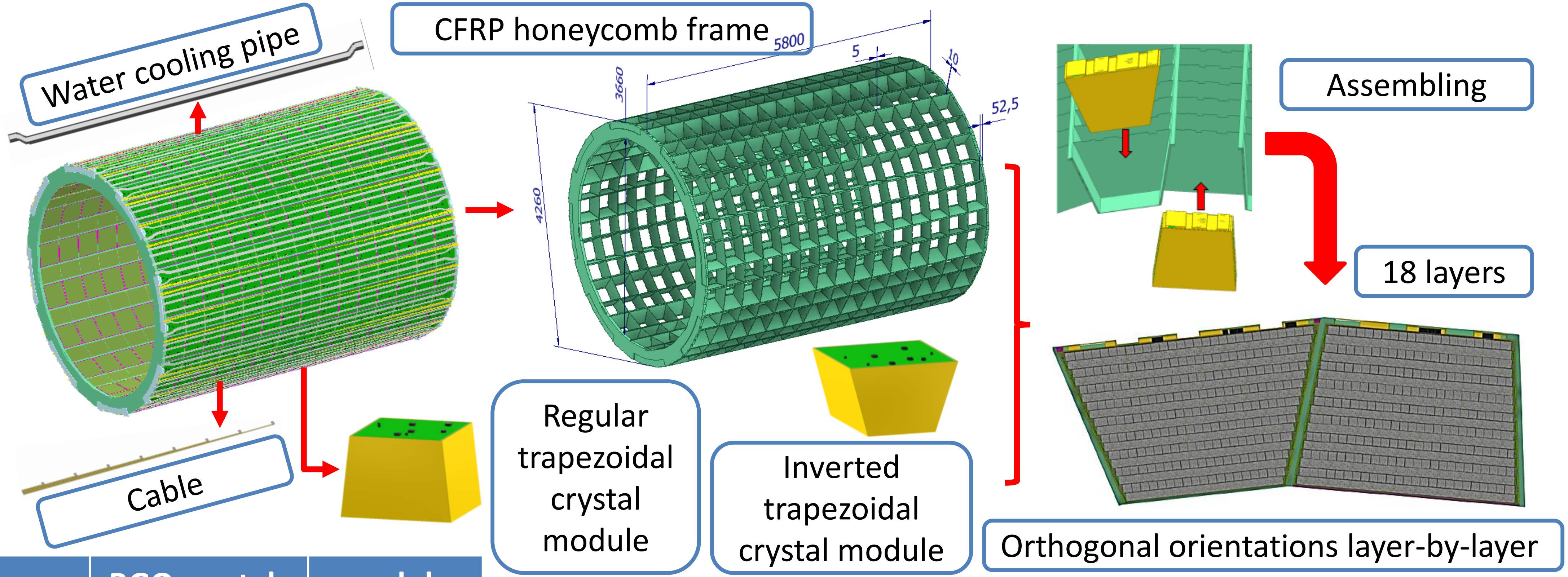

**Figure 7.37:** Structure of crystal detection module.

# ECAL mechanics design

## Barrel ECAL mechanics

Integration of barrel HCAL structure

- 32 segments in phi, 15 segments along Z-axis
- In each segment: two crystal modules in trapezoid-shape
- Main structure is based on carbon fibers



