Micro channel cooling for tracking detectors.

Jan Buytaert

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ECFA HL LHC Workshop Aix-les-bains 22/10/2014

HEP vertex detectors: thermal management challenge

- Very high track densities and rates impose pixel sensors, with readout ASICs dissipating up to ~2 W/cm^2.
- Very high irradiation doses O(10^{16}) N_{eq}/cm^2 :

  - require high voltage biasing (~1kV) and causes high power dissipation in sensors up to ~1W/cm^2.

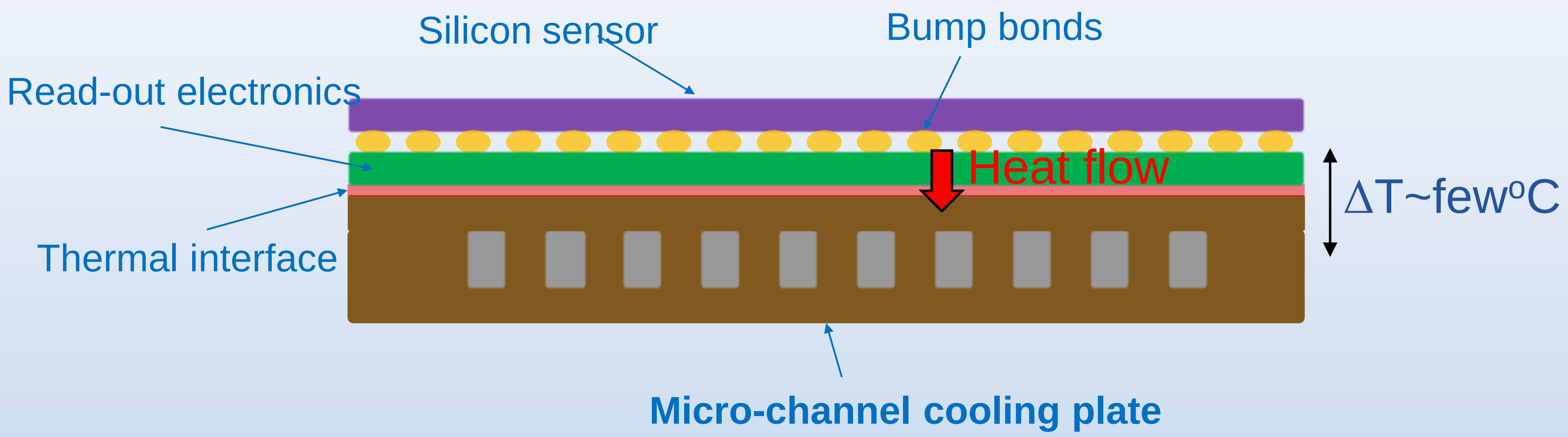
  - require sensor temperature < -20 ^{0}C to avoid thermal runaway and detrimental annealing.
- Material for cooling must add minimal X/X_0.
- Thermal management is a key aspect to consider early in the design and integration of the present and future generation of Vertex detectors.
- Micro channel cooling is a novel method meeting the above requirements.

What is “microchannel cooling”?

Use of a µfluidics device as a heat exchanger.

- Refrigerant is brought immediately underneath the heat source.

  -> minimal thermal resistance and temperature gradient



- Advantages:

  - Low mass : because the cooling substrate also serves as mechanical support.

  - No mismatch of thermal expansion coefficients (CTE) if sensors, ASIC and cooling substrate are silicon: -> No mechanical stress caused by ΔT.

- Large variety:

  - channel dimensions 10 um…<<1mm,

  - single or multichannel layout

  - mono or two-phase heat absorption.

  - refrigerants: CO_2, NH_3, water,C_4F_{10} …

  - substrate material: Polyimide, glass, Silicon, ceramic,…

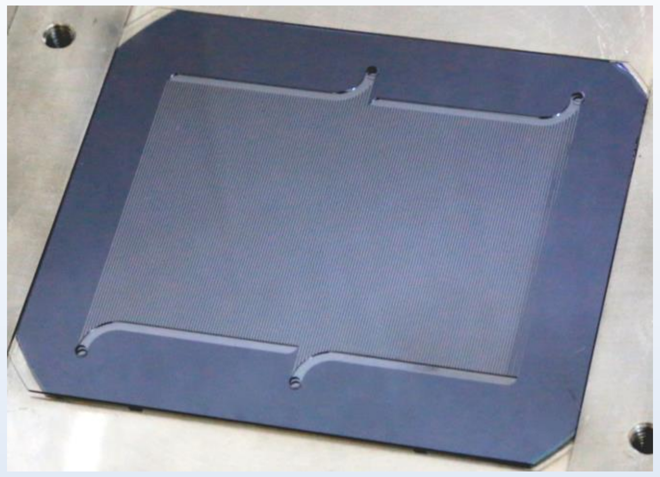
- Not unique to HEP: many other industrial application fields

  - µfluidics : cell development, lab-on-chip, … (low pressure & very low flows)

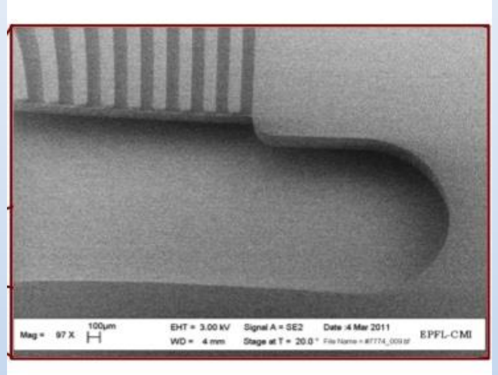
  - heat exchanger : photonics IC, concentrated photovoltaic cells ,…(up to 100W/cm2 !)

Si µchannel Projects in HEP

NA62 – GigaTracKer «GTK»



- $0.13\%\ X/X_0$
- $T_{sensor} < -20\ ^oC$
- C_6F_{14} single phase
- $2.5\ W/cm^2$
- Total power up to max 144 W
- In vacuum

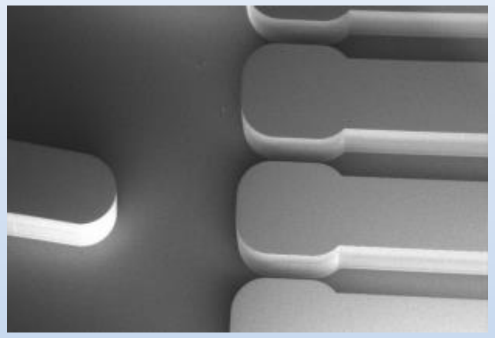


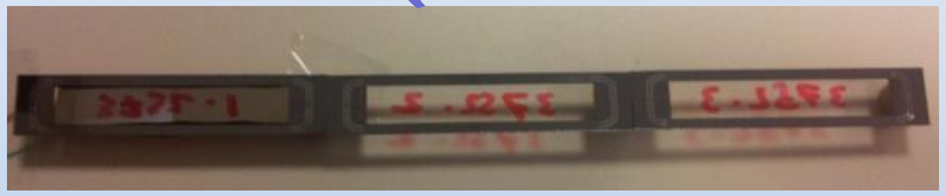
✓ Installating now

ALICE - ITS

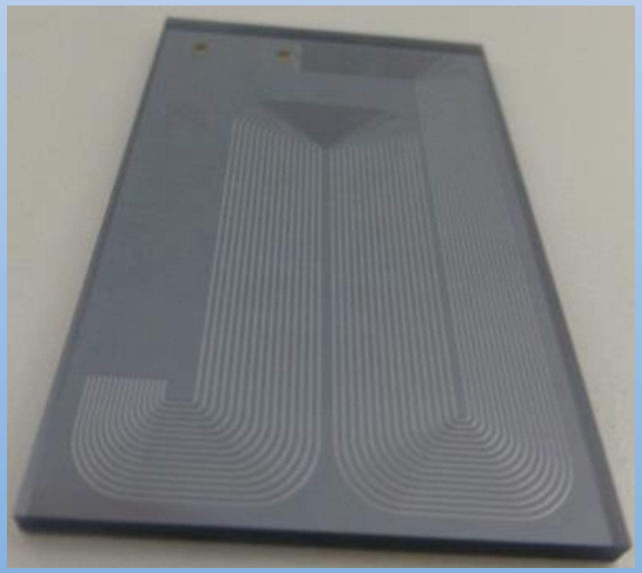
- No material in beam area
- $15 < T_{sensor} < 30\ ^oC$
- C_4F_{10} two-phase
- $0.1\ W/cm^2$
- Total power 170 W

Under development (backup option)

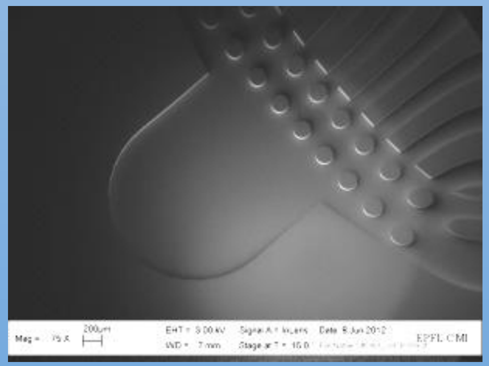




LHCb – Velo Upgrade



- Reduced material in beam area
- $T_{sensor} < -20^oC$
- CO_2 two-phase
- $1.8\ W/cm^2$
- Total power 1.9 kW
- In vacuum

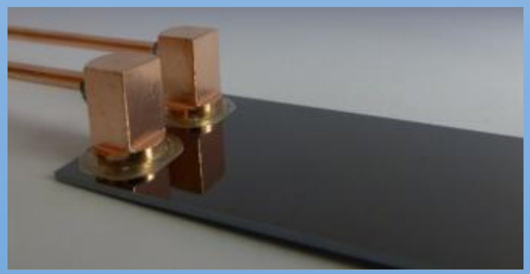


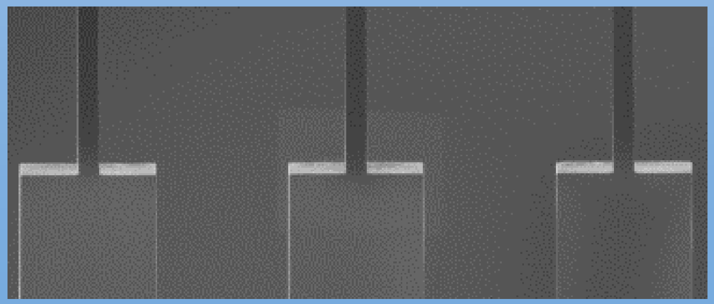
✓ Approved by experiment

ATLAS - Phase II pixel

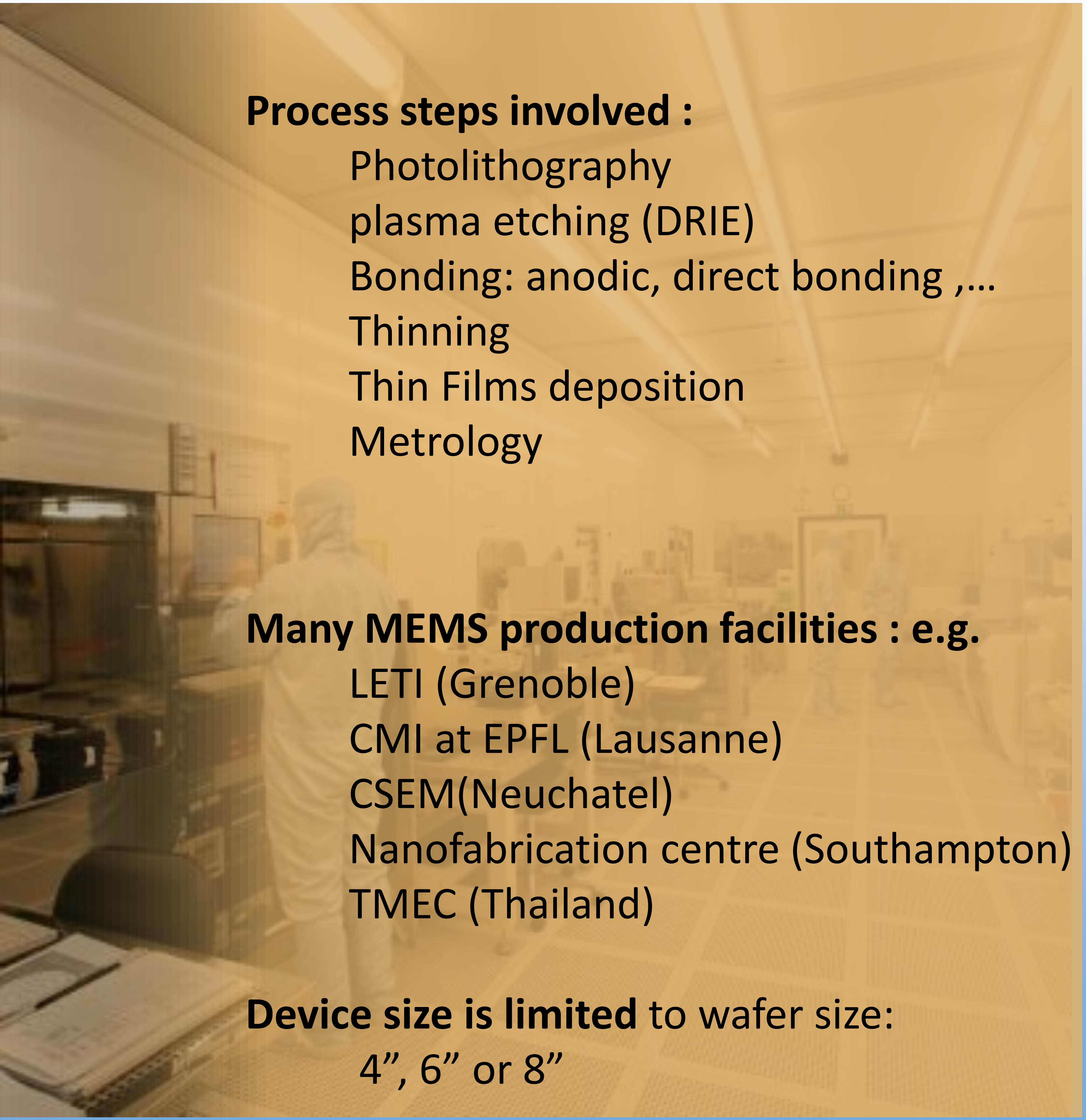
- Reduced material in beam area
- Refrigerant $< -30\ ^oC$
- CO_2 two-phase
- $0.4\ W/cm^2$
- Total power: ~40kW ($10m^2$)

Institutes interested





Micro-Fabrication of Si micro channels



Process steps involved :

