Experimental studies for an air cooling system for the FCC-ee inner vertex

Gherardo Ammirabile[1,2]

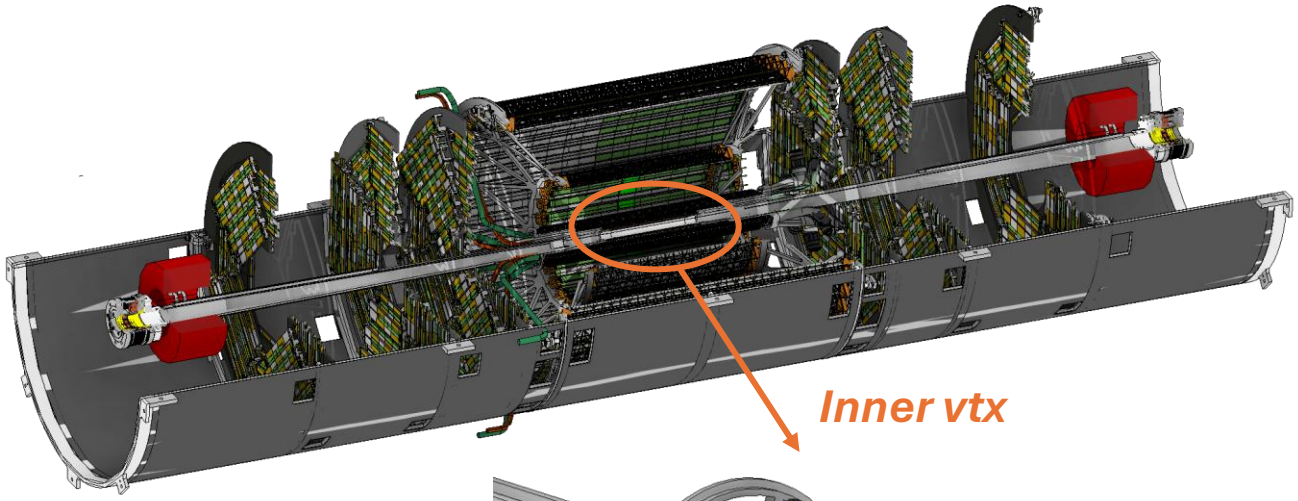
A.Mariotti[2], A.Moggi[1], F.Palla[1]

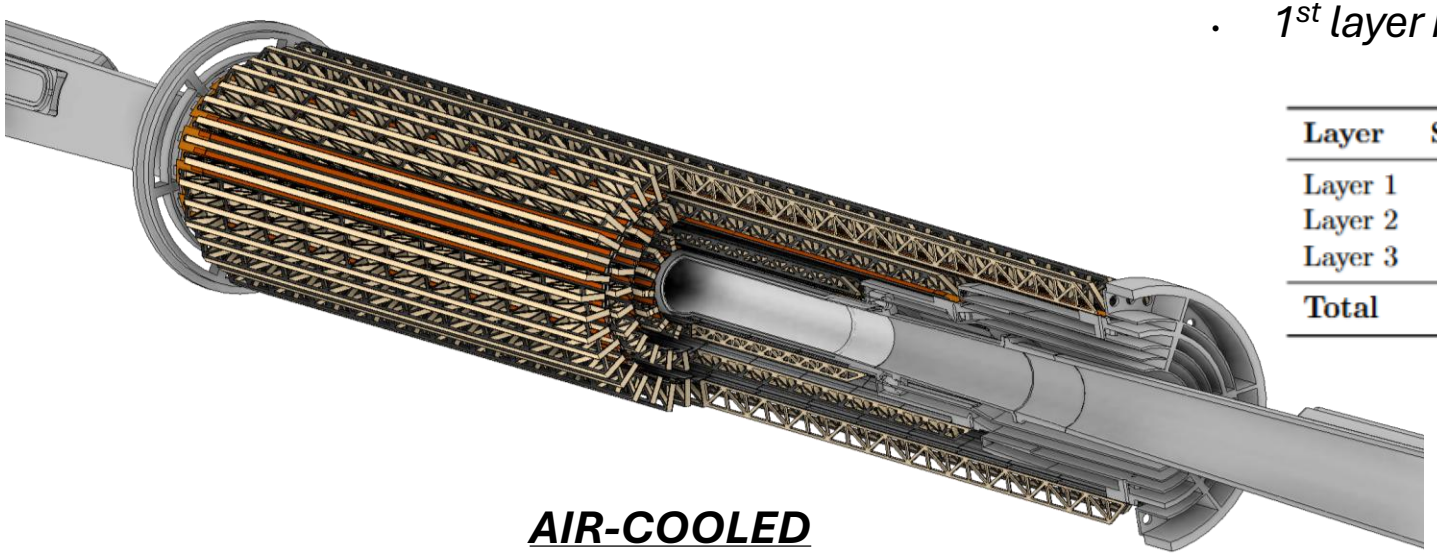
[1] INFN Pisa
[2] Civil and Industrial Engineering Department, University of Pisa

The 2026 International Workshop on the High Energy Circular Electron Positron Collider
Sheraton Shanghai Jiading Hotel
24/10/26

TARGET

Low material budget
Distance from the IP
Enable sector-based assembly and disassembly



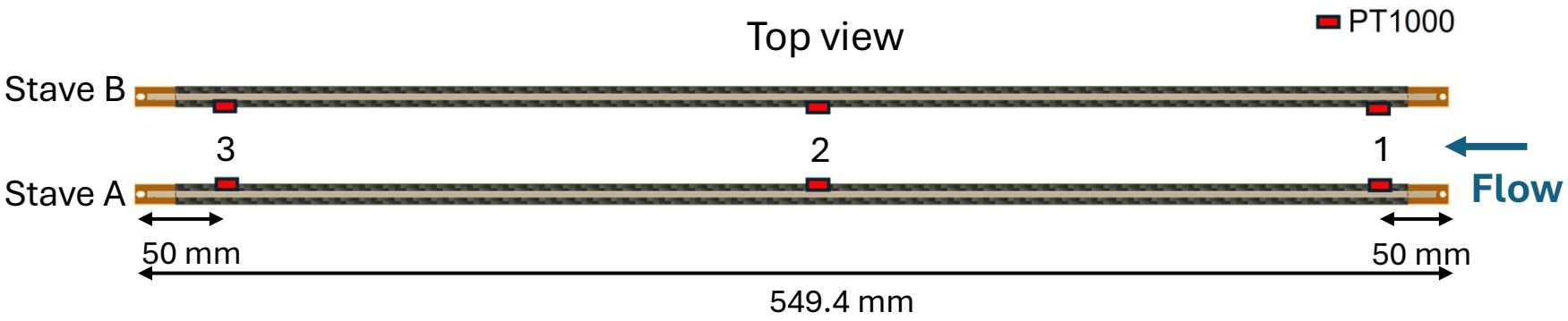


AIR-COOLED

Three Inner vertex layers:

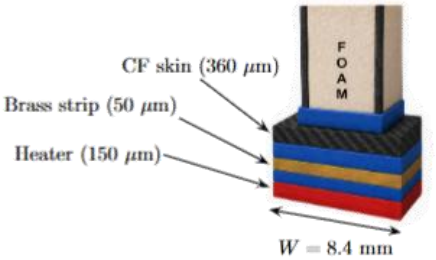
- *'T shape' staves*
- *ARCADIA-based flat sensor (50mW/cm^2 nominal power)*
- *1st layer radius: 13.7 mm*

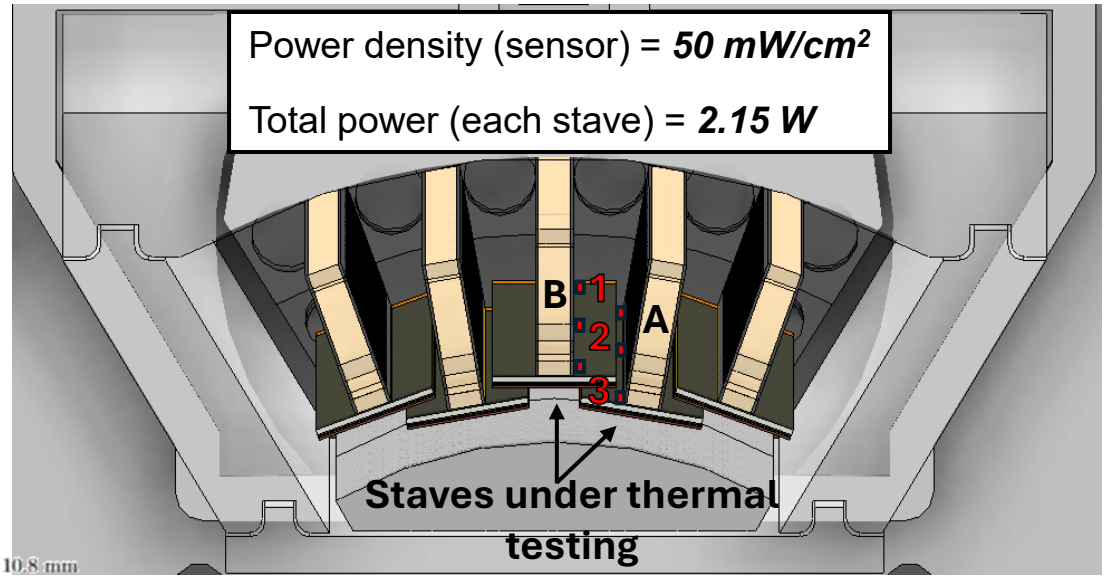
Layer	Staves	Power (W)
Layer 1	15	≈ 12
Layer 2	24	≈ 32
Layer 3	36	≈ 77
Total	**75**	≈ 121