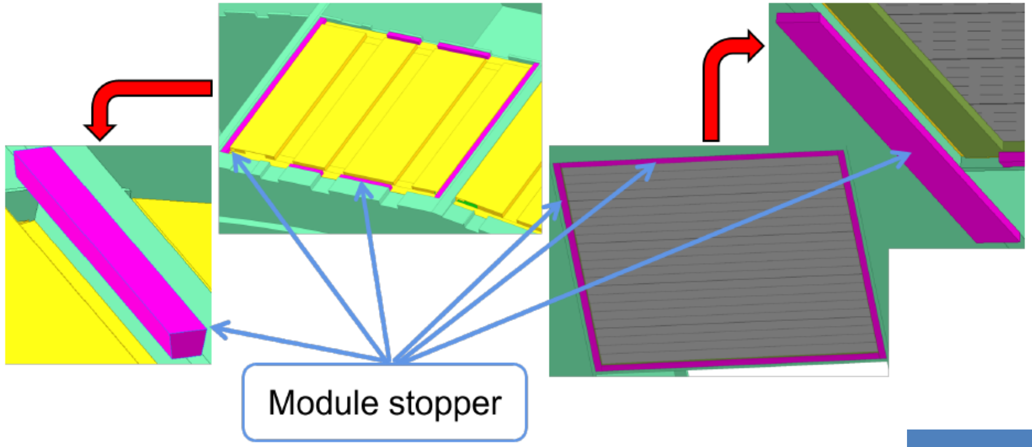

| | BGO crystals | module |
|---|---|---|
| **Quantities** | 201120 | 480 |

**Total weight: 130 tons**

# ECAL mechanics design

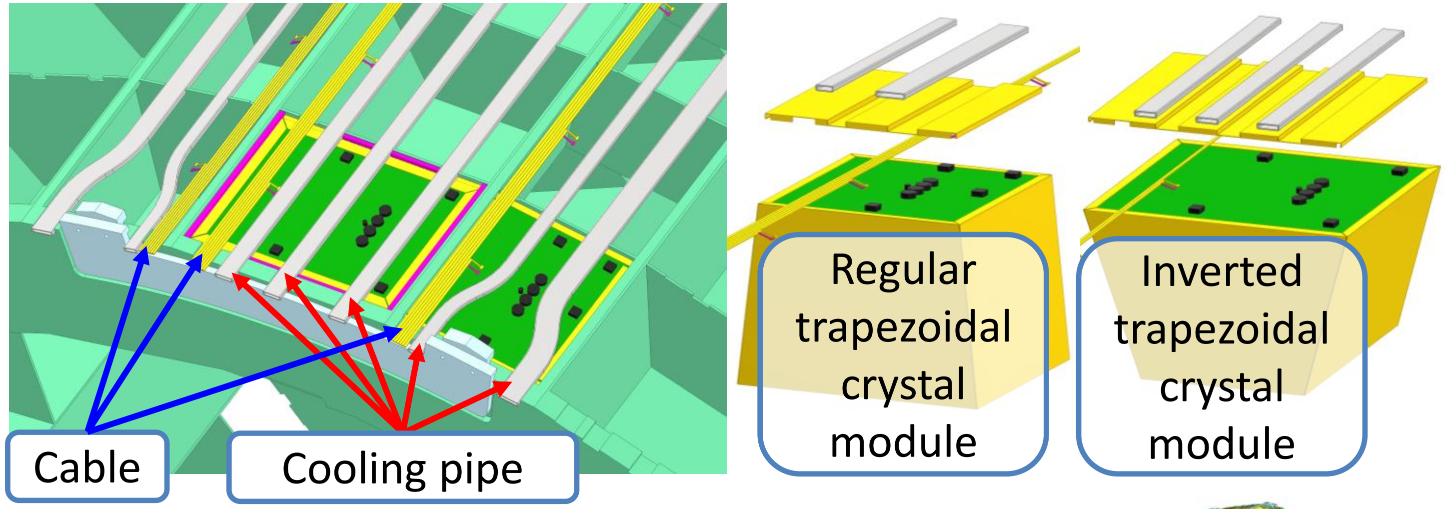
- **Connection structure of barrel ECAL**

