# Thermal and Mechanical issues in the module design of Layer 0 SuperB Factory

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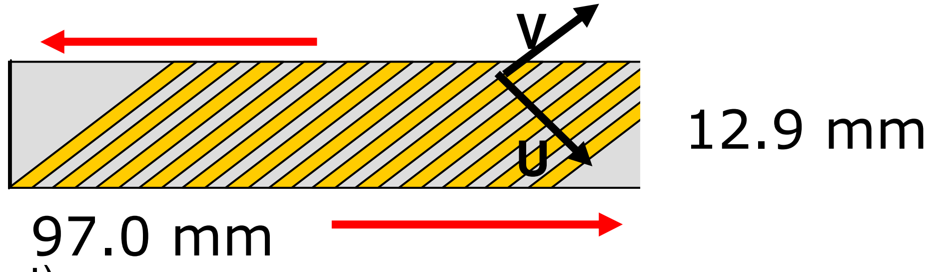
on behalf of the SuperB Group

# Outline

- Module L0 layout with the striplets sensor (baseline design)
- The candidate MAPS sensor for the L0
- Physics and mechanical requirements
- Module design developments and cooling efficiency
- Thermal simulation studies
- Minichannel Cooling Technology
- Present Activities in Pisa
- Work Plans
- Conclusions

# Layer 0 baseline design

(Lab.) Geometrical acceptance: 300 mrad both in FW and BW sides
Distance from the i.p. : R=15 mm

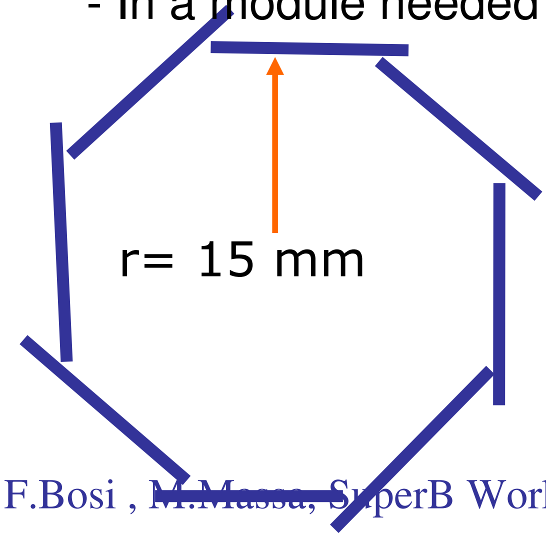


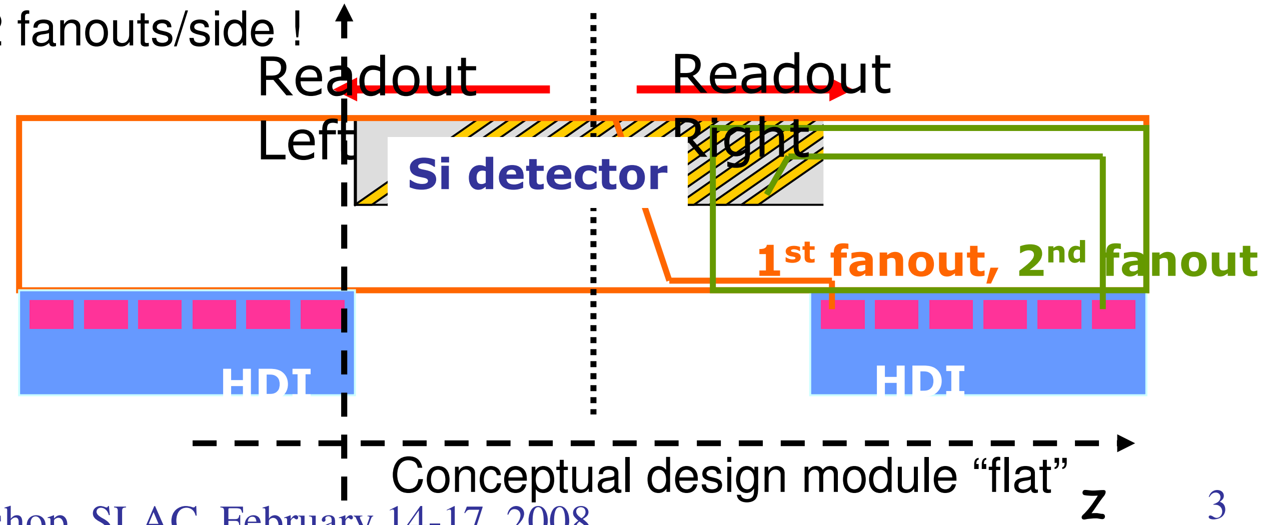

Choosing an Octagonal shape:

- Module active area = 12.9 x 97.0 mm2 (includes 4% area overlap for alignment)
- double sided Si detector, 200 μm thick with striplets (45° w.r.t det. edges) readout pitch 50 μm
- multi-layer fanout circuits (similar to SVT modules, z side) are glued on each sensor, connecting Si strips to Front End Electronics

(fanout extends twice wider than the detector, to allow a minimum of 50 μm between metal traces).

- In a module needed 2 fanouts/side !

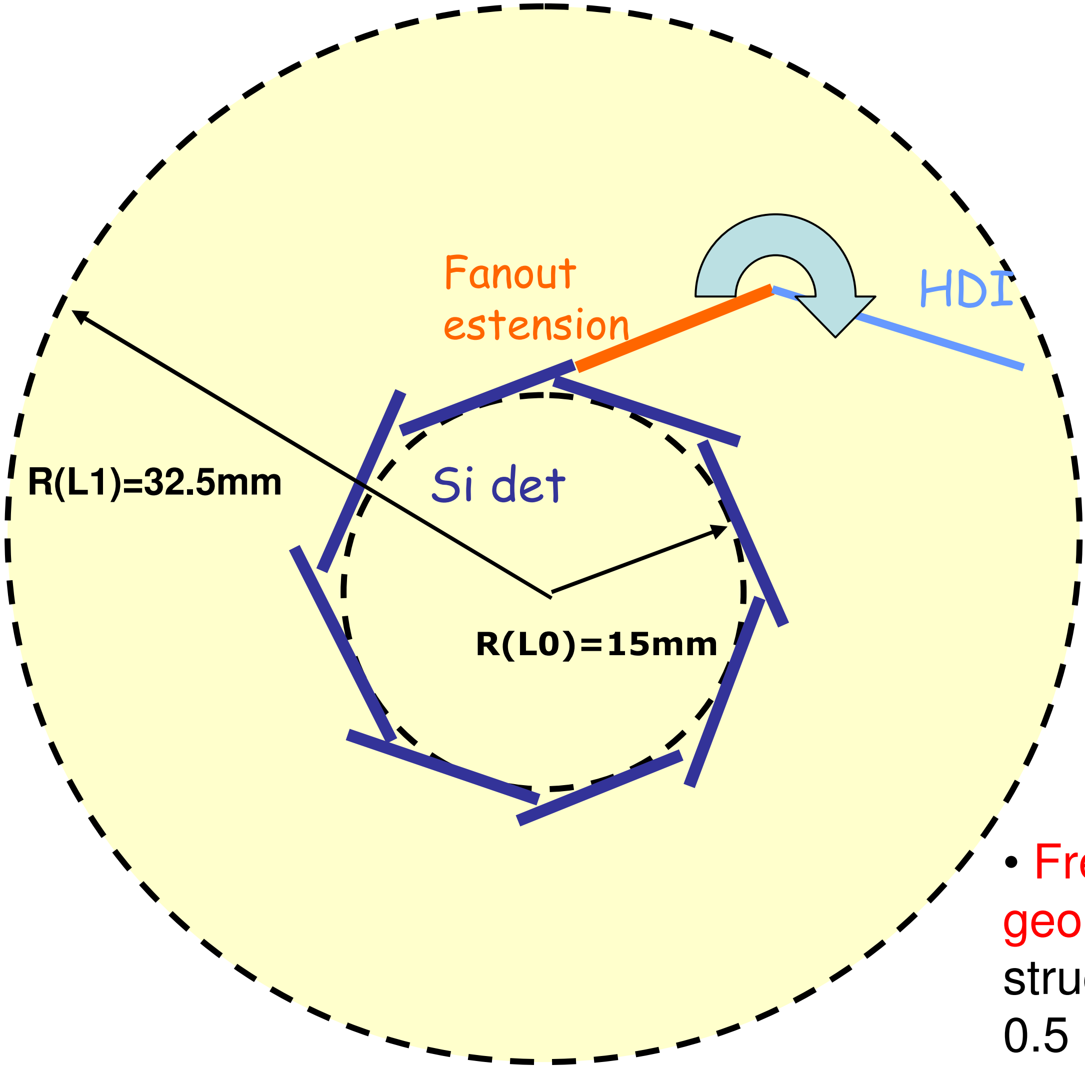



Conceptual design module "flat"

# Mechanical constraints & assembling procedures

- The Layer0 module must be bent (HDI w.r.t. sensor plane) to fit inside the radius of the current BaBar Layer1 ( R(L1)=32.5 mm )




- Each hybrid is mounting 6 chips (FSSR2: 7.5 x 5 mm2)

Assembly Procedure:

- The module is assembled FLAT (length=284 mm x width=54.5 mm)

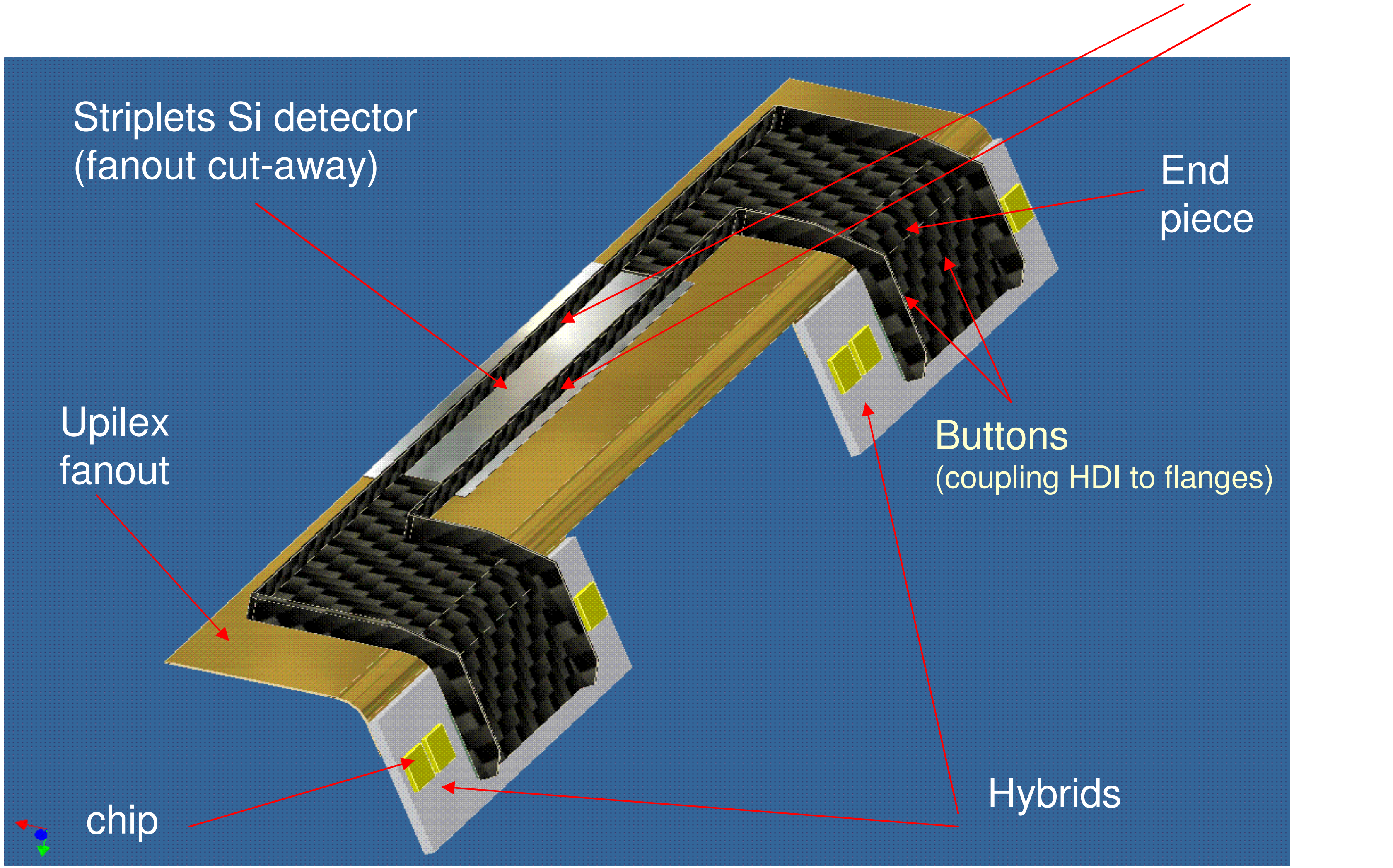
:

  - The fanouts are glued on the detector and micro-bonded
  - The DFA is electrically tested and defects eventually cured
  - The HDI is connected to the fanouts and bonded

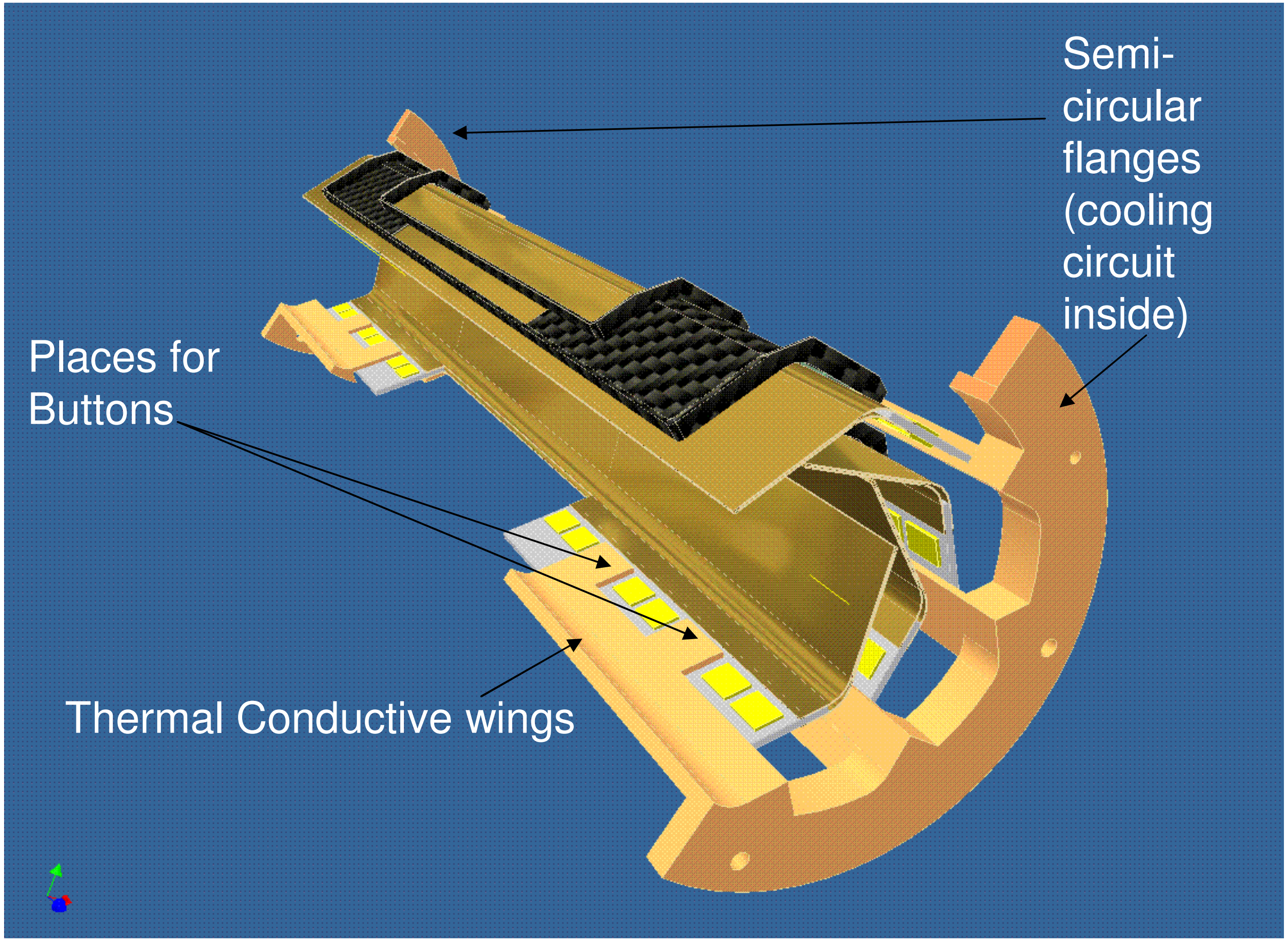
- Using bending masks we rotate the hybrids (using the flexibility of the kapton circuits).

- Freezing the module into the final geometry by a stiff carbon-fiber/kevlar structure (ribs & end-pieces “a la BaBar”: 0.5 mm thick and 4 mm height)

# Module Layer0 (3D-view)



# Placing the Layer0 module on the flanges

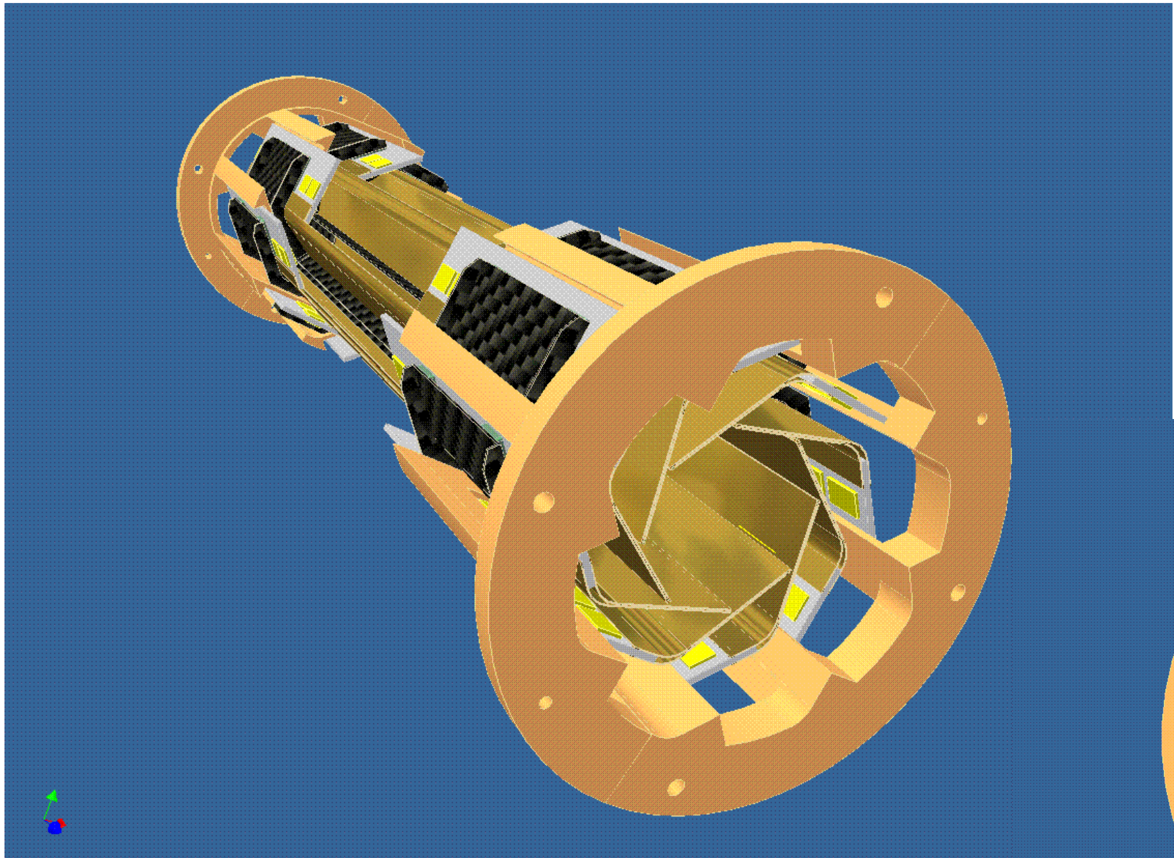


# Layer 0 mounting procedures

- Mechanical tolerances are very tight !
- Four modules are first mounted on semi-circular flanges .
- The cooling circuit is inside the annular region of the circular flanges, with thermal conductive wings

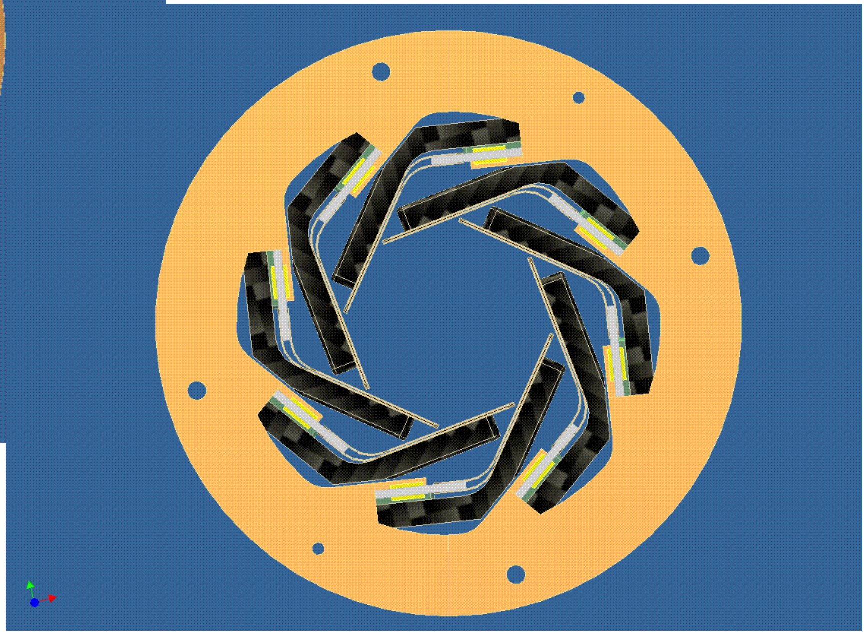
  to drain the heat from the hybrids .
- The two halves are then coupled to wrap the whole structure over the beam pipe cylinder .

# Final Layer 0 structure



3-D view

r-ϕ cross section



# The Layer 0 material budget

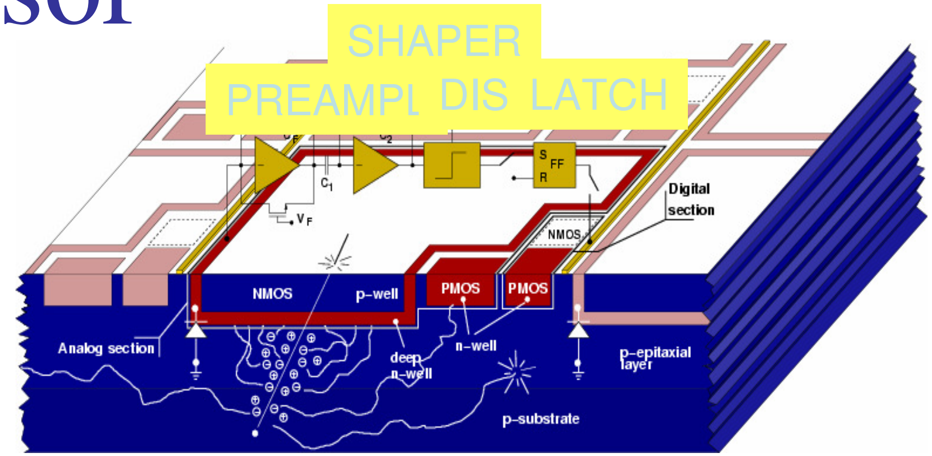
- Layer0 average thickness 0.46% $X_0$
  - Silicon detector 200 μm
  - Support structure 100 μm Si eq.
  - 3 fanout (eq.) layers/module 135 μm Si eq.

