Micro-channel cooling project for AIDA 2020 WP9.2a in Pisa

Micro channel experience in Pisa

- In silicon embedded
- CFRP

Plan for testing microchannel cooling for the new MCM board of TPC electronics

- Time schedule

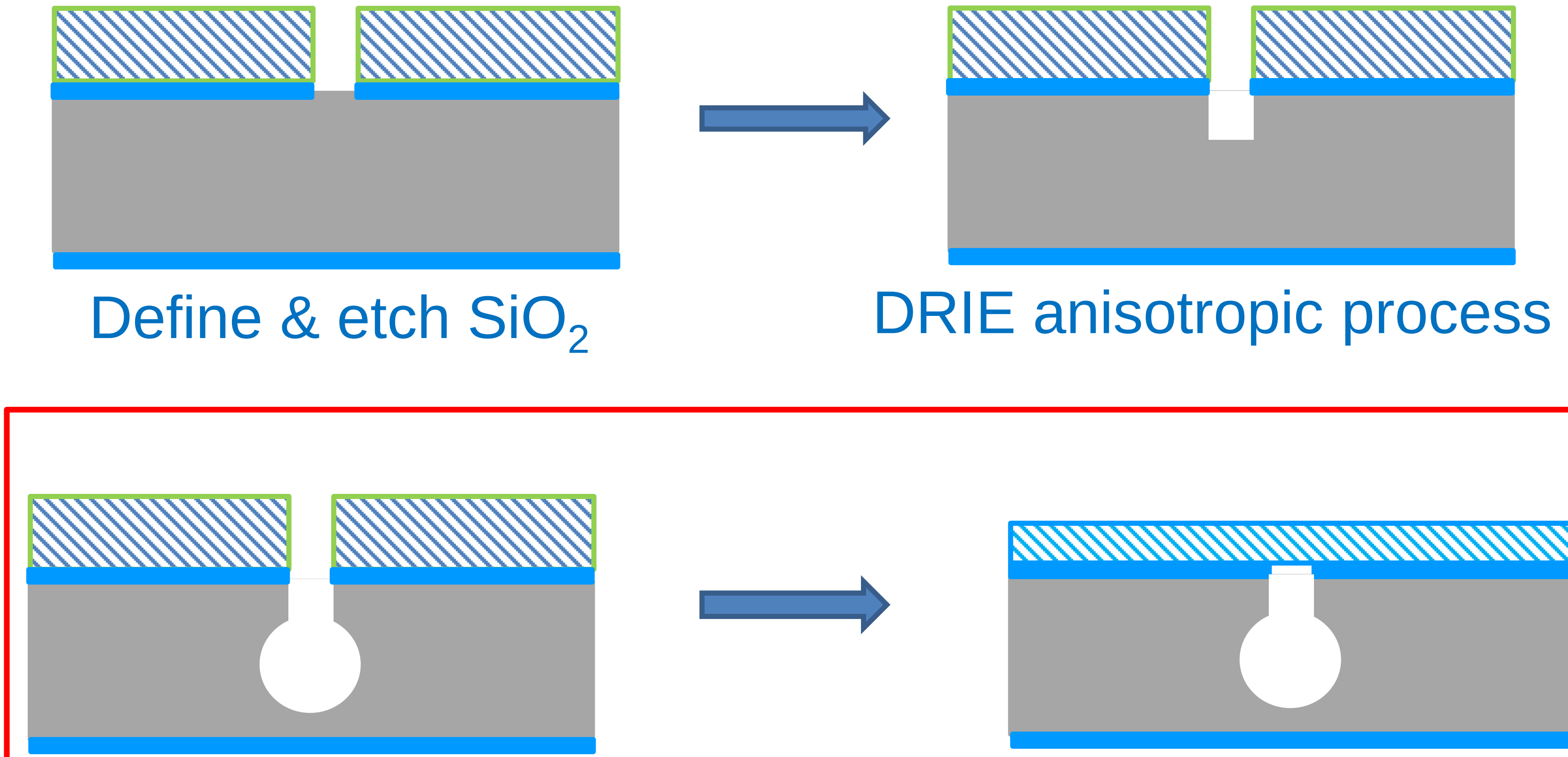
Cooling for HL-LHC pixel detectors

- Pixel detector for HL-LHC will have a high power density to be extracted in order to have stable detector operation
  - Interconnection density and radiation damage will imply power more than 1 W/cm^2
- Stable detector operation should be at low T (-20 : -30 ^{o}C)
- Cooling system should be material budget “light”:
  - Phase transition cooling with CO_2
  - Cooling system should be integral part of the detector
  - Compatible with Pixel detector technologies
- Our R&D proposal plans to develop micro-channel cooling:
  - Pultruded CFRP
  - Embedded in Si with DRIE Technology

DRIE PROCESS BY FBK TRENTO

Deep Reactive ion etching process

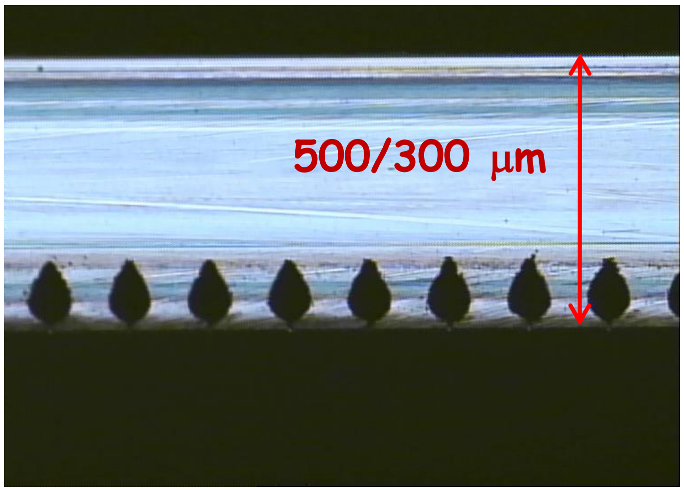
Process flow ion et

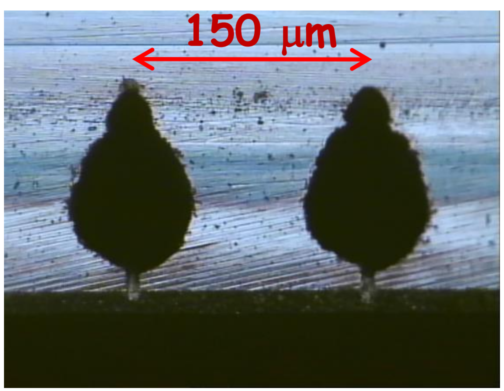


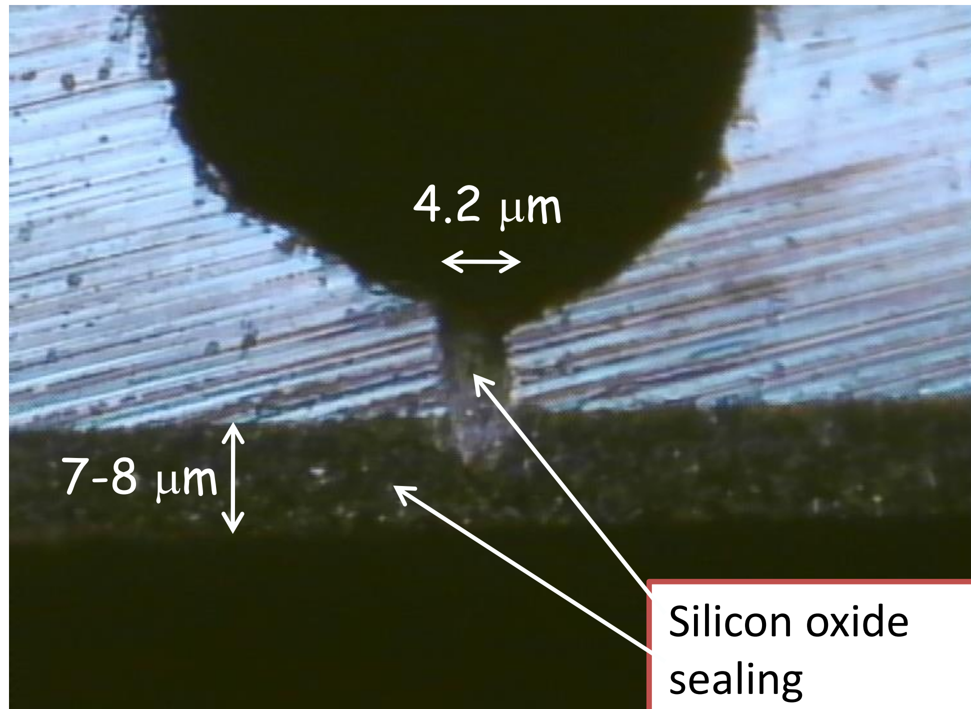
Micro-channel: embedded on carrier Si-wafer

- Past experience made in collaboration with FBK DRIE processing *

From a 4-inch wafer we build 5 silicon modules of 12.8 width mm x 60 mm length x 500 μm thick with 61 micro-channel embedded to perform cooling tests







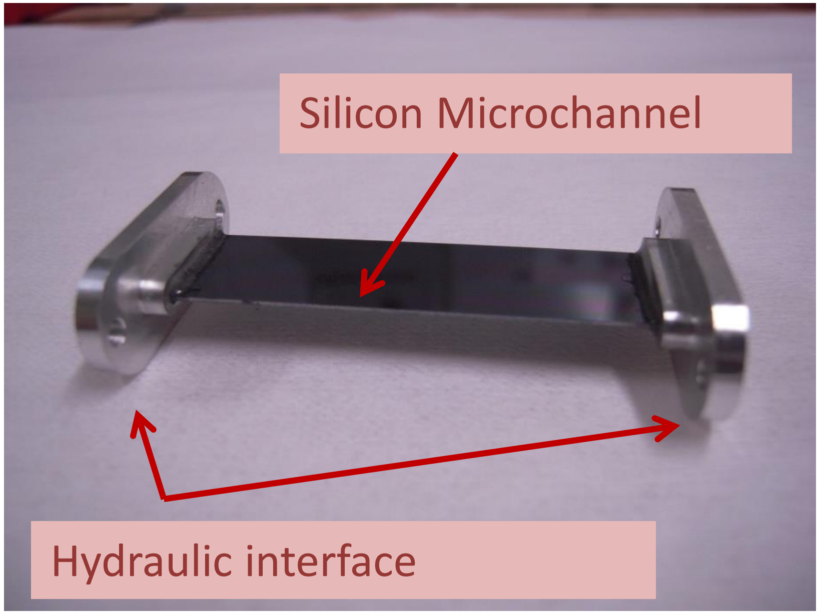
In the picture, the dimensions of the module prototypes already produced and qualified

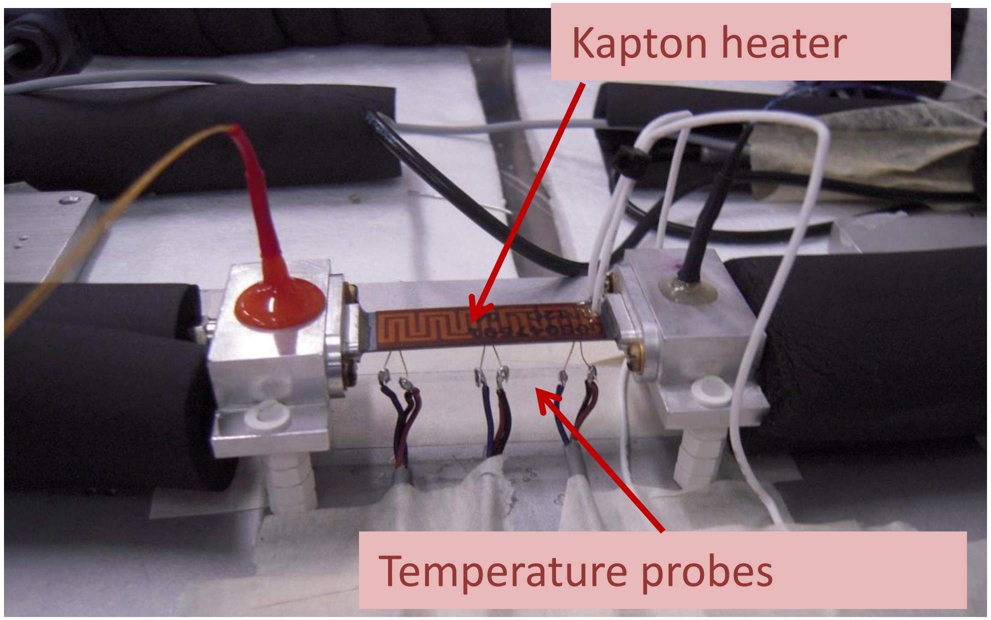
* INFN-SuperB experiment

M. Boscardin et al. , NIM A 718 (2013) 297–298

Microchannel silicon prototype test

In the test set-up we used the same hydraulic interface used for CFRP microchannel module, kapton heather on one side and N.3 temperature probes on the opposite side, coolant used is water-glycol 50% @ 10 °C .



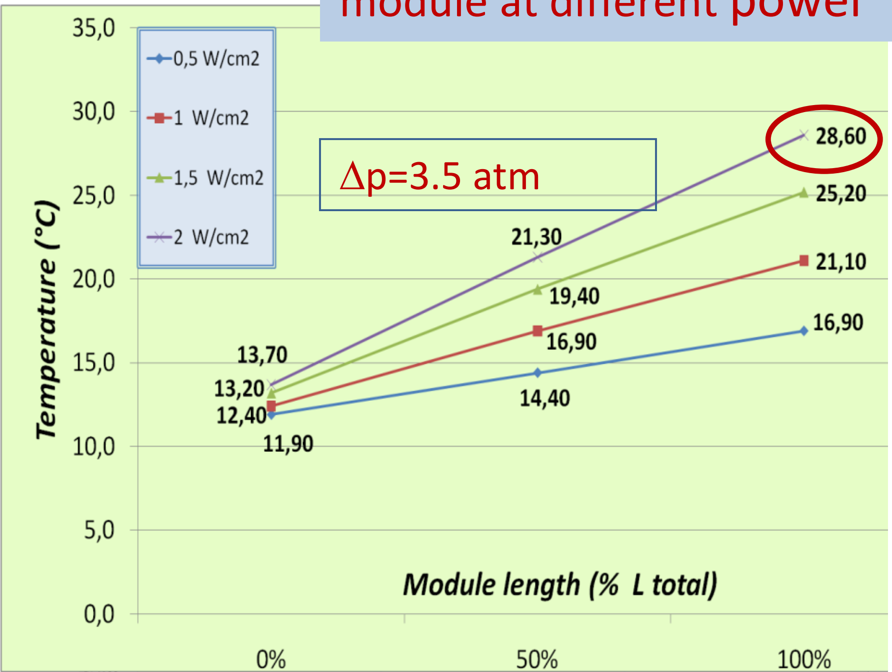


Tests on prototypes is done, test run have shown that the oxide layer sealing operates without leak at the test pressure of flow (7.0 atm) .

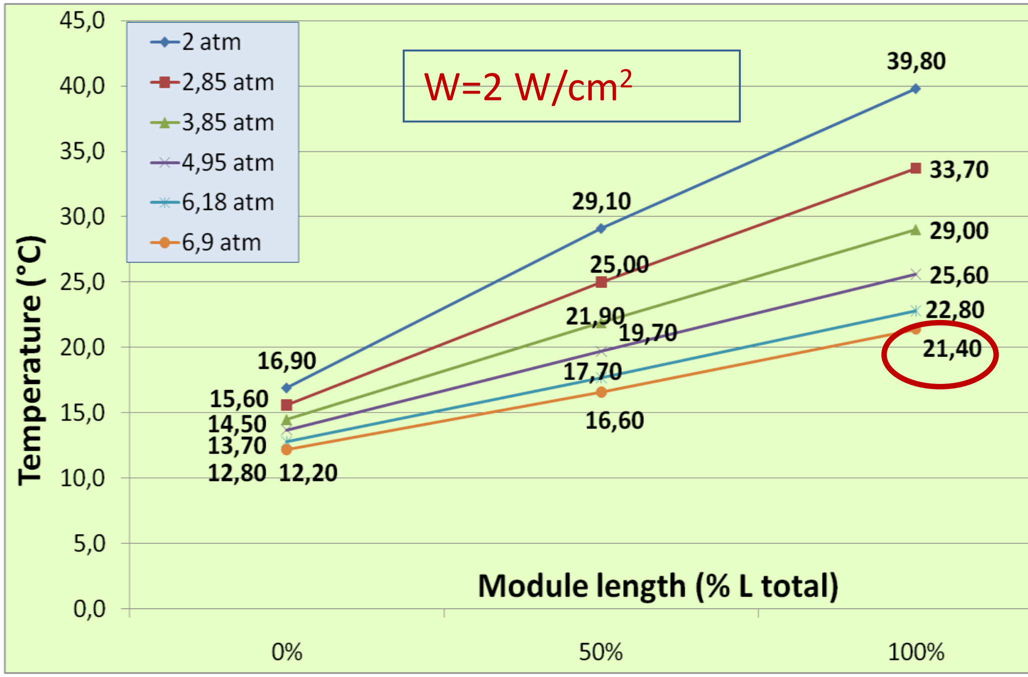
The oxide layer that seals the microchannels resists at pressures greater than 100 atm (limit of the pump of the circuit).

Microchannel silicon prototype test

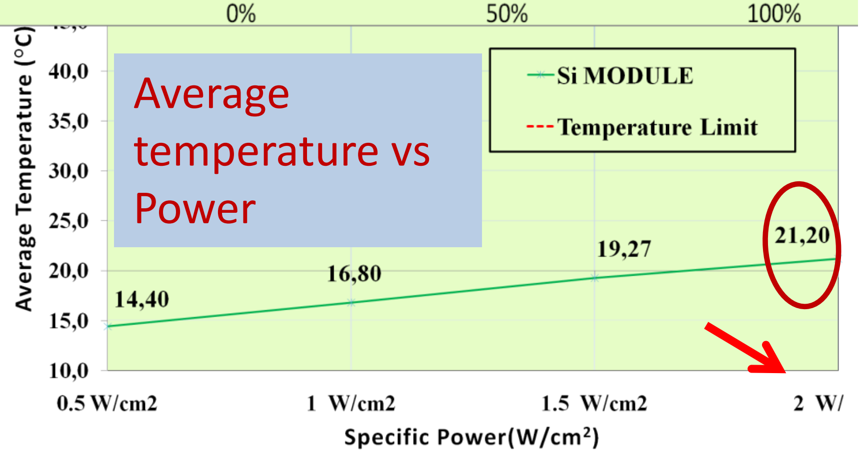
Temperature along the silicon module at different power



Temperature along the silicon module at different pressure



Average temperature vs Power



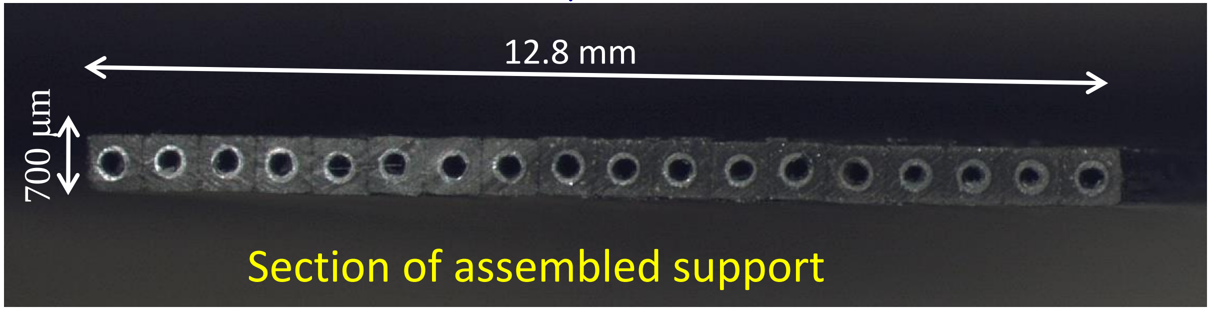
- Results

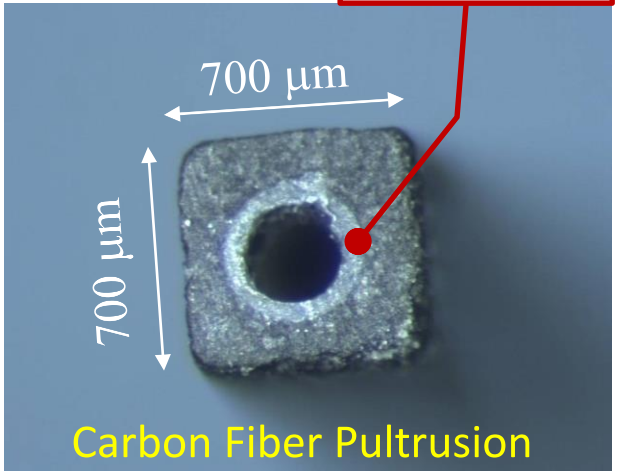
- Silicon module temperature strongly dependent from the value of coolant flow .

