Innovative Lightweight Cooling Systems for the Upgrade of the Inner Tracker System (ITS) of the ALICE Experiment at CERN

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In collaboration with the ALICE ITS Upgrade Project

Introduction

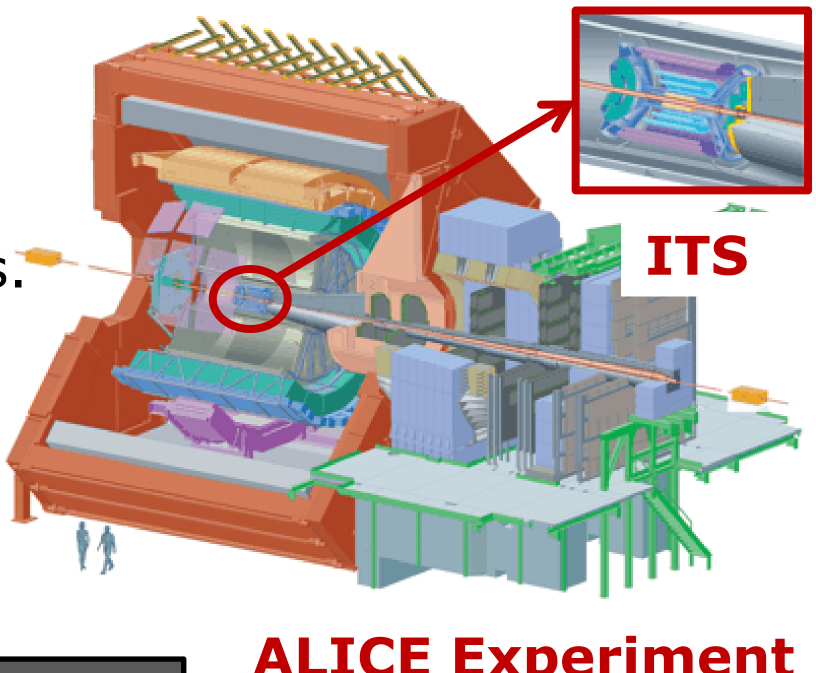
- ALICE: experiment at CERN LHC.
- ITS Upgrade Project: replace Inner Tracker System.
  - **Goal:** design & implementation of new cooling system.

PROJECT SCHEDULE

2012-2014 **R&D phase**

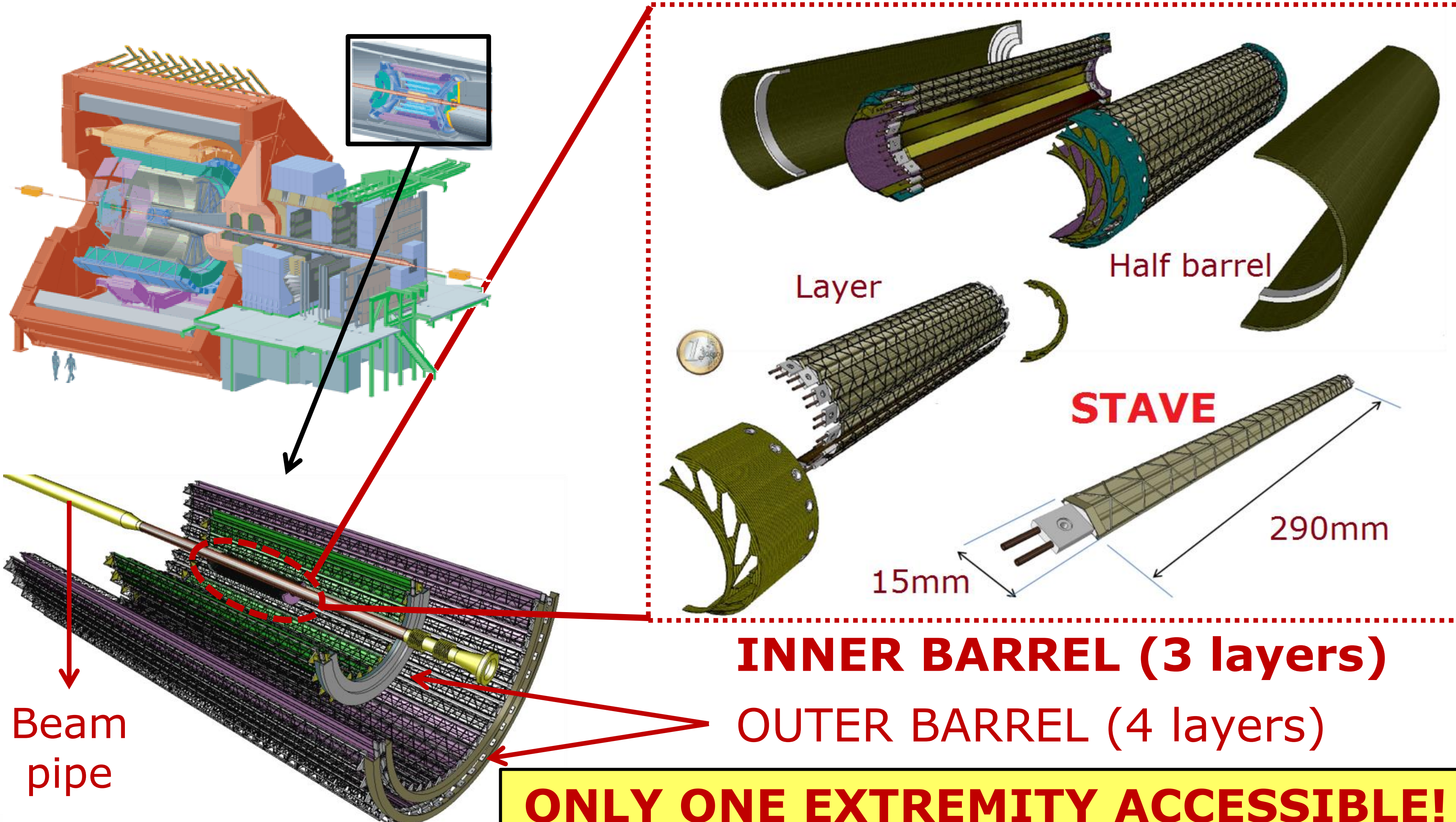
- **2012** Study technology proposals.
- **2013** Selection of technologies. Qualification studies.
- **2014** Final design and validation. Integration & final testing.

