Thermal Performance of Lightweight Cooling Systems for the ALICE ITS Upgrade

C. Gargiulo, M. Gómez Marzoa

European Centre for Nuclear Research (CERN), Geneva, CH
LTCM, École Polytechnique Fédérale de Lausanne (EPFL)

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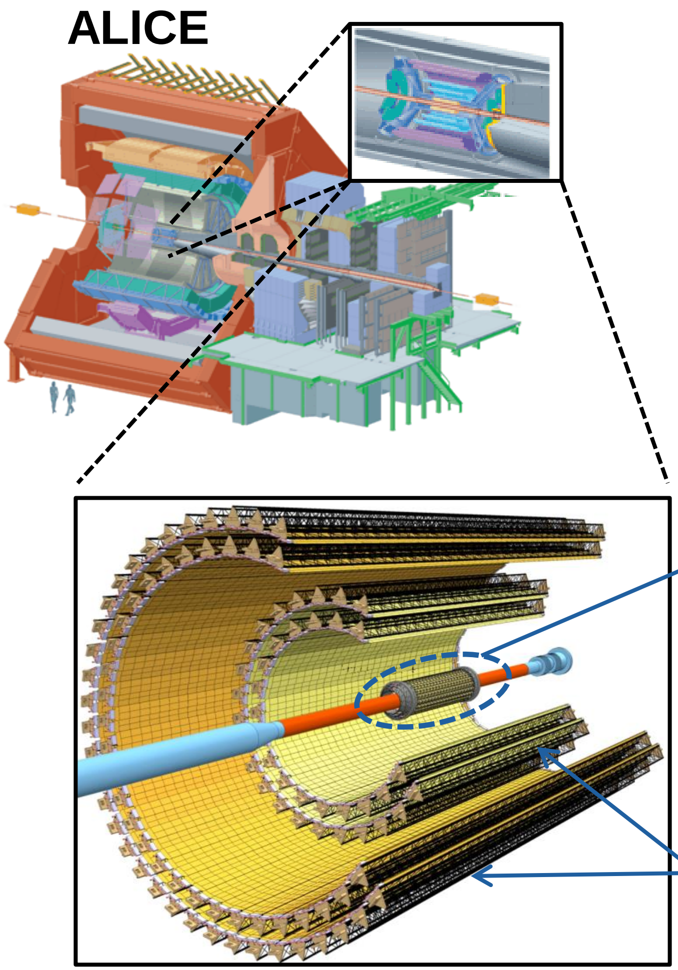
Outline

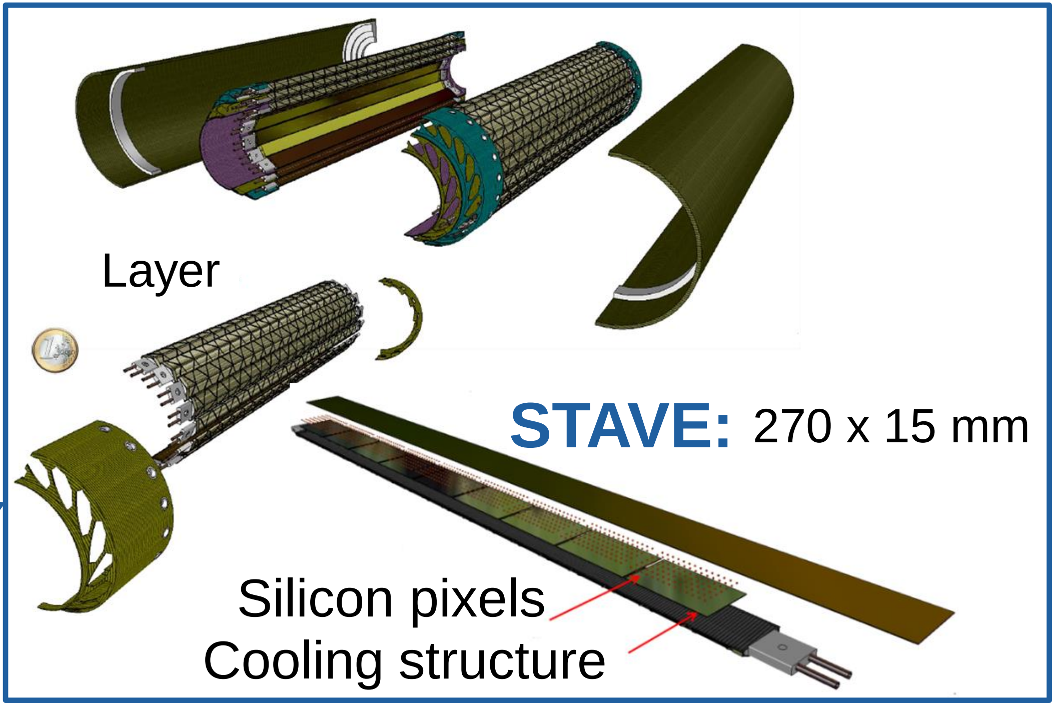
- Morphology & cooling concept
- Design Parameters
- Experimental Facility
- Methodology
- Baseline designs: Thermal characterization
  - ☐ Inner Barrel modules
  - ☐ Outer Barrel modules
- Alternative designs
- Conclusion

Morphology & Cooling Concept



ITS: Inner Tracker System

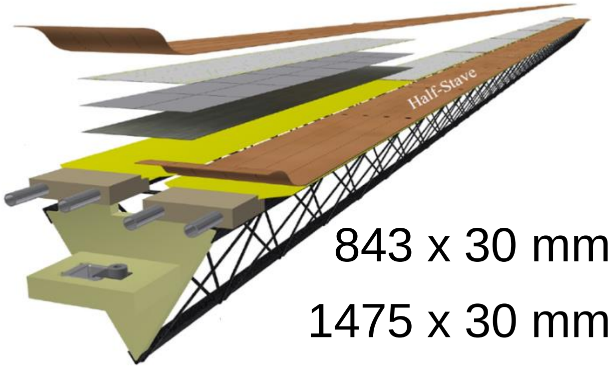
Inner Barrel (3 layers)



STAVE: 270 x 15 mm

Silicon pixels
Cooling structure

Middle & Outer Barrel (2+2 layers)



843 x 30 mm
1475 x 30 mm
x 2

Design Parameters

1. Power dissipation: pixel chip, electronics…

- ☐ **Max. 0.10 W cm^{-2}** (0.15 W cm^{-2} for safety margin)

2. Operational temperature and **uniformity:**

- ☐ **T_{PIXEL}< 30°C**
- ☐ Pixel maximum temperature non-uniformity < **5 K**

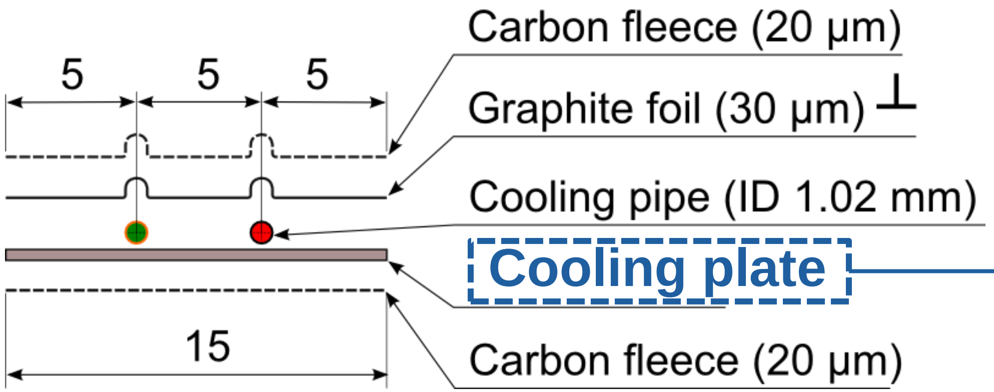
3. Minimize material budget:

IB: $x/X_0 \leq$ **0.30%** per layer

OB: $x/X_0 \leq$ **0.80%** per layer

Inner Barrel: Stave Layup

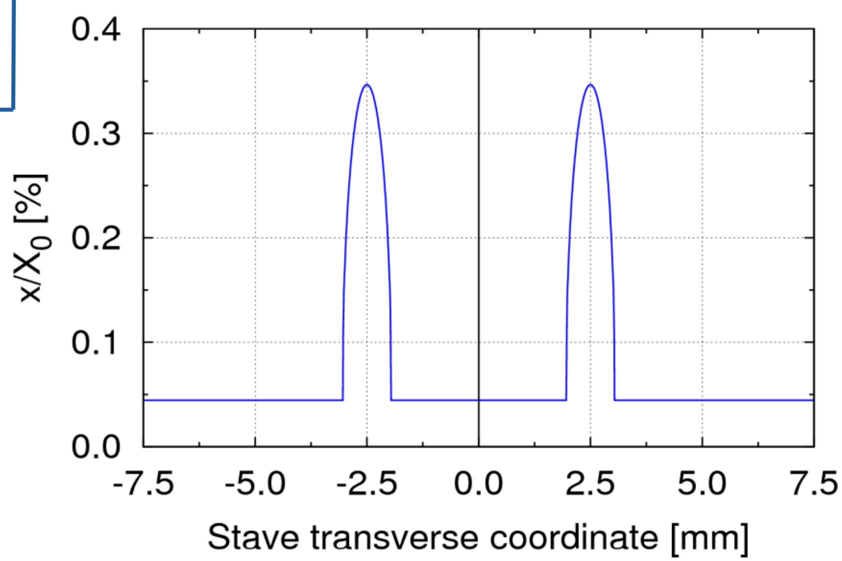
STAVE SECTION



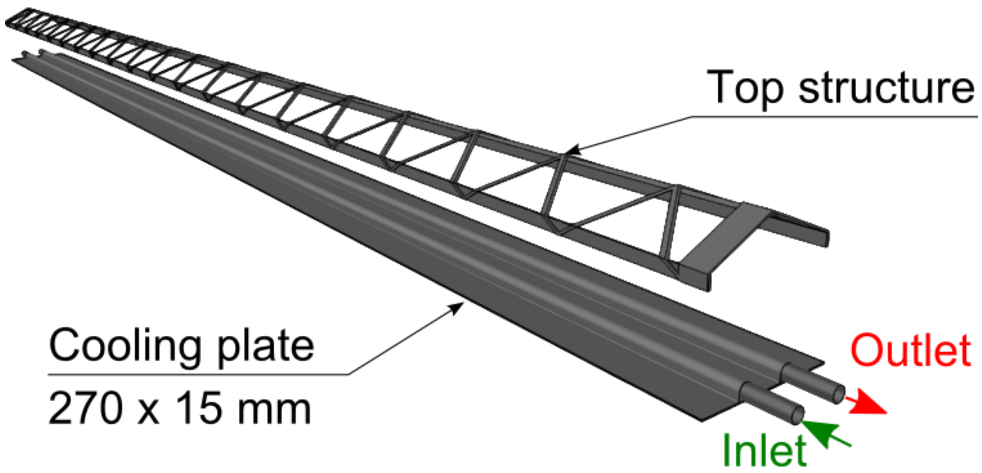
Baseline

1. K13 D2U 70 µm ⊥

- k_{K13D2U} ~ 800 W m^{-1} K^{-1}



Material budget x/X_0 [%]



1.4 g *(structure only) [1]*

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

[1] Ref: ALICE ITS Upgrade TDR

Coolant Selection

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

Coolant	Benefits	Concerns
Single-phase **H_2O**	Radiation hard Loop simplicity	Leak-less ($\Delta p < 0.5$ bar) 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 Flow Distribution (336 staves)

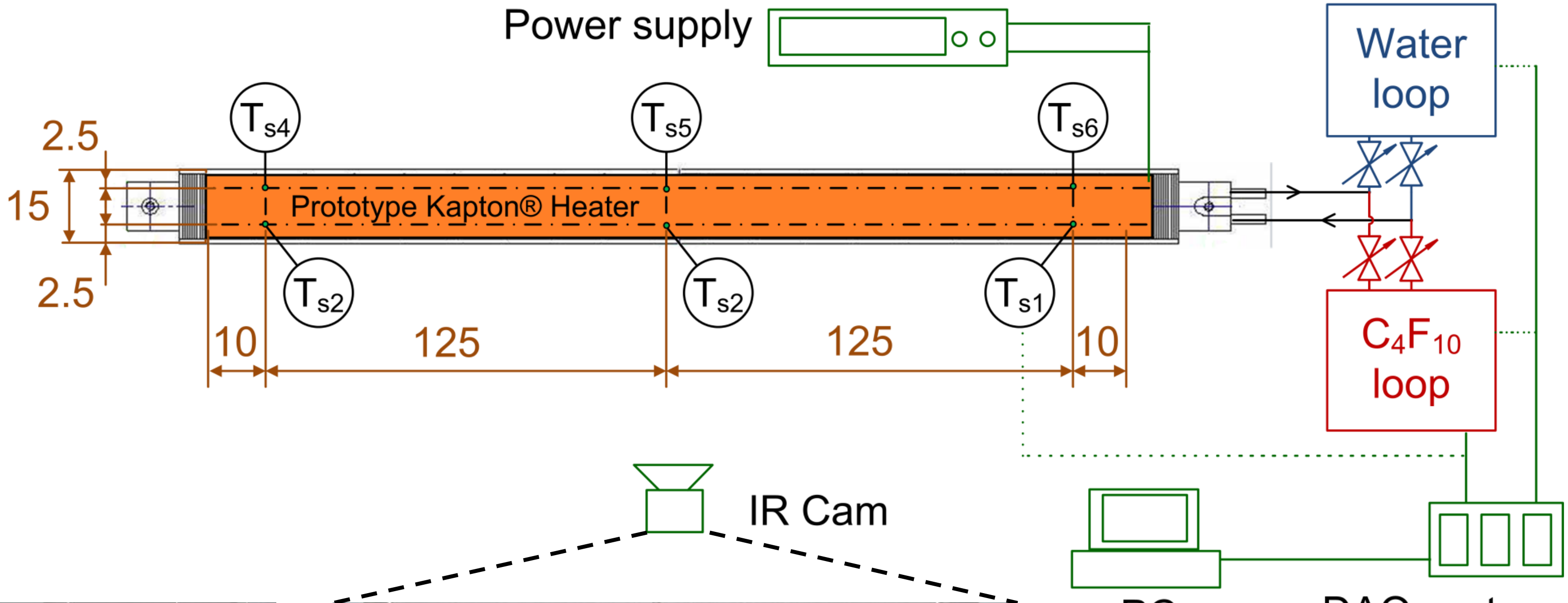
$T_{SAT} = 15°C$

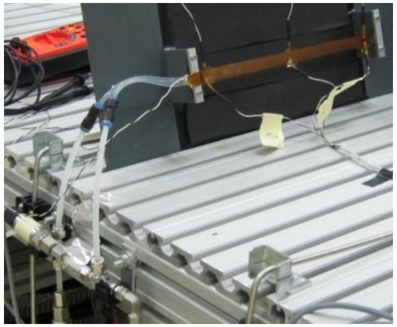
$P_{SAT} = 1.9$ bar ✓

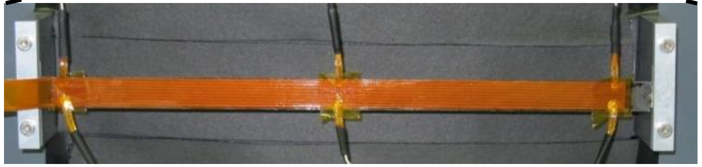
Chosen coolant: H_2O ($\Delta p < 0.5$ bar)

- ❑ **C_4F_{10}**: if ↓ x/X_0, ↓ ∇T_{STAVE} solution.

