Development of light prototypes support for silicon pixel detectors cooling based on microchannel technology

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on behalf of the Super-B SVT Group

Outline

- General mechanical requirements for the Super-B Layer 0.
- Miniaturization, cooling and Microchannel technology.
- Microchannel Full and Net Module design, prototypes and tests .
- Direct cooling on silicon chips.
- Conclusions

General Requirements

-Pixel detectors at future colliders need to match very stringent requirements on position resolution and X_0, requiring cooling system.

-The design for intelligent tracker has to consider problems related to high heat flux due to additional power dissipated.

-Concerning the support structure of pixel detectors, the used material must satisfy also requirements of low mass and stability in time.

More specifically :

- long radiation length
- high Young Modulus
- High radiation resistant
- Low thermal expansion coefficient
- Low coefficient of moisture absorption
- Stability in time
- Similar CTE to reduce bimetallic effect

The Super-B Maps sensor/1

For the Super-B L0 detector, there are other requirements that have an impact on the design :

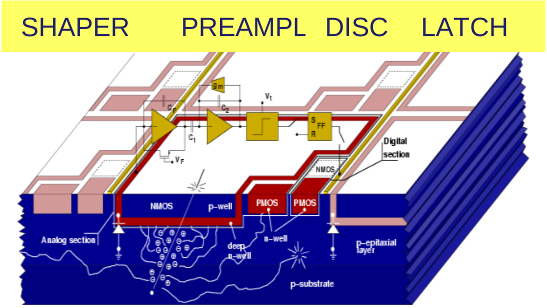
-Geometrical Acceptance:
Θ: sensitive region > 300 mrad
r-φ : small radius (as close as possible to the beam-pipe R~12 mm)

- Detector hit resolution ~ 10 μm →
modules very stiff with small and "stable" (in time) sagitta

-Minimize Multiple scattering for low-Pt tracking →
minimize the material thickness computed in radiation length X_0 (support + sensors) and uniform distribution of the mass support.

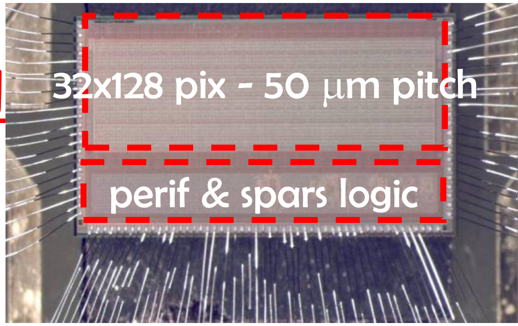
-The radiation length for the mechanical support, excluding cable and sensor materials, has to be as low as possible and remain in any case below 0.3 % X_0

The Super-B MAPS sensor/2



-The mechanical support is designed for a CMOS monolithic active pixel sensor (MAPS) :

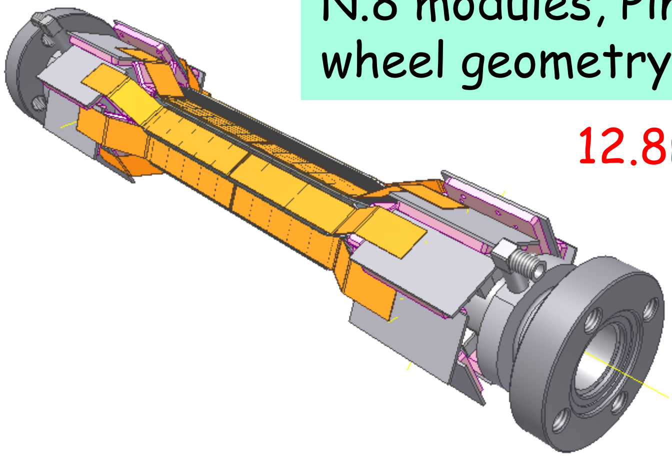
-Silicon thinned down to 50 μm
-Die of 256x 256 channels (12.8 mm x 12.8 mm)
-Elementary cell size: 50 μm x 50 μm
-Power = 30 μW/channel ⟶ 2 W/cm² including digital power (P = 210 W /layer)
-Electronics Working Temp. range: [0,50] °C

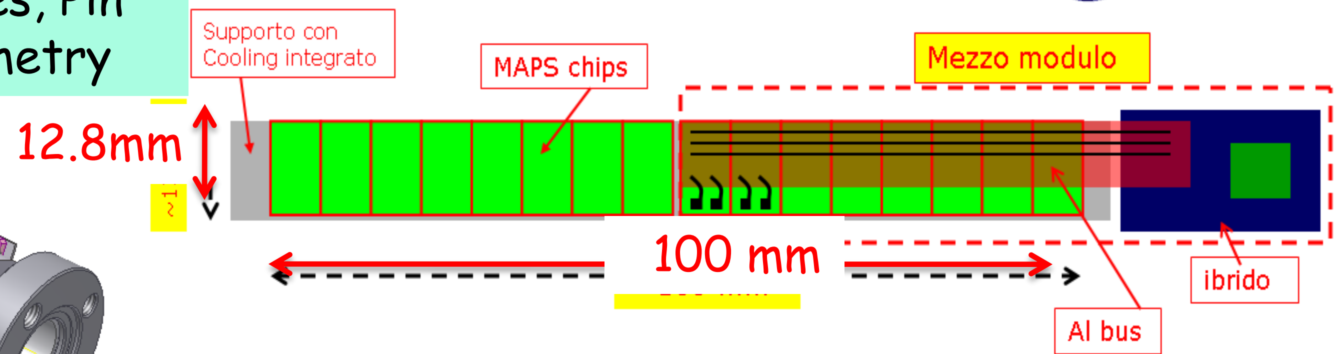


This power value means very high thermal dissipation on the active area and together to the X_0 requirements it drives the technological choice for the mechanical design.

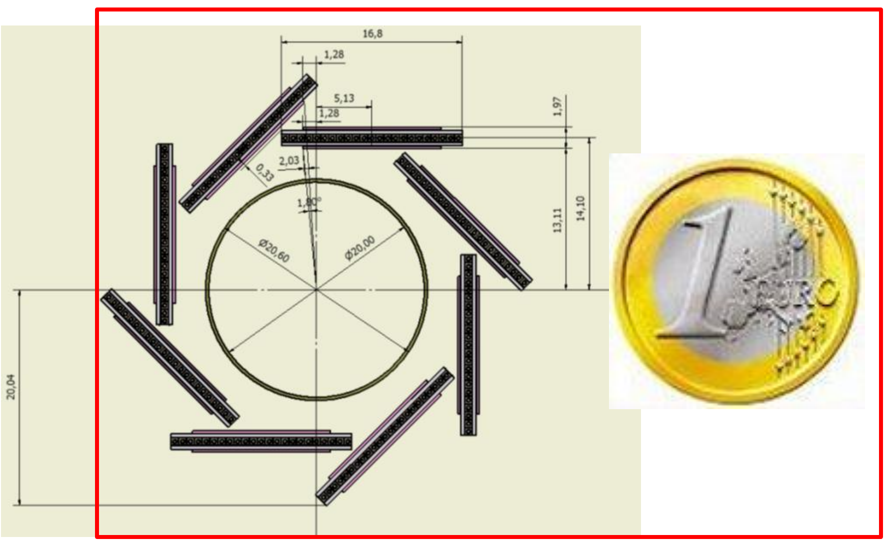
The Super-B module/3

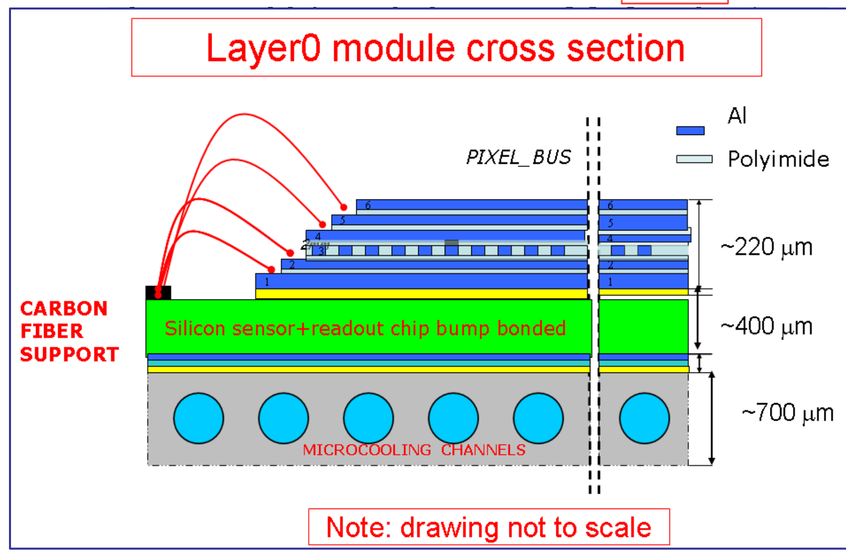
N.8 modules, Pin wheel geometry





Comparing Layer 0 & beam pipe dimensions





Cooling and mechanical miniaturization are important issue for this detector !

Basic hydraulic Concept

Because of the growing of the heat dissipation, conventional air cooling systems are inadequate for removing heat.

For the basic concepts behind micro-channels it's important to introduce the Newton's law for convective heat flux 1) and the Nusselt Number *Nu* which is related to the heat transfer coefficient *(h)*:

1) Q = h S (Tw – Tf)

2) $$h = \frac{K_f \cdot Nu}{D_h}$$

K_f :fluid thermal conductivity

D_h : hydraulic diameter whose value is: $D_h = 4A/P$

where:
A is the cross sectional area
P is the perimeter of the wet cross-section.

If the flow is laminar and fully developed, the Nusselt number is a constant. The small value of the hydraulic diameter D_h of micro-channels enhances significantly the heat transfer coefficient and thus the thermal exchange.

Micro-channel technology is a viable technology to reach acceptable cooling parameters.

Support Characteristic

Merging Super-B experiment specifications with the thermal and hydraulic concepts, we focused our attention on a CFRP supports with microchannel technology for an heat evacuation through a single phase liquid forced convection .

-Several prototypes with different geometries and material have been realized.
-Miniaturization of composites structures have been developed through close collaboration with companies.
-Prototypes have been submitted to test at the TFD laboratory of the INFN-Pisa.

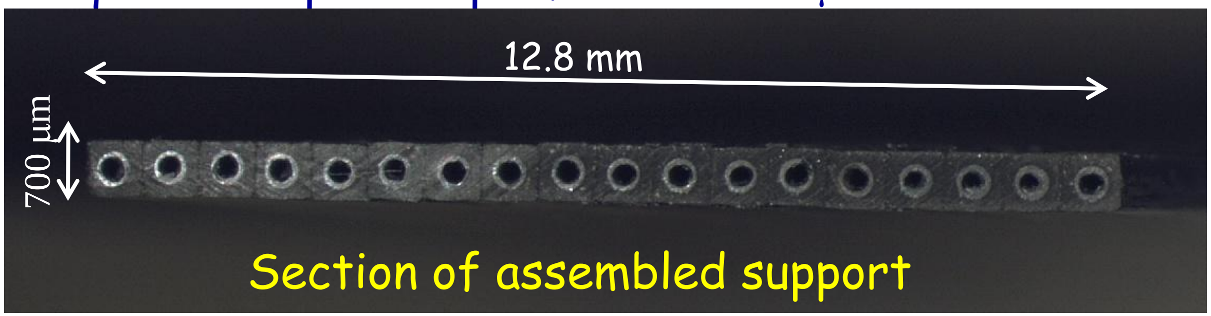
In particular two kinds of module support in CFRP have been produced and tested; the Full and the Net module.

Full Module support

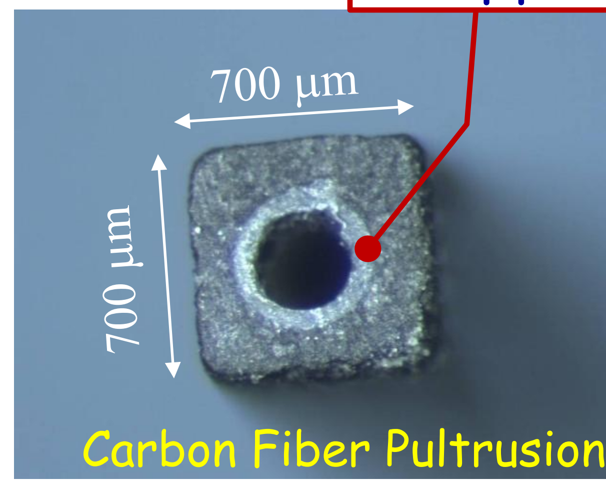
CFRP MICROCHANNEL MODULE

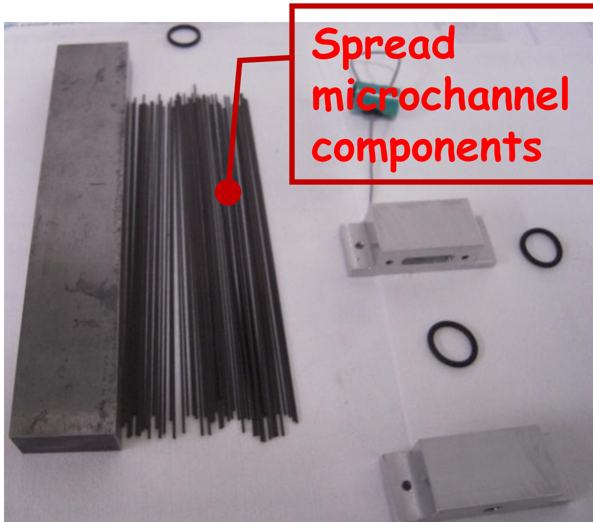
Obtained by pultrusion C.F. TohoTenax HTS 40 , adding and gluing in special masks, side by side, 18 single micro-tube.