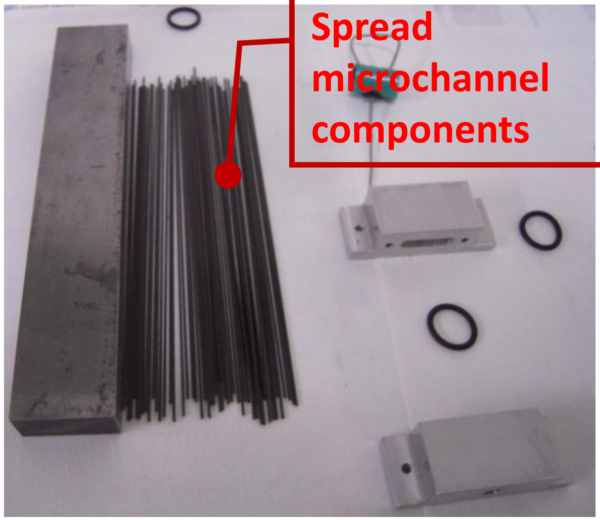
Full Module support

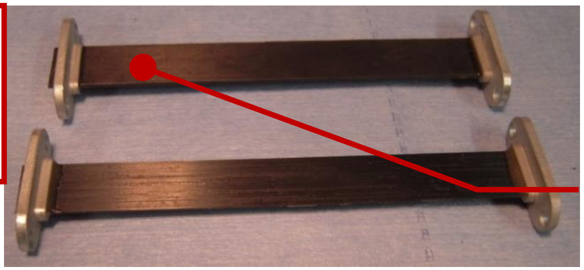
CFRP MICROCHANNEL MODULE

Obtained by pultrusion C.F. TohoTenax HTS 40 , adding and gluing in special masks, side by side, 18 single micro-tube.
The inner diameter of the peek micro-tube is 300 μm, the thickness of the square composite profile is 700 μm .





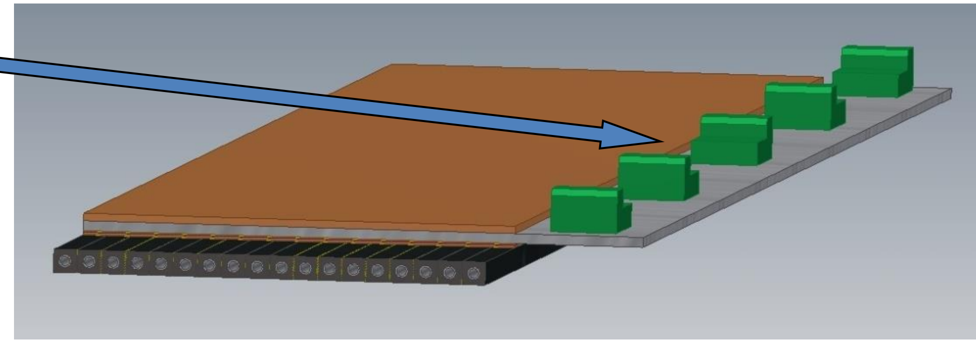




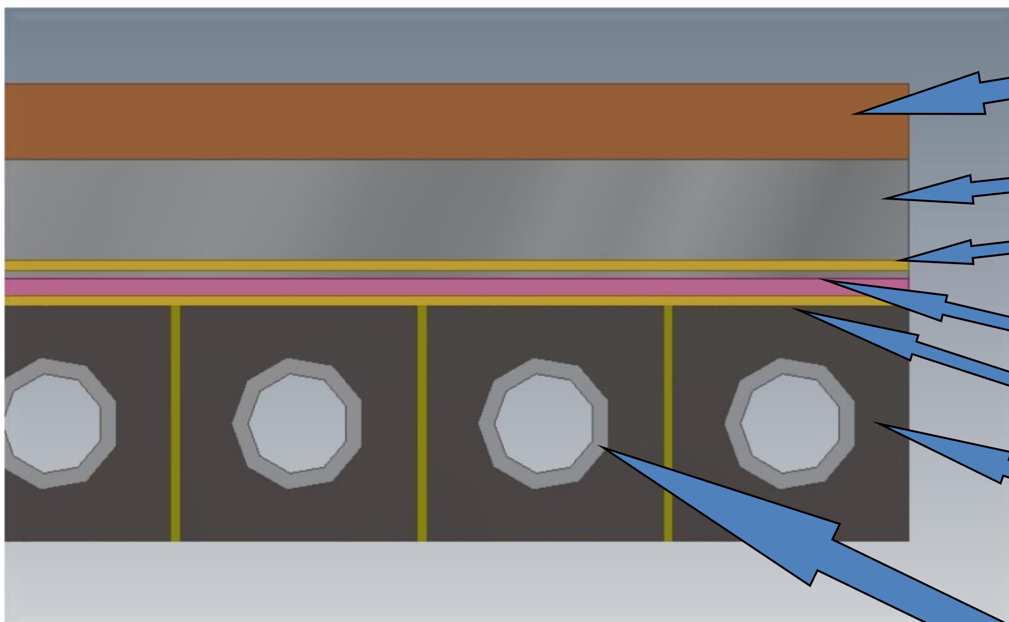
The total radiation length of this module is 0.28 % X_0
An internal peek tubes 50 μm thick is used to avoid moisture on carbon fiber.

Module Sample Structure

N°5 PT100 temperature probes/side on Aluminum



Single side configuration (cut view)



Kapton Heather 220 μm

Aluminum foil 300 μm

Glue 25 μm

Kapton+Aluminum 50μm +10μm

Glue 25 μm

CFRP micro-channel th=700 μm

Peek Tube/Di=300 μm, th=50 μm

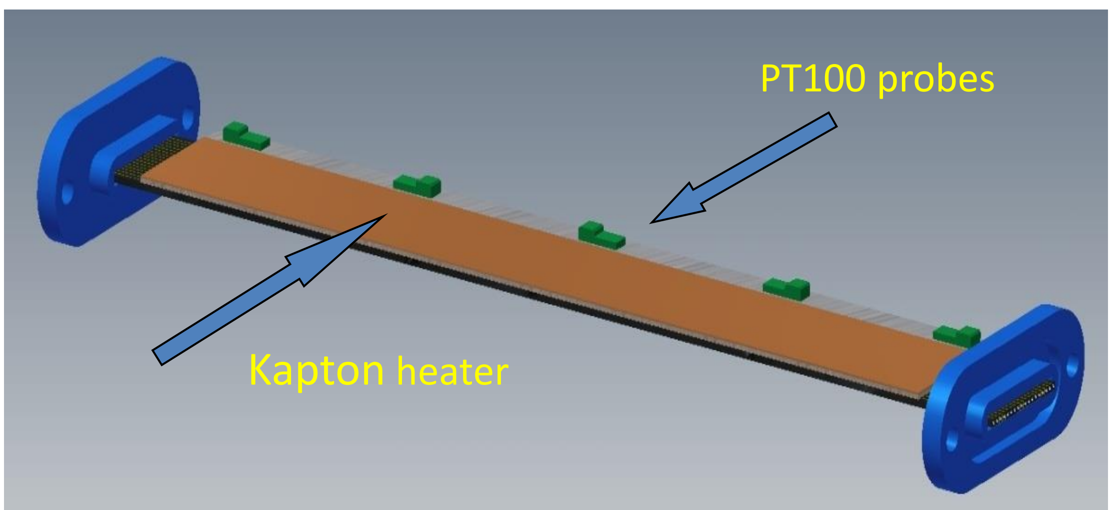
Module Samples

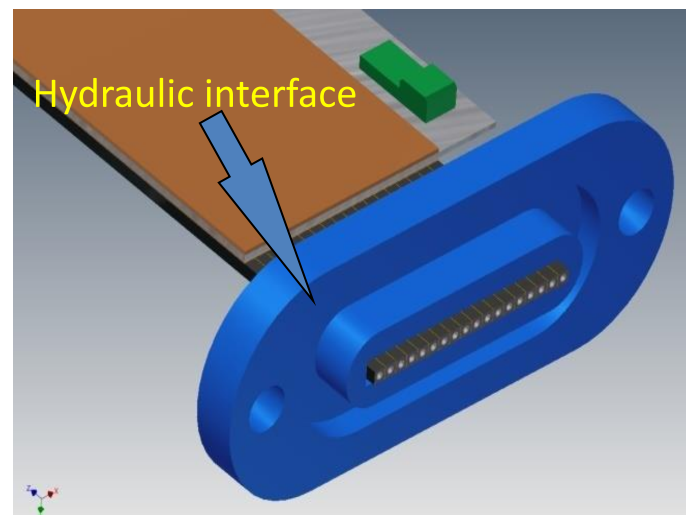
A kapton heater is glued on the Microchannel CFRP support structure to dissipate the power density.

On the bottom of the heater there is an aluminum foil 300 μm-thick, in place of the silicon detector. On the top, to read the temperatures, n.5 PT100-probes are glued, positioned just laterally to the heater.

An Aluminum kapton foil, 75 μm-thick, is sandwiched between the Microchannel support structure and the aluminum foil, simulating ground plane in the real detector. There is also a glue layer between each components (30μm-thick on average).

The power dissipated by the kapton heater could be tuned from 1.0 to 3.0 W/cm^2, coolant used is water-glycol 50% @ 10 °C .





Test Procedures

The power dissipated by the kapton heater could be tuned from 1.0 to 3.0 W/cm^2 , coolant used is water-glycol 50% @ 10 °C .

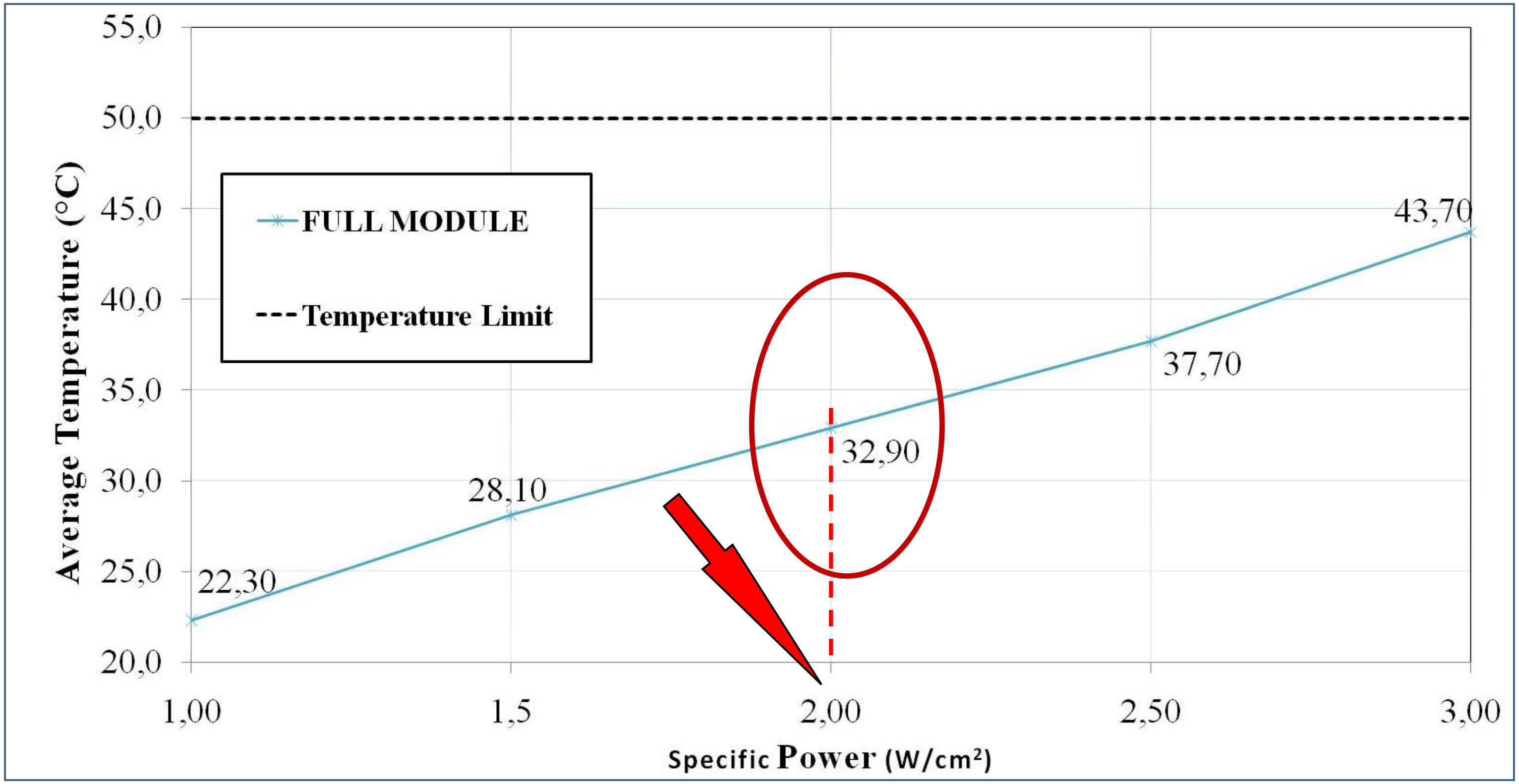
The tests have been performed in standard way for all kinds of module.
During the tests the average temperature of the environment was 22.0 °C (for these kind of test there is no need to avoid environment free convection and irradiation).

The test was performed by setting the fluid pushing pressure at 1.5 atm, the (suction) pressure 0.5 atm, the fluid temperature 10 °C. The electrical power was then switched on and set to the lower specific power (1.0 W/cm^2). The maximum pressure was set 3 atm and the heater power tuned up according to the experimental program (1.0 to 3.0 W/cm^2)

In all conditions, the DAQ system is able to record up to 24 parameters at the same time.

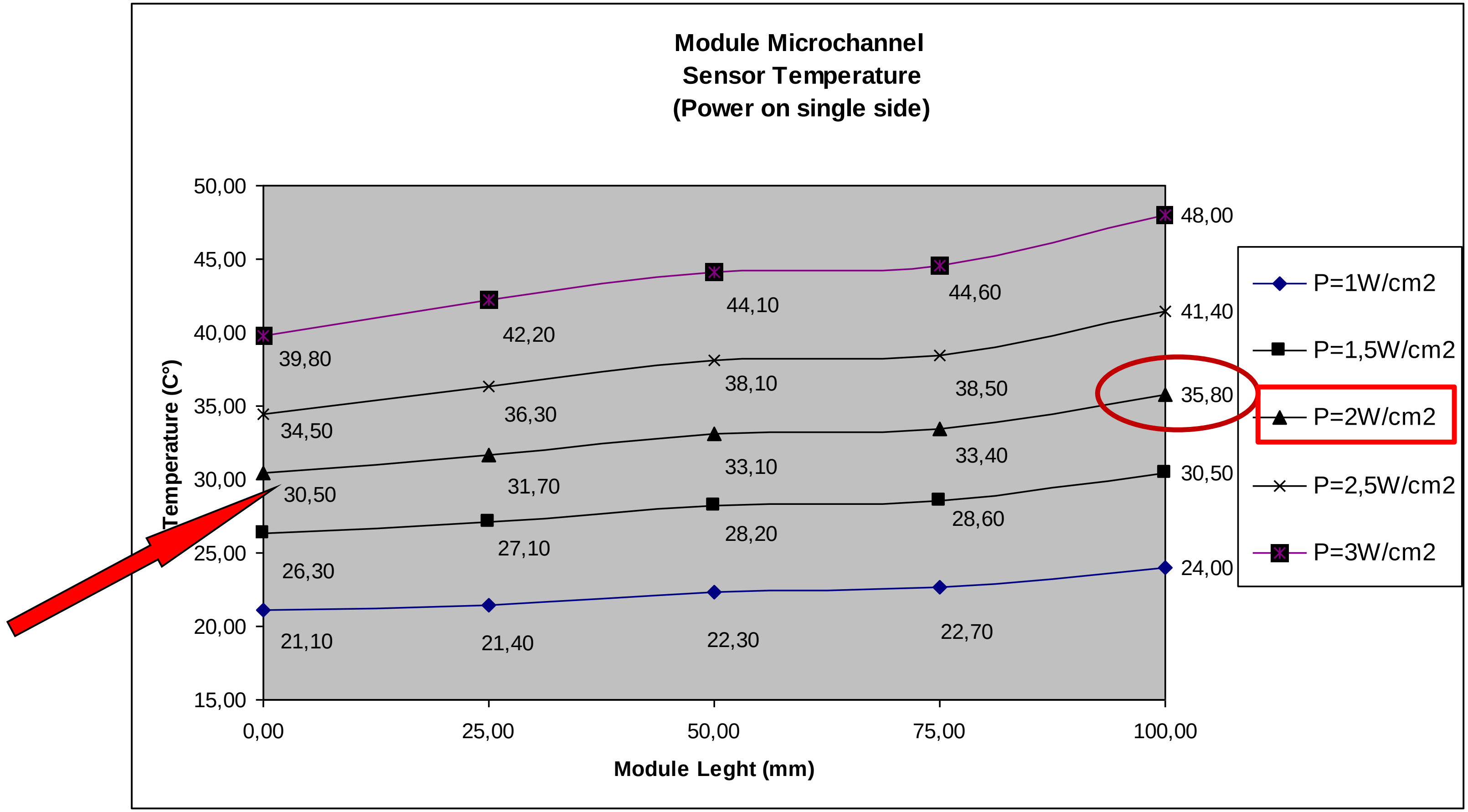
Full module test results/1

Tests performed on full module sample, length = 120 mm, at Δp =3.6 atm



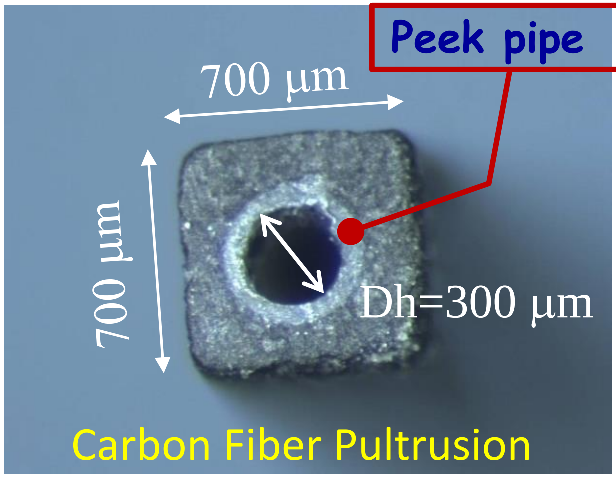
Average module temperature vs Specific Power

Full module test results/2



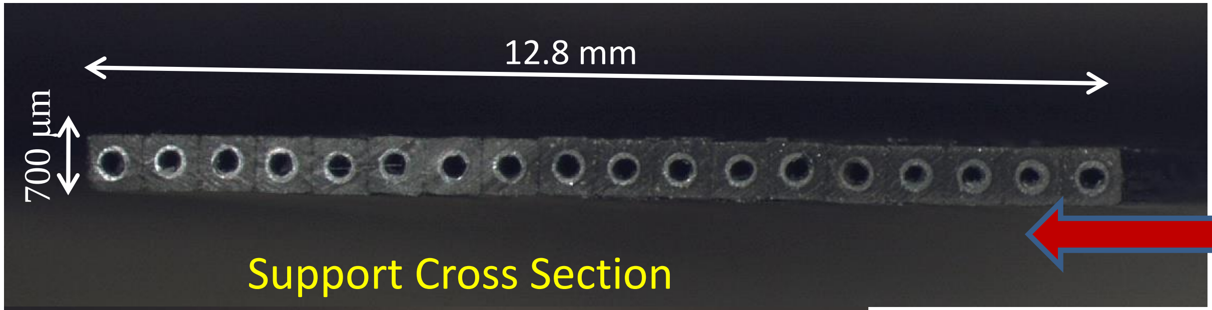
Temperature along the module: ΔT=5,3 °C at 2W/cm^2 and Δp=3,6 atm

Full/Net Module Support



The single base microchannel unit

A square CF micro-tube with an internal peek tube 50 µm thick used to avoid moisture on carbon fiber



Full micro-channel module

The total radiation length (*) of this support is 0.28 $\%X_0$

Net micro-channel module support

Same dimensions of full micro-channel but vacancies of tubes in the structure.