RTD positioning:

- 3 PT1000s on the CF skin
- 2 additional PT1000s in section 3 directly on the two heaters (labeled A4 and B4 in subsequent figures)

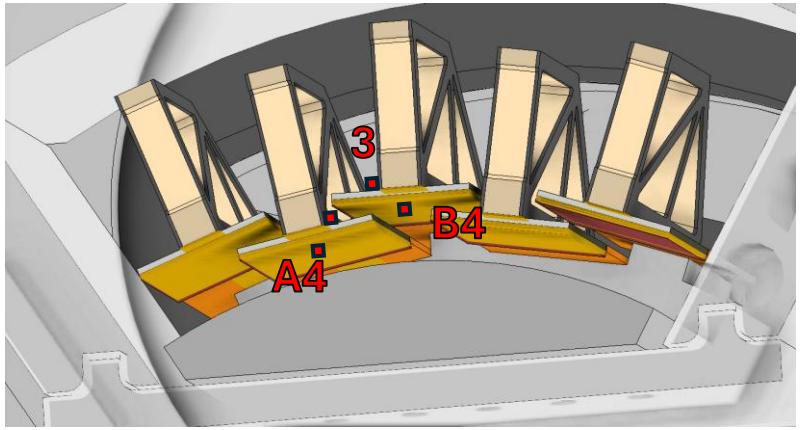




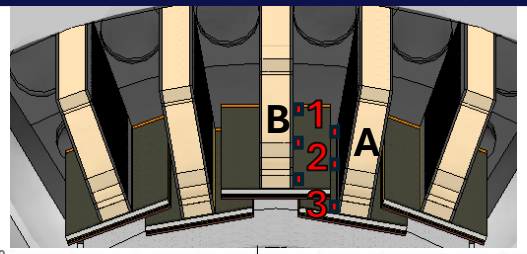
The maximum temperature at the measurement points depends on the:

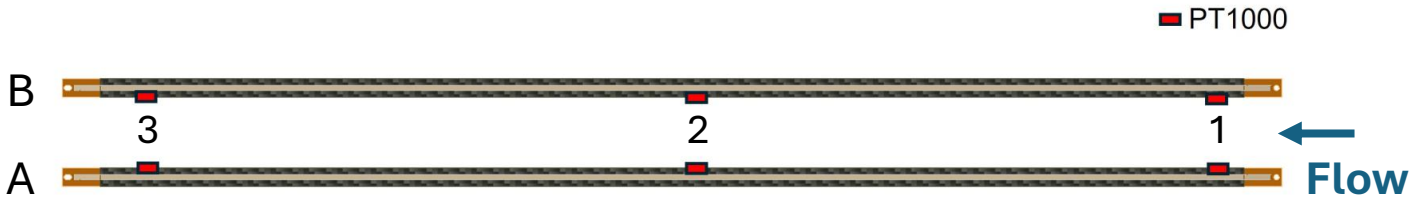
- **Fluid Inlet Temperature** (T_{in})
- ΔT **(Inlet-to-Bulk Section)**
- **Bulk-to-Surface Heat Transfer**

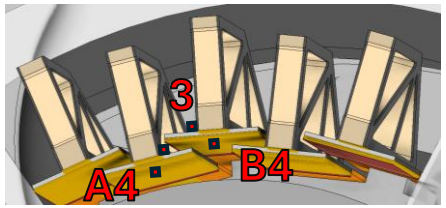
Therefore, the contributions were separately analyzed using dedicated steady-state and transient experimental tests.

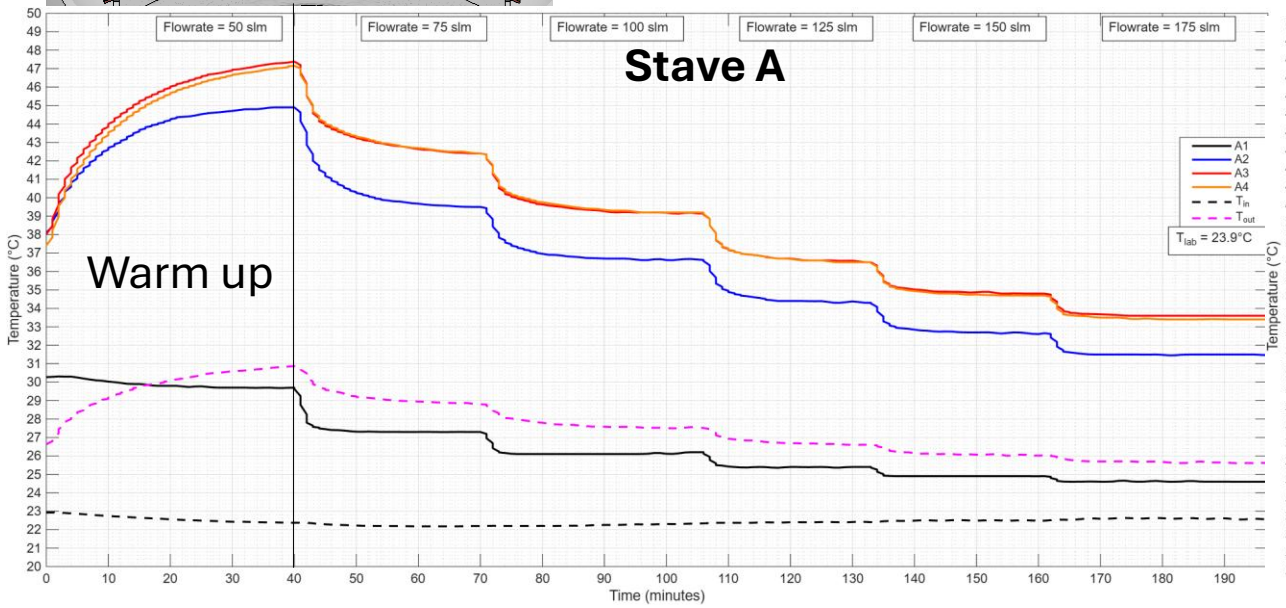


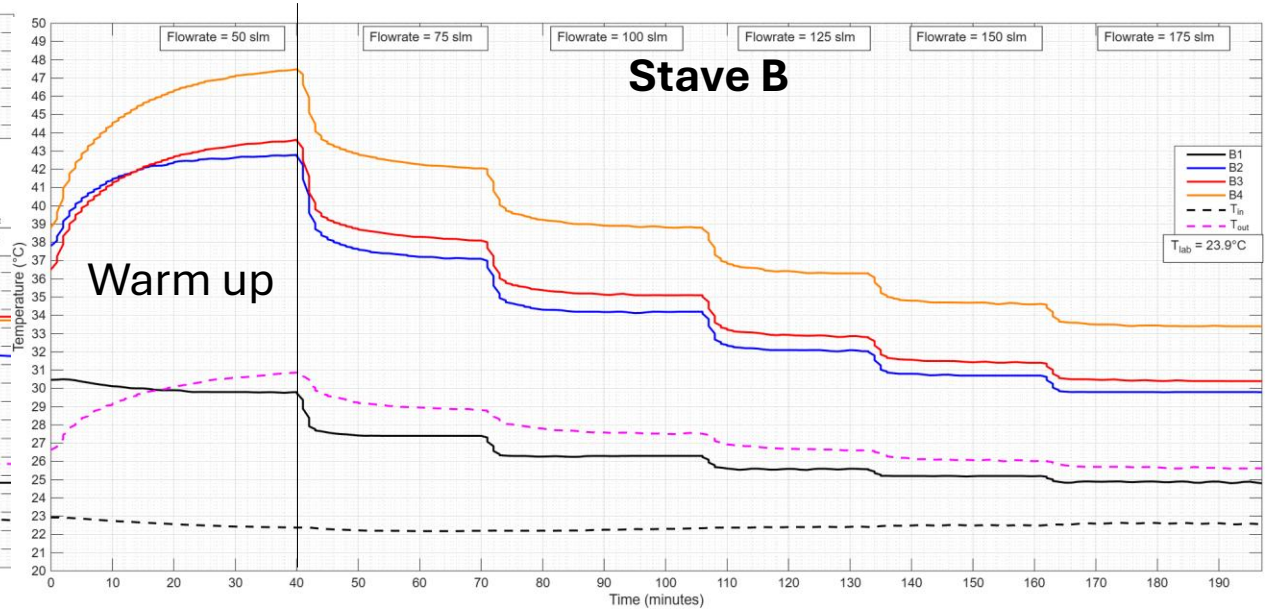
EFFECT OF THE FLOW RATE: T_{max}











Nearly constant inlet temperature ($\approx 22.5\,^{\circ}\mathrm{C}$)

