



Mass production of tungsten absorbers for the LHCb ECAL upgrade II

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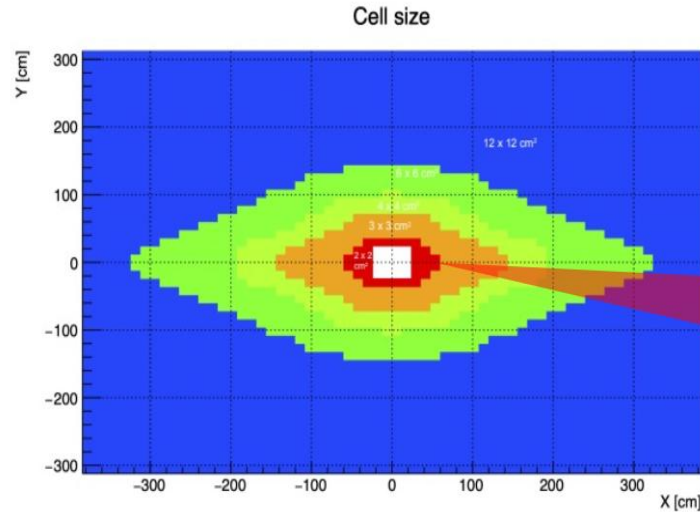
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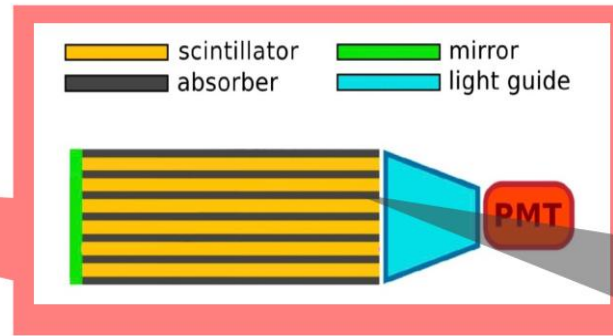
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1.1. Tungsten absorbers for LHCb ECAL upgrades

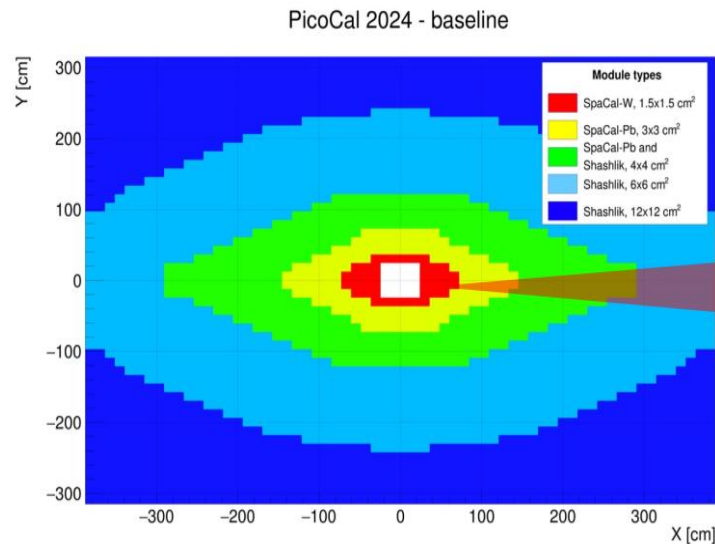
LS3



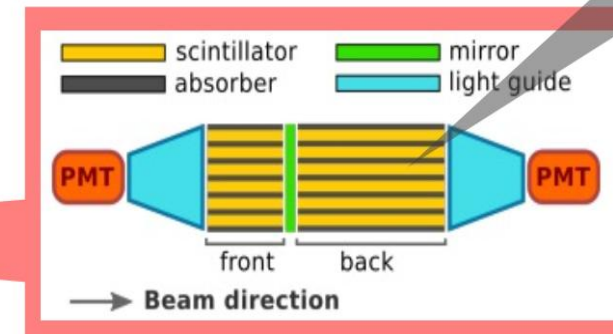
SPACAL-W+poly



LS4



SPACAL-W+GAGGG



1.24×1.24 mm² holes
In total 5180 (72 × 72)

Tungsten (W) absorbers used in innermost part of ECAL

- Key challenge: production of absorbers featuring **small, high-precision holes** into which scintillating fibers must **be inserted without damage**.

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).

The periodic table displays elements with their symbols, atomic numbers, and names. Tungsten (W) is highlighted in a red box. Above the table, icons represent various physical properties: Atomic Mass, Atomic Radius, Ionization, Melting Point, Heat Capacity, Density, Electronegativity, El. Resistivity, Boiling Point, and Th. Conductivity.

Element	Symbol	Atomic Number	Melting Point (K)
Hydrogen	H	1	14.01
Helium	He	2	0.95
Lithium	Li	3	453.7
Beryllium	Be	4	1570
Sodium	Na	11	370.9
Magnesium	Mg	12	923
Potassium	K	19	336.5
Calcium	Ca	20	1115
Scandium	Sc	21	1814
Titanium	Ti	22	1941
Vanadium	V	23	2183
Chromium	Cr	24	2180
Manganese	Mn	25	1519
Iron	Fe	26	1811
Cobalt	Co	27	1768
Nickel	Ni	28	1728
Copper	Cu	29	1357.8
Zinc	Zn	30	692.7
Gallium	Ga	31	302.9
Germanium	Ge	32	1211.4
Arsenic	As	33	1090
Selenium	Se	34	494
Bromine	Br	35	265.9
Krypton	Kr	36	115.8
Rubidium	Rb	37	312.5
Sr	Sr	38	1090
Yttrium	Y	39	1799
Zirconium	Zr	40	2128
Niobium	Nb	41	2750
Molybdenum	Mo	42	2896
Tech. Neutronium	Tc	43	3430
Ruthenium	Ru	44	2607
Rhodium	Rh	45	2237
Palladium	Pd	46	1628.1
Silver	Ag	47	1234.9
Cadmium	Cd	48	594.2
Indium	In	49	429.8
Tin	Sn	50	505.1
Antimony	Sb	51	903.8
Tellurium	Te	52	722.6
Iodine	I	53	386.9
Xenon	Xe	54	161.3
Cesium	Cs	55	301.6
Barium	Ba	56	1000
Lanthanoids	57-71		
Hafnium	Hf	72	2550
Tantalum	Ta	73	2520
Tungsten	W	74	3422
Rhenium	Re	75	3180
Osmium	Os	76	3045
Iridium	Ir	77	2738
Pt	Pt	78	2041.4
Gold	Au	79	1337.3
Mercury	Hg	80	234.3
Thallium	Tl	81	577
Lead	Pb	82	600.6
Bismuth	Bi	83	544.4
Polonium	Po	84	527
Astatine	At	85	575
Rn	Rn	86	252
Francium	Fr	87	300
Radium	Ra	88	973
Actinoids	89-103		
Rutherfordium	Rf	104	
Dubnium	Db	105	
Seaborgium	Sg	106	
Bohrium	Bh	107	
Hassium	Hs	108	
Meitnerium	Mt	109	
Darmstadtium	Ds	110	
Roentgenium	Rg	111	
Copernicium	Cn	112	
Nihonium	Nh	113	
Flerovium	Fl	114	
Moscovium	Mc	115	
Livermorium	Lv	116	
Tennessee	Ts	117	
Ognessium	Og	118	
Lanthanum	La	57	1193
Cerium	Ce	58	1071
Praseodymium	Pr	59	1204
Neodymium	Nd	60	1294
Europium	Eu	61	1324
Gadolinium	Gd	62	1327
Terbium	Tb	63	1329
Dysprosium	Dy	64	1685
Ho	Ho	65	1747
Er	Er	66	1727
Tm	Tm	67	1818
Yb	Yb	68	1062
Lu	Lu	69	1936
Actinium	Ac	89	1322
Th	Th	90	2023
Protactinium	Pa	91	1845
Uranium	U	92	1405
Np	Np	93	917
Pu	Pu	94	913
Am	Am	95	1449
Cm	Cm	96	1618
Bk	Bk	97	1223
Cf	Cf	98	1173
Es	Es	99	1133
Fm	Fm	100	1500
Md	Md	101	1100
No	No	102	1100
Lr	Lr	103	1900

