Light prototype support as high efficiency cooling system for Layer 0 of the Super-B Silicon Vertex Tracker

F. Bosi - M. Massa

INFN-Pisa

on behalf of the Super-B SVT Group

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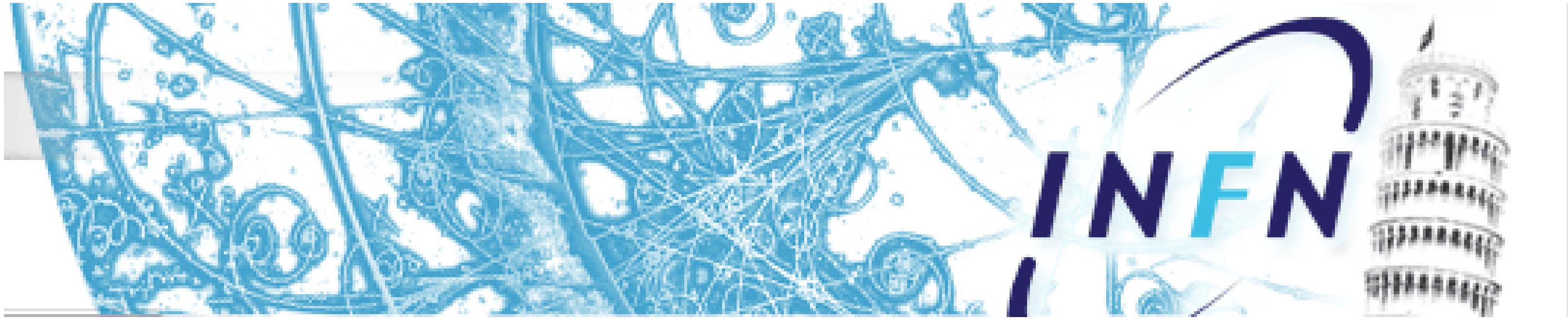


Outline

- General mechanical requirements for the Super-B Layer 0.
- Miniaturization, cooling and Microchannel technology.
- Microchannel module design and prototype production.
- Experimental results of the Microchannel Module test.
- Microchannel Net Module .
- Further developments to reduce X_0 and improve thermal efficiency.
- Conclusions

General Requirements

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

-Also 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 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)

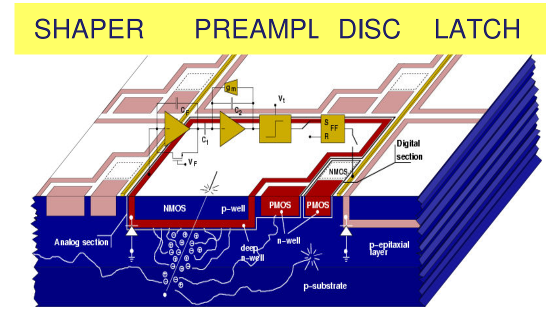
- Detector hit resolution ~ 10 μm →
modules very stiff with small and "stable" (in time) sagitta

-The redundancy on the 1st measured point.

-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

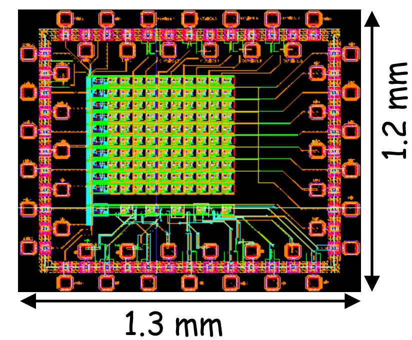
-The radiation length for the mechanical support, excluding cable and sensor materials, has to be as low as possible and remain in any case below 0.3 % X_0

The Super-B MAPS sensor/2



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

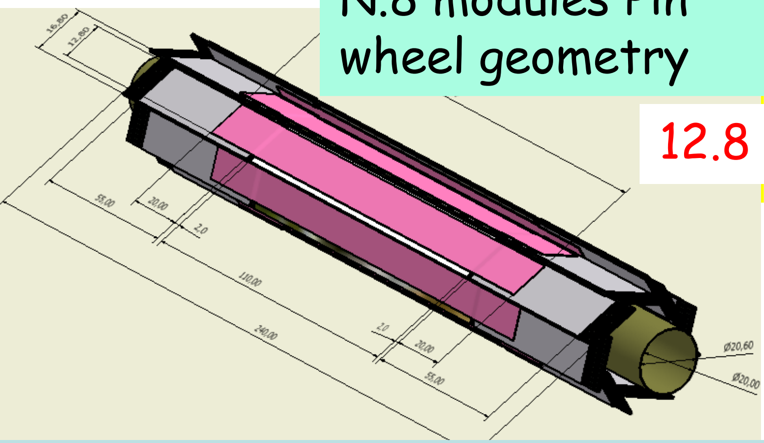
-Silicon thinned down to 50 μm
-Die of 256x 256 channels (12.8 mm x 12.8 mm)
-Elementary cell size: 50 μm x 50 μm
-Power = 50 μW/channel = 2 W/cm^2 (P = 210 W /layer)
-Electronics Working Temp. range: [0,50] °C

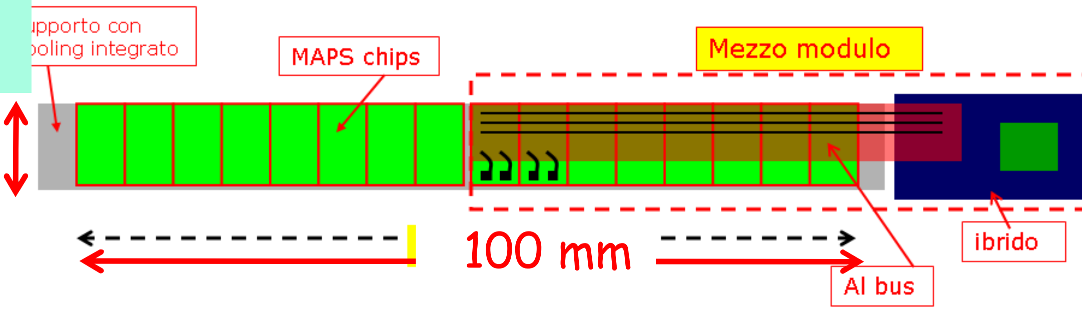


This power value means very high thermal dissipation on the active area and together to the X_0 requirements it drives the technological choice for the mechanical design.

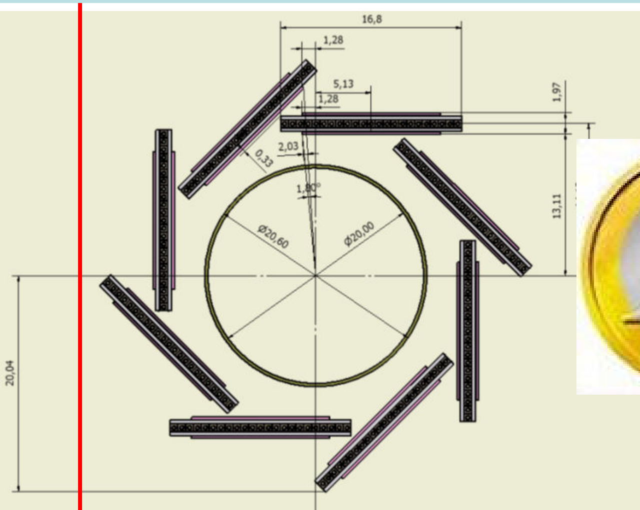
The Super-B module/3

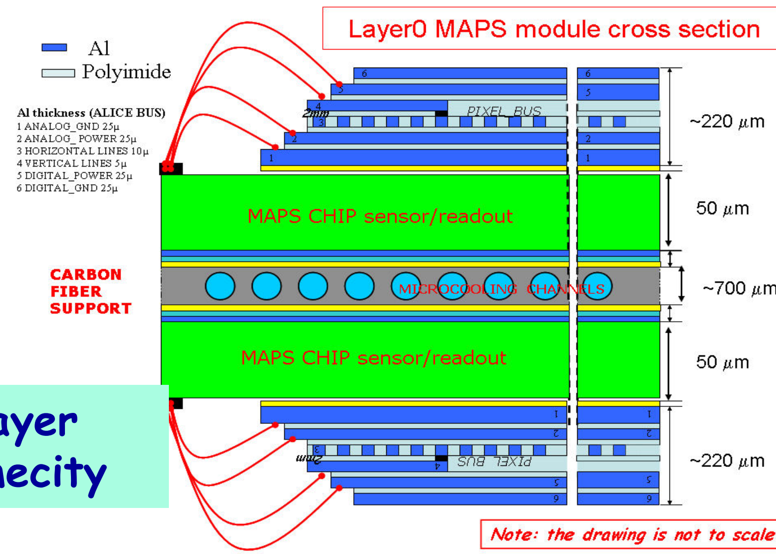
N.8 modules Pin wheel geometry





Comparing Layer 0 & beam pipe dimensions





Double layer for hermecity

Cooling and mechanical miniaturization are important issue for this detector !

Basic hydraulic Concept

Newton's law for convective heat flux :

$$Q = h\,S\,(T_w - T_f)$$

For the basic concepts behind microchannels it's important to introduce the Nusselt Number Nu which is related to the heat transfer coefficient *(h)*:

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

Where K_f is the fluid thermal conductivity and D_h is the hydraulic diameter, whose value is : $D_h = 4A/P$

where A is the cross sectional and 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 microchannels in the denominator enhances significantly the heat transfer coefficient.

Thermal Considerations

Remarks:

1. Minimize D_h means to go towards greater pressure drops. It must find a balance between pressure drops and film coefficient value.

2. Reducing fluid speed inside the cooling tube minimize pressure drops (Reynolds number < 2300, laminar flow).

3. Useful minimize ΔT of the liquid between inlet and outlet for sensors temperature

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 .

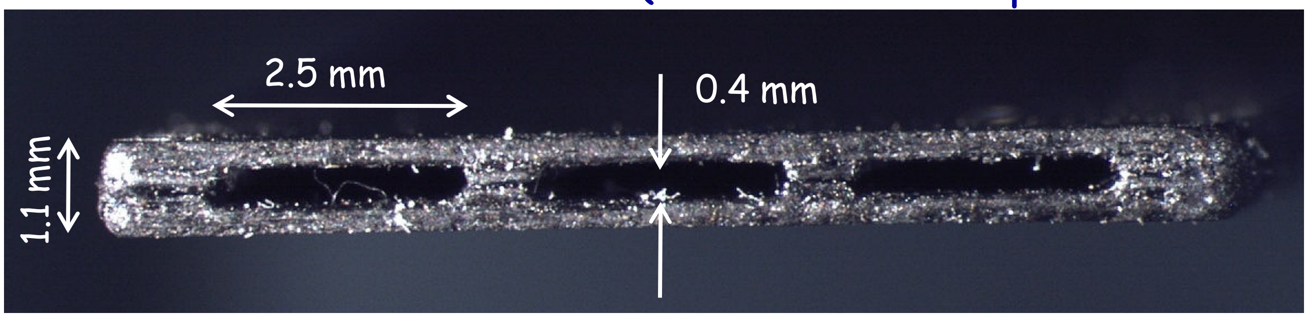
Several prototypes with different geometries and material have been realized; miniaturization of composites structures have been developed through close collaboration with companies. Prototypes have been submitted to test at the TFD laboratory of the INFN-Pisa.