2015-2018 **Construction and Installation**



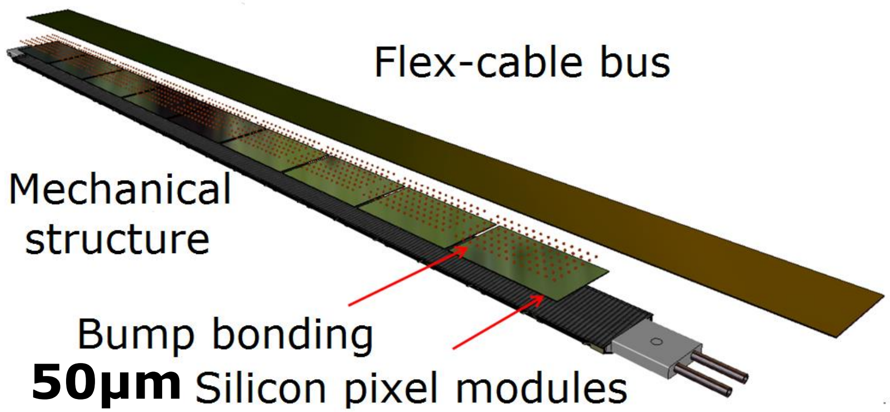
Introduction

Inner Tracker System (ITS): two-barrel, 7-layer structure



ONLY ONE EXTREMITY ACCESSIBLE!