Experimental Facility







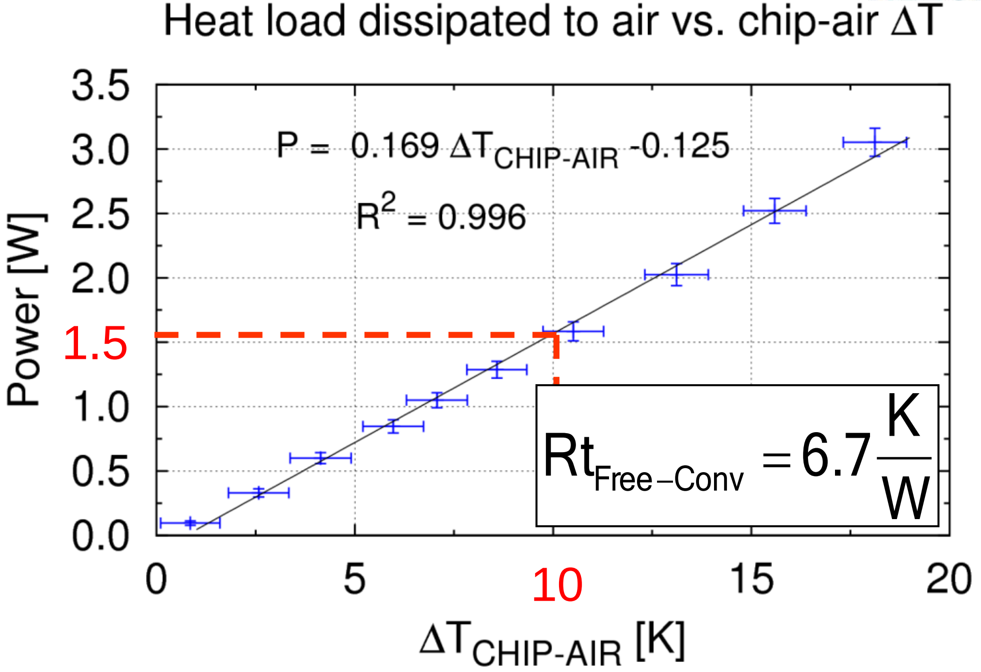
Methodology

1. No coolant flow tests:

- ❑ Heat exchange to room air.
- ❑ T sensors vs. IR Camera.

$$\overline{T_{STAVE}} = 30°C \quad T_{AIR} = 20°C$$

$$P_{TO\text{-}AIR} \sim 1.5\ W$$



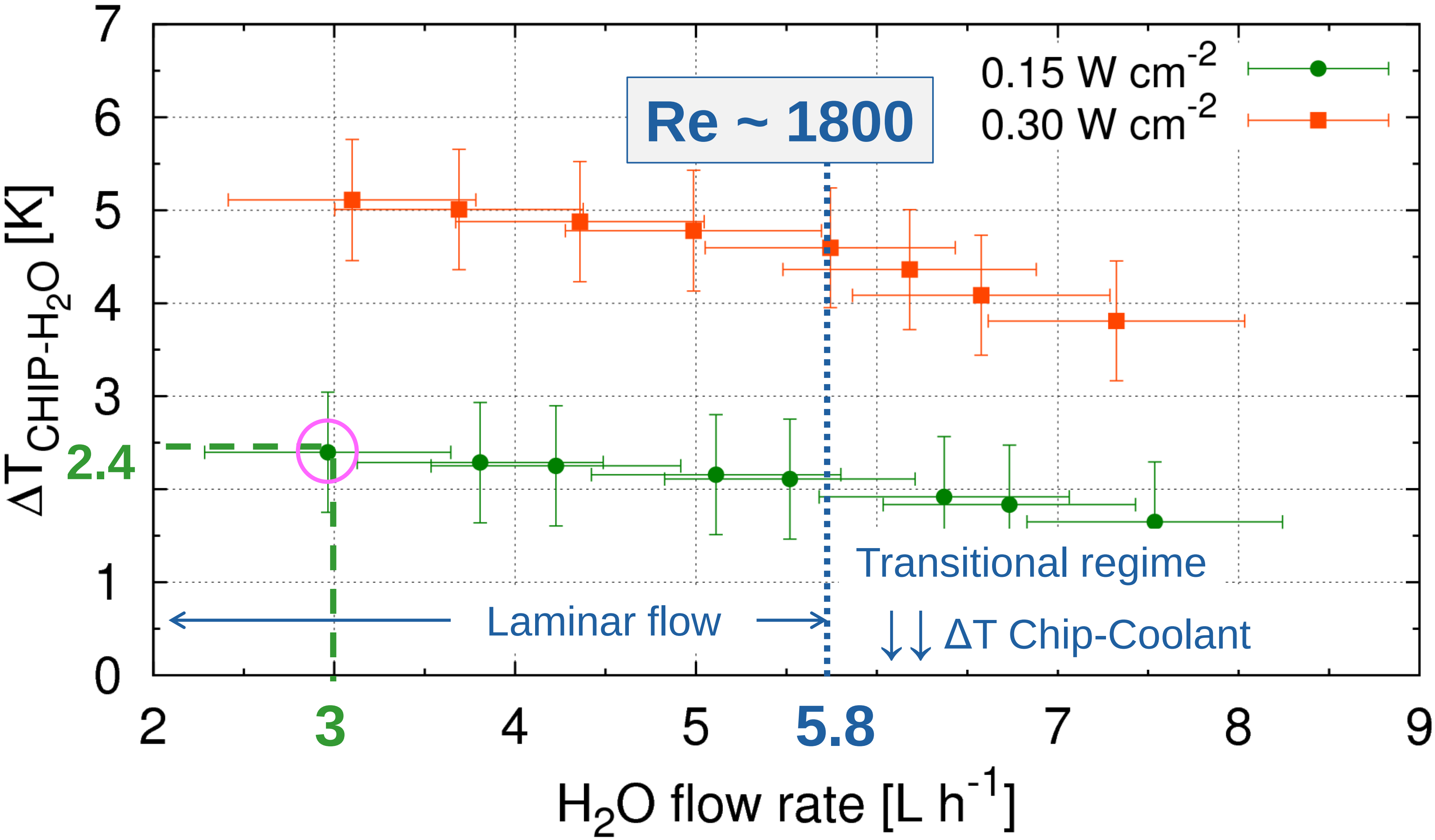
2. Single-phase flow tests: H_2O

- ❑ Refrigerant pressure drop.
- ❑ Average chip temperature.
- ❑ Refrigerant temperature rise.

Power density **q [W cm^{-2}]**	**Power to heater** **P [W]**
0.15	6.1
0.30	12.2

(0.30 W cm^{-2}, safety margin>2)

$\Delta T_{CHIP\text{-}COOLANT}$



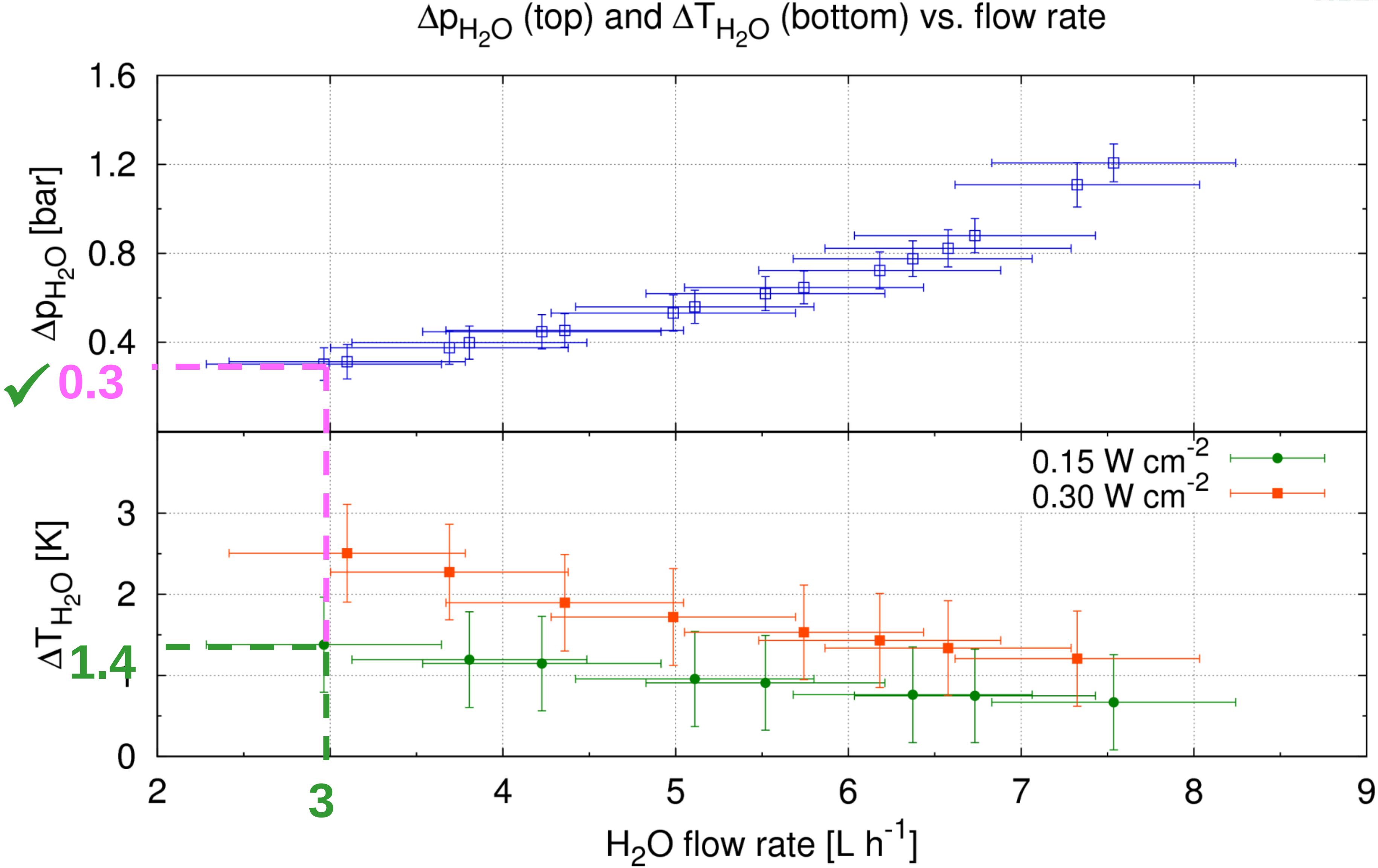
Re ~ 1800

Laminar flow

Transitional regime

↓↓ ΔT Chip-Coolant

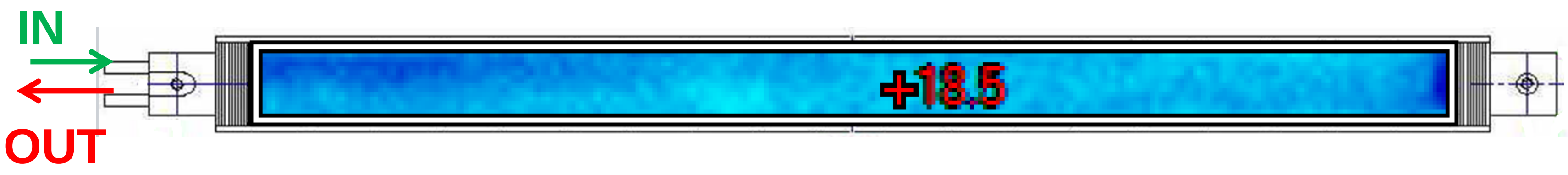
Refrigerant Δp and ΔT



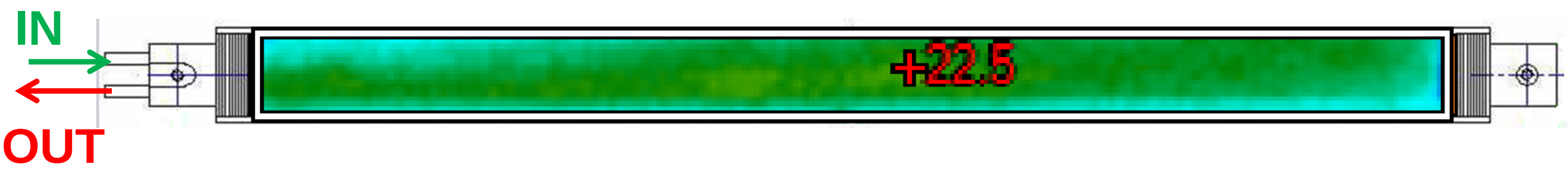
Inner Barrel: Nominal Cases

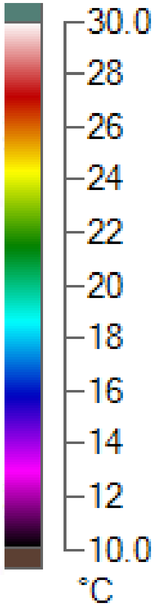
H_2O	q [W cm^{-2}]	G [L h^{-1}]	v_{H2O} [m s^{-1}]	$T_{Mean-H2O}$ [°C]	$T_{Mean-Chip}$ [°C]	ΔT_{H2O} [K]	Δp [bar]
K13 D2U 70 µm	**0.15**	3.0	1.0	16.2	18.6	1.4	0.3
	0.30	3.1	1.1	16.7	21.8	2.5	0.3

