PH-DT
Detector Technologies

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Micro-channel cooling for high precision vertex detectors: status and perspectives

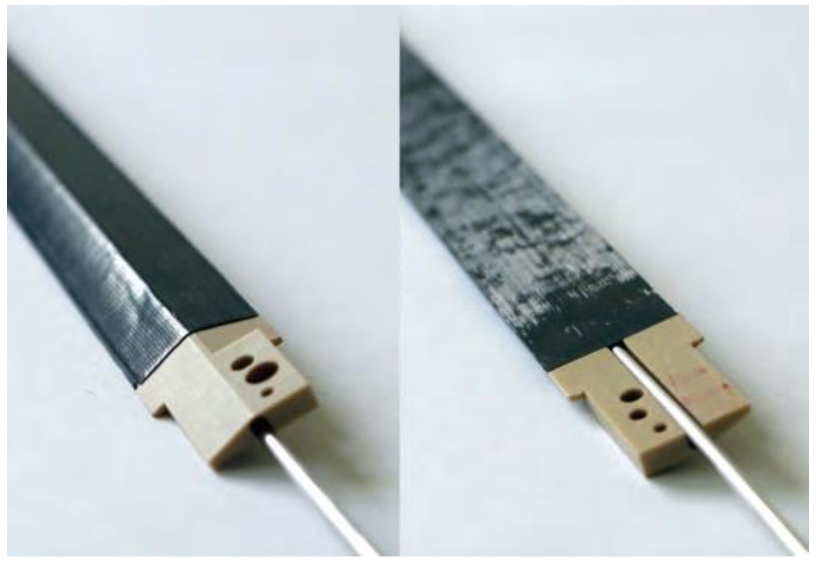
Paolo Petagna
(On behalf of the CERN PH-DT Group, of the ALICE ITS Team and of WP9 of AIDA-2020)

Forum on Tracking Detector Mechanics 2015

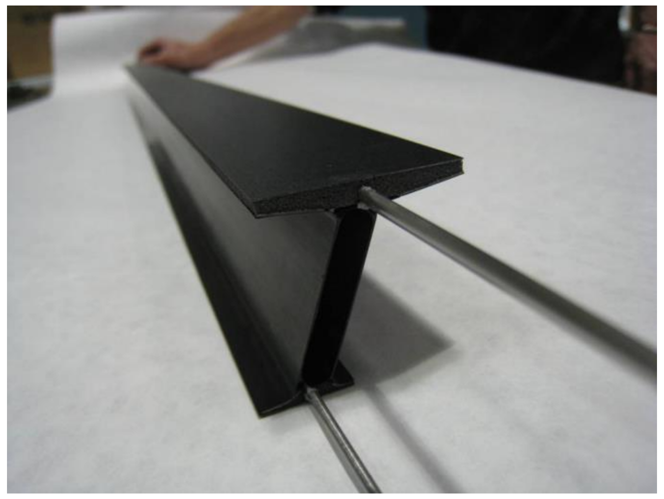
15-17 June 2015
Amsterdam Science Park

Cooling & Structure Optimization

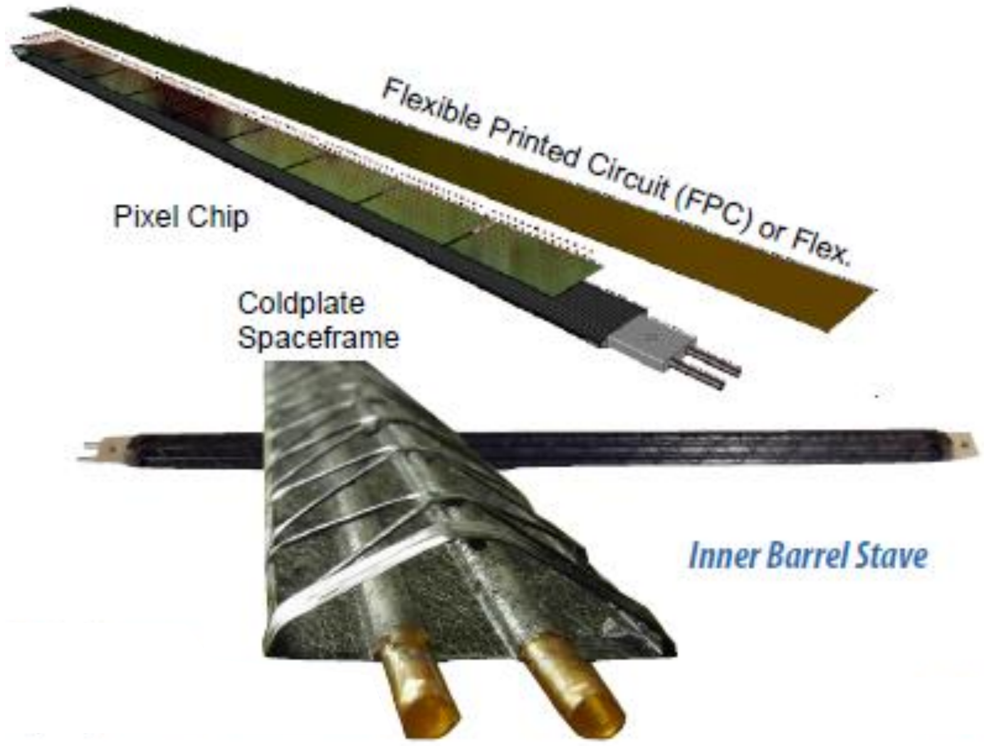
Growing attention to early design and integration of optimized support structures and thermal management solutions is **mandatory** for the present and the coming generation of Vertex detectors:



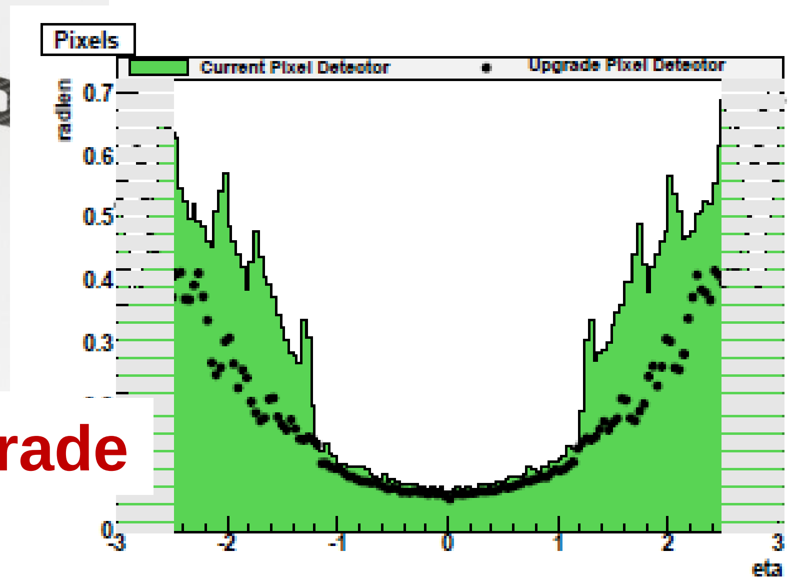
ATLAS IBL



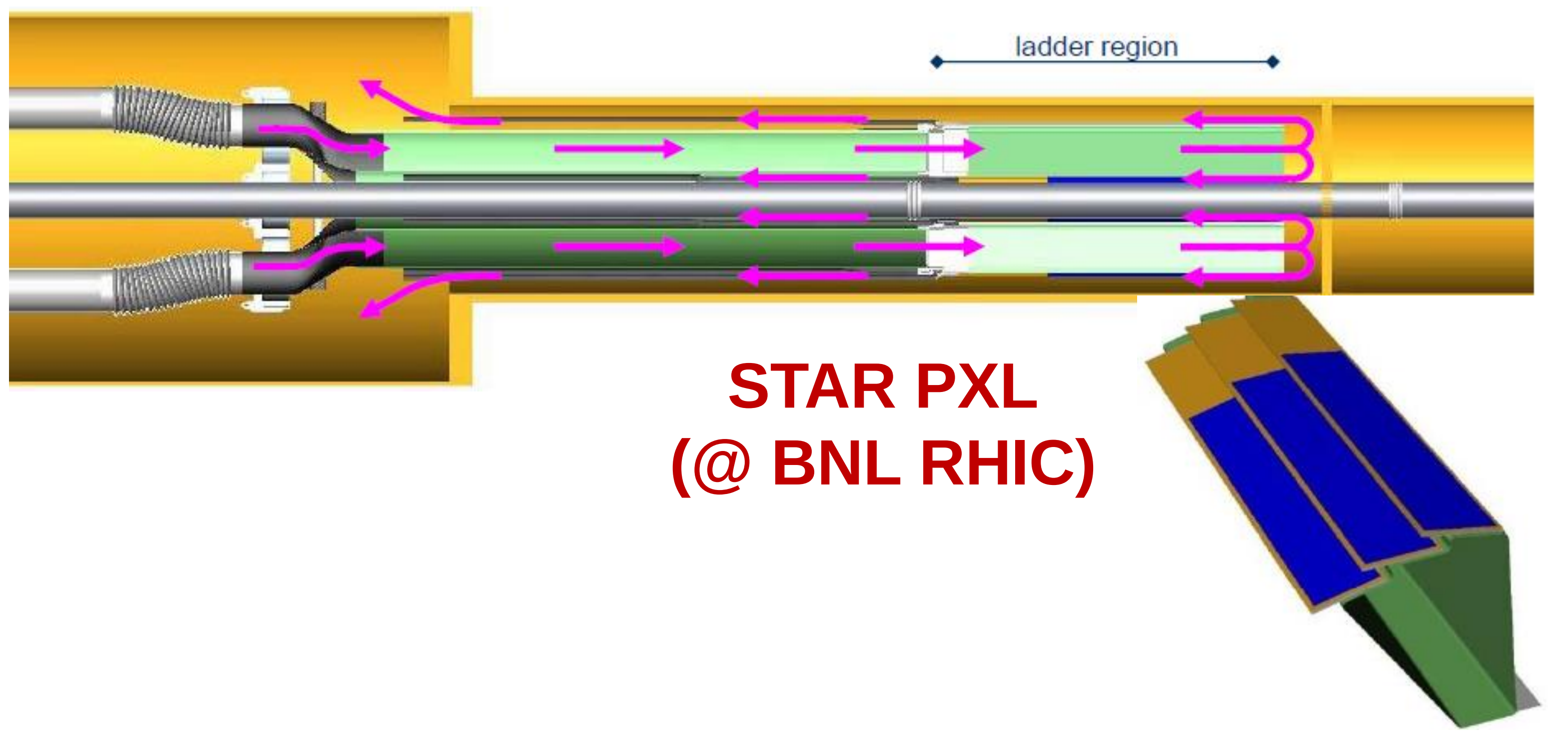
ATLAS PIXEL upgrade (study)



ALICE ITS upgrade



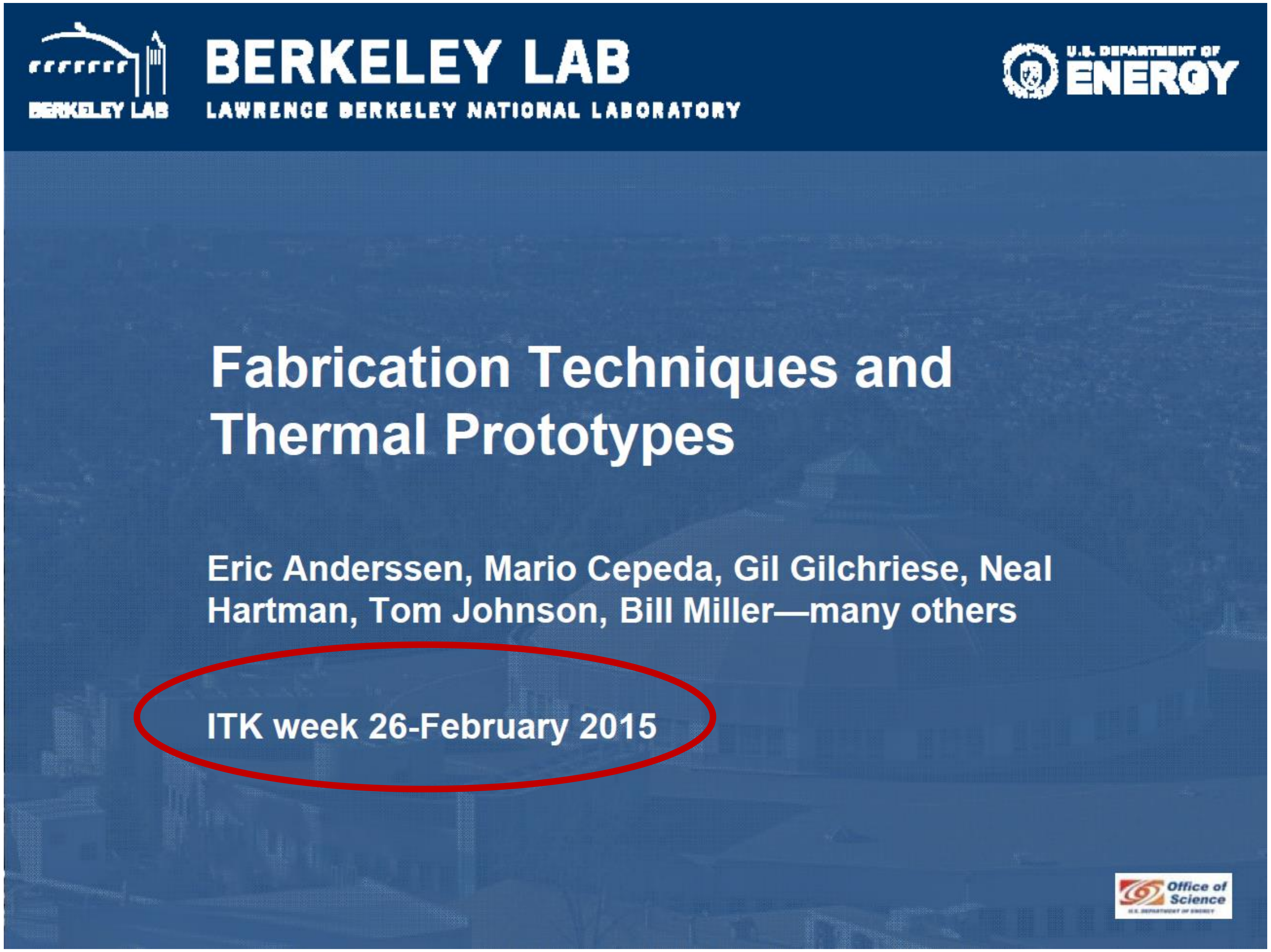
CMS PIX upgrade



STAR PXL (@ BNL RHIC)

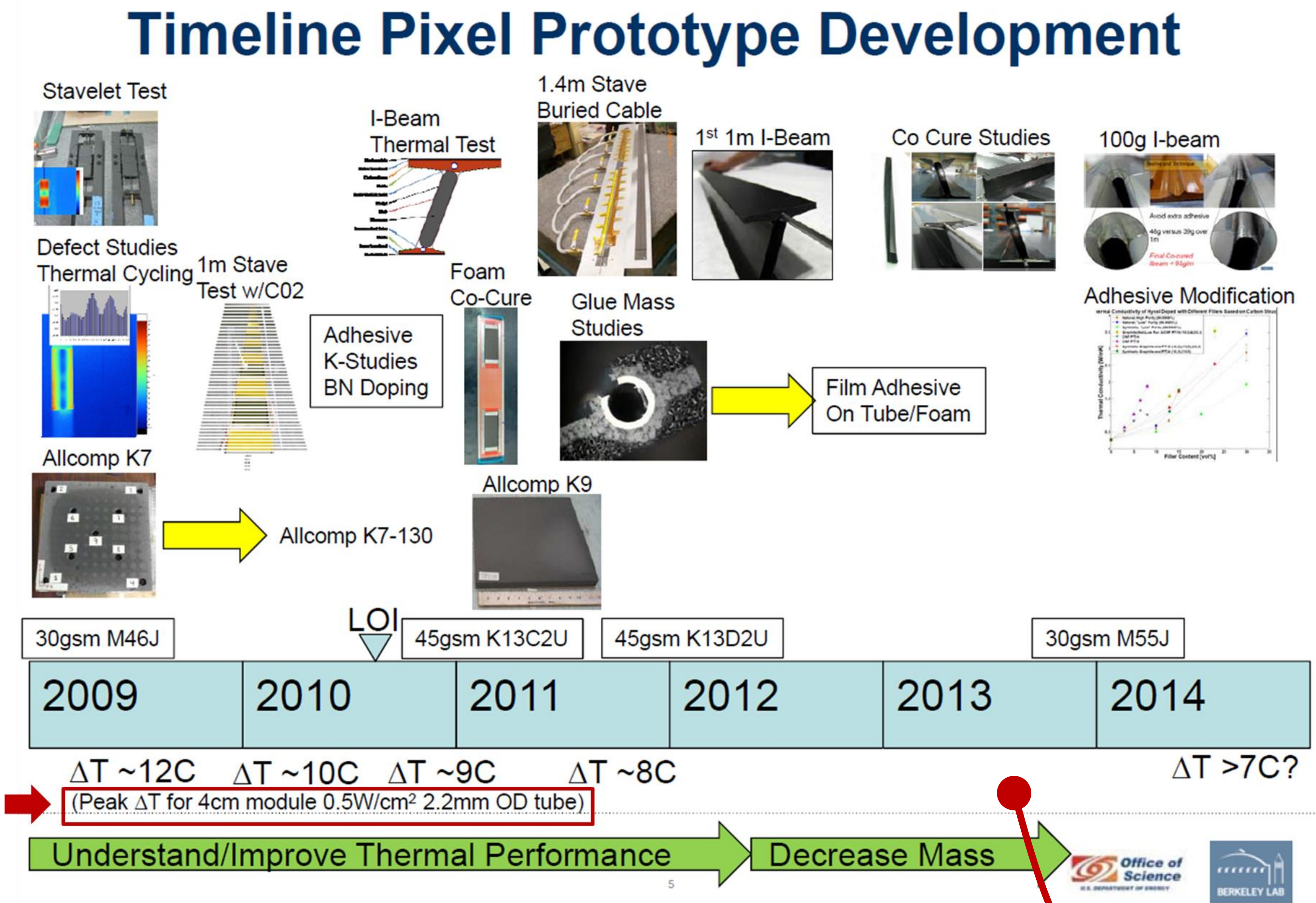
Cooling & Structure Optimization

Very nice overview presentation on the status of optimized cooling-structure integration for advanced Pixel staves (thanks to D. Giugni for pointing me at it):

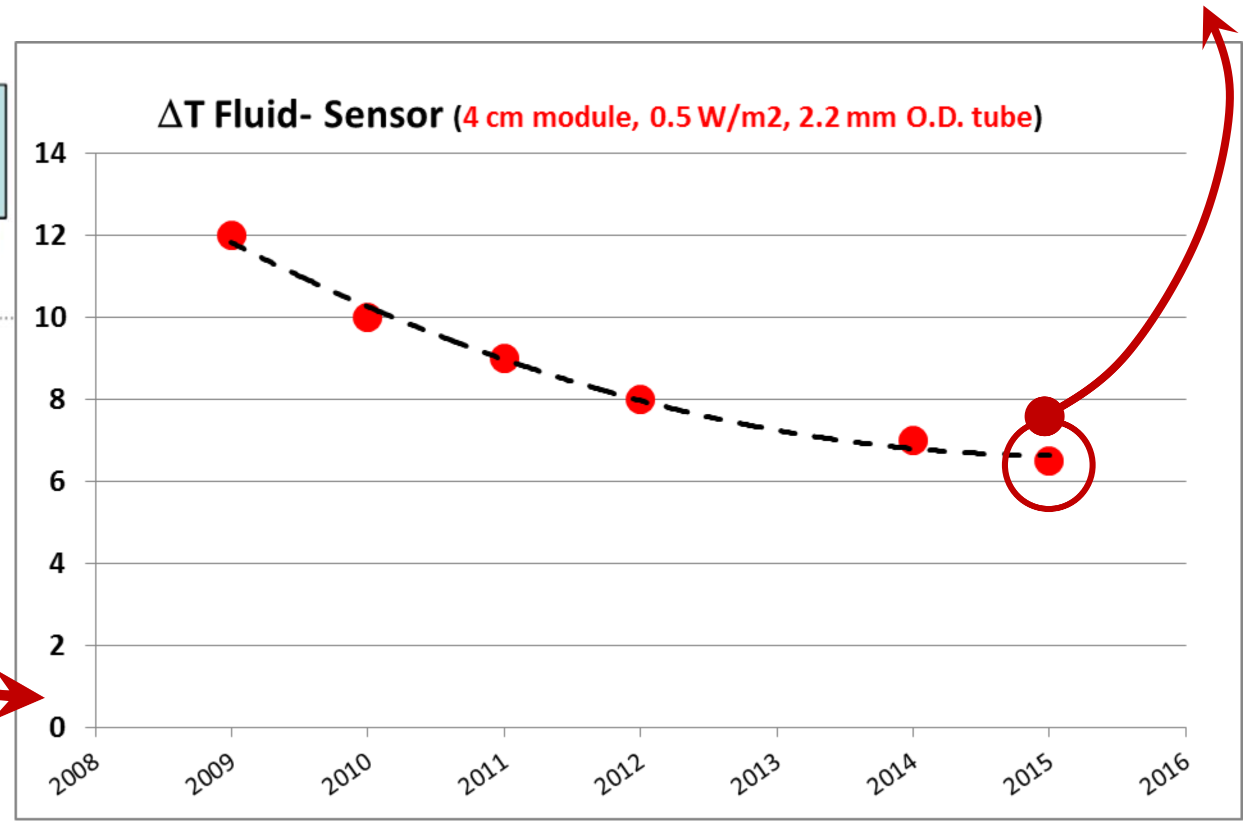


Cooling & Structure Optimization

From the previously quoted presentation by E. Anderssen:

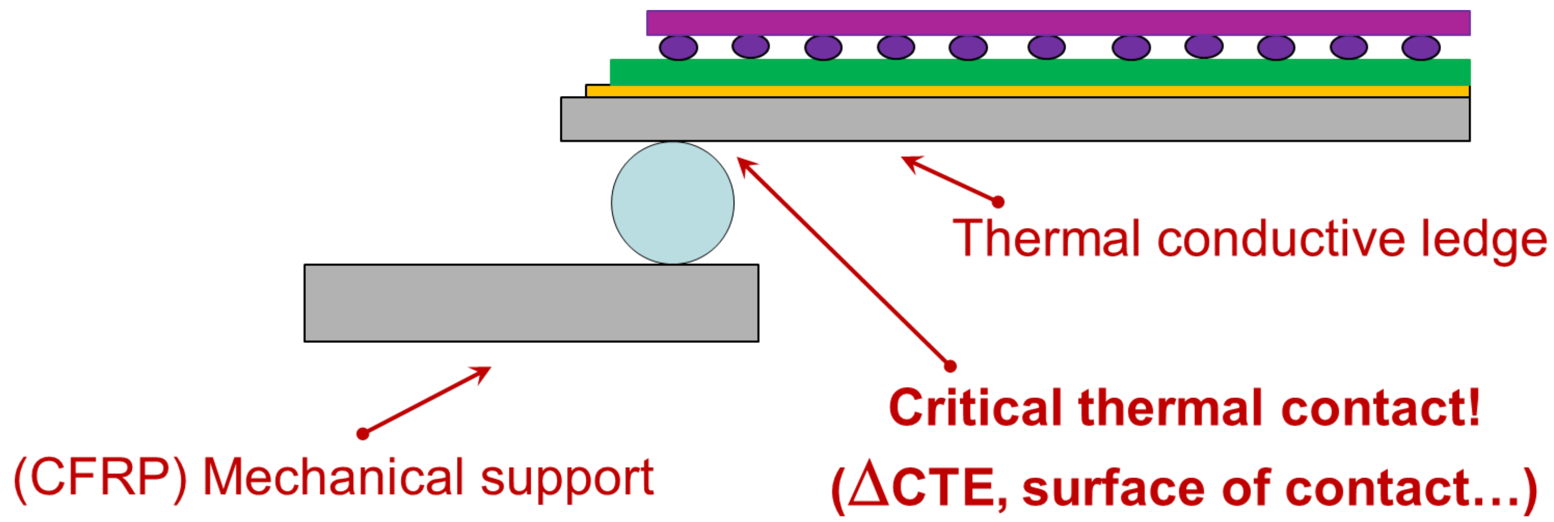


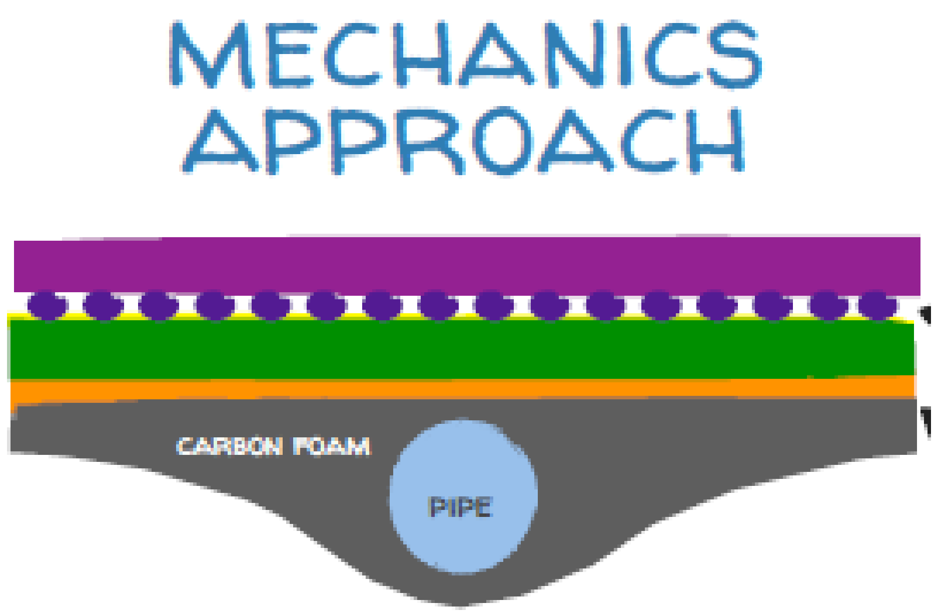
ADDITIONAL POINT
D. Giugni private communication June 2015:
"There are presently indications to about 6.5 ˚C"

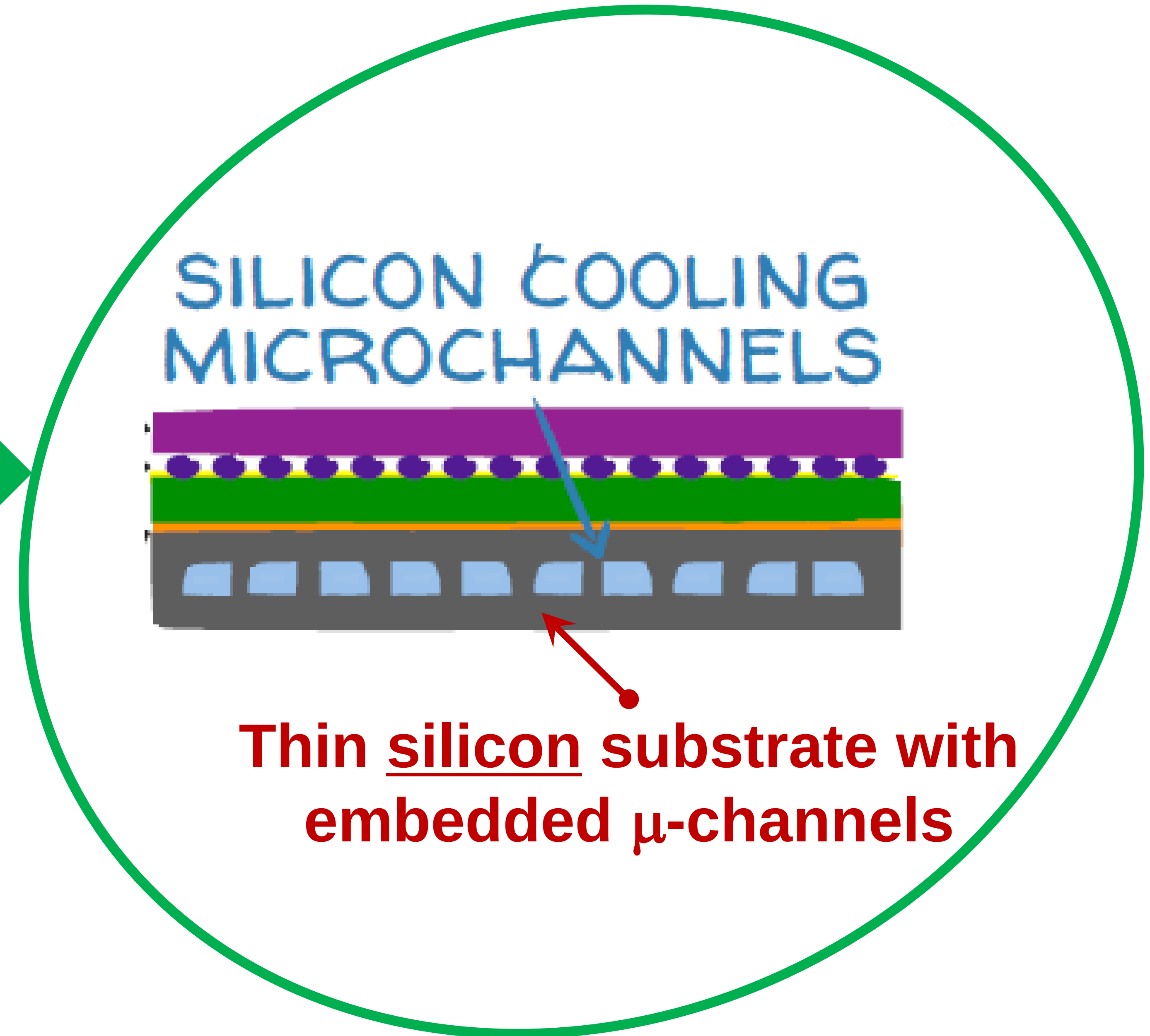


- Defining a "Thermal Figure of Merit" (TFM) as: (ΔT fluid-sensor) / (power density)
- And assuming a 2015 best ΔT of 6.5 ˚C for 0.5 W/cm^2
- One gets a 2015 best TFM performance of 13 [$K\cdot cm^2/W$]
- Asymptotic value…?