Interfaces between crystal module and CFRP frame

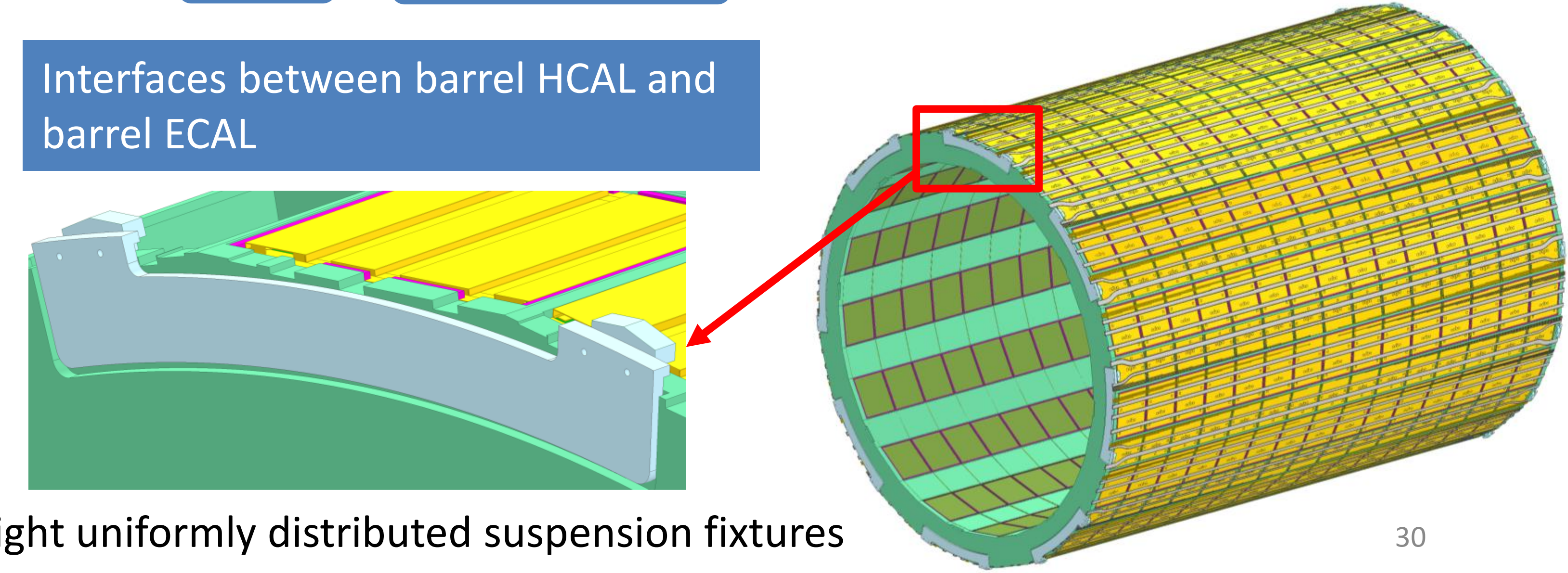



The smaller end is positioned and supported by the frame itself, while the larger end is secured using mechanical stoppers to prevent module slippage. These stoppers are fastened to the frame with screws and further reinforced with structural adhesive.