0.15 W cm^{-2}, 3.0 L h^{-1}

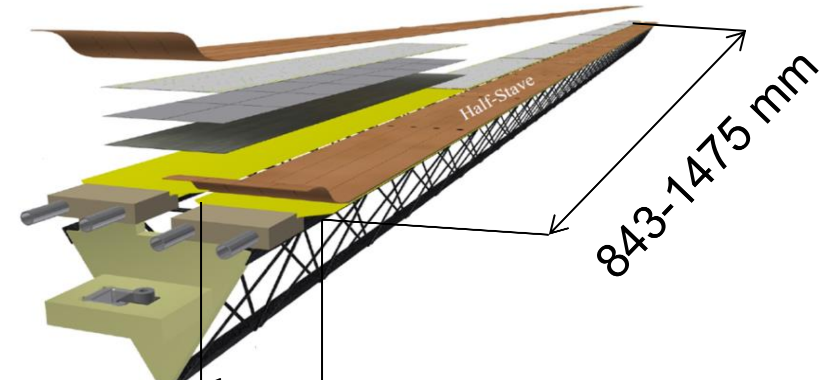


0.30 W cm^{-2}, 3.1 L h^{-1}



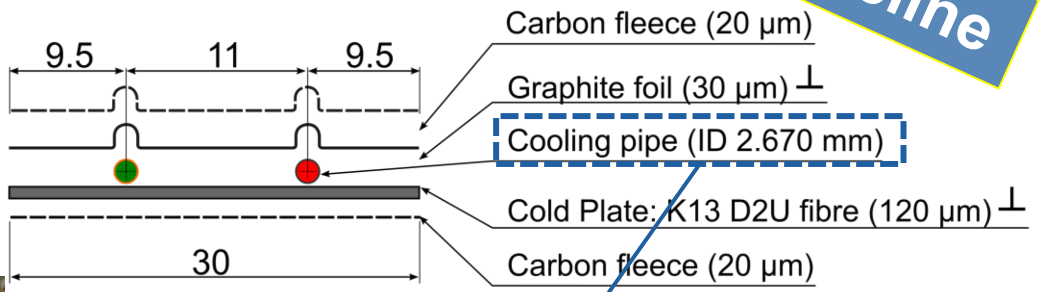


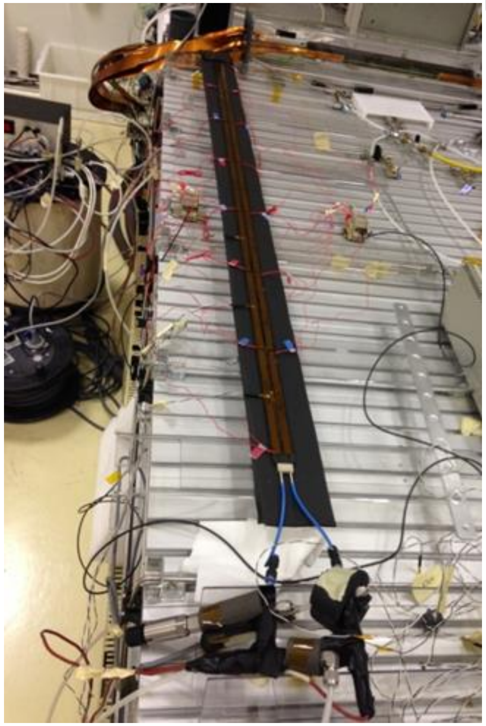
Outer Barrel: Stave Layup



HALF-STAVE SECTION

Baseline





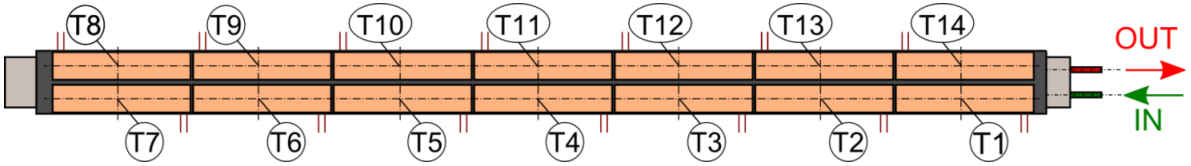
OPTIMIZED PIPE ID: ↓ to 2.05 mm

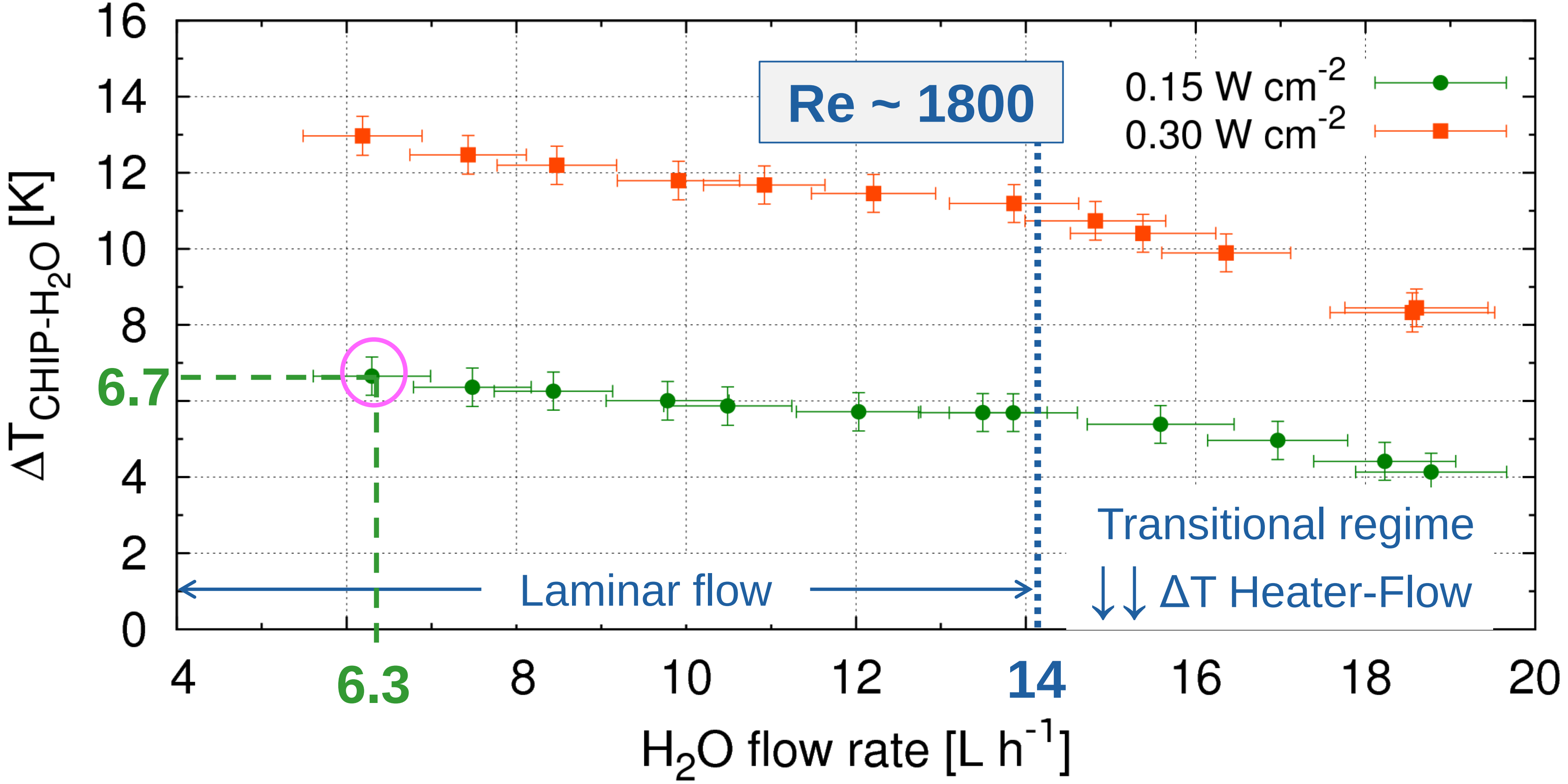
- Material budget decrease:
  - **x/X_0** half-stave decreases **22%**
- Same thermal performance