Microchannel cooling for HEP:







- Locally distributed cooling where needed
- Large thermal exchange surface
- Minimal path of thermal resistances
- Minimum material budget
- No CTE mismatch
- Radiation hard
- Compatible with "HEP fluids"

(first three items:) = minimal ΔT fluid-surface

What is it “microchannel cooling”?

Technically it means using a **μ-fluidics** device as **heat exchanger** for the thermal management of a heat source

Heat Exchanger Flow Type (examples)	
SINGLE PHASE	**PHASE CHANGE**
water	water (boiling)
HFC / CFC	HFC / CFC
alcohol	CO_2 (R744)
gas	NH_3 (R717)

“μ”-channel -> D_{eq} < 1 mm(*)	
SINGLE PIPE	**MULTI-CHANNEL**
metal	metal
polymer	polymer
glass	silicon
carbon	SiC / Al_2O_3 / SiN / Al_2SiO_5…

HUGE FIELD!

(*) The definition of “micro” channel is per se debatable as, more than to a simple geometrical dimension, it is related confinement effects and to the typical bubble departure size. Therefore it is in principle dependent on the specific fluid selected and the operational reduced pressure. There is no doubt, however, that the cases of interest for HEP detectors fall into the micro-scale word.

Distribution of efforts in μ-fluidics today

Based on a survey of 2014 international events:

Pure academic research / physics: ~43%

- Basic laws / correlations
- Flow properties
- Numerical simulation studies

Bio-medical applications: ~30%

- Cell manipulation
- Lab-on-chip
- In vivo / in vitro diagnostic

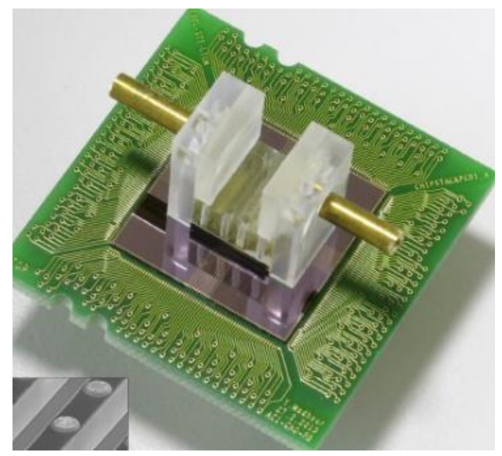
The bio-medical field dominates the "application market":
- Cost driven
- Polymer and glass substrates
- Low pressures
- Micro- or pico-flow rates

Thermal management: ~13%

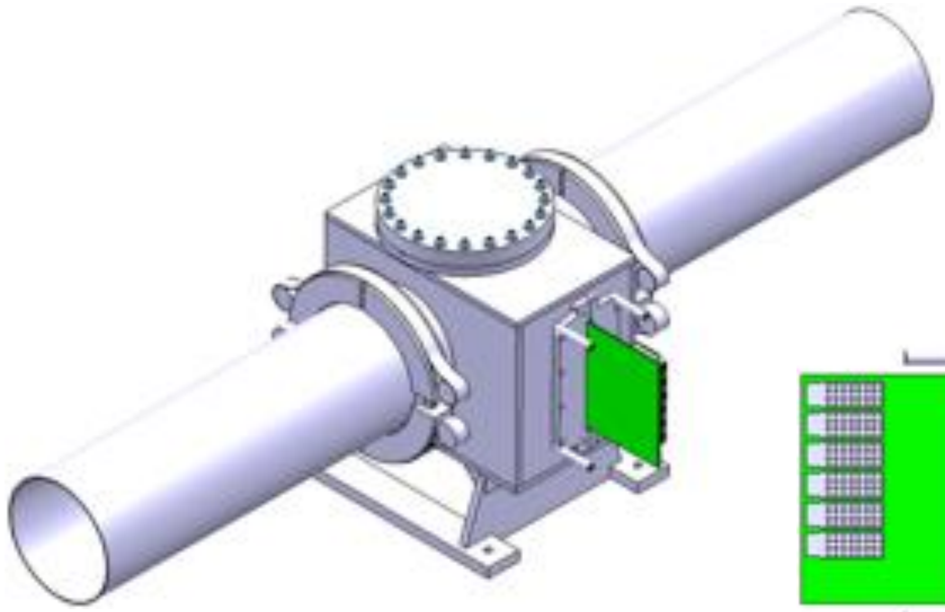
- High power chips
- 3D stacks
- MOEMS / Photonics integrated circuits
- Concentration photovoltaic cells

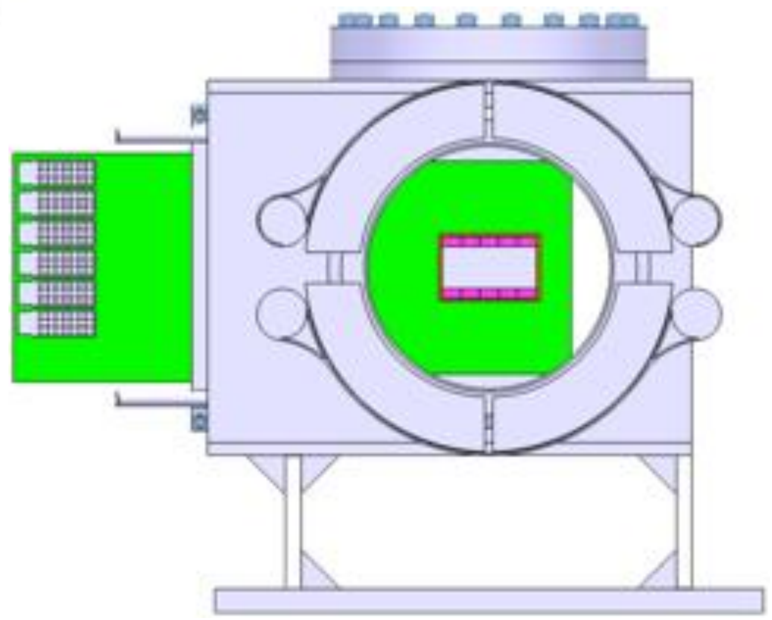
Thermal management applications:
- Focus on very high power densities
- **Time-to-market still long**

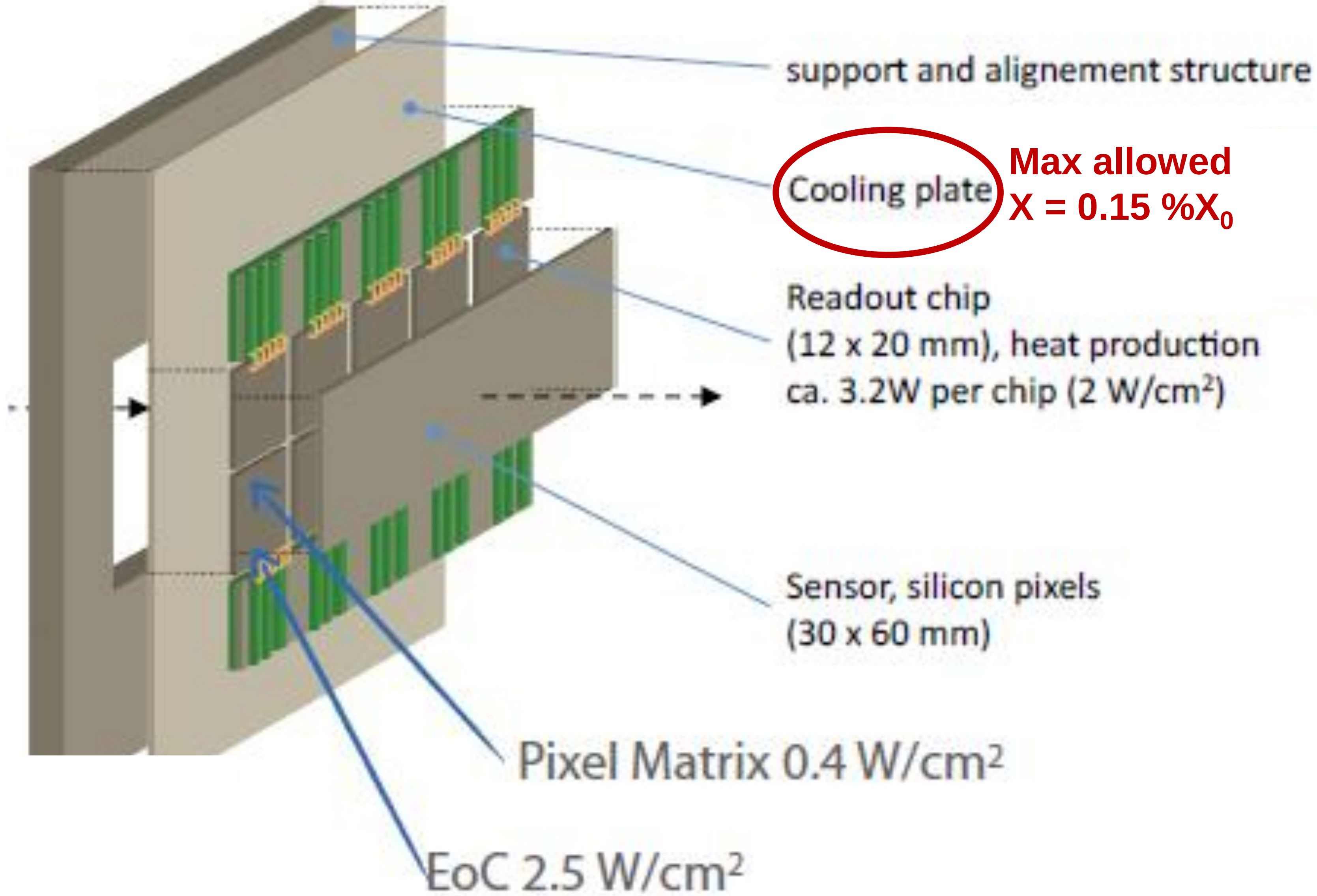
Other applications and technologies: ~14%



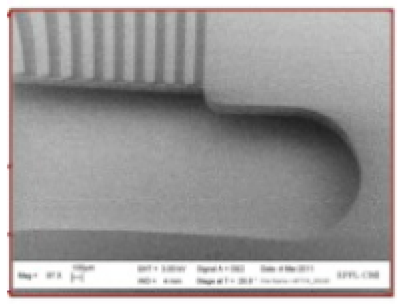
NA62 GTK: first μ-cooled detector



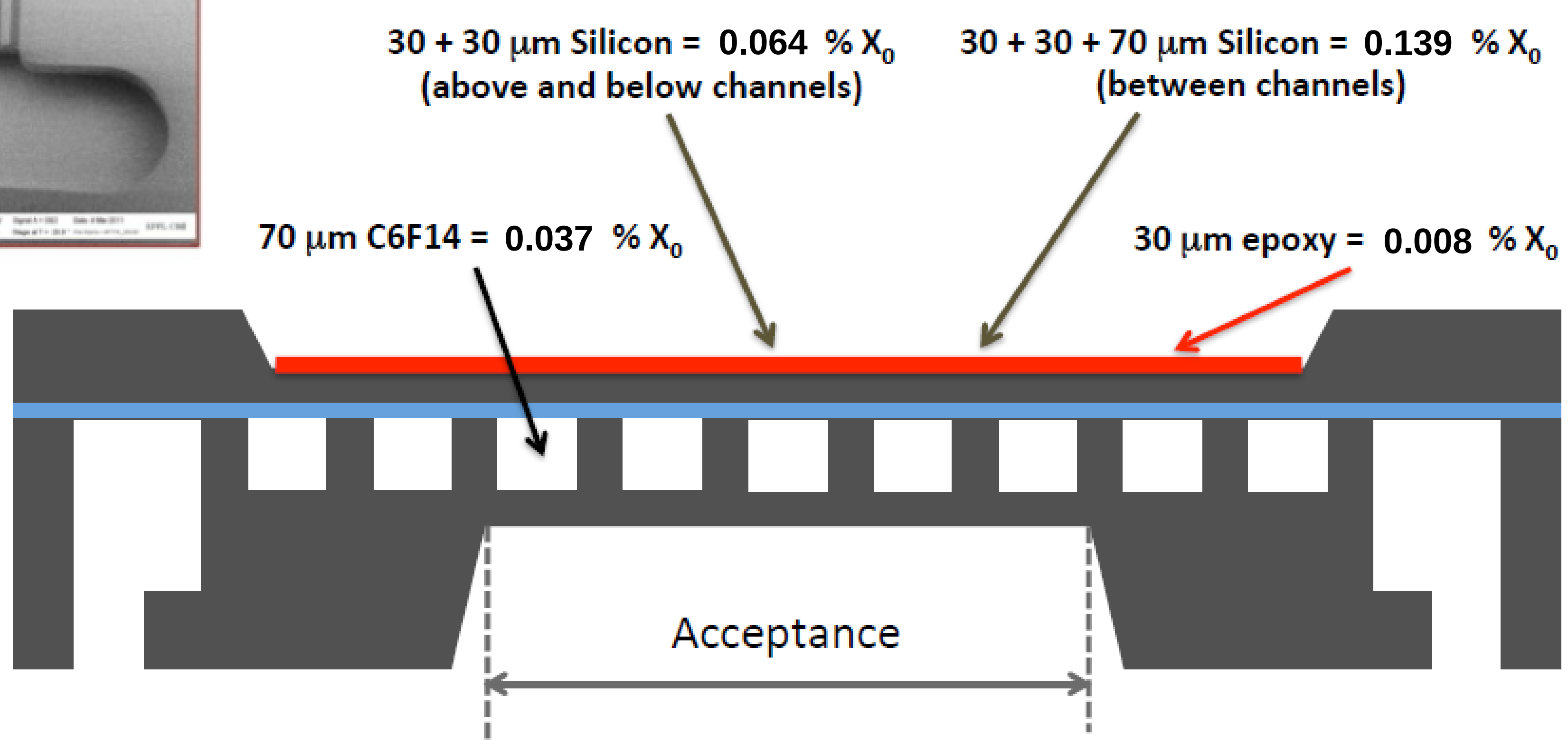




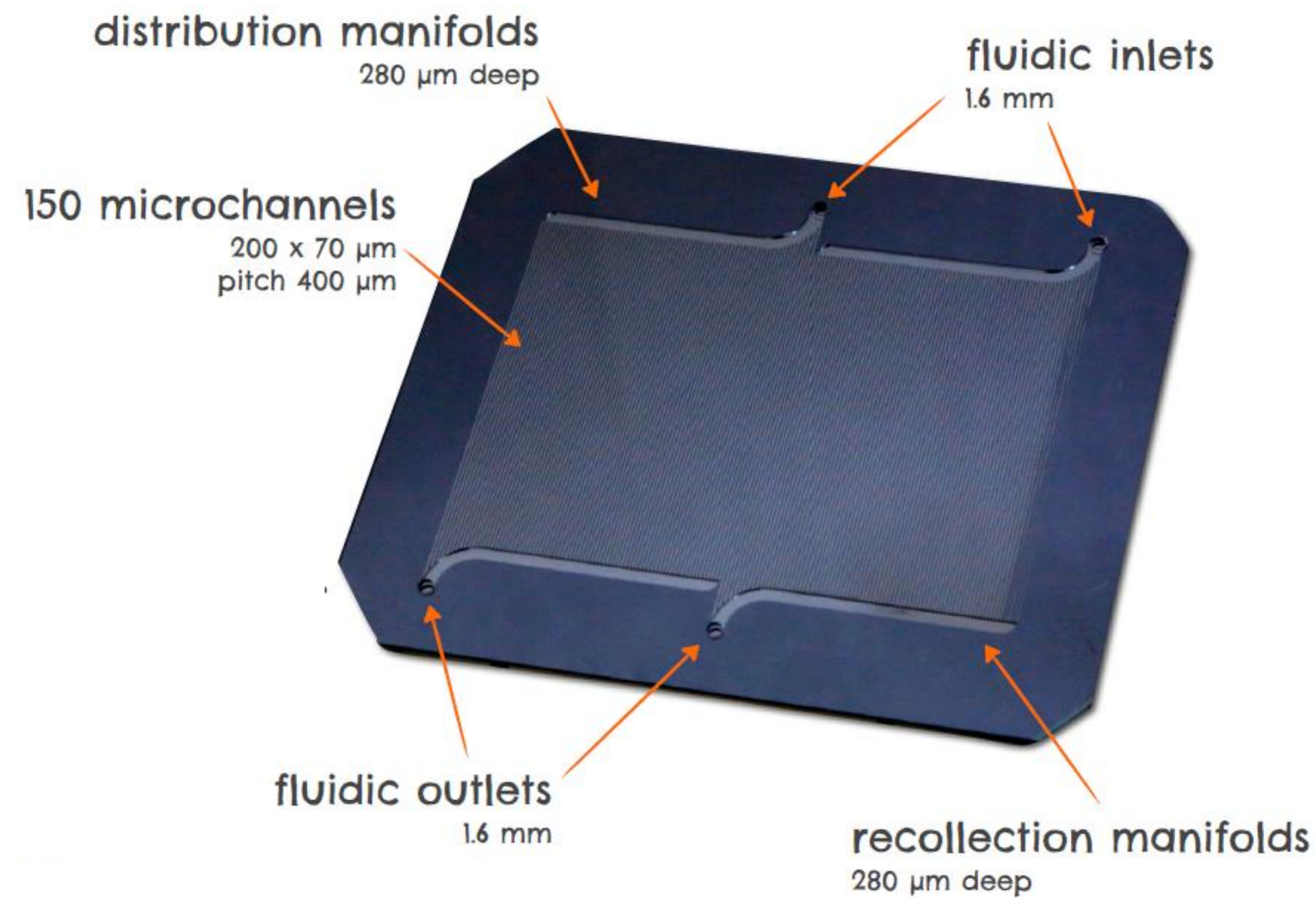
Channels = 200 x 70 μm
Wall thickness = 200 μm
Cover thickness = 30 μm



Final cross section of the **full silicon device**

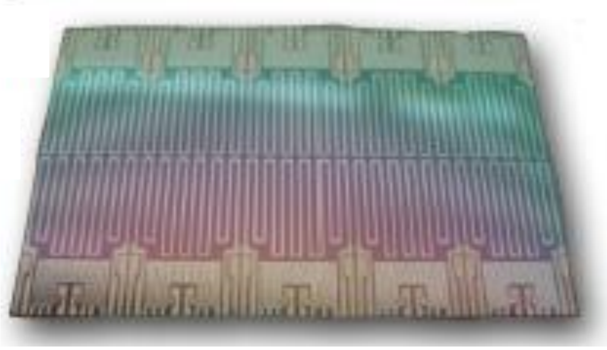


Total material budget in the acceptance area = 0.13 % X_0
(min 0.11 % - Max 0.15 %)



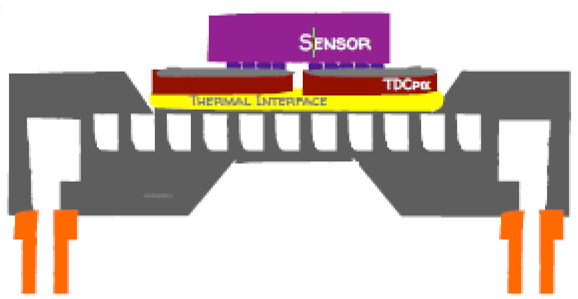
NA62 GTK: first μ-cooled detector

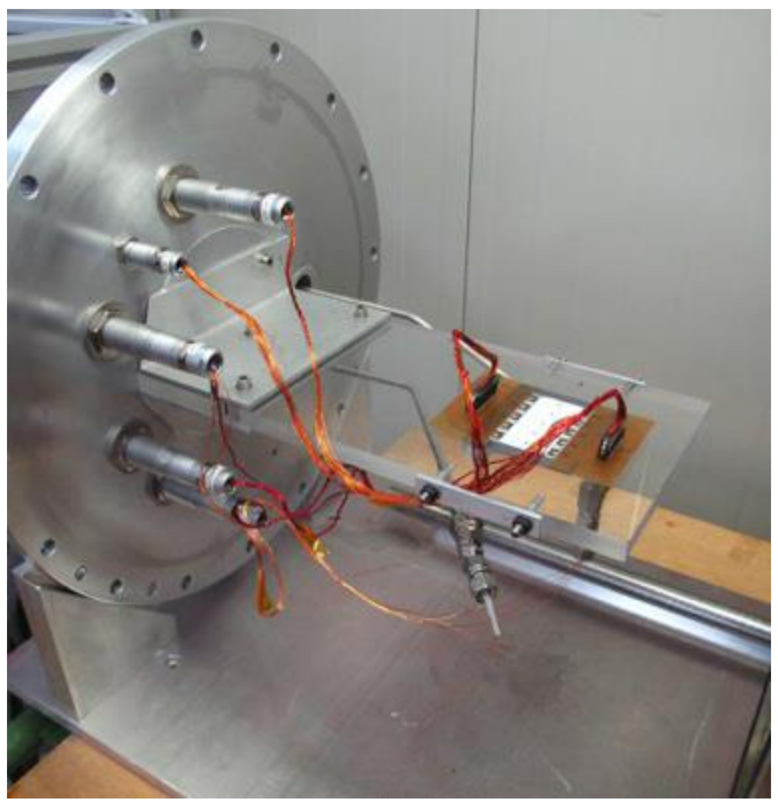
Sensor Dummy
200 μm thick Si



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

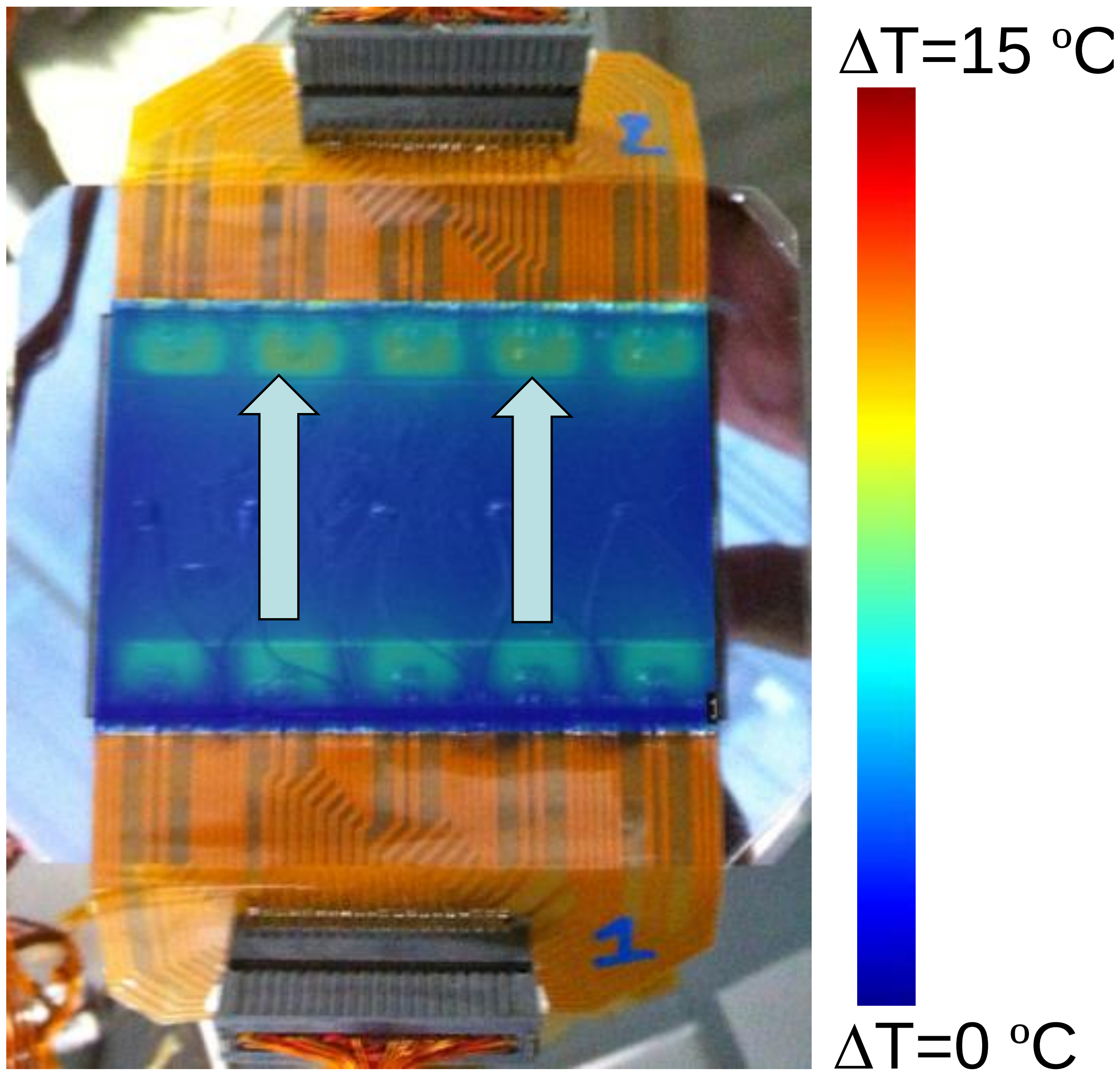
Performance verified both in vacuum and in ambient air through 1:1 scale Si dummies of both sensor and TDCPix chips, from nominal conditions up to worst-case scenario.