The inner diameter of the peek micro-tube is 300 µm, the thickness of the square composite profile is 700 µm .

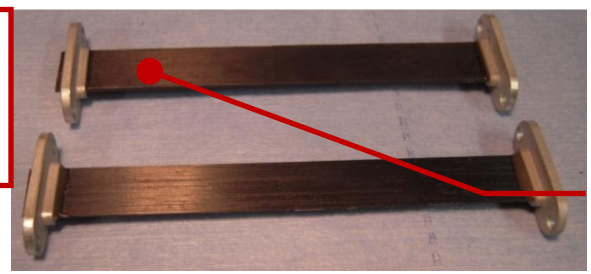


Peek pipe





Spread microchannel components

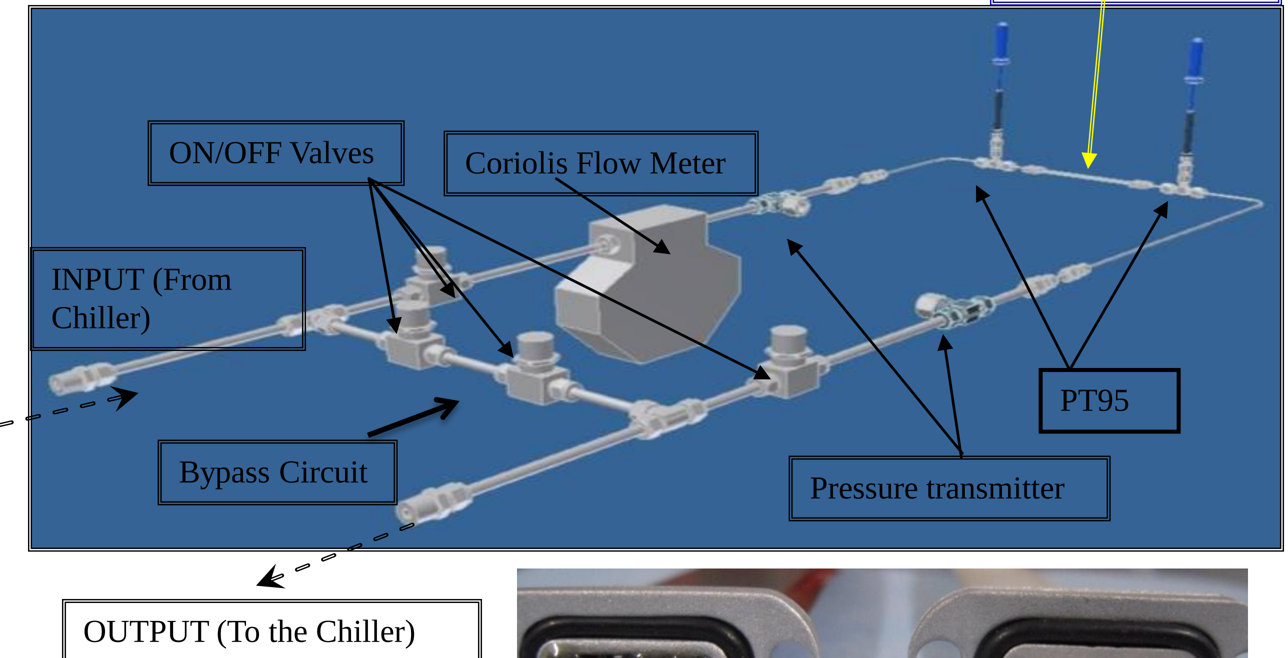


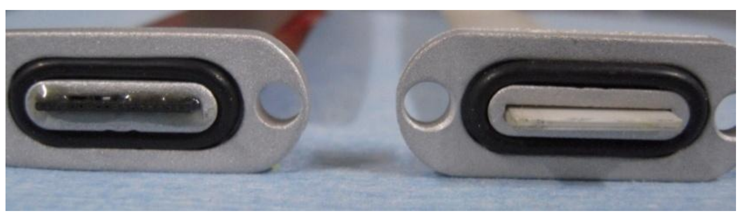
Support Module assembled

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. With a grinding operation on C.F. is possible to get down at 0.25% X_0 .

Test and set-up at TFD lab

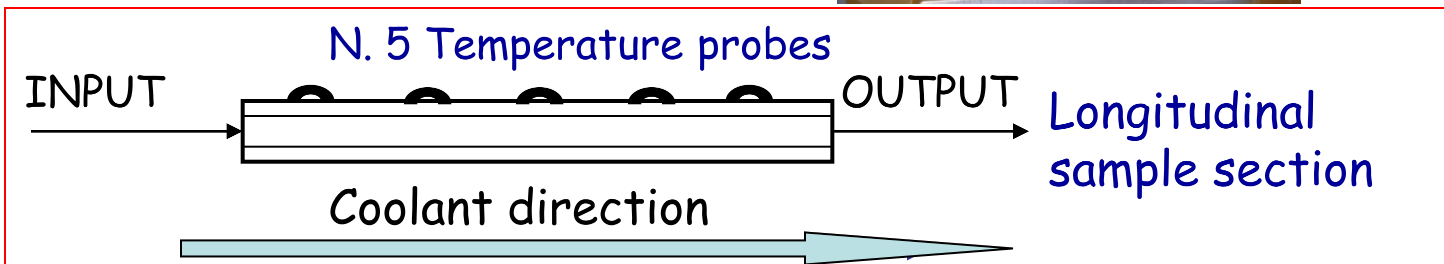
Cooling Circuit Schematic View:





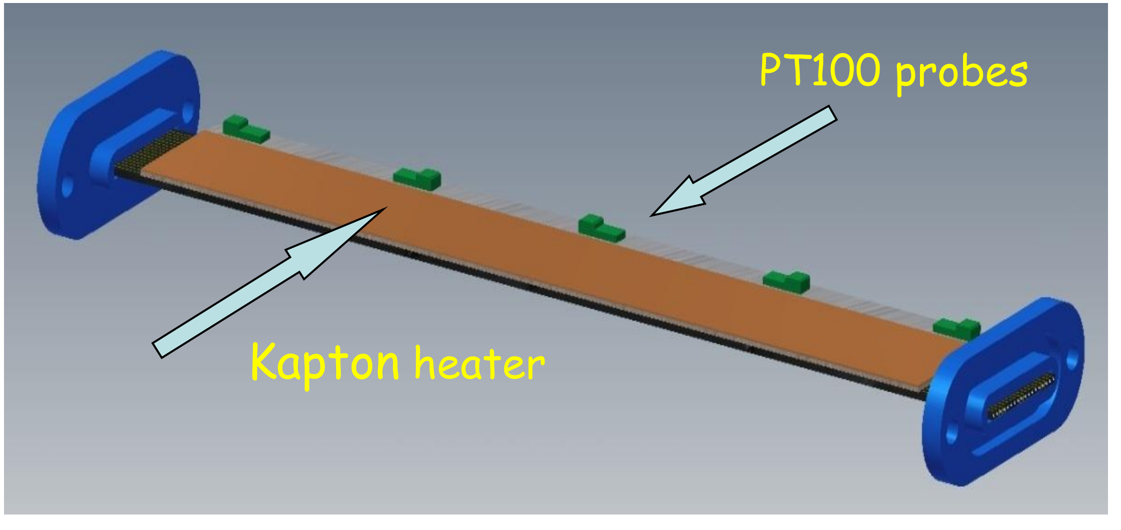
DAQ System:

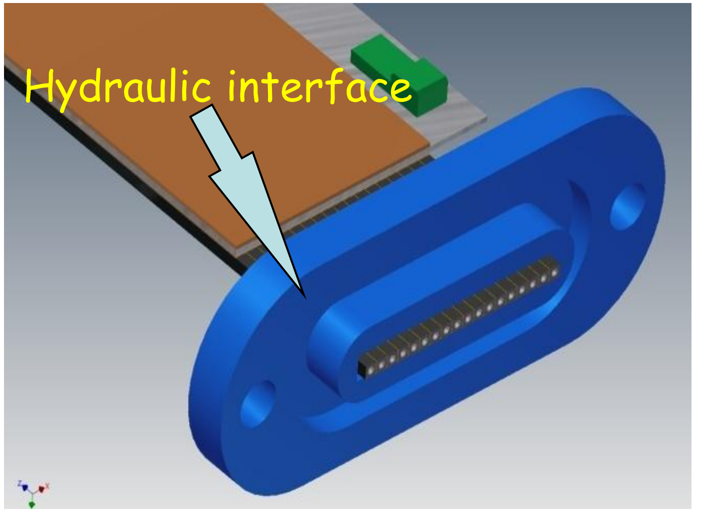
Test Section:



Module Samples

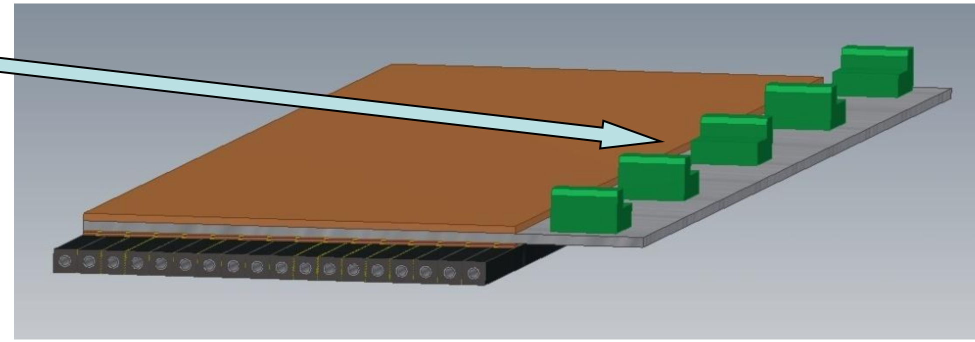
A kapton heater is glued on the Microchannel CFRP support structure to dissipate the needed power density.
On the bottom of the heater there is an aluminum foil 300 μm-thick, in place of the silicon detector. On the top, to read the temperatures, n.5 PT100-probes are glued, positioned just laterally 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).