Increasing flow rate reduces maximum measured temperature due to a lower $\Delta T_{\mathrm{stave}}$*(shown in next slide)*

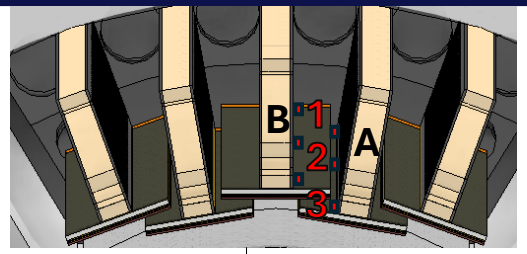
Stave A reaches higher temperatures than Stave B:

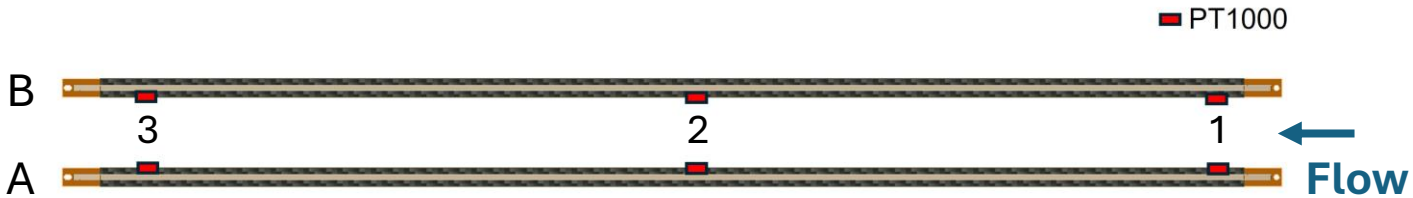
- Overlapping arrangement creates a **stagnation zone** on the recessed stave, reducing local heat transfer efficiency

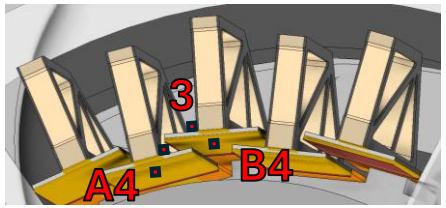
Stave B exhibits lower temperatures overall, except at position B4 (on the heater), which behaves like A3 due to being in the recessed area

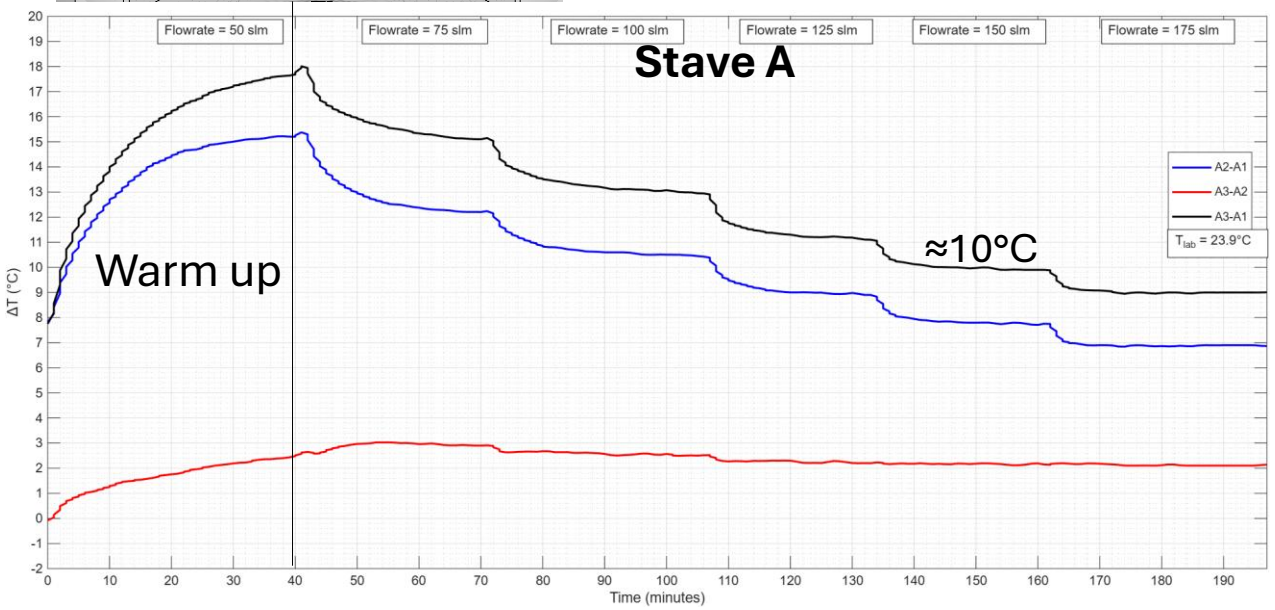
G. Ammirabile

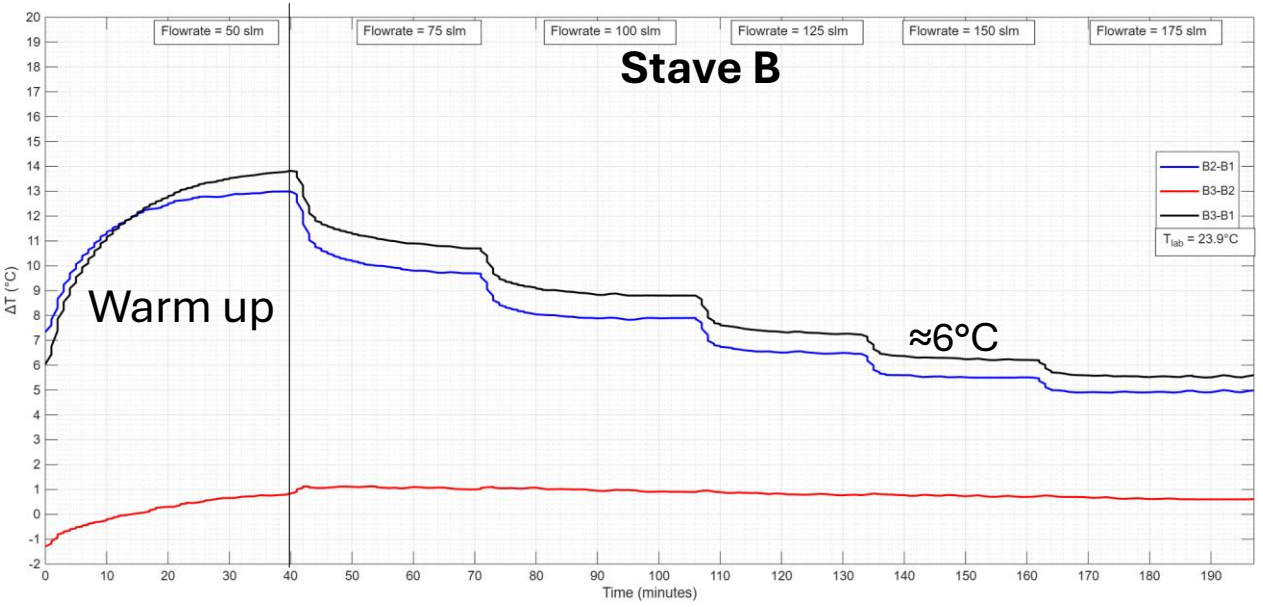
EFFECT OF THE FLOW RATE: ΔT







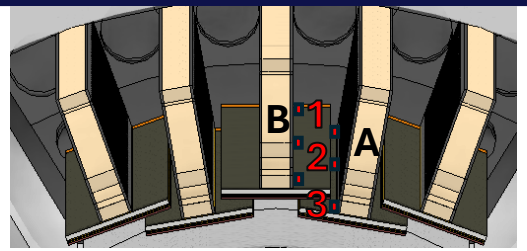


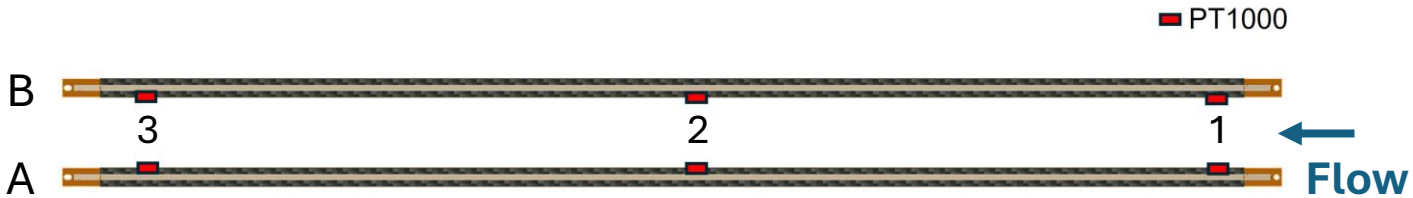


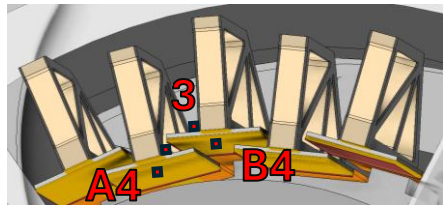
ΔT_{stave} trends show significantly enhanced heat transfer on Stave B, with temperatures in sections 3–1 up to 4 °C lower than on Stave A.