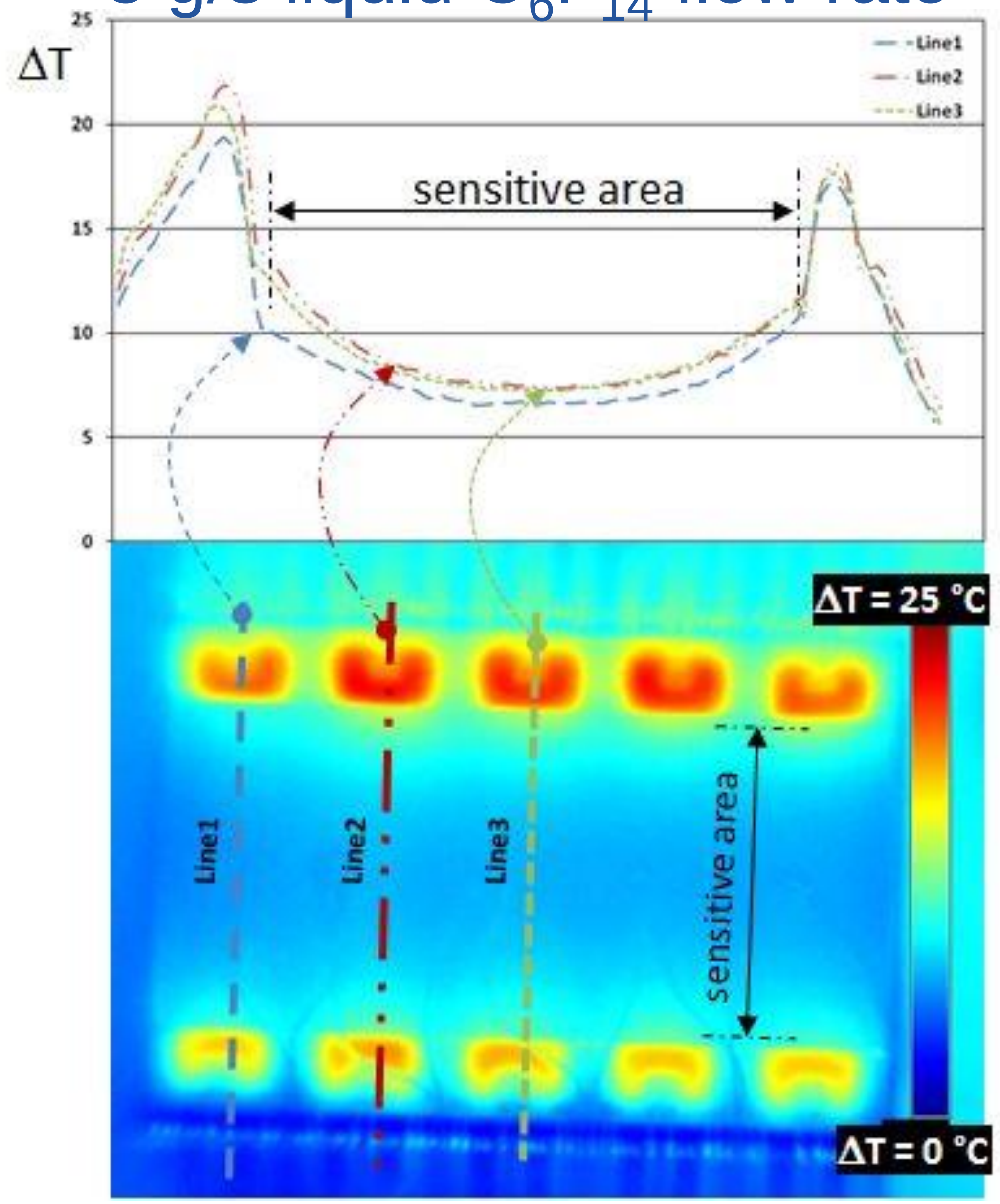


A.Francescon et al: *Application of micro-channel cooling to the local thermal management of detectors electronics for particle physics*,
Microelectronic Journal, Volume 44, Issue 7, July 2013, Pages 612–618

Nominal conditions:
- 20 W on ROC (~ 3 W/cm²)
- 4 W on Pix Matrix (~ 0.25 W/cm²)
- 8 g/s liquid C_6F_{14} flow rate



Worst case scenario:
- 38 W on ROC (~5.5 W/cm²)
- 10 W on Pix Matrix (~ 0.6 W/cm²)
- 8 g/s liquid C_6F_{14} flow rate

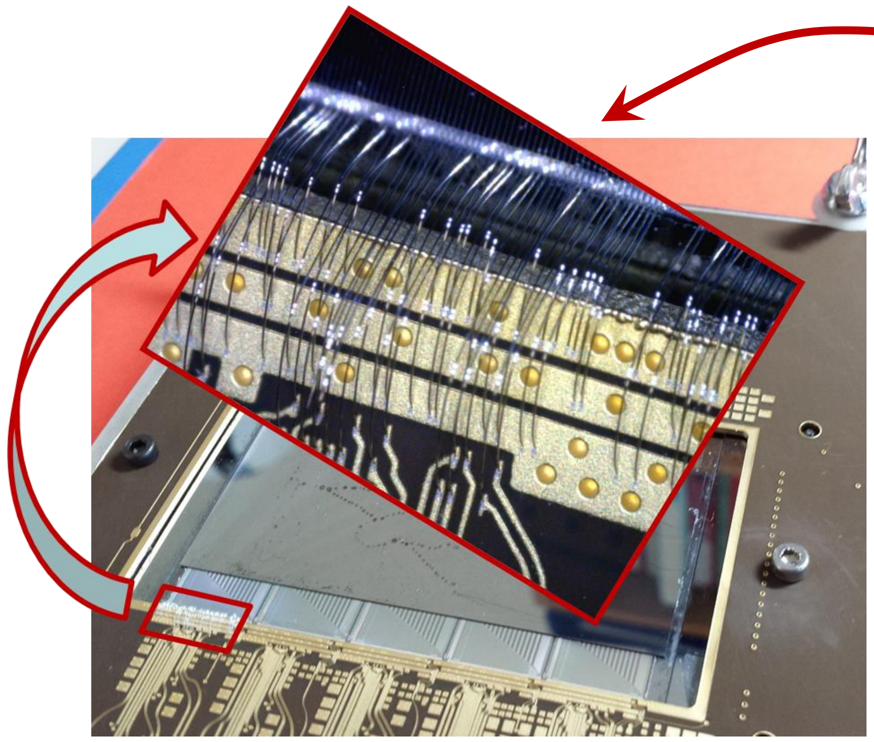


"ΔT" = (Surface T - Inlet Fluid T) ; (h~2500 W/m²K)

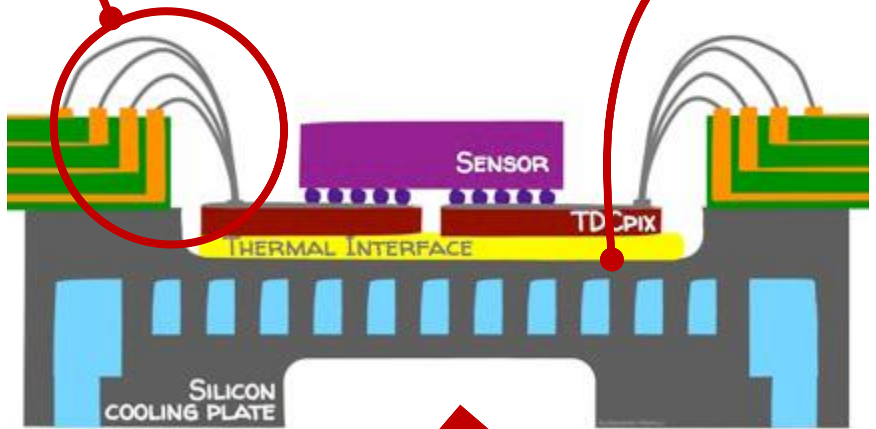
NA62 GTK: first μ-cooled detector

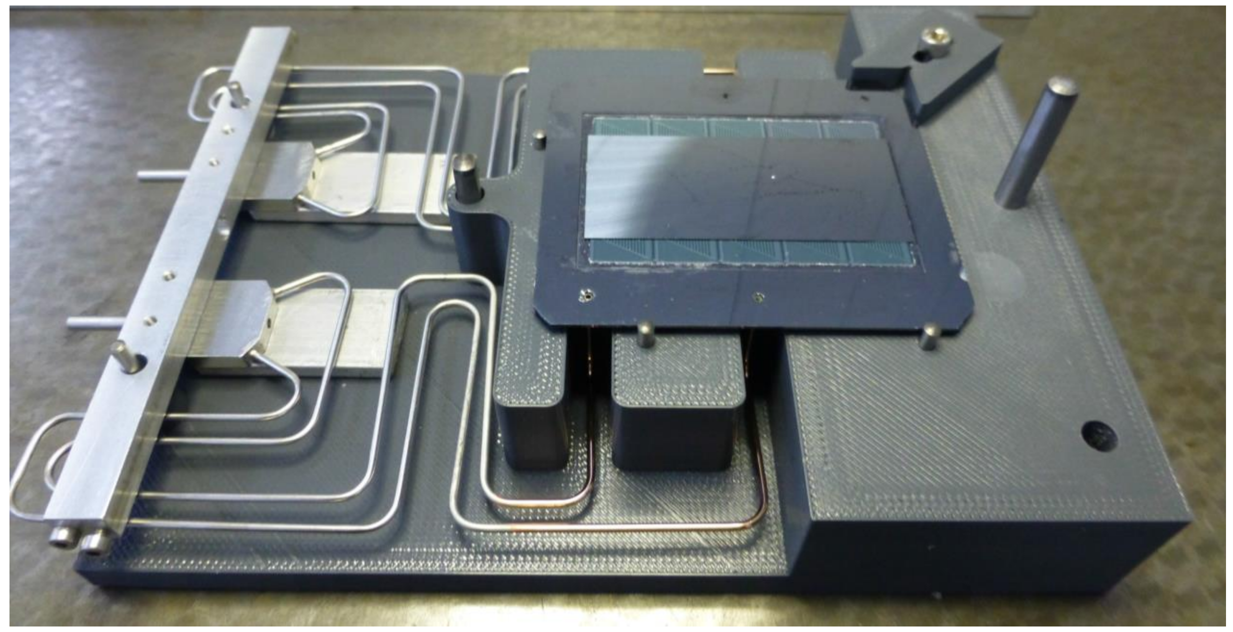
Integration far from trivial and requiring several jigs

(more than shown…)

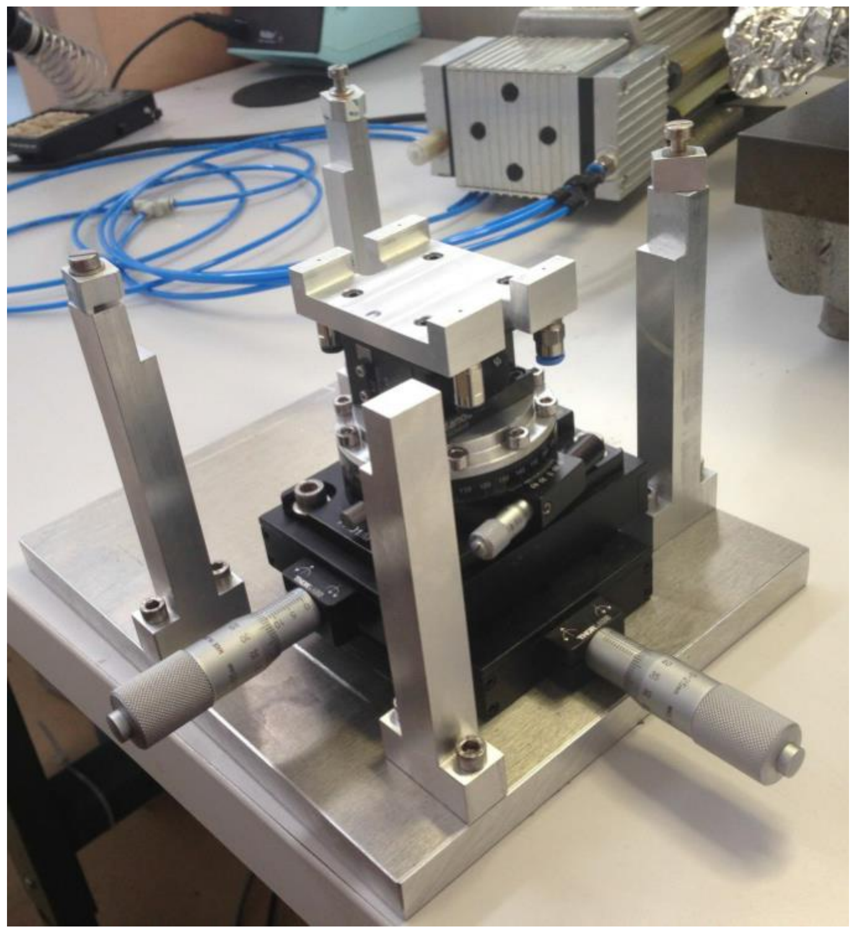


Chip to PCB wire bond



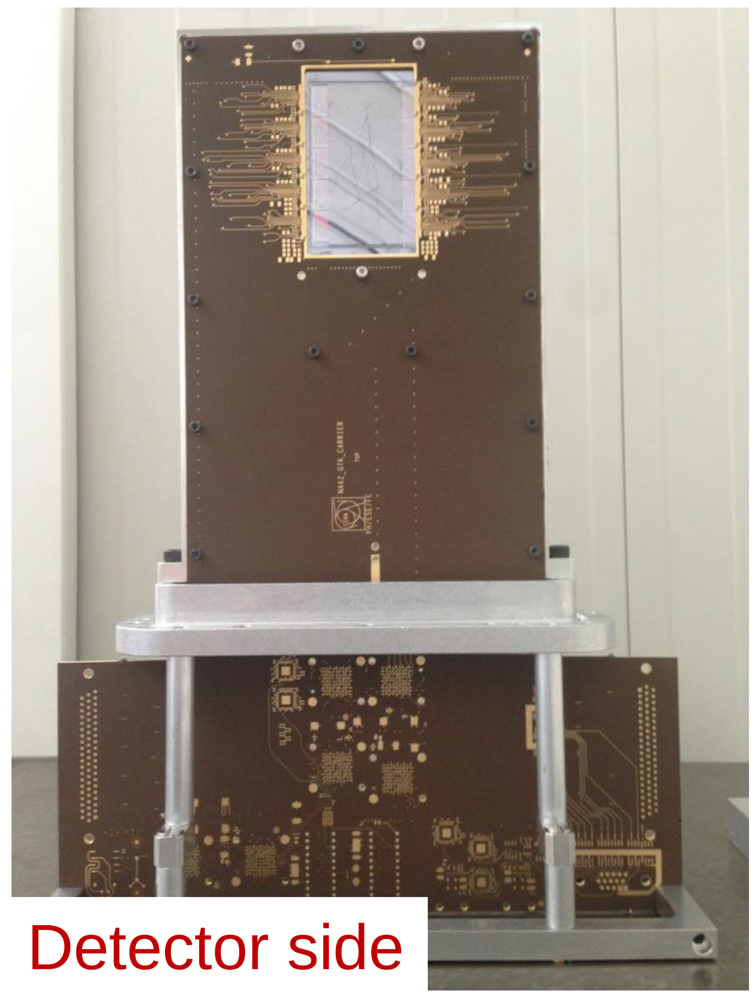


Jig for precision gluing of detector on pre-equipped μ-channel device



Jig for assembly on PCB & wire bond alignment

Cold-plate side



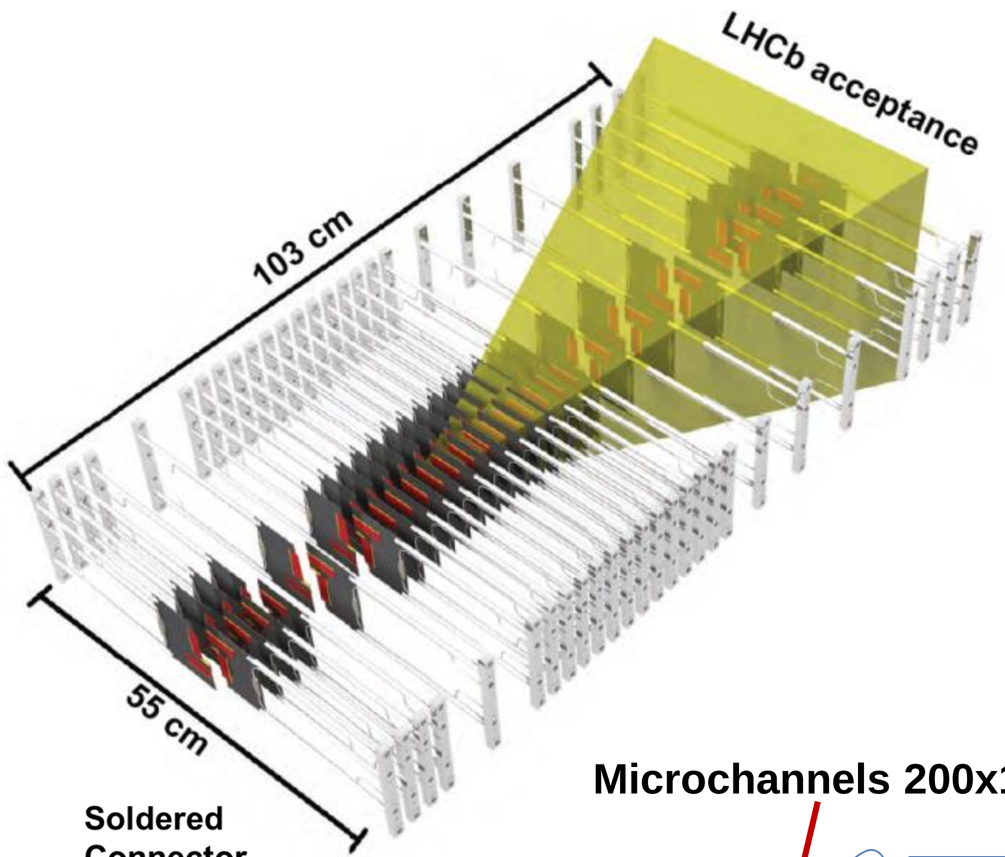
Detector side

G.Romagnoli et al: *Silicon micro-fluidic cooling for NA62 GTK pixel detectors*, Microelectronic Engineering, Volume 145, 1 September 2015, Pages 133-137

NA62 GTK: first μ-cooled detector

operation of 3 modules in the experiment since Oct. 2014

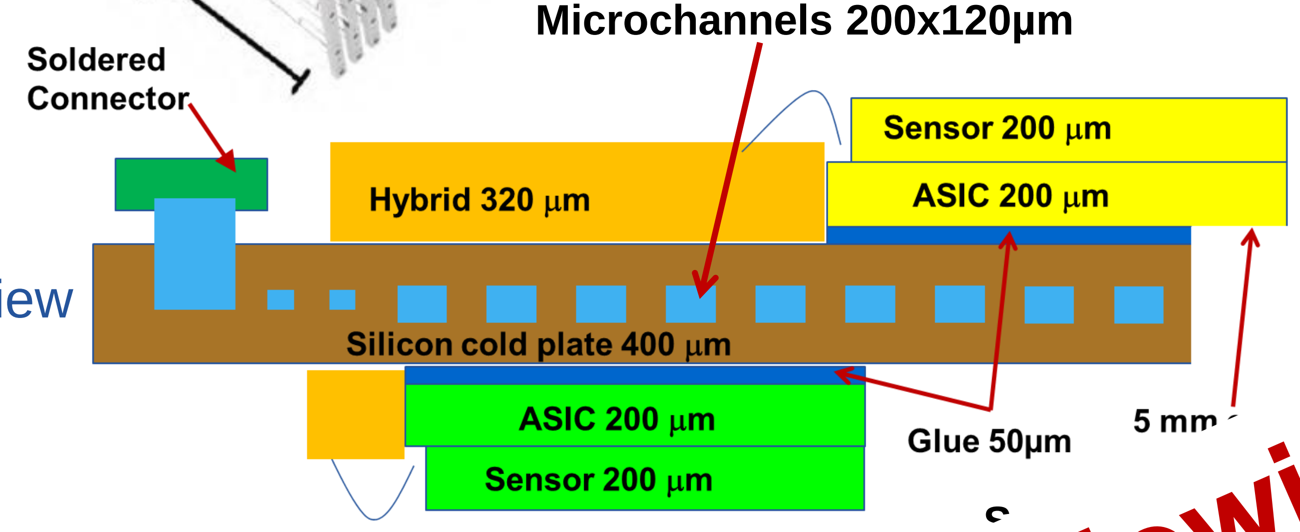
LHCb VELO: μ-cooled phase-I upgrade



VELO 2018 upgrade:

- high radiation environment (~5 10^15 n_{eq}/cm^2)
- silicon sensor temperatures < -20° C
- hybrid pixel detector power densities ~ 1.5 W/cm^2
- 2 rows of 26 modules each
- First application of μ-channel cooling with evaporati… CO_2 !

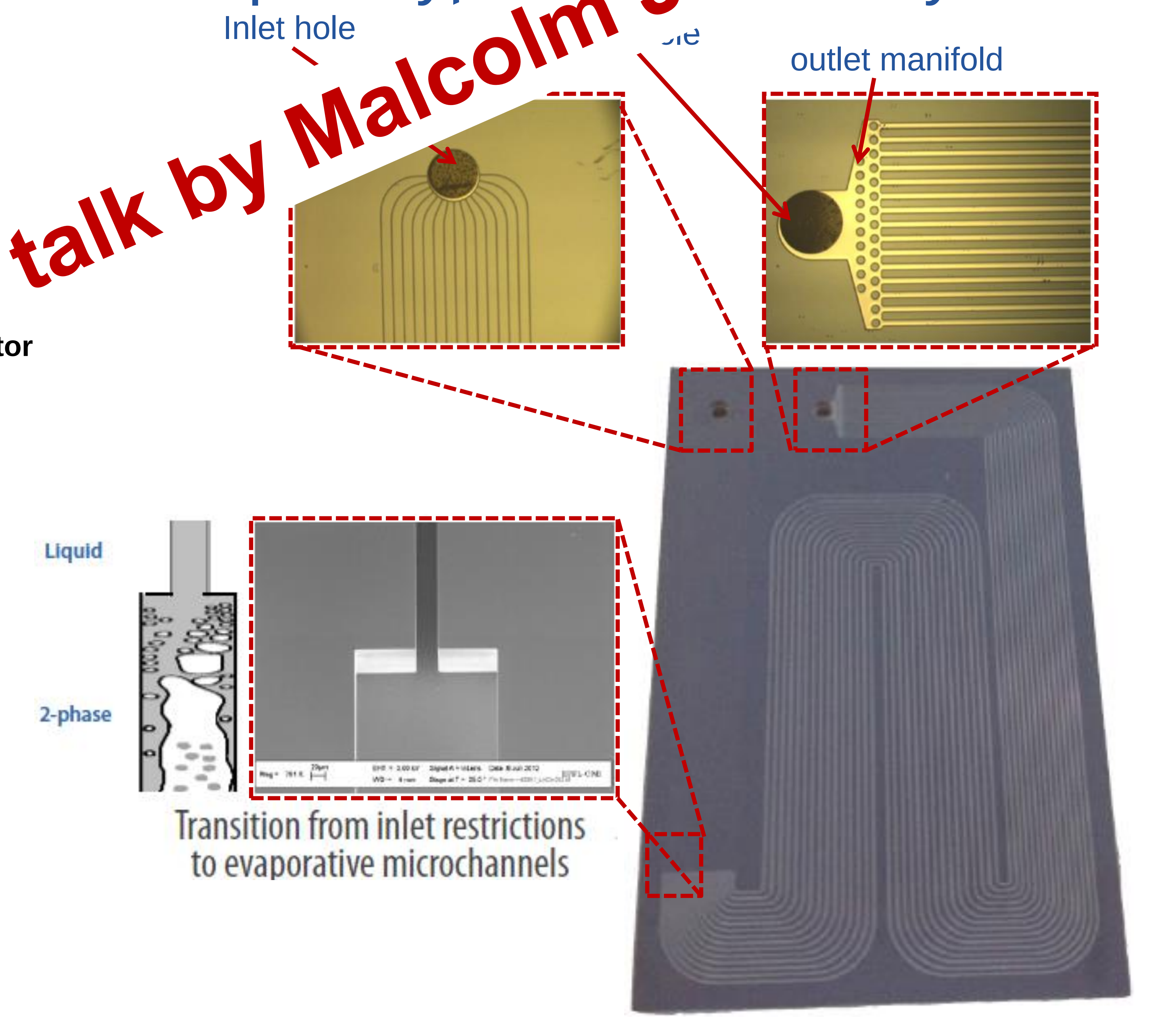
Side view



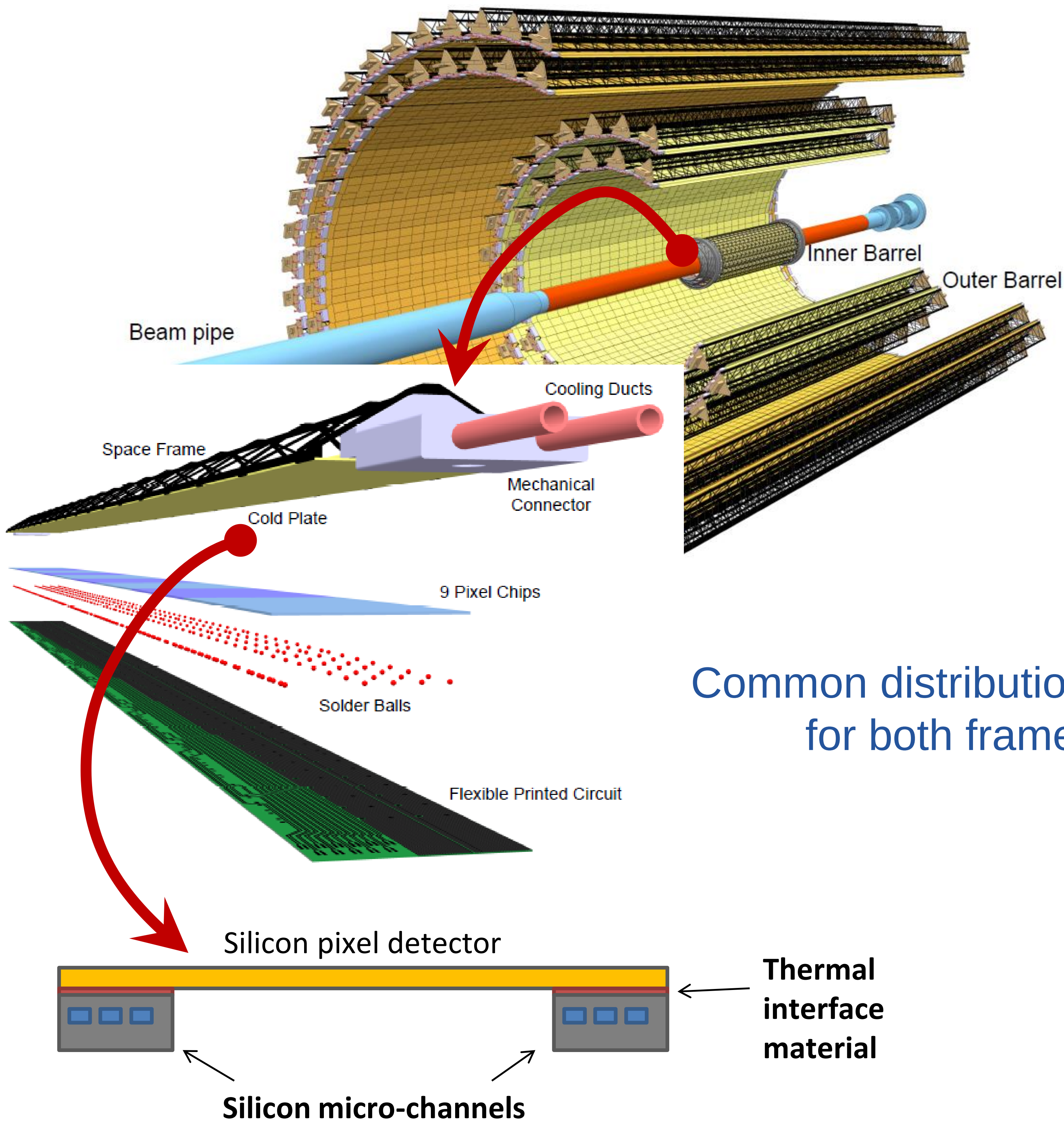
Front view

Details in the following talk by Malcolm John

First prototype f… …inary studies



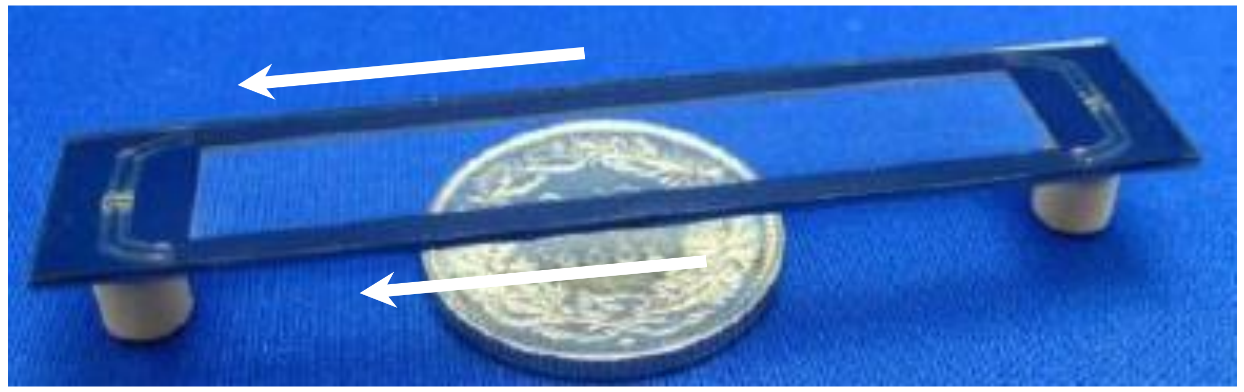
ALICE ITS: μ-cool alternative for upgrade