x/X_0=0.8% *(services included) [1]*

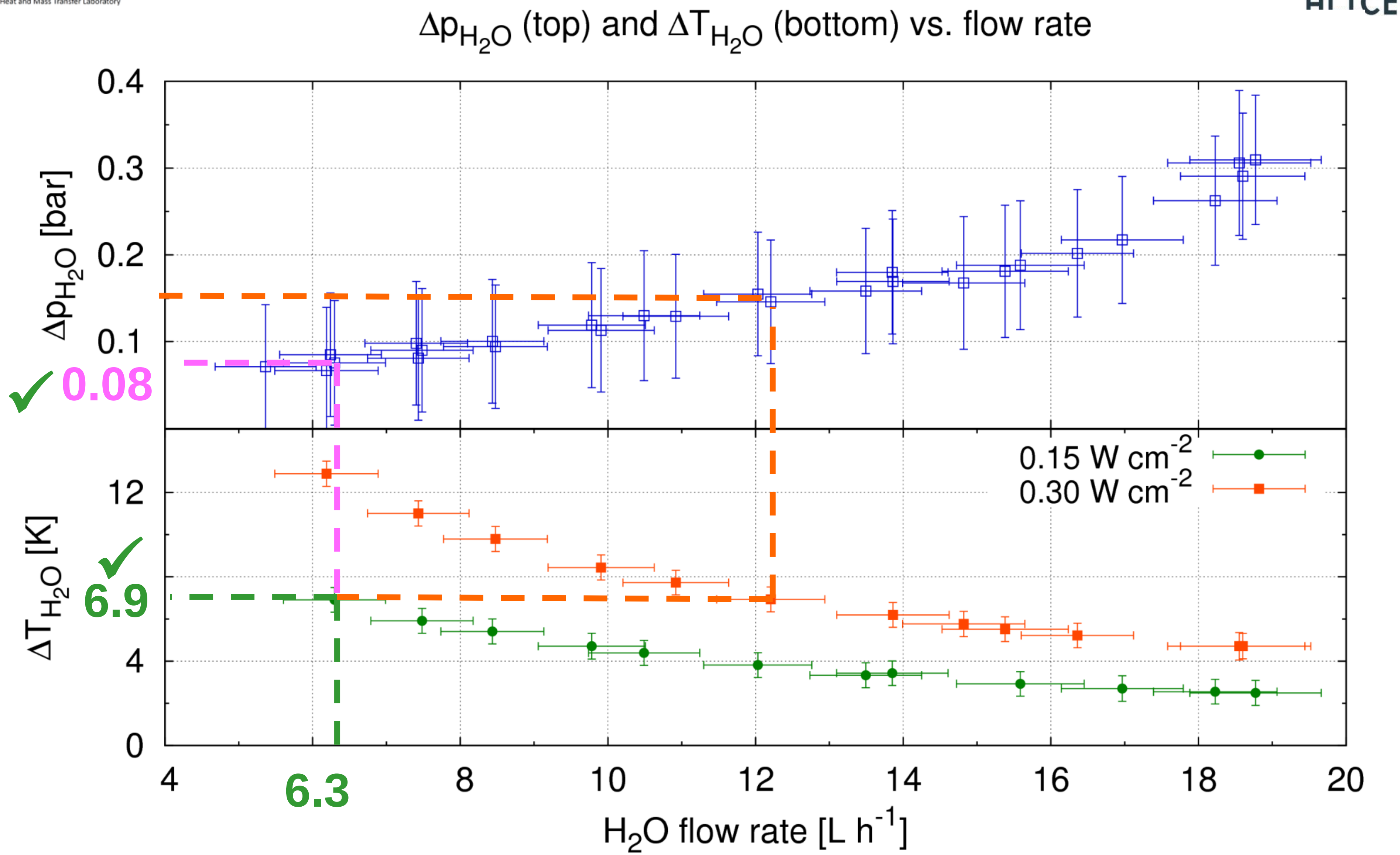
[1] Ref: ALICE ITS Upgrade TDR

$\Delta T_{CHIP\text{-}COOLANT}$

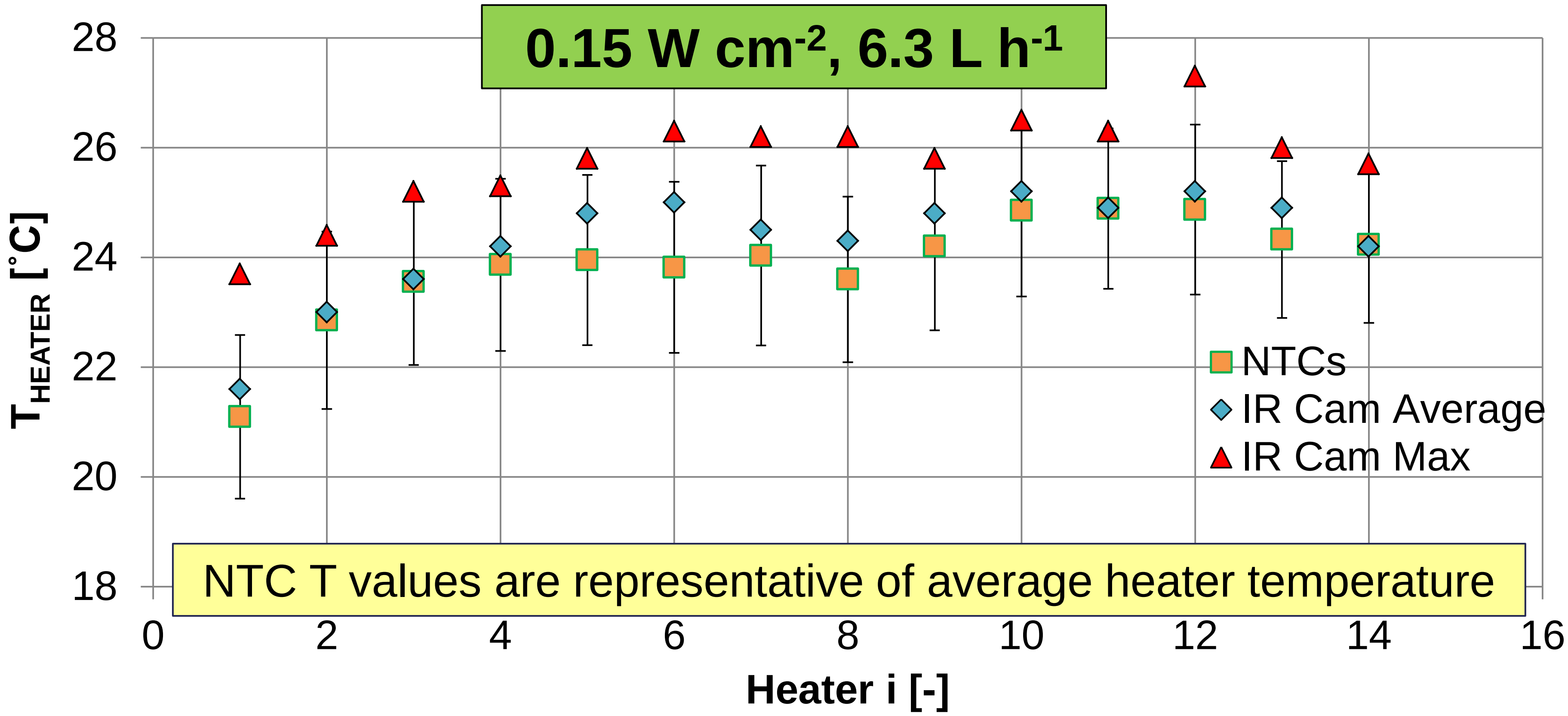




Refrigerant Δp and ΔT

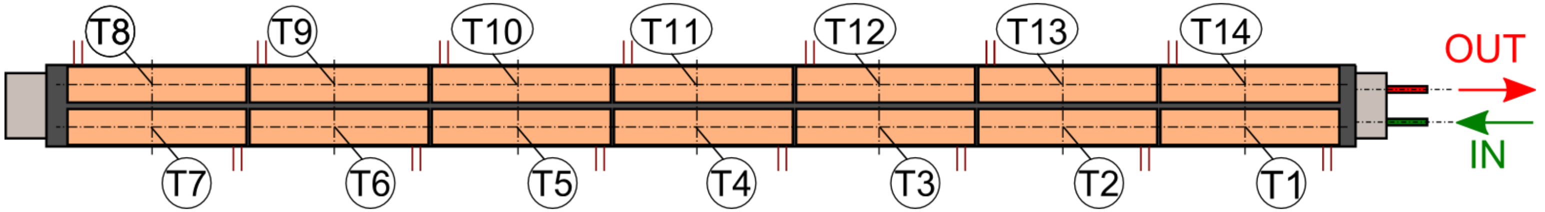


Outer Barrel stave: NTCs temperature vs. IR Camera



0.15 W cm^{-2}, 6.3 L h^{-1}

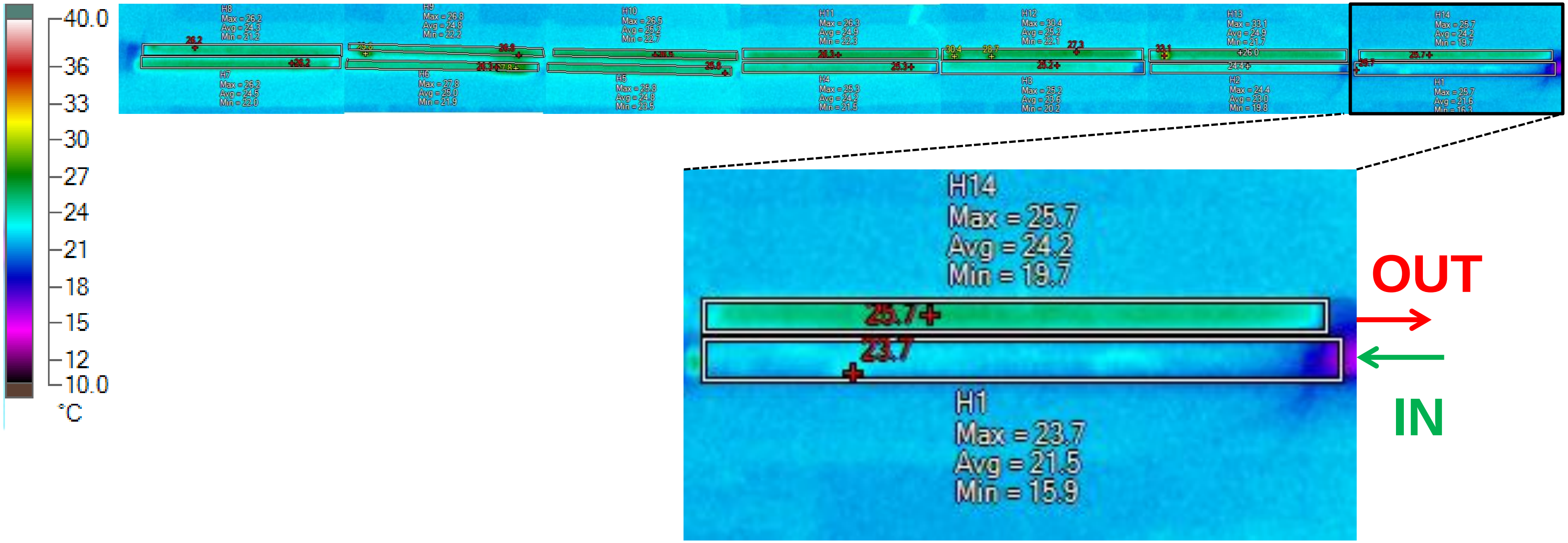
NTC T values are representative of average heater temperature



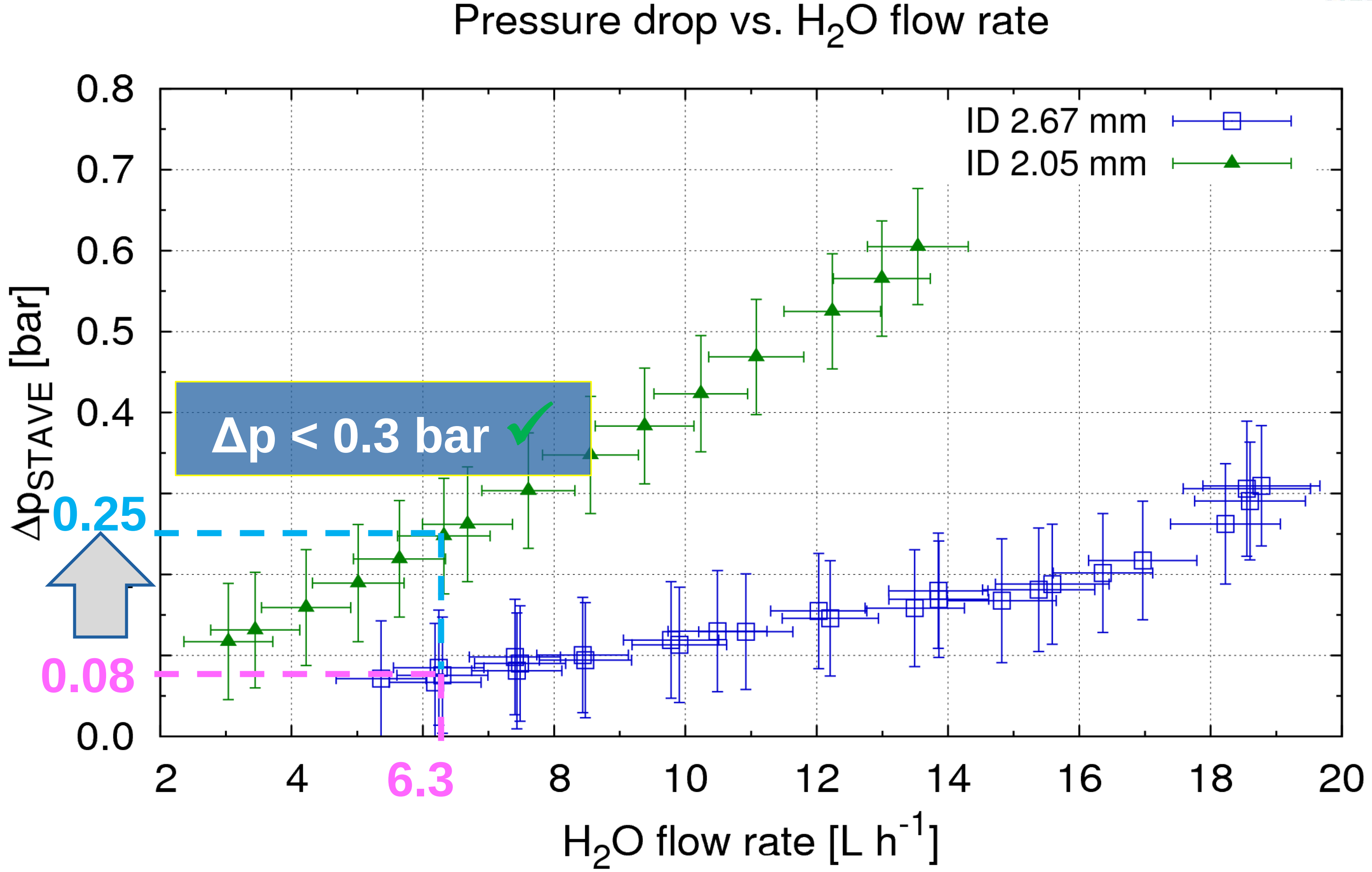
Nominal case: **0.15 W cm^{-2}**

H_2O	q [W cm^{-2}]	G [L h^{-1}]	v_{H2O} [m s^{-1}]	$T_{Mean-H2O}$ [°C]	$T_{Mean-Chip}$ [°C]	ΔT_{H2O} [K]	Δp [bar]
K13 D2U 120 µm	**0.15**	6.3	0.3	17.2	23.9	6.9	0.08

0.15 W cm^{-2}, 6.3 L h^{-1}



OB: pipe diameter optimization



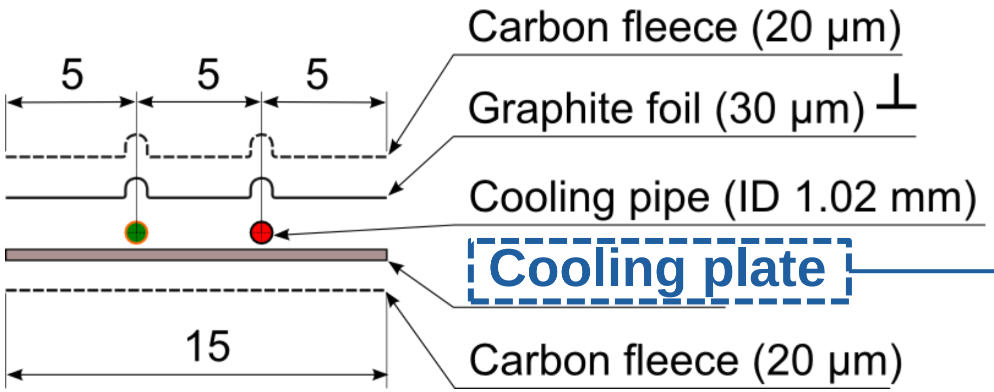
$\Delta p < 0.3$ bar ✓

Alternative Designs:
Inner Barrel

- ☐ Additional cooling plate layups
- ☐ Thermal performance with boiling C_4F_{10}
- ☐ $q<0.03$ W cm^{-2} peripheral stave cooling

Inner Barrel: Alternative Layups

STAVE SECTION



Carbon fleece (20 μm)

Graphite foil (30 μm) ⊥

Cooling pipe (ID 1.02 mm)

Cooling plate

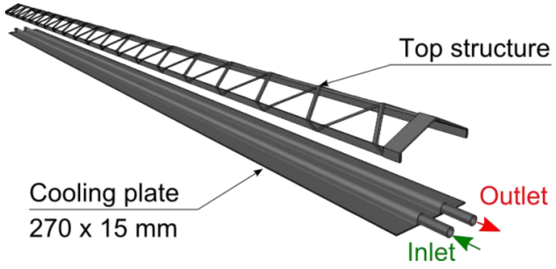
Carbon fleece (20 μm)

Baseline

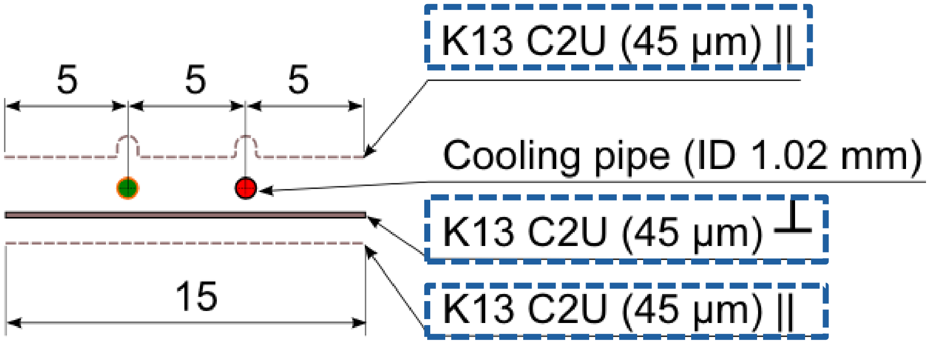
1. K13 D2U 70 μm ⊥
   - $k_{K13D2U} \sim 800\ W\ m^{-1}\ K^{-1}$

2. K1100-X 90 μm ⊥
   - $k_{K1100} \sim 1000\ W\ m^{-1}\ K^{-1}$

3 (alt). K13 C2U 45 μm x3
   - $k_{K13C2U} \sim 620\ W\ m^{-1}\ K^{-1}$



	H_2O	C_4F_{10}
1. K13 D2U 70 μm ⊥	✓	
2. K1100-X 90 μm ⊥	✓	✓
3. K13 C2U 45 μm x3	✓	