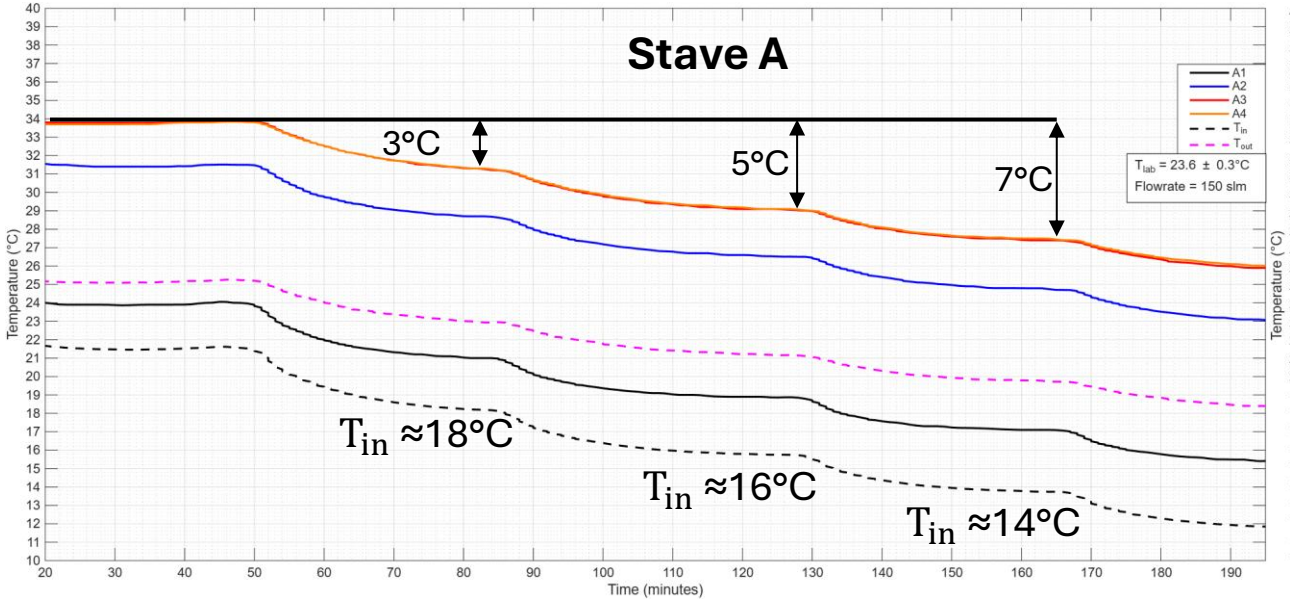
Notably, **section 3–2 is nearly insensitive to flow rate increases**, highlighting a fully developed thermal boundary layer already at relatively low flow rates.

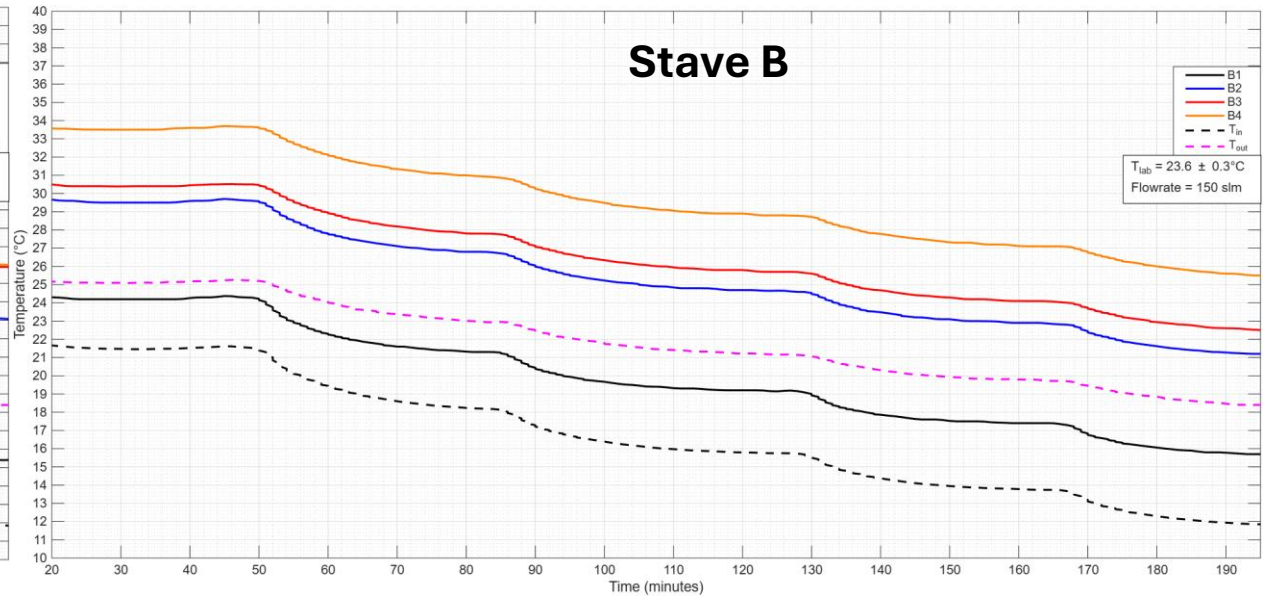
G. Ammirabile











Lowering inlet temperature (T_{in}) at constant flow rate (150 slm) reduces maximum recorded temperature.

Key for threshold control once ΔT is minimized:

- Ensures maximum temperature stays below operational limits (e.g., $T_{max} < 40\,^{\circ}C$ for ARCADIA)

Environmental parasitic effects:

- The gap between T_{in} and T_{out} curves increases as T_{in} decreases, highlighting non-negligible ambient thermal exchange

G. Ammirabile

EFFECT OF THE INLET TEMPERATURE

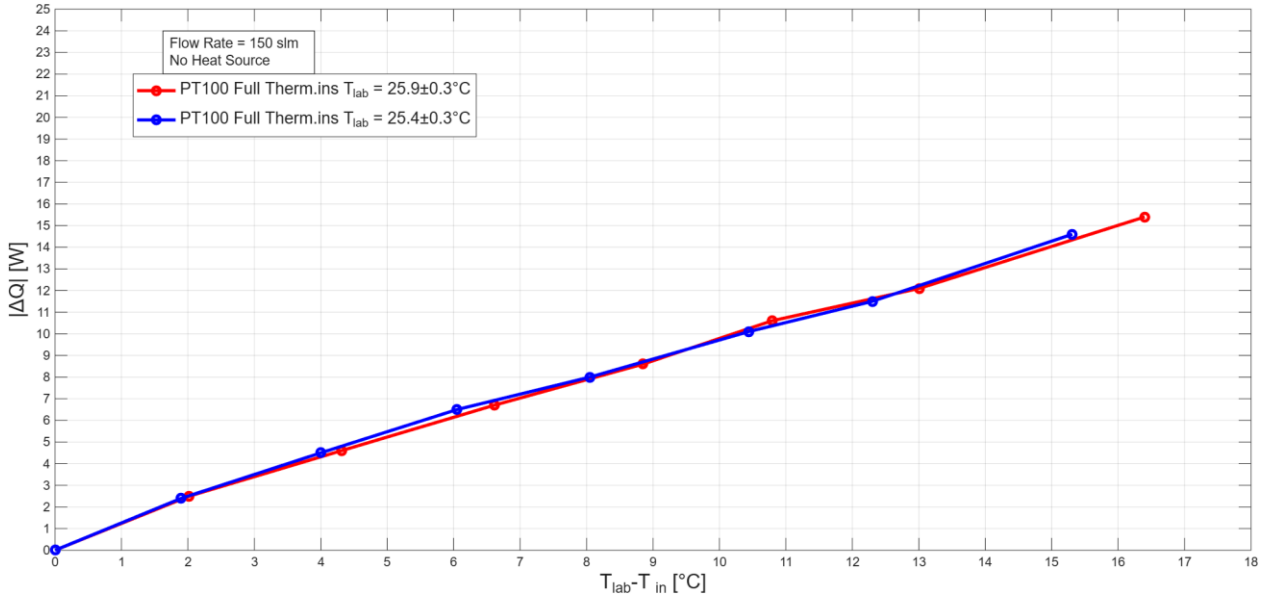
Lowering the inlet temperature causes an increase in thermal power absorbed by the fluid, which grows with the temperature difference between the inlet air and the surrounding environment.

$$\dot{Q}_{air} = \dot{m} \cdot c_p \cdot (\mathrm{T_{out}} - \mathrm{T_{in}})$$

Area	Min. T, °C	Max. T, °C
Alcove / Experimental Cavern	18	32 (run mode), 26 (access mode)
Service Cavern / Klystron Gallery	18	26

A.Coleman

Ventilation_FCCWeek_2026 final.pdf



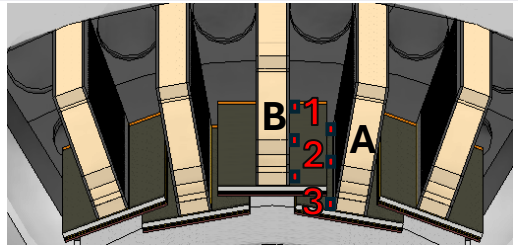
Most of the thermal power absorbed by the air occurs at the mechanical interfaces rather than in the fully insulated test section.