Interfaces between crystal module, cable and cooling pipe




Interfaces between barrel HCAL and barrel ECAL

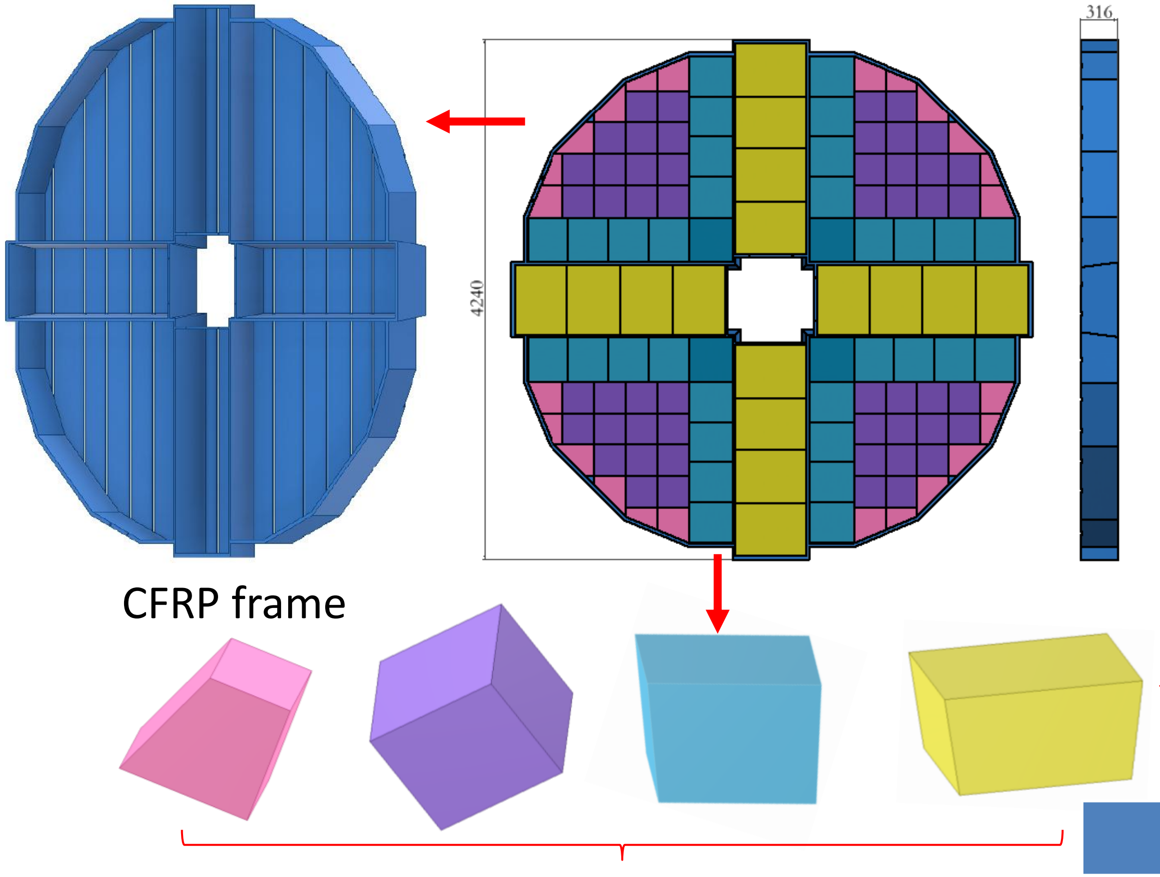


Eight uniformly distributed suspension fixtures

# ECAL mechanics design

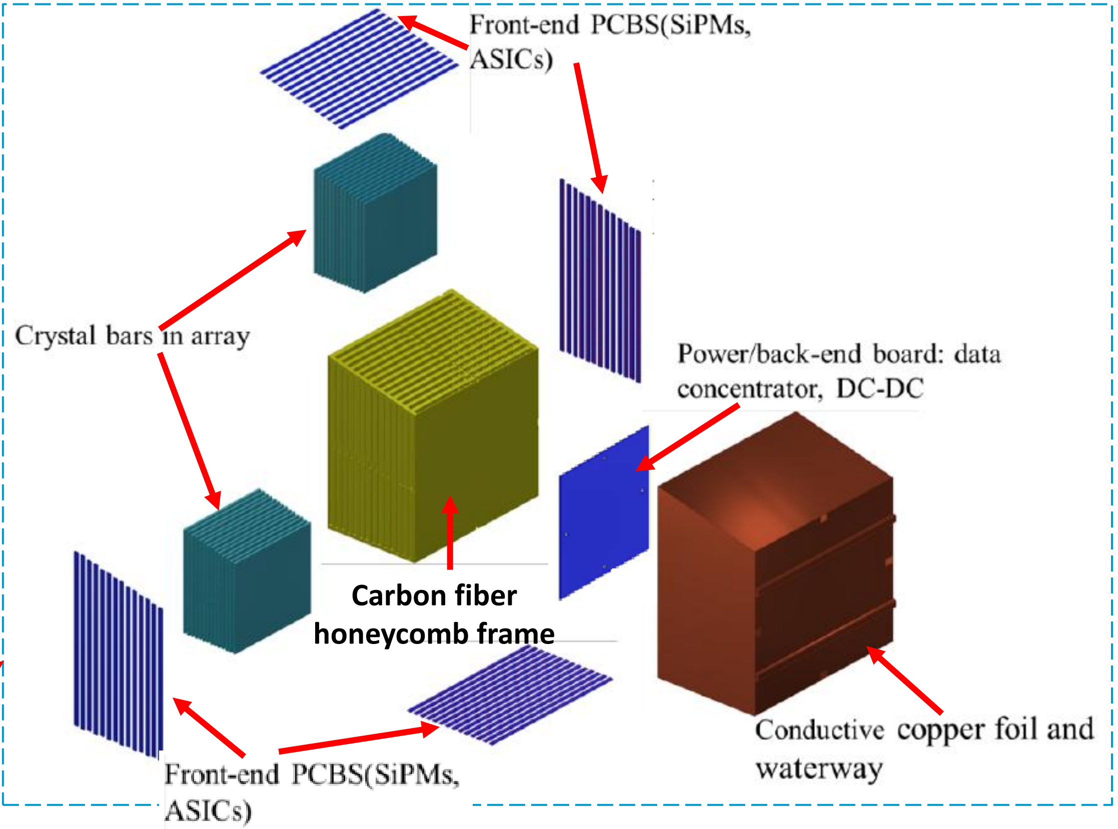
## Endcap ECAL mechanics

- 32 segments in phi
- Total of six types of modules




Integration of barrel HCAL structure

- Main structure is based on carbon fibers
- Crystal granularity:$15 \times 15\ \mathrm{mm}^2$