The total radiation length (*) is 0.15 $\%X_0$

(*): Material of the support structure: (C.F. material + peek tube + Water)

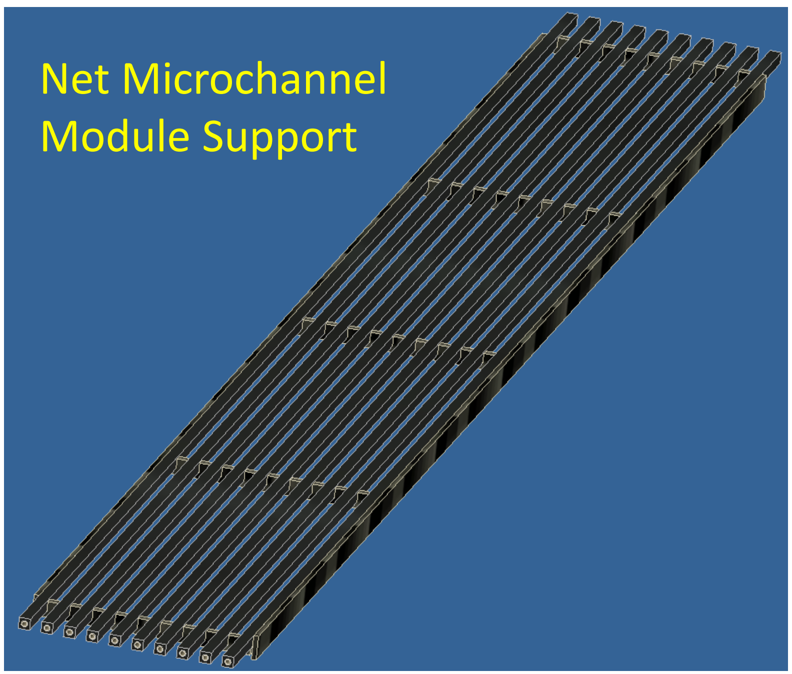
Net Module support/1

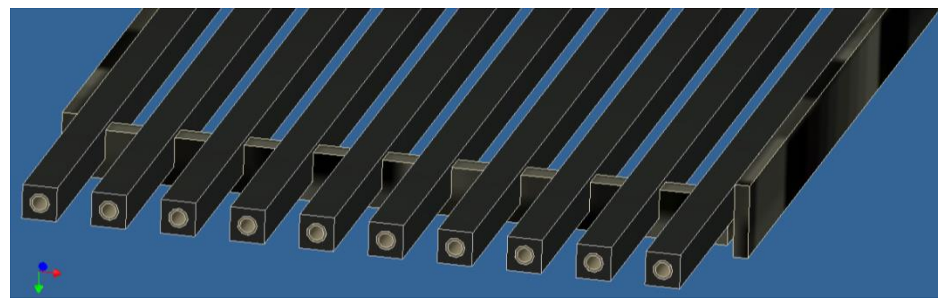
Assuming further progress in MAPS sensor design, and looking to actual hybrid pixel, the required Power (analog + digit), could step down to 1.5-1.0 W/cm^2.

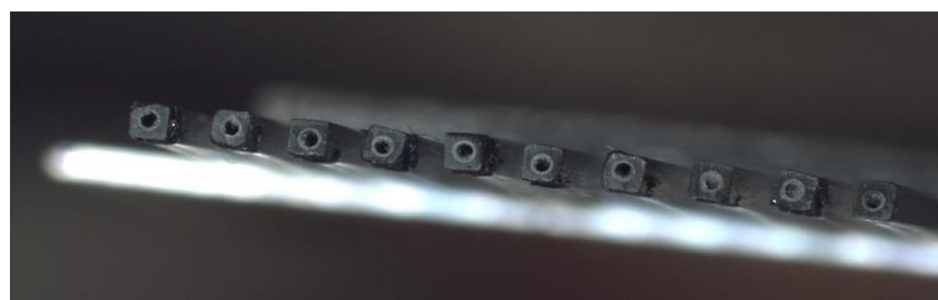
We choose to design a lighter solution for the support structure .

The Net Module is a micro-channel support with vacancies of tubes in the structure .

We admitted worse cooling performance for strongly gaining in X_0.

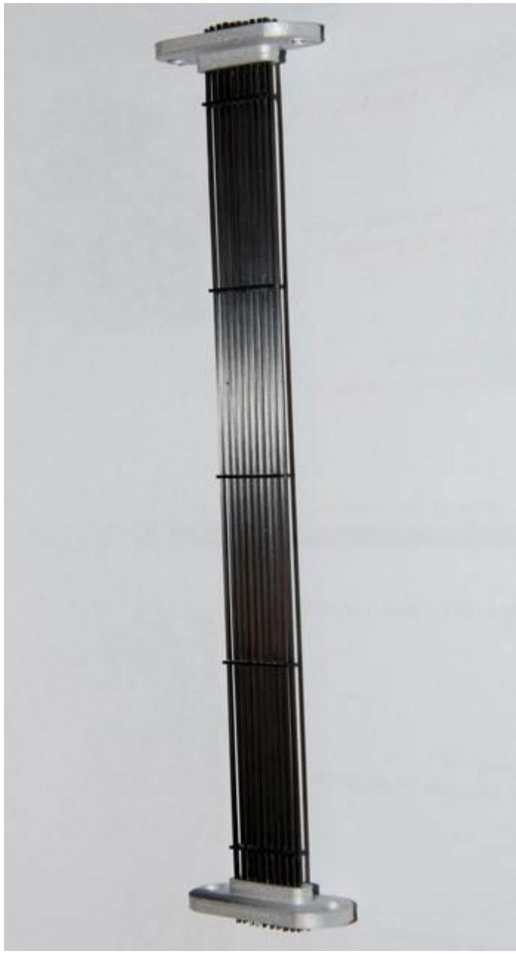






Material of the support structure: (CFRP + peek tube + Water + CFRP Stiffeners)

Net Module Support/2



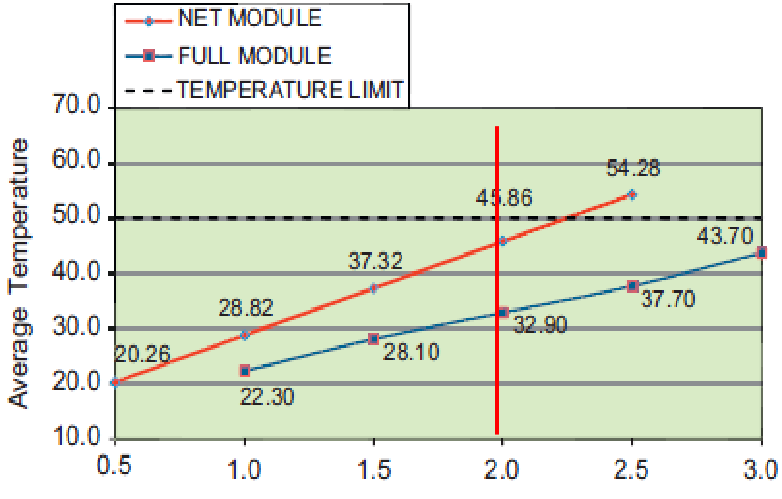
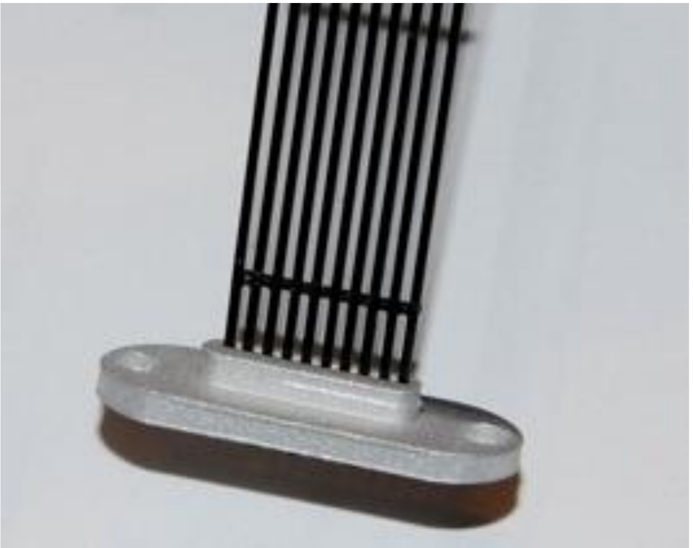


Fig. 5. Sensor average temperature vs. heating power for Net and Full Modules.



Very thin transversal CFRP stiffeners are glued to microchannels

Micropositioning and microgluing work required dedicated gluing masks .

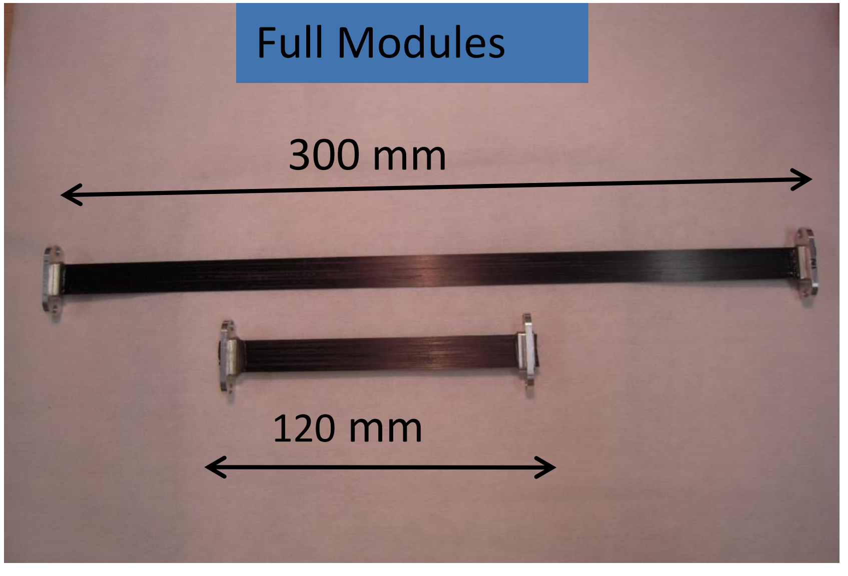
Sealing of the hydraulic interface is obtained with epoxy/CFRP .

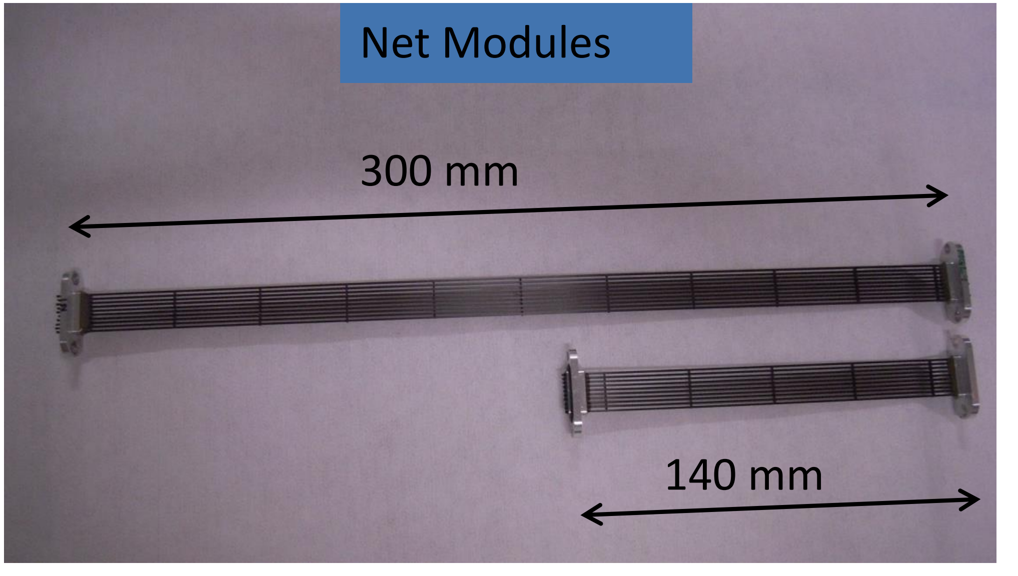
$X = 0.15\%\ X_0$

The Net Module has the same hydraulic parameter/microtube of the Microchannel Full Module.

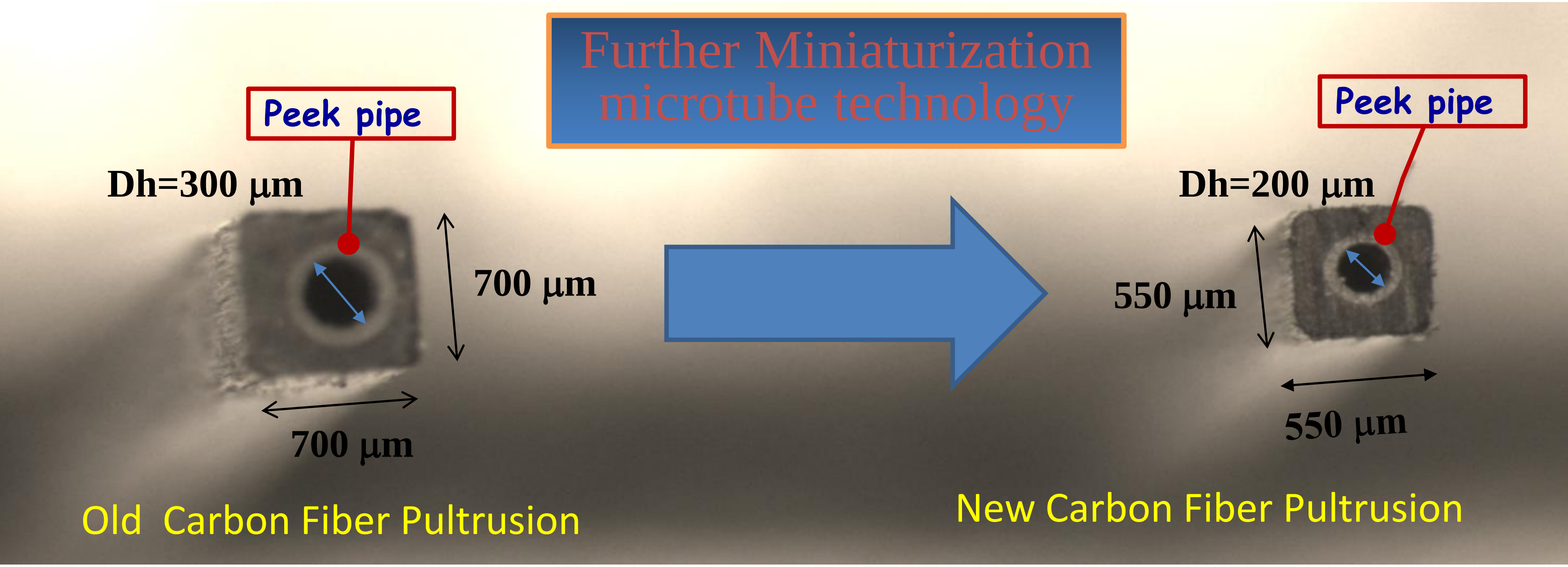
Full and Net Long Modules

In order to test longer microchannel support structures useful for different experimental layout, two supports structure have been assembled and tested . Both structure have been realized with the same pultruded micro-channel technology in full and net Microchannel version.
They have the same cross sections of short modules but the length is 300 mm instead 120 mm.