In fact, assuming a 50 μm pitch and using a lateral extension, on the short side of the detector, for fanout strip routing one needs about 1.5 fanout layers/view → 3 fanout layers/module (~ 45 μm Si eq/fanout)

Further development:

- Using Aluminum microcables, as used in Alice Si modules, we could reduce the material (10 μm Si eq/layer) and simplify the assembly (Tape Automated Bonding)
  - need to understand if 50 μm pitch is possible
  - Layer 0 average thickness could be ~ 0.35 % $X_0$ ( 330 μm Si eq.)

# The MAPS sensor



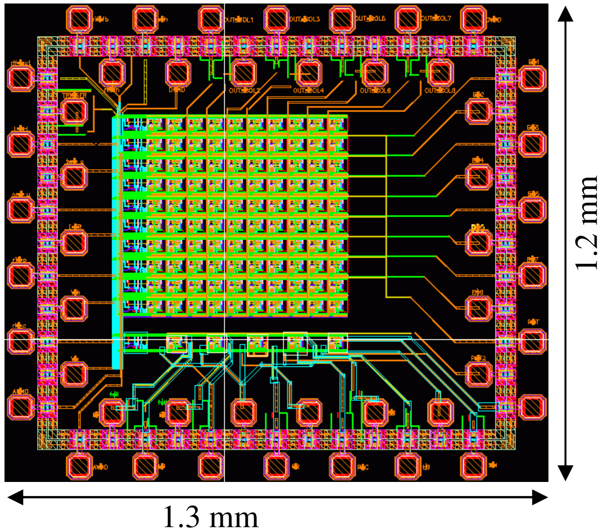

- CMOS monolithic active pixel

(see presentation of V. Re )

- Die of 128 x 128 channel (6.4 mm x 6.4 mm)

  256 x 256 channel (12.8 mm x 12.8 mm)

  elementary cell size: 50 μm x 50 μm




- Power = 50 μW/channel = 2 W/cm$^2$

  (improved in latest versions 30 μW/ch)

- Silicon may be thinned down to 50 μm

# *Physics Requirements*

- The main issue on the innermost layers of the Si tracker & beam-pipe is the material budget
- Geometrical Acceptance:

  Θ: sensitive region > 300 mrad

  r-ϕ : small radius

  (as close as possible to the beam-pipe R~15 mm)

- Redundancy on the 1st measured point
- Multiple scattering deteriorates low Pt track resolution →

  minimize the material thickness (support + sensors) computed in radiation length ($X_0$)

- Typical detector hit resolution ~ 10 μm →

  modules very stiff with small and "stable" (in time) sagitta

# *Design Requirements*

## Mechanics:

- 50 μm-thick sensor needs a support structure !
- Stiff structure and vibration modes under control
- Dimension stability
- Easy module construction and assembly:

  on a “ladder by ladder” basis: better for handling, part replacement, rework possibility, etc.

  Ladder: several (8) MAPS chips (256 x256 pixels) glued on the mechanical support
- Ideal Goal: $X^{support}(X_0) \sim X^{Si}(X_0)$

  CDR studies set Layer0 total thickness ~ 0.5% $X_0$
- Foresee detector overlaps (in r-ϕ) for track-based alignment.

# Design Requirements

**Power Dissipation:**

- Electronics & sensor integrated →
  great amount of heat dissipated on the active area.

- Layer 0 :
  - P = 210 W / layer
  - Electronics Working Temp. range: [0,50] $^{o}$C

Cooling is the main issue for these sensors !

# *Materials Data Sheet*

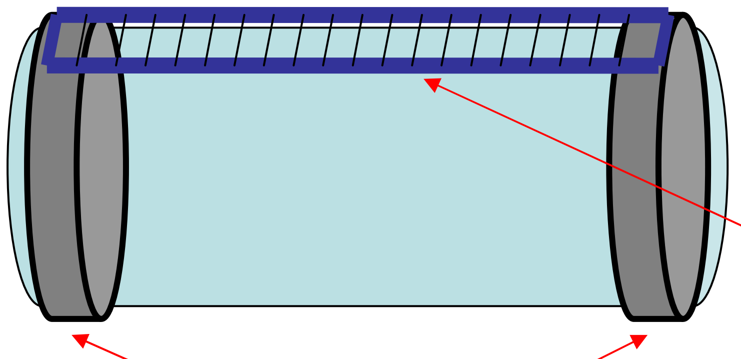
| Material | X0 (cm) | Density (gr/cm3) | K = Termal Cond.(W/ mK) | E (kg/mm2) | CTE(um/ mK) |
|---|---|---|---|---|---|
| Si | 9.4 | 2.3 | 124 | 11200 | 5.5 |
| Be | 35.3 | 1.8 | 216 | 28000 | 11.5 |
| Al | 9.0 | 2.7 | 210 | 7000 | 24.0 |
| C.F. | 25.0 | 1.6 | 160 | 12400 | |
| Upilex | 28.5 | 1.4 | 0,35 | 300 | 30.0 |
| Al2O3 | 7.0 | 4.8 | 30 | 35000 | 8.0 |
| Cu | 1.4 | 9.0 | 386 | 12000 | 16.4 |
| $H_2 0$ | 36.0 | 1.0 | 609x10 -3 | | |
| AlN | 9 | 3.3 | 180 | 27600 | 4.7 |
| BeO | 14.4 | 2.86 | 280 | 36000 | 7.5 |
| KX1100 | 25 | 2.2 | 600 - 2.5 | 600 | 0.1 |
| | | | | | |

We have to look materials for support structure with the following properties:

*Low CTE, low $X_0$, high K, high tensile modulus E, high temporal stability.*
*Important to use materials with similar CTE to reduce bimetallic effect.*

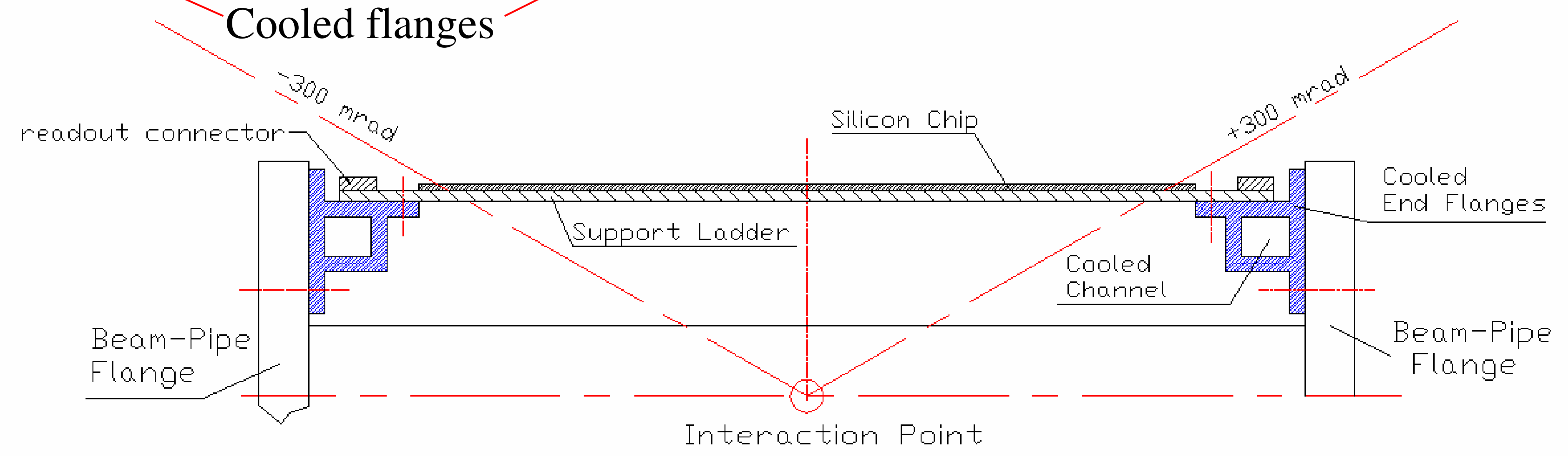
# Module Layout Development – Step-0

First trial : mechanical/thermal coupling of the ladder, structure mounted on cold flanges at the ends of the beam pipe.



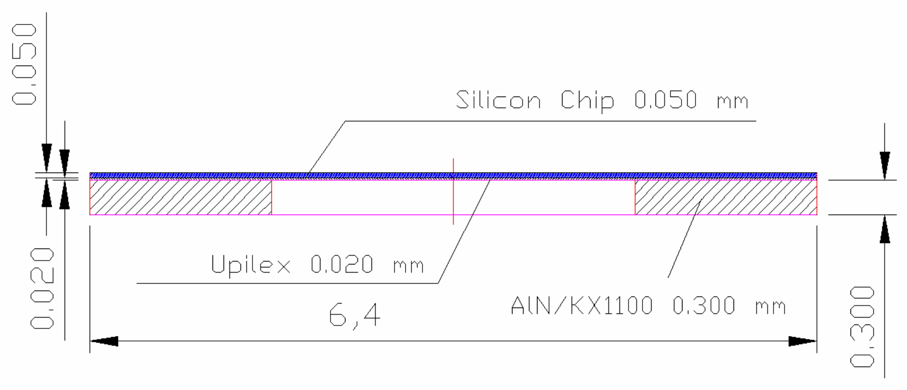
Silicon ladder: power dissipated in the active area

Cooled flanges



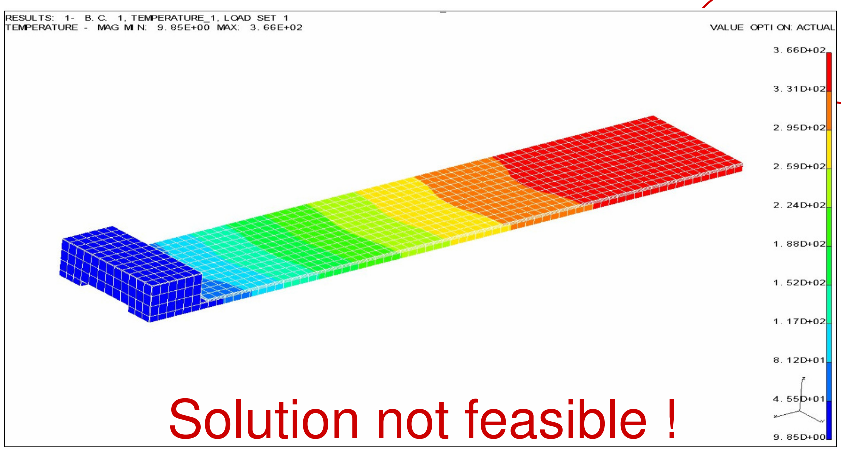

Use the ladder as thermal bridge to drain the heat generated by the chips to the cooled end flanges, mounted on the beam pipe flanges ($H_2O$ , T= 10 °C).

# Module Layout Development-Step-0




In this approach:

- Ladder realized on very high thermal conductivity: Carbon Fiber KX1100 or AlN .
- Even think about support structure based on pre-stressed carbon fiber sheet or pre-stressed AlN bars .
- No structural problems: sagitta below 0.010 mm .