To analyze this effect, zero thermal power was applied to the heaters

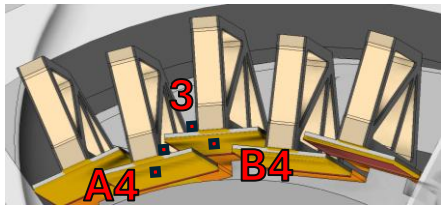
Evaluates the impact of **the internal vs. external fluid temperature difference** on absorbed thermal power, shown by the 2 colored lines from two performed tests

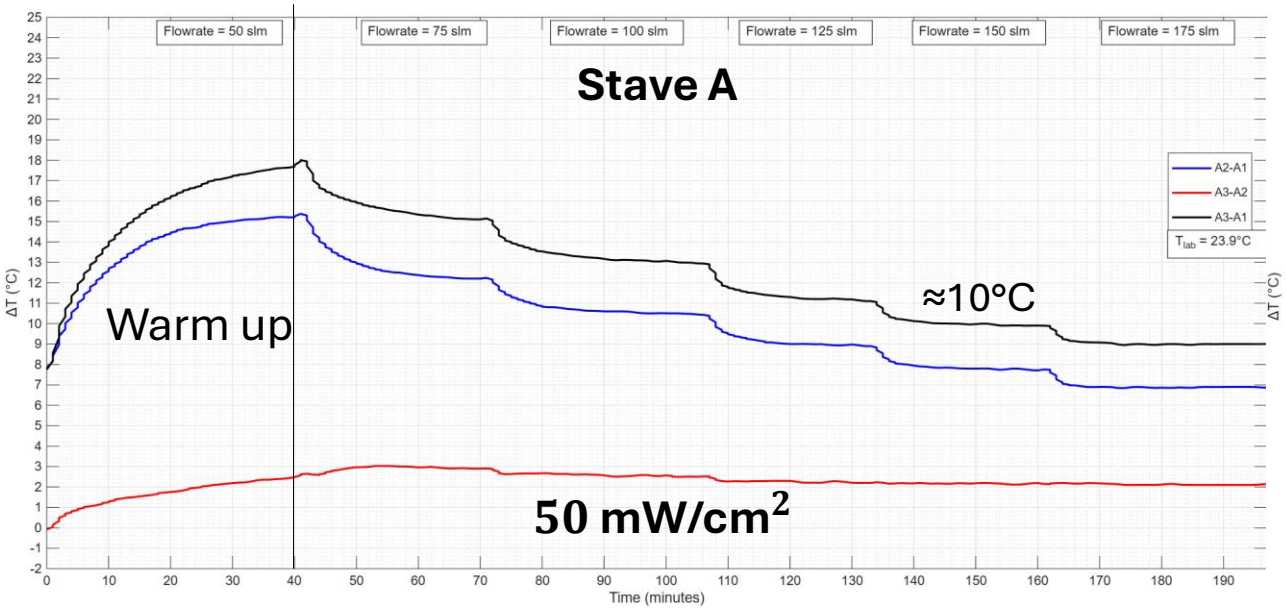
G. Ammirabile

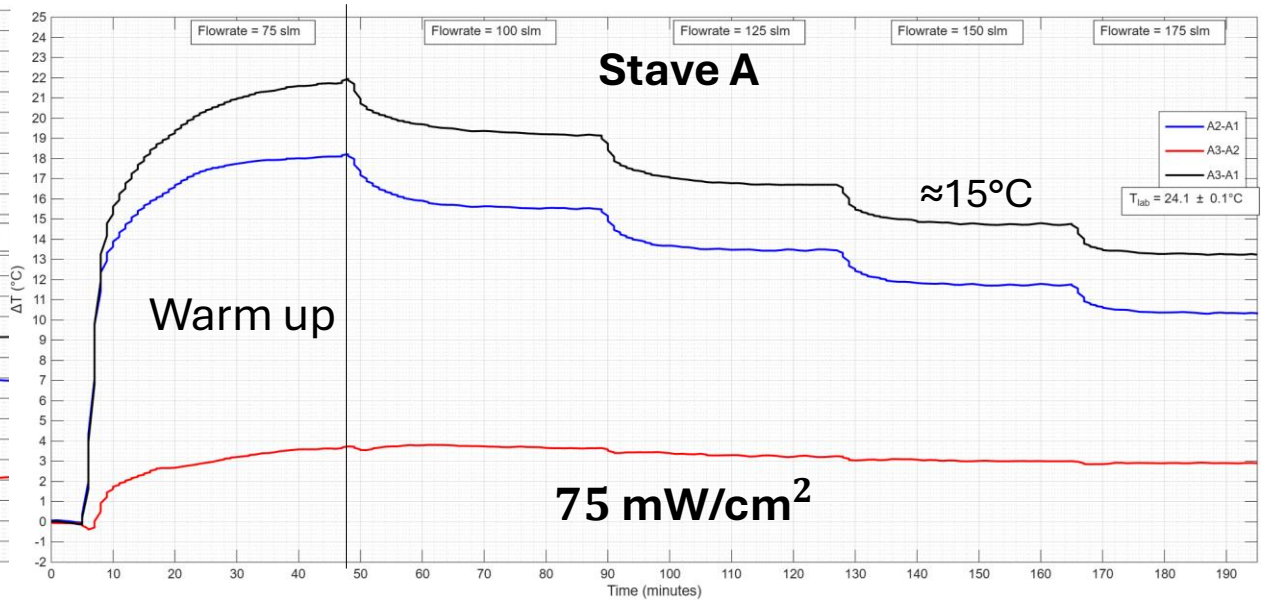
OFF-DESIGN POWER EVALUATION: ΔT STAVE A



To fully understand system response under off-design conditions, tests were performed with thermal power increased by a factor of 1.5 compared to nominal, simulating a load of 75 mW/cm^2 instead of 50 mW/cm^2







Note on increased power test (75 mW/cm^2):

- Initial flow rate set to 75 slm to prevent excessive temperatures that could compromise internal stave glue joints

Thermal performance & system robustness:

- At equal flow rates, ΔT is higher (5-6°C) under off-design conditions, as expected
- **Identical trends** confirm system robustness even beyond nominal conditions

G. Ammirabile

CONCLUSIONS

1. Experimental Set-up & Testing

- **Open-circuit air-cooling system** with independent control and monitoring of flow rate, humidity, and inlet temperature.

2. Thermal Performance & Flow Dynamics

- **Inlet temperature (T_{in}) and local** ΔT dictate maximum temperatures; increasing flow rate effectively lowers ΔT.

- **Layout Impact:** Overlapping stave arrangement creates a **stagnation zone** on the recessed stave (e.g., Stave A, B4), locally reducing heat transfer efficiency. The performed test is conservative: in reality, the airflow from Layer 2 directly cools the heaters in addition to the Layer 3 flow.

- **Thermal Boundary Layer:** Section 3–2 shows insensitivity to flow rate increases (>50 slm), indicating a **fully developed thermal boundary layer** even at low flow rates.

3. Parasitic Effects & Off-Design Robustness

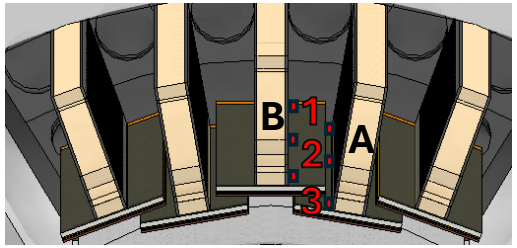
- **Environmental Parasitic Losses:** Most thermal power absorption occurs at mechanical interfaces rather than in the insulated test section. Lowering T_{in} increases the gap between T_{in} and T_{out}.

