Thermal Studies of an Ultra-Low-Mass Cooling System for ALICE ITS Upgrade Project at CERN

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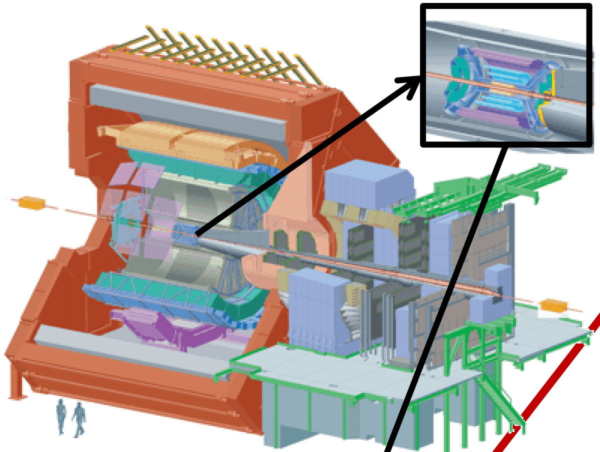
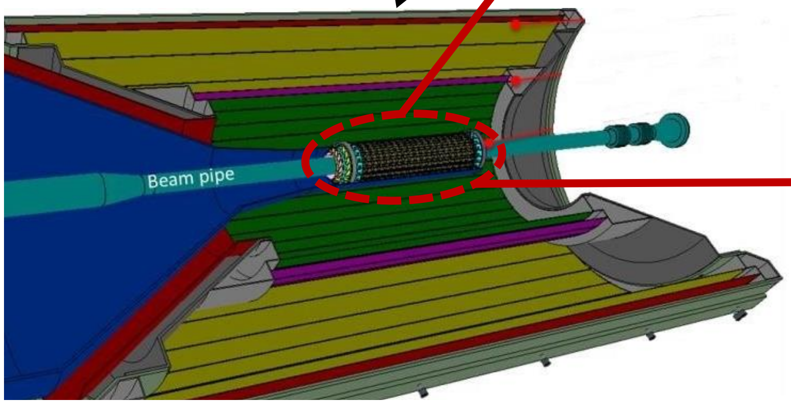
Outline

- Introduction
- Stave design and manufacturing
- Experimental facility
- Methodology
- Results
- Conclusion

Introduction

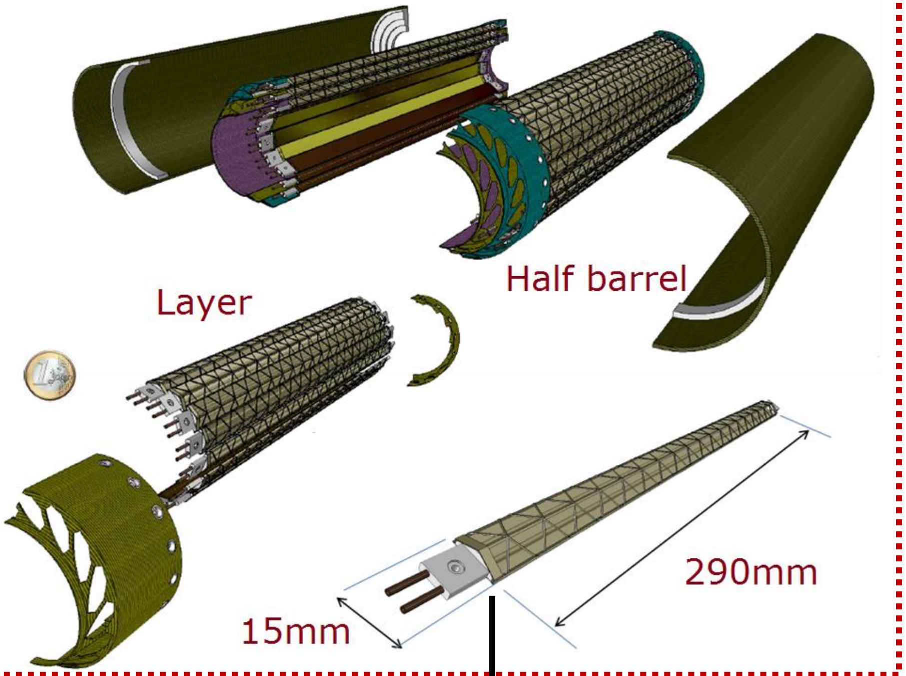
ALICE Experiment



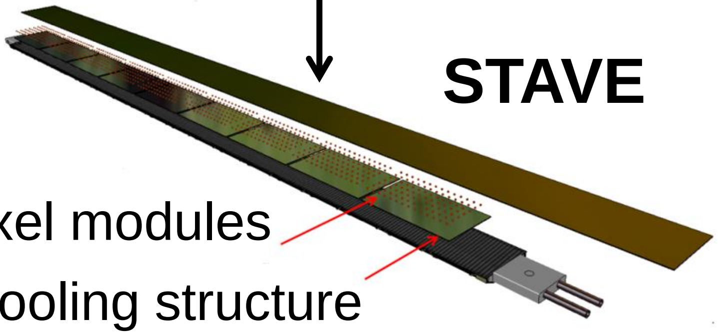


ITS: Inner Tracker System

Inner Barrel (3 layers)



STAVE



Silicon pixel modules

Stave cooling structure

Design Parameters

1. Power dissipation: pixel technology, electronics…

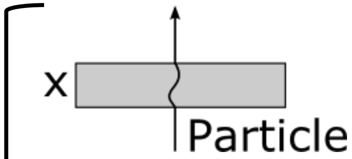
- 0.3 – 0.5 W cm^{-2}

2. Operational temperature and **uniformity:**

- $T_{PIXEL} < 30°C$
- Pixel maximum temperature non-uniformity < 10 K

3. Minimize material budget: critical in particle detectors.

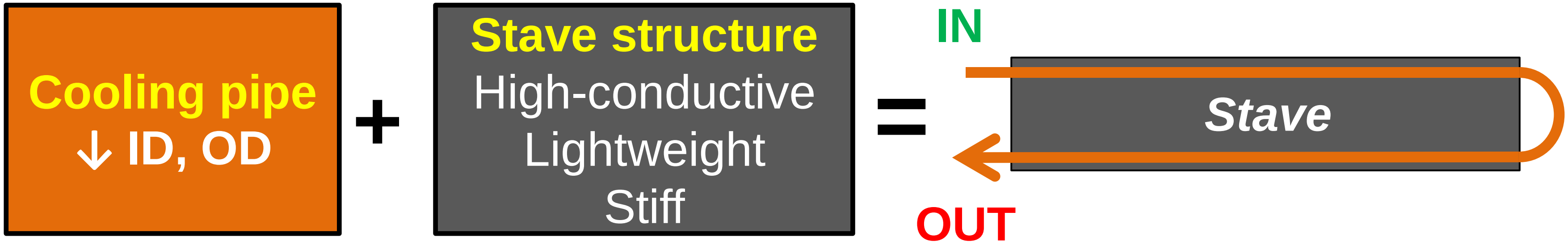
$$\boxed{\frac{x}{X_0}100\,[\%]}$$



$$X_0 = \frac{716.4 \cdot A}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}\,\rho}\ [cm]$$

$x/X_0 \leq 0.30\%$ per layer

Stave Manufacturing



Cooling pipe
↓ ID, OD

+

Stave structure
High-conductive
Lightweight
Stiff

=

IN

Stave

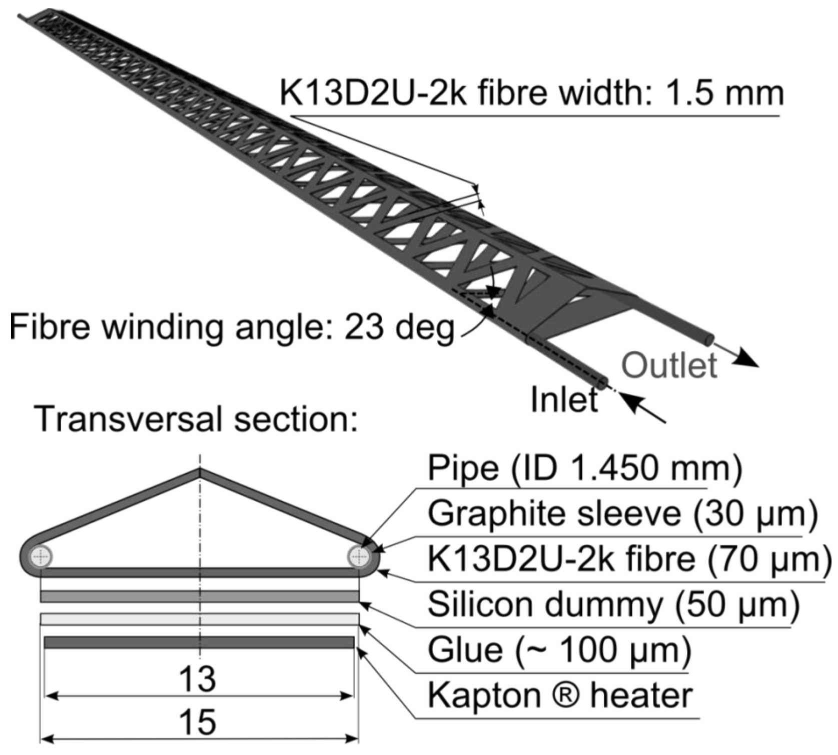
OUT

- **Tubes:** Polyimide (↓ wall thickness). PEEK considered.
- **Structure:**
    - Carbon fiber (K13D2U, K1100): λ up to **1000** W m^{-1} K^{-1}
    - Graphite foil (30 µm thick): λ **> 1000** W m^{-1} K^{-1}