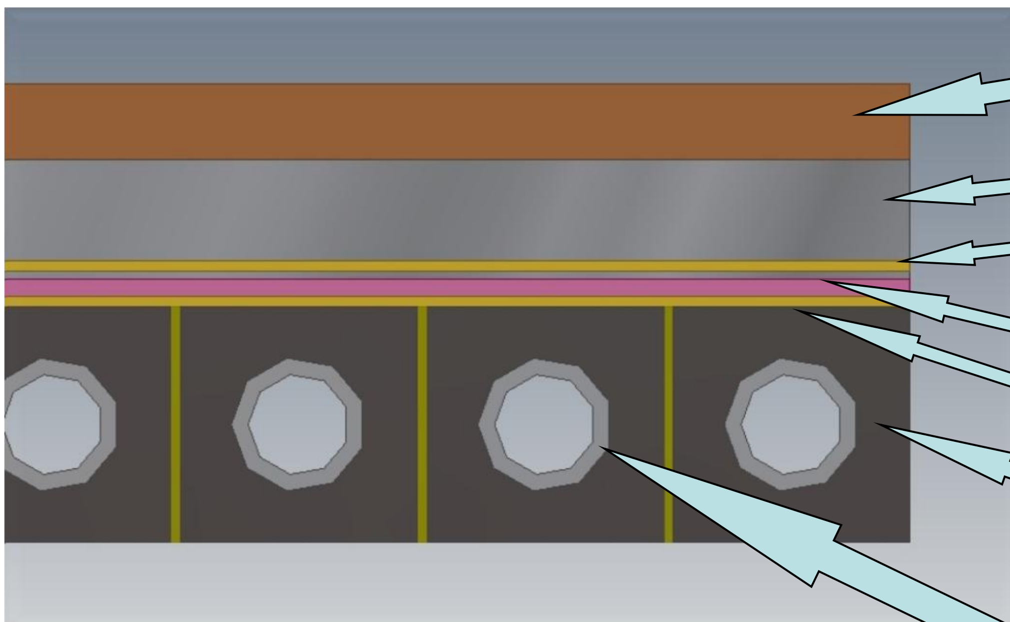


Module Sample Structure

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

Test Procedures

<u>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 .</u>

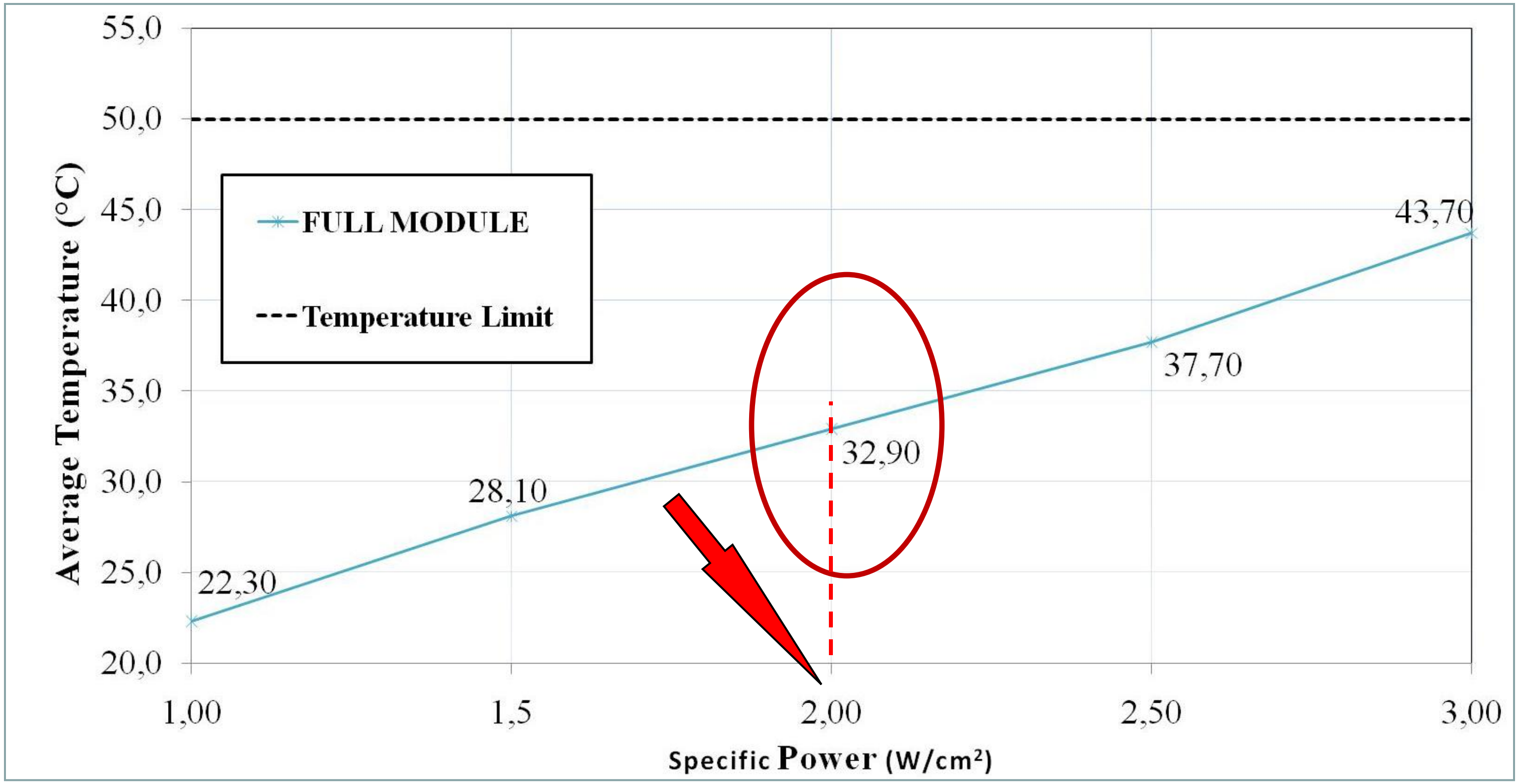
The tests have been performed in standard way for all kinds of module. During the tests the average temperature of the environment was 22.0 °C (for these kind of test there is no need to avoid environment free convection and irradiation).

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.

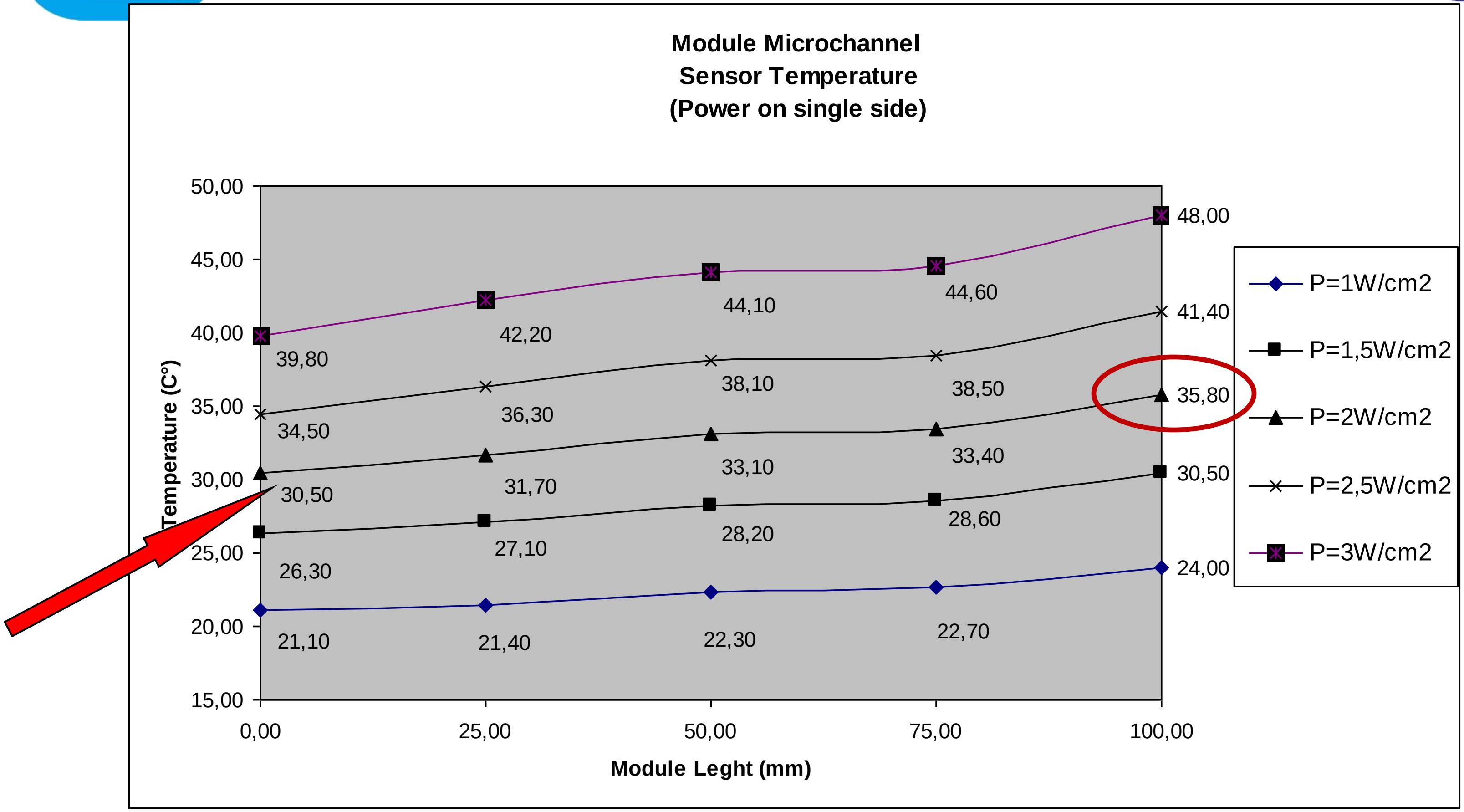
Full module test results/1

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

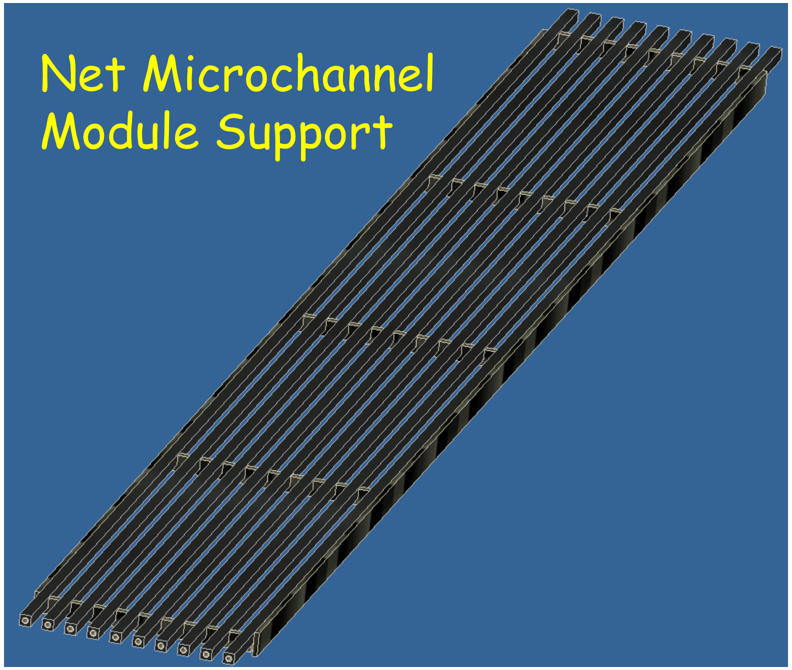


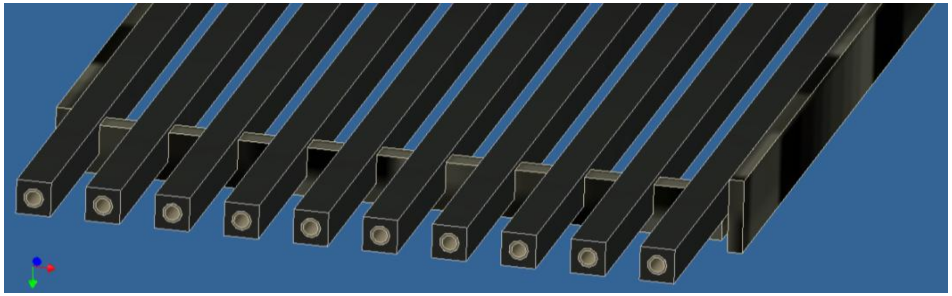
Temperature along the module: ΔT=5,3 °C at 2W/cm^2 and Δp=3,6 atm

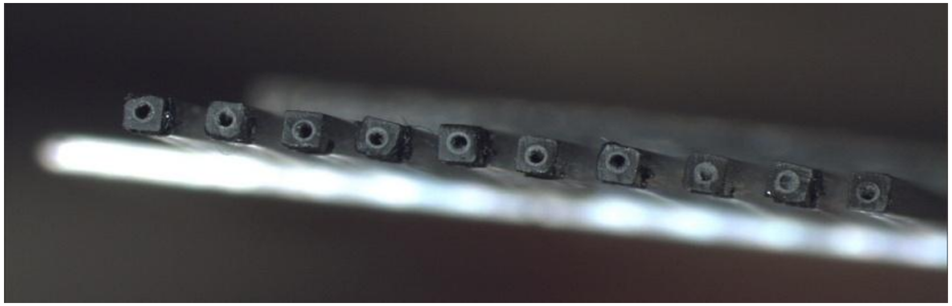
Net Module support/1

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.

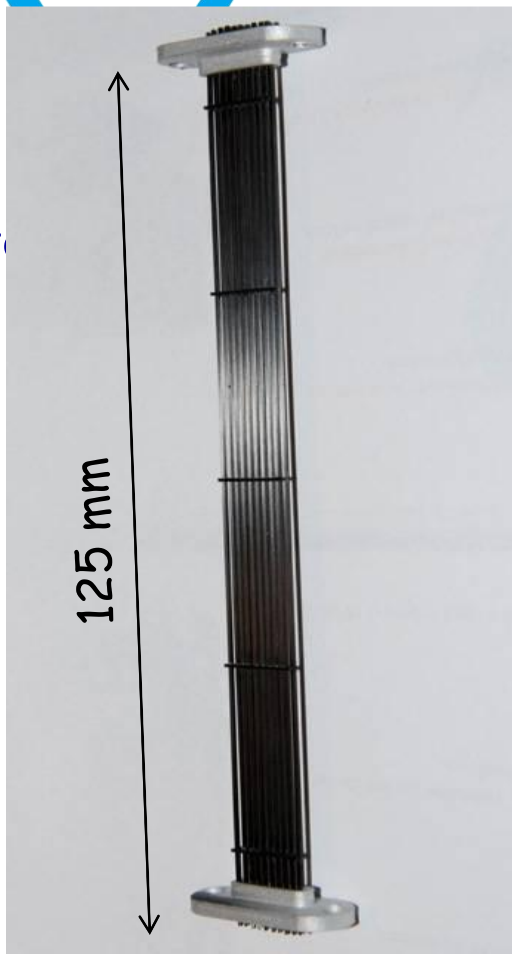


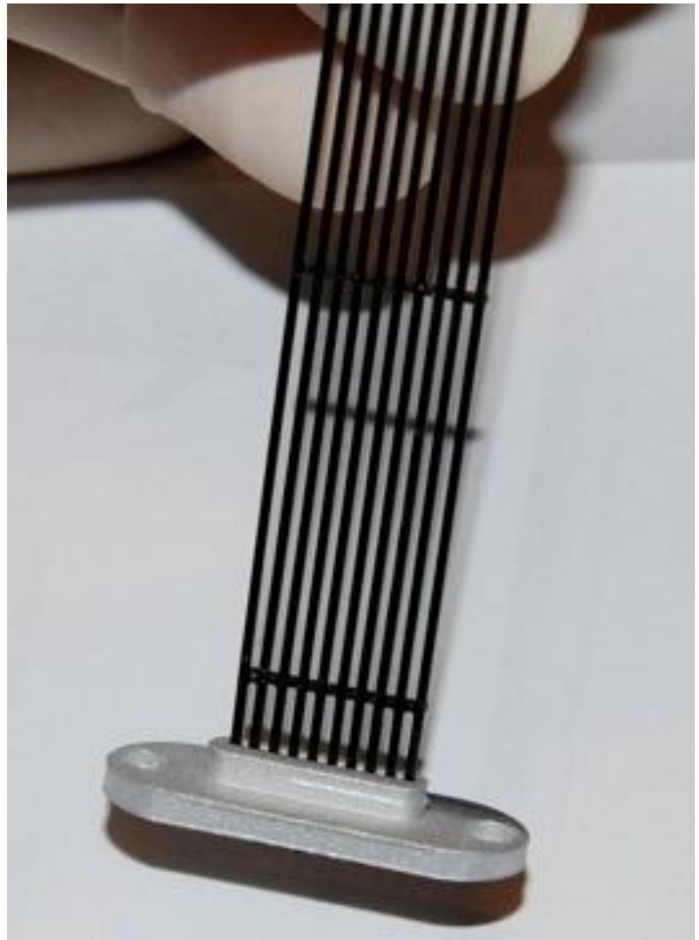




Material of the support structure: (CFRP + peek tube + Water + CFRP Stiffeners)

Net Module Support/2





Very thin transversal CFRP stiffeners are glued to microchannels

Micropositioning and microgluing work required dedicated gluing masks .