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

- Innovation methods for tungsten absorber production are needed to enable effective use in calorimeters.

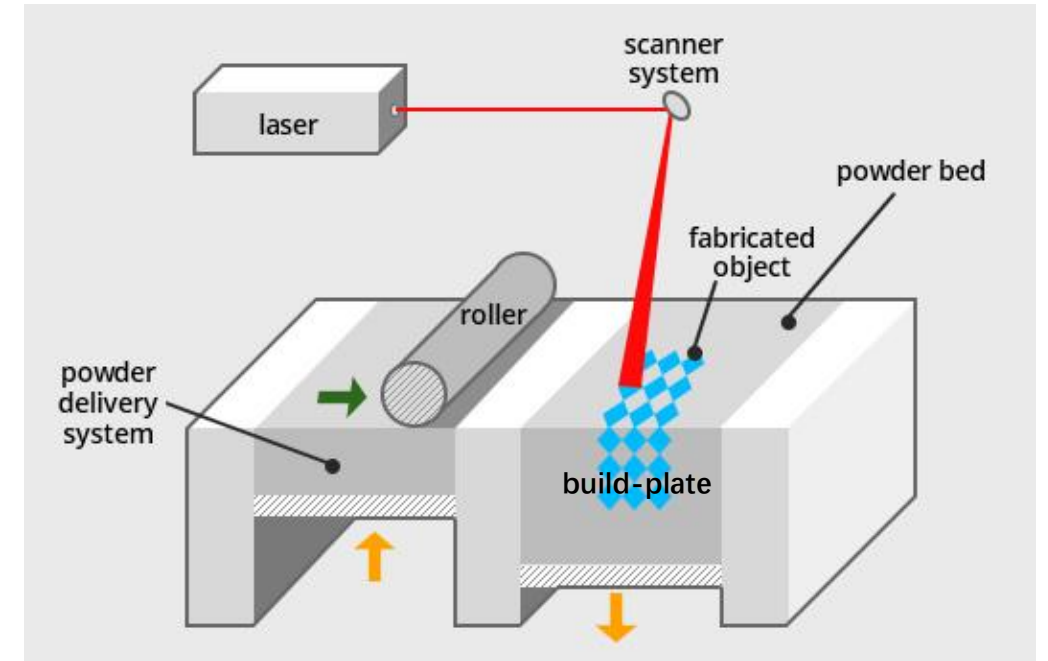
1.3. Selective laser melting (SLM)

➤ 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.

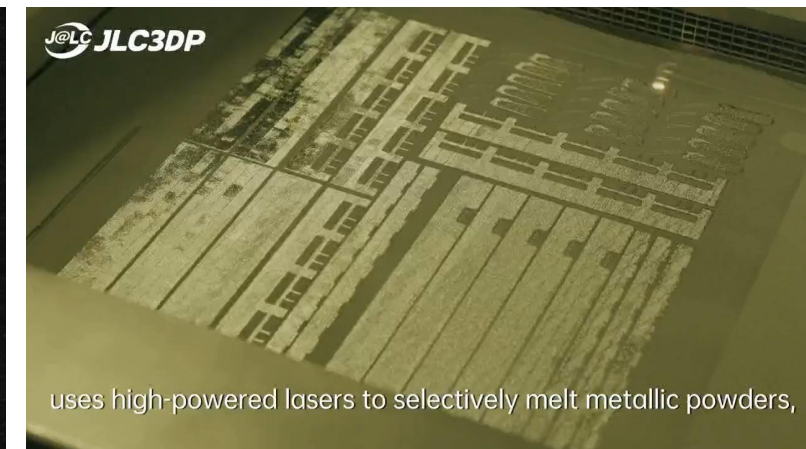
In SLM process:

- 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):