Introduction

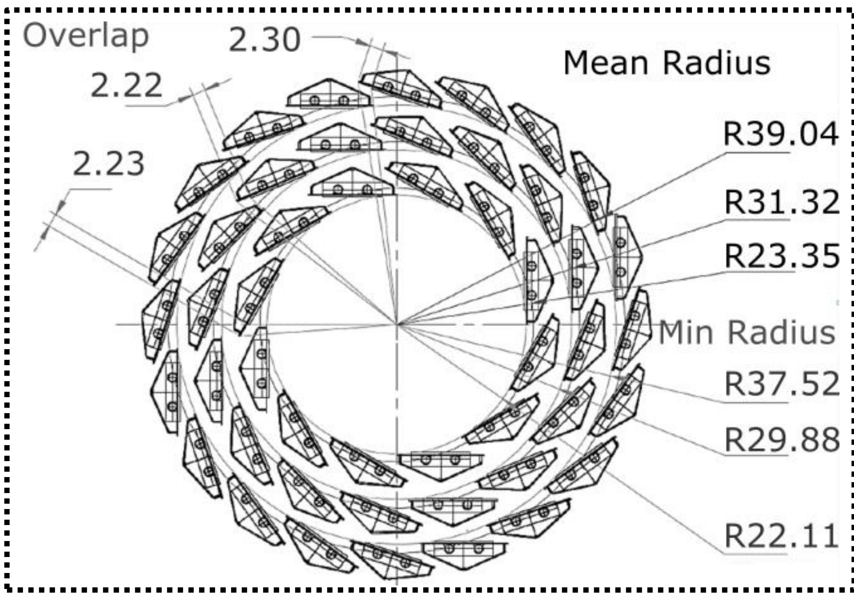


*Detector module: **STAVE***

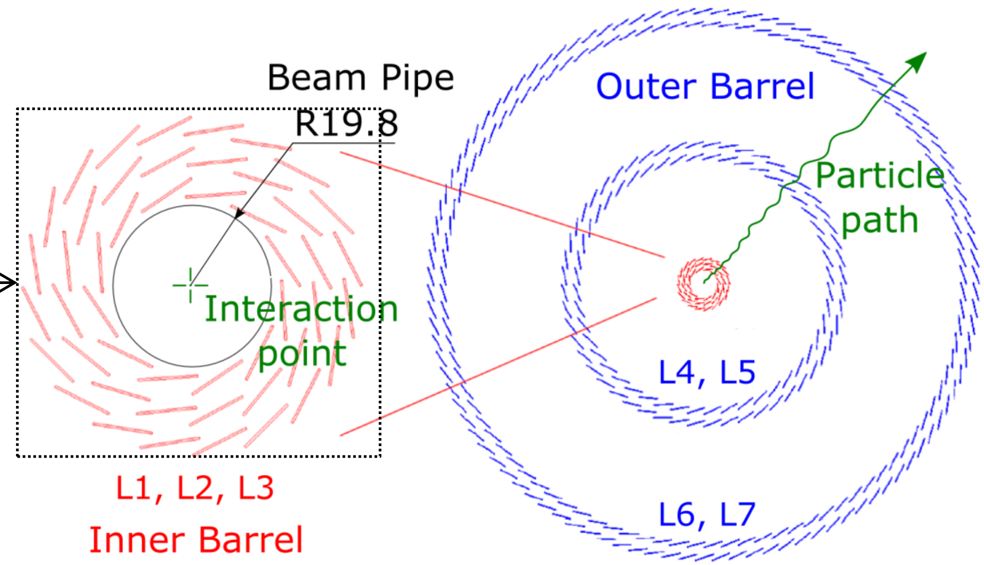
Charged and neutral particles cross pixel modules, leaving:

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

radiation damage → **energy loss**



Inner Barrel geometrical constraints.



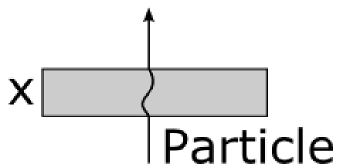
Full ITS sectional view.

Introduction

Stave mechanical/cooling design:

1. **Power dissipation =** f(pixel technology, electronics, read-out,…)
2. **Operational temperature** and **uniformity.**
3. **Minimize material budget:** critical in detector design.

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



;

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

Parameters	Inner Barrel	Outer Barrel
Power density to dissipate [W cm^{-2}]	≈ 0.40	≈ 0.40
Total material budget per layer [% of X_0]	≤ 0.30	≤ 0.80
Operation temperature [ºC]	< 30 (dew point: 13°C)	
Pixel max. temperature non-uniformity [K]	≈10	

Project Objectives

Innovative Lightweight Cooling Systems for the Upgrade of the Inner Tracker System (ITS) of the ALICE Experiment at CERN

- Study, develop, qualify and integrate ITS Upgrade cooling system.
- R&D on minimal material budget detector cooling technologies.
  - High-conductivity, light-weight materials.
  - Plastic piping for cooling.
  - Impact of material budget fluctuation of a two-phase flow.
- Provide ALICE ITS Upgrade with a lightweight cooling system as project final deliverable.

State of the Art

Cooling systems in high-energy particle detectors

System	Solution	Detector	Limitations
Air Cooling	High-conductive structure as cooling ducts	STAR	Low power dissipation Vibrations
Single-phase liquid cooling	Cooling pipe + carbon foam	IBL Outer layers Present ITS outer layers	$\uparrow x/X_0$ Leakless (water)
	Polyimide microchannels	ITS Upgrade	$\uparrow \Delta p$
Two-phase flow cooling	Channel	ATLAS I. Det.	Flow distribution
	Channel CO_2	ATLAS/CMS Upgrades	Low temperatures
	Heat pipes	ATLAS Pixel (proposal)	Integration $\uparrow x/X_0$
	Si microchannels	ITS Upgrade	$\uparrow x/X_0$ Stave integration