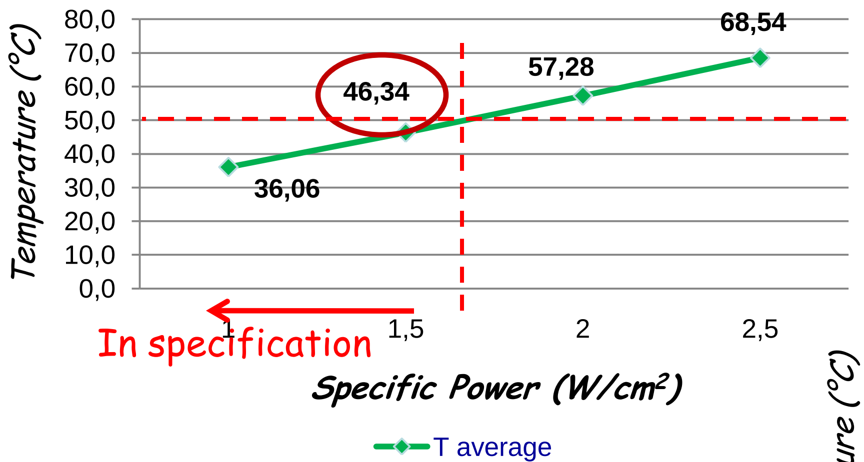
Sealing of the hydraulic interface is obtained with epoxy/CFRP .

$X = 0.15\%\ X_0$

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

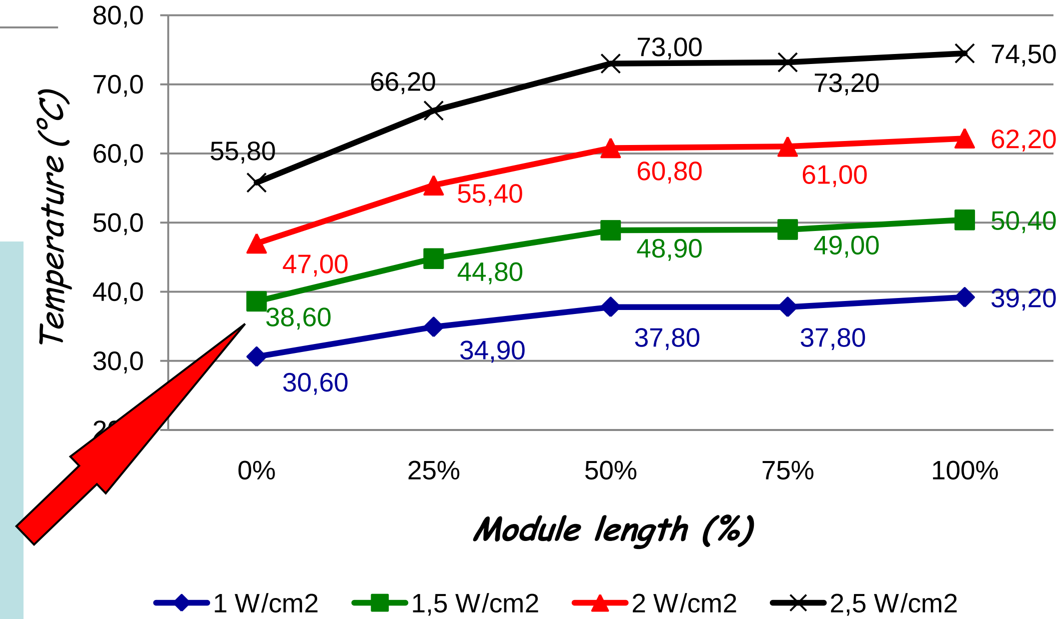
Net Module test results

Net module average Temperature
Vs. Specific power density



Tests performed on net module sample (length = 120 mm) with water-glycol @ 10 °C as coolant.

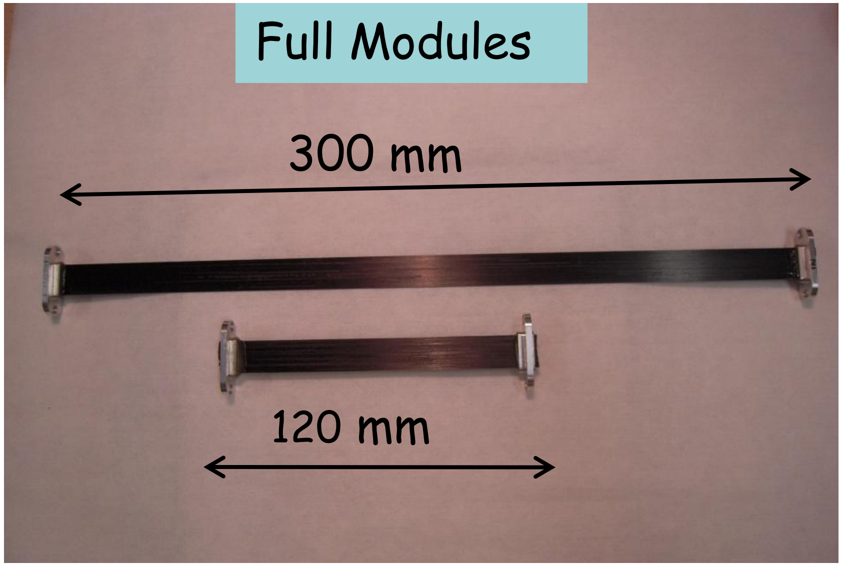
Temperature along the module

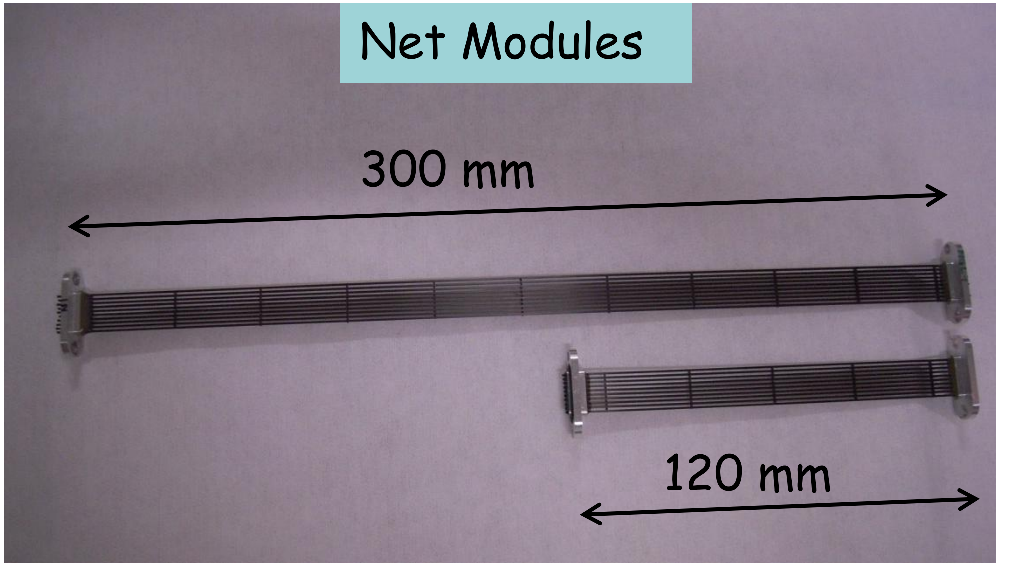


This experimental data shown that Net Module is able to cool power up to about 1.5 W/cm² at the max required Temperature (50 °C).
This goal can also be achieved with a greater safety factor by reducing the inlet coolant temperature.

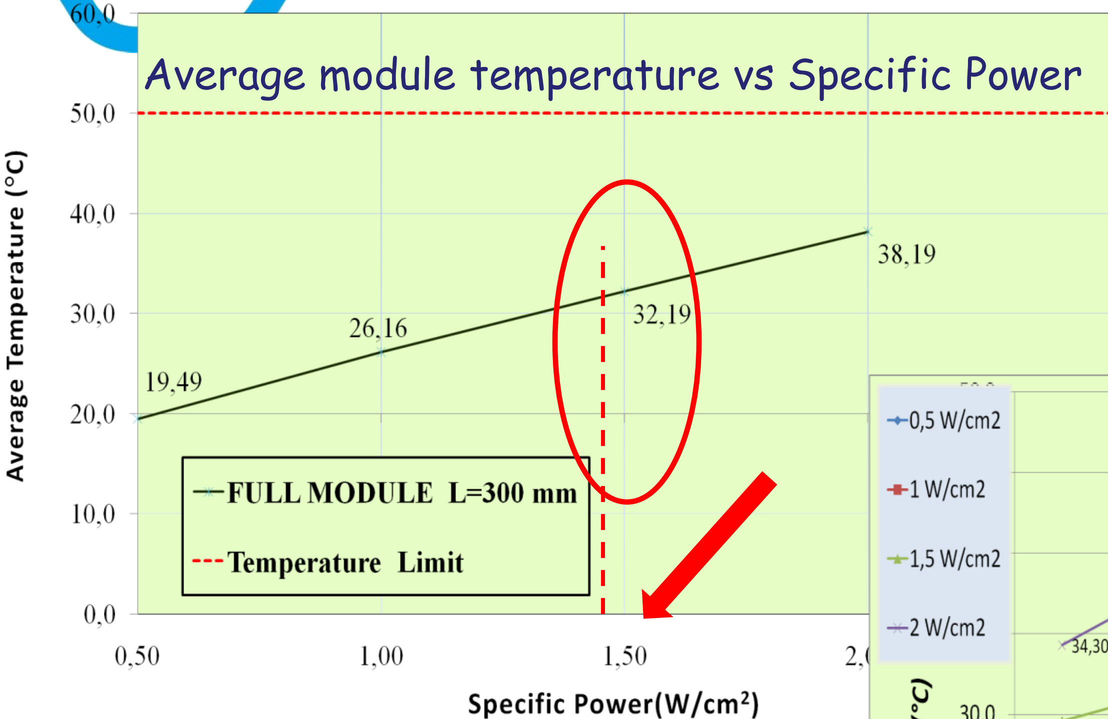
Full and Net Long Modules

In order to test longer microchannel support structures useful for different experimental layout, two new 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.