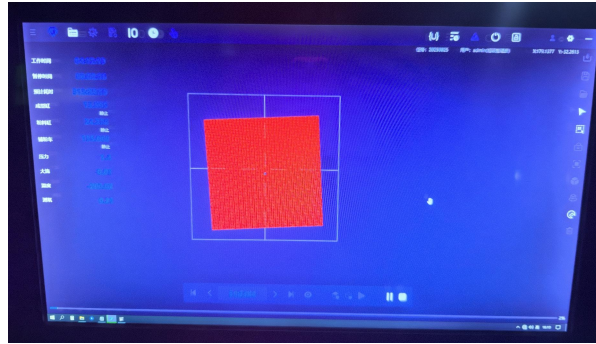
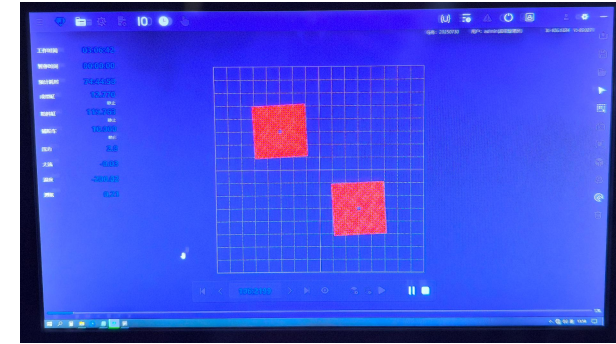
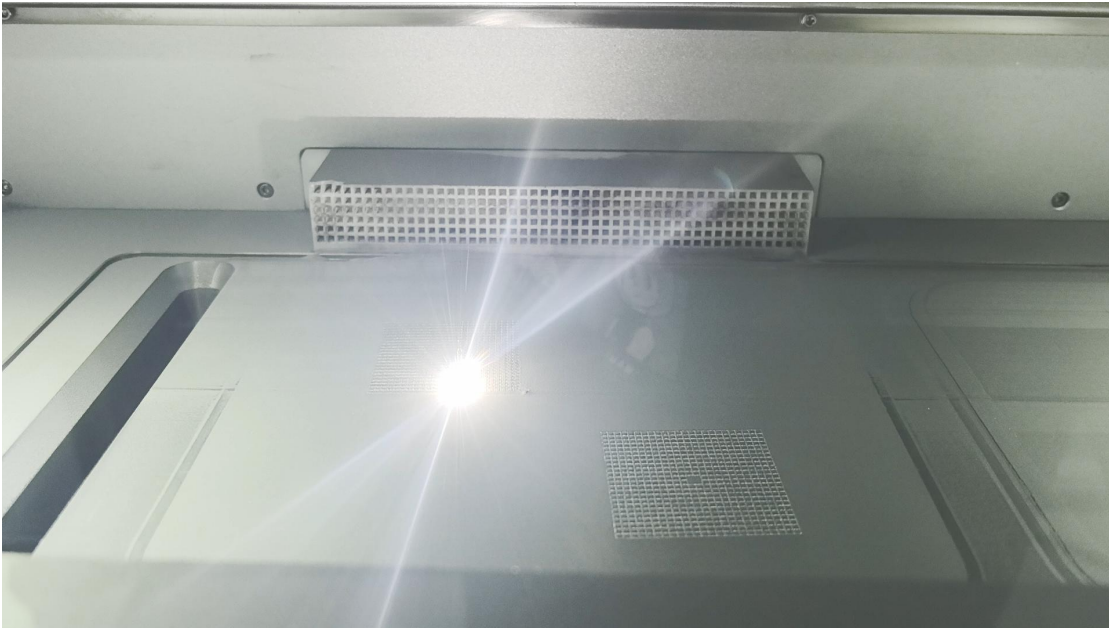
- High energy density
- Small spot diameter
- **High forming precision**
- **Exceptional processing freedom**



2.1. 3D Printing details

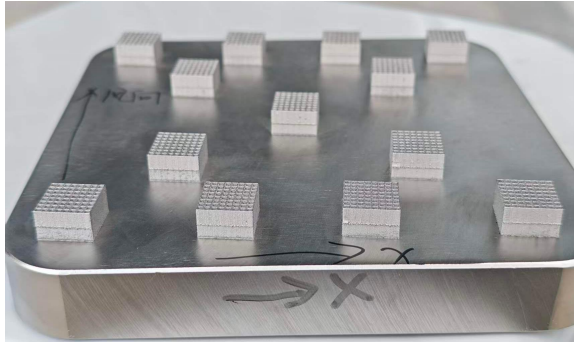
➤ We have commissioned four printers to print tungsten absorbers.

- **Layer thickness:** 0.02 mm ~ 0.1 mm
(We used 0.025 mm)
- **Maximum laser power:** 200 ~ 600 W
- **Printing accuracy:** 30 μ m



2.1. 3D Printing details

- An overall process spanning from process development to batch production has been established.
- The current status of the four printers at both companies is summarized below.

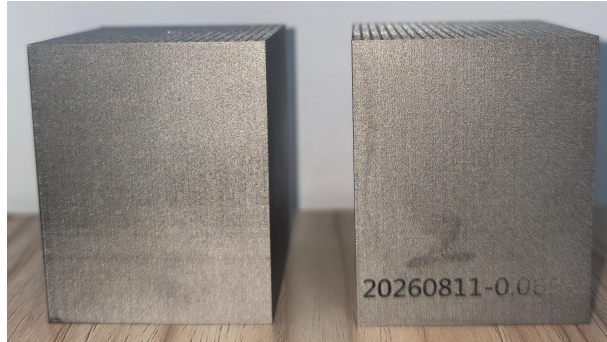


Process development

- Optimize printing parameters;
- Optimize scanning strategy;
- Optimize gas flow parameters

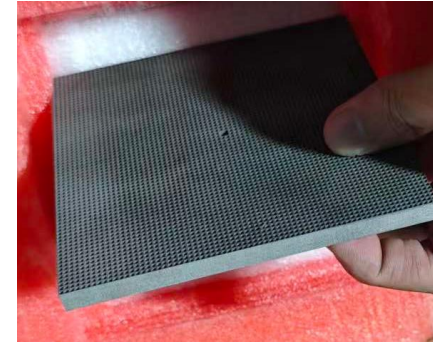


LaserAdd Printer No.2



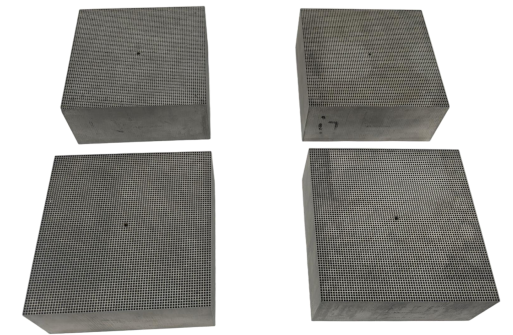
Reduced-size absorber validation

- Validate dimensional accuracy,
- Validate density and hole size
- Determine spot compensation



Full-size absorber printing

- Print full-size absorbers (thin slice)
- Verify overall dimensional accuracy
- Prepare for batch production