State of the Art

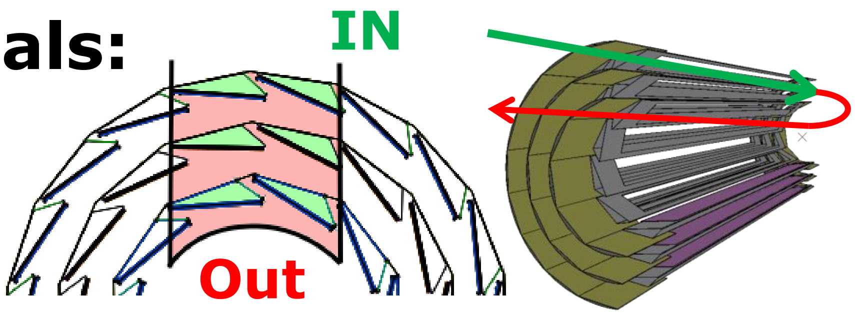
Cooling technologies/materials

Technology	Examples	Applications	Innovative features
High-conductivity materials	Carbon fiber Graphite foils Graphite foam	Thermal spreader	▪ Mechanical & thermal features
Small-scale plastic tubing	Polyimide PEEK	Medical industry	▪ Erosion/aging ▪ Cooling capabilities ▪ Radioactive environments
Connectors/filters	Integration issues		▪ One end accessible ▪ Out of detector area ▪ Flow distribution

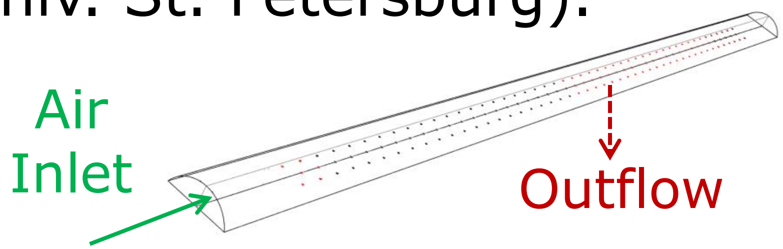
R&D phase

Inner Barrel Cooling proposals:

1. Air Cooling: **CFD**
   a) Layer-by-layer air cooling.



   b) Impinging jet proposal (w/ Univ. St. Petersburg).



2. Ultra Low-Mass Cooling Systems:
   a) Wound-truss structure.
   b) Wound-truss structure with high-conductivity plate.
      i. Cooling tubes over plate.
      ii. Cooling from stave extremities.

R&D phase

Inner Barrel Cooling proposals:

1. Air Cooling: **CFD**
   a) Layer-by-layer air cooling.
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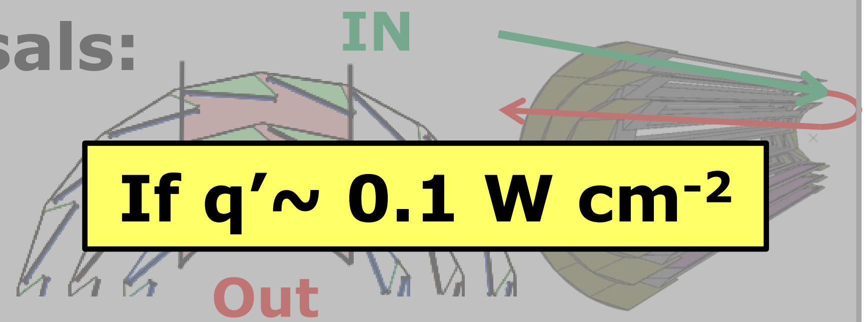
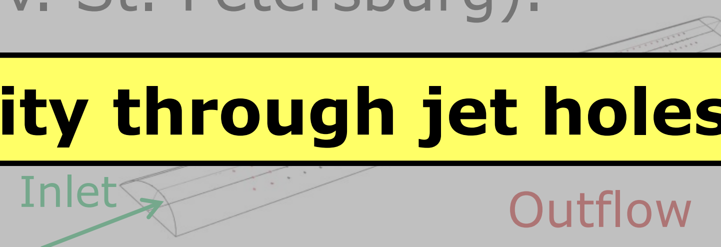


If q'~ 0.1 W cm^{-2}



Complex, risky, high air velocity through jet holes

2. **Ultra Low-Mass Cooling Systems:**
   a) **Wound-truss structure.**
   b) **Wound-truss structure w/ high-conductivity plate.**
      i. **Cooling tubes over plate.**
      ii. **Cooling from stave extremities.**

