# Development of 3D-Printed Tungsten Absorbers for the LHCb ECAL Upgrades

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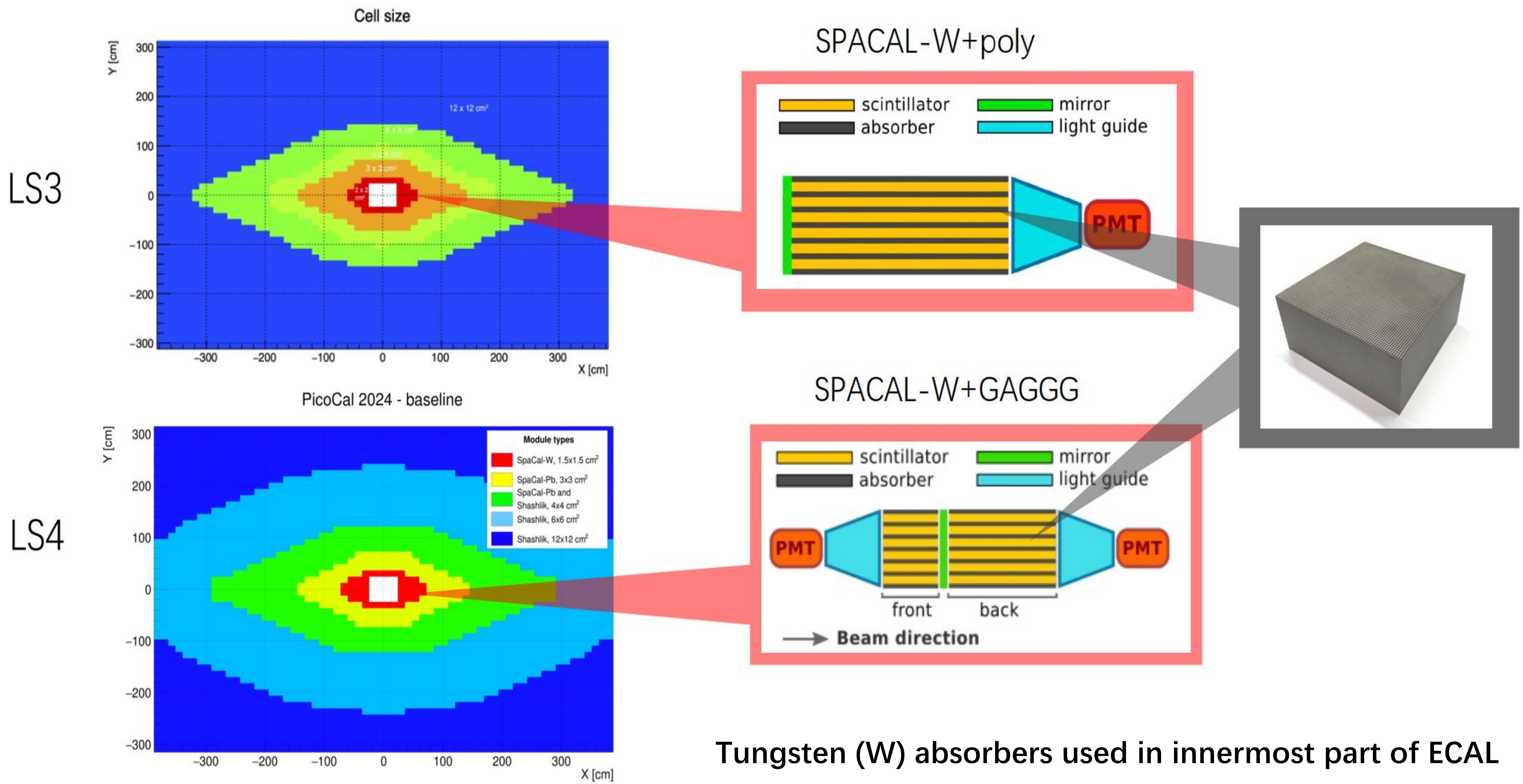
# Contents

# 1.1. Tungsten absorbers for LHCb ECAL upgrades




**Tungsten (W) absorbers used in innermost part of ECAL**

# 1.2. Challenges in tungsten absorber production

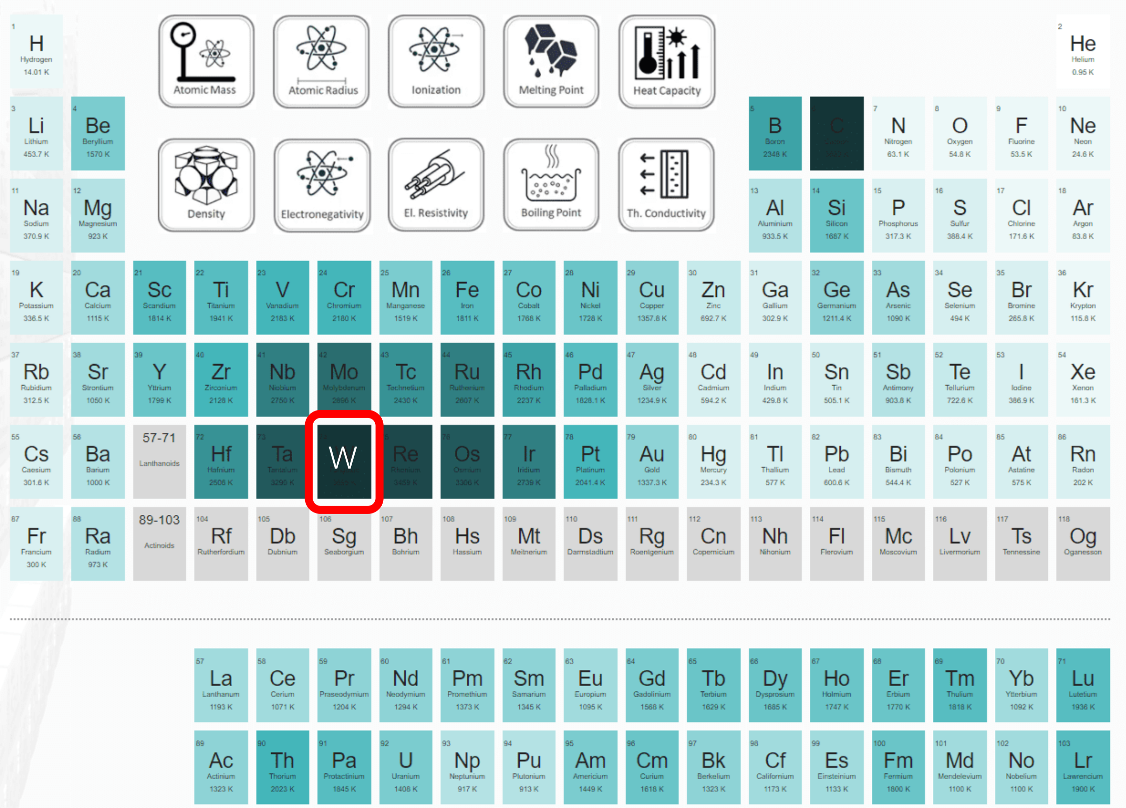
➢ **Key technical difficulties for tungsten absorber production:**

- **High melting point & low-temperature brittleness**
  Difficult to process with conventional methods.

- **Limitations of powder metallurgy**
  Low density, strength, and plasticity; impurities hard to control.

- **Complex structures hard to form**
  Challenges with thin walls, curves, holes, and channels.

- **Environmental & safety concerns**
  Production involves corrosive gases (e.g., hydrogen fluoride).



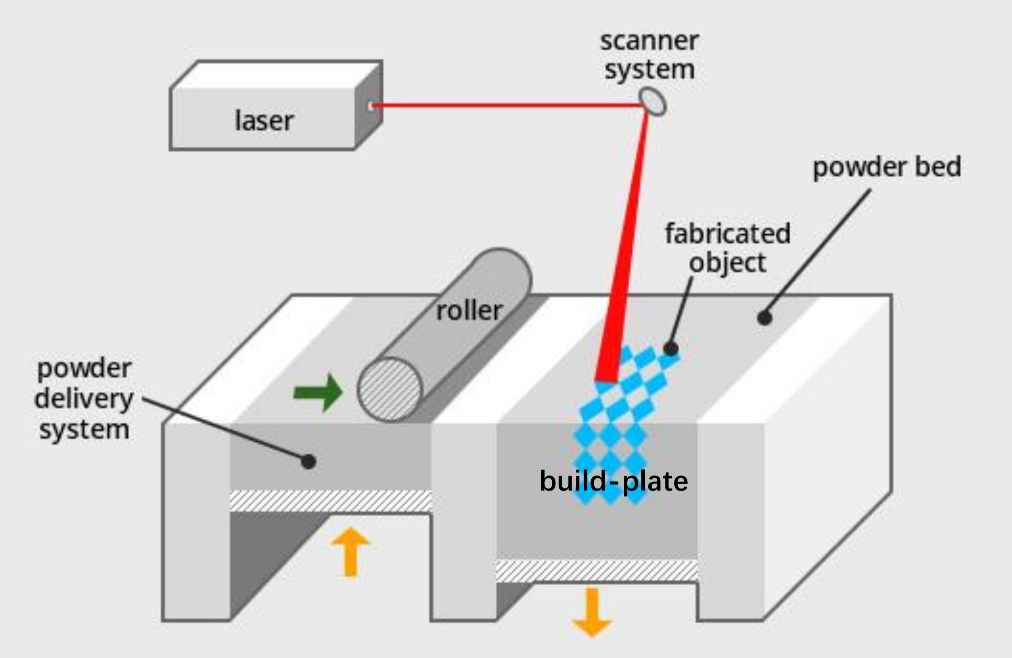

**Tungsten (W) is the metal with the highest melting point. (3422 °C, 6192 °F)**

- Key challenge: production of absorbers featuring **small, high-precision holes** into which scintillating fibers must **be inserted without damage**.
- Innovation methods for tungsten absorber production are needed to enable effective use in calorimeters.