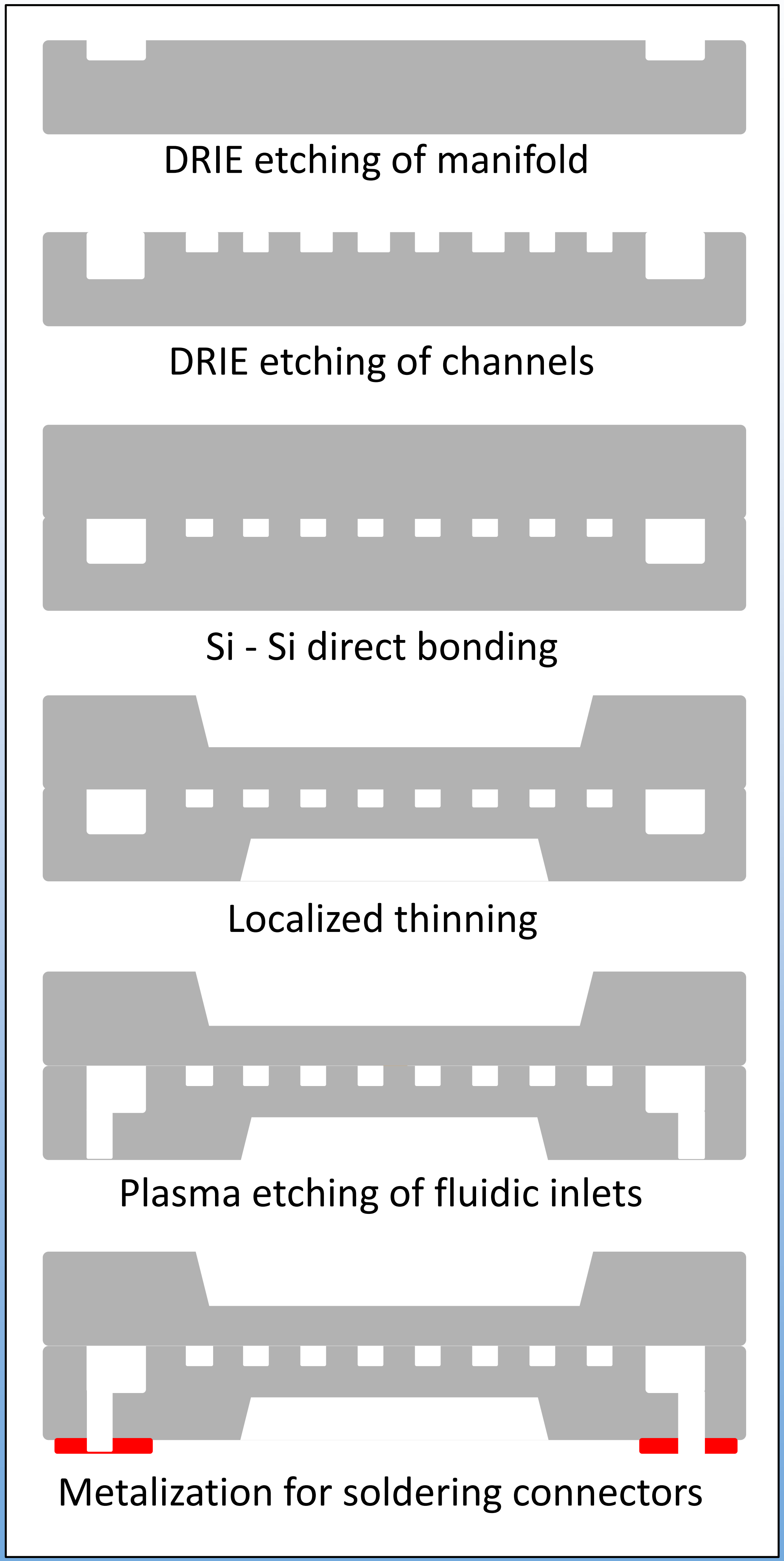
- Photolithography
- plasma etching (DRIE)
- Bonding: anodic, direct bonding ,…
- Thinning
- Thin Films deposition
- Metrology

Many MEMS production facilities : e.g.

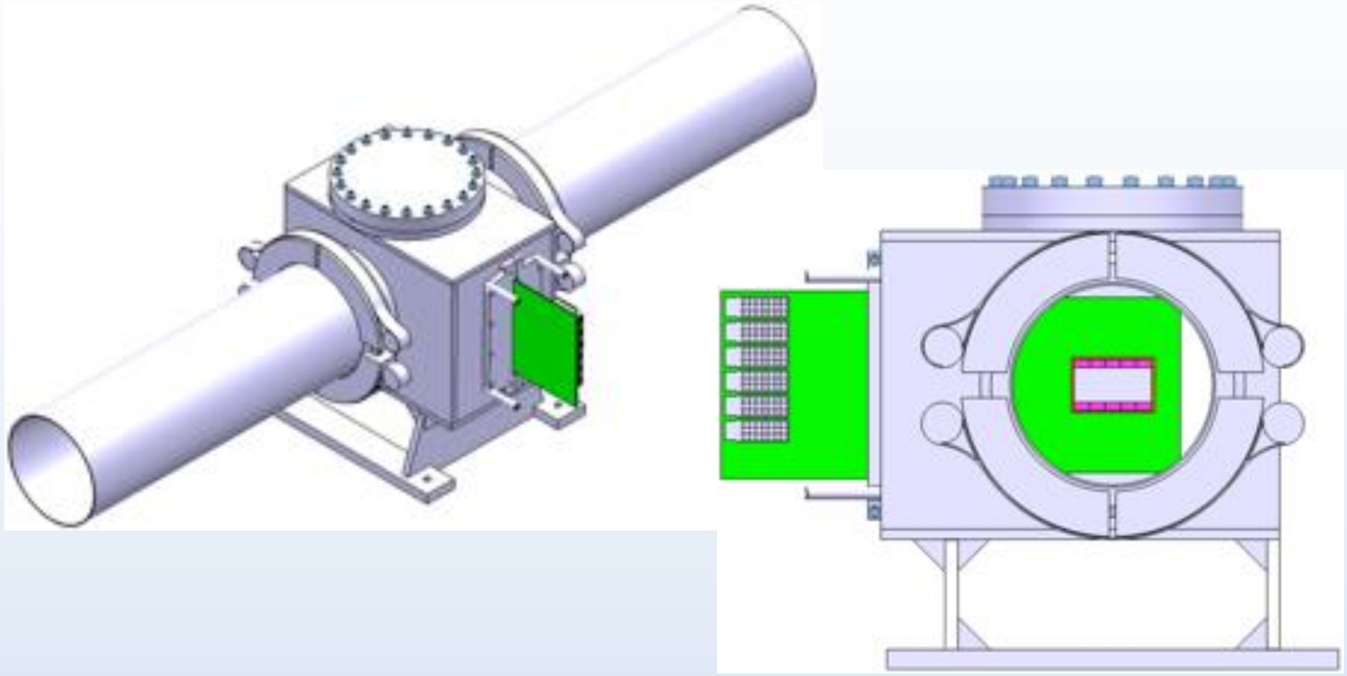
- LETI (Grenoble)
- CMI at EPFL (Lausanne)
- CSEM(Neuchatel)
- Nanofabrication centre (Southampton)
- TMEC (Thailand)

Device size is limited to wafer size:

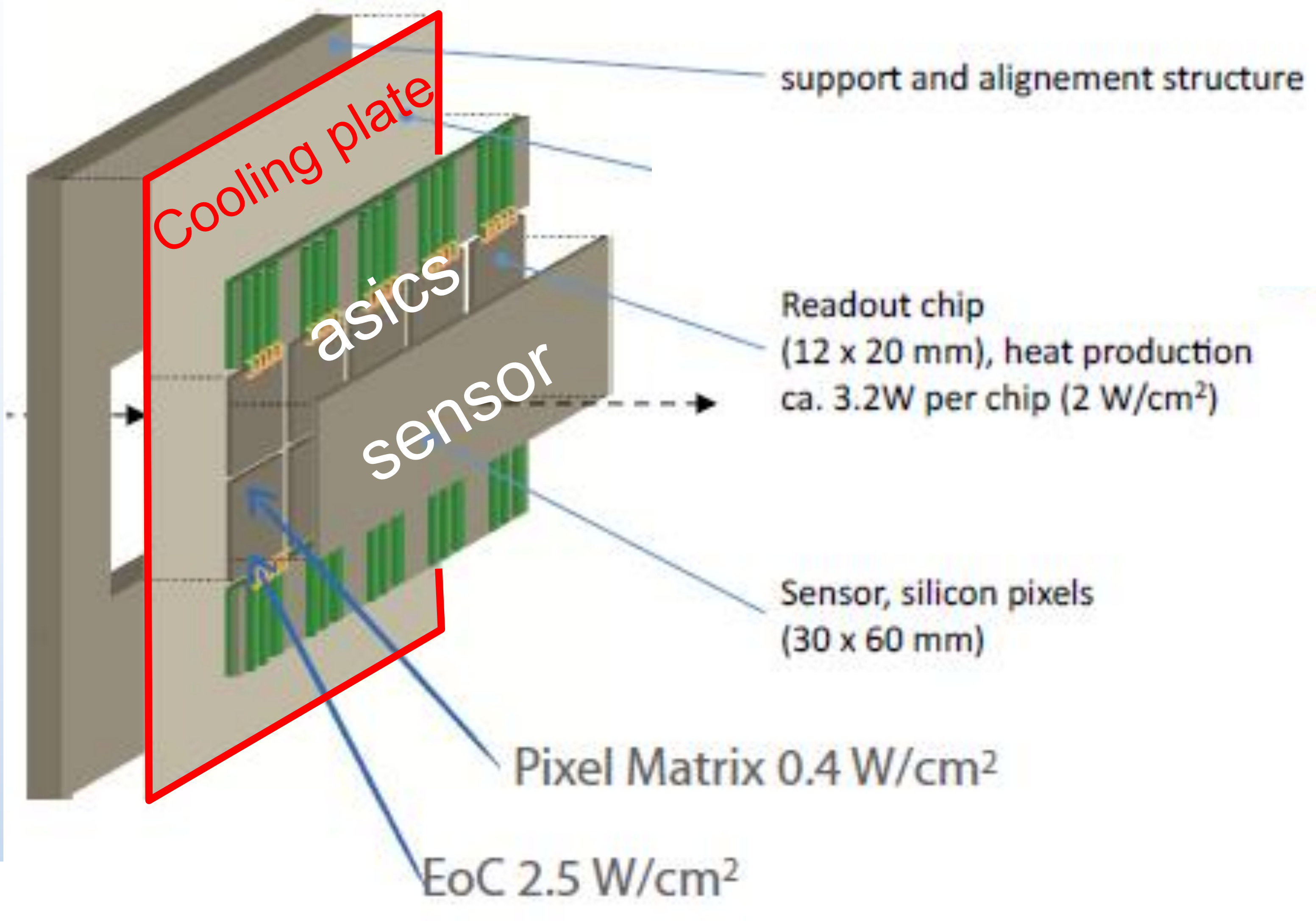
4”, 6” or 8”

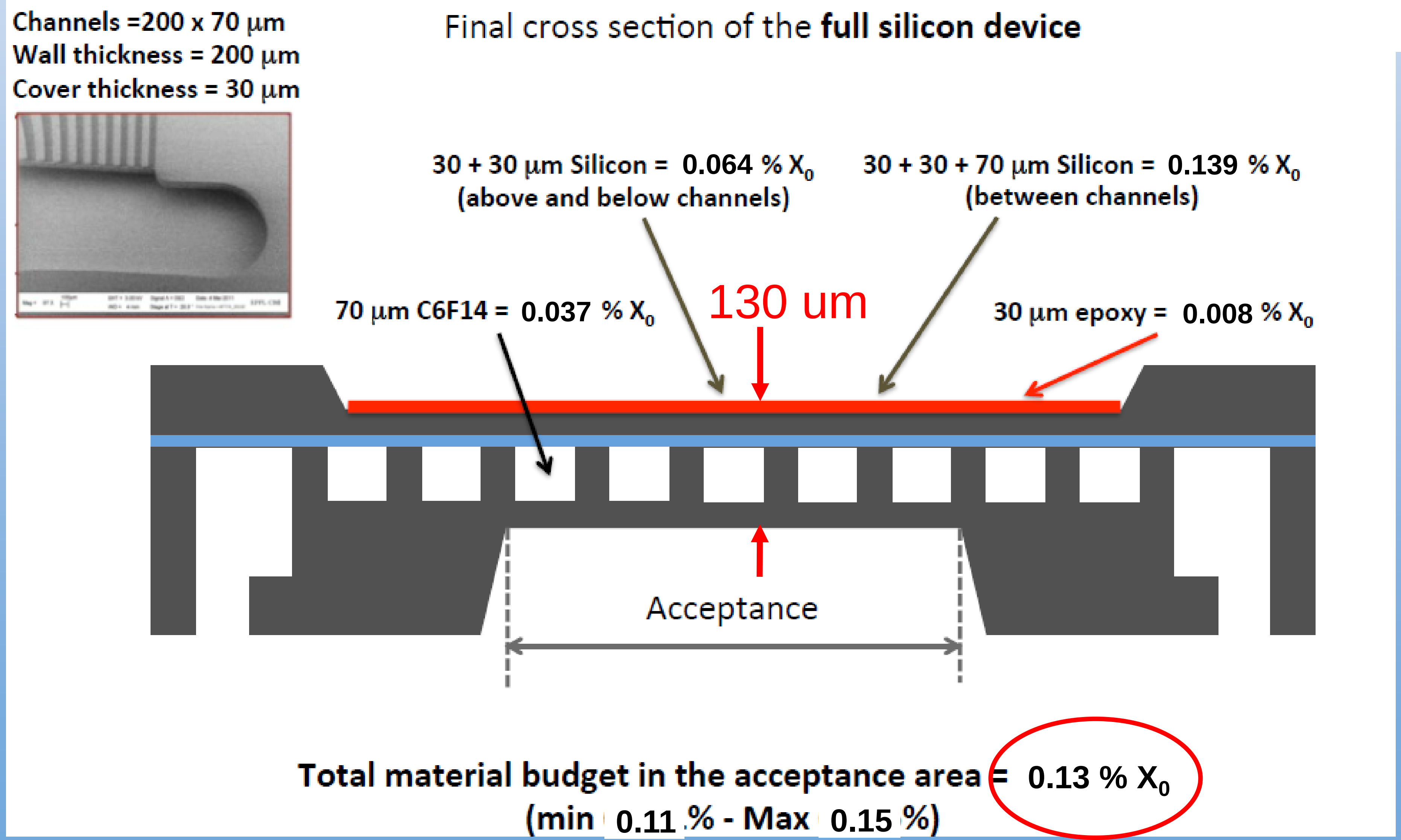


NA62 GTK: first micro channel cooling.