Analytical/CFD studies
Experimental tests

→ **Optimization of 2 geometries**

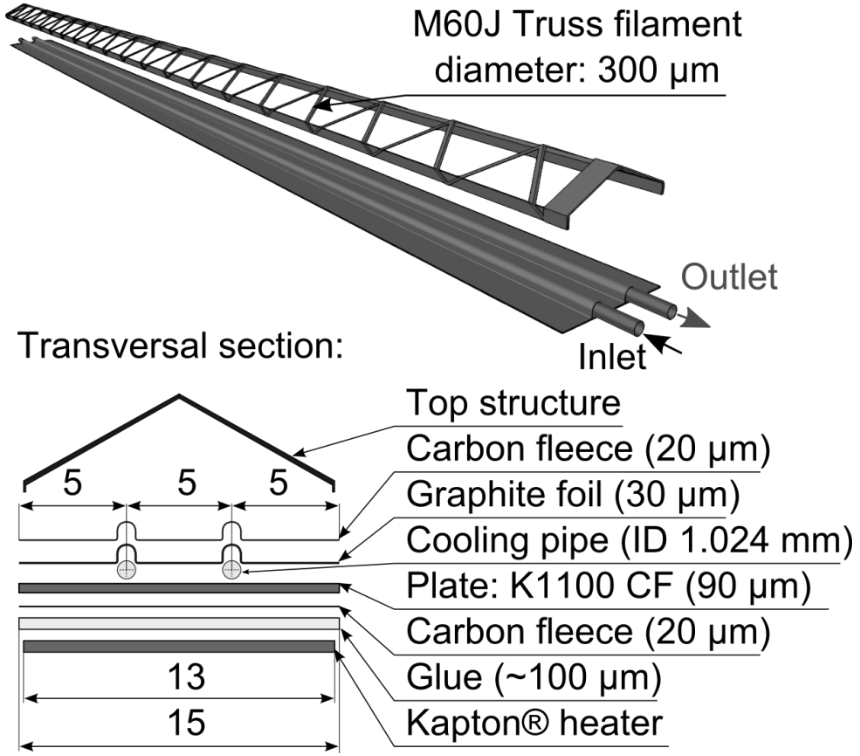
Two Different Concepts



P1

1.4 g *(structure only)*

x/X_0=0.23% *(services included)*

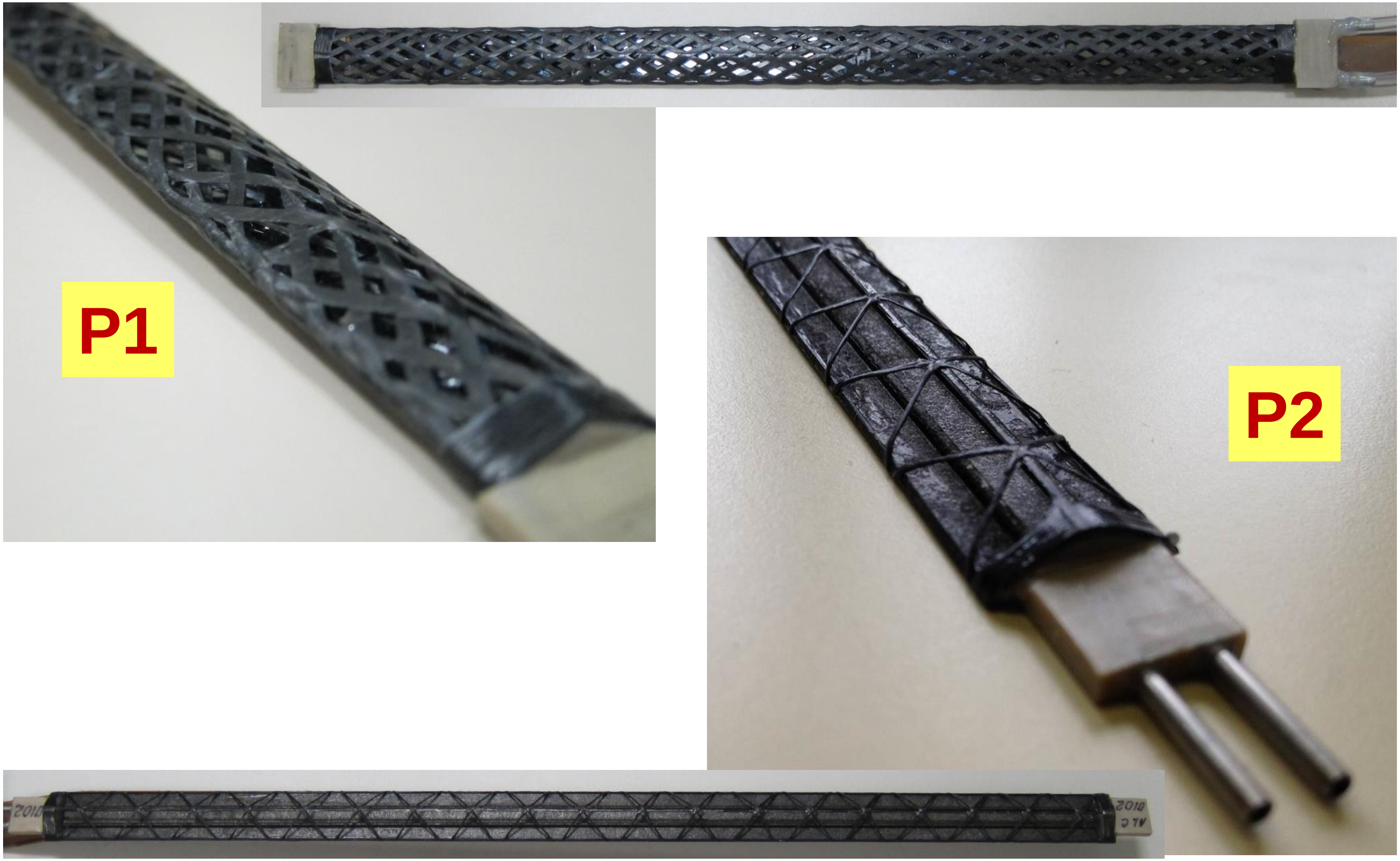


P2

1.8 g *(structure only)*

x/X_0=0.29% *(services included)*

Two Different Concepts



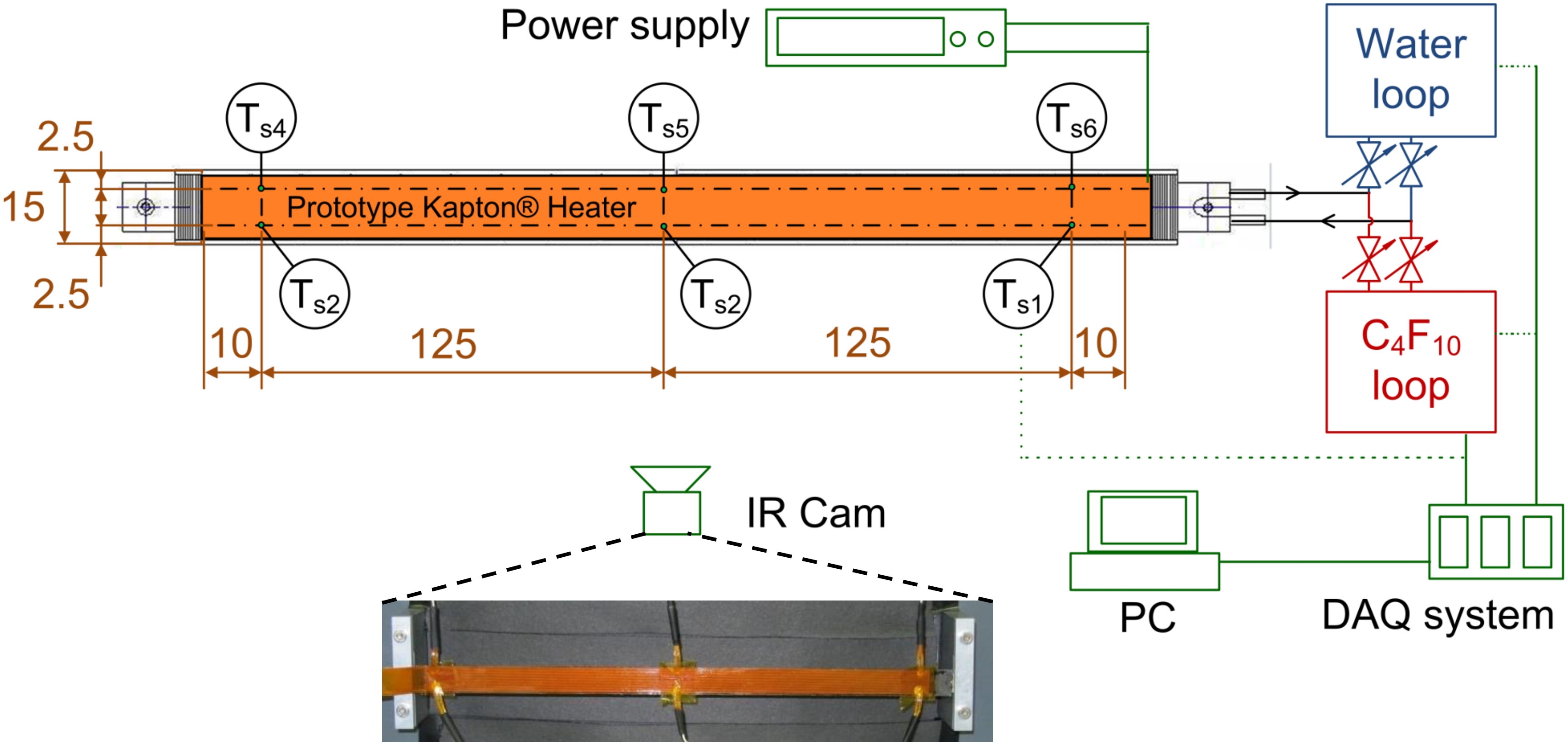
Cooling Fluid Selection

- **Requirement:** $T_{REFRIGERANT} > T_{DEW\text{-}POINT}$ (~12°C)

Fluid	**Benefits**	**Concerns**
Single-phase **H_2O**	Radiation hard Loop simplicity	Leak-less system Liquid: ↑ refrigerant x/X_0
Two-phase **C_4F_{10}**	Radiation hard Dielectric Vapor: ↓ refrigerant x/X_0 Cooling at constant T	More complex loop Distribution (346 staves ITS)

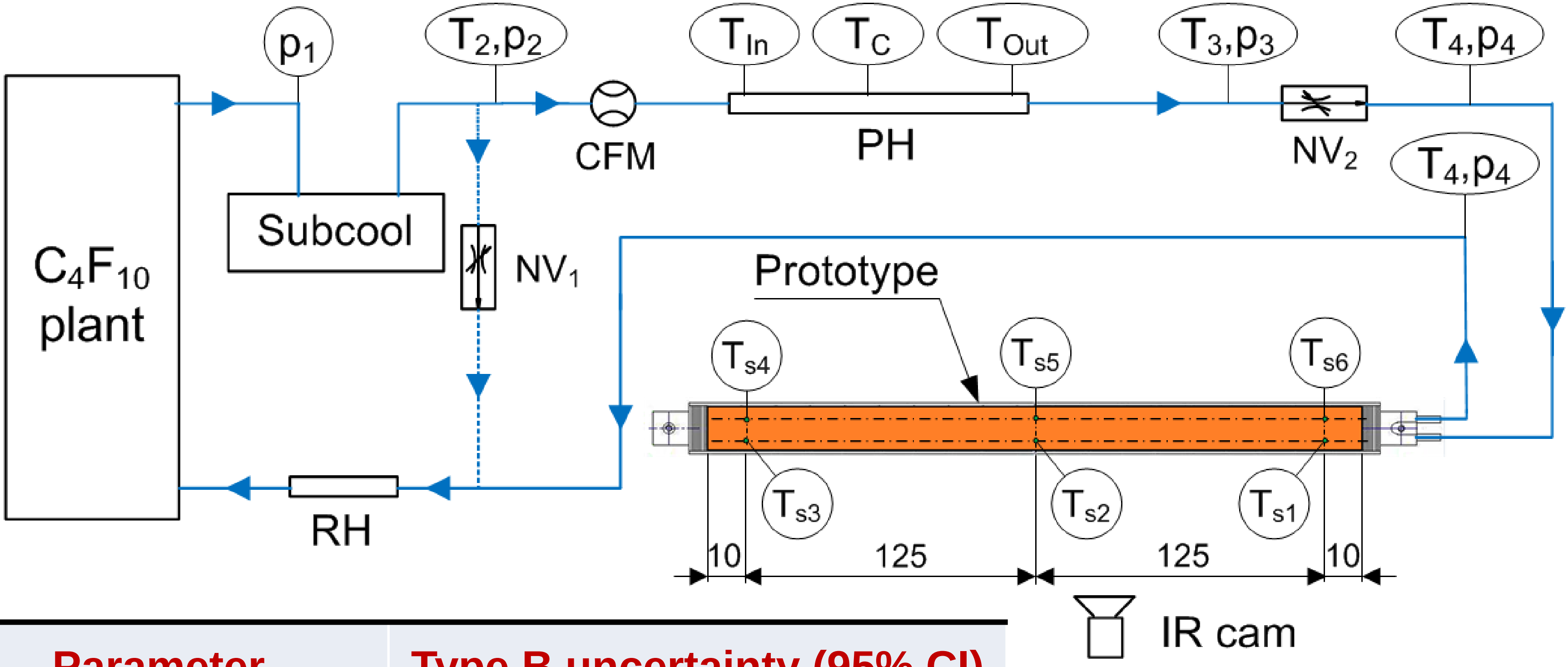
T_{SAT} = 15°C, P_{SAT} = 1.9 bar ✓

Experimental Facility



- Fast, simple way to characterize thermally the prototypes.
- Tested several prototypes with the 2 refrigerants.