Work in progress



Full Module $X = 0{,}28\ \%\ X_0$

Net Module $X = 0{,}15\ \%\ X_0$

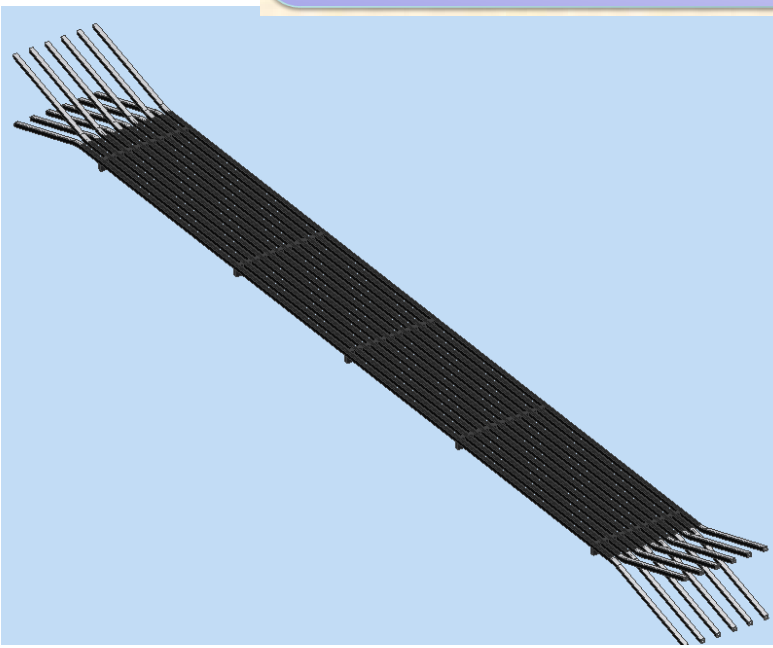
→

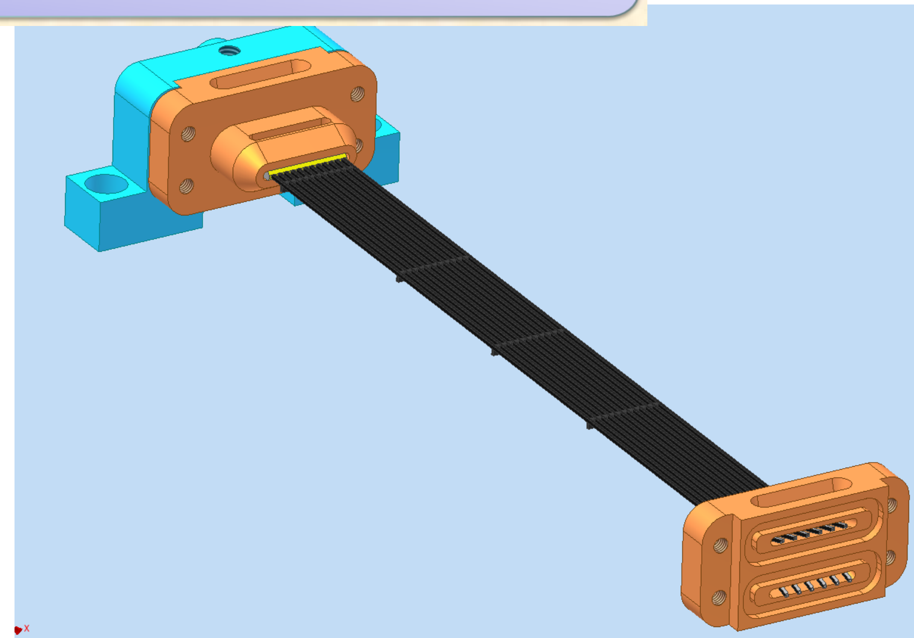
Full Module $X = 0{,}22\ \%\ X_0$

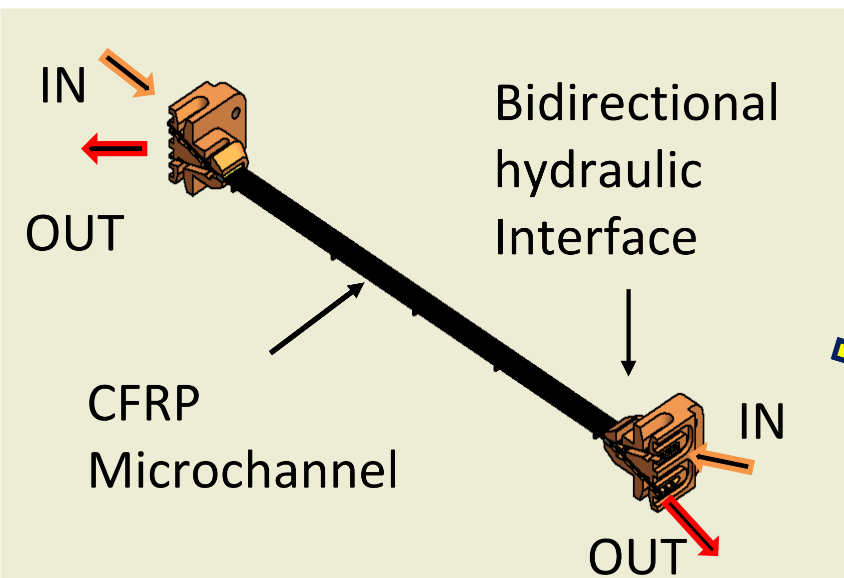
Net Module $X = 0{,}11\ \%\ X_0$

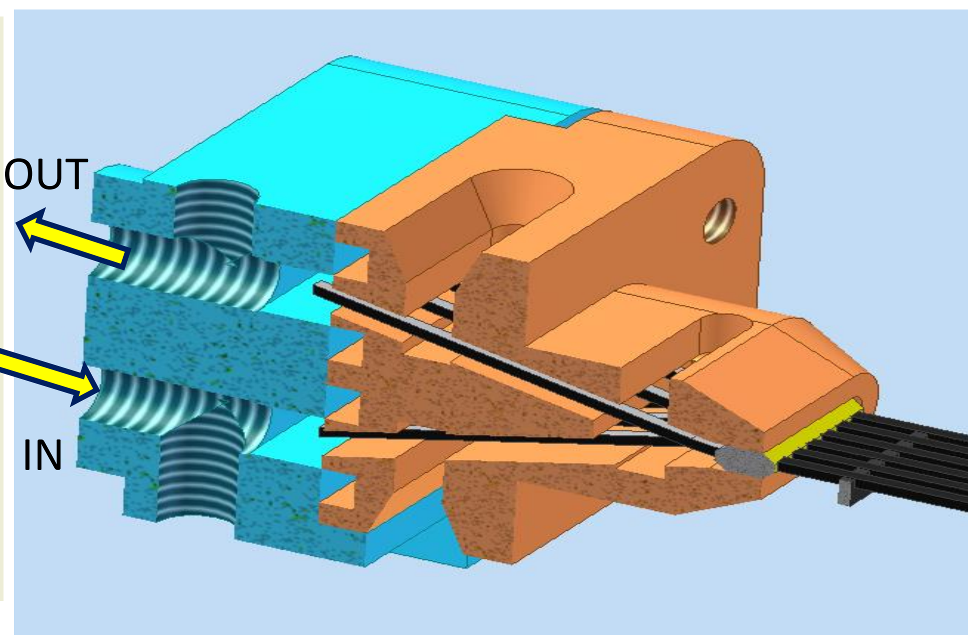
Module Microtubes 550 μm thick, Full and Net version tested at the TFD lab

Opposite flux bent module

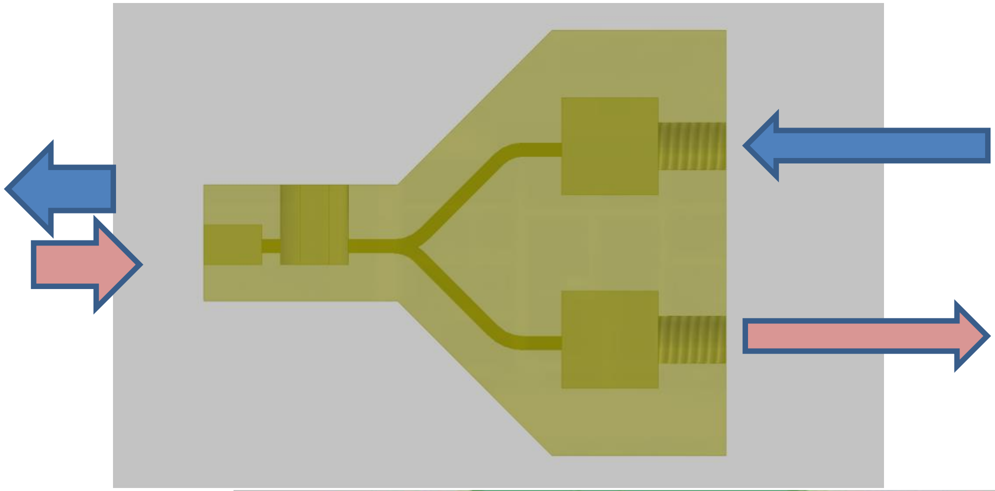




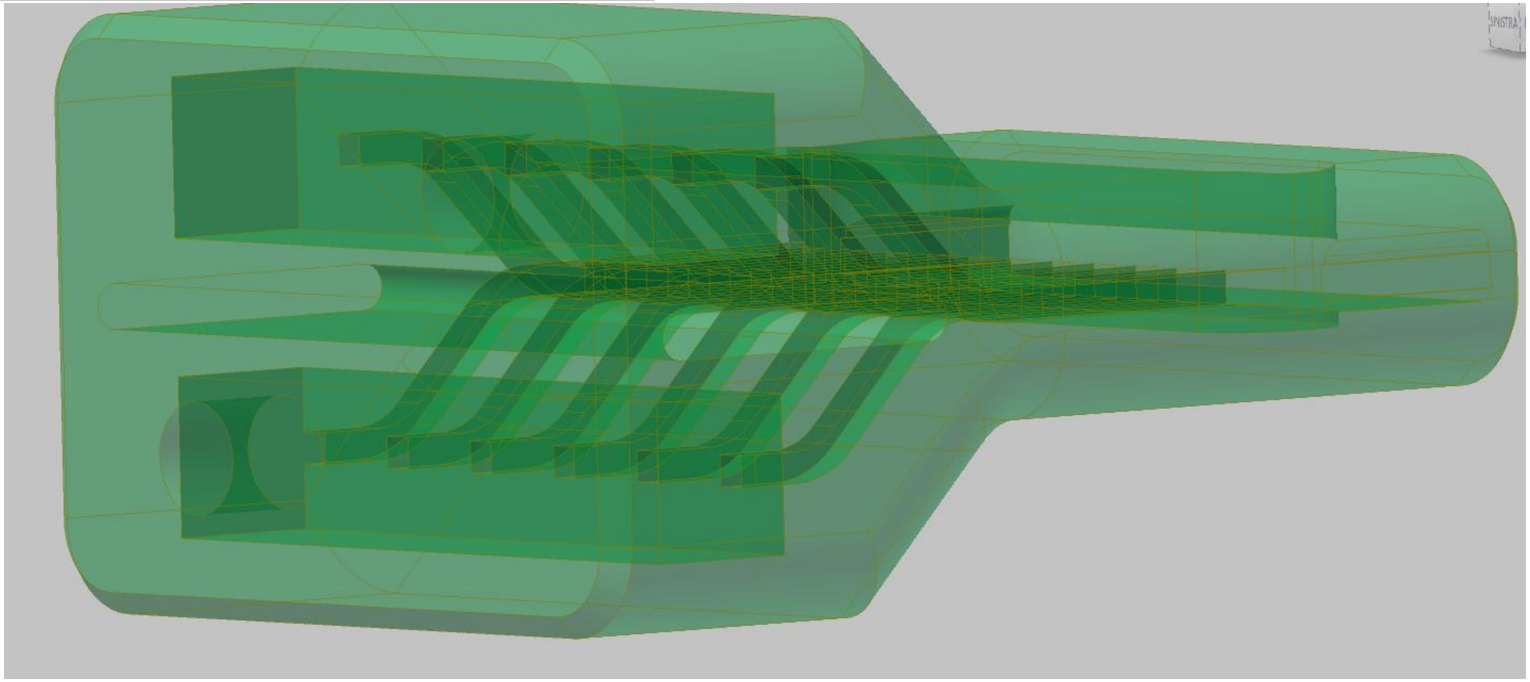


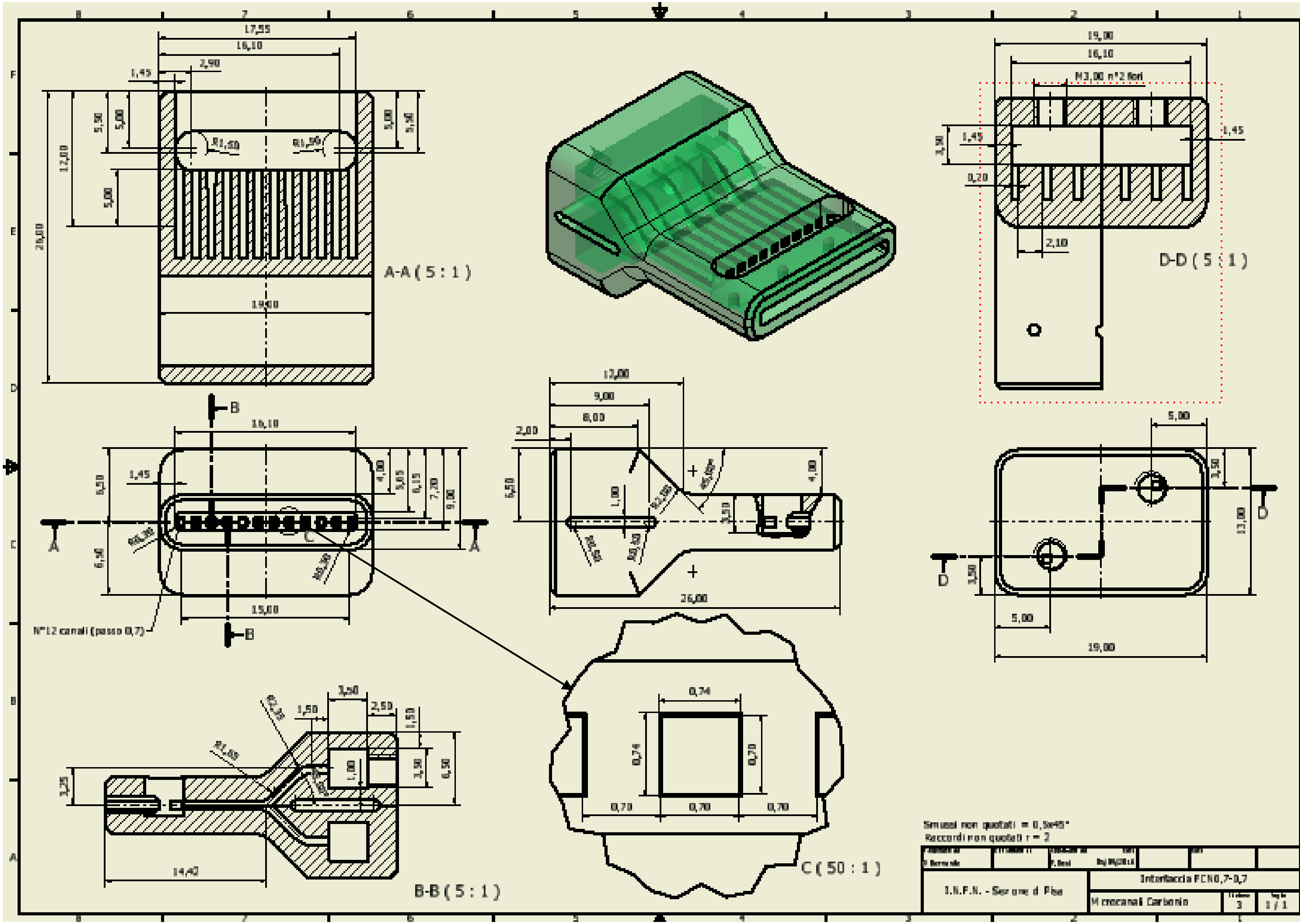


Bidirectional hydraulic interface

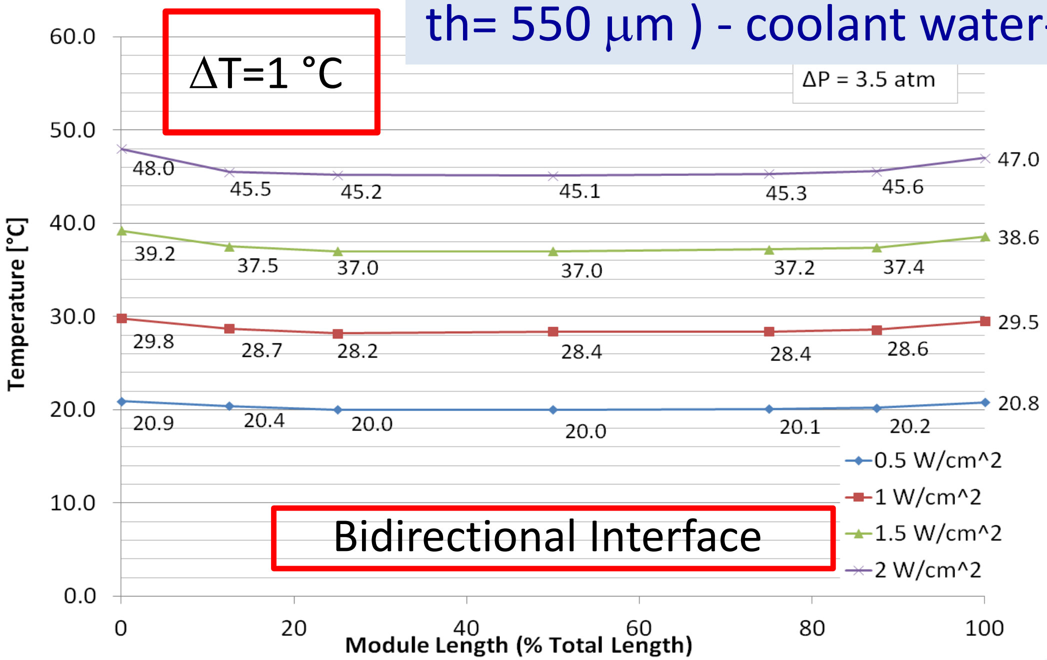


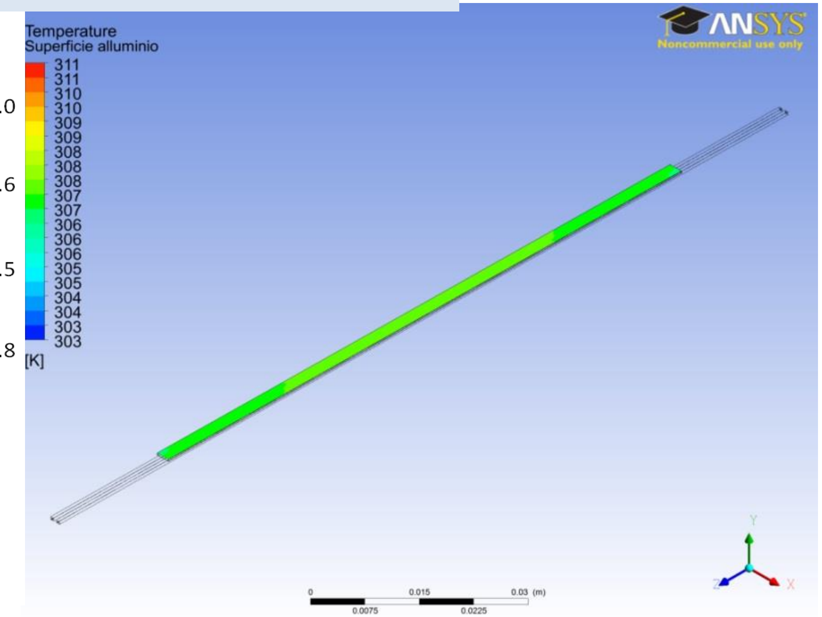
3D printing technology
Material: Peek

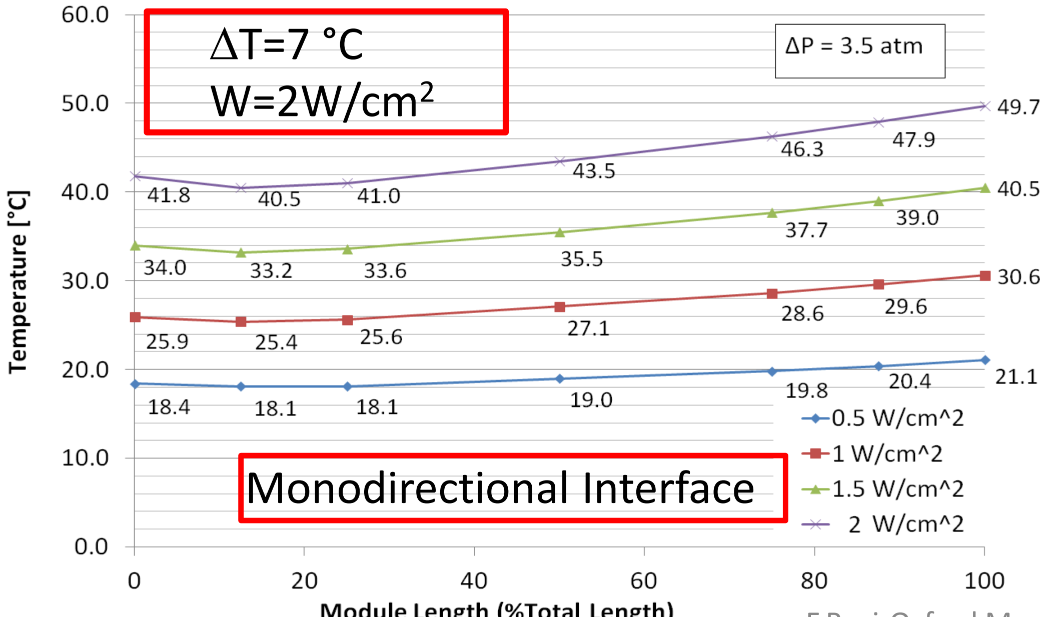


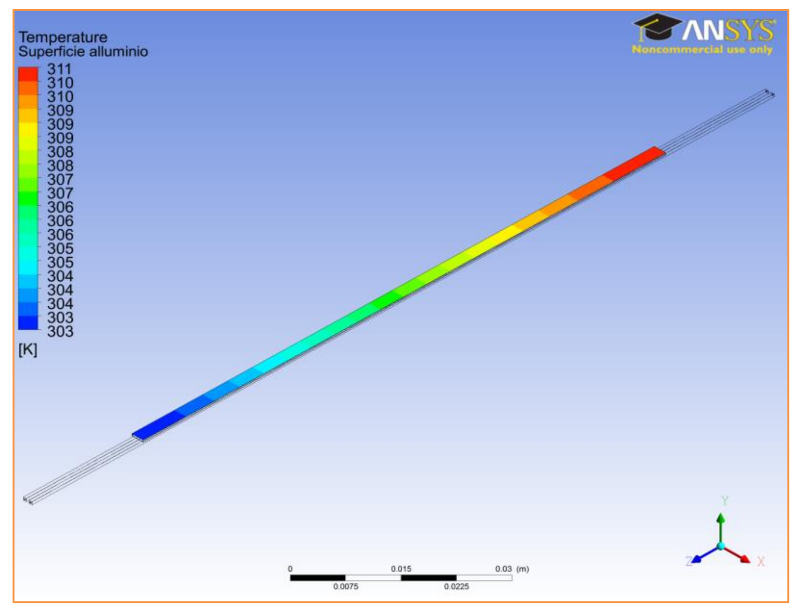

A-A (5 : 1)
D-D (5 : 1)
B-B (5 : 1)
C (50 : 1)
N°12 canali (passo 0,7)
Smussi non quotati = 0,5x45°
Raccordi non quotati r = 2
I.N.F.N. - Sezione di Pisa
Interfaccia FCN0,7-0,7
Microcanali Carbonio