Full-size absorber production

- Solidify process;
- Establish a repeatable and scalable production line

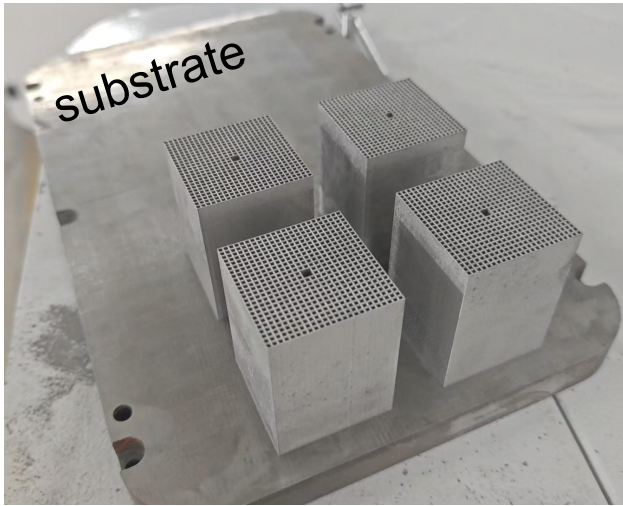
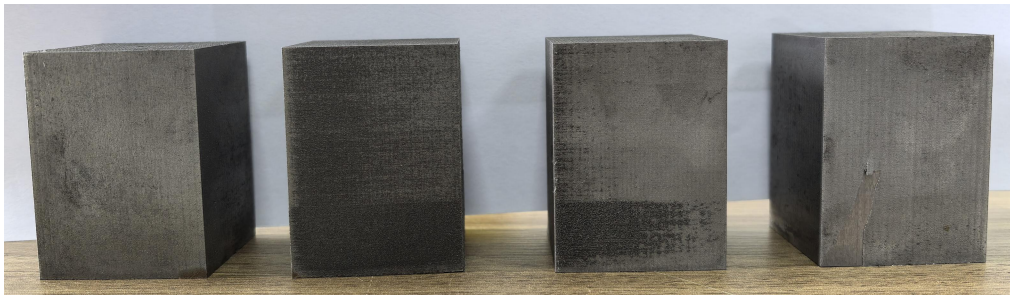


Riton Printer No.1
Riton Printer No.2
LaserAdd Printer No.1

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 Sandblasting

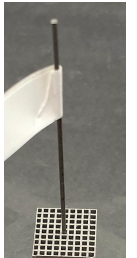
- Using compressed air as the power source, a high-speed jet beam is generated.
- Sands are applied at high speed to the surface of absorbers.
- To remove surface powder and reduces surface roughness.

Sandblasting machine



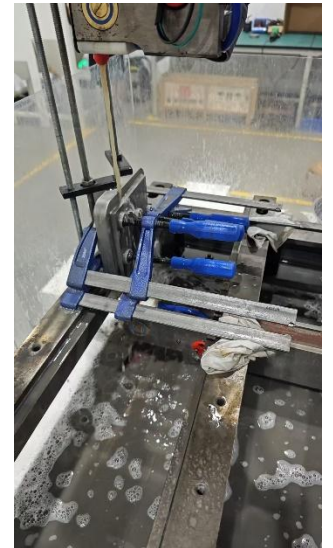
③ Hole insertion

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



④ 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

- We have successfully printed a number of absorbers, including reduced-size absorbers and full-size absorbers
- A density of 18.9 g/cm³ has been achieved, meeting the requirements



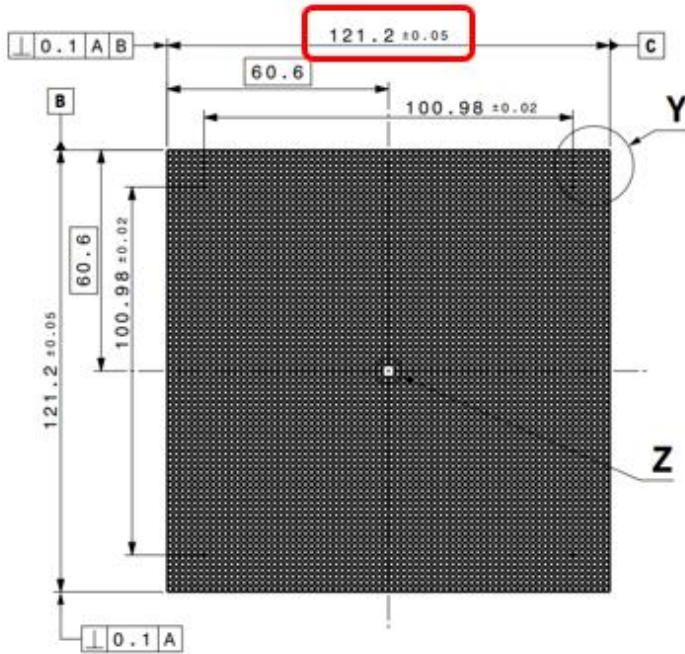
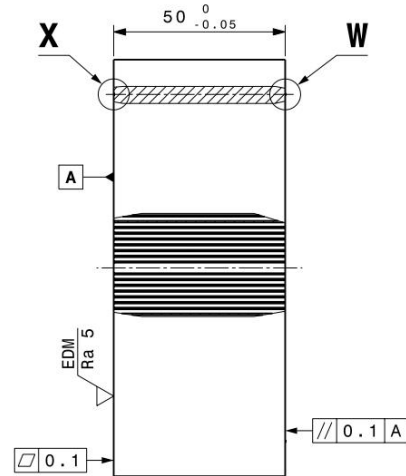
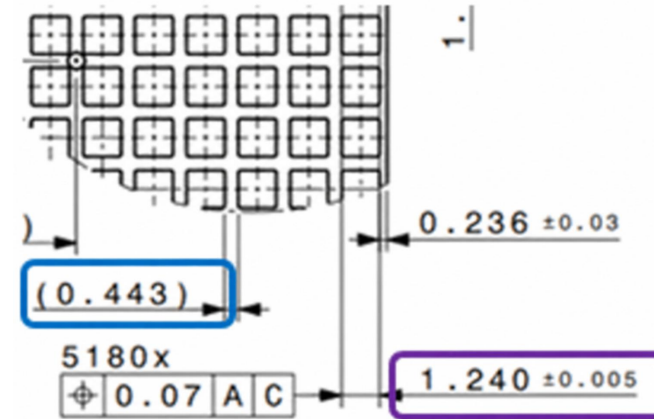
	Width (mm)	Height (mm)	Volume (mm)	Average hole size (mm)	Weight (g)	Density (g/cm ³)
Sample #1	121.20	49.96	335.40	1.240	6344.4	18.92

density of 18.9 g/cm³ is achieved.

3. Absorbers recently printed

➤ Full-size absorbers

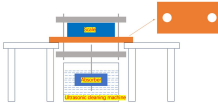
- Designed hole size: 1.240 mm × 1.240 mm (-0.005 ~ 0 mm)
- Wall thickness: 0.443 mm
- Designed overall dimensions:
121.20 mm × 121.20 mm × 50.0 mm
- Keep the funnel design as the reduced-size absorbers



- Quality assurance (QA) is required to check if the absorber can be further used.