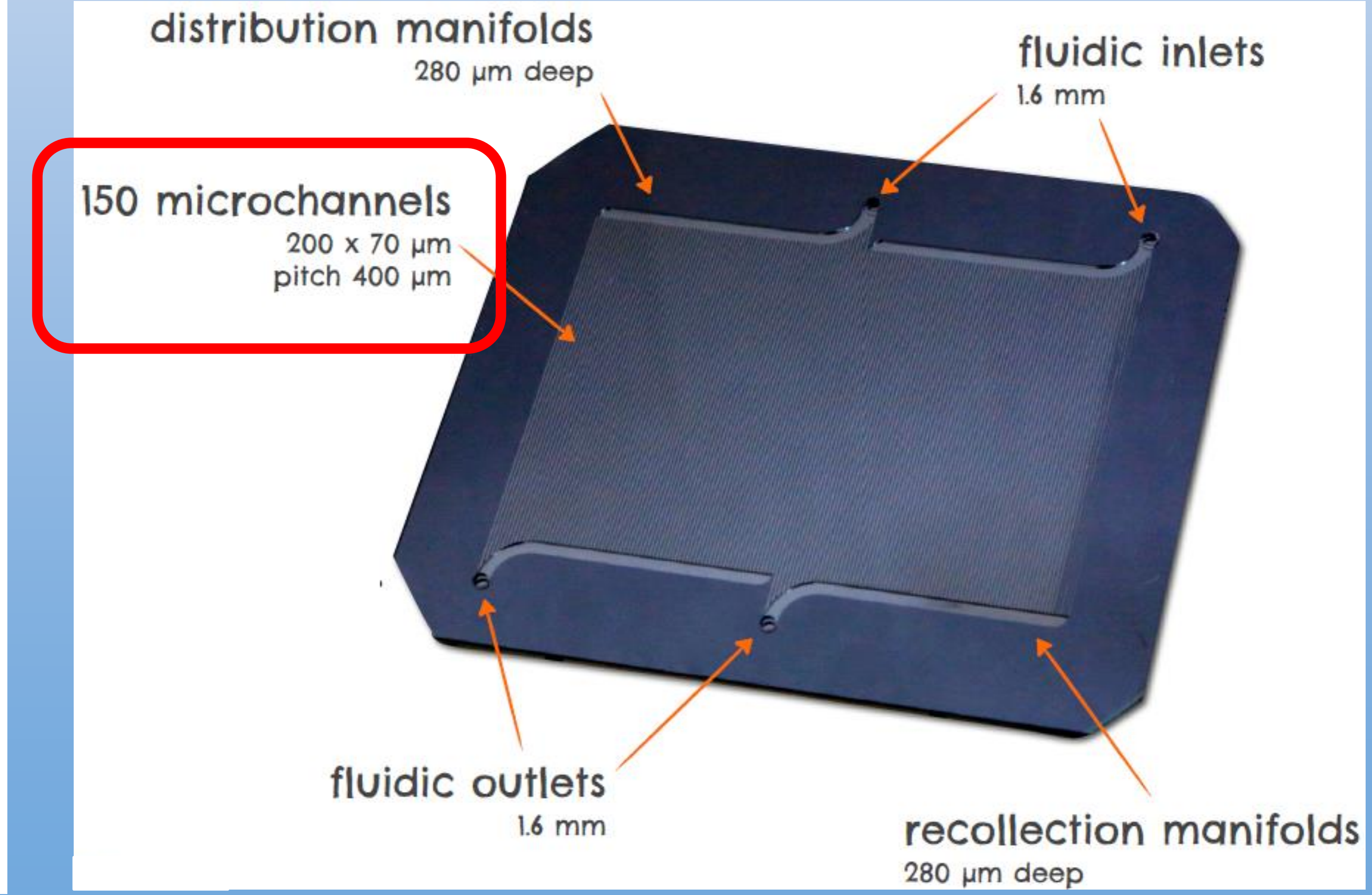


3 stations in the beam line

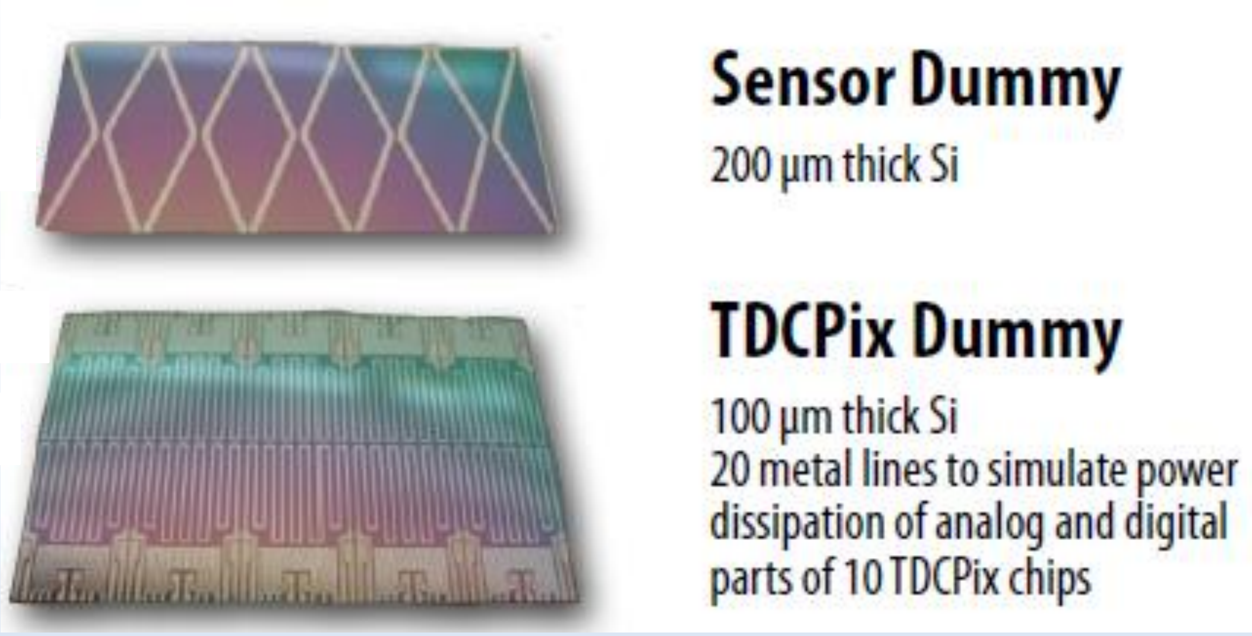




Total material budget in the acceptance area = 0.13 % X_0
(min 0.11 % - Max 0.15 %)



NA62 GTK: thermal performance



Sensor Dummy

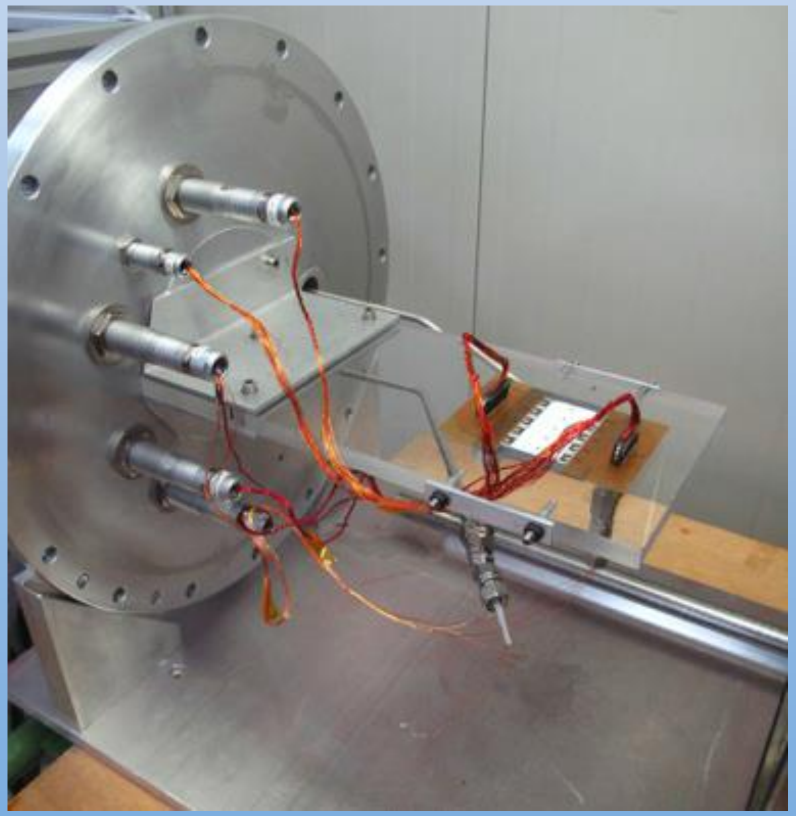
200 µm thick Si

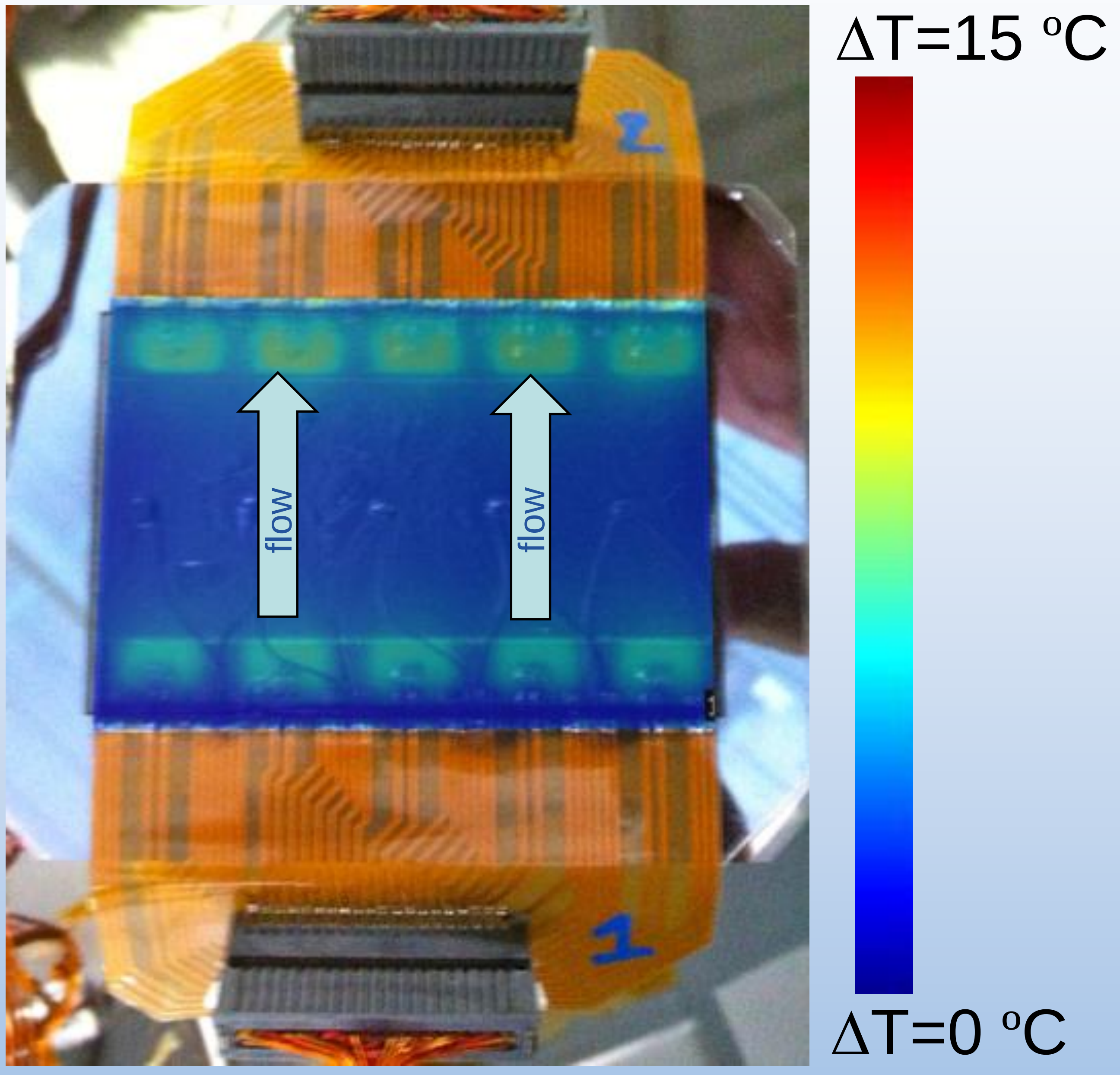
TDCPix Dummy

100 µm thick Si
20 metal lines to simulate power dissipation of analog and digital parts of 10 TDCPix chips

Dummy Si heaters

Measured in vacuum

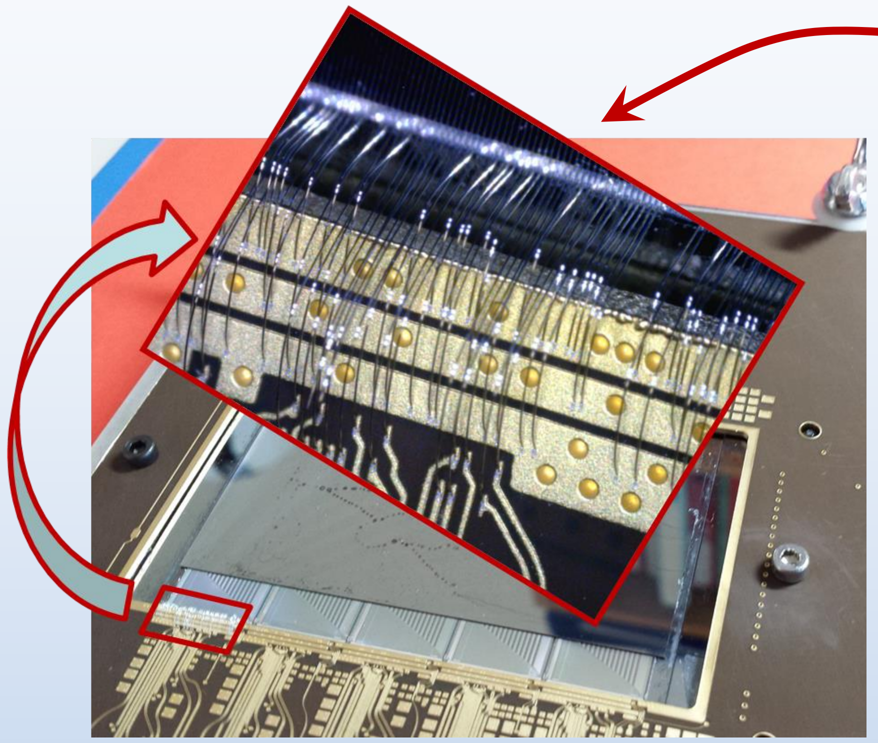




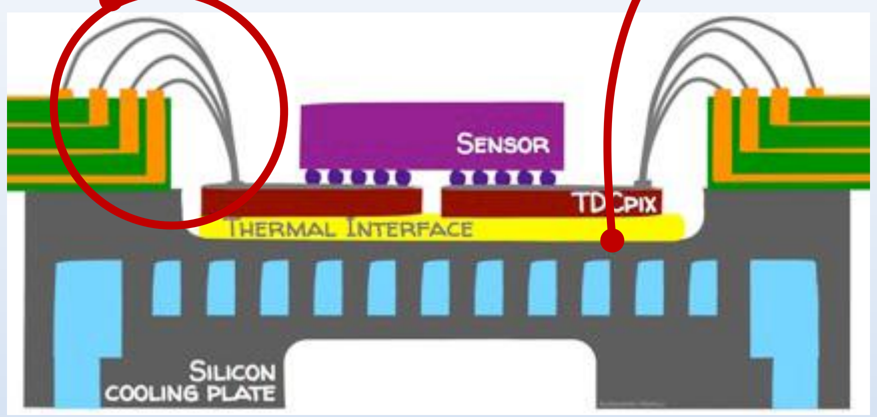
Nominal conditions:

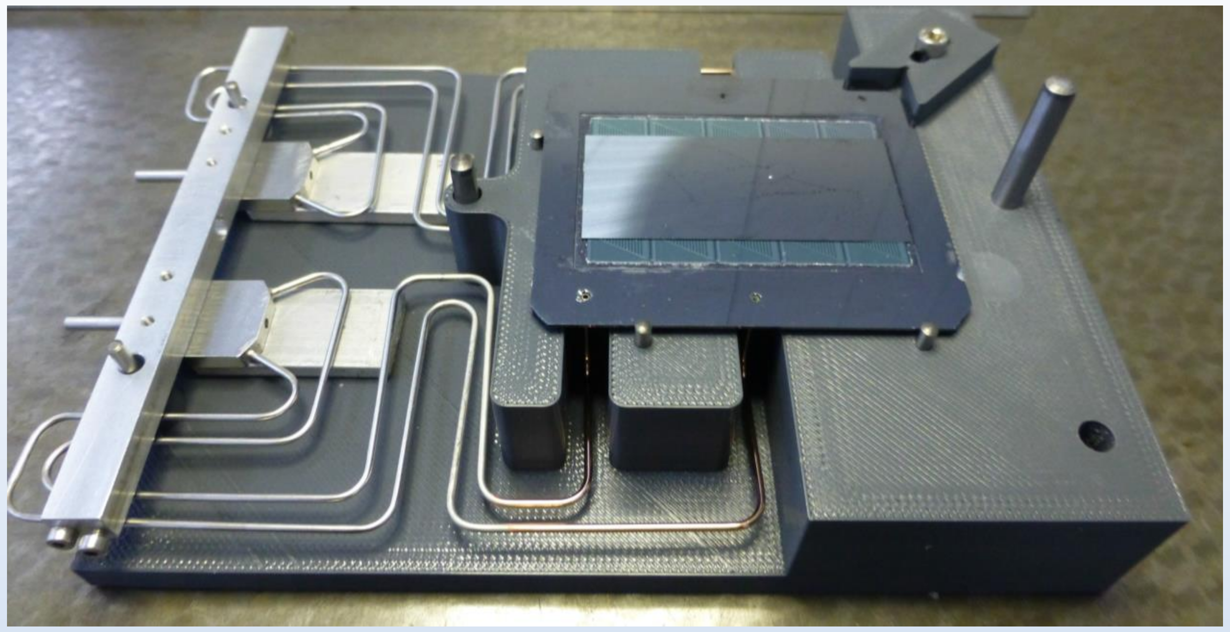
- 20 W on ASIC, 4 W on Pixel Matrix
- liquid flow: 8 g/s C_6F_{14} @ -21°C
- max ΔT_{sensor} = 1 °C,
- max ΔT_{chip} = 3 °C,
- max ΔT_{module} < 5 °C