Net Module sample (L= 120 mm - D_h=200 μm th= 550 μm) - coolant water-glycol @ 10 °C

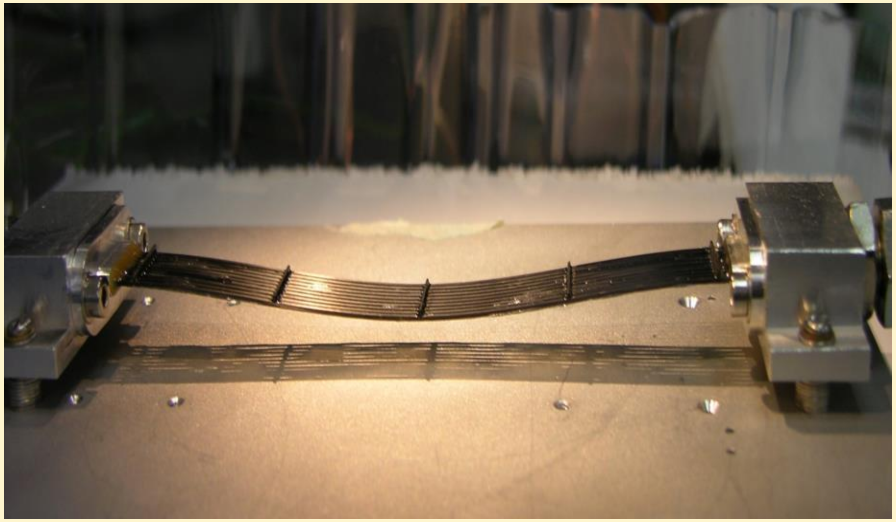








Breaking Test



Deformation at 140 atm

Structural test was realized on Net Module and Full Module prototypes. The test has been performed up to 140 atm .

At this pressure the flanges of hydraulic interface were deformed to extrude the seal and produced the failure.

The SALTRO16 chip and the Carrier Board

The basic unit of the readout electronics is the SALTRO16 chip, developed at CERN

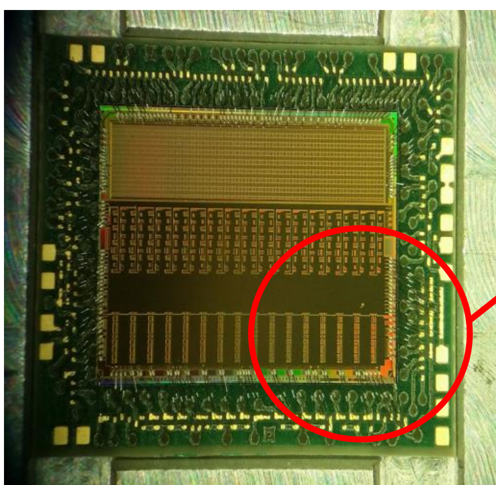
- the size of the die is 8.7 x 6.2 mm^2 and it contains 16 readout channels
- the chip integrates both the analogue and digital processing
- it can be switched off when no signal is expected ⇒ reduction of power consumption ⇒ less cooling

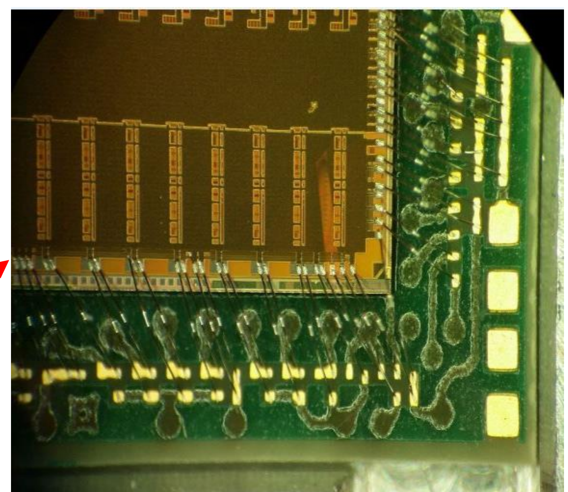
The SALTRO chip is mounted on a carrier board developed at Lund University

- the size of the carrier board is 12 x 8.9 mm^2
- the top surface is covered with an epoxy glob to protect the bonding wires and components
- the bottom surface contains small tin balls in a BGA pattern

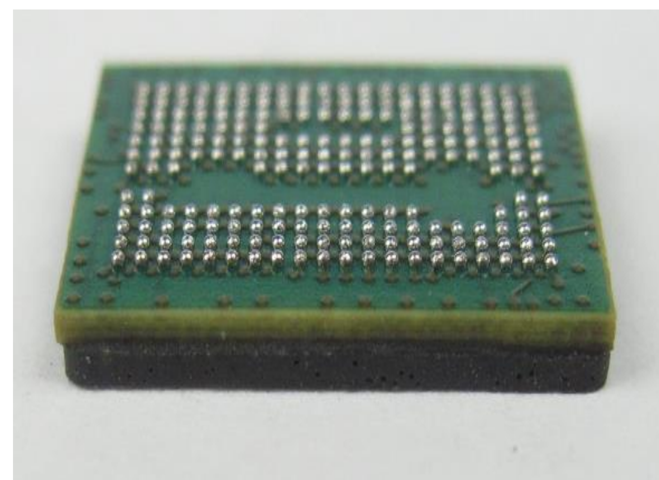
Status: A test system has been built and a few carrier board has been produced, both are presently under debugging.

Top surface

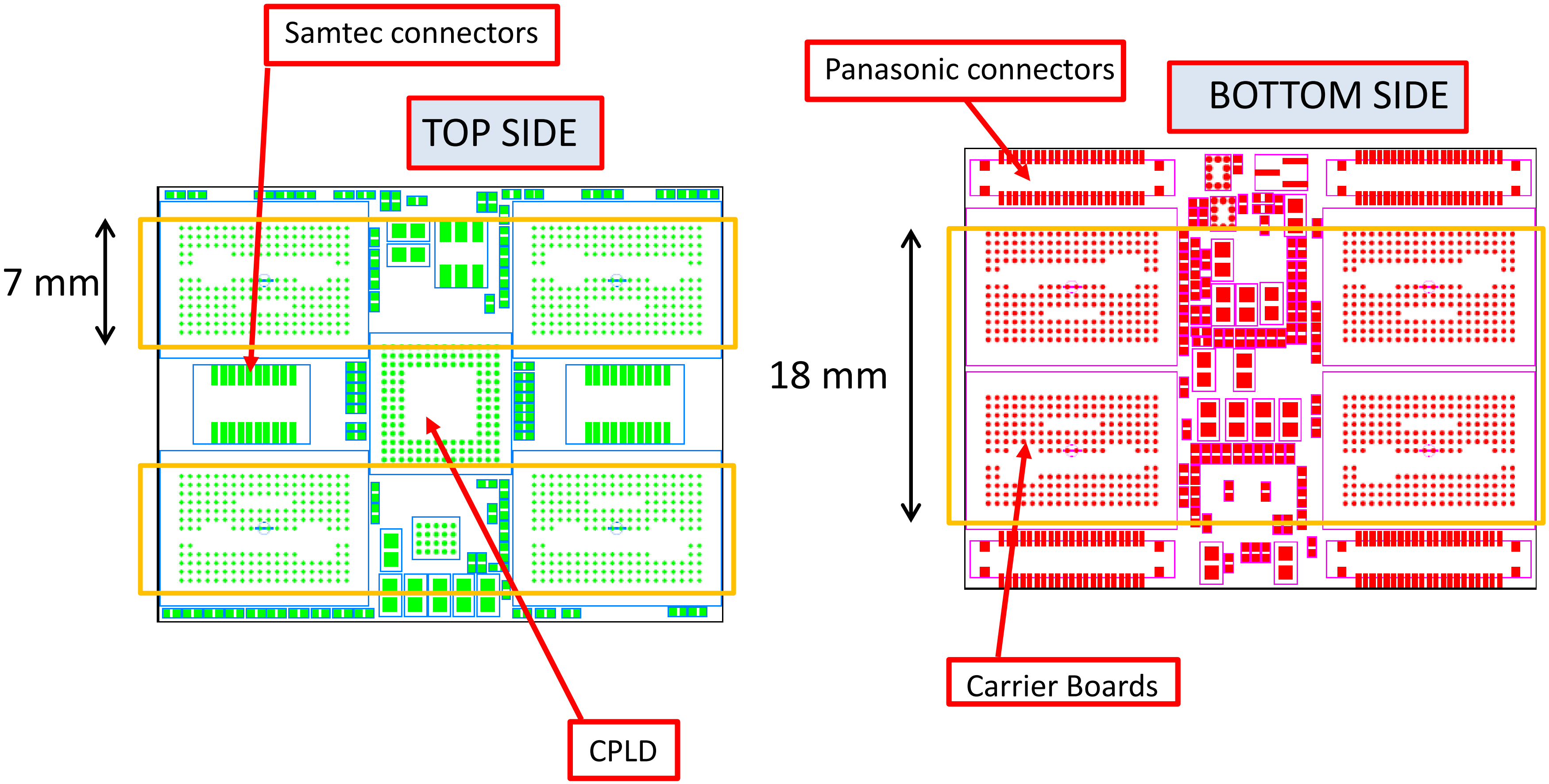




Bottom surface



The MCM faces



Distance defining the microchannel numbers

MCM LADDER LAYOUT

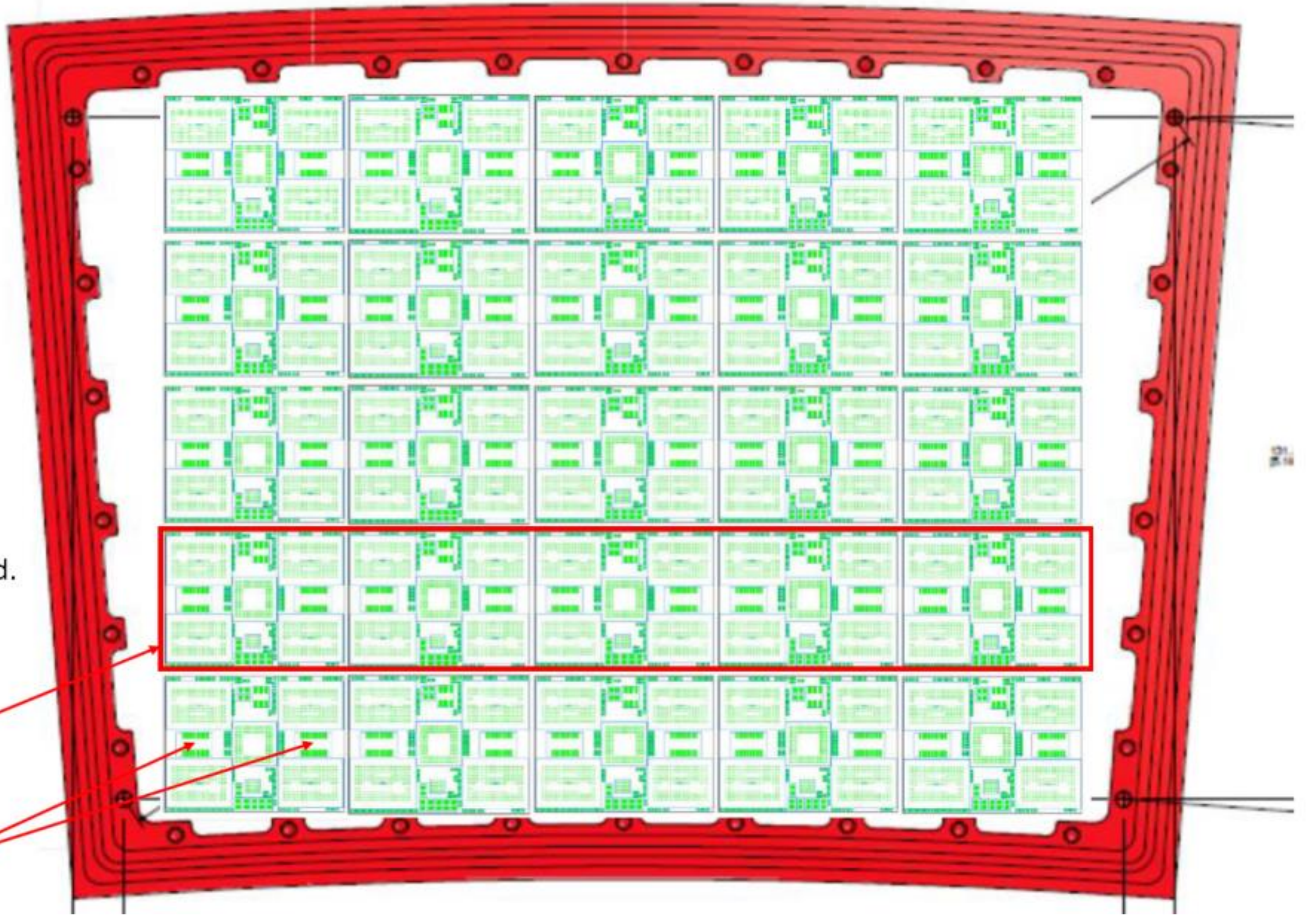
Top side

The MCM-boards are organized in 5 ladders, where each ladder contains 5 MCM boards.

The length of a ladder is 166.5 mm and the height is 25 mm.

The total area to be cooled Is 166.5 x 129 mm^2.

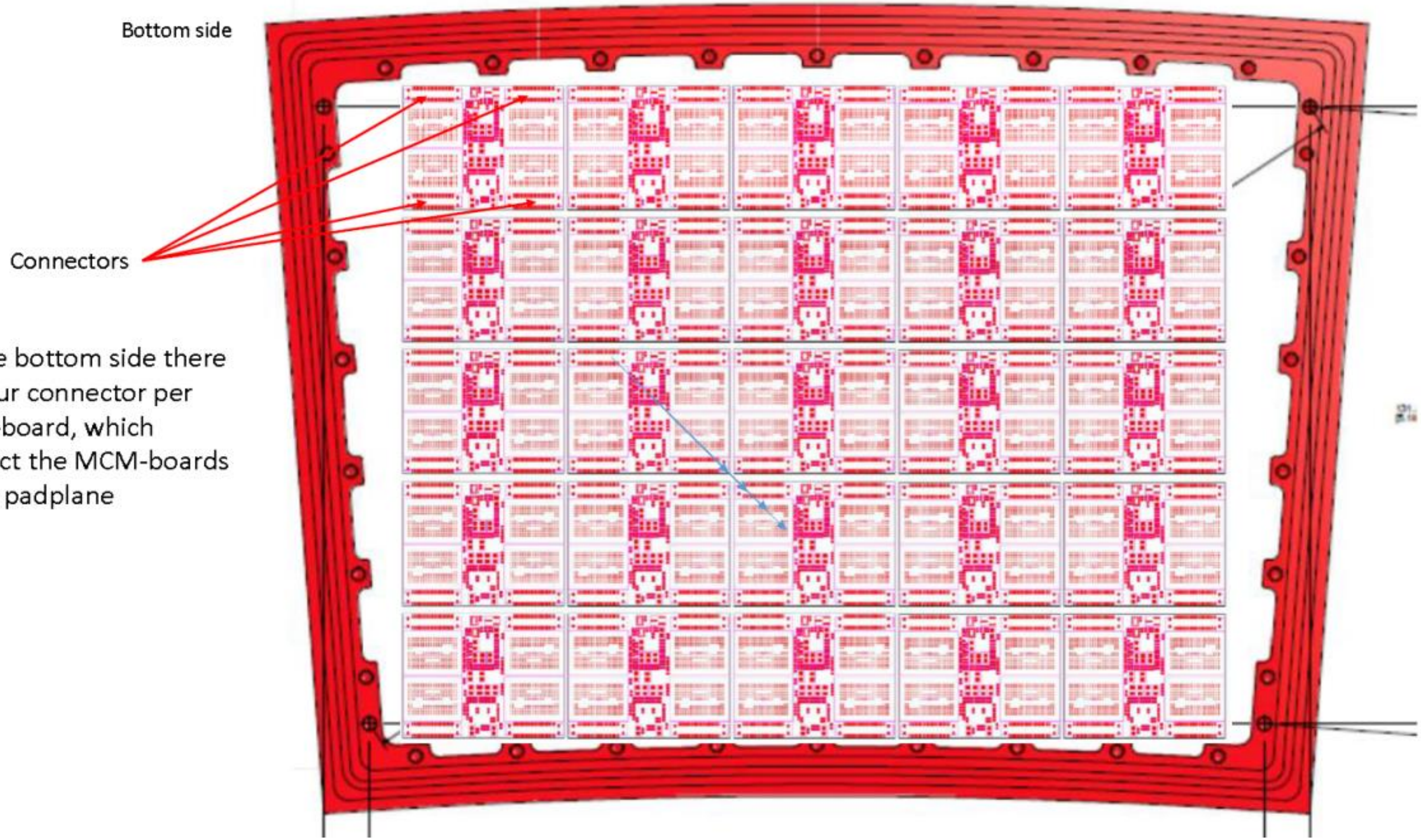
There has to be cut-outs for the connectors in the cooling system. On the top side there are two connectors per MCM-board. The connectors for one MCM-board are indicated in the figure.