C_4F_{10} Experimental Loop



Parameter	Type B uncertainty (95% CI)
Temperature (PT100)	±0.4°C
Temperature (NTC)	±1.4°C at 30°C
Absolute pressure	±0.05 bar
C_4F_{10} mass flow rate	$\pm(0.2\% + 8\ g\ h^{-1})$
Thermal imager	±5°C

Methodology

1. No-flow tests:

☐ Power dissipated/absorbed to/from to room air

☐ Agreement T sensors

2. Single-phase flow tests:

☐ Pressure drop

☐ Energy balance

☐ General uncertainty

3. Two-phase flow tests:

☐ Thermal characterization

☐ Two-phase pressure drop

Test Parameters

1. Power dissipation: 270 x 13 mm Kapton® Heater

Power density	Absolute heat load
q [W cm^{-2}]	P [W]
0.3	10.5
0.5	17.6

$\Delta T_{\text{STAVE}-\text{AMB})_{\text{MAX}}} < 9\ \text{K}$

P2: ~12% of power to air

2. Mass flow rate:

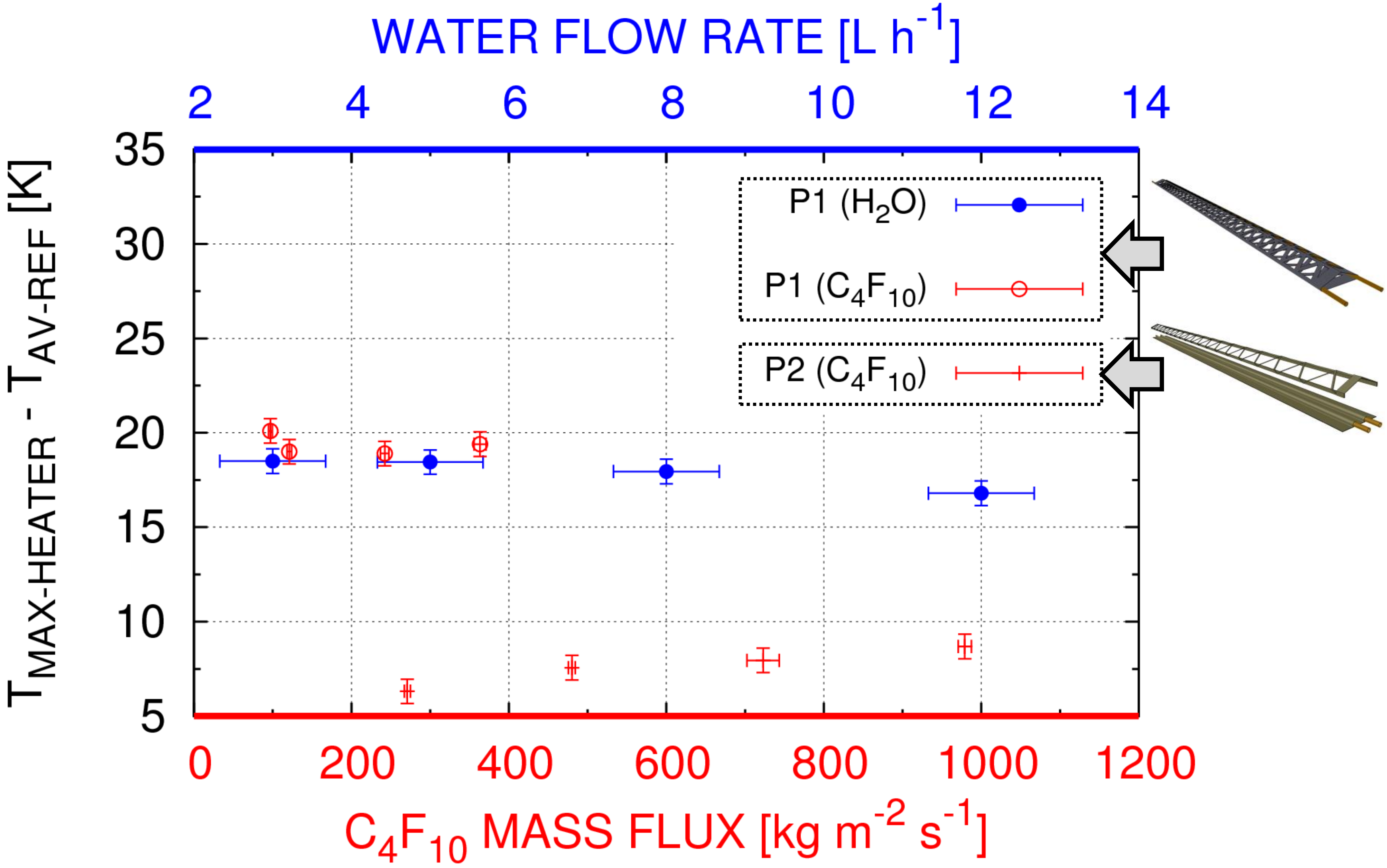
$$\dot{m} = \frac{q}{h_{LG}\Delta x_{IN-OUT}}$$

Assumptions

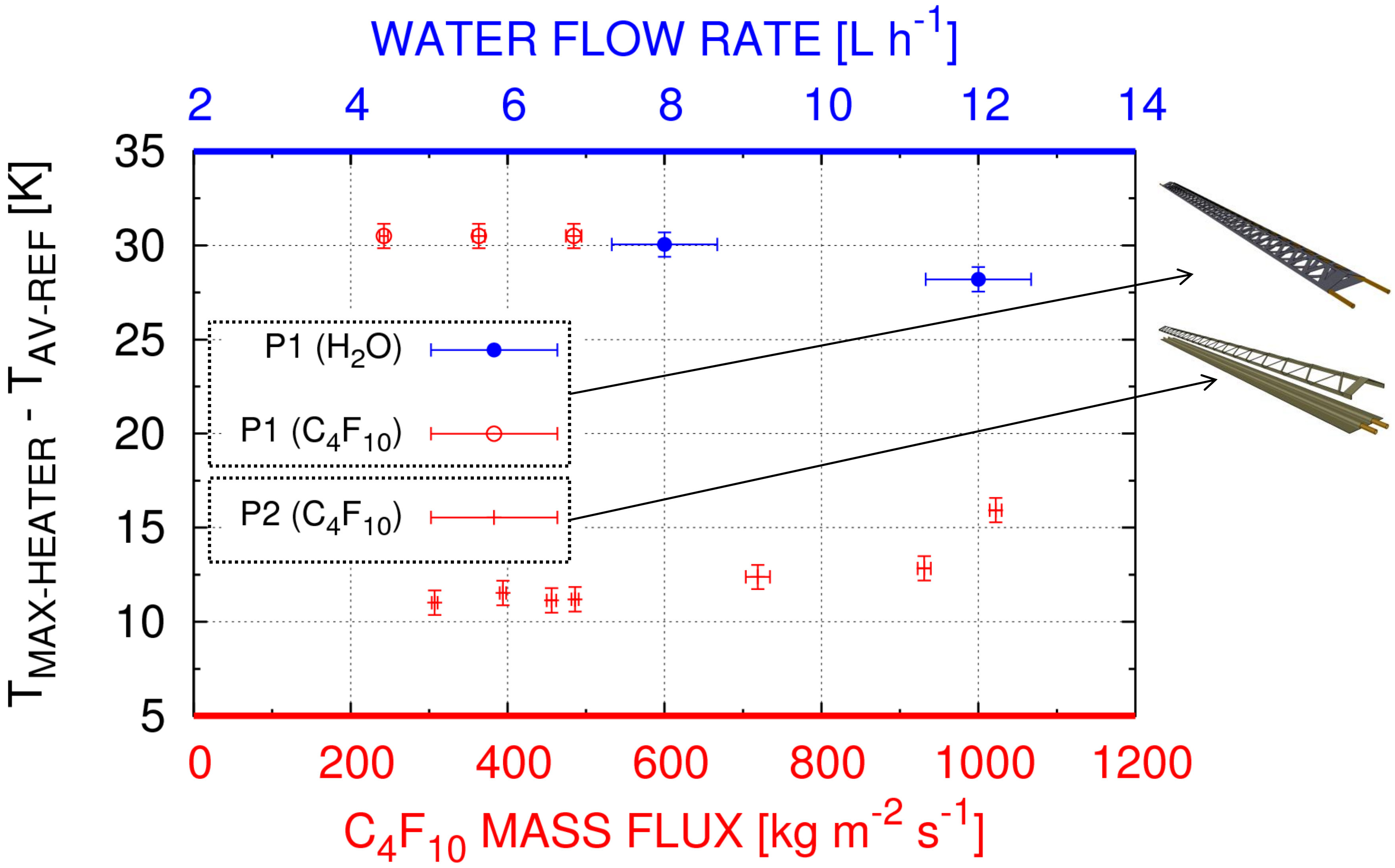
$$\begin{cases} \Delta x_{IN\text{-}OUT} = 0.40 \\ T_{REFRIGERANT} = 15^{\circ}\text{C} \end{cases}$$

Power density	Mass flow rate
q [W cm^{-2}]	$\dot{m}$ [g s^{-1}]
0.3	0.29
0.5	0.55