R&D phase

ULTRA-LOW-MASS COOLING SYSTEMS

Cooling pipe
↓ ID, OD
↑ X_0

+

Stave structure
↑ X_0
High-conductive
Lightweight
Stiff

=

Mechanical & cooling capabilities

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

Analytical/CFD studies
Experimental tests

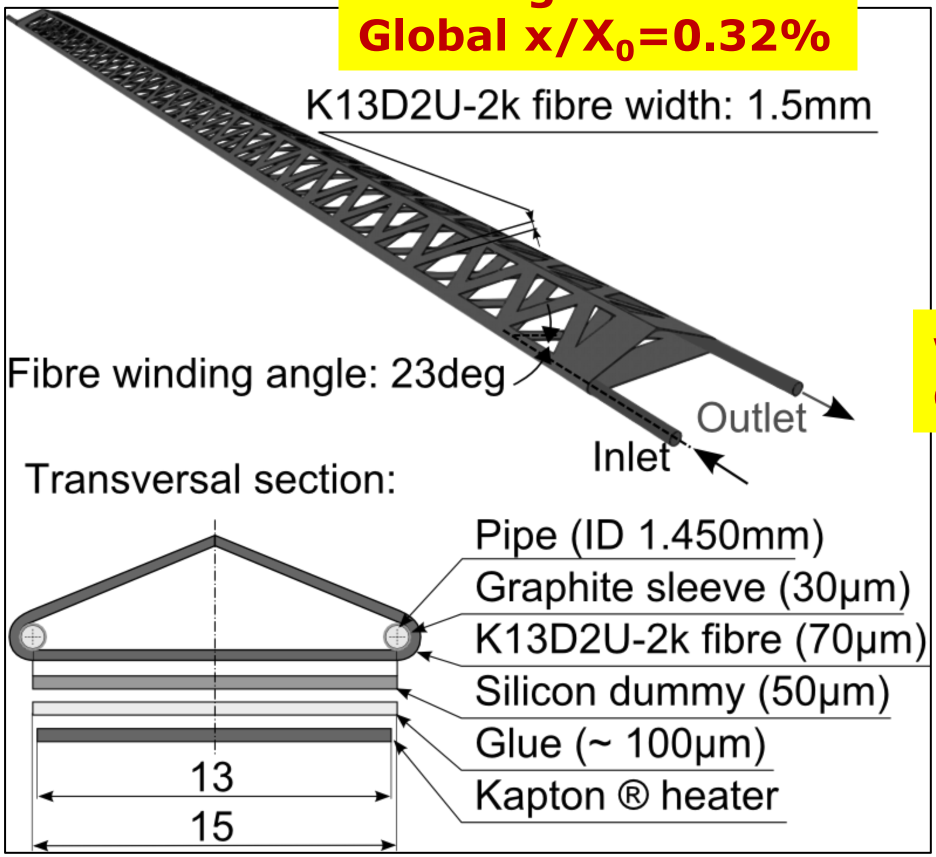
→ **Optimization of 2 geometries**

R&D phase

ULTRA-LOW-MASS COOLING SYSTEMS