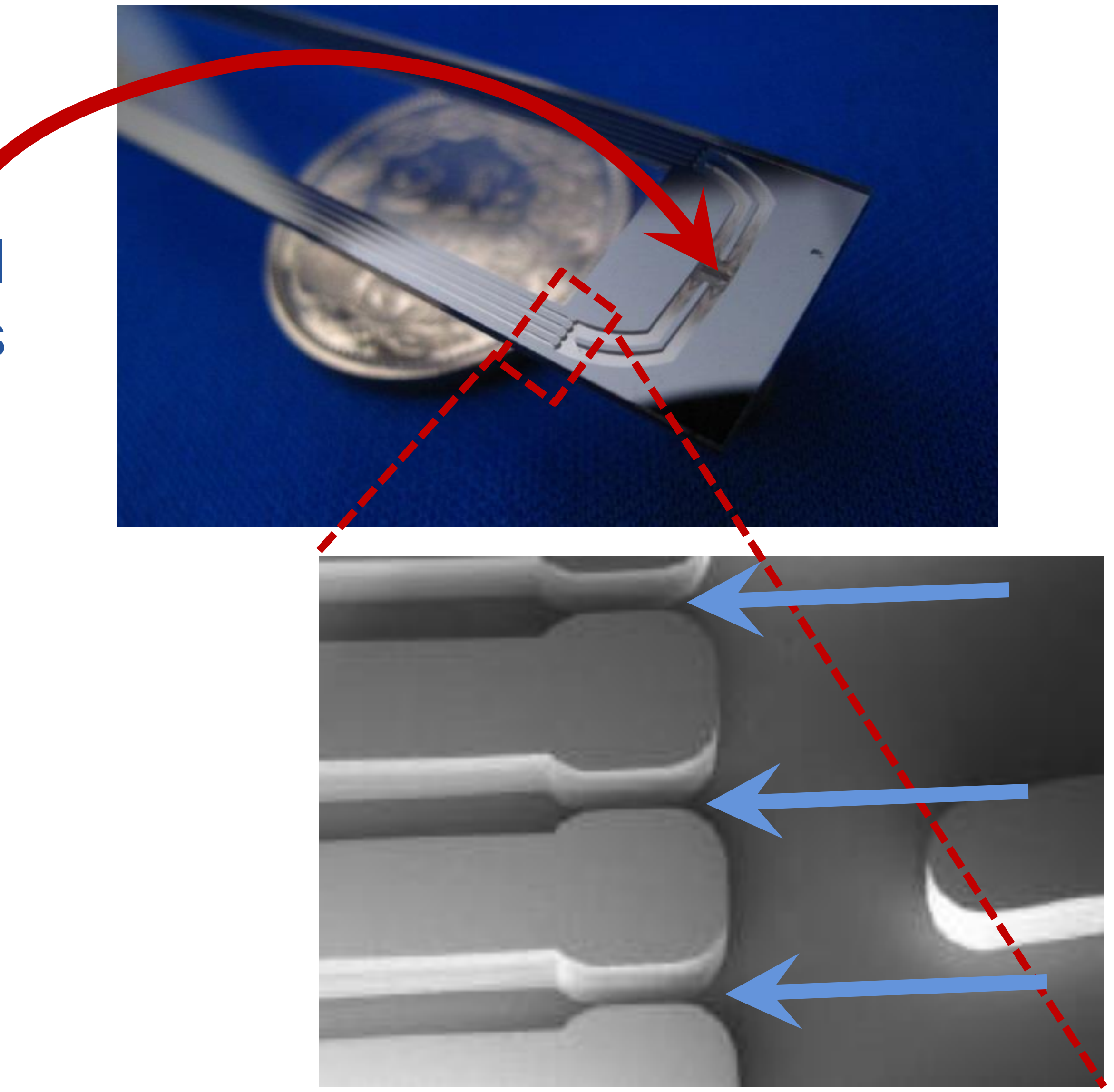
«Frame» design for microchannel device proposed:

- eliminates any material contribution in the central region of the sensor.
- higher power dissipation of the chip at the edges of the pixel

First μ-fabricated frame proto for preliminary tests with 2-phase (evaporative) C_4F_{10}



Common distribution manifold for both frame branches



Restrictions at the inlet of the channels stabilize the two-phase flow avoiding back-flow and non-uniform distribution

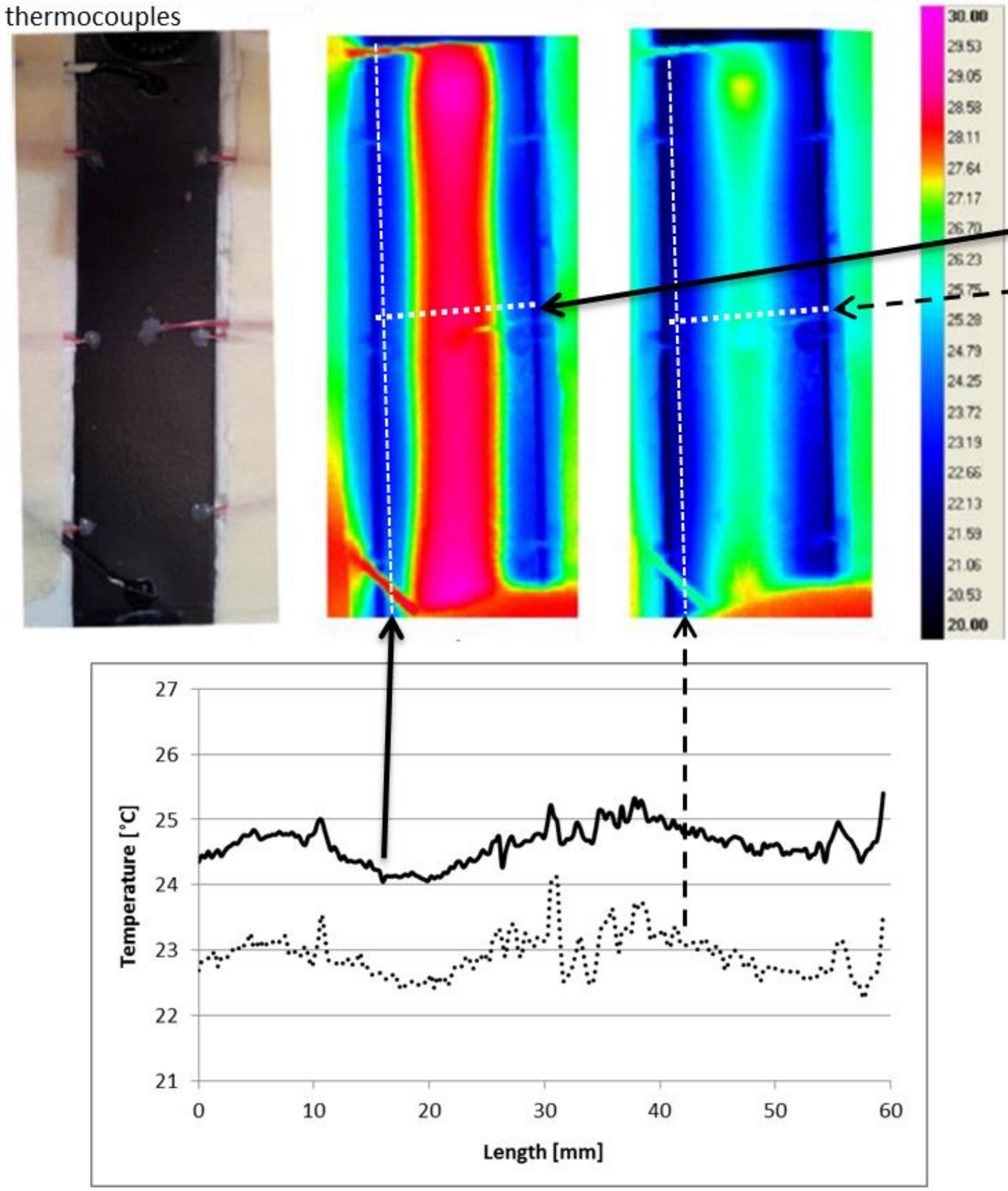
ALICE ITS: μ-cool alternative for upgrade

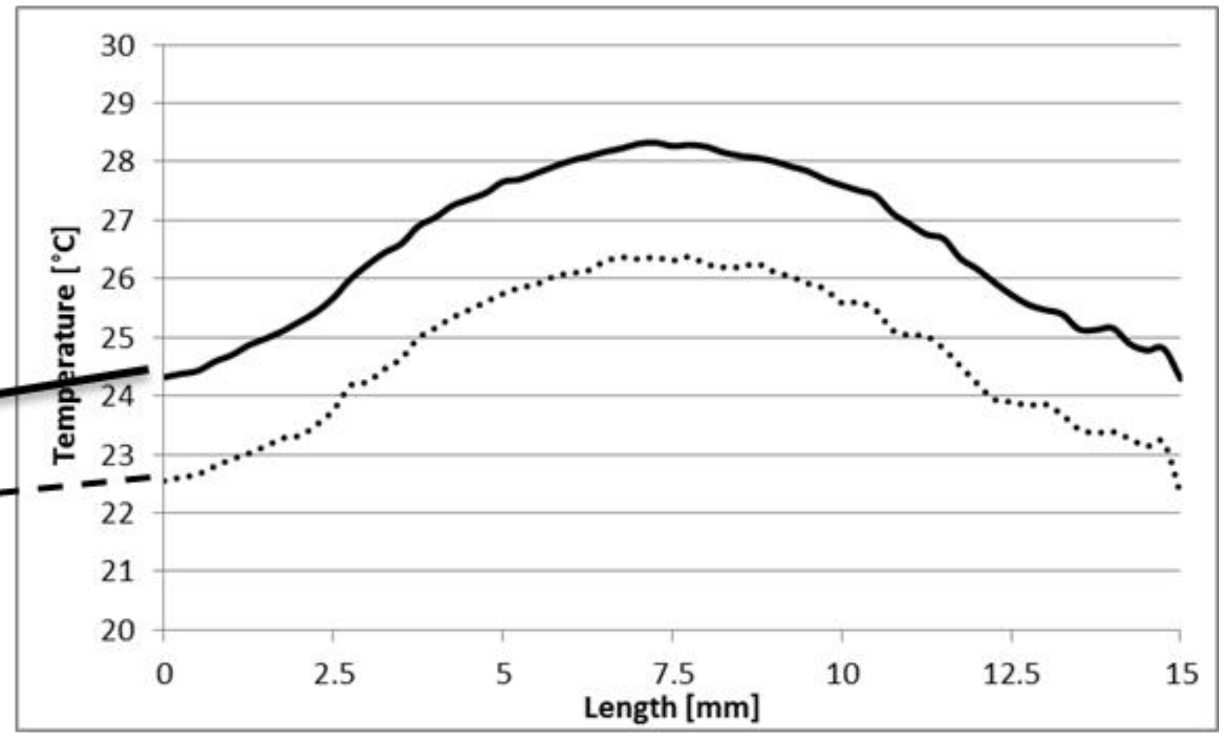
Preliminary measurements on single frame with P=0.3W/cm^2 uniformly distributed on the detector surface

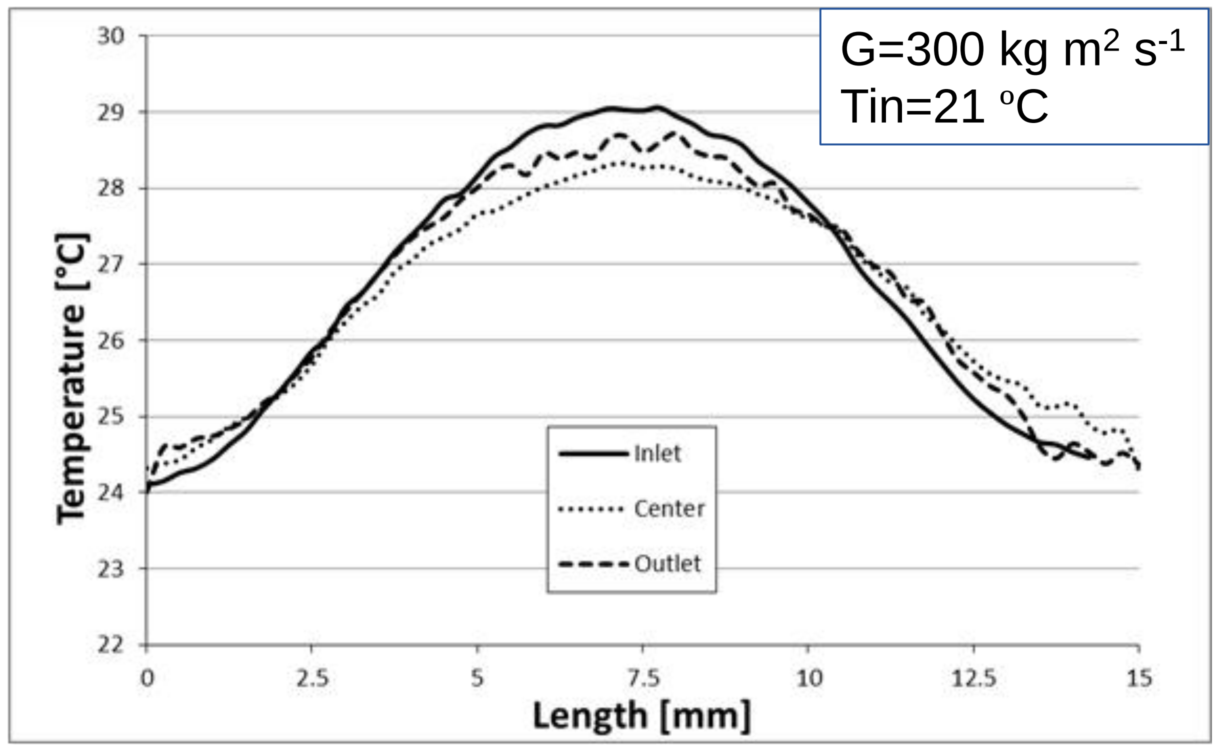
Dummy chip top surface with two electrodes and seven thermocouples

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

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







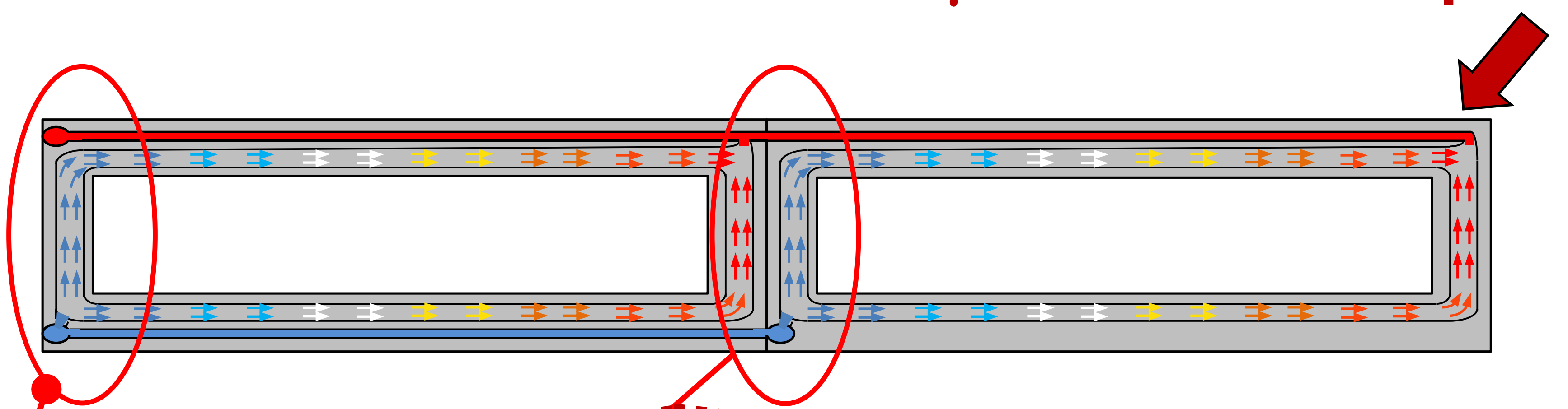
Very high efficient thermal management.
Very well in-spec (T_{max}<30 °C / ΔT_{sensor}<5 °C) even with uniform power distribution and T_{sat} well above the 15 °C cavern dew point

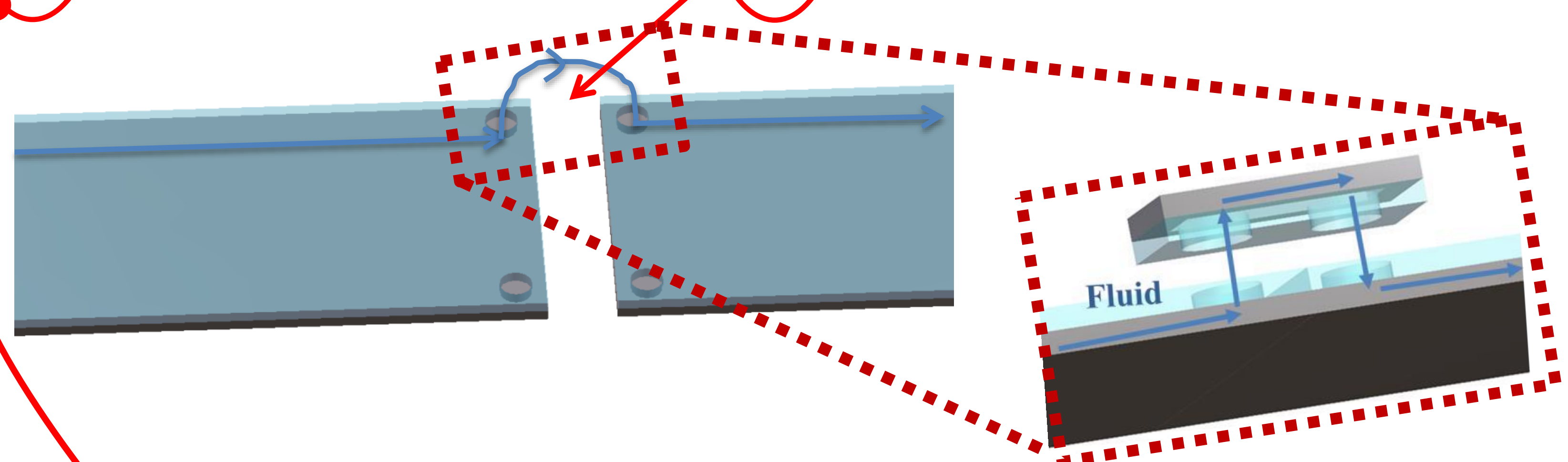
ALICE ITS: μ-cool alternative for upgrade

OK for one device: how to equip a full stave?

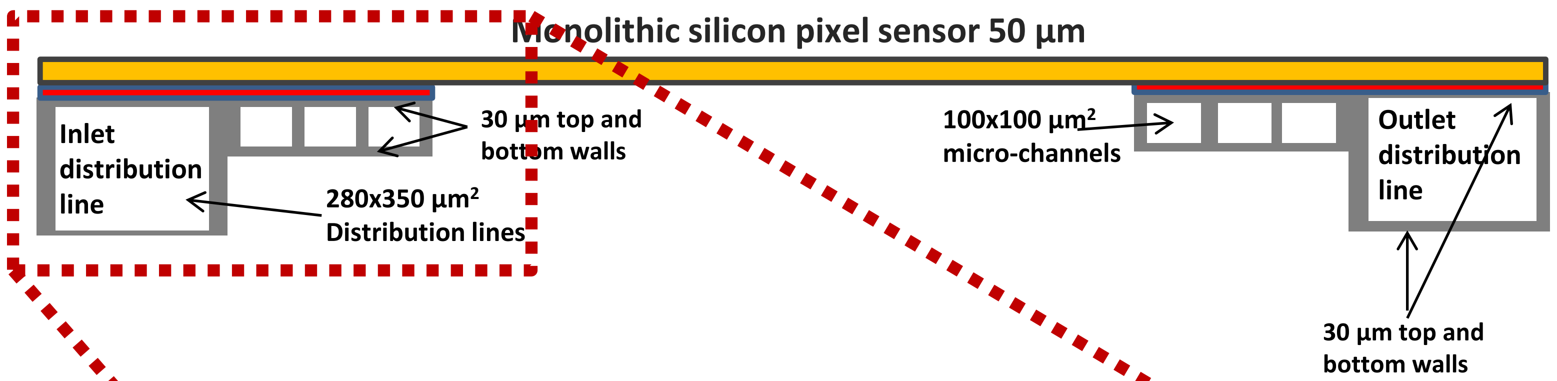
- Silicon μchannel devices are limited in dimensions by the diameter of the wafer used as μfab substrate.
- We use 4” wafers for prototyping, but outsourced fab tests on 6” wafers are on-going.
- Even using 8” wafers it would still not be possible to reach the length of the ITS inner layers stave.
- Using larger wafers would lead to a device very hard to handle during the following integration steps.

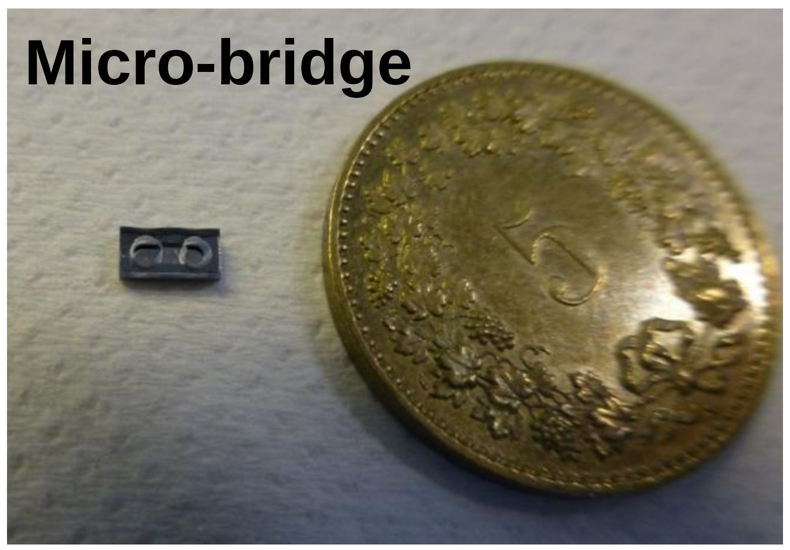
Interconnection of several μ-devices incorporating fluid distribution and recollection lines

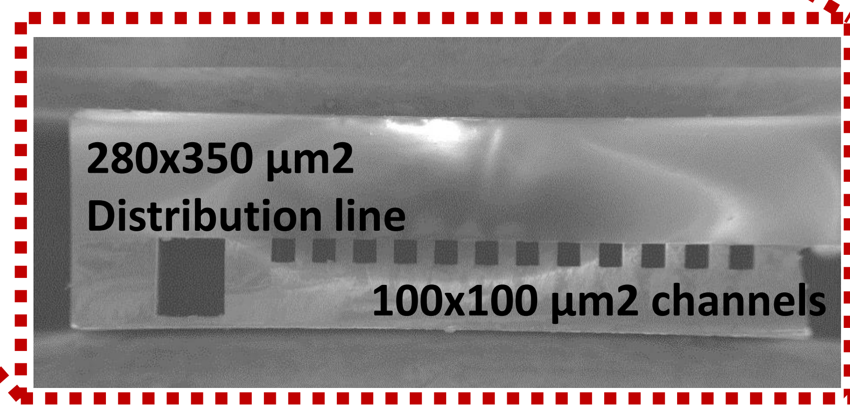




Redesigned frame concept for interconnected configuration





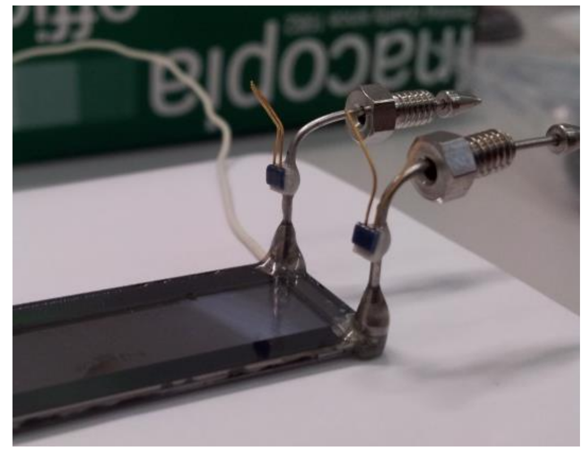


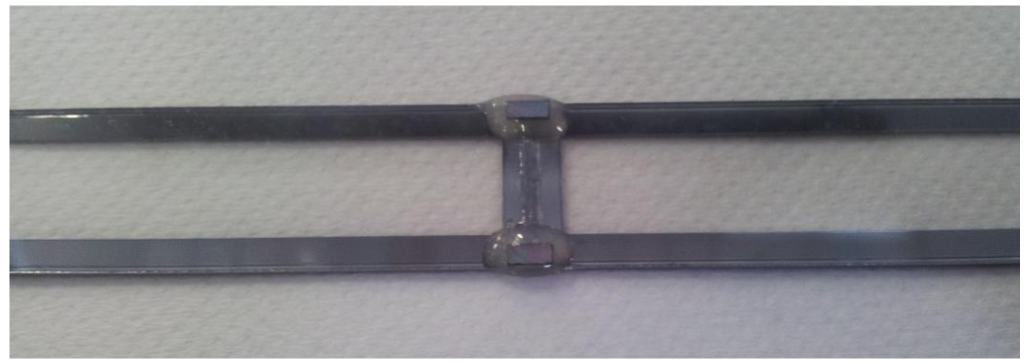
Device before thinning

ALICE ITS: μ-cool alternative for upgrade

Preliminary measurements on a 270 mm stave with $P=0.1 W/cm^2$ uniformly distributed on the detector surface

Stave equipped with dummy sensors (heaters)