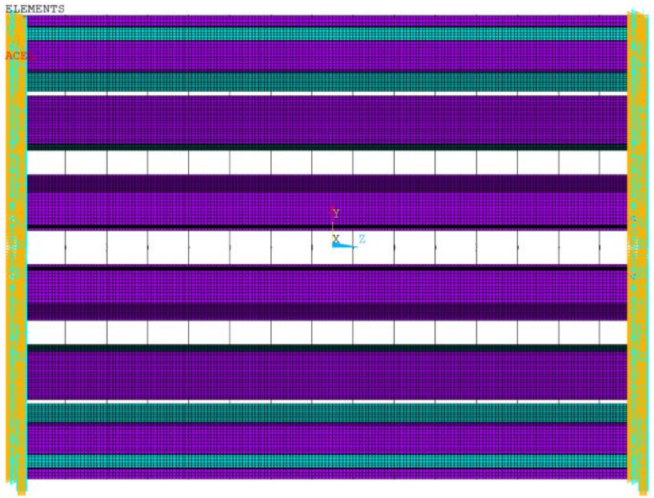



| | BGO crystals | module |
|---|---|---|
| Quantities | 8000 | 224 |

**Total weight: 25*2 tons**

# ECAL mechanics design

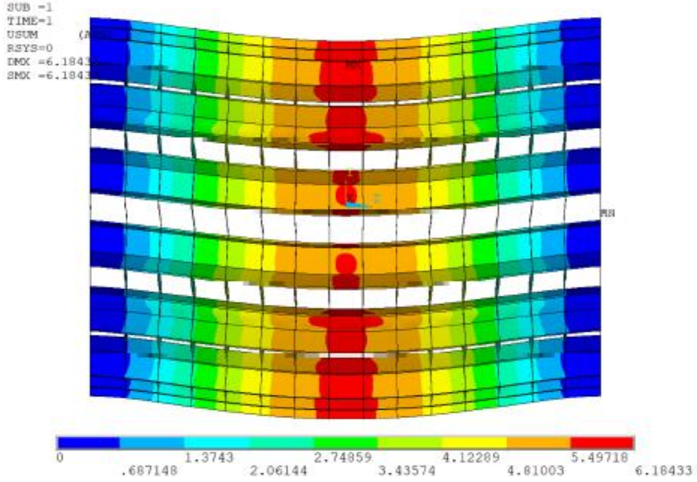
## FEA result of barrel ECAL



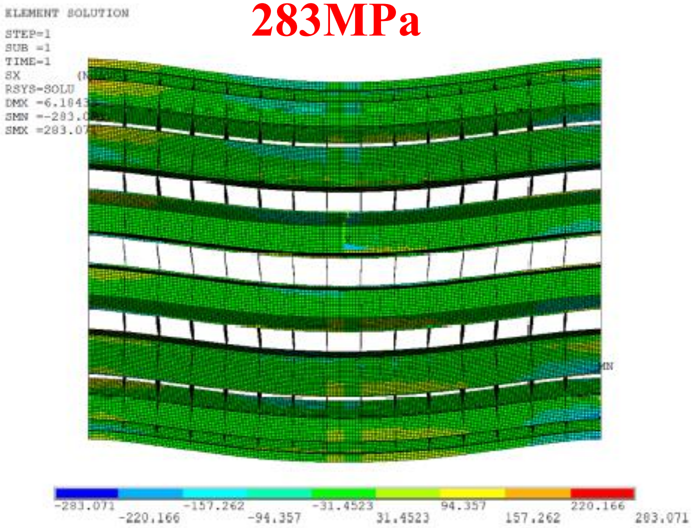

Boundary condition

Old version

6.2mm

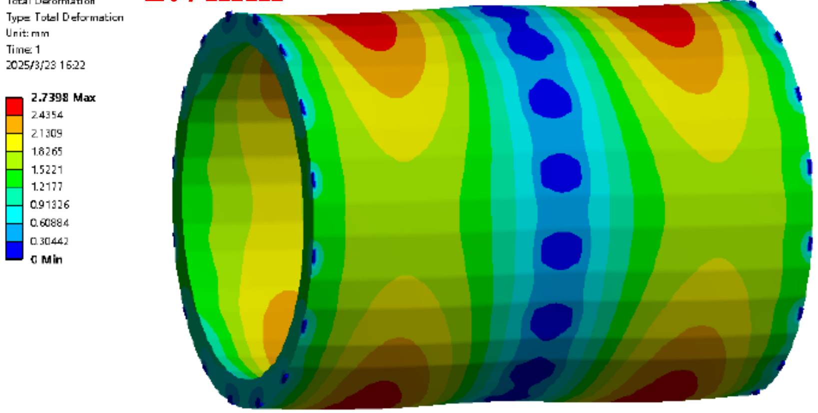



283MPa




New version

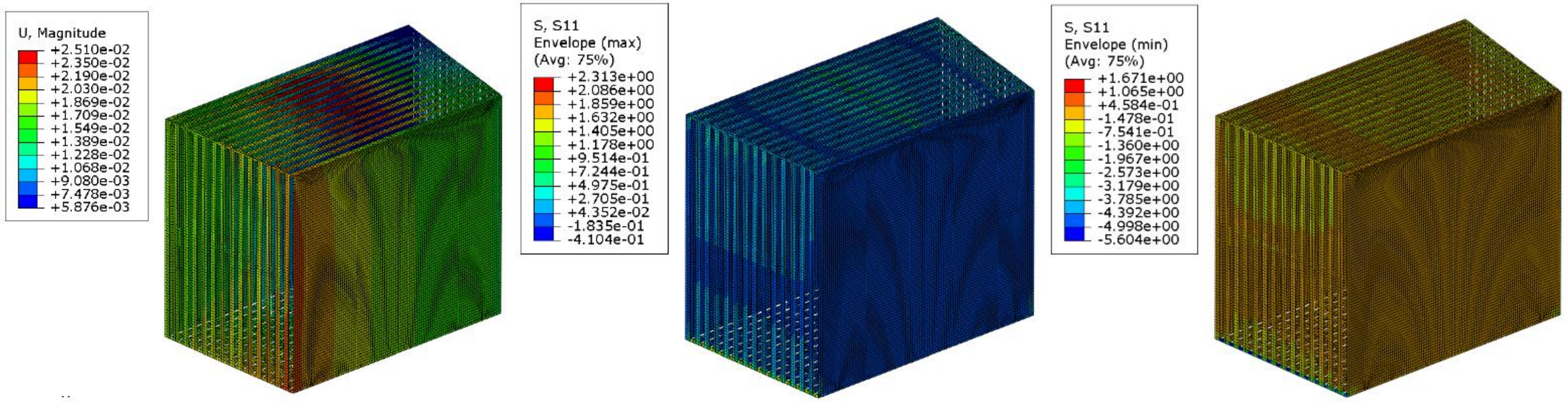
2.7mm



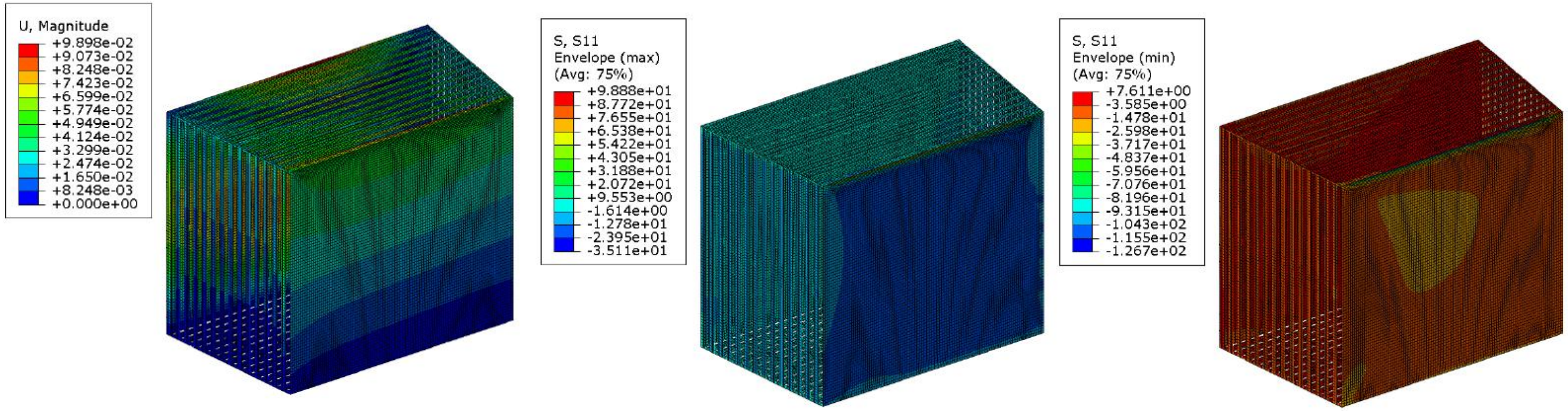

16 fixation points are added in the central region within the gaps between the ECAL and HCAL

# ECAL mechanics design

## FEA result of endcap ECAL composite frame




Deformation and stress in various directions of the composite frame under self-weight




Deformation and Stress in Various Directions of the Composite Frame Under Self-Weight and External Load

| Parameter | Self-weight | + External load | Standard |
|---|---|---|---|
| Deformation (mm) | 0.025 | 0.099 | |
| Fiber direction stress (MPa) | 2.3/-5.6 | 98.9/-126.7 | 1600/-900 |
| Lateral stress (MPa) | 0.12/-0.12 | 4.1/-3.0 | 22/-120 |
| In-plane shear stress (MPa) | 0.18 | 2.0 | 20 |

Trapezoidal crystal detection modules in the barrel ECAL is identical to that used in the endcap ECAL

# ECAL cooling system

- **FEA simulation of cooling system**

Requirements:

- Inlet cooling water temperature of 15°C
- Maximum operating temperature need to below 25°C.