One ladder

Connectors

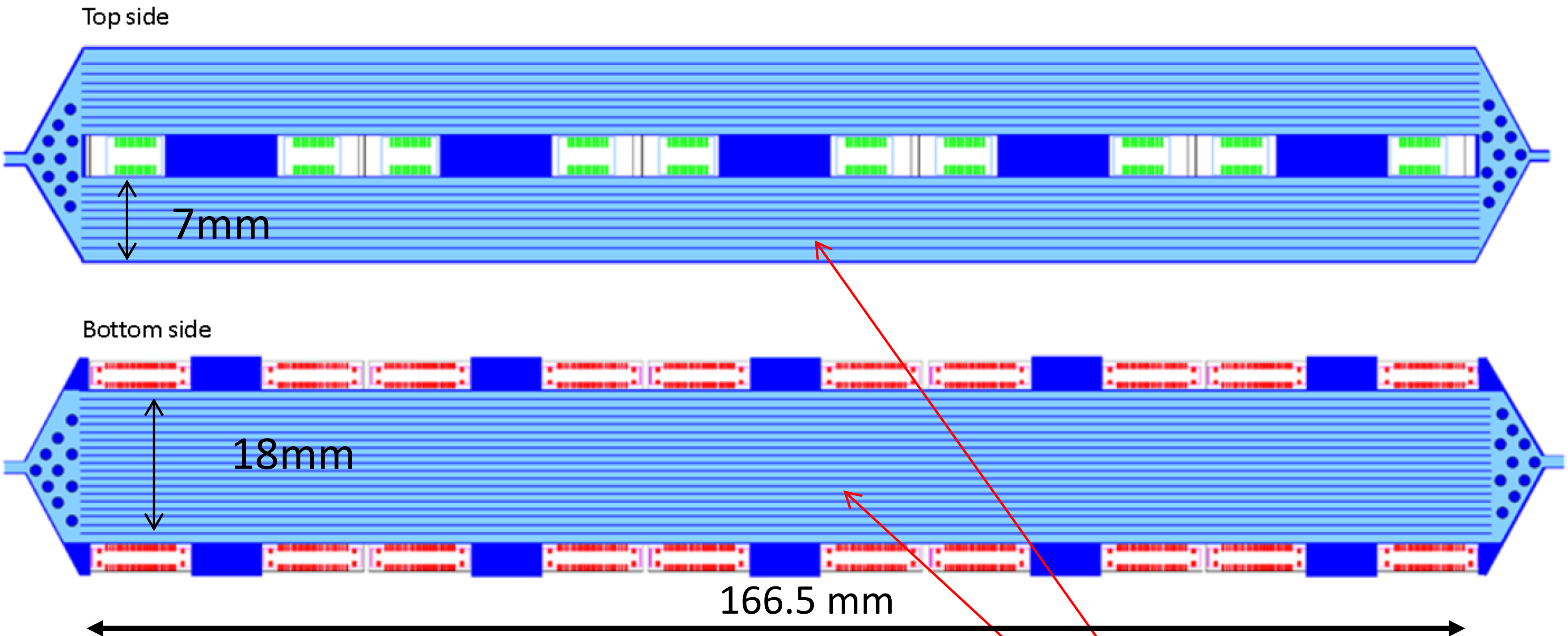
MCM LADDER LAYOUT



On the bottom side there are four connector per MCM-board, which connect the MCM-boards to the padplane

MCM ladder thermal specification

We propose to start a test with a 'one-ladder' prototype. Such a prototype system is illustrated below.



What we want to know:

- What is the optimal design of the in- and outlet to get a homogeneous flow (cooling) over the full surface?
- The dimensions and pitch of the cooling grooves in order to keep the temperature gradient over the full length within the requirements?
- What material is preferred? On the top side the CPLD is not covere by cooling grooves ⇒ needs material with good thermal conductivity?

Max 1.0 W/cm2

MCM ladder thermal specification

Power consumption:
Per chip: 757 mW
CPLD: 175 mW (can not be power pulsed)

Per MCM-board:
top side: 4 chips x 757 mW + 175 mW (CPLD) = 3203 mW
bottom side : 4 chips x 757 mW = 3028 mW

Per ladder:
Top ladder: 5 x 3203 mW ≈ 16 W
Bottom ladder: 5 x 3018 ≈ 15 W

Test beam: 5 ms beam at 10 Hz
-> P(test beam) = 9.2 + 10 Hz x 5 ms x 0.654 mJ = 42 mW/chip
Per MCM-board:
top side: 4 x 42 mW + 175 mW = 343 mW
bottom side: 4 x 42 mW = 168 mW

Per ladder:
Top side: 5 x 343 mW ≈ 1.7 W
Botton side: 5 x 168 mW ≈ 0.8 W

Requirements:
Operating temperature: 25-30º C
Temperature stability/gradient: <± 1º C

Some questions……

- Temperature uniformity / T variation =$\pm$ 1 °C ?

- Temperature uniform distribution on the whole surface of the ladder?

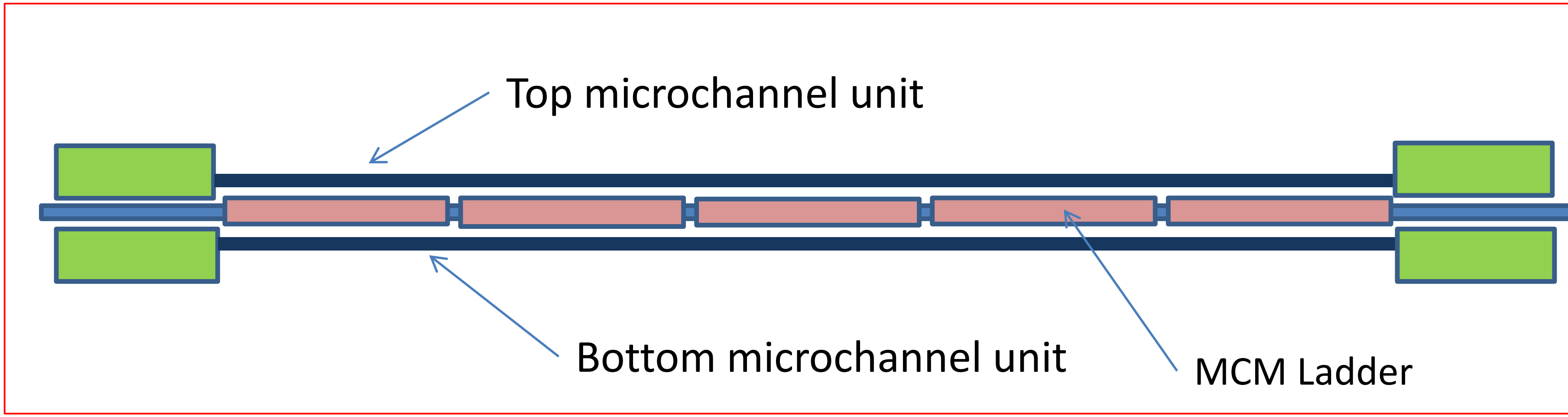
- Target of material budget. Which X/X0 for the thermal management device?

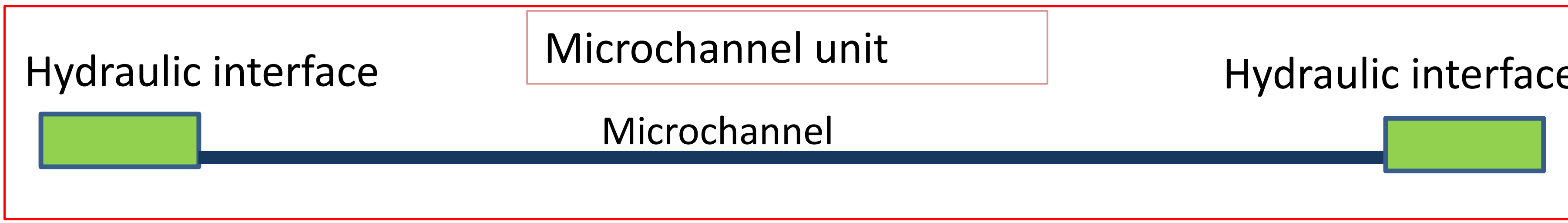
- Thermal interface.

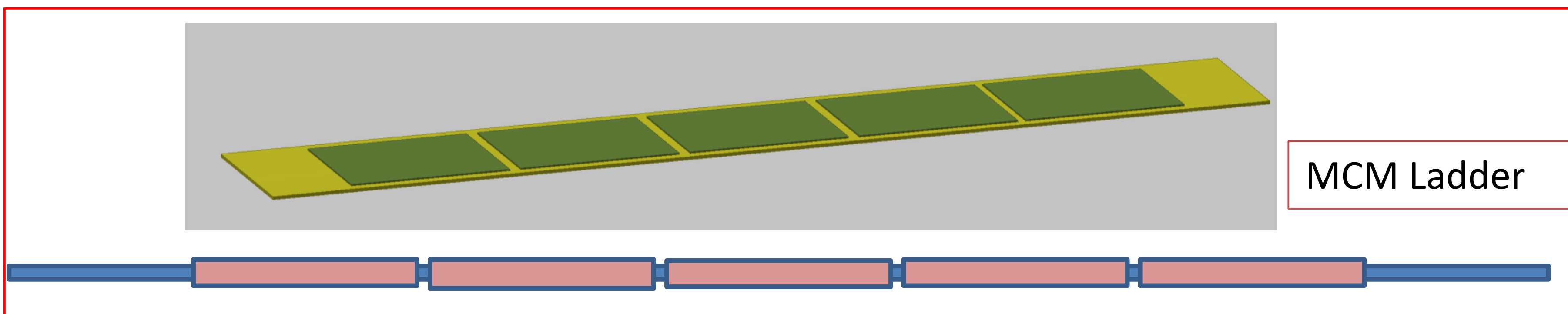
- Possible Problem for the surface of the SALTRO16 chip in contact with the cooling device (bottom surface) : the interface would be a series of discrete metallic bumps.

 Very poor surface for thermal exchange. Size of the metallic bump?

Possible ladder layout





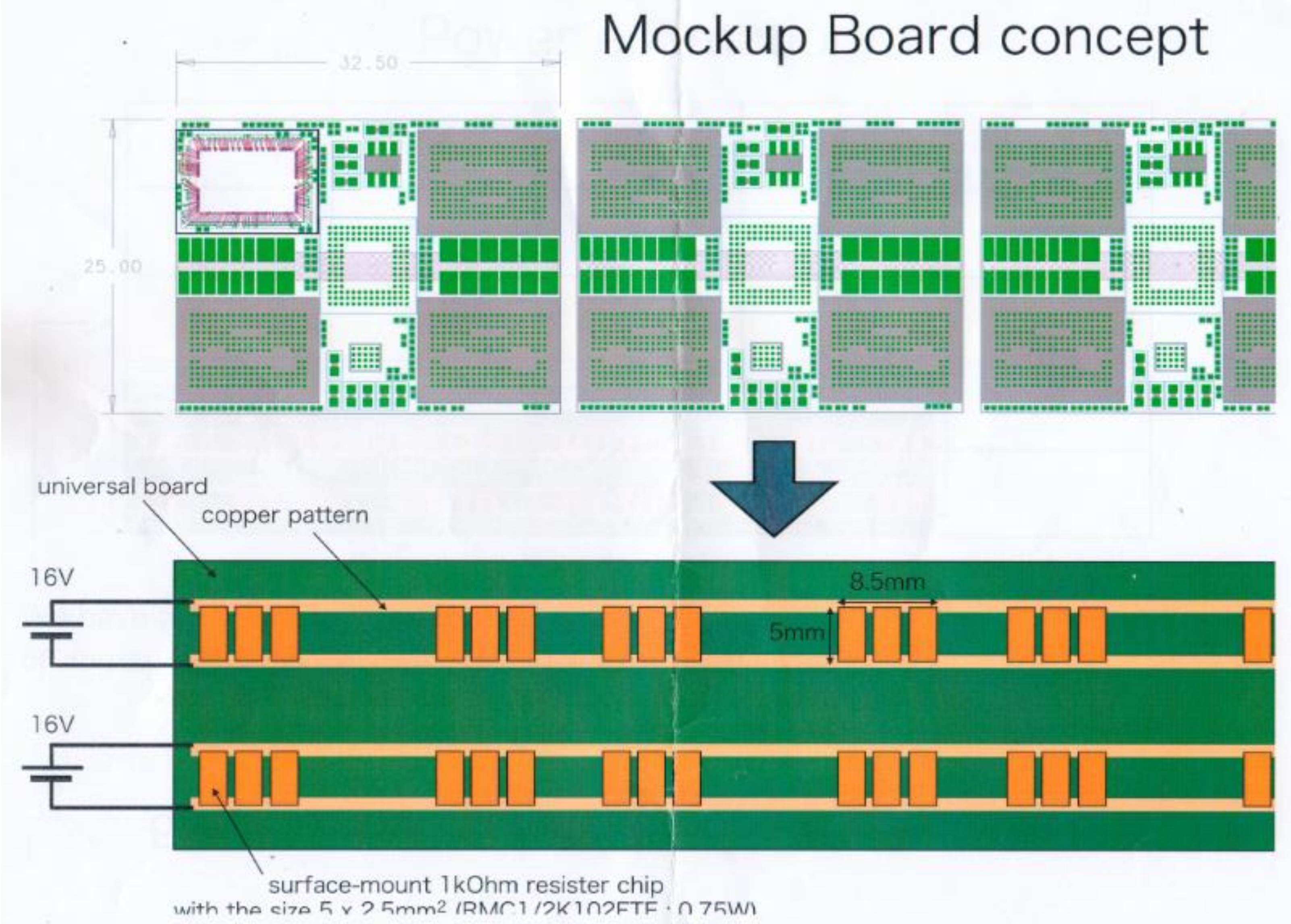


Work in progress

- Engineering solid model to rappresent the MCM Ladder and the microchannel unit
- More geometrical information on the MCM board thickness/material components
- Design for the right double hydraulic interface in 3D print
- Verify the layout with a first thermal simulation
- Production of the support in CF microchannel for hydraulic test
- Test on the prototype supplied by Lund University

Mockup Board

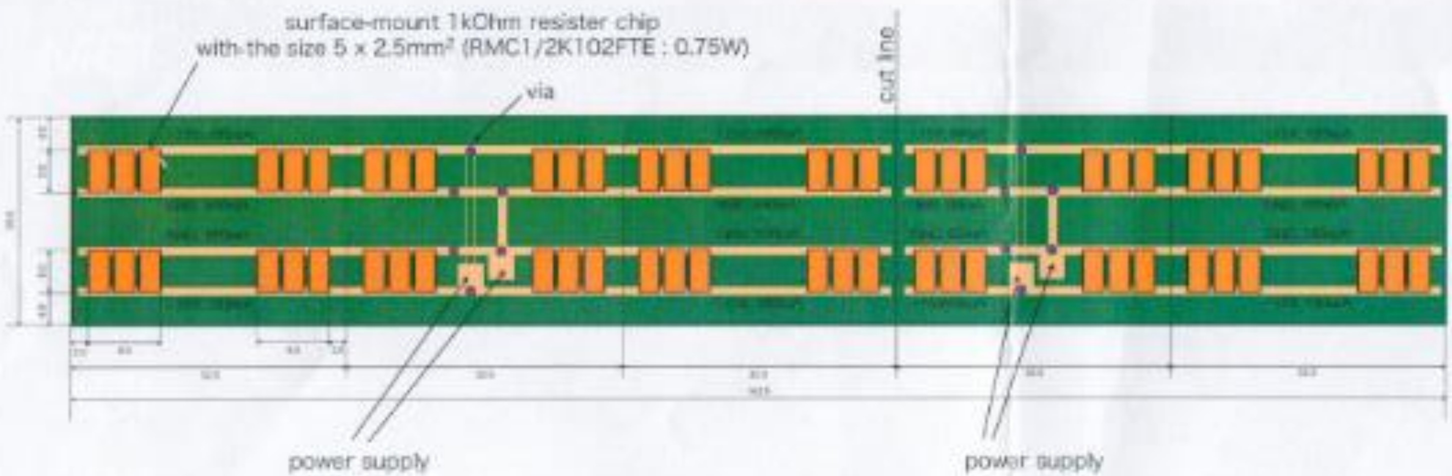
We want to test the performance of the microchannel cooling on the Mockup Board