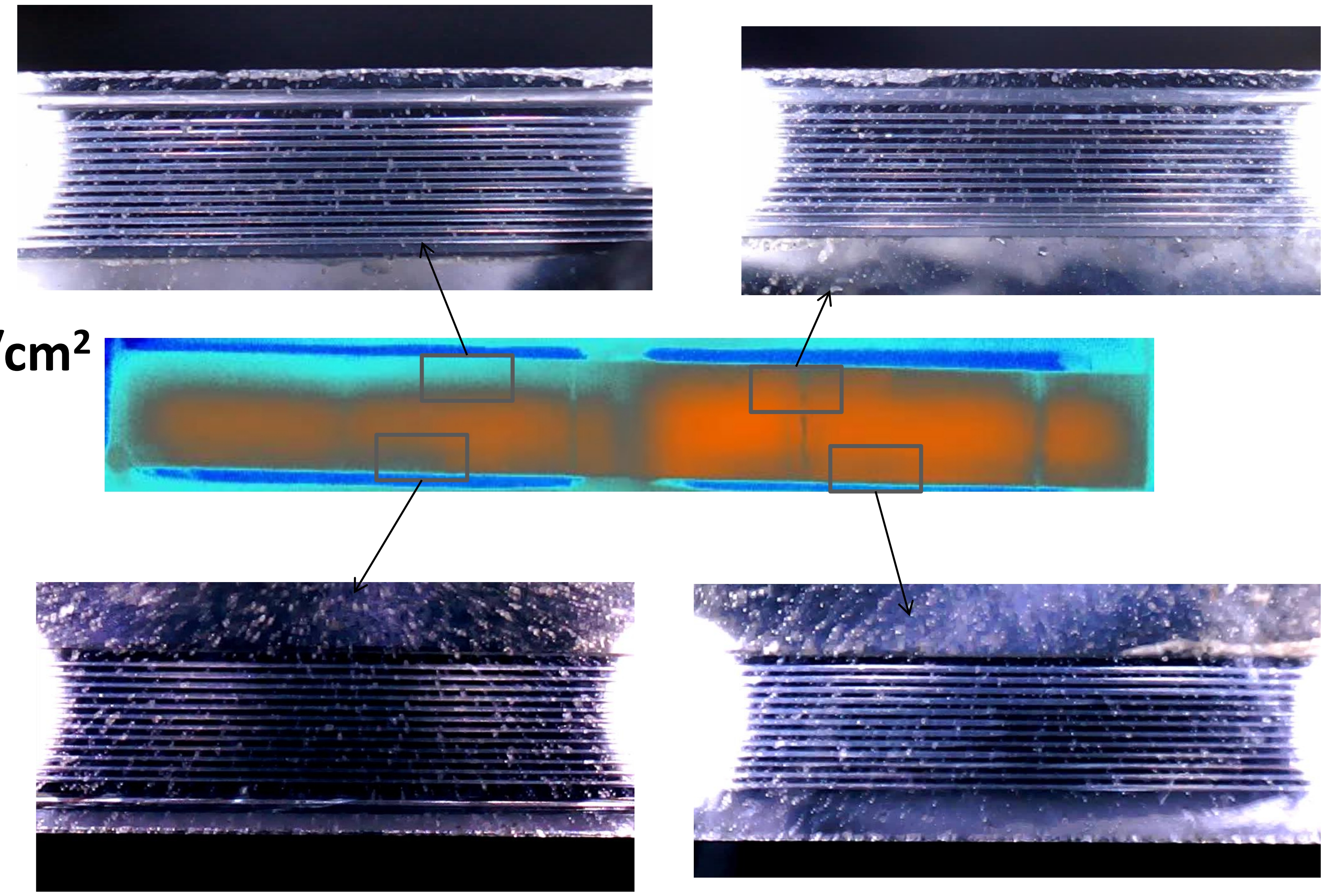


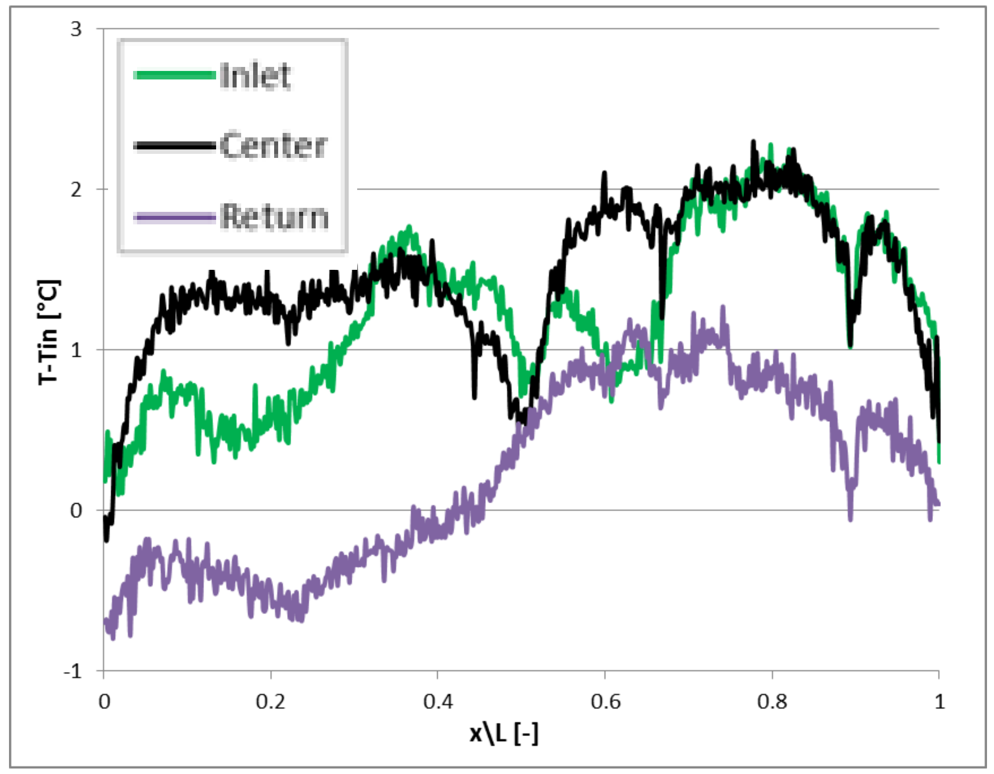
Bridges aligned and glued in place

$q_{chip}=0.1\ W/cm^2$

$\dot{m}=0.05\ g/s$

$T_{in}=23.2\ °C$





Longitudinal temperature profiles (ΔT fluid-surface)

Note the T drop in the return line

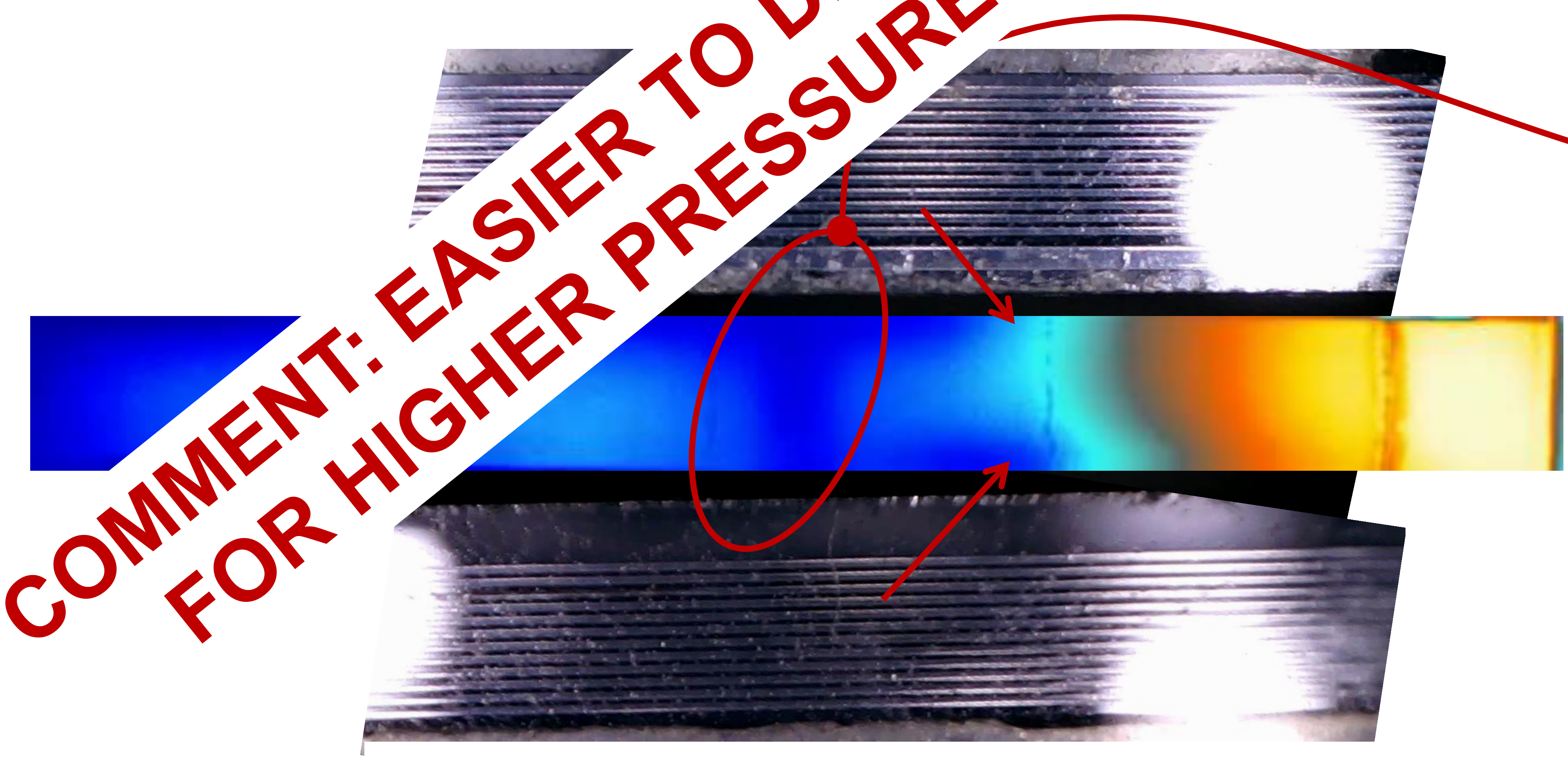
ALICE ITS: μ-cool alternative for upgrade

Tricky issues with 2-phase flows

For certain conditions (still under investigations) the flow is not equally distributed between the two frames: most of the fluid crosses the first frame while the remaining fluid rapidly dryout in the middle of the second frame.

Further investigations on this issues are on-going and enhanced design of the micro-evaporator has been adopted on the basis of pressure optimization in liquid-phase CFD simulations (in retrospective a few “stupid” errors in fluid dynamics design were still present in this second version) fabrication of the new evaporators is ongoing.

COMMENT: EASIER TO DESIGN FOR HIGHER PRESSURE



Due to an excessive pressure build-up in the distribution manifold and line of the 2nd device (already in two-phase), most of the fluid is distributed to the first device. Only a minor portion of fluid enters the second device, where it quickly reaches the dry-out conditions

A.Francescon et al: *Development of interconnected silicon micro-evaporators for the on-detector electronics cooling of the future ITS detector in the ALICE experiment at LHC*, MNF 2014 (London), accepted for publication in Applied Thermal Engineering (2015)

ALICE ITS: μ-cool alternative for upgrade

Tricky issues with 2-phase flows

Only high speed direct observations can provide adequate insight on fundamental features like nucleation sites, flow regimes and unexpected instabilities.
One example…

Boiling_9W_inlet_20150424_Reduced.wmv

High Speed Camera movie taken in Padova. Courtesy of A. Francescon

Compatibility of CO_2 with μ-channels

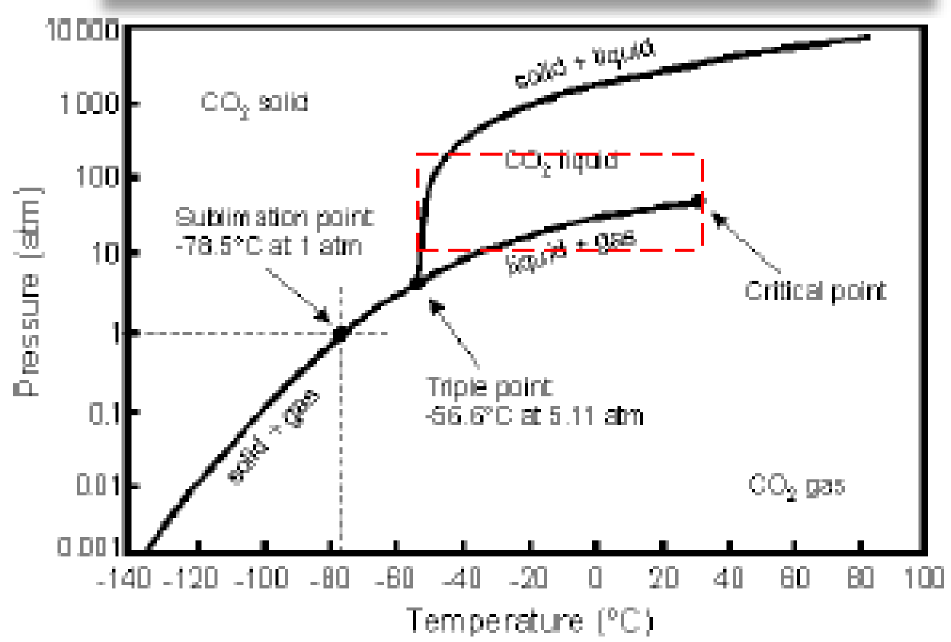
The CO_2 thermo-fluid properties are actually a problem solver!

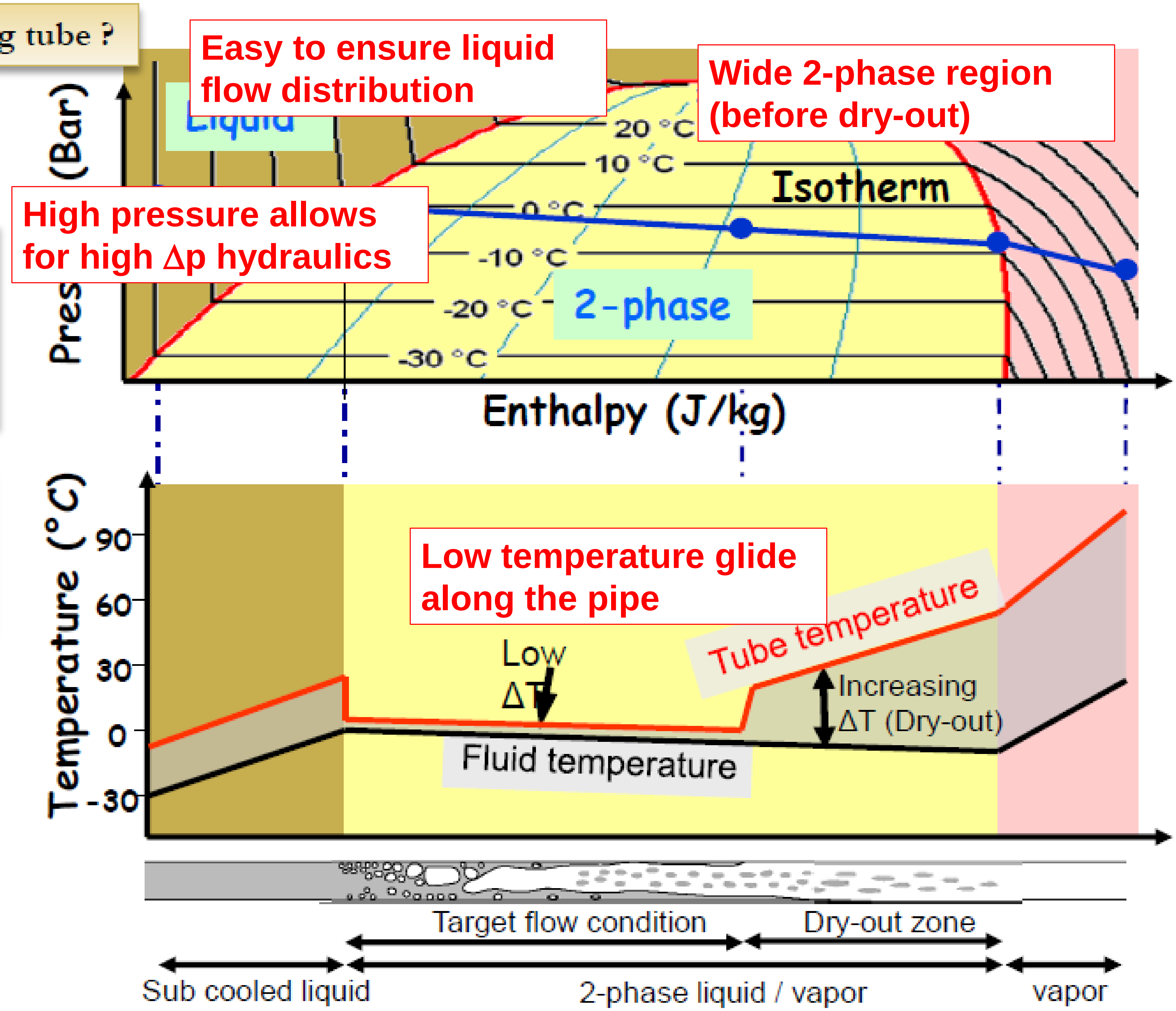
What happens inside a cooling tube ?

CO_2 is boiling

- CO_2 absorbs heat from environment to raise its enthalpy (internal energy).
- this happens at nearly constant temperature.

Temperature is defined by pressure.
-56 C < T < +31 C
5 bar< P < 73 bar



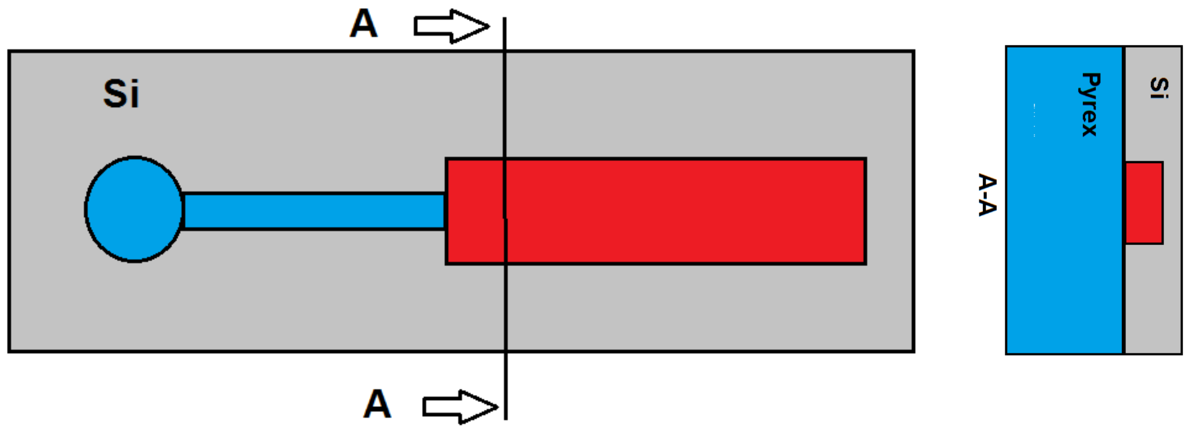


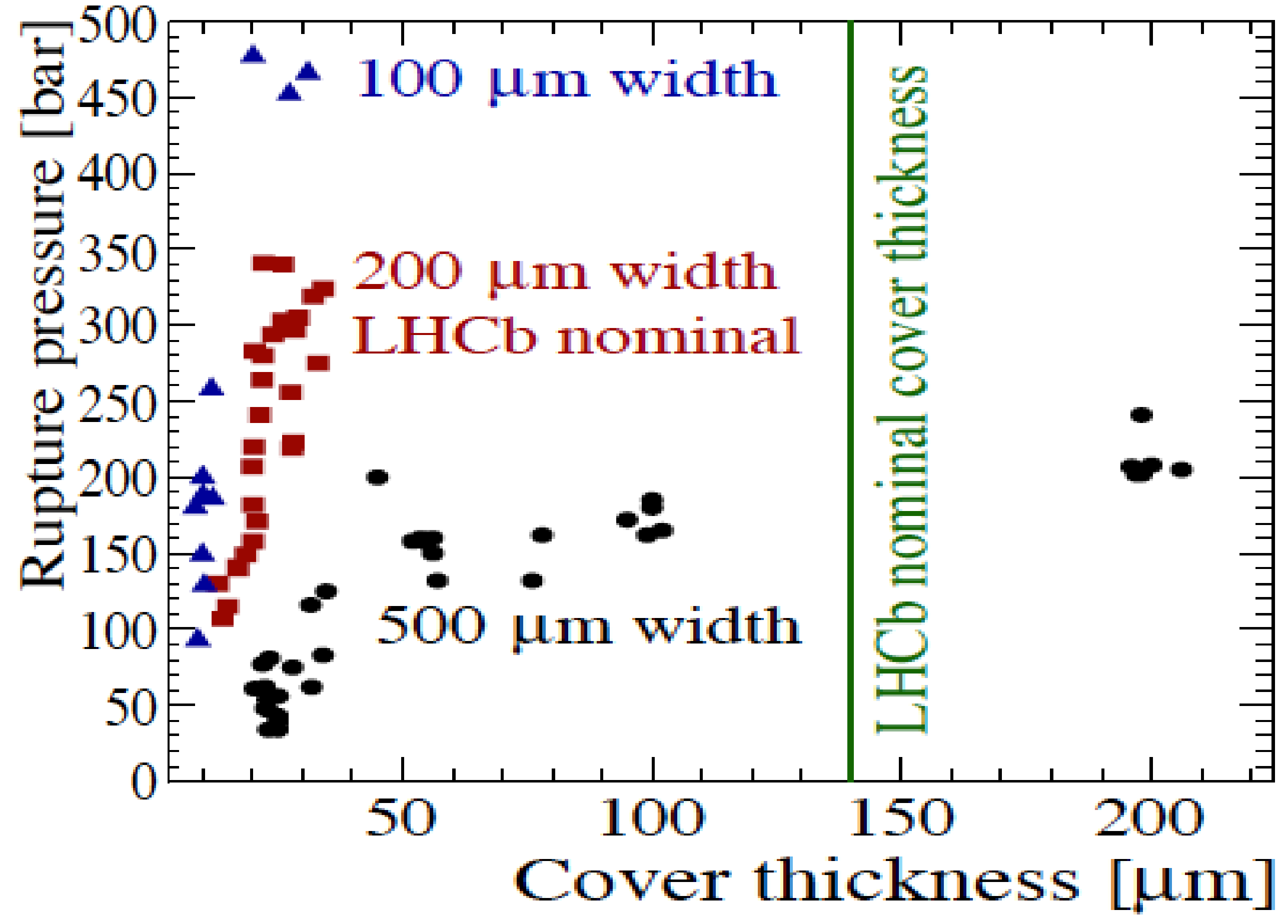
Background slide from: J. Buytaert, *PIXEL 2012*

Worried about high pressure?

Static pressure resistance tests

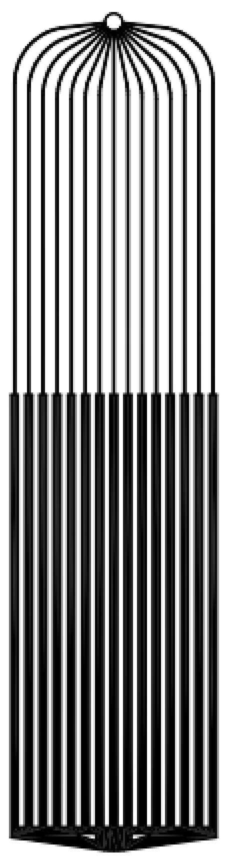
Single channel

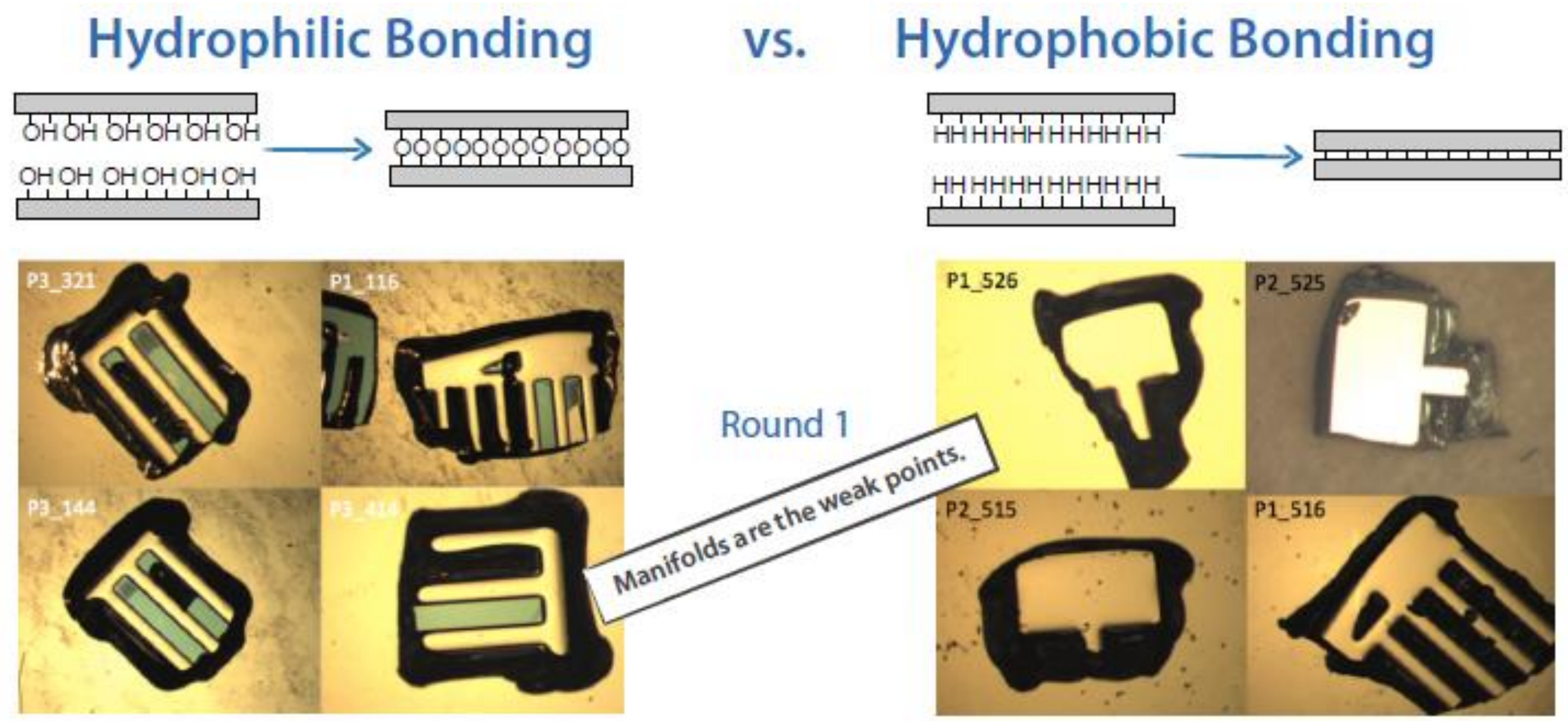




Multi channel + manifold

cover thickness 140 µm





Delamination + Si Rupture @ ~400 bars

No Delamination holds 700 bars

So far so good, but…

Although the technical progress has been satisfactory and relatively fast, a number of **open issues** need further development and deeper understanding before this technology can be declared “mature” for wide application.