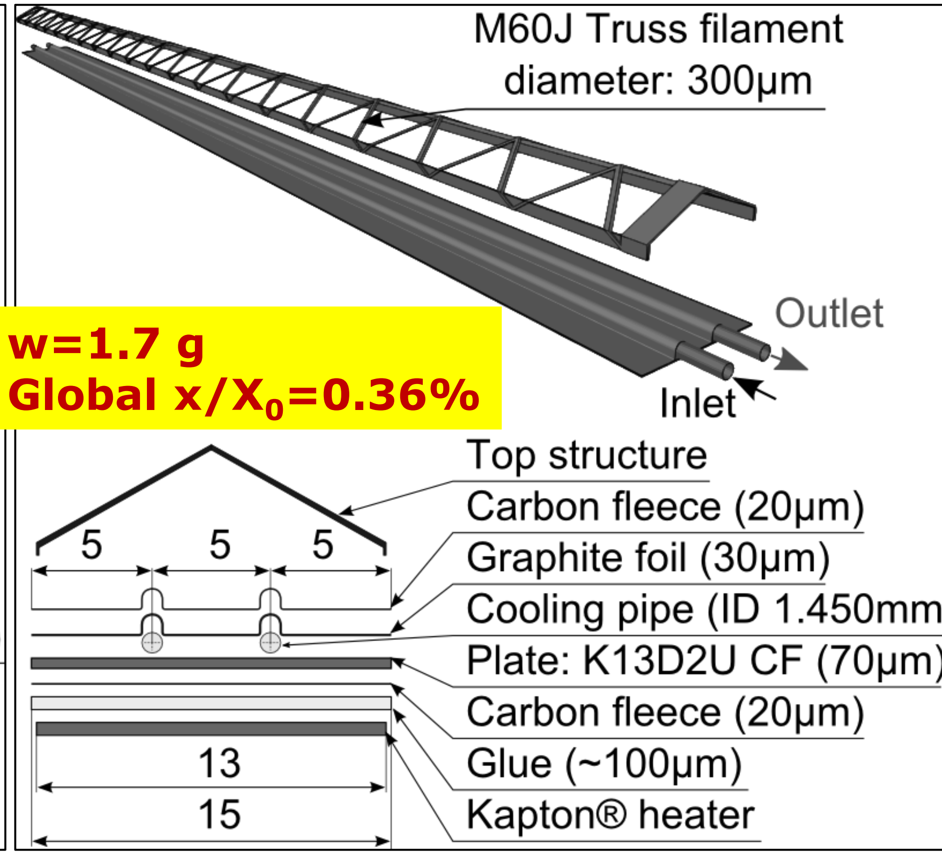
P1: *Wound-truss structure.*

w=1.4 g
Global x/X_0=0.32%



P2: *Wound-truss structure with high-conductivity plate.*

w=1.7 g
Global x/X_0=0.36%



R&D phase

ULTRA-LOW-MASS COOLING SYSTEMS

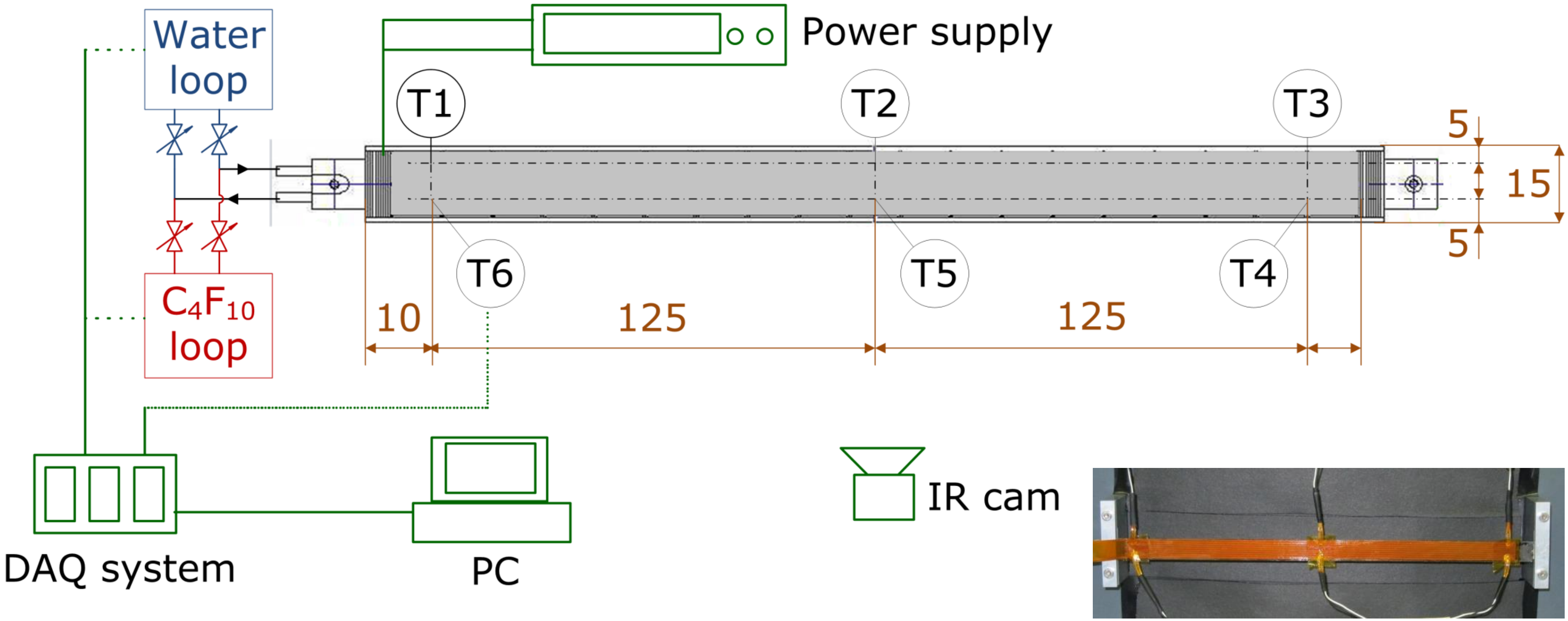
- **Prototype manufacturing and testing:**
  - Mechanical tests.
  - **Thermal tests:** real performance of prototypes.