4. Quality assurance (QA)

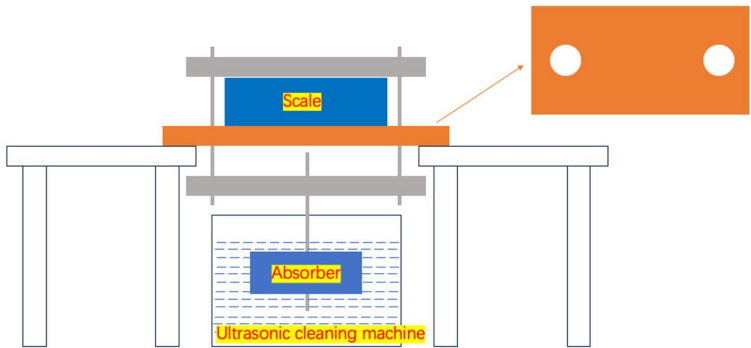
- After printing and post-processing, we will undergo a series of quality assurance (QA) tests for the absorbers

No.	Items	Testing equipment	Photo for equipment	Acceptance criteria
1	Appearance inspection	Visual check		<ul style="list-style-type: none"> The overall shape is intact, with no visible cracks or deformations. The surface is smooth and even, without irregularities. No obvious blockages inside of the hole.
2	Dimensional measurement	Vernier caliper		<ul style="list-style-type: none"> Length & Width: 0 mm to ± 0.05 mm tolerance Height: -0.05 mm to 0 mm tolerance Details see design drawings
3	Mass measurement	Analytical Balance		
4	Density measurement	Analytical balance Ultrasonic Cleaner Custom Stainless-Steel Stand		<ul style="list-style-type: none"> $\geq 18.9 \text{ g/cm}^3$
5	Surface roughness measurement	Surface Roughness Tester (Mitutoyo SJ-411)		<ul style="list-style-type: none"> $R_t < 35 \text{ }\mu\text{m}$; $R_a < 5 \text{ }\mu\text{m}$; Details see design drawings
6	Insertion testing	Stainless steel rod		<ul style="list-style-type: none"> Utilize a robotic arm to insert a steel needle into the hole and measure the magnitude of resistance
7	Flatness and perpendicularity measurement	Bridge-Type Coordinate Measuring Machine (CMM) (Hexagon PC-DMIS)		<ul style="list-style-type: none"> $< 100 \text{ }\mu\text{m}$
8	Non-Destructive Testing	Universal testing machine 2D digital image correlation		<ul style="list-style-type: none"> $\sim 9.5 \text{ kN}$ (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

Printer s	Absorber r No.	Mass, g	X, mm		Y, mm		Z, mm		Volume, cm ³	Density, g/cm ³	Average hole size, mm	
			Measure d value	Bias	Measure d value	Bias	Measure d value	Bias			Measure d value	Bias
	Designed		121.20	±0.05	121.20	±0.05	50.00	-0.05			1.240	-0.005
Printer No.1	Absorber 1-1	6344.4	121.20	0	121.22	+0.02	49.96	-0.04	335.40	18.92	1.240	0

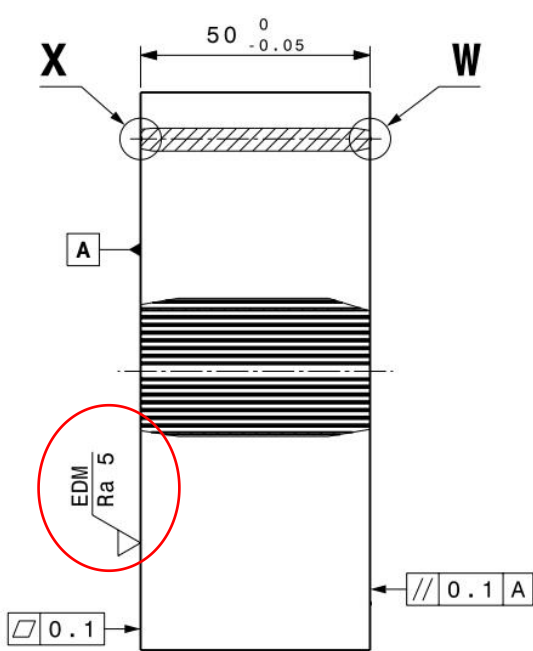
During the printing process, we adjusted numerous machine parameters, including spot compensation value, scaling factor, and galvanometer correction coefficient, etc, to ultimately achieve relatively accurate overall dimensions and hole sizes:

- The overall dimensional deviation in the X and Y directions can be maintained within less than 0.2 mm.
- The density can reach above 18.9 g/cm³.
- The hole sizes calculated based on density ranges from 1.239 to 1.240, which meets the nominal specification of 1.240 (- 0.005).

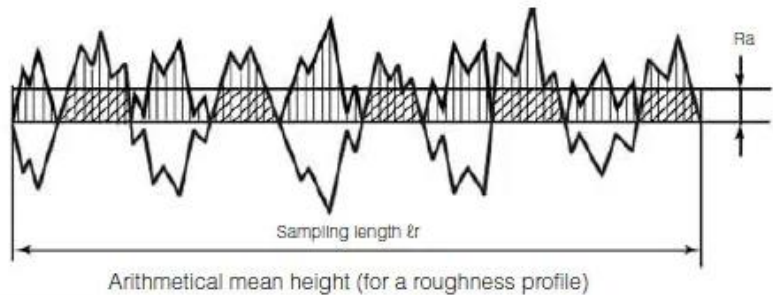
4. Quality assurance (QA)

4.2. Surface roughness measurement results at WHU ECAL Lab

- For side surfaces and bottom surface:
 $Ra < 5 \mu m$
- Can meet the roughness requirement for EDM cut surface the design drawing.



$$Ra, Pa, Wa = \frac{1}{l_r} \int_0^{l_r} |Z(x)| dx$$



Absorber 1-1				
		Ra	Rz	Rt
Side surface 1#	Top-left	4.969	26.981	34.443
	Top-right	4.556	24.678	27.448
	Bottom-left	4.994	32.257	37.090
	Bottom-right	4.713	25.766	30.007
	Middle	4.338	26.726	33.950
	Average	4.682	28.250	33.682
Side surface 2#	Top-left	4.713	27.993	34.242
	Top-right	4.994	31.763	41.114
	Bottom-left	4.708	26.091	33.923
	Bottom-right	4.991	29.940	37.499
	Middle	4.807	26.546	30.441
	Average	4.835	27.526	33.954
Side surface 3#	Top-left	4.974	31.831	50.462
	Top-right	4.989	28.886	37.004
	Bottom-left	4.399	26.781	31.284
	Bottom-right	4.843	30.246	39.559
	Middle	4.179	24.396	30.154
	Average	4.474	27.141	33.666
Side surface 4#	Top-left	4.946	28.207	36.844
	Top-right	4.725	25.542	30.703
	Bottom-left	4.909	35.538	35.584
	Bottom-right	4.696	26.133	30.626
	Middle	4.998	27.443	35.227
	Average	4.868	29.705	33.812
Cut surface 6# (Bottom)	Top-left	3.962	22.079	28.735
	Top-right	2.616	16.863	25.179
	Bottom-left	2.083	12.144	16.741
	Bottom-right	1.711	10.411	15.989
	Middle	2.543	14.803	21.627
	Average	2.112	12.453	18.119