# 1.3. Selective laser melting (SLM)

➢ **Principles of selective laser melting (SLM):**

Selective laser melting (SLM) is a powder bed fusion process that uses a **laser beam** to fuse metallic powders selectively, layer by layer.

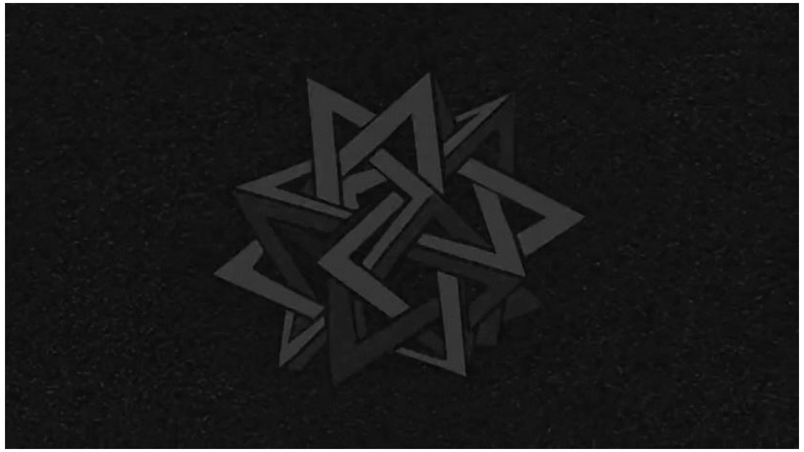


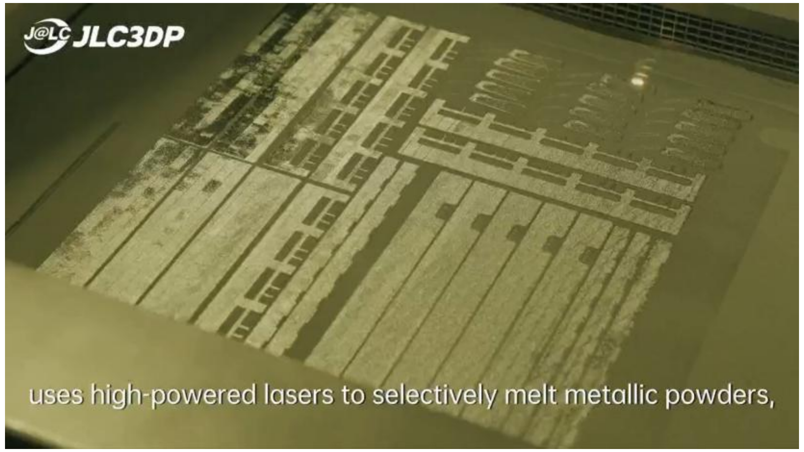

In SLM process:

- A layer of metallic powder is **spread over the build-plate**
- Powders are **melted together** using a **focused laser beam** in an inert atmosphere (nitrogen or argon)
- After scanning each layer, the **build-plate is lowered** over a distance of one-layer thickness
- Followed by **transferring the next layer of powder** to the build-plate.
- This process is repeated until the desired solid component is created.

➢ **Advantages of selective laser melting (SLM):**

- High energy density
- Small spot diameter
- **High forming precision**
- **Exceptional processing freedom**



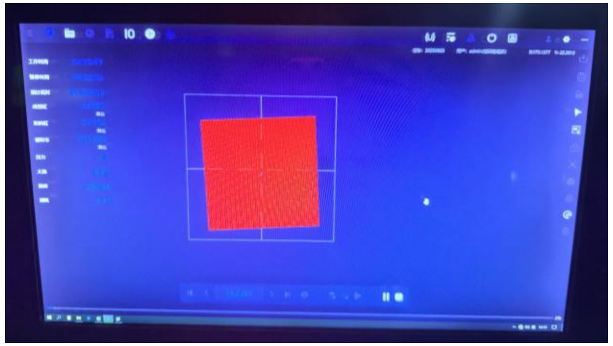


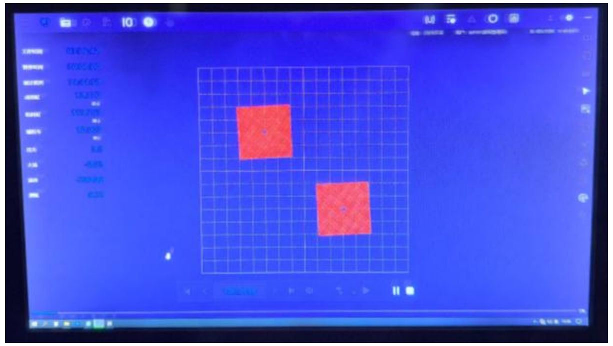

https://hanaamt.com/powder-production/slm-pbf/

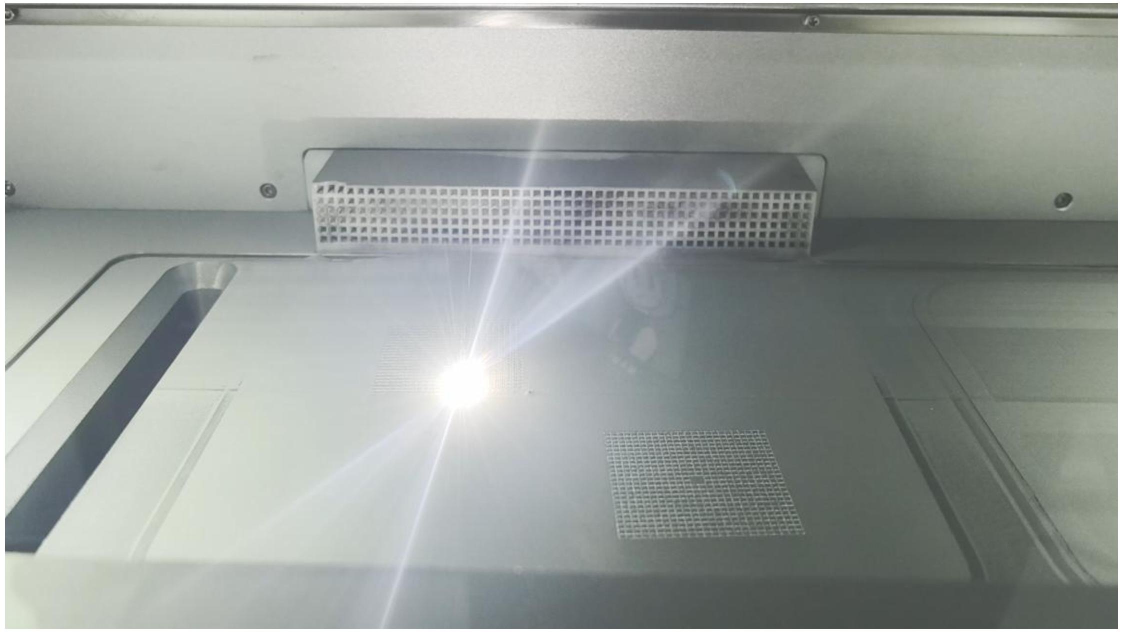
# 2.1. 3D Printing details

➢ **We have commissioned three printers to print tungsten absorbers.**

- **Layer thickness: 0.02 mm ~ 0.1 mm (We used 0.025 mm)**
- Maximum laser power: 500 W
- Optimal laser power we used: 350 W
- Maximum scanning speed: 7 m/s
- **Spot diameter: 60 ~ 80 μm**
- **Printing accuracy: 30 μm**





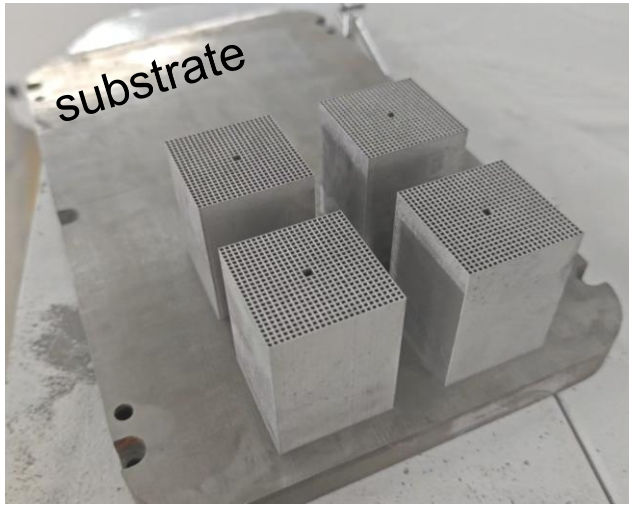


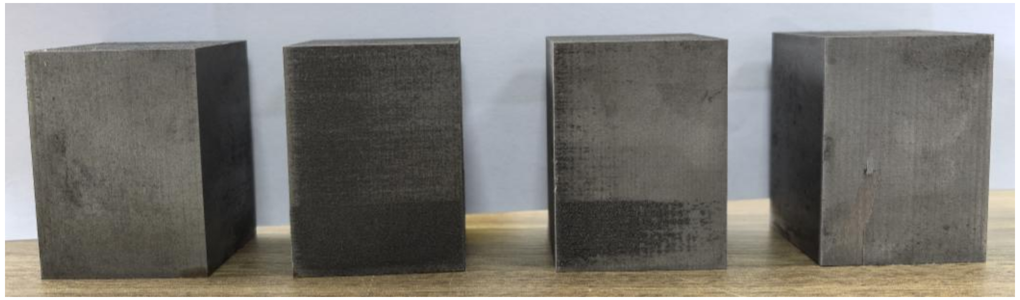

https://www.laseradd.com/

# 2.2. Post-processing after printing

## ① 1st EDM Wire cutting

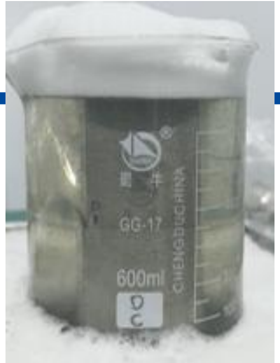
- After printing, the absorbers are connected tightly with the substrate.
- Using electrical discharge machining (EDM) wire cutting to remove the absorbers from the substrate.