Endcap ECAL is almost same with barrel ECAL

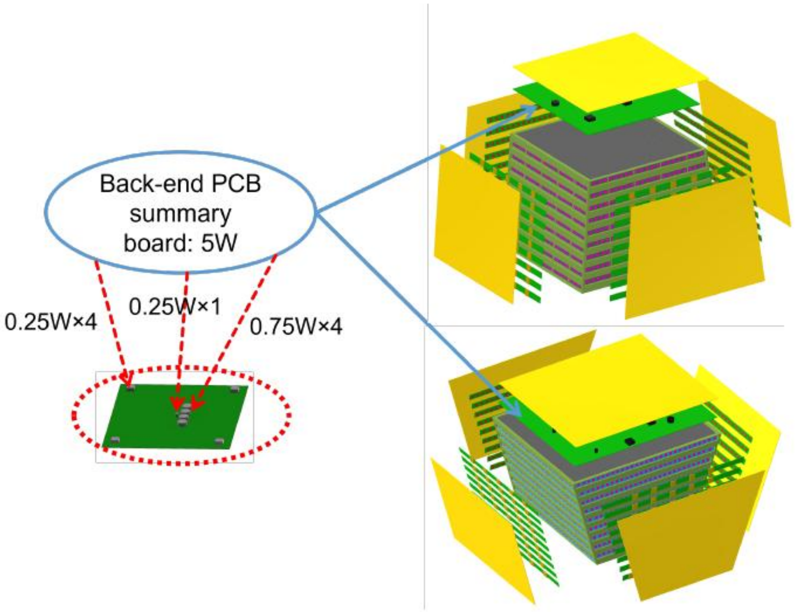



**Figure 7.44:** Heating power for a single trapezoidal detection module.

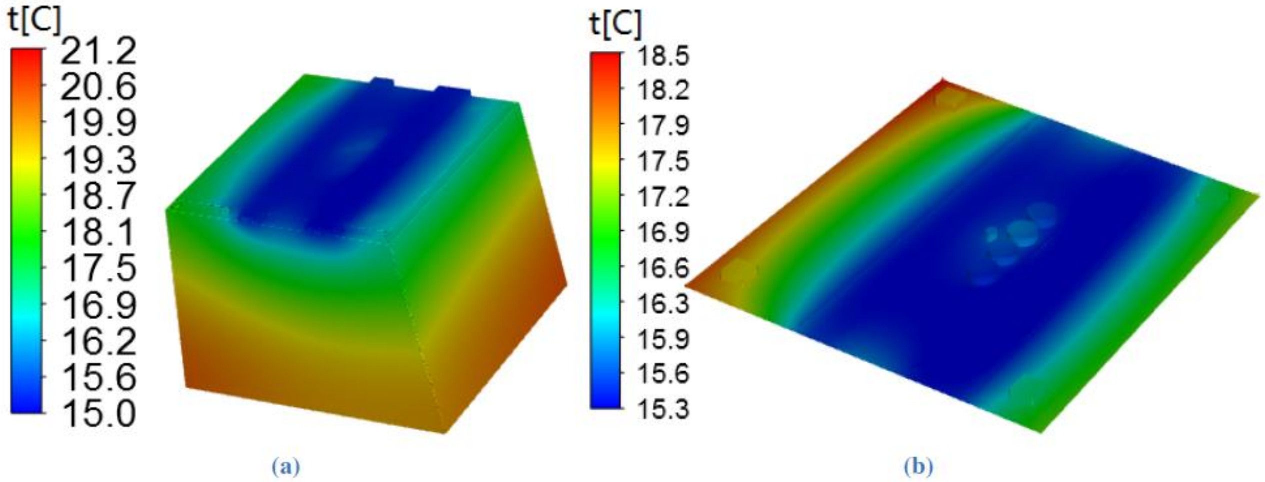



**Figure 7.45:** (a) Temperature distribution of a single trapezoidal module; (b) Temperature map of PCB and attached readout chips.

- The maximum module temperature is 21.2°C

**Table 7.9:** Temperature rise of cooling water.

| Parameter | Single Module Rise | Cumulative Rise (15 Modules) | Final Inlet Temperature |
|---|---|---|---|
| Cooling Water | 0.13 (°C) | 1.95 (°C) | 16.95 (°C) |

# Next plan

- **Magnet**
  - High strength and high RRR value aluminum stabilizer research.(2025)
  - Full size Aluminum stabilized superconducting cable development. (2025)
  - Detailed design of mechanical system. Optimize the thickness design of magnet.(2026)
  - Validation experiments for mechanical and cryogenic systems.(2027)
- **HCAL mechanics**
  - To further optimize GS-SiPM coupling, cooling scheme
  - To further optimize the support structure
  - To prepare full-size GS-HCAL prototype for beam test
- **ECAL mechanics**
  - Optimizing the CF structure
  - FEA crosschecks, CF structure production vendors (wider survey)
  - Full-scale crystal calorimeter prototype and beam tests: integrated with mechanics/cooling

# Thanks