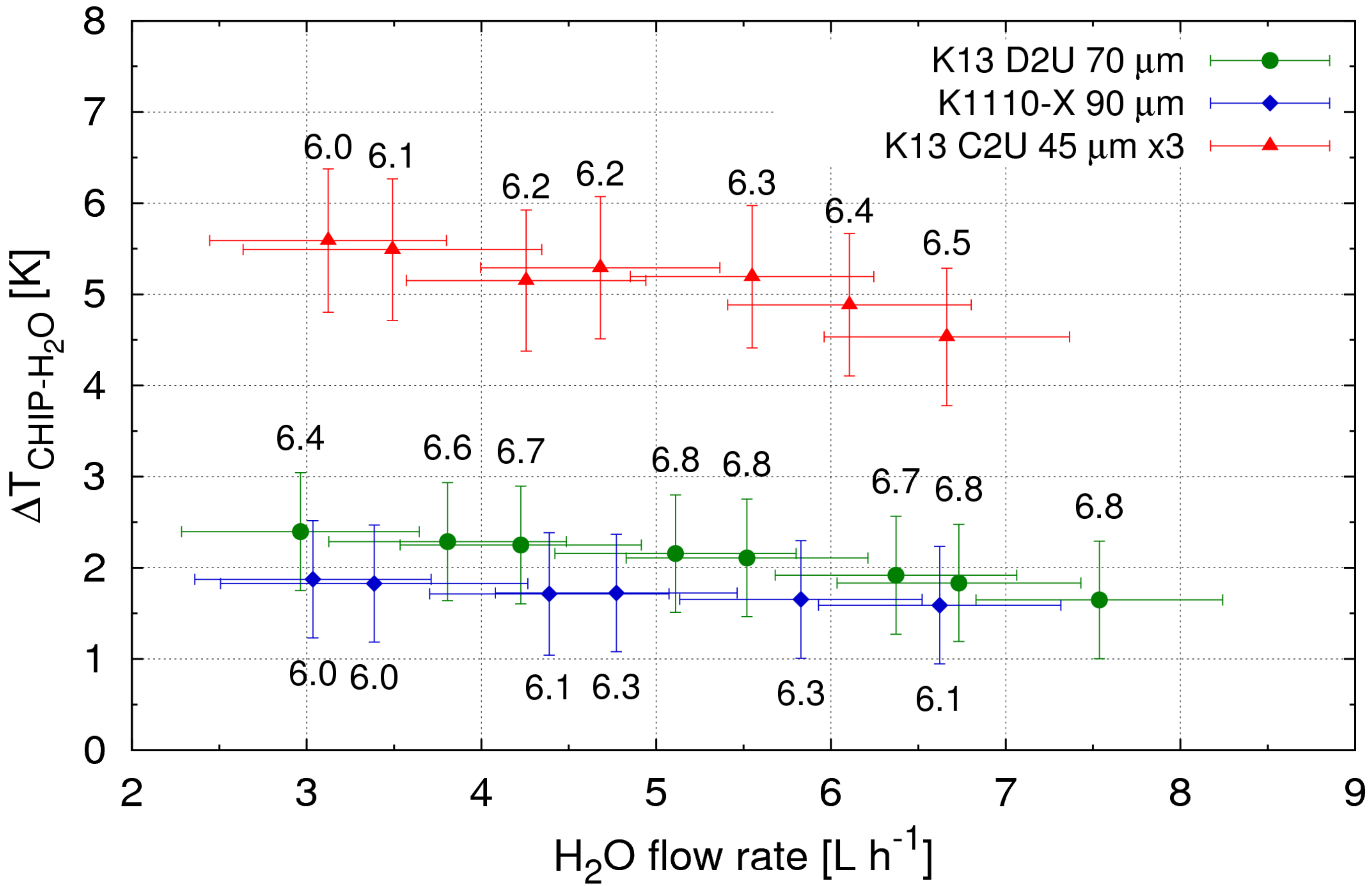
K13 C2U (45 μm) ||

Cooling pipe (ID 1.02 mm)

K13 C2U (45 μm) ⊥

K13 C2U (45 μm) ||

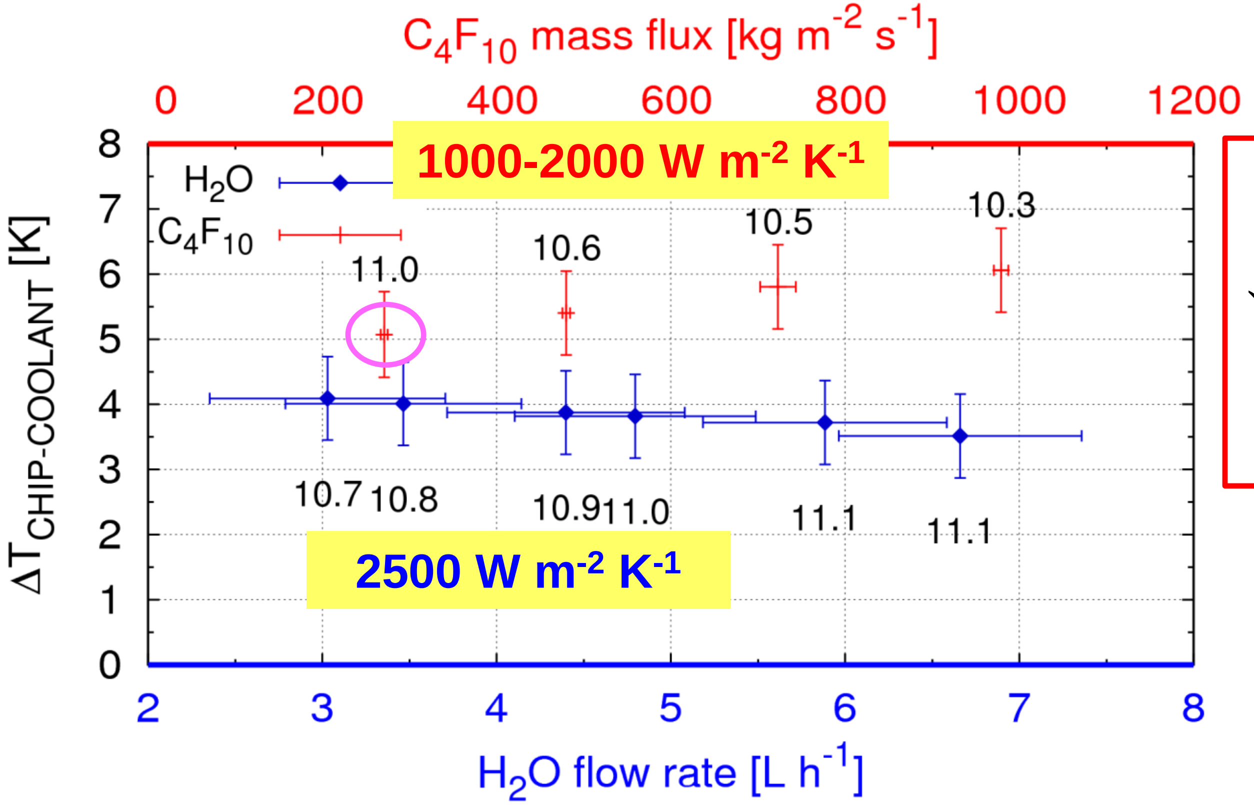
$\Delta T_{CHIP\text{-}COOLANT}$: 0.15 W cm^{-2}



Alternative Designs:
Inner Barrel

- ☐ Additional cooling plate layups
- ☐ Thermal performance with boiling C_4F_{10}
- ☐ $q<0.03$ W cm^{-2}: peripheral stave cooling

IB K1100-X 90 µm stave: C_4F_{10}



1000-2000 W m^{-2} K^{-1}

2500 W m^{-2} K^{-1}

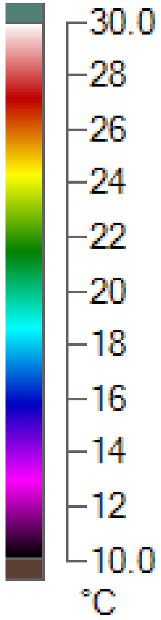
Boiling C_4F_{10}:

↓ x/X_0 cooling plate vs. H_2O of **12 %**

($\varepsilon = 0.84$) *[2]*

[2] G. Hewitt. Heat Exchanger Design Handbook 2002

G [kg m^{-2} s^{-1}]	Δp [bar]	ΔT_{C4F10} [K]	T_{C4F10} [°C]	T_{Chip} [°C]	x_{In} [-]	x_{Out} [-]
271	0.29	3.1	13.9	19.0	0.14	0.40

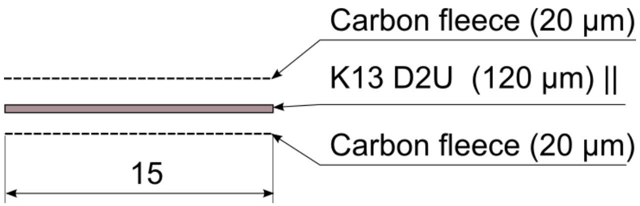


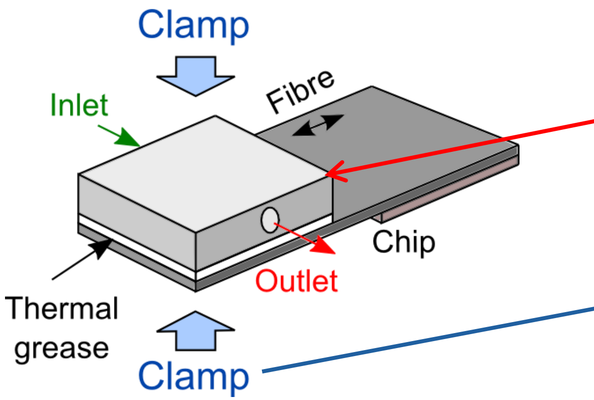
Alternative Designs:
Inner Barrel

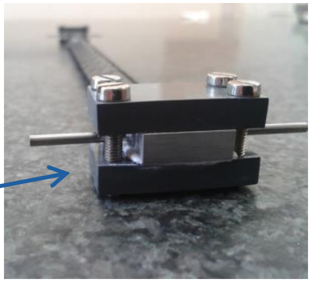
- ☐ Additional cooling plate layups
- ☐ Thermal performance with boiling C_4F_{10}
- ☐ $q < 0.03$ W cm^{-2}: peripheral stave cooling

Inner Barrel: peripheral cooling

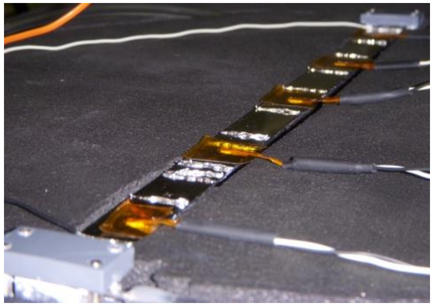
If $q < 0.03\ \mathrm{W\ cm^{-2}}$: cool from extremities of stave without on-stave tubing