NA62 GTK: assembly of detector module

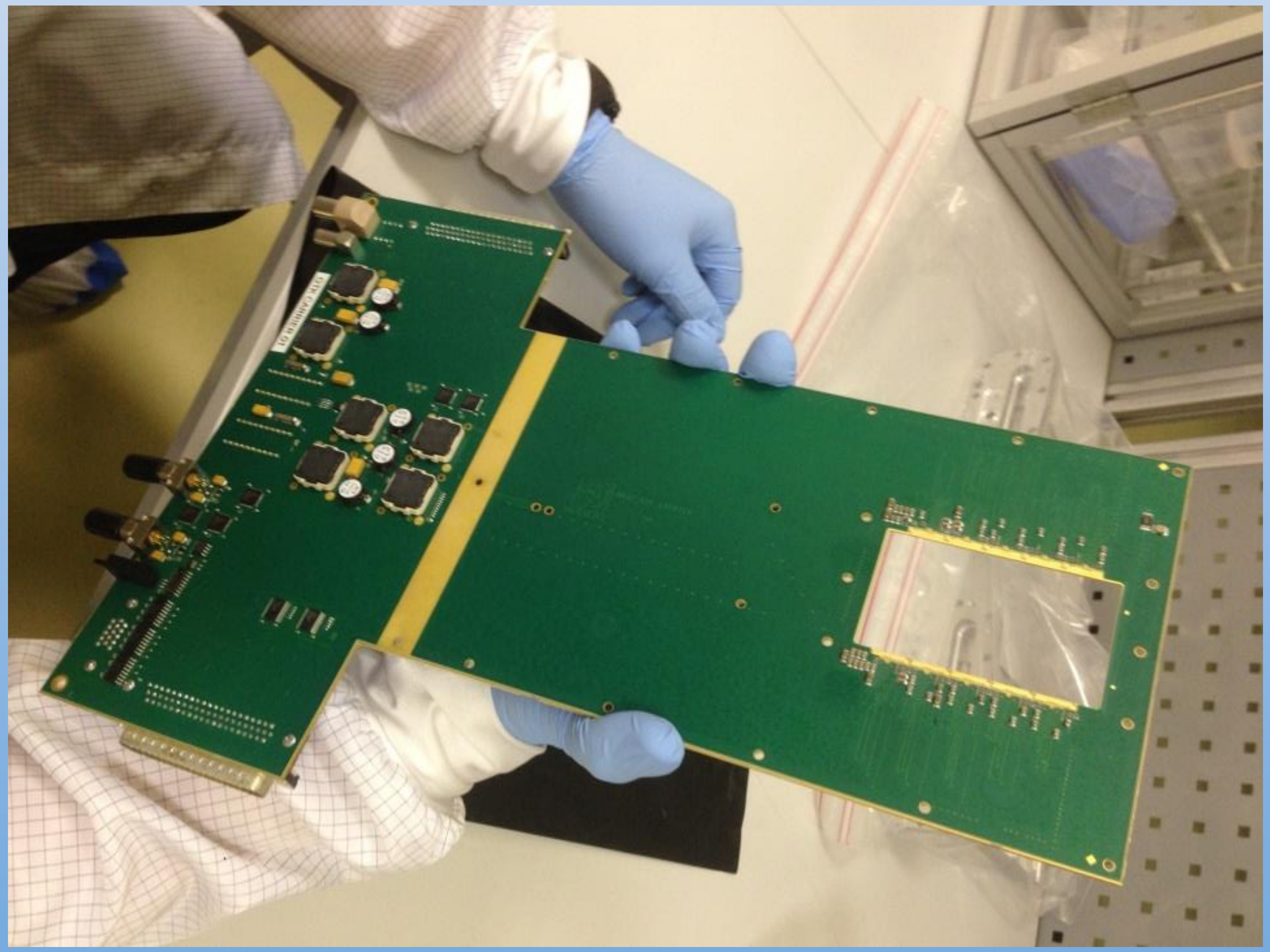


Chip to PCB wire bond





Jig for precision gluing of detector on pre-equipped μ-channel device



First GTK module in beam very soon !

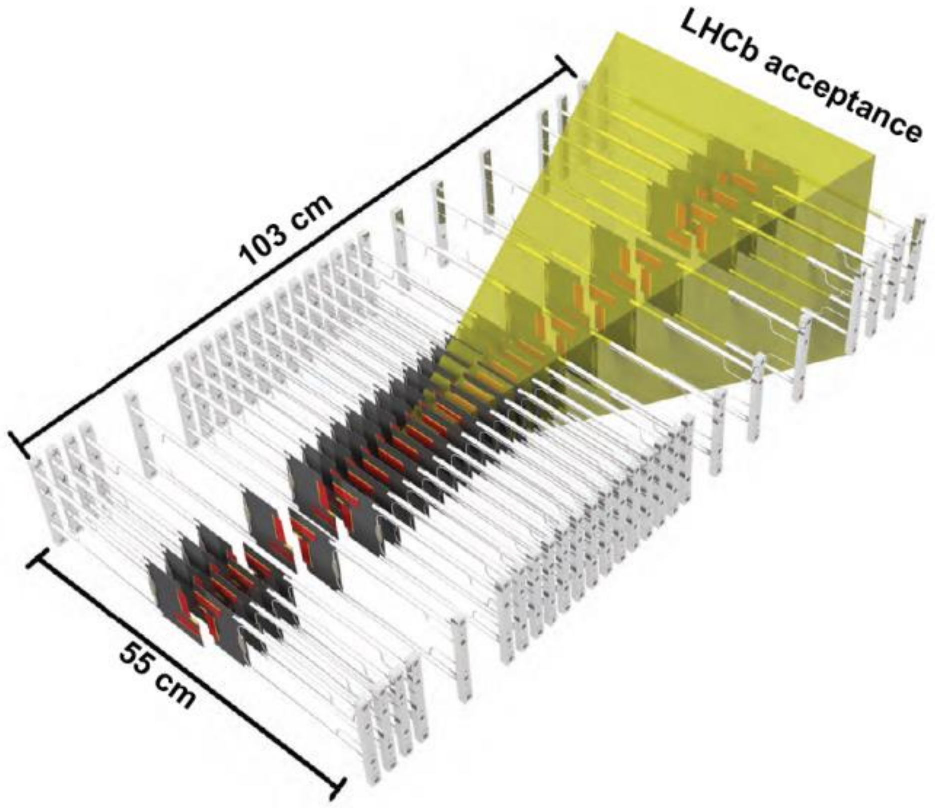
LHCb VELO: first CO_2 cooling in micro channels

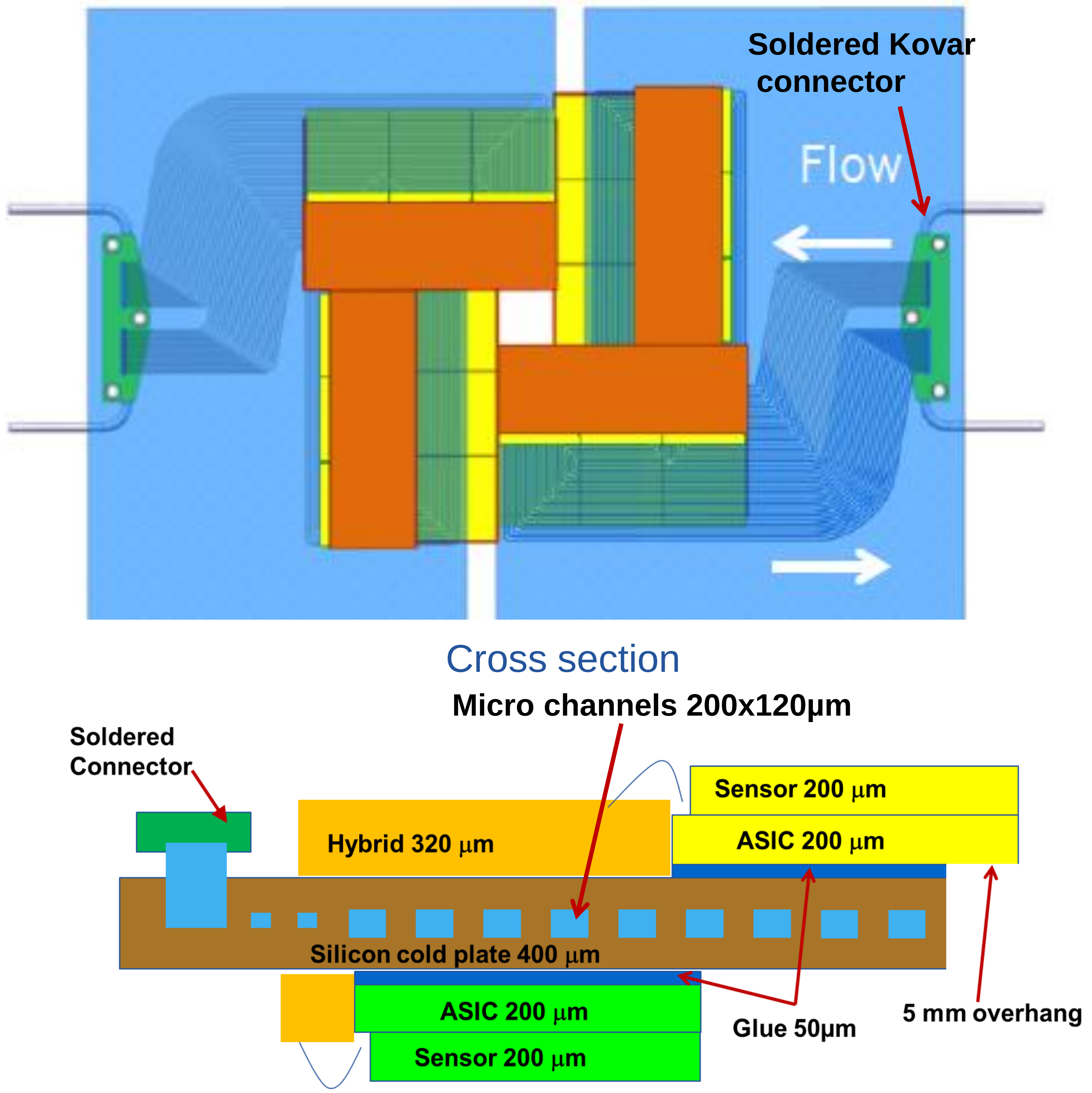
- Advantages of CO_2 :
  - High latent heat
  - Low viscosity
  - T_{sat} range from +30°C to -40°C
  - Radiation hard
  - Evaporative: stable vs load & isothermal
  - Chemical inert : no corrosion of Si
  - Non-toxic and environment friendly

Very well adapted to micro channels

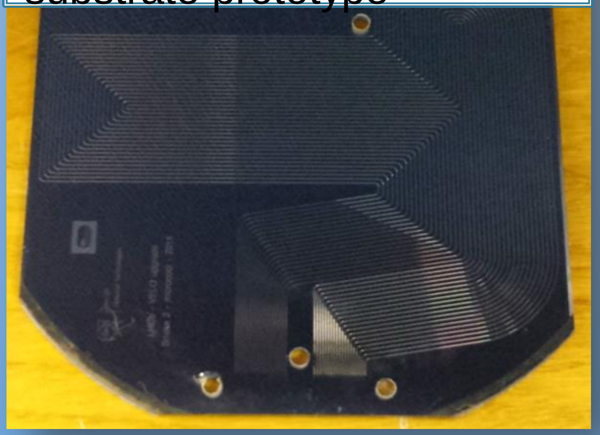
VELO upgrade installation in 2018

- **2 detector halves with 26 modules each**
- **high radiation environment (~8x10^15 n_{eq}/cm^2)**
- **silicon sensor temperatures < -20°C**
- **hybrid pixel detector power densities ~ 1.8 W/cm²**





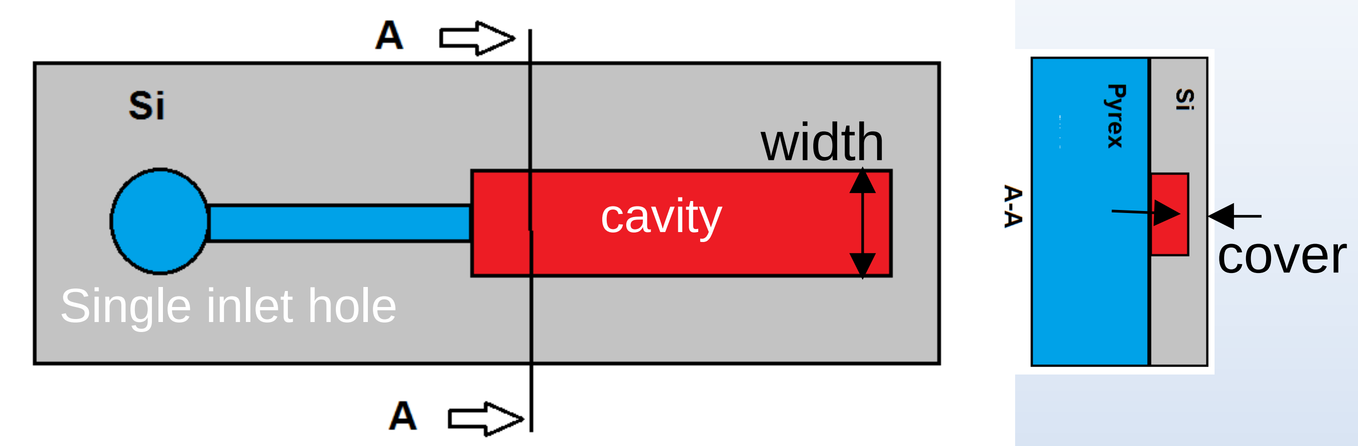
Si–Pyrex micro channel substrate prototype