## ② Chemical polishing

- Immerse the absorber in a polishing solution (5 wt.% NaOH: 30 g/L $H_2O_2$, 30 min)
- To reduce the surface roughness.



← Chemical polishing

## ③ Sandblasting

- Using compressed air as the power source, a high-speed jet beam is generated.
- Sands are applied at high speed to the surface of absorbers.
- To remove surface powder and reduces surface roughness.

→ Sandblasting machine

## ④ Hole insertion

- Use a stainless steel rod to insert into the hole
- To remove the powder on the inner wall

## ⑤ 2nd EDM Wire cutting

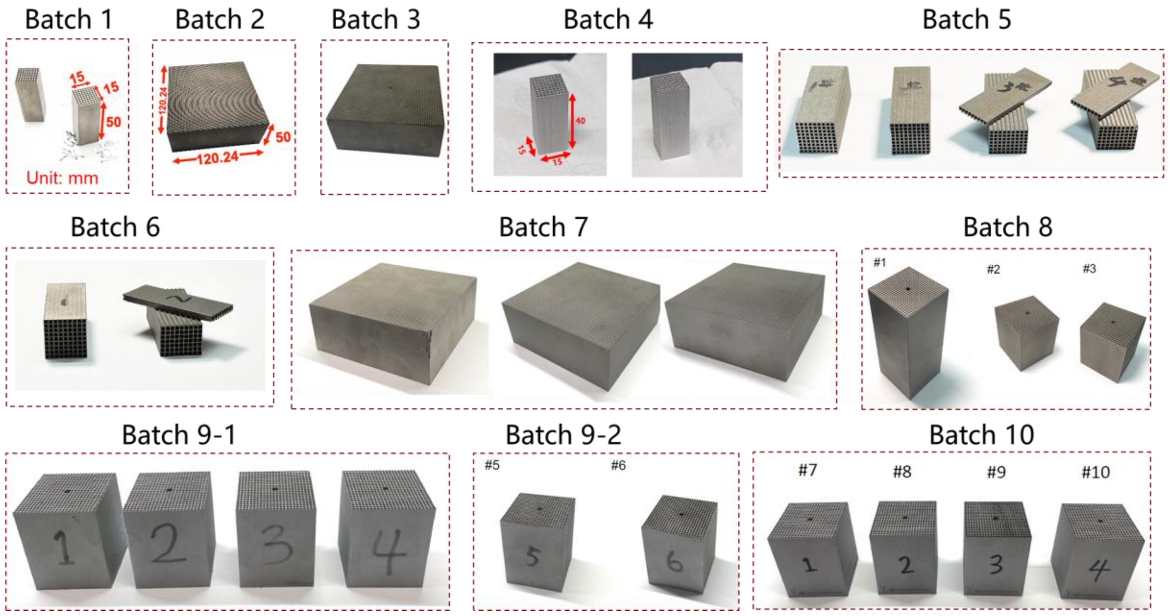
- The height obtained by the 1st EDM wire cutting is much greater than the nominal height (50 mm).
- A 2nd EDM wire cutting is required to cut the absorbers to the nominal height.

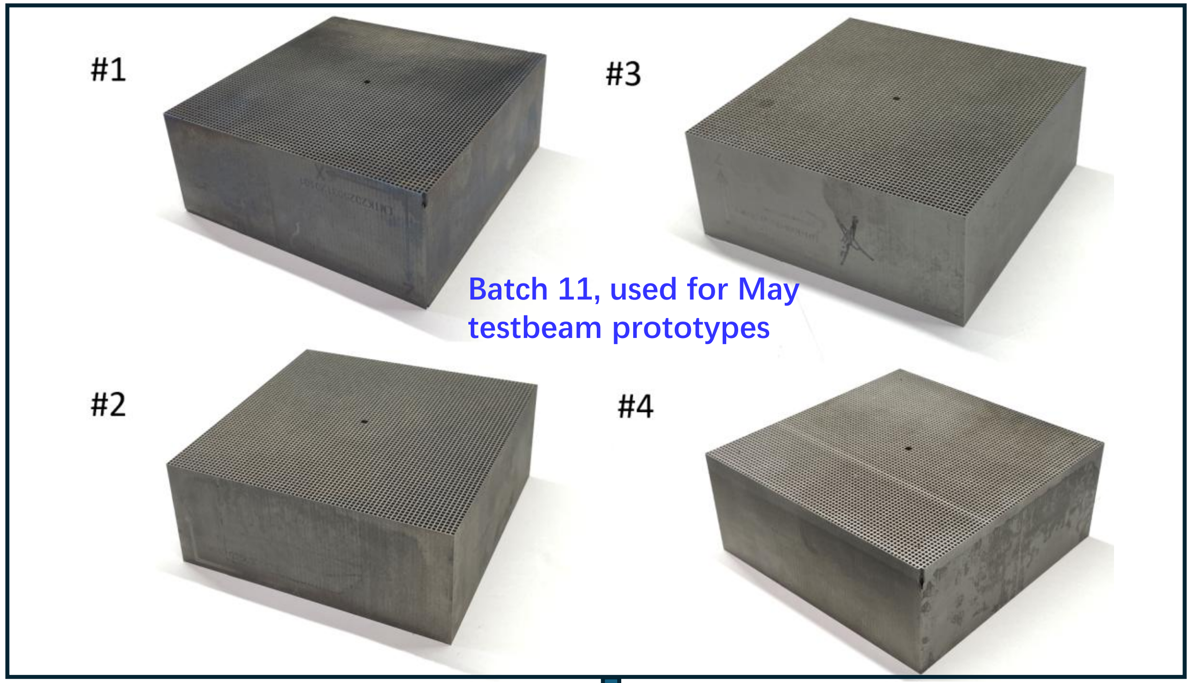
# 3. Absorbers we printed

- Together with LaserAdd, have successfully printed a number of absorbers, including reduced-size absorbers and full-size absorbers
- Notably, the most recently printed four full-size absorbers have been utilized in May test beam prototypes
- A density of 18.9 g/cm³ has been achieved, meeting the requirements


DiMetal-150 DiMetal-100H

雷佳 LASERADD




| | Width (mm) | Height (mm) | Volume (mm) | Average hole size (mm) | Weight (g) | Density (g/cm³) |
|---|---|---|---|---|---|---|
| Sample #1 | 120.94 | 50.08 | 360.9 | 1.196 | 6848.8 | 18.98 |
| Sample #2 | 121.08 | 49.85 | 363.6 | 1.192 | 6849.8 | 18.84 |
| Sample #3 | 121.01 | 50.29 | 362.3 | 1.198 | 6862.5 | 18.94 |
| Sample #4 | 120.97 | 49.95 | 362.5 | 1.193 | 6844.2 | 18.88 |

**density of 18.9 g/cm³ is achieved.**

# Evolution of the tungsten absorbers

Hole size:

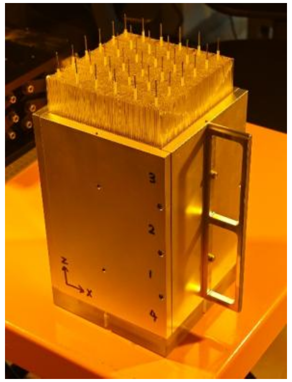
2024 Jun. Batch 7
W-GAGG
~1.25 mm

2024 Aug. Batch 8
~1.21 mm

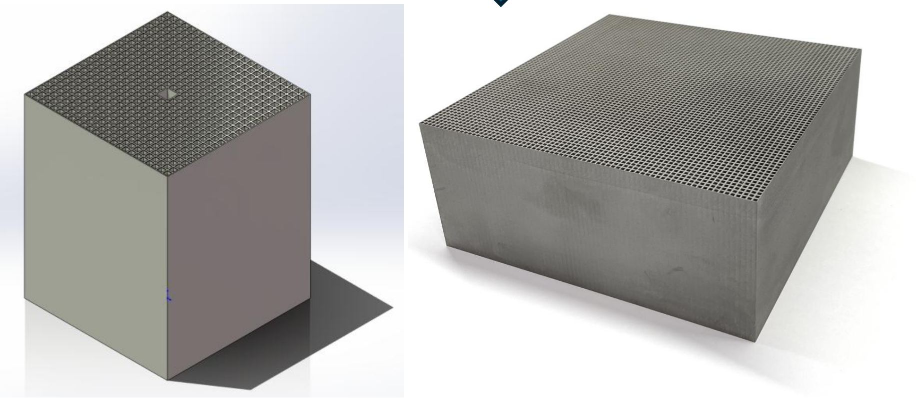
2024 Nov. Batch 9
~1.20-1.16 mm

2025 Jan. Batch 10
~1.20 mm

2025 Apr. Batch 11
W-Poly
~1.20 mm



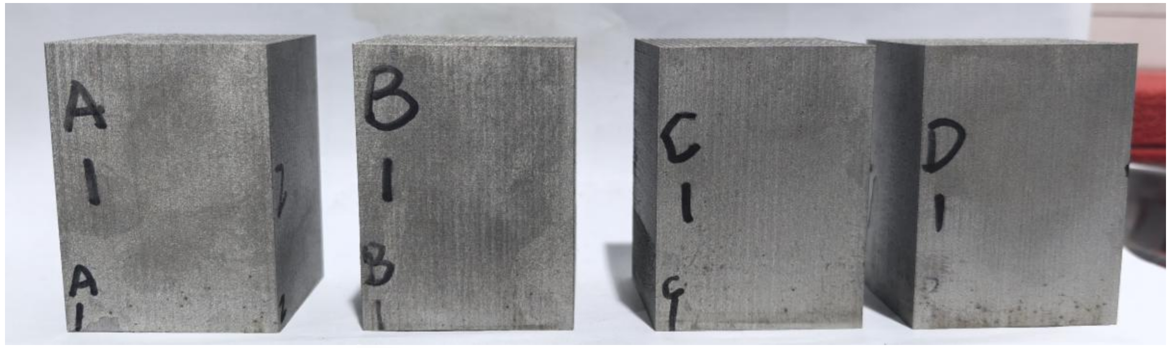
**2025 Oct. Batch 12**
**Move to 1.22 mm**
**hole size (+ funnel)**