In particular, by subtractive method or additive method two kinds of module in CFRP have been produced and tested .

Module support/1

- Subtractive method means a support realized by gluing machined parts .
- Additive method means a support realized by gluing single microtubes obtained by a pultrusion process;

Assembled /tested these two kinds of support structures:
length of 100 mm and width 12.8 mm (dimension of Super-B active region) :



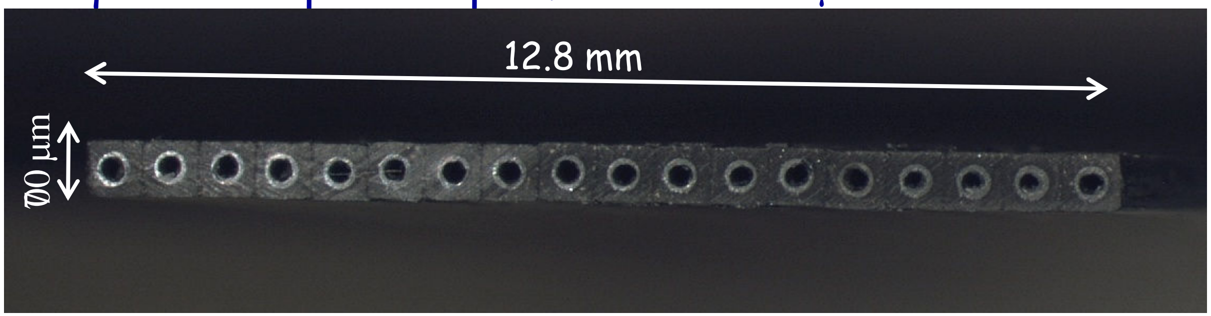
CFRP TRI-CHANNEL MODULE

Obtained with the subtractive method by Torayca M46J laminated . The hydraulic diameter is 0.84 mm, thickness is 1.1 mm.
The total radiation length is 0.40 % X_0 .
To avoid moisture problems, an internal coating of the channels is obtained by spraying an epoxy - isopropyl alcohol (50%) mixture (30μm th).

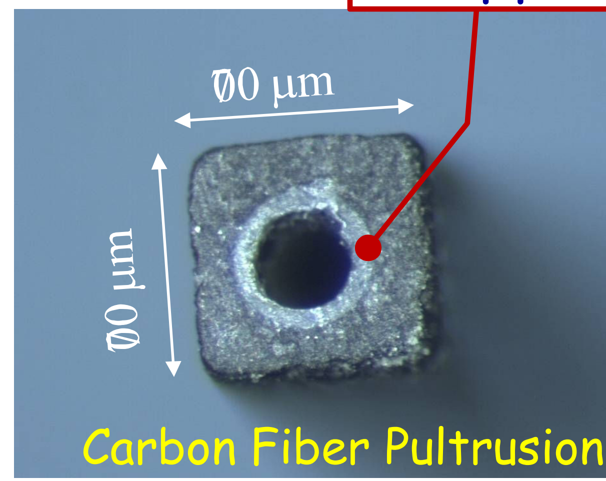
Module support/2

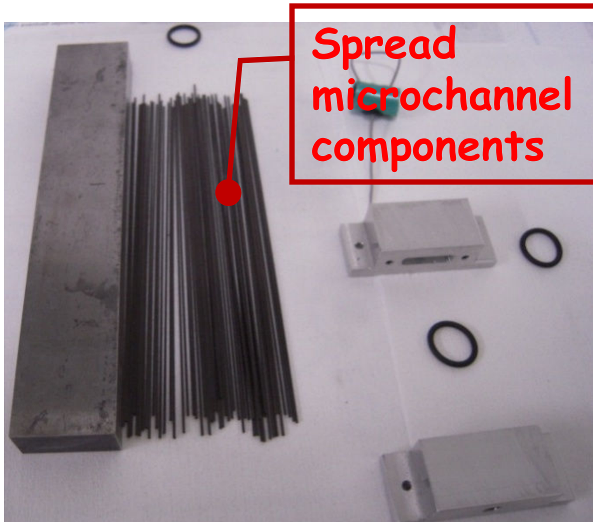
CFRP MICROCHANNEL MODULE

Obtained with additive method by pultrusion C.F. TohoTenax HTS 40 , gluing in special masks, side by side, 19 single microtube.
The inner diameter of the peek microtube is 300 μm, the thickness of the square composite profile is 700 μm .

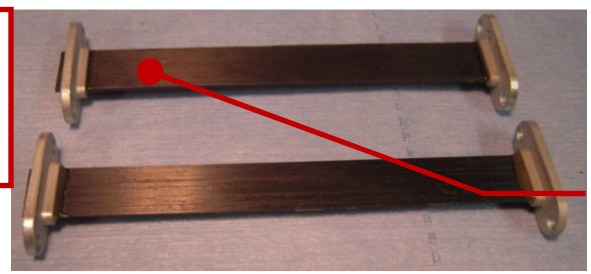


Peek pipe





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.

X_0 module support improvement

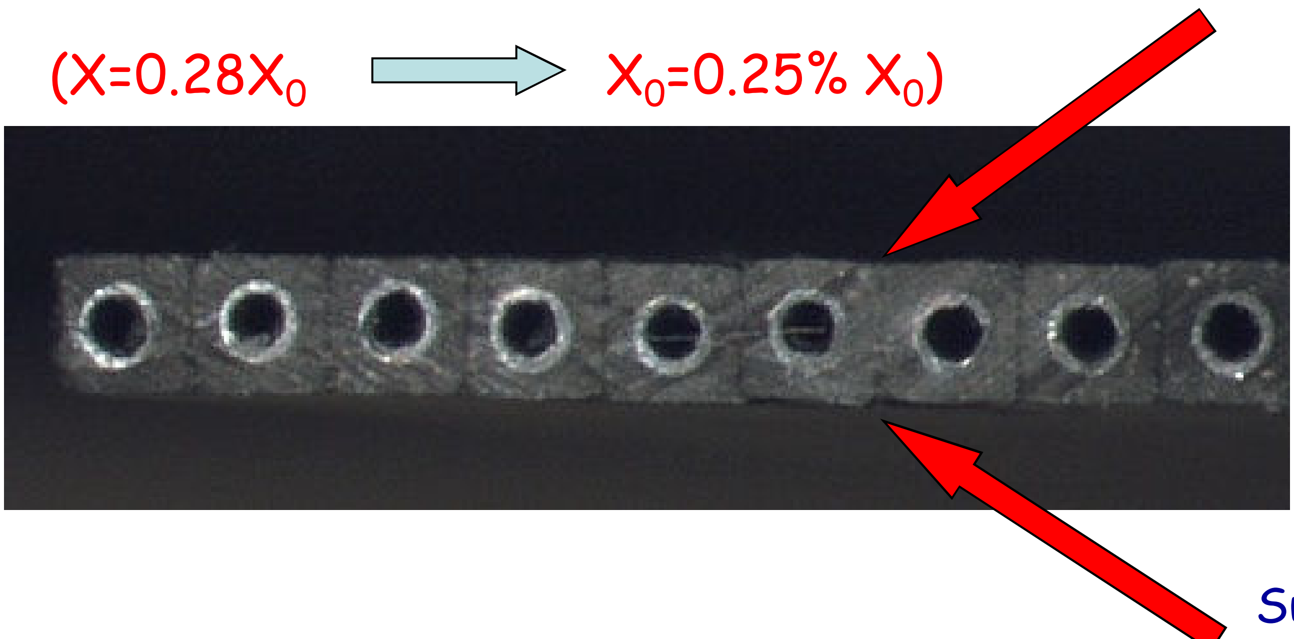
Planarity tollerance of the microchannel module is 40 μm .

Grinding about 40 μm on the top and bottom surfaces of microchannel module obtained a 620 μm-thick structure with further 15% reduction in X_0 .

better thermal interface between CFRP and the Aluminum-kapton foil (ground layer of the silicon detector).

Surface roughness

($X=0.28X_0$ → $X_0=0.25\%\ X_0$)