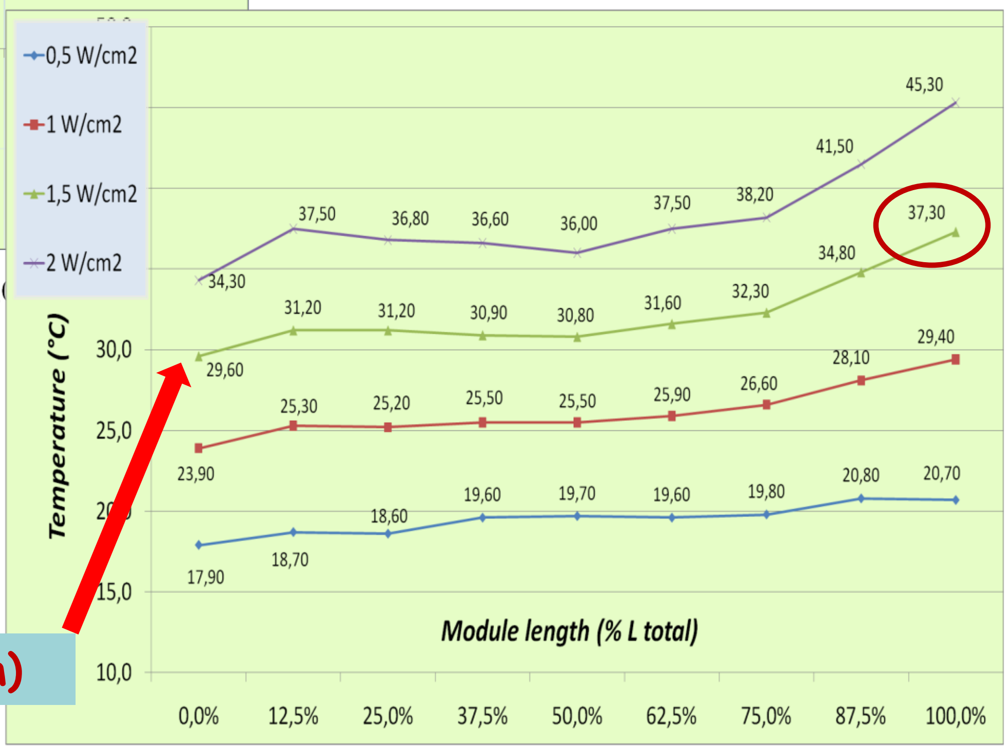




Full Long Module test results



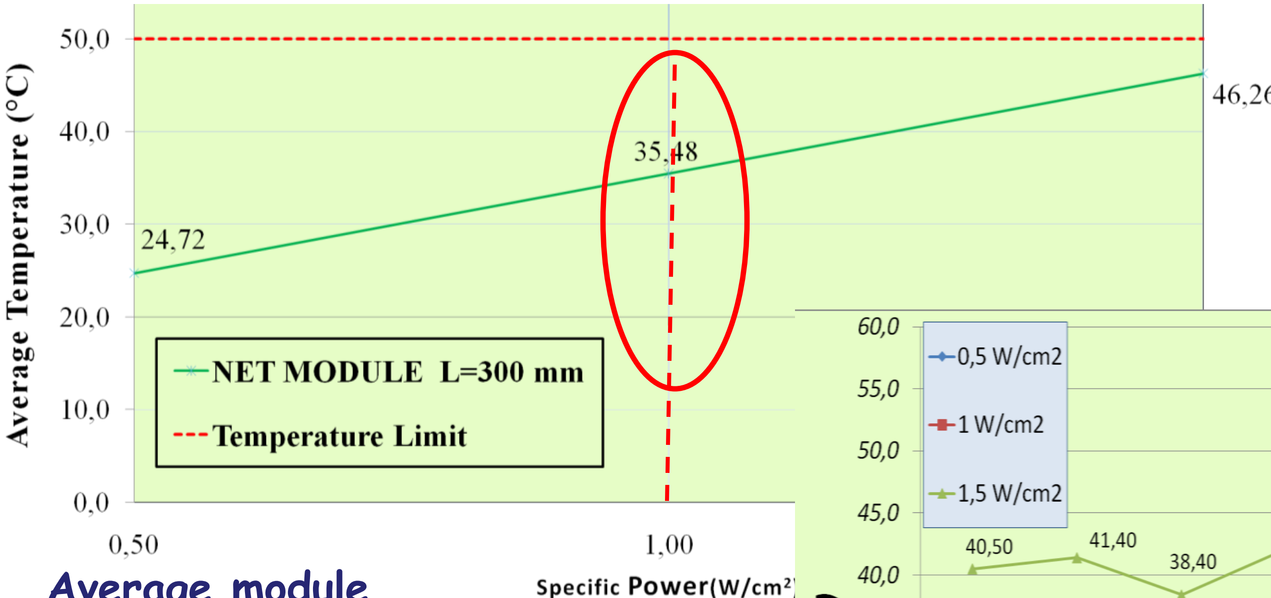
Tests performed on full module sample (length = 300 mm).



Temperature along the module: (ΔT = 7.7 °C at 1.5W/cm², Δp =3,5 atm)

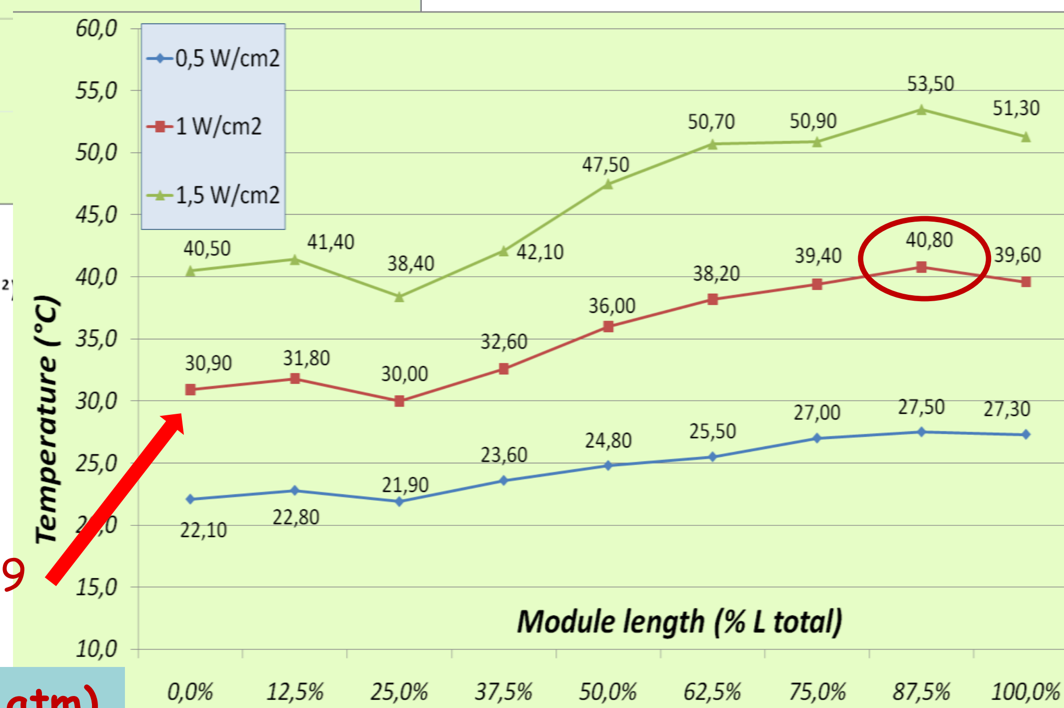
(ΔT = 4,8 °C at 1.5W/cm², Δp =7,0 atm)

Net Long Module test results



Average module Temperature vs Specific Power

Tests performed on Net Module sample (length = 300 mm).



Temperature along the module: (ΔT = 9,9 °C at 1.0 W/cm^2 , Δp =3,5 atm)

(ΔT=6,2 °C at 1.0 W/cm^2, Δp =7.0 atm)

Hydraulic parameter

The hydraulic parameters show that for the micro-channel geometry there is a laminar flow and a good thermal film coefficient.

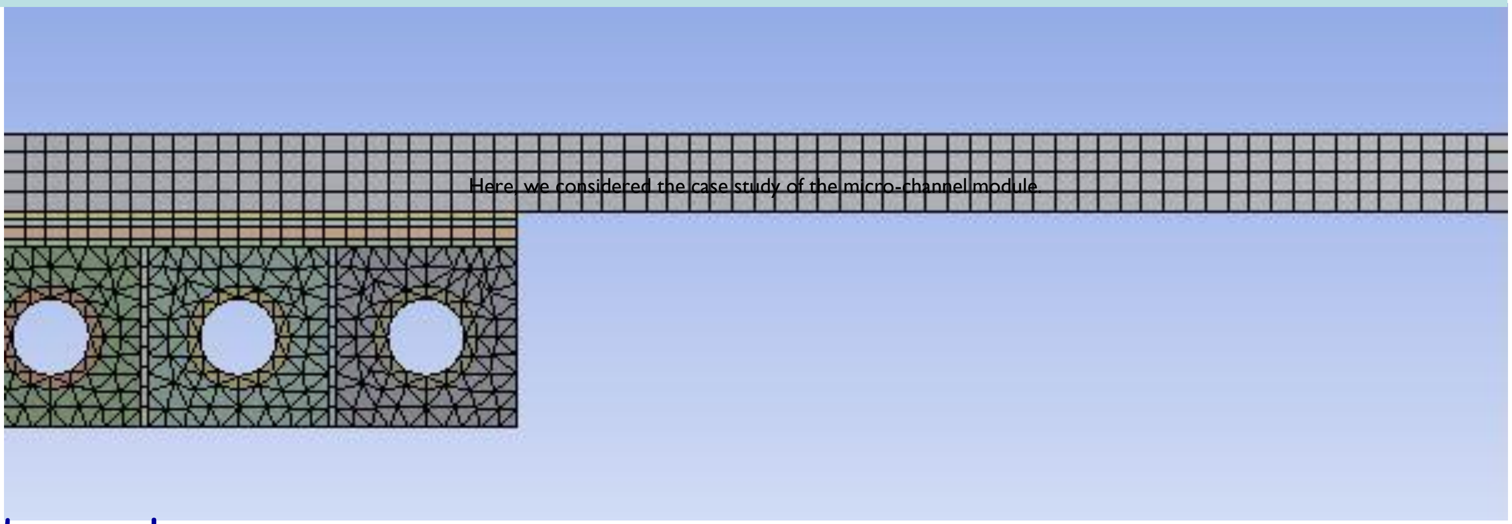
	Total Section	D_h	Total flow	Pressure drop	Flow characteristic	Fluid velocity	Re	h
	mm^2	mm	kg/min	atm	-	m/sec		W/m^2K
Net Module Micro-channel (10 micro-tubes)	0,7	03	0,128	~ 3,6	laminar	3,37	267	3275
Full Module Micro-channel (18 micro-tubes)	1,272	0.3	0,244	~ 3,6	Laminar	3,37	267	3275

It's important to find a balance between pressure drops and *h* value because minimize D_h means to go towards greater pressure drops.

A laminar flow inside the cooling tube minimizes the pressure drops. (Reynolds number < 2300).

Thermal Simulations/1

In order to validate the experimental tests have been performed simulation studies on the micro-channel module .



<u>Boundary values</u>:

<u>Power density: 2 W/cm2</u>

Water film coefficient*: 3275 W/m2K

Coolant Temperature: 10 °C

Air film coefficient: 5 W/m2K

Air Temperature: 22 °C

<u>Thermal conductivity of the materials</u>:

CFRP: 2 W/mK

PEEK: 0.25 W/mK

Kapton: 0.15 W/mK

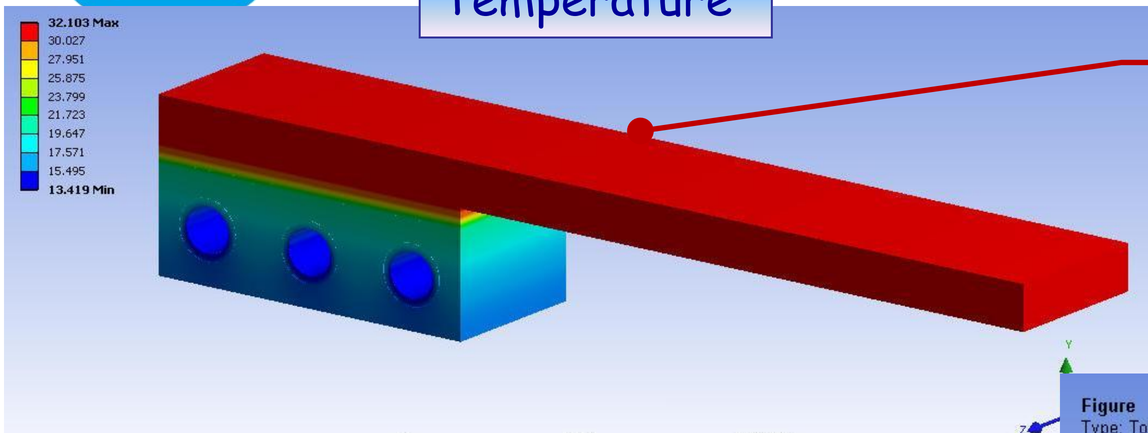
Aluminum: 210 W/mK

Glue: 0.22 W/mK

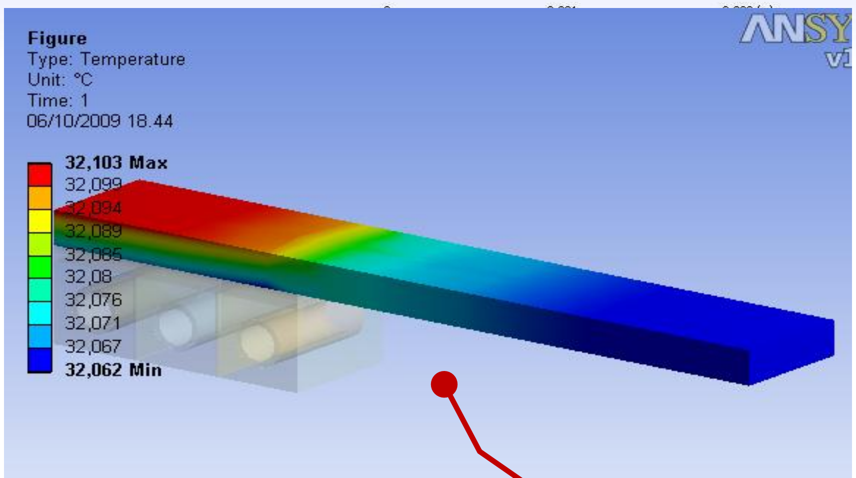
*: it is derived from experimental and geometrical data.

Thermal Simulations/2

Temperature

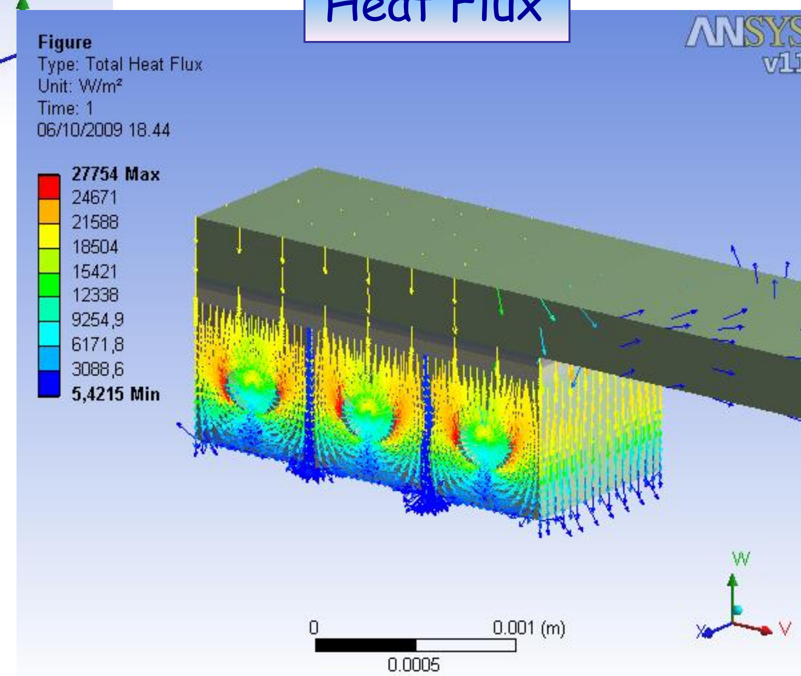


Maximum temperature reached: T_{max}=32.1 °C, in the entrance region (same position of the glued probes in the experimental test).