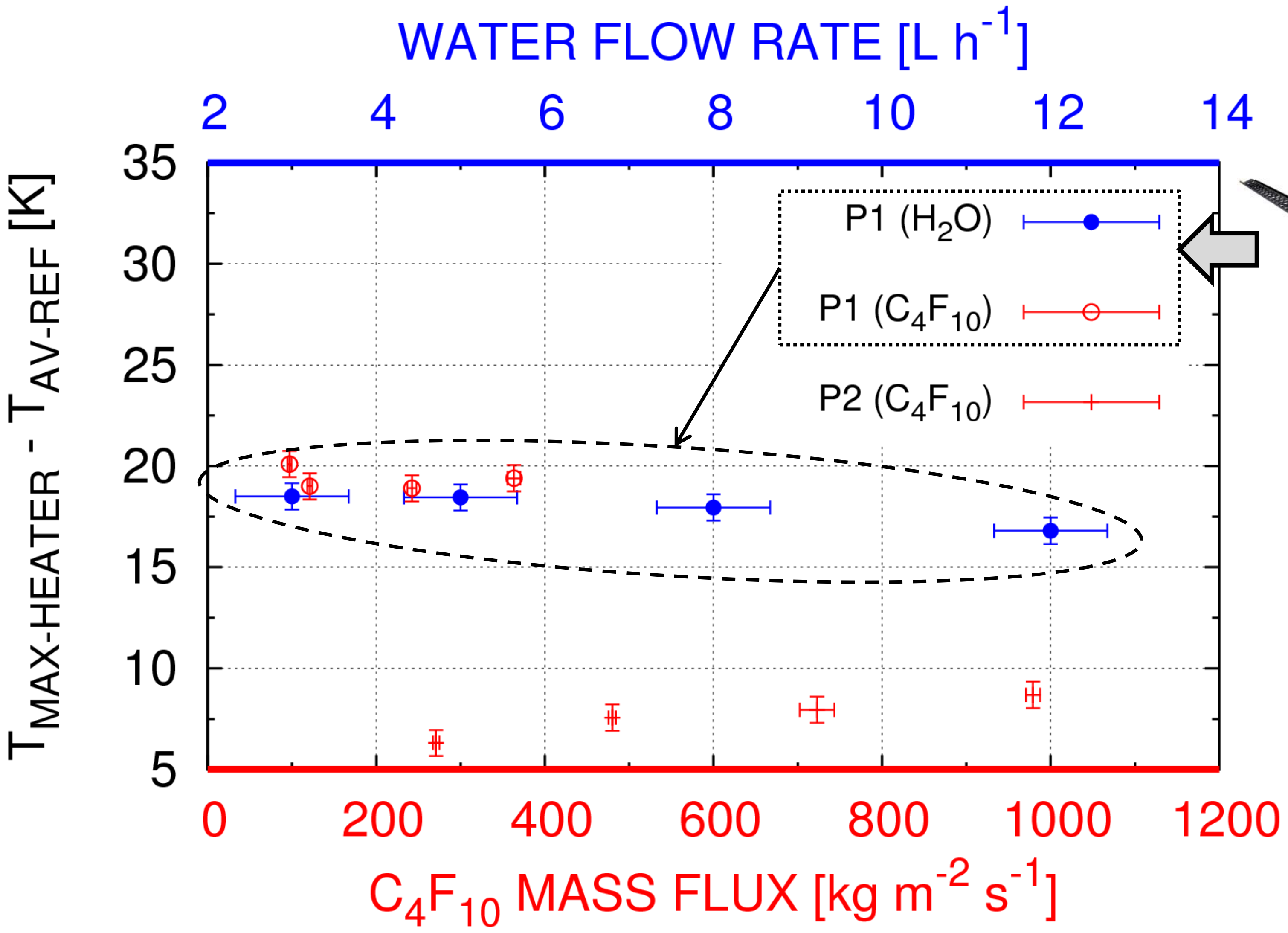
Results: **0.3 W cm^{-2}**



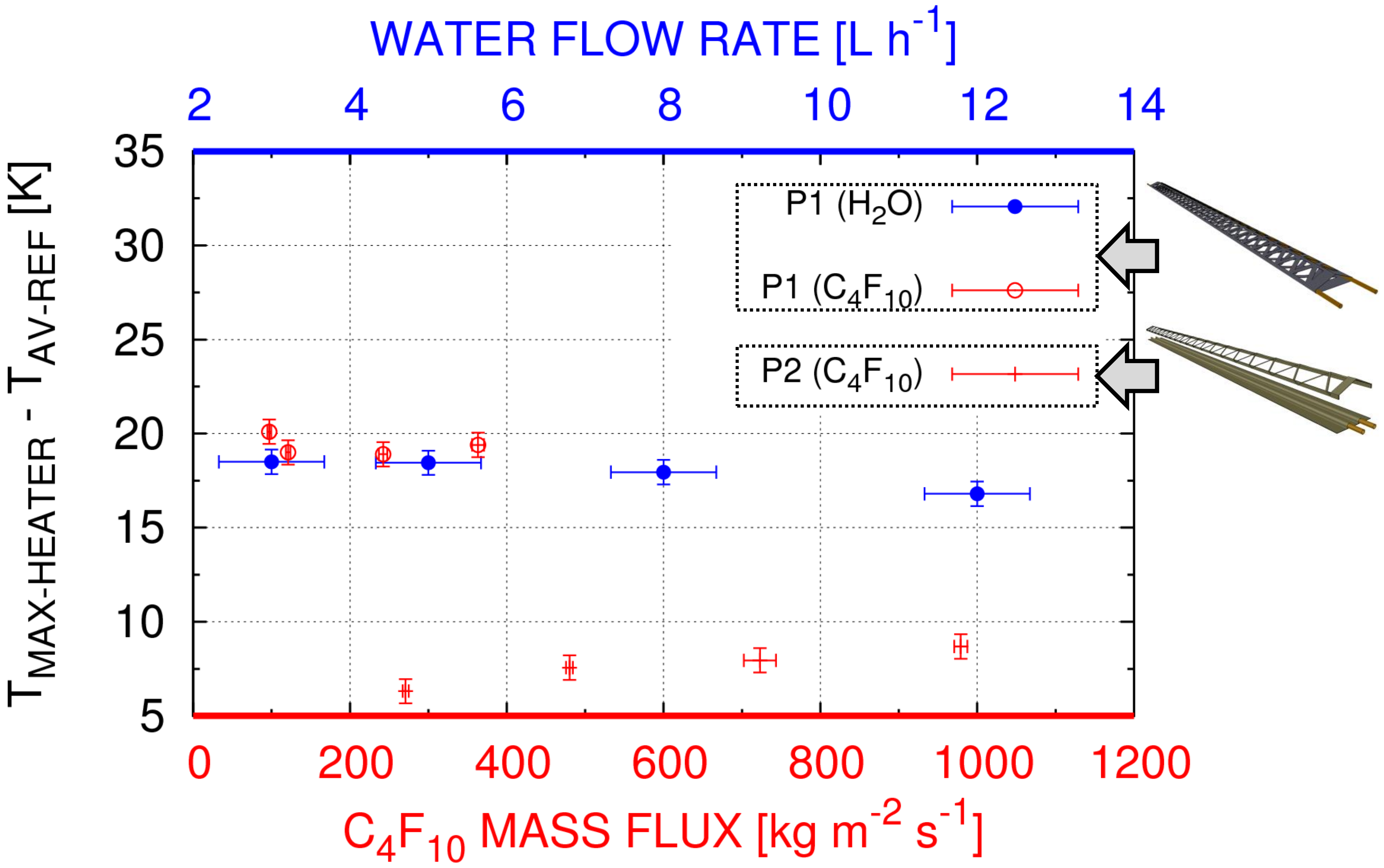
Results: **0.5 W cm^{-2}**



H_2O vs. C_4F_{10}


WATER FLOW RATE [L h^{-1}]
2
4
6
8
10
12
14
35
30
25
20
15
10
5
P1 (H_2O)
P1 (C_4F_{10})
P2 (C_4F_{10})
$T_{MAX\text{-}HEATER}$ - $T_{AV\text{-}REF}$ [K]
0
200
400
600
800
1000
1200
C_4F_{10} MASS FLUX [kg m^{-2} s^{-1}]

Low Flow Rate Sensitivity

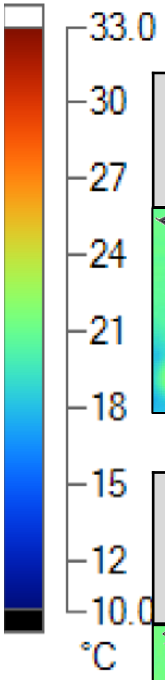


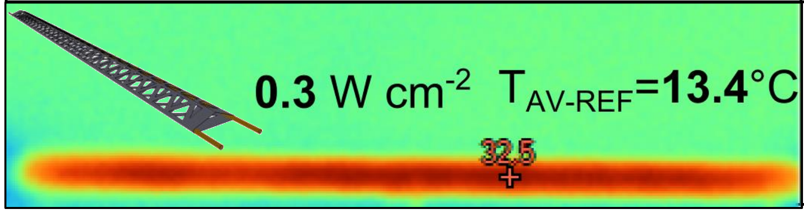
Two-Phase C_4F_{10}: P1 vs. P2

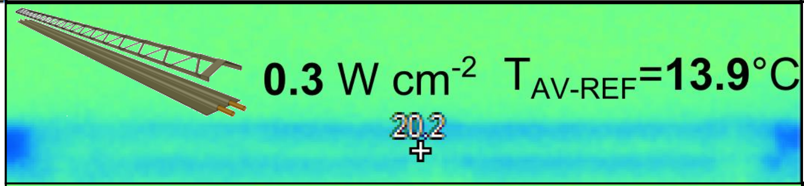
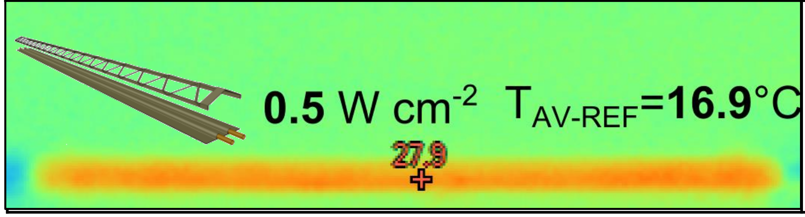
180° BEND

OUTLET

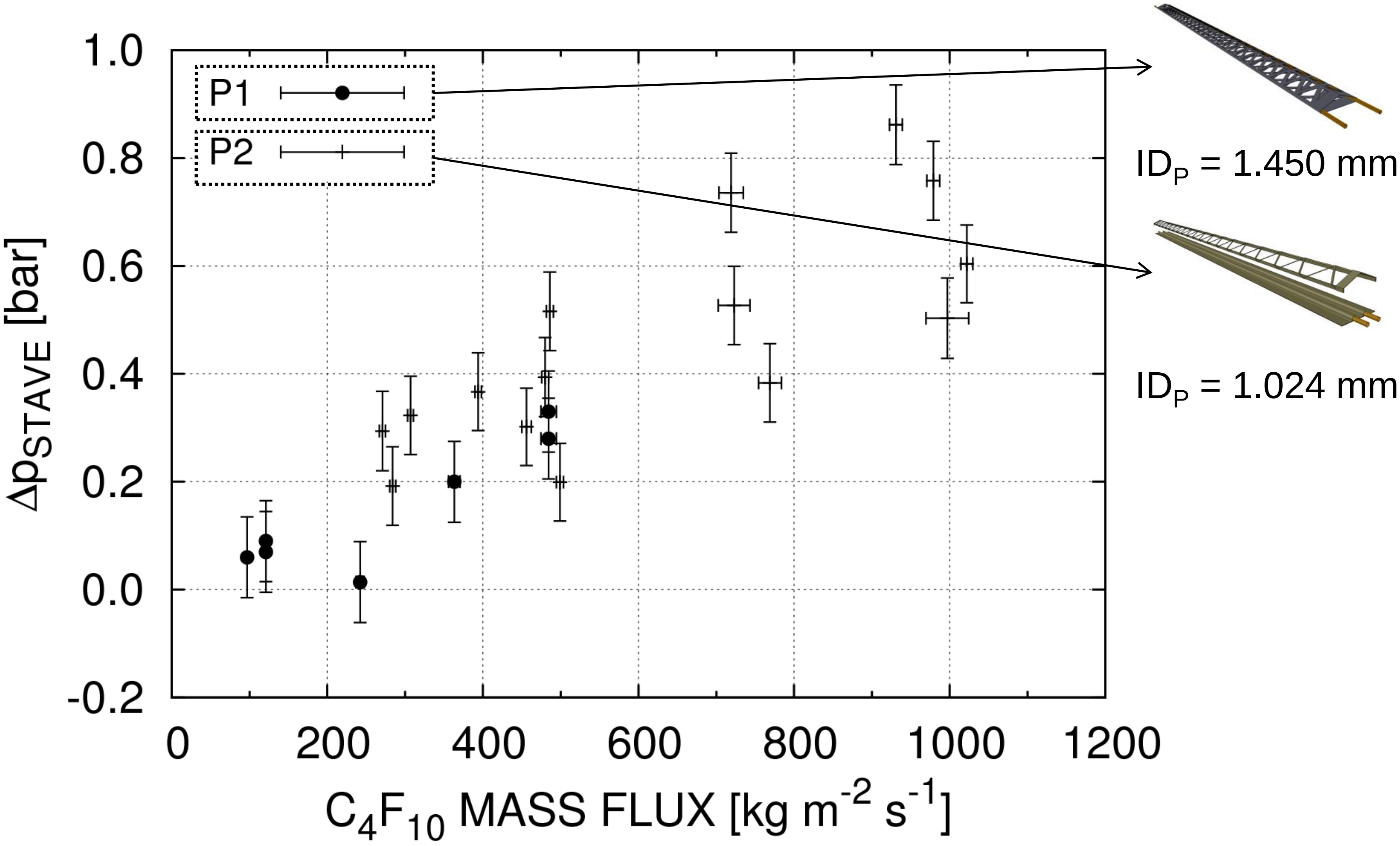
INLET



P1	**G** **[kg m^{-2} s^{-1}]**	**Δp_{ST}** **[bar]**	**ΔT_{REF}** **[K]**	**x_{In}** **[-]**	**x_{Out}** **[-]**
 **0.3** W cm^{-2} T_{AV-REF}=**13.4**°C	242	0.14	1.2	0.08	0.42