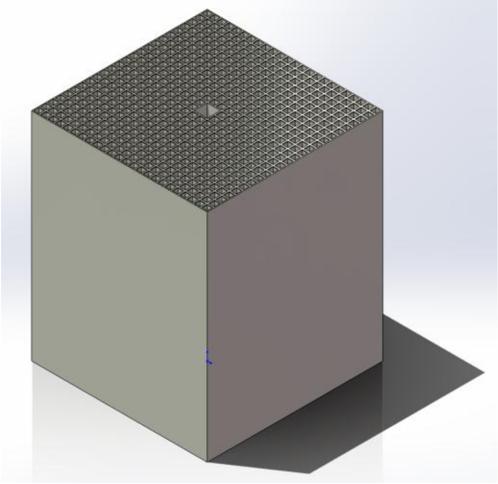


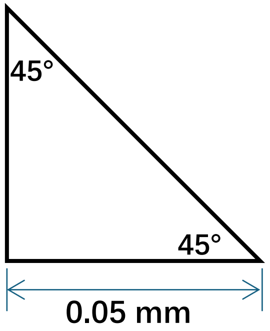
# 3. Absorbers recently printed

## ➢ Reduced-size absorbers

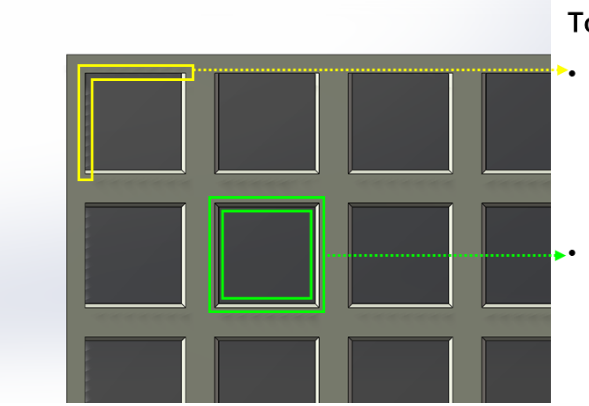
- Designed hole size: 1.22 mm × 1.22 mm
- Wall thickness: 0.467 mm
- Designed overall dimensions:
  40.5 mm × 40.5 mm × 50.0 mm



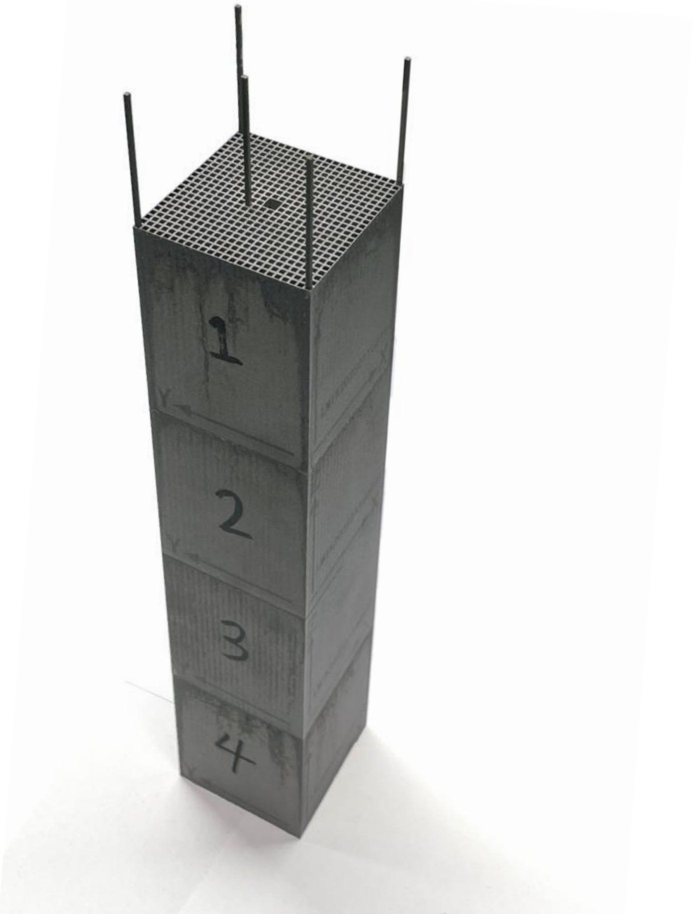





Top surface

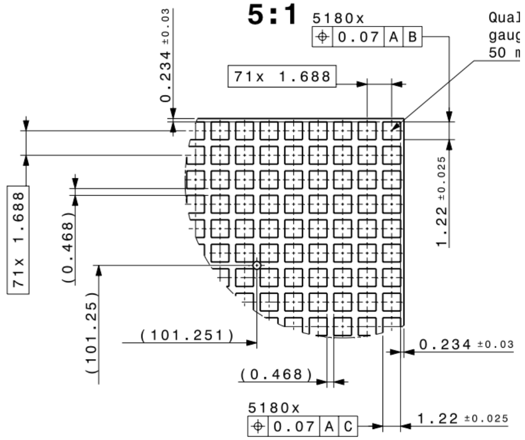


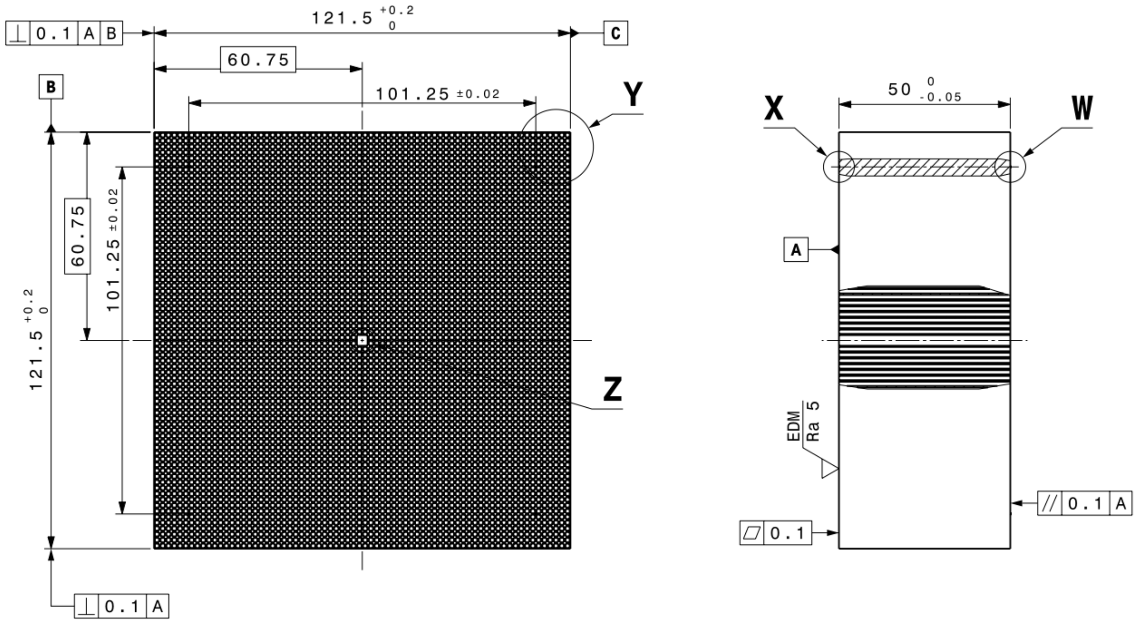
- **The outermost holes**: No funnels on the edges close to the outer wall
- **The inner holes**: All four edges have funnels



# 3. Absorbers recently printed

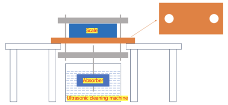
- **Full-size absorbers**
  - Designed hole size: 1.215 mm × 1.215 mm (± 0.005 mm)
  - Wall thickness: 0.467 mm
  - Designed overall dimensions:
    121.46 mm × 121.46 mm × 50.0 mm
  - Keep the funnel design as the reduced-size absorbers




# 4. Quality assurance (QA)

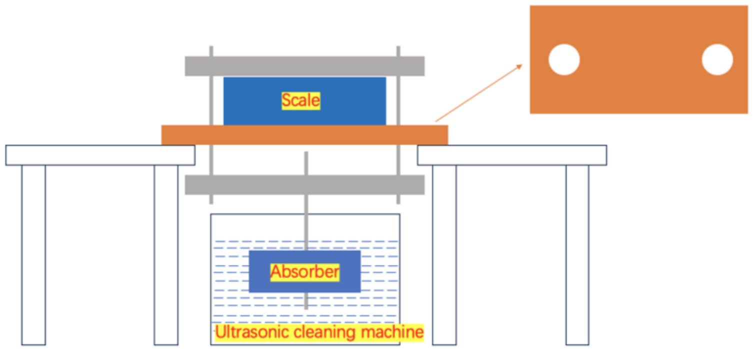
- After printing and post-processing, we will undergo a series of quality assurance (QA) tests for the absorbers

| No. | Items | Testing equipment | Photo for equipment | Acceptance criteria |
|---|---|---|---|---|
| 1 | **Appearance inspection** | Visual check | | • The overall shape is intact, with no visible cracks or deformations.<br>• The surface is smooth and even, without irregularities.<br>• No obvious blockages inside of the hole. |
| 2 | **Dimensional measurement** | Vernier caliper |  | • Length & Width: 0 mm to +0.2 mm tolerance<br>• Height: -0.05 mm to 0 mm tolerance<br>• Details see design drawings |
| 3 | **Mass measurement** | Analytical Balance |  | |
| 4 | **Density measurement** | Analytical balance<br>Ultrasonic Cleaner<br>Custom Stainless-Steel Stand |  | • ≥ 18.9 g/cm$^3$ |
| 5 | **Surface roughness measurement** | Surface Roughness Tester (Mitutoyo SJ-411) |  | • $R_t <$ 35 μm; $R_a <$ 5 μm;<br>• Details see design drawings |
| 6 | **Insertion testing** | Stainless steel rod |  | • Nearly all the holes allow the steel rod to pass through smoothly without the need for excessive force. |
| 7 | **Flatness and perpendicularity measurement** | Bridge-Type Coordinate Measuring Machine (CMM) (Hexagon PC-DMIS) |  | • < 100 μm |
| 8 | **Non-Destructive Testing** | Universal testing machine<br>2D digital image corelation |  | • ~8 kN (two times the expected load in the ECAL wall) |

# 4. Quality assurance (QA)

## 4.1. Density measurement at WHU ECAL Lab

- Archimedes' principle




Mass in the air
$m_1$

Mass in the water
$m_2$

$$\rho_{Absorber} = \frac{m_1}{m_1 - m_2} \cdot \rho_{water}$$

- Then the average hole size of the absorbers can be calculated according to the mass, density, and measured dimensions.