4. Quality assurance (QA)

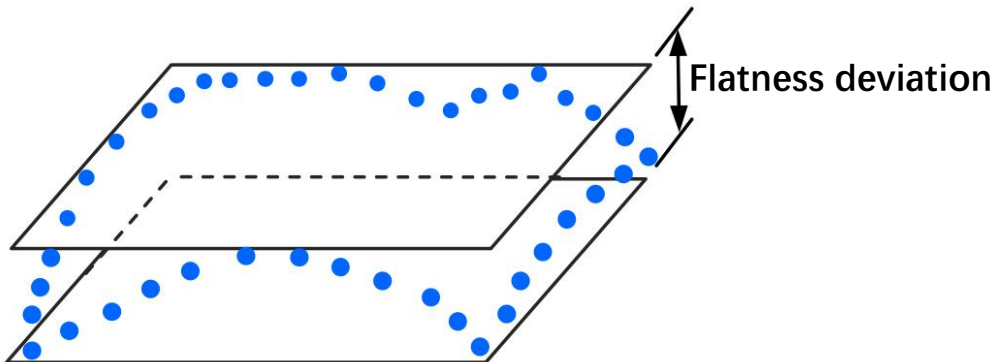
4.3. Flatness and perpendicularity measurement at WHU ECAL Lab

❑ 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.

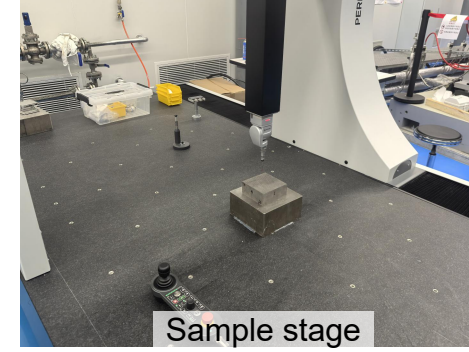
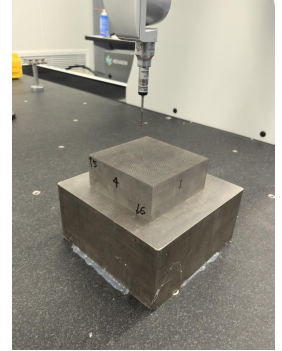
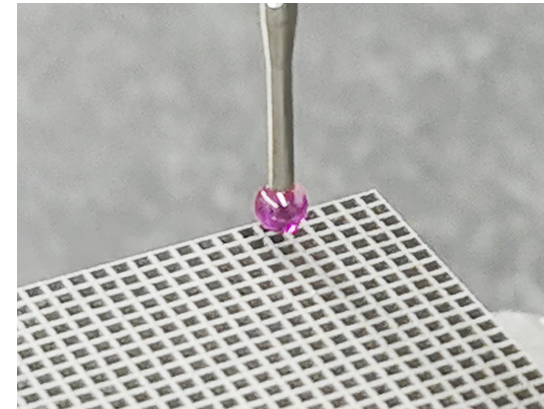
❑ Roughness evaluation parameter

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

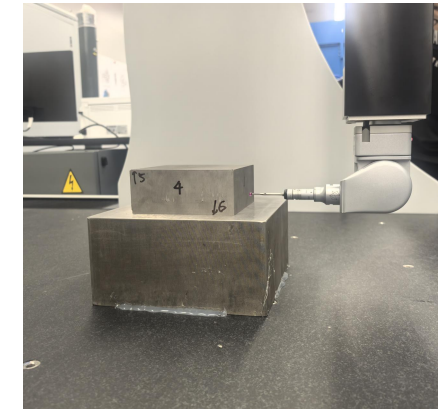
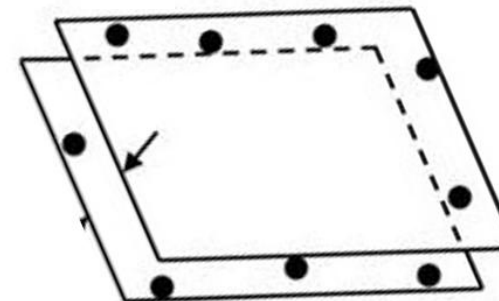


❑ Measuring equipment

- Coordinate measuring machine (CMM)



CMM



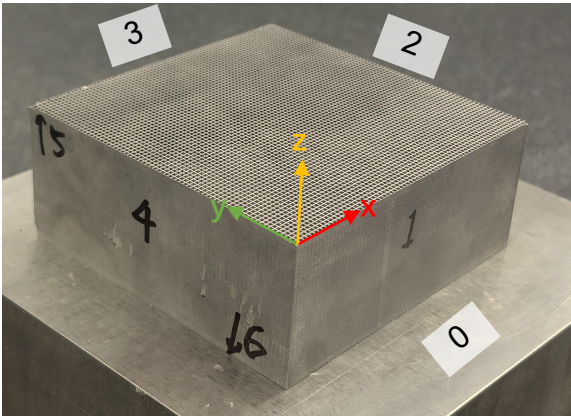
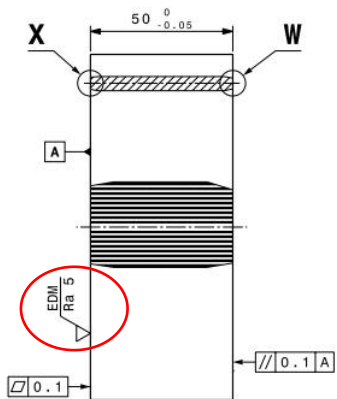
Scanning **multiple discrete points** on the surface

4. Quality assurance (QA)

4.3.1 Flatness measurement results

	Flatness, μm
	Absorber 1-1 (Riton Printer 1)
1	23.6
2	30.6
3	54.4
4	47.2
5 (Print surface)	97.6
6 (Cut surface)	44.8

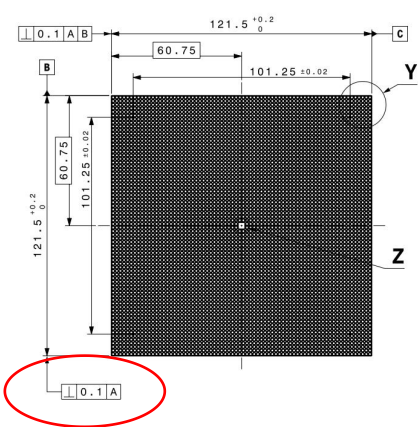
- Flatness requirements in design drawing: Less than 100 μm
- The flatness of the side surfaces (1# to 4#) is less than 100 μm



4.3.2 Perpendicularity measurement results

	Perpendicularity, μm
	Absorber 1-1 (Riton Printer 1)
1 $\perp$ 6	72.9
2 $\perp$ 6	38.3
3 $\perp$ 6	80.1
4 $\perp$ 6	56.5

- Perpendicularity requirements in design drawing: Less than 100 μm
- Measured perpendicularity (side surface to cut surface):
< 100 μm , within the tolerance.