P2	**G** **[kg m^{-2} s^{-1}]**	**Δp_{ST}** **[bar]**	**ΔT_{REF}** **[K]**	**x_{In}** **[-]**	**x_{Out}** **[-]**
 **0.3** W cm^{-2} T_{AV-REF}=**13.9**°C	271	0.29	3.1	0.14	0.40
 **0.5** W cm^{-2} T_{AV-REF}=**16.9**°C	307	0.32	3.1	0.05	0.71

Two-Phase Pressure Drop



Outcome

$0.3\ \mathrm{W\ cm^{-2}}$

Parameters	**P1**	**P2**
$\dot{m}$ [g s^{-1}]	0.40	0.22
G [kg m^{-2} s^{-1}]	242	271
$T_{Max\text{-}Heater} – T_{Av\text{-}Ref}$ [K]	19.1	6.3
Δp_{STAVE} [bar]	0.14	0.29

Material budget estimations	**P1**	**P2**
x/X_0 (Full stave + no refrigerant) [%]	0.23	0.29
x/X_0 (Full stave + water in tubes) [%]	0.30	**0.32**

Optimized prototype: ***x/X_0<0.29% per layer***

Conclusions

- Two lightweight cooling proposals for ITS Inner Barrel modules were thermally characterized experimentally.

- Innovative solutions: towards a minimum mass.
  - ✓ High conductivity carbon fiber composites.
  - ✓ Plastic (polyimide tubing)

- CF high-conductivity plate prototype: balanced solution.
  - ✓ Structural robustness at low mass (1.8 g).
  - ✓ Low material budget: x/X_0 <0.30% per module.
  - ✓ $\Delta T_{\text{HEATER-REFR}} < 15$ K at high power density (0.5 W cm^{-2}).
  - ✓ Refrigerant: open choice (↑ thermal resistance at prototype).

Thank you

Acknowledgements:

CERN EN-CV Group for financial support.

ALICE Collaboration for the opportunity to work in the ITS Upgrade Project.

Prof. J. R. Thome for valuable advice and help.

M. Battistin, E. Da Riva and C. Gargiulo (CERN) for their time and patience.

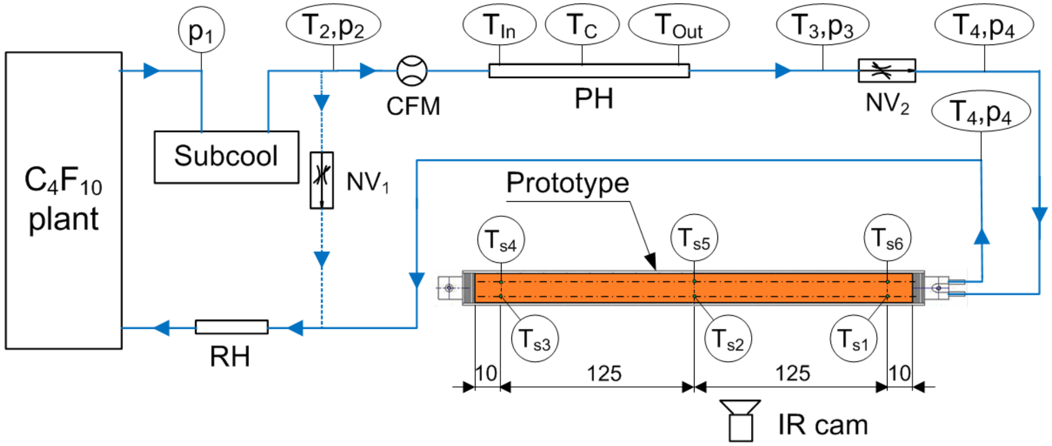
Backup slides

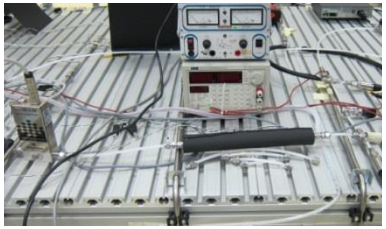
Material Benchmarking

Material	Type	Uses	Characteristics
K13D2U-2k	CF prepreg	Mechanical structure High-Conductivity Plate	$\lambda \sim 800\ \mathrm{W\ m^{-1}\ K^{-1}}$
K1100 Thornel		High-Conductivity Plate	$\lambda > 1000\ \mathrm{W\ m^{-1}\ K^{-1}}$
FGS003	Graphite foil	Enhance thermal contact	$\lambda \sim 1500\ \mathrm{W\ m^{-1}\ K^{-1}}$
Polyimide	Polymer	Tubes Bends (research ongoing)	Robust $X_0 = 29$ cm
PEEK	Polymer	Enclosures Tubes Connectors	Robust Not very flexible Thick wall $X_0 = 29$ cm

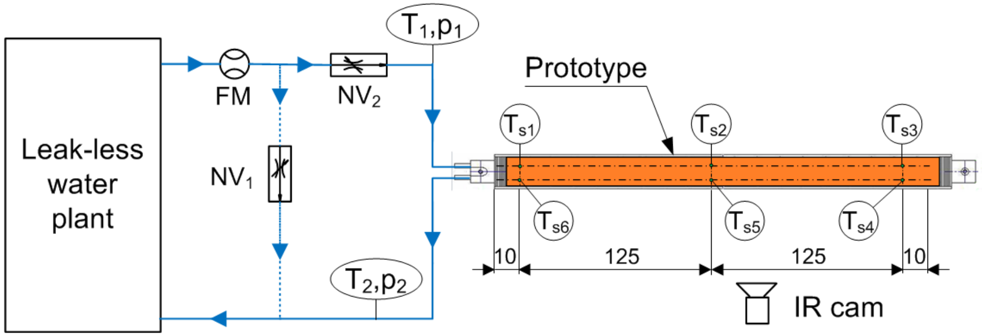
Experimental Facility

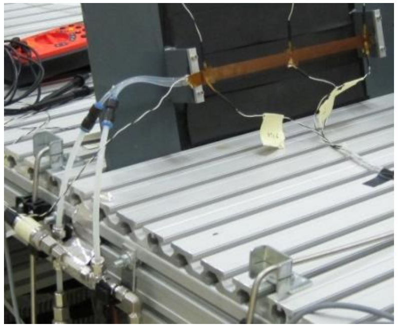
C_4F_{10} Loop



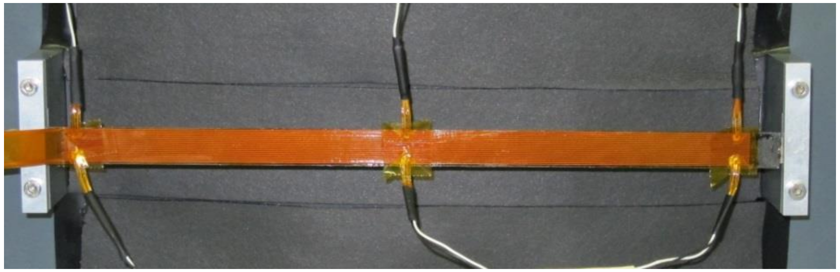


Water Loop



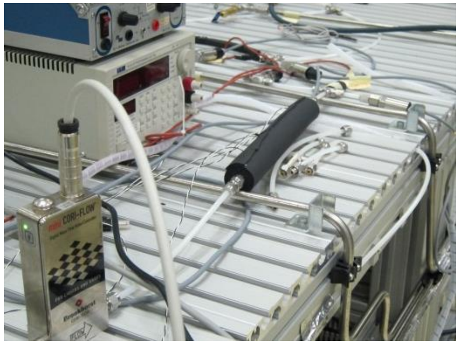


Experimental Facility

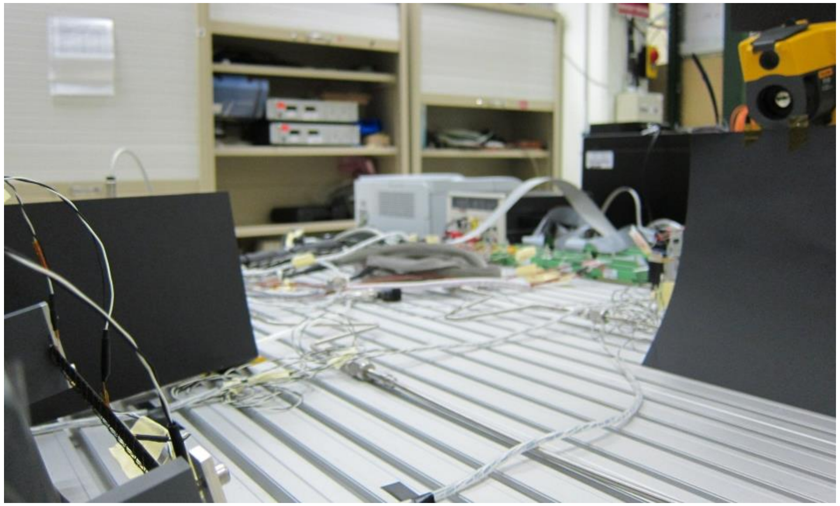


Stave view as from the IR camera.

P2 prototype.



Leak-less water plant.



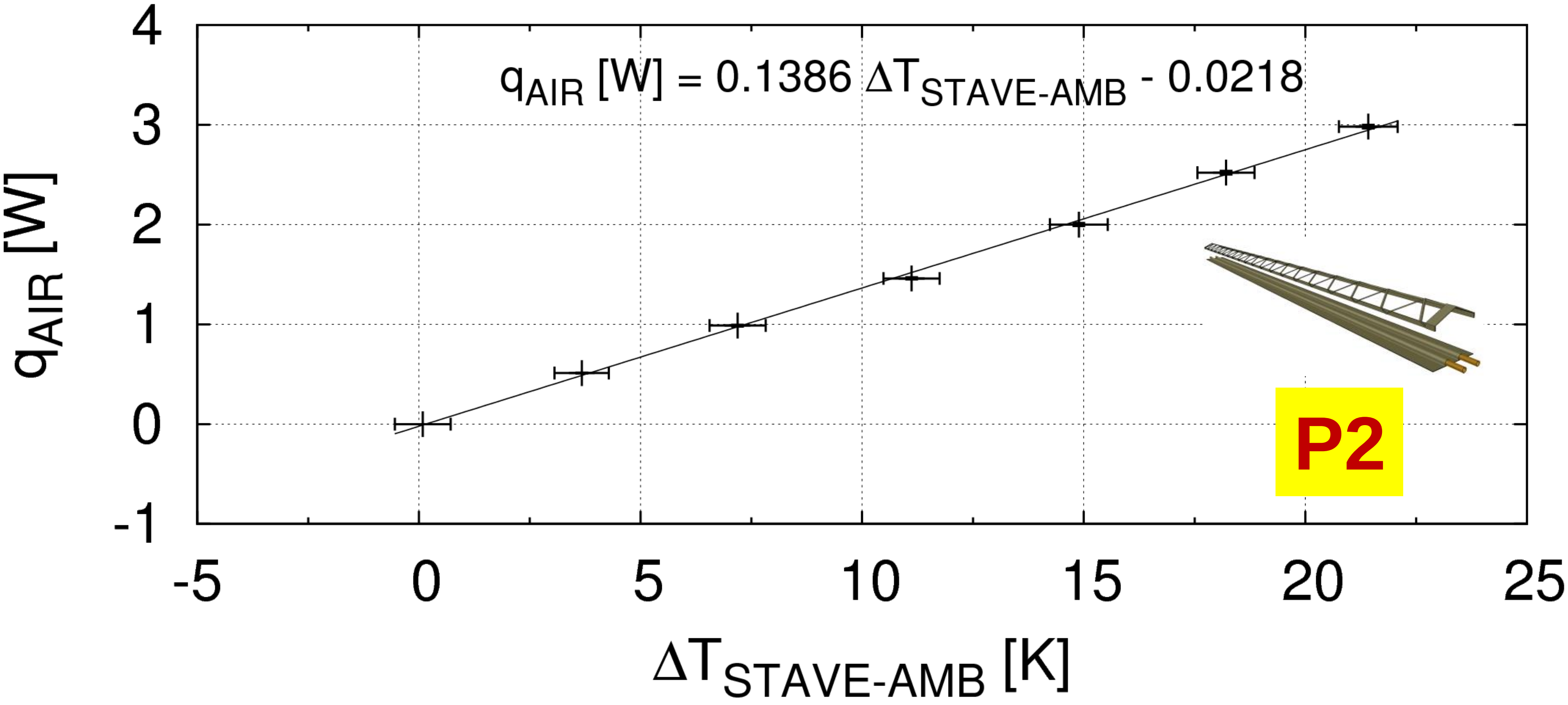
Stave test setup.