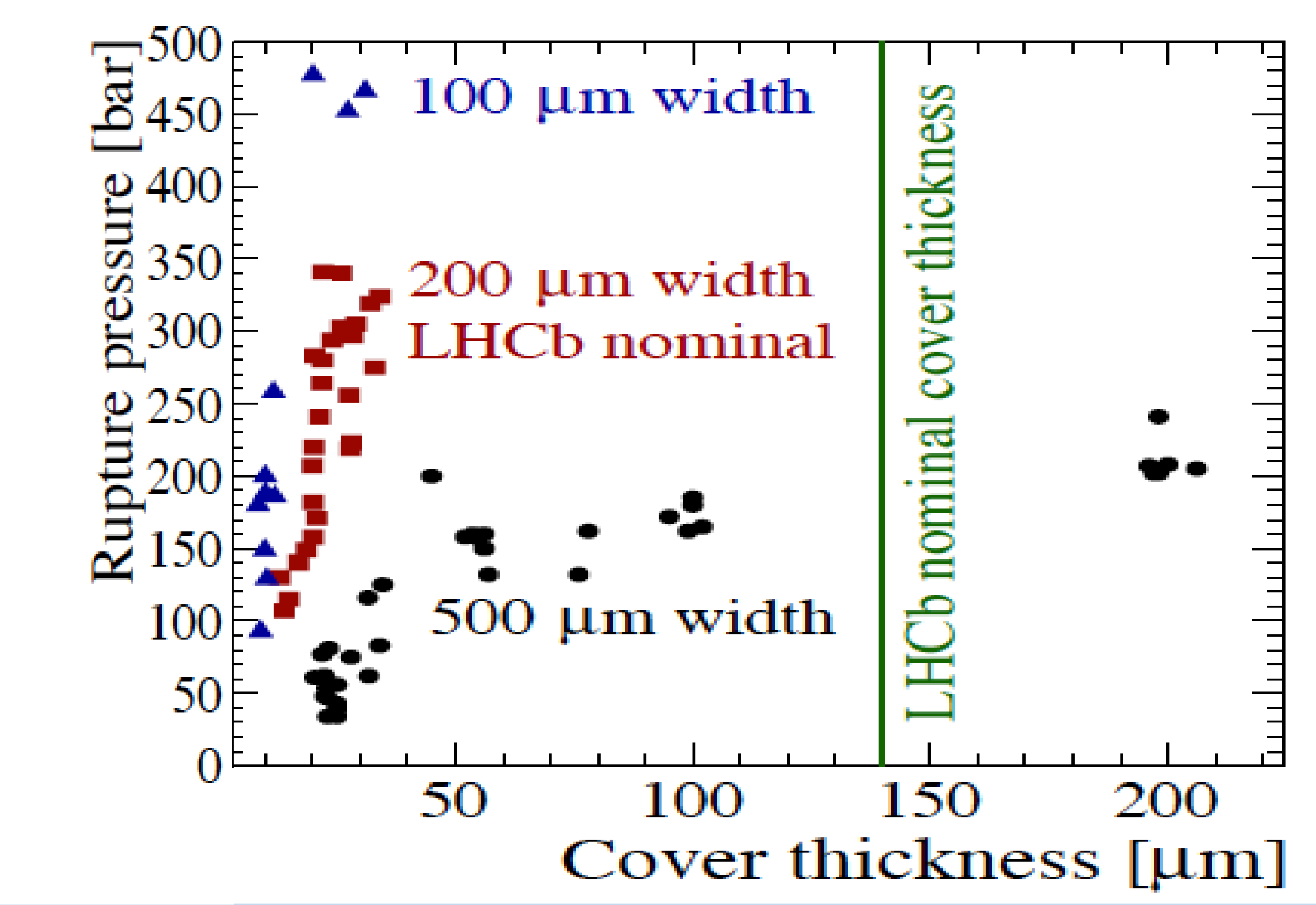


LHCb VELO: pressure tests.

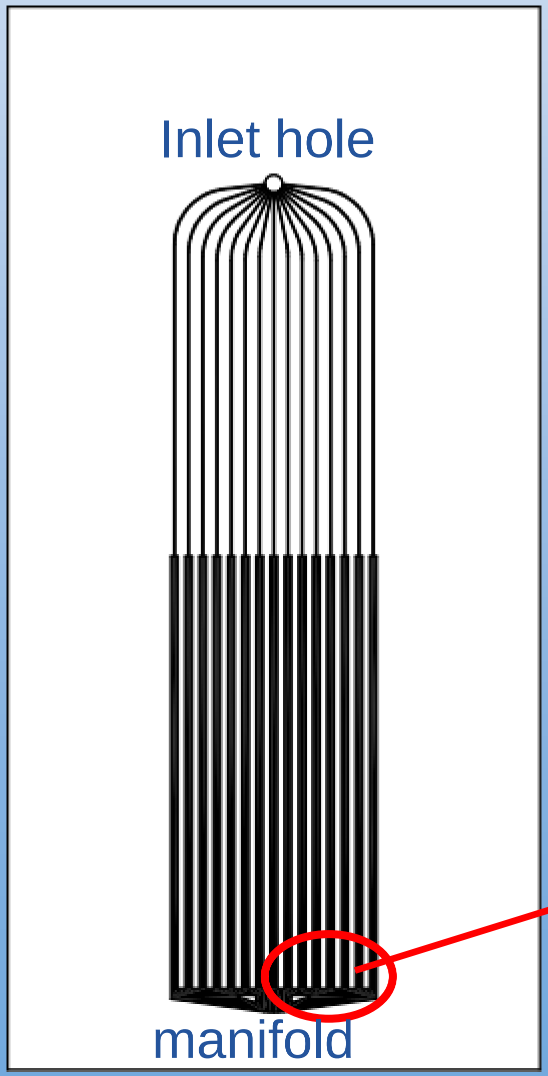
Required pressure resistance is 170 bar

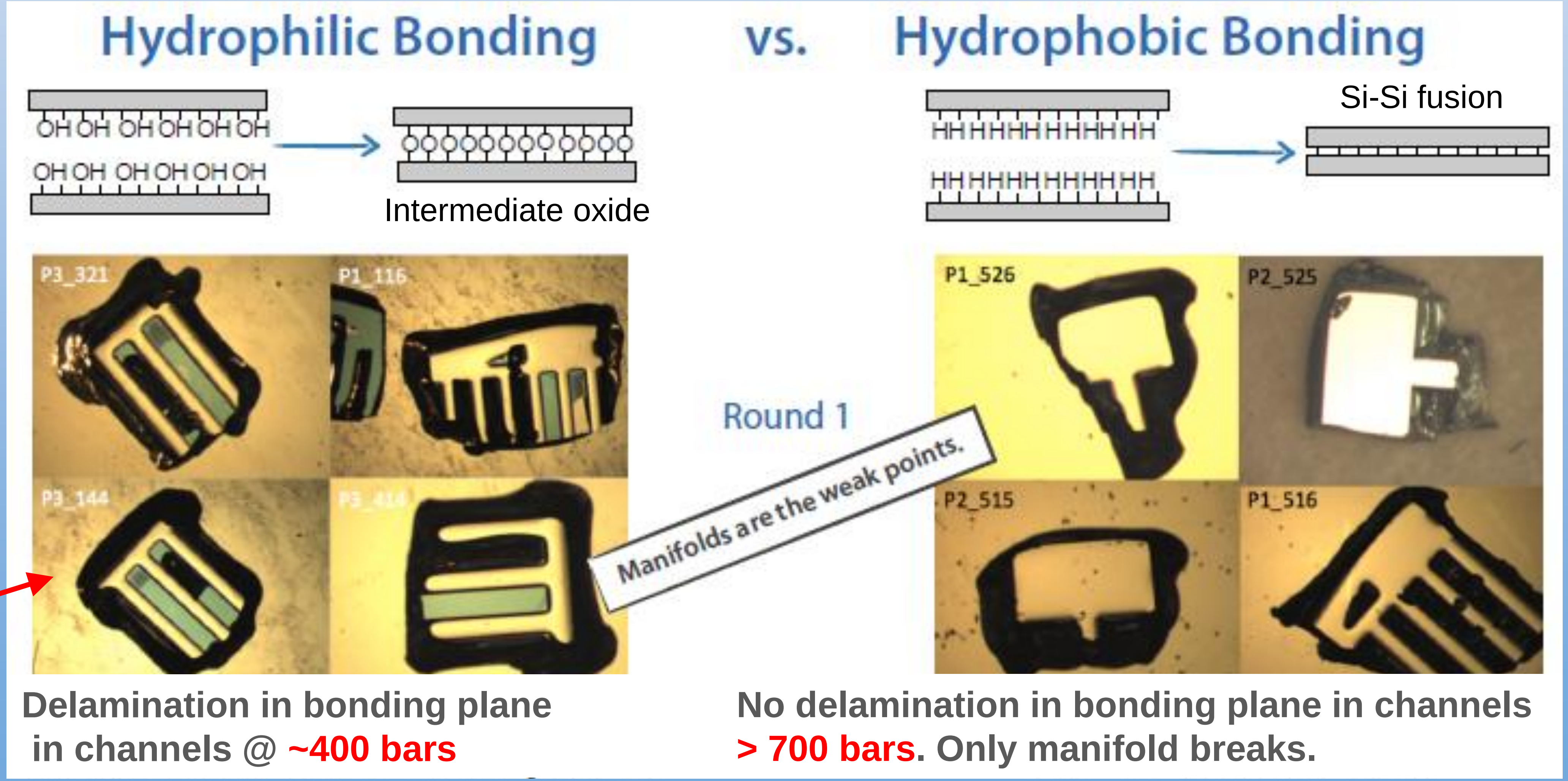
Test structures in Si-Pyrex





Test of multi channel & manifold in Si-Si





Delamination in bonding plane in channels @ ~400 bars

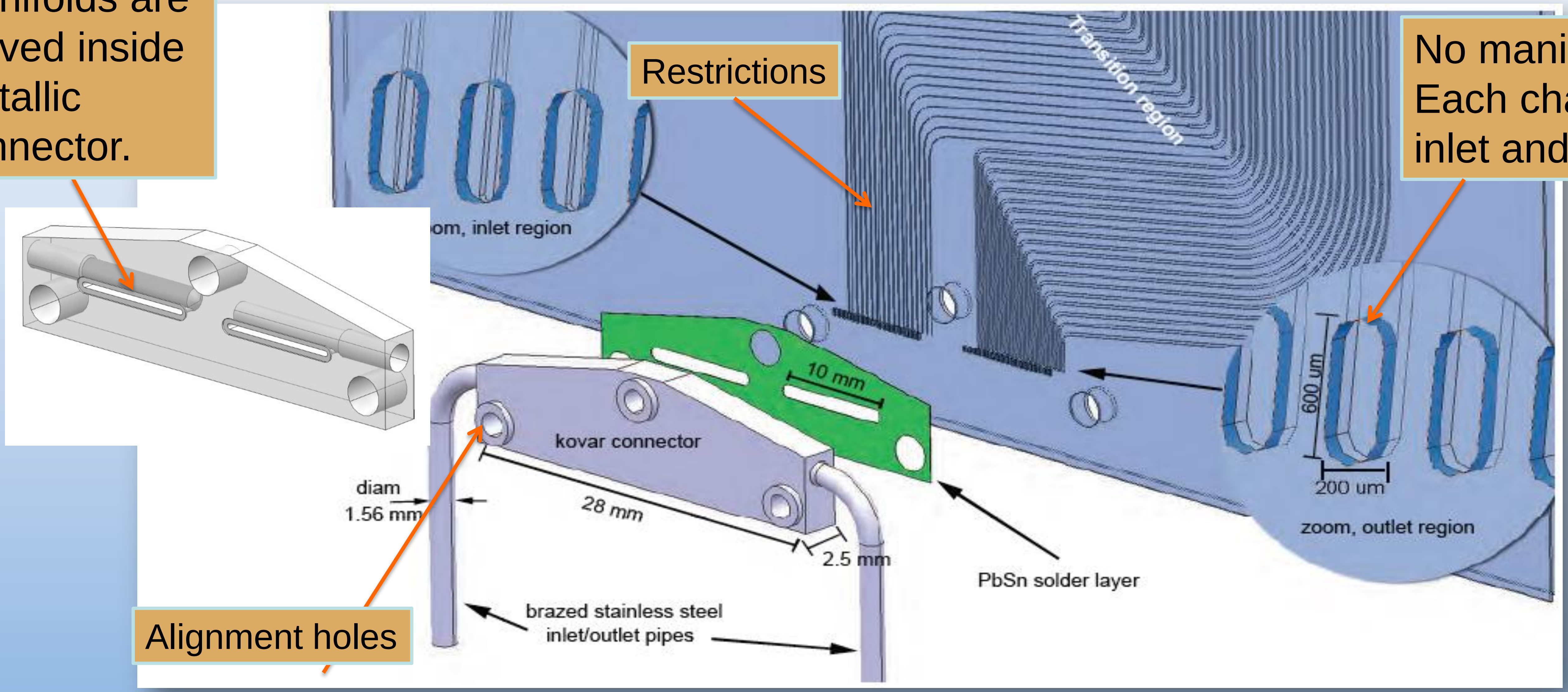
No delamination in bonding plane in channels > 700 bars. Only manifold breaks.

LHCb VELO: fluidic connector

Manifolds are moved inside metallic connector.