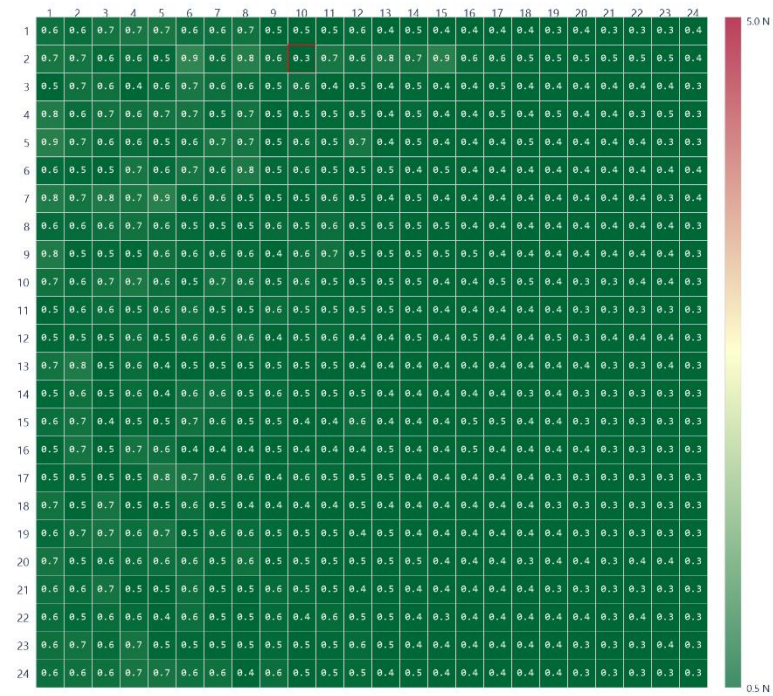


4. Quality assurance (QA)

4.4. Insertion test of full-size absorbers

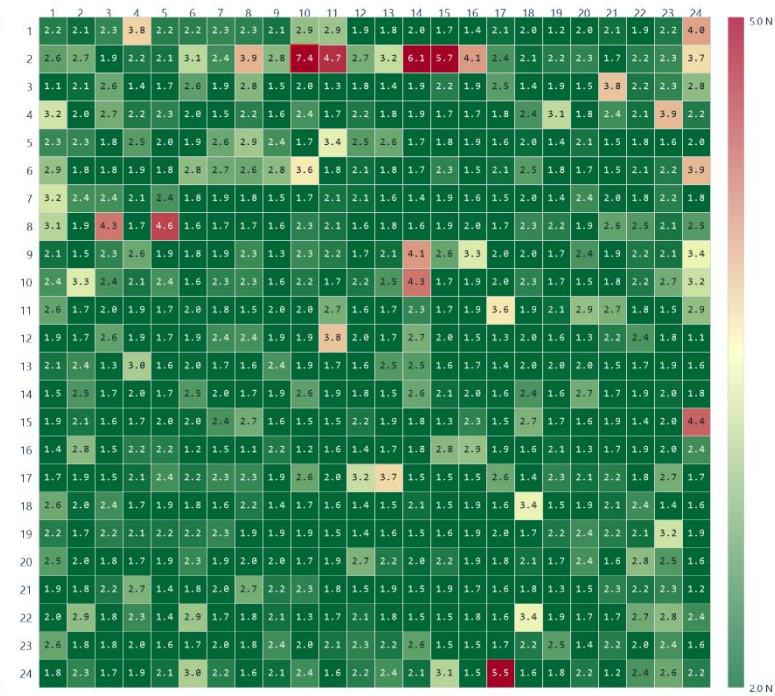
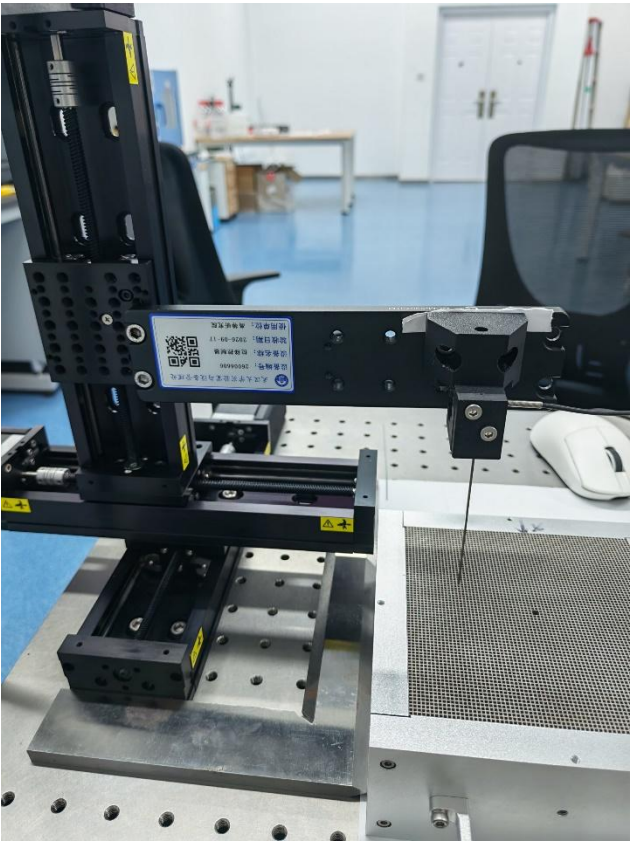
Average Force

Mean absolute force over recorded insertion samples, per hole



Peak Force

Actual peak values; color scale 2.0-5.0 N



The system integrates a motorized XYZ stage with an in-line strain-gauge force sensor for precise, automated probe insertion