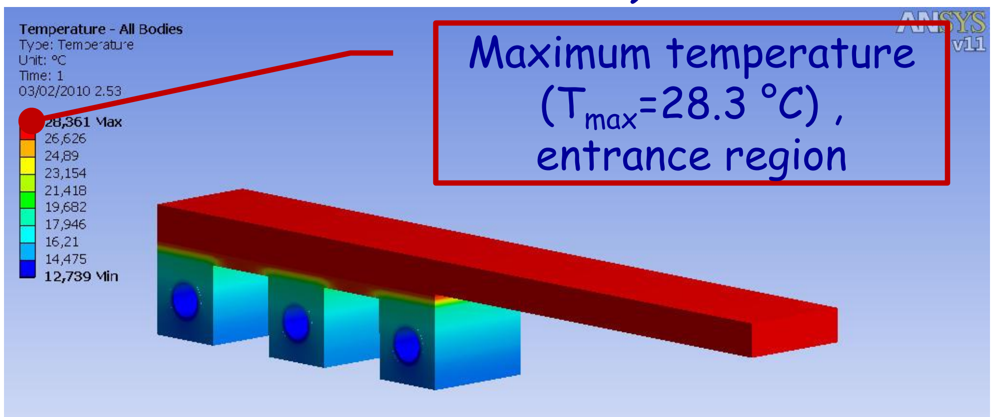
Temperature gradient (0.04 °C) on the aluminum foil

Heat Flux



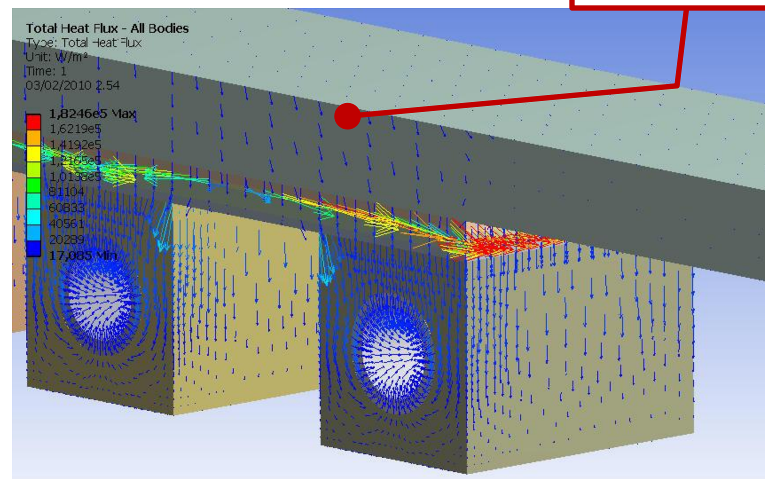
Thermal Simulations/3

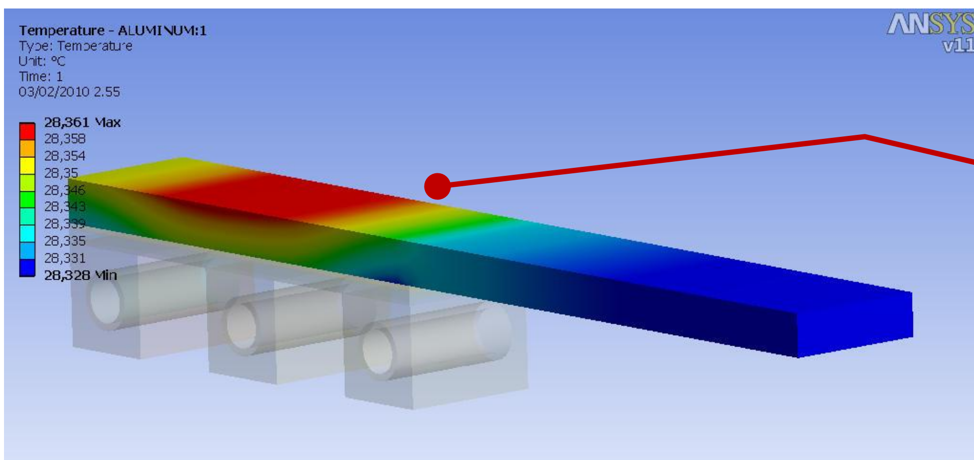
Case study: Net module with 1 W/cm^2 (the same boundary values used for microchannel Full Module)



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

Heat flux





Temperature gradient (0.4 °C) on aluminum.

2 °C difference between FEM results and experimental data.
It can be ascribed to the uncertainty of the thermal interfaces.

Module Support performance improvement

There are several lines to follow for further enhancing the performance of the microchannel support in single phase forced convection :

1) Further miniaturization of the base microtube profile:
CFRP thickness = 550 μm, peek tube inner diameter = 200/50 th μm ;
(actually in progress prototype manufacturing) .

2) Use of thermoplastic technology and composite material with higher conductive thermal coefficient.

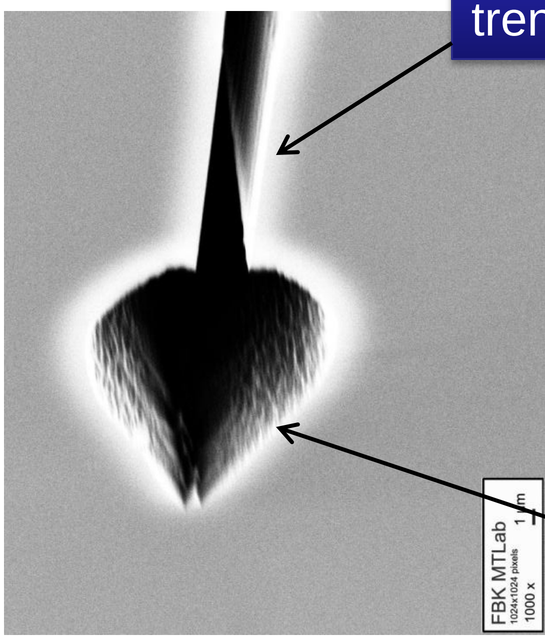
3) Use opposite flow directions of the coolant in the module in order to minimize the temperature variation along the module especially the long one ; (it requires a special design of the hydraulic interfaces)

4) Use of nano-carbon tube doping mixed in the coolant (5-6 %) to get a more efficient thermal exchange (200% better film coefficient).

Direct cooling on CMOS chip

For the VIPIX R&D experiment we are testing DIRECT COOLING in a silicon chip. This is a collaboration with the FBK of Trento (Italy) in the agreement INFN PAT MEM2 to realize in DRIE process special microchannels.

A DRIE process is used to obtain a special shape trenches in the silicon. These original shape allow an easy sealing of the microchannel with very thin layer semiconductor oxide (PECVD).

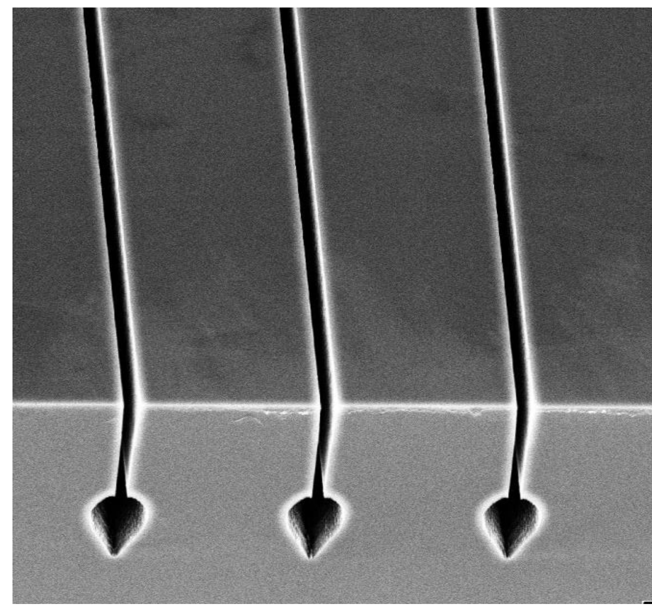


We expect :

-No heath sink

-High power removed

- High drop pressure

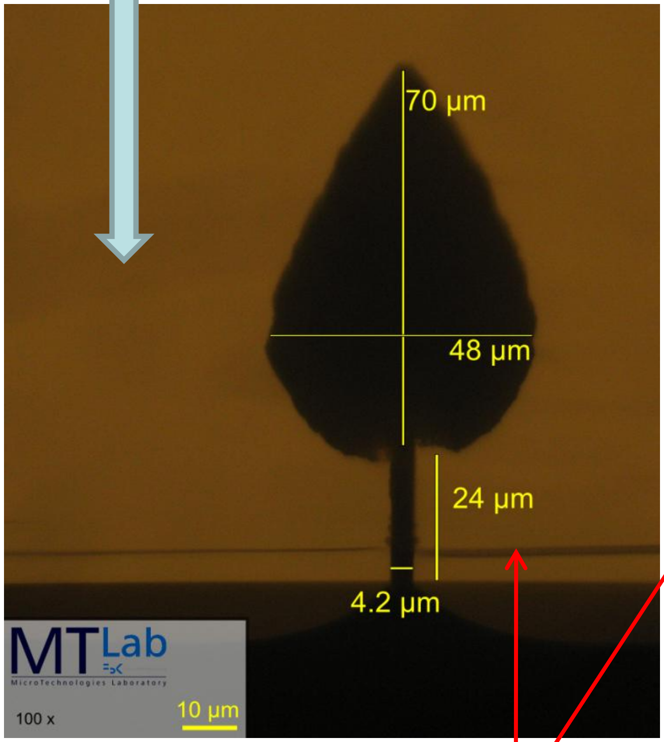


Microchannel integration on silicon prototype

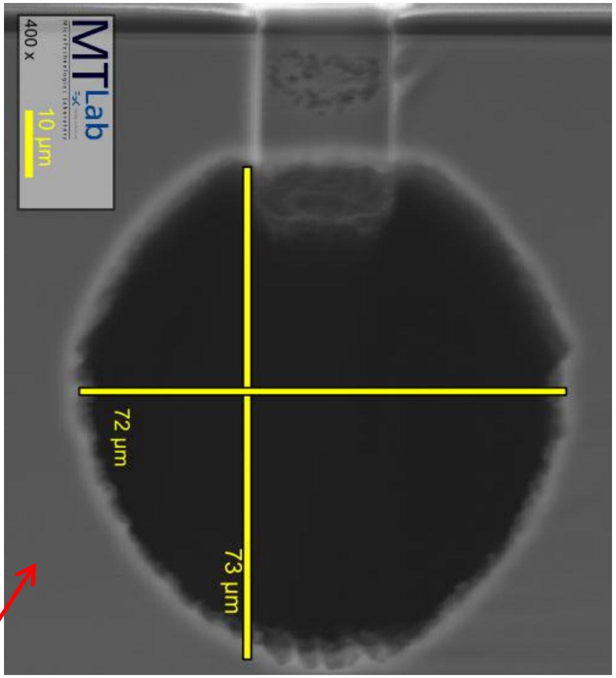
Two different mask design to obtain microchannel Dh = 50 μm and 100 μm