366℃

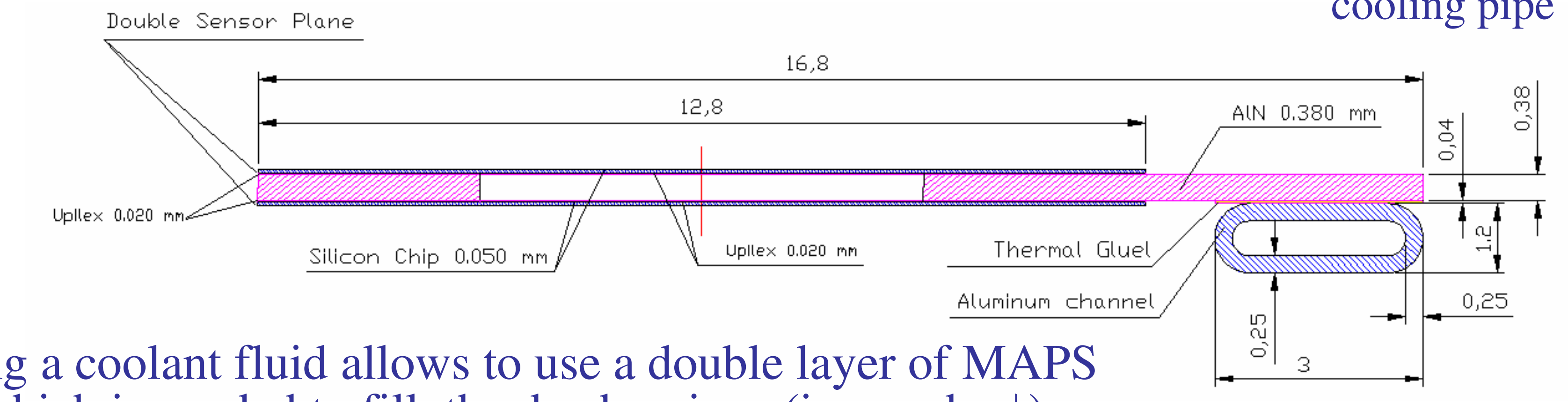
No possibility to evacuate the heat only by thermal conduction of the ladder !
(Unless to reduce P < 5 μW/channel )

Next step : use thermal convective exachange with coolant liquid .

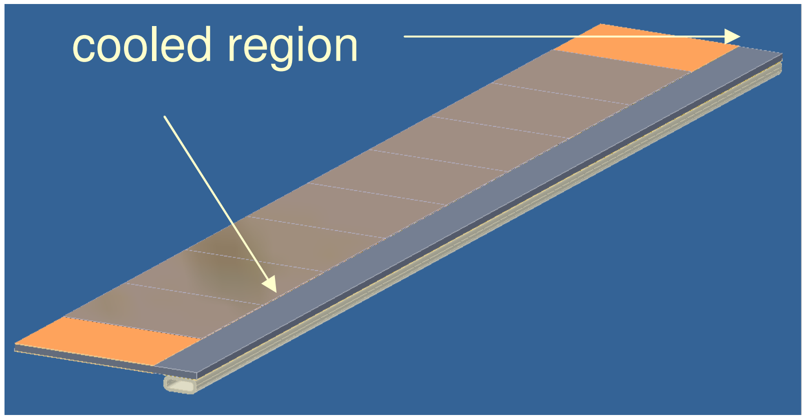
# Module Layout Development – Step-1

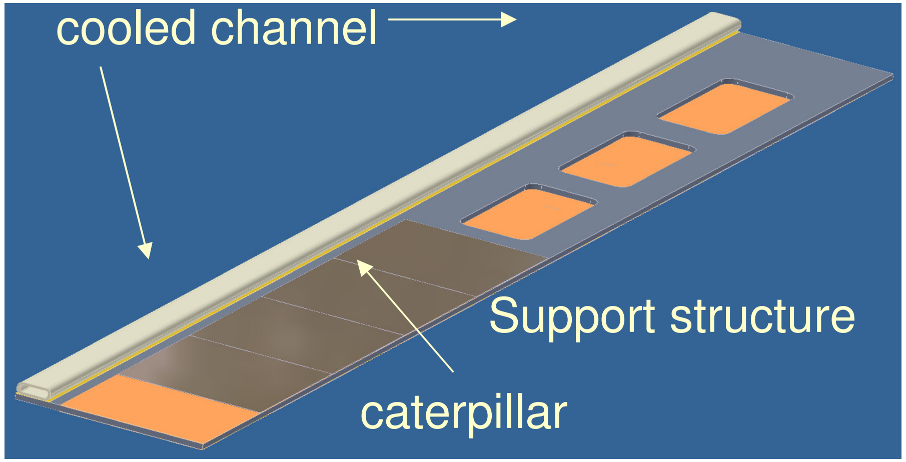
A high efficiency cooling system is required, with a flowing coolant taking away the heat directly along the ladder with high convective coefficient , h .

Ladder with a cooling pipe

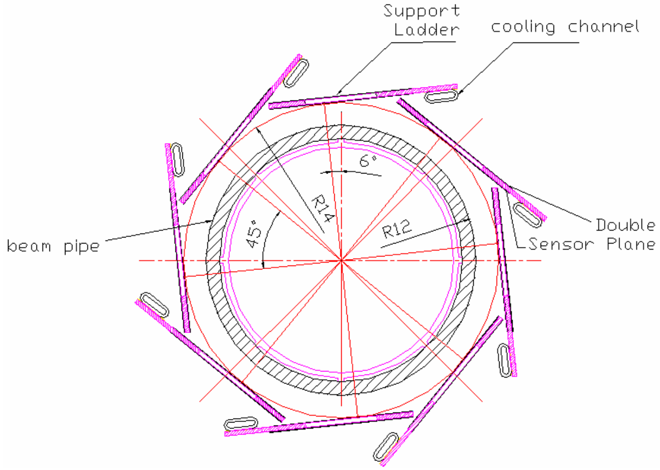



Using a coolant fluid allows to use a double layer of MAPS which is needed to fill the dead regions (in z and r-ϕ) between the chips!



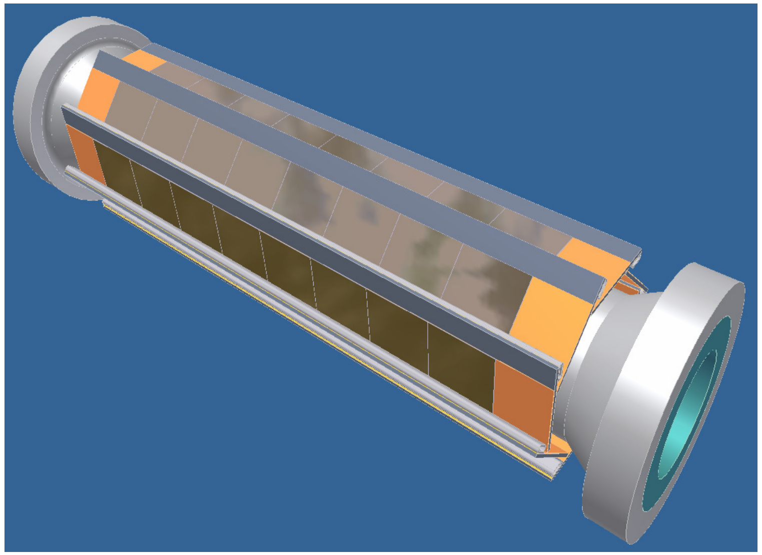



# Layer 0 Layout

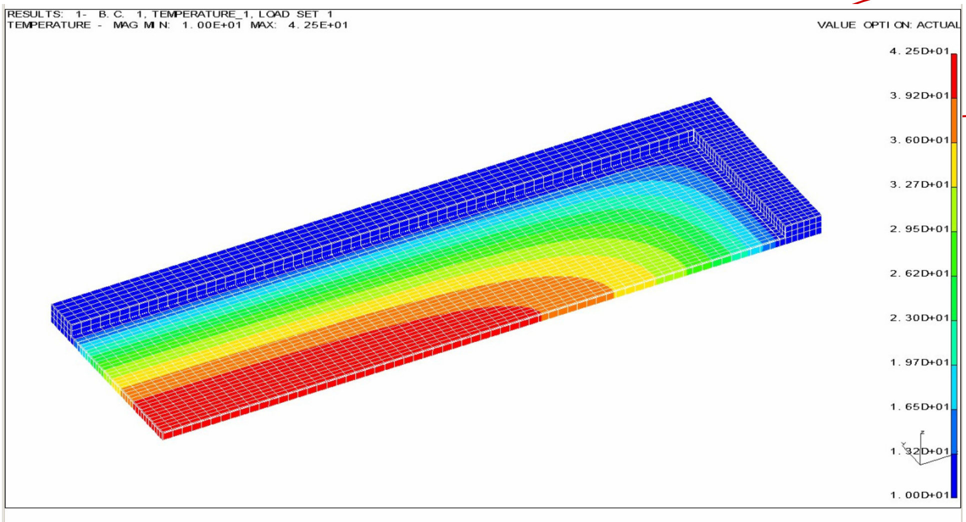



Comparing Layer 0 & beam pipe dimensions…..

Geometry with n° 8 ladder with cooling circuit <u>outside the double L0 sensitive region !</u>



# Module Layout Step-1: FEA results




42°C

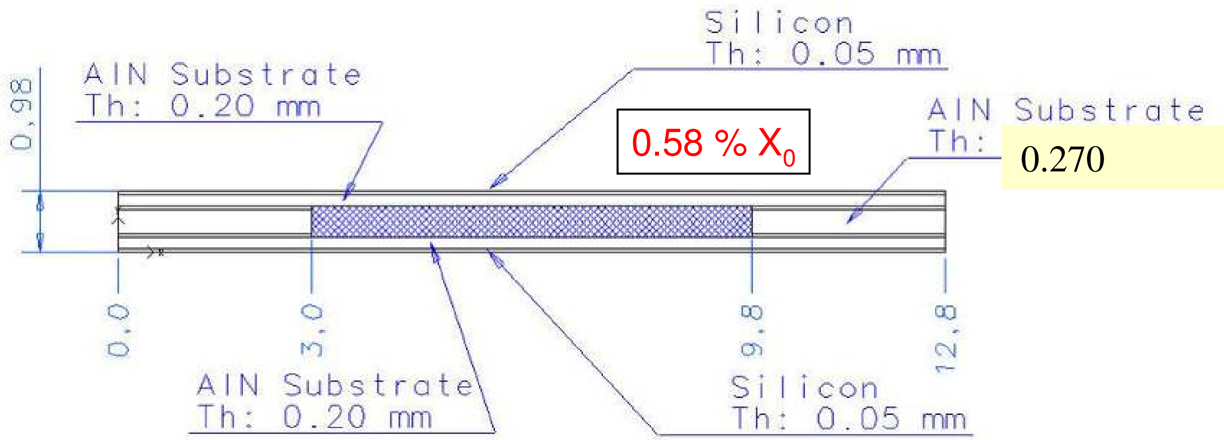
Hydraulic parameters of the circuit

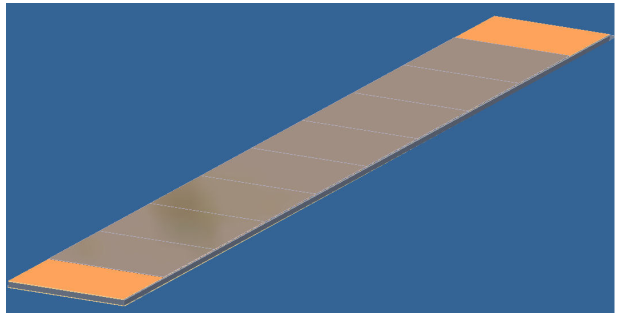
- $V_{(H2O)}$ = 1.8 m/sec
- Hydraulic diameter = 1.21 mm
- Pressure drop = 0.072 Atm
- Delta T = 3 °C
- T = 10 °C
- Reynold number = 2195
- Flow rate = 0.125 l / min

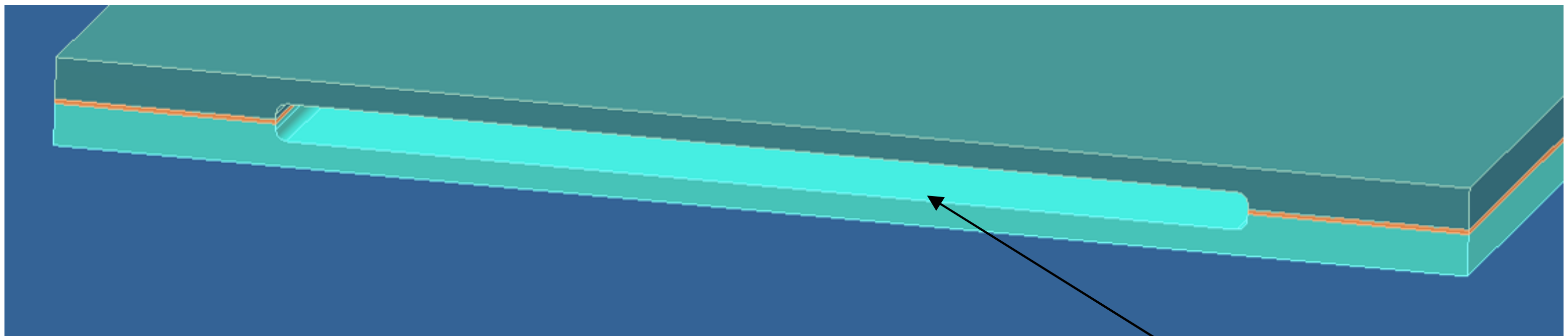
Thermal problem solved but too much material (thickness = 600 μm Si equivalent) and highly not uniform in r-ϕ ! )

# *Module Layout Step-2: Minichannel cooling in the support*

In order to distribute uniformly the material and optimize thermal exchange we designed a module with the coolant flowing inside the support structure.