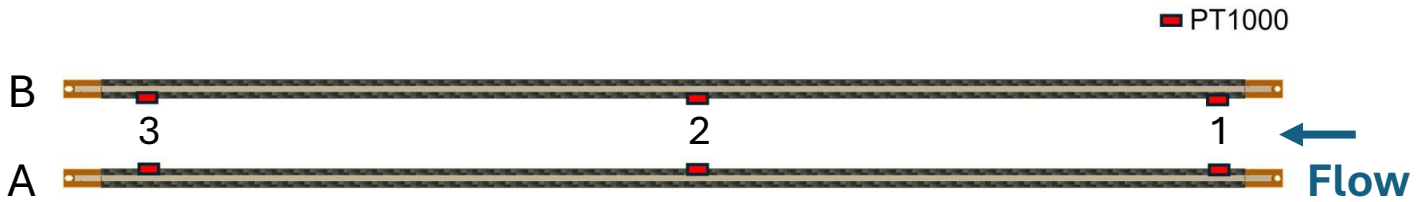
- **System Robustness:** Tests at $1.5\times$nominal power (75 mW/cm^2) confirmed **consistent thermal trends**, proving system stability even under off-design conditions.

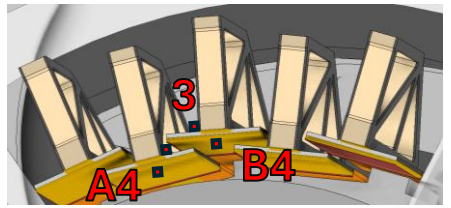
Thank you for your attention!

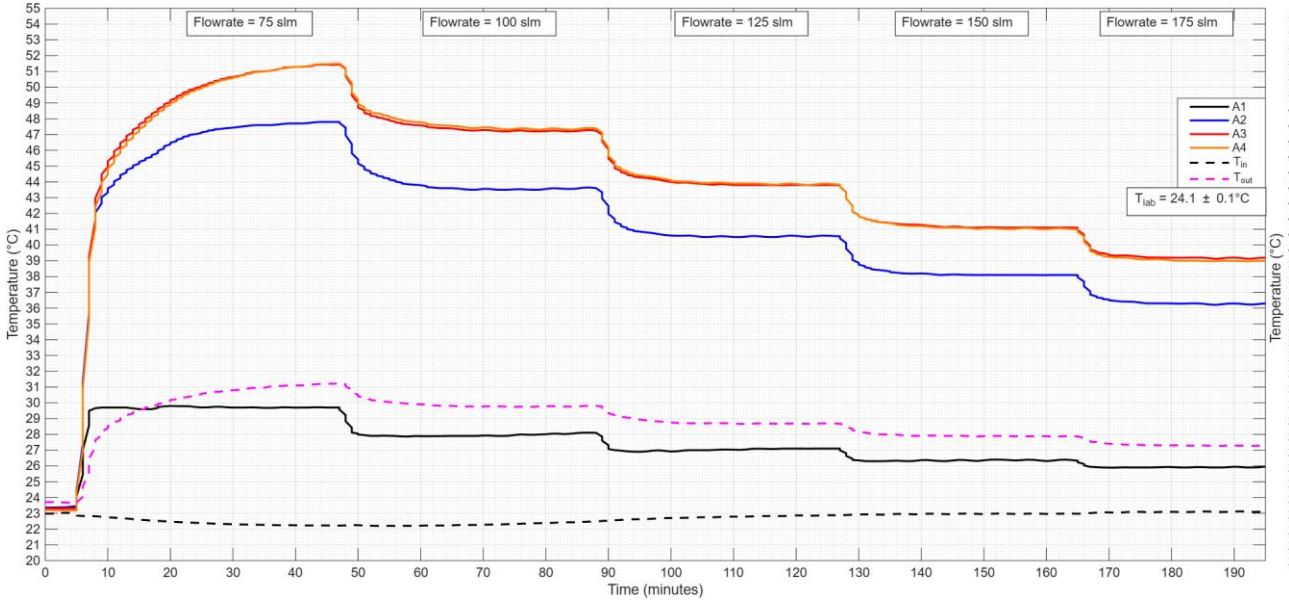
Backup

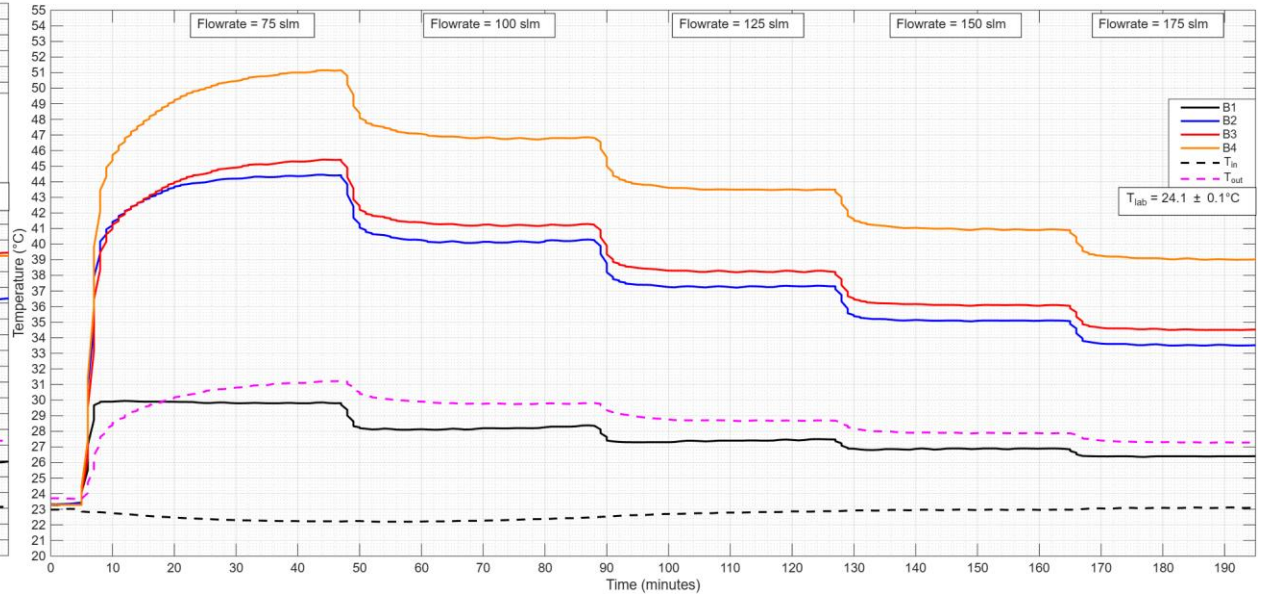
Temperatures measured at 75 mW/cm^2 power load instead of 50 mW/cm^2