**Pure W density : 19.25g/cm³**

| Printers | Absorber No. | Mass, g | X, mm | | Y, mm | | Z, mm | | Volume, cm³ | Density, g/cm³ | Average hole size, mm | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Measured value | Bias | Measured value | Bias | Measured value | Bias | | | Measured value | Bias |
| | **Designed** | | **121.46** | **0 ~ +0.20** | **121.46** | **0 ~ +0.20** | **50.00** | **-0.05 ~ 0** | | | **1.215** | **±0.005** |
| Printer No.1 | Absorber 1-3 | 6807.0 | 121.53 | +0.07 | 121.54 | +0.08 | 50.05 | **+0.05** | 358.1 | 19.01 | 1.212 | -0.003 |
| Printer No.1 | Absorber 1-4 | 6795.0 | 121.55 | +0.09 | 121.55 | +0.09 | 49.92 | -0.08 | 356.9 | 19.04 | 1.212 | -0.003 |
| Printer No.2 | Absorber 2-3 | 6868.1 | 121.54 | +0.08 | 121.52 | +0.06 | 49.93 | -0.07 | 358.6 | 19.15 | 1.210 | -0.005 |
| Printer No.2 | Absorber 2-4 | 6819.8 | 121.53 | +0.07 | 121.52 | +0.06 | 50.08 | **+0.08** | 358.4 | 19.03 | 1.211 | -0.004 |

During the printing process, we adjusted **numerous machine parameters, including spot compensation value, scaling factor, and galvanometer correction coefficient, etc**, to ultimately achieve relatively accurate overall dimensions and hole sizes:

- The overall dimensional deviation in the X and Y directions can be maintained within less than 0.2 mm.
- The density can reach above 19.0 g/cm³.
- The hole sizes calculated based on density ranges from 1.210 to 1.220, which meets the nominal specification of 1.215 ± 0.005.

# 4. Quality assurance (QA)

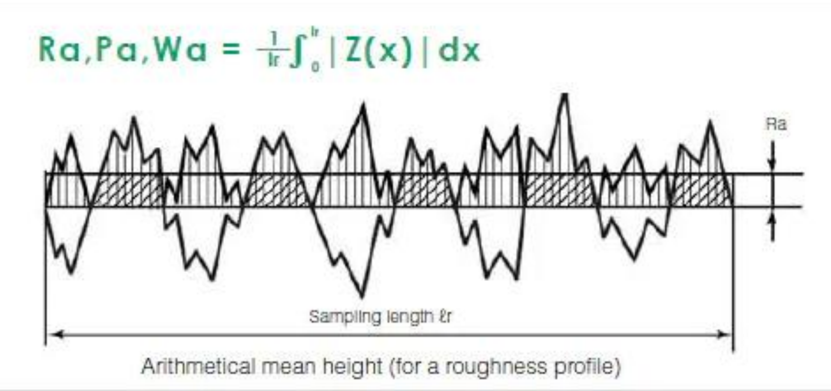
## 4.2. Surface roughness measurement at WHU ECAL Lab

### Roughness: a type of surface finish feature

- Refers to the fine irregularities on the **microscopic scale** of a surface.
- Represents the statistical characteristics of **localized microscopic surface** peaks and valleys.

### Roughness evaluation parameter

- ***Ra*** —— Arithmetic mean deviation of profile
- The arithmetic mean of the absolute values of the distances of all points relative to the mean line along the sampling length.




### Measuring equipment

- Probe-type: Surface roughness meter
- Optical-type: Ultra-deep-field 3D microscope


Probe-type: Surface roughness meter

Optical-type: Ultra deep field 3D microscope

**Continuously** traversing a defined distance along the surface profile

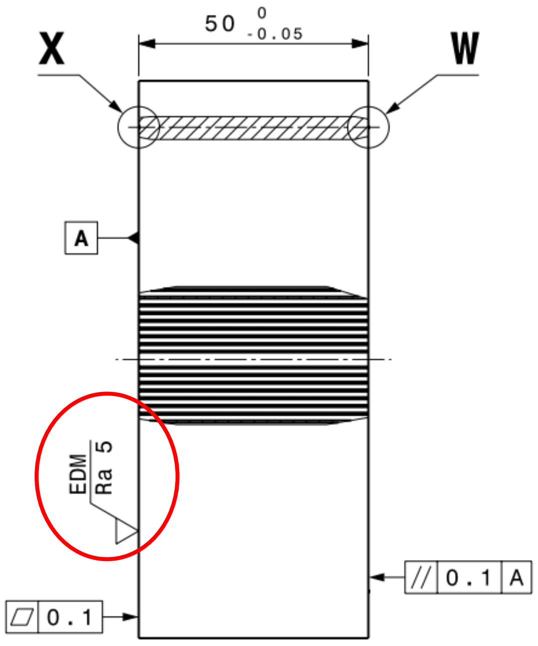
# 4. Quality assurance (QA)

## 4.2. Surface roughness measurement results at WHU ECAL Lab

- For side surfaces and bottom surface:

  Ra < 5 μm

- Can meet the roughness requirement for EDM cut surface the design drawing.




| | 1-3 | | | 2-3 | | |
|---|---|---|---|---|---|---|
| | Ra | Rz | Rt | Ra | Rz | Rt |
| Side surface 1# | 2.959 | 25.604 | 31.020 | 3.296 | 22.083 | 28.893 |
| | 3.839 | 29.361 | 37.947 | 3.350 | 24.817 | 31.950 |
| | 3.965 | 28.077 | 36.533 | 3.929 | 27.260 | 37.039 |
| | 4.056 | 30.313 | 42.184 | 3.894 | 27.742 | 36.632 |
| | 3.396 | 21.599 | 30.665 | 3.954 | 28.100 | 35.196 |
| Side surface 2# | 3.242 | 23.545 | 29.891 | 3.852 | 24.498 | 38.578 |
| | 3.748 | 33.151 | 55.440 | 2.949 | 18.419 | 22.637 |
| | 2.793 | 19.278 | 26.304 | 2.831 | 16.855 | 24.593 |
| | 3.218 | 23.745 | 33.240 | 2.902 | 15.761 | 20.562 |
| | 2.982 | 24.705 | 37.570 | 2.975 | 16.731 | 22.125 |
| Side surface 3# | 4.609 | 32.095 | 49.680 | 3.763 | 22.240 | 26.939 |
| | 3.877 | 25.759 | 34.796 | 2.909 | 19.324 | 28.715 |
| | 4.033 | 28.019 | 39.673 | 3.203 | 22.903 | 28.839 |
| | 3.396 | 27.467 | 56.893 | 3.207 | 17.979 | 22.253 |
| | 3.427 | 25.360 | 40.595 | 2.662 | 19.256 | 25.390 |
| Side surface 4# | 2.920 | 23.114 | 30.644 | 4.087 | 24.218 | 36.896 |
| | 3.311 | 22.262 | 30.290 | 3.256 | 20.312 | 24.892 |
| | 3.032 | 23.474 | 29.709 | 3.002 | 20.524 | 31.598 |
| | 3.844 | 27.838 | 35.494 | 3.333 | 24.460 | 36.987 |
| | 3.335 | 23.001 | 25.643 | 3.060 | 20.257 | 30.553 |
| Top surface (Printed surface) 5# | 10.108 | 51.638 | 68.533 | 11.536 | 56.386 | 73.840 |
| | 11.063 | 62.711 | 76.944 | 11.551 | 60.504 | 96.065 |
| | 10.607 | 57.903 | 83.032 | 10.712 | 52.975 | 68.535 |
| | 9.807 | 55.419 | 71.793 | 10.836 | 59.270 | 74.017 |
| | 11.004 | 58.075 | 70.435 | 10.922 | 57.096 | 66.332 |
| Bottom surface (Cut surface) 6# | 3.124 | 17.694 | 20.455 | 2.862 | 20.127 | 27.867 |
| | 3.115 | 18.473 | 21.053 | 3.496 | 19.490 | 22.834 |
| | 2.951 | 19.054 | 22.589 | 3.034 | 18.264 | 22.943 |
| | 2.952 | 18.518 | 22.533 | 3.279 | 21.555 | 30.428 |
| | 3.045 | 17.608 | 25.133 | 3.374 | 21.804 | 25.923 |

# 4. Quality assurance (QA)

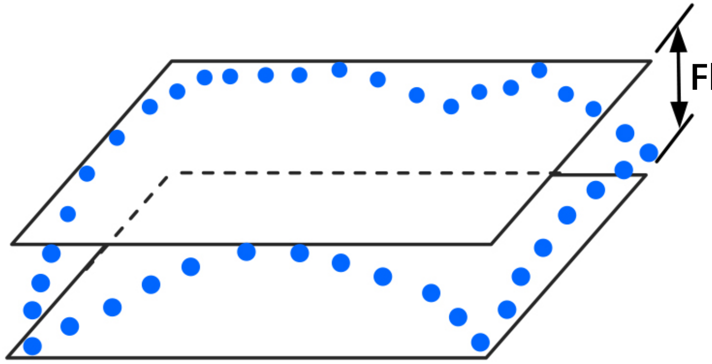
## 4.3. Flatness and perpendicularity measurement at WHU ECAL Lab

**Flatness: a type of surface finish feature**

- Quantifies the maximum deviation of all points on a **macroscopic surface** from an ideal reference plane.
- Characterizes the **overall** surface irregularities, such as waviness or curvature.