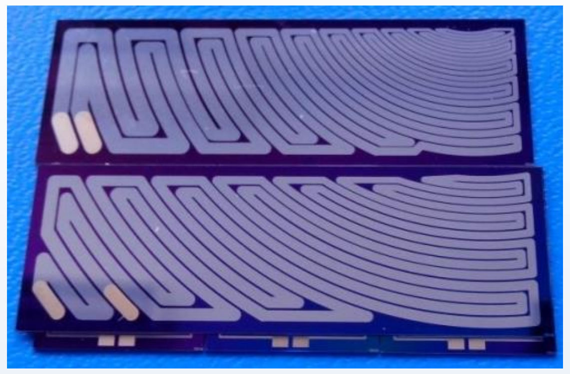
Restrictions

No manifolds in Silicon. Each channel has its own inlet and outlet



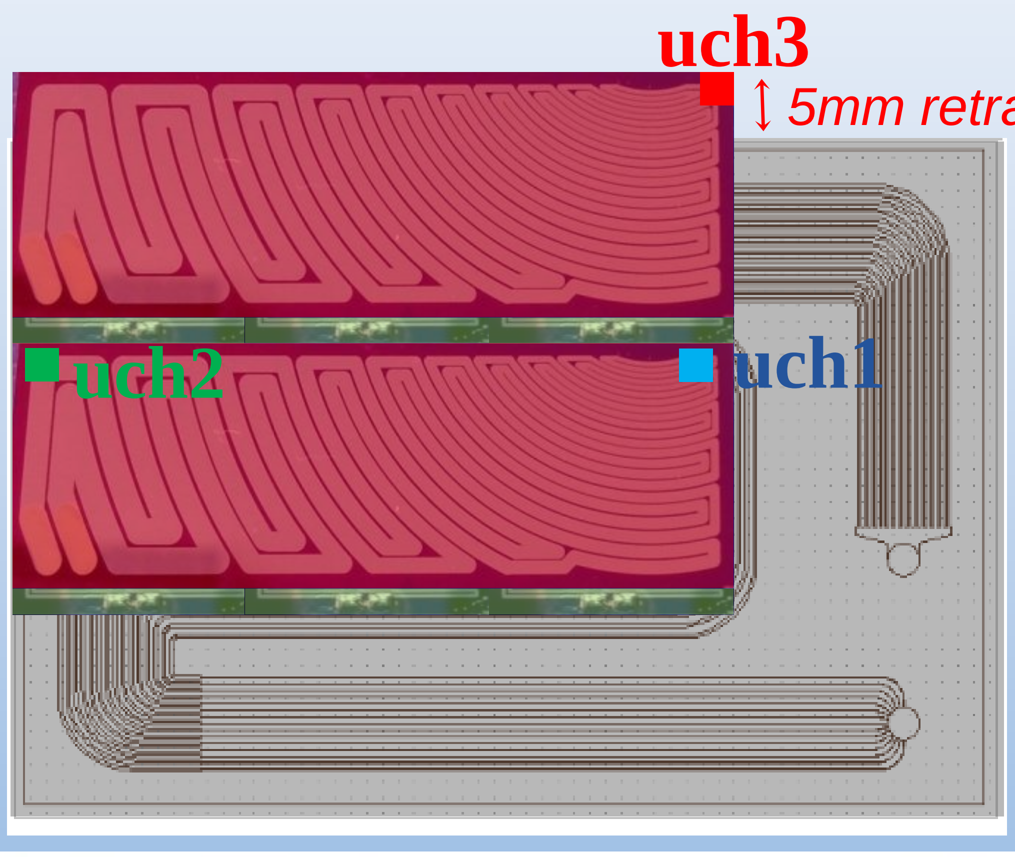
Alignment holes

LHCb VELO: thermal performance



Silicon sensor heater

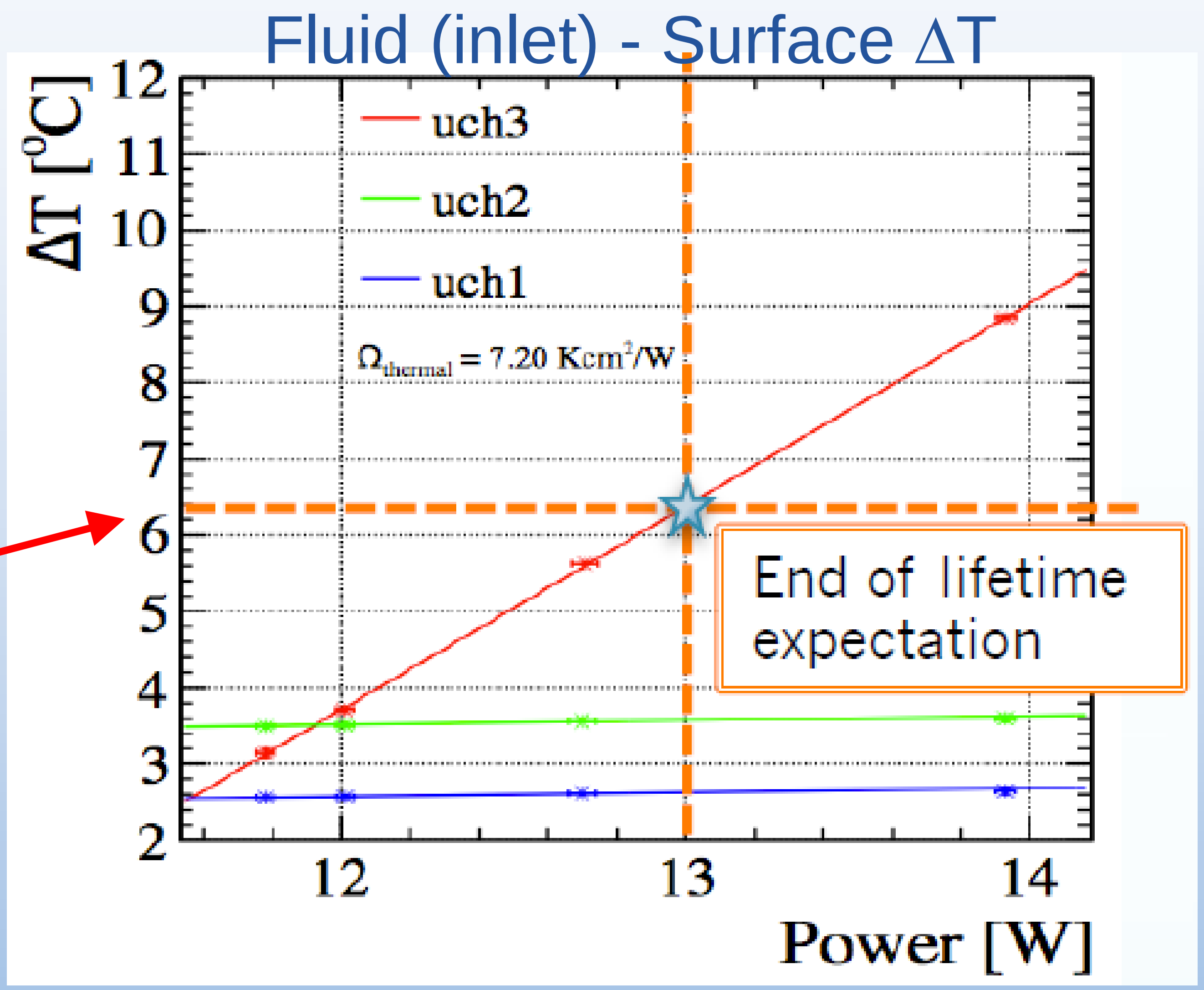
ASICS chips heaters

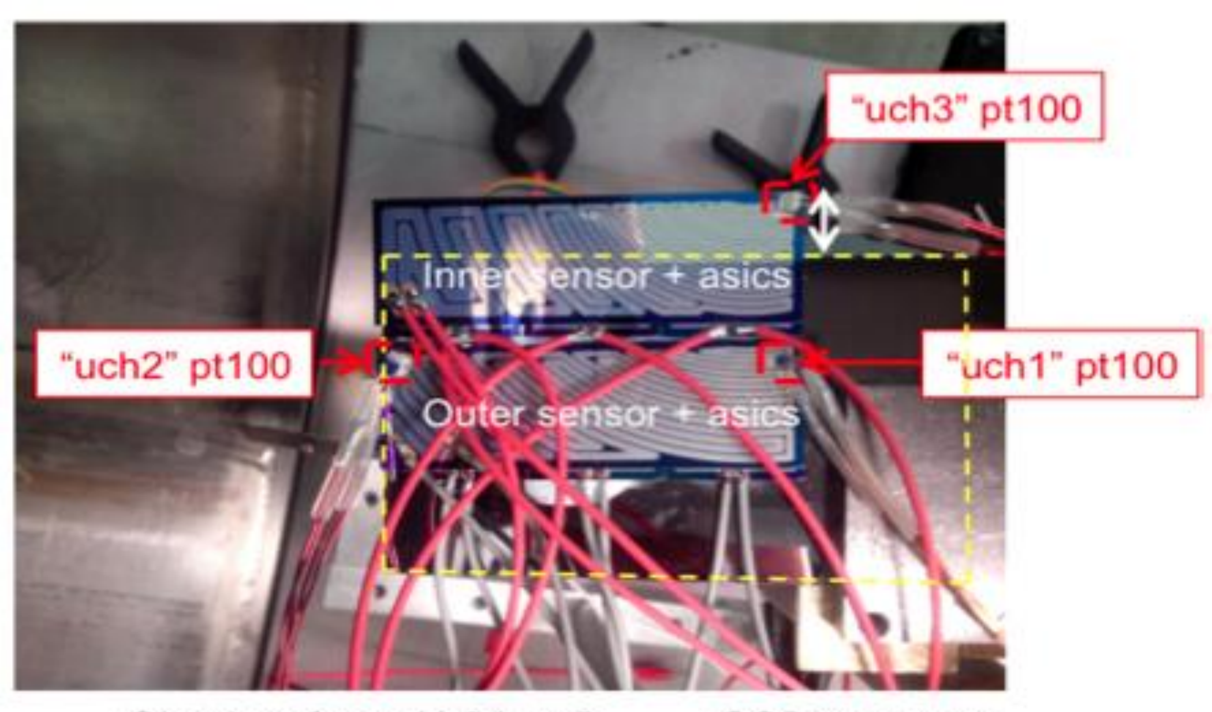


↕ 5mm retracted from detector tip!

- ***uch1*** **and** ***uch2*****: almost constant level**
- ***uch3*****: maximum ΔT is of 7 ºC at highest sensor power.**

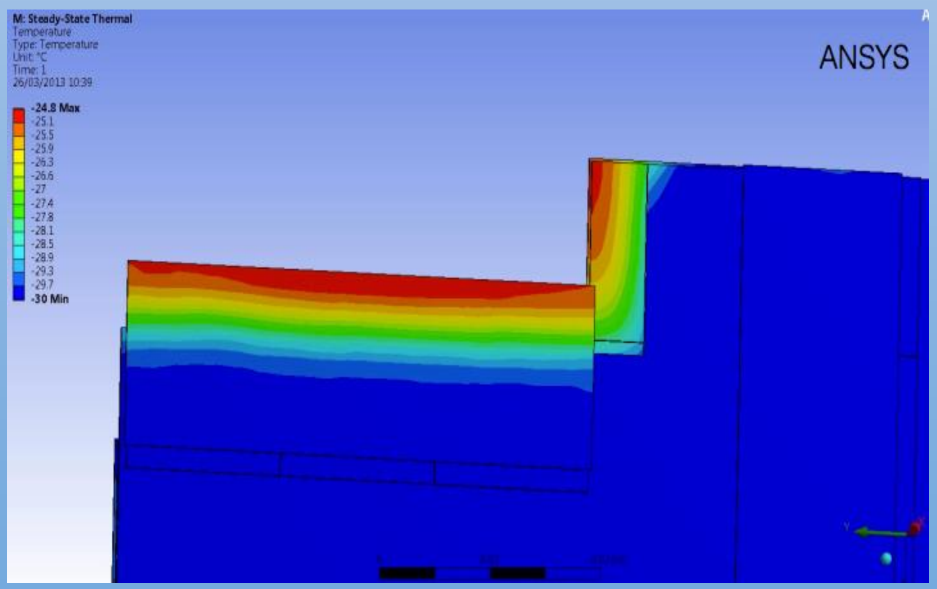
With an inlet fluid temperature of -30 ºC, the detector can be held at a temperature below -20 ºC with some margin.





Glued surface: 11,34 cm2 CO2 connector

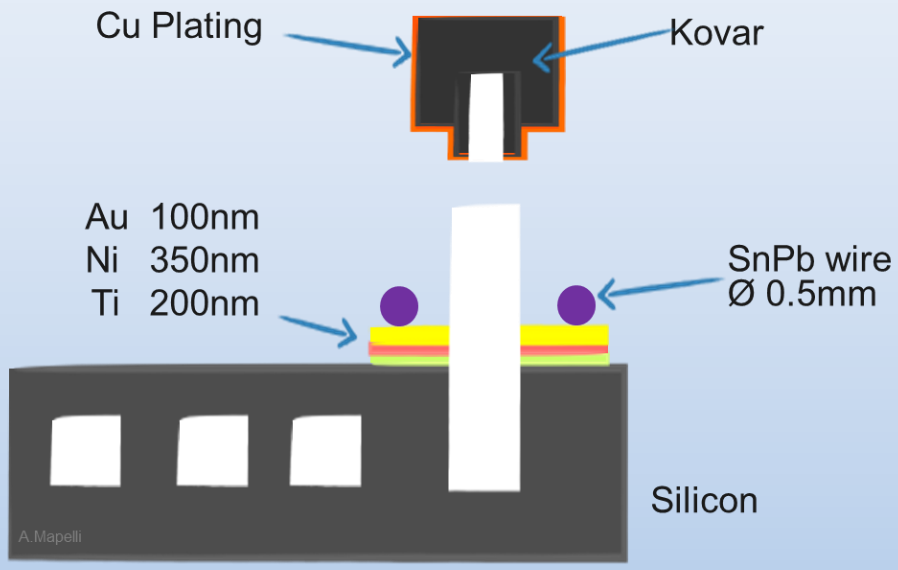
Well predicted by ANSYS simulations of on-module Thermal conduction

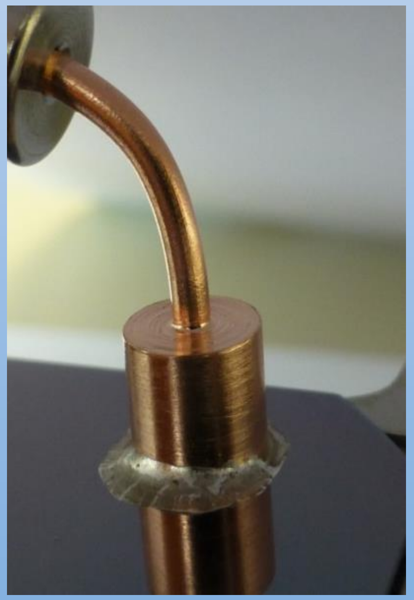


Hydraulic connections to micro channels

Flux-less SnPb reflow soldering in vacuum.