A) transversal strip

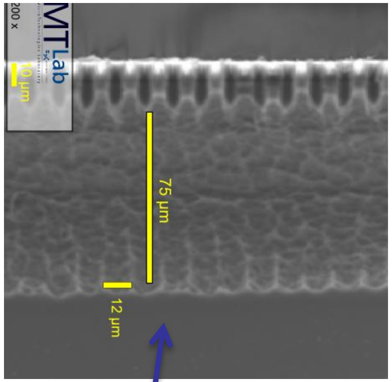
B) longitudinal strip

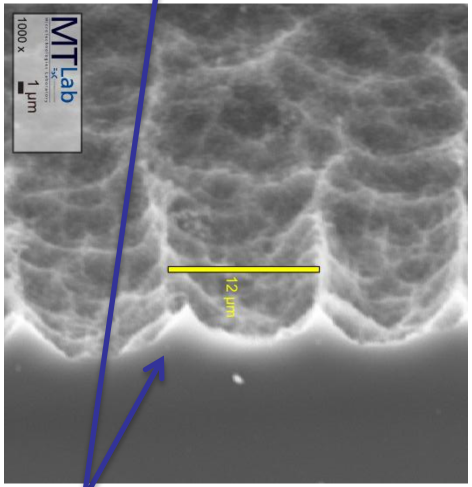


Silicon transversal section



At the moments we are testing prototypes type B) with Dh=50 μm

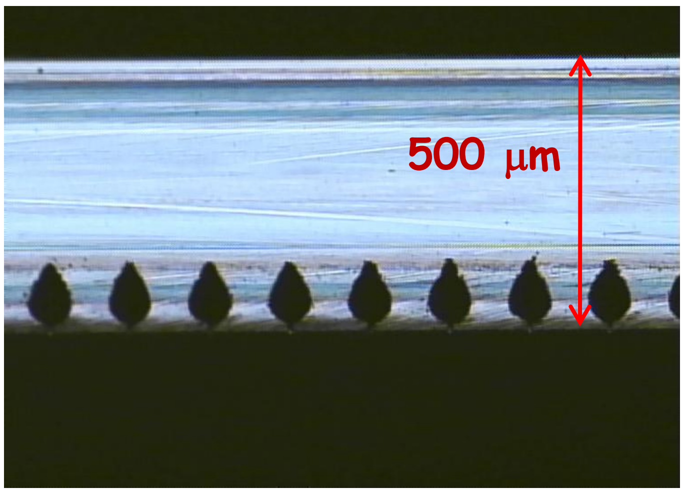


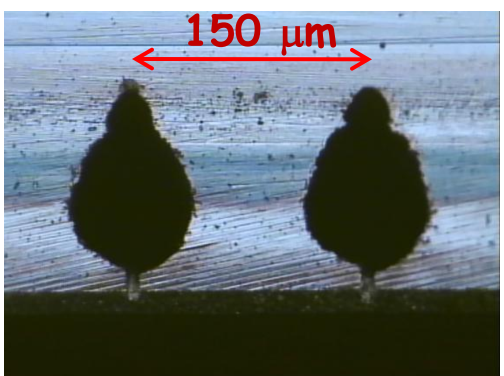


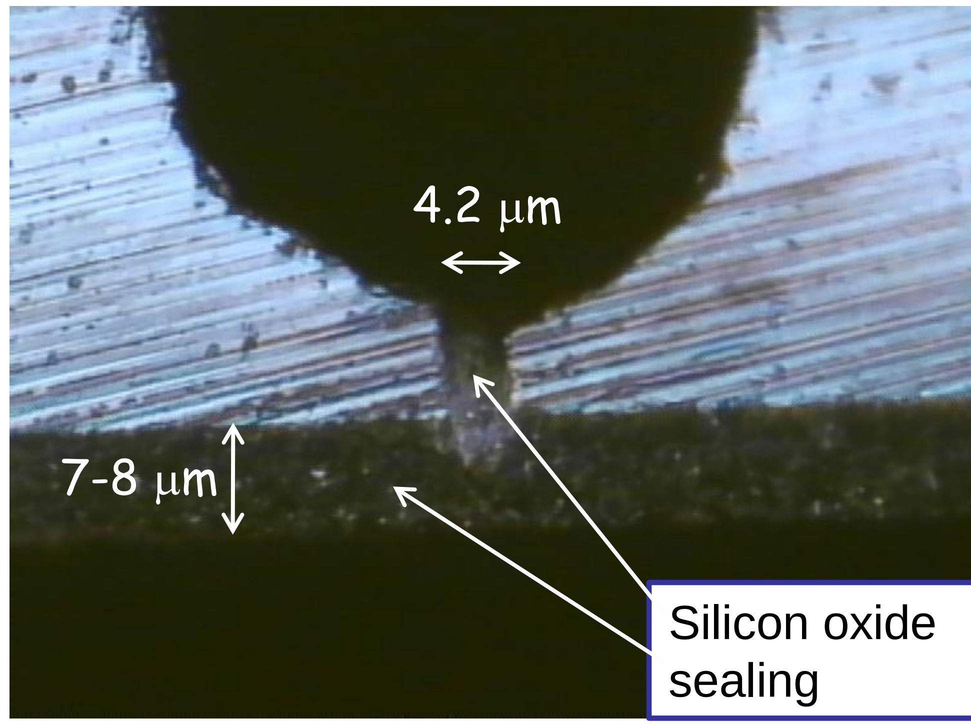
Silicon longitudinal section

Microchannel integration on silicon prototype

From a 4" wafer are obtained N.5 silicon prototypes of 12.8 width mm x 60 mm length x 500 μm thick with N.61 microchannel to perform cooling tests



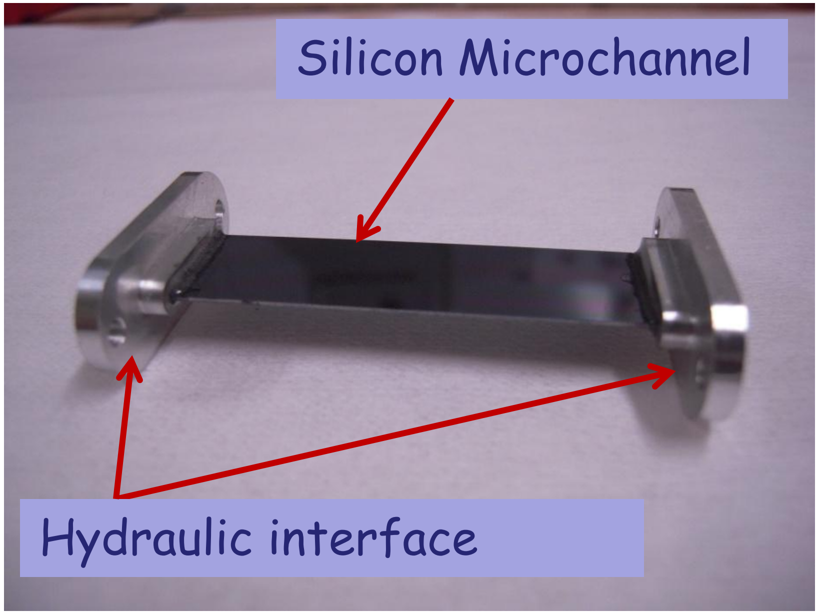


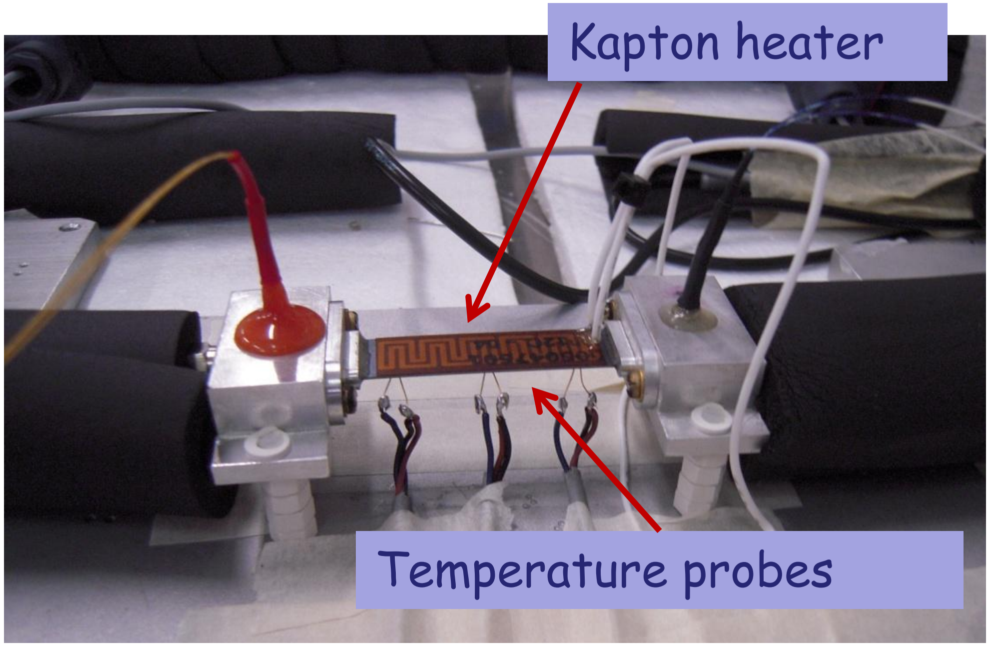


In the picture, the dimensions of the module prototypes in our hand .

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 .



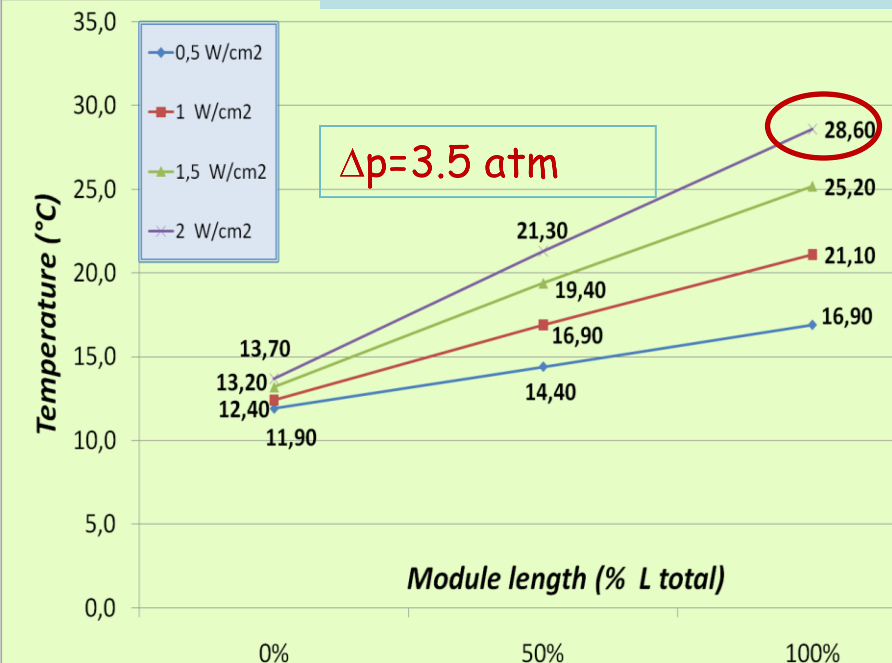


Tests on prototypes are on going, preliminary run have shown that the oxide layer sealing operates without leak at the test pressure (7.0 atm) .

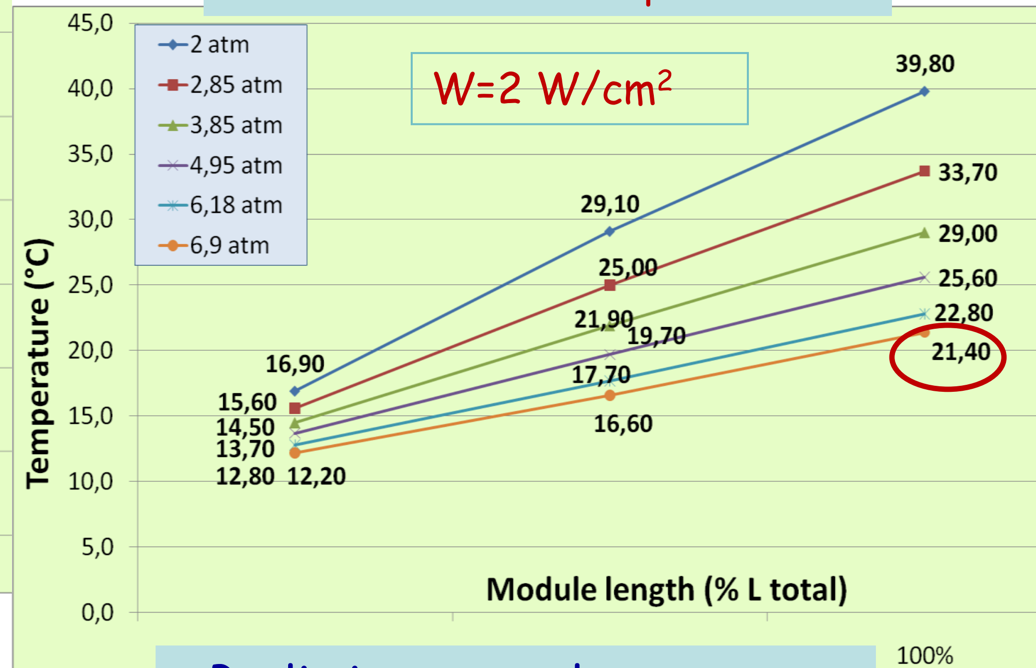
Microchannel silicon prototype test

SuperB INFN

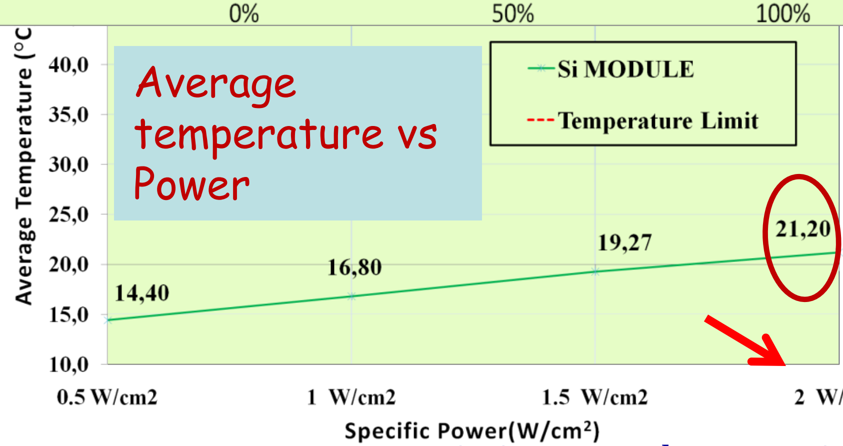
Temperature along the silicon module at different power



Temperature along the silicon module at different pressure



Average temperature vs Power



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

Conclusion

• We performed studies for a light mechanical/cooling support structure suited for the L0 of the Super-B experiment and in general also for detectors with high power dissipation in the active region (order of 2 W/cm^2).