**Roughness evaluation parameter**

- **Flatness deviation**
- The minimum distance between two parallel planes that sandwich all measured points.

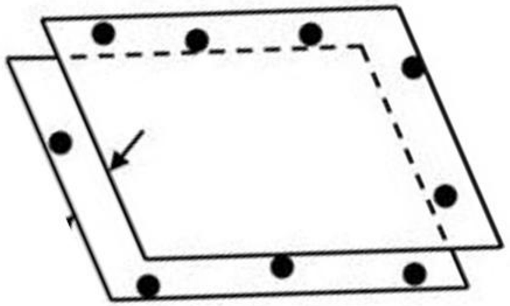



**Measuring equipment**

- Coordinate measuring machine (CMM)
- Laser tracker

CMM

Laser tracker

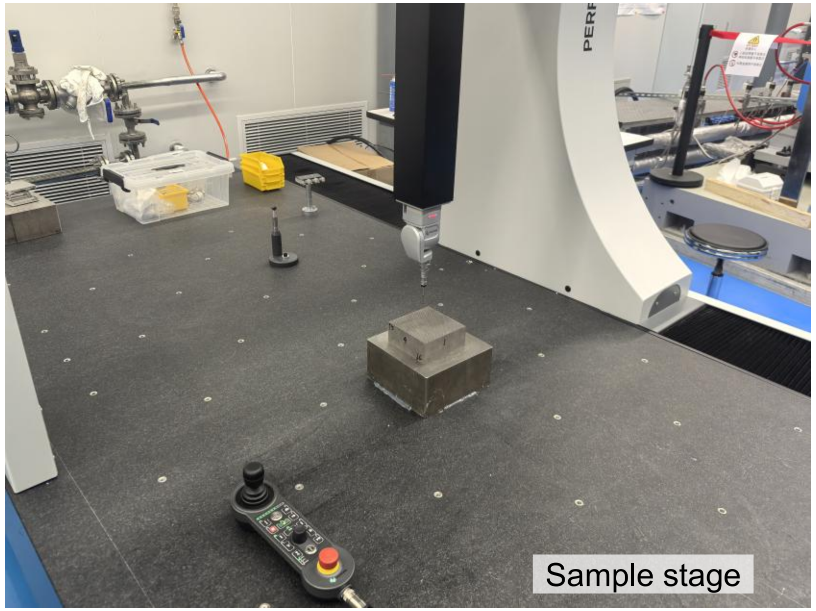


Scanning **multiple discrete points** on the surface

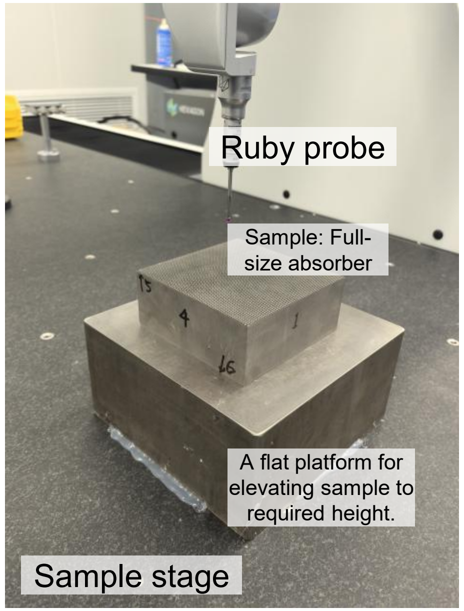
# 4. Quality assurance (QA)

## 4.3. Flatness and perpendicularity measurement at WHU ECAL Lab

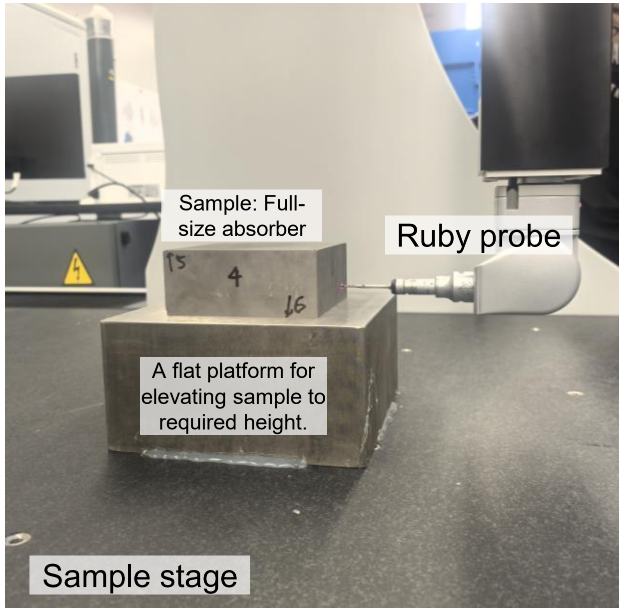
- Equipment: Hexagon bridge-type coordinate measuring machine



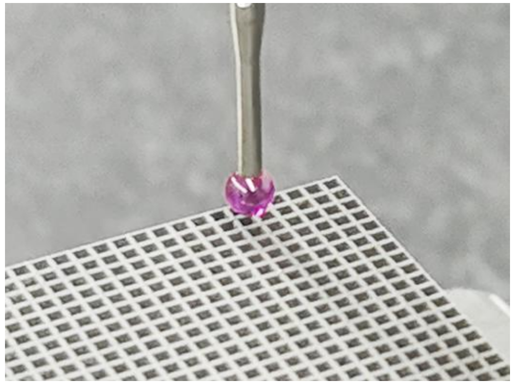

Hexagon bridge-type coordinate measuring machine (CMM)

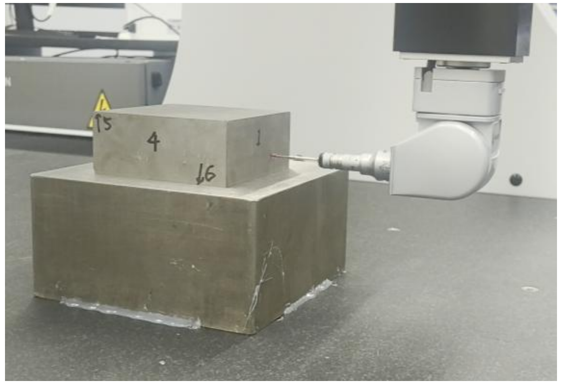


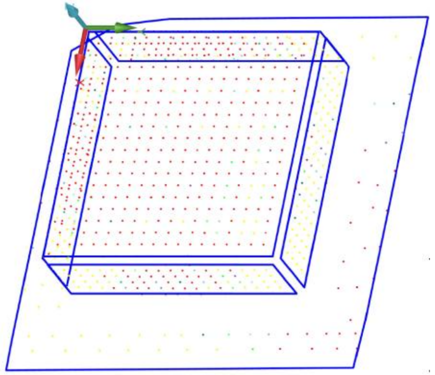

The setup for collecting data points on the side plane




The setup for collecting data points on the top plane



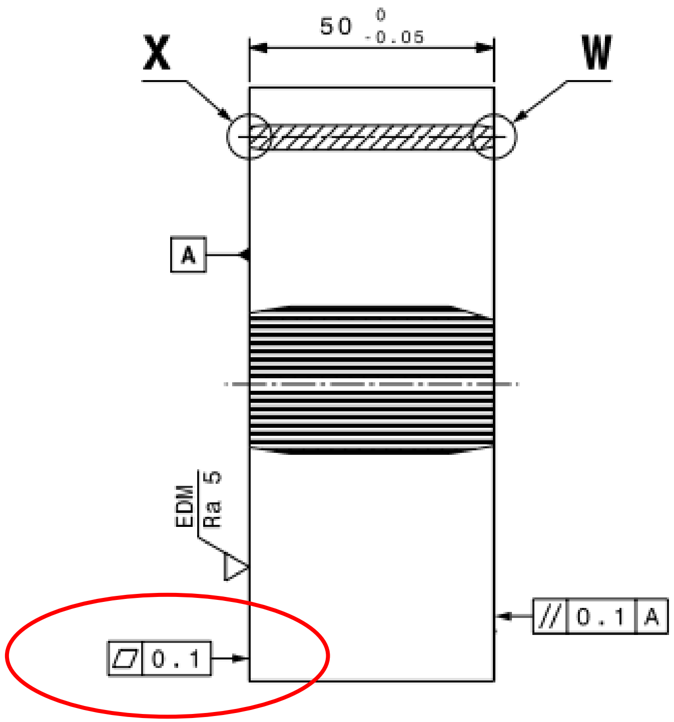




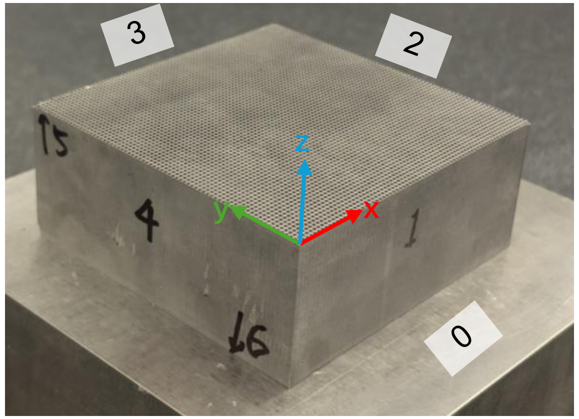
# 4. Quality assurance (QA)

### 4.3.1 Flatness measurement results

| | Absorber 1-1 (Printer 1) | Absorber 2-1 (Printer 2) | Absorber 3-1 (Printer 3) |
|---|---|---|---|
| | Flatness, µm | Flatness, µm | Flatness, µm |
| 1# | 73.2 | 30.2 | 49.9 |
| 2# | 55.1 | 58.6 | 31.4 |
| 3# | 75.0 | 47.4 | 34.2 |
| 4# | 63.8 | 63.7 | 81.7 |
| 6# (Cut surface) | 113.0 | 100.1 | 125.7 |