Cooled channel

# Simple Considerations on forced convection (1)

According to the Newton's law, the total convective heat flux is:

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

Q = Total convective heat flux
h = convective heat transfer coefficient or film coefficient
S = Surface area
$T_w$ = Temperature of the wall
$T_f$ = Temperature of the fluid

Because of the great amount of heat dissipated on the active area (2 W/cm$^2$) it is really important to maximize Q by acting on the values of the film coefficient and the surface area.

*How can we do that ?*

# Considerations on forced convection (2)

The expression for the film coefficient is:

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

Nu = Nusselt number

K = conductive heat transfer coefficient of the liquid

$D_h$ = Hydraulic Diameter of the cooling channel

In first approximation, in order to maximize h , we have to minimize the hydraulic diameter : this remarks, point us to the minichannel technology.

Important remarks:

1. Minimize $D_h$ means to go towards greater pressure drops. We are trying to find a compromise between pressure drops and film coefficient value.
2. We are trying to reduce fluid speed inside the cooling tube in order to minimize pressure drops (Reynolds number < 2000 , laminar flow ).
3. We want to minimize the ΔT of the liquid between inlet and outlet.
4. We want to use water @10 °C as cooling fluid in order to minimize the temperature difference of the various module components to take under control bi-metallic effects.

# *Mechanical considerations (1)*

Recalling the mechanical requirements for the design of the support structure of the L0 module :

1. Stability with time;
2. Light (use materials with high radiation length, $X_0$) ;
3. High Young modulus to minimize susceptibility to vibrations;
4. Radiation resistant;
5. Low Thermal Expansion Coefficient (CTE) to be insensitive to temperature variation;
6. Low Coefficient of Moisture Expansion, CME, and Moisture Absorption, for humidity variation ;

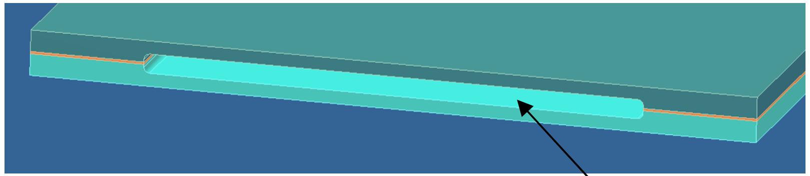
Joining all the thermal fluidodynamic considerations and mechanical design requirements, we started to investigate minichannel technology on an “easy” high thermal conductive ceramic (AlN ).

- Lighter ceramic like BeO , more difficult to manipulate
- Further studies on minichannel with Composite material with coating

# *Mechanical considerations (2)*

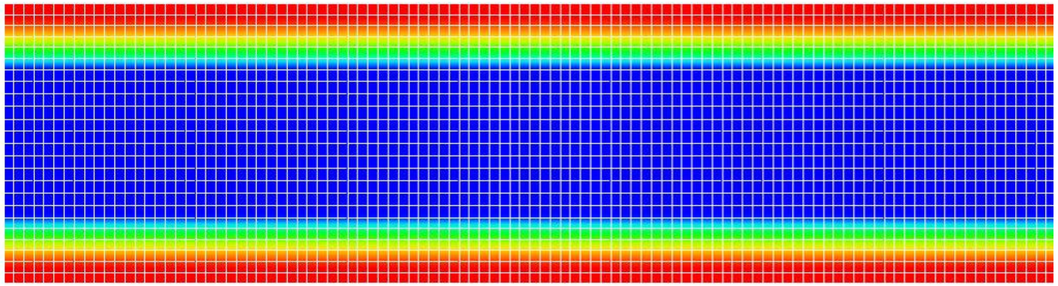
The most important characteristics of the AlN ceramics are:

- radiation length : $X_0$ = 9.0 cm
- density $\rho$ = 3.3 gr/cm$^3$
- thermal conductivity K = 180 watt/mK
- Young Modulus E = 276 GPa
- coefficient of thermal expansion CTE = 4.7 µm/mK
  (N.B.: to be compared with the silicon CTE, 5.5 µm/mK )




FEA simulations and theoretical calculations have confirmed that this design solution matches the thermal requirements (total support material 0.36 % X0)

TOP VIEW OF TEMPERATURE RATE ,
THIN SINGLE CHANNEL DOUBLE SIDE MAPS MODULE:



Tmax = 11.8℃ (2 watt/cm$^2$ on double sensor surface)

$T_{inlet}$ = 10 ℃
Delta T = 2 ℃
Hydraulic diameter = 0.482 mm
Flow = 0.376 l / min
$V_{(H2O)}$ = 3.6 m/sec
Pressure losses = 0.513 atm
Reynold number = 1778 (Laminar Flow)
h = 4550 watt/m$^2$K

# Present Mechanical activities in Pisa

We want to demonstrate feasibility with measurements on mechanical prototypes :

1) Design of MAPS module with support structure in AlN ceramics with minichannel obtained by subtracting methods (micromachining).
2) Drive out technological test on ceramics micromachining to produce L0 module prototype parts (with dicing technology).
3) Production of the mechanical masks for assembling the support prototype and the mechanical pieces for the hydraulic interface.
4) Set-up a thermalfluidynamic test-bench to accurately measure the thermal exchanges and the cooling variables (Pressure, T, humidity) on our prototypes under working condition.

# Module design (I)

At this moment we are implementing several types of module:

- Single thin channel
- Double thin channel/reticule fin
- Multiple minichannel

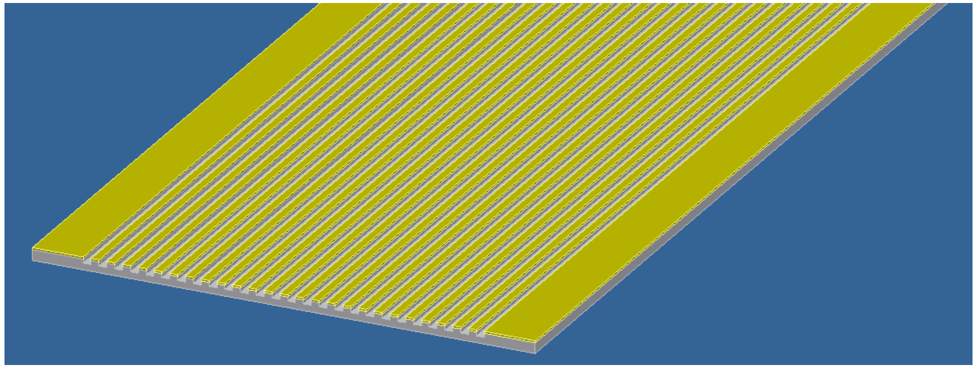
The basic concept for the production of the module prototypes is to produce micromachined elements ( initial thickness: 270-350-630 μm) and to glue together the two micromachined slats, in order to obtain one monolithic, minichannel structure.

For the first prototypes we think to glue with epoxy 2011, 50 μm thick.

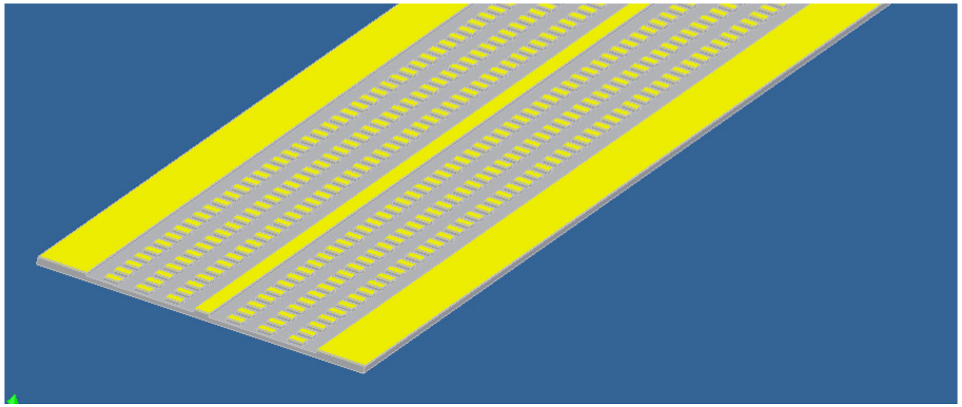
# Module design (II)