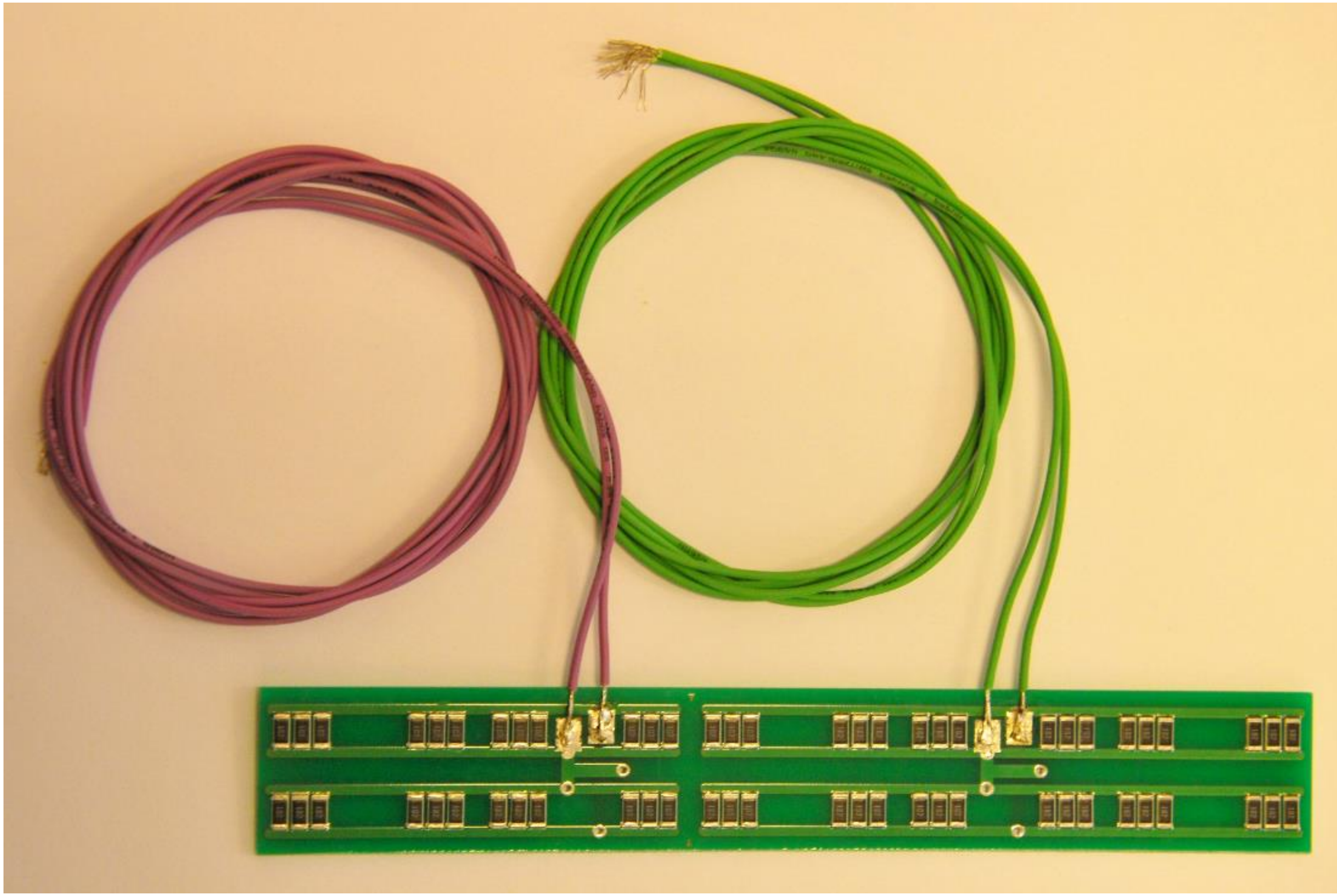
Mockup Board

5MCMs cooling mockup board specification

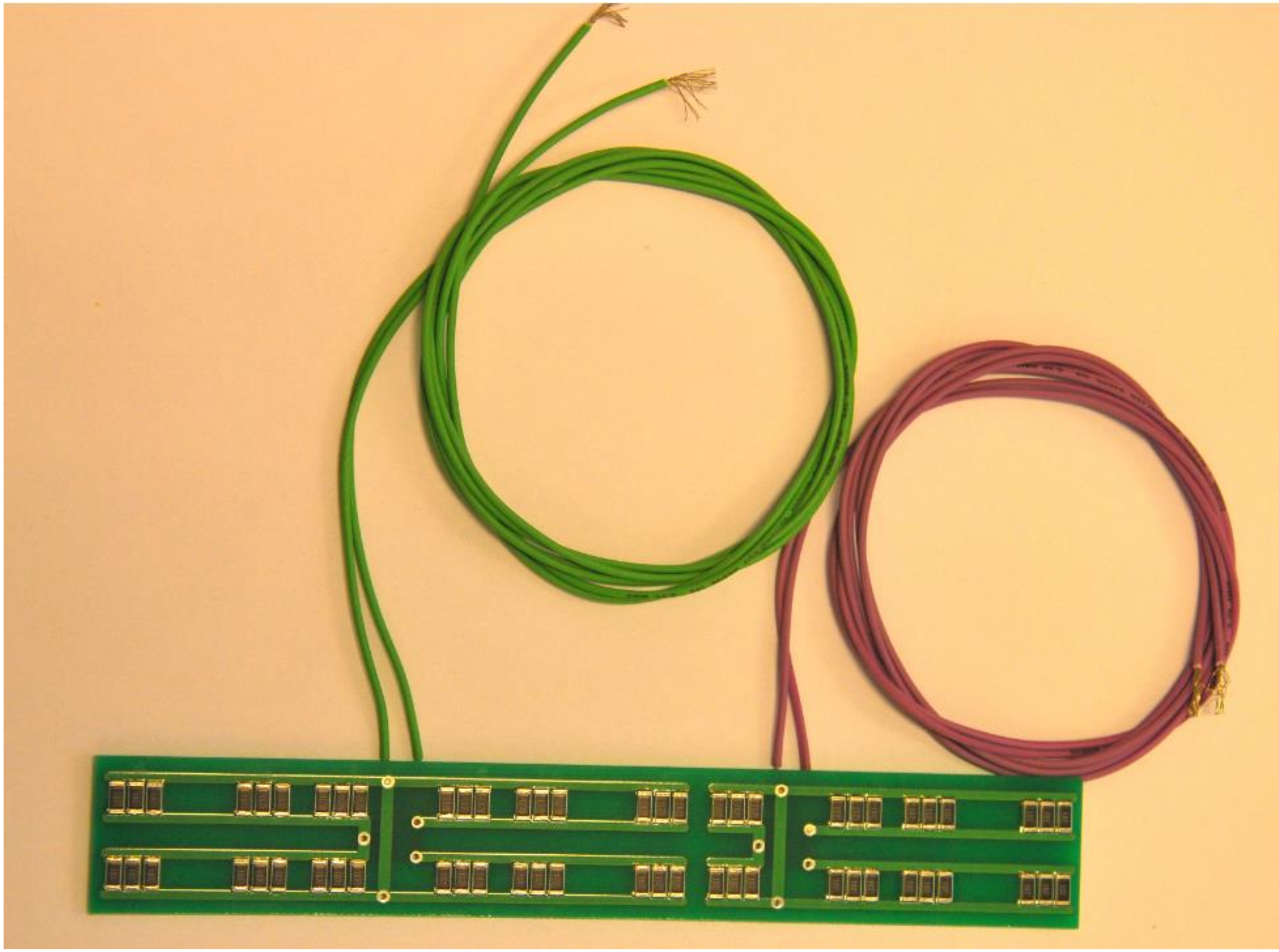
- This figure shows instructions to the board making company.
- Resistors are placed at the same position of top and bottom sides of the board.
- Copper patterns are not exactly same as the fabricated one.



MCM Mokup top side



MCM Mokup bottom side



Mockup Board

Power estimation

	W/resistor	W/saltro	W/board	A/board
16V	0.256	0.768	30.72	1.92
17.7V	0.313	0.94	37.59	2.124
20V	0.4	1.2	48	2.4
SALTRO @40MHz	-	0.94	37.6	-

We have tested up to this voltage,
of course with a proper (water or CO2) cooling device.

Mockup Board

Mockup board power consumption compared to MCMs

	5MCMs top side	5MCMs bottom side
Mockup 17.7V	3760mW	3760mW
MCM continuous operation	3203mW	3028mW
MCMs with ILC power pulsing	223mW	48mW
MCMs with DESY test beam power pulse	343mW	168mW
	total 3769	Total 3244

} based on Leif's description in the Liason report.

There are two power supply points on the mockup (5MCMs) board.
The same voltage is applied to all resistors, as you can see from the board.
The resistor part no. is "RMC1/2K102FTE", which is 1kOhm, 0.75W resistor.
Max voltage we tried is 17.7V as shown above, with which the power per resistor will be 313mW.

TIME PLANNING

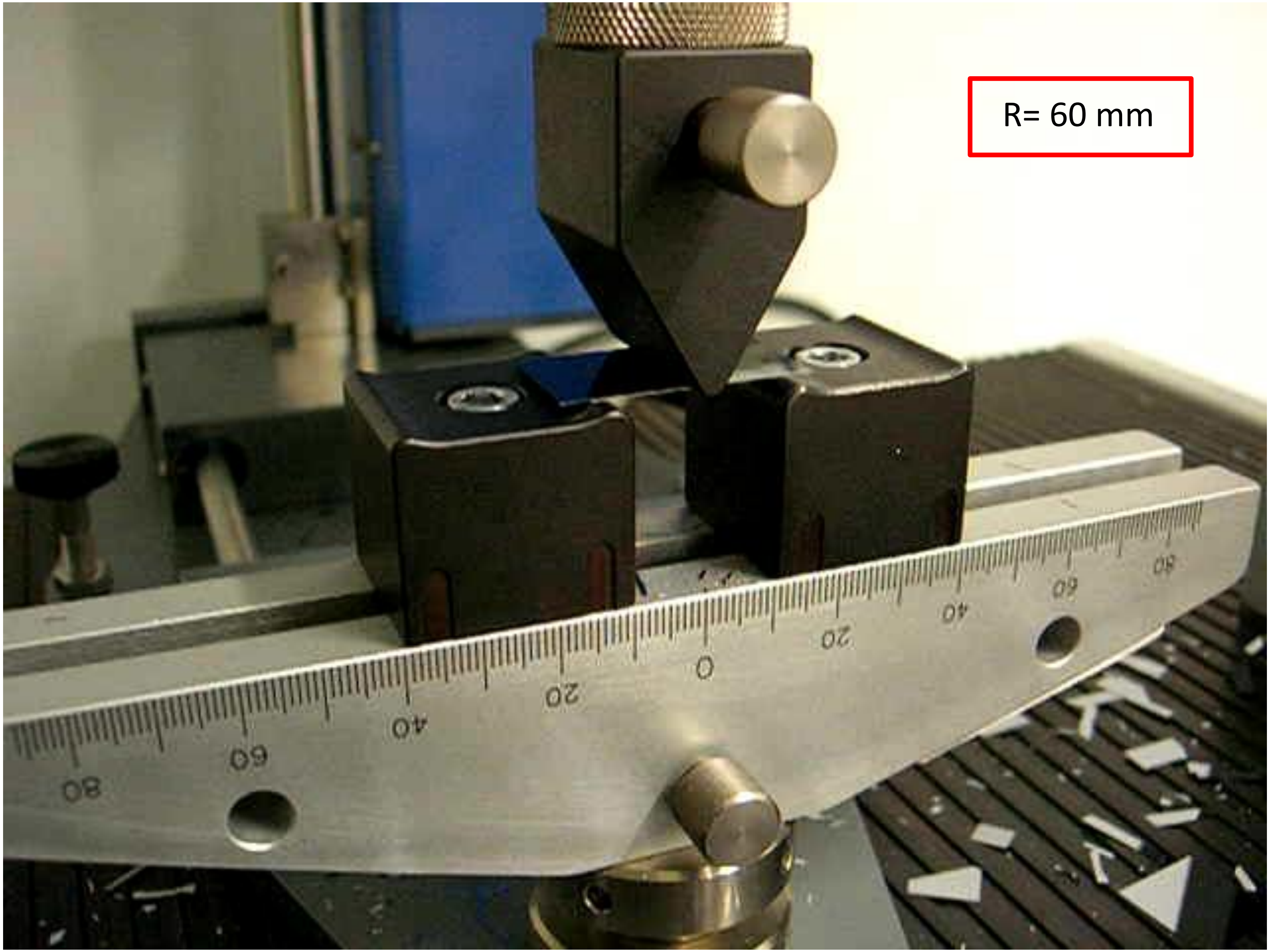
- FEA thermal analisys of the Carbon fiber cooled support on the MCM Board thermal charge;
  -April 2019

- Realization of the microtube support able with the dimension of MCM Board;
  -July 2019

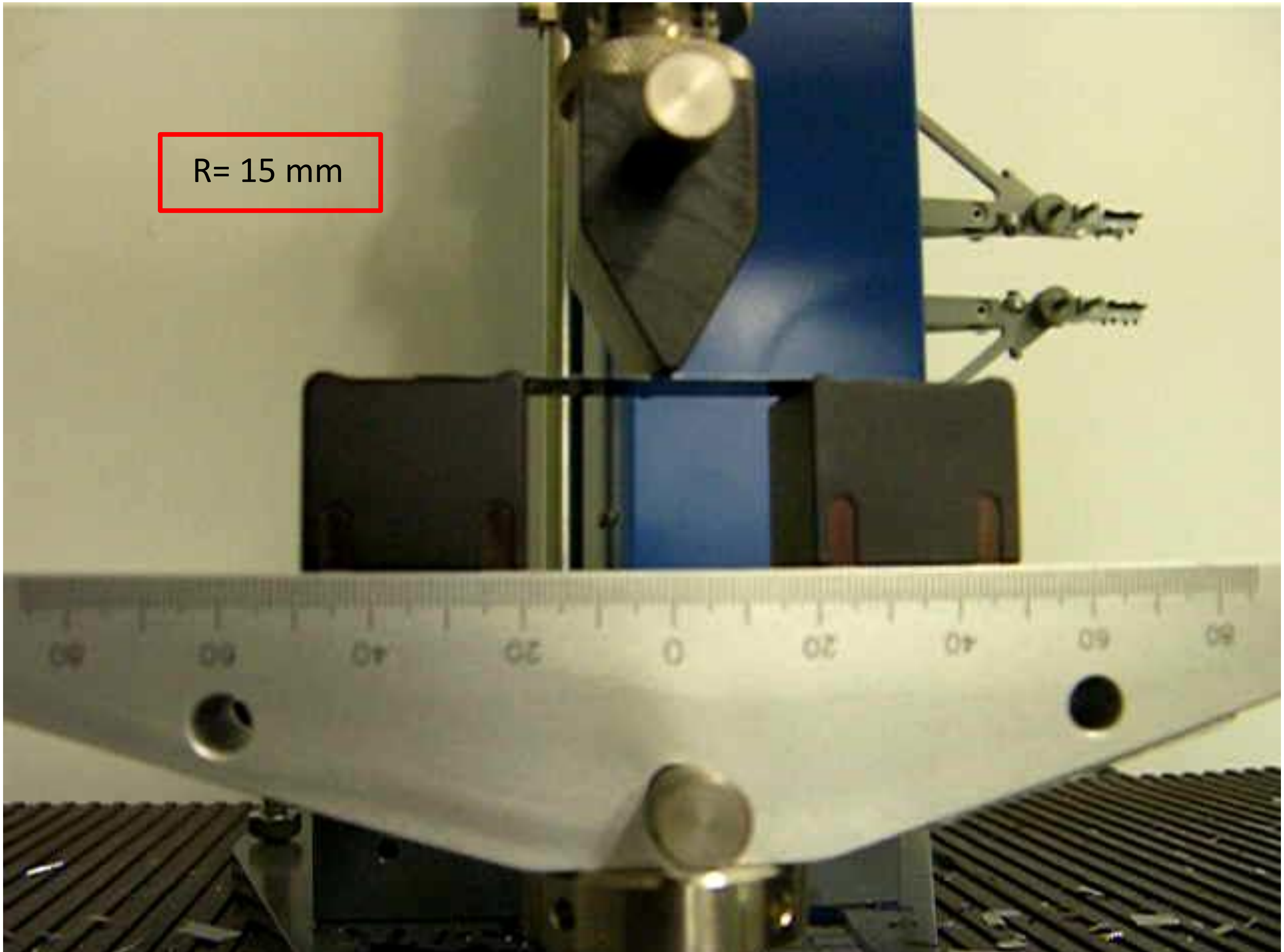
- Realization of the hydraulic interface in 3D print in Peek material
  -September 2019

- Start Test on the TMFD laboratory of the samples board
  -October 2019

Silicon thick 100 micron



Silicon thick 50 micron



SUMMARY

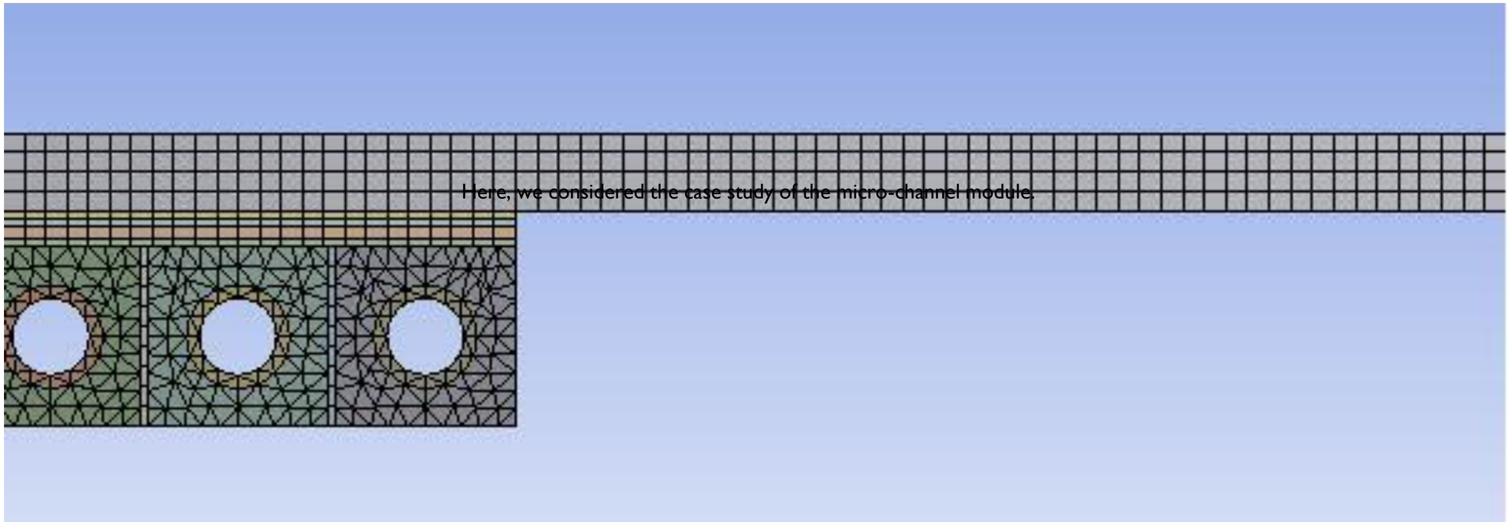
- We presented our history on microchannel technology in Pisa
- Silicon microchannel cooling and CFRP microchannel cooling
- Very low material budget for microchannel cooling in CFRP special for electron-positron experiments
- Possible application for SALTRO16 chip and MCM board realized by Lund University

THANKS FOR THE ATTENTION

BACKUP

Thermal Simulation/1

In order to validate the experimental tests we performed also simulation studies on the micro-channel single-side module. Given the geometry of the module, the problem is solved by considering only 3 tubes.



Boundary values:
Power density: 2 W/cm2
Water film coefficient*: 3275 W/m2K
Coolant Temperature: 10 °C
Air film coefficient: 5 W/m2K
Air Temperature: 22 °C

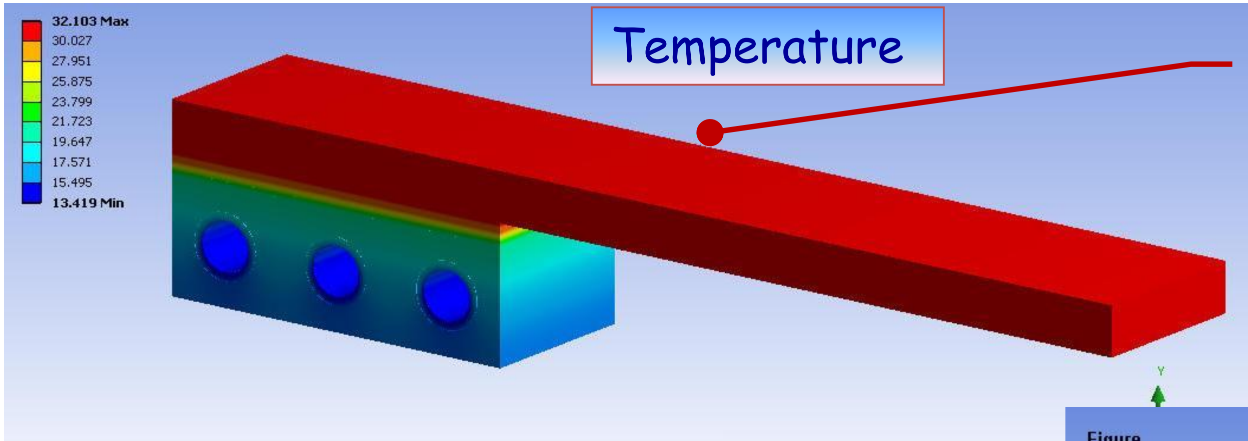
Thermal conductivity of the materials:
CFRP: 2 W/mK
PEEK: 0.25 W/mK
Kapton: 0.15 W/mK
Aluminum: 210 W/mK
Glue: 0.22 W/mK

*: it is derived from experimental and geometrical data.