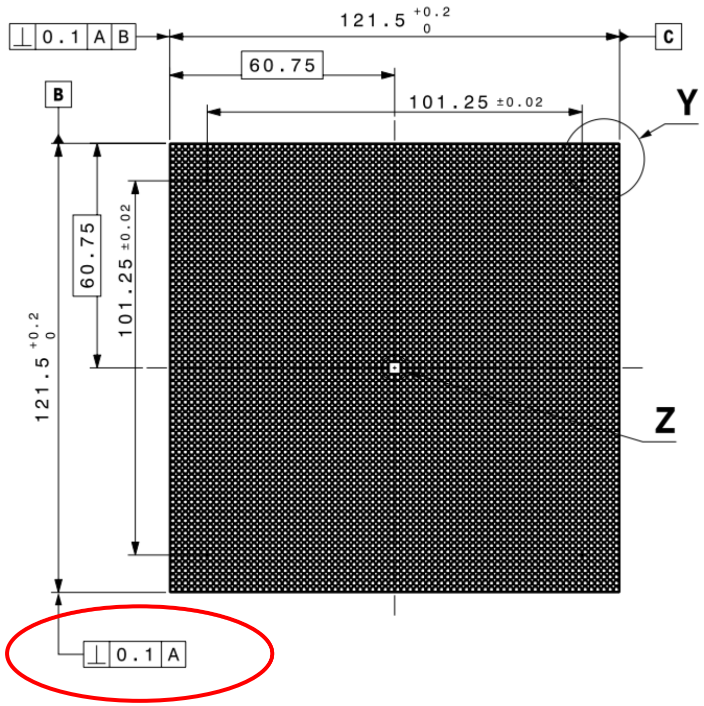

- The flatness of the side surfaces (1# to 4#) is less than 100 µm,
- The flatness of the cut surface (6#) is slightly greater than 100 µm.



# 4. Quality assurance (QA)

## 4.3.2 Perpendicularity measurement results

| | Absorber 1-1 (Printer 1) | Absorber 2-1 (Printer 2) | Absorber 3-1 (Printer 3) |
|---|---|---|---|
| | Flatness, µm | Flatness, µm | Flatness, µm |
| 1⊥6 | **133.4** | 32.2 | 94.6 |
| 2⊥6 | 57.6 | 99.2 | 66.2 |
| 3⊥6 | **103.4** | 49.6 | 42.3 |
| 4⊥6 | **116.9** | 79.3 | 91.6 |



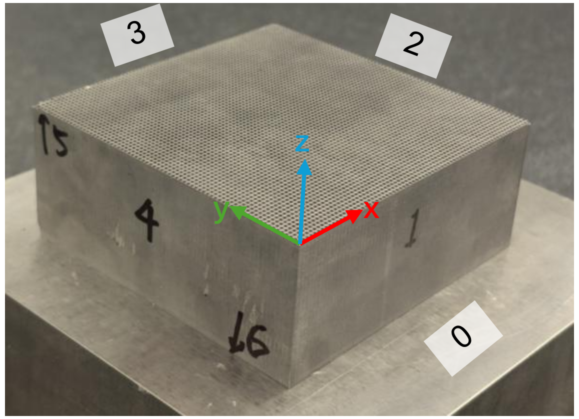

- Perpendicularity requirements in design drawing:

  Less than 100 µm

- Measured perpendicularity (side surface to cut surface):

  Absorber 2-1 and Absorber 3-1: Both within 100 µm, within the tolerance.

  Absorber 1-1: Higher than 100 µm, Exceeds tolerance due to inaccuracies in wire cutting operation. This is an issue we are further optimizing with LaserAdd.

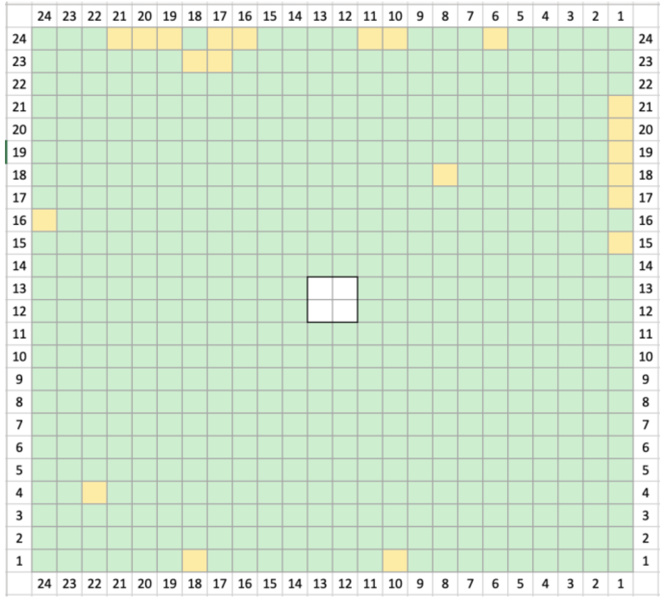


# 4. Quality assurance (QA)

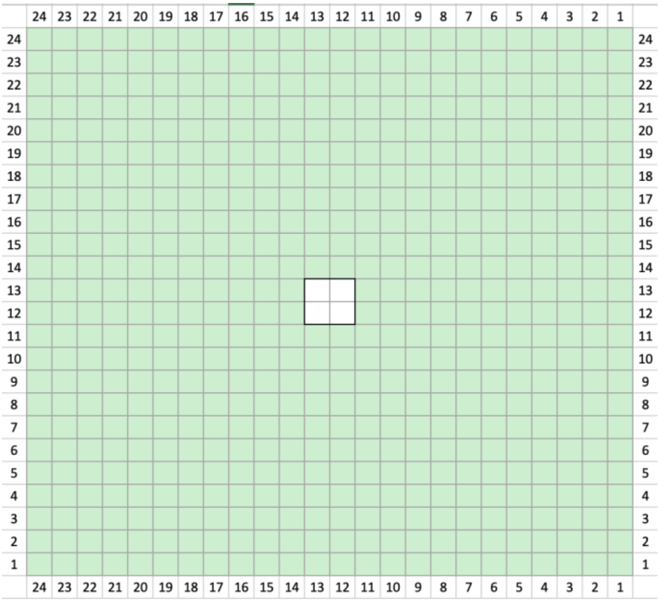
## 4.4. Insertion test of reduced-size absorbers (plots from PKU colleagues)

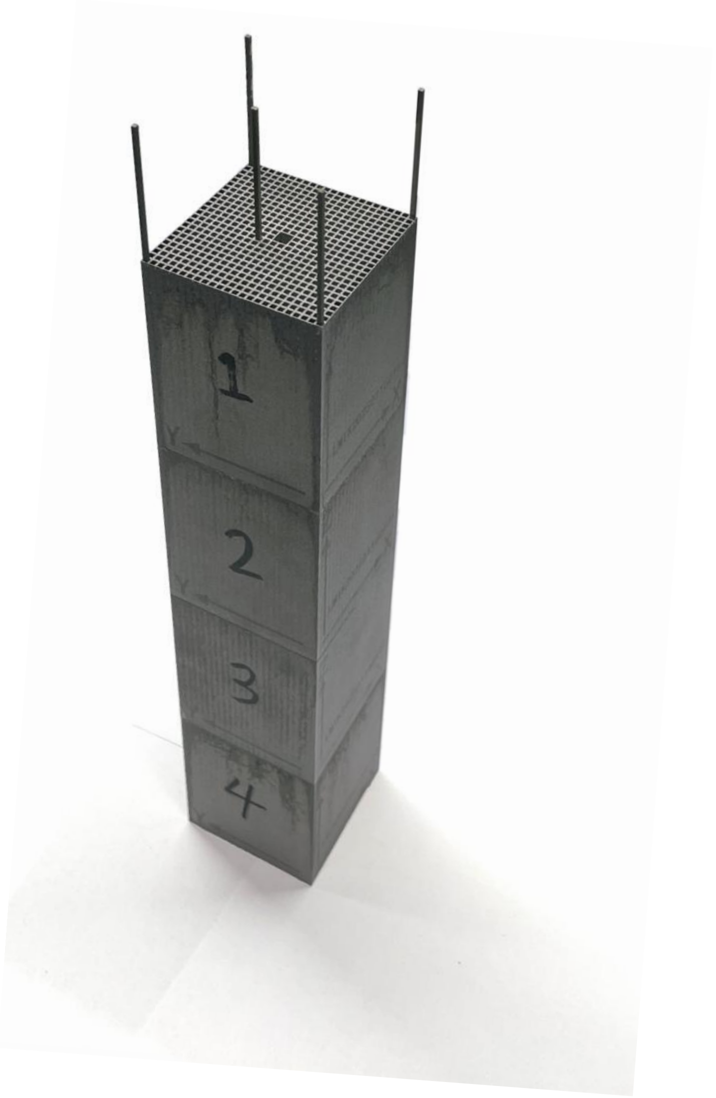
- To stack four absorbers together and conduct an insertion test.
- We use square metal rods with width of 1 mm for insertion test. (tolerance 0.01mm )
- Use 4 rods in the corner to align the absorbers.
- The resistance for all holes has been increased, but they are still easy to insert.