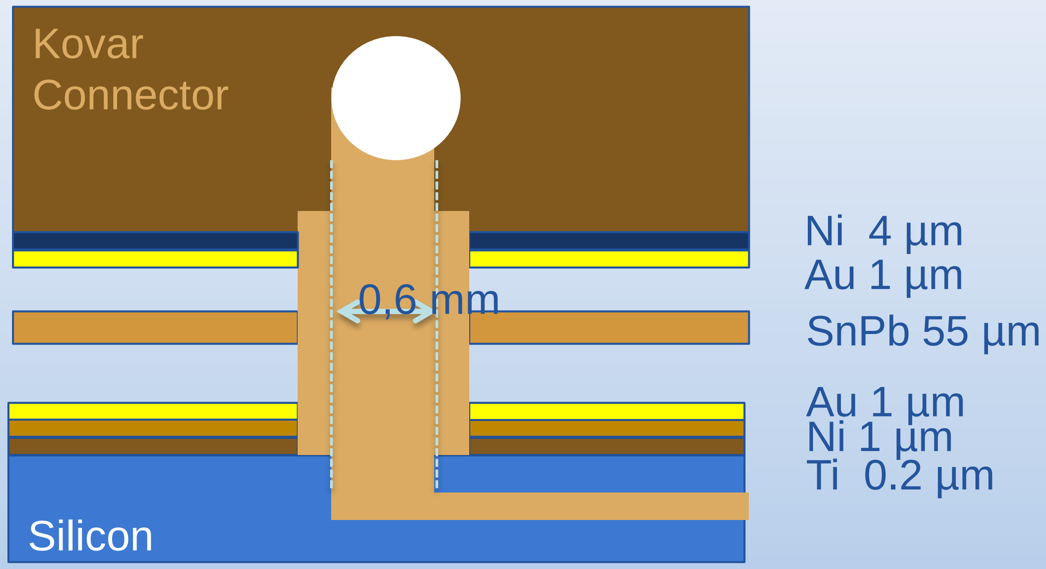
NA62 GTK : pressure 20 bar

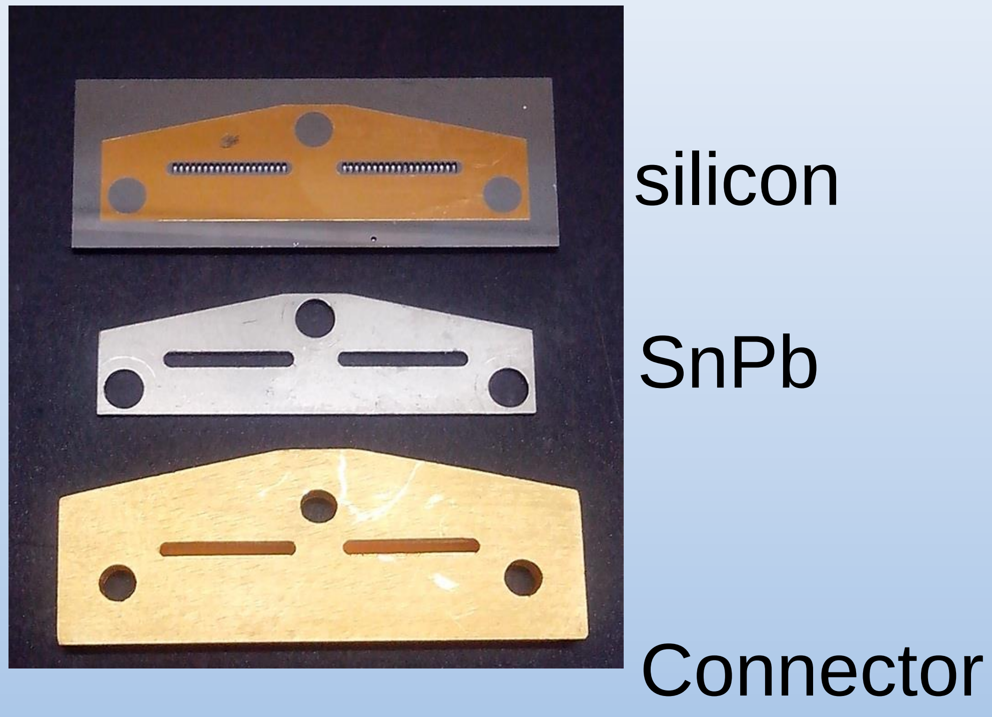


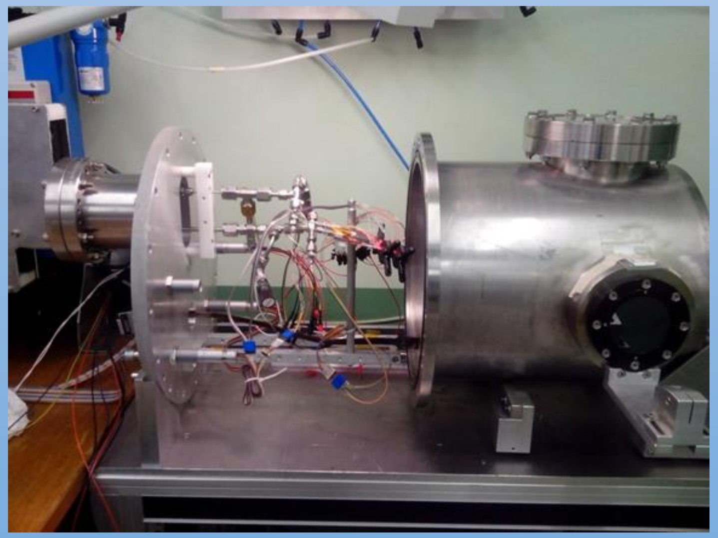


After soldering

LHCb VELO : pressure 170 bar

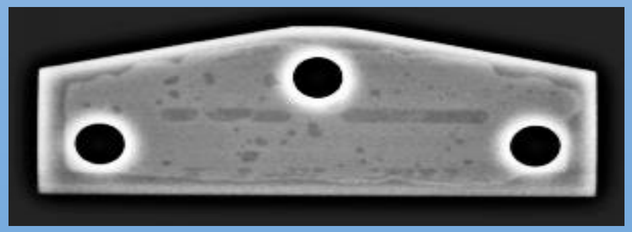






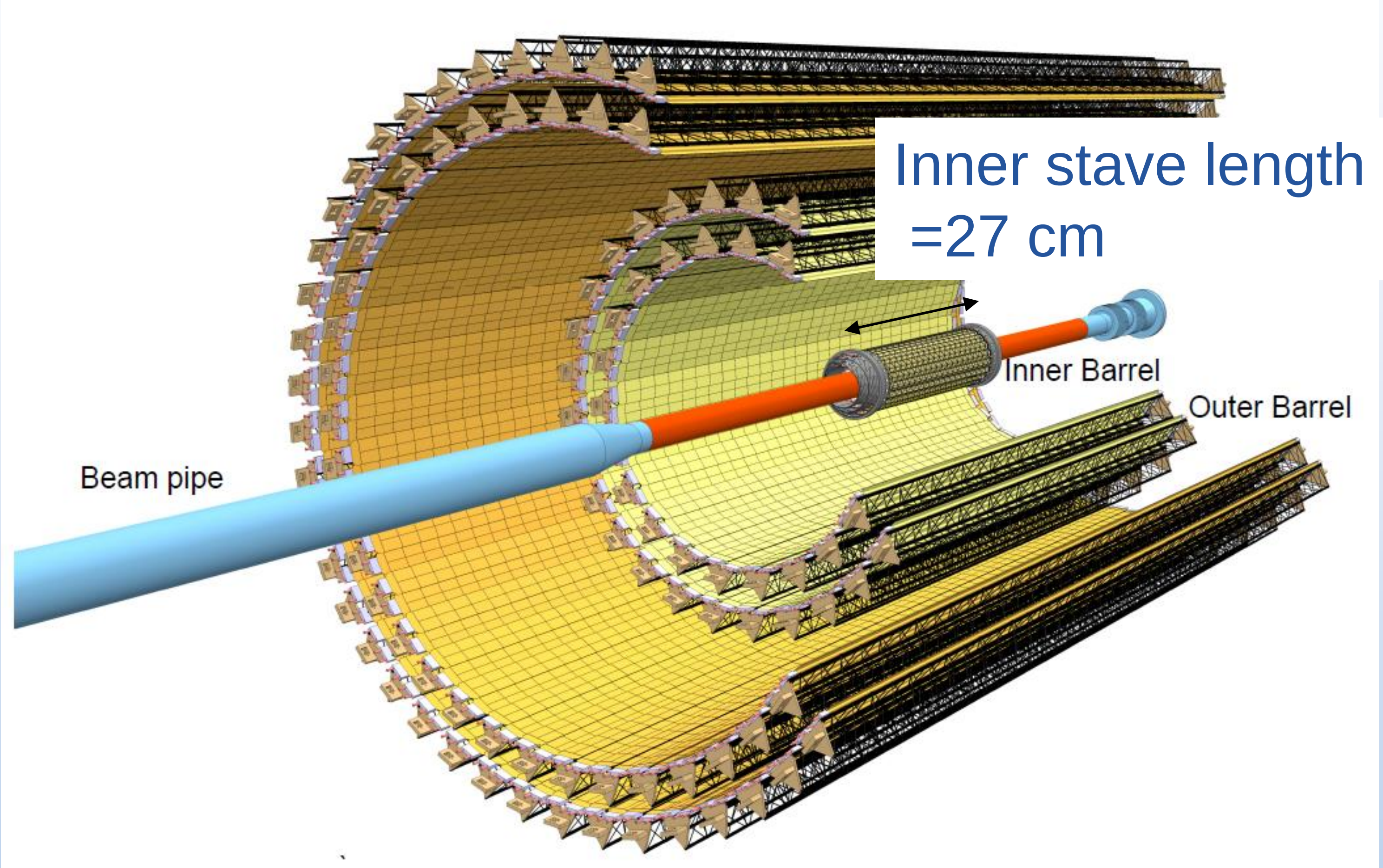
Vacuum reflow oven.

After soldering



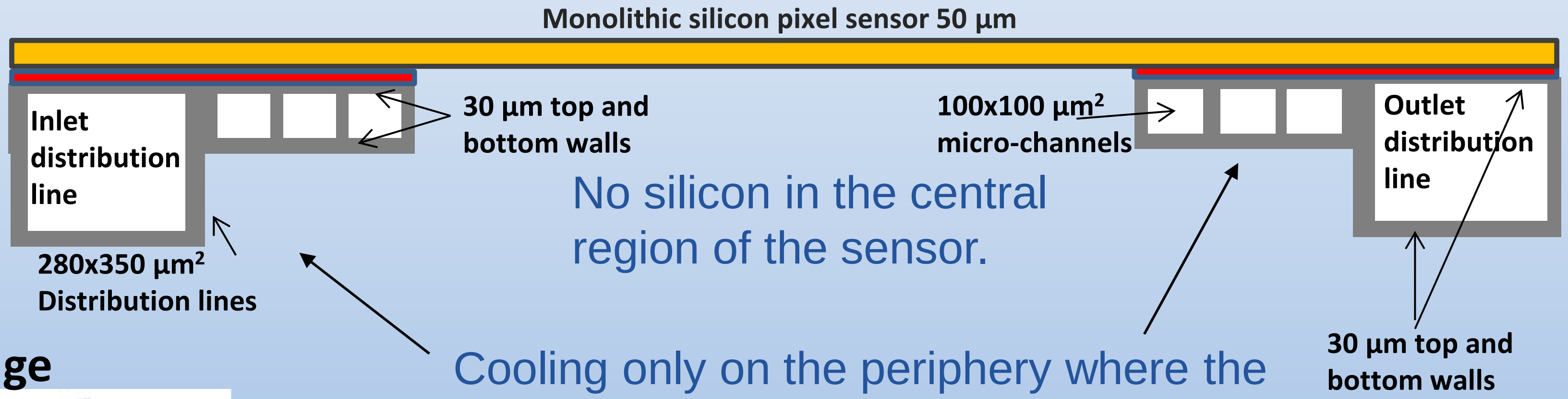
Xray image (small voids)

ALICE ITS upgrade option: building a stave.


Inner stave length =27 cm

«Frame» design :

Cross-section view :

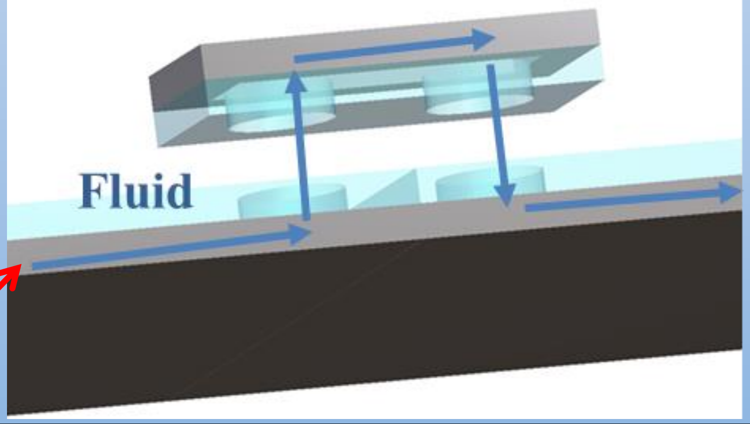


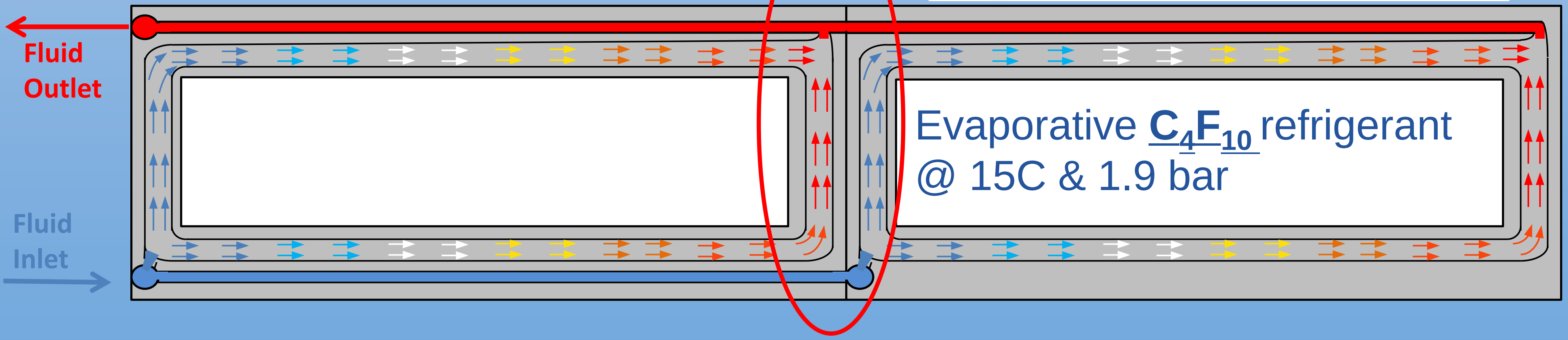
No silicon in the central region of the sensor.

Cooling only on the periphery where the ASIC dissipation is highest.

Total stave composed of 5 devices : interconnection using ˝micro-bridge˝.