## Different layouts:

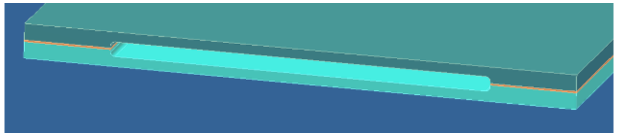
Parallel minichannel



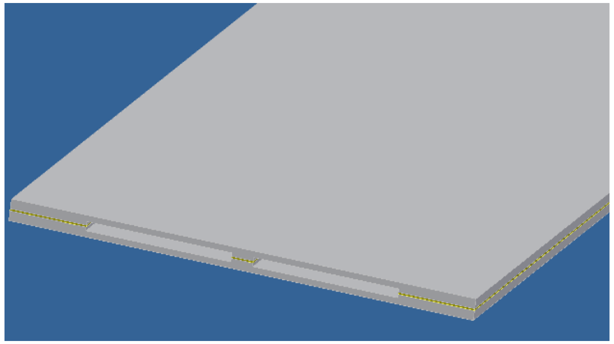
Double thin minichannel with reticule



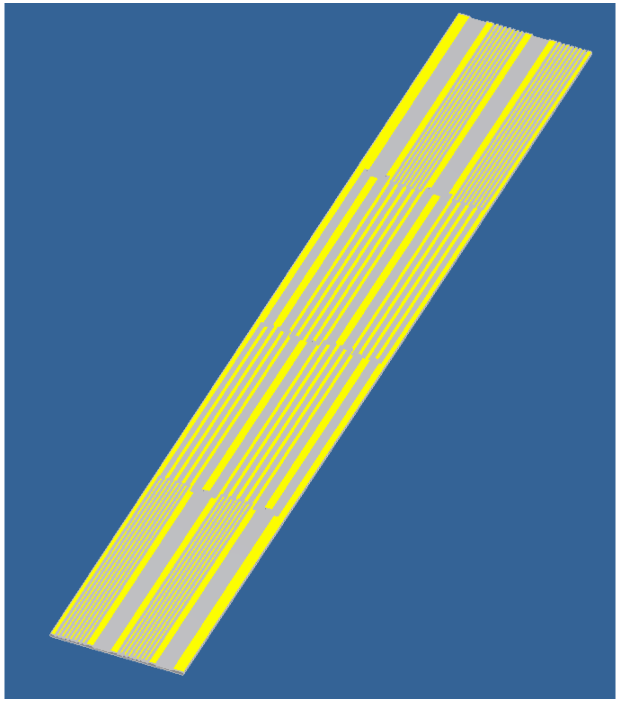
Single thin minichannel



Double thin minichannel

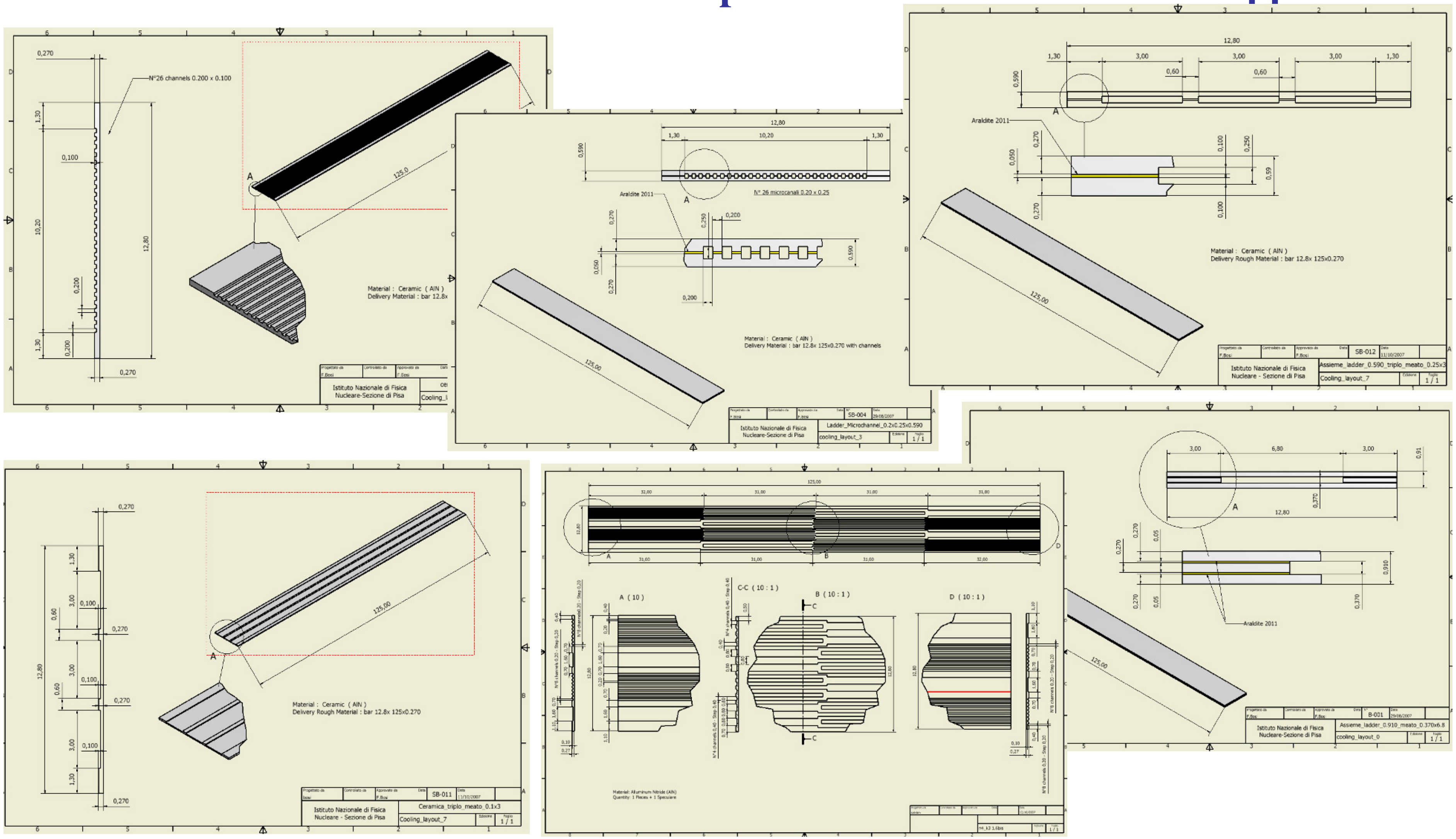


Trees thin minichannel



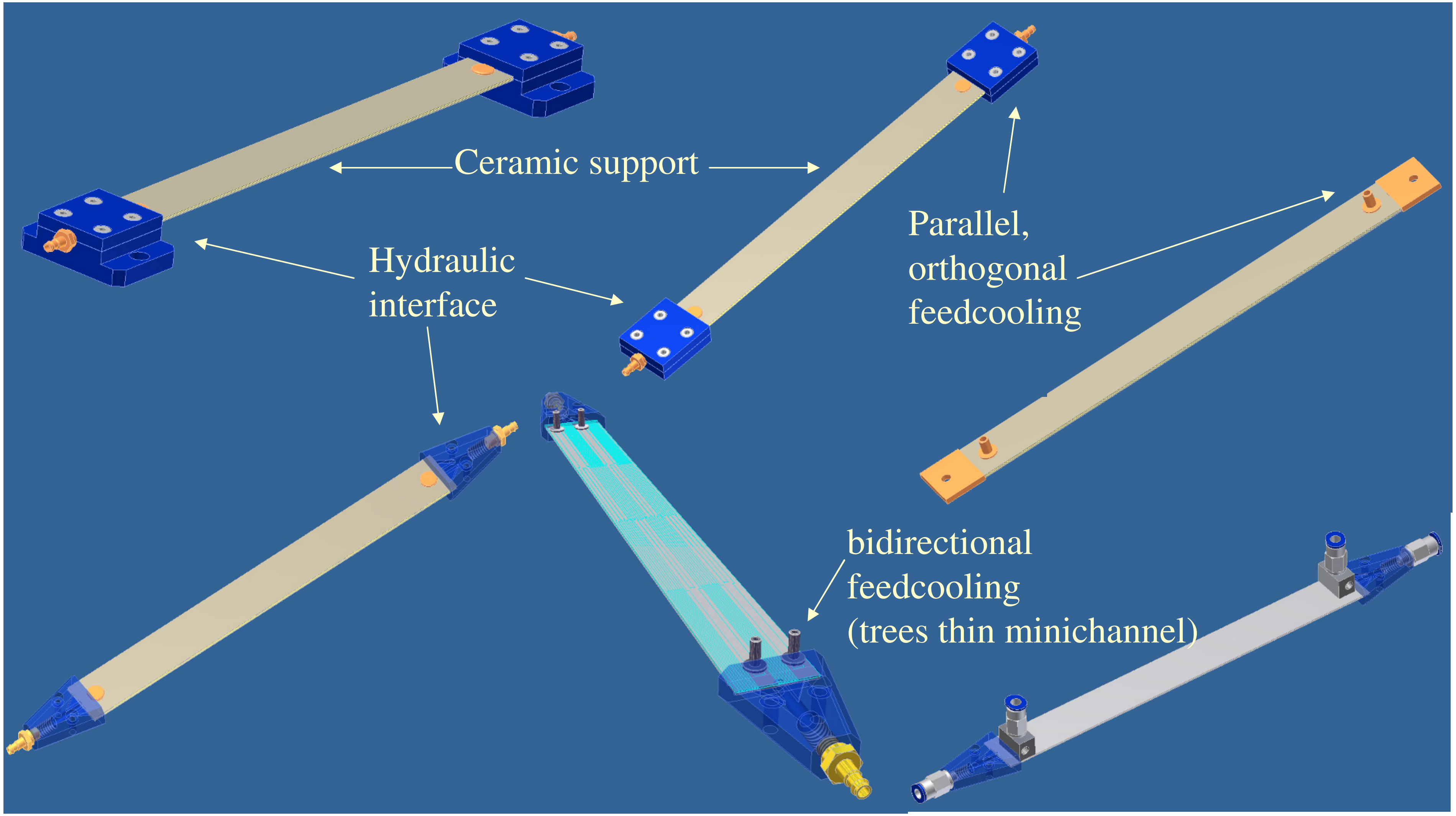
# Module design (III)

**Executive details for the components of the ceramic slab support**



# Module Design (IV)

Variety of module layout with hydraulic interface, to use in the testbench



# Micromachining tests

We have tested the first micromachining prototypes of thin single channel and minichannel, obtained by dicing tools on ceramic slats. Slats dimensions :

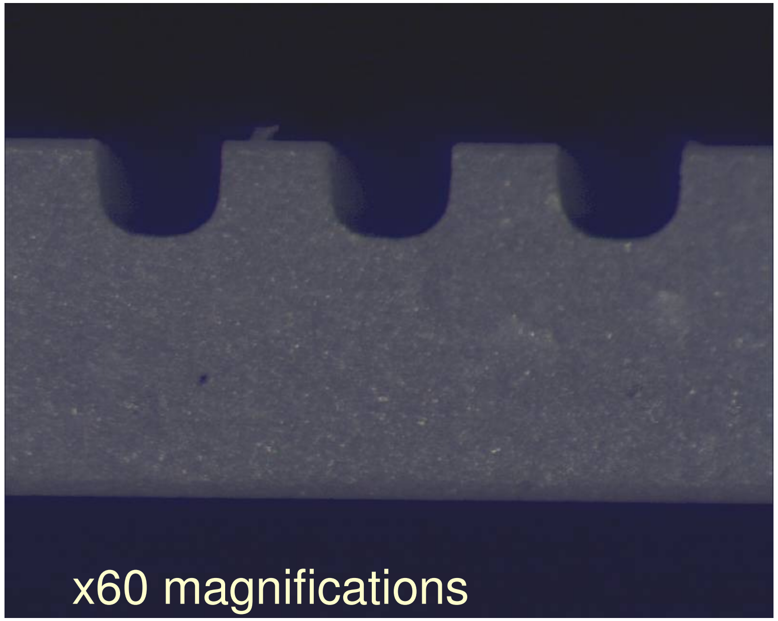
12.8mm x120 mm, (thickness 630-330-270 μm)

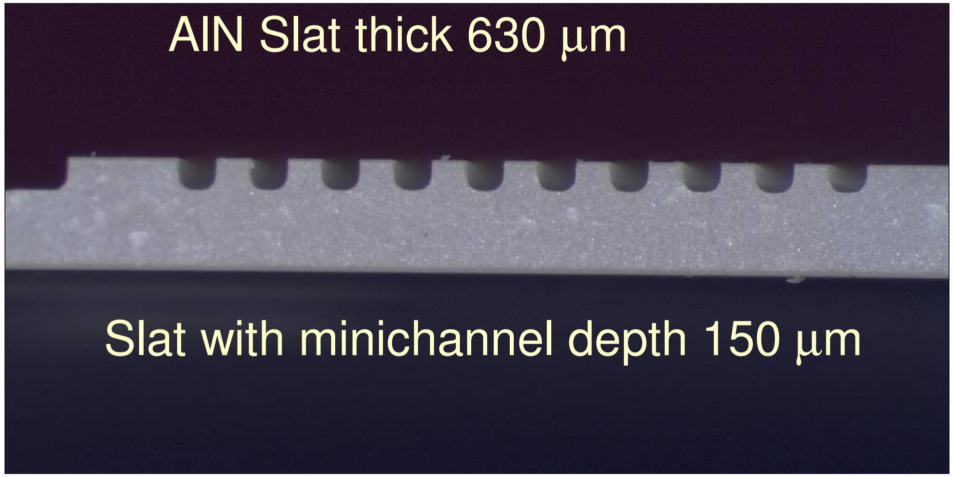
The first results of prototypes are encouraging:

- good surface roughness: < 5 μm
- good tolerance respect of the requested tooling precision: $\pm$20 μm
- Absence of cracks on the ceramic material after working .