A **non-exhaustive** list of important open issues includes:

Open issue #1: alternatives μ-fab approaches

Open issue #2: suited hydraulic μ-connections

Open issue #3: hydraulic interconnections

Open issue #4: tools for evaporative μ-fluidic design

AIDA-2020 WP9: a new Network

AIDA 2020

NA8 (WP9) Objectives
(from proposal's Annex1, Part A)

Task 9.1 Scientific coordination (CERN, UOXF)

- Coordinate and schedule the execution of the WP tasks
- Monitor the work progress (milestone and deliverable reports), follow-up on the WP budget and the use of resources
- Organise WP meetings

Task 9.2 Micro-channel cooling building blocks (CERN, CNRS-LPNHE, CSIC-IFIC)

- Provide access to the silicon fabrication technologies
- Development of a simulation library for micro-fluidics and bi-phase flows in distributed μ-channels
- Development of a standard for the connection of the devices
- Fabrication of prototypes to validate the models and characterise the different fabrication techniques
- Setup a specialised facility to implement the procedures and protocols established for characterisation and validation of models and fabrication techniques

Task 9.3 Low mass mechanical structures (CSIC-IFIC, UOXF)

- Setup a distributed facility to characterise advanced low-mass support structures in terms of both mechanical and thermal performance
- Define standards for characterisation and qualification of test structures
- Build test structures with and without integrated cooling systems
- Provide a library for FEA simulation models and validate them with measurements on test structures

WP9 meeting 4 June 2015 | WP9 in AIDA-2020 P. Petagna & G. Viehhauser | 5

AIDA-2020 WP9: a new Network

Task 9.2: detailed programme

- **Production of prototypes (D9.2, D9.3)**

Produce prototypes of devices with different fabrication techniques of the micro-channels as well as different channel distributions. Prototypes will be produced with increasing complexity: channels for pressure tests, channels plus heaters for thermal performance, mechanical devices to be used in system tests in Task 9.3. Vary the channel layout as a result of feedback from simulations and tests.

- **Develop a standard for the connectors (M77)**

Connecting the micro-channels with the services outside is a difficult technological challenge and the type of connection will depend on whether this is done orthogonal to the channel, on the device surface, or along the direction of the channel on the device edge. The connection should be able to withstand high pressures as required for CO_2 two-phase cooling.

- **Simulation models for μ-fluidics and two-phase flows in μ-channels (M24, M82)**

Develop simulation libraries based on computational fluid dynamics (CFD) of mono-phase as well as bi-phase flows in distributed micro-channels. The simulation models will be validated with measurements on produced devices so that they can be used to provide the basis for the optimal layout of the channels on the devices.

- **Develop a test setup to characterise the devices (D9.1, D9.4)**

Set up a measurement station where the devices can be reliably measured and characterised. Provide the procedures to validate the simulation models. The system will be focused on CO_2 two-phase cooling but should also provide means to characterise mono-phase cooling.

AIDA-2020 WP9: a new Network

WP9 T9.2 Beneficiaries (and friends...)

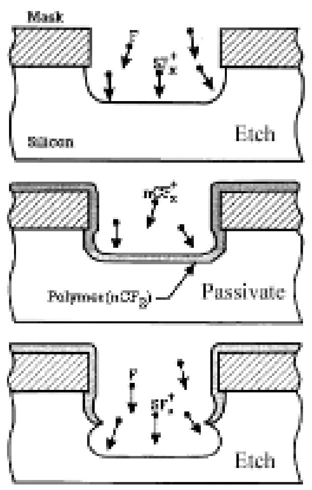
- **CERN**
  - INFN-Milano (INFN beneficiary in WP 4, 6, 7, 13, 14, 15)
  - UNIMAN (beneficiary in WP 3, 7)
  - University of Twente (external collaborator)
- **CNRS-LPNHE**
  - FBK (beneficiary in WP 7)
  - University of Goettingen (external collaborator)
  - CNRS-LAL Orsay (CNRS beneficiary in WP 1, 2, 3, 4, 6, 8, 9, 13, 14)
  - MPG-MPP Munich (MPG-MPP beneficiary in WP 4, 7, 13, 14)
  - INFN-Pisa (INFN beneficiary in WP 4, 6, 7, 13, 14, 15)
  - University of Padova (external collaborator)
- **CSIC-IFIC**
  - MPG-HLL Munich (external collaborator)
  - UBONN (beneficiary in WP 4, 6)

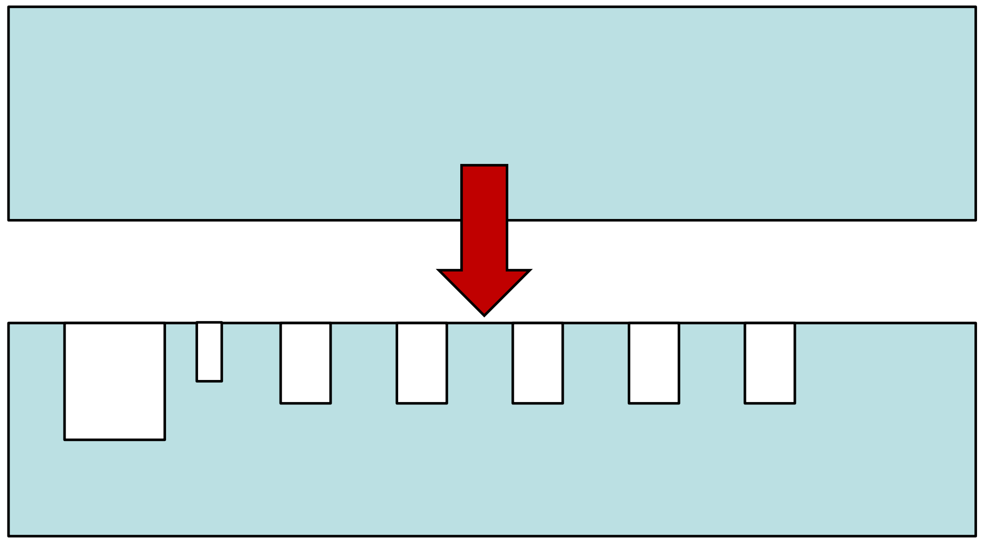
WP9 Summary 5 June 2015 | WP9 in AIDA-2020 P. Petagna on behalf of WP9 | 4

Tasks for the AIDA-2020 WP9 Network

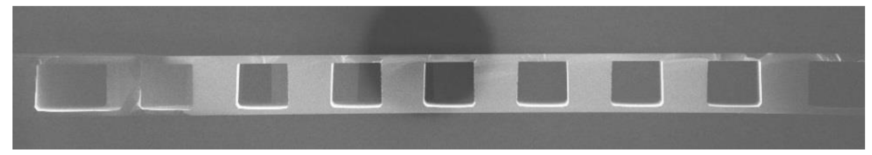
Open issue #1: which μ-fab approach?

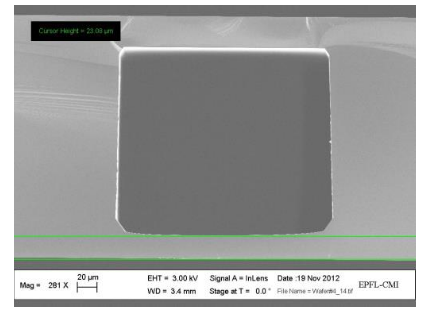
A)





1. DRIE etch circuits in 1st wafer
2. Bond 2nd wafer (cap)
3. Thinning, metal deposition, etc.

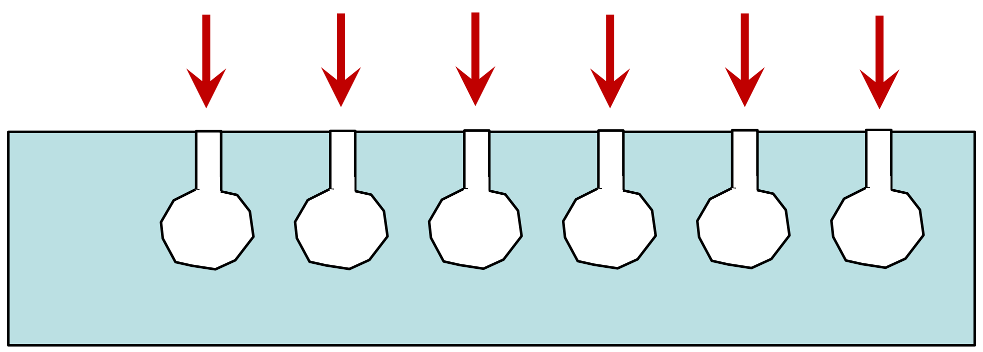




Used and tested @ CERN-EPFL, LETI, CSEM, IceMOS

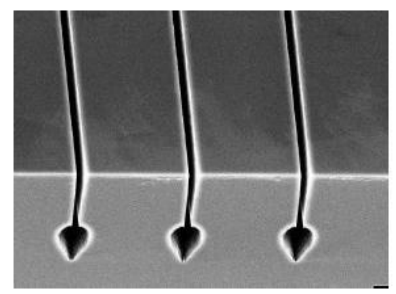
+ Maximum freedom for channel geometry (e.g. X-section variations…)
+ Maximum control of channel shape end surface quality (including post-fab measurements)
– Bonding quality critical for reliability (IR imaging resolution not enough to check)
– Direct Si bonding requires very high T annealing (other techniques? Reliability?)

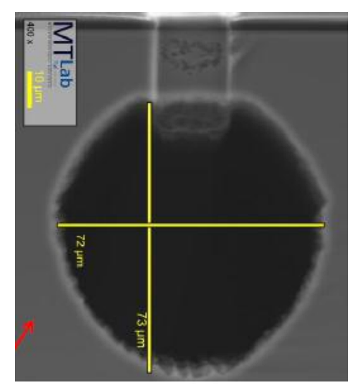
B)



Tested in 2009-2010 by FBK-INFN Pisa

1. DRIE etch trenches
2. Isotropic etch of circuits
3. SiO_2 deposit to close trenches
4. Thinning, metal deposition, etc.





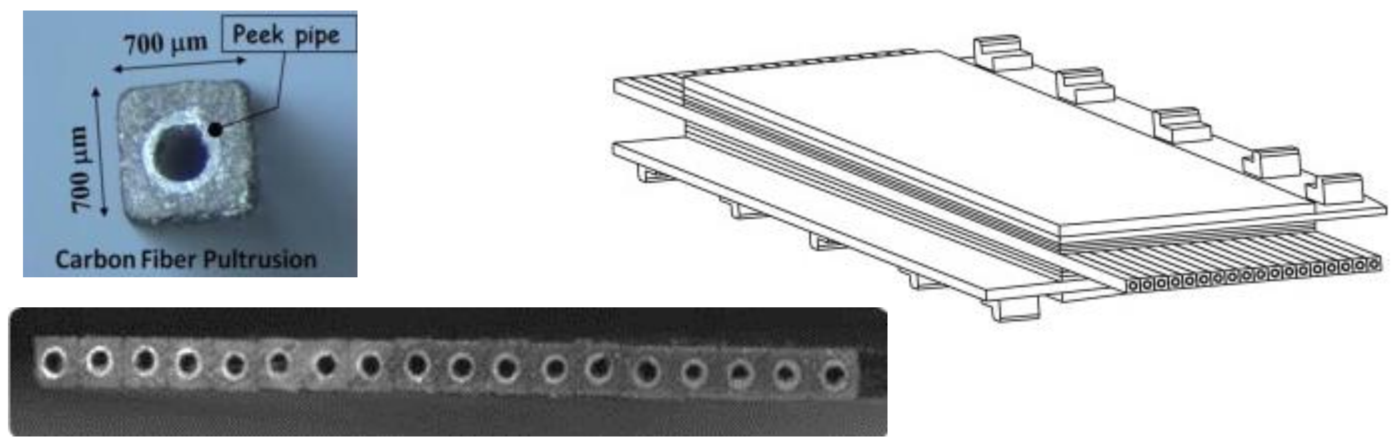
+ No wafer bonding required, channels closed by SiO_2 deposition
+ Process compatible with pre-processed wafers (metal, implants, components…)
– Difficult to introduce X-section variations (manifolds, orifices, “capillaries”, etc.)
– Poor control of channel shape and surface quality (destructive monitoring needed)

Tasks for the AIDA-2020 WP9 Network

Open issue #1: which μ-fab approach?

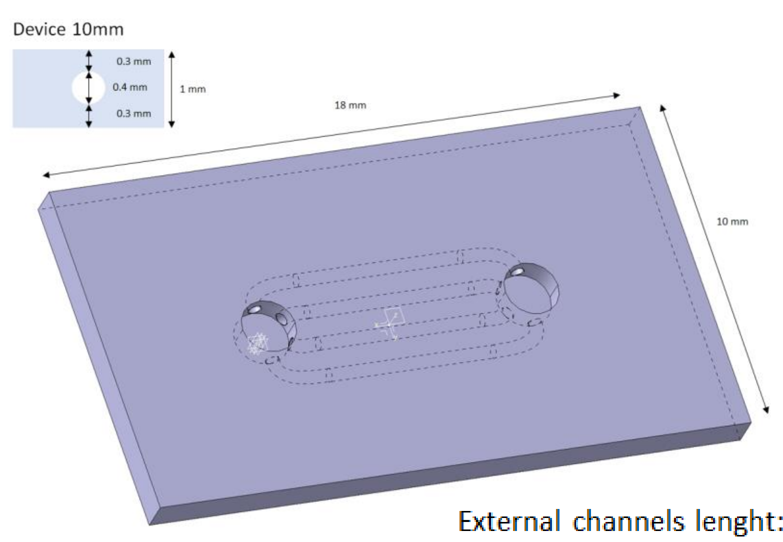
The choice of (monocristalline) Silicon as material for the micro-channel devices has a series of important advantages, but also limitations. The investigation on alternative materials and production techniques should not be abandoned. In particular targeting longer structures and reduced production costs.

An interesting example is the array of carbon fiber pultruded element developed by INFN Pisa in the context of the SuperB project.
Main advantage: long uninterrupted lines possible;
Main disadvantage: large surface of contact with CTE mismatch;
Secondary disadvantage: limited to simple geometrical design.

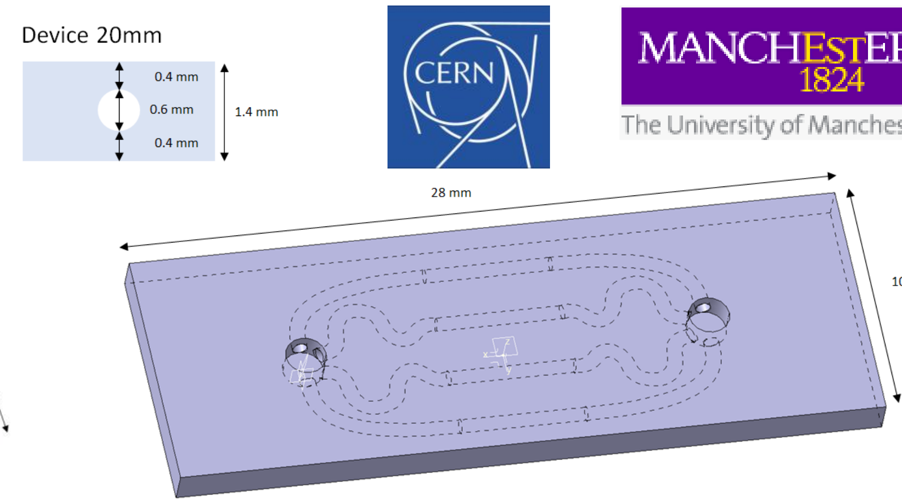


F.Bosi et al: *Light prototype support using micro-channel technology as high efficiency system for silicon pixel detector cooling*,
NIM A, Volume 650, Issue 1, 11 September 2011, Pages 213–217

Promising development might come from the appearance on the market of ceramic-based Additive Manufacturing (3D printing) processes.
Main advantage: complete freedom in geometrical design coupled to large dimensions;
Today disadvantages: limited precision, limited minimum dimensional features, CTE mismatch (with Al2O3: would disappear with AlN…!!)



External channels lenght: 10.364 mm
Internal channels lenght: 8.26 mm
Straight part lenght: 5mm
Distance between holes: 8 mm
Inlet holes diameter: 1.6 mm



Channels lenght: 20.52 mm
Straight part lenght: 5mm
Distance between holes: 16 mm
Inlet holes diameter: 1.6 mm

Technology demonstrator design prepared by G. Romagnoli.
Pre-production (evaluation) procurement launched.
Waiting for first devices for basic test to arrive soon.

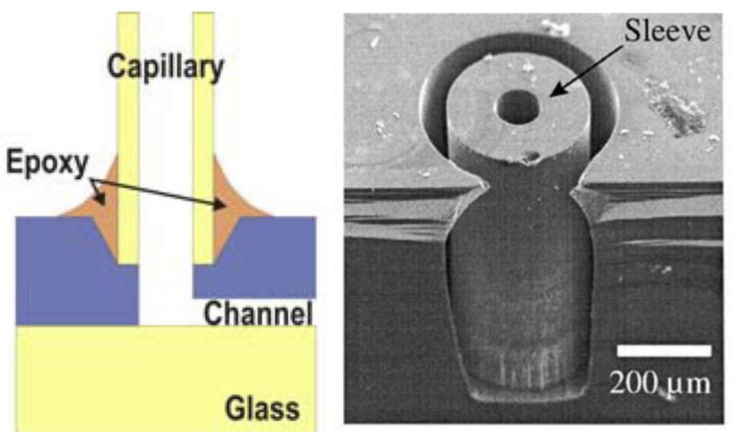
Tasks for the AIDA-2020 WP9 Network

Open issue #2: suited hydraulic μ-connections

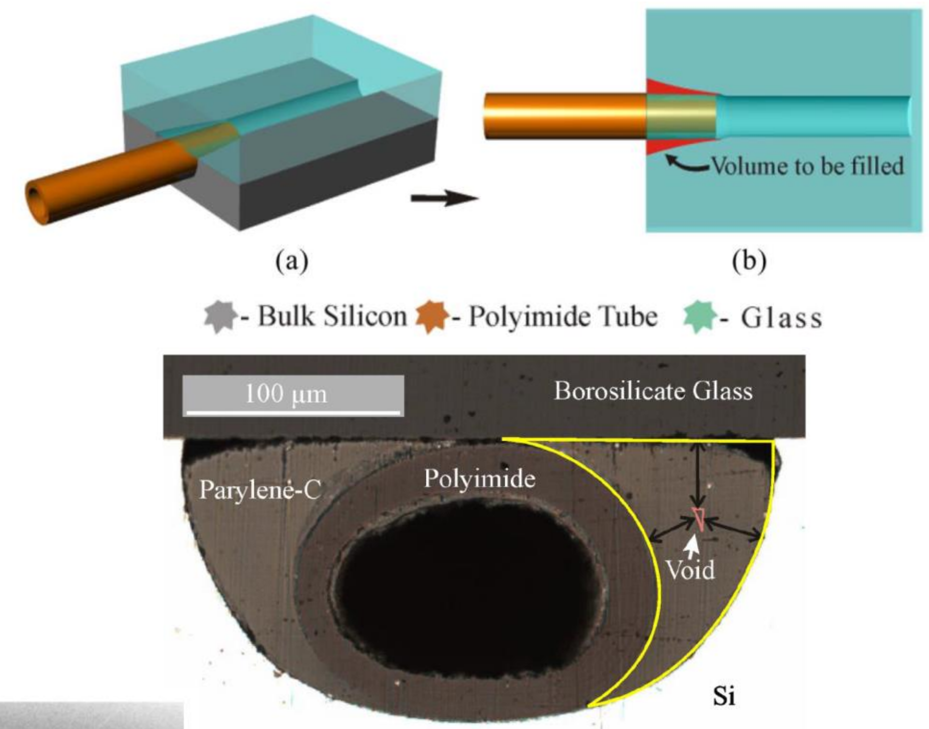
«One of the most common practical challenges encountered when working with microfluidic systems is the realization of a robust interface between the device and the outside world»

[Van Swaay, D., Mächler, J. P., Stanley, C., deMello, A. (**2014**). A chip-to-world connector with a built-in reservoir for simple small-volume sample injection. Lab on a Chip, 14, 178-181.]

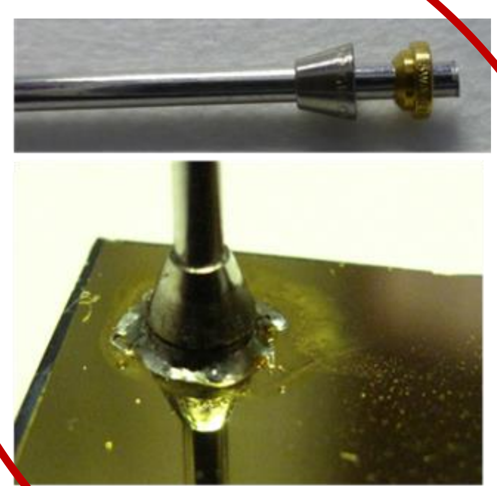
Commercial (PEEK + epoxy glue))



Adhesive

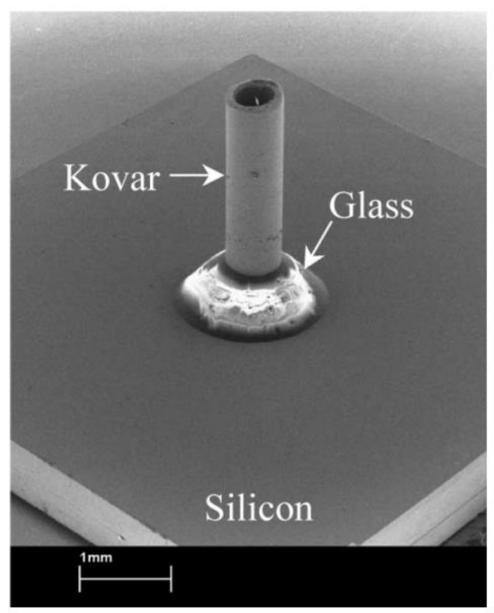


Adhesive

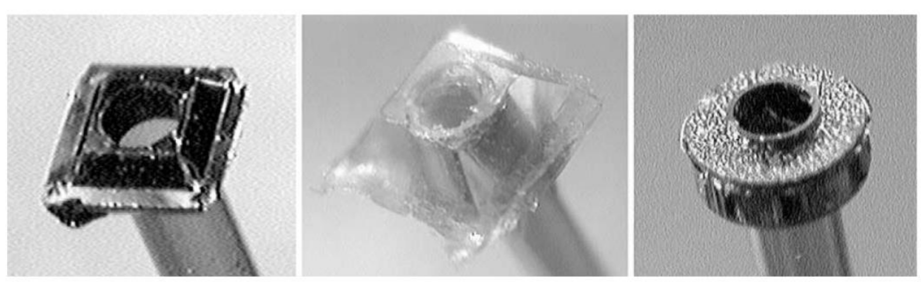


Solder-based

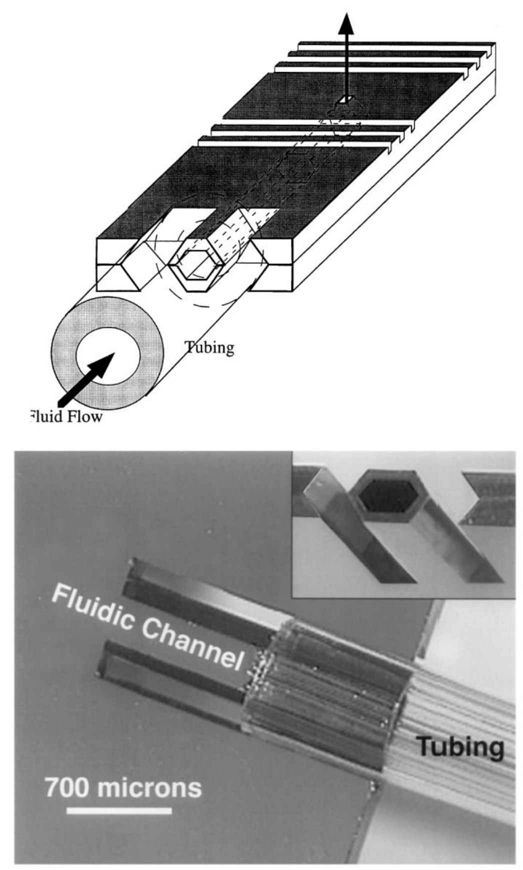
Successfully in use at CERN for rapid prototyping



Fused glass



Microfabricated

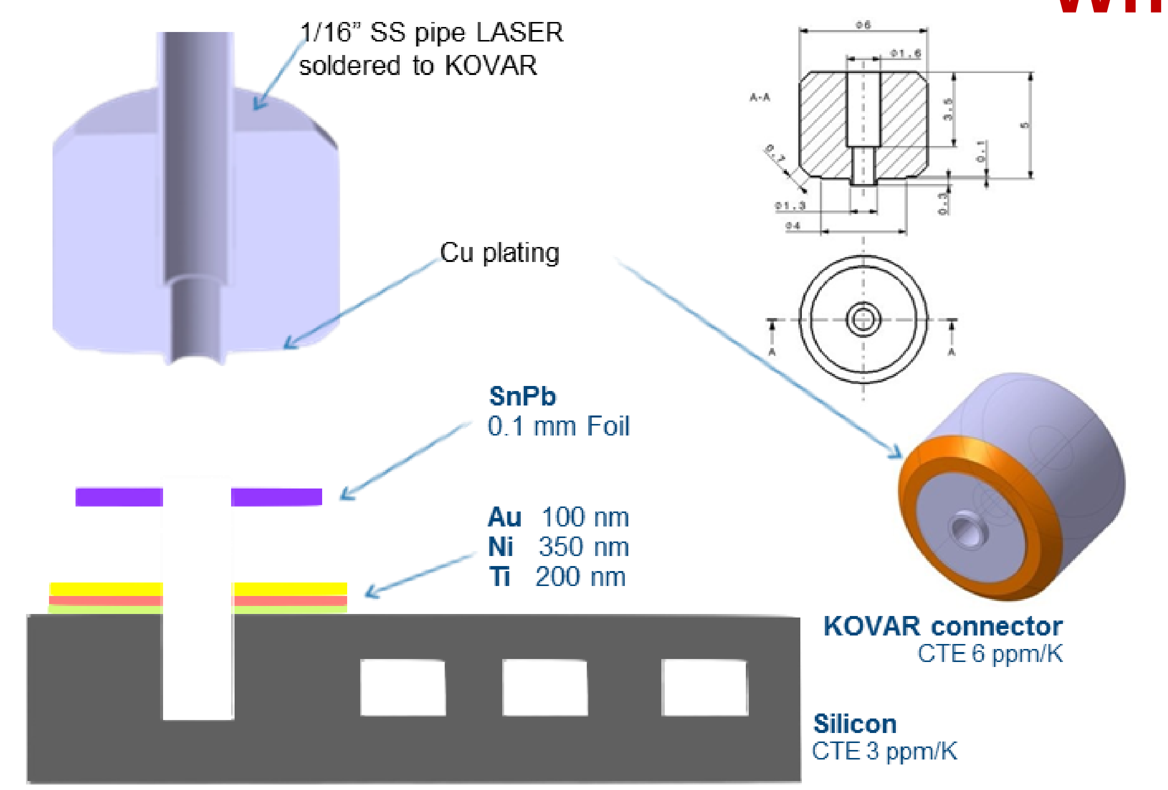


Microfabricated

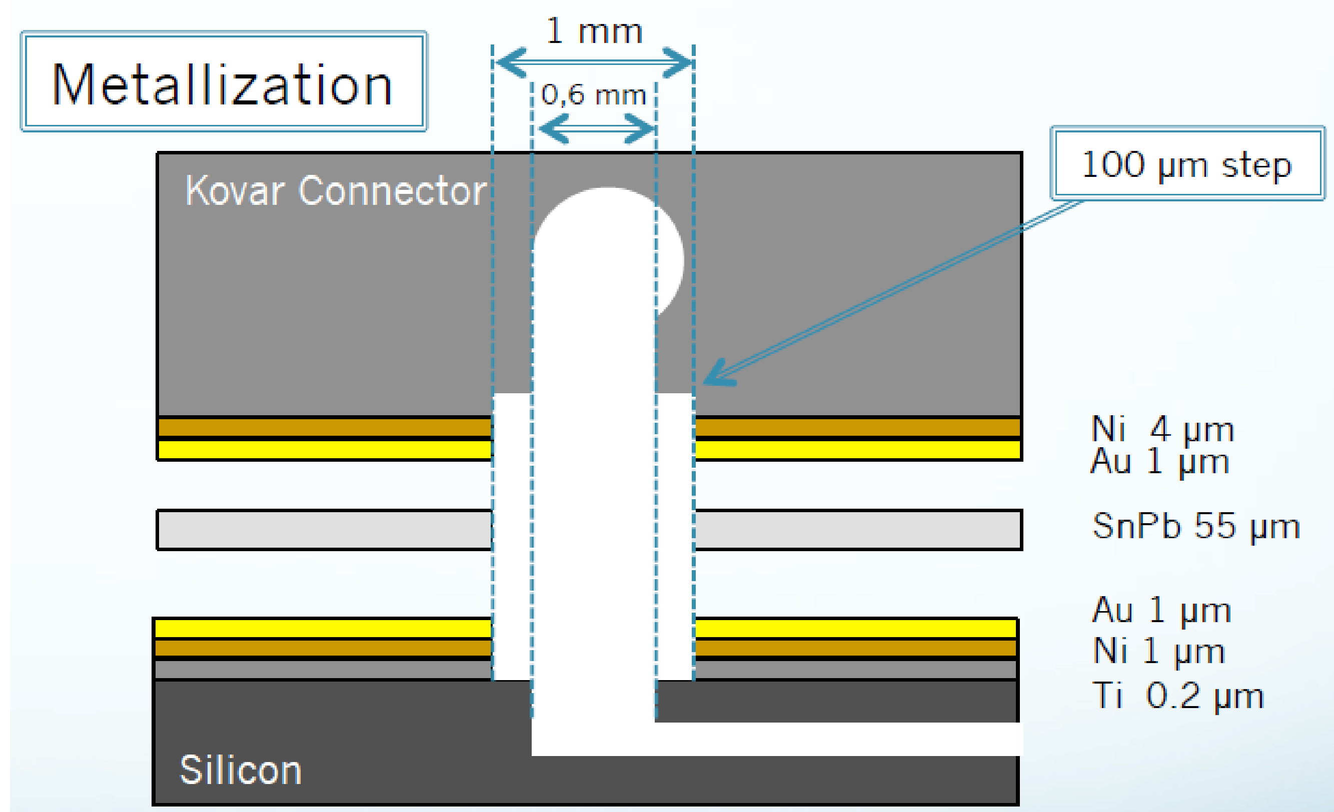
Tasks for the AIDA-2020 WP9 Network

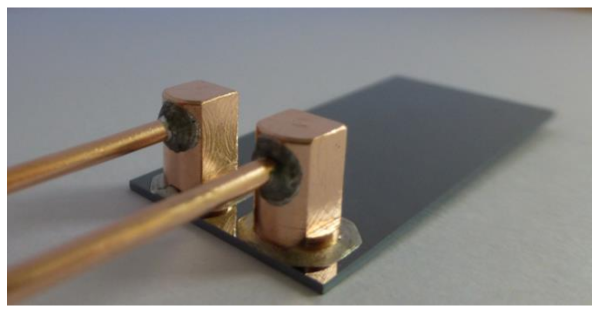
Open issue #2: suited hydraulic μ-connections

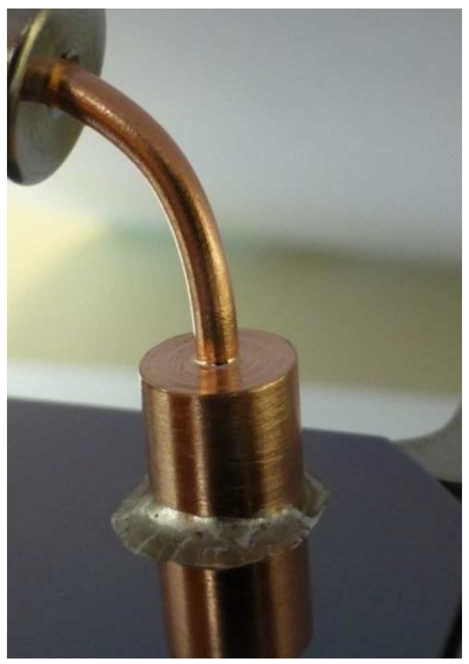
Where do we stand @ CERN?