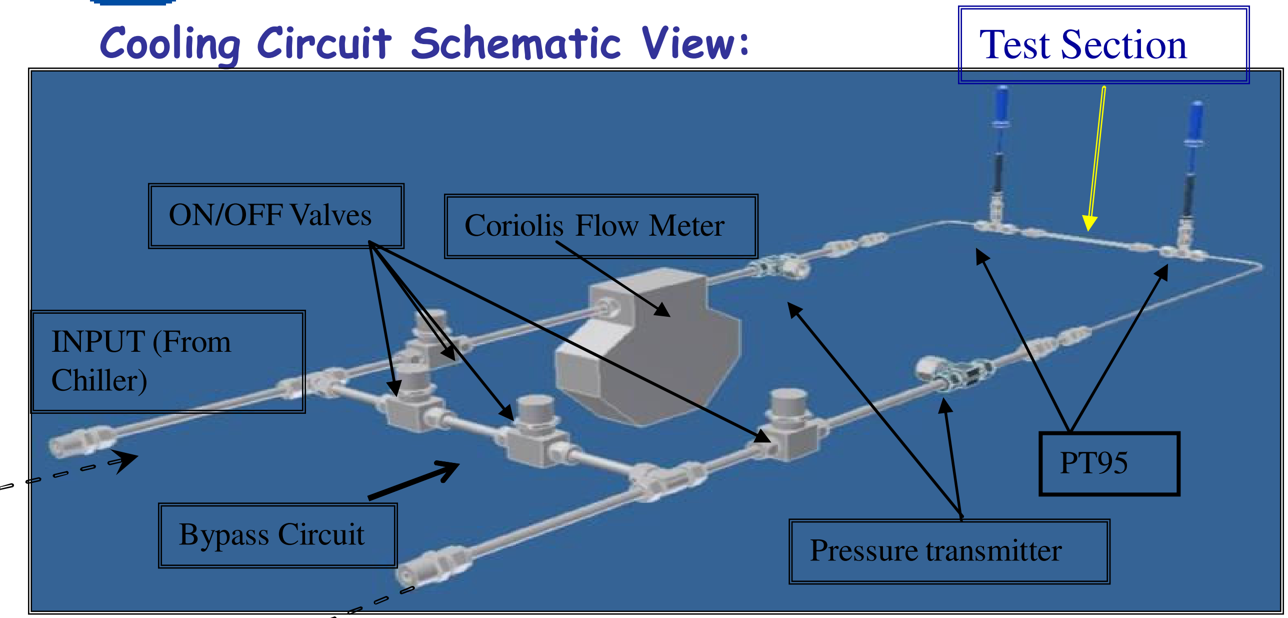


700 μm → **620μm**

Surfaces to grind

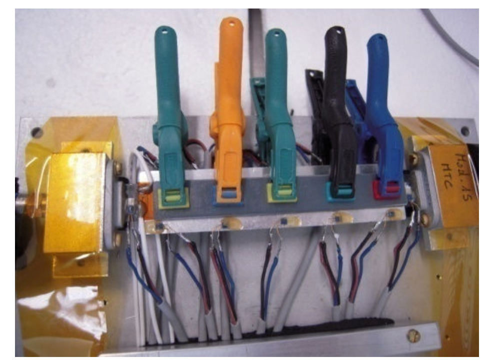
Test and set-up at TFD lab

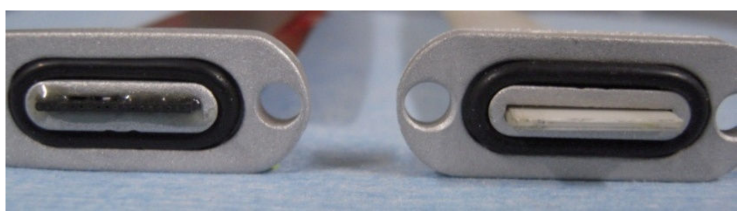
Cooling Circuit Schematic View:

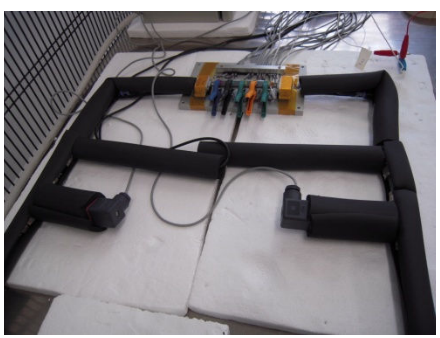


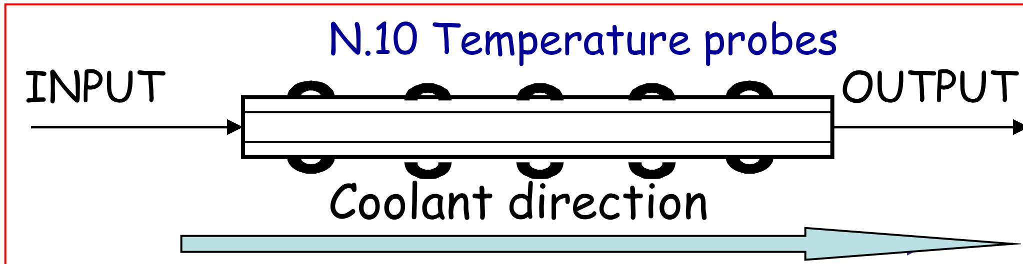
DAQ System:

Test Section:





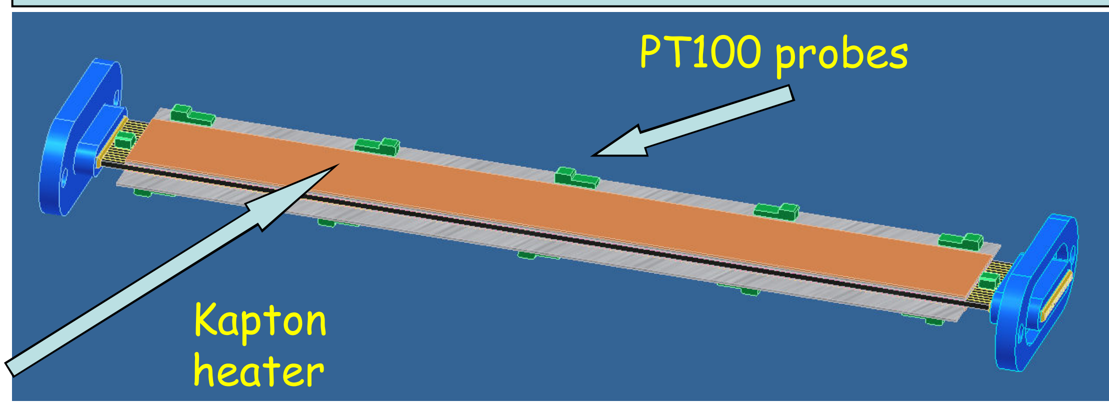


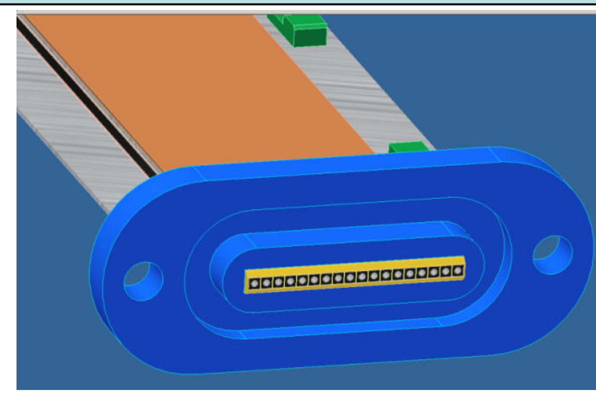


Longitudinal sample section

Module Samples

A kapton heater is glued on the 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 75 μm-thick is sandwiched between the 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).





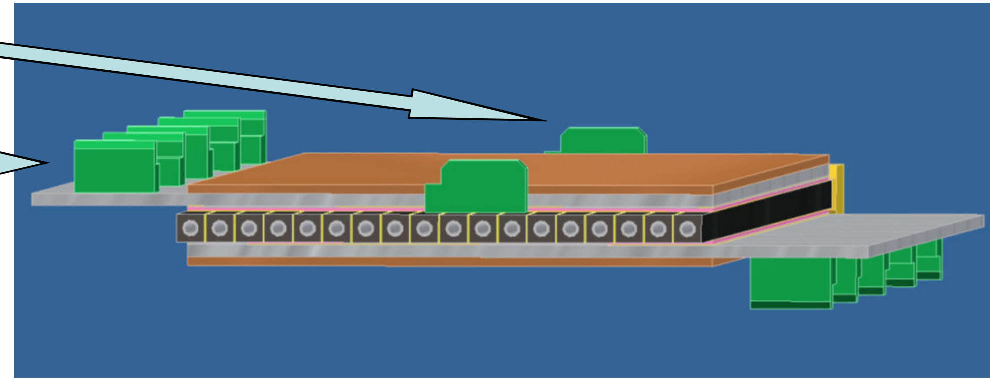
There are two kinds of tested configurations: the "double side", where the heat is dissipated both on the upper and the lower external faces, and the "single side" where the power is dissipated only on the upper face.

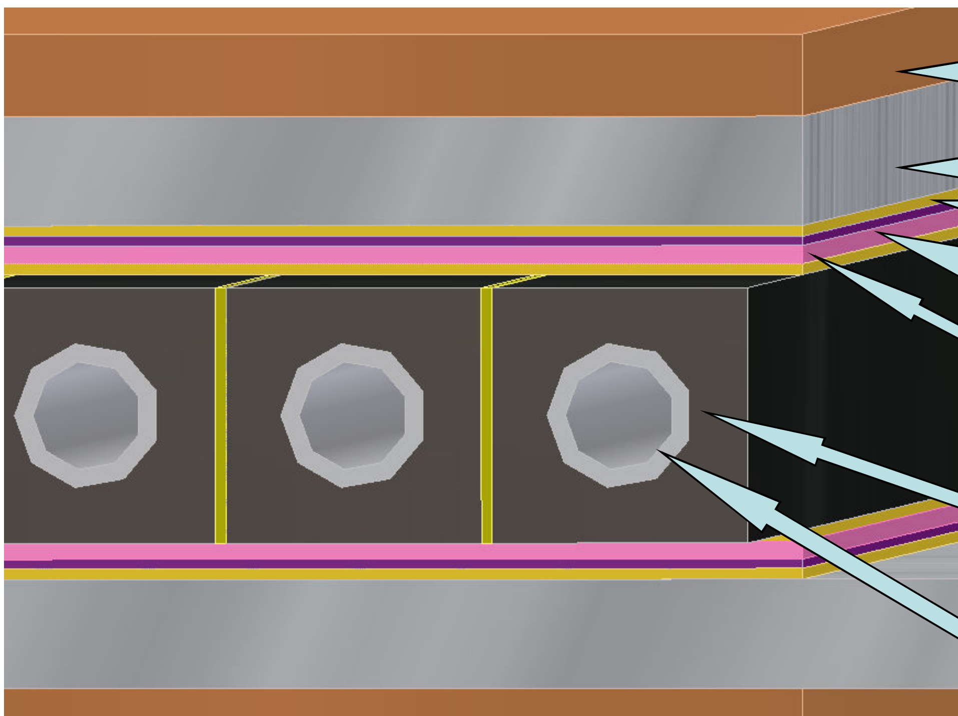
Module Sample Structure

N°2 PT100 temperature probe on CFRP

N°5 PT100 temperature probes/side on Aluminum

Double side configuration (cut view)





Kapton Heather 220 μm

Aluminum foil 300 μm

Glue 25 μm

Kapton+Aluminum 50μm +10μm

Glue 25 μm

CFRP microchannel Th=700 μm

Peek Tube/Di=300 μm, th=50 μm

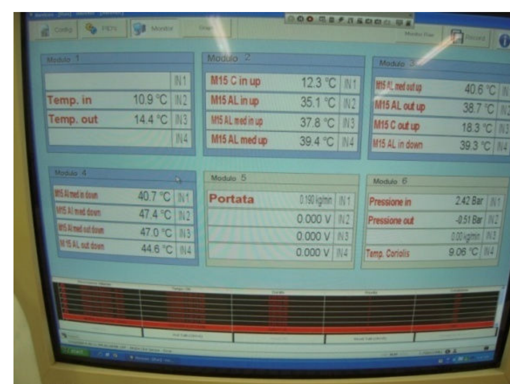
Test Procedures

The power dissipated by the kapton heater could be tuned from 1.0 to 3.0 W/cm^2.

The tests have been performed in standard way for both 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).