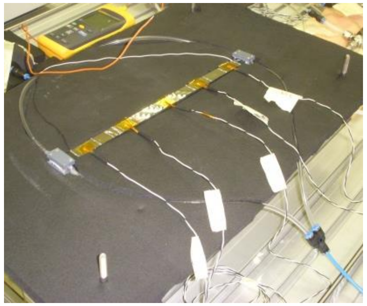


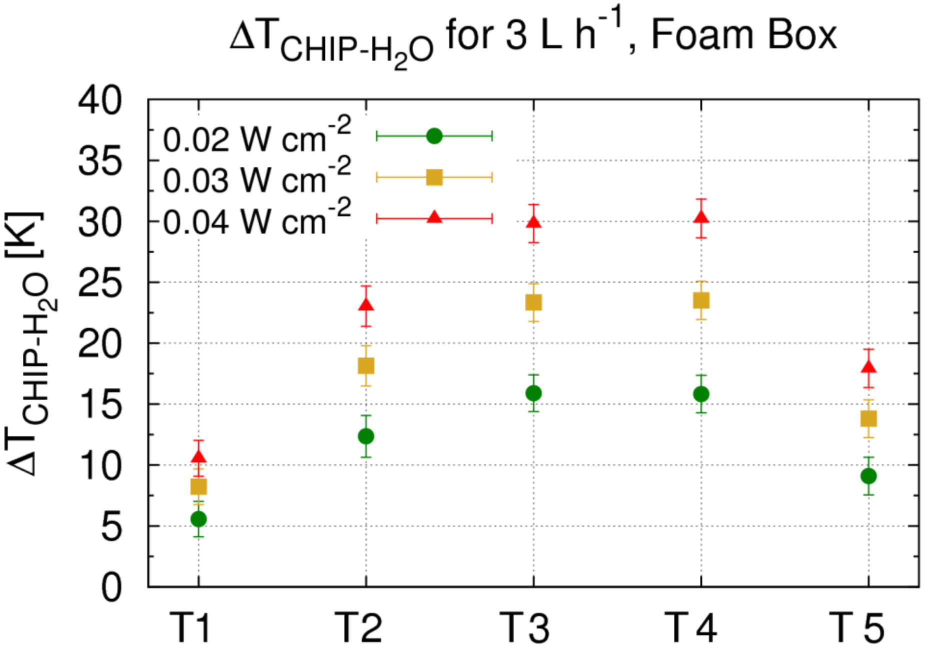




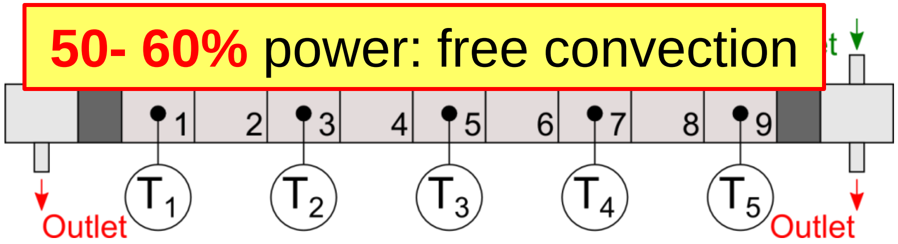
↓ x/X_0 vs. Baseline, H_2O of 32 %







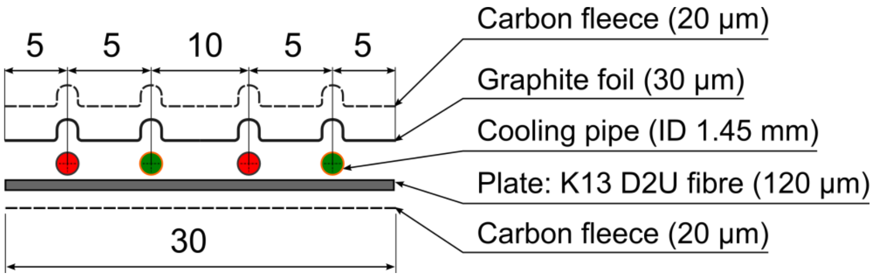
50- 60% power: free convection



Alternative Design:
Outer Barrel

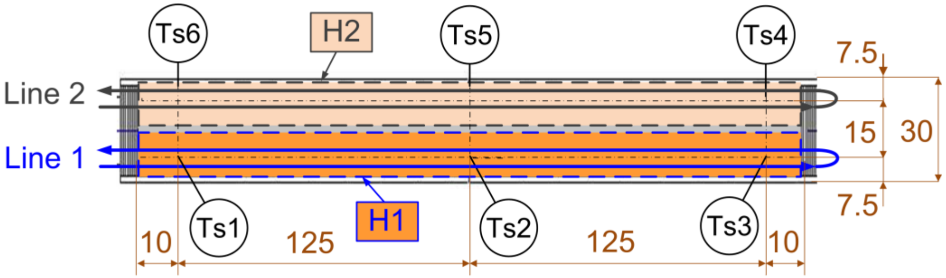
☐ 4-pipe half-stave layup

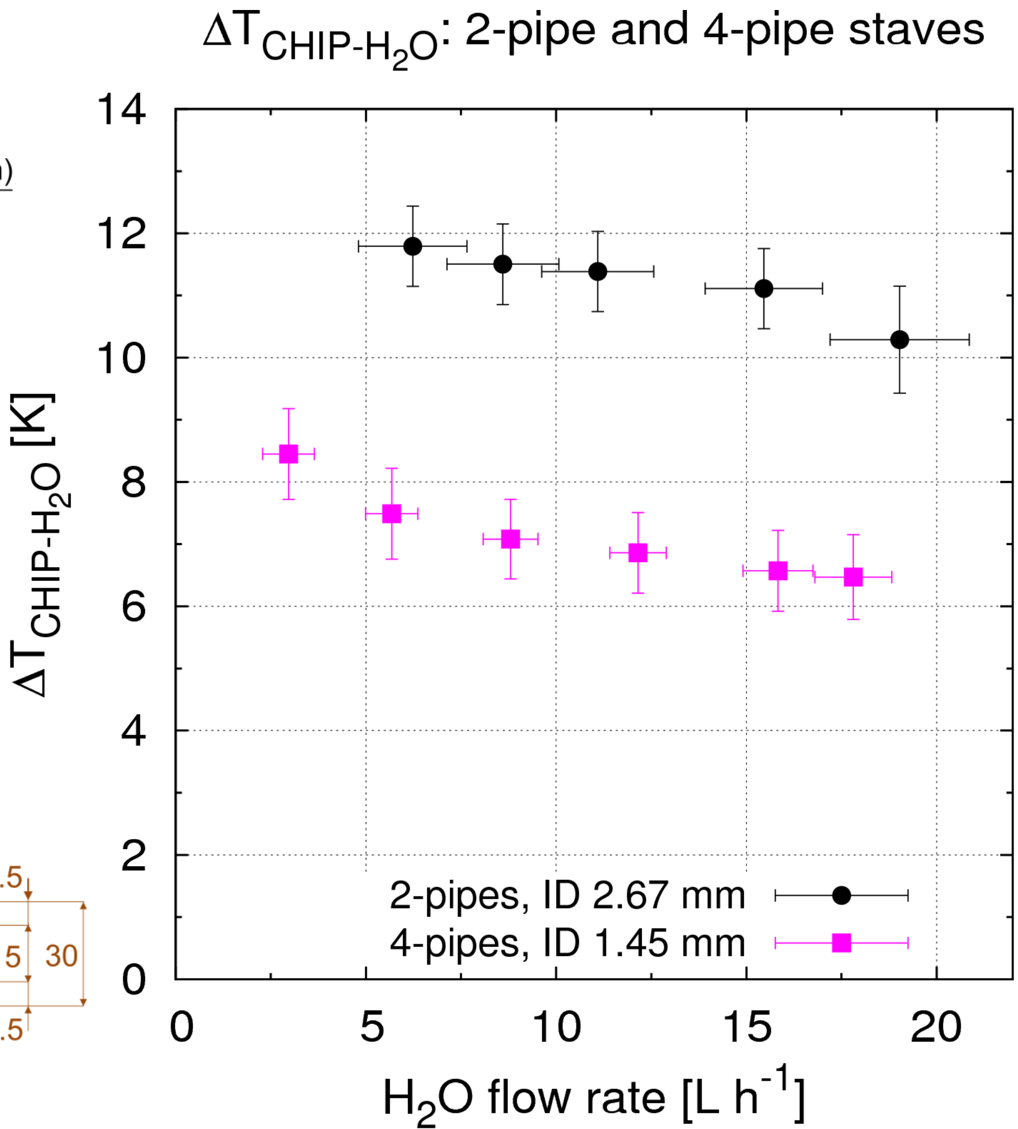
Outer Barrel: 4-pipe layup



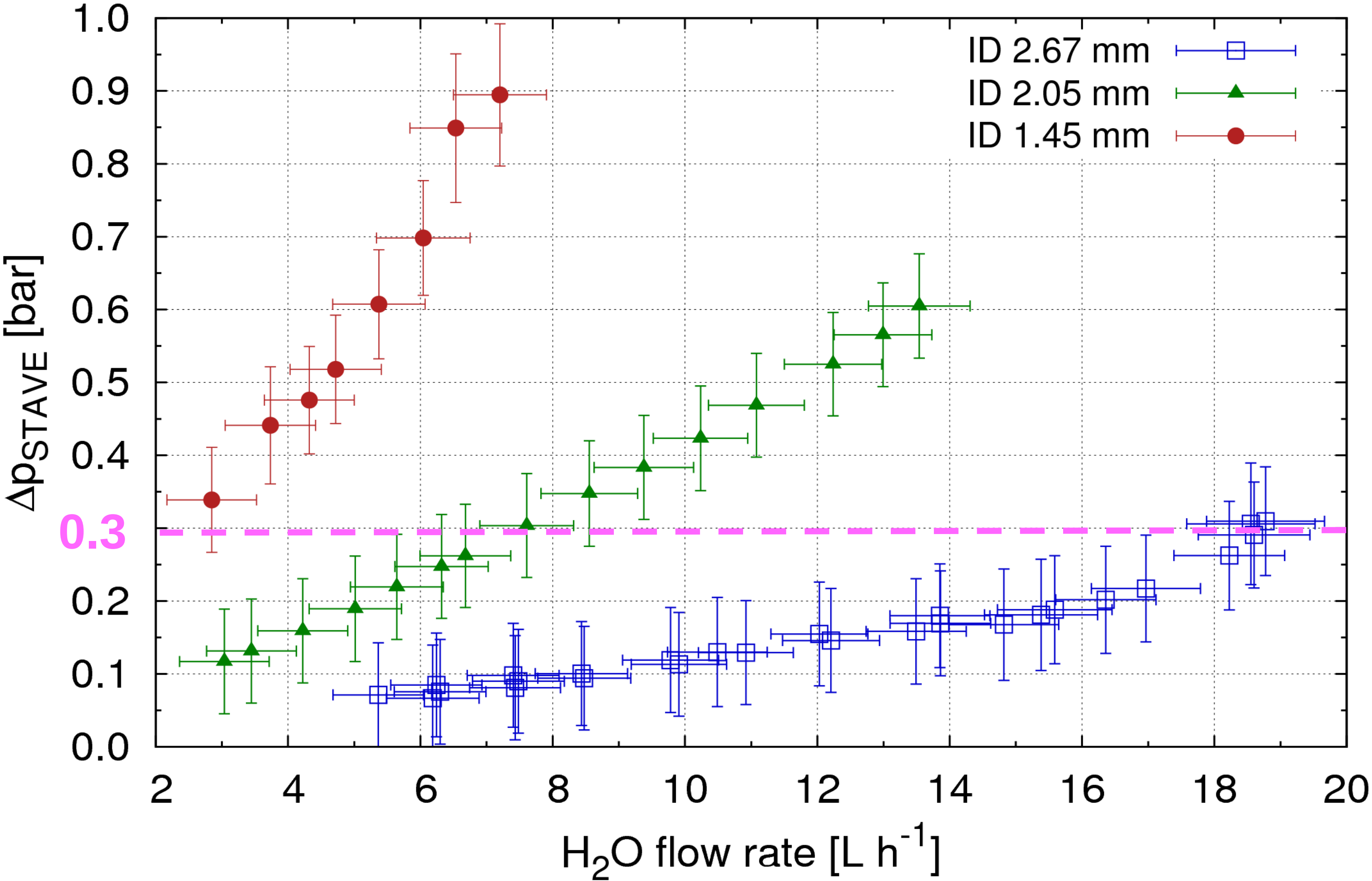
- ✓ Better thermal performance
- ✓ Lower x/X_0
- ✓ Better x/X_0 uniformity

- – Higher pressure drop
- – Complexity (double piping)





Pressure drop comparison



Conclusions

- Lightweight cooling systems for ITS Inner & Outer Barrel modules thermally characterized:
  - ✓ Innovative solutions: plastic tubing & carbon fibre composites.
  - ✓ Structural robustness at low mass (1.4 g for Inner Barrel stave).
  - ✓ Low material budget: x/X_0 < limits per layer.
  - ✓ $\Delta T_{HEATER\text{-}REFR} < 7$ K at 0.15 W cm^{-2} power density.
  - ✓ Robustness: open choice for coolant & flow rate.

- Several architecture & layups experimentally tested:
  - ✓ Better understanding of material behaviour.
  - ✓ Alternatives in case of change of requirements.

Thank you

Acknowledgements:

CERN EN-CV Group.

ALICE Collaboration.

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M. Battistin and C. Gargiulo (CERN).

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European Centre for Nuclear Research (CERN), Geneva, CH
LTCM, École Polytechnique Fédérale de Lausanne (EPFL)

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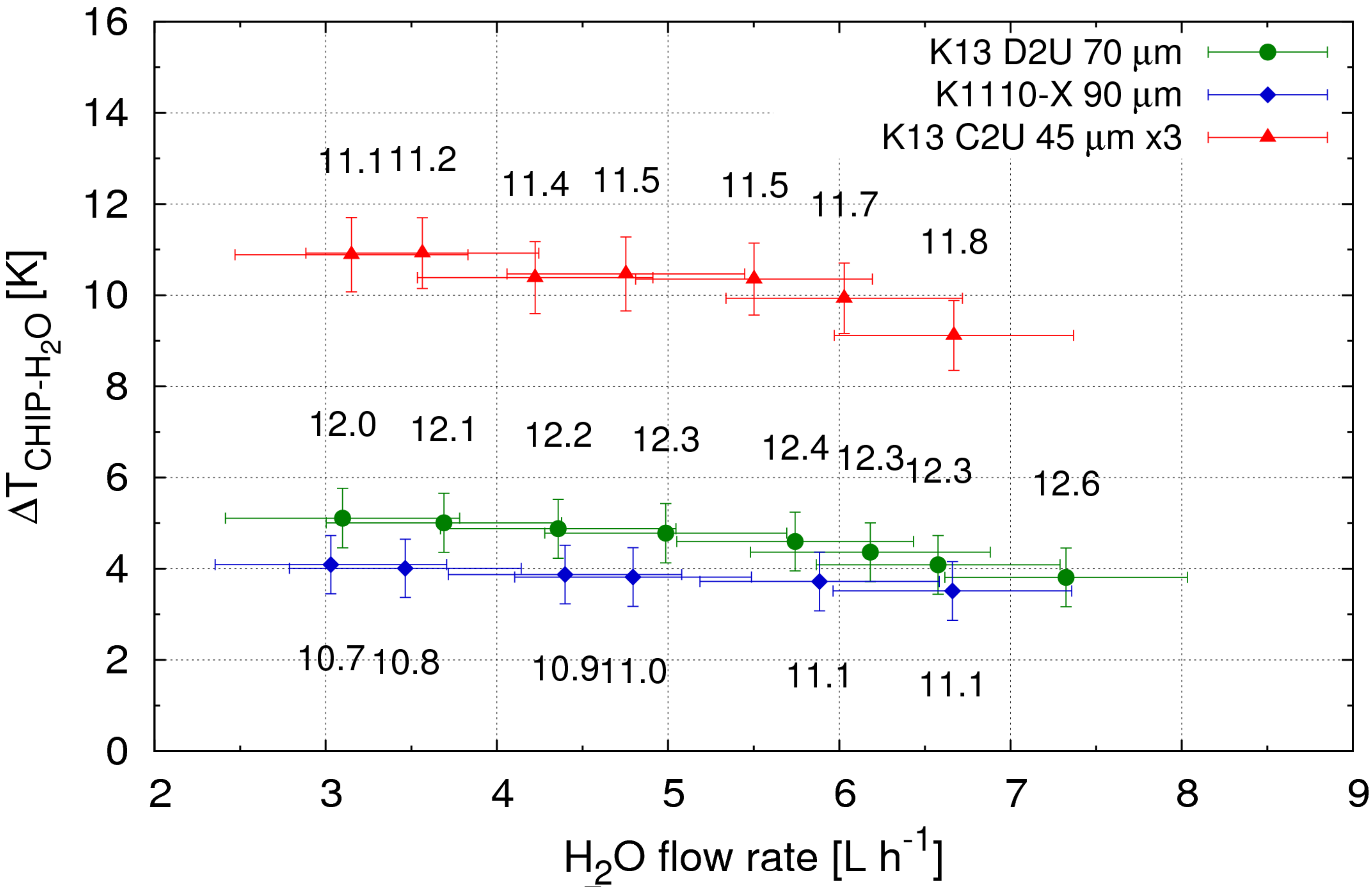
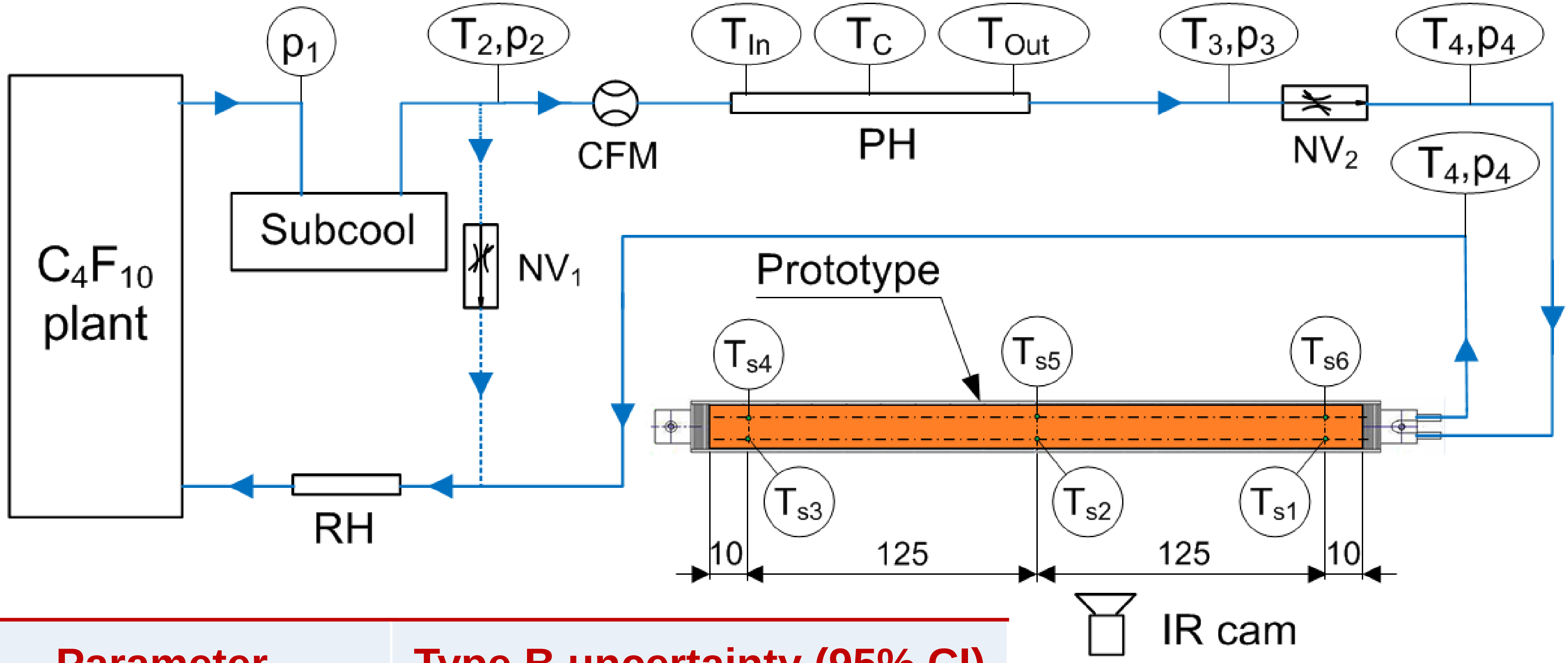
Backup