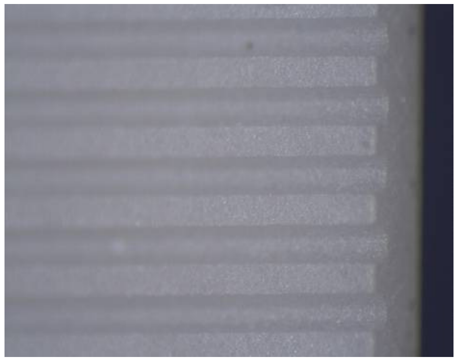
# AlN slat micromachining

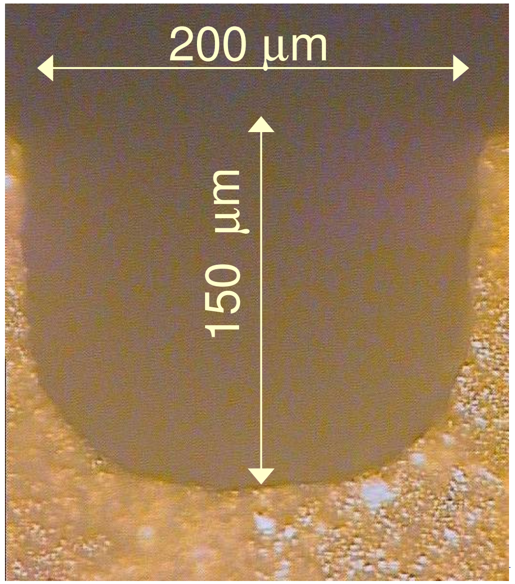
## Some micromachining example of ceramic slat thick 630 μm




AlN Slat 630μm thick ,
Minichannel top view
( pitch 400 μm )

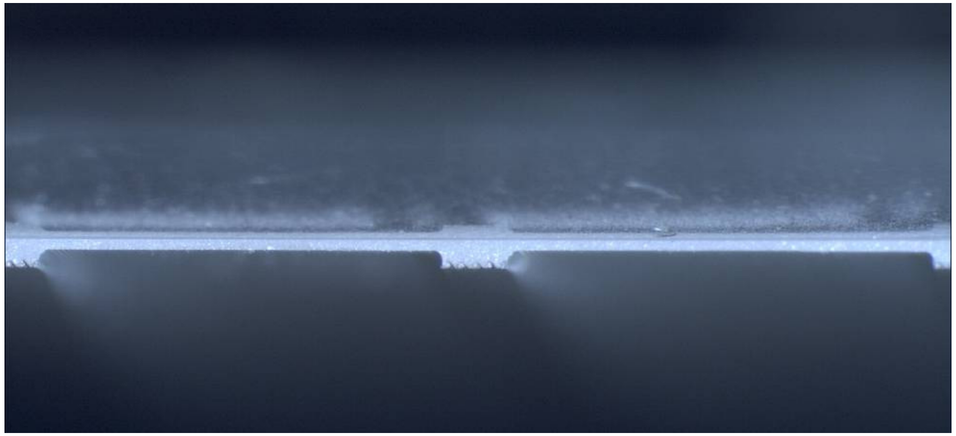




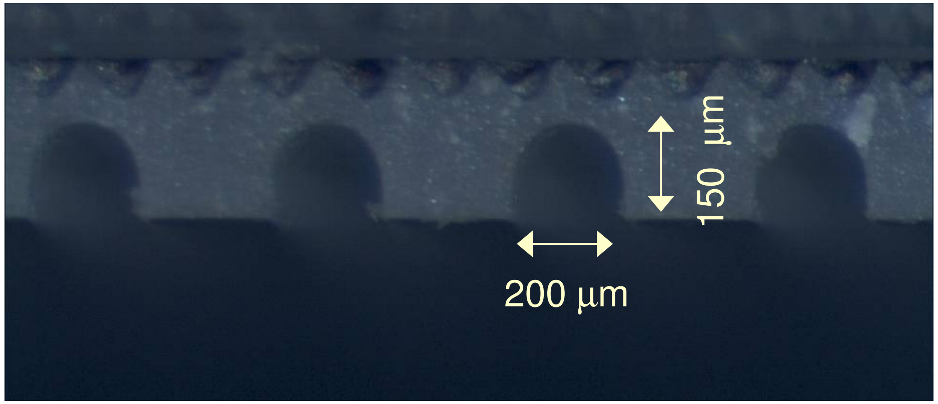
# AlN slat micromachining

Some example of micromachined ceramic slats, 270 μm thick

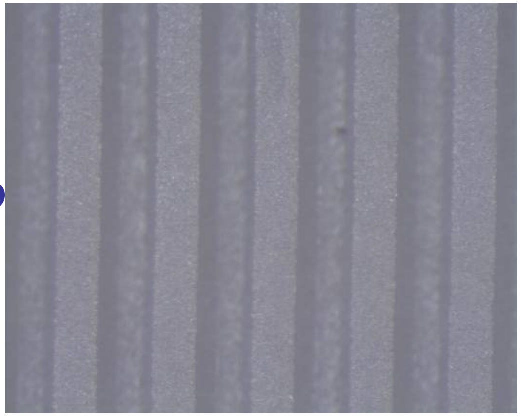
AlN Slat, 270 μm thick
with double thin channel



AlN Slat, 270 μm thick with minichannel




AlN Slat
270μm thick.
Minichannel top view
(pitch 400 μm )

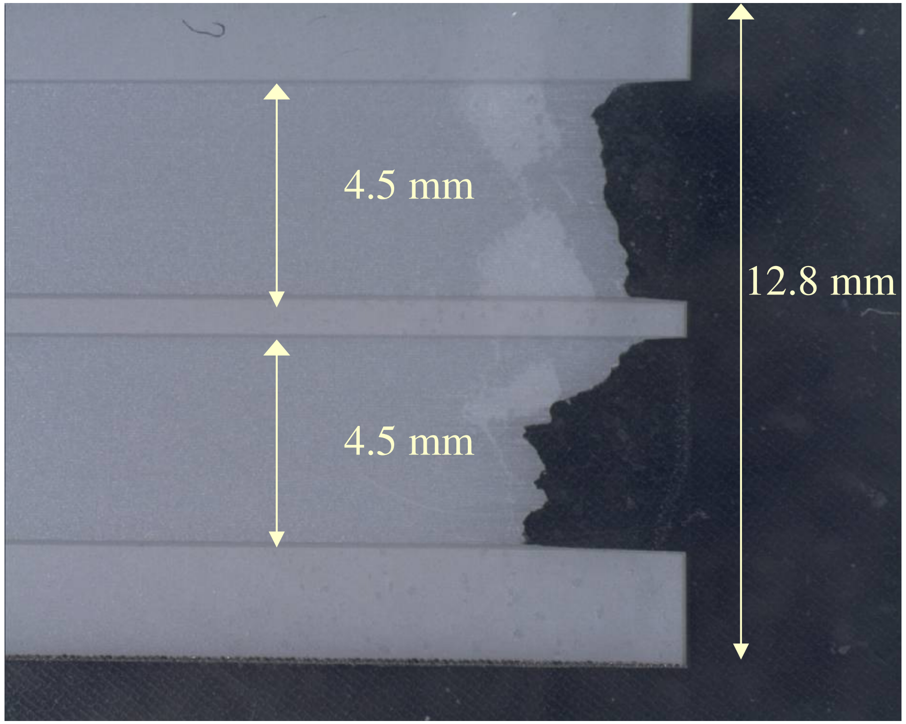


( pitch 400 μ )

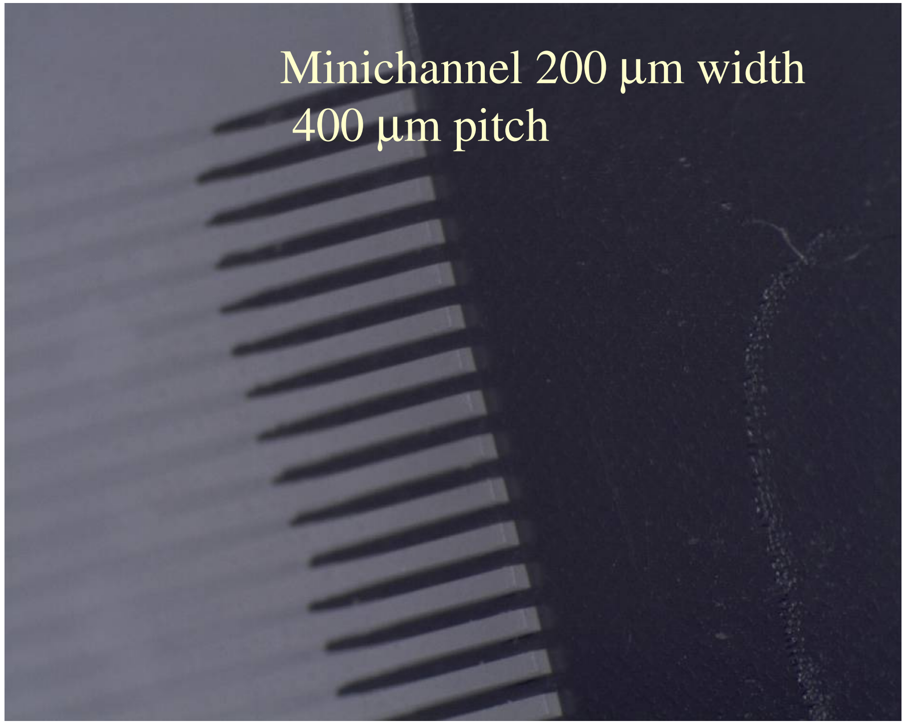
# AlN slat micromachining

Some micromachining problems on ceramics slat, 270 μm thick, easily solved by a more appropriate clamping technique of the sample.

- AlN slat thick 270 μm




- AlN Slat thick 270 μm

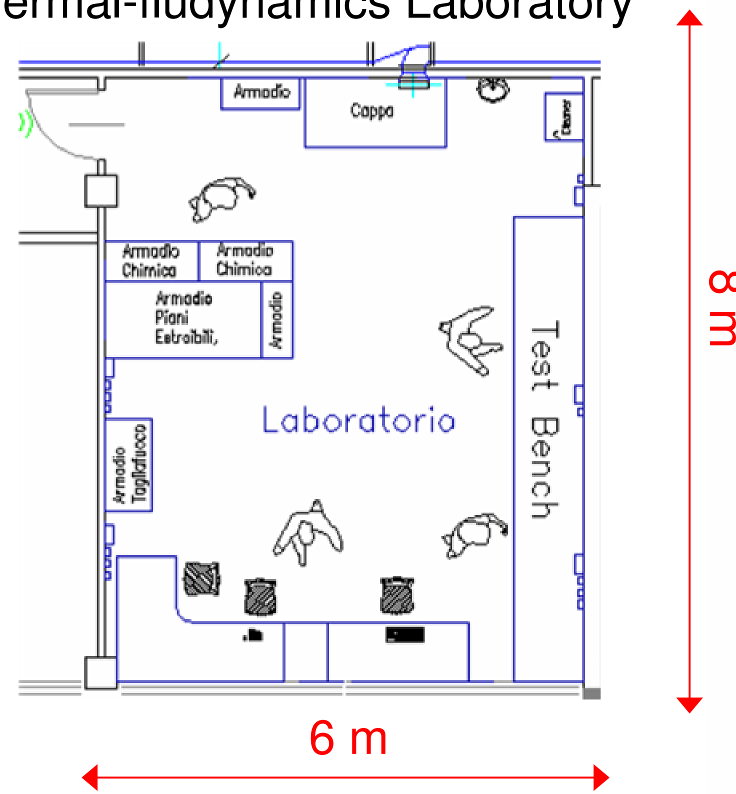


# The Thermal-fluidodynamic Laboratory

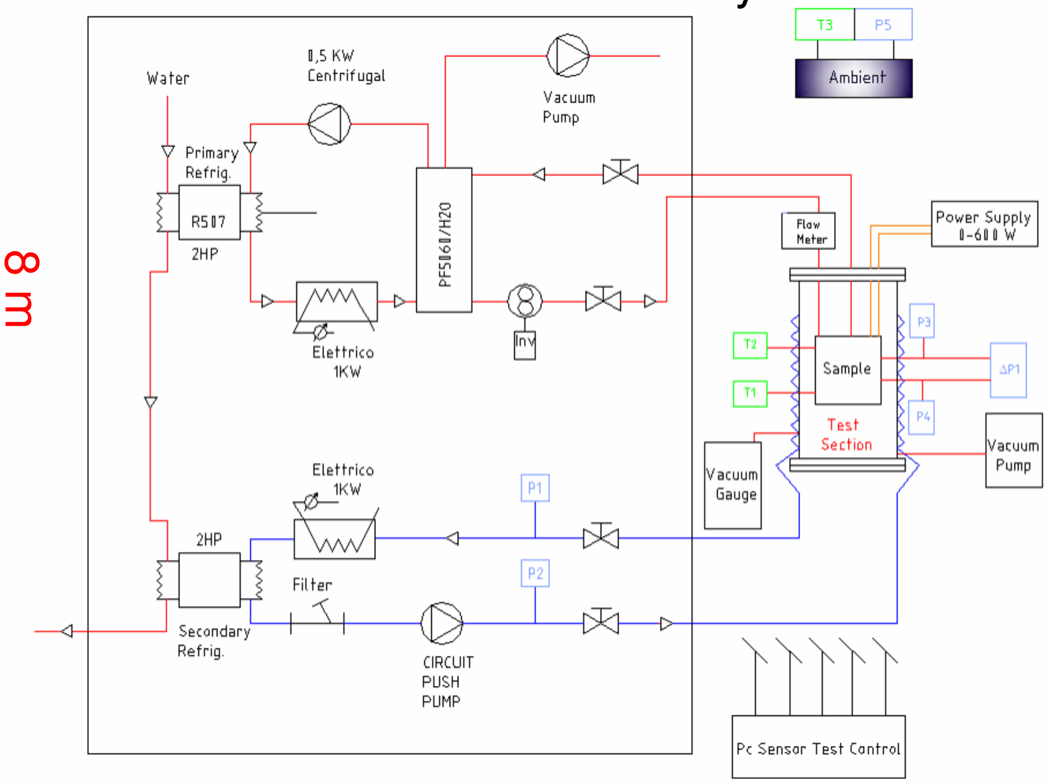
At the INFN-Pisa we started the setup of a Thermalfluidynamic Lab.