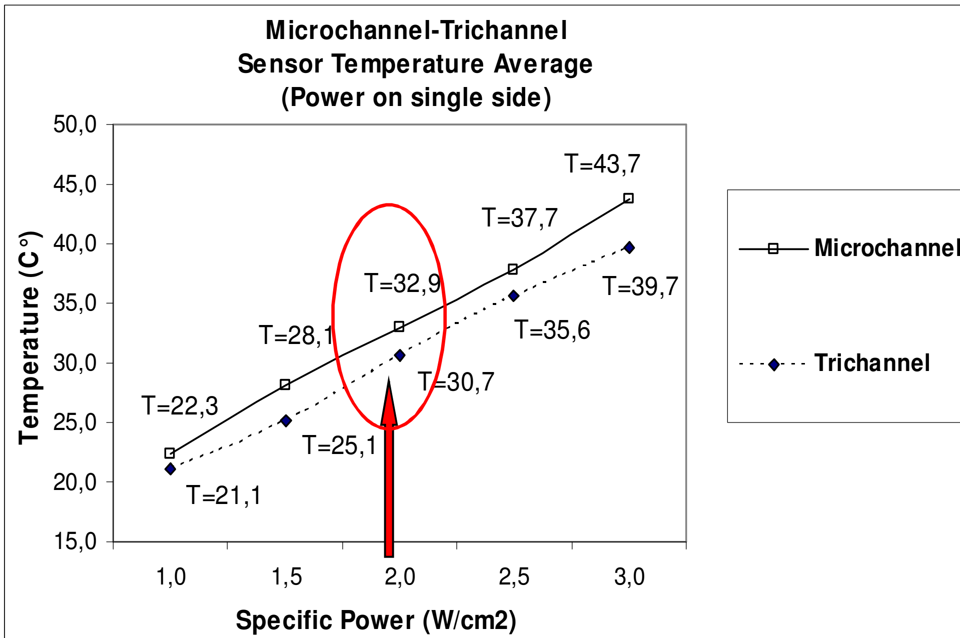
The test was performed by setting the fluid pushing pressure 1.5 atm, the (suction) pressure 0.5 atm, the fluid temperature 10 °C. The electrical power was then switched on and set to the lower specific power (1.0 W/cm^2). The maximum pressure was set 3 atm and the heater power tuned up according to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

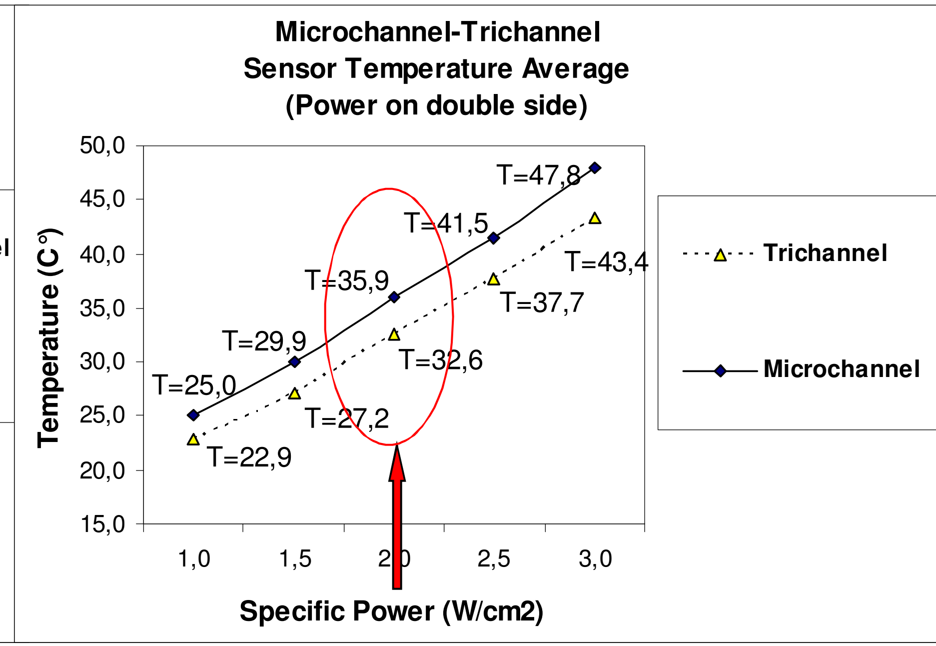
In all conditions, the DAQ system is able to record up to 24 parameters at the same time.



Experimental Results

Tests performed on N°2 samples for both microchannel and tri-channel modules.

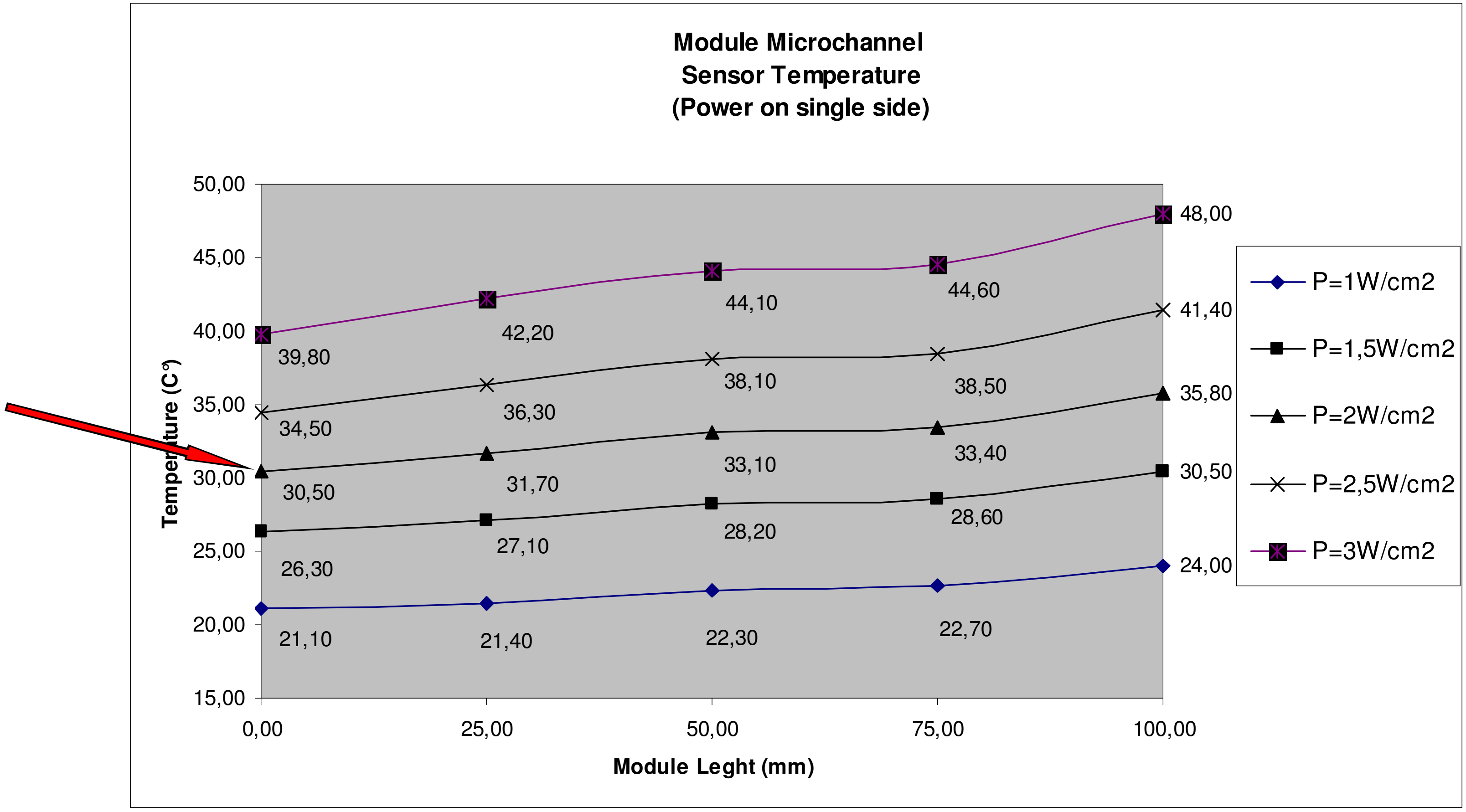




Average module Temperature vs Specific Power for single side

Average module Temperature vs Specific Power for double side

Test Results



Temperature along the module ($\Delta T = 5\,^{\circ}C$)

Hydraulic parameter

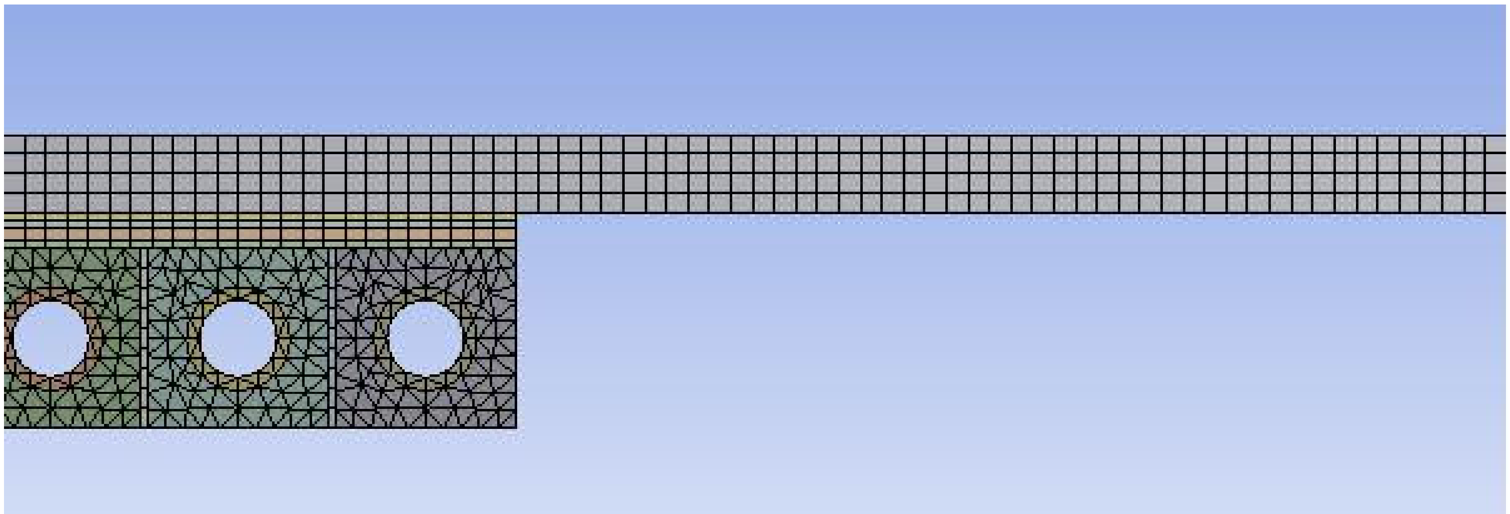
The hydraulic parameter shows that for the microchannel geometry there is a laminar flow and a good thermal film coefficient. For the tri-channel module, higher flow is still laminar .