4. Quality assurance (QA)

4.5. Non-Destructive Testing at WHU

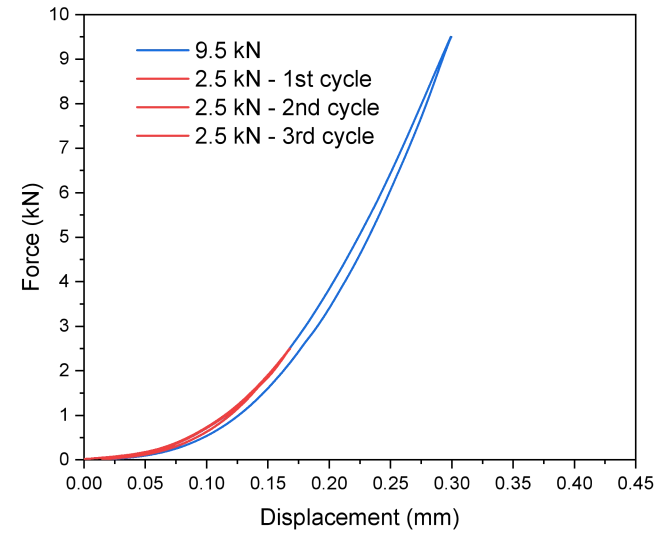
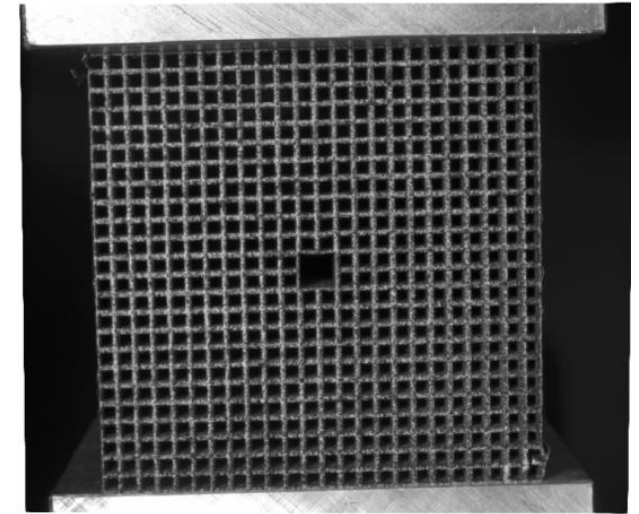
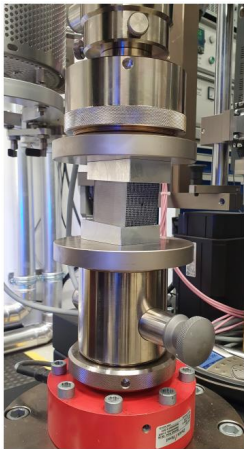
A. Cyclic Loading

Composed of the following loading stages:

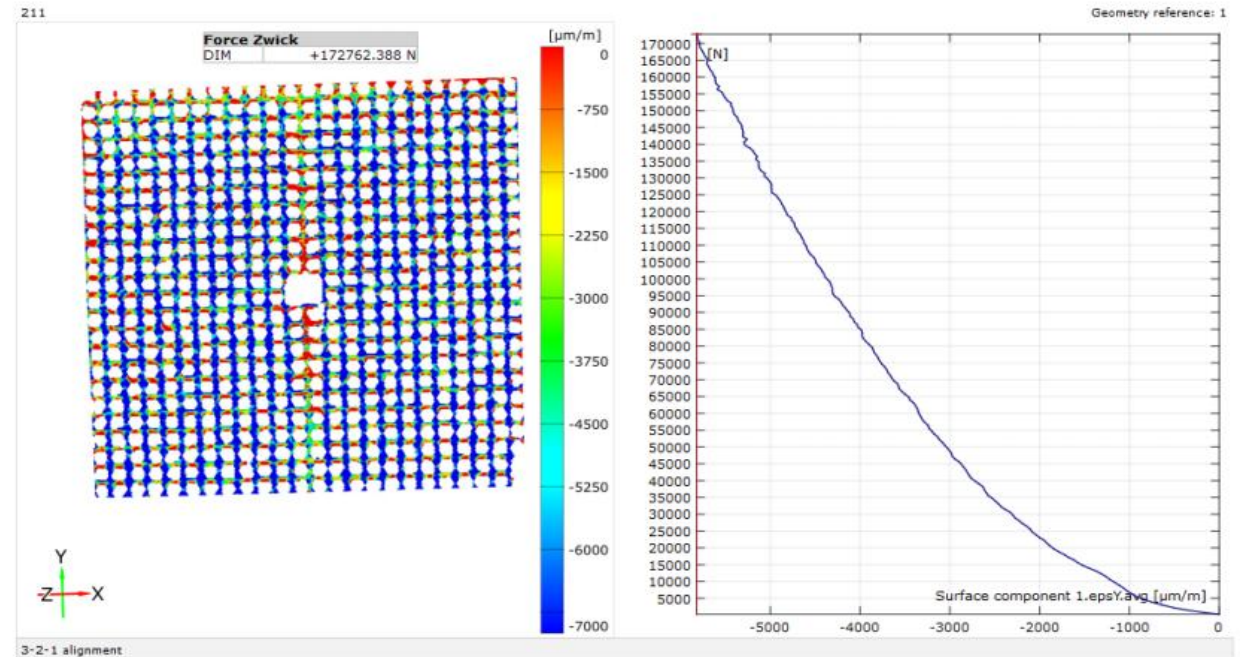
- 3x Load/Unload cycles to 2.5 kN
- 1x Load/Unload cycles to 9.5 kN

B. Monothonic Loading

- Monotohonic loading up to the failure of the absorber



The setup for Non-Destructive Testing



5. Challenges for batch production

Consistency across printers

- Qualify the process on each printer to control variations in density, overall dimensions and hole size.
- Use common reference samples and QA criteria to assess consistency across machines and production batches.

Production efficiency

- Establish a repeatable and scalable tungsten absorber production line.
- Improve the throughput of hole cleaning, insertion testing and inspection through automation.

- We have developed an SLM and post-processing route for reduced-size and full-size tungsten absorbers for the LHCb ECAL upgrades.
- The tested full-size prototype achieved a density of 18.92 g/cm^3 and a density-derived equivalent hole size of 1.240 mm.
- For this prototype, measured Ra is below $5 \text{ }\mu\text{m}$ and flatness and perpendicularity are below $100 \text{ }\mu\text{m}$.
- Automated insertion tests on full-size absorbers provide hole-by-hole force maps. Mechanical loading tests extend the QA programme.
- The next priorities are consistency across printers and improved production efficiency.



Thanks for your attention!