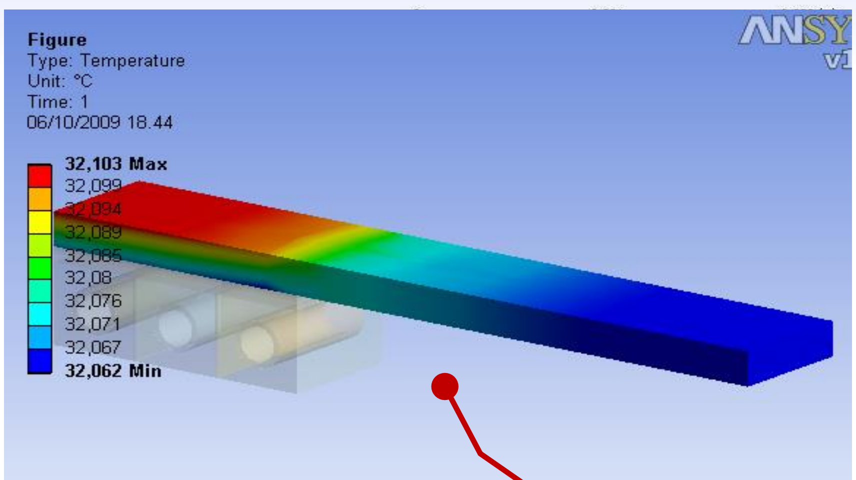
Thermal Simulation/2

Case study: 2W/cm^2 (the same Boundary values of the microchannel)

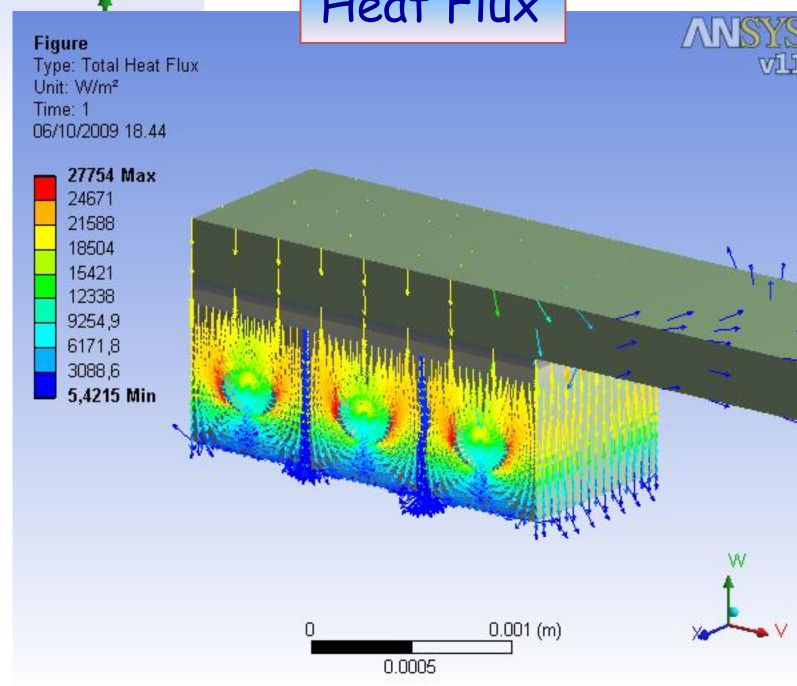
Temperature



Maximum temperature reached: T_{max}=32.1 °C, in the entrance region (same position of the glued probes in the experimental test).



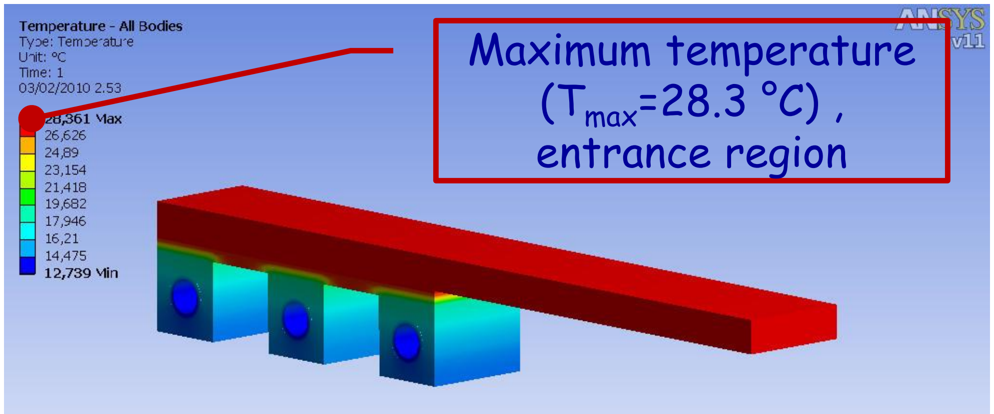
Heat Flux



Temperature gradient (0.04 °C) on the aluminum foil

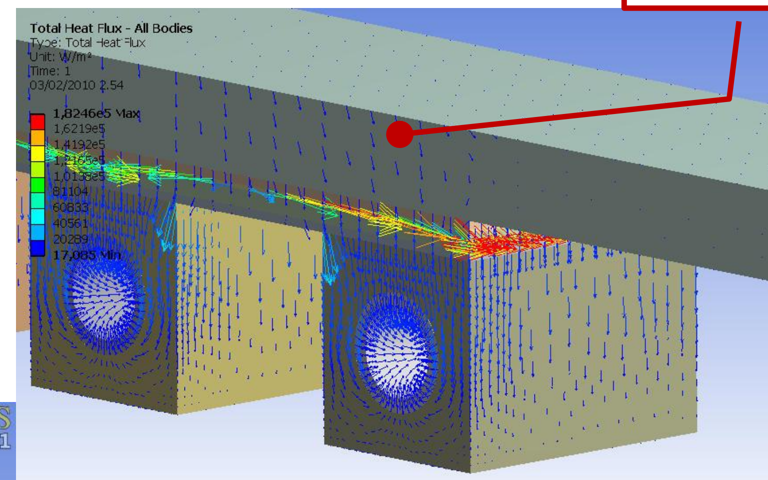
Net pixel module simulation results

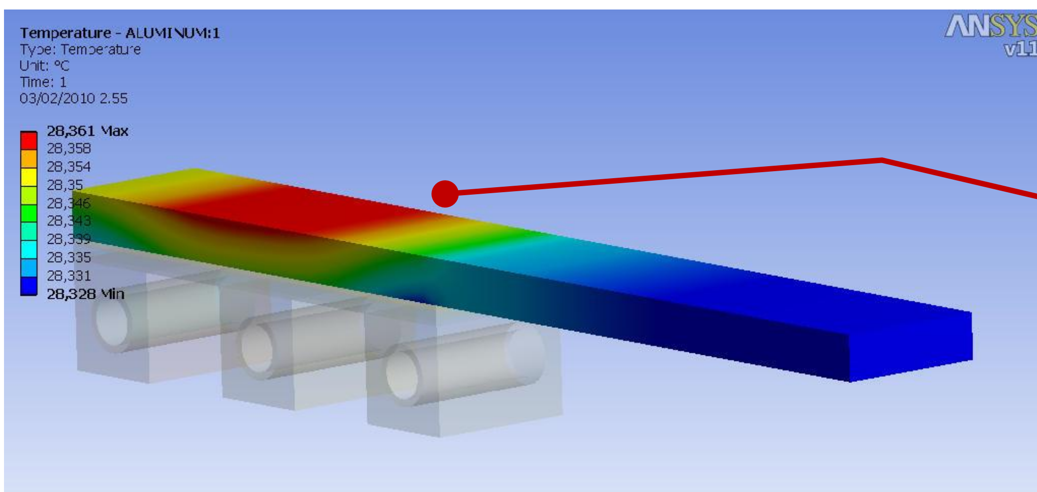
Case study: 1 W/cm^2 (the same Boundary values of the microchannel)



Maximum temperature (T_{max}=28.3 °C) , entrance region

Heat flux





Temperature gradient (0.4 °C) on aluminum.

The ~ 2 °C difference between FEA results and experimental data can be ascribed to the uncertainty of the thermal interfaces.

Quick INFN-Pisa Laboratory overview

- The high-technology workshop provides engineering and technological support to the experimental activities of the research groups of the INFN Section in Pisa. Many collaborations hosted (CERN, FNAL, Astro-particles).

Main technical activities:

- Development of Solid-State detector: <u>Clean Room(s):</u>
  - Space available for module construction
  - Metrology: manual/automatic CMMs
  - Mechanical/electrical micro-mounting
  - Micro-bonding
- R&D on cooling: <u>Thermo-Fluid-Dynamic Lab.</u>
  - Thermo-hydraulic test on micro-channels
  - Thermo graphic analysis
  - Climatic chambers
  - In progress set-up for evaporative cooling
- Design of mechanical support: <u>Structural test Lab.</u>
  - Dynamometer for material characterization
  - Vibrational analysis

Clean Rooms

We have two clean rooms (~600 + ~350 m^2) In each cleanroom work space area there are:

- Vacuum and air pressure facilities (8 atm).
- Dry air (dew point -40 °C)
- Thermo hygrometric condition are continuously monitored

Clean Room Cleaness Class: 100.000 - Class 10.000 (Federal Standard 209/E)

Temperature : 21 °C $\pm$ 1°C - Humidity : 50% $\pm$ 5%

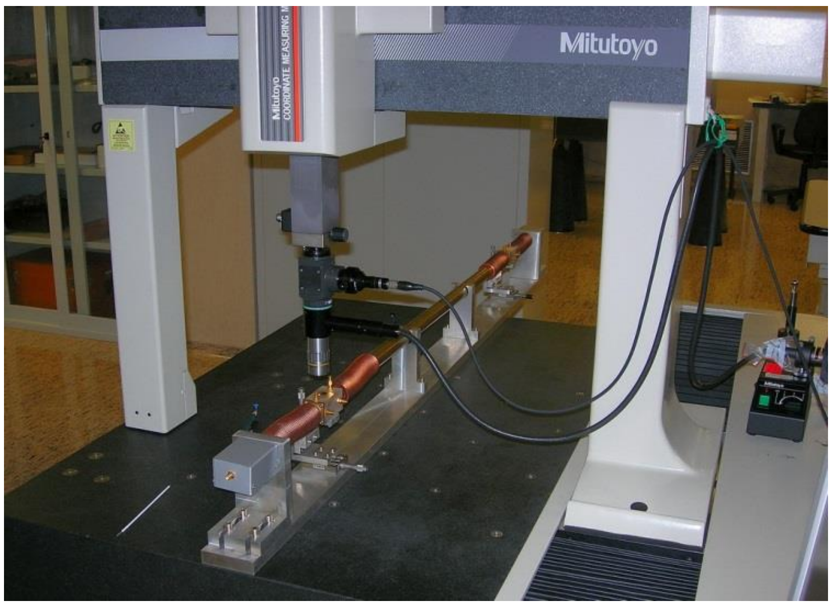
In some little specific working areas (laminar flow cabinet) class 100 can be reached.

Contamination control measurements are systematically performed.

3D Metrology (with and w/o probe contact)

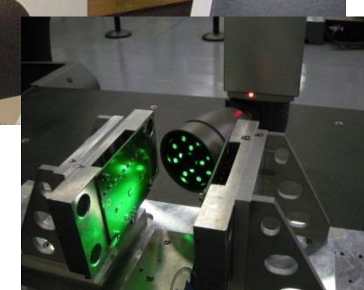
Coordinate Measuring Machines (4 machines)

- Mitutoyo BHN506 (500x600x300mm^3)
  Precision 3+4L/1000 um – res. 1 um
CNC controlled – PCDIMIS metrological sw



- DEA Hexagon – Global Image (1500x900x650mm^3)
  Precision 1.7+3L/1000 um – res. 1 um
Both the machine are CNC controlled – PCDIMIS metrological sw

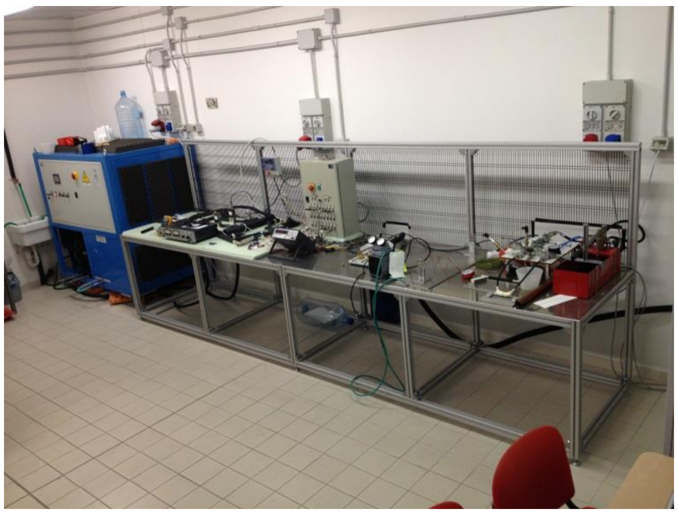
- Contactless Optical head: patter recognition and measurement in more than one plane orientation



Thermo-Fluid-Dynamic Lab (TFD)

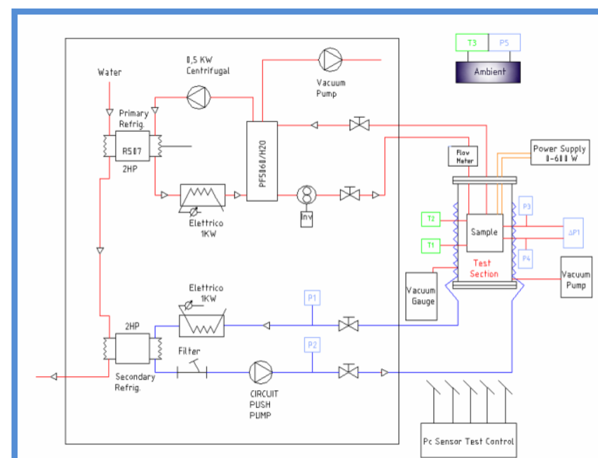
The lab is used for cooling tests and thermal characterization of low mass support structure based on micro-channel technology

- Test bench and chiller for forced convection of liquid monophase



The instrumentation allows to measure/store the values of temp/pressure/flow in the thermal exchange.

Scheme of the Test-bench hydraulic circuit



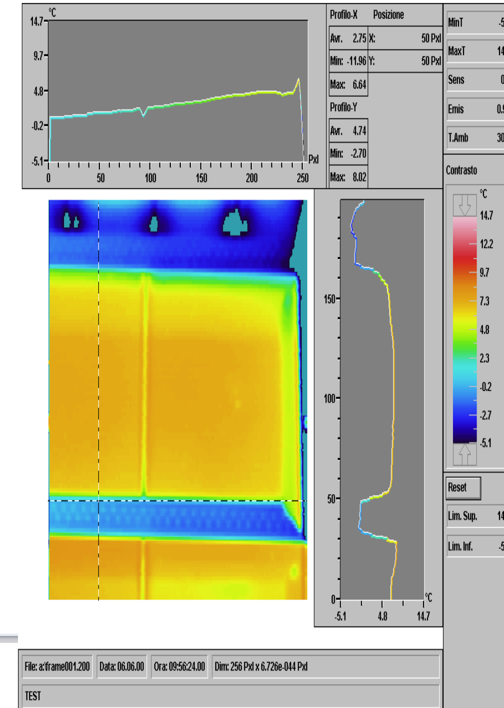
- DAQ HW system (N.24 probes for temperatures, pressure and flow).
- Chiller dimensioned for a cooling power > 1/2 kW primary and secondary cooling circuit

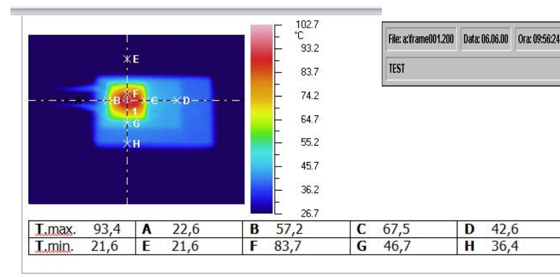
Thermography

Temperature measurement by I.R. thermo-camera (AVIO TVS-2000Mk II long wawe)

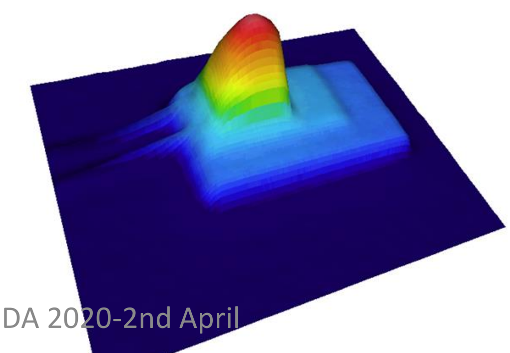
- Resolution: 0.1 °C
- Temperature range: -40/+250 °C
- Experimental thermal analysis on prototypes of cooled read-out electronic for semiconductor detector

Profile view





3D view

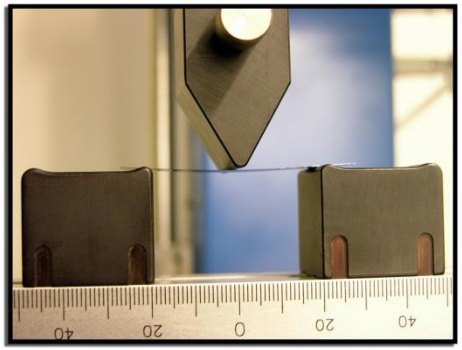


Structural test Lab

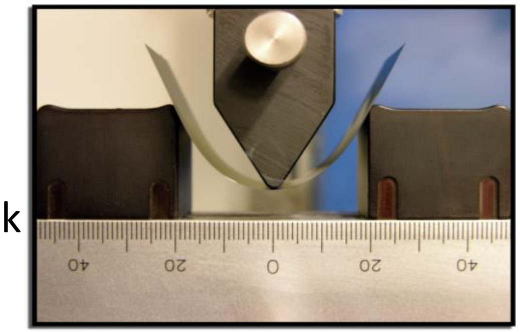
- Mechanical characterization

Materials Testing Machine Lloyd Instruments LR50KPlus

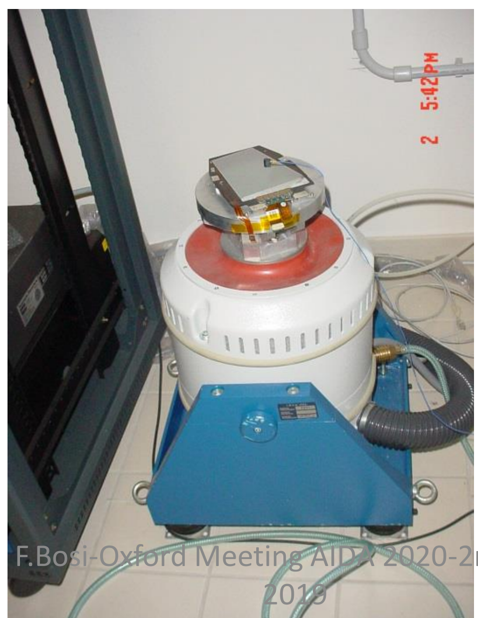
(test up to 50.000 Nw)

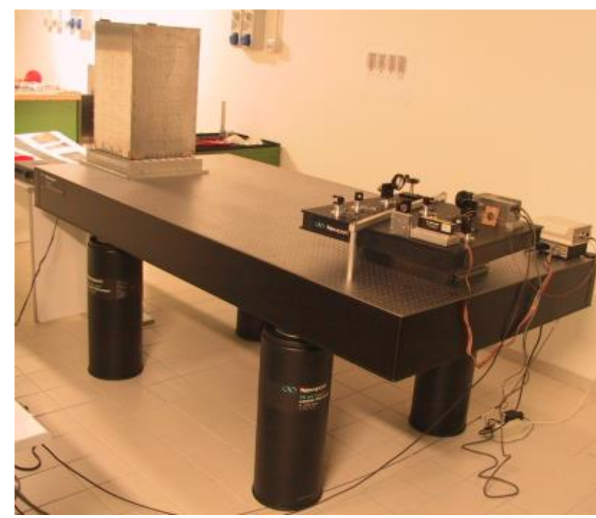


Si sample 50 um thick



•Vibrational Analisys
(Dynamic Shaker up to 10 Kg)





ESPI System (GLAST/FERMI)

Thermal Environment test

Humidity & temperature test chambers for thermal cycles on (large) detector assembly

Volume test 1000x1100x1000 mm^3
Temperature range:
-70°C - +180 °C

Environmental chamber
Angelantoni Challenge

Volume test 3300x3500x2500 mm^3
Temperature range:
-30°C - +80 °C

Environmental chamber - S.Piero lab
Angelantoni WZH30-A1