•There is at the INFN-Pisa a test-facility to perform experimental analysis of cooling circuits in liquid single phase thermal exchange. In future it is planned to test microchannel technology in change-phase cooling .

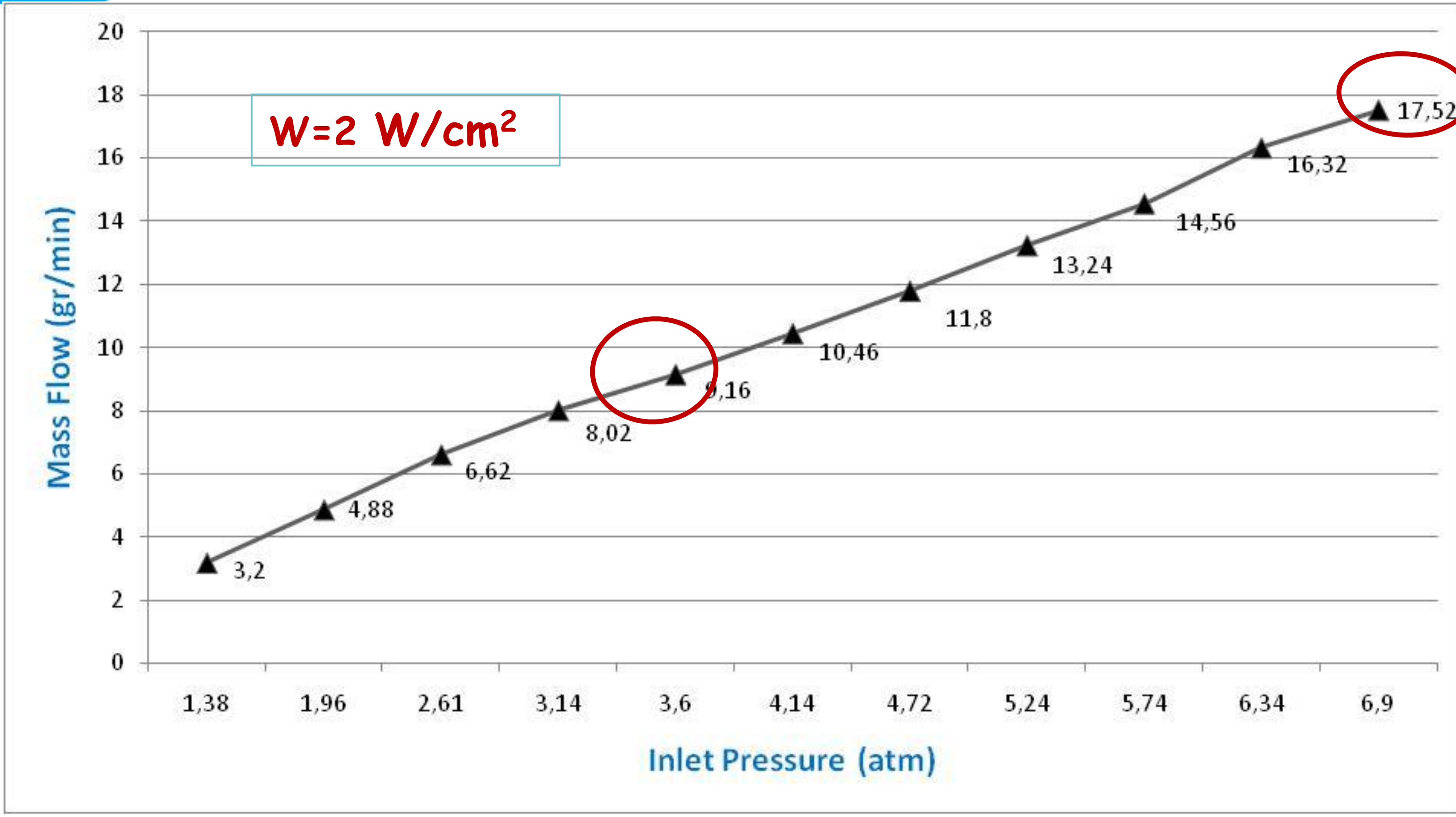
• Our prototypes support design for the L0 Super-B detector, based on microchannel technology in single phase forced convection, matches the requirements for pixel MAPS (P= 2W/cm^2, X_0= 0.25%) and for pixel hybrid sensors (P= 1.5-1,0 W/cm^2, X_0= 0.15%) .

• First experience for direct cooling on CMOS chip shown the feasibility of this technological line.

• Further enhancement are still possible within microchannel technology, gaining in X_0 and thermal efficiency.

BACK UP

Microchannel silicon prototype test



Mass Flow vs Inlet Pressure

Hydraulic parameter

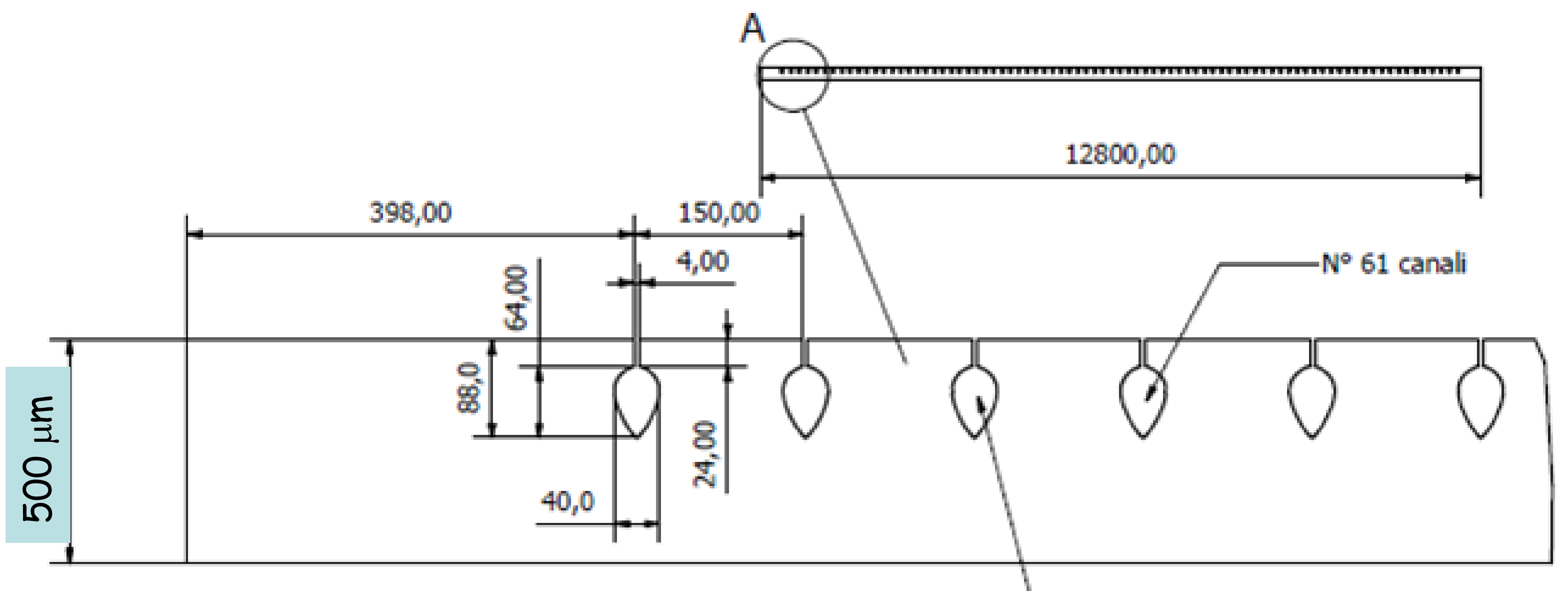
The hydraulic parameters of the micro-channel geometry show that there is a laminar flow and a good thermal film coefficient.

	Total Section	D_h	Total flow	Pressure drop	Flow characteristic	Fluid velocity	Re	h
	mm^2	mm	kg/min	atm	-	m/sec		W/m^2K
Full Module *Micro-channel (18 micro-tubes)*	1,272	0.3	0,244	~ 3,6	Laminar	3,37	~ 267	~ 3275
Net Module *Micro-channel (10 micro-tubes)*	0,7	0.3	0,128	~ 3,6	Laminar	3,37	~ 267	~ 3275
Full Module long *Micro-channel (18 micro-tubes)*	1,272	0.3	0,1	~ 3,6	Laminar	1,4	~ 110	~ 1200
Net Module long *Micro-channel (10 micro-tubes)*	0,7	0.3	0,06	~ 3,6	Laminar	1,4	~ 110	~ 1200

It's important to find a balance between pressure drops and *h* value because minimize D_h means to go towards greater pressure drops.

A laminar flow inside the cooling tube minimizes the pressure drops (Reynolds number < 2300).

Microchannel silicon prototype test



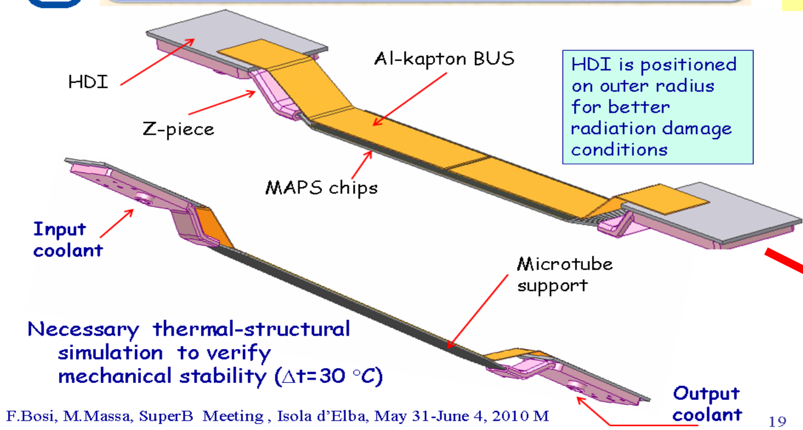
SVT Mechanics

Good progress on mechanical beam pipe design & integration of Layer0 modules on cooled flanges

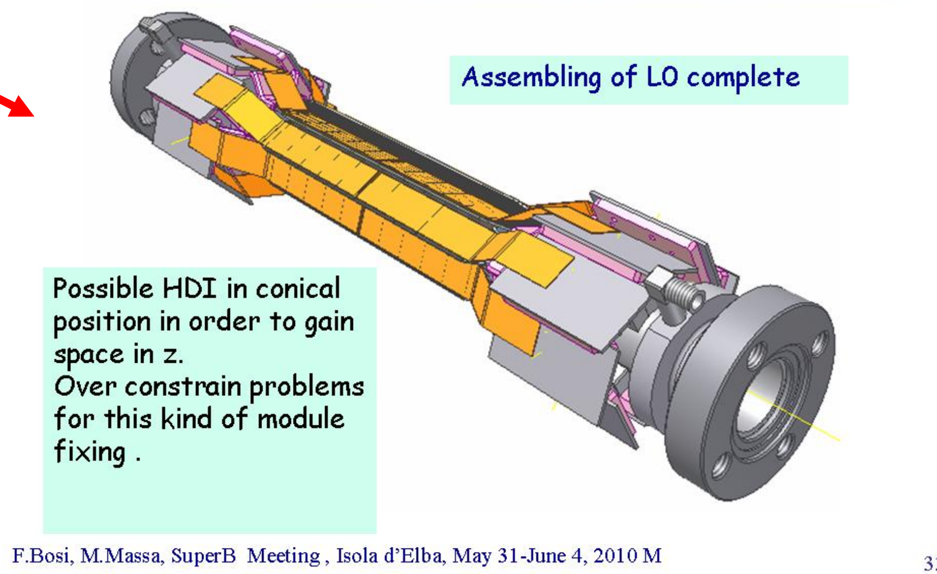
Next: conceptual design for quick removal of Layer0

F.Bosi-M.Massa

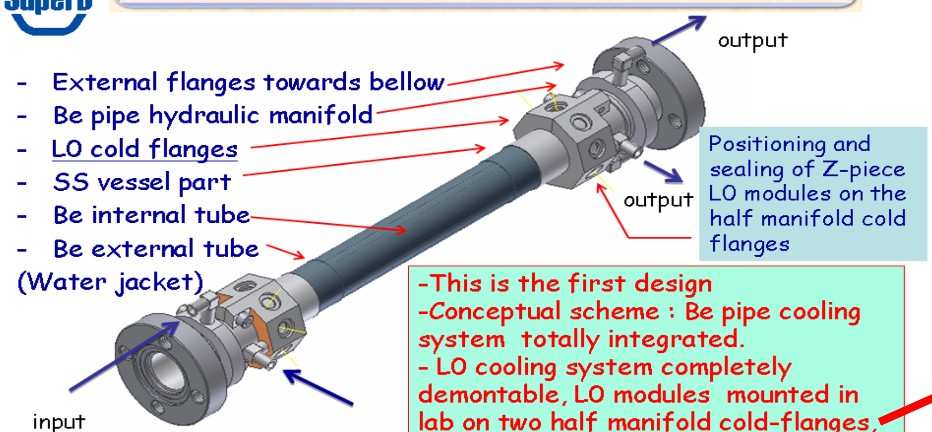
MAPS L0 module Design



L0 on Be pipe Design



Be pipe Design



-This is the first design
-Conceptual scheme : Be pipe cooling system totally integrated.
- L0 cooling system completely demontable, L0 modules mounted in lab on two half manifold cold-flanges, positioned and fixed on rigid SS part on the B.P.

F.Bosi, M.Massa, SuperB Meeting , Isola d'Elba