Fluid	Advantages	Limitations
Single-phase water	Radiation hard Loop simplicity	Conductive: 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 (340 staves ITS)

- **2 experimental loops to test 2 different concepts.**

R&D phase

ULTRA-LOW-MASS COOLING SYSTEMS: EXP. SETUP



- Fast and simple way to assess prototype performance.
- Tested several prototype configurations with the 2 refrigerants.

R&D phase

ULTRA-LOW-MASS COOLING SYSTEMS: RESULTS

1. Little difference when cooling with water or C_4F_{10} (Fig. 1a)
2. Prototype performance not subject to flow rate/mass flux (Fig.1)
3. Plate proto (**P2**) outperforms wound-truss stave (**P1**) (Fig. 1, 2)

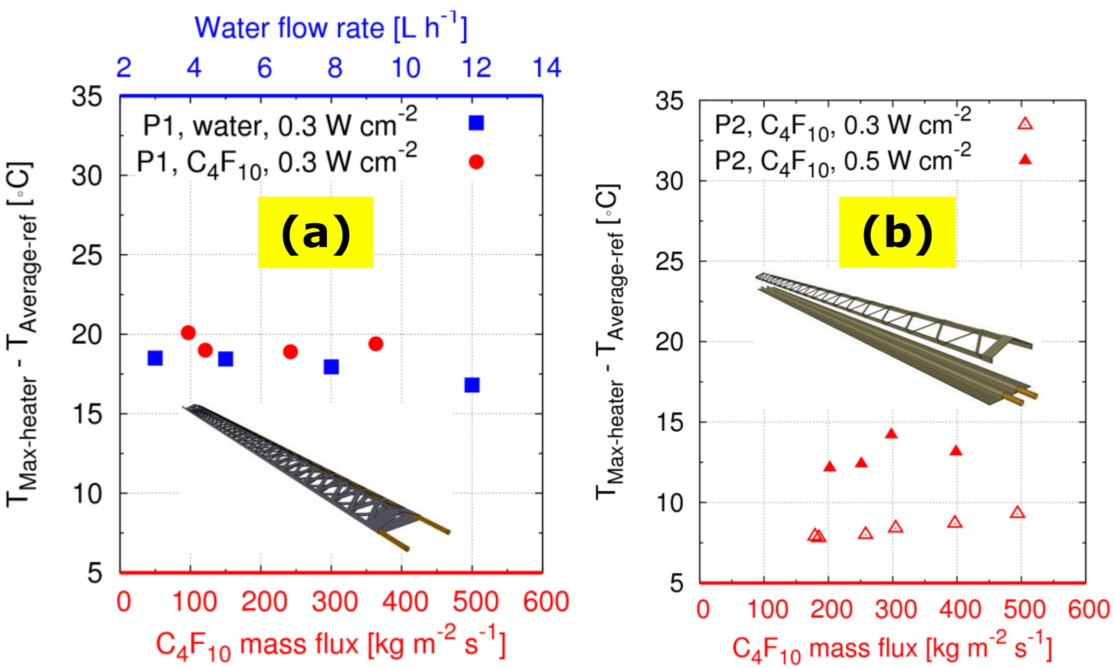


Fig. 1: Difference max. temperature in heater-mean fluid temperature for P1 (a) and P2 (b).

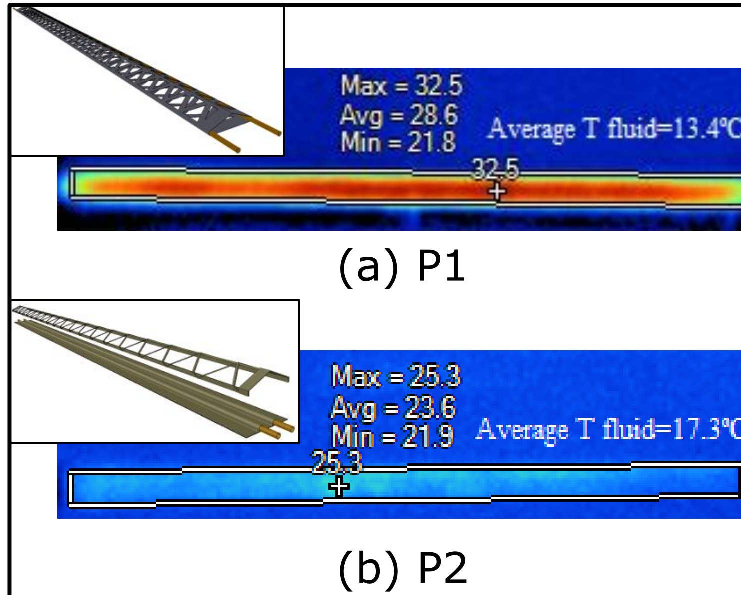
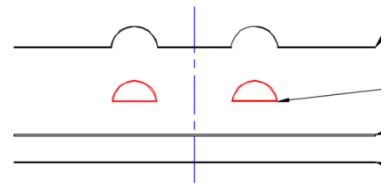
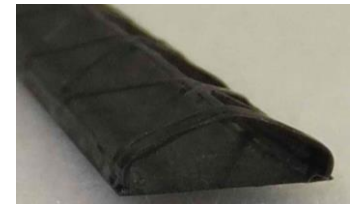