C_4F_{10} loop and plant.

No-Flow Tests

Procedure:

1. Apply low power and record the average stave temperature.
2. Correlate power dissipated to air vs. average stave temperature.
3. When cooling the stave with full power, the power dissipated/absorbed

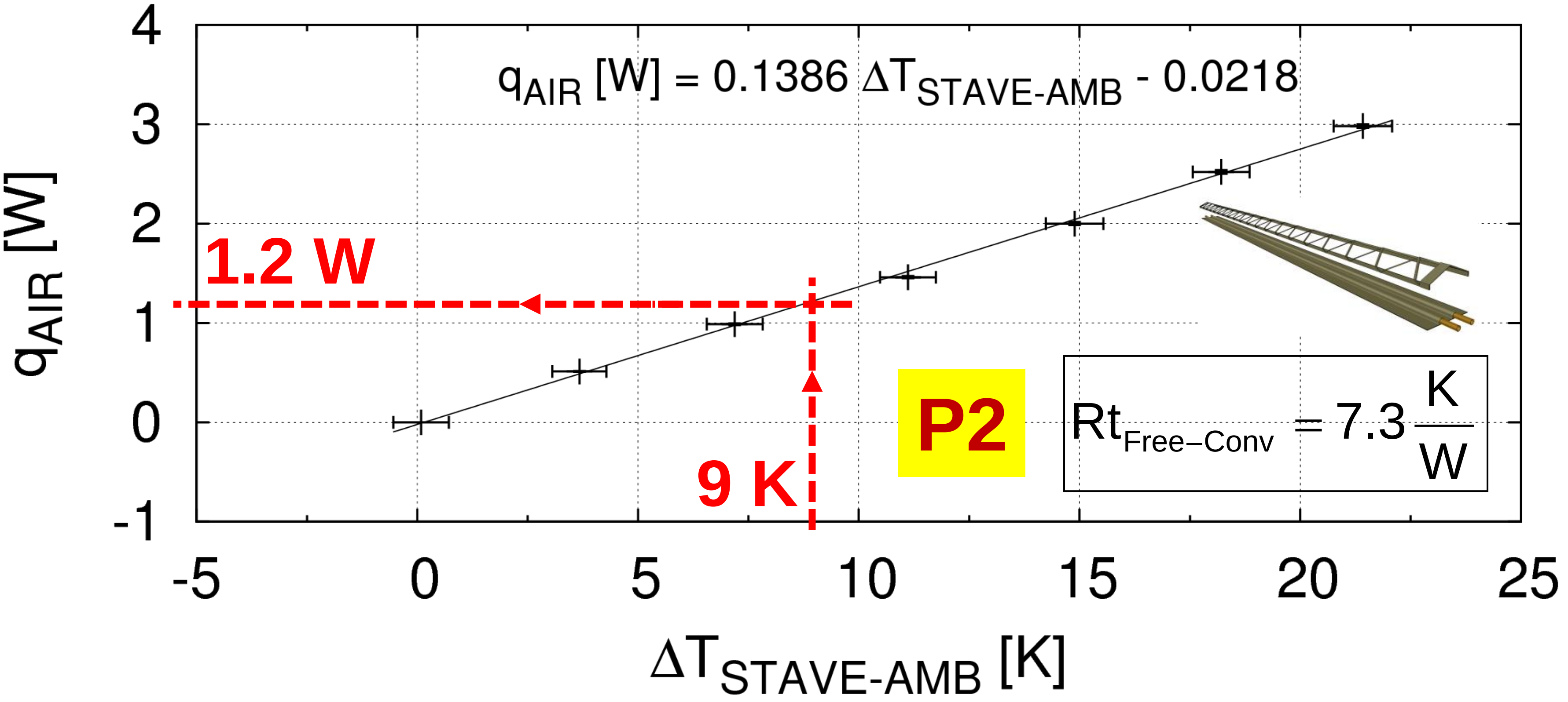


No-Flow Tests

Assumption: average ambient temperature = **21°C**

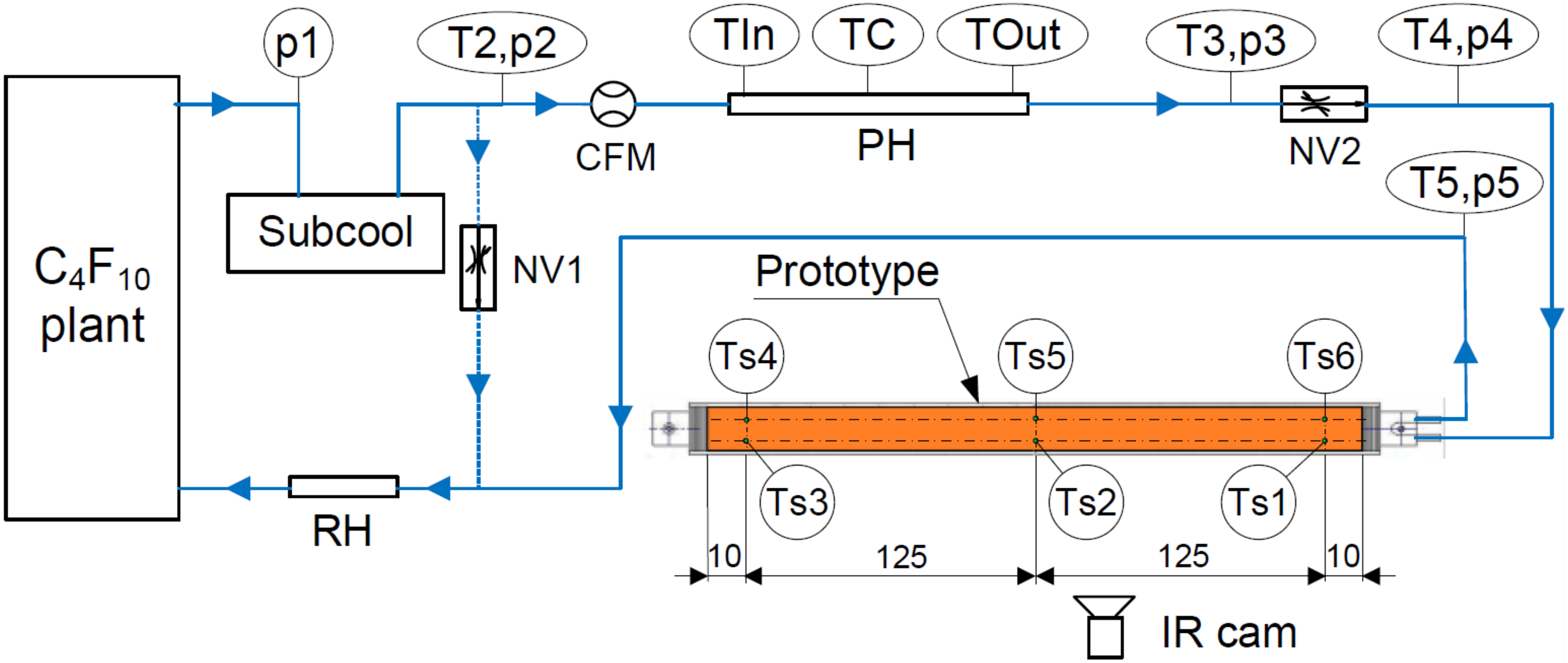
$T_{MAX\text{-}STAVE}$= **30°C** → $\boxed{\Delta T_{STAVE-AMB)_{MAX}} < \mathbf{9\ K}}$

P2: ***1.2 W*** *to room air (~****12%**** of power applied, 0.3 W cm*$^{-2}$*)*



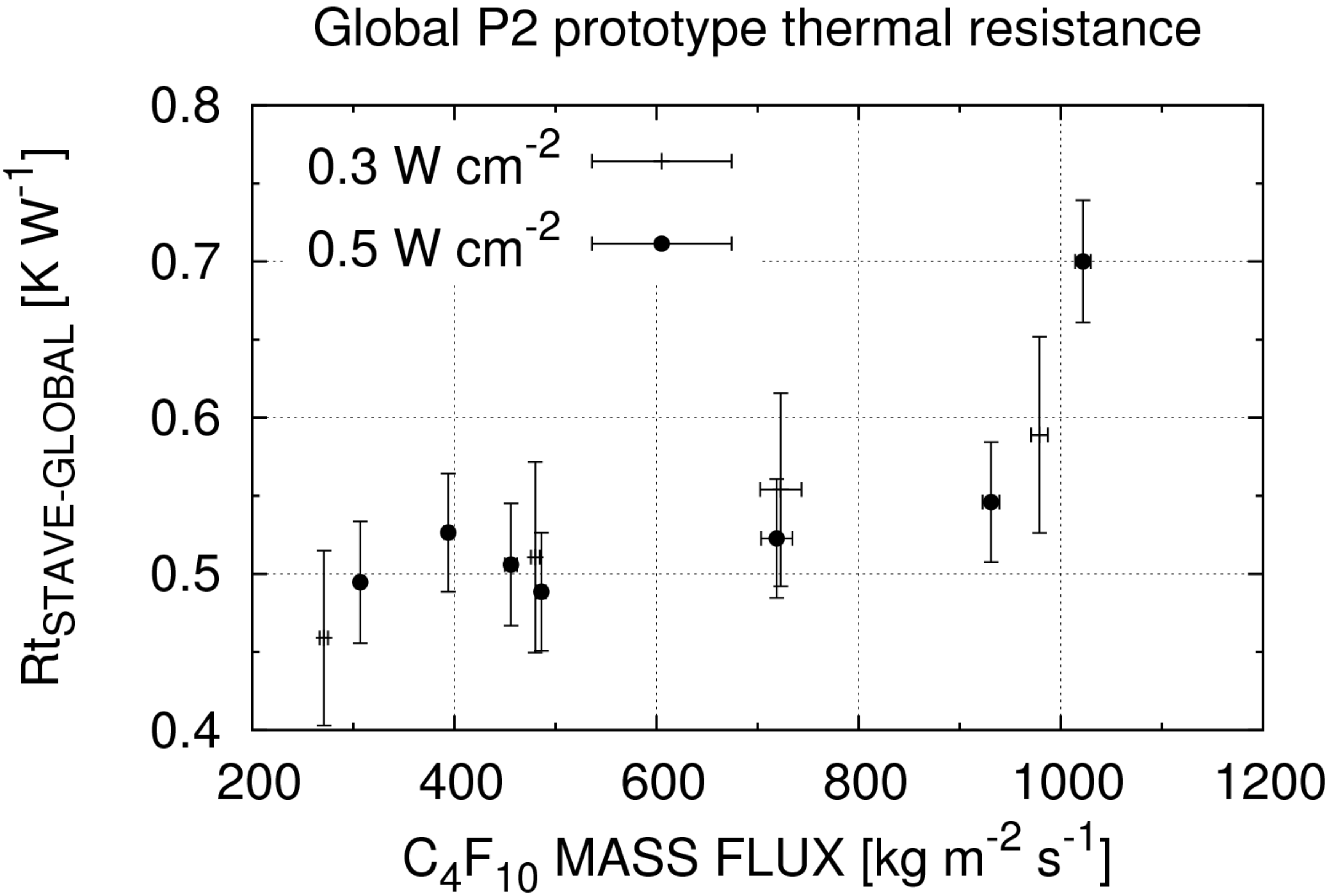
Two-Phase Flow Tests

VAPOUR QUALITY:



$$x_5 = \frac{q + q_{AIR}}{\dot{m}(h_{4G} - h_{4L})} - x_4 \longrightarrow 0.4 < x_5 < 0.7$$