The micro-bridge

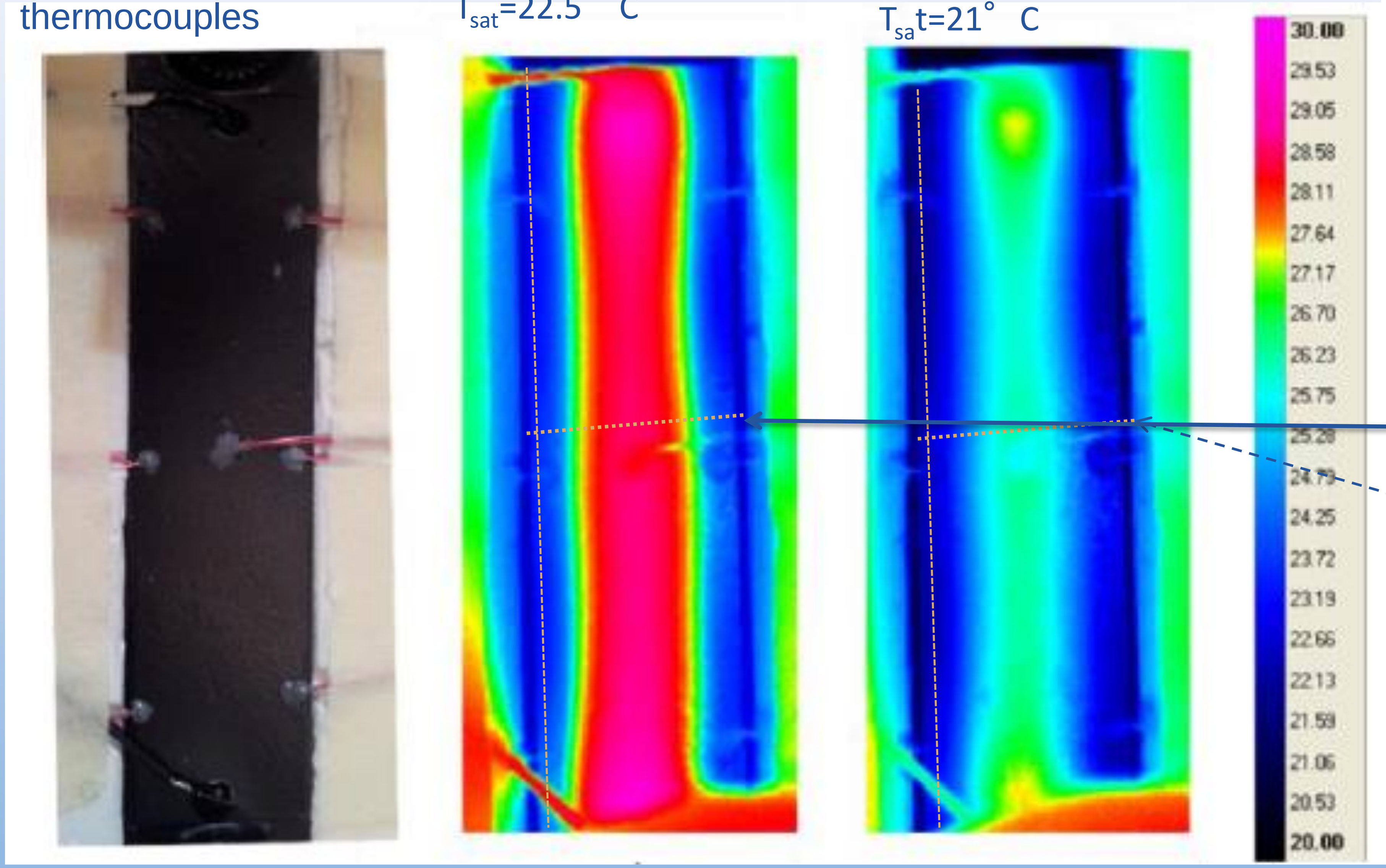




Evaporative C_4F_{10} refrigerant @ 15C & 1.9 bar

- Prototyped on 4” wafers
- produced on 6” wafers

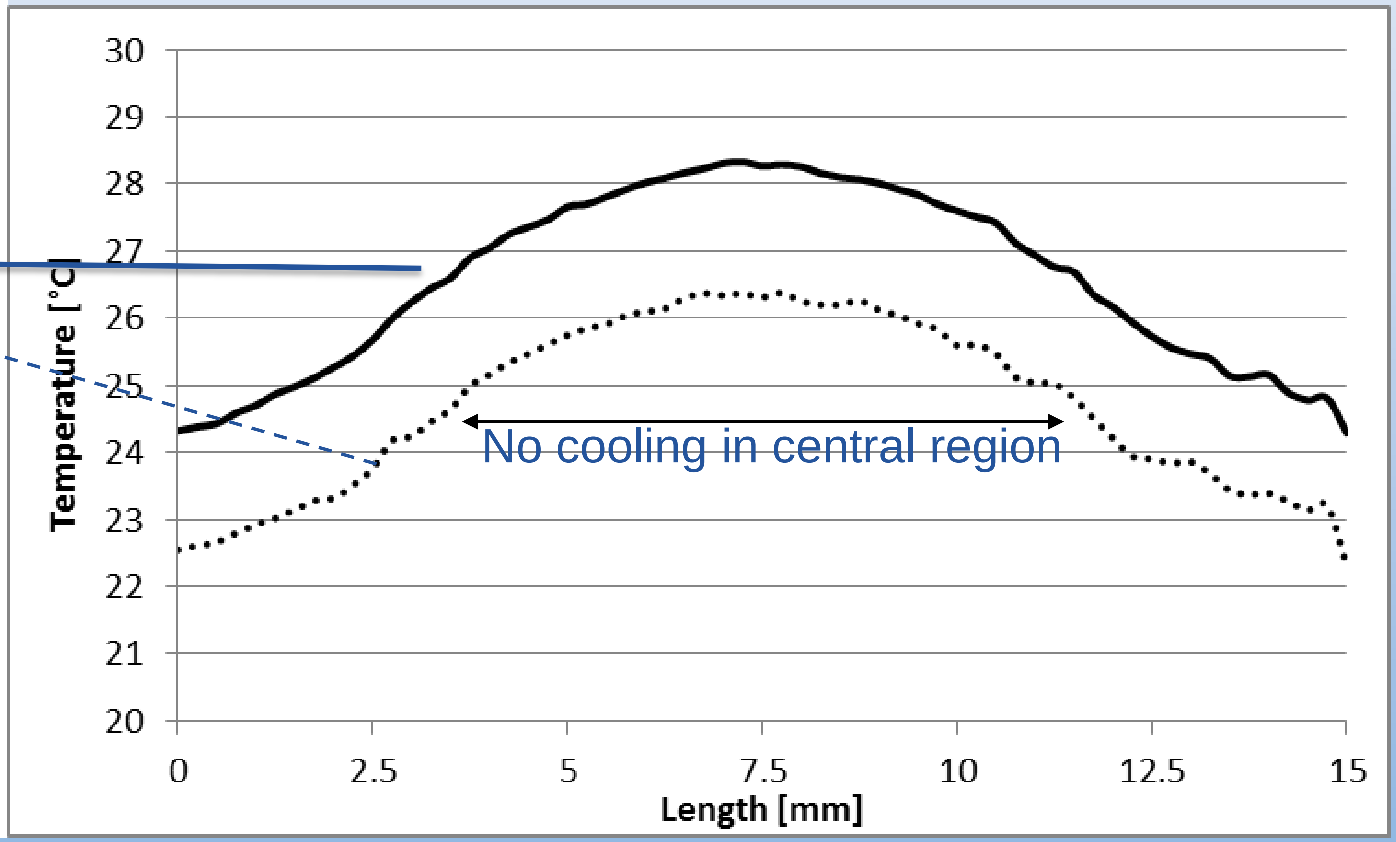
ALICE ITS: thermal measurements.


Dummy chip top surface with two electrodes and seven thermocouples

$G=300$ [$kg \cdot m^{-2} \cdot s^{-1}$]
$T_{in}=21$° C
$T_{sat}=22.5$° C

$G=750$ [$kg \cdot m^{-2} \cdot s^{-1}$]
$T_{in}=19.5$° C
$T_{sa}t=21$° C

single frame with uniform $P=0.3W/cm^2$



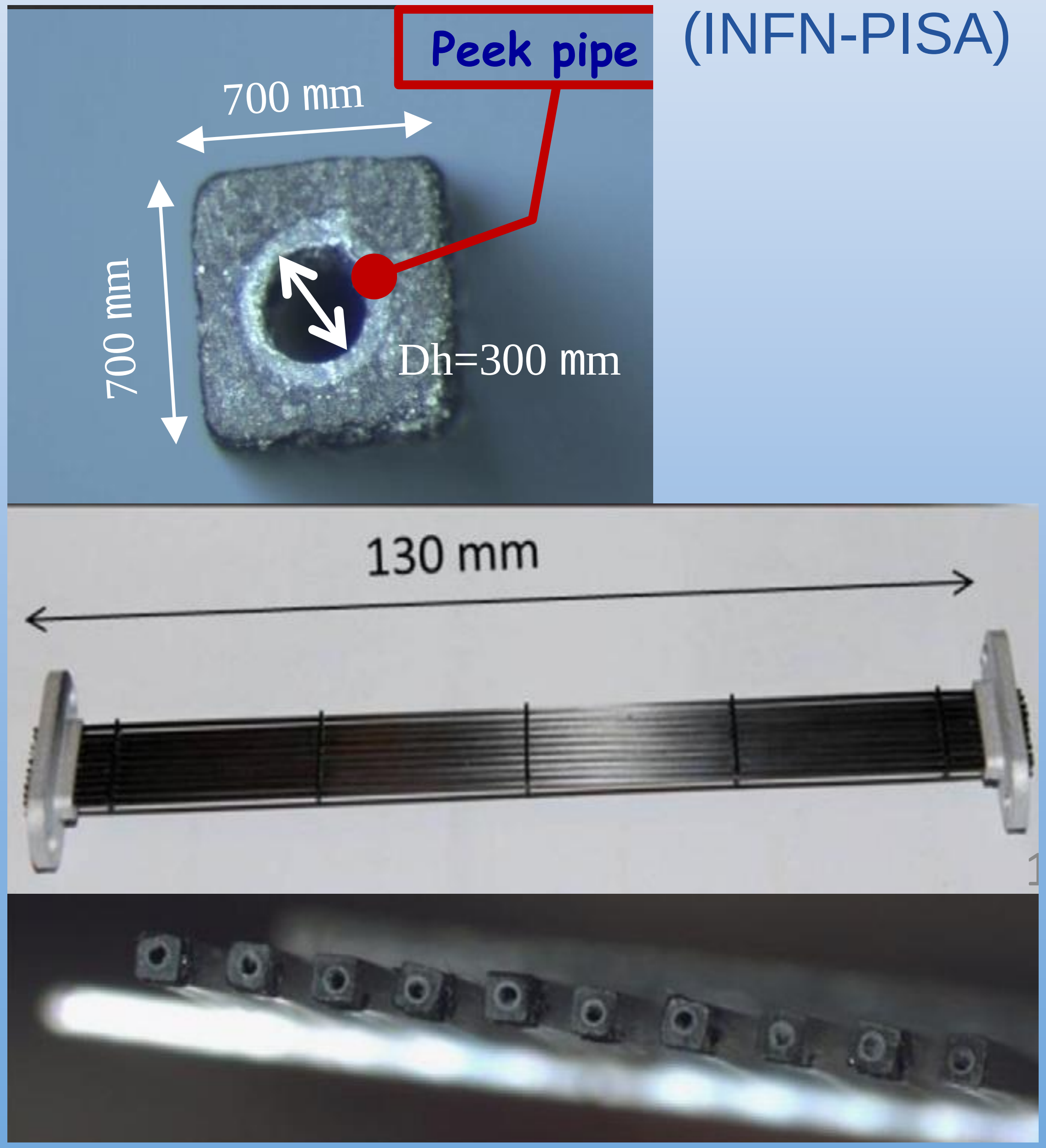
Conforms to spec: $T_{max}< 30$ °C and
$\Delta T_{sensor}<5$ °C
with $T_{sat}=21$ °C (well above the 15 °C cavern dew point).

Atlas & CMS: pixel phase 2.

No approved projects, but some ATLAS groups are very interested in Si CO_2 micro channels and are starting exploratory developments.

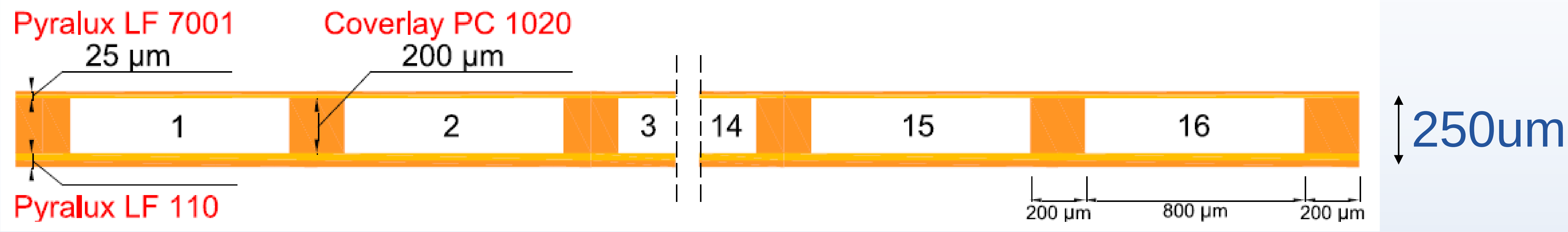
Also investigating 3D ceramic printing of micro channels substrate.

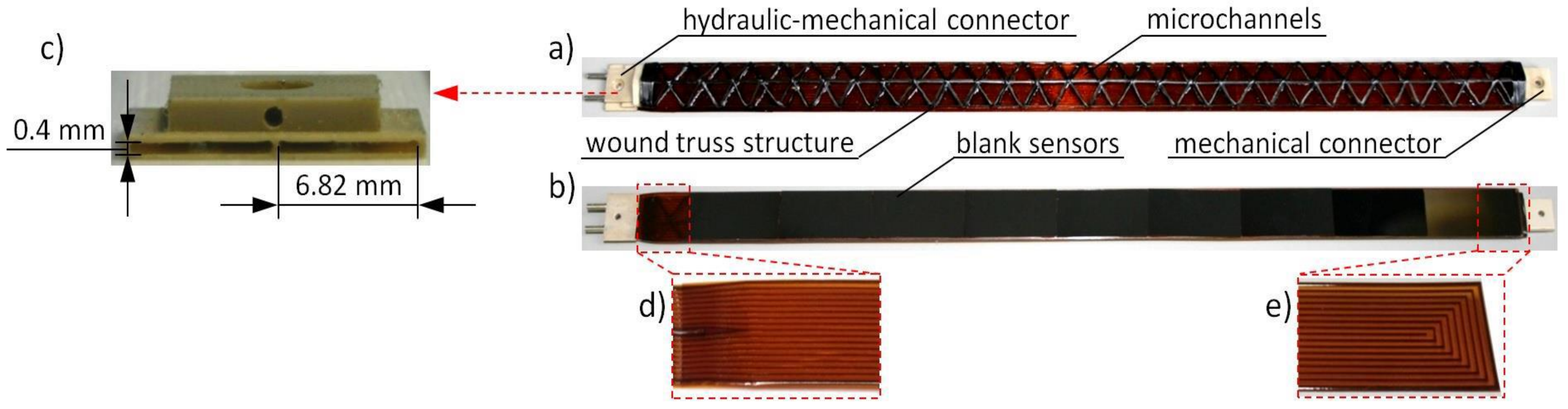
CO_2 micro channel prototype for FE-I4.



Carbon fibre reinforced plastic with CO_2 (INFN-PISA)

Polyimide micro channel.



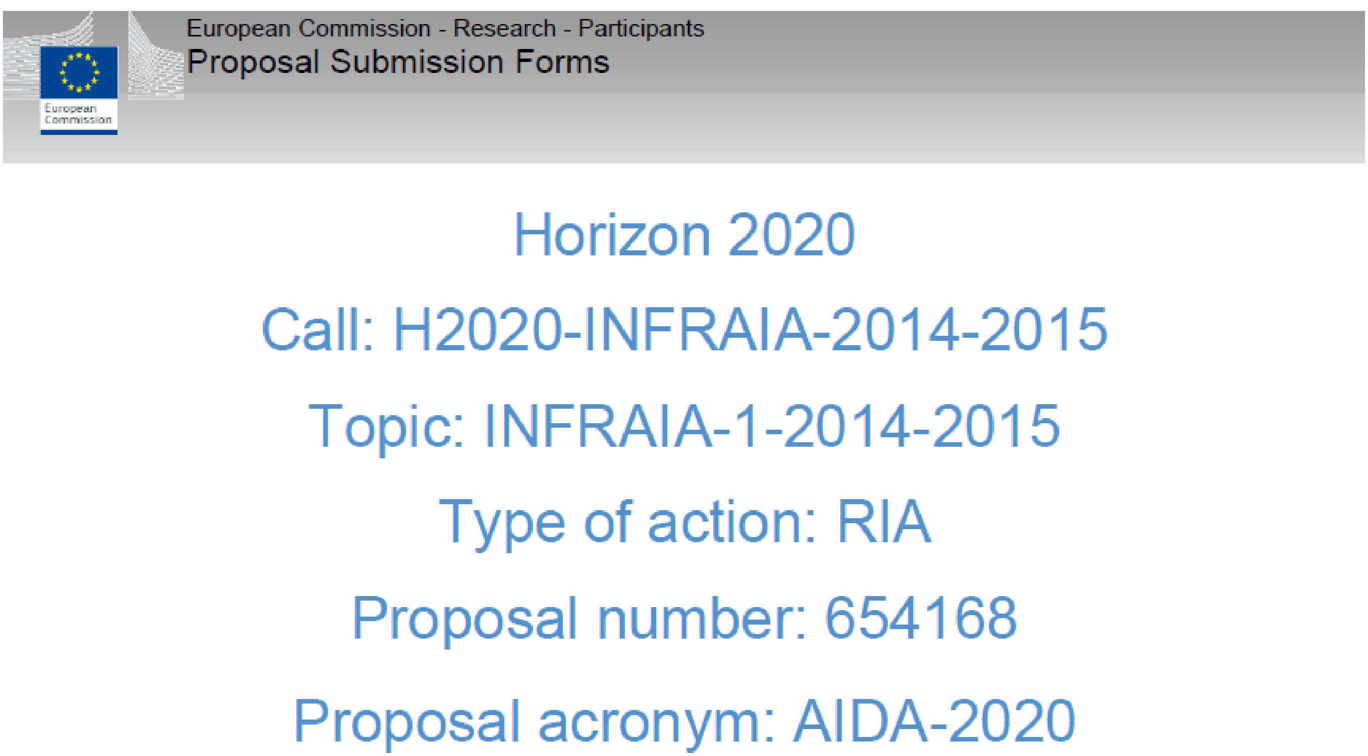


Proposal for ALICE ITS upgrade cooling.

- water or C_6F_4 mono-phase cooling at ~ 30C.
- Power requirement 0.5W/cm2
- Coolant pressure ~10bar.
- CERN & INFN development.

AIDA-2020 proposal: Work Package 9

- “New support and micro channel cooling”
  - Provide access to silicon fabrication technologies.
  - Development of a simulation library for micro fluidics and bi-phase flow in distributed micro channels.
  - Development of a standard for the connection of the devices.
  - Fabrication of prototypes to validate the models and characterise the different fabrication techniques.
  - Set up a specialised facility to implement the procedures and protocols established for characterisation and validation of models and fabrication techniques.



European Commission - Research - Participants

Proposal Submission Forms

Horizon 2020

Call: H2020-INFRAIA-2014-2015

Topic: INFRAIA-1-2014-2015

Type of action: RIA

Proposal number: 654168

Proposal acronym: AIDA-2020

Summary

- Current projects demonstrate that micro channel cooling is very well suited for thermal management of current vertex detectors:
  - high cooling performance, low X/X_0 , radiation hard, no CTE mismatch if all Si.
- It is a flexible technique:
  - Customized layout for optimal performance.
  - Different refrigerants, single-phase and two-phase.
  - Substrate choice: Si (favored), polyimide, …
- Device size is limited by wafer dimension: construction of long staves poses challenge for interconnecting many devices.
- Connection of a macro tube to a micro channel is delicate.
  - Sn/Pb soldering seems best suited but still needs further development & consolidation.
- AIDA proposal for development of micro channels.

References

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