Fig. 2: *Results with C_4F_{10}: $G=250$ kg m^{-2} s^{-1}, $q'=0.3$ W cm^{-2}*

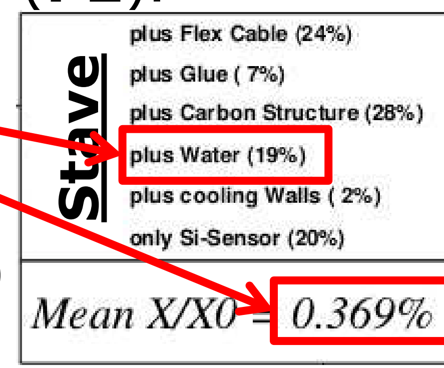
Current state of the work

1. Studied and tested several stave configurations, including:
   - Plate with squeezed pipes

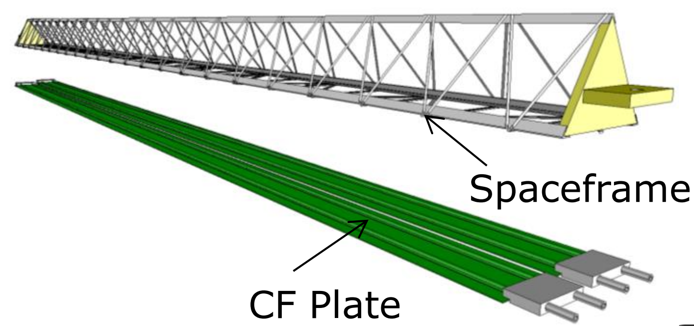




   - No-pipes stave + cooling from extremities (low power only).
2. Made new proposal adhering to the requirements (**P2**).
   - **Material budget:** to be reduced
     - Two-phase flow/reduce pipe size
     - Thin plate: ***K1100-X*** ($\lambda > 1000$ W m^{-1} K^{-1})

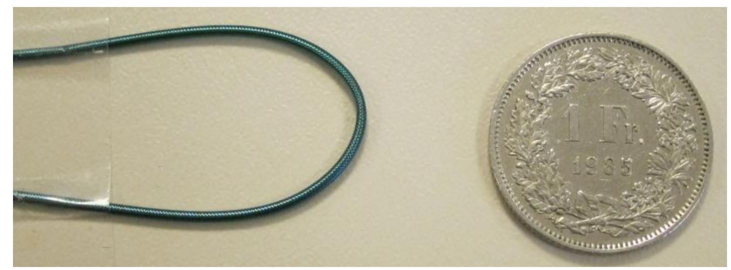


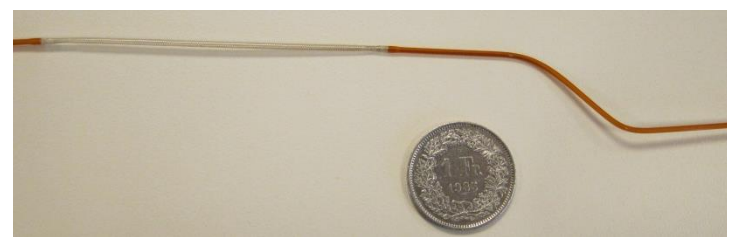
3. **Outer Layers:** similar concept
   - Same power dissipation expected.
   - Layers 30 mm wide (2 x 15 mm).
   - 850-1500 mm long.



Future steps

1. **Polyimide piping:** robust and suitable under radioactivity.
   - ***Erosion tests:*** facility under construction (water).
     - Measurements before/after: wall thickness, ε, SEM…
     - Water analysis (suspensions)
2. **Pipe integration:**
   - Avoiding connectors (pipe bend)
   - Prevent pipe kinking/buckling: embed reinforcing coil/braid
3. **Refrigerant:** C_4F_{10} availability?
   - ***Alternative:* R236fa** (HFC)
   - Radiation impact?





(top) Single-pipe stave concept
(centre) Polyimide/Pebax® tube bend
(bottom) Composite polyimide+coil PTFE/Pebax ®

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