IB: $\Delta T_{CHIP\text{-}COOLANT}$ (0.30 W cm^{-2})



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

Boiling C_4F_{10}: parameters

1. Mass flow rate:

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

Assumptions

$$\Delta x_{IN\text{-}OUT} = 0.40$$

$$T_{REFRIGERANT} = 15°C$$

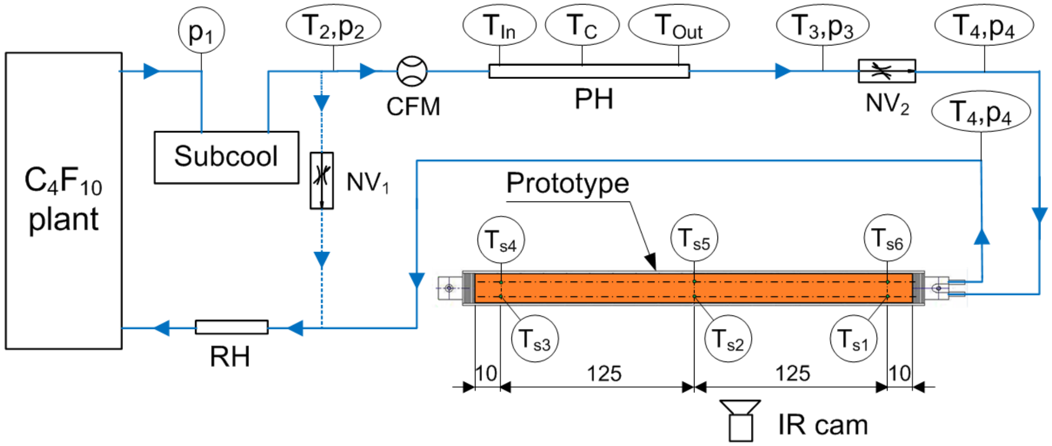
Power density q [W cm^{-2}]	Mass flow rate $\dot{m}$ [g s^{-1}]
0.3	0.29
0.5	0.55

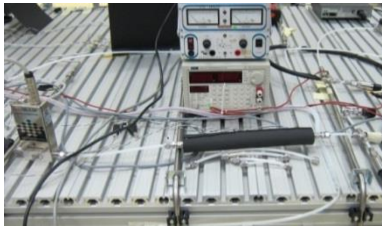
2. Vapour quality

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

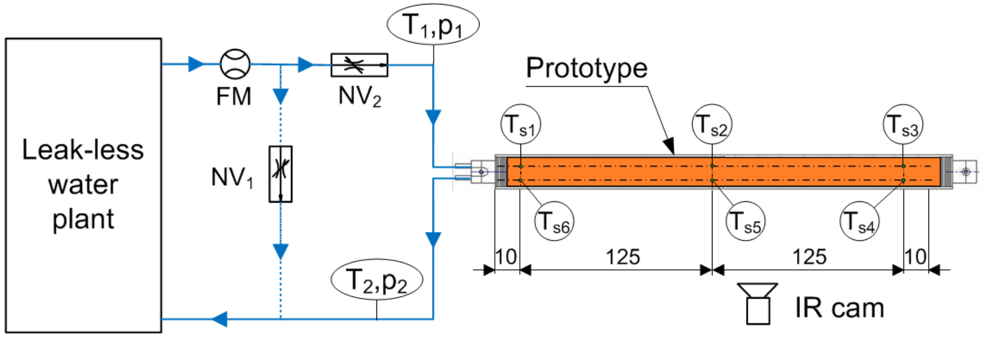
Experimental Facility

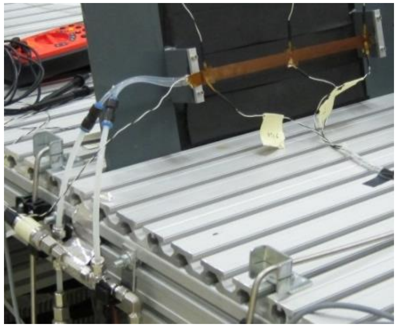
C_4F_{10} Loop



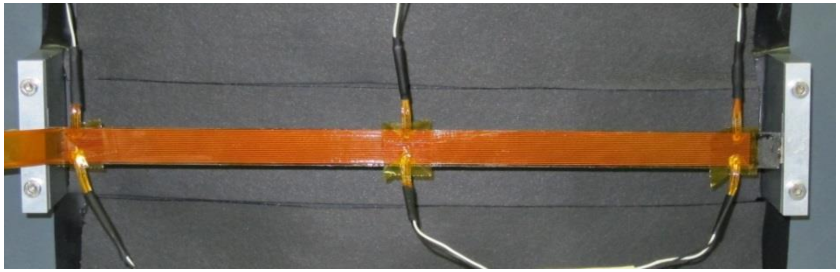


H_2O Loop



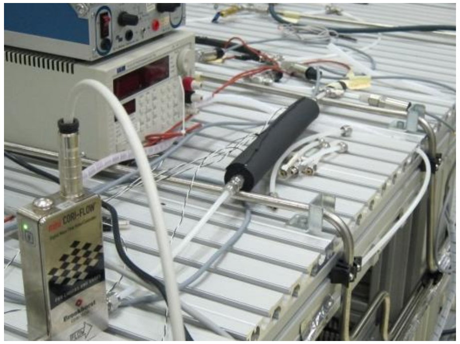


Experimental Facility

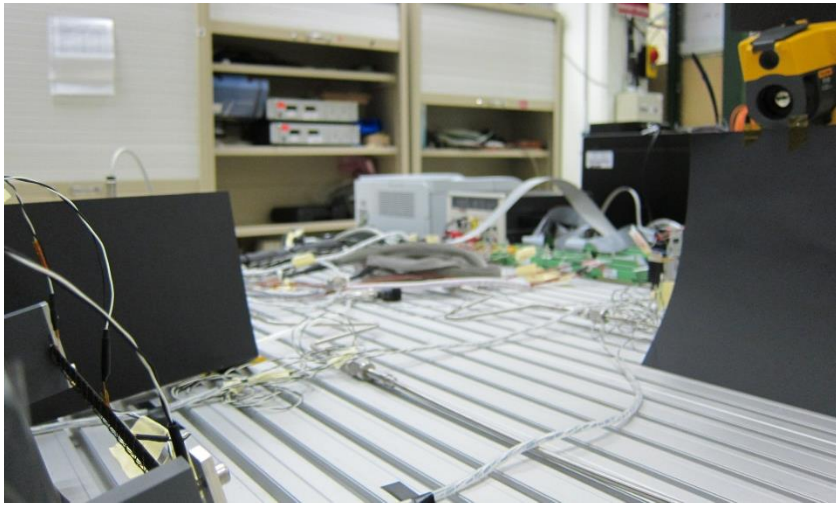


Stave view as from the IR camera.

Inner Barrel prototype.



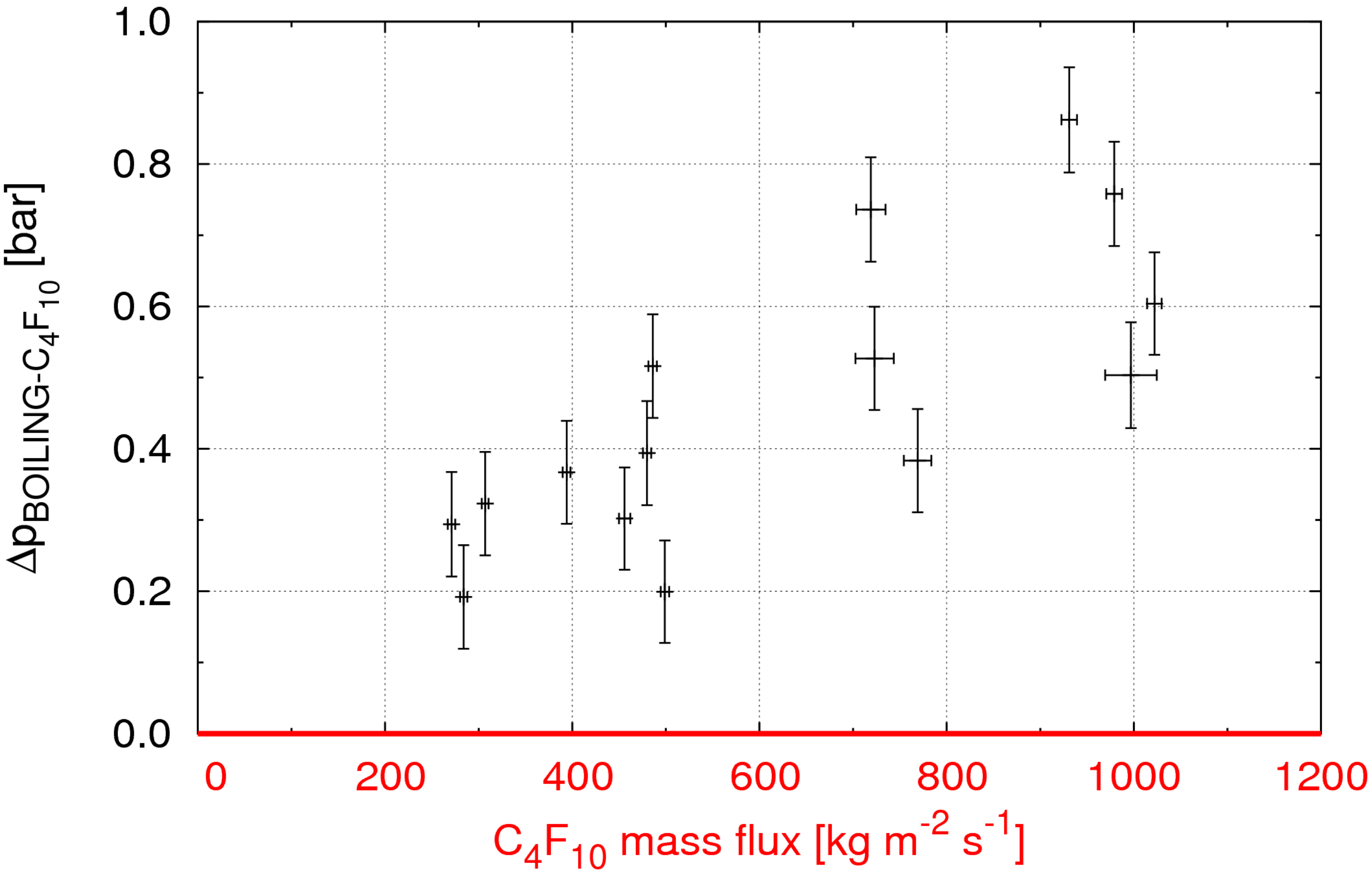
Leak-less water plant.



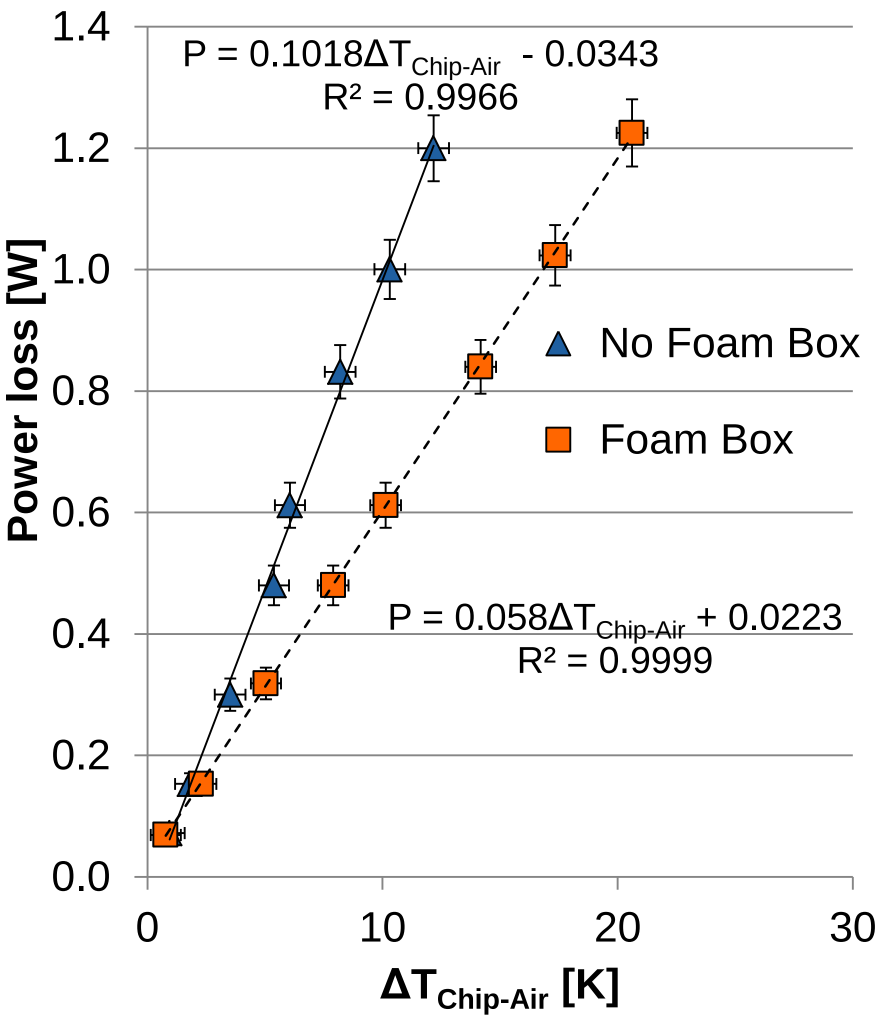
Stave test setup.