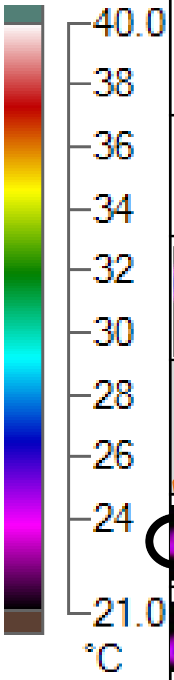
Thermal Characterization



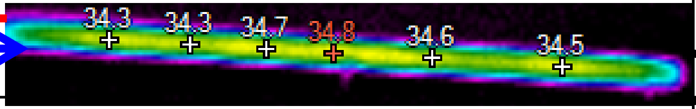
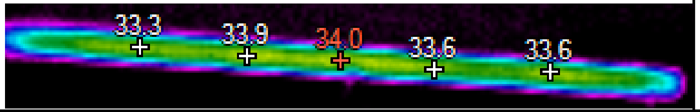
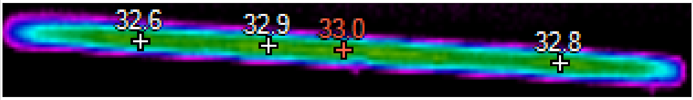
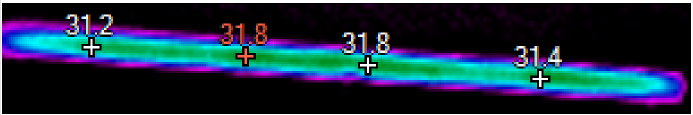
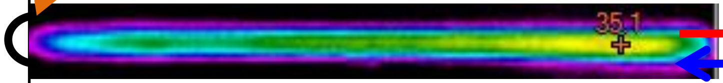
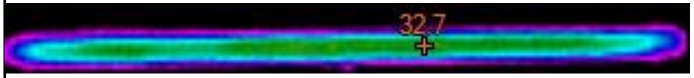
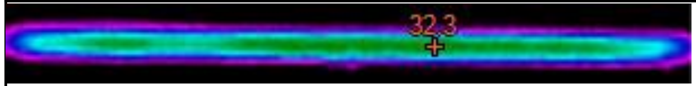
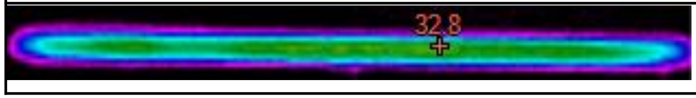
P1: H_2O vs. C_4F_{10} @**0.3 W cm^{-2}**

OUTLET

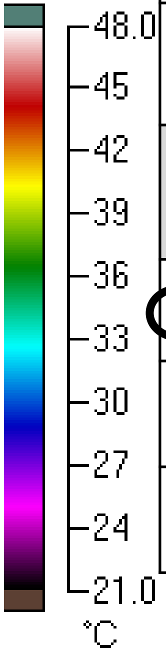
INLET

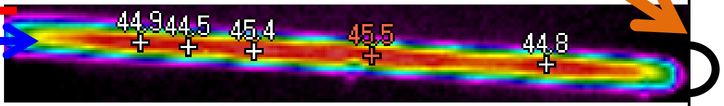
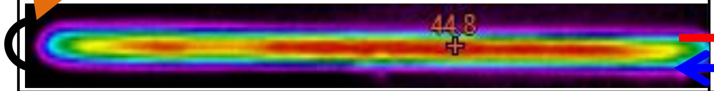
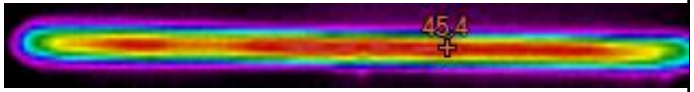


BEND

H_2O	**Q [L h^{-1}]**	**Δp_{St} [bar]**	**v [m s^{-1}]**	**$T_{H20\text{-}IN}$ [°C]**	**ΔT_{H20} [K]**
	3.1	0.06	0.54	15.1	2.4
	4.9	0.20	0.84	14.8	1.5
	8.5	0.46	1.47	14.7	0.7
	12.1	0.73	2.09	14.7	0.6
BEND **C_4F_{10}** **INLET/OUTLET**	**m [g s^{-1}]**	**Δp_{St} [bar]**	**x_{In} [-]**	**x_{Out} [-]**	**Av.T_{C4F10} [°C]**
	0.16	0.06	0.08	0.92	15.0
	0.20	0.07	0.08	0.75	13.7
	0.40	0.14	0.08	0.42	14.0
	0.60	0.20	0.06	0.31	14.5

P1: H_2O vs. C_4F_{10} @0.5 W cm^{-2}

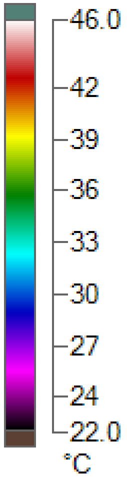


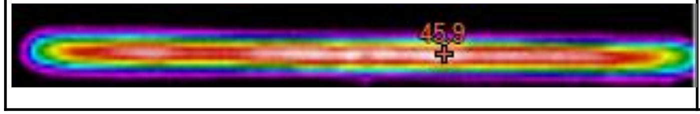
OUTLET INLET **H_2O** BEND	**Q [L h^{-1}]**	**Δp_{St} [bar]**	**v [m s^{-1}]**	**$T_{H20\text{-}IN}$ [°C]**	**ΔT_{H20} [K]**
	8.0	0.43	1.38	14.7	1.5
	12.2	0.77	2.11	14.8	1.2
BEND **C_4F_{10}** INLET/OUTLET	**m [g s^{-1}]**	**Δp_{St} [bar]**	**x_{In} [-]**	**x_{Out} [-]**	**Av.T_{C4F10} [°C]**
	0.4	0.17	0.06	0.65	14.3
	0.6	0.26	0.05	0.46	14.9
	0.8	0.33	0.03	0.36	15.5

- Results independent of the mass flow rates.
- Controlling the vapor quality at the inlet/outlet is very important.

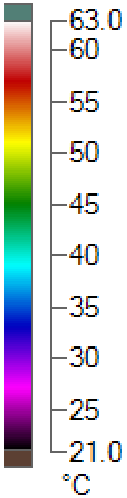
P1: C_4F_{10} tests discussion

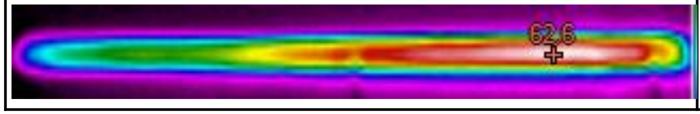
- **Two extreme cases:**



Case: 0.3 W cm^{-2}	**m** **[g s^{-1}]**	**Δp_{St}** **[bar]**	**x_{In}** **[-]**	**x_{Out}** **[-]**	**$T_{C4F10\text{-}Out}$** **[°C]**
	0.8	0.28	0.04	**0.26**	13.3

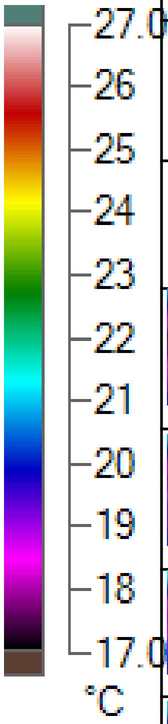
- Low vapor quality at stave entrance.
- ↑ m, ↑ HTC, but ↑ Δp. Since p_{Out} = constant, ↑ $p_{Inlet,}$ ↑ $T_{sat\text{-}Inlet,}$ ↑ ΔT_{Fluid}

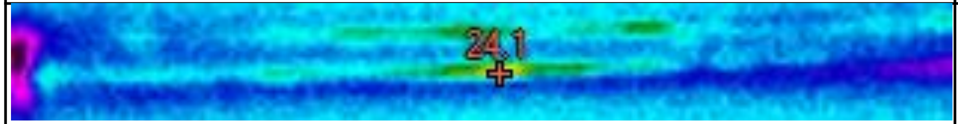
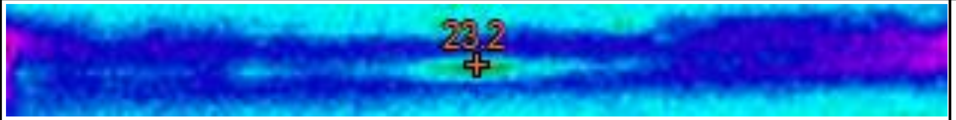
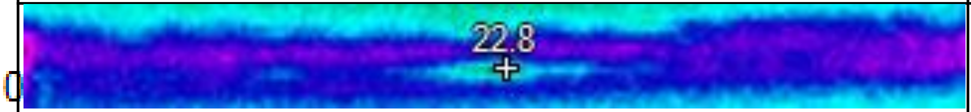
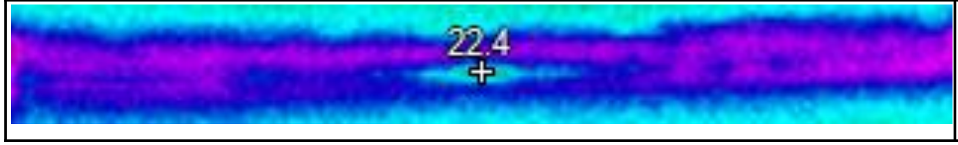


Case: 0.5 W cm^{-2}	**m** **[g s^{-1}]**	**Δp_{St}** **[bar]**	**x_{In}** **[-]**	**x_{Out}** **[-]**	**$T_{C4F10\text{-}Out}$** **[°C]**
	0.2	0.09	0.08	**1.20**	**21.0**

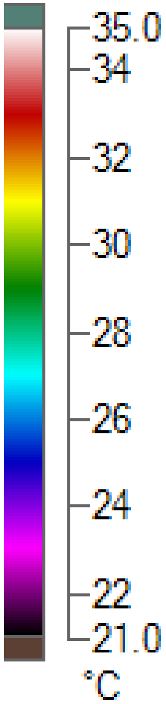
- Low vapor quality at stave entrance:
- Mass flow rate too low: superheated vapor at stave outlet