	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
Tri-channel	26,5	0.84	1,478	3,680	laminar	5,95	1321	7585
Micro channel	1,272	0.3	0,244	3,612	Laminar	3,37	267	3275

Clearly, the cooling performances of the tri-channel module are better than those of the micro-channel (higher film coefficient) but the favorite is the micro-channel because of the lower thickness (0.25 %X_0) with respect to the tri-channel module (0.4 %X_0).

Thermal Simulation/1

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



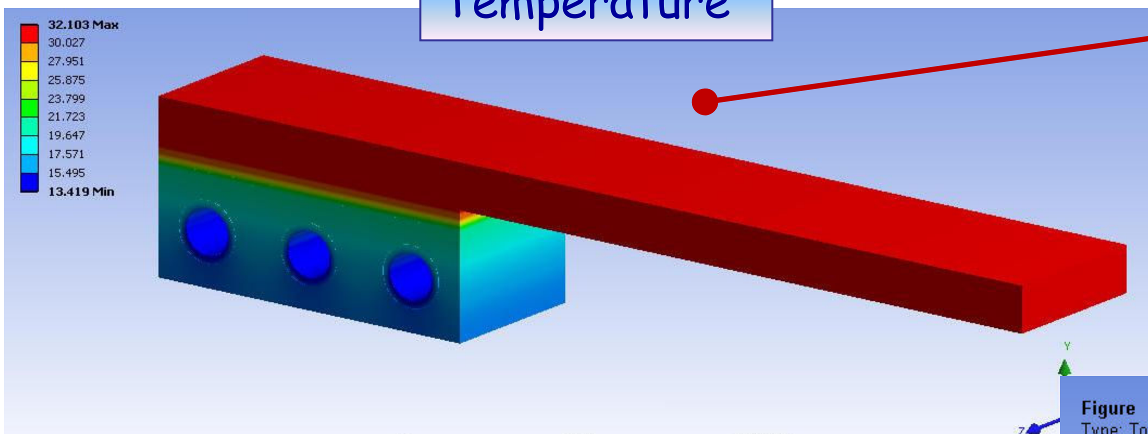
Boundary values:
Power density: 2 W/cm2
Water film coefficient*: 3275 W/m2K
Coolant Temperature: 10 °C
Air film coefficient: 5 W/m2K
Air Temperature: 22 °C

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

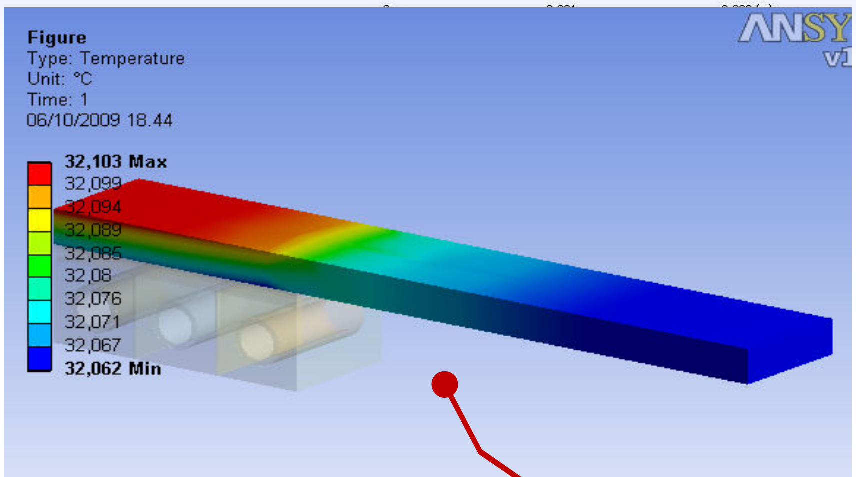
*: it is derived from experimental and geometrical data.

Thermal Simulation/2

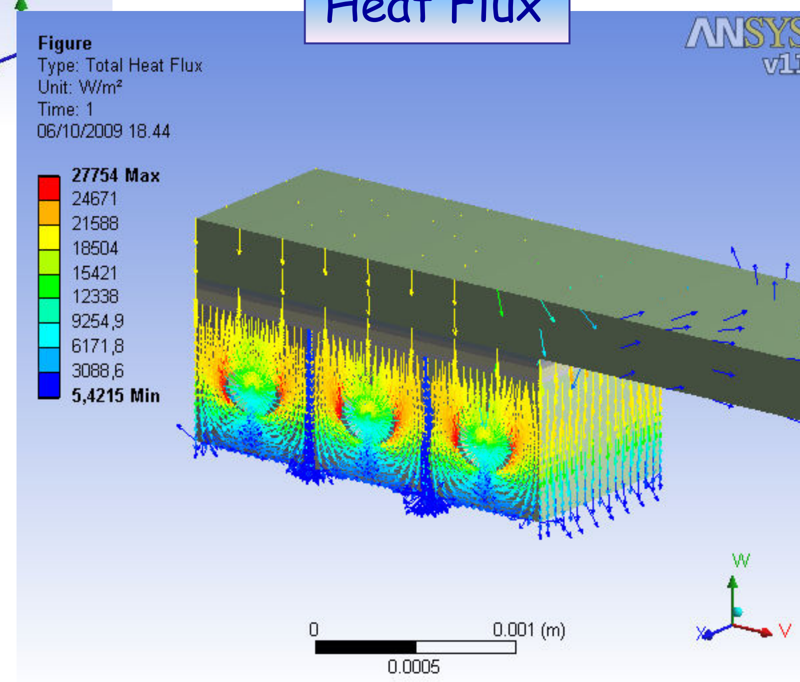
Temperature



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

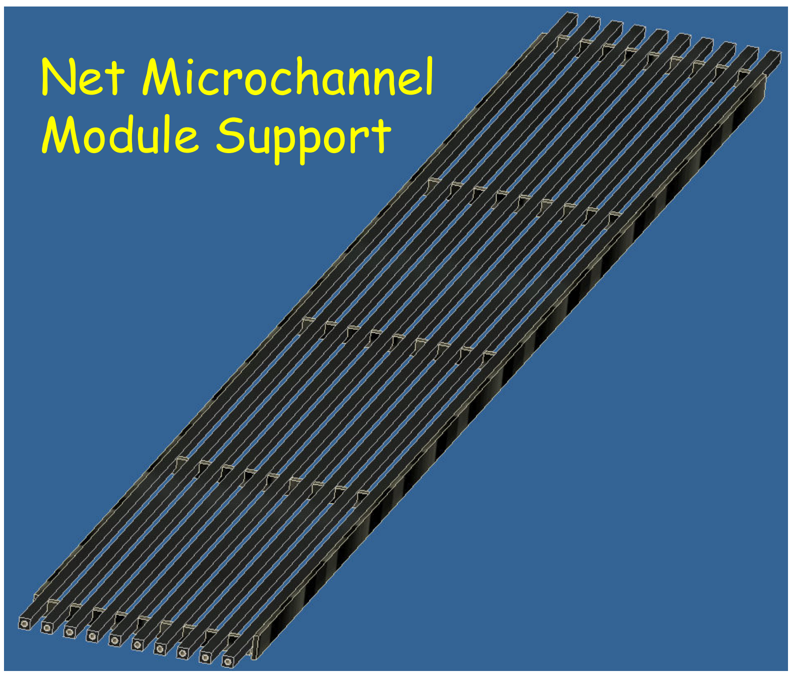
Net Module support/1

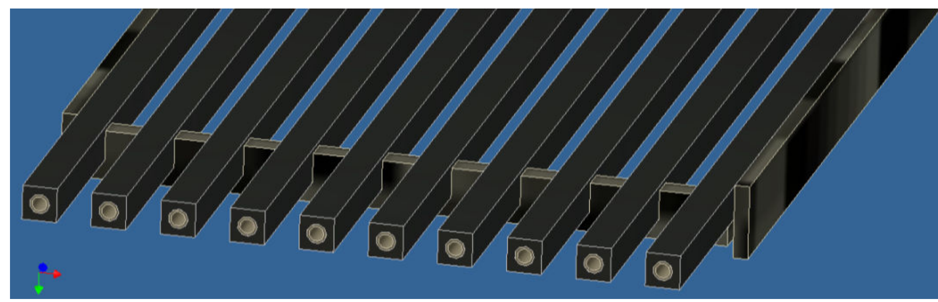
Assuming further progress in MAPS sensor design, and looking to actual hybrid pixel, the required Power (analog + digit), could step down to 1.5-1.0 W/cm^2.

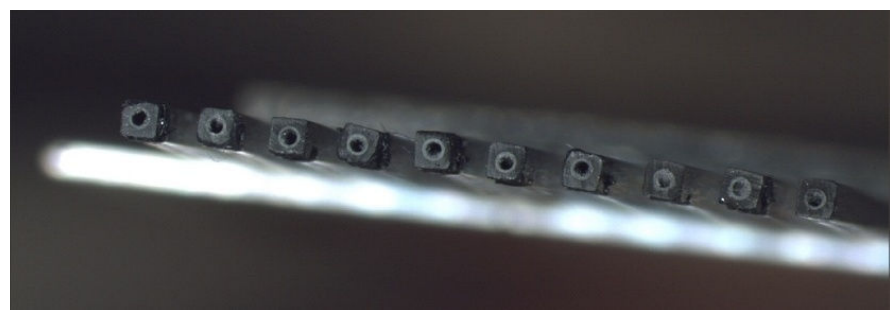
We choose to design a lighter solution for the support structure .

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.