We have already ordered most of the hydraulic components for the experimental test (chiller, pumps, temperature and pressure sensors, DAQ system , vacuum pump etc.) . In 3 months we'll have an operative test-bench, dimensioned for a cooling power > 1/2 kW (~1 Layer0 equivalent).

Termal-fludynamics Laboratory



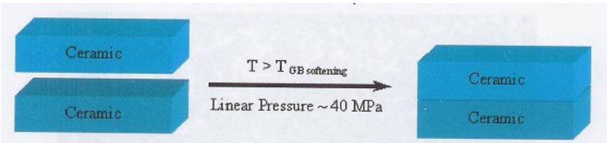

Scheme of the Test-bench hydraulic circuit

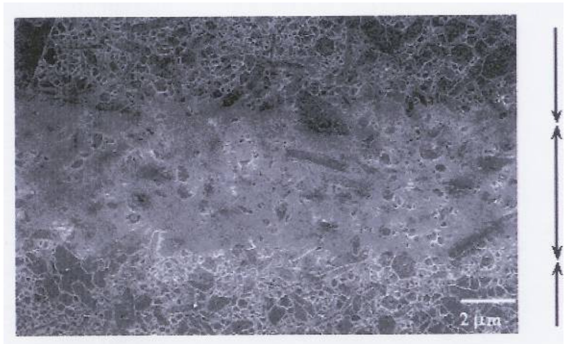


# A Technology to explore

In order to optimize the bonding of the 2 ceramic slats forming the module support structure, we are looking for ceramic technology able to put together the slats in very rigid way via thermal and pressure process (reducing junction thickness).

In general there are 3 possible processes to carry out this purpose:
- direct junction
- glass interlayer junction
- solid diffusion junction

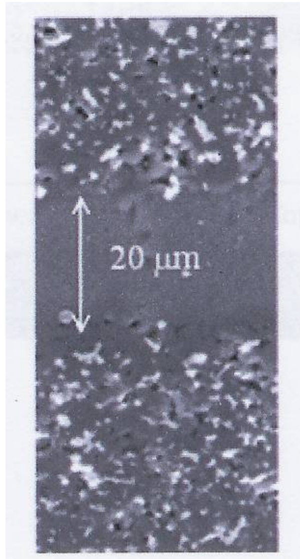



ceramic

15-20 µm glass

ceramic

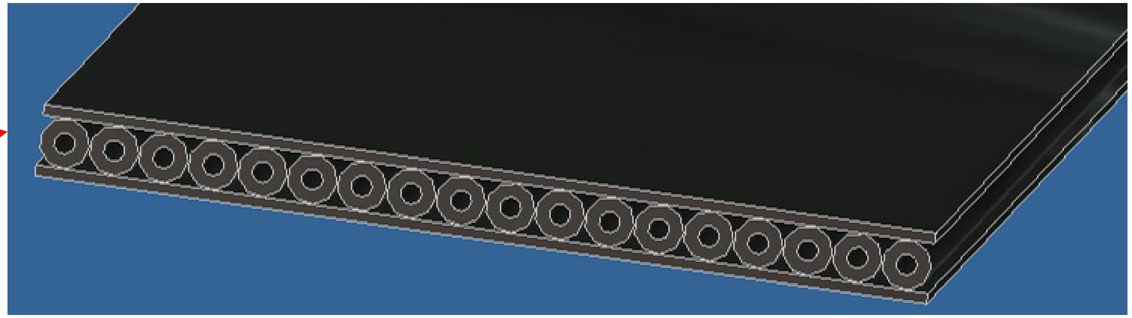


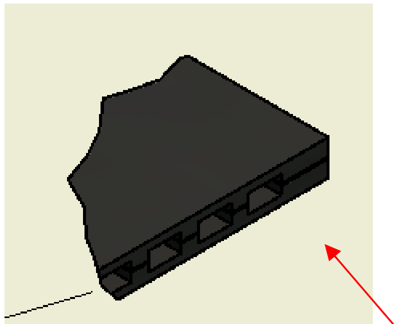

These are consolidated technology in the ceramic field.
We are developing the appropriate technology in contact with Italian Applied Research Institution .

# Minichannels in carbon fiber

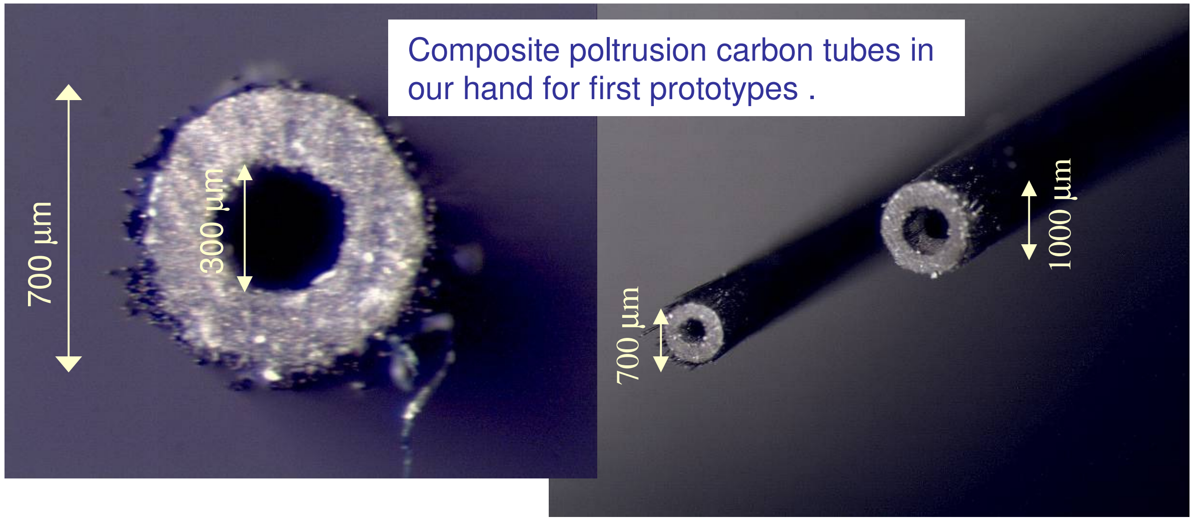
Looking also on other ideas, we try to design L0 support prototype in composite material with additive technique (mini-tubes glued together forming a support structure) .

General scheme of the additive technique support .



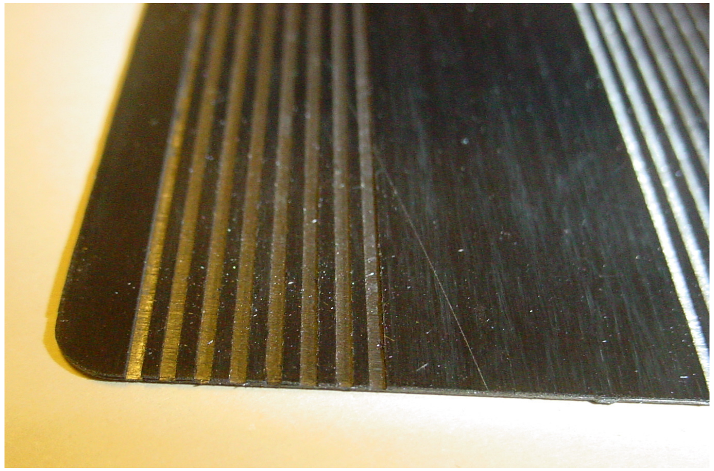


Minichannel in carbon fiber in production also with subtractive technique.

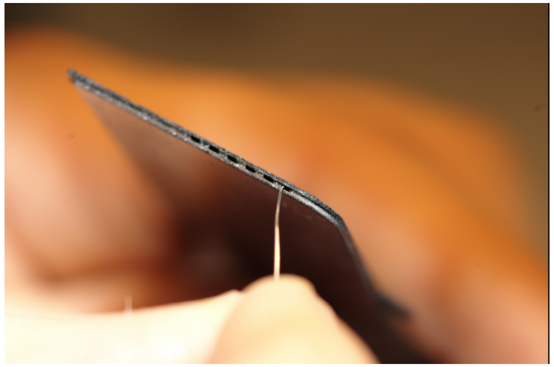


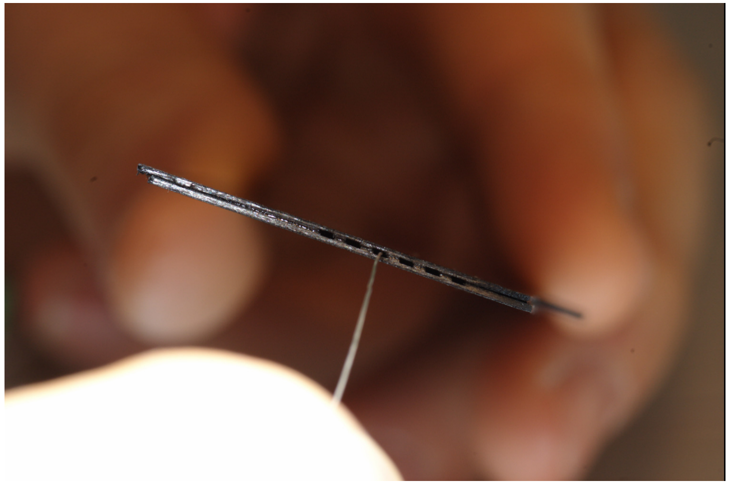

Composite poltrusion carbon tubes in our hand for first prototypes .

# Minichannels in carbon fiber



Minichannel in carbon fiber in production with subtractive technique.



C.F. Laminate th 500 µm , minichannel 0.5 x1 mm
( N.4 layer MJ46).
Coating in epoxy resin .

# Future design activity

- Design of the L0 system including the manifold/support/flanges system.

- Transferring of the know-how and experience of the L0 microcooling technology on the design of the SuperB beam pipe cooling system.

- Looking forward ➔ explore the two-phase convective thermal exchange with microchannel technology in order to optimize the efficiency.

# Next mechanical/laboratory activity

- Manufacturing and finalization of the various ceramic/carbon fiber module support structure with minichannel technology.
- Manufacturing and finalization of the various ceramic support structure for L0 module with microchannel (further reduction of channel dimensions $D_h < 100\ \mu m$) by laser ablation .
  - With a AlN support of 440 μm thickness and microchannels of 100 μm width x 200 μm depth, total support material 0.4% $X_0$ (0.26% $X_0$ with BeO).

Final goal: realize a full Layer 0 mechanical support with microchannel technology, cooled and tested at the T.F.D. testbench, to verify the FEA simulations. (Warming kapton circuit used to simulate MAPS power consumption)

- Investigate the integration of microcooling techniques on Si chips themselves.

# Conclusions

We are developing in Pisa a minichannel cooling system that seems promising to solve the high thermal power requirement of the L0 SuperB experiment.

A new T.F.D. facility, now in the setup phase @ Pisa, will be able to test experimentally all the developed manufactured prototypes.

In the next months we are going to produce and test a fully functional L0 mechanical prototype, with manifold feeding flanges.

We are going to demonstrate experimentally that a cooling system based on microchannels can be a viable solution to the thermal and structural problems of the L0 detector, matching the severe low mass requirements.