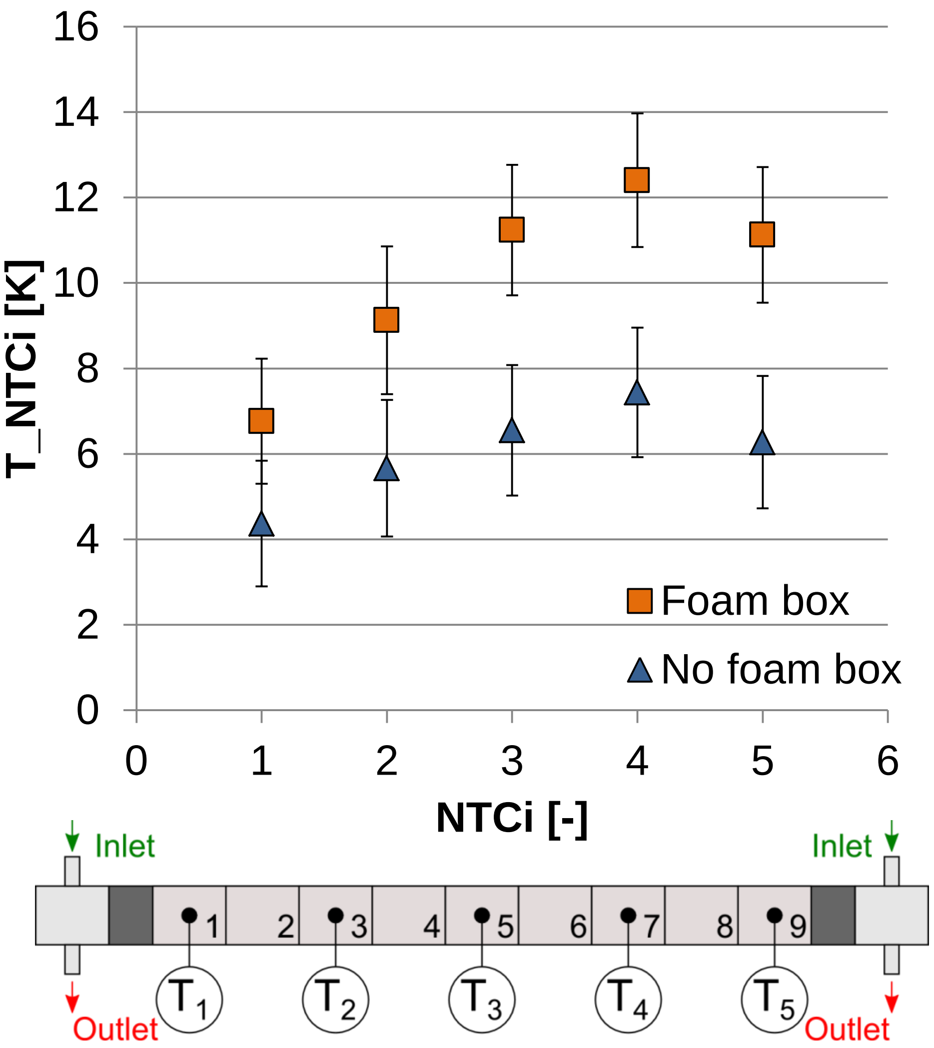
C_4F_{10} loop and plant.

Boiling C_4F_{10}: pressure drop



Heat exchange with air

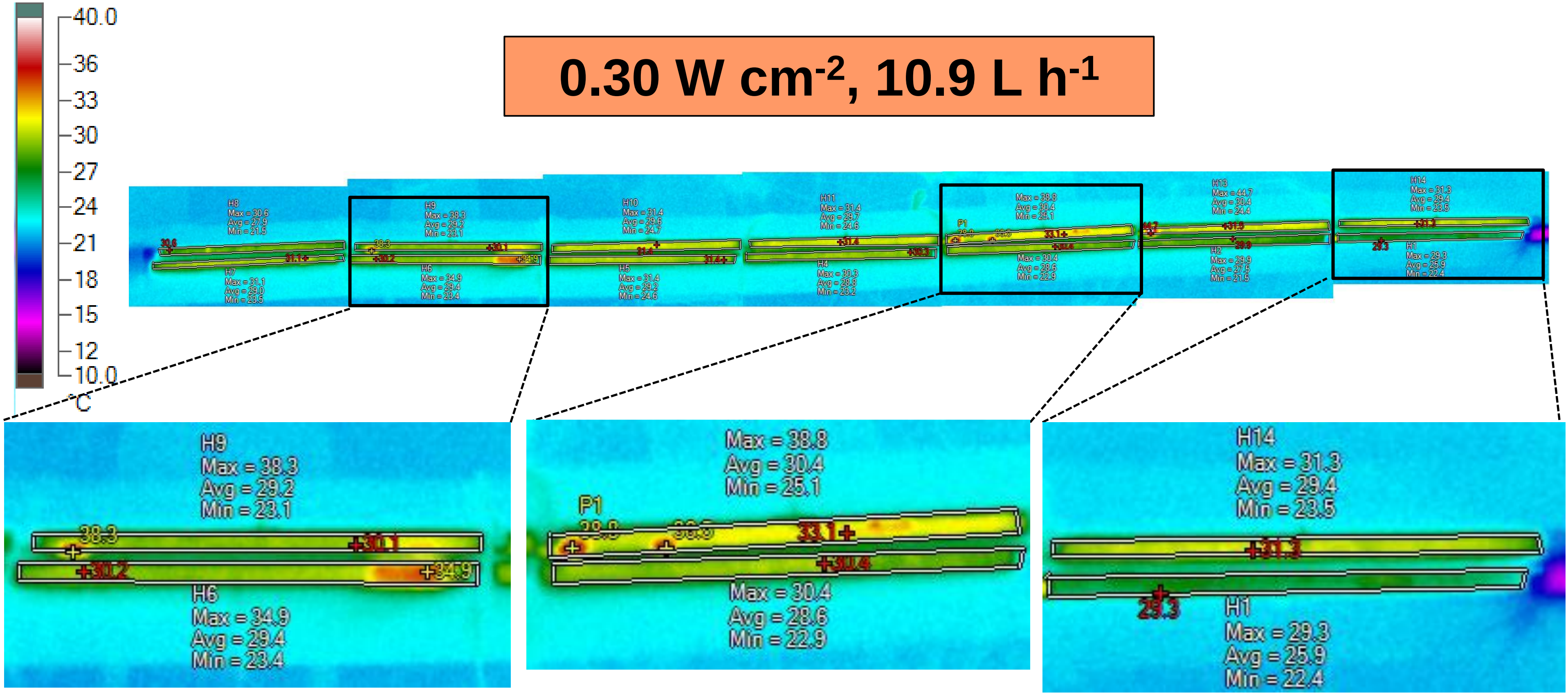

Heat load dissipated to air


NTC values for 0.60 W input

Nominal case: **0.30 W cm^{-2}**

H_2O	q [W cm^{-2}]	G [L h^{-1}]	v_{H2O} [m s^{-1}]	$T_{Mean-H2O}$ [°C]	$T_{Mean-Chip}$ [°C]	ΔT_{H2O} [K]	Δp [bar]
K13 D2U 120 µm	**0.30**	10.9	0.5	16.9	28.6	7.7	0.13

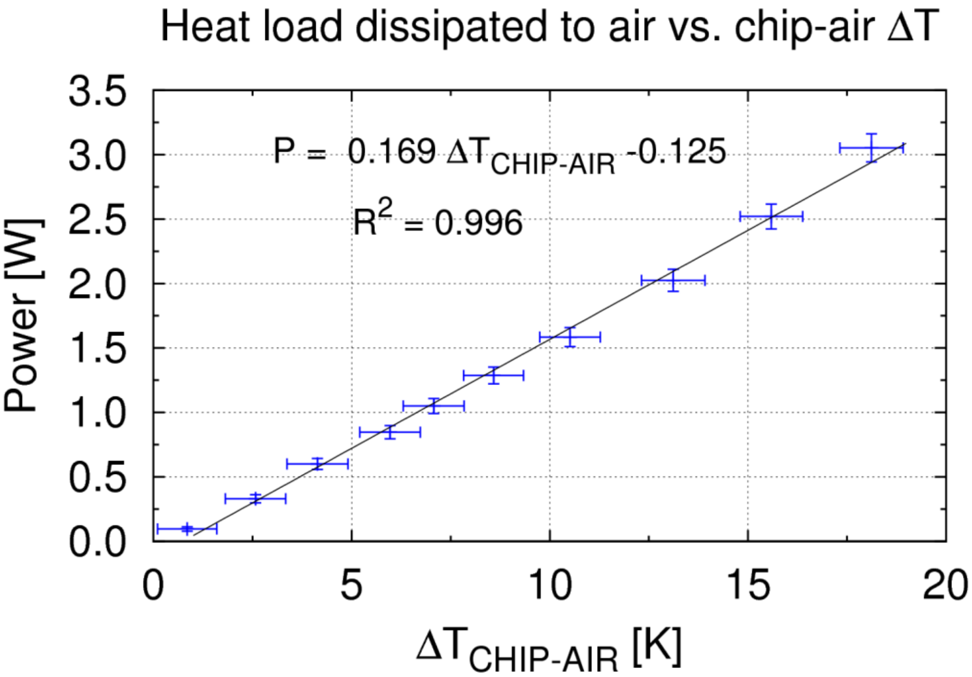
0.30 W cm^{-2}, 10.9 L h^{-1}



No-Flow Tests

Procedure:

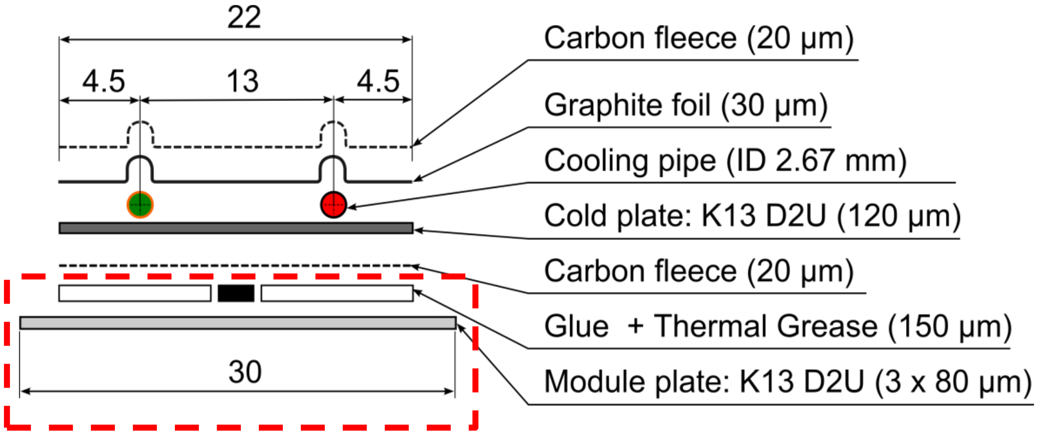
1. Apply low power and record the average stave temperature.
2. Correlate power dissipated to air vs. average stave temperature.
3. When cooling the stave with full power, the power dissipated/absorbed to/from air can be estimated.



Material Benchmarking

Material	Type	Uses	Characteristics
K13D2U-2k	CF prepreg	Mechanical structure High-Conductivity Plate	$\lambda_{eff} \sim 450\ \mathrm{W\ m^{-1}\ K^{-1}}$
K1100 Thornel		High-Conductivity Plate	$\lambda_{fibre} \sim 800\ \mathrm{W\ m^{-1}\ K^{-1}}$
FGS003	Graphite foil	Enhance thermal contact	$\lambda_{High} > 1000\ \mathrm{W\ m^{-1}\ K^{-1}}$
Polyimide	Polymer	Tubes Bends (research ongoing)	Robust $X_0 = 29$ cm
PEEK	Polymer	Enclosures Tubes Connectors	Robust Not very flexible Thick wall $X_0 = 31.5$ cm

Outer Barrel: 2 pipe narrow plate



Carbon fleece (20 μm)

Graphite foil (30 μm)

Cooling pipe (ID 2.67 mm)

Cold plate: K13 D2U (120 μm)

Carbon fleece (20 μm)

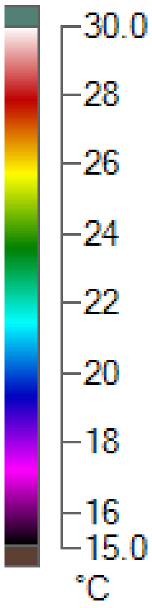
Glue + Thermal Grease (150 μm)

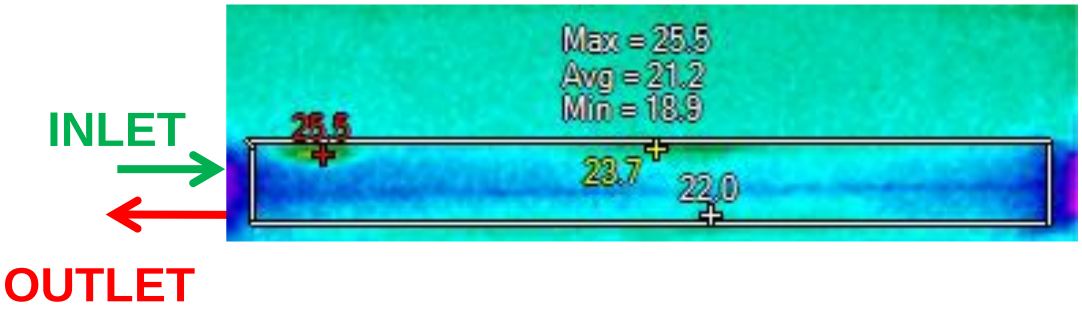
Module plate: K13 D2U (3 x 80 μm)

- ✓ Good thermal performance
- ✓ Lower material budget than equivalent full-width design
- – Needs conductive module plate
- – Thermal contact is critical

H_2O

q [W cm^{-2}]	G [L h^{-1}]	v_{H2O} [m s^{-1}]	$T_{Mean-H2O}$ [°C]	$T_{Mean-Chip}$ [°C]	ΔT_{H2O} [K]	Δp* [bar]
0.15	5.8	0.3	15.2	20.0	1.6	0.07





* Predicted for a 1.5 m long half-stave (thermal test on short prototype)

$\Delta T_{\text{CHIP-COOLANT}}$: 0.30 W cm^{-2}