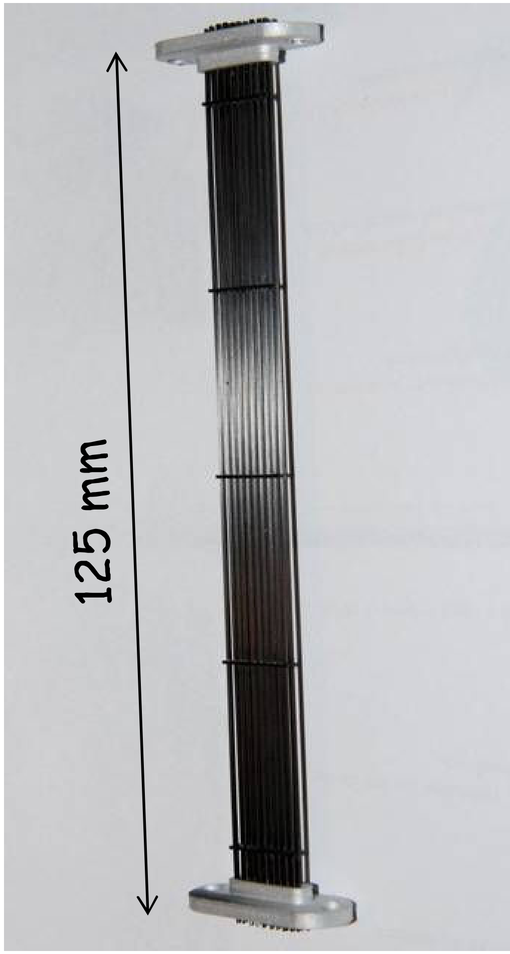


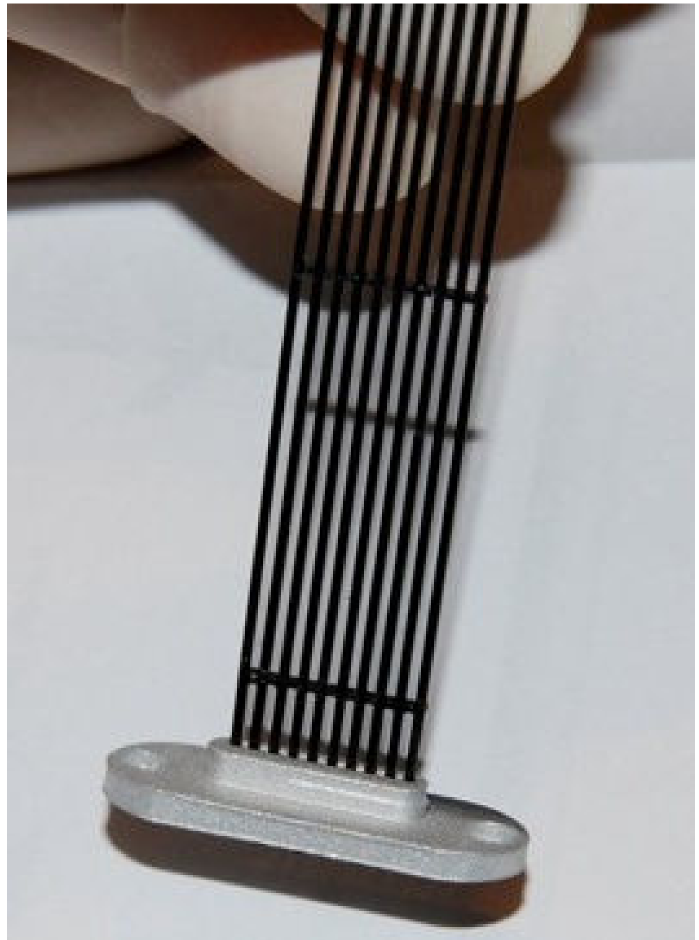




Material of the support structure: (CFRP + peek tube + Water + CFRP Stiffeners)

Net module support/2





Epoxy glue used to place microtube on very thin transversal CfRP stiffeners.

Micropositioning and microgluing work required a dedicated gluing mask!

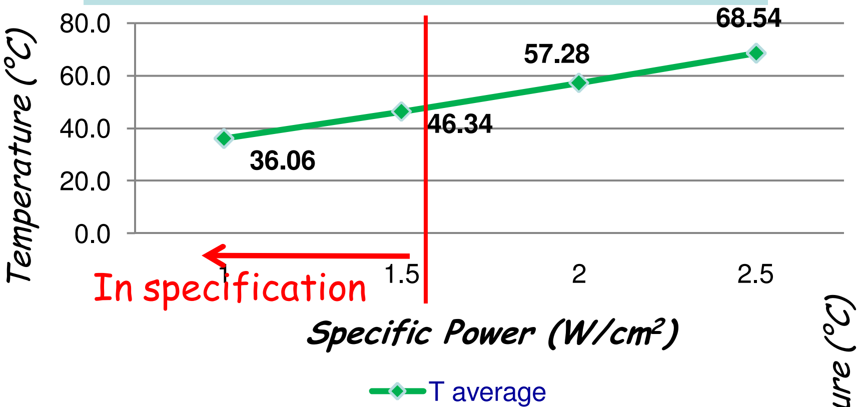
Sealing of the hydraulic interface obtained with epoxy/CFRP .

$X = 0.15\%\ X_0$

The Net Module has the same hydraulic parameter / microtube , already measured for Microchannel module.

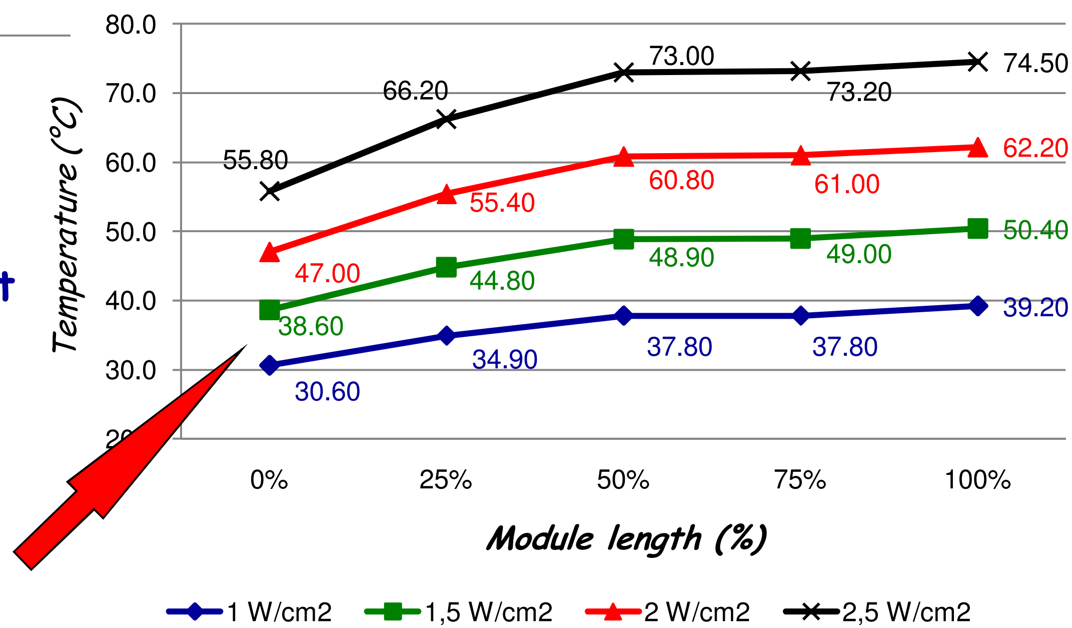
Net pixel module test results

Net module average Temperature
Vs. Specific power density
Power on Single Side



Tests performed with water-glycol @ 10 °C as coolant.

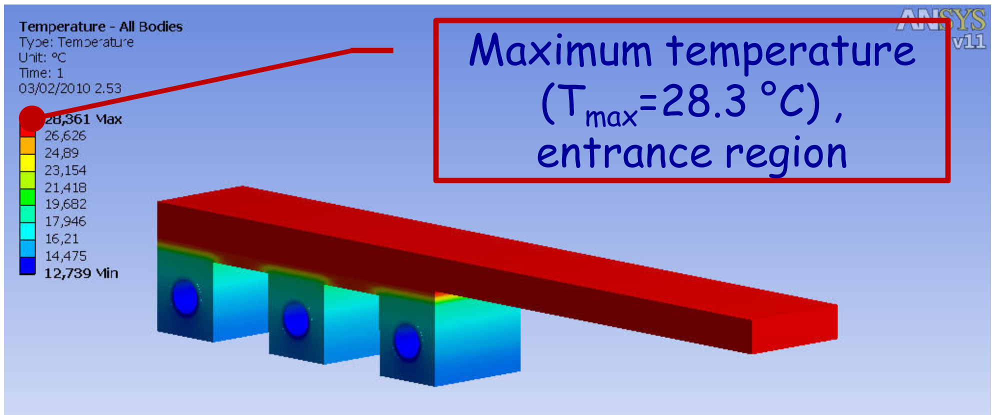
Net module, Sensor Temperature
Power on Single Side



From this experimental data the 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.

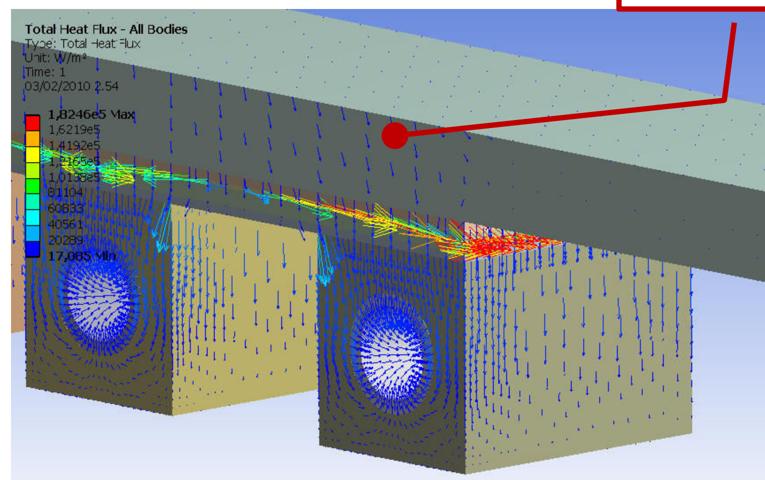
Net pixel module simulation results

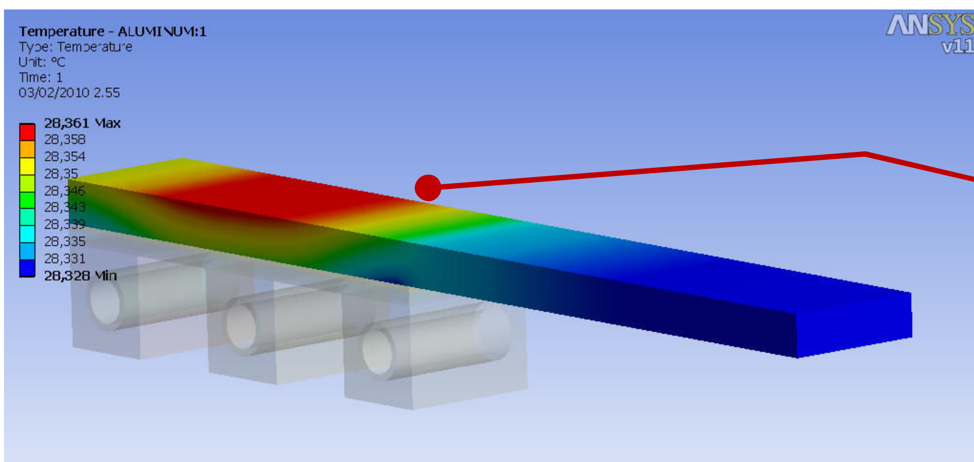
Case study: 1 W/cm^2 (the same Boundary values used for microchannel module)



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.