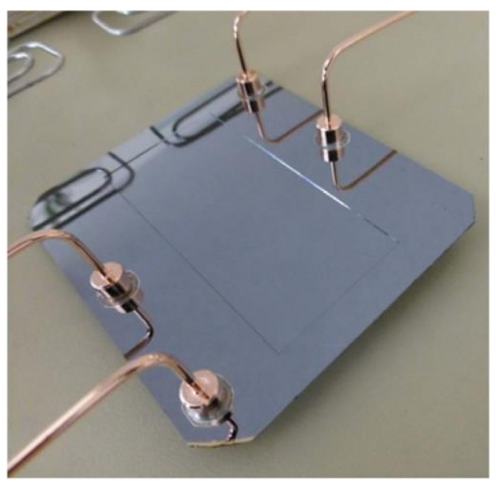


✔ *Static pressure tested up to 700 bar (pump limit)*
Pressure and temperature cycle testes (0 to 200 bar / -40 to +40 ºC)



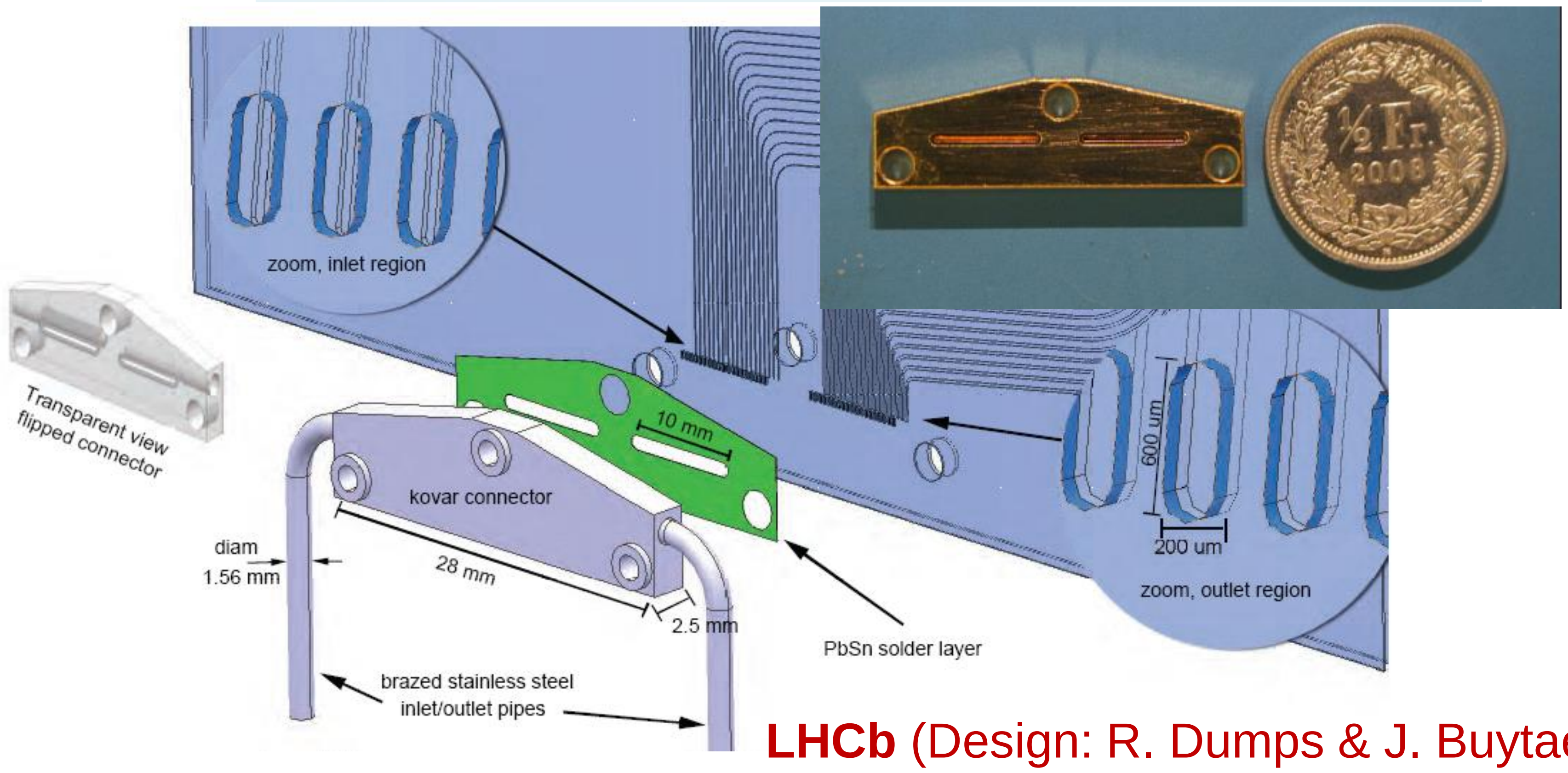






Before soldering After soldering

NA62 (Design: J. Degrange, A. Mapelli, J. Noel, G. Romagnoli)

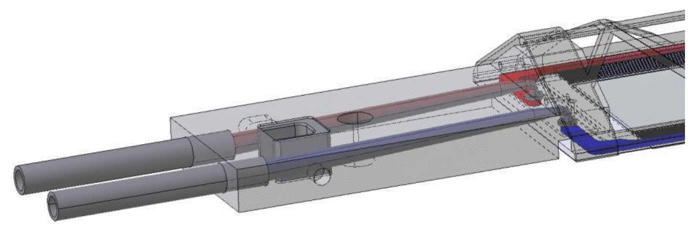


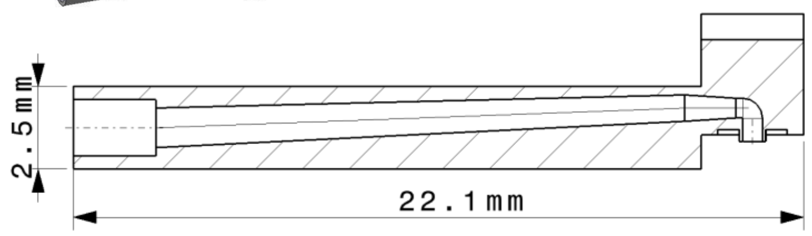
LHCb (Design: R. Dumps & J. Buytaert)

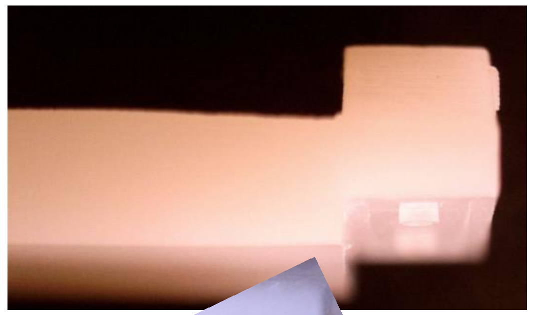
Tasks for the AIDA-2020 WP9 Network

Open issue #2: suited hydraulic μ-connections

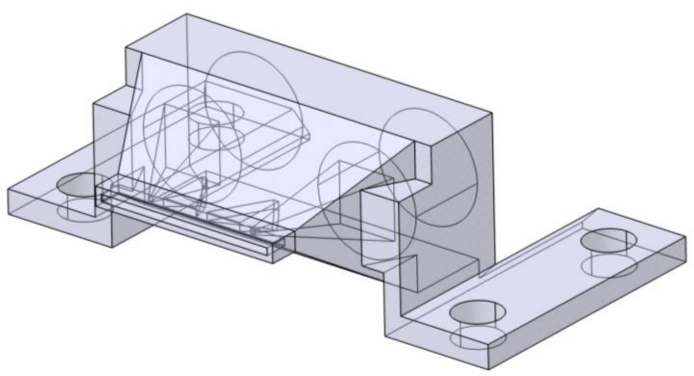
3D-printed μ-connectors under development

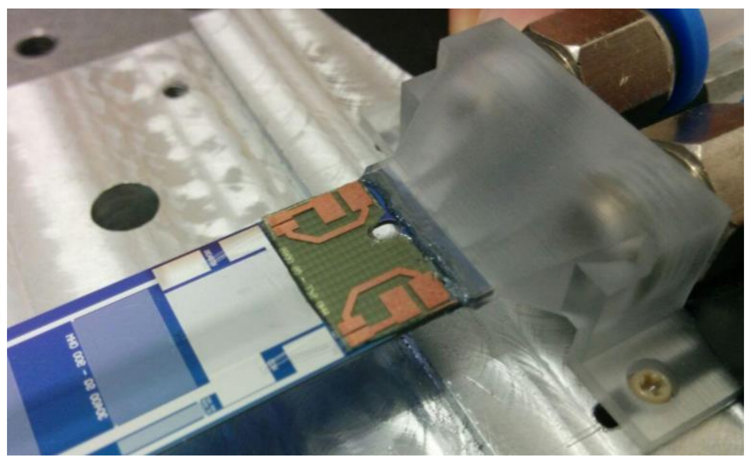




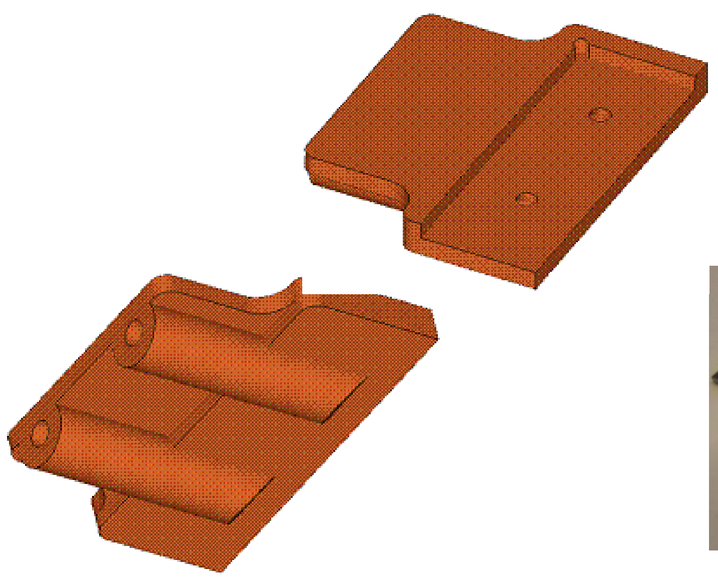


Connector compatible with ALICE ITS design. Realized by Stereolithography in 3D System “Accura 25” resin.
Integration by epoxy gluing.
Design: A. Francescon, C. Gargiulo, A. Mapelli, A. Toros





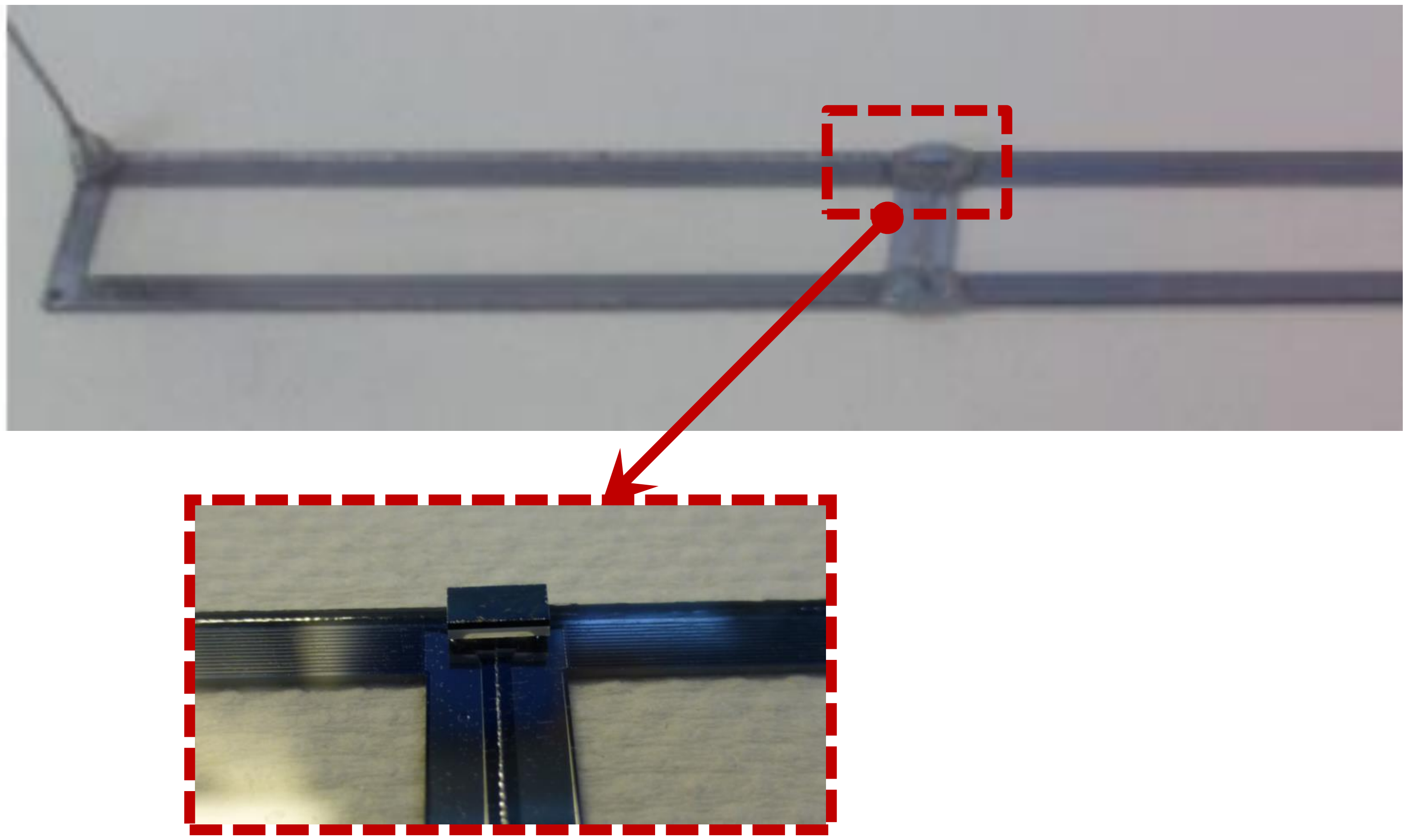
Connector compatible with DEPFET-based pixel detector. Realized by Stereolithography.
Integration: epoxy gluing.
See Wednesday’s talk by Ignacio Garcia for details on integrated all-silicon ladder + connector



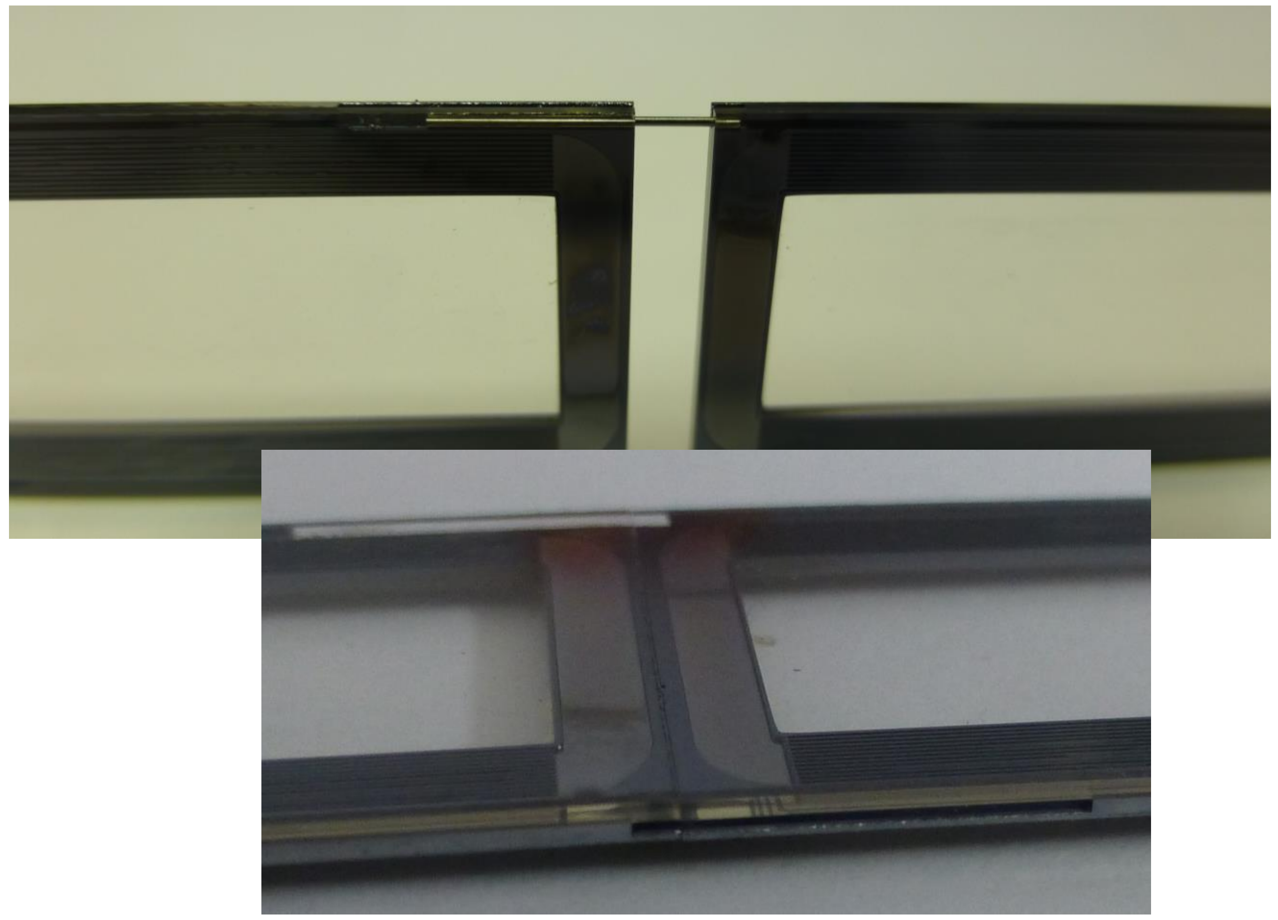
Connector compatible with the CERN-Manchester FE-I4 chip cooling test device design. To be realized by CERAMIC Stereolithography in Al_2O_3.
Integration: brazing on Silicon (planned).
Design: G. Romagnoli

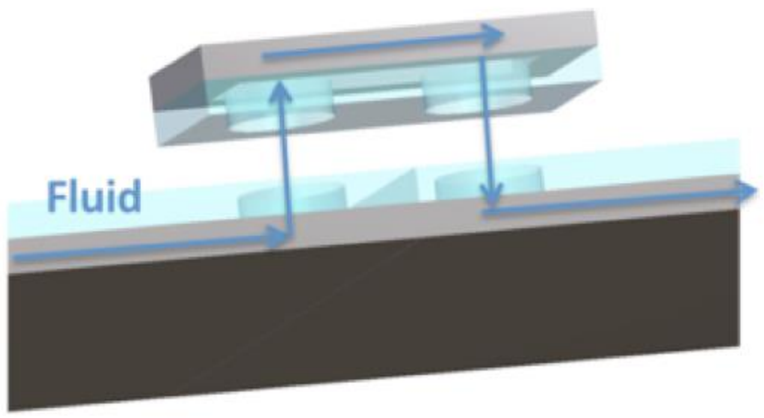
Tasks for the AIDA-2020 WP9 Network

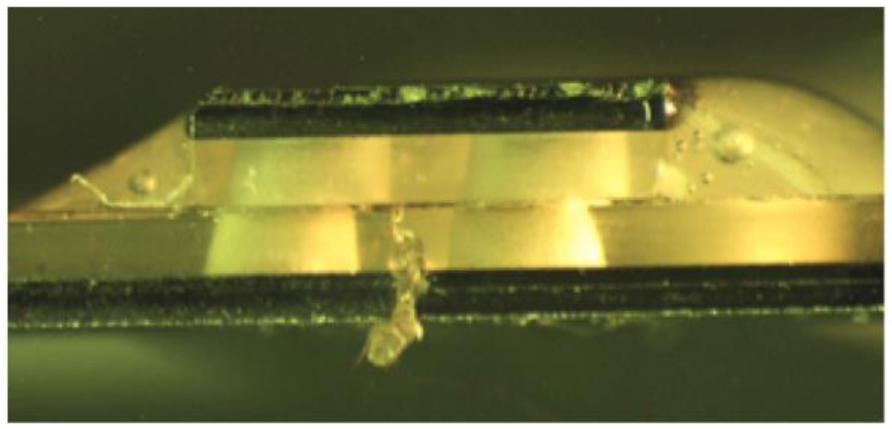
Open issue #3: hydraulic interconnections



Also tried…



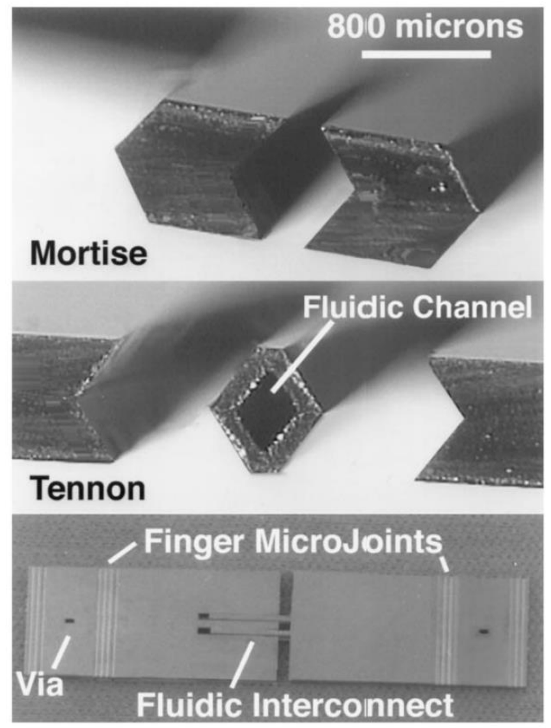




“Bridge” interconnection

Successfully implemented for ALICE ITS stave tests @CERN

Design: A. Francescon, A. Mapelli, J. Noel



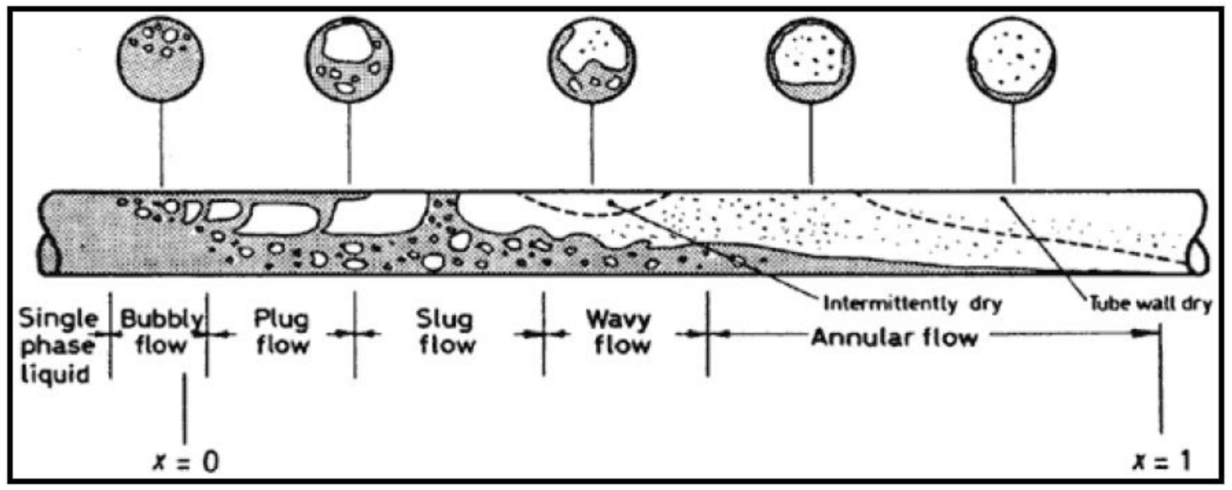
González, C., Collins, S. D., & Smith, R. L. (1998). *Fluidic interconnects for modular assembly of chemical microsystems*. Sensors and Actuators B, 49, 40-45