With metal rods




With fibers




- smooth
- noticeable resistance
- strong resistance
- can't insert

# 4. Quality assurance (QA)

## 4.5. Non-Destructive Testing at WHU

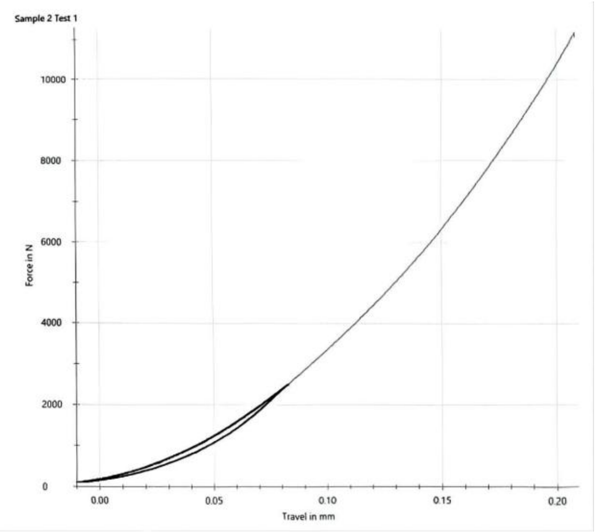
**A. Cyclic Loading**

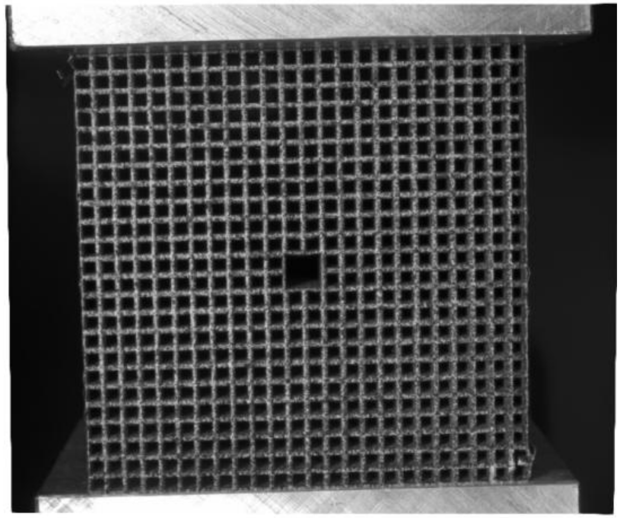
Composed of the following loading stages:

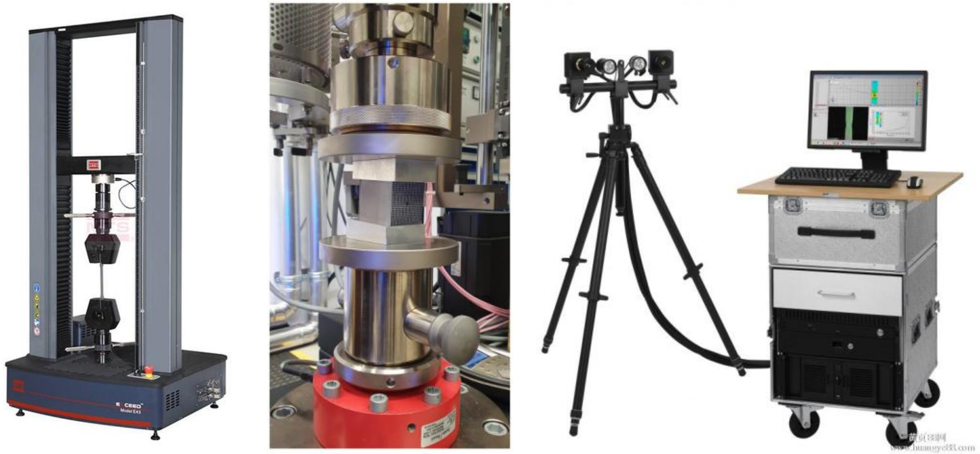
- 3x Load/Unload cycles to 2.5 kN
- 1x Load/Unload cycles to 9.5 kN

**B. Monothonic Loading**

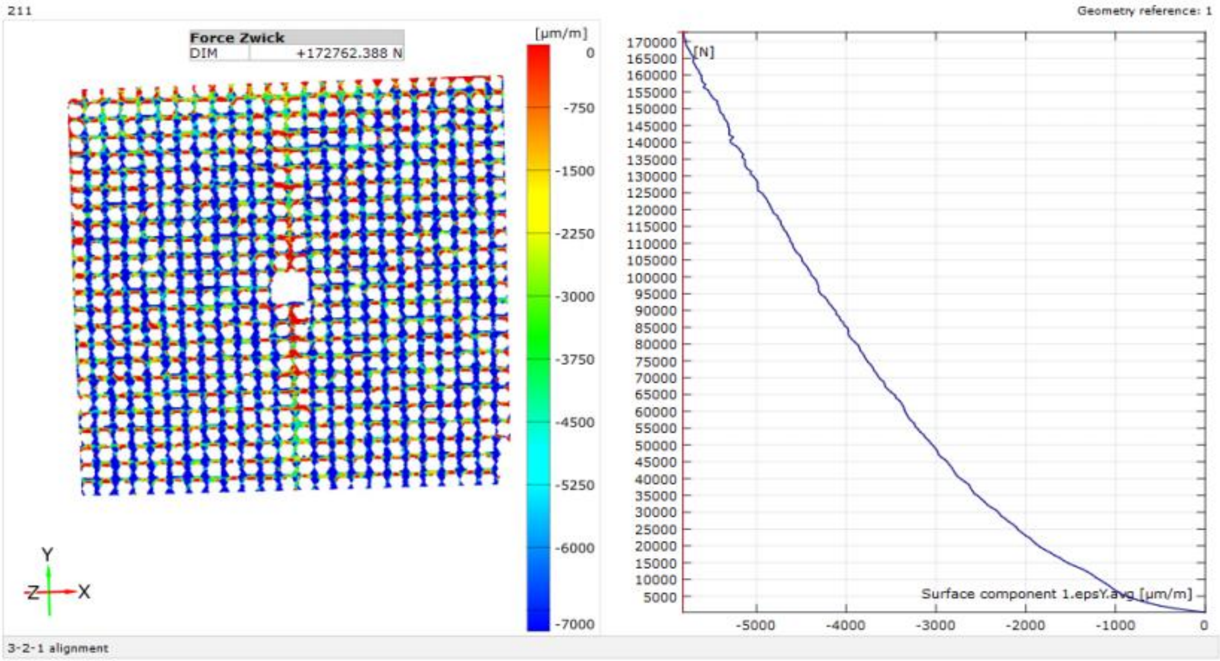
- Monotohonic loading up to the ~8 kN (two times the expected load in the ECAL wall)





The setup for Non-Destructive Testing



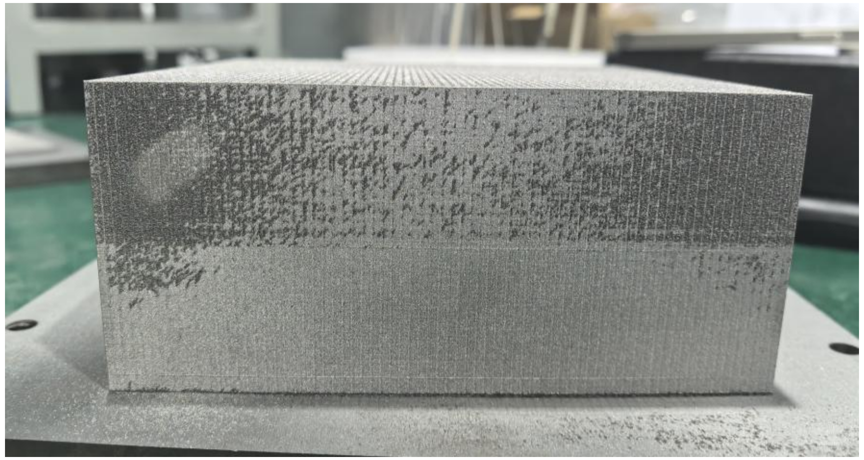
# 5. Problems need further optimization

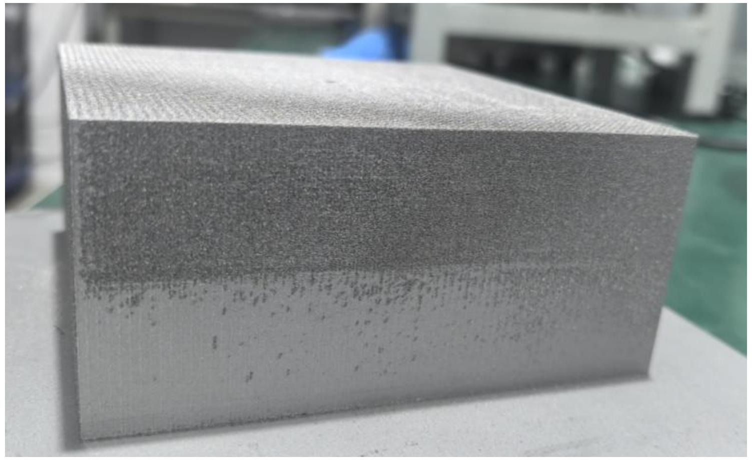
➢ **Atmosphere circulation filtration system:**

- A high-volume circulation fan generates negative pressure to rapidly remove smoke and dust, which are then isolated by the filtration device. The cleaned gas is returned to the forming chamber, forming a stable circulation process.
- This process is designed to filter out impurities of varying particle sizes, including large particles, powder, and smoke.
- By regulating the frequency of the circulation fan, we can controls the negative pressure suction force of the filtration system.

    **Excessively high frequency:** May disperse printing powder excessively, affecting print quality.

    **Excessively low frequency:** Reduces suctin force, hindering effective removal of large particles and dust.





Filtration system

- We are currently in discussions with LaserAdd to upgrade the equipment by integrating wind speed sensors and other monitoring devices. These enhancements will **capture real-time airflow distribution within the printing chamber**, provide feedback to the filtration system, and — combined with print slice information and impurity removal efficiency — **enable automatic adjustment of the fan frequency**.

# Summary

1. By optimizing the spot compensation value, scaling factor, and galvanometer correction coefficient, we can achieve relatively accurate overall dimensions and hole sizes:
    - The overall dimensional deviation in the X and Y directions can be maintained within less than 0.2 mm.
    - The height deviation in the Z direction can be controlled between -0.1 mm and 0 mm.
    - The density can reach above 19.0 $g/cm^3$.
    - The aperture calculated based on density ranges from 1.210 to 1.220 mm, which meets the nominal specification of 1.215 $\pm$ 0.005 mm.

2. With two full-size absorbers stacked, both the stainless steel rod and the fiber passed through the two absorbers relatively easily, and can be inserted to the bottom without much force.

3. There are still some issues that need to be optimized with LaserAdd, including:
    - Wire cutting accuracy
    - Automatic adjustment of fan frequency, etc

3. Time is very tight, the batch production was planned to start in Sep/2025

# Thanks for your attention!