Module Support performance improvement

There are several lines to follow for further enhancing the performance of the microchannel support:

1) Further miniaturization of the base microtube profile:
CFRP thickness = 500 μm, peek tube inner diameter = 200/50 th μm.
(in progress prototype manufacturing) .

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

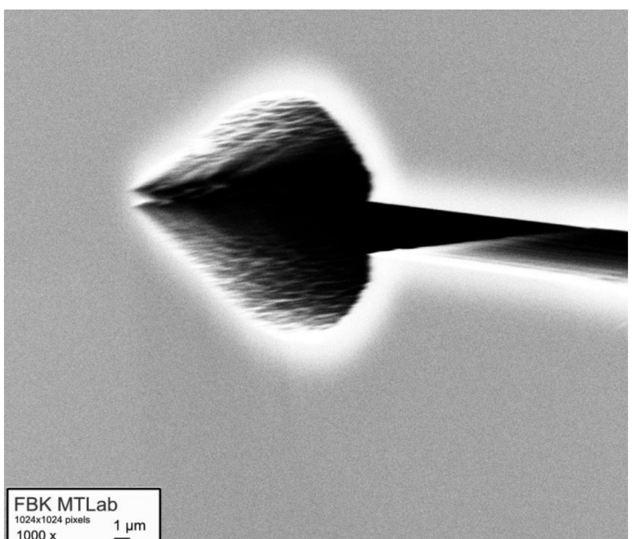
3) Opposite flow directions of the coolant in the module in order to minimize the temperature variation along the module
(it requires a special design of the hydraulic interfaces)

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

In the program of the VIPIX R&D experiment there is a part devoted to test direct cooling integrated in the silicon electronic substrate . There is a collaboration with the FBK of Trento (Italy) to realize in DRIE process these special microchannels.

Under development DRIE trenches for silicon-embedded microchannels. This shape allows the sealing of the trenches with the semiconductor oxide (PECVD).

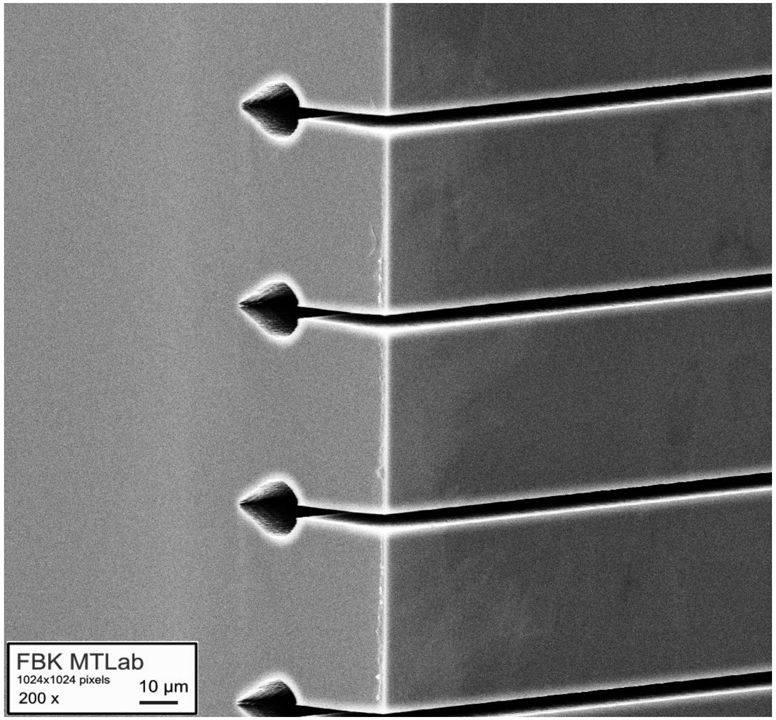


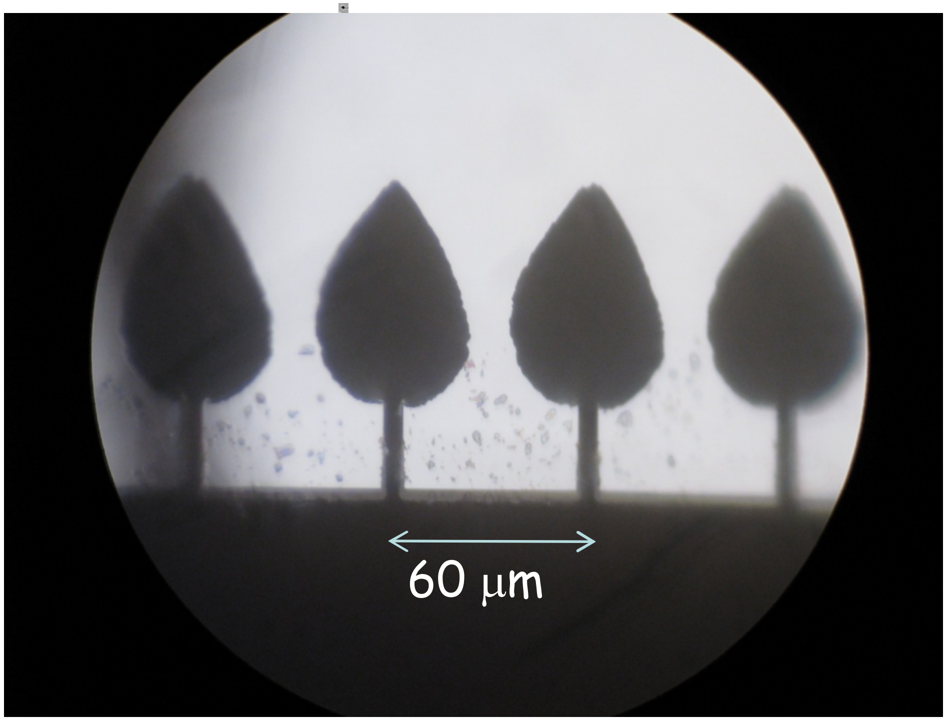
Obtained dimension for this structures:	Goal in production runs:
Trench width :4 μm	(4 μm)
depth channel : 50 μm	(80 μm)
Channel diameter : 20 μm	(80-100 μm)
Channel Pitch : 60 μm	(150-200 μm)

Microchannel integration on silicon prototype

The goal is to obtain a silicon prototypes from a 4" wafer of about 12.8 width mm x 60 mm length x 200 μm thick and to perform the cooling tests at the TFD lab in order to measure hydraulic and thermal parameters.

No heath sink, high drop pressure , very high power removed .





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).

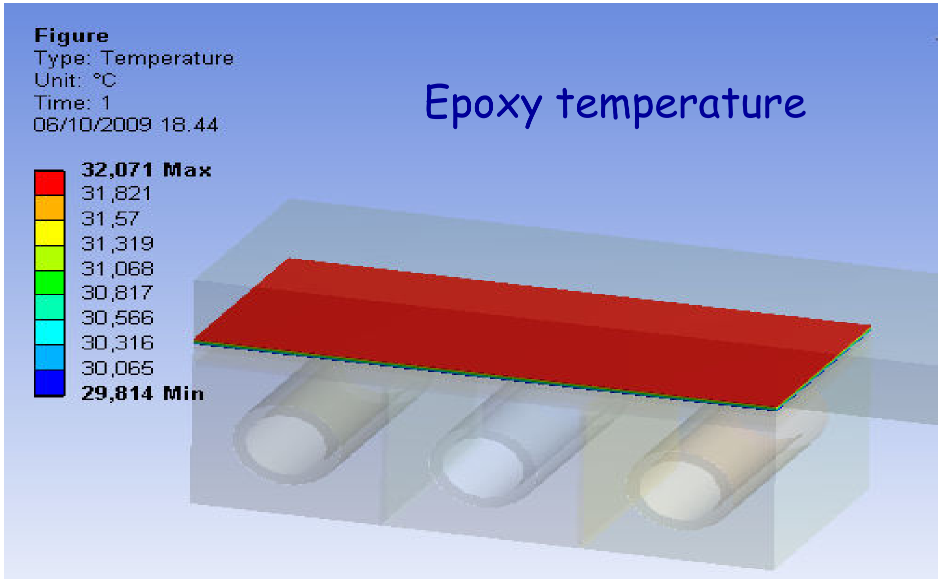
•There is at the INFN-Pisa a test-facility to perform experimental analysis of cooling circuits in single phase thermal exchange. In future it is plan to test microchannel technology in change-phase cooling (higher thermal performance) .

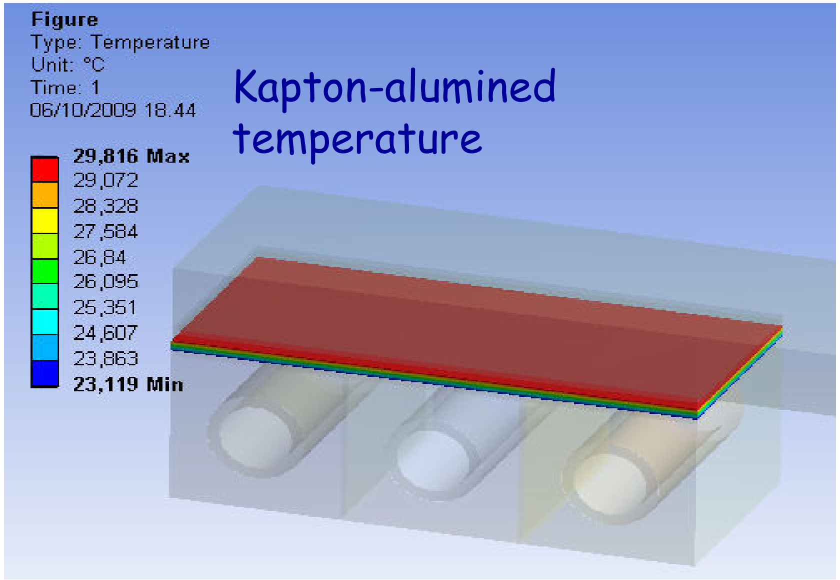
• Our prototypes design for the L0 Super-B detector, based on microchannel technology ins ingle phase forced convection, matches the requirements for pixel MAPS (P= 2W/cm^2, X_0= 0.25%) and for pixel hybrid sensors (P= 1.5-1,0 W/cm^2, X_0= 0.15%) .