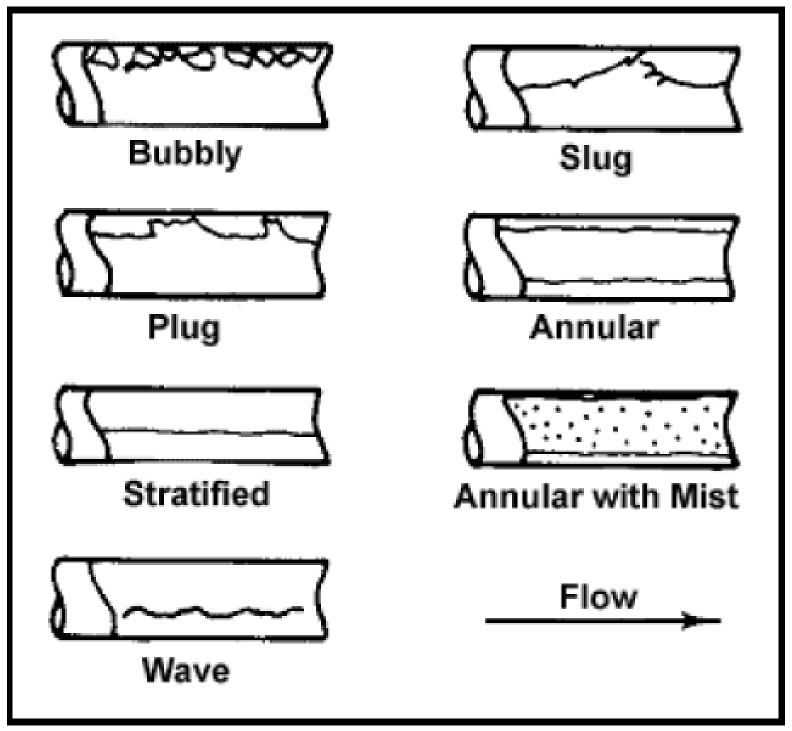
Tasks for the AIDA-2020 WP9 Network

Open issue #4: tools for evaporative μ-fluidic design

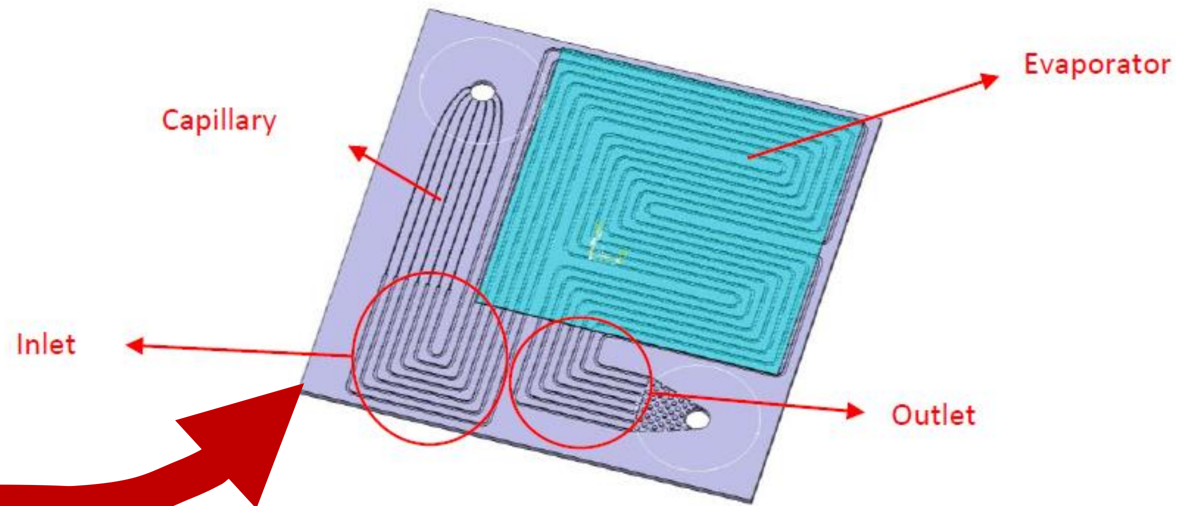
The preliminary simulation model developed until now for CO_2 is suited for horizontal evaporators with equivalent diameter down to 1.4 mm: **Efforts are required reliably to extend it to vertical evaporators and μ-channel devices.**

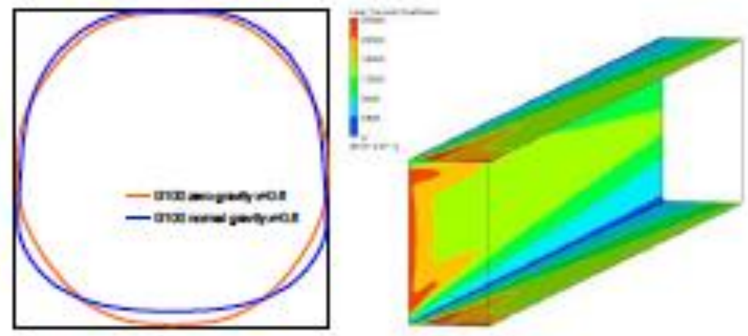
Horizontal pipe





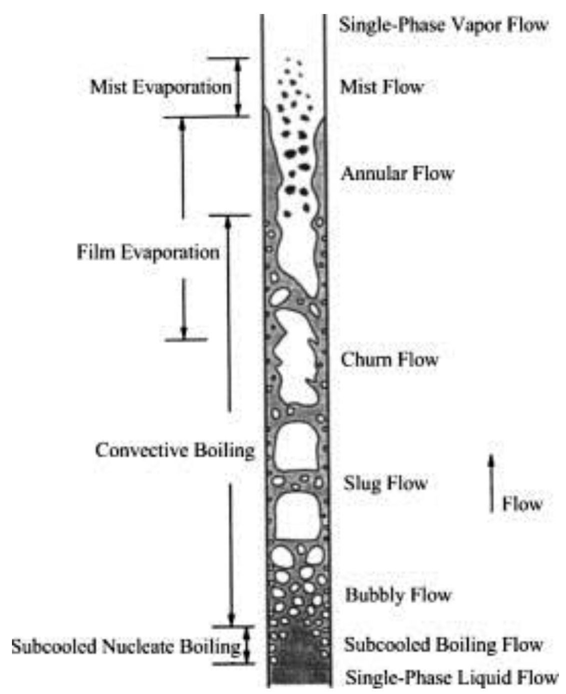
μ-channel device

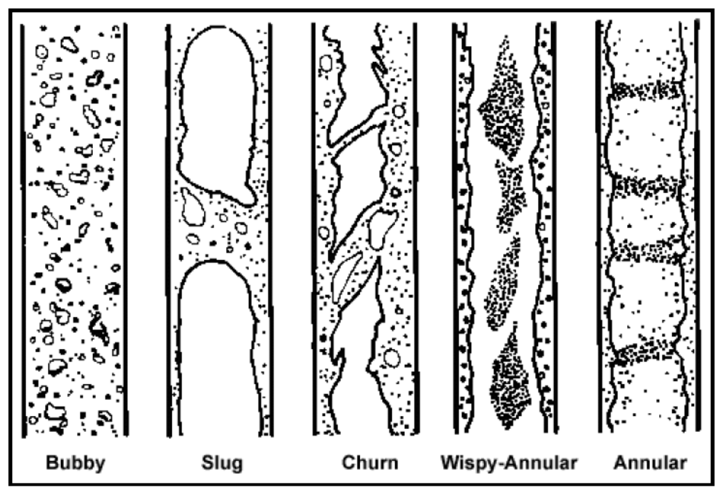


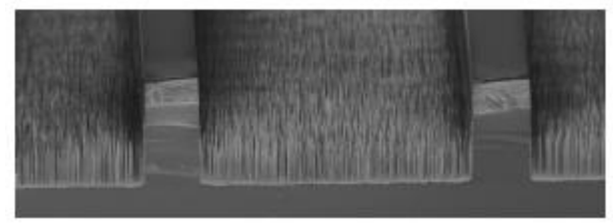


Nucleation and bubble departure models

Vertical channel







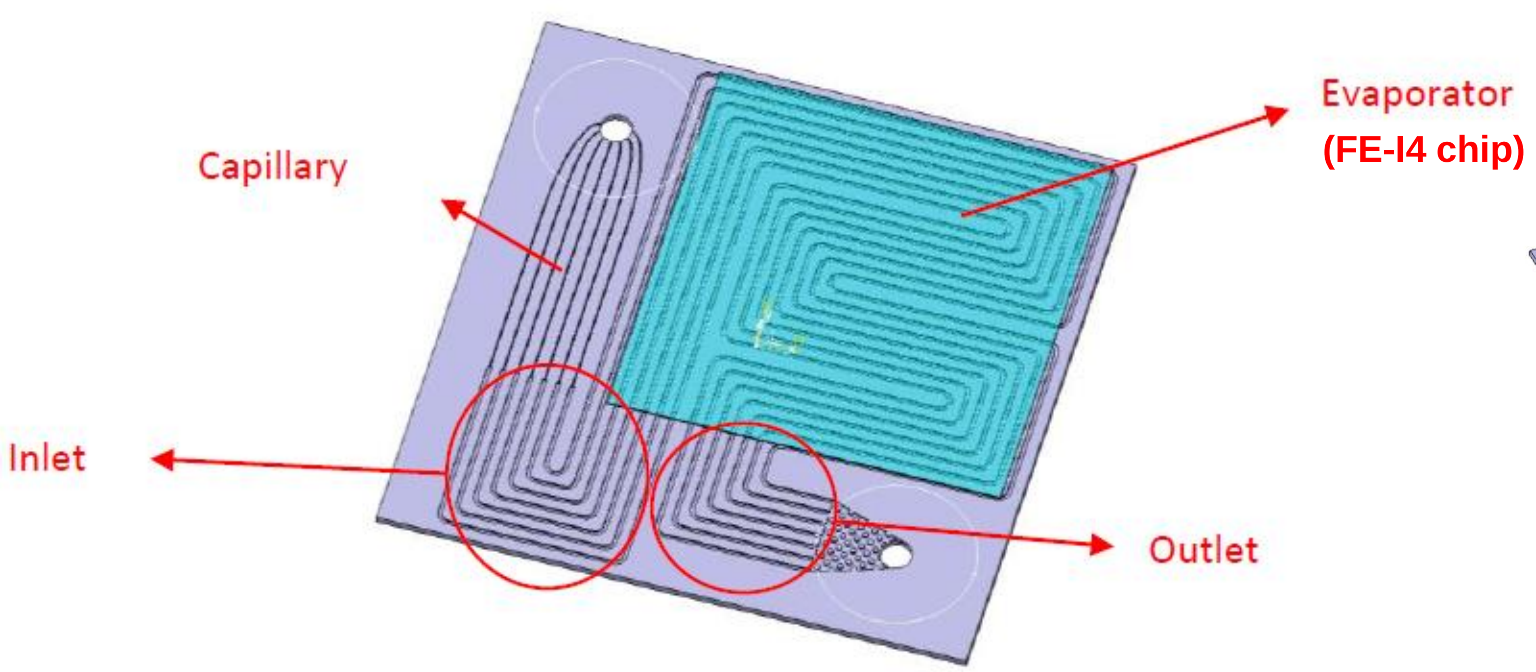
Effect of wall surface

LPNHE Paris · Università degli Studi di Padova · CERN · Manchester 1824 The University of Manchester · University of Twente The Netherlands

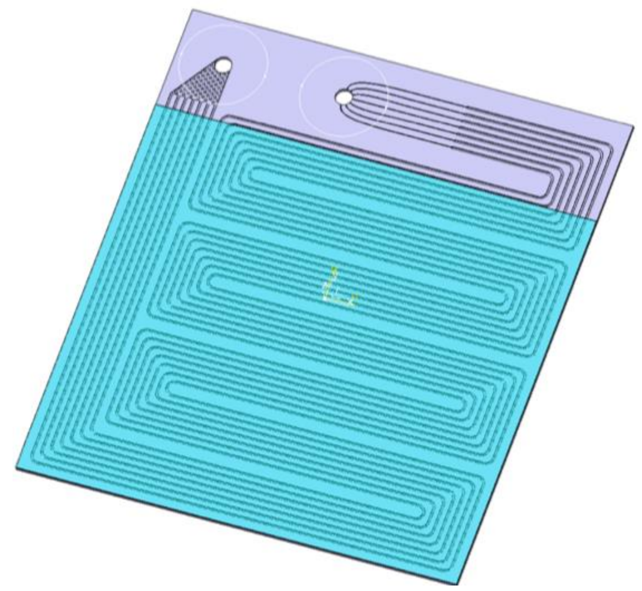
Tasks for the AIDA-2020 WP9 Network

Open issue #4: tools for evaporative μ-fluidic design

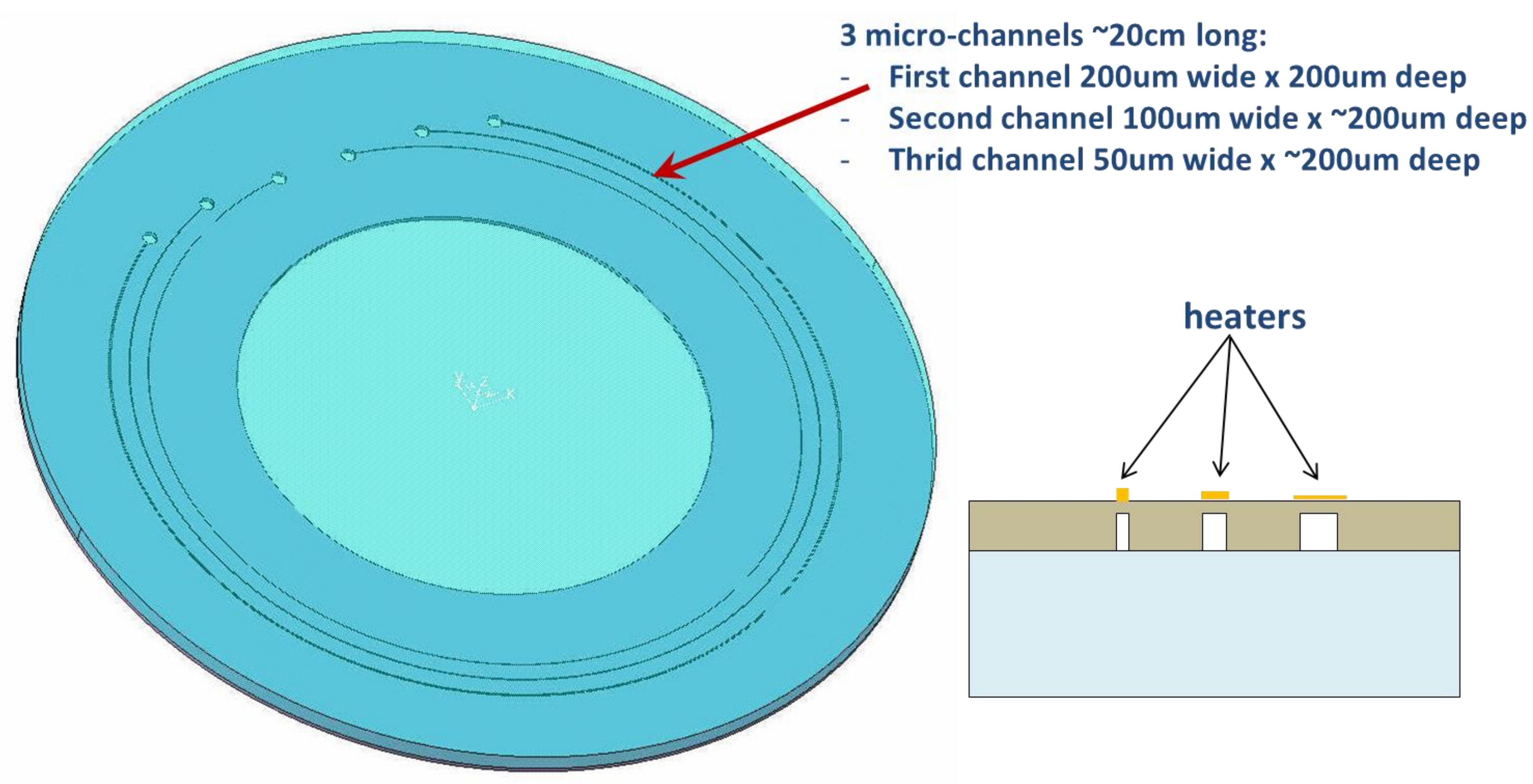
New μ-fabricated testing devices



(2-chip device)



(4-chip device)



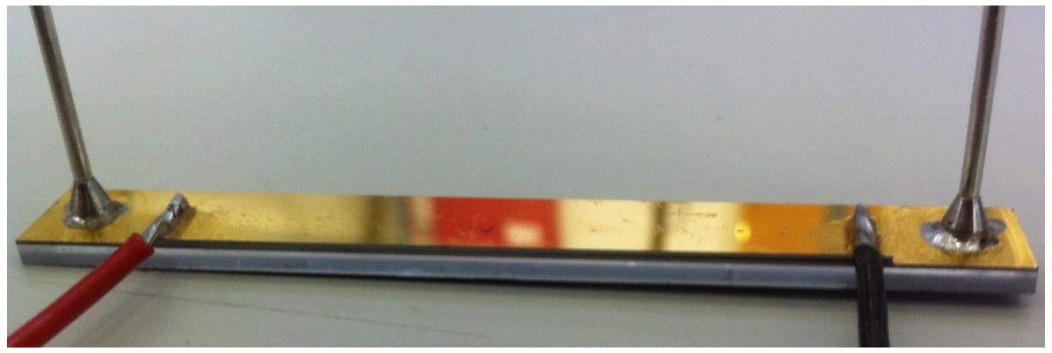
The common CERN-Paris-Padova (+ others?) "μ-channel donut" for measurements/evaluation of CO_2 heat transfer and 2-phase flow properties in μ-channels and model benchmarking (in production)

CERN LPNHE Paris Università degli Studi di Padova

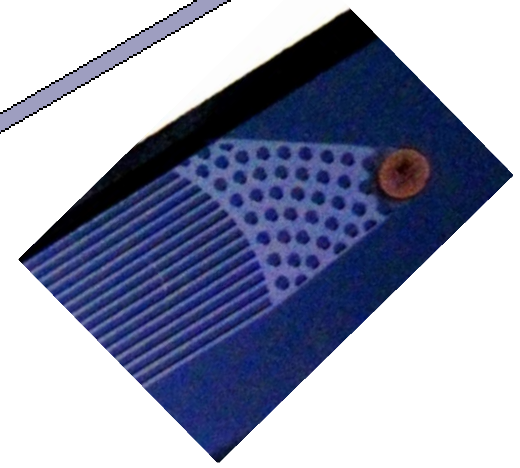
Tasks for the AIDA-2020 WP9 Network

Open issue #4: tools for evaporative μ-fluidic design

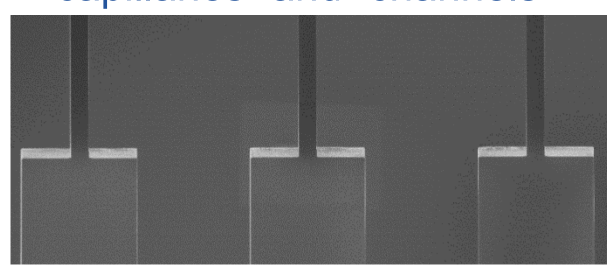
New μ-fabricated testing devices



Pillars in the outlet
to maximize the bonded surface

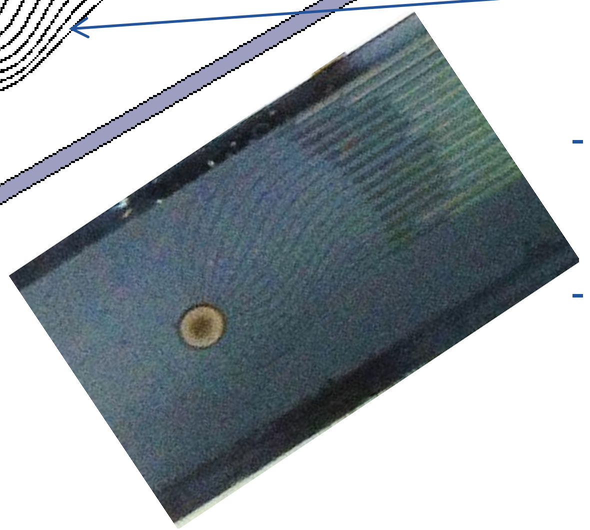


Detail of the transition between "capillaries" and "channels"



2 holes for fluidic inlet and outlet
(1.6 mm diameter)

«Capillaries»
(20 μm wide x 200 μm deep, 7 mm long)
To bring CO_2 in saturation conditions at the channel entrance



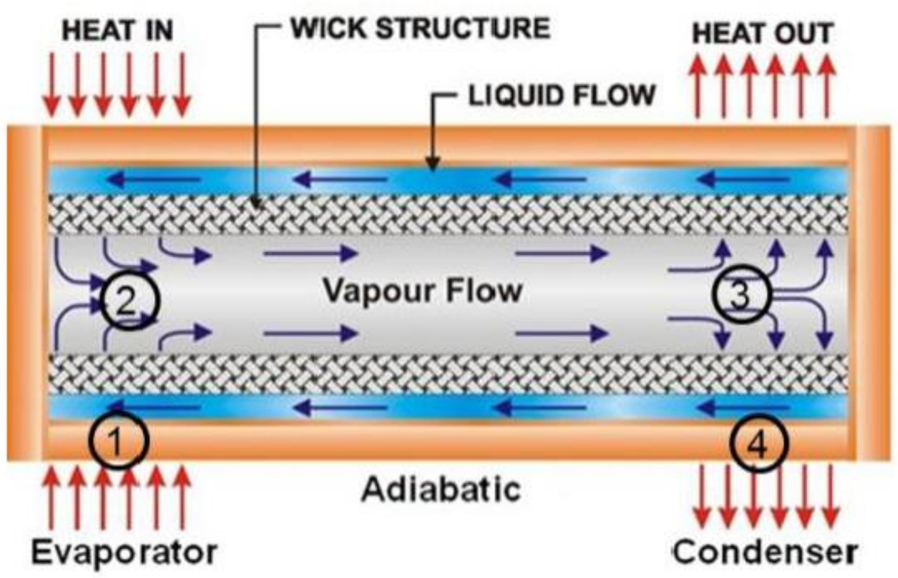
- Restrictions take advantage of the high pressure budget available for CO_2 to induce a strong pressure drop and to distribute liquid at the inlet but start evaporating under the heat source
- Restrictions are needed to avoid vapour bubble back-flow, inducing high instability in flow and thermal conditions

Device design and fabrication: CERN

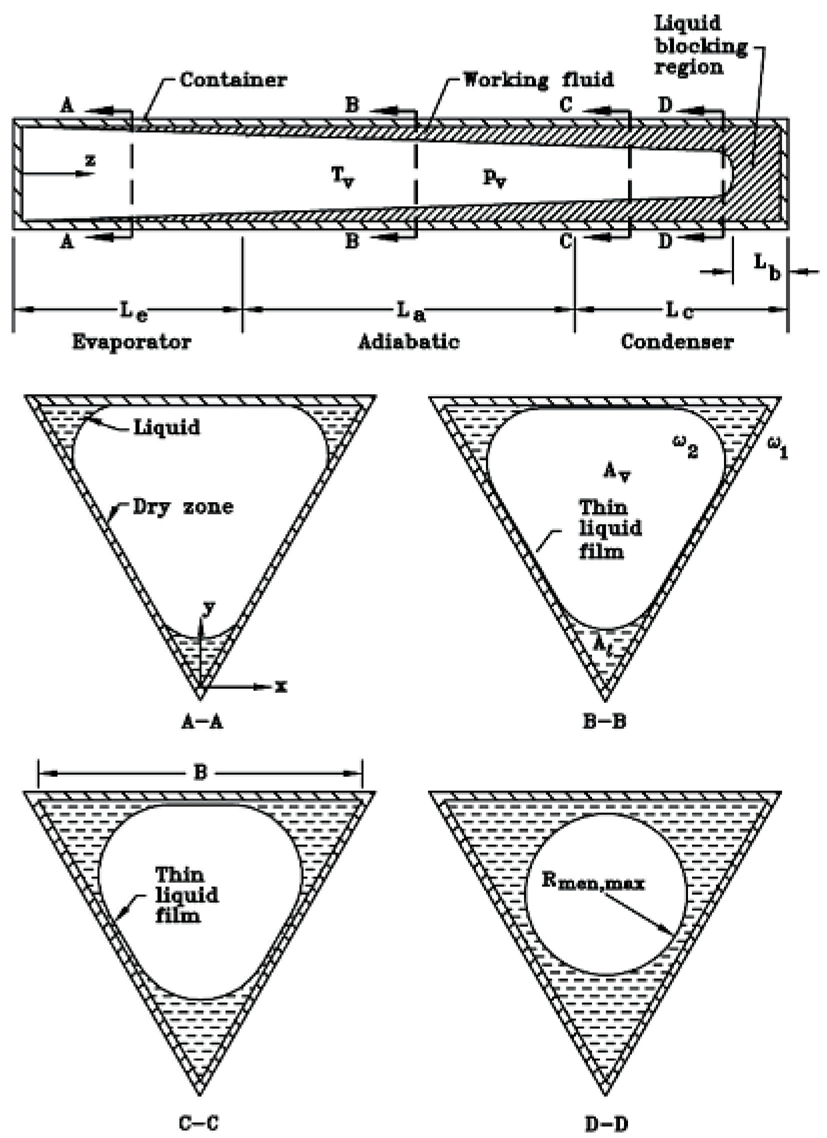
Sequence of testing: University of Twente The Netherlands; MANCHESTER 1824 The University of Manchester; CERN

An "aggressive" R&D line for future

μ-heat pipes devices for "stand-alone" thermal management



General scheme of a heat pipe



Example of μ-heat pipes

Silicon μ-heat pipes have been fist proposed for thermal management of integrated electronic circuits back in 1984, then basically discarded. From the early 2000's new studies are being presented (mainly in USA) under the increasing pressure of thermal limitations on advanced micro-electronic devices, and favoured by the great development (and "democratization") of micro-fabrication techniques brought by the development of the MEMS market.

Although, the working principle is perfectly known, the community is still far away from a clear understanding of the "design and dimensioning rules". Furthermore the integration of these devices in an industrial product is not simple and "standard" small size metallic heat pipes are still largely convenient from an economical point of view. Some interest (from NASA) is being shown for possible space applications.

One clear problem for application in Vertex detectors is the need for an external heat sink to condense the evaporated fluid: this can be achieved coupling the evaporating device with an external forced air convection scheme, but requires **additional space** in the device geometry **for the "radiator"**. This is difficult in a detector if the device is linked to the planar geometry of a Silicon wafer. However **additive manufacturing** might enable the creation of devices with **small "3D wings" attainable by the air flow** for effective heat exchange within the stringent geometrical and mass constraint of a future vertex detector.

The advantages would be clear: "stand-alone" thermal management, no piping, no connectors, no cooling plant, no maintenance.
IS IT FEASIBLE? I honestly don't know, but you must admit that the (long-term) perspective sounds exciting…

Conclusions

- μ-cool technique is well suited for thermal management of high performance vertex detectors (innermost layers)
- Extremely low X/X_0 coupled to very high thermal efficiency and no CTE mismatch problems
- First operation in real detector: NA62 GTK (October 2014). Next: LHCb VELO upgrade (2018/2019)
- Flexible technique: single-phase and two-phase (evaporative) cooling possible
- Perfectly adapted to run with CO_2
- No single “universal” solution: configuration-dependent design
- Many technical issues still require careful investigation, in particular for barrel (stave) configurations
- The AIDA-2020 WP9 network has all the potential to provide a perfect environment for fast progress
- Is there space for a long-term “wild an aggressive dream” vision?