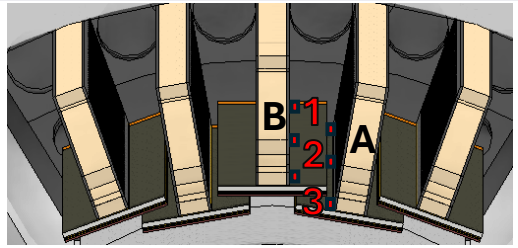




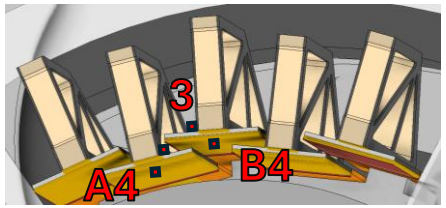


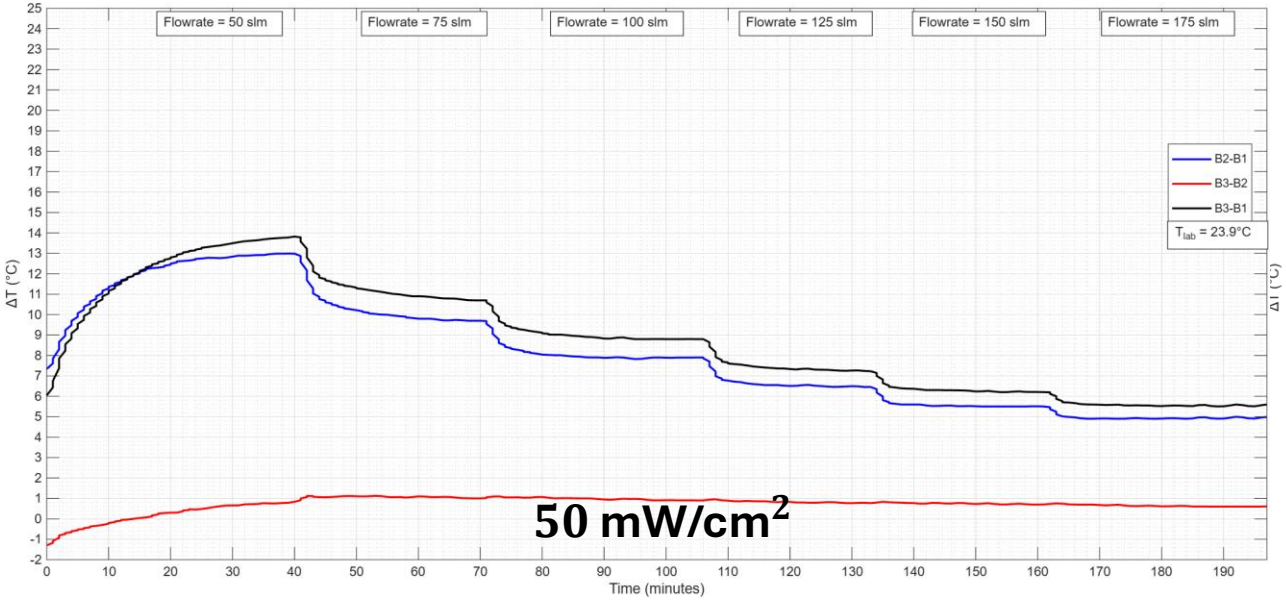


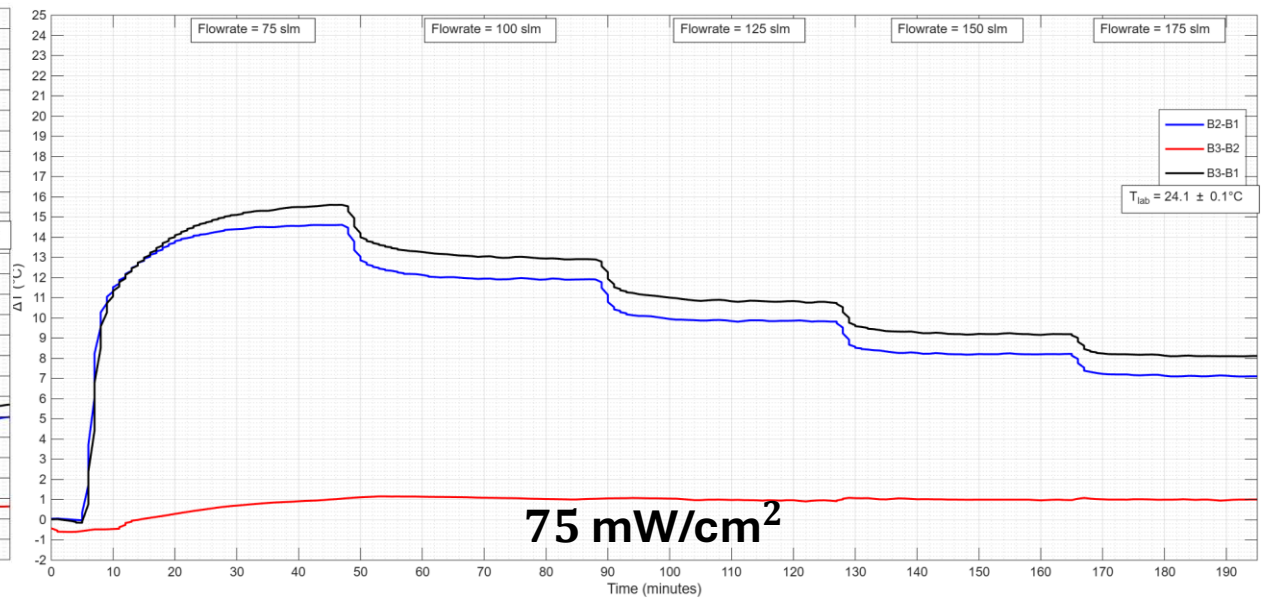
OFF-DESIGN POWER EVALUATION: ΔT STAVE B



To fully understand system response under off-design conditions, tests were performed with thermal power increased by a factor of 1.5 compared to nominal, simulating a load of 75 mW/cm^2 instead of 50 mW/cm^2







Note on increased power test (75 mW/cm^2):

- Initial flow rate set to 75 slm to prevent excessive temperatures that could compromise internal stave glue joints

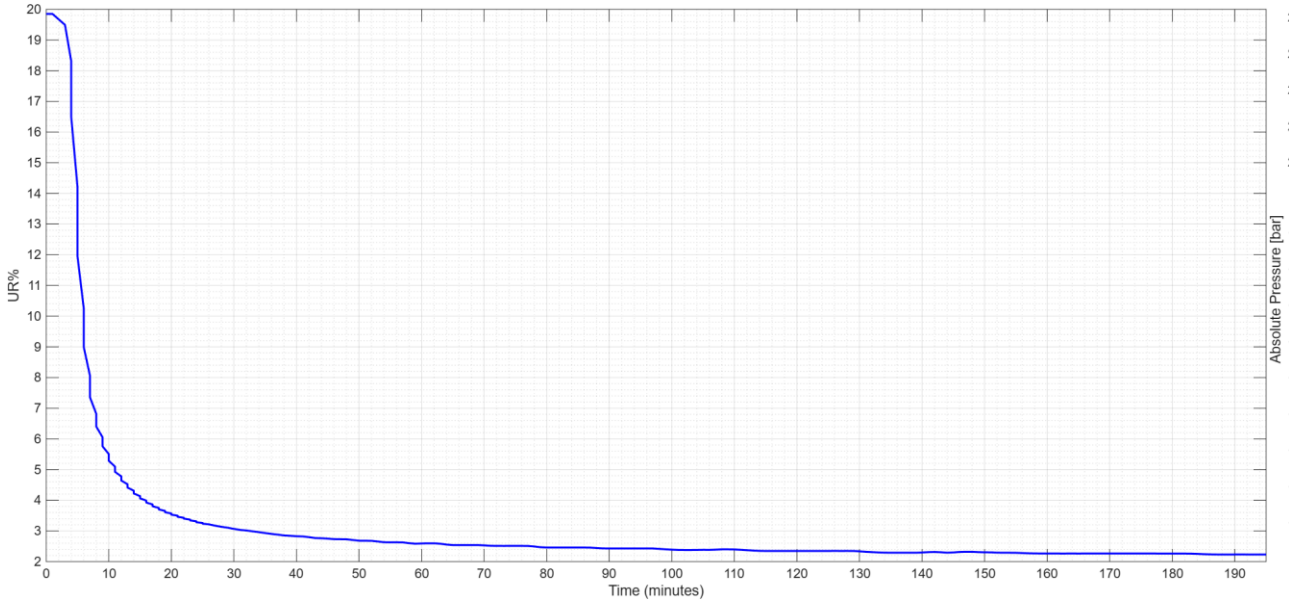
Thermal performance & system robustness:

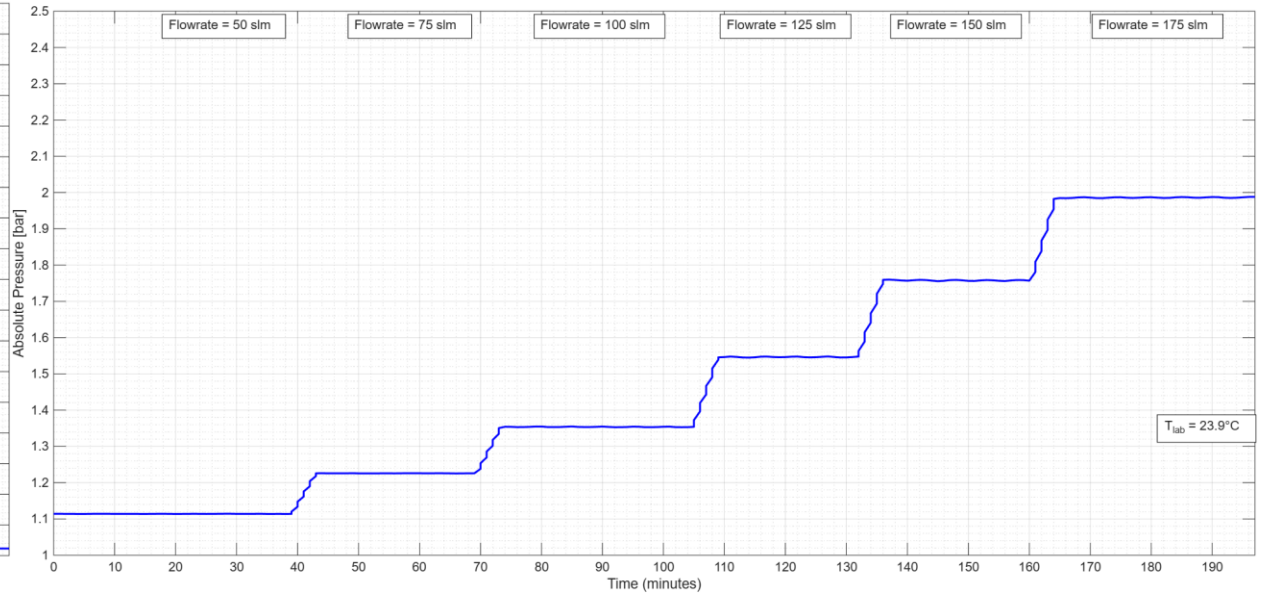
- At equal flow rates, ΔT is higher under off-design conditions, as expected
- **Identical trends** confirm system robustness even beyond nominal conditions

G. Ammirabile

Relative humidity drops below the required threshold (RH $< 10\%$) in just a few minutes, stabilizing at 2.7% after about 45 minutes.