P2: H_2O @0.3 W cm^{-2}



BEND **Case** **INLET/OUTLET**	**Q [L h^{-1}]**	**Δp [bar]**	**T_{H20-IN} [°C]**	**ΔT_{H20} [K]**
	3.0	0.23	15.2	2.4
	5.0	0.25	15.0	1.6
	6.5	0.34	15.0	1.2
	8.0	0.54	14.7	1.2
	10.0	0.62	14.9	0.7
	12.0	0.84	15.0	0.6
	15.0	1.18	14.8	0.6

P2: H_2O @0.5 W cm^{-2}

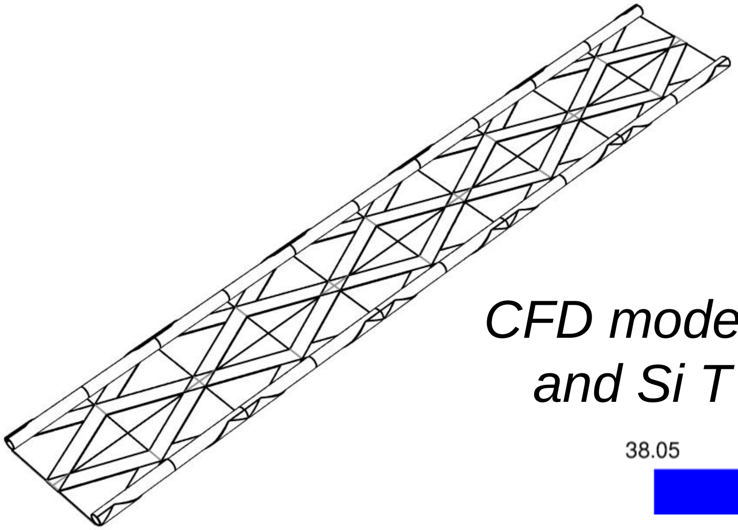


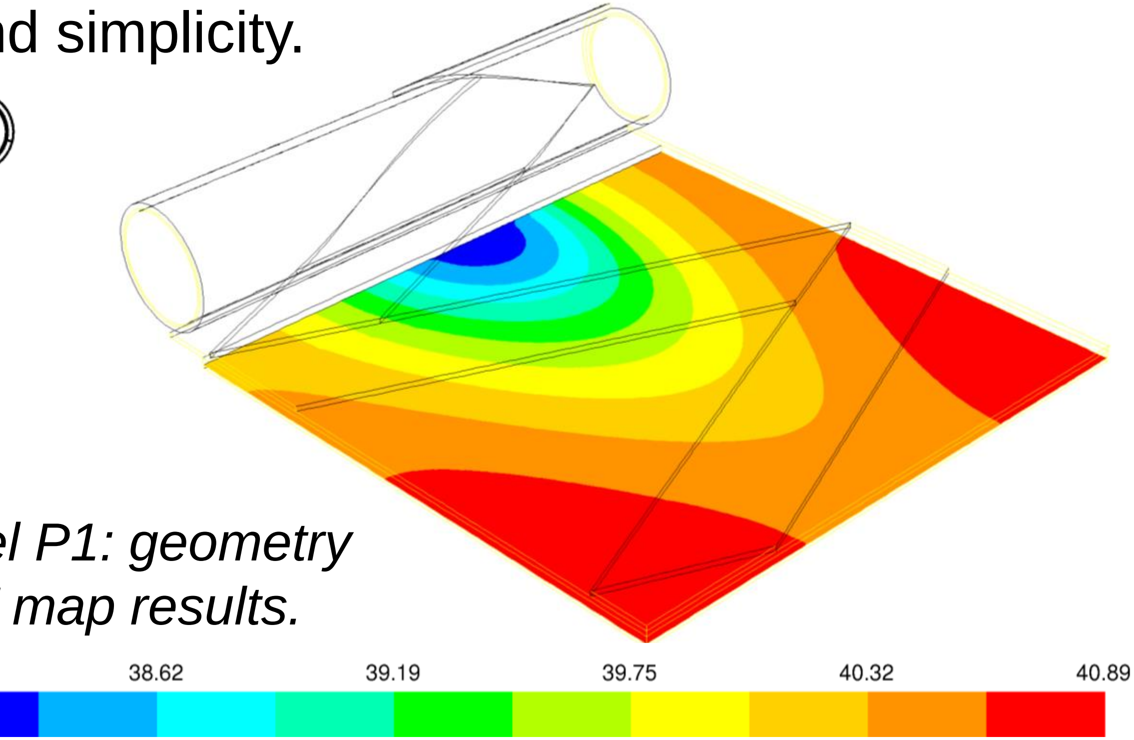
BEND Case INLET/OUTLET	Q [L h^{-1}]	Δp [bar]	$T_{H20\text{-}IN}$ [°C]	ΔT_{H20} [K]
	3.0	0.24	15.4	3.9
	5.0	0.30	14.9	2.5
	6.5	0.34	15.0	1.9
	8.0	0.54	14.9	1.5
	10.0	0.60	14.9	1.3
	12.0	0.84	15.0	0.9
	15.0	1.18	14.9	0.9

R&D Phase

ULTRA-LOW-MASS COOLING SYSTEMS

- **Analytical & CFD studies:** find optimal arrangement:
  - Minimal structural x/X_0 (materials, thicknesses).
  - Best thermal performance with minimum tube ID.
  - Mechanical stiffness and simplicity.





CFD model P1: geometry and Si T map results.

ALICE ITS Upgrade Project

- ALICE: experiment at CERN LHC.

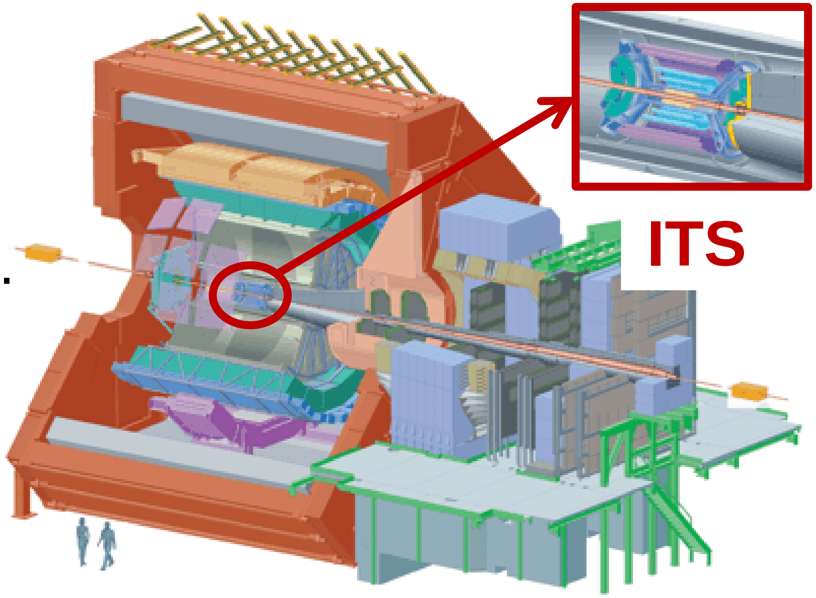
- ITS Upgrade Project: replace Inner Tracker System.
  - **Goal:** design & implementation of new cooling system.

PROJECT SCHEDULE

2012-2014 **R&D phase**

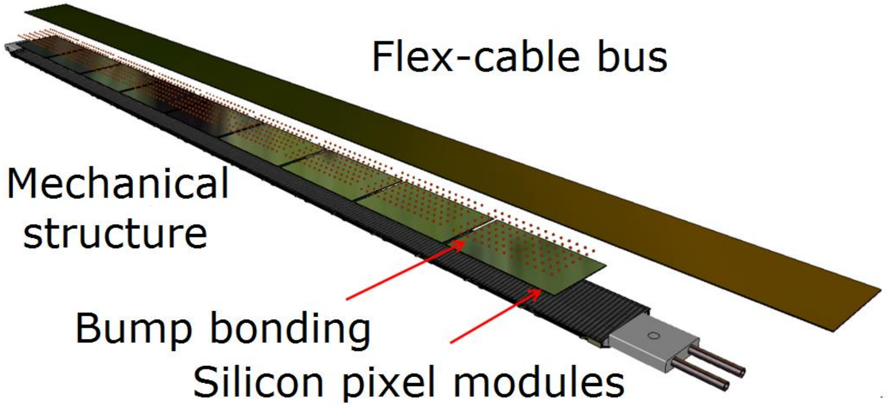
- **2012** Study technology proposals.
- **2013** Selection of technologies. Qualification studies.
- **2014** Final design and validation. Integration & final testing.

2015-2018 **Construction and Installation**



ALICE Experiment

Detector Power Dissipation

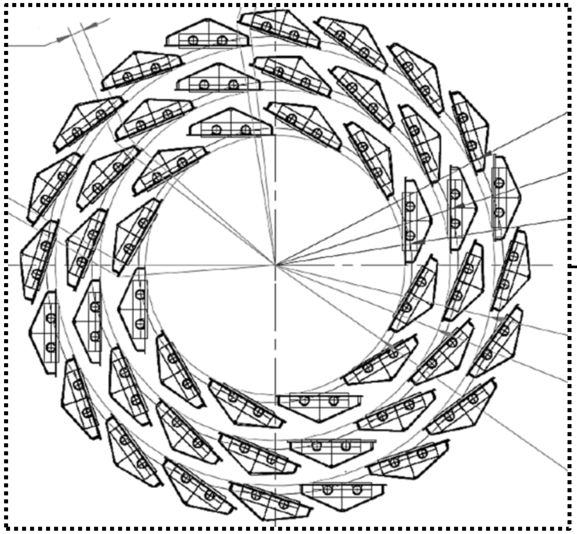


Detector module: ***STAVE***

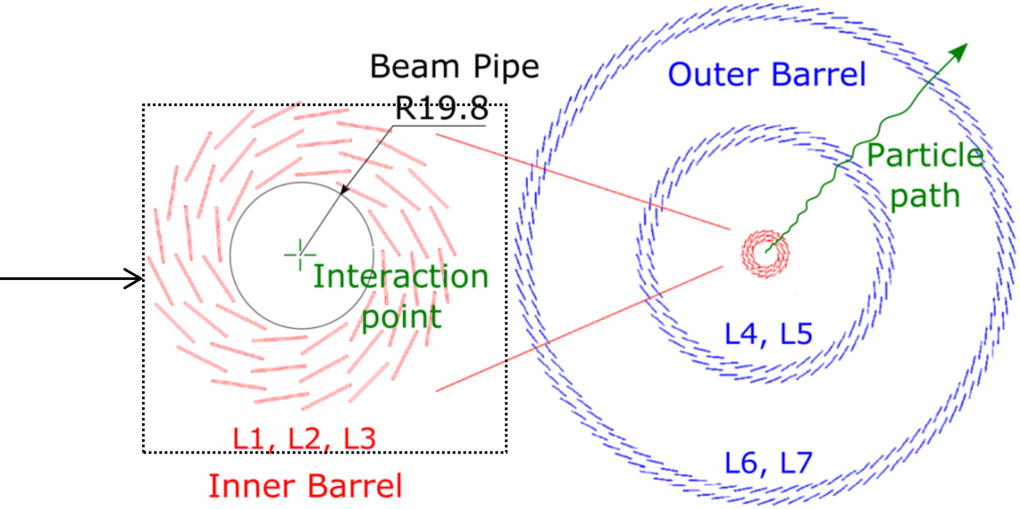
Charged and neutral particles cross pixel modules, leaving:

1. **Ionizing current:** signal
2. **Non-ionizing current:**

radiation damage → **energy loss**



Inner Barrel geometrical constraints.



Full ITS sectional view.