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

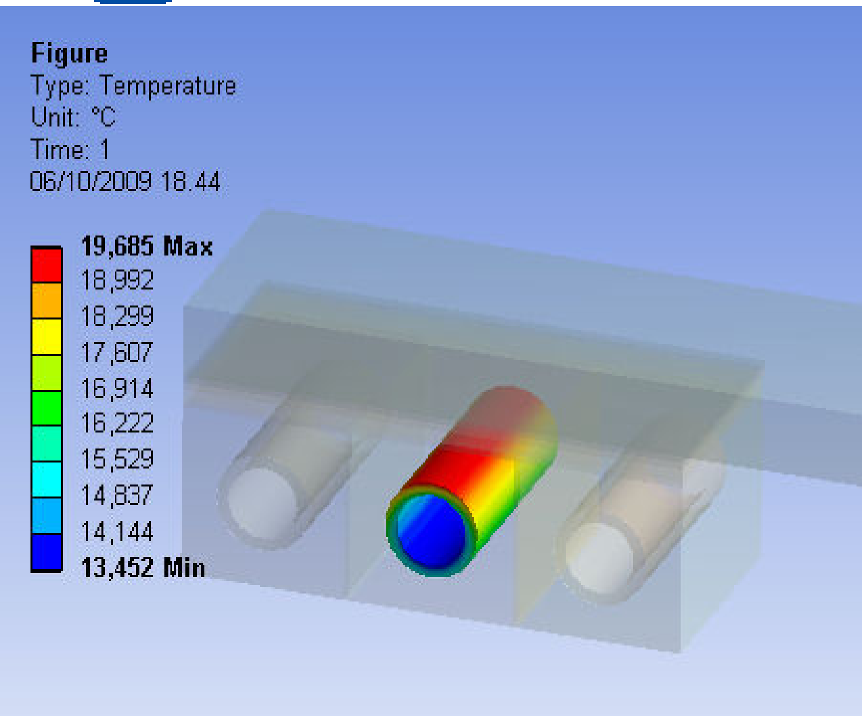
BACK UP

Thermal Simulation

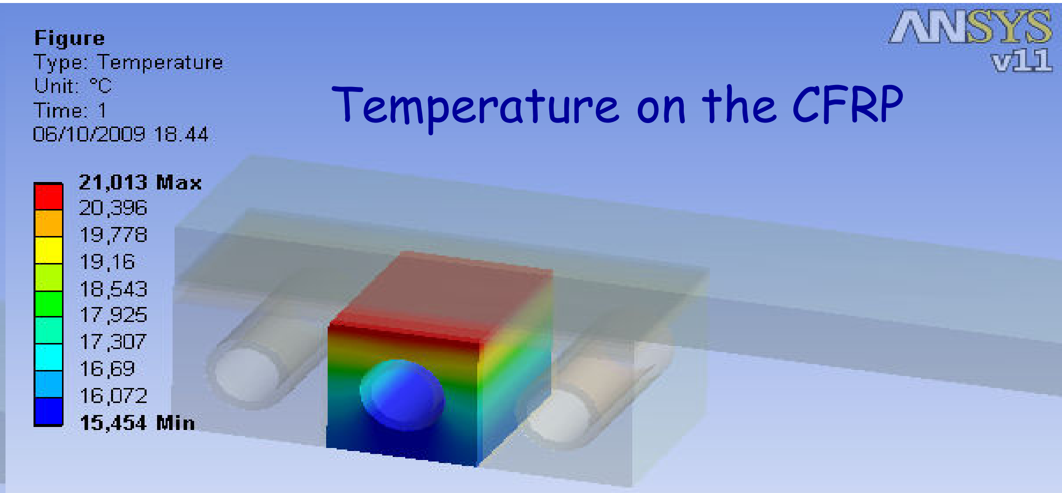




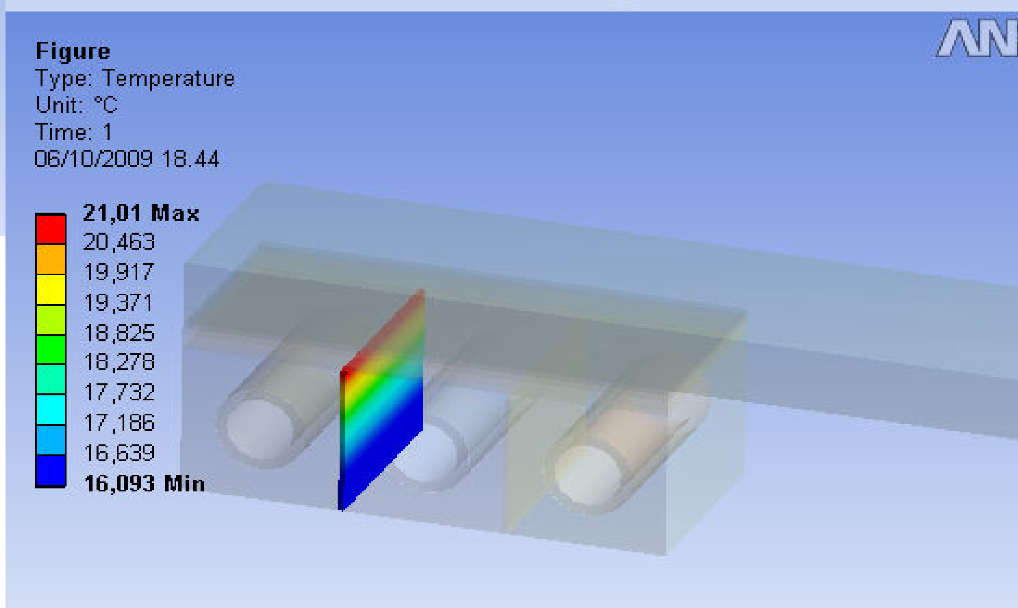
Thermal Simulation



Peek tube temperature

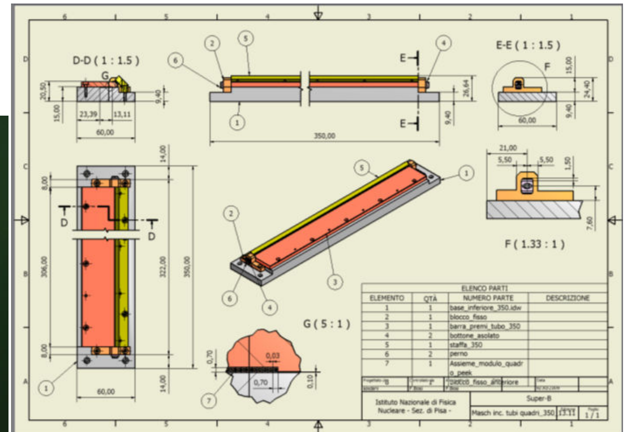


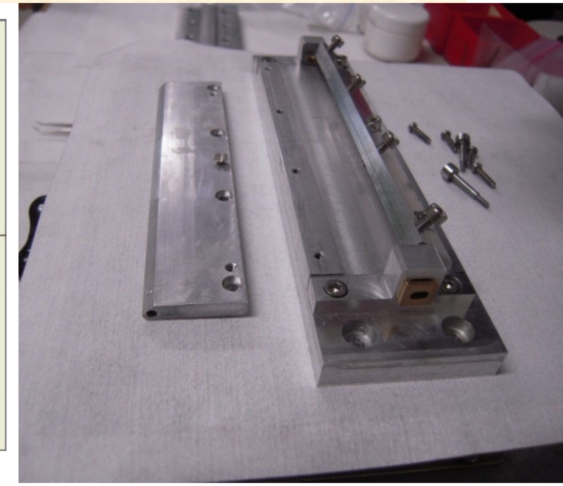
Temperature on the CFRP



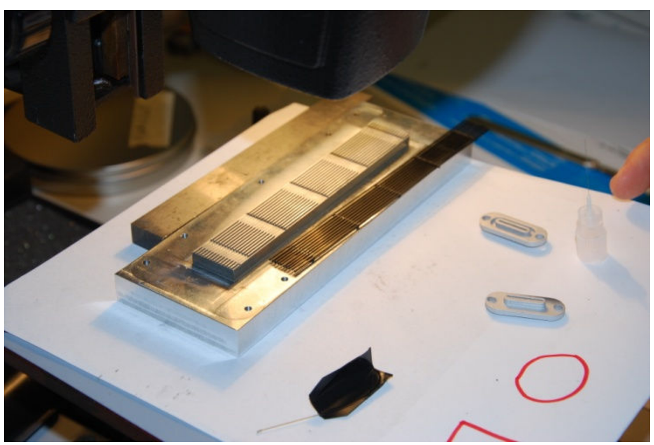
Tooling Construction Activities

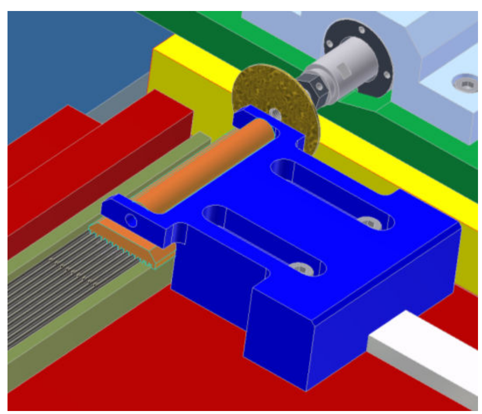
Module Gluing Mask

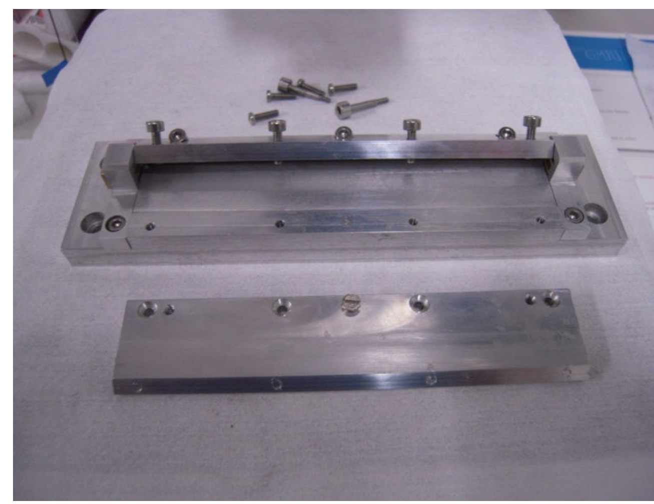




Net Microchannel
Module Support
high speed Saw







mask for 100-300 mm length
microchannel module

Net Module

The Net Module is well suited for the new specific power request. Building a structure by adding single microtubes allows matching the module specifications with a lower material budget.
(The radiation lenght for each microchannel tube is about $X=0.011\ \%\ X_0$)