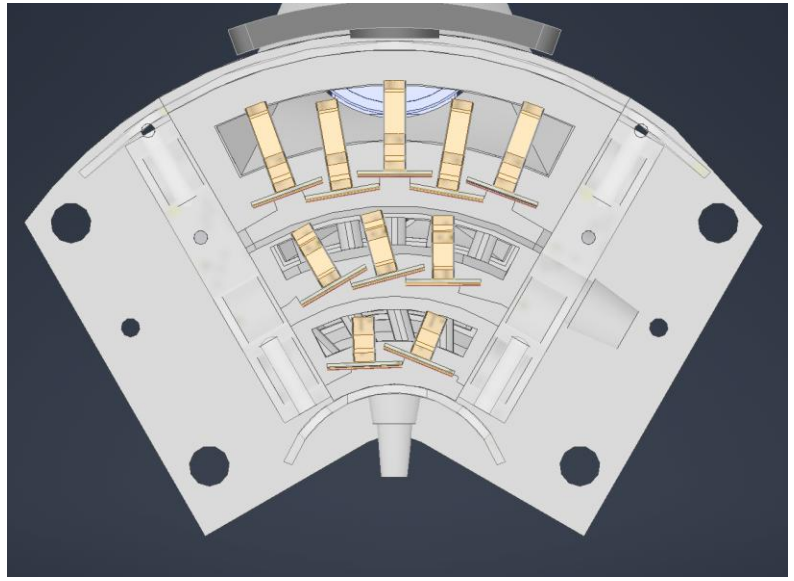
Pressure increases with flow rate, reflecting the total pressure drop across the line (from the settling chamber onward), dominated by the flow meters with a negligible contribution from the test section.

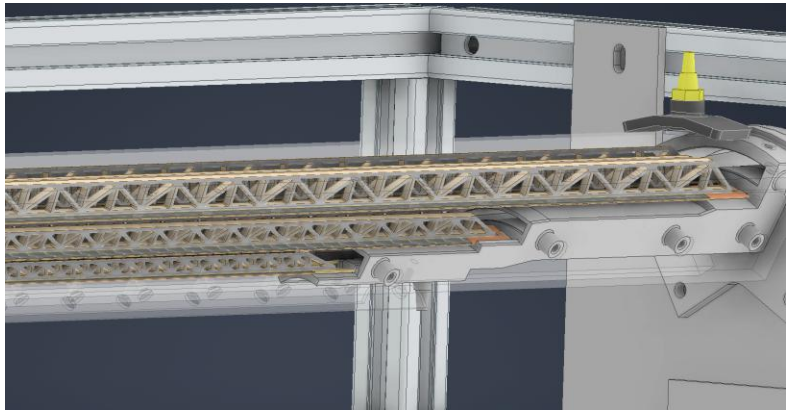




Staves:

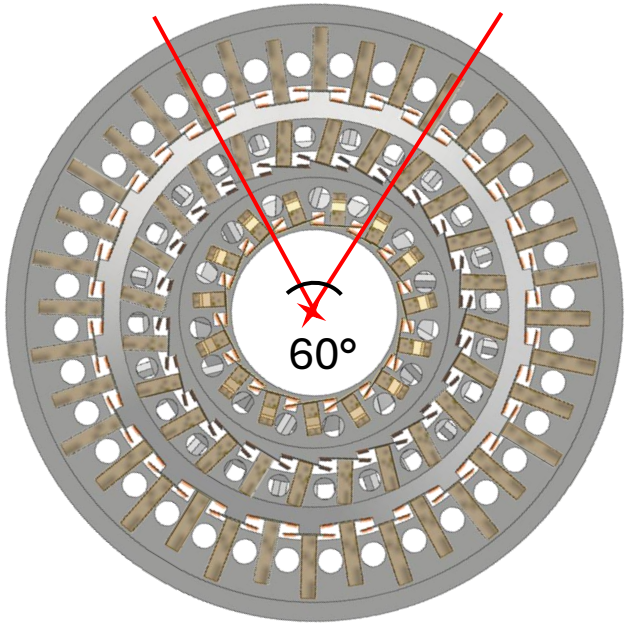
- 5 for Layer 3
- 3 for Layer 2
- 2 for Layer 1





Timeline for next steps:

Assembly on the same 60°angular sector of the staves of Layer 2 and Layer 1



Expected results:
few months

Details to study:

- Air induced vibrations with optical instrument and CFD
- Inlet shape:



Circular



Slotted

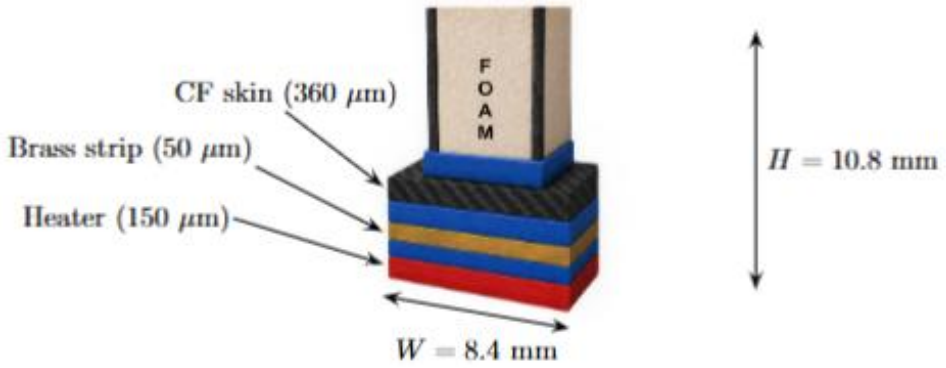
Targets:

- Flow rate to cool each layer
- Pressure drop
- Thermal connection between them

Advantage:
The compressed air system offers versatility, enabling specific testing for single and multi layer solution

G. Ammirabile

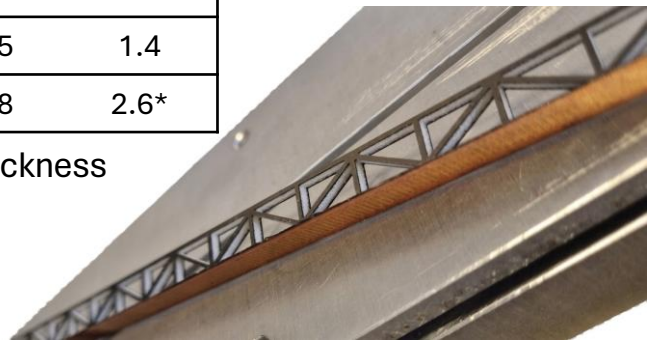
Stave design



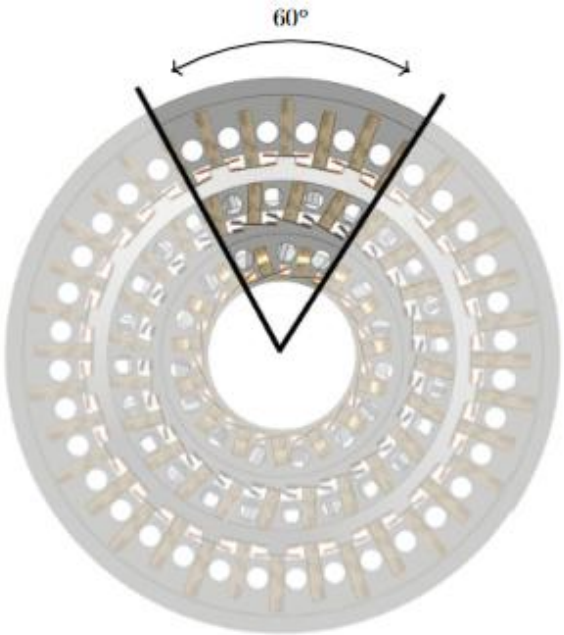
CF skin layup sequence:
[(±45°)w / (0°/90°)w / (±45°)w]

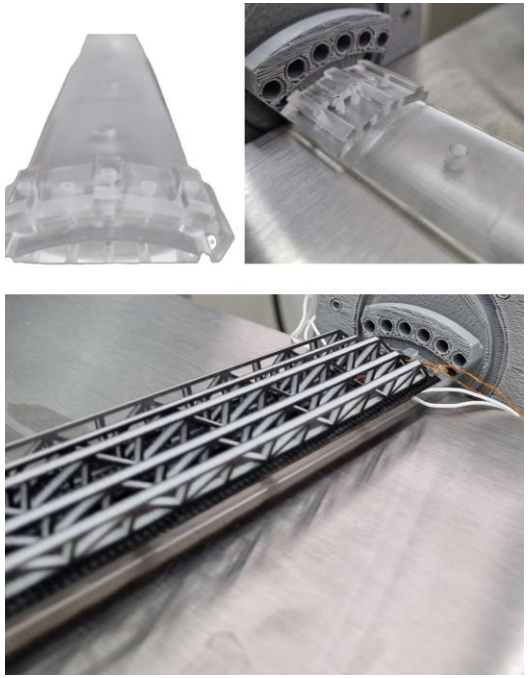
Stave dimensions (mm)		
	H	**W**
Design	10.5	1.4
Real	10.8	2.6*

* increase in thickness of foam



Air-cooled prototype





Air-cooling test performed on 5 Layer-3 staves enclosed in an airtight box